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System Cost/Performance Analysis (Study 2.3) Final Report

Volume I

Executive Summary

Prepared by T. KAZANGEY
Guidance and Control Division
Engineering Science Operations

28 SEPT 1973

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

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Systems Engineering Operations
THE AEROSPACE CORPORATION

Aerospace Report No.
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FOREWORD

This report covers those activities conducted under Study 2.3, System Cost/Performance Analysis, under NASA Contract No. NASW-2472 from 1 September 1972 through 31 August 1973. The Aerospace Corporation Task Manager was T. Kazangey. The NASA Technical Director was R. R. Carley. The NASA review team consisted of the following persons: C. M. Akridge, W. S. Rutledge, G. E. Mosakowski, D. B. Clemens, H. Mandell, R. W. Abel, T. Campbell, and W. Little.

The author acknowledges with gratitude the many individuals at The Aerospace Corporation who contributed to this effort.

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FIGURES

TABLE

1. INTRODUCTION

As the space program matures into an applications industry, greater emphasis will be placed on improving the ability to predict the effect of program requirements on cost and schedules. Current advanced studies are estimating benefits for standardized subsystems and components, on-orbit servicing, and ground refurbishment of spacecraft, etc. Cost-estimating techniques that give greater insight earlier in the program cycle are required. As a step in this direction, this study was initiated to identify and quantify the interrelationships between and within the performance, safety, cost, and schedule parameters as delineated in Table 1-1. These data would then be used to support an overall NASA effort to generate program models and methodology that would provide the needed insight into the effect of changes in specific system functional requirements (performance and safety) on a total vehicle program (cost and schedule).

Table 1-1. Model Parameters

- 1.0.0 PERFORMANCE
  - 1.1.0 Technical Characteristics
    - 1.1.1
    - 1.1.2
    - 1.1.3
    - 1.1.4

      System peculiar; (i.e., no fewer than four items, no more than ten items)
  - 1.2.0 Power
    - 1.2.1 Average
    - 1.2.2 Peak
  - 1.3.0 Weight
  - 1.4.0 Volume
  - 1.5.0 Vibration Specification
    - 1.5.1 Random (g rms)
    - 1.5.2 Non-random
  - 1.6.0 Temperature Specification
    - 1.6.1 Radiation
    - 1.6.2 Conduction
  - 1.7.0 Ambient Pressure Specification
- 2.0.0 SAFETY AND HAZARDS
  - 2.1.0 Failure Assessment
    - 2.1.1 Failure rate
    - 2.1.2 Number of single point failure locations
    - 2.1.3 Number of dual point failure locations
  - 2.2.0 Failure Detection Probability
  - 2.3.0 False Alarm Probability
  - 2.4.0 Hazard Potential
    - 2.4.1 Latent energy
    - 2.4.2 Radiation energy

Table 1-1. Model Parameters (Continued)

- 3.0.0 COST
  - 3.1.0 Design and Development
    - 3.1.1 Engineering
    - 3.1.2 Development
  - 3.2.0 Build and Checkout
    - 3.2.1 Tooling
    - 3.2.2 Manufacturing
    - 3.2.3 Quality control
    - 3.2.4 Clerical
  - 3.3.0 Test Hardware
  - 3.4.0 Training and Simulation
  - 3.5.0 Support for 10 to15 Years in Service Life
  - 3.6.0 Management
- 4.0.0 SCHEDULE (Time for Completion)
  - 4.1.0 Proposal
  - 4.2.0 Preliminary Design and System Analysis
  - 4.3.0 Subsystem Analysis, Design, and Breadboard Testing
  - 4.4.0 Prototype Design, Fabrication, and Test
  - 4.5.0 Subsystem Production Engineering, Fabrication, and Testing
  - 4.6.0 System Integration and Test
  - 4.7.0 Flight Test Phase (Flights 1 to 5)
  - 4.8.0 Initial Operational Phase (Flights 6 to 20)
  - 4.9.0 Operational Phase (Remaining Flights)

2. STUDY APPROACH

The initial planning of the task divided the effort into six subtasks. The effort began with two subtasks. The first, development of flow charts of the design process, included a literature search and the initial development of modeling methodology. The second subtask developed background information on other modeling methodologies and on data bases. The remaining tasks included data development to collect properly formatted component data for sample calculations, refinement of the modeling methodology, the calculation of a sample case, and the preliminary modeling of other related subsystems.

The attitude control system (ACS) was selected as the first space vehicle system to be used in the development of a modeling methodology described by such quantitative relationships. So that an early assessment of the modeling methodology could be obtained, the sample case was restricted to a single type of ACS to demonstrate the feasibility of the approach prior to a wider application. The actual modeling methodology selected for this study develops a consistent set of quantitative relationships among performance, safety, cost, and schedule, based on the characteristics of the components utilized in candidate mechanisms. These descriptive equations were developed for a three-axis, earth-pointing, mass expulsion ACS. A data base describing typical candidate ACS components was developed, and sample calculations were performed on a digital computer. This approach, implemented on a computer, is capable of determining the effect of a change in functional requirements to the ACS mechanization and the resulting cost and schedule. If this modeling methodology is extended to other systems in a space vehicle, a complete space vehicle model can be developed.

Section 3 reviews the development of background information and the modeling techniques considered that ultimately led to the cost/performance methodology developed under Task 2.3.

3. BACKGROUND INFORMATION STUDY

At the start of the study, a review of potentially applicable cost modeling techniques was conducted. Included in this model review were the SAMSO/Aerospace cost-schedule models, the General Electric Co. design guide for ACS, the Honeywell cost analysis, the Resource Data Storage and Retrieval (REDSTAR) data base, and the Optimized Design Integration System (ODIN) and Integrated Programs for Aerospace Vehicles Design (IPAD) Programs. The following paragraphs present a brief description of the material reviewed.

