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NEW MODEL FRAMEWORK AND STRUCTURE

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THE COMMONALITY EVALUATION MODEL

Report No. P21-R-001

Planning Systems and Sciences

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PROJECT FINAL REPORT

NEW MODEL FRAMEWORK AND STRUCTURE
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THE COMMONALITY EVALUATION MODEL

Report No. P21-R-001

August 26, 1977

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ABSTRACT

This Final Report documents the development of a new framework and structure for shuttle era unmanned spacecraft projects and the development of a Commonality Evaluation Model. It also discusses the methodology developed for model utilization in performing cost trades and comparative evaluations for commonality studies.

The new framework and structure are based upon functionally oriented rather than performance oriented elements. The model framework consists of categories of activities associated with the spacecraft system's development process. The model structure describes the physical elements to be treated as separate identifiable entities.

The Commonality Evaluation Model is a comparative cost model developed specifically for making comparative evaluations of cost savings in unmanned interplanetary spacecraft programs and/or projects using varying approaches to and varying degrees of commonality. The unit of value is not the usual US dollar, but a Normalized Cost Unit (NCU). New cost estimating relationships (CERs) for subsystem and program-level components have been calculated in NCUs.

The methodology supports cost trades and comparative evaluation for commonality including hardware, software, and firmware elements as well as standard components. The methodology was constrained to the use of existing data.

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ACKNOWLEDGMENTS

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The effort on this project has been undertaken by PS&SC's Cost Technology Improvement Team (CTIT) under the direction of Mr. H. Scott Watson. The principal members of the team are Messrs. William T. Hayes and Joseph J. Milkovich. Various other members of the PS&SC Technical Staff augmented the CTIT on an as-needed basis.

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I. SUMMARY

The objective of this project, called Commonality Evaluation Model Development, was to perform further investigations concerning the existing JPL cost models as well as providing analysis and experience toward extending the current JPL cost model to new areas in anticipation of potential new management approaches and a new era of spacecraft launch associated with the shuttle.

The contract effort was divided into three distinct sub-efforts, two of which were closely related and the third only loosely related. The first sub-effort was the development of a model framework and structure. The second sub-effort was the development of the Commonality Evaluation Model itself. The third was the quick development of four new cost estimating relationships (CERs).

The first sub-effort developed a new framework and structure compatible with the requirement of a contemplated new unmanned spacecraft cost model. This framework and structure is required to support several new features including element definition at a sufficiently low level to separately identify the lowest logical levels of commonality impact. The framework and structure is compatible with cost analysis of various modes of project management and with standard components, distributed data systems, and both hardware and software inheritance. The framework and structure were developed to meet broad scope requirements and then were recombined and compressed to accept existing CERs for the logic and methodology of the Commonality Evaluation Model.

The second sub-effort--development of the Commonality Evaluation Model--is closely related to the first. This sub-effort is both broader and narrower in scope than the title implies. It is somewhat narrower in that the model, as defined, is applicable only to unmanned, scientific interplanetary spacecraft and is constrained to utilize existing cost estimating relationships for the elements of a space project and therefore constrained to utilize a simpler framework and structure. It is broader, on the other hand, because the framework and structure developed as a precursor to the logic and methodology had to be the new framework and structure developed in the first sub-effort in order to assure model compatibility with futured developments.

During this effort, the CERs currently utilized by the JPL cost model were translated from "real" or "then" year dollars to 1975 dollars, normalized, and expressed in a cost called a Normalized Cost Unit (NCU) and replotted. In several cases, previous errors were also corrected. Due to an insufficient experiential data base, NCU standard components CERs could not be developed at this time. However, provisions have been made to accomodate standard components; therefore, when sufficient data becomes available, these CERs will be constructed and added.

The third sub-effort, only loosely related to the first two, developed new cost estimating relationships for the following four new elements:

- Penetrators
- Surface Mobility Systems
- Solar Sails
- Ion Drives

II. INTRODUCTION

As previously explained, the contractual effort encompassed three distinct areas of work. This document covers on the two closely related efforts; the development of the new framework and structure and the development of the Commonality Evaluation Model. The third effort is published separately in Planning Systems and Sciences Company Report P21-R-003.

For convenience and logic of thought and presentation, the two different sub-efforts are contained in separate parts. Section III contains the technical discussion concerning the new framework and structure. Section III also contains its own conclusion and recommendations.

In a like manner, Section IV contains the technical discussion concerning the Commonality Evaluation Model as well as its associated conclusions and recommendations.

This report contains two appendices. The first contains the bibliographic data identifying the data base documents. The second contains a handbook for exercising the Commonality Evaluation Model. This handbook has also been published separately.

Two items of note should be borne in mind by the reader.

1. In order to assure the compatibility with future developments, the new framework and structure discussed in Section III was developed as a precursor to the Commonality Evaluation Model. However, the framework actually used in the CEM and discussed in Section IV is a retrogression to a simpler set imposed by the constraints of using existing data.
2. Primarily due to a lack of sufficient experiential data, CERs for standard components could not be developed at this time. The CEM, however, incorporates provisions for treating standard components. The CERs can be added when adequate data is available for their development.

III. TECHNICAL DISCUSSION--NEW FRAMEWORK AND STRUCTURE

A. Overview

The rationale for the development of the new framework and structure is to determine if a functionally oriented rather than a performance oriented framework and structure could be developed for, and be compatible with, the requirements for a new, shuttle era unmanned spacecraft cost model. The framework and structure were required to support several new features, including element definition at a sufficiently low level to separately identify the lowest logical levels of commonality impact. The framework and structure also had to be compatible with cost analysis of various modes of project management and with standard components, distributed data systems, and both hardware and software inheritance.

The model framework consists of subdivisions of the model relating to categories of work effort or activities associated with the spacecraft system's development process. The framework was subsequently used to determine the hierachy of activities and phases of development to be considered separately when exercising the methodology. The model structure was developed to describe the physical elements to be treated as separate identifiable entities of the spacecraft and spacecraft support systems. PS&SC used the structure to identify the lowest level of commonality that could be considered directly without a supplementary breakdown.

Previously, most cost model structures have been oriented to the design characteristics of hardware such as weight, density and volume. These characteristics are suffieient so long as absolute governing constraints exist that make it mandatory that hardware be designed to minimize weight and volume. When these constraints are somewhat relaxed, as they are now with the advent of the Shuttle and increasing cost pressure, then the design characteristics no longer serve as reliable cost extimators. Therefore, performance parameters must then be turned to for the cost estimating relationships.

In order to provide maximum utility and compatibility with anticipated utilization and future developments, PS&SC developed the structure of the model after first identifying the "functional elements" of the spacecraft systems. A functional element is a hardware or software element of a space system that performs a specific job. It should be noted, however, that an element cannot and does not accomplish a mission objective without being combined with other functional elements. After identification, the functional elements were combined into composite functional elements, referred to as major functions.

