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Solid Rocket Motor Cost Model

Prepared by
ADVANCED VEHICLE SYSTEMS DIRECTORATE
Systems Planning Division

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Prepared for OFFICE OF MANNED SPACE FLIGHT
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D. C.

Contract No. NASw-2301

Systems Engineering Operations
THE AEROSPACE CORPORATION

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Prepared

Advanced Vehicle Systems Directorate
Systems Planning Division

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This report is based on preliminary investigations and is therefore of limited interest. The information presented herein is tentative and is subject to modification.

FOREWORD

This study was performed for NASA/OMSF as part of the FY 1972 effort under contract NASw-2301 and was intiated as a result of recommendations made by NASA/MSC for tasks under Study 2.3. The purpose of the study was to provide a solid rocket motor cost model based on the Space Transportation System (STS) cost methodology (Ref. 5). Configurations similar to those currently proposed for the shuttle cost model were examined.

Recognition is given to the excellent cooperation and assistance provided by the Aerojet Solid Propulsion Company, Lockheed Solid Propulsion Company, Rohr Corporation, Thiokol Chemical Company, and United Technology Center in the accomplishment of this task.

This report was prepared by the following members of The Aerospace Corporation Technical Staff:

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NOMENCLATURE

(XXXX)	Cost Element Number XXXX
ASPC	Aerojet Solid Propellant Company
C	Cost
C (XXXX)	Cost in Dollars Of Cost Element Number (XXXX)
CER	Cost Estimating Relationship
CPFH	New Fleet Hardware Propellant Cost Per Pound
CPTH	Test Hardware Propellant Cost Per Motor
CRF	Candidate Refurbishment Factors
CRFCI	Candidate Refurbishment Factor - SRM Case & Insulation
CRFN	Candidate Refurbishment Factor - SRM Nozzle
CRFO	Candidate Refurbishment Factor - SRM Other Subsystems
CRFR	Candidate Refurbishment Factor - Recovery System
CRFSS	Candidate Refurbishment Factor - Stage Structure
CRFTV	Candidate Refurbishment Factor - SRM Thrust Vector Control
CTFH	New Fleet Hardware Transportation Cost Per Motor
CTTH	Test Hardware Transportation Cost Per Motor
ED&D	Engineering, Design & Development
F	Fixed (Nozzle)
FREF	Refurbishment Factor
F (XXXX)	Complexity Factor
FTR	Rail Freight Cost Per 1000 Pounds
FTW	Water Shipment Cost Per Booster
GSE	Ground Support Equipment

LCE	Learning Curve Exponent
L/D	Length Divided By Diameter
LPC	Lockheed Propulsion Company
M	Movable (Nozzle)
MEOP	Maximum Expected Operating Pressure
MSC	Marshall Space Center
NASA	National Aeronautics & Space Agency
NFB	Number Of New Fleet Boosters
NFM	Number Of New Fleet Motors
NFT	Number Of Flight Tests
NFTM	Number Of Flight Test Motors
NGTM	Number Of Equivalent Ground Test Motors
NISM	Number Of Equivalent Initial Spare Motors
NLE	Average Number Of Launches Per Year
NLM	Maximum Number Of Launches Per Year
NMB	Number Of Motors Per Booster
NSSM	Number Of Equivalent Spares Support Motors
NUSE	Number Of Uses Per Motor
NYFT	Number Of Years Flight Test Operations
NYO	Number Of Years Operations Phase
NYTO	Number Of Years Test Operations
OMSF	Office Of Manned Space Flight
P	Parallel Burn
PFRT	Preliminary Flight Rating Test
PSC	Propellant Specific Cost

R&D	Research & Development
RDT&E	Research, Development, Test, & Evaluation
ROM	Rough Order Of Magnitude
S	Series Burn
SRM	Solid Rocket Motor
STS	Space Transportation System
TCC	Thiokol Chemical Corporation
TNOL	Total Number Of Operations Phase Launches
TT	Thrust Termination
TVC	Thrust Vector Control
UTC	United Technology Center
WBS	Work Breakdown Structure
$\dot{W}p$	Peak Annual Pounds Of Propellant Production
WCI	Weight Of The SRM Case & Insulation, (Pounds)
WG	Gross Weight Of Motor, (Pounds)
WN	Weight Of Nozzle, (Pounds)
WO	Weight Of Other SRM Subsystems, (Pounds)
WP	Weight Of SRM Propellant, (Pounds)
WPB	Weight Of Parachute System, (Pounds)
WR	Total Weight Of Recovery System = WPS + WRR, (Pounds)
WRR	Weight Of Retrorockets, (Pounds)
WSRM	Total SRM Weight = WCI + WN + WTVC + WO + WP, (Pounds)
WSS	Weight Of Stage Structure, (Pounds)
WTVC	Weight Of Thrust Vector Control System, (Pounds)

UNITS OF MEASUREMENTS

ft	Feet
in	Inch
kg	Kilograms
lbs	Pounds
lb_f	Pounds Force
m	Meters
$\bar{M}$	Millions
N	Newtons
PSI	Pounds Per Square Inch
sec	Seconds

1. INTRODUCTION AND RECOMMENDATIONS

1.1 INTRODUCTION

Development of cost models for large solid rocket motors began nearly a decade ago with the advent of the 3.05m (120 in.) and 3.96m (156 in.) motor development programs. In this current study, a solid rocket motor cost model has been developed for booster configurations of the type used on the Space Shuttle. Mostly, cost data were obtained from results of the Study of Solid Rocket Motors for a Space Shuttle performed by the solid rocket motor manufacturers for NASA. Since these studies were investigating 3.05m (120 in.) and 3.96m (156 in.) motors for either a parallel or series burn booster, the model provides life cycle costs representative of these types of configurations.

The purpose of the Solid Rocket Motor (SRM) cost model is to provide a systematic and standardized procedure for estimating life cycle costs of solid rocket motor booster configurations. The model consists of clearly defined cost categories and appropriate cost equations in which cost is related to program and hardware parameters. Cost estimating relationships are generally based on analogous experience. In this model the "experience" drawn on is from estimates prepared by the study contractors. Contractors' estimates are derived by means of engineering estimates for some predetermined level of detail of the SRM hardware and program functions of the system life cycle. This method is frequently referred to as "bottom-up". On the other hand, a parametric cost analysis is a useful technique when rapid estimates are required. This is particularly true during the planning stages of a system when hardware designs and program definition are conceptual and constantly changing as the selection process, which includes cost comparisons or trade-offs, is performed. The use of cost estimating relationships also facilitates the performance of cost sensitivity studies in which relative and comparable cost comparisons are significant.

B

A general attribute of the cost estimating relationship, which is often taken for granted or overlooked, is the reflection of cost effects resulting from engineering and programmatic changes. Because Cost Estimating Relationships (CERs) are generally derived from analogous esperience, estimates derived from CERs have a built-in allowance for engineering changes. Although the relative dollar magnitude of these changes is unique for each system in the data base, collectively the changes provide a representative experience that may be expected in new programs. Allowances for these changes cannot be as conveniently and confidently incorporated in the "bottom-up" or other costing techniques.

The background for this model including the data base, description of the configurations, and the limitations are discussed in Section 2. In Section 3, the format of the model is described with a cost element breakdown and definitions for each element. The approach in designing and constructing the model along with input data requirements are shown in Section 4. Section 5 presents Cost Estimating Relationships (CERs) for life cycle phases along with data and graphs used for deriving results. As an aid to the user, an example problem is provided in Section 6. Summary results are provided for an expendable program and details for a recoverable program.

This model was designed to be compatible in format with the STS Cost Methodology (Reference 5) such that booster costs can be added to orbiter and system costs at various program phase levels. In order to achieve complete compatibility, revisions and additions were made to the Operations Phase CERs of the STS Cost Methodology. The new operations CERs for the orbiter and system are presented in Appendix A.

The sensitivity of hardware costs to motor design/performance is a concern of the system designer. Equations describing the effect of such design parameters on weight of motor components are provided in Appendix B. These equations coupled with the cost model should enable the calculation of desired sensitivities. Relationships between cost, performance, safety, and schedules were not investigated in this study.

1.2 RECOMMENDATIONS

An important outcome from the work on the SRM Cost Model was the knowledge gained relating to desirable tradeoffs, quality of available cost data, and problems with costing guidelines. Recommendations regarding these items are presented below for possible consideration in future studies.

1.2.1 Recommendations for Desirable Tradeoffs

The SRM studies performed for NASA provided a selective viewpoint of solid rocket motors in the role of a space shuttle booster. Fundamentally, in the studies, a single family of motors constrained to state-of-the-art or proven technology and characterized by specifications indicated in Sections 2.1 and 2.2 of this document was examined. Anticipating the possibility that there will be an emerging need for an evaluation of alternative solid rocket motor designs, it is recommended that a follow-on study effort be undertaken to determine the cost consequences of the following:

- Integrated effect of recoverability on motor design including number or reuses
- Alternative case materials for reusability
- Case diameter sizes greater than 3.96m (156 in.)
- Fabrication of various segment lengths
- Comparison of alternative Thrust Vector Control (TVC) designs
- Manufacturing facility location and transportation mode
- Emphasis of reusability on nozzle design and materials
- Alternative propellants

1.2.2 Recommendations on Improving the Quality of Cost Data

a. Further cost/design analysis is needed to determine refurbishment costs of all components as a function of reuse life, recovery system development and unit costs, stage structure unit costs, and operations support costs at the launch site. These items were selected because of large data variance or lack of data among the SRM manufacturers. Data variance alone is not always indicative of the quality of data since variance could reflect a relative experience level among the manufacturers with respect to a particular component or a nonuniformity in specifications.

b. A possible factor in the variance of cost data and vendor quotes was the short response time available in the SRM studies for establishing designs and specifications. All subsystem designs and specifications for cost analysis and vendor quotes should be reexamined and defined in detail. Adequate schedules should be provided for responding to the request for quotes.

1.2.3 Recommendations for Future Cost Guidelines

In order to maximize the utility of future SRM tradeoff studies, it is necessary that definitive cost guidelines be well established with detailed work breakdown structures and clearly defined functional categories. The format should be compatible with the cost categories of the motor manufacturers and also serve the needs of the user. This recommendation is based on the difficulties encountered with the results from the SRM studies. Because of dissimilarities in cost elements, definitions, and reporting format, it was extremely difficult to determine and assign costs to the proper elements in the model.

2. BACKGROUND

The basic source of information for the cost model was obtained from the results of the Study of Solid Rocket Motors for a Space Shuttle Booster (References 1-4). Study contractors were the Aerojet Solid Propulsion Company (ASPC), Lockheed Propulsion Company (LPC), Thiokol Chemical Corporation (TCC) and United Technology Center (UTC). Each of the above companies was visited to obtain clarification on their study results and further cost details. In addition, discussions were held with the Rohr Corporation to obtain information on cases and nozzles. The contractor cost estimates were derived using a "bottom-up" approach. In contrast, this cost model was constructed using parametric cost relationships (CERs).

2.1 SOLID ROCKET MOTOR CONFIGURATIONS

Booster configurations which were studied for the shuttle consisted of parallel and series burn types with 3.05m (120 in.) or 3.96m (156 in.) diameter motors. Options of thrust vector control (TVC), thrust termination (TT), and recovery were investigated. For this model, the selected baseline expendable configuration was the parallel burn, 3.96m (156 in.) diameter, solid rocket motor (SRM) booster with TVC and TT. Characteristics for the baseline configuration, as determined by each of the SRM study contractors, are summarized in Table 2.1-1 in the International System of Units and Table 2.1-2 in English Units. The designs are found to be similar with a few differences. The major differences among the baseline configurations were the small size of the Aerojet configuration (A) and the variation in center segment lenghts. Aerojet does have an alternate configuration (B) with 566,988 kg (1,250,000 lb) of propellant which is comparable in size to the other configurations. Segment length variation is an indication of current fabrication limitations on the cases. Lockheed uses seven 4.06m (160 in.) length segments which are the longest one piece cases that can be currently made by spin forming. The other contractors use 2 to 3 of the double length segments which were mechanically joined or girth welded.

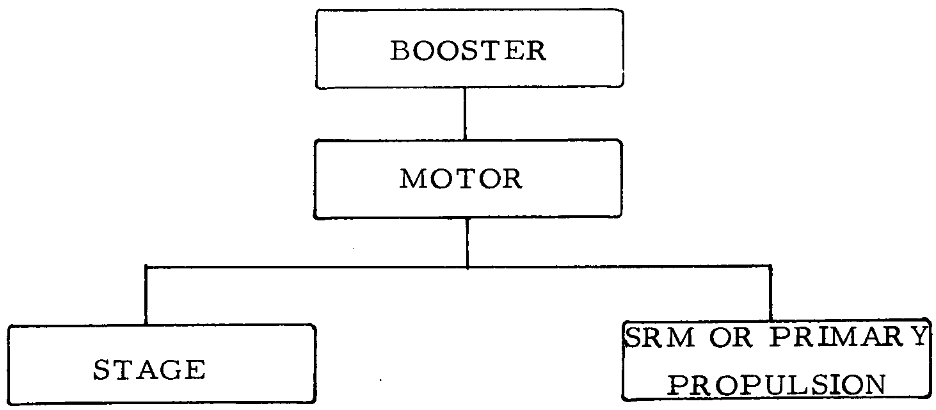
Table 2.1-1. SRM Booster Configuration Characteristics — Parallel Burn Expendable Baseline (International Units)

Configuration	ASPC-A	LPC	TCC	UTC
Dimensions				
Overall length, meters	30.48	37.95	35.15	39.04
Center segment length, meters	8.13	4.06	7.15	8.03
Cylinder diameter, meters	3.96	3.96	3.96	3.96
Performance				
Average thrust (vac.), Newtons	8.652×10^6	10.508×10^6	10.978×10^6	11.156×10^6
Total impulse (vac.), N-sec	1.207×10^9	1.450×10^9	1.474×10^9	1.463×10^9
MEOP, N/m^2	6.895×10^6	6.985×10^6	6.895×10^6	6.895×10^6
Weights, kg				
Booster	1,011,595	1,285,747	1,243,158	1,279,383
Motor with TVC & TT	505,797	642,873	621,579	639,691
SEM with TVC & TT	498,865	628,244	613,641	629,740
Propellant	453,592	558,386	552,323	566,991

Table 2.1-2. SRM Booster Configuration Characteristics — Parallel Burn, Expendable Baseline (English Units)

Configuration	ASPC	LPC	TCC	UTC
Dimensions				
Overall length, ft.	100.0	124.5	115.3	128.1
Center segment length, in.	320	160	281.5	316
Cylinder diameter, in.	156	156	156	156
Performance				
Average thrust (vac.), lb_f	1,945,000	2,362,400	2,468,000	2,508,000
Total impulse (vac.) lb_f-sec	271.3×10^6	326.01×10^6	331.3×10^6	328.8×10^6
MEOP, psi	1,000	1,000	1,000	1,000
Weights, lb				
Booster	2,230,184	2,834,586	2,740,694	2,820,556
Motor with TVC & TT	1,115,092	1,417,293	1,370,347	1,410,278
SRM with TVC & TT	1,099,808	1,385,041	1,352,847	1,388,340
Propellant	1,000,000	1,231,030	1,217,664	1,250,000

Summary weight statements of the expendable baseline and alternate configurations are presented on Table 2.1-3 in kilograms and in Table 2.1-4 in pounds. The total weights provided here correspond to the sum of the detailed weights used for the costing analysis and may not be identical to those reported in the contractors mass properties tables. In a few cases the design weights corresponding to the reported cost data were not the same weights for the reported final design. The format of the weight statement is arranged according to a definition tree for the booster shown below:



A booster consists of several motors. A motor consists of a stage and an SRM or primary propulsion unit. If a secondary propulsion system exists, it is additive to the motor. The stage consists of just the structure for the expendable type. All the avionics and other miscellaneous items are lumped into the item "Other" under SRM. There is one exception to the weight format in the CERs in that thrust termination for costing purposes is included under Case and Insulation rather than the item "Other".

Although baseline vehicle configurations in the Shuttle SRM studies were comparable in size and performance, the magnitude of unit cost varied significantly. This is illustrated in Table 2.1-5 where estimates of launch costs per flight are shown for the different configurations. A unique performance or design driver which might explain overall difference in the cost estimates could not be detected from study data. The cost estimates were considered as independent inputs to the probable cost of the SRM booster.

Table 2.1-3. SRM Booster Weight(1) Summary (kilograms)

Contractor	ASPC		LPC		TCC		UTC	
Configuration	Parallel	Parallel	Parallel	Series	Parallel	Series	Parallel	Series
Stage/Motor	(6,933)	(9,072)	(14,629)	(14,945)	(7,938)		(9,951)	(11,045)
Structure	6,933	9,072	14,629	14,945	7,938	NA	9,951	11,045
SRM/Motor	(497,904)	(626,638)	(612,140)	(548,494)	(611,679)	(743,089)	(621,234)	(543,912)
Case & insulation	37,943	53,215	49,598	44,113	52,010	61,867	52,509	52,509
Nozzle, fixed	4,926	5,630	0	0	6,441	0	0	0
Other (incl. TT)	1,443	805	4,156	3,016	905	550	1,735	1,523
Propellant & liner	453,592	566,988	558,386	501,365	552,323	680,672	566,990	489,880
Motor w/o TVC	(504,837)	(635,710)	-	-	(619,617)	-	-	-
Motors/Booster	2	2	2	3	2	3	2	3
Booster w/o TVC	(1,009,674)	(1,271,420)	-	-	(1,239,234)	-	-	-
TVC Delta/Motor	(960)	NA	(16,104)	(15,528)	(1,963)	(8,991)	(8,507)	(8,507)
Nozzle, Movable	688		11,568*	10,992*	986	7,966*	8,017*	8,017*
TVC	272		4,536	4,536	977	1,025	490	490
Motor with TVC	(505,797)		(642,873)	(578,967)	(621,580)		(639,692)	(563,464)
Motors/Booster	2	2	2	3	2	3	2	3
Booster with TVC	(1,011,594)		(1,285,746)	(1,736,901)	(1,243,160)		(1,279,384)	(1,690,392)

(1) - Represents values used for cost analysis; not identical with mass properties reports.

NA - Not available.

* - Total movable nozzle weight, not delta.

Table 2.1-4. SRM Booster Weight(1) Summary (pounds)

Contractor	ASPC		LPC		TCC		UTC	
Configuration	Parallel	Parallel	Parallel	Series	Parallel	Series	Parallel	Series
Stage/Motor	(15,284)	(20,000)	(32,252)	(32,949)	(17,500)		(21,938)	(24,350)
Structure	15,284	20,000	32,252	32,949	17,500	NA	21,938	24,350
SRM/Motor	(1,097,691)	(1,381,486)	(1,349,537)	(1,209,221)	(1,348,520)	(1,638,231)	(1,369,586)	(1,199,119)
Case & insulation	83,650	117,300	109,344	97,253	114,662	136,394	115,762	115,762
Nozzle, fixed	10,860	12,411	0	0	14,200	0	0	0
Other (incl. TT)	3,181	1,775	9,163	6,648	1,994	1,212	3,824	3,357
Propellant & liner	1,000,000	1,250,000	1,231,030	1,105,320	1,217,664	1,500,625	1,250,000	1,080,000
Motor w/o TVC	(1,112,975)	(1,401,486)	-	-	(1,366,020)		-	-
Motors/Booster	2	2	2	3	2	3	2	3
Booster w/o TVC	(2,225,950)	(2,802,972)	-	-	(2,732,040)		-	-
TVC Delta/Motor	(2,117)	NA	(35,504)	(34,234)	(4,327)	(19,823)	(18,754)	(18,754)
Nozzle, movable	1,517		25,504*	24,234*	2,173	17,563*	17,674*	17,674*
TVC	600		10,000	10,000	2,154	2,260	1,080	1,080
Motor with TVC	(1,115,092)		(1,417,293)	(1,276,404)	(1,370,347)		(1,410,278)	(1,242,223)
Motors/Booster	2	2	2	3	2	3	2	3
Booster with TVC	(2,230,184)		(2,834,586)	(3,829,212)	(2,740,694)		(2,820,556)	(3,726,669)

(1) - Represents values used for cost analysis; not identical with mass properties reports.

NA - Not available.

* - Total movable nozzle weight, not delta.

At the bottom of Table 2.1-5 are results obtained for a selected configuration using the cost model. The magnitude of the estimates falls approximately in the middle of the contract data indicating that the cost model in this context produces a "nominal" cost.

2.2 LIMITATIONS OF SRM COST MODEL

The limitations of the cost model in reference to application and expectations concerning the quality of the cost estimates the model will generate are defined by the characteristics of the data sources upon which the model is based. As presently constituted, the cost model represents the results of an analysis of the estimates provided by Aerojet, Lockheed, Thiokol and United Technology in SRM studies. Other sources (Ref. 5-15) were used, but served primarily to provide insight and perspective into SRM development and production costs. Limitations fall into two general categories:

a. applicability of the CERs developed from the data sources, and
b. the quality of the data base.

2.2.1 Applicability of the SRM Cost Model

The CERs in the cost model are valid for estimating costs of solid rocket motors having the following characteristics:

- Motor sizes ranging from 3.05m (120 in.) to 3.96m (156 in.) in diameter
  / Although some of the contractors provided costs for 6.60m (260 in.) motors, the detail required to develop CERs for costing an entire program was not available.
- PBAN propellant
- Cases spin-formed from 13,608 kg (30,000 lb) billets of D6aC steel
  / Because of the absence of sufficient data, complexity factors to measure the cost effects of larger billets and use of other fabrication techniques could not be developed.

Table 2.1-5. 3.96 m (156 in.) SRM Booster Cost Estimates (Parallel Burn with TVC and TT @ 60/year Maximum Launch Rate)

Expendable Booster Physical Characteristics			Booster Direct Launch Cost/Flight, 1970 Dollars			
Total SRM Length (meters)	SRM Segment Length (meters)	Weight (kg × 10^6)	Expendable $\overline{M}$ \$/Unit	Recoverable $\overline{M}$ \$/Unit	Reuse Savings $\overline{M}$ \$/Unit	Reuse Savings %
30.48	8.13	1.01 (ASPC-A)	4.18	2.55	1.63	39
41.10	8.89	1.27* (ASPC-B)	4.86*	2.90*	1.96*	40
37.95	4.06	1.29 (LPC)	6.65	4.95	1.70	25
35.15	7.15	1.24 (TCC)	4.60	2.91	1.69	37
39.04	8.03	1.28 (UTC)	6.24	4.52	1.72	28
		Numerical Example				
39.04	8.03	1.28	5.74	4.15	1.59	28

*Booster weight without TVC and TT; costs include TVC and TT.

2.2.2 Quality of Data

The utility of the contractors' estimates as a data base for developing CERs was impaired by the lack of uniformity in some of the ground rules and cost definitions used by the contractors. Some notable differences that surfaced when the data were analyzed are enumerated below:

- Facility costs amortized in overhead rates rather than excluding from overhead and reporting as separate cost category
- Tooling cost reported separately to identify ED & D requirements plus investment requirements in contrast to aggregating all tooling costs under ED & D
- Installation cost of raceway and separation motors reported as part of propellant cost instead of including this cost under a subassembly and installation category
- Reporting of all ED & D costs among three cost elements instead of assigning the cost to all the appropriate subsystem elements included in the ED & D function
- Reporting of spares costs for the SRM with the cost of GSE and GSE spares

Although approximate adjustments were made to accommodate the data to the CER definitions, the issue of comparability was not completely resolved.

3. COST ELEMENT STRUCTURE

3.1 COST ELEMENT BREAKDOWN

Program costs unique to the SRM booster are structured according to the life cycle phase: RDT&E, Investment, and Operations. The breakdown of each phase into cost elements is the device used to identify the major functions performed and hardware items peculiar to the phase. Cost estimating relationships (CERs) were developed for each of the cost elements listed in Tables 3.1-1, 3.1-2, 3.1-3 and 3.1-4. The referenced Tables are organized in terms of life cycle phase and provide identifying cost element numbers and corresponding section numbers for locating CERs. The format or Work Breakdown Structure (WBS) used in this model is compatible for use with the STS Cost Methodology (Ref. 5).

3.2 COST ELEMENT DEFINITIONS

Brief definitions of each cost element identified with a number in Section 3.1 are provided in this Section. The definitions cover the functions and hardware included in the cost elements. Further clarification may be obtained by referring to the corresponding CER in Section 5.

3.2.1 SRM Booster RDT&E Phase Definition

COST ELEMENT NUMBER	DEFINITION
1000	TOTAL RDT&E PHASE This cost element includes the cost to develop the SRM booster into an operational configuration and ready for mission operations. This phase may overlap the investment phase due to vehicle design modifications and production lead times. Included in this phase are design, development, and test of the SRM booster elements and associated ground equipment, plus the design and acquisition of initial tooling and facilities and the training of

Table 3.1-1. Cost Element Breakdown – RDT&E

Cost Element Number	Cost Element Designation	Section
1000	Total RDT&E Phase	5.2
1600	Engineering Development Phase	5.2.1
1610	Stage ED&D	5.2.1.1
1611	Stage Structure	5.2.1.1.1
1612	Recovery System	5.2.1.1.2
1620	Propulsion ED&D	5.2.1.2
1621	Primary - SRM	5.2.1.2.1
1622	Secondary	5.2.1.2.2
1630	Initial Tooling	5.2.1.3
1640	Initial Training	5.2.1.4
1650	Test Hardware	5.2.1.5
1651	Ground	5.2.1.5.1
1652	Flight	5.2.1.5.2
1660	Test Operations	5.2.1.6
1661	Ground	5.2.1.6.1
1662	Flight	5.2.1.6.2
1670	Facilities and GSE	5.2.1.7
1671	Facilities	5.2.1.7.1
1672	GSE	5.2.1.7.2
1680	Systems Integration Engineering	5.2.1.8
1690	Contractor Program Management	5.2.1.9

Table 3.1-2. Cost Element Breakdown — Investment

Cost Element Number	Cost Element Designation	Section
2000	Total Investment Phase	5.3
2500	Facilities & GSE	5.3.1
2510	Operational	5.3.1.1
2520	Production	5.3.1.2
2530	GSE	5.3.1.3
2600	Booster Fleet	5.3.2
2610	New Fleet Hardware	5.3.2.1
2611	Stage Hardware	5.3.2.1.1
2612	SRM Hardware (Less Propellant)	5.3.2.1.2
2613	Propellant	5.3.2.1.3
2614	Transportation	5.3.2.1.4
2620	Refurbished R&D Fleet Hardware	5.3.2.2
2630	Initial Spares	5.3.2.3
2640	Sustaining Tooling	5.3.2.4
2650	Engineering Support	5.3.2.5
2660	Contractor Program Management	5.3.2.6

Table 3.1-3. Cost Element Breakdown — Operations

Cost Element Number	Cost Element Designation	Section
3000	Total Operations Phase	5.4
3400	Operations Support	5.4.1
3410	Install., Assy, C/O & Launch Support	5.4.1.1
3420	Recovery Operations	5.4.1.2
3430	Replacement Training	5.4.1.3
3440	Facilities & GSE Maintenance	5.4.1.4
3441	Operational Facilities	5.4.1.4.1
3442	GSE	5.4.1.4.2
3450	In-Plant Engineering Support	5.4.1.5
3460	Contractor Program Management	5.4.1.6
3500	Refurbishment Support	5.4.2
3510	Refurbishment of Fleet Hardware	5.4.2.1
3520	Sustaining Tooling	5.4.2.2
3530	Engineering Support	5.4.2.3
3540	Contractor Program Management	5.4.2.4
3600	Spares Support	5.4.3

Table 3.1-4. Cost Element Breakdown — First Unit

Cost Element Number	Cost Element Designation	Section
4000	First Unit	5.5
4400	Stage	5.5.1
4410	Stage Structure	5.5.1.1
4420	Recovery System	5.5.1.2
4421	Parachute System	5.5.1.2.1
4422	Retro Rocket System	5.5.1.2.2
4500	Propulsion	5.5.2
4510	Primary - SRM (Less Propellant)	5.5.2.1
4511	Case & Insulation	5.5.2.1.1
4512	Nozzle	5.5.2.1.2
4513	TVC	5.5.2.1.3
4514	Other	5.5.2.1.4
4515	Motor Subassembly & Install.	5.5.2.1.5
4520	Secondary	5.5.2.2

COST ELEMENT NUMBER	DEFINITION
	personnel necessary to support the development program. Also included are necessary technology support costs.
1600	ENGINEERING DEVELOPMENT PHASE
	This phase involves the application of scientific and engineering effort to transform an operational need into an operational system possessing the desired performance parameters. Included in the effort is the integration of related technical parameters to assure compatibility of all physical, functional and program interfaces and to optimize total system definition and design along with the integration of reliability, maintainability, safety, human, and other similar factors into the total engineering effort. In addition to costs for design and development of the airborne vehicle elements, included are costs for the acquisition of all ground equipment, and facilities necessary to support the vehicle development, and tooling necessary for production of test vehicles.
1610	STAGE ED & D
	Included in this element are the costs associated with engineering, design, and development of structural components and recovery system equipment attached to each motor.
1611	STAGE STRUCTURE
	Refers to all the structural components necessary for supporting the booster on the launch pad, attaching the booster to the orbiter fairings and other miscellaneous structures.