Several distinct SAMSO/Aerospace cost-schedule models were reviewed during the early stages of Task 2.3. These models are discussed in some detail in Section 2 of Volume II. In general, the models all use a cost estimating relationship (CER) approach to cost-out a specific type of system. Separate CERs are often used for each program phase, such as the design, development, test, and evaluation phase; first article production; and ongoing operations. In each CER, cost is related to some distinct physical parameter such as weight or volume. Often a CER is developed using statistical least-squares regression on data obtained from previous programs; these "static" costs are distributed over time by a learning or improvement curve that takes into account reduced per-unit costs as production increases. In addition, inflation factors are usually included to account for reduction in purchasing power per dollar with increasing time. Finally, scheduling models are defined as a function of time and may run from simple, straight-line spreads to skewed variations of the normal distribution curve. Various input and output formats are employed, with input requirements primarily set by the type of CERs used and with output formats determined by the level of output detail in the work breakdown structure (WBS) and by schedule resolution.

In addition to the SAMSO/Aerospace models, other models and data bases were reviewed. These include a General Electric design guide for developing a satellite ACS, given mission requirements; the USAF 375 Series Manuals, which are structured along cost-accounting lines; and a Honeywell, Inc. cost analysis study. A portion of the Honeywell study consisted of a historical review of stabilization and control systems for Apollo, Gemini, and the F-104. An important conclusion of the Honeywell study was that an uncertain relationship exists between the weight of ACS space hardware and its cost. As mentioned previously, this relationship forms the basis of many CERs used by the space industry.

Included in the development of background information were reviews of several approaches to data base formulation and management. The REDSTAR system was one of those considered. It was the result of a 1972 fiscal year study, entitled Application of Engineering Cost Analysis, by Planning Research Corporation.

The WBS used in REDSTAR is divided inconveniently for an ACS designer; it tends to scatter ACS elements through a number of categories. This lack of correspondence between the WBS and the attitude control function does not mean that REDSTAR is not applicable to cost/performance modeling. However, a translation matrix, as developed in this study, would have to be used to interpret the WBS in a manner useful to a model that includes system performance as an integral part of its methodology.

Several in-house data base systems used by The Aerospace Corporation were also reviewed. Unfortunately, very little component data of the nature required for a cost/performance-oriented model of the type developed in this study were found.

As the final task in development of background information, the ODIN and IPAD Programs were investigated. The ODIN integrates computer-implemented models used for various aspects of system design and provides an optimum systems engineering approach to overall vehicle design. The IPAD supports the engineering design team by implementing, as much as possible, the computation and data management aspects of the design process. Conceptually, the Cost/Performance Model could be one module of the ODIN Program.

4. MODELING APPROACHES

In the conceptual stage of Task 2.3, effort was devoted to the initial formulation of an approach to cost/performance modeling. During this stage, a number of methodologies were conceived and required evaluation. The following criteria were formulated to judge each concept in a complete and objective manner and were used to evaluate the utility of each approach:

a. A prime objective is to determine sensitivity of cost to changes in requirements.
b. The modeling methodology must not impose a cumbersome reporting structure on the contractor.
c. The modeling methodology must reflect costs from all phases of development through operations.
d. The approach taken should reflect current design practice and tradeoff procedures.
e. The model should achieve a balanced total vehicle design, considering total life-cycle costs in terms of performance, safety, and schedule requirements.

In general, all modeling approaches considered can be subdivided into two basic categories. Bottom-up approaches, the first category, depend on development of a system design. Estimates of tasks, material costs, manpower requirements, and schedules are made at each identifiable level of system integration; total estimates are obtained by summing individual costs and schedules.

Top-down models, the second category, are essentially the CER approach described previously. As CERs have been unsuccessful in meeting the prime criterion of determining cost sensitivity to program requirement changes, top-down approaches were judged unacceptable for a Cost/Performance Model. Further, it was thought that a model oriented from the bottom up could lead to fulfillment of the previously stated criteria.

A model, called the "minimum" model, was hypothesized as a basis for development of a cost/performance methodology. The minimum model considered, but did not adequately quantify, the performance, safety, cost, and schedule of an ACS. The "minimum" model was later expanded and became the Cost/Performance Model. Starting with functional payload requirements, a filter algorithm would be developed to determine an attitude control method to satisfy these requirements. Once the basic type of ACS, such as momentum storage, mass expulsion, or other applicable method, was determined, various design configurations would be considered.

Several models were examined in attempts to implement the minimum model. Details of two of these approaches and their applicability to a cost/performance modeling viewpoint are given in Section 3 of Volume II.

5. COST/PERFORMANCE MODELING METHODOLOGY

The modeling approaches reviewed did not provide quantitative relationships among the performance, safety, cost, and schedule parameters for an ACS. When both the top-down and bottom-up approaches were reconsidered, it was decided that a Cost/Performance Model oriented from the bottom up could lead to a model employing quantitative expressions that would output performance and cost sensitivities. A set of basic equations, termed "aggregate equations," was written to describe the performance, safety, cost, and schedule of the ACS in terms of the equipment used in a selected configuration. The equations were termed "aggregate equations," because the independent variables describing the ACS were "aggregated" into fundamental relationships to the elements of performance, safety, cost, and schedule. For example, the aggregate equation for the pointing accuracy of a three-axis ACS considers variables such as attitude sensor noise and misalignment, gyroscope drift and misalignment, signal processor noise, and control system deadband. Each of these variables is multiplied by a computed sensitivity coefficient and combined in a worst case and/or root-sum-square manner to form the aggregate equation for the ACS pointing accuracy.

The Cost/Performance Model was developed using aggregate equations in conjunction with minimum model elements. The flow diagram from this model is shown in Figure 5-1. Starting with payload functional requirements, a filtering technique (search/sort/filter) is used to determine an attitude control method (such as a gravity gradient, mass expulsion control, momentum storage, or spin stabilization) that will satisfy the functional requirements. The selection of an attitude control method is made because each different ACS configuration has its own set of performance aggregate equations. Other relationships, such as the aggregate equations for safety, cost, weight, etc., remain unchanged or require only minor modifications, such as changing coefficients. Once a basic control method is determined, the type of equipment needed to mechanize the ACS can be selected by interation. Accessing a data base consisting of all ACS components suitable for this control method, the model first inserts the cheapest component into the pointing-accuracy

