NASA TECHNICAL MEMORANDUM

NASA TM X-58012
October 1967

N68-11956

A GRAPHICAL COSTING PROCEDURE FOR ADVANCED MANNED SPACECRAFT (MASCOT G)

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ABSTRACT

This technical memorandum has been prepared for two reasons: to present a new and easily used method for estimating spacecraft project costs and, more important, to make available a concise summary of the spacecraft cost data bank generated by the Manned Spacecraft Center and Manned Spacecraft Center contractors. The method presented is based on a series of graphs containing the reference cost data points and on computed ratios between various levels of historical costs. A sample problem is presented to illustrate the use of the historical data in cost estimation.

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A GRAPHICAL COSTING PROCEDURE FOR ADVANCED MANNED SPACECRAFT (MASCOT G)

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SUMMARY

This report is the first work to use recent cost data from spacecraft programs of the National Aeronautics and Space Administration for the development of a method to be used in advanced spacecraft cost estimation. Therefore, two areas are emphasized: the collection and analysis of cost data and the synthesis of the costing technique, with collection and analysis of cost data receiving priority.

Data are from two primary sources. The first is the Apollo cost study performed each year by the National Aeronautics and Space Administration Office of Manned Space Flight, largely an effort to obtain the contractors' own estimates of subsystem-level costs to completion for the command and service module and the lunar module. The second source is a study contract let by the National Aeronautics and Space Administration Manned Spacecraft Center to Booz-Allen Applied Research to analyze contractor cost reports (NASA Forms 533) submitted on the Gemini, command-and-service-module, and lunar-module projects, and to reduce these costs to recurring and nonrecurring elements at the subsystem level. (Booz-Allen then correlated these data with subsystem-performance parameters to produce cost-estimating relationships.)

This report, then, first summarizes the two data sources. Data points from these summaries are plotted in a series of log-log graphs which allow cost comparisons to be made in three parametric dimensions: absolute cost, subsystem size (weight), and subsystem complexity (cost per pound). Both nonrecurring and item costs are presented.

Finally, techniques are presented to build module and total project-level costs from the sums of subsystem-level costs. These techniques are a series of ratios between corresponding levels of historical program-level, module-level, and subsystem-level costs.

An example problem is presented to illustrate the use of the historical data for estimating the costs of an advanced module. The Apollo lunar module was chosen for the example so that results could be compared with actual program data.

INTRODUCTION

The purpose of this paper is to disseminate a concise abstract of work performed by Manned Spacecraft Center (MSC) contractors in cost data analysis of manned spacecraft (SC) programs and to demonstrate one method of using these data for a beneficial purpose, that is, approximating the costs of advanced SC. The procedure developed here is designed to aid in quick estimation of manned SC hardware and program costs. The technique should prove very useful for those engaged in advanced program planning, especially on those occasions when speed and ease of calculation outweigh the requirement for accuracy and detail.

The method, although comparatively simple, is capable of producing realistic gross estimates. It is a method from which the exercise of judgment has not been excluded, because judgment is essential to costing accuracy (regardless of the technique employed). Unlike the more elaborate techniques developed for detailed program planning, all basic estimates are made by comparisons with subsystems from present and past programs. Ideally, the user of the handbook should have some familiarity with the referenced Mercury-Gemini-Apollo command and service module (CSM) and Apollo lunar module (LM) programs; however, the only knowledge required of the item to be costed is a general idea of its complexity (relative to SC from the reference programs) and the weights of its subsystems.

It is emphasized that the procedure is designed only for gross-level work but is acceptable, however, for detailed estimation where the items to be costed do not depart radically from the referenced technologies. (For example, no means is provided for the costing of nuclear electrical power or propulsion systems.)

Since there are almost as many costing techniques as there are cost estimators, it is often difficult to determine which technique to use in a particular situation, or conversely, when to employ a particular technique. An acceptable rule for employing this procedure may be stated as follows.

> "The techniques presented herein are sufficiently accurate to estimate SC costs at the module level for comparing one SC with another. Where comparisons or tradeoffs at the subsystem level are required, another method should be employed. When technologies are substantially different from those found in the Mercury, Gemini, and Apollo programs, other techniques or additional techniques should be used; if detailed knowledge of the new SC exists, use of a more detailed technique should be considered."

The estimating charts in this report do not contain analytical relationships (cost-estimating relationships (CER)), other than the ones implied by weight and cost-per-pound values. The estimator is presented only historical data points (from which CER may be constructed).

These techniques result from and are greatly benefited by recently completed and ongoing cost analysis efforts conducted by both MSC and NASA Headquarters (ref. 1). The purpose of this report is to make a summary of these results available to the aerospace community.

Problem areas, especially those involving the data, will be illuminated to insure that the user is aware of all limitations of the method. Since data continually are being updated, this report reflects the status at only one point in time.

SYMBOLS

AO NASA administrative operations cost, millions of dollars

b learning exponent

C_1 first-flight-item cost of SC module, millions of dollars

C(1) cost of the first flight unit, millions of dollars

C(n) cost of the nth flight unit, millions of dollars

C_i cost of the ith subsystem, millions of dollars

F facility costs, millions of dollars

L launch vehicle and launch operations costs, millions of dollars

Nm module nonrecurring costs, millions of dollars

Np SC project nonrecurring costs, millions of dollars

n_i nonrecurring cost of subsystem i, millions of dollars

P total program-level costs, millions of dollars

Rm module recurring costs, millions of dollars

Rp SC project recurring costs, millions of dollars

Sp SC project total costs, millions of dollars

Σ summation

COST DEFINITIONS

Generally, all costs discussed are contract costs to NASA and do not include NASA in-house costs.

Nonrecurring Costs

Subsystem nonrecurring costs. - (A subsystem is a major module element which performs an autonomous function.) Subsystem nonrecurring costs are the costs of developing and qualifying each individual subsystem. Included are all design, test, and evaluation efforts which occur only once, regardless of the number of subsystems built. Flight testing costs are not usually included.

Module-level nonrecurring costs. - (A module is an autonomous SC element usually designed to perform a given portion of a space mission such as transporting men from lunar orbit to the lunar surface.) Module-level nonrecurring costs include the preceding plus systems integration, module ground support equipment (GSE)/aerospace ground equipment (AGE), trainers and simulators peculiar to the module, and all other nonrecurring costs directly allocable to the particular module.

Spacecraft project nonrecurring costs. - (An SC is the union of one or more autonomous modules; it is a vehicle capable of performing an entire space mission but does not include the launch vehicle.) Spacecraft project nonrecurring costs include subsystem nonrecurring costs and module-level nonrecurring costs plus automatic checkout equipment (ACE) and/or GSE for more than one module, contracted supporting development efforts, SC contractor engineering and developmental testing, Government-furnished equipment procured by NASA, and all other nonrecurring costs incurred by the SC project. These are costs not usually incurred by the module contractors but by NASA in support of the SC project.

Recurring Costs

Recurring costs are those which are a function of the number of flight units (and occasionally those which are a function of program length). As developed in this report, recurring costs are functions of the item costs of the hardware.

Subsystem item costs. - Subsystem item costs are the hardware costs of each subsystem at some referenced item number (usually the first manned flight article). They include manufacturing, assembly, quality control, production and acceptance testing, burden, and all other costs allocable to each manufactured production item, including fee. Test items are not included. Sustaining engineering and sustaining tooling are included when they are definitely subsystem-level costs.

Module-level item costs[1]. - Module-level item costs include the preceding plus subsystem installation and physical integration into the module, launch site support for the module, spares (a pro rata share), sustaining GSE (a pro rata share), module acceptance and checkout, transportation of the module, prime contractor training to familiarize flightcrews with the module (a pro rata share), module-level mission planning, and all other module-level costs which are a function of the number of modules produced for flight.

Module-level recurring costs. - Module-level recurring costs are defined as the sum of all module item costs, determined by multiplying the appropriate cumulative total (learning curve) factor by the module first-item cost.

Spacecraft project-level recurring costs (contracted). - Spacecraft project-level recurring costs (contracted) include all module-level recurring costs plus flight operations support, flightcrew training (that which is not module level), mission control operations, backup flight modules, SC recovery and postflight operations, SC project experiments, and all other contracted costs of a recurring nature associated with the SC or its crew.

EXPLANATION OF THE DATA

This method is based entirely on the data presented in tables I and II. These data are the result of two separate NASA studies and of much subsequent analysis by NASA to make cost categories comparable. (See the section entitled "Conclusions and Comments.") The four columns shown (table I) are products of separate cost analyses, which explains why, for the LM, two separate sets of data exist.

The Apollo data are based on estimates to program completion made early in 1966; the Gemini data, while also based on estimates to completion, were made much closer to the end of the program and are likely to be closer to actual.

Originally, two columns of data, similar to those shown for the LM, were available for the Apollo CSM. The single column shown is the result of a separate study to reconcile the differences in accordance with the ground rules of this procedure. Unfortunately, a similar analysis of the LM data was not possible at this writing, since a nonrecurring breakdown by subsystems was not available; therefore, the presentation of both data sources was necessary. The large differences shown are apparently the result of differences in allocating sustaining engineering and subsystem integration costs, but this has not been verified yet.

The major manipulations made to the basic referenced data are footnoted in table I and should be self-explanatory.

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[1]If learning effects are to be included, this is the module first-item cost, derived from subsystem first-item estimates. When learning effects for small quantities are considered negligible, "item" and "first-item" have the same meaning.

All costs shown are in dollars valued at the years of the respective studies (1965-66) and have not been adjusted for differences in dollar values between the beginnings and the endings of the particular programs. These effects are small in comparison with other data inconsistencies; but the inflationary effect should be considered when extrapolating estimates far into the future.

The remaining data used in the charts, the weights of the various subsystems, are given in table IV (ref. 3).

On the structure chart (fig. 1), the X-15 data point is shown for comparison. This point is from the report done at the NASA Flight Research Center by Love and Young (ref. 2).

SUMMARY OF THE PROCEDURE

This cost estimating method, like others developed at MSC, divides costs into nonrecurring (one-time) and recurring categories. It is designed to accelerate estimation by allowing the calculation of the sum of many numbers from the detailed estimation of only a few. Since errors in the aggregate estimate will be magnified by errors in the "few" estimates, these base calculations must be made with care; hence, recurring hardware costs of the subsystems have been chosen for detailed analysis because they are inherently more easily estimated than costs in the nonrecurring categories.

In summary, the procedure begins with the estimation of hardware costs for each subsystem in the module; these are then summed and all other costs which make up the cost of a complete module are added (by multiplicative factors). From this module hardware item cost (primarily manufacturing and manufacturing support), the nonrecurring program costs (primarily design, development, and testing) may be estimated. Modules are then summed and other SC-level costs added to make up the cost of a complete SC.

Total recurring costs are calculated by multiplying the item costs by the number of items (or, more accurately, by applying learning methods in conjunction with the number of items).

All of the steps discussed previously are presented graphically in the following pages; all operations except the addition of the several numbers may be done on the enclosed charts.

The final step is merely to add the recurring and nonrecurring items to obtain total program costs.

ESTIMATION OF RECURRING COSTS

Recurring costs are those which are a function either of the number of flight units or of program length and are broken out to allow analysis of programs of varying magnitudes which employ the same types of flight hardware.

Subsystem Description

The procedure begins with a listing of the subsystems in the SC to be costed. Along with each subsystem, all known technical data to aid in weight estimation should be listed. While weight estimation is a subject not dealt with in this report, it is a necessary preliminary step to cost estimation by this method. For the steps which follow, it will be assumed that weight estimates have been made. The listing of technical data also will aid in estimating system complexity, another step vital to this costing method.

First-Item Cost Estimation, Graphical

The greatest advantage of this method is that it will quickly illuminate differences in SC costs down to the subsystem level, the level at which the basic cost estimates are made. The concept of a first-item cost is relatively simple; it is a theoretical value for the first unit of hardware produced (ref. 3). It is theoretical, rather than actual, because it is usually determined by extrapolating backward to unit 1, from data collected on subsequent units, an exponential regression line fit of actual unit costs. The concept is useful because the cost of any single SC or any grouping of SC may be calculated from the first unit cost in conjunction with a learning curve. (See the section entitled "Module-Level Recurring Cost Estimation.")

The concept of learning is somewhat more complex; the only comment necessary for this paper is merely that studies of the trend of hardware fabrication costs have revealed that costs decrease as quantities increase and that a functional relationship exists between cost and quantity (ref. 3). This relationship has been approximated in several ways, the most common being $C(n) = C(1)^{-b}$.

In addition to being the essential quantity in recurring cost estimation, the first unit cost has been found to be useful in predicting developmental costs. (Refer to method 1 in section entitled "Estimation of Nonrecurring Costs.") Therefore, it is clear why the most important single calculation in cost estimation by this method is the estimation of the hardware first-item cost.

Since all cost estimation is in some measure dependent upon historical cost data, accurate analysis and clear presentation of these data are essential. This model takes advantage of much data collection and analysis which have been performed both in house at MSC and on contract. Figures 2 to 13 have been prepared from the MSC Advanced Spacecraft Technology Division (ASTD) cost data bank to present a great deal of cost data in a highly visible form. Upon this visibility rests the entire concept of this technique of estimation, for from these charts costs will be estimated directly. Each chart is entered with a value for the weight of the subsystem to be costed. Since it is obvious that weight alone is not an adequate predictor of cost, another parameter, some measure of complexity, must be employed. Therefore, the charts contain lines of constant cost, lines of constant cost per pound (complexity), lines of constant weight (size), and all pertinent historical data points to serve as references for complexity, size, and absolute cost comparisons. Figure 1, especially the instructions with the figure, provides guidelines to be used in estimating costs from the charts. Some practice in using these charts will show that the order of magnitude of the cost of any item is easily established, but since the charts are log-log plots, large errors may be introduced by uncertainties on the part of the estimator. Therefore, the ease with which an estimate is made should not be confused with the ease of achieving accuracy.

First-Item Cost Estimation (Alternate Method)

Cases where quantitative complexity comparisons may be made between the new item and some historical item may occur. If such quantitative factors are available, the individual estimator may prefer to work directly with the historical cost data. For this reason, historical subsystem data are presented in tables I and III.

Module-Level First-Item Cost Estimation

Module-level first-item costs are defined as the total of all subsystem first-item costs plus all recurring-type costs required to integrate and install subsystems, perform systems checkout, transport the SC, and provide any other service (such as mission planning and prelaunch checkout) of the item. (Refer to the section entitled "Module-Level Item Costs.") A more general definition is all costs which can logically be allocated to the hardware item prior to flight. Sustaining engineering, spares, and recurring GSE are included.

Figure 14 presents an estimating relationship for total module-level first-item costs as a function of total subsystem-level costs. A least-squares linear fit was made to the data, with all data points given equal weight (except that since there were two LM data points, each received only one-half the weight of other points). An alternate method for predicting total subsystem-level item costs is presented in figure 15. To use this figure, only six or seven subsystems are costed with the above method (seven if the module has a launch escape subsystem (LES), but six if it does not). Totals are read from the curves which predict total subsystem costs as a function of the sum of the costs of the following.

1. Structure subsystem
2. Environmental control subsystem (ECS)
3. Electrical power subsystem (EPS)
4. Guidance and navigation (G&N) subsystem
5. Stabilization and control subsystem (SCS)
6. Reaction control subsystem (RCS)
7. LES

If the module being costed has no LES, the upper curve of the figure is used; if it has an LES, the lower curve is used. This alternative is presented primarily as a time-saving shortcut and is not meant to be used where more detail is important.

Module-Level Recurring Cost Estimation

Module-level recurring costs are defined as the product of the first-item cost and the appropriate cumulative total cost factor from table IV (ref. 3).

Spacecraft Project-Level Recurring Cost Estimation

The calculation of project-level (SC) recurring costs is made by summing total module flight item costs and adding other costs of a recurring nature. Because these "other" costs are a function of the particular costing exercise, methods for their individual prediction are not included, although their total may be estimated with the method of figure 16. Some typical examples are flight operations support, recovery operations, and mission control operations.

ESTIMATION OF NONRECURRING COSTS

Two ways to estimate nonrecurring costs from the available data are used. Either a process like the one described previously for recurring costs can be used, with each subsystem nonrecurring cost estimated individually and then all accumulated; or a system may be devised for estimating nonrecurring costs from first-item costs, again based on the referenced programs. The latter method has the advantage of simplicity but the disadvantage of being much less general than the former. Curves are presented to permit the use of either method.

Method 1, Estimating Spacecraft Project Nonrecurring Costs from Module First-Item Costs

The calculation of module-level first-item costs was described previously. Figure 17 gives the linear relationships for estimating project-level nonrecurring costs from module first-item costs. Use of any of the given ratios would naturally imply that the new program would enjoy the same relationships between development and manufacturing complexities as the referenced program. These referenced programs represent a considerable range of values, as shown in figure 17.

Method 2, Estimating Spacecraft Project Nonrecurring Costs from the Sum of Subsystem Nonrecurring Costs

Subsystem level nonrecurring costs may be estimated from charts similar to those used previously to estimate first-item costs. However, the use of the nonrecurring cost charts (figs. 18 to 29) is much more difficult than the use of the first-item cost charts because the dollar-per-pound comparison has much less significance in developmental cost estimation. To aid in overcoming this limitation, much work has been done by MSC, NASA Headquarters, and their support contractors in the development of CER for developmental and hardware costs (ref. 1). Nevertheless, it is believed that from the charts in this report the educated cost analyst can make estimates comparing favorably to those produced by the best available analytical relationships.

Even further, all magnitudes of estimates made by analytical relationships must be checked, and these charts are a time-saving aid to this checking process. As before, actual cost histories (table II) may be used in lieu of the charts. Once individual subsystem developmental cost estimates have been made, they are summed and converted to module-level and SC project-level costs by use of figures 30 and 31, respectively.

ESTIMATION OF TOTAL PROGRAM-LEVEL COSTS

In addition to the SC projects, a space program includes other elements such as launch vehicles, launch operations, facilities, and NASA administrative operations costs. This report deals only with SC, the total costs of which are expressed by the equation $Sp = (Np + Rp)$. Total program-level costs are expressed $P = Sp + L + F + AO$. For advanced program budgetary planning, the administrative operations costs are often omitted, since they are more directly relatable to the level of effort of all programs combined than to the technical characteristics of a single program.

CONCLUSION AND COMMENTS

This report has presented a generalized method for predicting the costs of manned SC. The method was based on data from the Gemini and Apollo SC programs. Since data from these two programs were not collected in a manner designed to be useful for future cost estimation, much analysis of the data was necessary prior to the creation of these techniques. These analyses were performed both on NASA contracts and in house at MSC within the ASTD. Even after this considerable analysis, many unresolved questions remain — primarily in the area of dividing historical costs into recurring and nonrecurring categories. The uncertainties in the Grumman LM data were such that two sets of numbers were employed throughout this development.

To resolve these discrepancies, at least two areas of research are underway. First, under the direction of NASA Headquarters, the Apollo contractors presently are reanalyzing their historical and projected runout estimates for submission in a reporting format designed to aid the advanced program cost estimator. Second, MSC, in conjunction with Texas A. & M. University, is building a program-cost data bank and is performing analyses designed to separate recurring and nonrecurring costs in a rigorous manner.

It is believed that until these additional analyses are completed, the data presented here are the best available for SC cost estimation.