As developed, the methodology is capable of performing comparisons of standard hardware components, standard software componenets, hardware inheritance, software inheritance and the impact of operations commonality. However, in order to maintain a relationship with the current JPL practice, the composite functional elements are compatible with the structure of existing cost estimating relationships.

B. Model Framework and Guidelines

In order to describe the framework of the model, PS&SC collected unmanned spacecraft cost data applicable to development of the commonality evaluation cost model. During the period of data collection, a analysis of the constraints and applicability of all the data was undertaken.

From this analysis, PS&SC characterized and defined the major developmental and operational activities of an unmanned spacecraft project. A synthesis of the characteristics was used to derive the framework of the model. The analysis and synthesis determined the functional elements that constitute the spacecraft system, supporting system, and mission elements.

These functional elements provide definitions of major separable activities and sub-activities involved in the design, development, fabrication, testing and operation of an unmanned spacecraft project. The primary goal was to select definitions for the framework descriptors that are generally accepted.

This section describes the framework that was initially derived for the model and presents the general guidelines for model inputs.

The framework of the model is defined as consisting of seven distinct phases and/or activities of a project. Each of these principal phases is subdivided into as many parts as necessary to account for differences in approach or purpose.

The seven principal phases and the phase subdivisions are presented in Exhibit 1. In addition, a brief set of framework guidelines is presented to help define the scope and activities making up each of the seven phases. Exhibits 2 through 8 present the guidelines for the subdivisions of each of the seven principal phases.

C. Initial Model Structure and Technical Descriptors

With these functional element characteristics and utilizing available CERs, PS&SC was able to develop a structure for the model. The structure of the model is defined as consisting of 13 subsystems and one system management element. The 13 subsystems are further divided into two or three major functions. The System Management element is also subdivided into two major functions. The purpose of the structure as defined is to allow the separation of functionally different hardware/firmware/software elements in order to enhance the ability of the model to handle the inter-element influences of commonality variations. Separation of the two major functions of the system management element achieves the same purpose.

Descriptors were developed in a two-step process. The spacecraft system was first divided into its functional elements. After achieving satisfactory and workable functional element definitions and descriptors, the functional elements were recombined into composite functional elements compatible with existing CERs. Definitions and descriptors were subsequently derived for the composite functional elements to provide a clearer understanding of the inputs required to adequately define portions of the systems. These descriptors include the hardware elements, software elements, system level elements, and mission additives.

The subsystems (including Systems Management) and their related major functions are shown in Exhibit 9. Also presented in the exhibit are the technical descriptors that define the input paramenters that must be specified for each of the major functions or subsystems.

EXHIBIT 1 - MODEL FRAMEWORK AND GUIDE

F I

REQUIREMENTS DEFINITION

- Starts with the first efforts specifically oriented toward analyzing the elements of the mission with the goal of formulating the requirements for the system.
- All effort is conceptual and/or analytical and directed toward determining requirements.
- Complete when system-level performance requirements have been determined and specified.

Mission Analysis
System Analysis
Performance Requirements

F II

DESIGN AND DEVELOPMENT

- Starts with specific design effort oriented toward producing subsystems that achieve system performance requirements.
- Effort is analytical and/or conversion of analytical results to hardware, firmware and/or software elements.
- Complete when all necessary elements exist as proven prototypes or item specifications capable of producing results required to achieve system performance requirements specified.

Design
Development
Prototyping
Test

F III

PROCUREMENT AND MANUFACTURING

- Starts with preparation of procurement specifications for elements to be purchased.
- Effort is conversion of prototypes and/or specifications to production hardware, firmware and/or software elements and interfaces.
- Complete when all required subsystems, stand-alone elements and interface provisions have successfully passed acceptance tests that verify required performance

Procurement
Fabrication
Assembly
Acceptance Test

F IV

INTEGRATION

- Starts with physical assembly of elements
- Effort is physical assembly and electronic integration of hardware, firmware and/or software subsystems and elements and interim checkouts performed in process
- Complete when all interim checkouts have been successfully completed

Assembly and Integration

FOLDOUT FRAME 2

RAMEWORK AND GUIDELINES SPACE PROJECT

F IV

INTEGRATION

tarts with physical assembly of lements

ffort is physical assembly and lectronic integration of hardare, firmware and/or software ubsystems and elements and nterim checkouts performed n process

omplete when all interim heckouts have been successully completed

- Assembly and Integration

F V

TEST AND EVALUATION

- Starts with full-scale functional test of integrated system
- Effort is testing of total system to verify performance
- Complete when specified performance verification and assurance testing have been successfully completed

- System Test
- Design Verification
- R&M Demonstration

F VI

LOGISTICS

- Starts with scheduling and application of support elements of system
- Effort is implementation of all elements of support required to achieve mission objectives
- Complete when mission has ended and system documentation has been completed

- Logistic Support
- Ground Support Equipment
- Spares
- Maintenance Support
- Training
- Documentation

F VII

OPERATIONS AND MAINTENANCE

- Starts when system is in place at launch site(s) and ready for pre-launch check and/or support elements are in place and ready to be put into operation
- Effort is operation and monitoring of performance of the system and its elements
- Complete when mission is terminated and results have been distributed

- Launch Operations
- Flight Operations
- Maintenance
- Data Processing & Mgt.

EXHIBIT 2 - MODEL FRAMEWORK AND GUIDELINES

F I REQUIREMENTS DEFINITION

A. MISSION ANALYSIS

- Conceptual and analytical efforts performed to assess the implications of mission objectives and synthesize definitions of system-oriented performance necessary

B. SYSTEM ANALYSIS

- Conceptual and analytical efforts performed to formulate concepts of systems, make tradeoffs and select approaches
- Determination of system-level performance requirements for specific parameters of selected system approach

C. PERFORMANCE REQUIREMENTS

- Development of system-level performance requirement specifications
- Translation of specifications to a level sufficient to allow design requirements to be derived for subsystems and interfaces

EXHIBIT 3 - MODEL FRAMEWORK AND GUIDELINES

F II DESIGN AND DEVELOPMENT

A. DESIGN

- Derivation of subsystem and lower element requirements
- Conceptual and analytical derivation of hardware/firmware/software solutions to achieve the requirements
- Translation of the solutions to graphic and/or written disclosures

B. DEVELOPMENT

- Analytical and/or experimental refinement of designs to prove concepts and perfect performance
- May involve breadboards, brassboards and/or simulation

C. PROTOTYPING

- Producing functional models of the designs similar in physical characteristics to production units but often incorporating substitute materials and manufacturing methods