COST ELEMENT NUMBER	DEFINITION
1612	RECOVERY SYSTEM This item consists of the parachute system, and retro-rockets. For a listing of the major components of the parachute system, refer to the definition of cost element (4421).
1620	PROPULSION ED & D Refers to the primary SRMs and a possible secondary (abort rockets) propulsion system.
1621	PRIMARY – SRM This task consists of engineering design and development of the solid motor case, insulation, nozzle, propellant, liner, TVC, and accessories. It includes the cost for manufacturing and testing of the development and preliminary flight rating test (PFRT) motors.
1622	SECONDARY PROPULSION This element reserved for secondary propulsion system or other costs.
1630	INITIAL TOOLING, RDT&E PHASE The cost of initial tooling covers planning, design, maintenance, and rework of all tools including assembly tools, dies, fixtures, gauges, handling, equipment and special test equipment for the SRM and SRM stage. Included are costs for the determination of tooling requirements, planning of fabrication and assembly operations, maintaining tooling records, scheduling and controlling all tooling orders, programming and preparing of tapes for numerically controlled machine parts, and preparing templates. Standard off-the-shelf tools and test equipment costs are excluded here, but included in facilities costs.

COST ELEMENT NUMBER	DEFINITION
1640	INITIAL TRAINING

1640 INITIAL TRAINING

This element includes the cost of instruction, audio and visual teaching aids, and parts and accessories required to train ground crew personnel to maintain, assemble, and checkout the booster vehicles. Also included is the cost to determine training requirements and planning of the training program.

1650 TEST HARDWARE

Refers to costs of all major units of hardware purchased in the RDT&E Phase.

1651 GROUND TEST HARDWARE

Includes the cost of manufacturing major vehicle subsystems and complete vehicle elements needed for structural/dynamic testing, propulsion system integration testing and all systems testing. Mock-ups and hardware for subsystem test and qualification are excluded from this element but are included with engineering design and development costs, as are special purpose test rigs. Quantities of hardware are based on equivalent units.

1652 FLIGHT TEST HARDWARE

Includes the cost to manufacture all test articles and spares required for the flight test program.

1660 TEST OPERATIONS

Includes the costs of performing system development tests using prototype hardware to acquire engineering data and confirm engineering hypotheses. Test operations costs include those for the detail planning, conduct, support, data acquisition and analysis, reports, and materials consumed in ground and flight tests.

COST ELEMENT NUMBER	DEFINITION
1661	GROUND TEST This task involves major ground tests of the booster systems and includes the cost of supporting inert structural vehicle tests and all systems testing. Motor development and PFRT tests are excluded from this category.
1662	FLIGHT TEST Includes the operations costs of supporting the vertical flight program to test ascent characteristics and the recovery procedures for the reusable SRM booster concept. Cost of flight test spares are excluded here but included under Flight Test Hardware.
1670	FACILITIES & GSE Refers to the cost associated with the vendor, motor manufacturer, site facilities, and GSE necessary to support the SRM booster RDT&E Program.
1671	FACILITIES Refers to the cost of new facilities and off-the-shelf tooling, and/or modificationof existing facilities required by the motor manufacturers and their vendors for the support of the SRM booster RDT&E Program.
1672	GSE Includes the cost of development engineering, testing, and production of all ground-based equipment to support the launch, recovery, and maintenance of the SRM motors during the RDT&E program. Cost includes the GSE necessary to transport and handle the SRM.

COST ELEMENT NUMBERS	DEFINITION
1680	SYSTEM INTEGRATION ENGINEERING
	Refers to the cost of the overall integration of development activities. Included are establishment of engineering design characteristics, determination of criteria for design review, establishment of procedures for testing components, subsystems or SRM elements, integration of ground and flight test results into the booster design, development procedures for booster maintenance, and quality planning and administrative engineering.
1690	CONTRACTOR PROGRAM MANAGEMENT
	Refers to costs associated with the "Prime" contractor centralized direction of effort in the areas of program planning, control, and administration. Includes all activities within the program management disciplines.

3.2.2 SRM Booster Investment Phase Definitions

COST ELEMENT NUMBERS	DEFINITION
2000	TOTAL INVESTMENT PHASE
	Includes the cost of acquiring additional facilities, equipment, fleet vehicles, propellant, and spares. The additional facilities, ground equipment, and tooling supplement those acquired during RDT&E to accommodate all necessary production and operational launch rates. The initial quantities of all reusable boosters and total quantities of expendable elements required to support the operational fleet are costed herein, including all necessary support and management of the acquisition activities.

COST ELEMENT NUMBERS	DEFINITION
2500	FACILITIES & GSE
	Included in this category are costs for additional manufacturing, propellant production facilities, and ground equipment over and above that purchased in the RDT&E phase and required to support the operational phase.
2510	OPERATIONAL FACILITIES
	Refers to those additional facilities in addition to those purchased during RDT&E which are required at the launch site to support the operational program.
2520	PRODUCTION FACILITIES
	Includes the cost for additional manufacturing and propellant facilities required to meet the operational flight rates.
2530	GSE
	Refers to the cost associated with acquiring additional ground support equipment necessary to support the operational program.
2600	BOOSTER FLEET
	Includes all cost associated with the procurement of new fleet hardware, initial spares, and refurbishment of R&D hardware for the operational fleet.
2610	NEW FLEET HARDWARE
	Includes the cost to manufacture and transport the SRM hardware, stage hardware, and propellant in the quantities required to satisfy operational program requirements. The refurbishment cost of reusable fleet hardware is included in the operational phase.

COST ELEMENT NUMBER	DEFINITION
2611	STAGE HARDWARE Includes the cost to manufacture operational quantities of SRM structures and recovery subsystems.
2612	SRM HARDWARE Includes the cost to manufacture the center segments, fore and aft closures, TVC, power subsystems, electrical/ electronic subsystems, and nozzles in quantities required for the operational program.
2613	PROPELLANT Refers to the cost of propellant raw materials, mixing of materials, pouring, casting, and curing of propellant in operational quantities.
2614	TRANSPORTATION Refers to the cost to transport by rail or water of new SRM boosters from the SRM manufacturers plant to the launch sites. It excludes costs of shipping the refurbished SRM back to the launch site. The cost of shipping vendor items to the prime contractor is included in the component cost.
2620	REFURBISHED R&D FLEET HARDWARE Refers to the cost of refurbishing the flight test vehicle for use in the operational SRM booster fleet. The cost to transport the refurbished hardware back to the launch site by either rail or water route is included.
2630	INITIAL SPARES Refers to the cost of spares required to support the manufacturing operations.

COST ELEMENT NUMBER	DEFINITION
2640	SUSTAINING TOOLING, INVESTMENT PHASE Includes the cost for additional tooling to meet SRM booster peak production rates and cost of tooling maintenance, replacement, modification, and rework as needed in support of SRM booster manufacturing.
2650	ENGINEERING SUPPORT Includes cost for engineering support of the manufacturing program covering such tasks as configuration changes and product improvement, updating system definition and interfaces with other shuttle elements, updating the ground support definition and providing support to the reliability, producibility, and maintainability functions.
2660	CONTRACTOR PROGRAM MANAGEMENT Refers to costs associated with the "Prime" contractor centralized direction of effort in the areas of program planning, control, and administration. Includes all activities within the program management disciplines.

3.2.3 SRM Booster Operations Phase Definitions

COST ELEMENT NUMBER	DEFINITION
3000	TOTAL OPERATIONS Includes all direct and indirect labor, materials (spares) and propellant costs (for reusable concept only) required to operate and maintain the vehicles, facilities, and equipment developed and produced in the RDT&E and Investment Phases. For the reusable concept it also includes all costs related to the refurbishment of the recovered motors.

COST ELEMENT NUMBER	DEFINITION
3400	<u>OPERATIONS SUPPORT</u> Refers to the costs incurred in operating and providing services relative to launching, recovery, maintenance, training, and refurbishment of booster vehicles during the mission and operational phase.
3410	<u>INSTALLATION, ASSEMBLY, CHECKOUT, AND LAUNCH SUPPORT</u> Refers to the launch site effort required for all booster preflight assembly, checkout, maintenance, and launch. It also includes receiving, inspection, and storage of SRM and stage subsystems and subassemblies prior to assembly.
3420	<u>RECOVERY OPERATIONS</u> Includes the cost associated with water retrieval, booster deactivation, washing, inspection, and disassembly for transportation back to vendors or to the motor receiving and inspection area. Also includes maintenance of recovery fleet and equipment.
3430	<u>REPLACEMENT TRAINING</u> Includes the cost of training qualified ground personnel to replace those lost by rotation or attrition in order to maintain manning levels necessary to meet flight and ground operations schedules.
3440	<u>FACILITY & GSE MAINTENANCE</u> Refers to the cost associated with the maintenance of the booster-peculiar operational facilities and GSE and GSE spares. It does not include the maintenance of the recovery fleet which is covered in cost element (3420).

COST ELEMENT NUMBER	DEFINITION
3441	OPERATIONAL FACILITIES Includes the cost of maintaining the booster-peculiar facilities required at the launch site.
3442	GROUND SUPPORT EQUIPMENT AND SPARES Includes the cost for maintenance of GSE and the spares for the GSE peculiar to the booster.
3450	IN-PLANT ENGINEERING SUPPORT Includes cost associated with normal product improvement characterized by engineering changes and modifications to the booster hardware or to the method of operation.
3460	CONTRACTOR PROGRAM MANAGEMENT Refers to the costs associated with the overall program support for the operational phase and consists of such tasks as program planning, financial control, contracts, and procurement.
3500	REFURBISHMENT SUPPORT Refers to all costs necessary to refurbish recovered SRMs to a condition ready for reuse in launch operations. Includes sustaining tooling, engineering support, and program management.
3510	REFURBISHMENT OF FLEET HARDWARE Includes costs to refurbish recovered SRMs to a new condition ready for reuse in launch operations. Excludes sustaining tooling, engineering support, and contractor program management.

COST ELEMENT NUMBER	DEFINITION
3520	SUSTAINING TOOLING Refers to the cost for additional tooling to meet SRM and SRM stage refurbishment rates. Includes tooling maintenance, replacement modification, and rework as needed in support of the SRM booster refurbishment.
3530	ENGINEERING SUPPORT Includes cost for engineering support of the refurbishment program.
3540	CONTRACTOR PROGRAM MANAGEMENT Refers to the costs associated with the central direction of effort of the program planning and management of the refurbishment program.
3600	SPARES SUPPORT Refers to the cost to manufacture and stock spare SRMs and stage hardware for the operational phase.

3.1.4 SRM Booster First Unit Cost Definitions

COST ELEMENT NUMBER	DEFINITION
4000	FIRST UNIT Includes the costs associated with all direct labor, material, subcontract, and overhead costs incurred in the manufacture of the following elements: • Stage structure • Recovery System • Case and Insulation • Nozzle • Other • Motor subassembly

COST ELEMENT NUMBER	DEFINITION
4400	STAGE Refers to the cost to manufacture the first unit stage structure and recovery system. It includes all labor, material, and vendor costs incurred in the manufacture of these elements. Excludes engineering, tooling, and management costs.
4410	STAGE STRUCTURE Refers to the cost to manufacture structure components for the first unit. Included are the attachments to the orbiter, fore and aft skirts, fairings, separation rockets, and clustering structure for a series configured booster.
4420	RECOVERY SYSTEM Refers to the cost to manufacture the first unit of the recovery system. It includes all labor, material, and vendor cost incurred in the manufacture of the parachute system, retro-rockets, and related equipment. Excludes engineering, tooling, and management costs.
4421	PARACHUTE SYSTEM Includes the cost to manufacture the first unit of the parachute system consisting of the drogue and main parachutes, motors, liners, risers, reefing system, beacons and retrieval aids, flotation bags, and inflation devices.
4422	RETROROCKETS Includes the first unit cost to manufacture the retrorocket system used in the recovery of the SRM and stage.

COST ELEMENT NUMBER	DEFINITION

4500 PROPULSION

Refers to the cost incurred in the manufacture of the first SRM. It includes the labor, material, and vendor costs for the primary and secondary propulsion systems.

4510 PRIMARY – SRM (LESS PROPELLANT)

Includes the cost to manufacture the first units of case and insulation, nozzle, TVC, other subsystems, subassembly, and insulation. It excludes system final assembly, installation, test and checkout costs which are considered functions under Operations Support (3400).

4511 CASE & INSULATION

Refers to the first unit cost to manufacture the SRM case and insulation and covers the following items:

- Forward closure assembly
- Cylinder assembly (center segment)
- Aft closure assembly
- Nozzle adapter
- Thrust termination assembly
- Attaching assemblies
- Insulation

4512 NOZZLE

Includes the cost of manufacturing a fixed or movable nozzle. Includes labor, material, and vendor costs for the throat, exit cone, and in the case of the moveable nozzle, the gimbaling mechanism.

4513 TVC

Refers to the cost associated with the manufacturing of the thrust vector control (TVC) system. The TVC

COST ELEMENT NUMBER	DEFINITION
	system includes a nozzle gimbaling mechanism, actuators to position the nozzle, and an auxiliary power system to drive the actuators. The cost of the gimbaling mechanism is included with the movable nozzle (4512).
4514	OTHER SUBSYSTEM
	This category includes all SRM and Stage items not included in other categories and when individually considered constitute one percent or less of the SRM and stage costs. The major subsystems in this group are: • SRM Igniter • SRM and Stage Electrical Components, Instrumentation and Avionics • Destruct System and Ordnance
4515	MOTOR SUBASSEMBLY AND INSTALLATION
	This task includes all minor assembly and installation of component parts and subsystems into the SRM. In addition to the labor, the cost to perform the subassembly and installation includes interfacing assembly materials and parts in support of this task. This effort is distinct from Installation Assembly and Checkout which constitutes final assembly of the SRM and involves the assembly of the major components, motor segments, and stage structures into the SRM booster configuration ready for mating with the orbiter stage. Specifically this task includes: • Propellant trimming and X-ray • Assembly of nozzles, forward and aft closures and igniters • Installation of wiring and minor subassemblies • Painting

COST ELEMENT NUMBER	DEFINITION
4520	SECONDARY
	This element reserved for secondary propulsion system or other costs.

4. COST ESTIMATING APPROACH

The cost model was developed with the objective of providing cost estimates of SRM boosters. The cost model can be used to estimate booster life cycle costs for expendable and recoverable vehicles in either parallel or series configurations. Since the data base used in constructing the cost model consists primarily of information obtained from the NASA SRM studies (Ref. 1-4), the cost estimates provided by the model represent nominal values.

The basic parameter used for the hardware CERs was weight. For the purpose of cost/weight/performance sensitivity studies, the relationship of the SRM design/performance parameter to weight is provided in Appendix B.

4.1 LIFE CYCLE COSTS

The SRM cost model is designed and constructed to provide cost for the SRM booster program life cycle. The life cycle is divided into three phases:

- RDT&E Phase
- Investment Phase
- Operations Phase

Costs are defined and classified according to life cycle phase and further subdivided into smaller cost elements. These cost elements were selected so as to conform to specific tasks or functions, or hardware elements. The level of subdivision was determined by the data base and the relative magnitude of the cost at that level.

As an estimating device, to facilitate costing of the booster hardware, another category referred to as the first unit cost was provided. As a cost tool, first unit cost is convenient to use for computing motor hardware cost of the total vehicle or subsystem thereof for whatever quantities specified for the RDT&E, Investment and Operations Phases.

The definitions of each of the three life cycle phases, first unit cost, and respective cost elements is provided in Section 3.2.

4.1.1 RDT&E Phase Cost Elements (1000)

The total RDT&E Phase usually consists of four major functional categories: Conception and Definition Phase, Technology Support Phase, Engineering Development Phase, and Government Program Management. The SRM cost treats with the Engineering Development Phase (1600) only. The major cost elements that define this phase are detailed in Fig. 4.1-1. Costs for the other functions can be estimated using the corresponding categories provided for in the STS Cost Methodology (Ref. 5).

4.1.2 Investment Phase Cost Elements (2000)

The cost elements comprising the Investment Phase are shown in the block diagram, of Fig. 4.1-2. Included are the facilities and GSE required to support the production program and the Booster Fleet required for the operational program.

4.1.3 Operations Phase Cost Elements (3000)

The cost elements comprising the Operations Phase are shown in the block diagram of Fig. 4.1-3. These elements comprise those functions related only to the booster and exclude any orbiter or systems functions. The functions can be categorized as direct (associated with hands-on-vehicle effort) and indirect (support functions). Elements (3410), (3420), (3500), and (3600) are considered direct.

4.1.4 First Unit Cost Elements (4000)

The hardware elements of the stage and propulsion which are amenable to a first unit cost definition are shown in the block diagram of Fig. 4.1-4. Propellant and transportation costs which contribute to the cost of a motor are not included.

4.2 BOOSTER PROGRAM REQUIREMENTS

The cost model is structured to accommodate the characteristics of expendable SRM booster and recoverable SRM booster programs. The two concepts generate different cost profiles because certain aspects of the program requirements are unique. The expendable booster requires more manufacturing facilities, tooling, and GSE than does the recoverable booster. For a

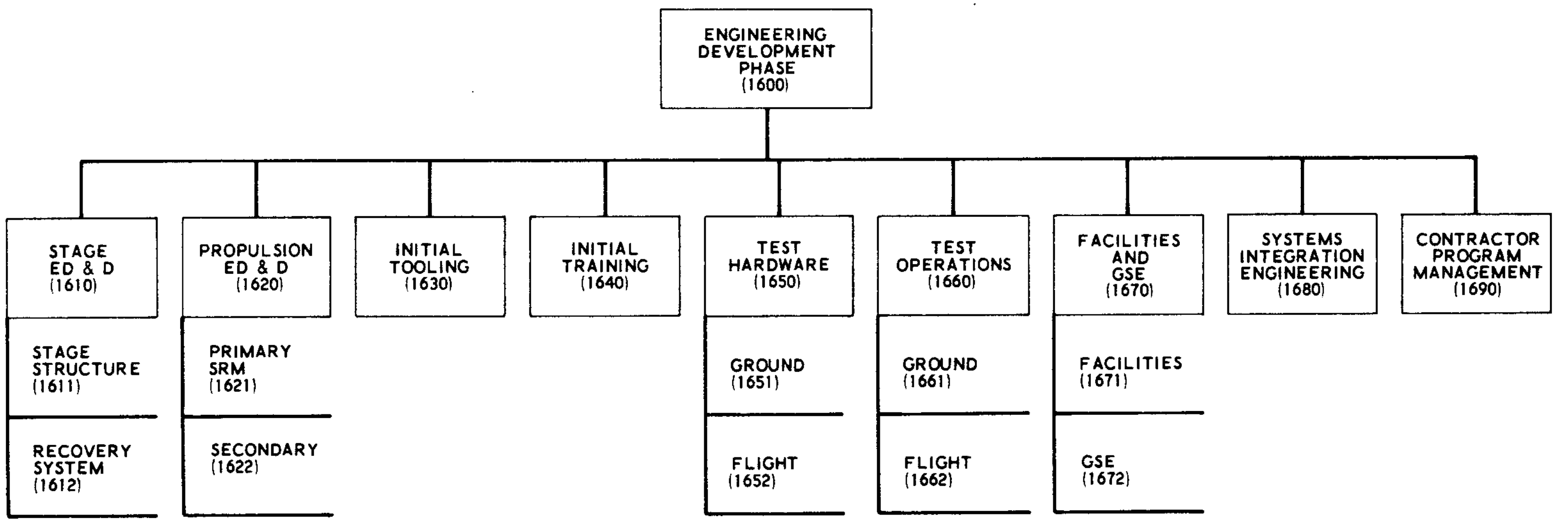


Fig. 4.1-1. Engineering Development Phase Elements

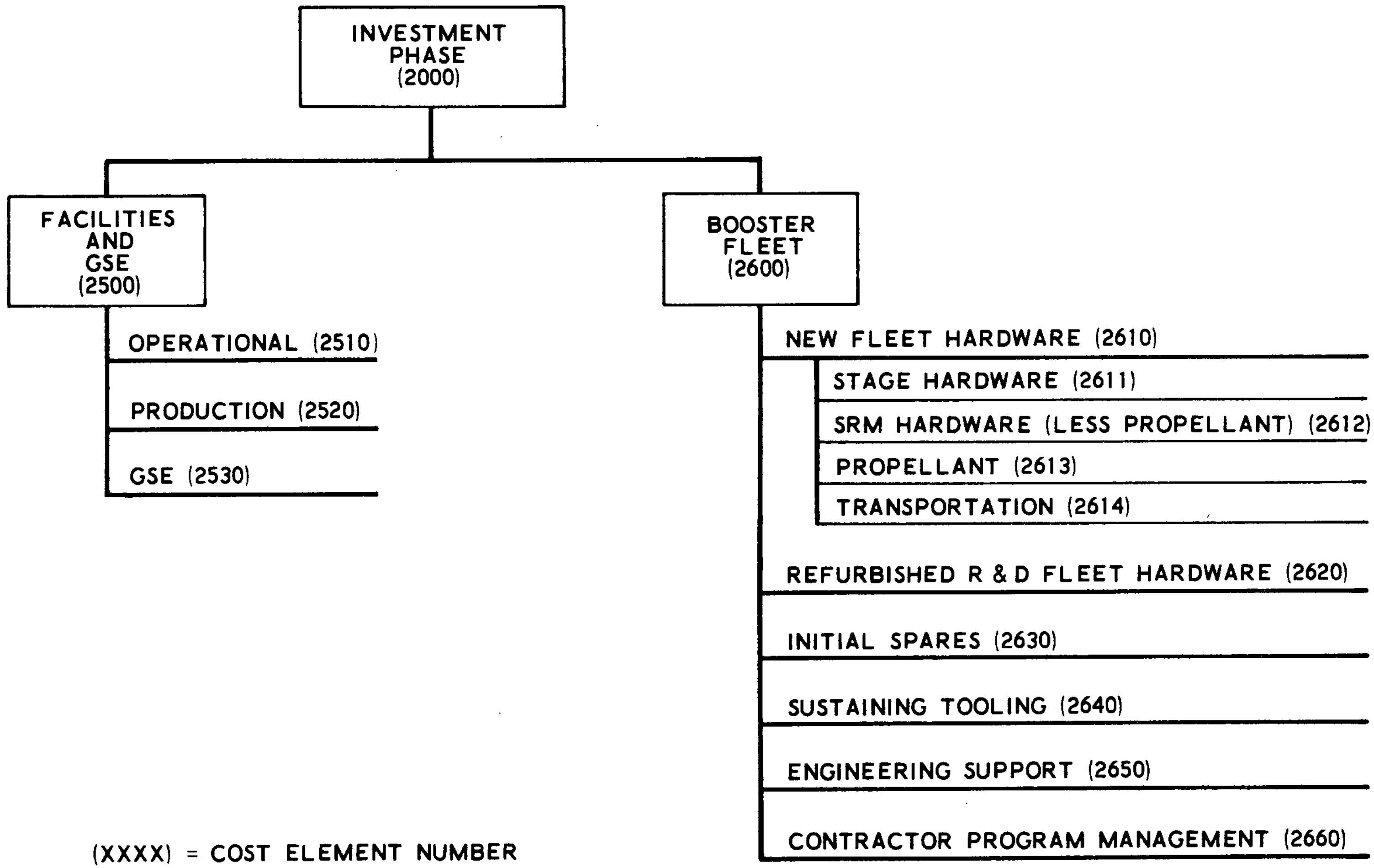


Fig. 4.1-2. Investment Phase Elements

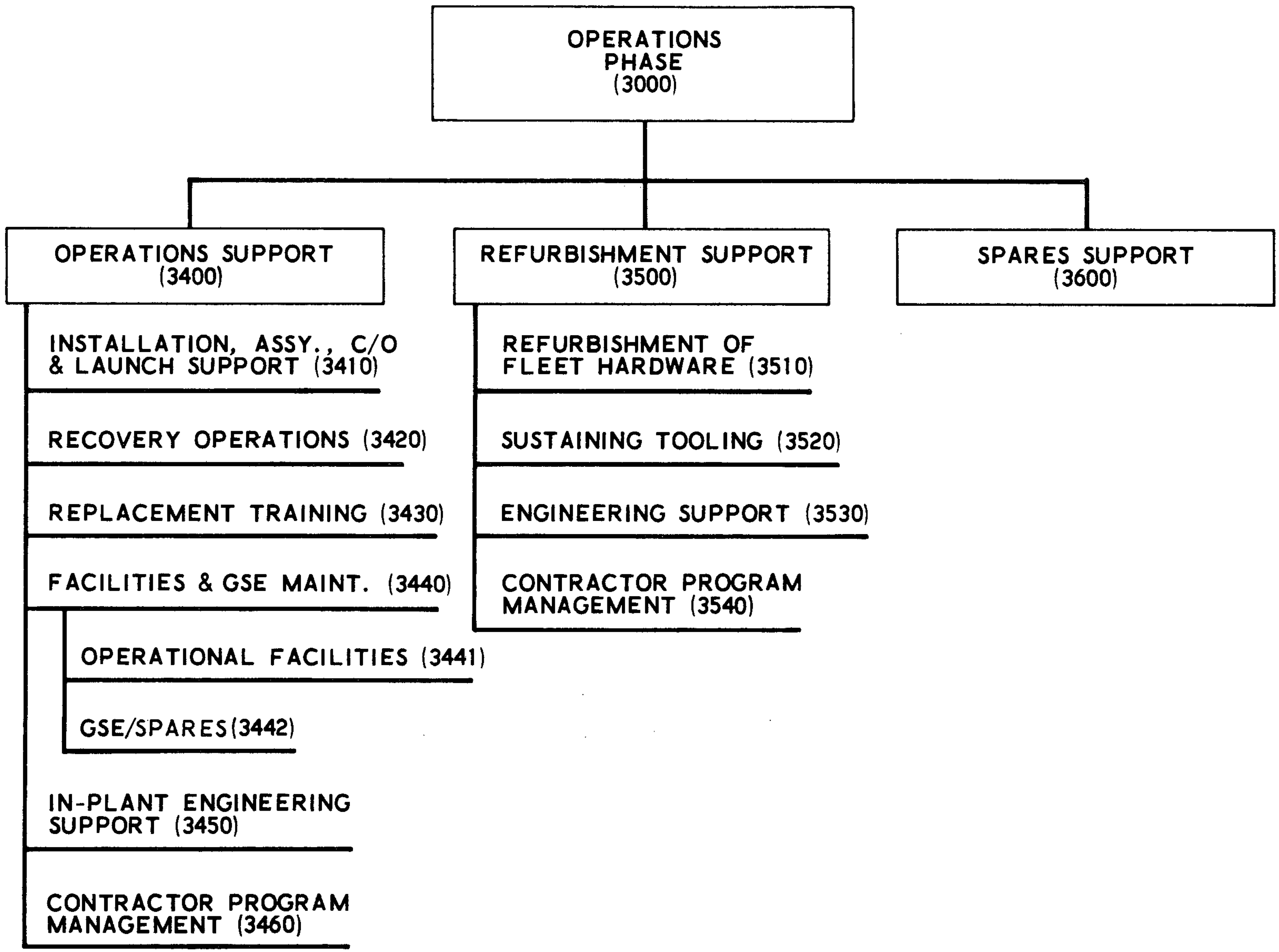


Fig. 4.1-3. Operations Phase Elements

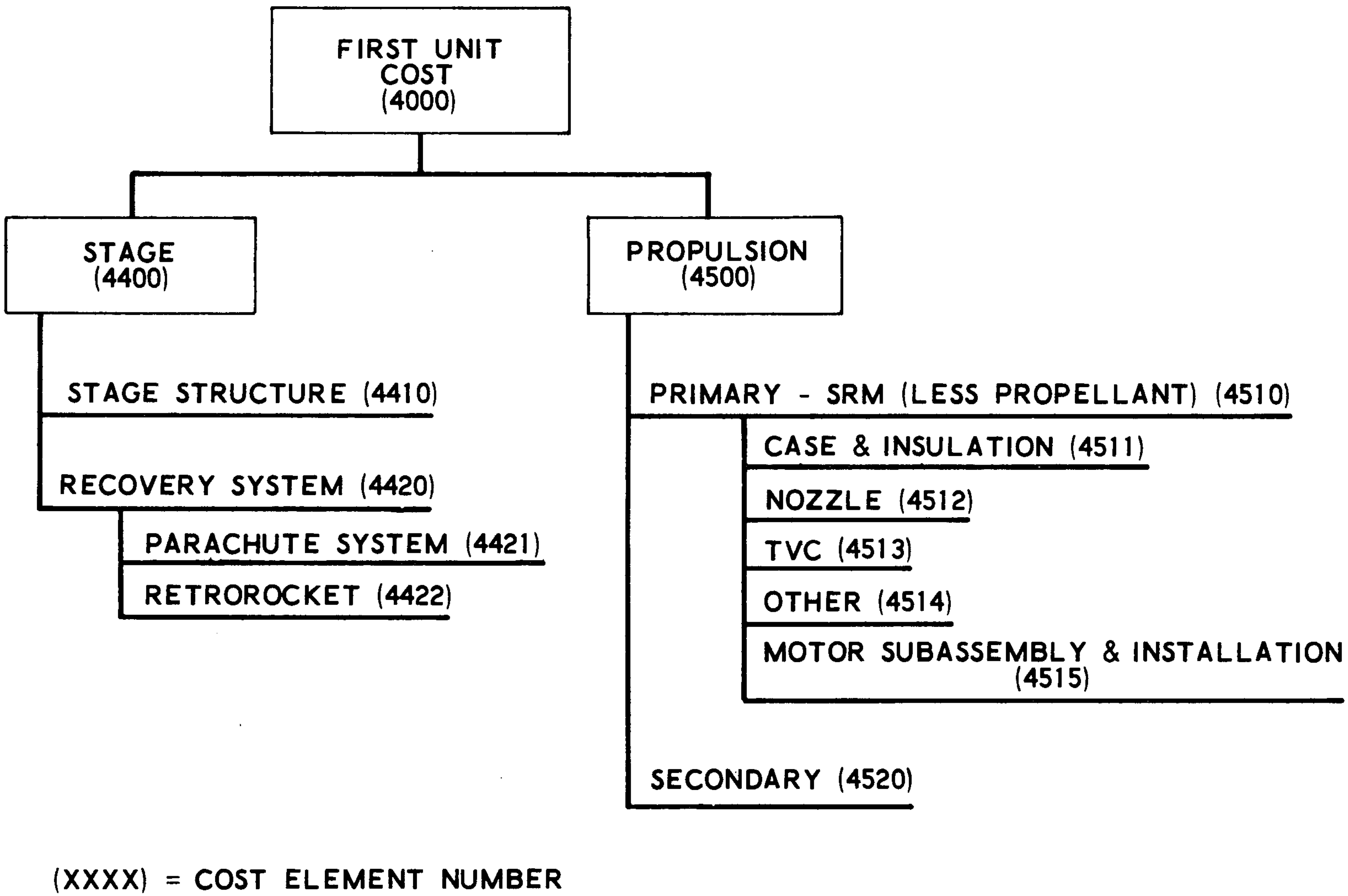


Fig. 4.1-4. First Unit Elements

defined program, however, the additional facilities and equipment needed to refurbish the recoverable SRMs partially offset the manufacturing facilities and tooling necessary for the relatively high production rates of the expendable booster. The functions and equipment unique to the recoverable booster program are listed below:

RDT&E

- Recovery System
- Training of Recovery Personnel
- Test Operations, Recovery of Flight Test Vehicles
- Recovery Facilities & GSE

Investment

- Additional Recovery Facilities & GSE
- Refurbishment of R&D Hardware

Operations

- Recovery Operations
- Maintenance of Recovery Fleet
- Replacement Training of Recovery Personnel
- Maintenance of Recovery Facilities & GSE
- Refurbishment Support

Another consideration is that the propellant and transportation costs for the total expendable vehicle program are displayed in the Investment Phase under their cost element designation (2613 and 2614, respectively). In contrast the total program costs for propellant and transportation in the recoverable concept are divided among three cost elements: Propellant (2613) and Transportation (2614) applicable only for the New Fleet Hardware quantities, in the Refurbished R&D Hardware (2620), and in the Refurbishment of Fleet Hardware (3510).