Manned Spacecraft Center
National Aeronautics and Space Administration
Houston, Texas, October 31, 1967
981-89-00-00-72

TABLE I. - SUBSYSTEM FIRST-ITEM COSTS[a]

Module level first item	Cost, millions of dollars			
	Apollo CSM (b)	Apollo LM (c)	Apollo LM (d)	Gemini SC (e)
Subsystems				
Structure[f]	4.355	2.633	13.007	7.116
ECS	1.176	1.667	1.711	1.650
G&N (including software)[g]	5.350	8.817	15.922	4.211
SCS	1.863	3.165	3.733	.919
RCS	2.484	2.174	3.286	6.357
EPS	3.743	1.280	4.306	4.430
Communications[h]	3.448	1.933	4.231	2.017
Instrumentation[h]	2.300	1.631	6.047	.664
Crew provisions	1.050	1.160	.668	.304
Landing and recovery	.741	.797	.532	.879
LES	1.128	--	--	1.479
Propulsion	1.928	5.073	17.135	.276
Adapter	1.161	--	--	--
Total subsystems	30.727	30.330	70.578	30.302
Sustaining tooling	--	1.271	--	--
Launch site support	2.829	4.823	2.375	4.155
Mission planning and analysis	(i)	(i)	4.230	.407
Subsystem installation and integration	4.757	1.739	4.652	2.715
Spares (per launch)	6.383	1.521	2.483	1.592
GSE (recurring) (per launch)	5.408	.140	--	--
Sustaining engineering	(j)	(j)	(j)	(j)
Module acceptance and checkout	3.939	--	--	--
Other	6.020	2.549 .928	--	--
Total module level first item	60.063	43.301	84.318	39.171

[a]Including contractor fee: the Apollo cost study numbers include the contractor fee and change allowances.

[b]SC 101 cost, 1966 Apollo cost study (North American Aviation, Inc.).

[c]Cost of LM 1 from the 1966 Apollo cost study, Grumman Aircraft Engineering Corp. The item is considered the first of 16 equivalent SC, of which 15 are flight items.

[d]MSC/Booz-Allen cost analysis study.

[e]Twelve items.

[f]Structure cost has had systems installation and integration removed.

[g]G&N estimates from arbitrary allocation of costs between CSM and LM projects.

[h]Arbitrary 60:40 split, since instrumentation not shown separately by North American Aviation, Inc.

[i]Costs included in structure and/or other categories.

[j]Pro rata in subsystems.

TABLE II. - SPACECRAFT PROJECT NONRECURRING COSTS[a]

SC project level nonrecurring	Cost, millions of dollars			
	Apollo CSM (b)	Apollo LM (b)	Apollo LM (c)	Gemini SC (c)
Module level nonrecurring				
Subsystem nonrecurring				
Structure[d]	169.793	(e)	36.355	24.793
ECS	75.382	--	15.131	13.006
G&N[f, g]	200.568[g]	42.880	32.716	33.058
SCS	220.341	--	17.946	6.083
RCS	84.307	--	11.911	21.055
EPS	181.560	--	13.276	23.875
Communications[h]	123.302	--	10.503	8.120
Instrumentation[h]	82.202	--	12.159	3.388
Crew provisions	30.509	--	2.409	1.423
Landing and recovery	71.453	--	3.717	.739
LES	43.198	--	--	2.667
Propulsion	132.732	--	37.490	.973
Adapter	46.261	--	--	--
Total subsystem nonrecurring	1461.608	596.371	193.613	139.180
Subsystem installation and integration	196.564	181.122	72.970	16.069
GSE	406.664	183.459	214.122	85.450
Ground tests	178.036	64.408	52.725	15.625
Trainers and simulators	62.641	32.753	11.988	18.425
Other module level	239.485	81.644	--	--
Total module level nonrecurring	2544.998	1139.757	545.418	274.749
Supporting development	--	--	--	29.914
Other	--	--	--	6.271
Total SC project level nonrecurring	--	--	--	310.934

[a]All subsystem costs include pro rata share of fee, change allowances, initial tooling, and flight test hardware. Other categories include fee.

[b]1966 Apollo cost study.

[c]MSC Booz-Allen cost analysis study.

[d]Systems integration separated from structure.

[e]Nonrecurring cost breakdown not submitted by Grumman Aircraft Engineering Corp.

[f]G&N costs include software.

[g]Arbitrary allocation of G&N between CSM and LM.

[h]Arbitrary 60:40 split; North American Aviation, Inc., did not separate communications and instrumentation costs.

TABLE III. - APPROXIMATE SUBSYSTEM WEIGHTS

Subsystem	Weight, lb			
	LM	CSM	Gemini	Mercury
Structure	2511	10 990	2257	1400
ECS	380	600	523	135
G&N	110	392	266	45
SCS	90	190	40	115
RCS	280	600	540	71
EPS	1550	3 342	617	327
Communication	128	480	92	113
Instrumentation	233	68	280	139
Crew provisions	75	95	137	126
Landing	463	725	238	345
LES	--	8 772	--	1790
Propulsion	1606	1 242	1253	--
Adapter	--	3 746	--	185

TABLE IV. - CUMULATIVE TOTAL COST FACTORS[a]

Number of items	100 percent	95 percent	90 percent	85 percent	80 percent	75 percent
1	1	1.00	1.00	1.00	1.00	1.00
2	2	1.95	1.90	1.85	1.80	1.75
3	3	2.87	2.75	2.62	2.50	2.38
4	4	3.77	3.56	3.35	3.15	2.95
5	5	4.66	4.34	4.03	3.74	3.46
6	6	5.54	5.10	4.69	4.30	3.93
7	7	6.40	5.84	5.32	4.83	4.38
8	8	7.26	6.57	5.94	5.35	4.80
9	9	8.11	7.29	6.53	5.84	5.20
10	10	8.95	7.99	7.12	6.32	5.59
11	11	9.79	8.69	7.69	6.78	5.96
12	12	10.62	9.37	8.24	7.23	6.31
13	13	11.45	10.05	8.79	7.66	6.66
14	14	12.27	10.72	9.33	8.09	6.99
15	15	13.09	11.38	9.86	8.51	7.32
16	16	13.91	12.04	10.28	8.92	7.64
17	17	14.72	12.69	10.90	9.32	7.94
18	18	15.52	13.33	11.41	9.72	8.25
19	19	16.33	13.97	11.91	10.10	8.54
20	20	17.13	14.61	12.40	10.48	8.83
25	25	21.10	17.71	14.80	12.31	10.19
30	30	25.00	20.73	17.09	14.01	11.45
35	35	28.86	23.67	19.27	15.64	12.62
40	40	32.68	26.54	21.43	17.19	13.72
45	45	36.47	29.37	23.50	18.68	14.77
50	50	40.22	32.14	25.51	20.12	15.78

[a]Abstracted from reference 3.

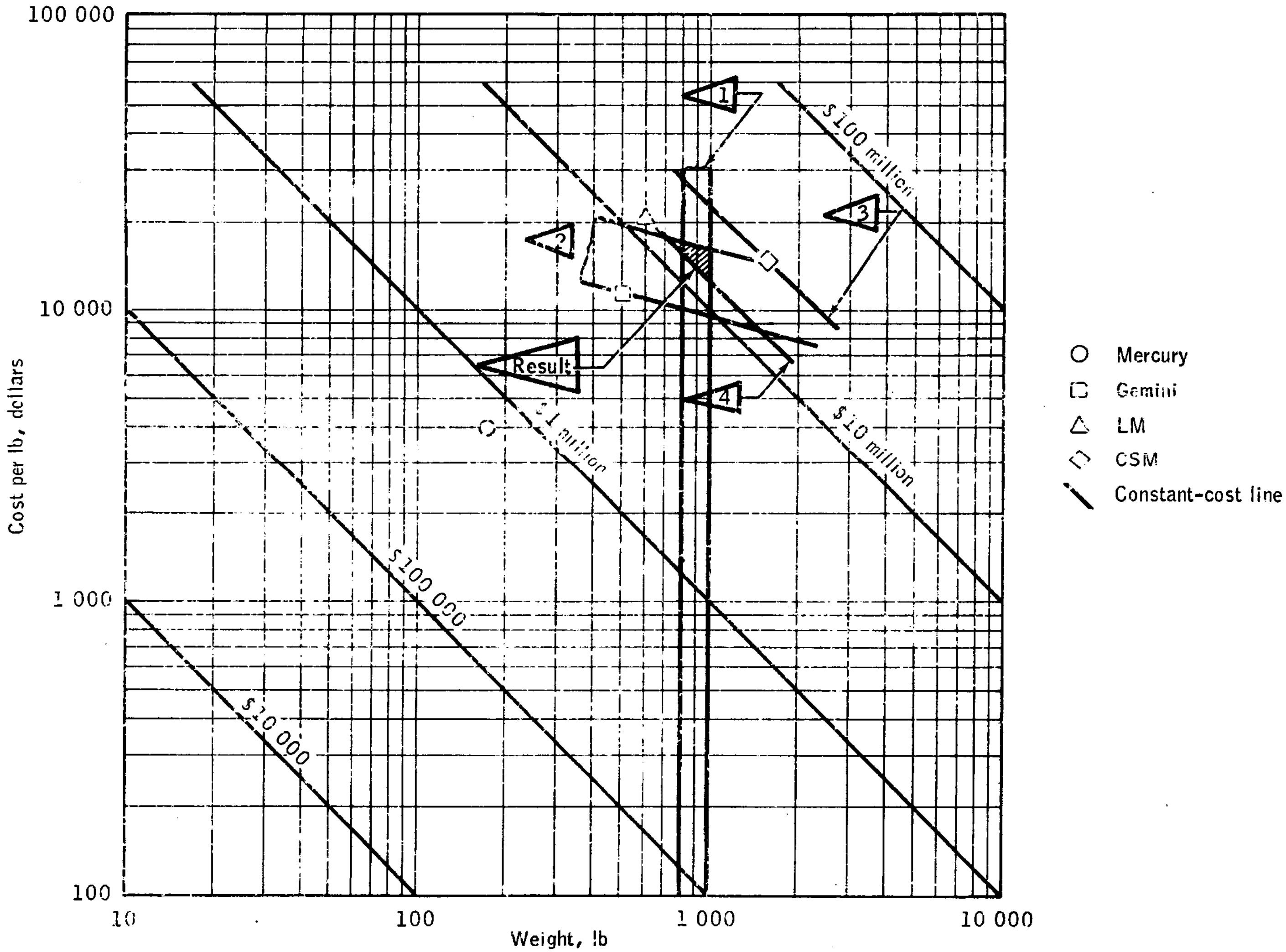

Figure 1. - Use of cost-estimating charts.

1. The item weighs between 800 and 1000 pounds. Draw vertical (constant-weight) lines at 800 and 1000 pounds. The area between the lines is valid.

2. This item is more complex than the Gemini subsystem, but less complex than the CSM. A more correct statement of this judgment rule would be the following. If the item were constrained to weigh the same amount as the Gemini item, it would be more costly per pound; if it were constrained to weigh the same amount as the CSM item, it would be less costly per pound. Curves of constant complexity should run diagonally downward and to the right on the chart, with slopes somewhere between constant cost and constant cost per pound. These curves would be projections only onto the cost/weight plane of any analytical cost-estimating relationships derived from the data. Draw constant-complexity lines if available from an external source. Those shown are exponential curves, but are only examples. (Note also that the method will work without step 2.)

3. The cost is less than the CSM subsystem cost. Draw a constant-cost line through the CSM data point; the area below and to the left of this line is valid.

4. The cost is greater than the Gemini cost. Draw a constant-cost line through the Gemini data point; the area above and to the right of this line is valid.

Result: The lines mentioned previously have outlined an area within which the answer must lie; therefore, the cost is between $12.5 and $16.5 million (shaded area). Judgment (or other available quantifications) is now exercised to choose the value to be used; usually, the higher value would be chosen for conservatism.

Figure 1.- Concluded.

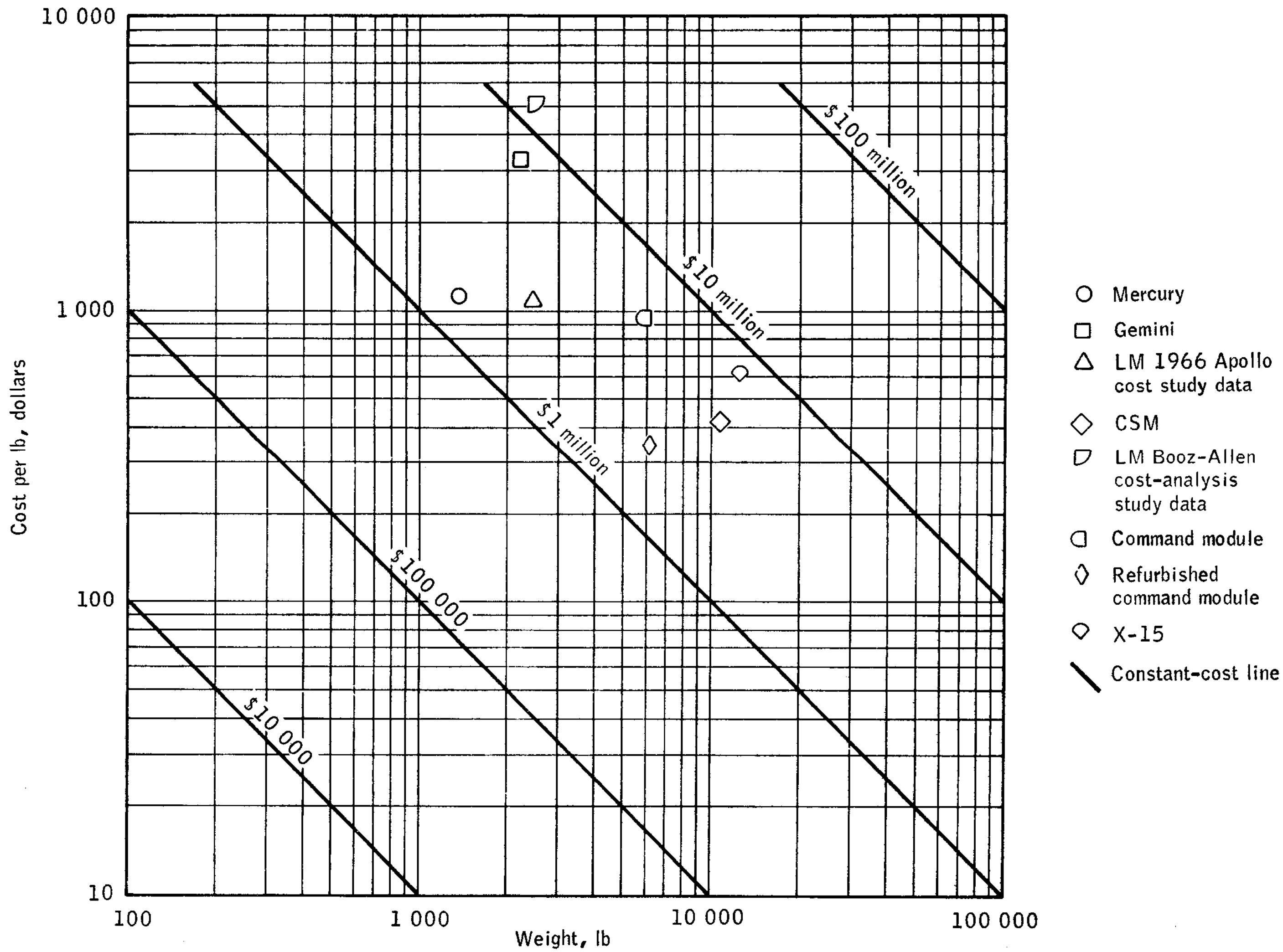

Figure 2. - Structure first-item costs.

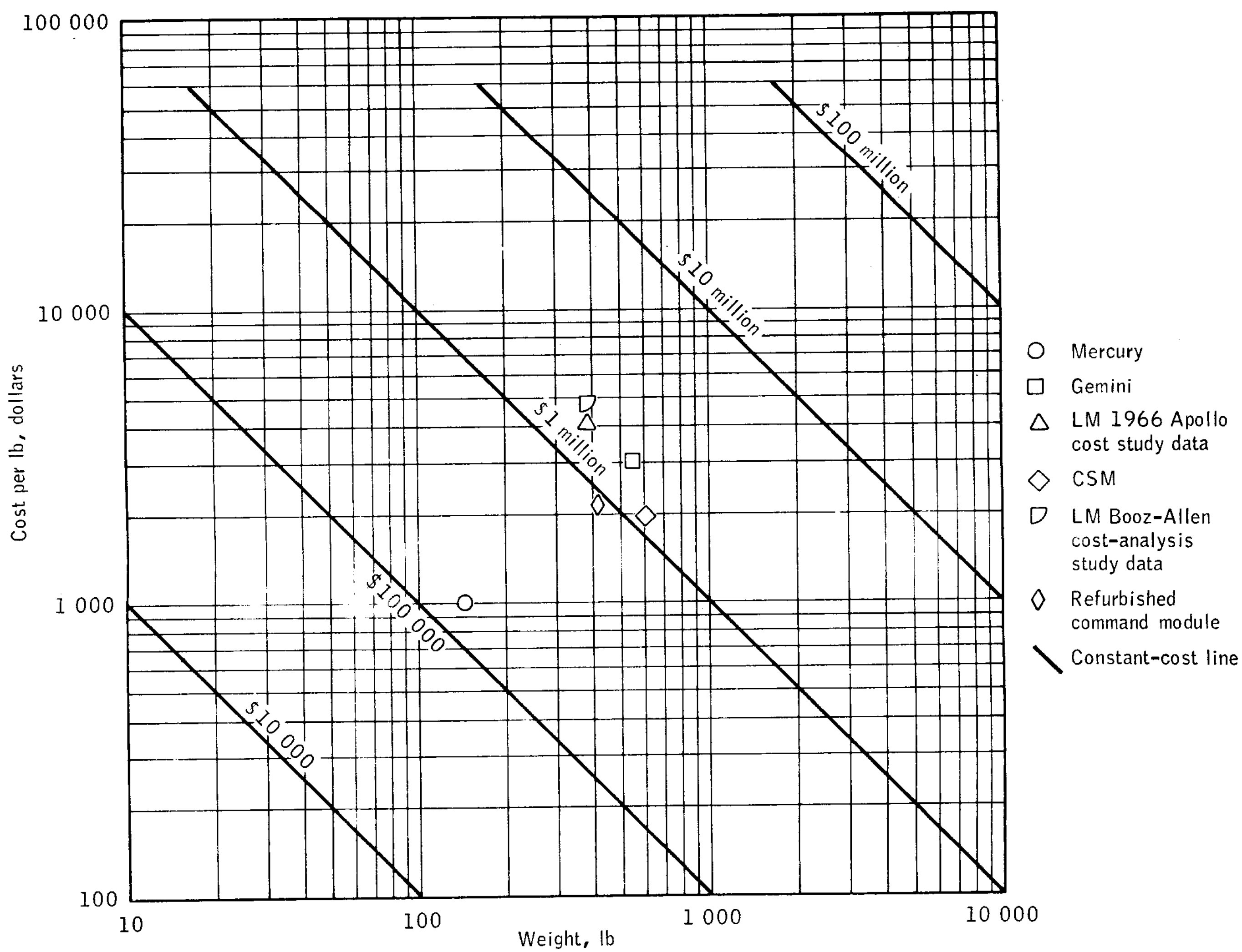

Figure 3. - Environmental control subsystem first-item costs.