D. TEST

- Conducting testing of an experimental and exploratory nature to provide information necessary for the development process

EXHIBIT 4 - MODEL FRAMEWORK AND GUIDELINES

F III PROCUREMENT AND MANUFACTURING

A. PROCUREMENT

- Preparation of procurement specifications
- Carrying out of contracting or purchasing process
- Monitoring and acceptance of procured items

B. FABRICATION

- Conversion, using "production" methods and materials, of specifications and/or prototypes to finished hardware, firmware and/or software elements and subassemblies

C. ASSEMBLY

- Physical assembly and electronic interconnection of procured and/or fabricated items into subsystems and major stand-alone elements

D. ACCEPTANCE TEST

- Testing of assembled subsystems, stand-alone elements and subassemblies to assure that they are capable of meeting their performance requirements

EXHIBIT 5 - MODEL FRAMEWORK AND GUIDELINES

F IV INTEGRATION

A. ASSEMBLY AND INTEGRATION

- Physical assembly and electronic integration of subsystems and stand-alone elements into a complete and integrated system capable of accomplishing the mission objectives
- Incorporates interim tests and checkouts necessary to confirm proper integration

EXHIBIT 6 - MODEL FRAMEWORK AND GUIDELINES

F V TEST AND EVALUATION

A. SYSTEM TEST

- Full-scale functional test of the integrated system to ascertain that all functions perform as intended

B. DESIGN VERIFICATION

- Performance of full-scale test to verify that integrated system meets performance specifications

C. R&M DEMONSTRATION

- Conduct of tests to demonstrate that specified levels of reliability and/or maintainability have been met with stated degrees of confidence

EXHIBIT 7 - MODEL FRAMEWORK AND GUIDELINES

F VI LOGISTICS

A. LOGISTIC SUPPORT

- Planning, scheduling, arranging, controlling and monitoring the provisioning of supplies and support services required
- Movement of system and support equipment to site locations

B. GROUND SUPPORT EQUIPMENT

- Planning and provisioning of ground support equipment items required for system launch, operations and maintenance

C. SPARES

- Planning and provisioning of spare systems and/or items that may be required to support the mission

D. MAINTENANCE SUPPORT

- Planning, arranging and provisioning of maintenance services
- Providing pre-launch maintenance services

E. TRAINING

- Planning, scheduling and providing required training for operations and/or maintenance

F. DOCUMENTATION

- Planning and providing system documentation required for accomplishment of mission objectives

EXHIBIT 8 - MODEL FRAMEWORK AND GUIDELINES

F VII OPERATIONS AND MAINTENANCE

A. LAUNCH OPERATIONS

- Performance of pre-launch checkout and control of system during launch period

B. FLIGHT OPERATIONS

- Control and monitoring of system functions during transit and encounter phases of mission

C. MAINTENANCE

- Performance of preventive and/or corrective maintenance actions that may be required during pre-launch, launch, transit and encounter phases of mission

D. DATA PROCESSING AND MANAGEMENT

- Processing and management of data and its distribution

EXHIBIT 9 - MODEL STRUCTURE AND TECHNICAL DESCRIPTORS

HARDWARE, FIRMWARE, SOFTWARE AND SYSTEM MANAGEMENT ELEMENTS

S I. SYSTEMS MANAGEMENT

A. Program Management

1. Duration of total program (months)
   (a) Pre-launch (months)
   (b) Transit (months)
   (c) Encounters (months)
2. Start date (month, yr)
3. Number of S/C
4. Number of major subsystem contractors (S/C, landers, probes, etc.)
5. Number of separate experiments
   (a) Total data frames from each experiment (picture scans, IR scans, etc.)
6. Sample returns to be attempted?
7. Target bodies this mission--Primary mission objectives
8. Contract mode (S) (inhouse, systems integrator, systems contractor, etc.) (Management)
9. Level of configuration control (parts, assemblies, units, etc.)

B. Systems Integration

1. Number of major subassemblies per S/C
2. Number of S/C
3. Fraction of new subsystems per S/C
4. Number of prior S/C programs similar to this one
5. Number of launches
6. Launch mode
   (a) Earth booster + staging
   (b) Shuttle + staging
   (c) Shuttle + S/C propulsion (sail, ion drive, etc.)
7. Number of new contractors this S/C project
8. Number of experimenters
9. Systems interface mode
10. Redundancy mode (functional or block)

EXHIBIT 9 (Continued)

HARDWARE, FIRMWARE, SOFTWARE AND SYSTEM MANAGEMENT ELEMENTS		
S II. SCIENCE		
A. Active Data Acquisition (for each experiment)	B. Semi-Active	C. Passive
1. Is this a primary experiment? 2. Power required (kW) (a) Max (b) Min (c) Duty cycle 3. Weight (mass-Kg) 4. Data rates: (a) Production (bits/sec) (b) Storage--at experiment (bits) (Buffer) (c) Control commands (wds/operations, total ops at one time) (d) Output frame size, bits; or other similar measure 5. Does the experiment require a special position on the S/C (scan platform, min fov, etc. 6. Number of prior interplanetary missions with this type experiment (i.e., TV, etc.) 7. How much of the hardware of this experiment is new (%) to interplanetary S/C?	As for A	As for A

EXHIBIT 9 (Continued)

HARDWARE, FIRMWARE, SOFTWARE AND SYSTEM MANAGEMENT ELEMENTS

S II. SCIENCE (Continued)

A. Active Data Acquisition (for each experiment)		
8. Volume of experiment (m^3) (a) Total (b) Of each physically separate element		
9. Contracting mode (Grant, CPFF, etc.) for hardware		
10. Contracting mode for data reduction (a) Is organization same as 9.?		
11. Can this instrument be used beyond the primary mission?		
12. Pointing requirements for this instrument (if not rigidly afixed to S/C structure) (a) Angular accuracy (az, el) ($\theta \pm \delta\theta$ rad) (b) Slew rates (az, el (rad/sec))		
13. Is any part of this experiment deployed after: (a one-time deployment) (a) Earth orbit insertion (b) Start of transit (c) Target orbit insertion		

EXHIBIT 9 (Continued)

HARDWARE, FIRMWARE, SOFTWARE AND SYSTEM MANAGEMENT ELEMENTS		
S II. SCIENCE (Continued)		
A. Active Data Acquisition (for each experiment)		
14. Environmental limits on each part of experiment (max-min temp, radiation, etc.) (a) While non-active (b) While active 15. Is a degraded mode of operation possible? 16. What percentage this experiment contributes to science objectives?		