4.3 COST ESTIMATING PARAMETERS

Weight, for the hardware items, and time, for labor related functions in operations, are the principal cost estimating parameters used in the cost model. The selection of these parameters was made after a thorough evaluation of contractors' opinions, current industry practices, and past studies in terms of the objectives of the cost model.

Discussions with the SRM manufacturers indicated weight as the most commonly used parameter for scaling, but most manufacturers performed detailed "bottom-up" cost estimates where scaling did not apply. For hardware components of similar design, weight would be appropriate for items such as cases and nozzle. One contractor also indicated weight and throat diameter as parameters for the nozzle since most of the expensive metal is located around the throat. For rough correlation with program costs, total impulse was used in another case. In general, the SRM contractors used the "bottom-up" cost estimating technique.

A review of past studies and cost models (Ref. 7, 8, 9, 11 and 12) provided background material on parameters used. The most significant information was found in Ref. 8 which contains a statistical analysis of production cost performance and design parameter data for solid motors weighing less than 45,400 kg, or 100,000 lb. The design and performance parameters examined for developing CERs were thrust, total impulse, motor weight, mass fraction, and propellant specific impulse. Conclusions were that a combination of quantity and either total impulse or weight provides good estimates of solid motor production costs.

Inputs from the various sources as well as limitations of the data base were considerations in selecting weight as the primary cost parameter for the hardware components. Because of the limited scope of the data base, and the similarity of design and performance characteristics of the SRM boosters represented in the base, cost/weight relationships are restricted in application. Complexity factors are provided, when the data base permitted, to indicate deviations from the baseline characteristics.

In order to provide the user with greater flexibility, equations showing the effect of design parameters on weight are provided in Appendix B. These parameters were originally developed for the large solid motor sizing program (Ref. 7) and were updated in this study to correlate with the current SRM designs. Equations are provided for the individual components corresponding to those listed under the SRM first unit element. Use of the cost model in conjunction with the equations of Appendix B will permit SRM optimization studies to be conducted similar to those performed by R. Krueger in Ref. 10.

4.4 INPUT DATA

FREF = Refurbishment factor

FTR = Rail freight cost per 1000 pounds

FTW = Water shipment cost per booster

NFB = Number of new fleet boosters

NFM = Number of new fleet motors

NFT = Number of flight tests

NFTM = Number of flight test motors

NGTM = Number of equivalent ground test motors

NISM = Number of equivalent initial spare motors

NLE = Average number of launches per year

NLM = Maximum number of launches per year

NMB = Number of motors per booster

NSSM = Number of equivalent spares support motors

NUSE = Number of uses per motor

NYFT = Number of years flight test operations

NYO = Number of years operations phase

NYTO = Number of years test operations

TNOL = Total number of operations phase launches

WEIGHT DATA - POUNDS

SYMBOL	STAGE
WSS	STAGE STRUCTURE
WR	RECOVERY SYSTEM
WPS	PARACHUTE SYSTEM
WRR	RETRO ROCKETS
	PROPULSION
WSRM	PRIMARY - SRM
WCI	CASE & INSULATION

SYMBOL	PROPULSION
WN	NOZZLE
WTVC	TVC
WO	OTHER
WP	PROPELLANT
WS	SECONDARY
WG	TOTAL MOTOR GROSS WEIGHT

5. COST ESTIMATING RELATIONSHIP

5.1 INTRODUCTION

The cost estimating relationships provided herein constitute a consensus estimate of the costs of each element described in Section 3. In those cases where a consensus could not be determined, a selection was made as to the most representative cost. The approach was to establish a nominal cost within the data scatter and not to bias the estimates toward a conservative "ceiling" estimate. The quality of the CER estimates does vary because it is a reflection of the data base. However, in analyzing the data, emphasis was placed on the items that were major cost contributors in order to provide a consistent level of quality in the composite costs. Those CERs which are subject to significant uncertainties because of data limitations are identified as providing rough-order-of-magnitude (ROM) estimates.

The reader is reminded that the costs are in 1970 dollars and <u>do not</u> include the SRM contractor fee.

In using the CERs, the reader should consult the nomenclature list (Appendix C), the cost element breakdown (Tables 3.1-1 through 3.1-4), and the cost element definitions (Section 3.2). The cost element number and designation will be identified in brackets as (XXXX). The element number when preceded by a "C" denotes the cost of that element. In other words,

C (XXXX) denotes the cost of element (XXXX)

5.2 TOTAL RDT&E PHASE (1000)

Cost estimates in the RDT&E Phase for the shuttle booster with 3.96m (156 in.) diameter motors are strongly influenced by the applicable experience and available production capacity of motor contractors. Much of the research and development was conducted during the 3.96m (156 in.) development program in the mid 1960s and applicable experience was gained in the current production of Minuteman, Poseidon and 3.05m (120 in.) diameter motors. With a motor design based on current state-of-the-art materials and established production techniques, the RDT&E Phase is essentially a demonstration program to qualify the booster. The major cost item is, therefore, test hardware with most of the remainder consisting of SRM ED & D, facilities required for only the RDT&E Phase, and recovery system ED & D for a recoverable booster. Usually, the total RDT&E Phase consists of a Conceptual and Definition Phase, an Engineering Development Phase, a Technology Support Phase, and a Government Program Management Phase. Only the Engineering Development Phase is considered in this model.

$$C\ (1000) = C\ (1600)$$

where

C (1600) = Engineering Development Phase

5.2.1 Engineering Development Phase (1600)

The development program for the solid rocket motor booster includes the cost of engineering, design, development, hardware tests, production of test hardware, required facilities and GSE. The cost for this phase is obtained by adding all (1600) cost element numbers in the form

$$C\ (1600) = [C\ (1610) + C\ (1620) + C\ (1630) + C\ (1640) + C\ (1650) + C\ (1660) + C\ (1670) + C\ (1680) + C\ (1690)]$$

where

C (1610) = Stage ED & D Cost
C (1620) = Propulsion ED & D Cost
C (1630) = Initial Tooling Cost
C (1640) = Initial Training Cost
C (1650) = Test Hardware Cost
C (1660) = Test Operations Cost
C (1670) = Facilities & GSE Cost
C (1680) = Systems Integration Engineering Cost
C (1690) = Contractor Program Management Cost

5.2.1.1 Stage ED & D (1610)

The stage includes all additional structural components and recovery system equipment attached to each SRM. The cost of engineering, design and development of these hardware items is:

$$C\ (1610) = C\ (1611) + C\ (1612)$$

where

C (1611) = Stage Structure Cost
C (1612) = Recovery System Cost

5.2.1.1.1 Stage Structure (1611)

This task includes all the design and development of structural components necessary for supporting the booster/SRM on the launch pad, attaching the SRMs to the orbiter drop tanks, separation of SRMs, fairings for enclosing or aerodynamic shaping, and other miscellaneous structure and brackets. All labor and materials for design, development, manufacture of components for subscale tests, and component testing for verification prior to full scale hardware tests are assigned to this cost element. The CER established for this task is:

$$C\ (1611) = 1.9 \times 10^{6}\ [WSS]^{0.118}$$

where weight of the stage structure is in pounds.

Data points used for this CER represent those for the parallel SRM booster and are shown in Table 5.2-1 below and Figure 5.2-1.

Table 5.2-1. Structure Weight and Cost

Contractor	Weight/Motor kg	(lb)	Cost (millions of dollars)
ASPC - A	6933	15,284	6.718
ASPC - B	9072	~20,000	7.119
LPC	1462	32,252	4.993
TCC	7938	~17,500	1.663

The slope of the curve was assumed to be similar to that for the body/tank structure CER indicated in Ref. 6.

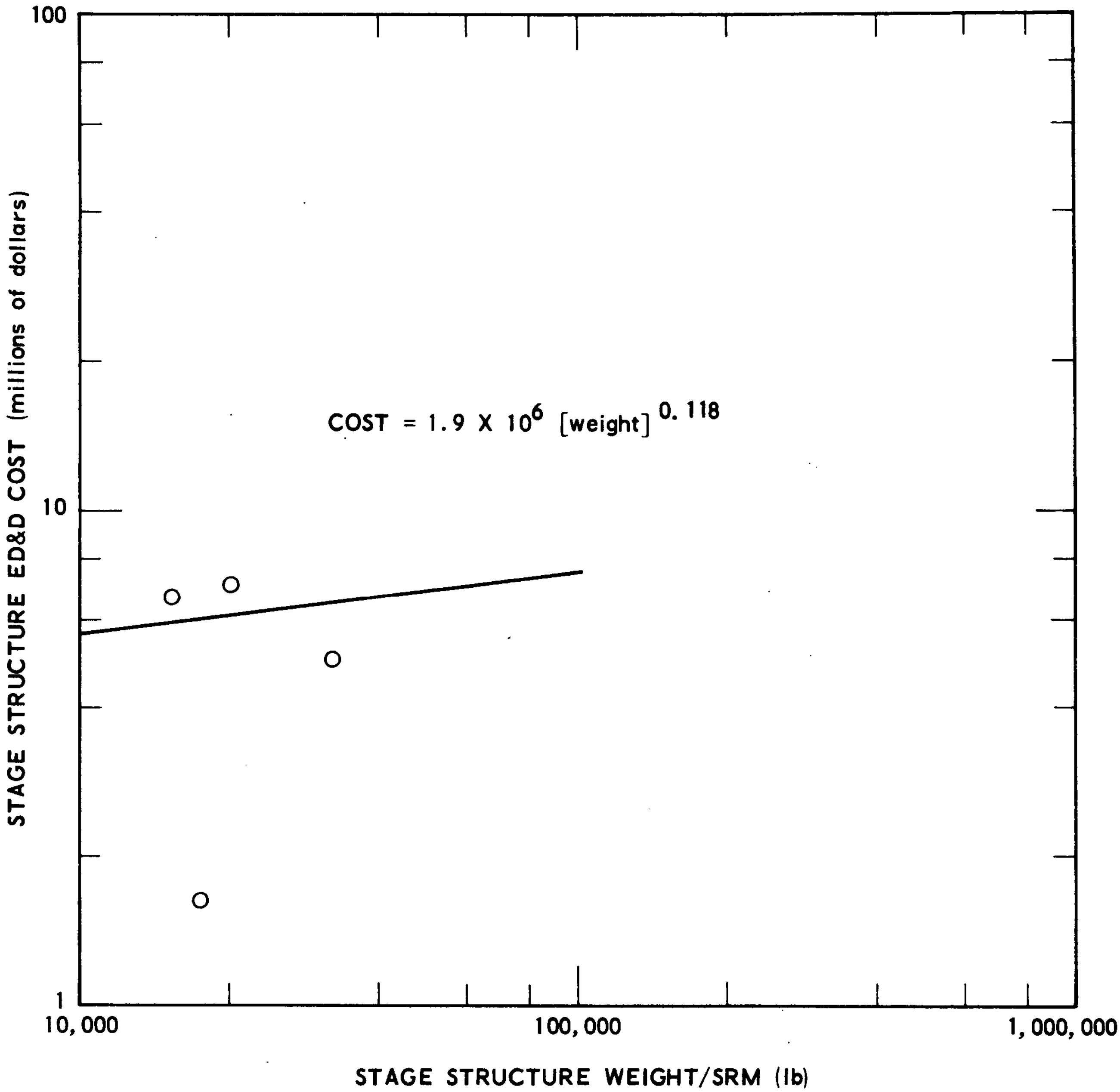


Fig. 5.2-1. Stage Structure ED&D Costs

5.2.1.1.2 Recovery System Development Costs (1612)

The recovery system consists of the parachute system plus retrieval aids such as the beacon, orientation system, and inflation system. Facilities were not included in this category. The development costs include modifications to the SRM design to contain the parachute system, plus a recovery demonstration and test program.

Recovery system development costs quoted by the SRM contractors or by their vendors range from a minimum of $12 million to a maximum of about $100 million. The variance in estimates is probably a reflection of the inadequate time available to determine the requirements and prepare valid cost estimates. The data based on recovery system costs is presented in Table 5.2-2 and represent contractor estimates for the parallel burn SRM. The highest costs shown are similar in magnitude to the estimates made for the series pressure-fed booster. With the lower recovery weight and reliability requirements of the SRM's a reduction in the development cost should be expected.

It was not possible to construct CER's for this element because of the lack of consistent cost data. In the absence of a consensus, ROM point estimates are provided which are based on a review of the costs and judgment of recovery specialists. The ROM costs presented in Table 5.2-3 below attempt to reflect the above considerations.

Table 5.2-2. Data Base for Recovery System RDT&E Costs
(Millions of Dollars)

Contractor	ASPC	LPC	TCC	UTC
Parachute System	86.8	14.0	76.0	3.0
Retrieval Aids	12.0	5.0	4.0	-
Recovery Demonstration	5.0	(included)	(included)	7.9
SRM Modifications	-	-	-	0.74
Retro Rockets	1.1	-	-	-
Recovery System Subtotal	104.9	19.0	80.0	12.0
Facilities				
Recovery	17.7	-	17.4	1.9
Refurbishment	7.2	6.0	-	-
Totals	122.6	25.0	97.4	13.9

Table 5.2-3. ROM Estimate for Recovery System RDT&E Costs

Items	Costs (millions of dollars)
Parachute System	20
Retrieval Aids	5
Recovery Demonstration	5
SRM Mods	1
Retro Rocket	1
Total	32

5.2.1.2 <u>Propulsion ED & D (1620)</u>

The propulsion system for the booster consists of the primary system, which is the SRM, and a possible secondary system. A secondary system is not defined but a cost element is reserved in case one is specified, e.g., abort rockets. The cost for engineering, design, and development of these items of hardware is:

$$C\ (1620) = C\ (1621) + C\ (1622)$$

where

$C\ (1621)$ = Primary SRM Cost

$C\ (1622)$ = Secondary Propulsion Cost

5.2.1.2.1 Primary-SRM (1621)

This category covers the cost to engineer, design, and develop the case, insulation, nozzle, propellant, liner, TVC, thrust termination, and other accessories. The other accessories are avionics, power, igniter, and pyrotechnics. The functions associated with this task include analysis, design, materials procurement, component manufacturing, test, and inspection. Also included here is the manufacture and test of development motors, PFRT motors, and static firings to qualify the motors. These qualification tests represent 40 to 50 percent of the ED & D SRM cost since the development of the baseline 3.96m (156 in.) is basically a demonstration program. The costs apply to the baseline expendable design with from 3 to 7 center segment cases made of D6aC steel, using PBAN propellant, and equipped with either a gimballed or fixed nozzle. The applicable data points (Table 5.2-4) valid for this CER were obtained by adjusting the results of two contractors. These were plotted on Fig. 5.2-2 where the slope for scaling the costs was taken from Ref. 12 in which gross costs of a smaller solid rocket motor are analyzed. The CER is

$$C\ (1621) = (F\ 1621) \left| 89{,}000\ (WSRM)^{0.41} \right|$$

where

$$\begin{aligned} WSRM &= \text{SRM Weight in pounds} \\ F\ 1621 &= 1.00 \text{ without TVC and TT} \\ &= 1.28 \text{ with TVC and TT} \end{aligned}$$

The impact of a change in propellant type, case material, and motor diameter on these baseline ED & D costs could not be ascertained from the contractors as their studies were still in progress. Based on initial comparisons, however, propellant type and case material did not appear to offer cost advantages. The size of the motor diameter appears to be the area most cost sensitive. The development problems relate to the fabrication of the case because of limits on billet sizes, transportation of motor cases, and modifications to existing facilities. The ED & D impact is therefore the result of additional engineering analysis required for solving fabrication and transportation problems, additional design effort for the motor and modification of facilities, and the higher cost of component test hardware.

Table 5.2-4. SRM ED&D Costs (Millions of Dollars)

Contractor	LPC		TCC	
TVC & TT	No	Yes	No	Yes
SRM[1] (Basic)	7.590	7.590	23.892	25,586
SRM Other [2]	2.587	5.162	3.333	11.315
Δ for Development Hardware [3]	15.018	17.480	Incl.	Incl.
Stage Other [4]	5.658	7.150	Incl.	Incl.
Total ED&D	30.853	37.382	27.225	36.901

(1) Includes ED&D for case, insulation, nozzle, propellant, and liner.

(2) Includes ED&D for Igniter, TVC, and other miscellaneous accessories.

(3) Includes development & PFRT firing hardware.

(4) Includes avionics, electrical power, and pyrotechnics.

5.2.1.2.2 Secondary Propulsion (1622)

This cost element is reserved for a secondary propulsion system.

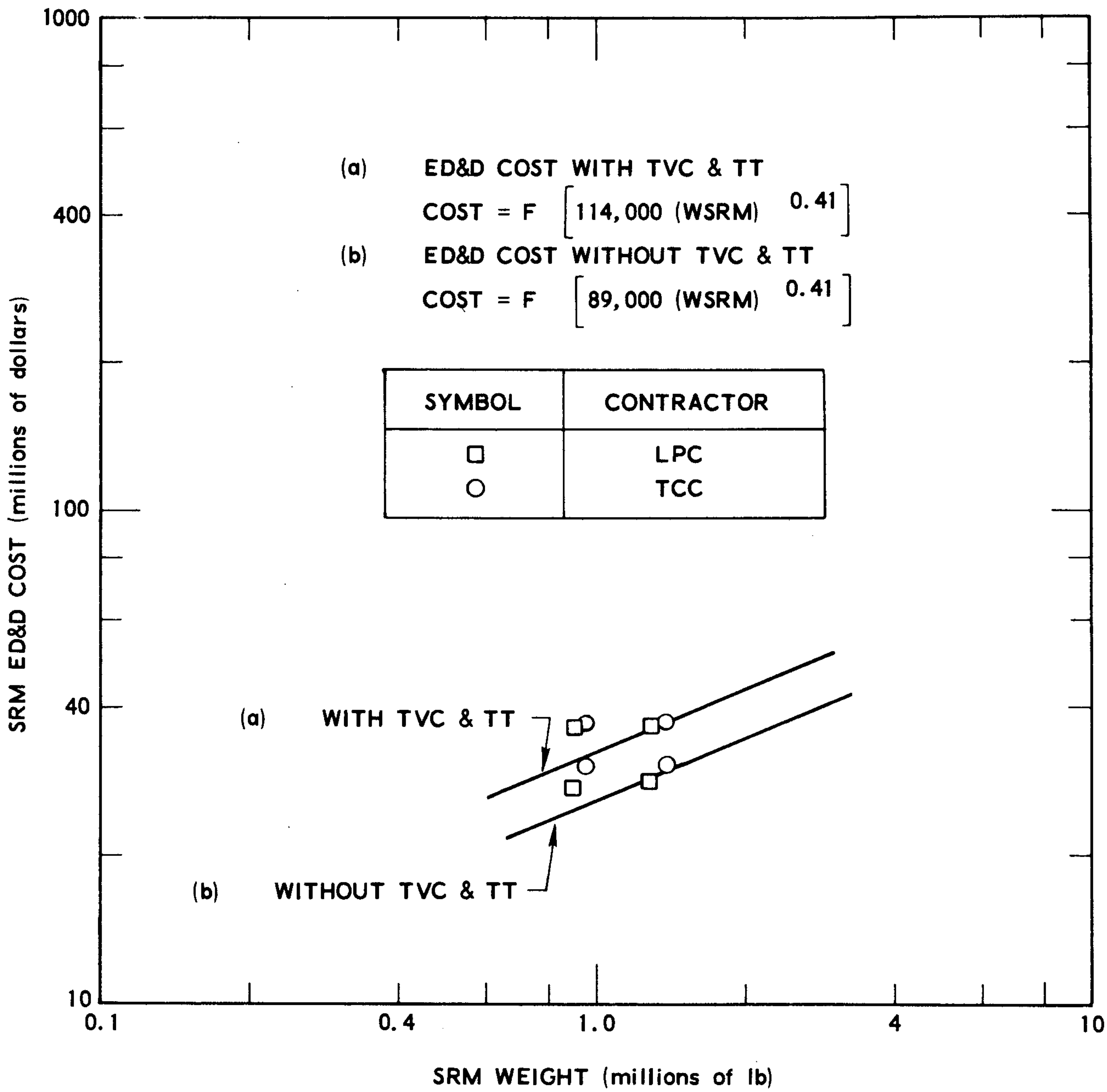


Fig. 5.2-2. SRM ED&D Costs

5.2.1.3 Initial Tooling (1630)

Initial tooling requirement for the RDT&E Phase is derived as 2.5% of the ground and flight test hardware costs for the stage and solid rocket motor. The costs include new tooling design, development, and fabrication as defined in Section 3.2.1 for cost element number (1630). The CER is written as:

$$C\,(1630) = 0.025\,[C\,(1651) + C\,(1652)]$$

where

$C\,(1651)$ = Ground Test Hardware Cost

$C\,(1652)$ = Flight Test Hardware Cost

The derivation of the cost factor was based on a review of all SRM study results which are compared on Table 5.2-5. The tooling factors which represent the tooling as a percentage of total hardware cost are for the combined RDT&E and investment phases with a program peak rate of 60 launches/year. Most estimates are in the vicinity of $30 million. In order to break out the RDT&E contribution and to show the effect of production rate, the Thiokol data were used exclusively since the other contractors did not provide this information. Cost factors applicable to both the RDT&E phase and the investment phase are presented in Table 5.2-6. These values apply to the 3.96 m (156 in.) diameter motors for either the parallel or series burn cases. Costs for larger diameter motors should increase because of new fabrication and handling requirements for cases.

Table 5.2-5. Comparison of Estimated Tooling Costs

Contractor	RDT&E Plus Production 60/yr ($$10^3$)	Tooling Factor (%)*
ASPC	$33,862	1.81
TCC	33,710	1.86
UTC	29,021	1.24
LPC	53,354	2.07

* Percentage of total hardware production costs.

Table 5.2-6. Tooling Costs Data Base and Derivation of CER Cost Factor (Thousands of Dollars)

Peak Annual Flight Rate	Thiokol			Tooling CER Cost Factor % Used
	Costs		Tooling Factor %	
	Hardware	Tooling		
RDT&E	38,664	9,702	2.51	2.5
60/yr	1,769,495	24,008	1.36	1.4
40/yr	1,474,581	21,143	1.43	1.4
20/yr	901,060	19,452	2.16	2.0
10/yr	586,546	11,149	1.96	2.0

F

5.2.1.4 Initial Training (1640)

This cost item includes the cost of instruction, audio and visual teaching aids, parts, and accessories required to train a ground crew to perform the task covered in Paragraph 5.4.1.1, Installation Assembly, Checkout, and Launch Support.

Reference 5, indicated the cost of $15, 000 to train a man in 1969 dollars or about $16, 000 in 1970 dollars. It was assumed that one complete ground crew is trained initially to perform the function costed in Paragraph 5.4.1.1. CER (3410) was divided by $35, 000, the cost associated with one man year, to obtain the average number of ground personnel required for this initial training. The number of personnel multiplied by $16, 000 gives CER (1640) for initial training as

$$C\ (1640) = 17.25 \times 10^{4}\ (NLE)^{0.737}$$

where

NLE is the average launch per year at a given site

Note: For values of NLE < 10 use NLE $= 10$

5.2.1.5 Test Hardware (1650)

The cost of test hardware is estimated separately for hardware used in ground tests and that used for flight testing and is defined by the equation:

$$C\ (1650) = C\ (1651) + C\ (1652)$$

where

C (1651) = Ground Test Hardware Cost

C (1652) = Flight Test Hardware Cost

5.2.1.5.1 Test Hardware, Ground (1651)

The SRM required for major ground tests are included in this category. The cost of this hardware is calculated as follows:

$$C\ (1651) = NGTM\ [C\ (4410) + C\ (4510) + CPTH + CTTH]$$

where:

NGTM = Number of equivalent ground test motors

C (4410) = Stage Structure First Unit Cost

C (4510) = Primary Propulsion - SRM First Unit Cost

CPTH = Test hardware propellant cost per motor

$= 1.15\ [WP \times (NGTM + NFTM)/NYTO]^{-0.0589} \times WP$

WP = Propellant weight per motor (lb)

NFTM = Number of flight test motors

NYTO = Number of years of test operations

CTTH = Test hardware transportation cost per motor

= FTR 1.1 WG/1000 (Railroad)

or

= FTW/NMB (Water)

WG = Gross weight per motor (lb)

FTR = Rail freight cost per 1000 pounds (See Table 5.3-5)

FTW = Water shipment cost per booster (See Table 5.3-5)

NMB = Number of motors per booster

Ground test hardware costs are assumed as first unit values and propellant costs are based on the average production rate during the test operations period. The number of major ground test units assumed in the SRM studies were four inert motors for the structural test vehicles. Propellant cost for inert motors is the same as that for the regular motors.