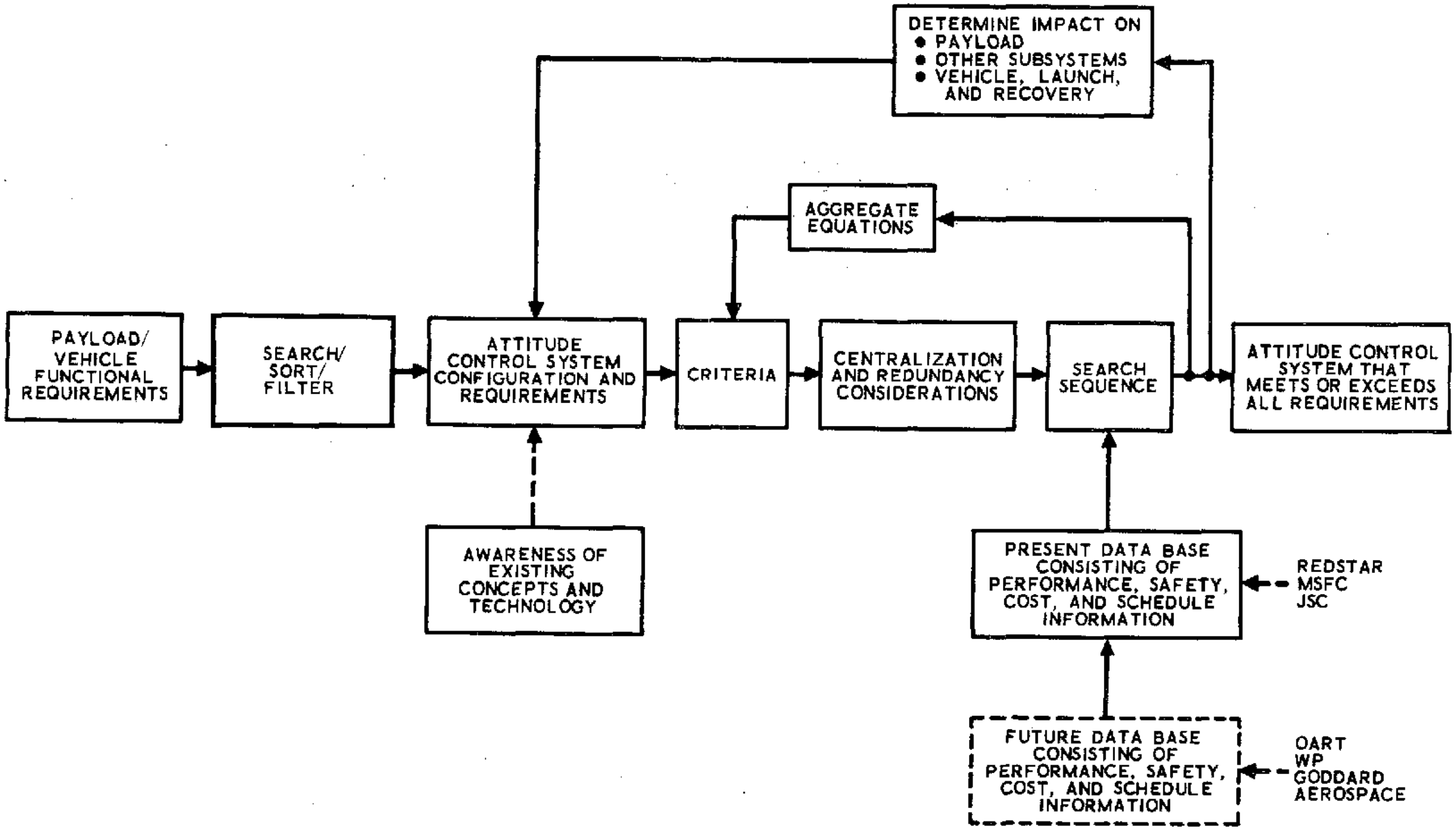

Figure 5-1. Cost/Performance Model

aggregate equation, assuming low-cost ACS is our objective, and computes the pointing accuracy. If the pointing accuracy is poorer than desired, the model then selects the next least expensive set of components, iterating until the desired pointing accuracy is met.

The next step is to use the safety aggregate equations to evaluate those hardware configurations that have met or exceeded the desired pointing accuracy requirement. The safety considerations consist of failure rate, failure detection probability, and the false alarm probability and hazard assessment (single point failures and TNT equivalent[1]). The failure rate aggregate equation determines the necessary level (and configuration) of redundancy (and component quality) to satisfy the payload and mission reliability requirements. The failure detection and false alarm probability aggregate equations quantify the level of system monitoring (onboard or ground-based) needed to meet system success criteria. Those ACS hardware configurations that meet or exceed all safety requirements are recorded by the computer program. The power, weight, volume, thermal specification, vibration specification, and ambient pressure specification for the selected hardware configurations are then computed using the appropriate aggregate equations. Thus, for a given configuration, a set of applicable components is chosen (based for example, on minimum cost or on schedule requirements) from the data base. This configuration satisfies all the performance and safety requirements. After the set of applicable components has been selected, the centralization of major components is considered. For example, should the ACS use a centralized power supply or separate power supplies? Also, the trade between centralized signal processing versus separate signal processing must be considered. Finally, the total ACS cost and schedule are predicted using the cost and schedule aggregate equations. This process may be iterated to meet cost or schedule requirements. One feature of this aggregate equation approach is the ability to establish sensitivities to changes in functional requirements. One need only change the performance requirement (for example, pointing accuracy) and let the process iterate again to produce new results.

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[1] The model only considers these parameters conceptually.

The following sections describe the major elements of the Cost/Performance Model, starting with the search/sort/filter technique that selects an attitude control method based on a set of performance requirements. Following the filter description, the aggregate equations and their relationship in forming the Cost/Performance Model are discussed.

A. SEARCH/SORT/FILTER TECHNIQUE

In the development of the search/sort/filter technique, the usual problem of attempting to find a system that meets certain requirements was inverted. The approach is based on the existence of only a finite number of attitude control methods. The problem is then worked in a manner to determine what requirements are met or exceeded by each individual method. Once this information has been tabulated for all attitude control methods, sorting the possible attitude control techniques by searching through the search/sort/filter matrix to find systems meeting the requirements is a straightforward problem.

The input to the filter is based on ACS requirements originating from the character of the mission and the nature of the payload. The requirements delineate orbital characteristics, spacecraft orientation, spacecraft performance, and general vehicle characteristics. For example, the mission and payload requirements determine the orbit of the spacecraft, the duration of lifetime of the vehicle, the nominal orientation, the attitude and attitude accuracy of the ACS, and the stationkeeping and reorientation requirements.