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EXHIBIT 9 (Continued)

HARDWARE, FIRMWARE, SOFTWARE AND SYSTEM MANAGEMENT ELEMENTS

S III. PRIMARY STRUCTURE (Not designed to move relative to S/C fixed coord systems)

A. Unpressurized (i.e., no internal pressure)

1. Weight (mass- Kg)
2. What fraction of design similar to any prior S/C structure of past engineering generation?
3. Any new materials of construction?
   (a) If yes; what, prior experience with this material, list similar structures of this material in last 3 years for earth orbit or interplanetary S/C
4. Any new features in this design (i.e., shape; torques, stresses, etc., more than 20% of last design)
5. Contractor-project relation for design/develop (in-house, etc.)
6. Contractor-project relation for fabrication
7. Are new design methods being used?
8. Unusual dynamic requirements (stress, high loads, etc.)

B. Pressurized Structure (external structure surface has design pressure drop across surface--tanks, special atmosphere, etc.)

1. Weight (mass- Kg)
2. Pressure level (bars, psia, etc.)
3. Volume (m^3)
4. Is this a new design? Or a new material of construction?
5. Any new fabrication methods to be used?
   (a) Indicate prior use these methods for S/C uses
6. Contractor-program relationship for Des/Dev & Fabrication
7. Are new design methods being used?
8. Unusual dynamic requirements (stress, high loads, etc.)

EXHIBIT 9 (Continued)

HARDWARE, FIRMWARE, SOFTWARE AND SYSTEM MANAGEMENT ELEMENTS

S IV. ENVIRONMENTAL REGULATION

A. Active	B. Passive (Point, etc.)
1. Controlled parameter--temp, radiation, EMI, etc. 2. Weight of control device(s) (kgms-mass) (a) Sensor(s) (b) Effector(s) 3. Power required (KW) (a) Max-pwr (b) Duty cycle (c) Min-pwr 4. Prior history of similar devices (a) % common this design and last design in past engineering generation (b) % common this fabrication and last fabrication in past engineering generation 5. Any special requirements for location on S/C (radiators, etc.) 6. Any special tests or equipment needed for S/C integration? (new methods)	1. Weight not otherwise accounted for (as structure, etc.) 2. Prior use of this method in similar missions--% common to prior use 3. Special fabrication methods or prelaunch handling required?

EXHIBIT 9 (Continued)

HARDWARE, FIRMWARE, SOFTWARE AND SYSTEM MANAGEMENT ELEMENTS

S V. SECONDARY STRUCTURE

A. Fixed

1. Weight (mass-kgms)
2. Area (m^2 if "flat plate")
3. Any special materials or handling constraints--what?
   (a) If new material, designs, or fab technique--what is history of use in space?
4. Function on S/C
5. Shape and form

B. Movable

1. Function (sail, solar panel, arm, etc.) (scan platform)
2. Number of motions
   (a) One deployment
   (b) Intermittant extension/retraction/slew
   (c) Continuous
3. Weight (mass, kgm)
4. How moved--gas/hydraulic/electrical
   (a) Power required
      Max
      Min
      Duty cycle
5. Number and type of control sensors--position/velocity/etc.
6. Number and size of commands to controller (bits, wds, vocab)
7. On-board or earth-generated commands
8. New materials or methods in fab?
9. Fraction of this design/devel/job used in prior S/C

EXHIBIT 9 (Continued)

HARDWARE, FIRMWARE, SOFTWARE AND SYSTEM MANAGEMENT ELEMENTS

S VI. PROPULSION (Attached to S/C, not staging) (does not include solar sails)

A. Non-Restartable

1. Thrust (lbs or newtons)
2. Fuel/oxidizer--or monopropellant?
3. Purpose--injection, etc.
4. Fraction of this design used in prior S/C project
5. Prior fabrication experience this type, this class thrusters
6. Proof test models fabricated and tested
7. Power to start--kW-sec
8. Total ΔV propulsor(s)

B. Restartable

1. Type--ion, chemical, other
2. Elect power required - (kW)
   - Max
   - Min
   - Continuous
3. Weight of working fluid if ion drive
4. Thrust (chemical) (lbs or newtons)
5. Number of thruster elements if ion drive
6. Fraction of design new this time?
7. Any new materials or fuels this design (for S/C projects)?
8. Variable thrust?
   (a) Ion drive matrix
   (b) Throttleable chem
9. Duration of chemical burn--total
   Number of restarts (if any limit)
10. New design methods used on this item
11. Total ΔV propulsors

EXHIBIT 9 (Continued)

HARDWARE, FIRMWARE, SOFTWARE AND SYSTEM MANAGEMENT ELEMENTS

S VII. POWER

A. Generated

1. Method =(solar cells, RTG, other)
2. If solar cells:
   (a) Array size (m^2) and kW/Kg of array at 1AU
   (b) Total power (1AU) of array (kW elect)
   (c) Are concentrators used?
   (d) Total area of array (Weight of array if concentrators used)
   (NB: Tilting, furling, etc., under movable structure)
   (e) Any new materials this S/C power array?
3. If RTG's:
   (a) Power per unit RTG (Th- kW)
   (b) Number of RTG's/SC
   (c) Total electrical power at start of mission, end of primary mission, max useable life of RTG this mission (yrs, pwr load)
   (d) New materials this design
4. Number of different services:
   (a) Supply frequencies (DC, 400 AC, etc.) (1ϕ, 3ϕ, etc.)
   (b) Voltages (24, 440, etc.)
   (c) Inverters
5. Weight of conditioning and cabling (Kg) for S/C
6. (All of above for each element of a separable S/C)
7. Prior design/job history of similar equip on S/C

B. Stored

1. Weight of cells (mass Kg all up, except structure)
2. Type of cells (NiCd, etc.)
3. Capacity of battery (each, if more than one)
4. Prior S/C use of this kind of battery and cell
5. Number of independent batteries

EXHIBIT 9 (Continued)

HARDWARE, FIRMWARE, SOFTWARE AND SYSTEM MANAGEMENT ELEMENTS		
S VIII. ATTITUDE REGULATION		
A. Real Time (Earth)	B. Real Time (Sensor)	C. Pre-Programmed
1. On-board sensors (a) Star/sun trackers (b) Horizon sensor (c) Stable platform (d) Required accuracy of the above 2. Effectors (a) Momentum wheels (b) Cold gas jets--stored gas (c) Photons momentum exchange (d) ion drive elements (e) S/C spin on one or two axes 3. Weight of systems not otherwise accounted for (mass-Kg) 4. Data words and rate to effect control 5. Number of axes controlled 6. Prior design/development/fabrication experience with devices 7. Power required (kW) (a) Duty cycle (b) Max	1.-7. Same as A 8. On-board computer capacity and access required; interrupt priority 9. New design/dev/fab this system this S/C	1.-8. Same as B

EXHIBIT 9 (Continued)