5.2.1.5.2 Test Hardware, Flight (1652)

The hardware in this category includes the cost of all SRM motors required for SRM booster flight tests, unmanned and manned. The cost of these motors is estimated as follows:

$$C\ (1652) = NFTM^{0.926} \left|C\ (4410) + C\ (4420)\right| + NFTM^{0.941} \left|C\ (4511)\right| + NFTM^{0.971} \left|C\ (4512) + C\ (4513) + C\ (4514)\right| + NFTM^{0.848} \left|C\ (4515)\right| + NFTM \left|CPTH + CTTH\right|$$

where:

NFTM = Number of flight test motors
C (4410) = Stage Structure First Unit Cost
C (4420) = Recovery System First Unit Cost
C (4511) = Case & Insulation First Unit Cost
C (4512) = Nozzle First Unit Cost
C (4513) = TVC First Unit Cost
C (4514) = Other First Unit Cost
C (4515) = Motor Subassembly and Installation First Unit Cost
CPTH = Test hardware propellant cost per motor
CTTH = Test hardware transportation cost per motor

5.2.1.6 Test Operations (1660)

Test operations covers the cost of both the ground and flight test support. The cost is calculated as:

$$C\ (1660) = C\ (1661) + C\ (1662)$$

where

C (1661) = Ground Test Operations Cost
C (1662) = Flight Test Operations Cost

5.2.1.6.1 Ground Test Operations (1661)

The cost of supporting major ground tests such as the inert structural vehicle test is estimated as $250,000 per test. The CER is written as:

$$C\ (1661) = (NGTM)\ (0.25 \times 10^{6})$$

where

NGTM = Number of equivalent ground test motors

Contractor cost estimates ranged from about $100 thousand to over $5 million for ground tests. The larger estimates included inert structural tests and up to 10 development and PFRT tests. In view of the large variation in cost and definition, a ROM estimate was made for the CER which excludes the development and PFRT tests and includes only inert structural vehicle tests.

5.2.1.6.2 Flight Test Operations (1662)

The cost of this function includes all planning, analysis, and data acquisition and reduction in support of the flight test as well as operations support functions normally conducted at the launch site. A major portion of the latter is the cost for installation, assembly, checkout, and launch support of the booster. Contractor definitions for this function were not very explicit. The estimates ranged from $700 thousand to over $6 million for a 6 flight test program for an expendable booster. Because of the variance in estimates, a gross CER is derived as $300 thousand per flight test plus $2 million per year for test operations. The CER is written as:

$$C\ (1662) = (0.3 \times 10^{6})\ (NFT) + (F1662)\ (2 \times 10^{6})\ (NYFT)$$

where

NFT = Number of flight tests
NYFT = Number years of flight test operations
F1662 = 1.0 For Expendable Concept
= 1.5 For Recoverable

5.2.1.7 Facilities and GSE (1670)

The cost for facilities and GSE (ground support equipment) required to develop and operate the solid rocket motor booster is highly sensitive to launch rate (production rate) and to the contractor involved. The latter sensitivity reflects the contractor plant facilities currently available, the degree of excess capacity at each plant, and the decision to make or buy components. The facilities and GSE costs developed herein are those peculiar and dedicated to the booster and are based on a booster with the size and characteristics of the baseline configuration with:

- Parallel burn
- Twin solid rocket motor stage
- 3.96 m (156 in.) diameter motors

$$C\ (1670) = C\ (1671) + C\ (1672)$$

where

C (1671) = Facilities Cost

C (1672) = GSE Cost

5.2.1.7.1 Facilities (1671)

In general, the facilities fall into two functional categories: those required at the launch site for booster operations, and those required by the solid motor manufacturer and his vendor for booster production. Operational facilities at the launch site are defined as those required to receive, inspect, maintain, and store all motor components. Production facilities include those for processing, mixing, fabricating, manufacturing, inspecting, casting, etc. Cost estimating relationships are developed for both types of facilities and are separated into an expendable and a recoverable program. Facility cost data used were those reported by the SRM Study contractors (Ref. 1a, 2, 3, and 4) for the vendor and motor manufacturer and by Parsons, (Ref. 13), for the operational facility. Items identified as facilities cost include those for brick and mortar, fixed equipment, equipment activation, and tooling. The case vendor's estimate, however, includes only his tooling cost since he assumed that brick and mortar and fixed equipment will be government furnished. The tooling included here is standard off-the-shelf items and is separate from the special tooling costs identified in Sections 5.2.1.3, Initial Tooling, and 5.3.2.4, Sustaining Tooling.

Expendable Booster Program

Estimates for each type of facility were collected from all contractors and then summed to obtain the extreme bounds of total facility estimates. Results are shown on Table 5.2-7 for a 60/year launch rate. The maximum of $171 million shown exceeds the individual contractor maximum of about $112 million, since it includes facilities not reported in all individual estimates. The values indicated for the CER are an average of the reported values except in the case of the propellant (oxidizer) producers where two of the three estimates were about $25 million. For the lower peak flight rate of 10 launches per year, the estimates ranged from $30 to $50 million and an average of $40 million was used. The above data, and others at 20 and 40 launches per year, indicate a linear relationship between maximum launch rate and facilities cost. Therefore, the following base facility cost equation was developed:

$$C = (2.2 \text{ NLM} + 18) \times 10^6$$

Table 5.2-7. Facilities Cost — Expendable @ 60 Flights/Year (Millions of Dollars)

Facility	Range		CER
	Minimum	Maximum	
Production	(111)	(164)	(143)
Vendors	(97)	(120)	(113)
Case	77*	77	77
Nozzle	1	10	4
Insulation	6	7	7
Propellant	13	26	25
Motor Manufacturer	(14)	(44)	(30)
Operational	2	7	7
Totals	113	171	150

*Adjusted for omission ($45 million) of the case manufacturer's vendor facilities requirements.

where

NLM = Maximum number of launches per year

For accounting purposes, 25% of the total facilities cost is allocated to RDT&E. Therefore, the cost of (1671) is

$$C\ (1671) = (0.55\ NLM + 4.5) \times 10^6$$

where

NLM = Maximum number of launches per year

Note: for NLM < 10 use NLM = 10

Recoverable Booster Program

The recovery and reuse of boosters requires additional motor manufacturer facilities for refurbishment. This amounts to about $7 million at the 60 launches per year rate. This increase is more than offset by a decrease in the case manufacturers'facilities requirement. At the same peak launch rate of 60 per year, the estimated decrease is $40 million. The net effect of these changes result in the recoverable facilities cost being about 75 percent of the expendable facilities cost. Thus (1671) for RDT&E is

$$C\ (1671) = (0.41\ NLM + 3.4)\ 10^6$$

where

NLM = Maximum number of launches per year

Note: For NLM < 10 use NLM = 10

5.2.1.7.2 GSE (1672)

GSE includes all non-airborne equipment required to checkout, operate, maintain and transport the solid motor booster vehicle not included in facilities categories.

Table 5.2-8 shows data reported from Ref. 1a, 2, 3 and 4. It can be observed that the values for the initial GSE buy are relatively small and range from 2 to 6% of SRM booster costs. Therefore, 4% of the stage and propulsion RDT&E costs was used for the following CER (1672):

$$C(1672) = 0.04((C(1610) + C(1620))$$

where

C (1610) = Stage ED & D Cost
C (1620) = Propulsion ED & D Cost

Table 5.2-8. RDT&E GSE Cost — Expendable/Recoverable (millions of dollars)

Contractors	Cost			
	TCC	ASPC	UTC	LPC
Ave. Launch Rate				
44	1.8	*	5.3	3.1
35	1.8	NA	5.3	NA
20	1.8	NA	5.3	NA
10	1.8	NA	5.3	NA
% of Booster Costs	2	NA	6	3

*Included in production costs.

NA - Not Available

5.2.1.8 <u>Systems Integration Engineering (1680)</u>

System Integration Engineering refers to all system level engineering design and development functions and activities necessary to integrate all development, production, and test activities within the RDT&E Phase. This CER was derived from an average of SRM contractor RDT&E Systems Engineering cost estimates as a ratio of the combined RDT&E costs of the elements listed below. The value for the CER is 4 percent of those elements and is expressed as:

$$C(1680) = 0.04\,[C(1610) + C(1620) + C(1630) + C(1640) + C(1650) + C(1660) + C(1672)]$$

where

$C(1610)$ = Stage ED & D Cost
$C(1620)$ = Propulsion ED & D Cost
$C(1630)$ = Initial Tooling Cost
$C(1640)$ = Initial Training Cost
$C(1650)$ = Test Hardware Cost
$C(1660)$ = Test Operations Cost
$C(1672)$ = GSE Cost

5.2.1.9 Contractor Program Management (1690)

Contractor Program Management includes not only contractor administrative costs of managing the program, but also all the costs of program functions such as financial management, data management, configuration management, change control, etc. A value of 3 percent of the RDT&E program costs excluding facilities was derived by taking a consensus of the SRM Study data. The CER is written as

$$C\ (1690) = 0.03\ [C\ (1610) + C\ (1620) + C\ (1630) + C\ (1640) + C\ (1650) + C\ (1660) + C\ (1672)]$$

where

C (1610) = Stage ED & D Cost
C (1620) = Propulsion ED & D Cost
C (1630) = Initial Tooling Cost
C (1640) = Initial Training Cost
C (1650) = Test Hardware Cost
C (1660) = Test Operations Cost
C (1672) = GSE Cost

5.3 TOTAL INVESTMENT PHASE (2000)

Program costs for this phase include those for production facilities, GSE, fleet hardware, and sustaining tooling. The major item, fleet hardware, is obtained from component CERs listed in Table 5.3-1. The CERs are divided into two groups. The group identified with the "First Unit" cost element numbers are those components for which the cumulative average costs are a function of a production learning curve. The second group contains those items which are characterized by an "Average Unit" cost and have cost element numbers for the investment phase.

The key component in the first unit CERs is the case plus insulation. At about $10/lb, the first unit cost for a 3.96m (156 in.) case exceeds a million dollars per SRM. This cost is a composite for the higher cost end closures and lower cost center segments which were fabricated from D6aC steel, spin formed, and attached by pin and clevis joints. The number of center segments varied from 2 to 7 among the contractors. No variation in case costs owing to the number of segments was detectable. Possible savings in fabrication cost may occur from longer (around 7.62m, 300 in.) one-piece segments; however, the cost of developing large billet sizes, tooling and fabrication techniques, and processing facilities may offset those gains. Another consideration reviewed was the cost tradeoff of using oh other materials. From a total case cost standpoint, our review and preliminary findings by the contractors indicate no advantage of changing from D6aC steel. A major concern of many regarding the case is the impact of larger diameters on the fabrication cost. From our review there appears to be no significant cost factor on fabrication as long as the production techniques, tooling, and facilities can be developed. If the transportation solution requires shorter segments ($L/D < 1$) then total case cost will go up because of the joint penalty. Further cost analysis will be required to

Table 5.3-1. Primary SRM Booster Cost Estimating Relationships (CER)

Cost Element	Designation	First Unit Cost CER
4410	Stage Structure	$C(4410) = F\,[185.8\,(WSS)^{0.821}]$
4421	Parachute System	$C(4421) = \$50\,(WPB)$
4422	Retro Rocket	$C(4422) = \$15\,(WRR)$
4511	Case & Insulation	$C(4511) = F\,[838.7\,(WCI)^{0.623}]$
4512	Nozzle	$C(4512) = F\,[252.4\,(WN)^{0.793}]$
4513	TVC	$C(4513) = 32876\,(WTVC)^{0.263}$
4514	Other	$C(4514) = 503\,(WO)^{0.660}$
4515	Motor Subas'y. & Install.	C (4515) = 7% of SRM Components
		Average Unit Cost
2613	Propellant	$\text{Cost}\,(\$/\text{lb}) = 1.15\,(\dot{W}_P)^{-0.0589}$
2614	Transportation	Rail: \$9 to \$60 per 1,000 lb Barge: \$8,000 to \$200,000/Booster

Note: $\dot{W}_P$ denotes maximum propellant production in lb/year.

incorporate this sensitivity into the CER. In the interim, the current CERs should be adequate to portray the cost/weight trend of large diameter cases.

The key component in the "Average Unit" group of Table 5.3-1 is propellant. This CER represents the cost of raw materials and propellant processing. Because of the effect of production efficiency, quantity buy discounts, and the burden rate dependence on total production, the cost of propellant was displayed as a function of the maximum production rate per year. The CER represents the mean of data points provided by the contractors. Data scatter was quite significant with a range from 34¢/lb to 42¢/lb at the 60/year launch rate. Possible reasons for this cost spread are overlap in the definition of propellant costs among the contractors and the variation in transportation charges for raw material. It is possible that some of the difference is accounted for in the CER for Motor Subassembly and Installation. The CER as constructed provides a nominal cost of the propellant. A "ceiling cost" would be about 20 percent higher.

For a recoverable SRM program, the quantity of new fleet hardware built is less than that of an expendable program and, therefore, investment costs are lower. Costs for operational refurbishments are carried in the Operational Phase even though some of the functions are similar to those in the investment phase for the expendable program.

The total booster costs for the Investment Phase are obtained as follows:

$$C\,(2000) = C\,(2500) + C\,(2600)$$

where

C (2500) = Facilities & GSE Cost
C (2600) = Booster Fleet Cost

5.3.1 Facilities & GSE (2500)

The costs and cost estimating relationships for facilities and ground support equipment required to support the operational program over and above that purchased in the RDT&E Phase are discussed in subsequent paragraphs. The same set of booster characteristics as noted in Paragraph 5.2.1.7 apply here.

$$C\ (2500) = C\ (2510) + C\ (2520) + C\ (2530)$$

where

C (2510) = Operational Facilities Cost

C (2520) = Production Facilities Cost

C (2530) = GSE Cost

5.3.1.1 Operational (2510)

These facilities are for the additional facilities required for the solid motor booster configuration at the launch site.

Expendable

As noted in Table 5.2-7 of Paragraph 5.2.1.7, the operational launch site facility cost used was $7 million. A total of $2 million was apportioned to RDT&E. The remainder ($5 million) applies to investment as a constant. Any increase in flight rate is assumed to increase the number of ground crew reported in Paragraph 5.4.1.1, CER (3410) and not the facility size. Therefore CER (2510) becomes:

a. $C\ (2510) = 5 \times 10^6$

Recoverable

The recoverable concept requires the $5 million receiving, inspection, and stage facility noted above. In addition, the contractors indicate that $3 to $5 million more is required for a recovery ship. Therefore, CER (2510) becomes:

b. $C\ (2510) = 9 \times 10^6$

The assumption is made that the docking facilities for the orbiter drop tanks are sufficient to handle SRM recovery.

5.3.1.2 Production (2520)

The facilities costed in the subsequent paragraphs are for additional production facilities required by the motor manufacturer and his vendors to meet the production schedule. The CERs are based on the data derived in Paragraph 5.2.1.7.1.

Expendable

The base equation $C = 2.2\ NLM + 18$ was derived in Paragraph 5.2.1.7.1 and 25% of it was assigned to CER (1671) for RDT&E. In addition $5 million of operational facilities were removed for CER (2510). These adjustments result in

$$C\ (2520) = (1.65\ NLM + 8.5) \times 10^6$$

where

NLM = maximum number of launches in one year

Note: For values of $NLM < 10$ use $NLM = 10$

Recoverable

The base facility cost equation, derived in Paragraph 5.2.1.7.1, was adjusted to account for the effect of recovery on facility costs, for non-RDT&E use, and for non-operational use. The remainder is therefore

$$C\ (2520) = (1.24\ NLM + 5.1) \times 10^6$$

where

NLM = Maximum number of launches per year

Note: For $NLM < 10$ use $NLM = 10$

5.3.1.3 GSE (2530)

Table 5.3-2 presents the contractor supplied cost data from Ref. 1a, 2, 3, and 4 for additional ground equipment required to support the operational program. In addition these values contain spares and maintenance allowances.

There are several observations to be made from Table 5.3-2. The first is that the data are displayed as a function of average annual launch rate (total number of launches divided by total number of operational years) rather than the maximum annual launch rate used in facilities costing. Whereas facilities must be constructed to meet a peak rate, GSE and people costs are increased to meet peak rates. Total program costs can be arrived at by using the costs corresponding to average annual launch rates over the operational years of the program.

The UTC data were selected to generate the investment GSE CER because of the large degree of variance in the contractor furnished data. Table 5.3-3 shows the UTC data separated into GSE investment hardware and spares. The spares cost will be used to combine with the maintenance/spares CER (3442) in the Operations Phase.

A least square fit to the investment data produces

$$C\ (2530) = [2.03\ (NLE)^{0.802}] \times 10^6$$

where

NLE = Average launch rate (total launches divided by total years of program)

Note: For values of $NLE < 10$ use $NLE = 10$

Table 5.3-2. Investment/Operations GSE Cost Expendable/Recoverable (Millions of Dollars)

Contractors	Cost*			
	TCC	ASPC	UTC	LPC
Average Launch Rate				
44	4.0	6	47	25
35	3.3	NA	40	NA
20	2.8	NA	25	NA
10	2.3	NA	15	NA

*Includes additional GSE (Investment), GSE operational spares, and maintenance (approximately 10 years).

NA - Not Available

Table 5.3-3. UTC GSE Cost Breakdown (Millions of Dollars)

Average Launch Rate	Costs	
	Investment	Spares
44	42	5
35	36	4
20	22	3
10	13	2

5.3.2 Booster Fleet (2600)

The Booster Fleet investment cost includes the cost of the hardware and other support elements. The resulting Booster Fleet cost element (2600) is:

$$C\ (2600) = C\ (2610) + C\ (2620) + C\ (2630) + C\ (2640) + C\ (2650) + C\ (2660)$$

where:

C (2610) = New Fleet Hardware Cost
C (2620) = Refurbishment R&D Fleet Cost
C (2630) = Initial Spares Cost
C (2640) = Sustaining Tooling Cost
C (2650) = Engineering Support Cost
C (2660) = Contractor Program Management Cost

5.3.2.1 New Fleet Hardware (2610)

New Fleet Hardware investment costs consist of the cost of hardware, propellant, and transportation. The resulting cost element (2610) is:

$$C\ (2610) = C\ (2611) + C\ (2612) + C\ (2613) + C\ (2614)$$

where:

C (2611) = Stage Hardware Cost
C (2612) = SRM Hardware (less propellant) Cost
C (2613) = Propellant Cost
C (2614) = Transportation Cost

5.3.2.1.1 <u>Stage Hardware (2611)</u>

Stage hardware investment costs include the cost to manufacture all quantities of the stage structure and recovery systems for the operationally required vehicle fleet, if the boosters are to be recovered for reuse. The cost of both and learning curve values specified in Table 5.3-4 are as follows:

$$C\ (2611) = [C\ (4410) + C\ (4420)]\ [(NFTM + NFM)^{0.926} - (NFTM)^{0.926}]$$

where:

C (4410) = Stage Structure First Unit Cost
C (4420) = Recovery System First Unit Cost
NFTM = Number of Flight Test Motors
NFM = Number of New Fleet Motors

Table 5.3-4. Learning Curve Exponents (LCE)

Cumulative Average Learning Curve (%)	Learning Curve Exponent	SRM Subsystem
80	0.678	
81	0.696	
82	0.714	
83	0.731	
84	0.748	
85	0.766	
86	0.782	
87	0.799	
88	0.816	
89	0.832	
90	0.848	← Motor Subassembly & Installation
91	0.864	
92	0.880	
93	0.895	
94	0.910	
95	0.926	← Parachute System, Retro Rockets, Structures
96	0.941	← Case & Insulation
97	0.956	
98	0.971	← Nozzle, TVC, Other Sybsystems
99	0.985	
100	1.000	

$$\text{Cumulative Cost} = \left[\text{First Unit Cost}\right]\left[\text{Quantity}\right]^{(\text{LCE})}$$

5.3.2.1.2 SRM Hardware (Less Propellant) (2612)

The SRM hardware investment costs include the cost to manufacture all of the required quantities of the following items for the operational program:

- Case & Insulation
- Nozzle
- TVC
- Other Subsystems
- Motor subassembly and installation

Excluded are the final assembly, installation, and checkout tasks which involve assembly of all the motor segments, structures recovery systems, and other subsystems. These costs are incurred at the launch site and are classified as operational. The investment cost of SRM Hardware (less propellant) is derived using the First Unit Costs (TFU) for each of the elements listed above, fleet quantities, and the learning curve values specified in Table 5.3-4 as follows:

$$
\begin{aligned}
C\,(2612) = {} & [(NFTM + NFM)^{0.941} - (NFTM)^{0.941}]\,[C\,(4511)] \\
& + [(NFTM + NFM)^{0.971} - (NFTM)^{0.971}]\,[C\,(4512) + C\,(4513) \\
& + C\,(4514)] + [(NFTM + NFM)^{0.848} - (NFTM)^{0.848}]\,[C\,(4515)]
\end{aligned}
$$

where:

NFTM = Number of Flight Test Motors

NFM = Number of New Fleet Motors

C (4511) = Case & Insulation First Unit Cost

C (4512) = Nozzle First Unit Cost

C (4513) = TVC First Unit Cost

C (4514) = Other Subsystems First Unit Cost

C (4515) = Motor Subassembly & Installation First Unit Cost

5.3.2.1.3 Propellant (2613)

The cost to produce propellant for the SRM is defined to include:

- Raw materials
- Processing of propellant
  - / Lining of segments and closures
  - / Raw material preparation
  - / Propellant mixing
  - / Propellant casting, curing, and cool down

It should be noted that propellant costs estimated by UTC (Figure 5.3-1), cover, in addition to the elements listed in the above definition, raceway installation and painting. In this cost model, the cost is included in Motor Subassembly and Installation (4515). The cost to produce propellant for given program quantities is sensitive to the rate (pounds per year) of production. The principal cost considerations related to rate are:

- Material quantity discounts
- Efficient use of facilities and tooling
- Effect of overhead, primarily in facilities write-offs.

The last consideration is not significant after the facilities are fully depreciated or when government furnished. The burden portion of the propellant costs estimated by UTC includes facilities. Thiokol reports facility costs as a separate element.

The cost data base used in deriving the CER is presented in Figure 5.3-1. The cost variation as suggested above is due to differences in the definition of propellant processing and ground rules pertaining to facility costs. The CER is expressed in terms of propellant specific cost (dollars per pound) and relates to production rate as follows:

$$PSC = 1.15\, \dot{W}_p^{\,-0.0589}$$

wherein:

$\dot{W}_p$ = Peak annual pounds of propellant production

PSC = Propellant specific cost in dollars per pound

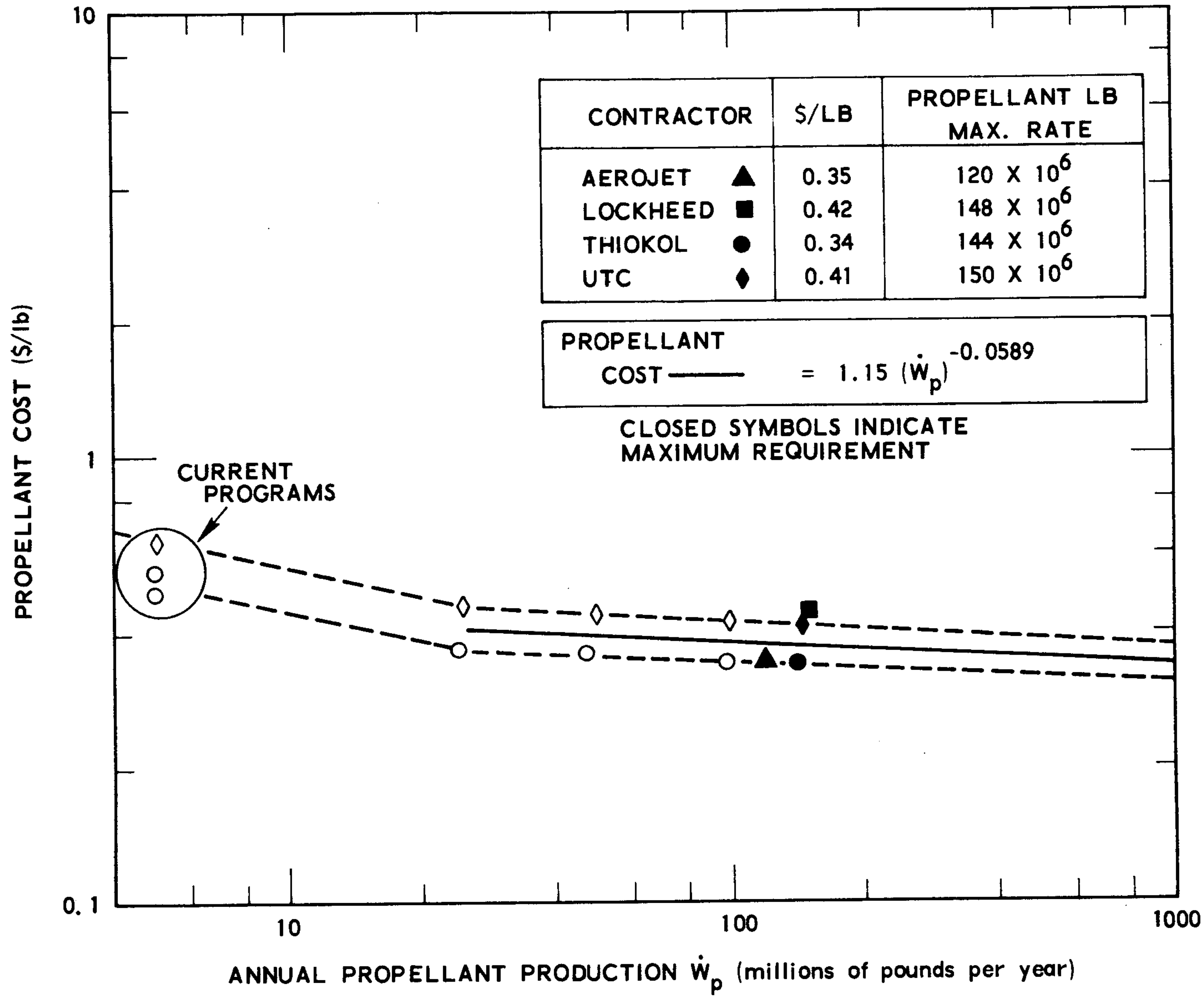


Fig. 5.3-1. Propellant Specific Costs

The CER derived costs are for solid propellants using PBAN binder. HTPB binder propellant is a potential candidate for the SRMs but, because there is no large scale rocket motor experience using this formulation; a full cost analysis was not performed by the SRM study contractors. PBAN is considered the baseline since it is a proven, fully reliable standard off-the-shelf propellant. The investment cost for propellant is computed in the following manner:

$$C\ (2613) = 1.15\ (\dot{W}_p) - 0.0589\ (WP)\ NFM$$

where:

$\dot{W}_p$ = Peak annual pounds of propellant production

= NLM (WP) NMB

WP = Propellant Weight per motor (lb)

NFM = Number of new fleet motors

NLM = Maximum launch rate per year

NMB = Number of motors per booster

For the expendable booster concept, the above formulation defines the total cost of propellants required for the operational phase of the program. For the recoverable concept, C (2613) reflects the propellant cost of only a portion of the operational requirements (initial fleet buy), the rest is calculated separately and is included in the cost for refurbished R&D Fleet Hardware (2620) and Refurbishment of Fleet Hardware (3510), Sections 5.3.2.2 and 5.4.2.1 respectively.

5.3.2.1.4 Transportation (2614)

Because of the large shipping weight involved, transportation costs are a significant part of the program costs. Shipment of the SRM can be either overland by rail (when routing restrictions on maximum dimensions or weight are not exceeded) or by waterways. Estimated shipment charges by rail or ship are shown on Table 5.3-5 for a number of possible routes depending upon manufacturing plant location and launch sites. The costs shown represent transportation modes which are not too different in elapsed time in-transit. Transportation costs are computed with the following equations:

$$C\ (2614) = NFM\ (FTR)\ (1.1)\ (WG)/1000 \qquad \text{(Railroad)}$$

or

$$= (NFB)\ (FTW) \qquad \text{(Water)}$$

where:

NFM = Number of new fleet motors

FTR = Rail freight charge per 1000 lb (See Table 5.3-5)

WG = Gross Weight per motor (lb)

NFB = Number of new fleet boosters

FTW = Water shipment cost per booster (See Table 5.3-5)

Separate freight charges are provided in Table 5.3-5 for rail transportation of loaded motors to the launch site and of empty motors back to the manufacturing plant for refurbishment. For water shipment, the indicated ship charges are for a round trip. All new and refurbished units should use this full charge. No additional charge is required for the return of empty motors since accommodation of empty motors is within the total program costs.