ACS requirements derived from the basic mission and payload requirements are categorized, and, in general, multiple control methods may seem appropriate for a given set of ACS requirements. Therefore, a rationale is required to choose among the possible candidates. This rationale is provided by functional requirements, with performance, safety, cost, and schedule providing quantitative criteria for tradeoff studies in the detailed analysis of the ACS.

The output of the filter is the one or more control methods appropriate for the mission under consideration. For the Task 2.3 study, various attitude control methods are classified as active, semi-active, or inactive.

An active control method uses one or more feedback loops to maintain the vehicle attitude within specified limits. Such a closed-loop system is completely self-contained by the spacecraft.

An inactive attitude control technique directs the vehicle orientation by a passive feedback system. No sensors, control logic, or actuators are required by an inactive attitude control technique.

The semi-active category covers all schemes that employ some of the elements of an active control technique. This may take the form of attitude sensors so that the spacecraft orientation may be estimated by ground-based data processing.

In all, nine distinct types of attitude control were considered, in which inactive and semi-active configurations are possible for five of the attitude control techniques. Three methods employ active or at least semi-active control methods to provide stabilization. Finally, a method was included to cover those cases where multiple sources of control torque can be used successfully in concert (for example, combined gravity gradient and magnetic stabilization).

B. AGGREGATE EQUATIONS AND FUNCTIONAL BLOCK DIAGRAMS

Aggregate equations are the primary elements of the Cost/Performance Model; however, these equations depend on the particular ACS mechanization selected. Thus, as a starting point in the determination of aggregate equations, functional requirements are translated into functional block diagrams to determine general ACS mechanizations and associated aggregate equations. Next, centralization and redundancy would be considered, leading to specific block diagrams from which more detailed aggregate equations are ultimately derived.

Functional requirements are considered for the following four classes of vehicles:

Class	Type of Vehicle
1	Unmanned, expendable, autonomous
2	Unmanned, reusable, autonomous
3	Manned, reusable, autonomous
4	Manned, reusable, using ground support

Requirements for these vehicles are tabulated, and their functional ACS block diagrams are discussed for both coast and powered-flight phases. The aggregate equations for each ACS type that can be selected by the filter must be formulated and available to the Cost/Performance Model. Thus, following selection of a particular ACS mechanization by the search/sort/filter, a specific set of aggregate equations would be selected. These equations quantitatively relate performance, safety, cost, and schedule of the mechanization. As a demonstration of how this is accomplished, aggregate equations are discussed in the context of their implementation as a digital computer simulation. This discussion is presented to aid illustration of the flow of information through the Cost/Performance Model and to provide a natural transition to the description of the Cost/Performance Simulation following the discussion of aggregate equations.

1. PERFORMANCE AGGREGATE EQUATIONS

Aggregate equations were developed for a Tug-type vehicle with a three-axis mass expulsion ACS, using horizon scanners for pitch and roll reference and gyrocompassing for yaw reference. This particular type of mechanization is typified by the Agena vehicle.

Vehicle attitude is sensed by a three-axis, body-mounted inertial reference unit containing integrating gyros referenced to earth coordinates by horizon scanning and gyrocompassing. Fixed attitude with respect to the earth is maintained by a pitch program giving the required orbital pitch-over rate.

An illustration of a typical performance aggregate equation is the pitch attitude error equation. This equation is derived in Volume II and quantifies pitch attitude error in coast flight in terms of the control system deadband and errors associated with components such as the pitch gyro, horizon sensor, and electronics. If the instrument or component errors are known and stored in a computer-implemented data base, the pitch attitude error may be calculated and compared to an allowable error entered as an input to the computer-implemented Cost/Performance Model. Furthermore, the same sort of calculation and comparison could be performed for each

ACS channel and for each complete combination of sensors stored in the data base. Thus, if the data base contains information characterizing three distinct inertial measurement units (IMUs) and five horizon sensors, a total of 15 IMU/horizon sensor combinations would be available to implement the ACS, and each would have a distinct pitch channel attitude error as calculated by the pitch aggregate equation.

The above described method of forming and evaluating ACSs is basic to the Cost/Performance Model. Only systems (combinations of data base components) meeting performance requirements are stored and subjected to further processing as defined by additional performance, safety, cost, and schedule aggregate equations. Additional performance-oriented processing includes calculation of propellant consumption, power, weight, or vibration.

Not all performance aggregate equation results are subject to an evaluation or comparison procedure. While ACS accuracy in a given channel is compared to an allowable error, system weight, power, or propellant consumption typically is merely calculated and stored as a characteristic descriptive of a specific ACS. These items often represent impacts on subsystems other than the ACS, and would provide information to other modules of an expanded Cost/Performance Simulation. Subsequent iterations would be performed to ensure a balance between the impact on various subsystems to ensure a balanced vehicle design.

2. SAFETY AGGREGATE EQUATIONS

As a result of satisfying certain performance aggregate equations, a finite number of ACS configurations are formed by the Cost/Performance Model. As the next step in processing these configurations, the safety aggregate equations are introduced. These equations are categorized as failure rate, failure detection probability, and false alarm probability aggregate equations.

The failure rate equation is used to calculate the reliability of each ACS configuration. This calculation is performed at a module level, with the ACS viewed as consisting of four separate modules. The modules considered are the sensor, processor, actuator, and energy source modules. Each identifiable ACS component is considered as an element of one of these modules. Thus, horizon sensors and IMUs would be categorized in the sensor module; computers or control logic, in the processor module; pumps, in the actuator module; and propellant tanks, in the energy source module. Failure rate information stored in the data base for each component is extracted as needed by the Cost/Performance Model. These are combined by safety aggregate equations to form failure rates for each module of the first ACS configuration stored as a result of previous processing by performance aggregate equations. Module failure rates are combined by still other safety aggregate equations to calculate total ACS reliability for a given mission duration.