HARDWARE, FIRMWARE, SOFTWARE AND SYSTEM MANAGEMENT ELEMENTS		
S IX. GUIDANCE (On-board & terrestrial (other external) facilities) (Does not include S/C computer)		
A. Real Time (Earth)	B. Real Time (Sensor)	C. Pre-Programmed
1. Up-link data words (a) Max rate 2. Down link status reporting words required before a maneuver 3. On-board decoding and control of effectors (computer function) 4. Terrestrial DSN time per maneuver--planned worst case, planned expected case 5. Terrestrial (SFOF) computer time per maneuver--data reduction plus maneuver calculation and check 6. Total number of maneuvers contemplated (interacts with propulsion here) and ΔV expected and maximum for guidance 7. Any otherwise unaccounted for weight (mass-Kg)	1. Sensor mode for guidance (may be same as for VIII) and accuracy of sensing 2. Programming of on-board computer--and words required 3. Down-link words required to report proposed maneuver and intended commands to effectors 4. On-board computer capacity for calculations and control (cf = X, XI, XII, XIII) 5. Any otherwise unaccounted for weight (mass-kgm)	See A & B, computer system capacity dedicated to this function

EXHIBIT 9 (Continued)

HARDWARE, FIRMWARE, SOFTWARE AND SYSTEM MANAGEMENT ELEMENTS	
S X. COMMAND AND CONTROL	
A. Real Time	
1. Up-link capacity for C&C (cf: XI) 2. Computer capacity for C&C (cf: XIII) 3. System response time to effect commands--seconds/hrs/days	

EXHIBIT 9 (Continued)

HARDWARE, FIRMWARE, SOFTWARE AND SYSTEM MANAGEMENT ELEMENTS

S XI. COMMUNICATIONS (Radio, laser, etc.)

A. Transmitters	B. Antennae	C. Receivers
1. Number of different transmitters	1. Number of antennae	1. Number of receivers
2. Power (max) of each Xmitter (total elect requirement)	2. Size of each (m^2 if parabolic) (m-length for omni's)	2. Power required for operations (max, standby)
3. Frequency (carrier or center) of each Xmitter	3. Weight of each antenna (mass kgms)	3. Weight of receiver system including feeds
4. Weight of all Xmitters & associated cables, feeds, etc. (Kg mass)	4. Are any new construction techniques or new design requirements contemplated? What are they?	4. Any new design requirements since last S/C?
5. Modulation of each Xmitter (AM, FM, PM, etc.)	5. Antenna surface accuracy	5. Any new technology since last S/C?
6. Prior S/C usage of each Des/Dev/Fabrication for this S/C	6. Antenna pointing accuracy required	6. Frequencies and modes of each receiver
7. Band width each Xmitter		7. Any switches activated by S/C? Where and what is switched?
		8. Redundancy mode
		9. Sensitivity in receiver

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EXHIBIT 9 (Continued)

HARDWARE, FIRMWARE, SOFTWARE AND SYSTEM MANAGEMENT ELEMENTS

S XII. DATA HANDLING

A. On Board	B. Ground Based
1. Storage volume (max) (in bits or words)	1. Number of experiments on S/C
2. Memory form--tape, array, etc.	2. Down-link data rate--raw and decoded
3. Format data before or after store?	3. Hours of data expected (reels of tape, etc.)
4. Code before or after store (input or at Xmitter time)	4. Decode and distribution time (hours/Mbit)
5. Weight of non-computer memory (Kg mass)	5. On-site initial data processing--kind, amount
6. Power requirements (kW) Max Min Standby	6. Temporary storage capacity preprocessing and post local processing
7. Central or local controller on mass memory	7. Security provisions for data and facility
8. Read in/read out rates	
9. Memory volitility protection device	

EXHIBIT 9 (Continued)

HARDWARE, FIRMWARE, SOFTWARE AND SYSTEM MANAGEMENT ELEMENTS

S XIII. COMPUTING (S/C)

A. Control

1. Weight--(mass Kg)
2. Prior requirements (kW)
   (a) Max
   (b) Standby
3. CPU description (functions, cycle time, etc.)
4. Main memory volume
5. Auxiliary memory volume
6. Word size
7. A-D, D-A converter
   Power required
8. Programming language--is there an assembler, compiler?
9. Is the language new, fraction used before?
10. Is this a new computer--how much is common to prior S/C?

B. Distributed

1. Number of processors
2. Auxiliary bulk memory size
3. Total weight of computing system not otherwise accounted for
4. Power required (kW)
5. Is there a compiler and/or an assembler for the processors?
6. How much of system is new this time? How much is common to prior S/C?
7. Number of A-D, D-A converters in system (if any)
8. Is there a system controller processor, or is the supervisor distributed?
9. Word size

EXHIBIT 9 (Continued)

HARDWARE, FIRMWARE, SOFTWARE AND SYSTEM MANAGEMENT ELEMENTS	
S XIV. STATUS MONITORING	
A. Active	B. Passive
1. Weight of monitors, cables, and converters 2. Power required to monitor (kW) 3. Data word format for status messages 4. Frequency of monitor output(s) 5. Is there command sensing? 6. Does monitor function affect on-board controllers? 7. Prior use of this design on S/C, how much is new? 8. Is there command interrogation of status from Mission Controller(s)?	As in A. (1-8)

The descriptors are shown at the major function level wherever possible. In those instances where available and usable Cost-Estimating Relationships (CERs) imposed restrictions at the subsystem level, the descriptors are not shown for the missing major functions.

D. Framework and Structure Maturity

During the course of the analysis, the new framework and structure concept matured and grew. Utilizing the functional element characteristics presented and the structure developed in Section III B and C, and the available CERs, the initial integrated framework and structure is as shown in Exhibit 10.

Refinement of the framework and structure continued during the subsequent project period. Through a process of synthesis and analyses of technical interplay with JPL, adjustments were made in the structure. During the performance of the project, the structure was also changed to incorporate the System Management elements which were reomved from the definition of the framework. This change is shown in Exhibit 11.

As additional development effort was expended, the final refinement was made when the framework and structure were changed further by introducing a third dimension. In creating the three dimensional aspect, management elements (both system and program) were removed from the existing two dimensional presentation, and established as a second structure dimension of system level elements. The three dimensional framework and structure is illustrated in Exhibit 12. Although the three dimensional approach makes the framework and structure appear to be more complex, this approach does facilate adequate treatment of the variations in management approach.

In the three dimensional aspect, the framework, as one dimension (Exhibit 12), defines those phases and activities of a project which constitute essentially separate entities from two standpoints: first, the standpoint of cost accumulation and second from the standpoint of impact due to differing project philosophies.