Table 5.3-5. Estimated Transportation Rates (1970 dollars)

A. Land Shipment (One Way)

Railroad GBL* Freight Charge, Dollars/1000 Pounds				
KSC		Shipment From (To)	WTR	
To	(From)		To	(From)
Loaded SRM	Empty SRM		Loaded SRM	Empty SRM
60	50	Northern California		
		Coyote	12	10
		Sacramento	24	20
60	50	So. California	10	9
10	9	So. Florida	60	50
60	50	Utah	30	25

B. Water Shipment (Round Trip)

Shipment Charge, Dollars/Booster				
To KSC		Shipment From	To WTR	
Carrier	Cost		Carrier	Cost
LSD	200,000	So. or No. California	Tug/Barge	6,000
Tug/Barge	8,000	So. Florida	LSD	200,000

* Government bill of lading taken at 65% of first class freight rate.

5.3.2.2 Refurbished R&D Fleet Hardware (2620)

This cost element is used only in connection with the recoverable booster concept. The cost to refurbish flight test booster hardware for the operational fleet is charged to the investment phase. Refurbishment cost includes inspection, cleaning, the reworking or refitting of consumed or damaged components, and testing. The cost to refurbish flight test vehicles is obtained from the following equation:

$$C(2620) = FREF\ (C\ (1652))$$

wherein:

FREF = Refurbishment Factor

The derivation of the refurbishment factor is discussed in Section 5.4.2.1, Refurbishment of Fleet Hardware.

5.3.2.3 Initial Spares (2630)

The booster requirements for the initial spares inventory compared to liquid propellant boosters is very low. The equivalent of one SRM and associate stage hardware is considered adequate. The cost of the initial spares is estimated as follows:

$$C\ (2630) = NISM\ [C\ (4000) + CPFH]$$

where:

NISM = Number of equivalent initial spare motors
(4000) = Motor First Unit
CPFH = New fleet hardware propellant cost per motor
= C (2613)/NFM
C (2613) = New Fleet Hardware Propellant Cost
NFM = Number of new fleet hardware motors

The initial spares are considered as spares required in the manufacturing operations, hence no transportation costs are included.

5.3.2.4 Sustaining Tooling (2640)

This element refers to the cost incurred for additional tooling, tooling maintenance, and replacement required to support the production of new fleet hardware and to refurbish flight test hardware. Costs are estimated as a percentage of the new fleet hardware costs less transportation charges. For production rates of up to and including 80 motors per year, the factor is 2.0%; for production rates in excess of 80 per year the factor is 1.4%. Derivation of these factors is described in Section 5.2.1.3. The CER for sustaining tooling is:

$$C\,(2640) = F\,(2640)\ \left|C\,(2611) + C\,(2612) + C\,(2613)\right|$$

where:

$F\ 2640 = 0.020$ for maximum production rates ≤ 80 motors per year

$F\ 2640 = 0.014$ for maximum production rates > 80 motors per year

$C\,(2611)$ = Stage Hardware Cost

$C\,(2612)$ = SRM Hardware (less propellant) Cost

$C\,(2613)$ = Propellant Cost

5.3.2.5 Engineering Support (2650)

This element refers to engineering support for configuration changes and product improvement, updating system definition and interfaces with other shuttle elements, updating the ground support definition, and providing support to the reliability, producibility, and maintainability functions. The CER was derived from contractor estimates for systems engineering in the production phase and was approximated at 1 percent of the hardware, spares and sustaining tooling costs.

The CER is written as

$$C\,(2650) = 0.01\ \left|C\,(2610) + C\,(2620) + C\,(2630) + C\,(2640)\right|$$

where:

$C\,(2610)$ = New Fleet Hardware Cost

$C\,(2620)$ = Refurbished R&D Hardware Cost

$C\,(2630)$ = Initial Spares Cost

$C\,(2640)$ = Sustaining Tooling Cost

5.3.2.6 Contractor Program Management (2660)

Contractor program management which is described in Section 5.2.1.9 applies to the cost for management of Facilities and GSE (2500) investment as well as for the Booster Fleet (2600) even though the cost is derived by taking one percent of the hardware production cost. Estimates in the SRM studies varied from a few million dollars to $30 million which in terms of personnel represents a range of from 5 to about 50 people. The costs are estimated using the following CER:

$$C\ (2660) = 0.01\ \left[C\ (2610) + C\ (2620) + C\ (2630) + C\ (2640)\right]$$

where

C (2610) = New Fleet Hardware Cost
C (2620) = Refurbished R&D Hardware Cost
C (2630) = Initial Spares Cost
C (2640) = Sustaining Tooling Cost

5.4 OPERATIONS PHASE (3000)

In this methodology the Operations Phase was divided into three major categories:

- Operations Support (3400)
- Refurbishment Support (3500)
- Spares Support (3600)

A discussion of the formulation of cost estimating relationships for each of these cost elements is provided in subsequent pages. The CERs developed herein are based on a booster with the following characteristics:

- Parallel burn
- Twin solid rocket motors
- Recoverable/expendable configurations
- Segmented solid rocket motors

The cost associated with (3000) is:

$$C\ (3000) = C\ (3400) + C\ (3500) + C\ (3600)$$

where

C (3400) = Operations Support Cost

C (3500) = Refurbishment Support Cost

C (3600) = Spares Support Cost

5.4.1 Operations Support (3400)

Costs in this category are basically those associated with personnel. However, due to the manner in which the SRM contractors furnished data, GSE spares were included with GSE maintenance cost (3442). In addition, the costs were defined as a function of annual launch averages which,when multiplied by the number of years of operations,gives the total program cost of the specified function. This has the effect of creating higher than expected early year costs and lower than expected later year costs. Finally, the data indicated that a minimum sized crew can handle up to 10 launches per year. Therefore, when the average number of launches per year (NLE) is less than 10, ten should be used in the CER for NLE.

The cost for Operations Support (3400) is

$$C\ (3400) = C\ (3410) + C\ (3420) + C\ (3430) + C\ (3440) + C\ (3450) + C\ (3460)$$

where

C (3410) = Installation, Assembly, C/O, & Launch Support Cost
C (3420) = Recovery Operations Cost
C (3430) = Replacement Training Cost
C (3440) = Facilities & GSE Maintenance Cost
C (3450) = In-Plant Engineering Support Cost
C (3460) = Contractor Program Management Cost

5.4.1.1 Installation, Assembly, Checkout & Launch Support (3410)

This cost element includes cost associated with receiving, inspection, and storage of booster components at the launch site, booster preflight assembly, checkout, maintenance, and launch support.

Aerojet and UTC compile cost for the above activities under the functional heading of Operations Support and Flight Operations, respectively. Lockheed and Thiokol show the cost for these activities under two functional groupings: Operations Support and Installation, Assembly and, Checkout.

In Table 5.4-1 are presented the data from Ref. 1a, 2, 3 and 4. It is evident that a large difference, from 1 million dollars to 19 million dollars, exists in the average cost reported. Since this is primarily a handling function, an effort was made to correlate the cost data with number of segments being handled. This effort met with only slight success. In the case of the average annual launch rate of 44, the cost for this activity ranges from 1/2% (ASPC and TCC) to 7% (LPC) of the direct operating cost per launch for the expendable configuration. The UTC data are about 2% of the direct operating cost per flight at the average annual launch rate of 44. In addition, UTC furnished data for the 35, 20 and 10 average annual launch rates. A log linear equation was fitted to the UTC data to obtain the following CER.

$$C\ (3410) = 37.5 \times 10^4\ (NLE)^{0.737}\ (NYO)$$

where

NYO = Number of years operational

NLE = Average launches per year

Note: For values of NLE < 10 use NLE = 10

Table 5.4-1. Installation Assembly, Checkout, and Launch Support Cost Data (Millions of Dollars per Year)

Contractors / Launch Rate	ASPC	TCC	UTC	LPC
44	1.06	1.10	6.27	19.20
35	NA	.93	5.20	NA
20	NA	.79	3.13	NA
10	NA	.66	2.14	NA

5.4.1.2 Recovery Operations (3420)

Costs covered in this category include those associated with water retrieval and the handling and inspection required to deactivate, wash, inspect, and transport the recoverable booster.

Table 5.4-2 shows the spread of the recovery cost data from Ref. 1a, 2, and 4 as well as the results of some inhouse studies. Inhouse study conclusions are that the recovery effort could be subcontracted on a yearly basis and the yearly costs would remain constant for 1 to 60 recoveries. Since this value is highly dependent on a recovery concept, it is recommended that a conservative 4 million dollars per year be used for this cost element which results in the following CER:

$$C\ (3420) = 4 \times 10^6\ (NYO)$$

where

NYO = Number of years operational

Table 5.4-2. Recovery Operations Cost Comparison (Millions of Dollars/Year)

Peak Launch Rate	60/Year		10/Year	
	Min.	Max.	Min.	Max.
SRM Contractors	1.7	5.6	0.3	1.4
Inhouse Estimates	1.0	4.0	1.0	4.0

5.4.1.3 <u>Replacement Training (3430)</u>

Costs associated with this category are for the training of qualified ground personnel to perform the function described in Paragraph 5.4.1.1. Ref. 5 indicated that a replacement factor of 25 percent of the initial training costs per year was required. Therefore, CER (3430) becomes:

$$C\ (3430) = 0.25 \left[C\ (1640) \right] NYO$$

where

NYO = Number of years operational

C (1640) = Initial Training Cost

5.4.1.4 <u>Facilities & GSE Maintenance (3440)</u>

The costs covered in this category are generally estimated as a percent of original costs and are for the maintenance of the booster-peculiar operational facilities and GSE.

$$C\ (3440) = C\ (3441) + C\ (3442)$$

where

C (3441) = Operational Facilities Cost

C (3442) = GSE Cost

5.4.1.4.1 Operational Facilities (3441)

Reference 5 states that 5 percent of the original facility costs per year for maintenance costs is a reasonable estimate. This is somewhat substantiated by the overall 4 percent value shown in Ref. 13. The RDT&E and Investment point estimate of operational facility requirements were $7 million for the expendable configuration and $11 million for the reusable concept. Therefore, CER (3441) for the expendable and recoverable configurations is as follows:

$$C\ (3441) = 35 \times 10^4\ (NYO)\ (\text{Expendable})$$

$$C\ (3441) = 45 \times 10^4\ (NYO)\ (\text{Recoverable})$$

where

NYO = Number of years operational

5.4.1.4.2 GSE (3442)

Costs in this category contain the maintenance and spares costs for the GSE purchased in the RDT&E and Investment Phases. Table 5.3-2 indicates that the spares cost average about 1.2 percent of the Investment Phase GSE cost $\left[C\ (2530) \right]$ per year. Assuming that the maintenance cost per year is 5 percent of the total GSE buy $\left[C\ (1672) + C\ (2530) \right]$, the cost for GSE maintenance and spares in the Operational Phase becomes:

$$C\ (3442) = \left[0.05\ C\ (1672) + 0.062\ C\ (2530) \right]\ NYO$$

where

NYO = Number of years operational
C (1672) = RDT&E GSE Cost
C (2530) = Investment GSE Cost

5.4.1.5 In-Plant Engineering Support (3450)

In-Plant support is not directly a function of flight rate. Ref. 14 and 15 indicate about 20 men are required for this function and, at $40,000 a year, CER (3450) becomes:

$$C\ (3450) = 0.8 \times 10^6\ (NYO)$$

where

NYO = Number of years operational

5.4.1.6 Contractor Program Management (3460)

The cost of program management for operations support functions was estimated at 4 percent of the basic cost of that function based on a consensus of the SRM Study inputs. The CER is written as:

$$C\ (3460) = 0.04\ \left[C\ (3410) + C\ (3420) + C\ (3430) + C\ (3440) \right]$$

where :

C (3410) = Installation, Assembly, Checkout and Launch Support Cost

C (3420) = Recovery Operations Cost

C (3430) = Replacement Training Cost

C (3440) = Facilities & GSE Maintenance Cost

5.4.2 Refurbishment Support (3500)

This support refers to the cost to refurbish reusable fleet hardware and includes propellants, transportation, replacement parts, sustaining tooling, engineering support, and program management.

$$C\ (3500) = C\ (3510) + C\ (3520) + C\ (3530) + C\ (3540)$$

where

C (3510) = Refurbishment of Fleet Hardware Cost

C (3520) = Sustaining Tooling Cost

C (3530) = Engineering Support Cost

C (3540) = Contractor Program Management Cost

5.4.2.1 Refurbishment of Fleet Hardware (3510)

The cost to refurbish the fleet hardware involves all the effort performed at the manufacturing facility to recondition reusable SRM hardware, replace expendable items, load propellant, and transport from and back to the launch site. These costs are estimated using the following CER:

$$C\ (3510) = FREF \left[1 - \frac{1}{NUSE}\right] \left|(TNOL)(NMB)\right| \left|C\ (2610)/NFM\right|$$

where:

NMB = Number of motors per booster
NUSE = Number of uses per motor
TNOL = Total Number of Operation Launches
FREF = Refurbishment Factor
C (2610) = New Fleet Hardware Cost
NFM = Number of new fleet hardware motors

Derivation of Refurbishment Factor, FREF

The factor, FREF, represents a weighted average of the factors identified in Table 5.4-3. The factors represent the ratio of refurbishment cost to the original cost of each item. These factors were obtained from the Thiokol report (Ref. 3) and are used here on an interim basis pending further study. Because transportation and propellant costs are treated separately from the stage hardware and SRM hardware, they are not included in the replacement factor Table 5.4-3, but are nevertheless involved in the calculation of FREF. For each of these items the factor is 100%. The mathematics of deriving FREF using the individual component refurbishment cost factors is detailed in the example in Table 6.4-1, Applications of Sample Problems.

Table 5.4-3. SRM Booster Candidate Refurbishment Factors (CRF)

Cost Element Number	SRM Booster Component	Symbols	Candidate Reburbishment Factors (%)
4410	SRM Stage Structure	CRFSS	15
4420	Recovery System	CRFR	47
4511	Case and Insulation	CRFCI	20
4512	Nozzle	CRFN	90
4513	TVC	CRFTV	45
4514	Other Subsystems	CRFO	80

5.4.2.2 Sustaining Tooling (3520)

Cost element (3520) pertains to the cost of sustaining tooling for refurbished fleet hardware. The same tooling cost factor used in Section 5.3.2.4 provides the CER in the form:

$$C\ (3520) = F\ 3520\ \left[0.95\ C\ (3510)\right]$$

where the tooling cost factor is:

$F\ 3520 = 0.020$ for maximum refurbishment rates ≤ 80 motors per year
$\ 0.014$ for maximum refurbishment rates > 80 motors per year
$C\ (3510)$ = Refurbishment of Fleet Hardware Cost

In order to exclude the transportation cost from C (3510) an approximate factor of 0.95 is used to obtain actual hardware cost.

5.4.2.3 Engineering Support (3530)

This CER is identical to that described in Section 5.3.2.5 and,when applied to refurbishment it is written as:

$$C\ (3530) = 0.01\ \left[C\ (3510) + C\ (3520)\right]$$

where

$C\ (3510)$ = Refurbishment of Fleet Hardware Cost
$C\ (3520)$ = Sustaining Tooling Cost

5.4.2.4 Contractor Program Management (3540)

This CER is identical to that described in Section 5.3.2.6 and when applied to refurbishment it is written as

$$C\ (3540) = 0.01\ \left[C\ (3510) + C\ (3520)\right]$$

where

$C\ (3510)$ = Refurbishment of Fleet Hardware Cost
$C\ (3520)$ = Sustaining Tooling Cost

5.4.3 Spares Support (3600)

Spares support includes the cost to manufacture and transport acceptable replacement spares for the operational fleet. Based on results of discussions with the SRM study contractors, two equivalent motors are sufficient to support operational programs having up to a maximum of 440 launches over a ten year period. The cost of this element which includes the stage hardware and primary SRM is based on first unit cost and is estimated as follows:

$$C\ (3600) = NSSM \left[C\ (4000) + CPFH + CTFH\right]$$

where:

NSSM = Number of equivalent spares support motors

C (4000) = Motor First Unit Cost

CPFH = New fleet hardware propellant cost per motor

= C (2613)/NFM

CTFH = New fleet hardware transportation cost per motor

= C (2614)/NFM

C (2613) = New Fleet Hardware Propellant Cost

NFM = Number of new fleet hardware motors

C (2614) = New Fleet Hardware Transportation Cost

5.5 FIRST UNIT COST (4000)

This element refers to the First Unit Costs of the following elements of the booster:

- Stage Structure
- Recovery System
- Case + Insulation
- Nozzle
- Other
- Motor Subassembly

The costs include those for all direct labor, material, subcontract, and overhead incurred in the manufacture of the elements enumerated above. Sustaining tooling, engineering and program management costs are excluded.

$$C\ (4000) = C\ (4400) + C\ (4500)$$

where

C (4400) = Stage First Unit Cost

C (4500) = Propulsion First Unit Cost

DERIVATION

The subsystem First Unit Cost was determined generally from contractor cost estimates for flight test hardware and production hardware which provided cumulative costs for two quantities. With these data points, learning curve rates were computed and First Unit Costs obtained. When learning curve rates were specified by the contractor,these were used instead. The learning curves used are presented in the sections devoted to the particular subsystems.

DISCUSSION

The CERs developed for the SRM Cost Model are listed in Table 5.5-1. For the most part all are based on data analyzed in the contractors' SRM Booster Studies (Ref. 1a, 2, 3, and 4) which were evaluated against information from other sources and studies. All costs were intentionally expressed as a function of a single variable,weight. Other subsystem characteristics that were found to influence cost are included in the CER as complexity factors.

Table 5.5-1. First Unit Cost Estimating Relationships

Cost Element Number	Subsystem	Cost Estimating Relationships
4410	Stage Structure	$F4410 \left[(185.8)\,(WSS)^{0.821}\right]$
4421	Parachute	$50\,(WPS)$
4422	Retro Rocket	$15\,(WRR)$
4511	Case & Insulation	$F4511 \left[(838.17)\,(WCI)^{0.623}\right]$
4512	Nozzle	$F4512 \left[(252.44)\,(WN)^{0.793}\right]$
4513	TVC	$(32876)\,(WTUC)^{0.263}$
4514	Other	$(1503)\,(WO)^{0.660}$
4515	Motor Subassembly and Installation	$.07 \left[C\,(4400) + C\,(4511)\right] + C\,(4512) + C\,(4513) + C\,(4514)$

Available data from the studies and other sources suggest that the production rate has a small unmeasurable influence on subsystem hardware-costs, however; production rate is a significant factor in the cost of propellant.

5.5.1 Stage (4400)

The First Unit Cost of the Stage includes the cost of the Stage Structure (attach structure, fairings and separation system) (4410) and Recovery system (Parachutes and related components, retro rockets) (4420), or

$$C\ (4400) = C\ (4410) + C\ (4420)$$

where

C (4410) = Stage Structure Cost

C (4420) = Recovery System Cost

5.5.1.1 Stage Structure (4410)

The First Unit Cost for Stage Structure covers the attach structures, fairings, fore and aft skirts, and separation system. Except for UTC, the magnitude of the costs estimated by the other contractors could not be rationalized and were, therefore, not used in developing the CER. The UTC estimate based on the program quantity related to the 60 SRM per year peak production rate was used. A 96% log-linear cumulative average learning curve was applied to the UTC average unit cost to obtain a First Unit Cost (Fig. 5.5-1). With this value as a reference point to determine the level or magnitude of structures costs, the cost/weight exponential relationship for the STS Body/Tank Structure First Unit Cost CER (Ref. 6) was used. The resultant CER (Fig. 5.5-2) is:

$$C\ (4410) = (F\ 4410)\ (185.8)\ (WSS)^{0.821}$$

where

$$\begin{aligned} F\ 4410 &= 1.00 \text{ parallel configuration} \\ &= 1.10 \text{ series configuration} \end{aligned}$$

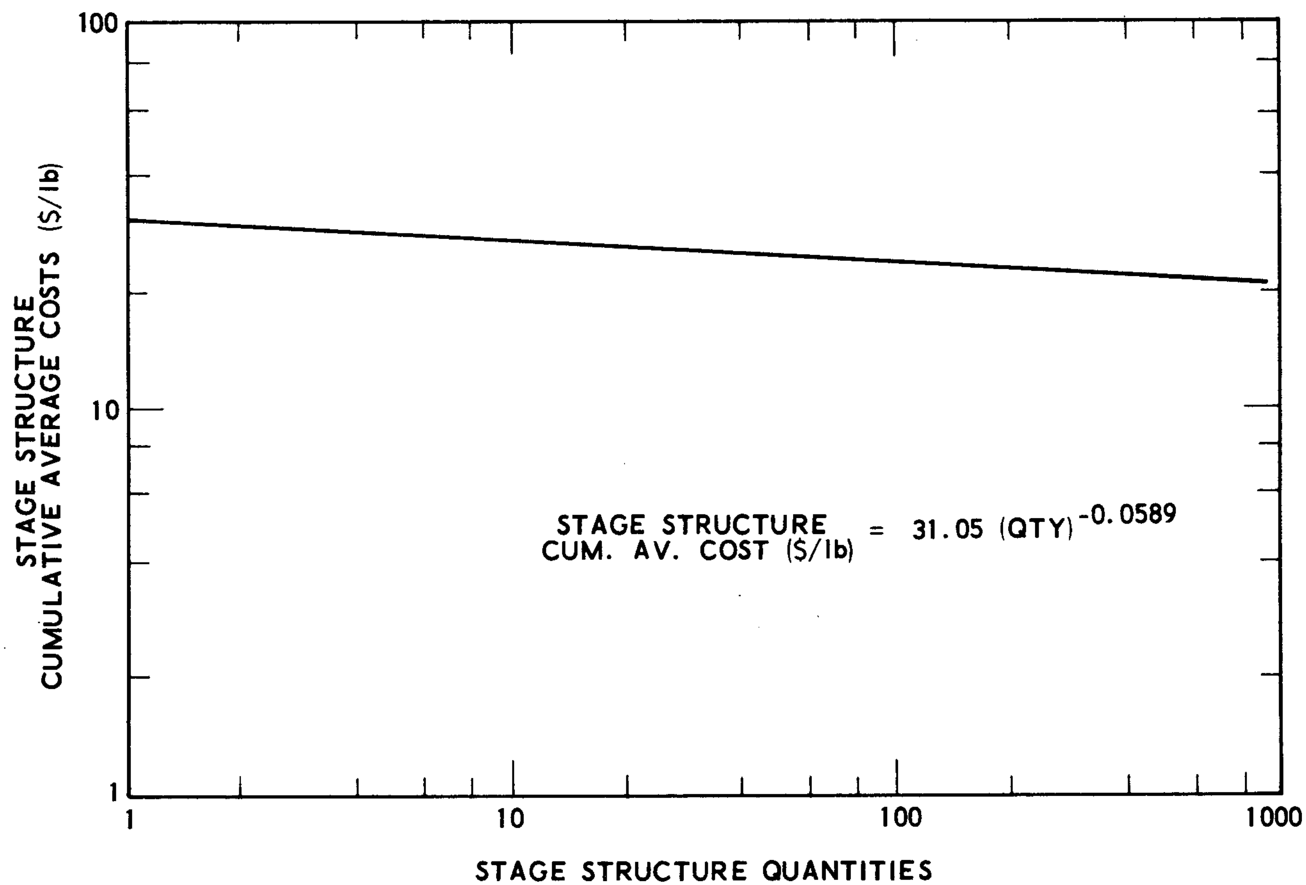


Fig. 5.5-1. Stage Structure Cumulative Average Costs

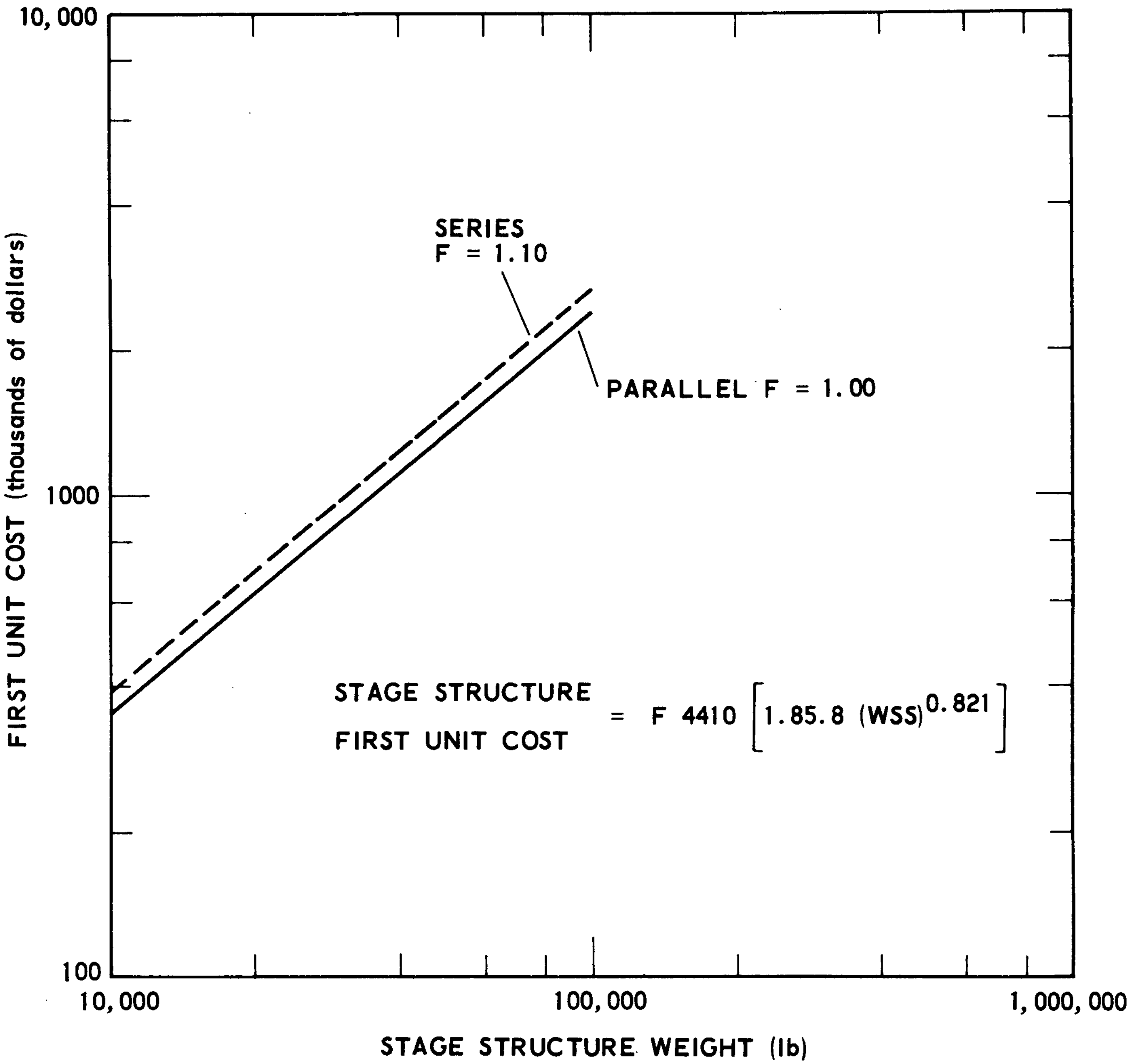


Fig. 5.5-2. Stage Structure First Unit Costs

5.5.1.2 Recovery System First Unit Cost (4420)

The Recovery System First Unit Cost is equal to the sum of Parachute (4421) and Retrorocket (4422) First Unit Costs, or

$$C\ (4420) = C\ (4421) + C\ (4422)$$

where

$C\ (4421)$ = Parachute System Cost
$C\ (4422)$ = Retrorocket System Cost

5.5.1.2.1 Parachute System (4421)

The major components included in the parachute recovery system are:

- Drogue and main chutes
- All deployment accessories
- Flotation bags in inflation devices
- Beacons and other retrieval aids

The CER for the parachute system was derived using data from other sources to supplement the cost in the SRM contractors' studies. In the SRM studies, average unit costs for this system ranged from \$20 to \$50 per lb. However, since the information required to construct a valid CER was not available, ROM estimates were made. The First Unit Cost of the parachutes alone were estimated at \$75/lb and \$20/lb for the recovery aids and accessories, resulting in a composite first unit cost of \$50/lb for the parachute recovery system. The equation for this CER is:

$$C\,(4421) = (50)\ (WPS)$$

where

WPS = Weight of parachute system

5.5.1.2.2 Retrorocket System

The retrorocket system CER for use in SRM recovery was based on cost information in Ref. 9 and 12. A ROM estimate for motors of the size likely to be used as part of an SRM recovery system is \$15/lb for the First Unit. The equation for the CER is:

$$C\ (4422) = 15\ (WRR)$$

where

WRR = Weight of retrorocket system

5.5.2 Propulsion (4500)

The Propulsion First Unit Costs consists of the costs of the SRM hardware (less propellant) and a secondary propulsion system, if required. This cost element (4500) is

$$C\ (4500) = C\ (4510) + C\ (4520)$$

where

C (4510) = Primary SRM (less propellant) Cost
C (4520) = Secondary Propulsion Cost

5.5.2.1 Primary – SRM (Less Propellant) (4510)

The First Unit Cost of this element consists of SRM hardware and assembly and subsystem installation. The cost of element (4510) is

$$C\ (4510) = C\ (4511) + C\ (4512) + C\ (4513) + C\ (4514) + C\ (4515)$$

where

C (4511) = Case and Insulation Cost
C (4512) = Nozzle Cost
C (4513) = TVC Cost
C (4514) = Other Cost
C (4515) = Motor Subassembly and Installation Cost

5.5.2.1.1 Case & Insulation (4511)

The First Unit Cost for SRM Case and insulation includes the following hardware items:

- Forward closure assembly
- Cylinder assembly (center segment)
- Aft closure assembly
- Nozzle adapter
- Thrust termination assembly
- Attaching assemblies
- Insulation

In Table 5.5-2 the cost base is summarized and the learning curve rates used in deriving the First Unit Cost CER for case and insulation are listed (Fig. 5.5-3 and 5.5-4),

$$C\ (4511) = F\ 4511\ \left[(838.17\ (WCI)^{0.623}\right]$$

where

WCI = Weight of case and insulation in lb
F 4511 = 1.02 for thrust termination

When the complexity factor F 4511 is equal to 1.0, the CER provides the cost of a 3.96 M (156 inch) diameter SRM insulated motor case made of D6aC low alloy steel spin formed from 13,608 kg (30,000 lb) billets, see Table 5.5-3.