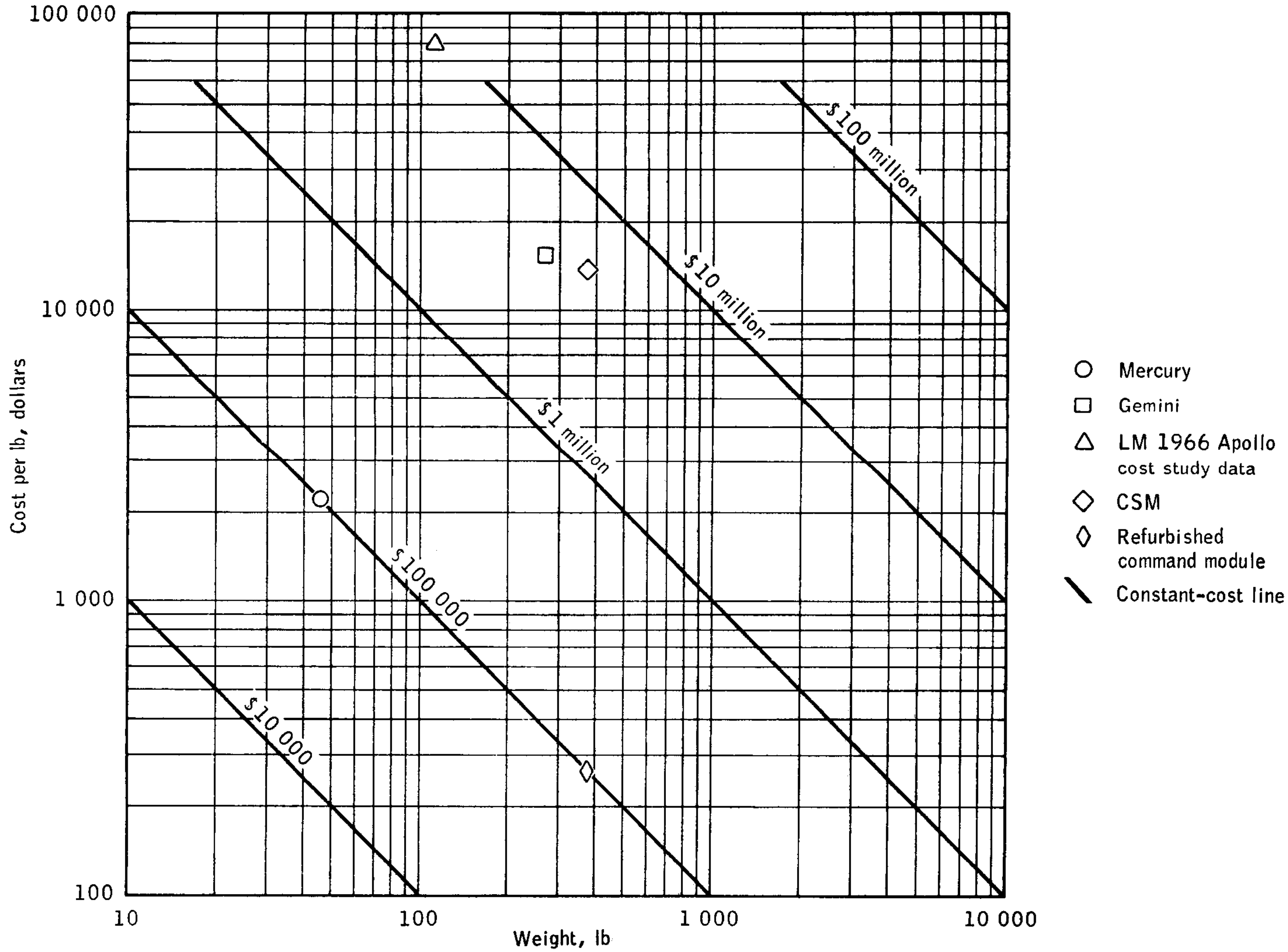

Figure 4. - Guidance and navigation subsystem first-item costs. (Apollo guidance and navigation costs are based on arbitrary allocation.)

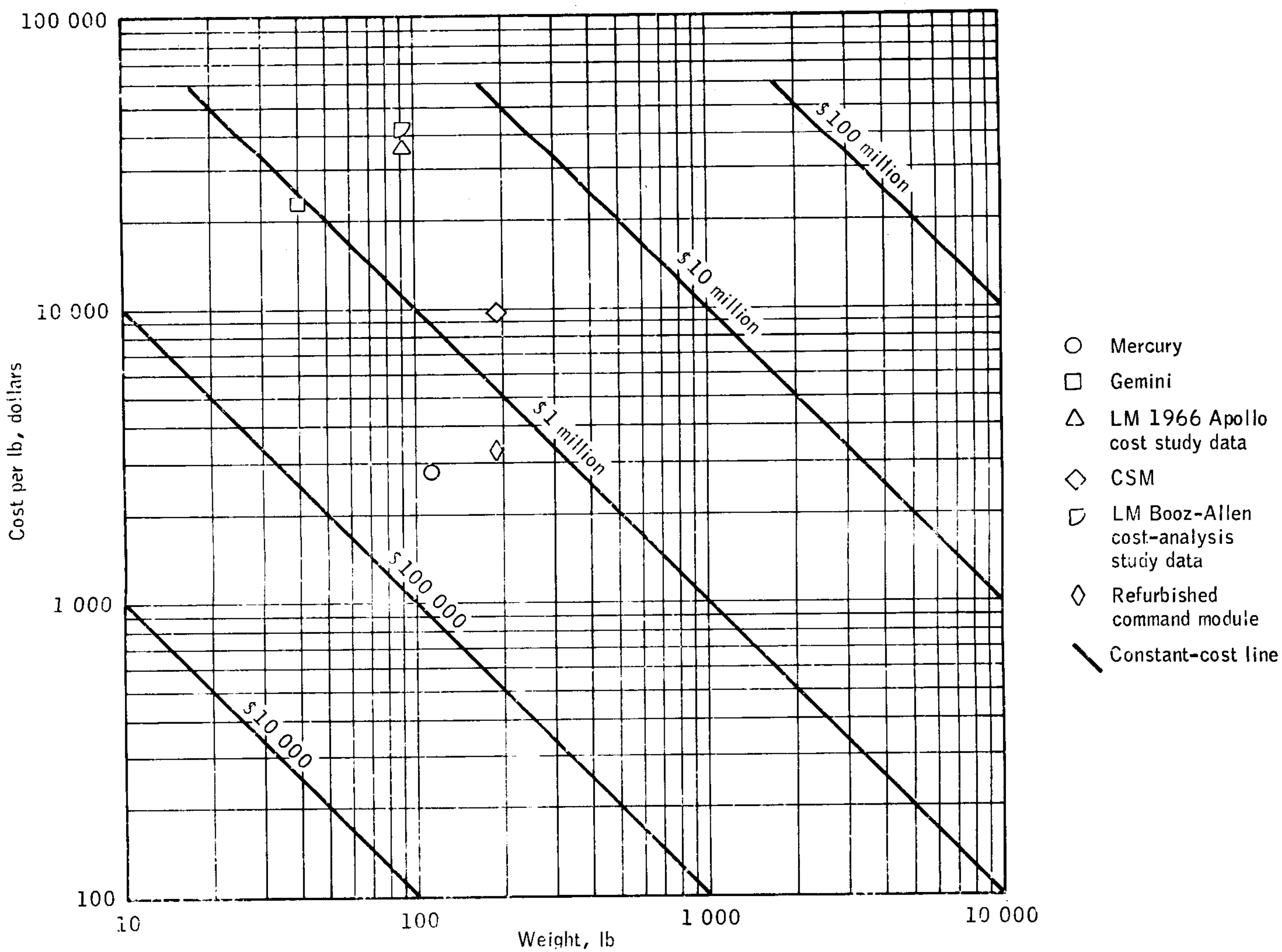

Figure 5. - Stabilization and control subsystem first-item costs.

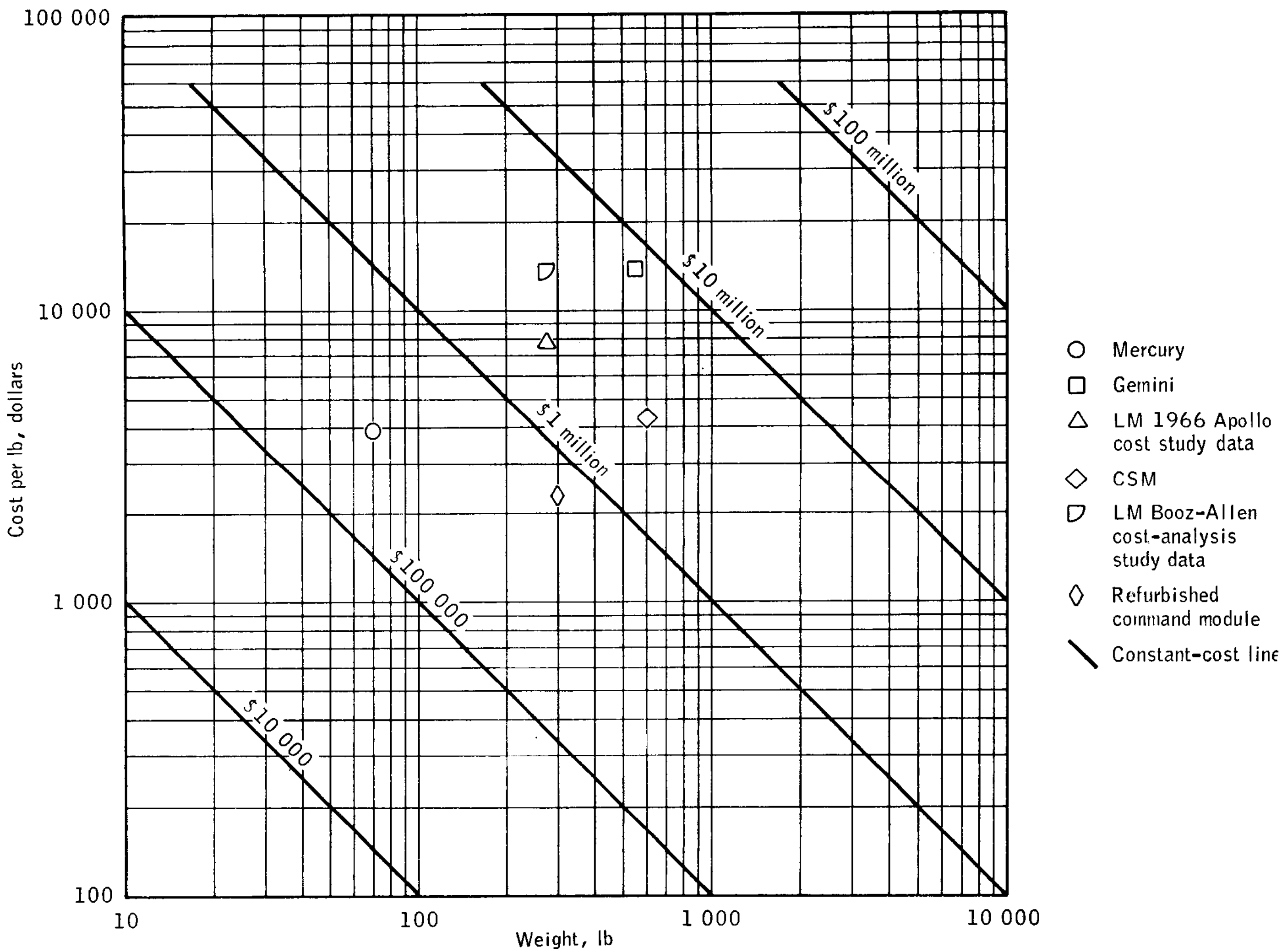

Figure 6. - Reaction control subsystem first-item costs.

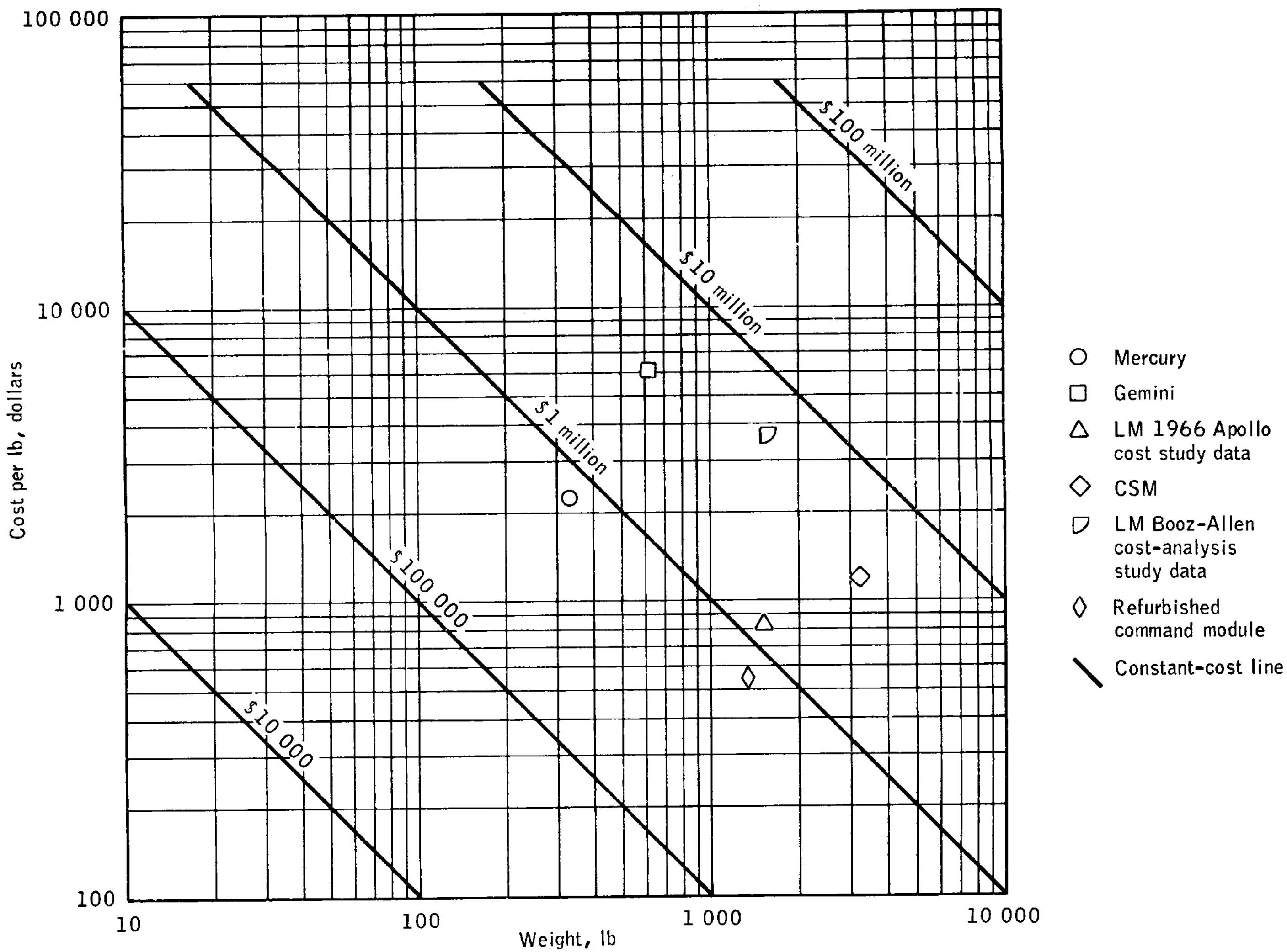

Figure 7. - Electrical power subsystem first-item costs.

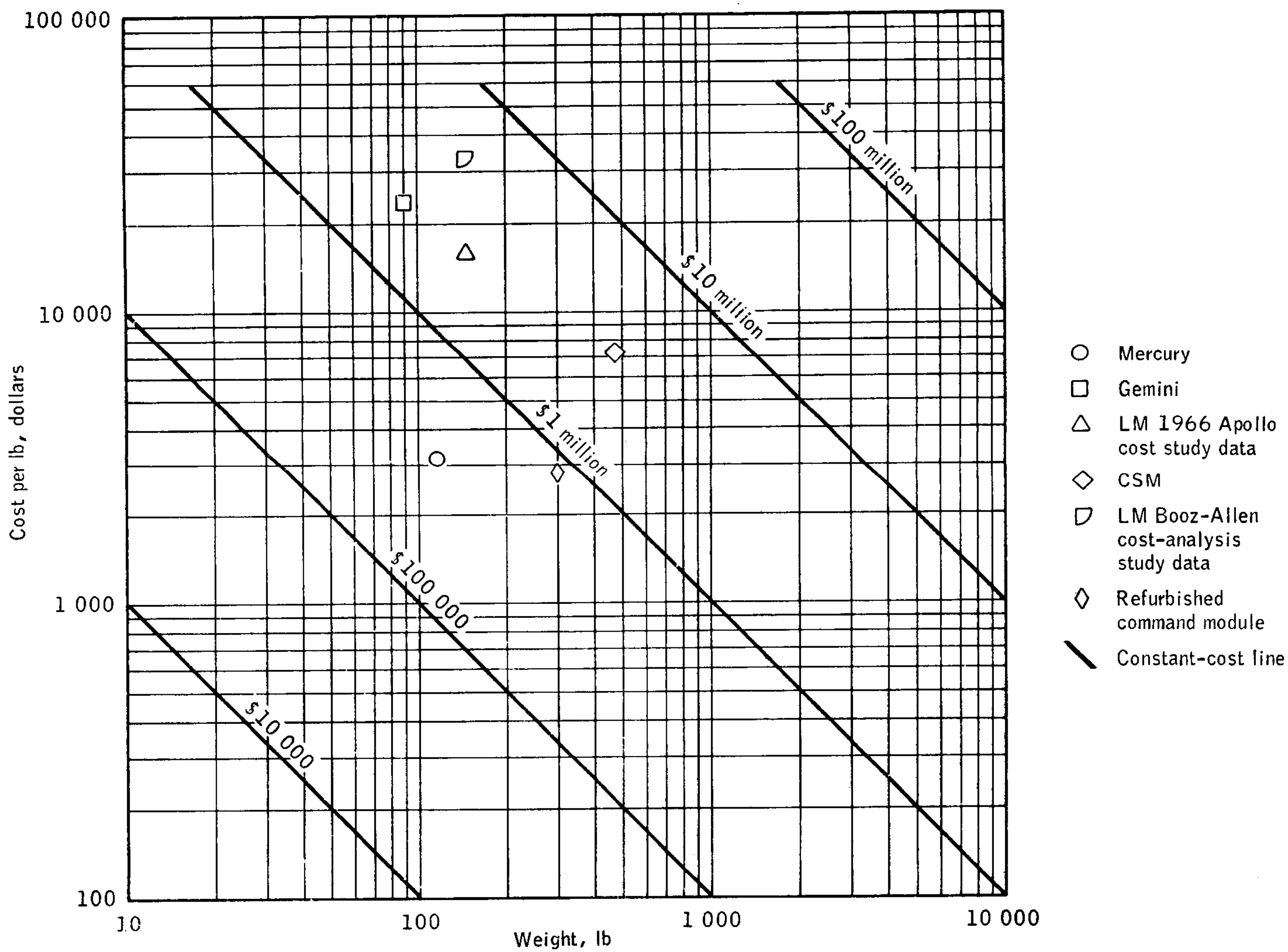

Figure 8. - Communications first-item costs.