Again, as in the previous performance aggregate equation processing scheme, the calculated reliability of each particular ACS configuration is evaluated against a specified or acceptable level provided as a model input. However, the ACS configuration is not discarded, as it was during performance evaluation, if it does not meet the specified reliability level. Instead, a search for the lowest reliability module is initiated. Upon identification, this module is paralleled by an identical unit, and suitable aggregate equations are used to recalculate the system reliability. The evaluation and paralleling process continues until the lowest reliability module is triply redundant. If the system still does not meet the specified reliability, it is deleted from consideration as a viable single-string ACS. However, should it, at any time, meet or surpass the required input reliability level, aggregate equations are used to calculate system failure detection and false alarm probabilities. In addition, system characteristics such as weight, volume, and total component cost are updated and stored. These items must be updated in case the paralleling process has changed ACS total system characteristics. This process continues until each ACS stored as a result of meeting performance requirements has been processed.

The safety aggregate equation procedure described above essentially constitutes one-third of the total safety aggregate equation process. Following completion of the basic scheme, the whole procedure is repeated with each ACS configuration mechanized, first as an active/standby (dual string) ACS, and then as a triply redundant ACS using voting. The terms "active/standby" and "triply redundant" here refer to complete ACSs, in addition to modular levels of redundancy. For this reason, a separate set of safety aggregate equations is used for processing single-string, active/standby, and triply redundant systems.

The possible number of acceptable ACS mechanizations following safety aggregate equation processing is triple the number of systems that successfully passed the performance aggregate equation process. This fact is accounted for in the computer-implemented Cost/Performance Model, by keeping track of three complete sets of system characteristics for each ACS configuration originally meeting or surpassing performance requirements.

Details of safety aggregate equations and flow charts depicting the processing schemes discussed above are presented in Volume II.

3. COST AGGREGATE EQUATIONS

Two costing techniques are presented in Volume II. The first develops cost aggregate equations, using a data base structured in a manner similar (but not identical) to the REDSTAR data base mentioned previously. This technique results in six cost categories, each described by an aggregate equation that is a function of various labor rates, task man-hours, material costs, and the number of specific items required, such as engineering drawings. Summation of costs for each category determines the total cost of the ACS. These cost aggregate equations, to be a useful tool, require data in a very detailed WBS format. Unfortunately, such data generally are not available until a design has progressed into its intermediate phase. An alternate component costing technique was therefore developed to calculate costs in the very early design phase. This alternate technique, described below, is the one used in the cost/performance computer simulation.

The component cost approach, which is the second costing approach, develops cost aggregate equations based on the cost of ACS components selected via the performance and safety aggregate equations and requirements. This costing technique requires each ACS component to have non-recurring and recurring cost information as part of its data base. This cost information is available from the REDSTAR data base. Aggregate equations then sum non-recurring material costs for each component used in a specific ACS mechanization to determine total non-recurring material costs for each program phase, such as the design and development or the build and checkout phase. The form of the non-recurring material cost aggregate equation is a sum of the non-recurring costs of the ACS components, multiplied by an inflation factor. Phase costs are then summed to determine total non-recurring material costs.

ACS non-recurring systems engineering costs are defined as a function of total non-recurring material costs, and the material and systems engineering costs are finally summed to give total ACS non-recurring costs.

Total recurring cost aggregate equations are structured in much the same manner as the non-recurring cost equations. Finally, ACS total costs are obtained by adding recurring, non-recurring, and management costs, where management cost is a percentage of total ACS cost. If more than one ACS is produced, a learning curve is used to account for reduced unit cost as additional units are built.

4. SCHEDULE AGGREGATE EQUATIONS

Schedule aggregate equations determine the amount of series time required to develop an operational ACS. This determination is accomplished by dividing the life cycle of the system into nine phases, beginning with the proposal phase and ending with the operational phase. Aggregate equations then describe each phase time in terms of the manpower available to complete a specific phase.

So that required manpower can be estimated, manpower aggregate equations are formulated, based on activities associated with each phase. Schedule analysis matrices and flow charts are used as a master list from which to select pertinent activities. The charts and matrices take into account various schedule parameters, such as sequence constraints, manloading limitations, production quantity, production rate, and delivery span.

6. COST/PERFORMANCE SIMULATION

This section presents a brief summary of the Cost/Performance Simulation to show the manner in which aggregate equations interact with the cost performance data base and among themselves.

Figure 6-1 presents an overview of the ACS Cost/Performance Simulation. The flow is the same for batch process operations as for on-line terminal operation.

As depicted in Figure 6-1, entry of model variables and matrices initializes the program. A complex data base results from the many inputs required to define various ACS components. Therefore, the program is structured to allow entry of a stored data base, followed by easy program data base modifications or additions.

The data base actually implemented is the Table 1-1 data base presented in detail in Section 6 of Volume II. It is essentially a list of all components available to configure various types of ACSs, with each component described in terms of parameters required as inputs to performance, safety, cost, and schedule aggregate equations.

Following the first initialization phase, consisting of data base entry and modification, data are provided for the various performance, safety, cost, and schedule criteria to be used in the program during execution. For example, performance criteria (such as the required coast flight attitude control accuracy in roll, pitch, and yaw axes) are the inputs during this second phase of the program initialization procedure. These inputs are used to evaluate acceptability of specific ACS configurations as described in the discussion of aggregate equations. A similar input would specify a required ACS mission success probability, and set a criterion for acceptance of each candidate ACS configuration during program execution of safety aggregate equations. Final inputs prior to program execution provide sort criteria that will format program outputs by ranking acceptable ACS configurations according to cost, reliability, accuracy, or any other criterion calculable, using aggregate equations implemented in the simulation.