The Case and Insulation CER was developed by first constructing the dollar per pound curve illustrated in Figure 5.5-4. The straight line logarithmic cost/weight relationship does not reflect a statistical fit to the data points, but was based on an analysis of estimates related to Rohr's experience on 3.05 m (120 in.) diameter and evaluation of 3.96 m (156 in.) diameter insulated motor cases. From this analysis, the exponential relationship -0.377 of weight to cost (i.e., slope of the curve) was derived. Since the vendor estimates represent the FOB costs to the customer, those estimates were not used to determine the level of the cost curve denoted by the "a" value in the generalized expression for the curve, $Y = a\ X^b$. The level of

Table 5.5-2. SRM Case and Insulation First Unit Cost CER Data Base

Contractor	SRM Config.	No. of Center Sgmts.	Weight		Cost		Learning Curve (%)	SRM Quantity
			kg	(lb)	Total Production ($ × 10^6)	First Unit ($/lb)		
ASPC	P	2	37,943	83,650	655.11	10.35	98.5	880
	P	3	53,215	117,320	782.24	8.81	98.5	880
LPC	P	7	49,597	109,344	793.37	13.57	95.0	883
	S	6	44,112	97,253	992.78	13.13	95.0	1,323
TCC	P	3	52,010	114,662	763.81	10.23	97.0	880
	S	4	61,867	136,394	1,313.41	10.04	97.0	1,320
UTC	P	3	52,508	115,762	907.71	11.70	97.0	876

P - Parallel

S - Series

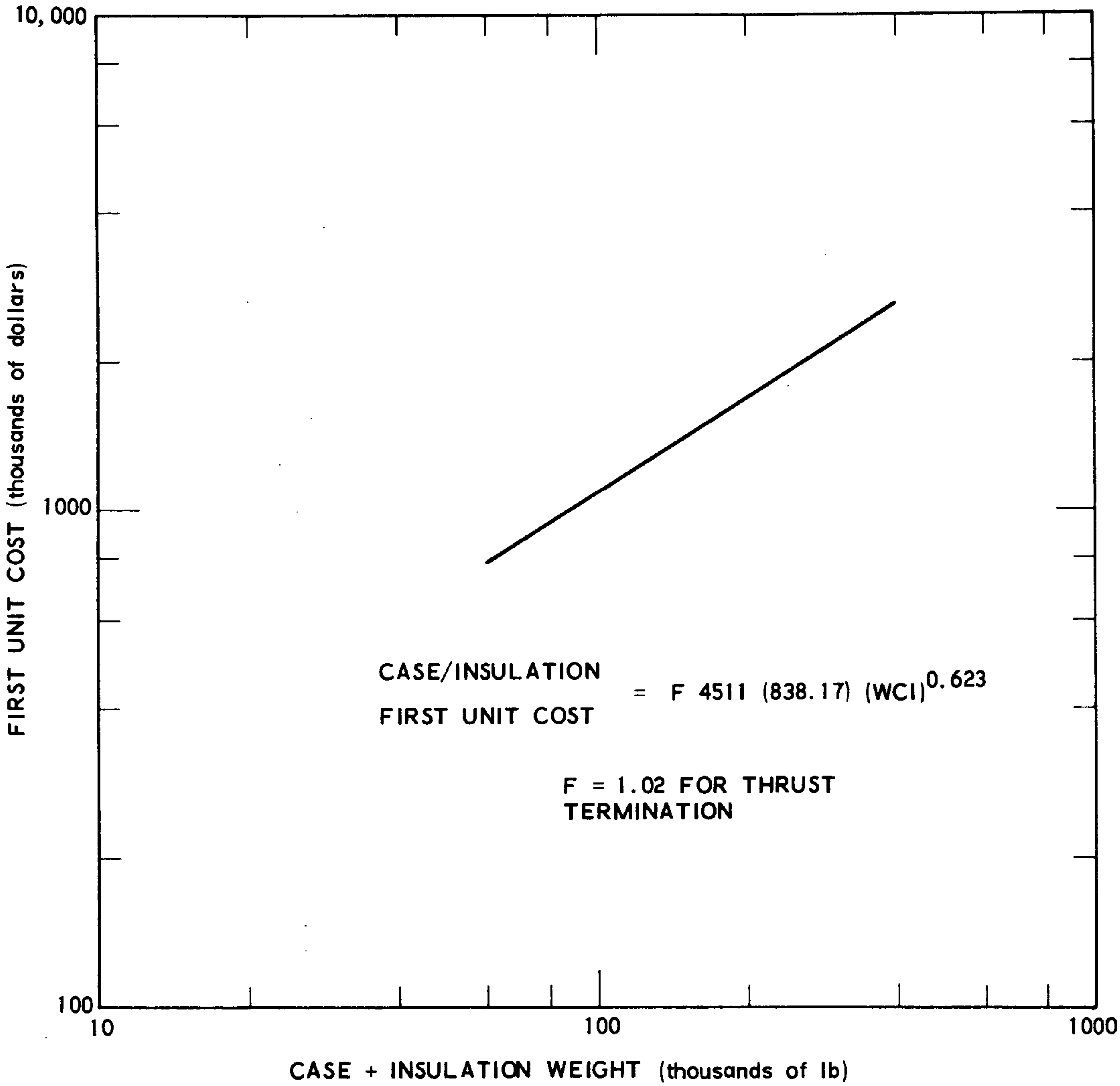


Fig. 5.5-3. Case and Insulation First Unit Costs

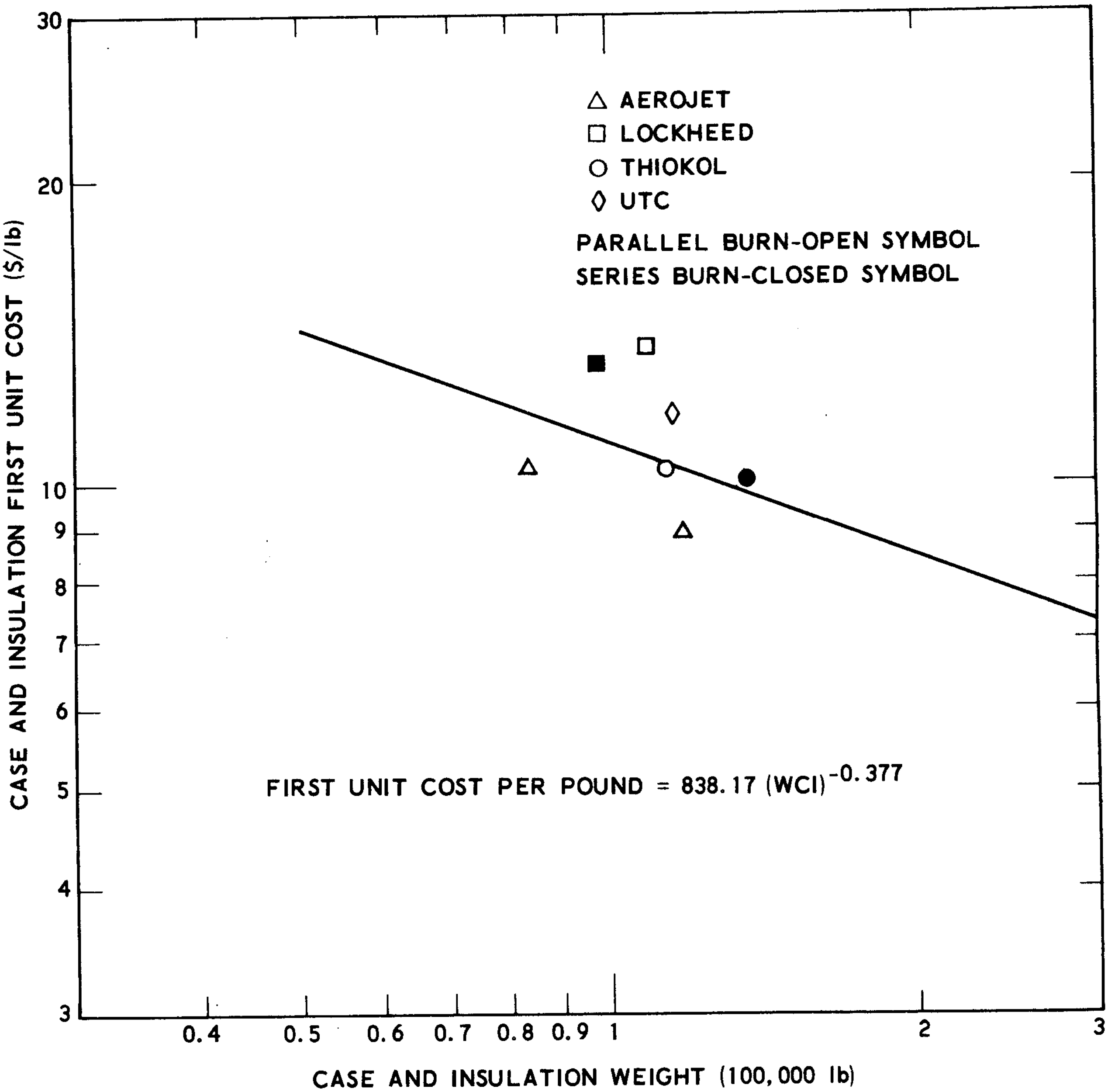


Fig. 5.5-4. Case and Insulation Specific First Unit Costs

Table 5.5-3. Case Material Cost Complexity Factors

Material	Case Material Characteristics			Case Unit Cost Complexity Factors		
	Wt/Area Factor(1)	Material Cost Factor(2)	Processing Cost Factor(3)	R. Krueger(3)	UTC(2)	Consensus
D6aC	1.0	1.0	1.0	1.0	1.0	1.0
HY - 140/150	1.3-1.46	1.05	0.9	0.96-1.0	0.94-0.99	~1.0
Maraging Steel 18% Ni (200)	1.06	1.9	0.9	0.90-0.97	0.94-1.0	~1.0

(1) Aerospace and SRM Contractors (Worksheets)

(2) Study of Solid Rocket Motors For a Space Shuttle Booster, Volume II, UTC, 15 March 1972

(3) "Comparison of Large Solid Rocket Motors Optimized for Recurring Cost of Gross Weight (U)," Briefing, 7 May 1969.

the curve selected was considered as best representing the magnitude of case and insulation costs as indicated by the contractors' estimates.

Experience using other likely candidate case materials (HY - 140/150, maraging steels) for solid motor is nonexistent. The studies performed thus far indicate no clear cost advantage for any of the high or low alloy steels that merit serious consideration as case material. The findings on these materials are shown in Table 5.5-4.

Other design and fabrication aspects of the SRM considered as potential cost parameters were segment size, number of segments, welded versus mechanically joined segments, and thrust termination. The cost effect of incorporating thrust termination in the forward closure is small and can be adjusted by a 1.02 complexity factor. The cost sensitivity of the other items could not be determined from available data sources.

Table 5.5-4. SRM Nozzle Assembly First Unit Cost CER Data Base

Contractor	Parallel or Series Config.	Movable or Fixed	Nozzle Assembly Weight		Cost		Learning Curve (%)	Production Quantity
			(kg)	(lb)	Total Production ($ × 10^6)	First Unit $/lb		
ASPC	P	M	5,613	12,377	318.77	35.66	98	880
	P	F	4,925	10,860	255.77	32.61	98	880
LPC	P	M	10,990	24,234	402.14	31.05	95	883
	S	M	11,566	25,504	584.36	29.48	95	1,323
TCC	P	F	6,440	14,200	225.70	29.83	95	880
	P	M	7,425	16,373	295.73	33.90	95	880
	S	M	7,965	17,563	397.48	29.18	95	1,320
UTC	P	M	8,015	17,674	331.38	26.08	98	876
	S	M	8,015	17,674	492.39	26.14	98	1,314

P - Parallel
S - Series
F - Fixed
M - Movable

5.5.2.1.2 Nozzle (4512)

The flexible or movable nozzle design was selected as the baseline for the nozzle First Unit Cost (CER), (Fig. 5.5-5 and 5.5-6),

$$C\ (4512) = F\ 4512 \left|(252.44)\ (WN)^{0.793}\right|$$

where

WN = Weight of nozzle in lb

F 4512 = 1.0 for movable nozzle

= 0.88 for fixed nozzle

The availability of more data points (Table 5.5-4) for the movable nozzle provided a sounder basis for establishing a cost relationship. The two cost values for the fixed nozzle served to determine the magnitude of the complexity value for this design relative to the movable nozzle.

Nozzle weight serves as a good parameter for the CER. Changes to other design characteristics such as throat diameter, exit diameter, and expansion ratios induce proportional changes to the nozzle weight.

The data base used reflected costs for nozzles made of carbon phenolic, silica phenolic, fiberglass and low cost steel (for the forward exit cone). A different mix of materials, particularly one which includes aluminum honeycomb, requires the determination of an appropriate F value.

The first unit cost of a movable nozzle is on the average higher than that for a fixed canted nozzle. The different gimbaling mechanism designs recommended by the four study contractors for thrust vector control do not appear significant in terms of production cost sensitivity.

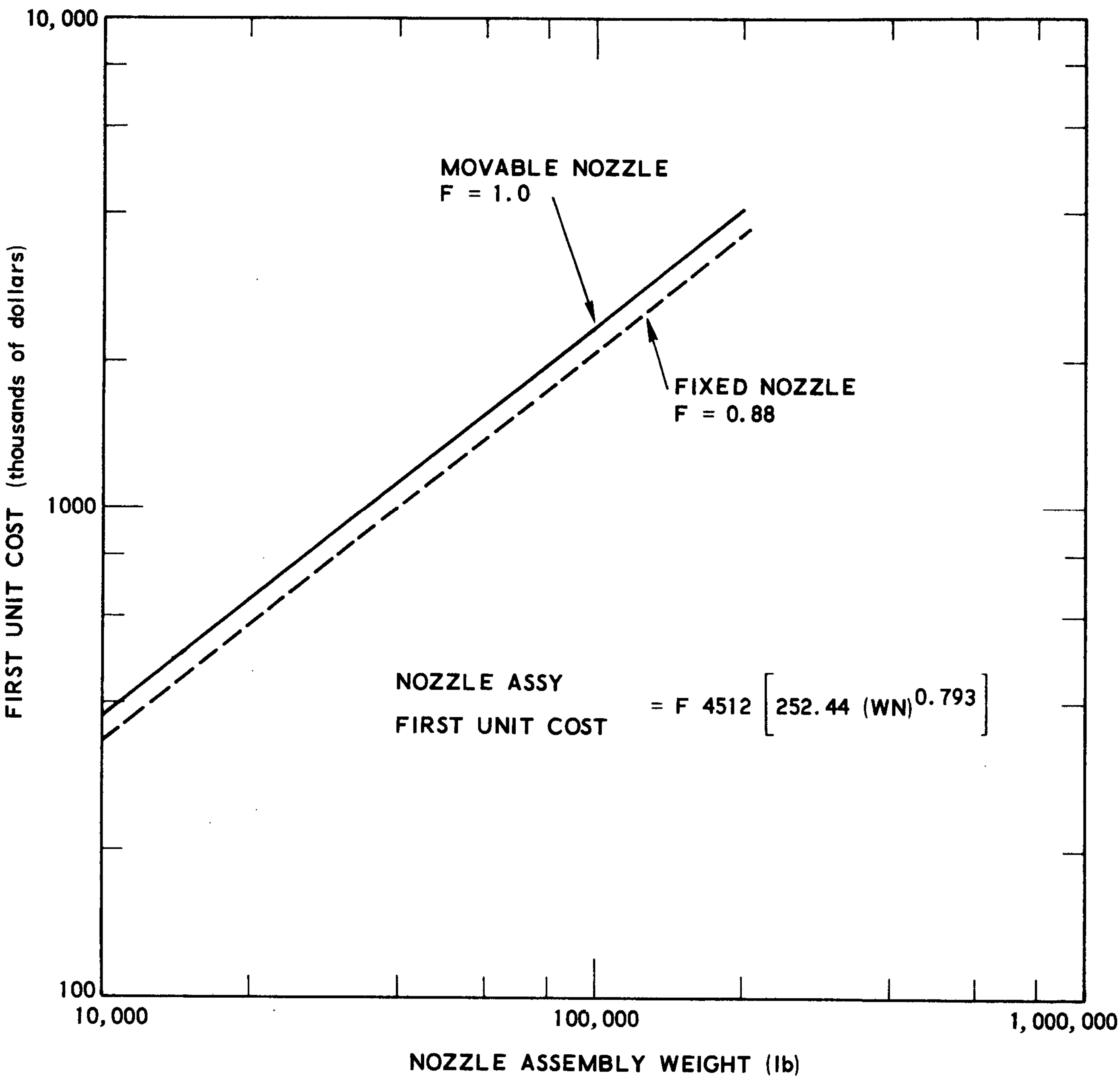


Fig. 5.5-5. Nozzle Assembly First Unit Costs

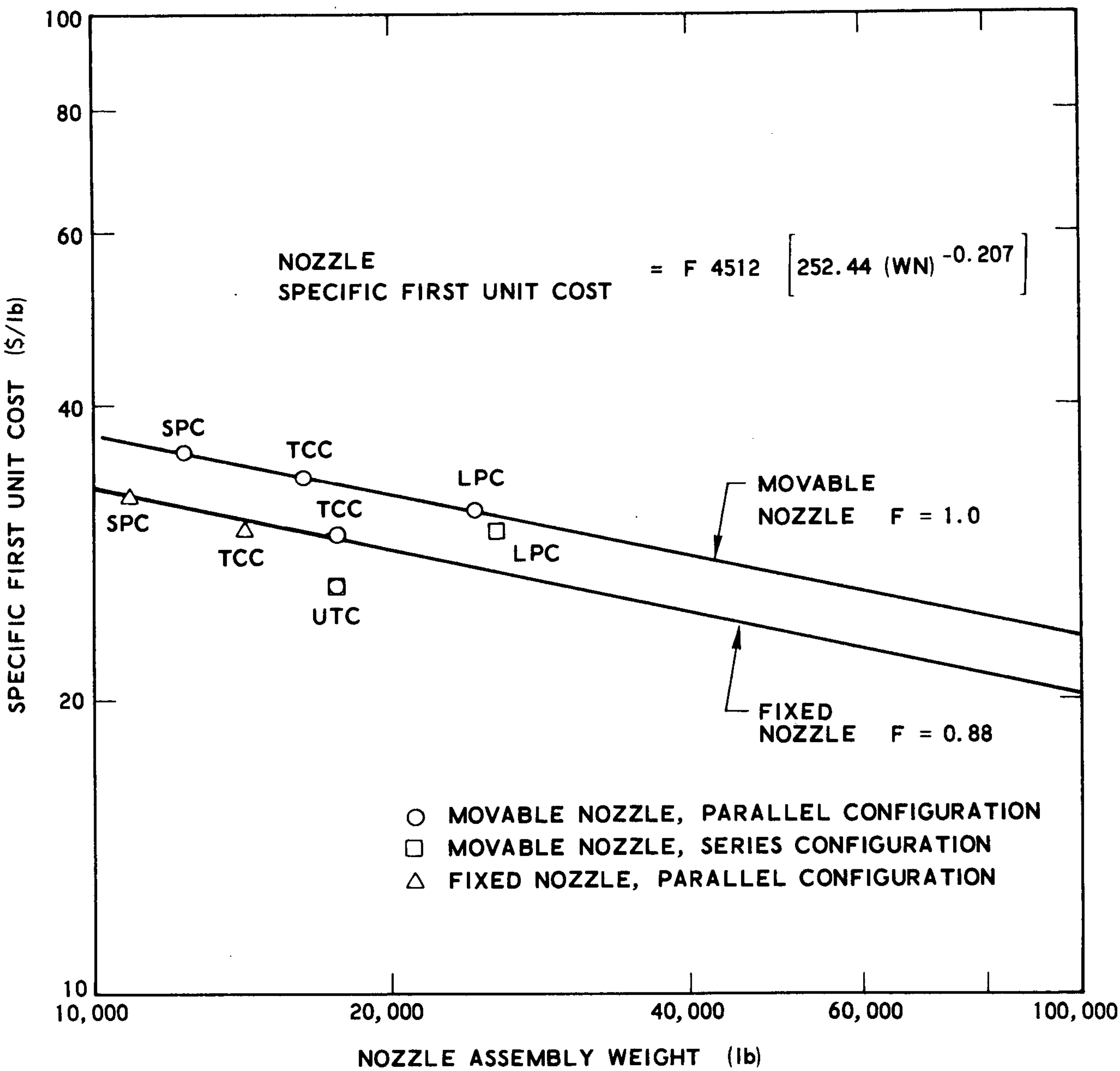


Fig. 5.5-6. Nozzle Assembly Specific First Unit Costs

5.5.2.1.3 TVC (4513)

The major components of the TVC System for the SRM booster consists of a nozzle gimbaling mechanism, actuators to position the nozzle, and an auxiliary power system to drive the actuators. The TVC First Unit Cost CER, $32876\ (WTVC)^{0.263}$, only includes the actuators and auxiliary power; cost of the gimbaling mechanism is incorporated into the movable nozzle CER. The TVC First Unit Cost CER is shown in Fig. 5.5-7.

The cost data which were used as the basis for the deriving the CER are presented in Table 5.5-5. The dollar per lb data scatter and curve fit thereto is depicted in Fig. 5.5-8.

Table 5.5-5. Data Base and Derivation of First Unit Cost CER for TVC

SRM Configuration	Weight of TVC - kg (lb)			First Unit Cost (Dollars per Pound)[1]		
	LPC	TCC	UTC	LPC	TCC	UTC
Series	454 (1,000)	1,025 (2,260)	421 (930) 490 (1,080)	$39.3	$105.4	$223.7[a] $109.7[b]
Parallel	4,536 (10,000)	977 (2,154)	490 (1,080)	$35.6	$107.5	$187.1[c]

(1) Based on 95% Log-Linear Cumulative Average Learning Curve

(a) S-6 - 120

(b) S-3 - 156

(c) P-2 - 156

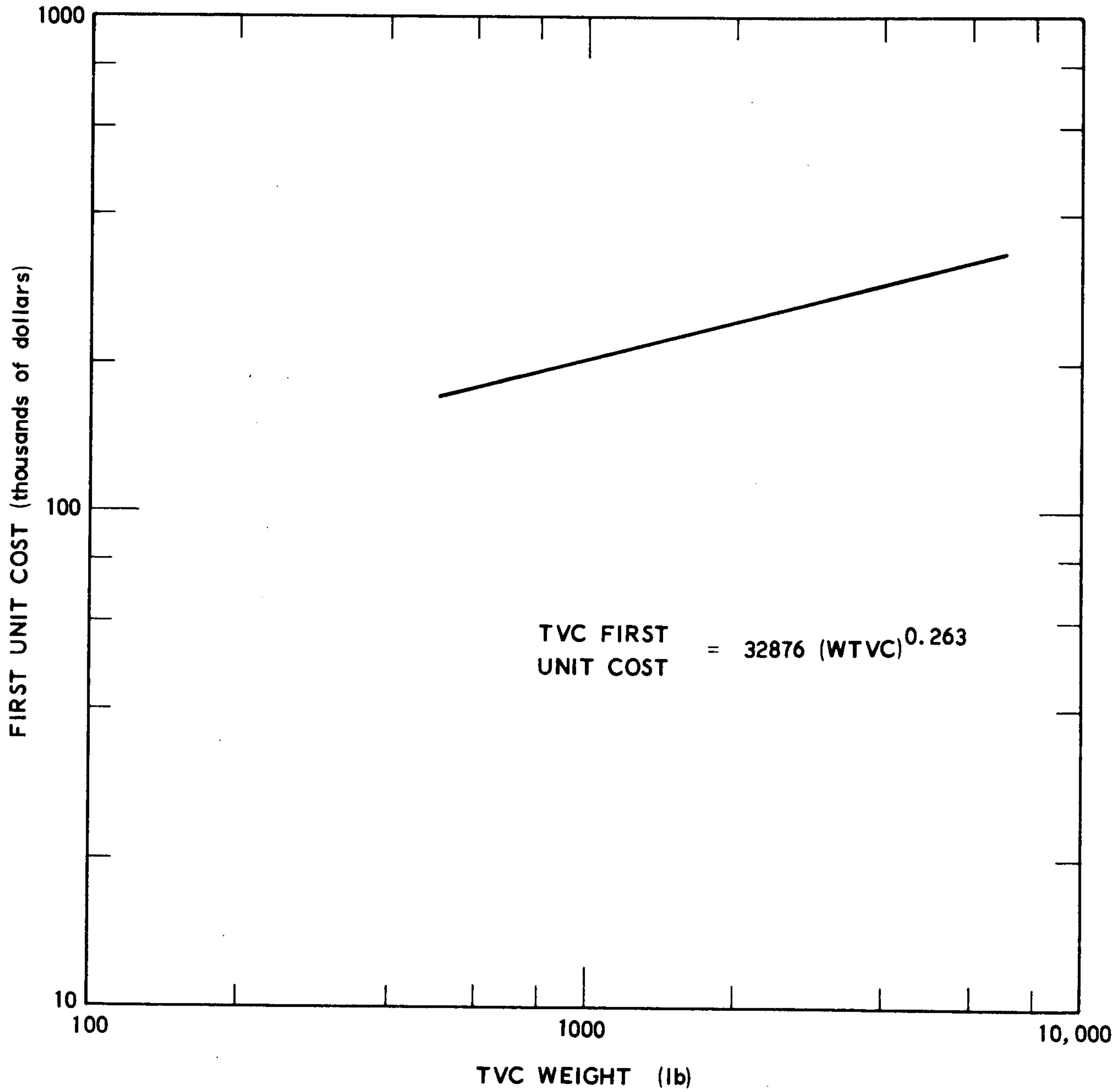


Fig. 5.5-7. TVC First Unit Costs

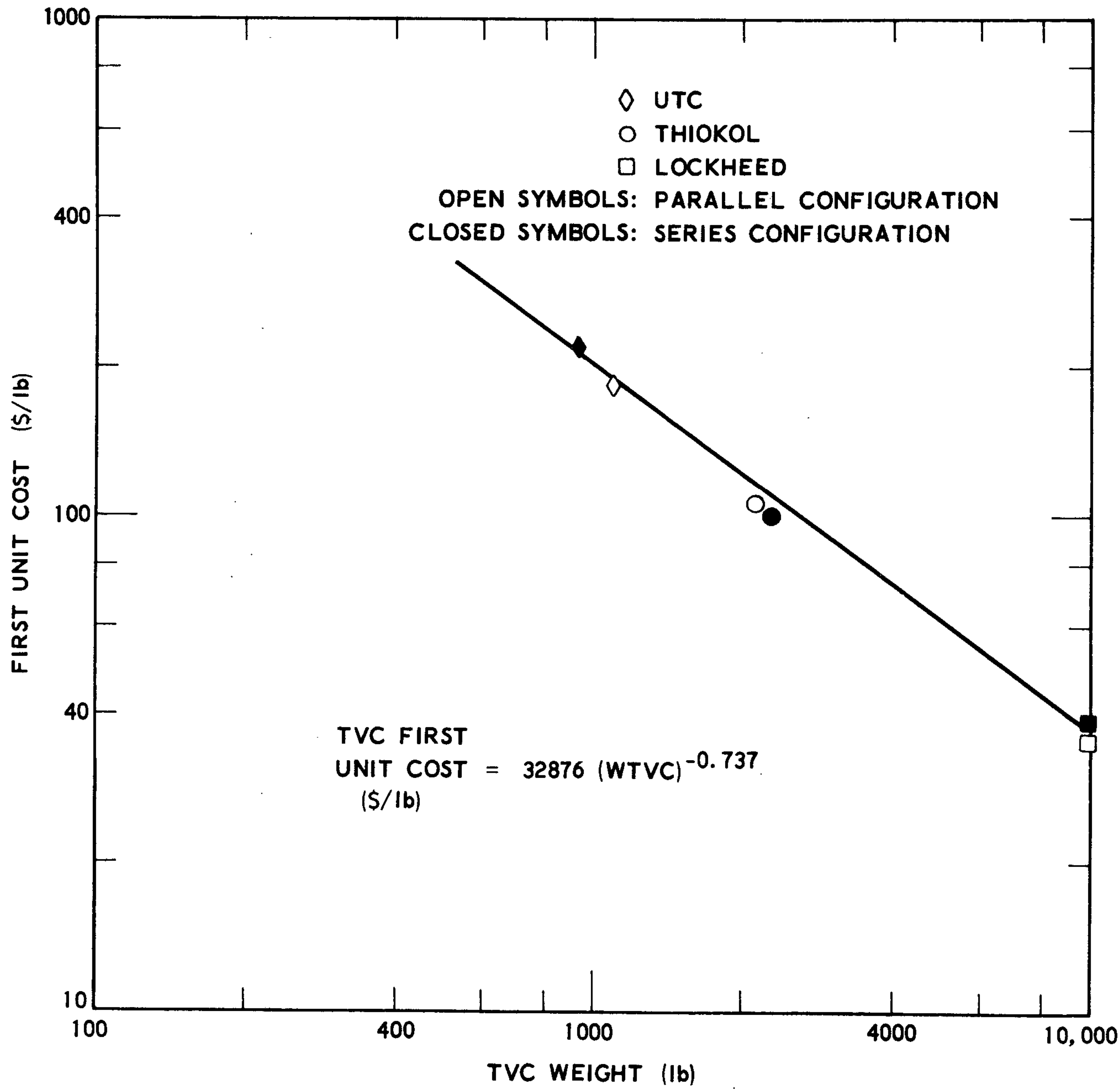


Fig. 5.5-8. TVC Specific First Unit Costs

5.5.2.1.4 Other (4514)

This category includes the First Unit Cost of all other subsystems which individually represent about one percent or less of the motor or structure costs. The subsystems represented are the igniter, electrical components, instrumentation, avionics, and ordnance. The First Unit Cost CER is as follows:

$$C\ (4514) = 1503\ (WO)^{0.660}\ \text{(Figs. 5.5-9 and 5.5-10)}$$

where WO = weight or other subsystems.