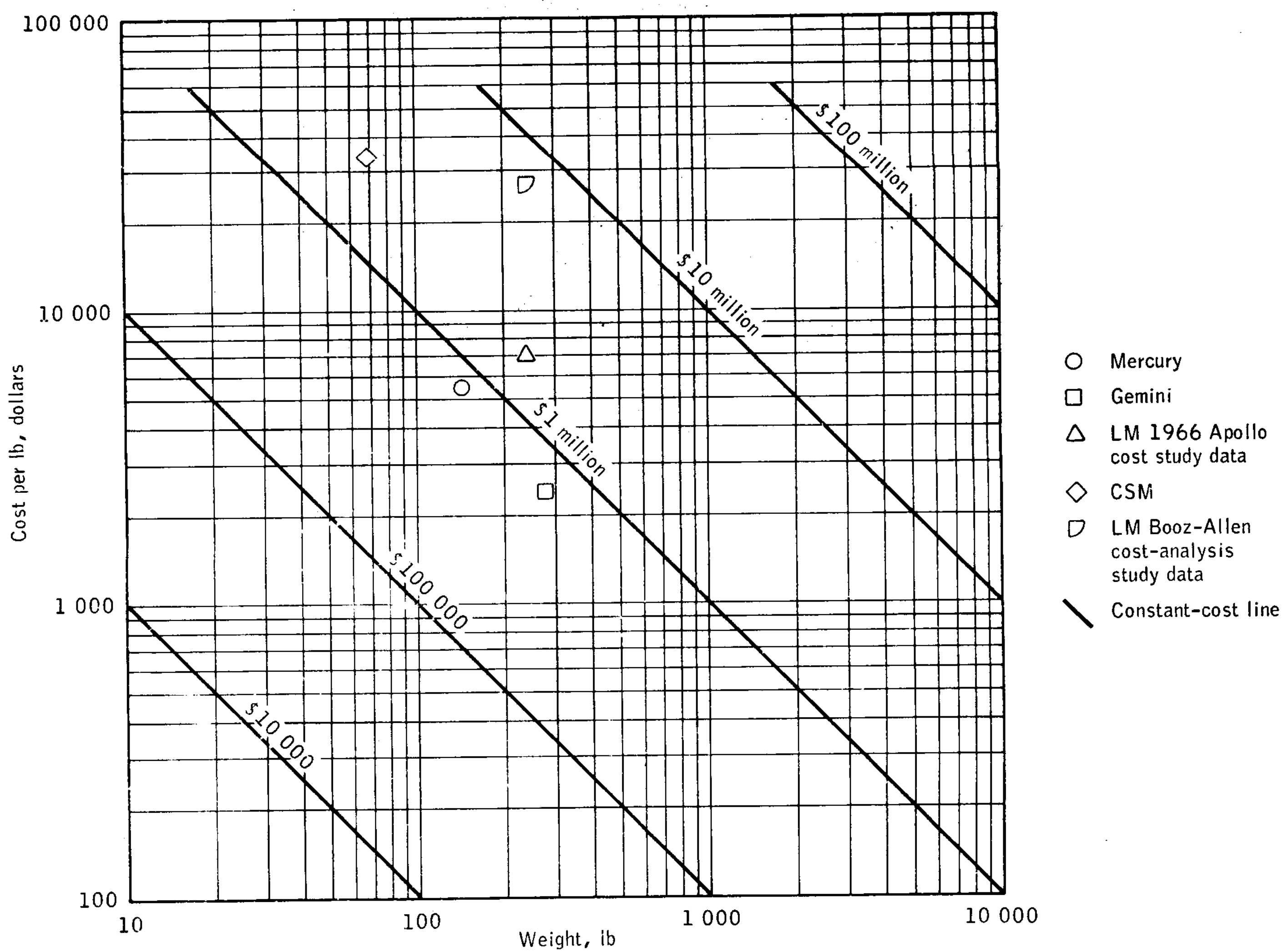

Figure 9. - Instrumentation first-item costs.

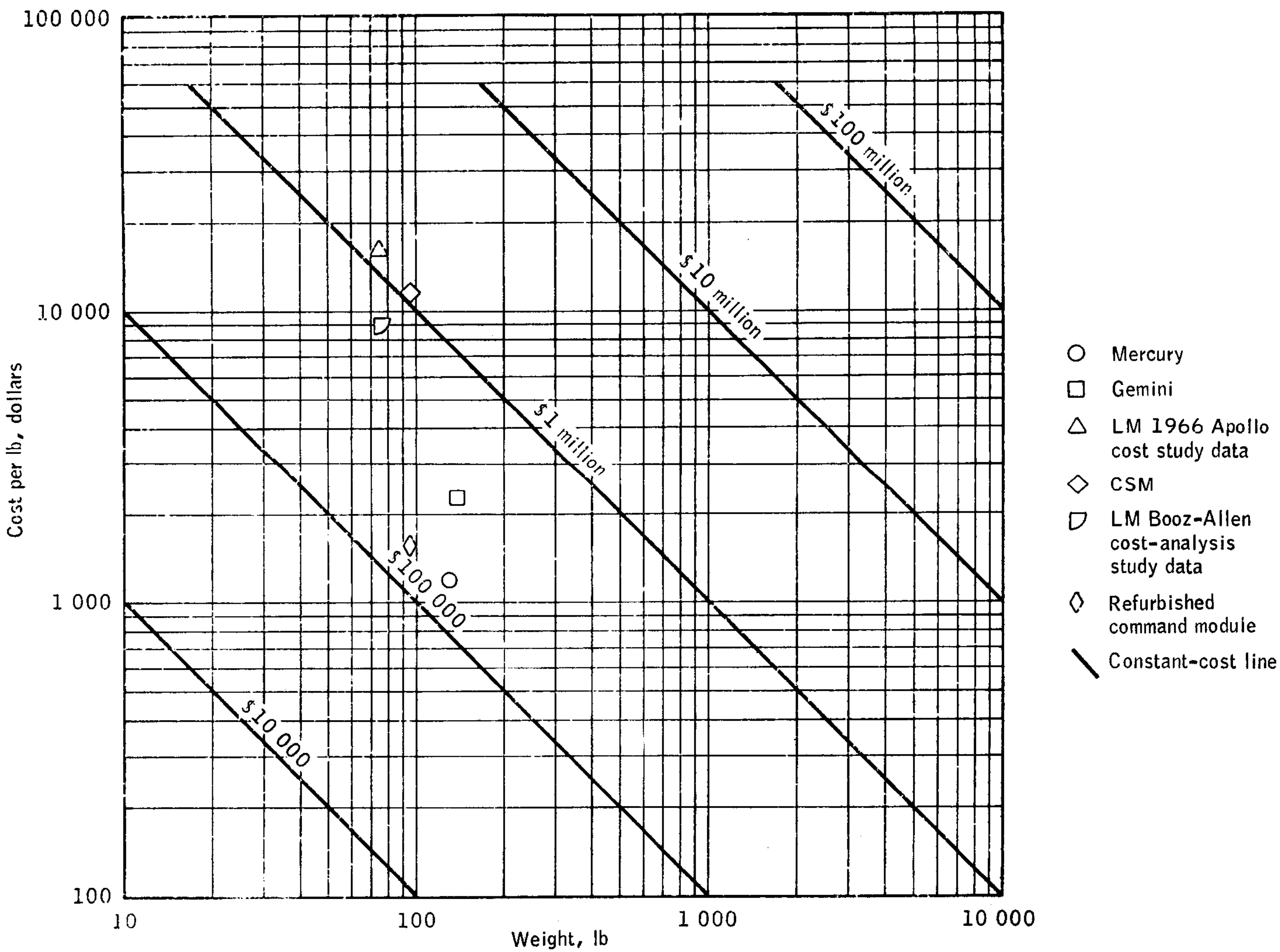

Figure 10. - Crew systems first-item costs.

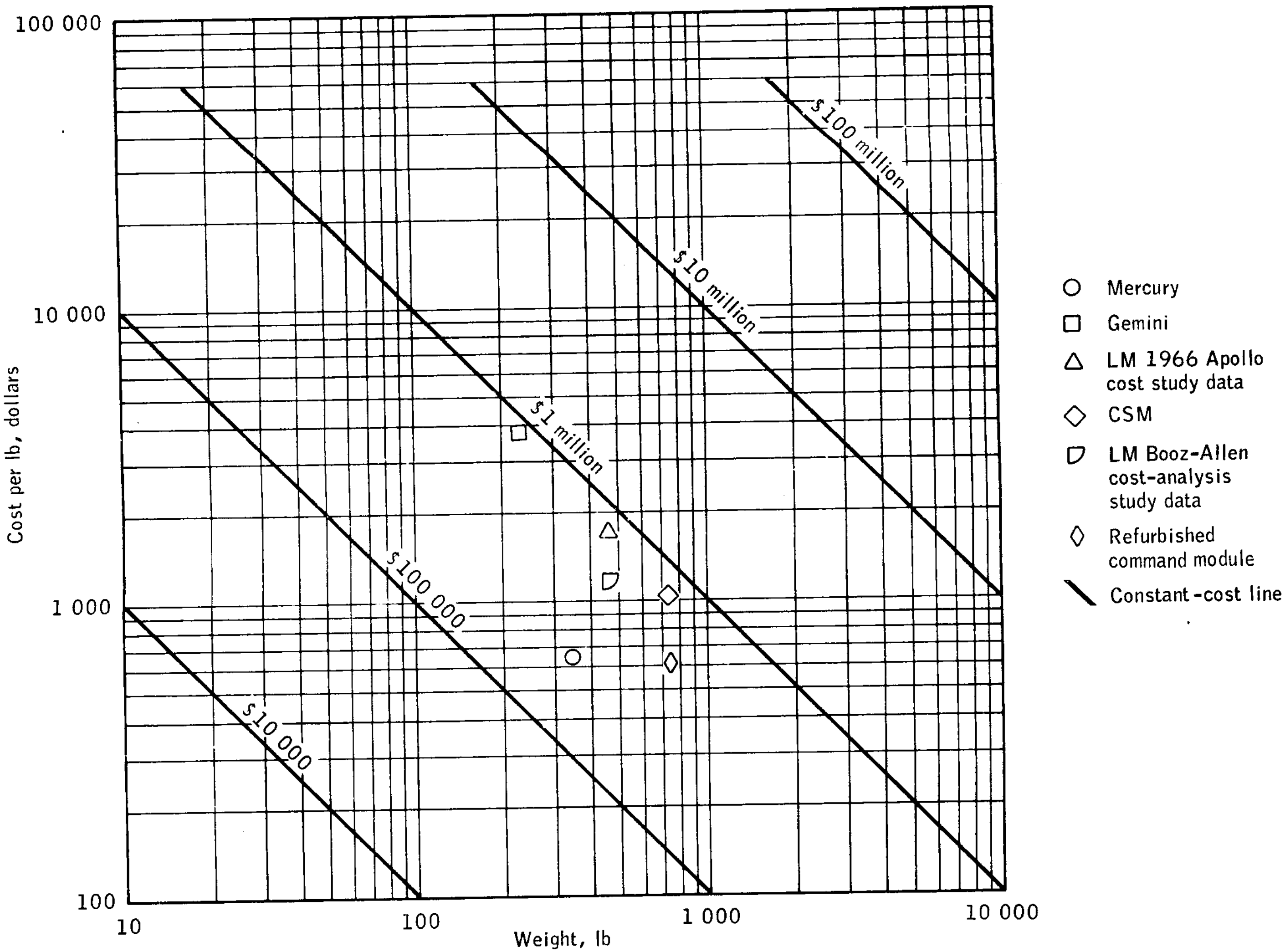

Figure 11. - Landing subsystem first-item costs.

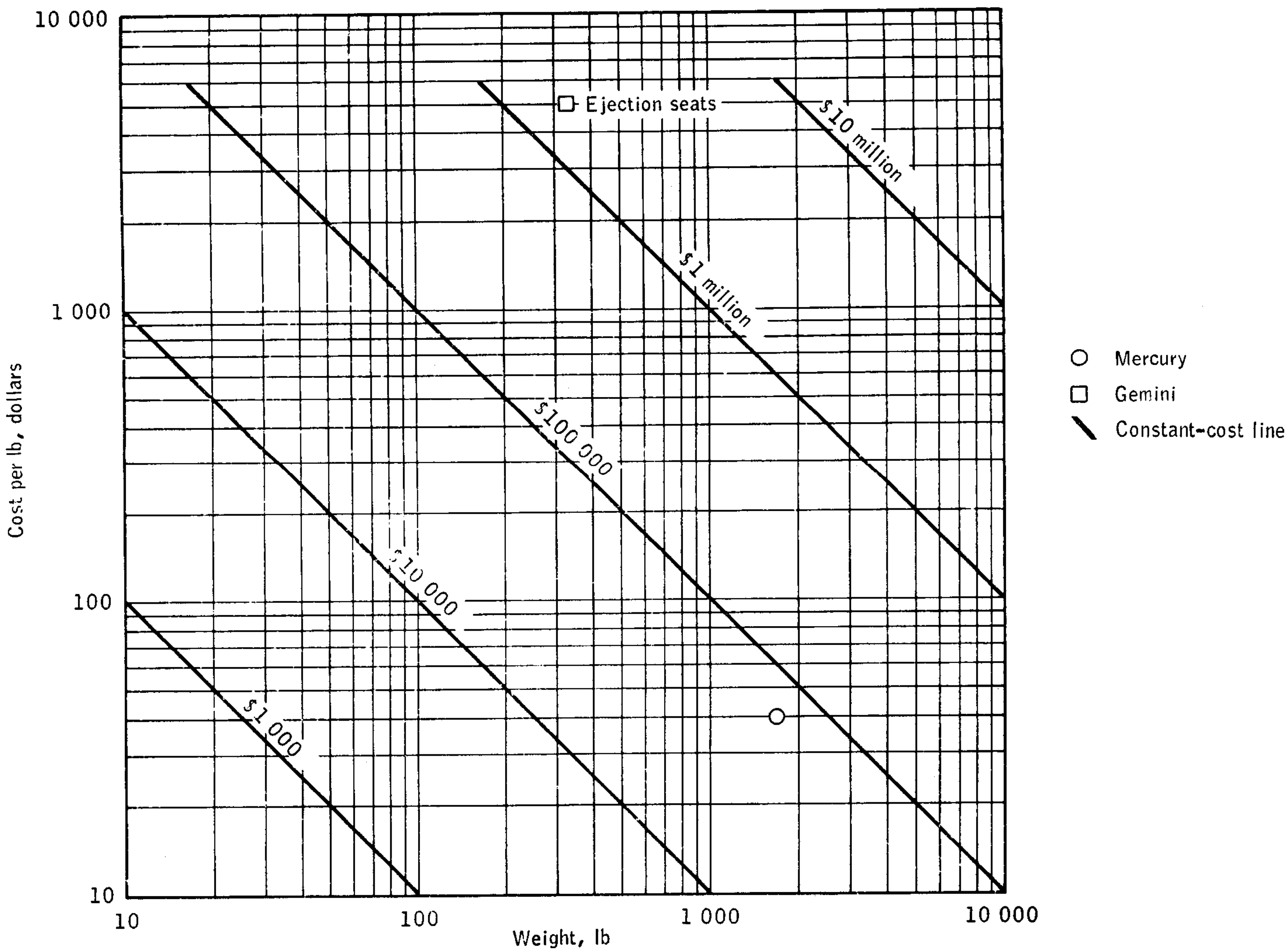

Figure 12. - Launch escape subsystem first-item costs.

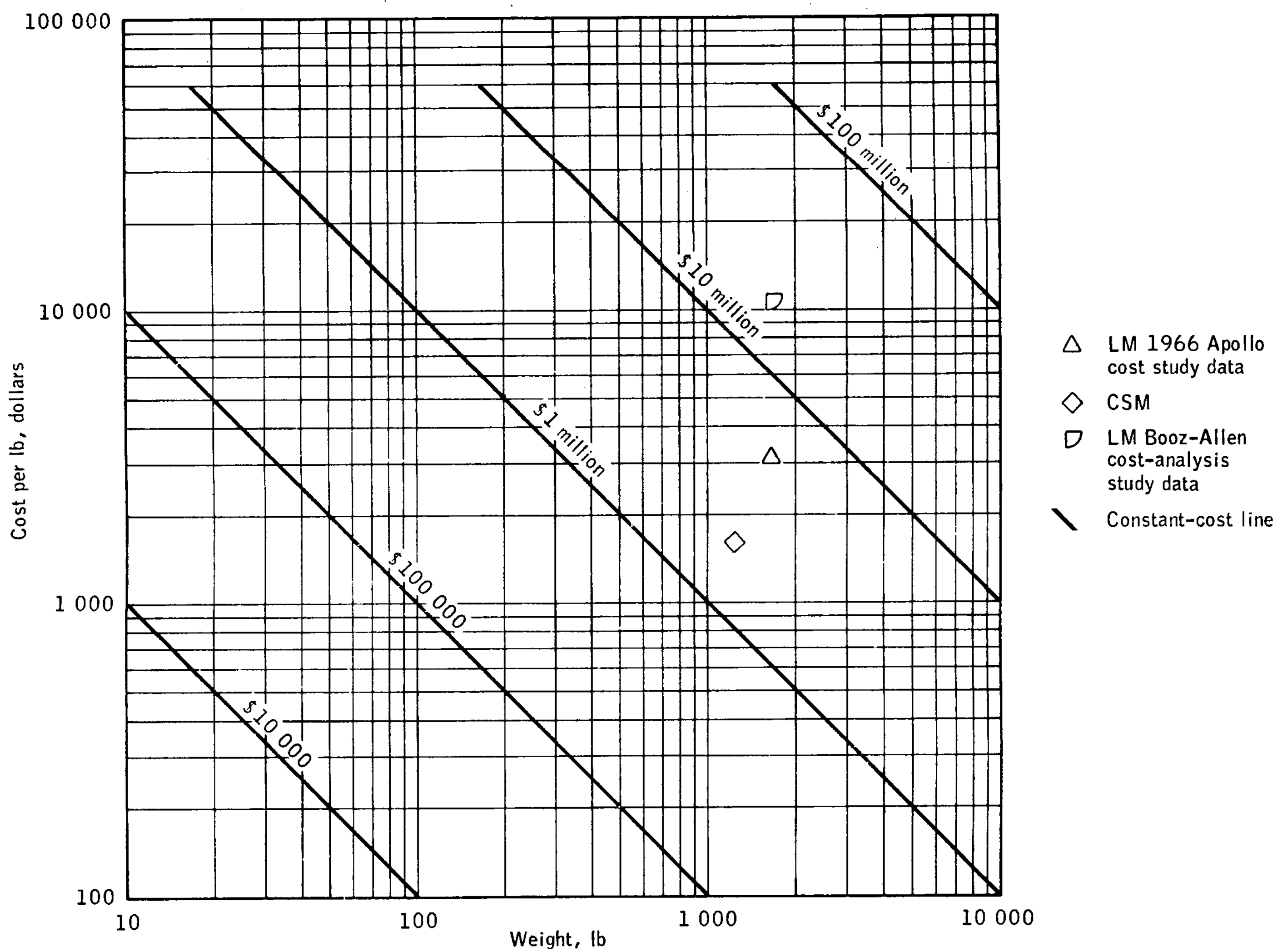

Figure 13. - Propulsion first-item costs.