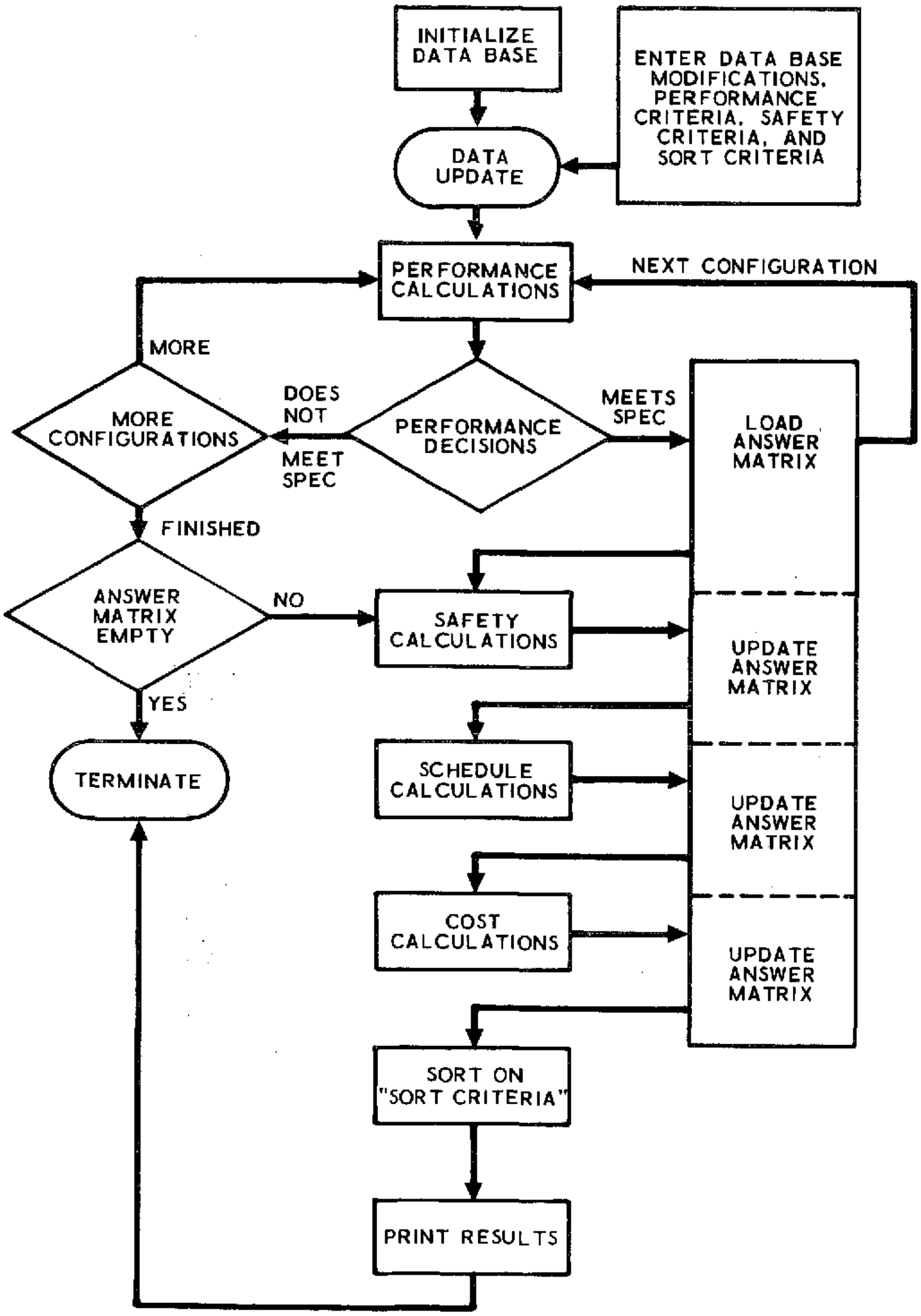

Figure 6-1. Cost/Performance Simulation Overview

As described previously, the safety aggregate equation module immediately follows implementation of the performance module in the sequence of operations performed during execution of the Cost/Performance Simulation. All ACS configurations that have successfully passed performance criteria and are stored in the answer matrix are screened by the safety module, as indicated in Figure 6-1. Those single-string systems not meeting reliability criteria are upgraded by paralleling the lowest reliability module in the ACS sensor, processor, actuator, energy source module string. The total reliability of the improved system is then recalculated and checked for compliance with reliability specifications. If the system is still unacceptable, paralleling of the weakest module continues. (The weakest module may or may not be the same module paralleled previously.) This process is continued until the system is acceptable, or until a module exceeds triple redundancy, at which point the program rejects the configuration as unacceptable in a single-string mechanization and proceeds to evaluation of the next configuration. Should the system meet reliability criteria, failure detection probability and false alarm probability are calculated for the configuration, and the system is stored in the answer matrix as an acceptable single-string mechanization.

After all configurations stored in the answer matrix have been evaluated for compliance with reliability criteria when mechanized as a single-string ACS, the program proceeds to evaluate each configuration in an active/standby ACS mechanization. As before, paralleling of modules is allowed to upgrade reliability of the active/standby mechanizations, and individual modules are held to maximums of triple redundancy. Systems meeting reliability criteria have failure detection and false alarm probabilities calculated, and are then stored in the answer matrix as an acceptable active/standby mechanization.

Following evaluation of all answer matrix entries as active/standby mechanizations, the program evaluates each entry in the answer matrix mechanized as triply redundant ACS with voting. In this sample mechanization, upgrading of individual modules by paralleling is not allowed, as the total

ACS is already triply redundant. Other calculcations proceed much as described for previous mechanizations, and detailed flow charts of the procedures described above are provided in Section 5 of Volume II.

Configurations not meeting reliability criteria after safety module processing are deleted from the answer matrix, and the program proceeds to processing of schedule and cost aggregate equations.

Upon completion of the ACS requirements phase of initialization, the program begins execution of performance aggregate equations and decisions.

In the performance module of the Cost/Performance Simulation, the acceptability of each candidate ACS is evaluated by comparing calculated ACS performance, as determined by performance aggregate equations, to required ACS performance parameters entered during program initialization. The flow of calculations in this module may be relatively simple, such as those shown in Figure 6-1, or they may be more complex and essentially represent a basic error analysis of a particular ACS configuration. In general, use of the simulation during early conceptual phases of a program would rest on several baseline ACSs, with each specific baseline defined by a separate set of aggregate equations. Later applications could be based on a single ACS configuration requiring a single set of performance aggregate equations. The program is structured to accept these intermodule changes without disrupting the basic intramodule interactions that form the basis of the Cost/Performance Simulation.

Regardless of the level of sophistication of the performance aggregate equations, all ACS configurations passing the performance criteria are stored in the answer matrix. This matrix maintains a dynamic record of the characteristics of ACS configurations that have met or surpassed criteria entered during program initialization, such as total ACS weight or an identifier of a particular data base component that is a part of a specific ACS configuration.