The items included in the above subsystems differ with each contractor. For example, UTC identifies the combination of staging rockets, igniter, safe and arm, and thrust termination as ordnance. Collectively under the umbrella of other subsystems the degree of comparability achieved is sufficient for deriving a CER that reasonably represents the cost for this group of hardware items (Table 5.5-6).

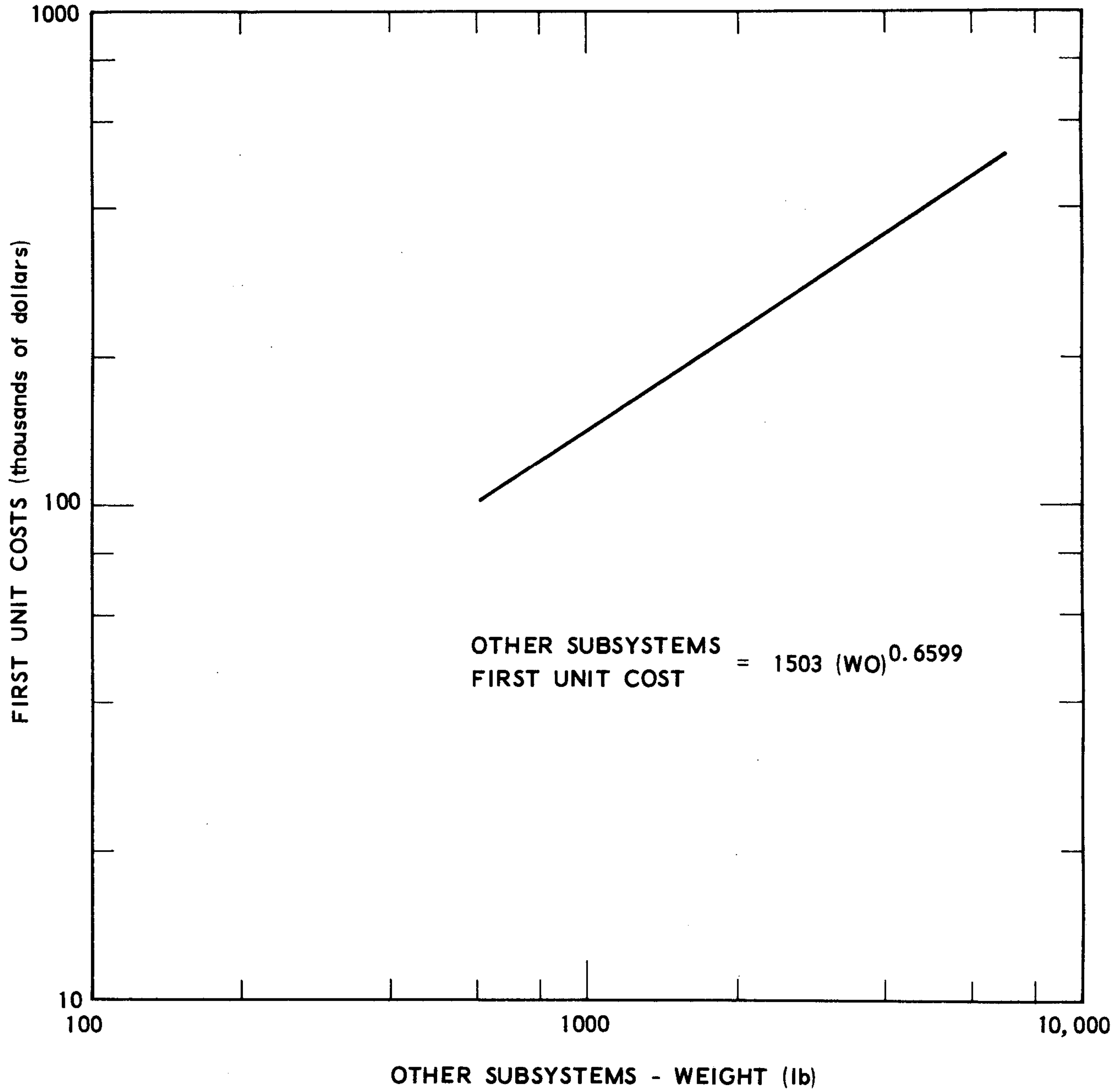


Fig. 5.5-9. Other Subsystem First Unit Costs

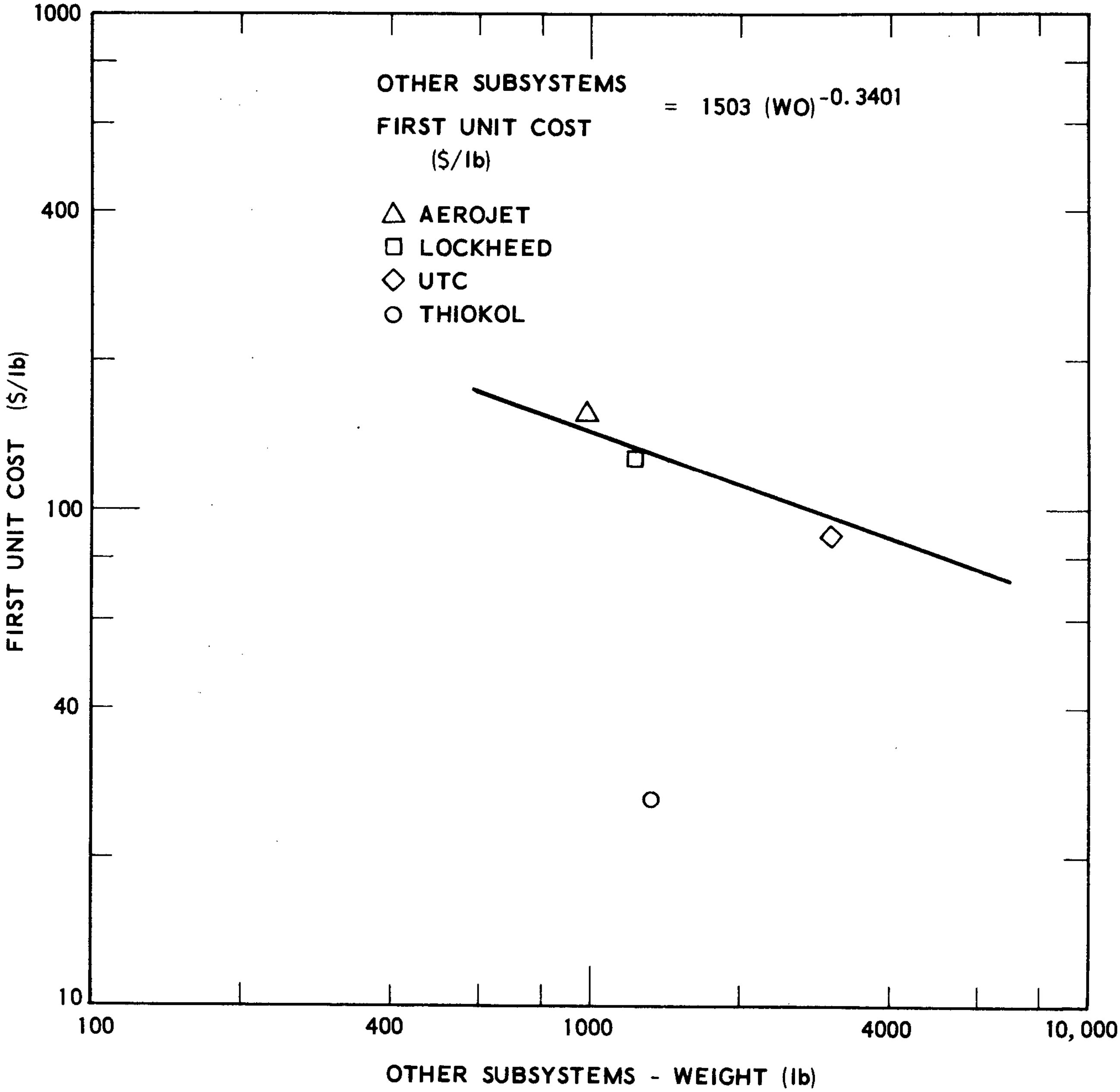


Fig. 5.5-10. Other Subsystem Specific First Unit Costs

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Table 5.5-6. Data Base and Derivation of First Unit Cost CER for Other SRM and Stage Subsystem (Total Production Costs in Millions of Dollars)

Subsystems	ASPC	LPC	TCC	UTC
Igniter				
Weight - kg	200	454	259	171
- lb	(441)	(1,000)	(571)	(378)
Total Prod. Cost ($)	7.04	33.96	7.80	91.67
Electronics/Avionics/ Instrumentation				
Weight - kg	136	88	250	636
- lb	(300)	(195)	(552)	(1403)
Total Prod. Cost ($)	26.06	50.88	22.75	50.80
Destruct Subsystem				
Weight - kg	109	25	96	562
- lb	(240)	(55)	(211)	(1238)
Total Prod. Cost ($)	14.90	-----	----	----
Total				
Weight - kg	445	567	605	1369
- lb	(981)	(1250)	(1334)	(3019)
Total Prod. Cost ($)	48.00	84.84	30.55	142.47
Dollars per Pound ($)	93.90	76.90	26.00	53.90
Average Production Costs First Unit Cost (1)	155.08	127.04	42.94	88.99

(1) Based on 95% Log-Linear Cumulative Average Learning Curve

5.5.2.1.5 Motor Subassembly & Installation (4515)

The cost element for Motor Subassembly and Installation is referred to as Motor Processing and Subassembly by Aerojet SPC; Installation, Assembly and Checkout (Production) by Lockheed PC; and Final Assembly by Thiokol. UTC does not identify the task involved in this cost element but includes it with its cost estimates for case and propellant.

The data on which the CER is based, Table 5.5-7, are for the SRM without TVC and thrust termination. This configuration was used because Aerojet did not provide complete cost data on a configuration with TVC and thrust termination. Inasmuch as the factors were not significantly different when computed for the latter configurations of Lockheed and Thiokol, the factors may be considered as representative for either SRM configuration.

Although Stage Hardware (4400) was not used in the derivation of the 7% Factor (Table 5.5-7), it is included in the CER to account for subassembly and installation of the stage structure and recovery system. The CER is as follows:

$$C\ (4515) = 0.07 \left| C\ (4400) + C\ (4511) + C\ (4512) + C\ (4513) + C\ (4514) \right|$$

where

C (4400) = Stage First Unit Cost
C (4511) = Case & Insulation First Unit Cost
C (4512) = Nozzle First Unit Cost
C (4513) = TVC First Unit Cost
C (4514) = Other First Unit Cost

5.5.2.2 Secondary (4520)

This cost element is reserved for a secondary propulsion system.

Table 5.5-7. Data Base and Derivation of First Unit CER Cost Factor for SRM Subassembly and Installation (Costs in Millions of Dollars)

SRM Component	Production Costs, 60 Per Year Peak Rate			
	ASPC	LPC	TCC	UTC
Case	692.7	823.4	763.8	1,237.8
Nozzle	287.7	333.6	225.7	331.4
Igniter	8.4	35.7	7.8	- (1)
Other (2)	40.1	372.3	22.7	142.5
Component Total (CT) (3)	1,028.9	1,565.0	1,020.0	1,711.7
Subassy. & Installation (S&I)	72.0	111.8	72.4	NR
S & I ÷ CT (%)	7.0	7.1	6.5	-

First Unit

CER Cost Factor = 7.0% ($\sum$ first unit SRM component costs)

NR = Not Reported.

(1) Included with other.

(2) Includes avionics, power, and ordnance.

(3) Excludes propellant cost.

6. APPLICATION TO EXAMPLE PROBLEM

The purpose of this section is to demonstrate the procedures involved in using the cost model to estimate the program life cycle costs of the SRM booster. The example problem serves to confirm at a practical level the sequence and mechanics of estimating costs and interpreting CERs.

6.1 DEFINITION OF PROBLEM

The problem used to illustrate the cost methodology is based on the following assumptions:

- SRM Booster
  - Parallel 3.96 m (156 in.) diameter motor
  - Configuration characteristics those of UTC motor, P2-156 (Reference 4)
- Program Characteristics
  - Recoverable motor concept
  - 60 launches/year, peak rate
  - 440 launches over ten years
  - 6 Flight test boosters (2-year flight test program)
  - 4 equivalent ground test motors
  - Initial spares, one equivalent motors
  - Spares support, two equivalent motors
- Other Assumptions
  - Costs in 1970 dollars
  - Fee excluded

6.2 INPUT DATA

FREF	=	0.545 (calculated internally)
FTR	=	60 full, 50 empty
FTW	=	Not applicable
NFB	=	38
NFM	=	76
NFT	=	6

NFTM	=	12
NGTM	=	4
NISM	=	1
NLE	=	44
NLM	=	60
NMB	=	2
NSSM	=	2
NUSE	=	10
NYFT	=	2
NYO	=	10
NYTO	=	2
PSC	=	0.379425
TNOL	=	440

Weight Statement Recoverable Example

	Weight (lb)
Stage	(29, 438)
Stage Structure (WSS)	(21, 938)
Recovery System (WR)	(7, 500)
Parachute System (WPS)	7, 500
Retro Rockets (WRR)	0
Propulsion	(1, 388, 340)
Primary - SRM (WSRM)	(1, 388, 340)
Case and Insulation (WCI)	117, 805
Nozzle (WN)	17, 674
TVC (WTVC)	1, 080
Other (WO)	1, 781
Propellant (WP)	1, 250, 000
Secondary (WS)	0
Total Motor Gross (WG)	(1, 417, 778)

6.3 SUMMARY RESULTS

6.3.1 Recoverable

An example problem is provided in this section in which costs of recoverable SRM motor are determined to show the magnitude of program costs and the distribution of the costs by life cycle phase and among the cost elements. The cost results are found in the following tables:

Table 6.3-1	Program Cost Estimate Summary
Table 6.3-2	First Unit Cost
Table 6.3-3	RDT & E Cost
Table 6.3-4	New Fleet Hardware Cost
Table 6.3-5	Investment Cost
Table 6.3-6	Operations Cost
Table 6.3-7	Direct Operating Cost

6.3.2 Expendable

Table 6.3-8 presents a summary cost estimated for the expendable SRM motor. The costs are not for the total program life cycle, but the costs represent estimates of what are considered to be direct operating costs. In addition to the booster fleet, the costs include installation, assembly, checkout, launch, and spares support. The expendable vehicle configuration used in this example is the same as the recoverable concept in Section 6.3.2, excluding the recovery equipment.

6.4 REFURBISHMENT FACTOR COMPUTATION

The refurbishment factor (FREF) to use in estimating the cost to refurbish the recoverable SRM motors is illustrated in Table 6.4-1. To obtain the refurbishment factor, FREF, a series of refurbishment factors was applied to the average fleet cost for each of the SRM motor subsystems. For

Table 6.3-1. Program Cost Estimate Summary: Recoverable Booster Program Example

Cost Element Number	Cost Element	Cost $\overline{M}$ 1970 $
1000	RDT & E	189.241
2000	Investment	412.494
3000	Operations	1,598.976
	Total Booster Program	2,200.711

Average Unit Cost of Booster Fleet (44 Boosters)	6.40

Direct Operating Cost/Flight (440 Flights)	4.15

example, the cost to refurbish a recovered stage structure was calculated as follows:

$$\text{Refurbishment Cost, Stage Structure} = \text{CRFSS}\ [\text{C}\ (4410)/\text{NFM}]\ [(\text{NFTM} + \text{NFM})^{\text{LCE}} - (\text{NFTM})^{\text{LCE}}]$$

The subsystem refurbishment factors used in the example were obtained from the Thiokol study (Ref. 3) and are suggested as candidate values to be used until a more extensive study is made of the recovery and refurbishment of SRM motors.

The refurbishment factor (FREF = 0.545) is not intended as a CER input value for FREF in the cost model. It is valid only for the motor configuration used in the example. The value of FREF is dependent on the relative distribution of the SRM motor subsystem costs.

FOLDOUT FRAME 1

FOLDOUT FRAME 2

Table 6.3-2. First Unit Cost Per Motor: Recoverable Example

Cost Element Number	Cost Element	Cost Estimating Relationship	Numerical Example	First Unit Cost/Motor $
4400	Stage	C (4400) = C (4410) + C (4420)	C (4400) = 681, 033 + 375, 000 =	(1, 056, 033)
4410	Stage Structure	C (4410) = (F4410) $[(185.8)\ (WSS)^{0.821}]$	C (4410) = 1 $[(185.8)\ (21,938)^{0.821}]$	681, 033
4420	Recovery System	C (4420) = C (4421) + C (4422)	C (4420) = 375, 000 + 0 =	(375, 000)
4421	Parachute	C (4421) = 50 (WPS)	C (4421) = 50 (7, 500) =	375, 000
4422	Retro Rocket	C (4422) = 15 (WRR)	C (4422) = 15 (0) =	0
4500	Propulsion	C (4500) = C (4510) + C (4520)	C (4500) = 2, 470, 266 + 0 =	(2, 470, 266)
4510	Primary-SRM	C (4510) = C (4511) + C (4512) + C (4513) + C (4514) + C (4515)	C (4510) = 1, 233, 864 + 589, 243 + 206, 381 + 210, 086 + 230, 692 =	(2, 470, 266)
4511	Case & Insulation	C (4511) = (F4511) $[(838.17)\ (WCI)^{0.623}]$	C (4511) = 1.02 $[(838.17)\ (117,805)^{0.623}]$ =	1, 233, 864
4512	Nozzle	C (4512) = (F4512) $[(252.44)\ (WN)^{0.793}]$	C (4512) = 1 $[(252.44)\ (17,674)^{0.793}]$ =	589, 243
4513	TVC	C (4513) = 32, 876 $(WTVC)^{0.263}$	C (4513) = 32, 876 $(1080)^{0.263}$ =	206, 381
4514	Other	C (4514) = 1, 503 $(WO)^{0.660}$	C (4514) = 1, 503 $(1,781)^{0.660}$ =	210, 086
4515	Sub Assy & Instl	C (4515) = .07 [C (4400) + C (4511) + C (4512) + C (4513) + C (4514)]	C (4515) = .07 [1, 056, 033 + 1, 233, 864 + 589, 243 + 206, 381 + 210, 086] =	230, 692
4520	Secondary	C (4520) = 0	C (4520) = 0 =	0
4000	First Unit Cost Per Motor (W/O Propellant)	C (4000) = C (4400) + C (4500)	C (4000) = 1, 056, 033 + 2, 470, 266 =	3, 526, 299

FOLDOUT FRAME 1

FOLDOUT FRAME 2

Table 6.3-3. RDT&E Cost: Revoerable Example

Cost Element Number	Cost Element	Cost Estimating Relationship	Numerical Example	RDT&E Costs $M
1610 1611 1612	Stage ED&D Stage Structure Recovery System	C (1610) = C (1611) + C (1612) C (1611) = 1.9×10^6 (WSS)$^{0.118}$ C (1612) = 32×10^6	C (1610) = $6.180 \times 10^6 + 31.000 \times 10^6$ = C (1611) = $1.9 \times 10^6 (21,938)^{0.118}$ = C (1612) = $32 \times 10^6 - 1 \times 10^6$ =	(37.180) 6.180 31.000(Note 1)
1620 1621 1622	Propulsion ED&D Primary-SRM Secondary	C (1620) = C (1621) + C (1622) C (1621) = (F1621) [89,000 (WSRM)$^{0.41}$] C (1622) = 0	C (1620) = $37.586 \times 10^6 + 0$ = C (1621) = 1.28 [89,000 (1,388,340)$^{0.410}$] = C (1622) = 0 =	(37.586) 37.586 0
1630	Initial Tooling	C (1630) = 0.025 [C (1651) + C (1652)]	C (1630) = 0.025 [$37.180 \times 10^6 + 37.586 \times 10^6$] =	1.869
1640	Initial Training	C (1640) = 17.25×10^4 (NLE)$^{0.737}$	C (1640) = $17.25 \times 10^4 (44)^{0.737}$ =	2.806
1650 1651 1652	Test Hardware Ground Flight	C (1650) = C (1651) + C (1652) C (1651) = NGTM [C (4410) + C (4510) + CPTH + CTTH] (Note 2) C (1652) = NFTM$^{0.926}$ [C (4410) + C (4420)] + NFTM$^{0.941}$ [C (4511)] + NFTM$^{0.971}$ [C 4512) + C (4513) + C (4514)] +NFTM 0.848 [C (4515)] + NFTM [CPTH + CTTH] (Note 2)	C (1650) = $15.205 \times 10^6 + 44.255 \times 10^6$ = C (1651) = 4 [681,033 + 2,470,266 + 556,298 + 93,573] = (Note 3) C (1652) = (12)$^{0.926}$ [681,033 + 375,000] + (12)$^{0.941}$ [1,233,864] + 120.971 [589,243 + 206,381 + 210,086] + (12)$^{0.848}$ [230,692] + 12 [556,298 + 93,573] = (Note 3)	(59.460) 15.205 44.255
1660 1661 1662	Test Operations Ground Flight	C (1660) = C (1661) + C (1662) C (1661) = NGTM (0.25×10^6) C (1662) = 0.3×10^6 (NFT) + (F1662) [2×10^6 (NYFT)]	C (1660) = $1.000 \times 10^6 + 7.800 \times 10^6$ = C (1661) = 4 (0.25×10^6) = C (1662) = 0.3×10^6 (6) + 1.5 [2×10^6 (2)] =	(8.800) 1.000 7.800
1670 1671 1672	Facilities & GSE Facilities GSE	C (1670) = C (1671) + C (1672) C (1671) = (0.41 NLM + 3.4) 10^6 C (1672) = 0.04 [C (1610) + C (1620)]	C (1670) = $28.0 \times 10^6 + 2.991 \times 10^6$ = C (1671) = [0.41 (60) + 3.4] $\times 10^6$ = C (1672) = 0.04 (37.180 + 37.586) $\times 10^6$ =	(30.991) 28.000 2.991
1680	Systems Intg. Engr.	C (1680) = 0.04 [C (1610) + C (1620) + C (1630) + C (1640) + C (1650) + C (1660) + C (1672)]	C (1680) = 0.04 [37.180 + 37.586 + 1.869 + 2.806 + 59.460 + 8.800 + 2.991] $\times 10^6$	6.028
1690	Contractor Prog. Mgt.	C (1690) = 0.03 [C (1610) + C (1620) + C (1630) + C (1640) + C (1650) + C (1660) + C (1672)]	C (1690) = 0.03 [37.180 + 37.586 + 1.869 + 2.806 + 59.460 + 8.800 + 2.991] $\times 10^6$	4.521
1000	RDT&E	C (1000) = C (1600) = C (1610) + C (1620) + C (1630) + C (1640) + C(1650) + C (1660) + C (1670) + C (1680) + C (1690)	C (1000) = C (1600) = [37.180 + 37.586 + 1.869 + 2.806 + 59.460 + 8.800 +30.991 + 6.028 + 4.521] $\times 10^6$ =	189.241

① One million dollars removed for unused retrorockets

② Where CPTH = 1.15 [WP (NGTM + NFTM)/NYTO]$^{-0.0589}$ (WP) and CTTH = FTR (1.1) (WG/1000)

③ Where CPTH = 1.15 [1,250,000 (4 + 12)/2]$^{-0.0589}$ (1,250,000) = 556,298 and CTTH = 60 (1.1) (1,417,778/1000) = 93,573

FOLDOUT FRAME 1

FOLDOUT FRAME 2

Table 6.3-4. New Fleet Hardware Cost: Recoverable Example

Cost Element Number	Cost Element	Cost Estimating Relationship	Numerical Example	New Fleet Hardware Cost $ $\overline{M}$	New Fleet Hardware Cost/Motor (Note 1)
2611	Stage Hardware	$C(2611) = [C(4410) + C(4420)] [(NFTM + NFM)^{LCE} - (NFTM)^{LCE}]$	$C(2611) = [681,033 + 375,000] [(12 + 76)^{0.926} - (12)^{0.926}] =$ (Note 2)	56.178	739,184
2612	SRM Hardware	$C(2612) = [(NFTM + NFM)^{LCE} - (NFTM)^{LCE}] [C(4511)] + [(NFTM + NFM)^{LCE} - (NFTM)^{LCE}] [C(4512) + C(4513) + C(4514)] + [(NFTM + NFM)^{LCE} - (NFTM)^{LCE}] C(4515)$	$C(2612) = [(12 + 76)^{0.941} - (12)^{0.941}] (1,233.864)$ (Note 2) $+ [12 + 76)^{0.971} - (12)^{0.971}] [589,243 + 206,381 + 210,086] + [(12 + 76)^{0.848} - (12)^{0.848}] (230,692) =$	145.465	1,913,997
2613	Propellant	$C(2613) = 1.15 (\dot{W}_p) - 0.0589 (WP)\ NFM$ (Note 3)	$C(2613) = 1.15 (150 \times 10^6) - 0.0589 (1,250,000) 76 =$ (Note 4)	36.045	474,281
2614	Transportation	$C(2614) = NFM (FTR) (1.1) (WG/1000)$	$C(2614) = 76 (60) (1.1) (1,417,778/1000) =$	7.112	93,573
2610	New Fleet Hardware	$C(2610) = C(2611) + C(2612) + C(2613) + C(2614)$	$C(2610) = [56.178 + 145.465 + 36.045 + 7.112] 10^6 =$	244.800	3,221,035