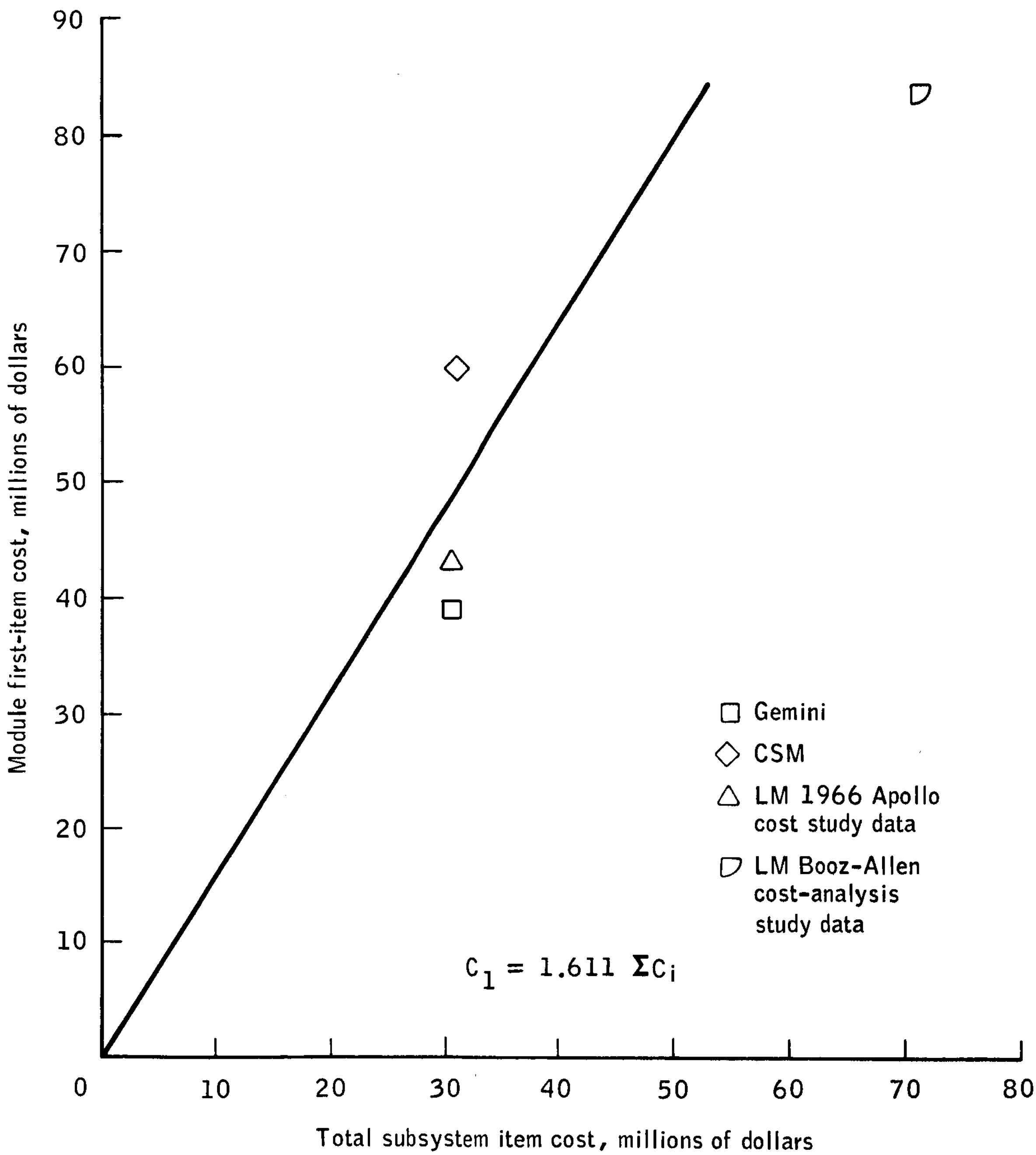

Figure 14. - Estimation of module first-item cost.

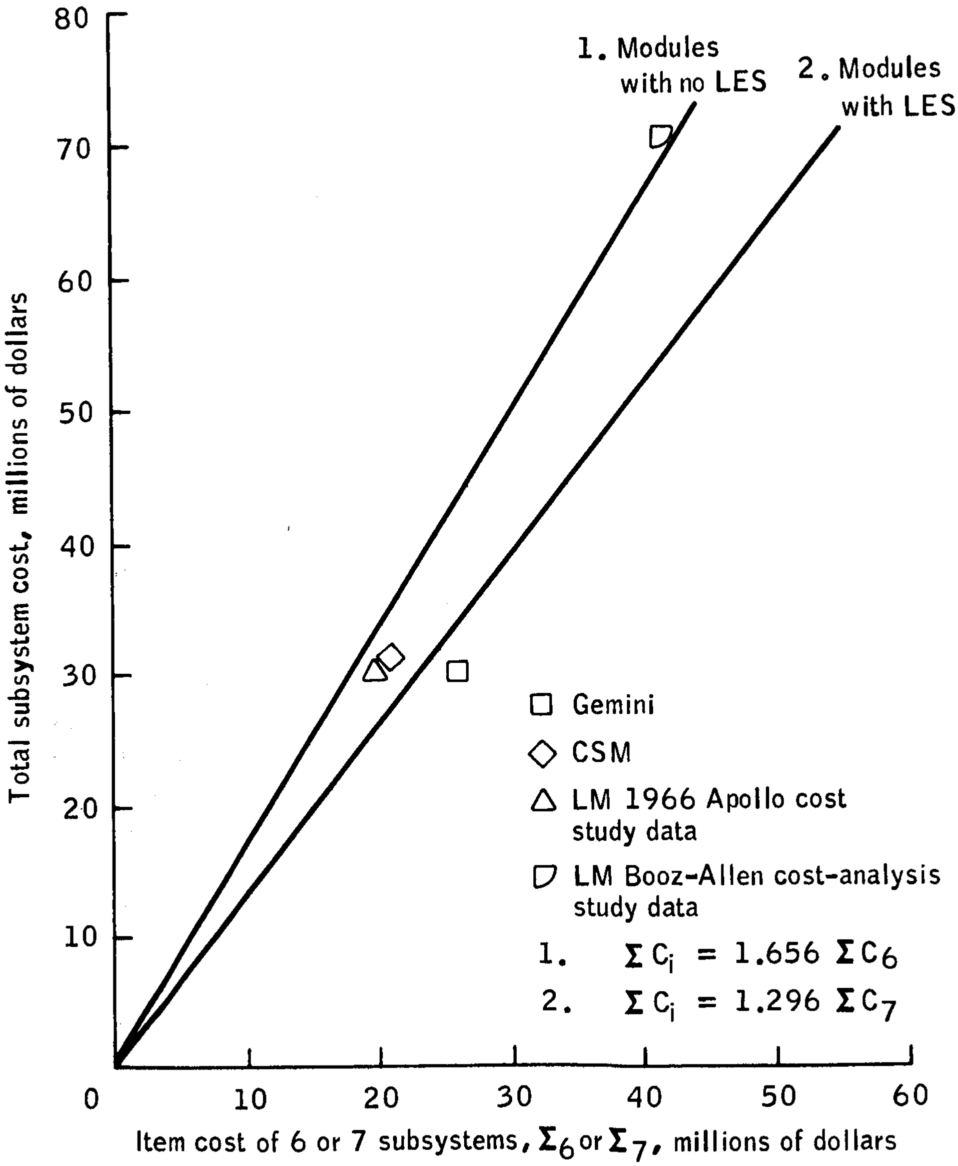

Figure 15.- Estimation of total subsystem first-item cost (alternative method).

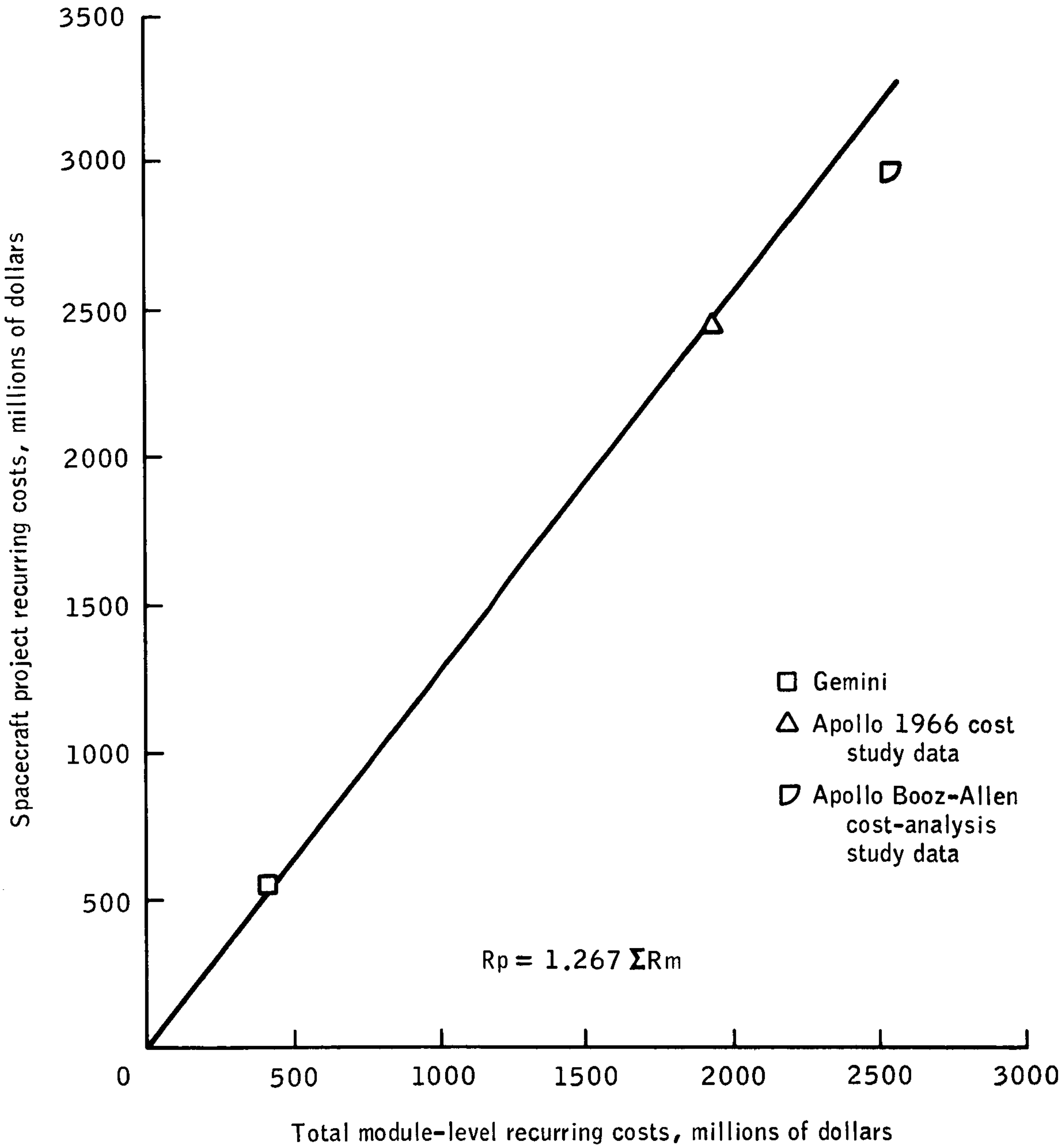

Figure 16. - Estimation of spacecraft project-level recurring cost.

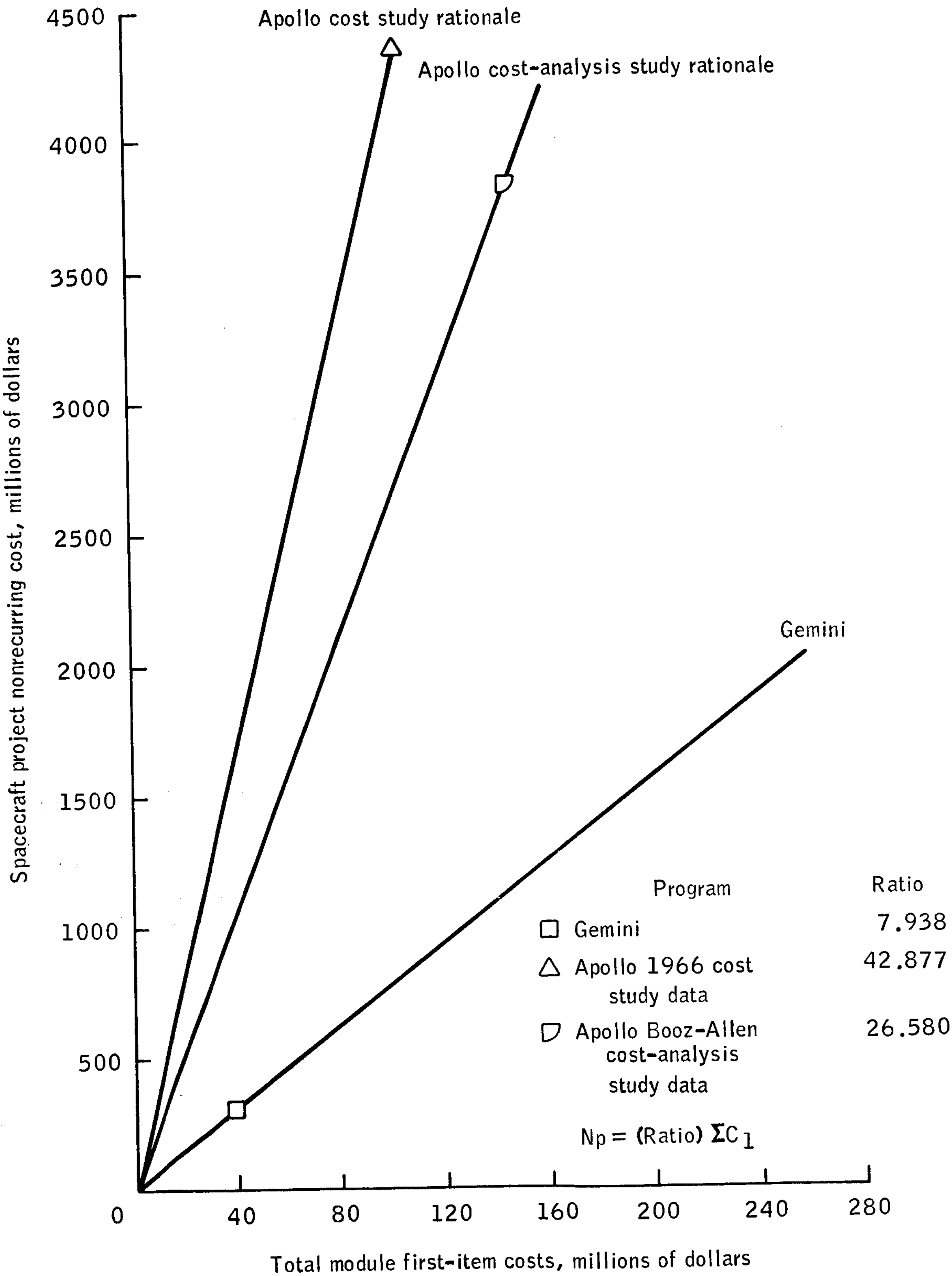

Figure 17. - Approximation of spacecraft project nonrecurring costs from module first-item costs.

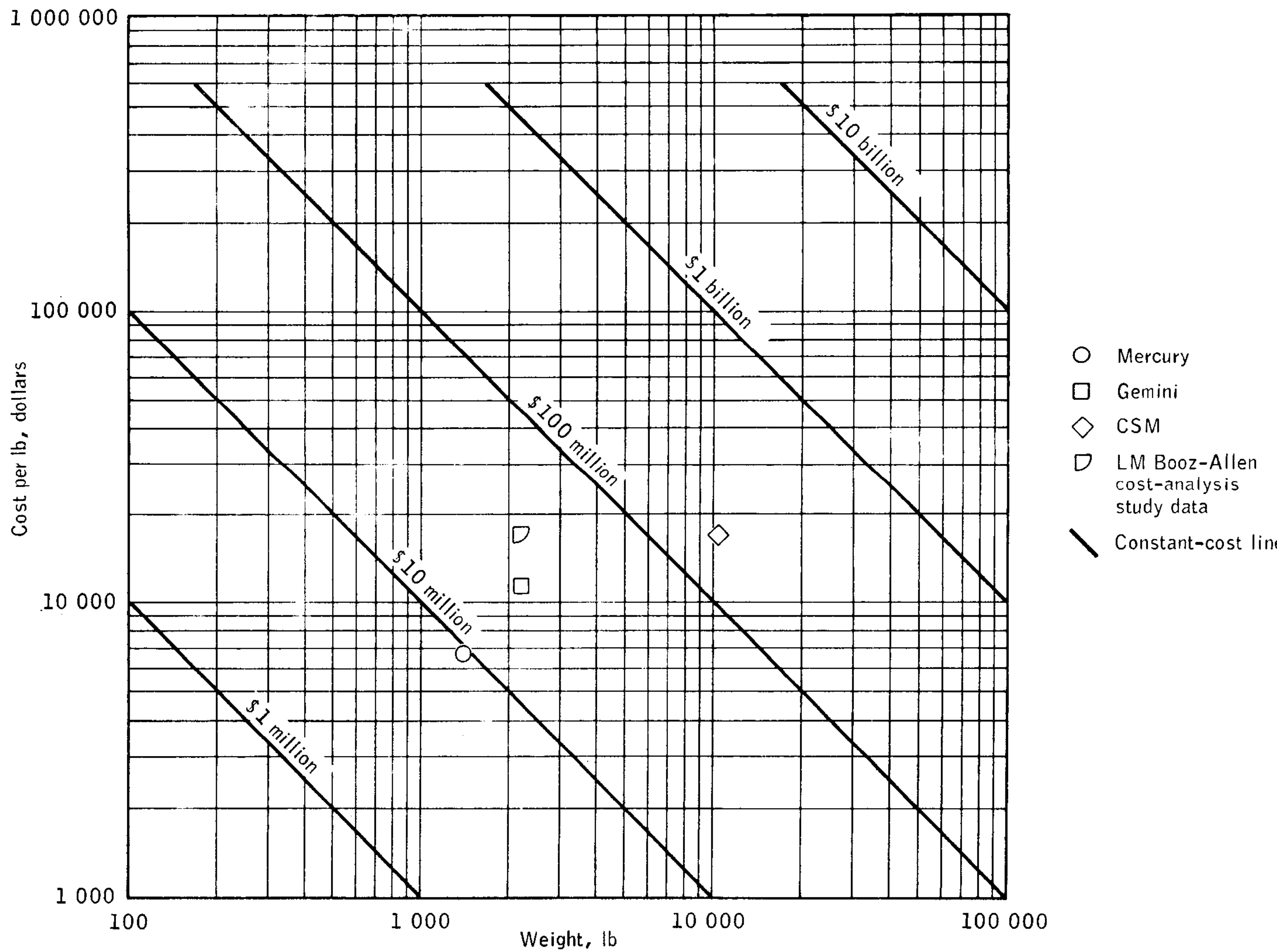

Figure 18. - Structure nonrecurring costs.