The remaining two dimensions consist of two structures, I and II. Structure I defines the hardware elements of the system and the software

EXHIBIT 10 - INITIAL INTEGRATED FRAMEWORK AND STRUCTURE

FRAMEWORK

PROGRAM MANAGEMENT	DESIGN & DEVELOP	PROCESS & MANUFACTURING	INTEGRATED LOGISTIC SUPPORT	TEST & EVALUATION	OPERATIONS & MAINTENANCE

STRUCTURE

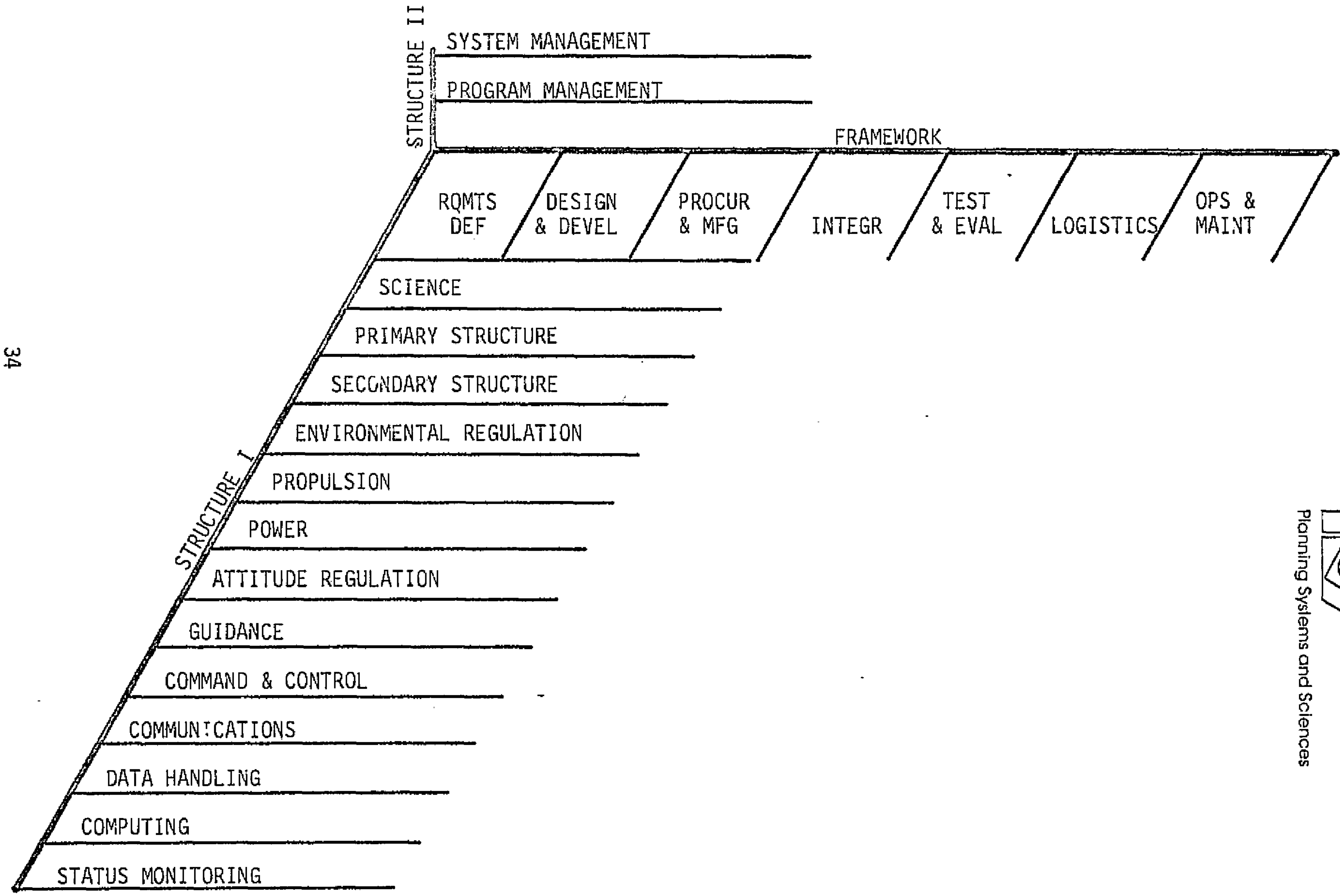
- SCIENCE
- PRIMARY STRUCTURE
- SPECIAL PURPOSE STRUCTURE
- PROPULSION
- POWER
- GUIDANCE
- ATTITUDE REGULATION
- COMMUNICATIONS
- DATA HANDLING
- COMMAND & CONTROL
- ENVIRONMENTAL REGULATION
- STATUS MONITORING

EXHIBIT 11 - MODIFIED INITIAL INTEGRATED FRAMEWORK AND STRUCTURE

FRAMEWORK

STRUCTURE	REQUIREMENTS DEFINITION	DESIGN & DEVELOPMENT	PROCUREMENT & MANUFACTURING	INTEGRATION	TEST & EVALUATION	LOGISTICS	OPERATIONS & MAINTENANCE
SYSTEMS MANAGEMENT							
SCIENCE							
PRIMARY STRUCTURE							
ENVIRONMENTAL REGULATION							
SECONDARY STRUCTURE							
PROPULSION							
POWER							
ATTITUDE REGULATION							
GUIDANCE							
COMMAND & CONTROL							
COMMUNICATIONS							
DATA HANDLING							
COMPUTING							
STATUS MONITORING							

EXHIBIT 12 - FINAL FRAMEWORK AND STRUCTURE: THREE DIMENSIONAL



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elements related directly to the hardware elements. These elements are in turn defined by a three-level hierarchy similar to Exhibit 9, that starts at the subsystem level, proceeds to the major function level and then to the functional element level. These three levels of definition proceed from functionally separate elements that are consistent with our understanding of "subsystems" downward to functional elements. These functional elements are closely related to the performance parameters that determine the capabilities of the space system. This capability to relate to performance parameters is absolutely necessary in a new cost model.

Structure II defines the system management elements that cut across all hardware elements and all activities of the project.

E. Conclusions and Recommendation

1. Conclusions

- The framework and structure developed constitutes an ideal starting point for the development of a new space project cost model.
- Adequate analysis has been performed to demonstrate that the desired framework and structure could be developed. Initial analysis also shows that adequate CERs and "raw" cost data exist to proceed with model development with reduced risk.

2. Recommendation

- The framework and structure developed during this project should be used as the point of departure for a totally new unmanned space project cost model. A cost model built on this foundation would overcome many of the difficulties encountered in the existing models.