① New fleet hardware cost/motor = New fleet hardware cost divided by number of new fleet motors (NFM)

② Learning curve exponents (LCE), Table 5.3-4

③ Where $\dot{W}_p$ = NLM (WP) NMB

④ Where $\dot{W}_p = 60 (1,250,000) 2 = 150 \times 10^6$

FOLDOUT FRAME 1

FOLDOUT FRAME 2

Table 6.3-5. Investment Cost: Recoverable Example

Cost Element Number	Cost Element	Cost Estimating Relationship	Numerical Example	Investment Cost $ M
2500	Facilities & GSE	C (2500) = C (2510) + C (2520) + C (2530)	C (2500) = [9.000 + 79.500 + 42.223] × 10^6 =	(130.723)
2510	Operational	C (2510) = 9 × 10^6	C (2510) = 9 × 10^6 =	9.000
2520	Production	C (2520) = (1.24 NLM + 5.1) 10^6	C (2520) = [1.24 (60) + 5.1] × 10^6 =	79.500
2530	GSE	C (2530) = 2.03 $(NLE)^{0.802}$ 10^6	C (2530) = 2.03 $(44)^{0.802}$ × 10^6 =	42.223
2600	Booster Fleet	C (2600) = C (2610) + C (2620) + C (2630) + C (2640) + C (2650) + C (2660)	C (2600) = [244.800 + 24.119 + 4.000 + 3.328 + 2.762 + 2.762] × 10^6 =	(281.771)
2610	New Fleet Hardware	C (2610) = C (2611) + C (2612) + C (2613) + C (2614)	Calculated for Table 6.3-4	244.800
2620	Refurb. R& D Fleet Hdwe.	C (2620) = FREF [C (1652)]	C (2620) = .545 (44.255) × 10^6 = (Note 1)	24.119
2630	Initial Spares	C (2630) = NSIM [C (4000) + CPFH] (Note 2)	C (2630) = 1 [3.526 + .474] × 10^6 = (Note 3)	4.000
2640	Sustaining Tooling	C (2640) = (F2640) [C (2611) + C (2612) + C (2613)]	C (2640) = 0.014 [56.178 + 145.465 + 36.045] × 10^6 =	3.328
2650	Engineering Support	C (2650) = 0.01 [C (2610) + C (2620) + C (2630) + C (2640)]	C (2650) = 0.01 [244.800 + 24.119 + 4.000 + 3.328] × 10^6 =	2.762
2660	Cont. Program Mgt.	C (2660) = 0.01 [C (2610) + C (2620) + C (2630) + C (2640)]	C (2660) = 0.01 [244.800 + 24.119 + 4.000 + 3.328] × 10^6 =	2.762
2000	Investment Cost	C (2000) = C (2500) + C (2600)	C (2600) = [130.723 + 281.771] × 10^6 =	412.494

Average Unit Cost of Booster Fleet	Average Unit Cost = C (2600) (NMB)/(NFM + NFTM)	Cost = 281.117 × 10^6 (2)/(76 + 12) = 6.40 × 10^6

1. FREF derived in Table 6.4-1
2. CPFH = C (2613)/NFM
3. CPFH = [36.045/76] × 10^6 = .474 × 10^6

6.8

FOLDOUT FRAME 1

FOLDOUT FRAME 2

Table 6.3-6. Operations Cost: Recoverable Example

Cost Element Number	Cost Element	Cost Estimating Relationship	Numerical Example	Operations Cost \$ $\overline{M}$
3400	Operations Support	C (3400) = C (3410) + C (3420) + C (3430) + C (3440) + C (3450) + C (3460)	C (3400) = [60.990 + 40.000 + 7.015 + 32.174 + 8.000 + 5.607] $\times 10^6$	(153.786)
3410	Install, Assy, C/O & Launch	C (3410) = 37.5 $\times 10^4$ (NLE)$^{0.737}$ (NYO)	C (3410) = 37.5 $\times 10^4$ (44)$^{0.737}$ (10) =	60.990
3420	Recovery	C (3420) = 4 $\times 10^6$ (NYO)	C (3420) = 4 $\times 10^6$ (10) =	40.000
3430	Replacement Train.	C (3430) = 0.25 [C (1640)] (NYO)	C (3430) = 0.25 [2.806 $\times 10^6$] (10) =	7.015
3440	Facilities & GSE Maint.	C (3440) = C (3441) + C (3442)	C (3440) = (4.500 + 27.674) $\times 10^6$	32.174
3441	Operational Facil.	C (3441) = 45 $\times 10^4$ (NYO)	C (3441) = 45 $\times 10^4$ (10) =	4.500
3442	GSE	C (3442) = [0.05 C (1672) + 0.062 C (2530)] (NYO)	C (3442) = [0.05 (2.991) + 0.062 (42.233)] $\times 10^6$ (10) =	27.674
3450	In-Plant Engr. Support	C (3450) = 0.8 $\times 10^6$ (NYO)	C (3450) = 0.8 $\times 10^6$ (10) =	8.000
3460	Cont. Program Mgt.	C (3460) = 0.04 [C (3410) + C (3420) + C (3430) + C (3440)]	C (3460) = 0.04 [60.900 + 40.000 + 7.015 + 32.174] $\times 10^6$	5.607
3500	Refurbishment Support	C (3500) = C (3510) + C (3520) + C (3530) + C (3540)	C (3500) = 1390.335 + 18.491 + 14.088 + 14.088] $\times 10^6$ =	(1,437.002)
3510	Refurb. of Fleet Hardw.	C (3510) = FREF [1-1/NUSE] [(TNOL) (NMB)] [C (2610)/NFM]	C (3510) = .545 [1-1/10] [(440) (2)] [244.800 $\times 10^6$/76] = (Note 1)	1,390.335
3520	Sustaining Tooling	C (3520) = (F3520) [0.95 C (3510)]	C (3520) = 0.014 [0.95 (1390.335)] $\times 10^6$ =	18.491
3530	Engineering Support	C (3530) = 0.01 [C (3510) + C (3520)]	C (3530) = 0.01 [1390.335 + 18.491] $\times 10^6$ =	14.088
3540	Contractor Prgm. Mgt.	C (3540) = 0.01 [C (3510) + C (3520)]	C (3540) = 0.01 [1390.335 + 18.491] $\times 10^6$ =	14.088
3600	Spares Support	C (3600) = NSSM [C (4000) + CPFH + CTFH] (Note 2)	C (3600) = 2 [3.526 + 0.474 + 0.094] $\times 10^6$ = (Note 3)	(8.188)
3000	Operations Cost	C (3000) = C (3400) + C (3500) + C (3600)	C (3000) = [153.786 + 1,437.002 + 8.188] $\times 10^6$	1,598.976

1. FREF derived in Table 6.4-1
2. CPFH = C (2613)/NFM and CTFH = C (2614)/NFM
3. CPFH = [36.045/76] $\times 10^6$ = .474 $\times 10^6$ and CTFH = [7.112/76] 10^6 = 0.094 $\times 10^6$

FOLDOUT FRAME 1

FOLDOUT FRAME 2

Table 6.3-7. Direct Operating Cost: Recoverable Example

Cost Element Number	Cost Element	Cost Estimating Relationship	Numerical Example	Direct Operating Cost $\$ \overline{M}$
2600	Booster Fleet	C (2600) = C (2610) + C (2620) + C (2630) + C (2640) + C (2650) + C (2660)	Calculations in Table 6.3-5	281.771
3410	Install, Assy, C/O & Launch Ops.	C (3410) = 37.5×10^4 (NLE)$^{0.737}$ (NYO)	Calculations in Table 6.3-6	60.990
3420	Recovery Operations	C (3420) = 4×10^6 (NYO)	Calculations in Table 6.3-6	40.000
3500	Refurbishment Support	C (3500) = C (3510) + C (3520) + C (3530) + C (3540)	Calculations in Table 6.3-6	1,437.002
3600	Spares Support	C (3600) = NSSM [C (4000) + CPFH + CTFH)]	Calculations in Table 6.3-6	8.188
	Direct Operating Cost (DOC)	DOC = C (2600) + C (3410) + C (3420) + C (3500) + C (3600)	DOC = $[281.771 + 60.990 + 40.000 + 1,437.002 + 8.188] \times 10^6$ =	1,827.951
Direct Operating Cost/Flight = $1,827.951 \times 10^6/440 = 4.154 \times 10^6$				

6-10

Table 6.3-8. Expendable Booster Cost Example: Parallel Burn 156-inch SRM 440 Flight Program

Element	Weight		First Unit Cost $	Average Unit Cost $
	kg	(lb)		
Stage Structure	9,951	21,938	31/lb	409,838
Case & Insulation	52,509	117,805	10/lb	823,149
Nozzle (Movable)	8,017	17,674	33/lb	482,998
TVC	490	1,080	191/lb	169,169
Other	808	1,781	118/lb	172,206
Motor Subass'y. & Install.			204,442	71,880
Propellant	566,991	1,250,000		474,281
Transportation				93,078
Miscellaneous				172,981
Total/Motor	639,692	1,410,278		2.870×10^6
Total/Booster	1,279,384	2,820,556		5.740×10^6

FOLDOUT FRAME 1

FOLDOUT FRAME 2

Table 6.4-1. Refurbishment Factor: Recoverable Example

Cost Element	Cost Estimating Relationship	Numerical Example (1)	Refurbishment Cost Per Motor $
Stage Hardware			(194,873)
Stage Structure	Cost = CRFSS [C (4410)/NFM] $[(NFTM + NFM)^{LCE} - (NFTM)^{LCE}]$	Cost = 0.15 (681,033/76) $[(76 + 12)^{0.926} - (12)^{0.926}]$ =	71,505
Recovery System	Cost = CRFR [C (4420)/NFM] $[(NFTM + NFM)^{LCE} - (NFTM)^{LCE}]$	Cost = 0.47 (375,000/76) $[(76 + 12)^{0.926} - (12)^{0.926}]$ =	123,368
SRM Hardware			(984,421)
Case & Insulation	Cost = CRFCI [C (4511)/NFM] $[(NFTM + NFM)^{LCE} - (NFTM)^{LCE}]$	Cost = 0.20 (1,233,864/76) $[(76 + 12)^{0.941} - (12)^{0.941}]$ =	185,752
Nozzle	Cost = CRFN [C (4512)/NFM] $[(NFTM + NFM)^{LCE} - (NFTM)^{LCE}]$	Cost = 0.90 (589,243/76) $[(76 + 12)^{0.971} - (12)^{0.971}]$ =	461,370
TVC	Cost = CRFTV [C (4513)/NFM] $[(NFTM + NFM)^{LCE} - (NFTM)^{LCE}]$	Cost = 0.45 (206,381/76) $[76 + 12)^{0.971} - (12)^{0.971}]$ =	80,797
Other	Cost = CRFO [C (4514)/NFM] $[(NFTM + NFM)^{LCE} - (NFTM)^{LCE}]$	Cost = 0.80 (210,086/76) $[(76 + 12)^{0.971} - (12)^{0.971}]$ =	146,218
Sub Assy & Instal.	Cost = [C (4515)/NFM] $[(NFTM + NFM)^{LCE} - (NFTM)^{LCE}]$	Cost = (230,692/76) $[(76 + 12)^{0.848} - (12)^{0.848}]$ =	110,284
Propellant	Cost = C (2613)/NFM	Cost = $[36.045 \times 10^6/76]$ =	474,281
Transportation			
To Contractor	Cost = 1.1 (FTR) (WG-WP-WS) $\times 10^{-3}$	Cost = 1.1 (50) (1,417,778 - 1,250,000 - 0) $\times 10^{-3}$ =	9,228
To Launch Site	Cost = C (2614)/NFM	Cost = $[7.112 \times 10^6/76]$ =	93,573
		Total Refurbishment Cost Per Motor =	1,756,376

Refurbishment Factor (FREF)	FREF = Total Refurbishment Cost Per Motor (NFM)/C (2610)	FREF = 1,756,376 (76)/244,800,000 = .545

(1) Learning Curve Exponents (LCE), Table 5.3-4 and Candidate Refurbishment Factors (CRF XX), Table 5.4-3.

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APPENDIX A

ORBITER AND SYSTEM OPERATIONAL PHASE CERS

CONTENTS

TABLES

A. 1 INTRODUCTION

In the STS Cost Model, Reference 5, the Operations Phase consisted of liquid Booster plus Orbiter and total systems CERs. The solid motor booster operations CERs presented in the main body of this document, will derive program costs associated with the SRM Booster only. Therefore, additional orbiter/systems CERs are necessary to arrive at a total STS Program Cost. The purpose of this Appendix is to supply these CERs.

A. 2 APPROACH

In March of 72 North American Rockwell and McDonnell Douglas completed the "Shuttle System Impact Study", References 14 and 15. One of the major purposes of this study was to produce orbiter/booster cost data as a function of varying launch rates for specified operational functions. About this same time the Parsons Company, Reference 13, completed their study on basing concepts together with appropriate cost estimates.

The following new CERs were derived by taking the "Shuttle Impact Study" results, which were in the form of manpower requirements, and fitting them to the general equation of

$\text{Cost} = a\,(\text{Launch Rate})^b$ by the least square method

- Launch Operations
- Recovery Operations
- Vehicle Maintenance
- Program Integration & Management

Command and Control, In-Plant Engineering Support, and Range and Base Support were relatively constant and are shown as such.

The following CERs remained unchanged from the STS Cost Model because they are either not directly dependent on the booster:

- Replacement Training
- Facilities and Equipment Maintenance
  - / Launch and Maintenance Facilities
  - / Ground and Support Equipment

- Spares and Propellant Support

However, they do require some rework to incorporate the SRM CER notations or to remove booster effects covered elsewhere. The following ground rules and assumptions are part of the presented results:

- All dollars are 1970
- Costs per man year used were:

$35,000	$40,000
Launch Operations	In-Plant Engineering Support
Recovery Operations	Command and Control
Vehicle Maintenance	Program Integration & Management

- Phase B type orbiter
- Drop tank costs included in orbiter costs
- For launch rates less than 10 per year the costs are constant and equal to those at a launch rate of 10 per year

A. 3 RESULTS

Table A. 3-1 presents the orbiter/system CERs which together with the solid booster CERs will produce total STS program costs.

The use of the new equations are self explanatory. The use of the unchanged STS Cost Model CERs require some explanation and caution.

(0344) Replacement Training

The cost is dependent on the number of ground personnel trained in the RDT&E Phase, C (O 1291-1) and C (O 1291-2). Training cost per man was 925,000 dollars and 15,000 dollars, respectively. These were in 1969 dollars and should be changed to 1970 dollars. (O1291-1), Flight Crew, should be $1,000,000 and (O 1291 -2), ground crew, should be $16,000.

(Y 3450) Facilities and Equipment Maintenance

(Y 3451) Launch and Maintenance Facilities

This CER is a function of the Launch (Y 1283) and Operational and Maintenance (Y 1284) RDT&E Facilities CERs. These cost an entirely new site for the

F

Table A. 3-1. Operational Phase CERS for Orbiter and System (Cost in Millions of 1970 Dollars)

Cost Element Number	Cost Element Designation	CER
O 3410	Launch Operations	$C\ (O\ 3410) = 3.4 \times 10^6 \{(NLE_1)^{0.32}\ (NYOE_1) + (NLE_2)^{0.32}\ (NYOE_2)\}$
O 3420	Recovery Operations	$C\ (O\ 3420) = 3.4 \times 10^5 \{(NLE_1)^{0.34}\ (NYOE_1) + (NLE_2)^{0.34}\ (NYOE_2)\}$
Y 3430	Command and Control	$(Y\ 3430) = 1.2 \times 10^6 \{NYOE_1 + NYOE_2\}$
O 3440	Replacement Training	*
Y 3450	Facilities & Equipment Maintenance	C (Y 3450) = C (Y 3451) + C (Y 3452)
Y 3451	Launch & Maintenance Facilities	*
Y 3452	Ground Support Equipment	*
O 3460	Vehicle Maintenance	$C\ (O\ 3460) = 1.9 \times 10^6 \{(NLE_1)^{0.34}\ (NYOE_1) + (NLE_2)^{0.34}\ (NYOE_2)\}$
O 3470	In-Plant Engineering Support	$C\ (O\ 3470) = 1.6 \times 10^6 \{NYOE_T\}$
Y 3480	Program Integration & Management	$C\ (Y\ 3480) = 3.3 \times 10^6 \{(NLE_1)^{0.33}\ (NYOE_1) + (NLE_2)^{0.33}\ (NYOE_2)\}$
O 3600	Spares & Propellant Support	*
Y 3700	Range & Base Support	$C\ (Y\ 3700) = 15.0 \times 10^6 \{NYOE_1 + NOYE_2\}$

$NLE_{1\ (2)} = \dfrac{\text{Total No. of Operational Flights at Site 1 (2)}}{\text{Total No. of Operational Years at Site 1 (2)}}$

$NYOE_{1\ (2)}$ = Total No. of Operational Years at Site 1 (2)

$NYOE_T$ = Total No. of Operational Years of Program Without Regard to Site

O = Orbiter
Y = System

*Same as CER on page 4.4-11 of Vol I of "STS Cost Methodology" dated 31 Aug 70. Spares & Propellant Support CER is on page 4.4-15 of same report.

liquid booster configuration. A revision of the operational and maintenance facilities was not part of this effort; therefore, to be able to derive approximate cost for the maintenance of these facilities as well as to cost them from a total program cost standpoint, the following must be done:

- Use the RDT&E Launch Facility CER (Y 1283) as is
- Set the booster area parameters, NB and AB of (Y 1284) equal to zero in the Operational and Maintenance Facilities CER
- The Investment Phase is for a second site. Therefore, (Y 3451) can be set to zero.

(Y 3452) Ground Support Equipment

This CER can be used by setting C (E 1287), C (E 1288), C (E 2140), and C (E 2160), equal to zero and by only using the orbiter part of C (E 1250) and C (E 2150).

(O 3600) Spares & Propellant Support

Only the orbiter part (O 3200) of this CER should be used as the booster is covered in the solid motor section of this report.

A.4 DEFINITIONS

In order to derive total program costs, the SRM booster cost equations must be augmented by similar orbiter and system cost equations. These must satisfy the following functional definitions:

COST ELEMENT NUMBER	DEFINITION
O/Y 3400	OPERATIONS Refers to the costs incurred in operating and providing services relative to launching, tracking, command and control, recovery and maintenance of the orbiter vehicles during its mission and operational phase.
O 3410	LAUNCH OPERATIONS Refers to direct cost of orbiter launch operations. Includes final pre-flight assembly and checkout and actual count-down and launch operations.

COST ELEMENT NUMBER	DEFINITION
O 3420	RECOVERY OPERATIONS
	Includes cost of assisting in recovery operations and the cost of operations at air fields that involve launching, propellant purging, vehicle deactivation and servicing.
Y 3430	COMMAND & CONTROL
	Includes cost associated with ground command, control, and tracking from vehicle launch through mission completion and return. Includes such functions as flight control telemetry, communications, data processing and data analysis.
O 3440	REPLACEMENT TRAINING
	Includes the cost of training qualified flight and ground crew personnel to replace those lost by rotation or attrition in order to maintain manning at levels necessary to meet flight and ground operations schedules.
Y 3450	FACILITY & EQUIPMENT MAINTENANCE
	Includes the cost to maintain, preserve and repair launch and maintenance facilities and ground support equipment.
Y 3451	LAUNCH & MAINTENANCE FACILITIES
	Refers to all launch, recovery, operations and maintenance facilities used in operational program.
O 3452	GROUND SUPPORT EQUIPMENT
	Refers to all ground support equipment used in operations program.
O 3460	VEHICLE MAINTENANCE
	Includes cost to restore the reusable elements of the orbiter vehicles, after mission completion, to a readiness

COST ELEMENT NUMBER	DEFINITION
	condition for subsequent missions. All costs of inspection, maintenance, replacement of necessary parts and testing are included. This activity is completed when the orbiter is ready for launch operations. Includes both normal turnaround between flights and regularly scheduled overhauls.
O 3470	IN-PLANT ENGINEERING SUPPORT Includes cost associated with normal product improvement or evolution, characterized by engineering changes and modifications to the orbiter hardware or to the method of operation. This category also includes cost of in-plant engineering liaison support of operational activities. Excluded are costs that pertain to major hardware modifications required to meet new performance specifications.
Y 3480	PROGRAM INTEGRATION AND MANAGEMENT Refers to the costs associated with the management and unification of the operations phase. All operational activities are coordinated by this function to ensure the successful accomplishment of the mission objectives. Includes planning and scheduling of flights, flight modes, payload - vehicle assignments, etc.
O 3600	SPARES AND PROPELLANT SUPPORT Refers to the recurring costs of manufacturing and stocking spare parts and propellants during the operational phase.
O 3610	FOLLOW-ON SPARES Includes the costs of spare parts and components produced to replenish initial spare stocks and in support of the orbiter maintenance and overhaul.

COST ELEMENT NUMBER	DEFINITION
O 3620	PROPELLANTS AND GASES Refers to the costs of propellants and gases consumed by the orbiters during the operations phase.
Y 3700	RANGE AND BASE SUPPORT Includes the indirect costs of range services that support the direct launch and maintenance operations. Covered are: range safety and control, shop and repair services, standards and instrument calibration, base services such as food, mail, reproduction, security, fire protection, utilities, communications, transportation, health and custodial services, and logistics support.

APPENDIX B

SOLID ROCKET BOOSTER
DESIGN PARAMETER EFFECT ON WEIGHT

CONTENTS

TABLES

B. 1 INTRODUCTION

Over the past several years, methods for estimating cost of potential hardware have been developed. One of the key input parameters to each of these methods is weight and the functional breakdown of that weight.

Weight scaling laws have been formulated following industry manufacturing techniques and control systems and are used extensively in making performance evaluations of rocket motor and missile proposals and options.

In response to interest shown in the effect key design parameters have on costs, a brief study has been made to provide an arrangement of the weight scaling laws tailored to the particular requirements of the large solid rocket motor configurations compatible with the Space Shuttle.

A second task involved performing a comparison of Shuttle SRM weights submitted in a contractor study, Reference B. 1, with those developed by using the equations just described. Design and propulsion data used by the contractor in developing the SRM weights were used in The Aerospace Corporation computations.

B. 2 APPROACH

The weight scaling laws of Reference B. 2 were first checked with data from contractor proposals and, where gross differences consistently occurred, adjustments were made to provide new formulations in consonance with existing data. Equations were then simplified by elimination of certain variables where first stage characteristics could be reasonably assumed and incorporated into the coefficients.

Where further breakdown of subsystems could be made without extensive study, equations were formulated and are included in the attachment.

B. 3 RESULTS

Table B. 3-1 presents a direct comparison of Reference B. 1 weights with those derived from Reference 2 except that the scaling equation for thrust termination has been reworked to provide compatibility with Shuttle SRM design. While some of the subsystem values show appreciable differences, note that

Table B.3-1. Shuttle SRM Weight Comparisons

Case Diameter (inch)	120			156		
	wA (lb)	wC (lb)	wA/wC	wA (lb)	wC (lb)	wA/wC
Weights						
Case	55927	49252	1.136	108447	99799	1.087
Internal Insulation	16749	12230	1.370	17931	15963	1.123
Nozzle	9714	10522	0.923	20948	17674	1.185
Thrust Termination	1526	1556	0.981	2272	2043	1.112
TVC	638	930	0.686	1014	1080	0.939
Miscellaneous*	2074	1501	1.382	3771	1781	2.117
Total Inert	86628	75911	1.141	154383	138340	1.116
Propellant	591800	591800	---	1250000	1250000	---
Total Motor	678428	667711	1.016	1404383	1388340	1.012

wA results from using the equations in Reference B.2.

wC are data from contractor proposal (Reference B.1).

*Miscellaneous Subsystems here include raceways, base heat protection, igniters, and ordnance.

total inert is within 15 percent and total motor weight is within 2 percent. Some of the differences in subsystem inert weight is due to differences in functional assignment to the groups represented.

The following presents a set of simplified equations in consonance with Reference B.2 expanded to provide some additional component and subsystems weight estimates for cost purposes. Their use should be limited to large solid boosters since, in the simplification, some characteristic weight-dependent parameters have been incorporated into the constants; notably nozzle expansion ratio (= 10), closure shape (b/a = 1), internal backface design temperature (T_D = 350°), propellant characteristic velocity (C* = 5200), nozzle half angle ($\theta/2$ = 15°), and the ratio $[W_p/(Pc \cdot T_b)]$ used for scaling thrust termination subsystem must be greater than 3.9.

A. CASE:

<u>WC1</u> Unjointed case less skirts

$$= 228 \left\{ \left[\frac{(Wp/1000)}{N_p} \right]^{0.95} \frac{[Pc\ (FS)]}{(F_{tu}/1000)} \frac{0.7}{0.9} P_{cm} \right\}^{1.013} \qquad (1)$$

<u>WC2</u> Case joint penalty

$$= 7.7\ D^2 \frac{(MEOP)\ (FS)\ (N_j)}{F_{tu}} \qquad (2)$$

<u>WC3</u> Fore and aft skirts

$$= 0.087\ (WC1) \qquad (3)$$

where

W_p	= propellant weight	lb
N_p	= Propellant loading fraction	
P_c	= average chamber pressure	psi
FS	= safety factor	
P_{cm}	= density of case material	lb/cu. in.

F_{tn}	=	material ultimate tensile strength	psi
MEOP	=	maximum expected operating pressure	psi
N_J	=	number of joints	
D	=	case outside diameter	in.
W(case)	=	WC1 + WC2 + WC3	

B. Insulation:

unsegmented (WINS[1]):

$$0.312 \left[\left(\frac{Wp}{1000\ N_P} \right)^{0.8} \left(\frac{Tc}{1000} \right)^{2} T_b^{\ 0.5} \right]^{0.86} \tag{4}$$

where

W_p	=	propellant weight	lb
Tc	=	combustion temperature	°F
N_p	=	propellant loading fraction	
T_b	=	burn time	sec
N_J	=	number of joints	
L	=	cylindrical length	in.

Joint Insulation (WJINS):

$$N_j \left(\frac{D^2}{10,000} \right) (2.7\ T_b + 80) \tag{5}$$

where

N_j	=	number of joints	
D	=	case outside diameter	in.
T_b	=	burning time	sec.

Total Insulation WINS (6)

$$WINS = WINS^{1} + WJINS - WLINER$$

where

WLINER = weight of liner (see C)

C. LINER:

$$WLINER = \frac{9D}{1000} \quad (L + D) \tag{7}$$

where

D	=	case outside diameter	in.
L	=	cylindrical length	in.

D. NOZZLE (WN)

$$WN = 16850 \left[\frac{\left(\frac{W_p}{1000}\right)^{1.2}}{P_c^{0.8} \quad T_b^{0.6}} \right]^{0.916} \tag{8}$$

where

W_p	=	propellant weight	lb
P_c	=	average chamber pressure	psi
T_b	=	burning time	sec

E. THRUST TERMINATION (WTT)

$$WTT = 555 \left(\frac{W_p}{P_c T_b} \right)^{0.585} \tag{9}$$

This equation is suitable for large SRM's only.

where

W_p	=	propellant weight	lb
P_c	=	average chamber pressure	psi
T_b	=	burning time	sec

F. NOSE CONE

$$W = 12\ D^2 \qquad (10)$$

where

D	=	case diameter	ft

G. WTVC (Omnivectoring nozzle)

$$WTVC = K\ (W_n)^{0.604} \qquad (11)$$

where

W_n	=	nozzle weight	lb
		gimbaled nozzle	K = 2.7
		flexseal (hydraulic actuator)	K = 2.5
		flexseal (turbopneumatic actuator)	K = 1.64
		techroll (turbopneumatic actuator)	K = 1.05

H. MISCELLANEOUS (Wmisc)

$$Wmisc = 0.05\ W_p^{0.8} \qquad (12)$$

W_p	=	propellant weight	lb

INCLUDES RACEWAYS, BASE HEAT PROTECTION, IGNITERS AND ORDNANCE

B.4 REFERENCES

B-1 UTC TECHNICAL REPORT, "STUDY OF SOLID ROCKET MOTORS FOR THE SPACE SHUTTLE BOOSTER; FINAL REPORT VOLUME II", 15 MARCH 1972

B-2 J. KIMBLE, "PARAMETRIC WEIGHT SEALING EQUATIONS FOR SOLID PROPELLANT LAUNCH VEHICLES", TR 669(6560)-2, APRIL 1966

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