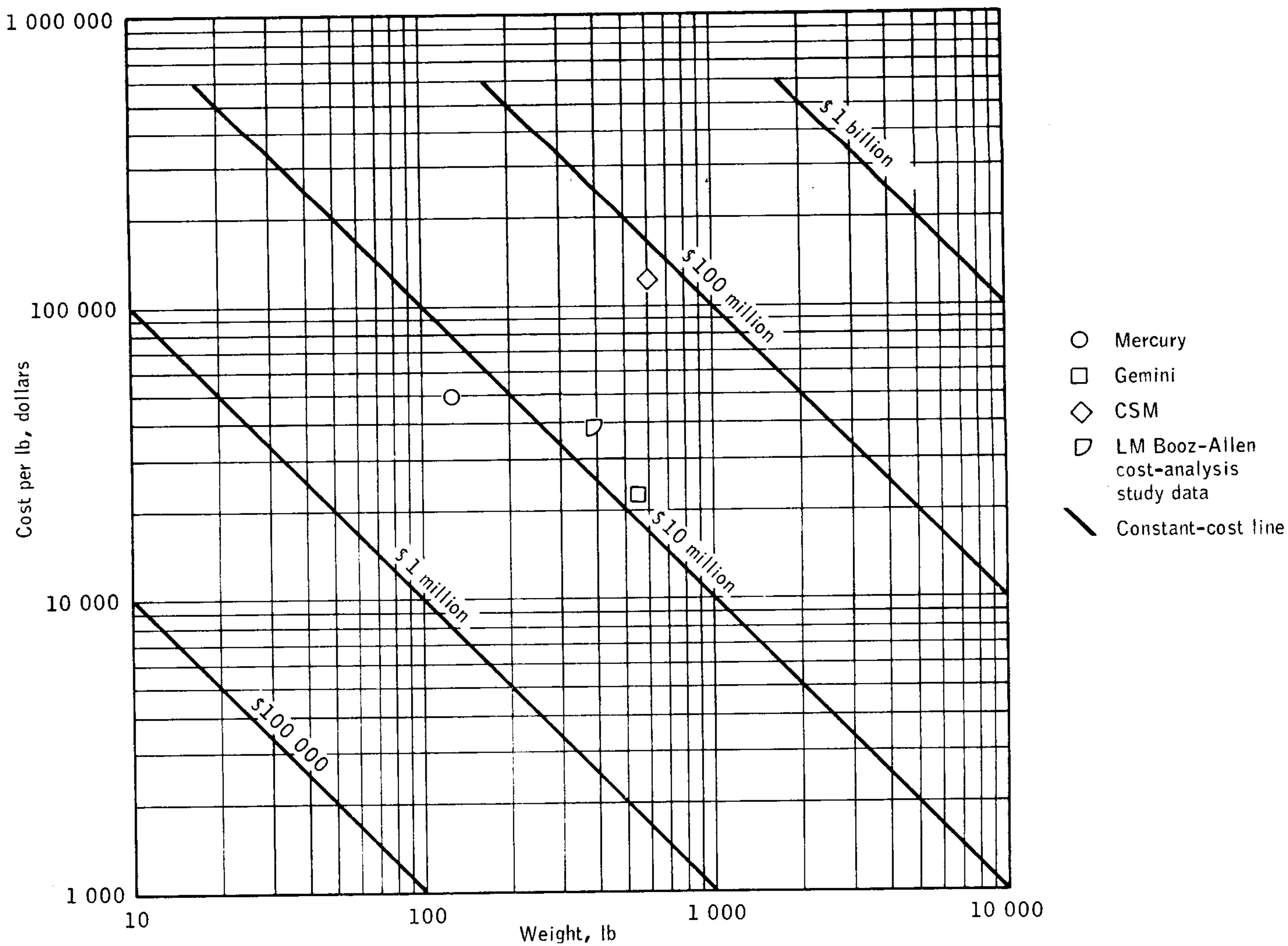

Figure 19. - Environmental control subsystem nonrecurring costs.

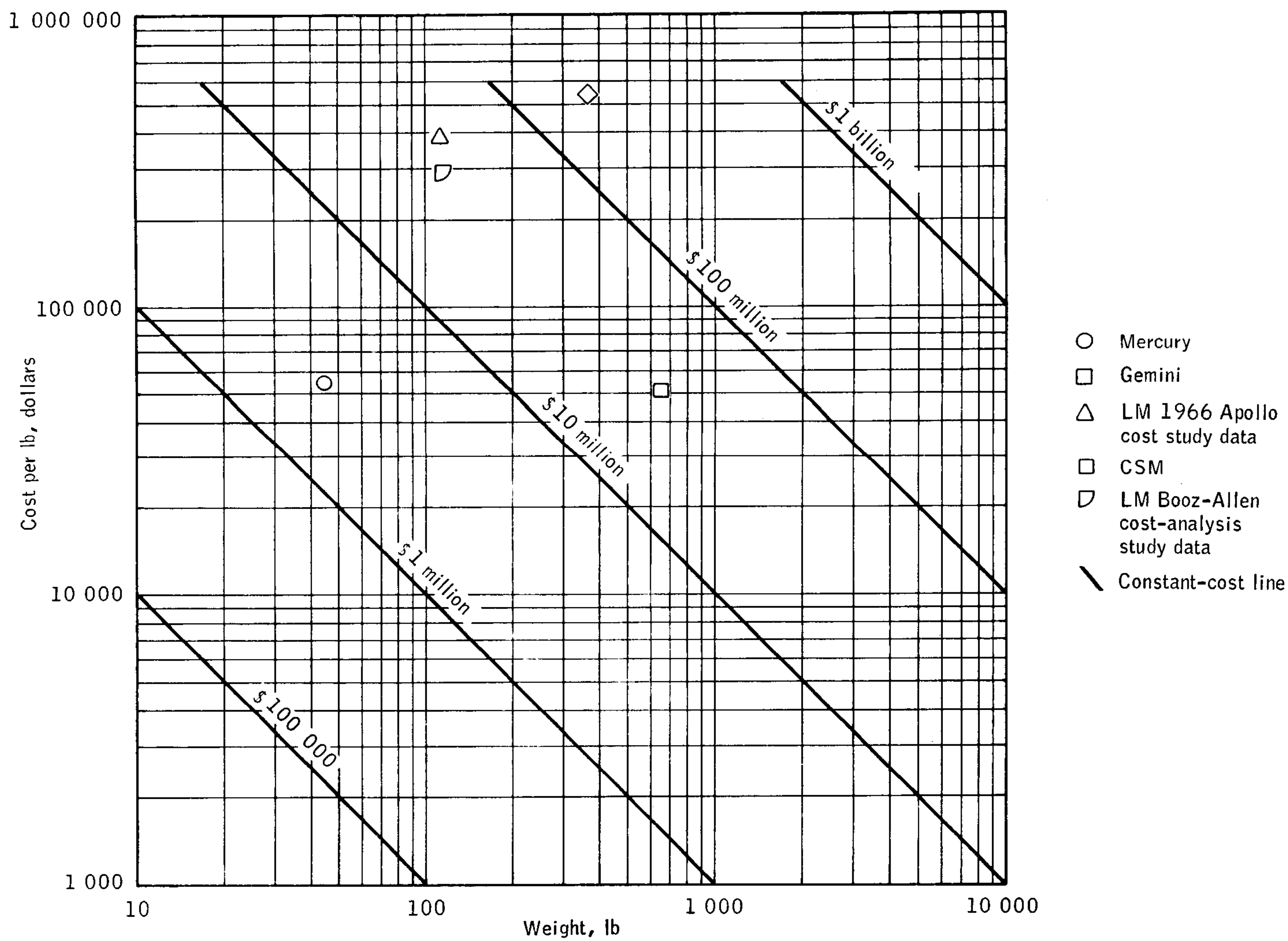

Figure 20. - Guidance and navigation nonrecurring costs.

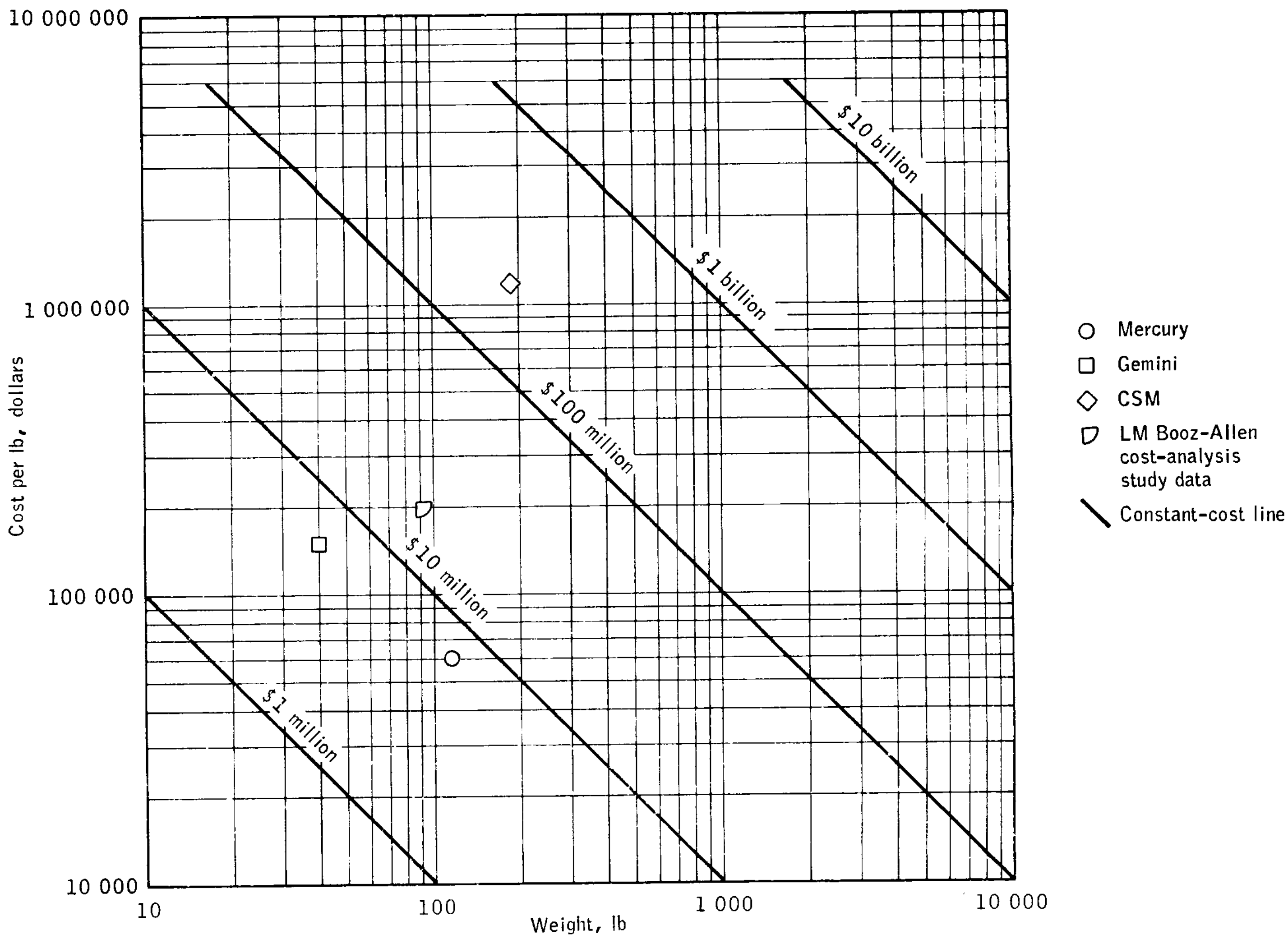

Figure 21. - Stabilization and control subsystem nonrecurring costs.

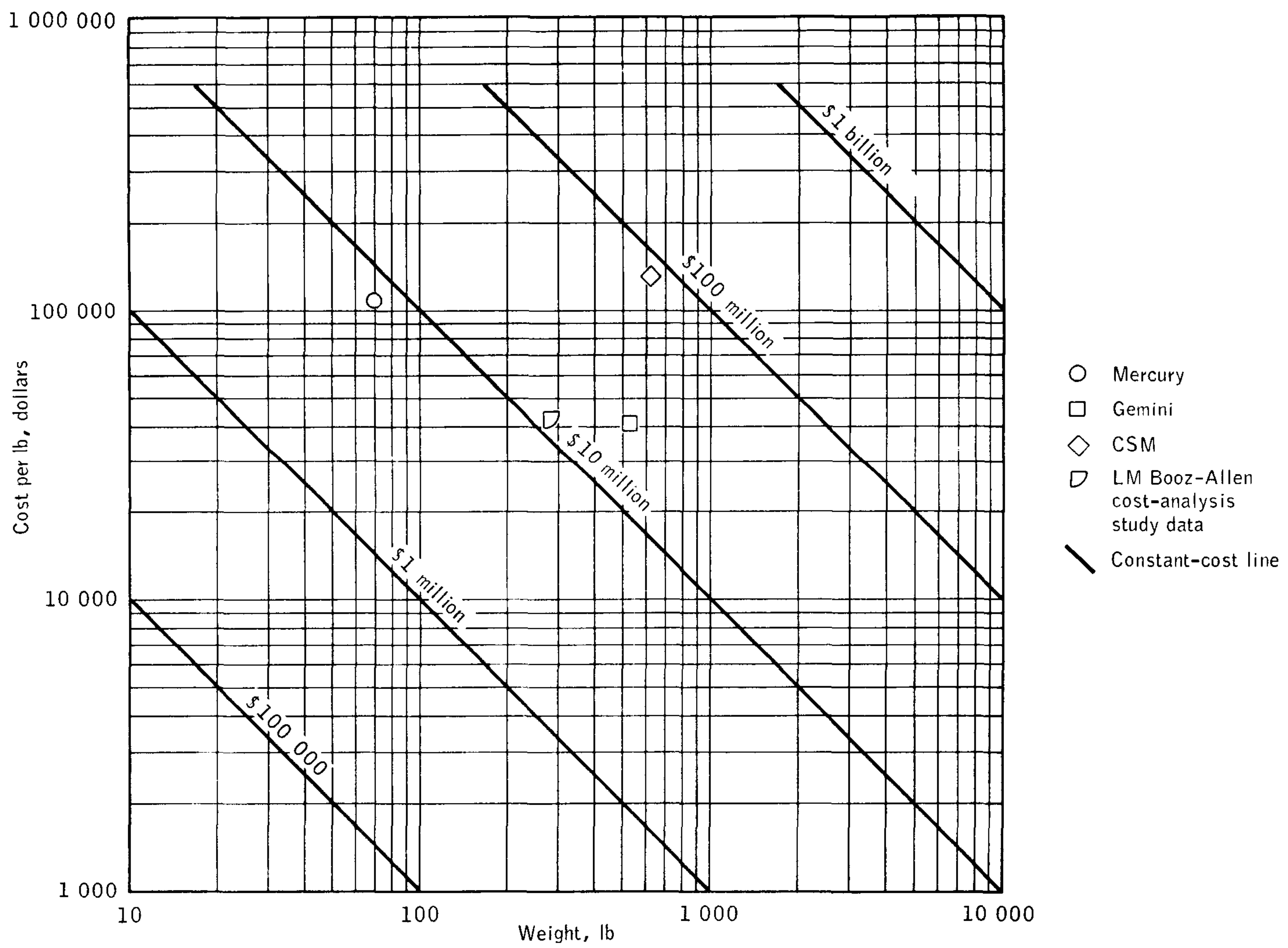

Figure 22. - Reaction control subsystem nonrecurring costs.

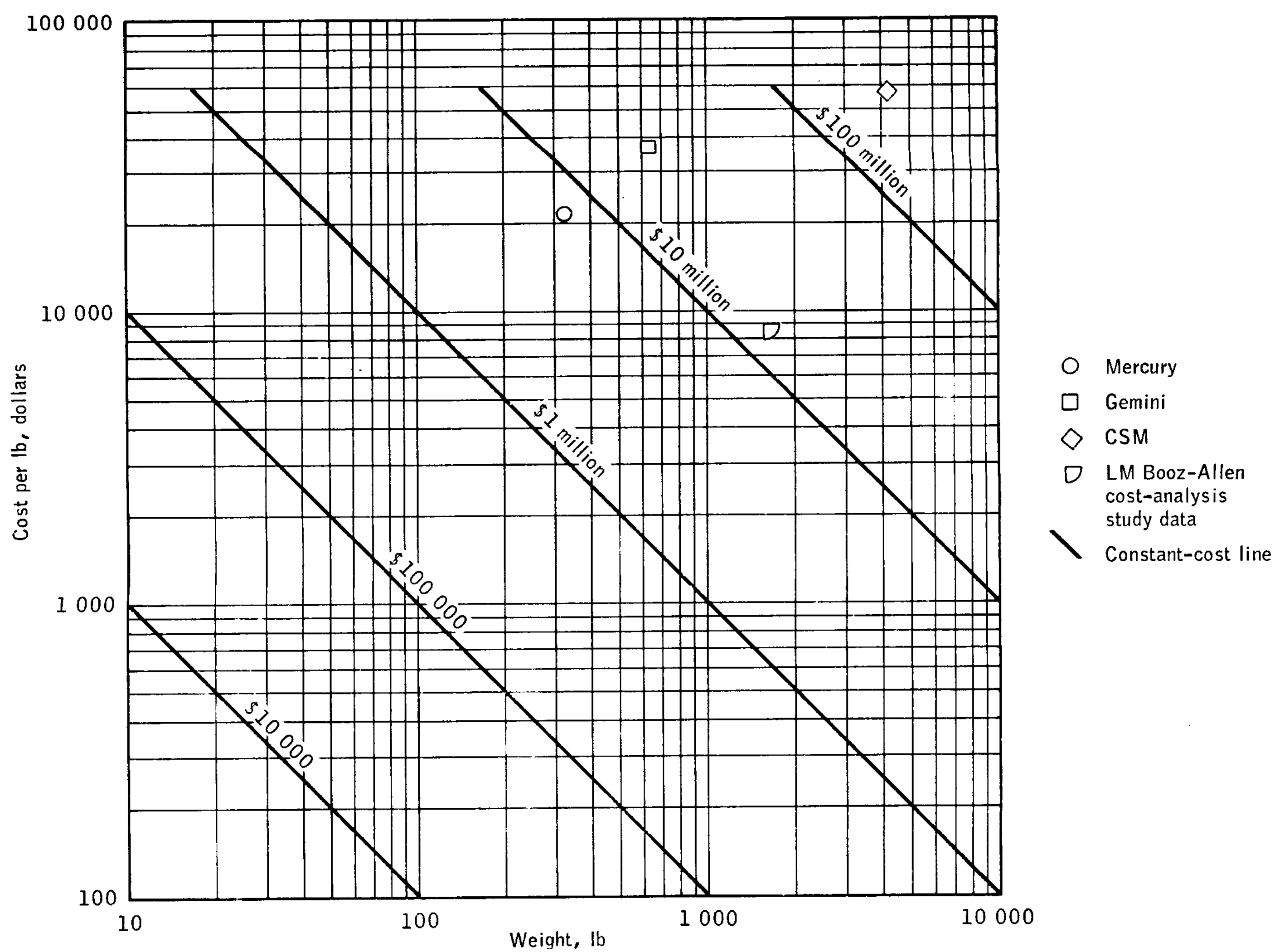

Figure 23. - Electrical power subsystem nonrecurring costs.

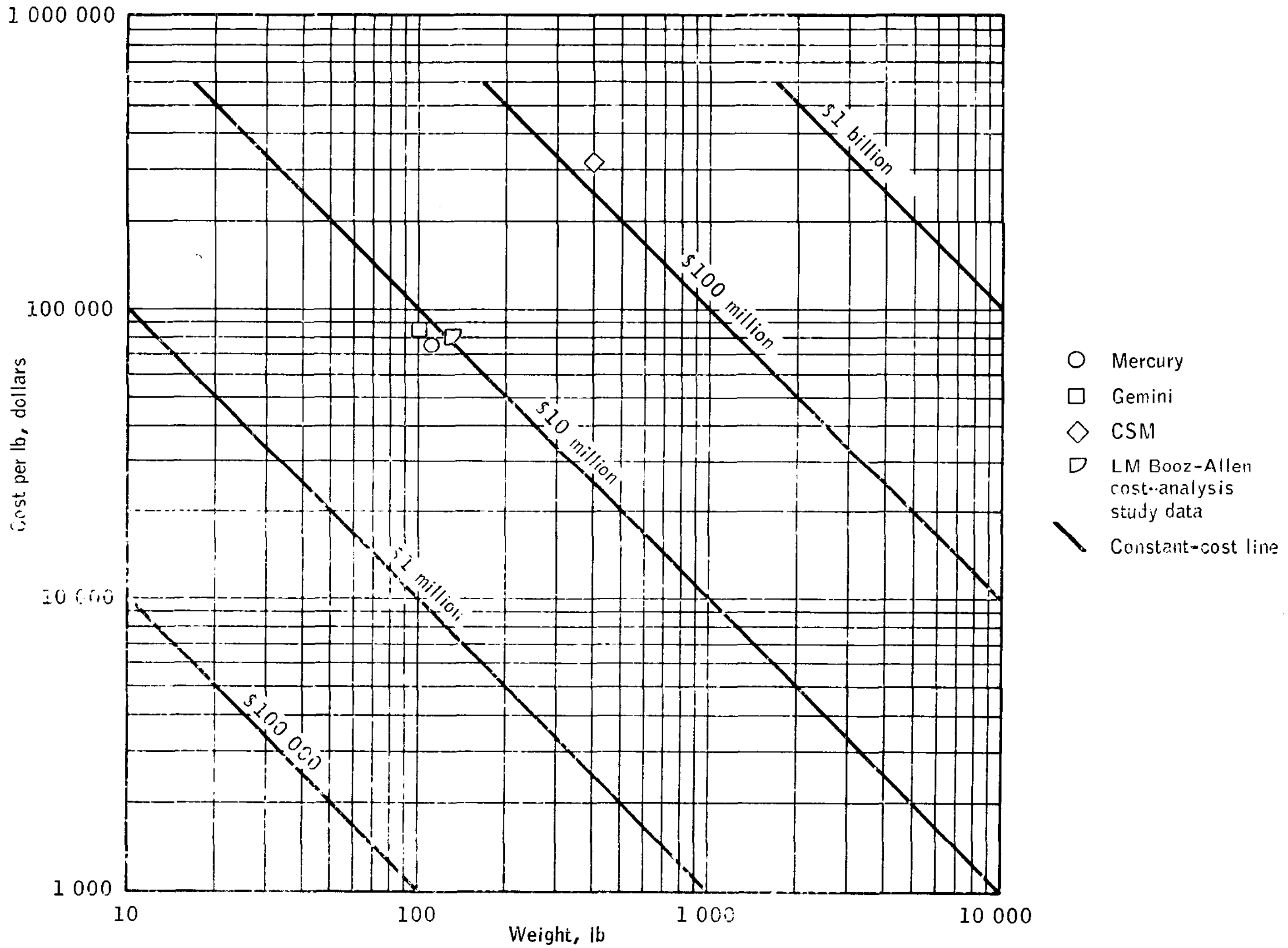

Figure 24. - Communications nonrecurring costs.