IV. TECHNICAL DISCUSSION--COMMONALITY EVALUATION MODEL

A. Overview

Utilizing concise mathematical methdology, the Commonality Evaluation Model (CEM) generates relative cost comparisons between program and/or project commonality alternatives incorporating different levels and/or different applications of commonaltiy. The intermediate model results provide relative, pre-launched phase costs of the alternatives, and the final model results are comparative savings attributable to commonality.

The model is optimized specifically for the purpose of making comparative evaluations of potential cost savings in the construction of spacecraft for unmanned interplanetary scientific missions. As implemented, these cost savings accrue through the use of components or entire subsystems commont to more than one program or to more spacecraft than would normally be assembled for a single interplanetary project. Consequently, the Model explicitly incorporates the effects of learning on two different but related aspects; first, on the production processes of the subsystems and second on the system or project-level costs of such spacecraft programs. With these two features, the CEM departs from the existing cost estimating models for unmanned spacecraft.

A smaller difference from mast models of this type is in the treatment of technological inheritance. In the Commonality Evaluation Model, an estimate of the fraction of each subsystem which is new, either in materials or technology-design is made. Empirically derived functions relate the potential savings in design and development and type approval testing for that part which is not new.

In addition to these hardware and performance related features, the unit of value is not the usual US dollar, but a specially defined unit of account, the Normalized Cost Unit (NCU). The model does not estimate the realized costs, in current value money, of the spacecraft construction portion of an interplanetary scientific mission. No provision is made for inflation correction. Therefore, the model results can best be throught of as providing relative cost at the time of construction, independent of the value of the dollar at that time.

The development of first the framework and structure and then the model logic and methodology was accomplished through a theoretical analysis and application of experimental data collected from past space projects. During the CEM development effort, numerous variables were investigated including most of the performance and design parameters of unmanned space systems. In addition, the relationship of project costs to variations in testing requirements, operational approaches, hardware maturity and weight and volume constraints were also investigated. An additional area of variables investigated was the contribution of the learning factor to reducing the cost of both manufacturing and engineering tasks.

1. Constraints

The Commonality Evaluation Model (CEM) had, of necessity, to be derived under certain constraints; primarily the resources available and the time schedule which had to be met. As a result of the resources constraint, only existing data could be employed in this effort; no new data could be collected or analyzed. After a thorough search of the literature and the accumulation of an extensive collection of possibly relevant reports, the amount of useful data and prior modeling experience which was relevant to this effort was determined. With some small later additions it was found that there was one report with apparently reliable cost information for a number of missions of the type of concern here and there were two, related, cost models which could be used to hlep in the analysis of the cost data.

In a conventional sense, spacecraft programs consist of five well-defined phases. The Commonality Evaluation Model was specifically developed to assess commonality during only the pre-launch phases of unmanned space programs. Emphasis upon commonality only during spacecraft production is due primarily to a very weak cost dependence between that phase and the other phases of pre-program, launch and cruise operations, encounter, and post encounter.

Emphasis has been placed upon a particular type of spacecraft which is applicable to the JPL mission; i.e., the three-axis stabilized spacecraft. Utilizing the necessary CERs for the specialized functions and interactions involved, the CEM will accommodate any type of spacecraft.

2. CEM Framework and Structure

Due to the constraint of working with existing CER's as well as changes in the accounting baseline, it was necessary to retreat from the newly developed framework and structure and utilize the more conventional framework and structure of the current JPL Cost Model. However, because we are only working with the spacecraft development/production phase, some modification to that structure was permitted.

For purposes of the CEM, a standardized subsystem set was defined. This list is shown in Table 1. It must be recognized that it is at the subsystem level that a very significant portion of the costs of a spacecraft program are incurred. Therefore, it is at this level that the potential for savings by the use of subsystems common to more than one program or containing a large fraction of common subassemblies exists. Moreover, it is at the subsystem level that the greatest effects of technological maturity are observed.

In all programs of the type considered here, the subsystems acquisition has been the single largest cost. Other non-subsystem costs incurred. Since these are attributable to system level activities, the model attributes them to Program Component Costs. These cost categories are shown and defined in Table 2.

3. Commonality Definition

A spacecraft is composed of a number of functional subsystems. These functional subsystems are then integrated into the finished flight article or spacecraft. Commonality is obtained when major components of the spacecraft subsystems are common to either a series of programs or when a program with a significant number of spacecraft will have one or more components common to each of the spacecraft.

Table 1

COMMONALITY EVALUATION MODEL SUBSYSTEMS

1. Structure I (fixed, immovable mechanical structure and supporting members of the spacecraft)

2. Structure II (mechanical devices, hinges, springs, dampers, rotating joints, pin-pullers, etc.)

3. Structure III (pressurized structure, typically cold gas vessels and rocket fuel and oxidizer tankage)

4. Propulsion (specify kind, may be ion-drive, chemical rockets, or solar sails)

5. Guidance (includes star trackers, sun sensors, and the Central Computer and Sequencer, if any, in the spacecraft)

6. Attitude Control (includes the roll, pitch, and yaw sensors, the means for rotating the spacecraft about its axes, and any expandable stores associated with such control)

7. Communications (includes the on-board radio system from the modulators to the antennae for X-mitters and the antennae to the demodulators for the receivers; it will include any special power conditioning which is used by the radios exclusively)

8. Data Handling (includes all data collection and on-board data storage devices and all encoding and pre-modulation modification of the on-board generated data stream)

9. Power (includes the power generation, solar cell or other, and all conditioning for the spacecraft power service, but not any dedicated power conditioning associated with a particular instrument or subsystem)

10. Science (includes all scientific instruments on board the spacecraft; does not include supporting structure or scan platforms unless a functional part of the instrument, not just supports or pointing aids)

Table 2

Commonality Evaluation Model Program-Level Components

1. Program Management (all the costs of administering the spacecraft program which are program specific)

2. Systems Analysis and Systems Engineering (the costs usually paid for the systems level technical effort in design and in such areas as the engineering part of systems integration)

3. Systems Test (the costs of all systems level testing of the assembled spacecraft, but not of any single subsystem or component)

4. Quality Assurance and Reliability (the costs of all the system level QA&R effort, but, again, not that of any component)

5. Assembly and Integration (the costs of assembling the subsystem and integrating them into a functioning spacecraft, exclusive of testing)

6. Operational Support Equipment (the necessary test and checkout equipment for the spacecraft at the system level; subsystem OSE is part of the cost of subsystem hardware)

In either case, it is expected that the amortization of the costs of design, development, testing, and manufacture can be an effective means of cost savings. Clearly, there will be savings at the level of the individual subsystem from quantity production, each spacecraft being then charged only the costs of the (amortized) hardware plus the flight acceptance testing. Even further savings can be anticipated at the systems level of the programs.