Schedule and cost calculations are a straightforward implementation of the schedule/cost aggregate equations; however, the present sample program does not implement schedule equations. Present plans call for presenting schedule results as charts showing major program milestones for each configuration stored in the answer matrix. Each chart would be keyed to the printout of other information for the particular configuration that it represents; the total package represents complete assessment results of all ACS configurations meeting performance and safety criteria. For ease in evaluating various ACS configurations, printouts are ordered according to the particular criteria entered by the operator.

7. INTERACTION WITH OTHER SUBSYSTEMS

The interaction of the ACS with some of the other subsystems was briefly considered. A generalized guideline for the development of a power conditioning system for the ACS is given in Section 7 of Volume II. The major thermal drivers that influence the design and operation of typical ACS components are identified in Section 8 of Volume II. The nature of the requirements placed on the ground support equipment (GSE) by the ACS is discussed in Section 9 of Volume II.

8. COST/PERFORMANCE MODEL SAMPLE CALCULATION-CER COMPARISON

Figure 8-1 compares sample calculations of the Cost/Performance Simulation with a cost-versus-weight CER developed at SAMSO. The Cost/Performance Simulation output of cost versus weight for a three-axis ACS is consistent with the cost-versus-weight CER developed at SAMSO. CER results were obtained by summing DDTE costs, with first article cost adjusted by a learning curve to obtain the cost of 20 systems. These results were obtained using a data base consisting of three distinct horizon sensors, three star references, and three IMUs. This gives a total of 27 unique ACS component combinations or 81 ACSs, counting single-string, active/standby, and triply redundant mechanizations.

Figure 8-2 shows the cost-versus-reliability relationship for the same 20 systems. Details of this and other simulation results are given in Appendix C of Volume II.

It is concluded, based on the curves of Figure 8-1, that Cost/Performance Model results are in substantial agreement with results obtained using conventional approaches. However, the Cost/Performance Model provides a more detailed insight and a potential for accomplishing sensitivity studies, using up-to-date data bases, and for performing trade studies between various subsystems unobtainable using conventional approaches; it also indicates regions where components are not available.