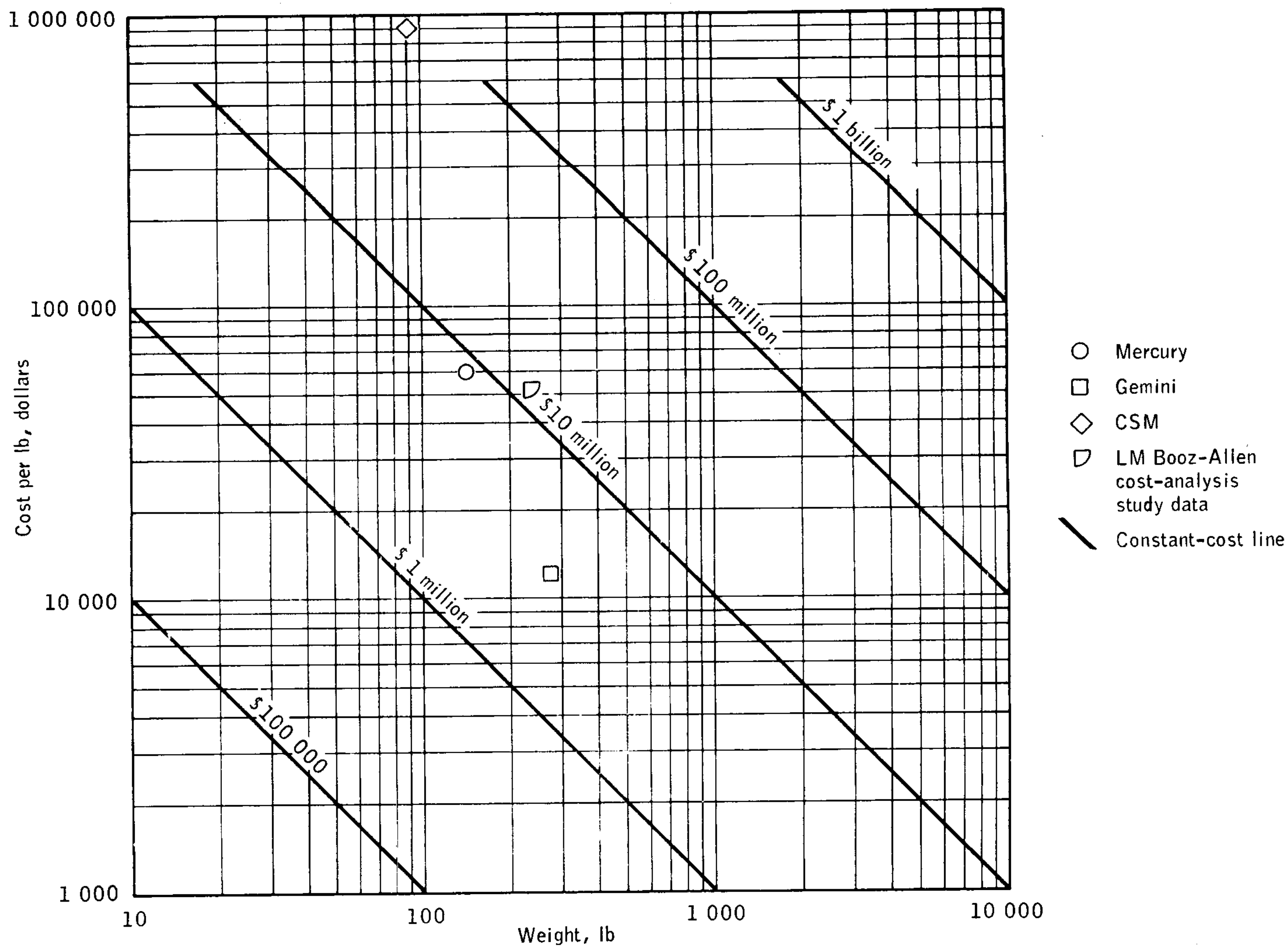

Figure 25. - Instrumentation nonrecurring costs.

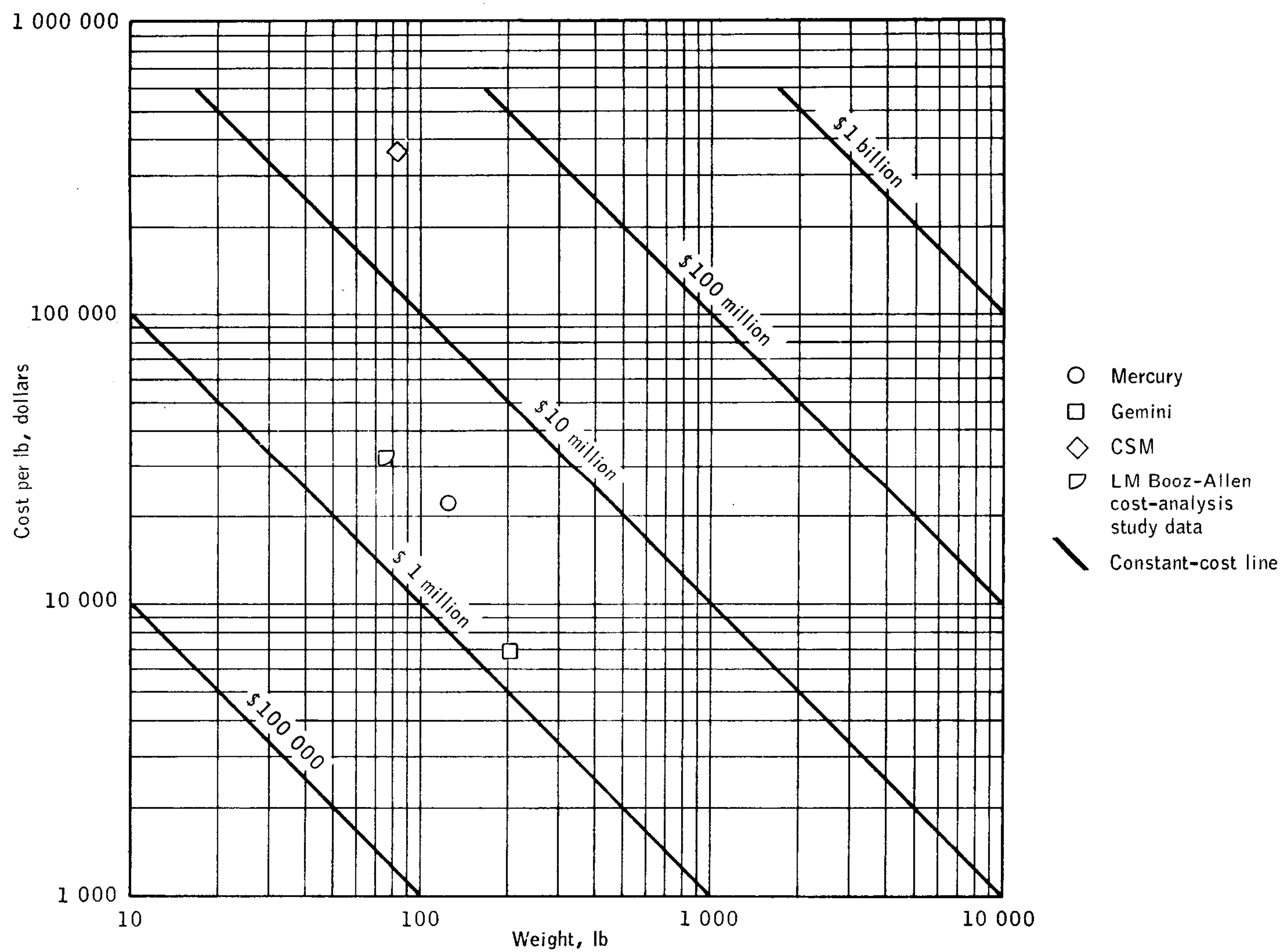

Figure 26. - Crew subsystems nonrecurring costs.

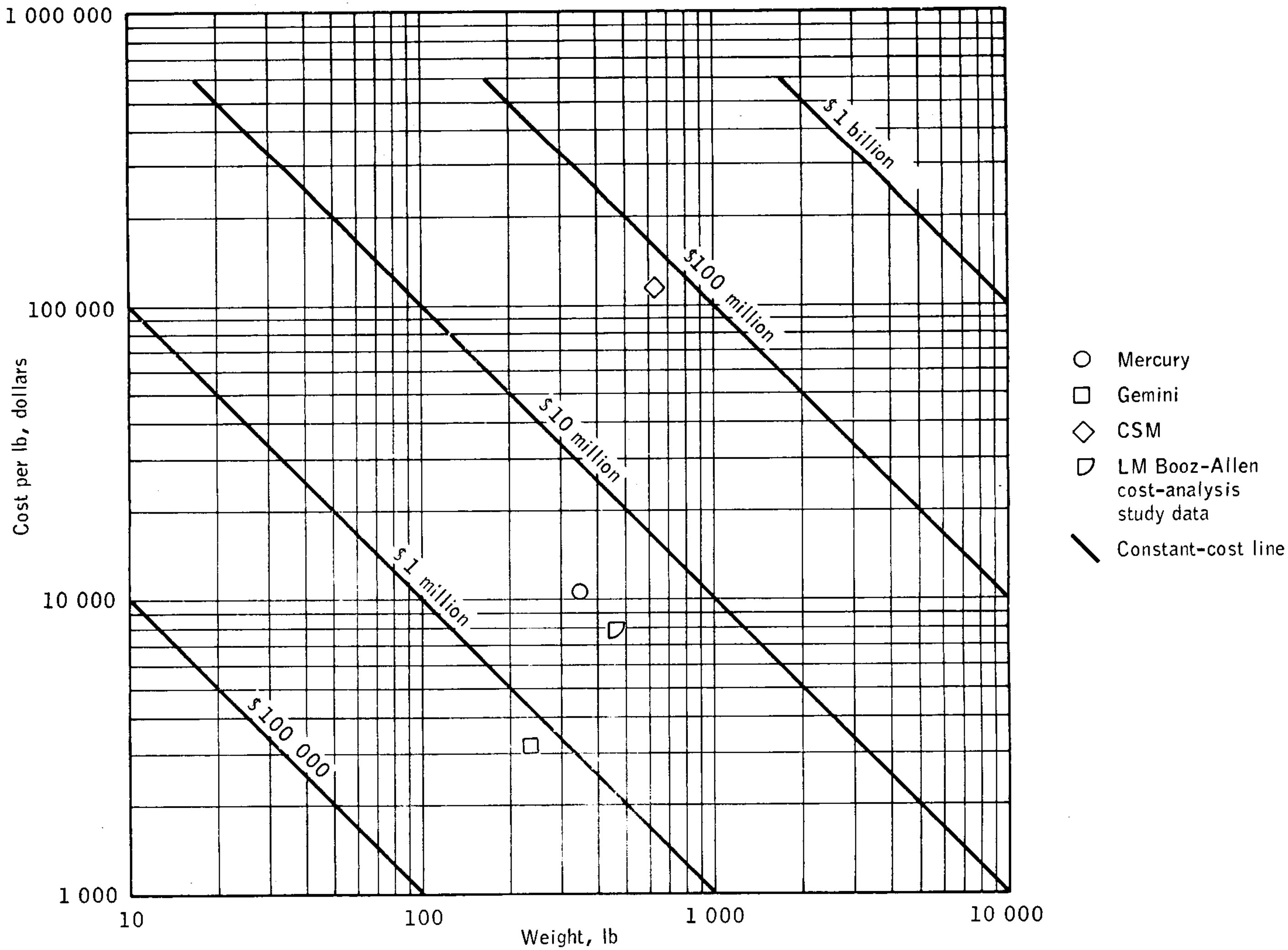

Figure 27. - Landing subsystem nonrecurring costs.

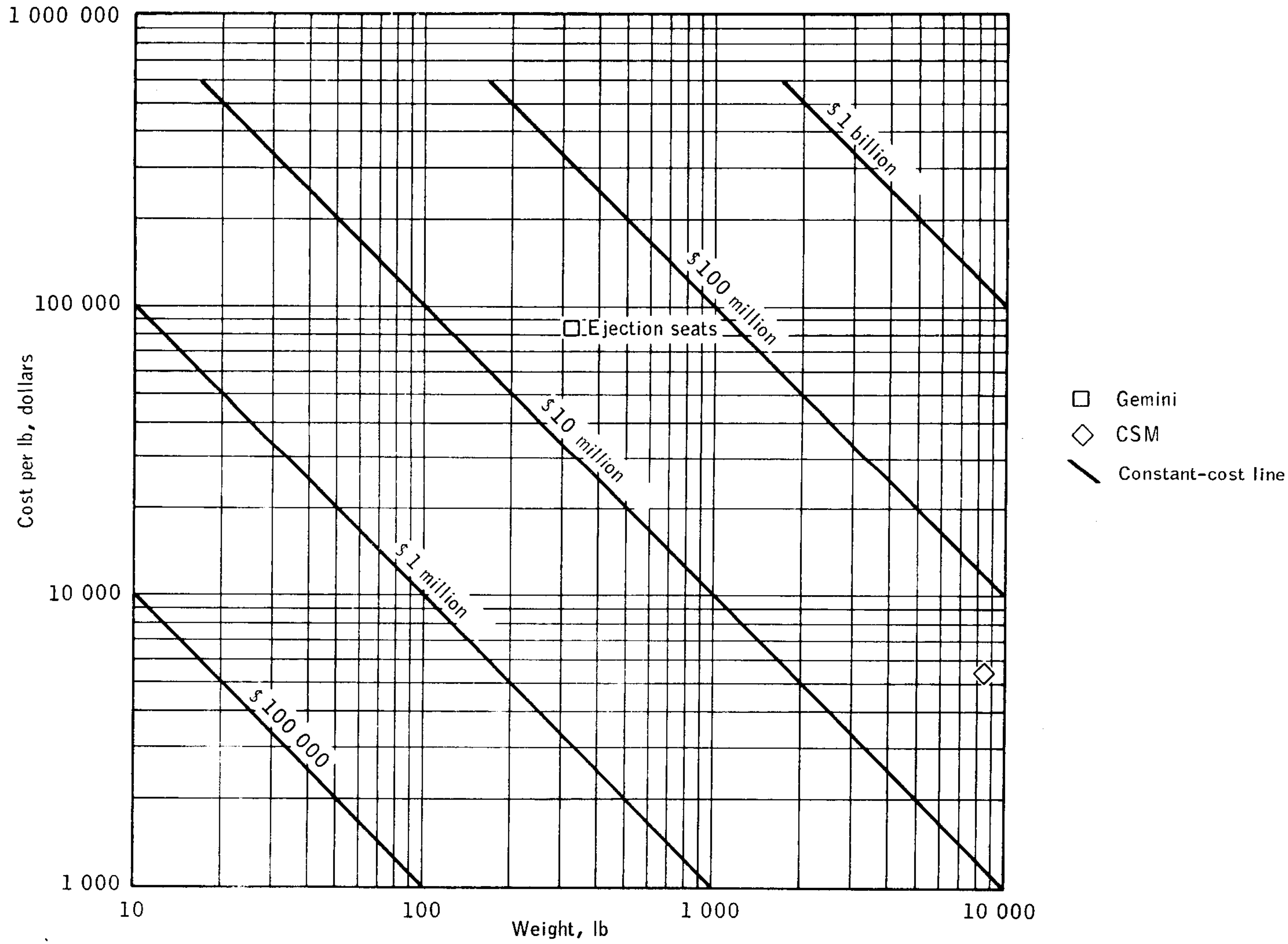

Figure 28. - Launch escape subsystem nonrecurring costs.

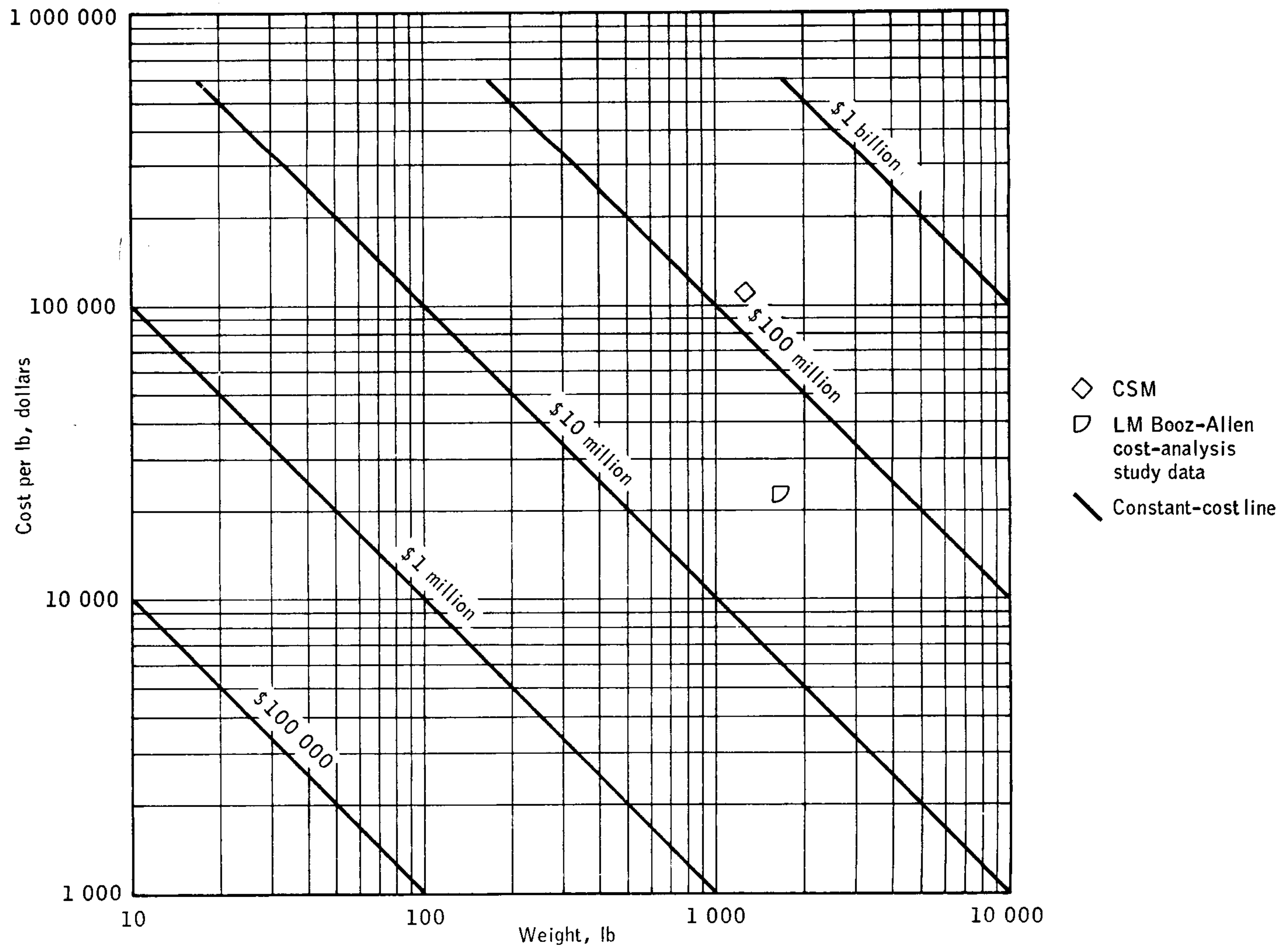

Figure 29. - Propulsion nonrecurring costs.