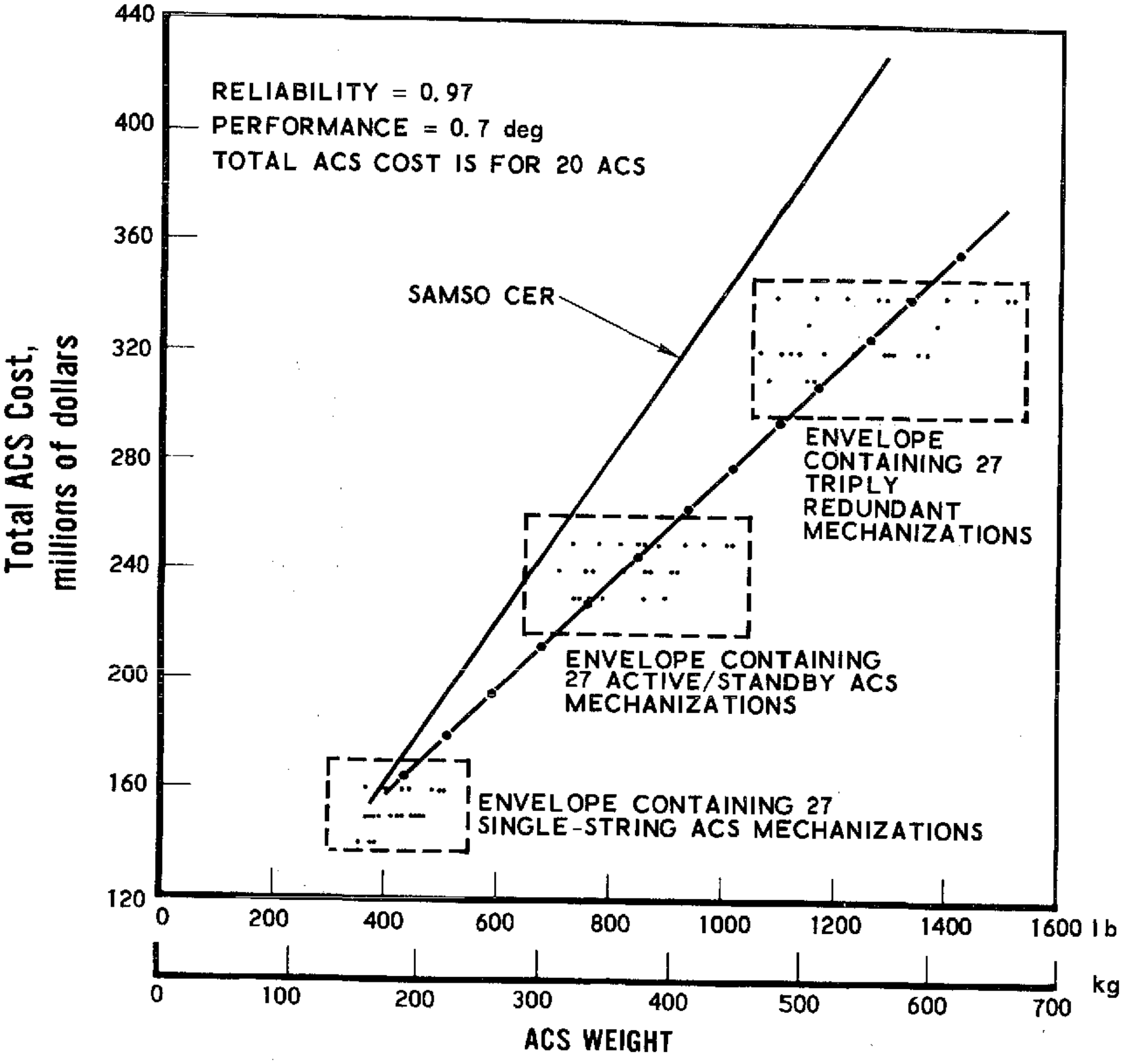

Figure 8-1. Total ACS Cost vs ACS Weight

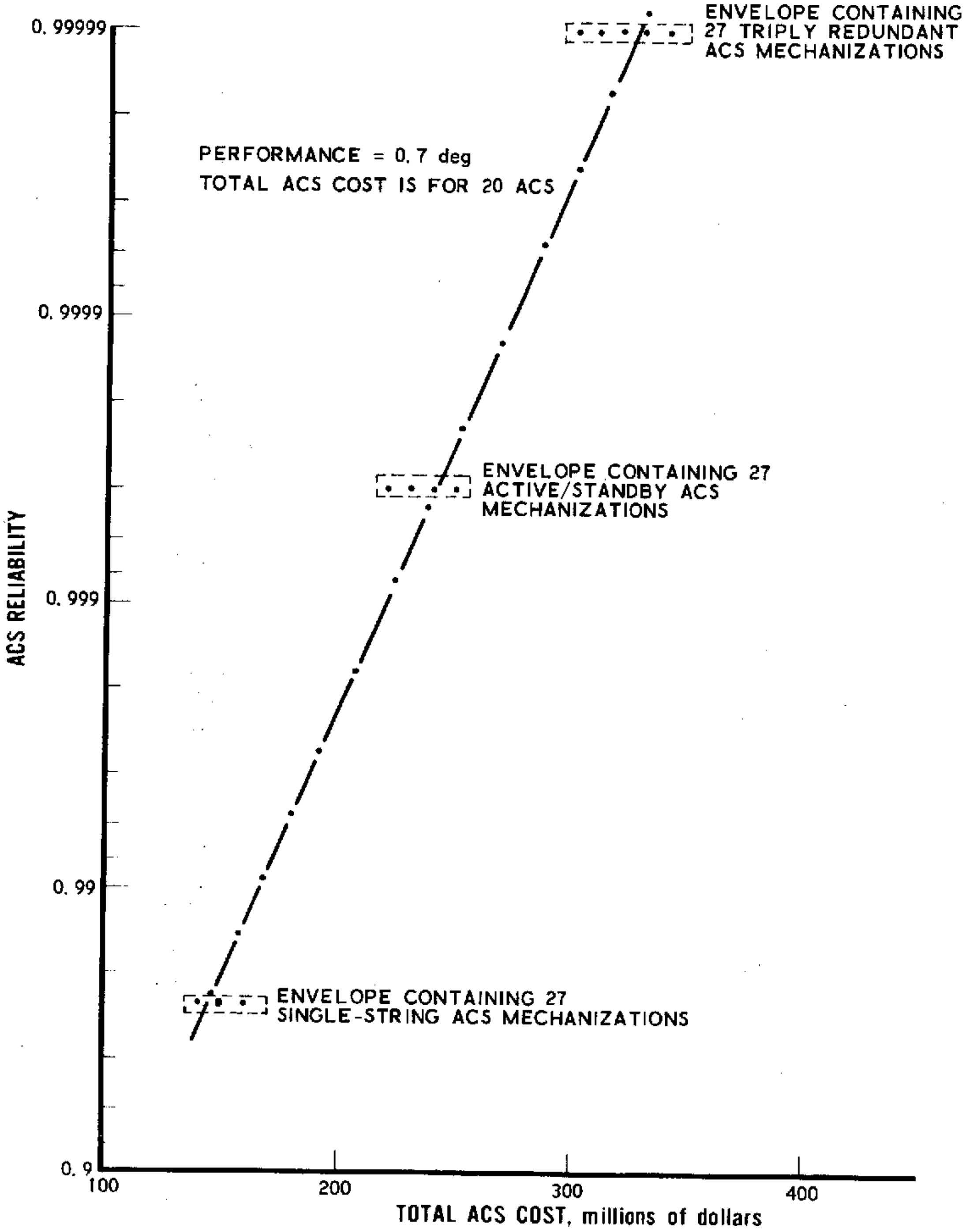

Figure 8-2. ACS Reliability vs Total ACS Cost

9. CONCLUSIONS AND RECOMMENDATIONS

A viable cost/performance modeling methodology was developed, which quantified the interrelationships among performance, safety, cost, and schedule for an ACS by means of "aggregate equations." This methodology is designed to be applicable to all phases of a project. As the design progresses, the model and the supporting data base may be updated with more definitive information. A sample case of the model was implemented on a CDC 7600 computer for a three-axis stabilized, earth-pointing, mass expulsion ACS. In its computerized form, the model will aid the designer in evaluating trade studies, and will simplify the achievement of a balanced system design, since the impact of ACS requirement changes on the other space vehicle systems and on the total vehicle can readily be determined. This model will also be useful for evaluating the effect of new technology or standardized components, by making suitable entries in the data base representing proposed component characteristics.

Example calculations were run for several performance and safety requirements, using a sample data base. For these restrictive cases, the model results are consistent with conventional cost-versus-weight CERs. At the same time, the model can provide insight into the effect of many variables on system cost; this capability is not available using conventional CERs. For a specific system, Figure 8-1 shows the typical results for weight versus cost of development and a 20-unit purchase of ACS units; Figure 8-2 shows the cost-versus-reliability relationship for the same 20-unit basis. This model emphasizes the fact that there are discrete cost/weight points with some significant gaps.

As a result of successful preliminary development of this Cost/Performance Model, further work should be undertaken to

a. Develop aggregate equations for other ACS methods, other space vehicle systems, and support systems (e.g., GSE, flight operations) as a step toward developing a vehicle model.

b. Refine the existing aggregate equations, especially for parameters such as power, weight, volume, specifications, and schedule.

c. Consider centralization and hazards quantitatively.

d. Continue development of the data base to support this model.

The model presently provides a means of determining a unified estimate of performance, safety, cost, and schedule on a single type of ACS for the use of both performance and cost analysts. With refinement of some aggregate equations and extension to other ACS types, this model will be applicable to trade studies concerning most ACS requirements. Similarly, it can be applied to other space vehicle systems as the required aggregate equations become available. If fully developed, the model will provide a single tool for determining a unified estimate of performance, safety, cost, and schedule for a vehicle that supports both cost and performance analyses.

It is recommended that the fiscal year 1974 effort include extension of the model to other space vehicle systems; improvement of the data base to be acceptable for both performance and cost analyses; testing of the capability of the model to predict space vehicle interrelationships; and a user review to evaluate the potential of the model to assist in programmatic change control, such as configuration management.