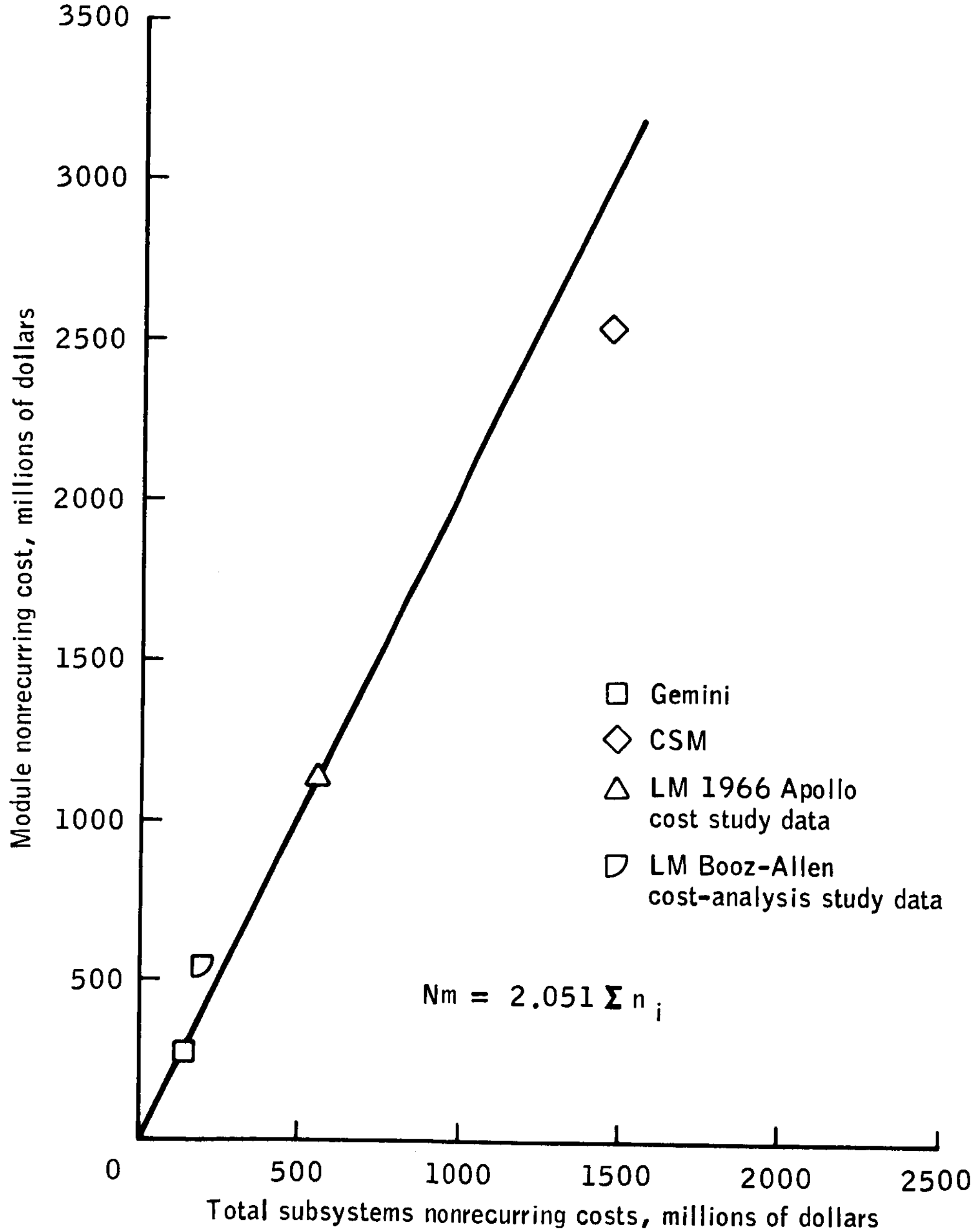

Figure 30. - Estimation of module-level nonrecurring costs from total subsystem nonrecurring costs.

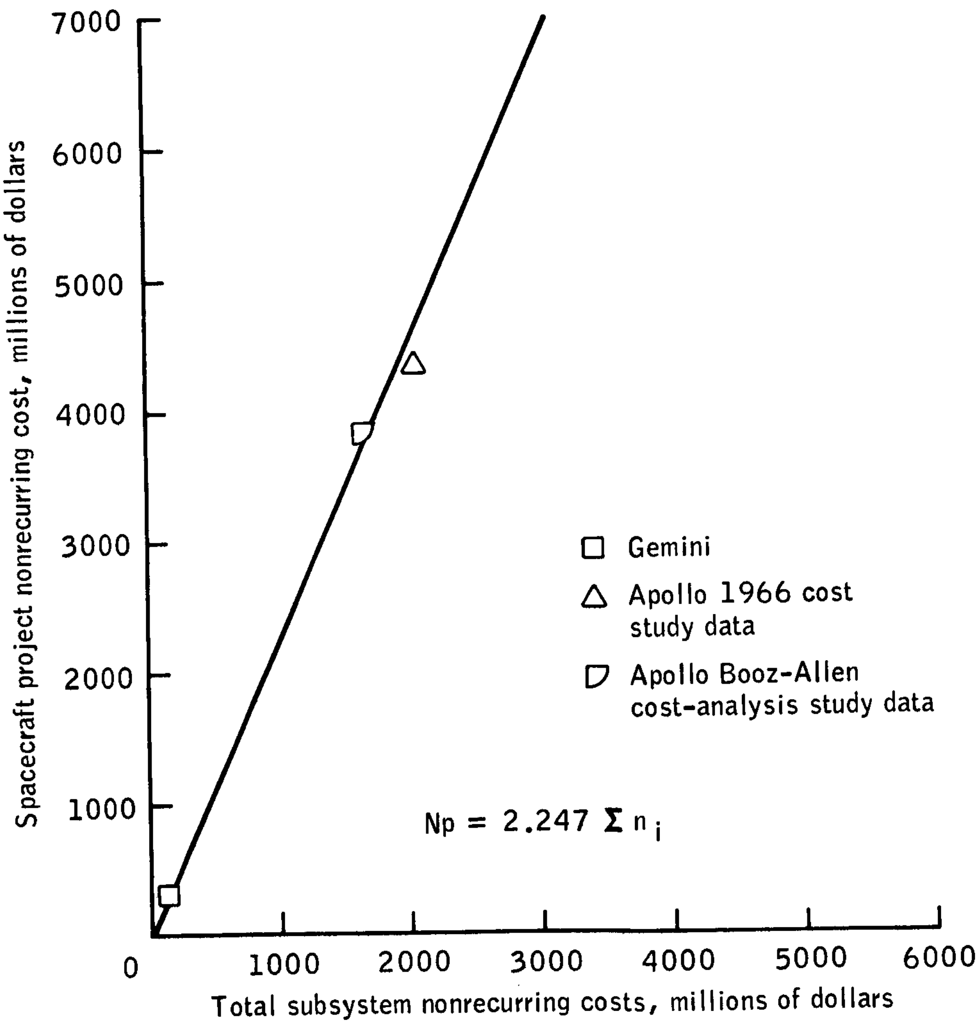

Figure 31. - Estimating spacecraft project-level nonrecurring costs.

APPENDIX A

BASIC COST DATA SUMMARY

This appendix contains, in summary form, the data employed in deriving the equations in the body of this report. All values are consistent with those given in tables I and II.

Apollo Cost Data Summary

Data from the various levels of the Apollo CSM and LM programs are summarized in figure A-1 and table A-I.

Gemini Cost Data Summary

Similarly, Gemini data are summarized in figure A-2 and table A-II.

TABLE A-I. - APOLLO NONRECURRING/RECURRING COST SUMMARY

	Cost, millions of dollars	
	Data source A	Data source B
Module-level[a]		
LM ronrecurring	1139.737	545.418
LM recurring	605.811	1190.867
LM total	1745.548	1736.285
CSM nonrecurring	2544.998	--
CSM recurring	1330.518	--
CSM total	3875.516	--
Spacecraft project-level[b]		
Module-level nonrecurring		
CSM nonrecurring	2544.998	2544.998
LM nonrecurring	1139.757	545.418
Total module-level nonrecurring	3684.755	3090.416
Project-level nonrecurring		
GSE (ACE) nonrecurring	260.344	260.344
Support development nonrecurring	310.212	310.212
Other research and development nonrecurring	176.663	176.663
Total project-level nonrecurring	4431.974	3837.635
Module-level recurring		
CSM recurring	1330.518	1330.518
LM recurring	605.811	1190.867
Total module-level recurring	1936.329	2521.385
SC support, integrated checkout and reliability, experiments, and other recurring	429.776	439.059
TOTAL	6798.079	6798.079

[a]Costs include fee; data source A is the 1966 North American Aviation, Inc., Apollo cost study.

[b]Source B is the MSC Booz-Allen cost analysis study; guidance and navigation costs are arbitrarily allocated between the LM and CSM projects.

TABLE A-II. - GEMINI NONRECURRING/RECURRING COST SUMMARY

	Cost, millions of dollars
Module-level	
Nonrecurring	
Subsystems	139.180
Subsystem installation and integration	16.069
GSE	85.450
Ground tests	15.625
Trainers and simulators	18.425
Total module-level nonrecurring	274.749
Recurring	
Subsystems	297.052
Subsystem installation and integration	26.974
Spares	19.100
Launch site support	49.837
Mission planning and analysis	4.883
Flight crew training	12.255
Total module-level recurring	410.101
Project-level	
Nonrecurring	
Module-level nonrecurring	274.749
Supporting development	29.914
Other	6.271
Total project-level nonrecurring	310.934
Recurring	
Module-level recurring	410.101
Flight operations	59.337
Recovery operations	20.980
Backup hardware	22.682
Other	34.791
Total project-level recurring	547.891

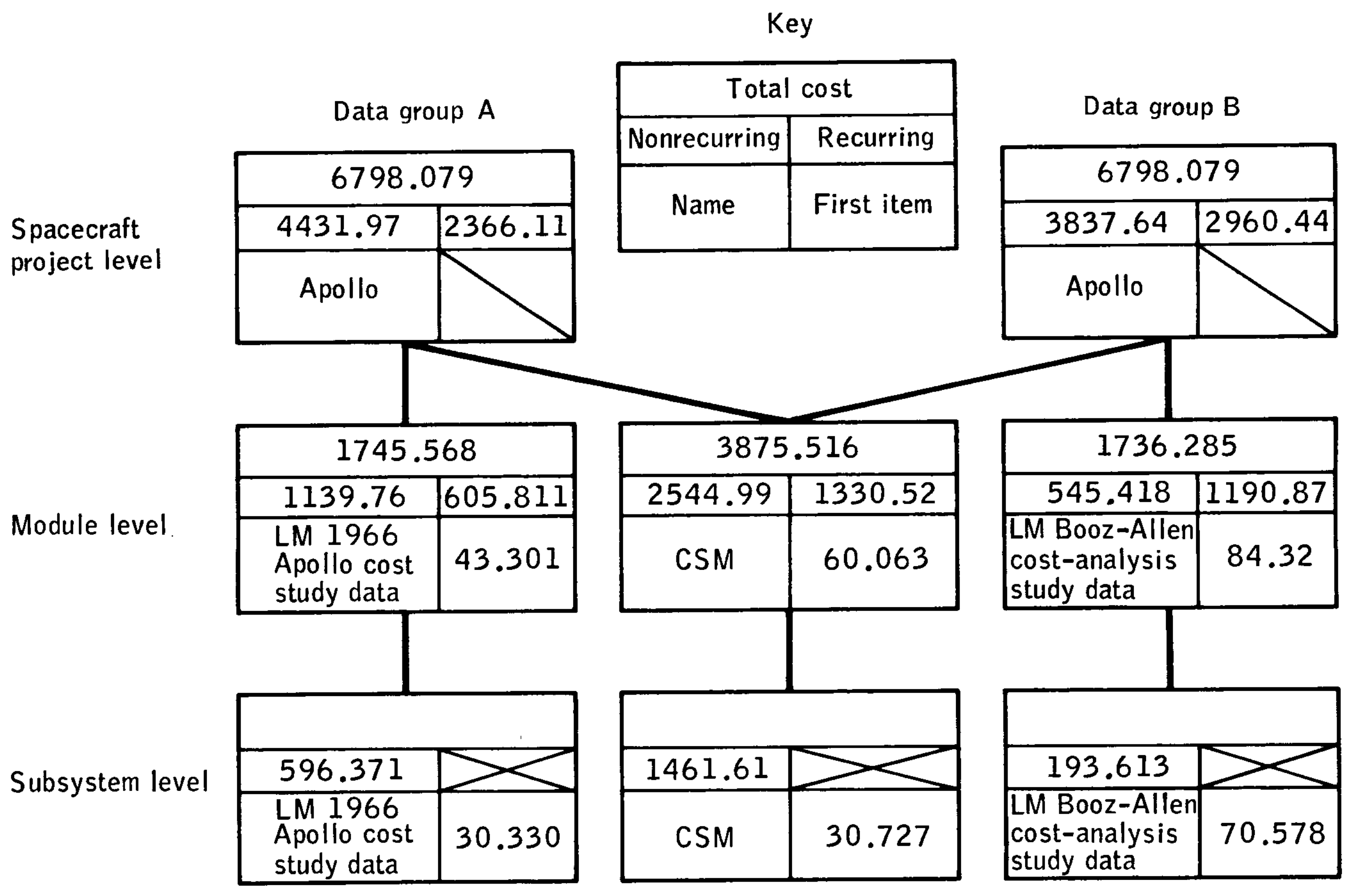

Figure A-1. - Apollo cost summary, millions of dollars.

Key

Total cost	
Nonrecurring	Recurring
Name	First item

Spacecraft project level

858.825	
310.934	547.891
Gemini	

Module level

684.850	
274.749	410.101
Gemini	39.171

Subsystem level

436.232	
139.180	297.052
Gemini	30.302

Figure A-2. - Gemini cost summary, millions of dollars.

APPENDIX B

SAMPLE PROBLEM

As both a demonstration of the use of the procedure and a check on its accuracy, the following problem is presented. The Apollo LM will be used as the unknown program. Following the steps presented previously, the first requirement is to list all subsystems with their respective weights.

Subsystem	Weight, lb
Structure	2500
ECS	390
G&N	113
SCS	91
RCS	281
EPS	1389
Communications	130
Instrumentation	333
Crew provisions	75
Landings	469
Propulsion	1612

The next step is to employ figures 2 to 13 to estimate first-item costs.

Recurring Costs

Decision rules (steps 1 to 4 in fig. 1) for the various subsystem estimates will recognize the relative complexity of the LM subsystems, compared to the other items shown in the charts. Using the techniques of figure 1, the following values are obtained.

Subsystem	Cost range, millions of dollars	
	Low	High
Structure	2.10	2.50
ECS	.90	1.40
G&N	3.00	5.30
SCS	1.25	1.45
RCS	2.60	4.40
EPS	4.10	4.10
(No LES)		
	ΣC_6 = 13.95	19.15

From figure 15, if ΣC_6 is 13.95, ΣC_i is 1.656 (13.95) or 23.10. Similarly, for the 19.15 value, ΣC_i is 31.71. This higher value will be selected arbitrarily to avoid underestimation.

The total module-level first-item cost is found from figure 14:

$$C_1 = 1.611\ (31.71) = 51.08$$

Total module-level recurring costs are found by multiplying C_1 by the appropriate total learning factor. Assuming 95 percent learning for 16 items, the factor is (from table II) 13.91. Therefore,

$$Rm = 13.91\ (51.08) = 710.52$$

To find SC project-level recurring costs, figure 16 is employed.

$$Rp = 1.267\ \Sigma Rm = 1.267\ (710.52) = 900.23$$

Note that the LM does not represent by itself the entire SC project for Apollo and, therefore, true project-level costs would include those of the CSM.

Nonrecurring Costs

To estimate nonrecurring costs, two methods are presented in the text. Since the first is merely a repetition of that used for recurring costs, demonstration is not necessary; therefore, the second method will be shown. It requires only one calculation from a ratio such as those found in figure 17. The ratios for estimating module-level nonrecurring costs from ΣC_1 (the sum of module-level first-item costs) are the following (appendix A).

Program	Ratio
Gemini	7.014
CSM	42.372

Since a wide range of ratios is available, both extreme values are employed.

$$Nm_1 = 7.014\ (51.08) = 358.28$$

$$Nm_2 = 42.372\ (51.08) = 2164.26$$

It is known that the lower value represents a development program of complexity similar to that of Gemini and the higher value represents one similar to that of the CSM. Judgment is now exercised to choose the appropriate value, bounded by the above costs.

Total Module-Level Costs

	Low cost, millions of dollars	High cost, millions of dollars
Nonrecurring	358.28	2164.26
Recurring	710.52	710.52
Total	1068.80	2874.78

Comparison to LM Data Points

The results are now to be compared with the LM data points as an assessment of the value of the method.

	Estimates		Data points	
	High cost, millions of dollars	Low cost, millions of dollars	A	B
Nonrecurring costs	2164.26	358.28	1139.76	545.42
Recurring cost (module)	710.52		605.81	1190.87
Total costs	2874.78	1068.80	1745.57	1736.29
(Averages)	(1971.79)		(1740.93)	
First item (module)	51.08		43.30	84.32
First item (subsystems)	31.71		30.33	70.58

The results of this sample problem correspond more closely to the data points of source A (the Apollo cost study) for item and recurring costs. If the average of the two nonrecurring estimates of this problem is compared, again data points of source A give the closest correlation (1261 versus 1140). However, there is no rigorous reason for averaging the estimates, and the range of values is probably more useful than any single estimate derived from the range.

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1. Brents, T., et al.: Manned Spacecraft Systems Cost Model. FZM4671-3, General Dynamics Corp. (Contract NAS 9-3954), July 18, 1966.

2. Love, J. E.; and Young, W. R.: Survey of Operation and Cost Experience of the X-15 Airplane as a Reusable Space Vehicle. NASA TN D-3732, 1966.

3. Anon.: The Experience Curves, Vol. 1 and 2, Army Missile Command, Redstone Arsenal, Alabama, September 1962.