Savings are accrued due to more expeditious assembly and integration of each spacecraft primarily through familiarity with the subsystem components at assembly time. That is, if fewer problems arise during integration, less time need be allocated for that step. Other program components will also show cost savings through the reduction in systems testing required, the reduction in reliability problems, and in the shorter time it will take to conduct the spacecraft pre-launch part of the program. These improvements do not necessarily come about because the individuals working on the programs have gained hands-on experience with the common elements, although this may be the case. Of much greater importance is the fact that, since the elements are programmed to be produced and used more than one time at the outset, documentation is produced, corrected, and updated. Consequently, errors are found and corrected and interfaces are better defined, described, and delineated. These factors, error correction and documented experience, allow the repetitive experience to be transferred and applied each time the common components are used.

4. Inheritance and Novelty Fraction

While commonality considers the transference of entire subsystems from one spacecraft program or project to another, cost reductions can also be affected by using basically tried and proven methods; i.e., indirect rather than direct transference.

For example, a particular device or design is "technically mature" when it is very similar to a recent predecessor in both design and materials of construction. As a design group becomes more and more familiar with its task and as the ways of doing that task are explored, one method is finally decided upon and used several times in succession. With the requirement to design the next number in the sequence, the design group will proceed to implement the design with the familiar approach at a considerably savings in time. The design group will not be faced with problems which require alternatives to be tried, such as the materials of construction and methods of assembly. In addition to what to do, they will have learned what not to do. Thus, savings in the pre-production stage of prototype production and testing are achieved.

In the CEM, the degree of technological maturity is measured in terms of the "novelty fraction" (N_F) of the subsystem (Table 3). A value of unity (1.0) indicates an entirely new design and/or new materials for the intended application. This does not imply that the technology or design is being done for the first time ever. A "novelty fraction" of 0.0 indicates a tried design and previously used materials being utilized by a new spacecraft program or project.

The complement of the "novelty fraction" in a subsystem is the "heredity." Previous JPL cost models utilize the concept of design inheritance. Inheritance is usually the most obvious feature and recognizable at a glance. However, inheritance is not the feature which causes increased cost to the design and development. Neither novelty nor inheritance have a measurable impact on first unit production cost.

B. The Commonality Evaluation Model

This section presents the Commonality Evaluation Model (CEM). In simplist terms, the CEM consists of three items. The first and most important is the generalized mathematical model itself. The other two are supporting but integral data--the CERs (Exhibits 13 through 28) and the Tables of Factors (Tables 3 through 8) for various model parameters.

1. Mathematical Model

In this section, the Commonality Evaluation Model (CEM) is delineated in general terms. Details of the actual computational procedure are contained in the Handbook (Appendix B).

EXHIBIT 13. SUBSYSTEM CER: STRUCTURE-I (FIXED STRUCTURE)

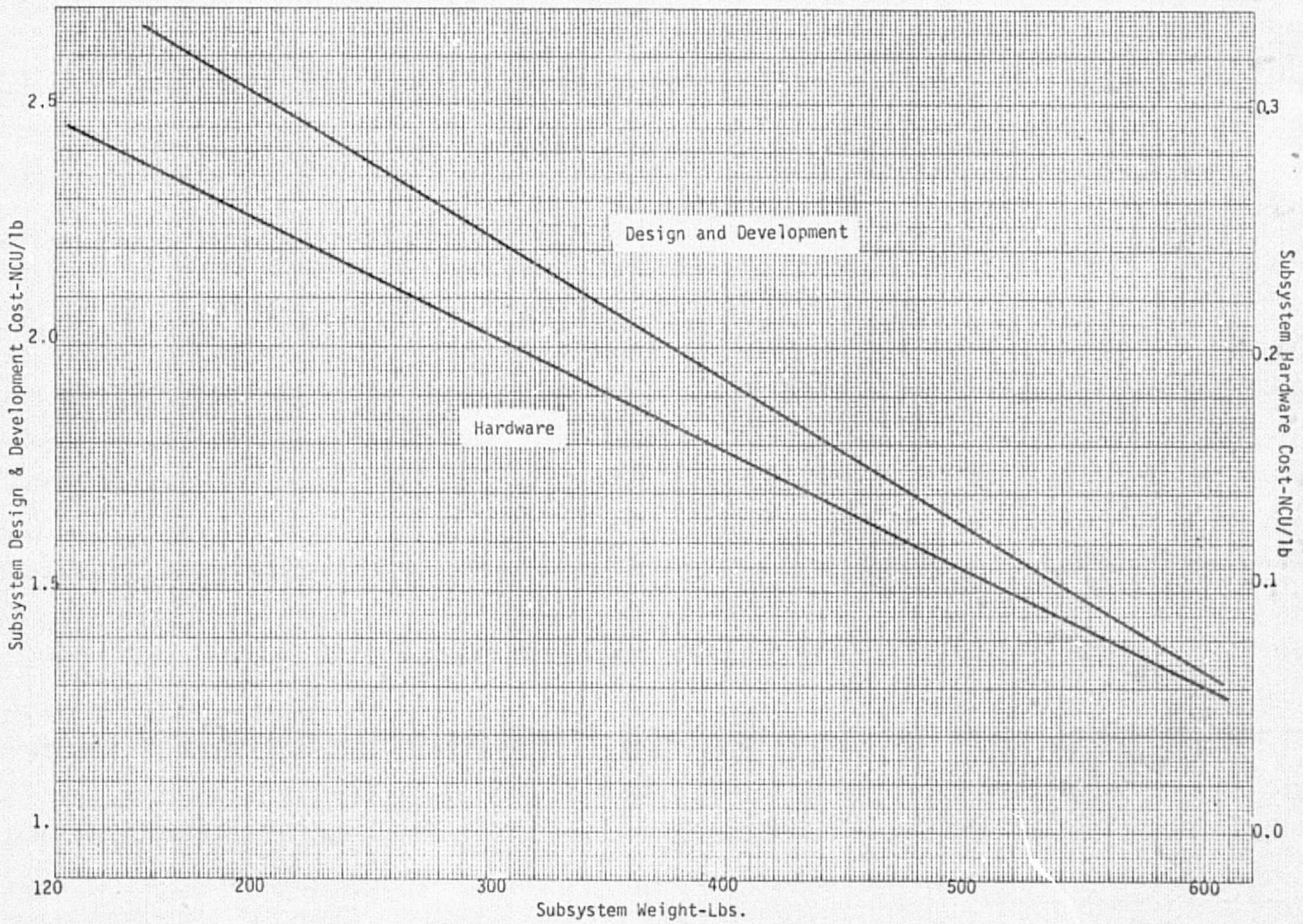

EXHIBIT 14. SUBSYSTEM CER: STRUCTURE-II (MECHANICAL DEVICES)

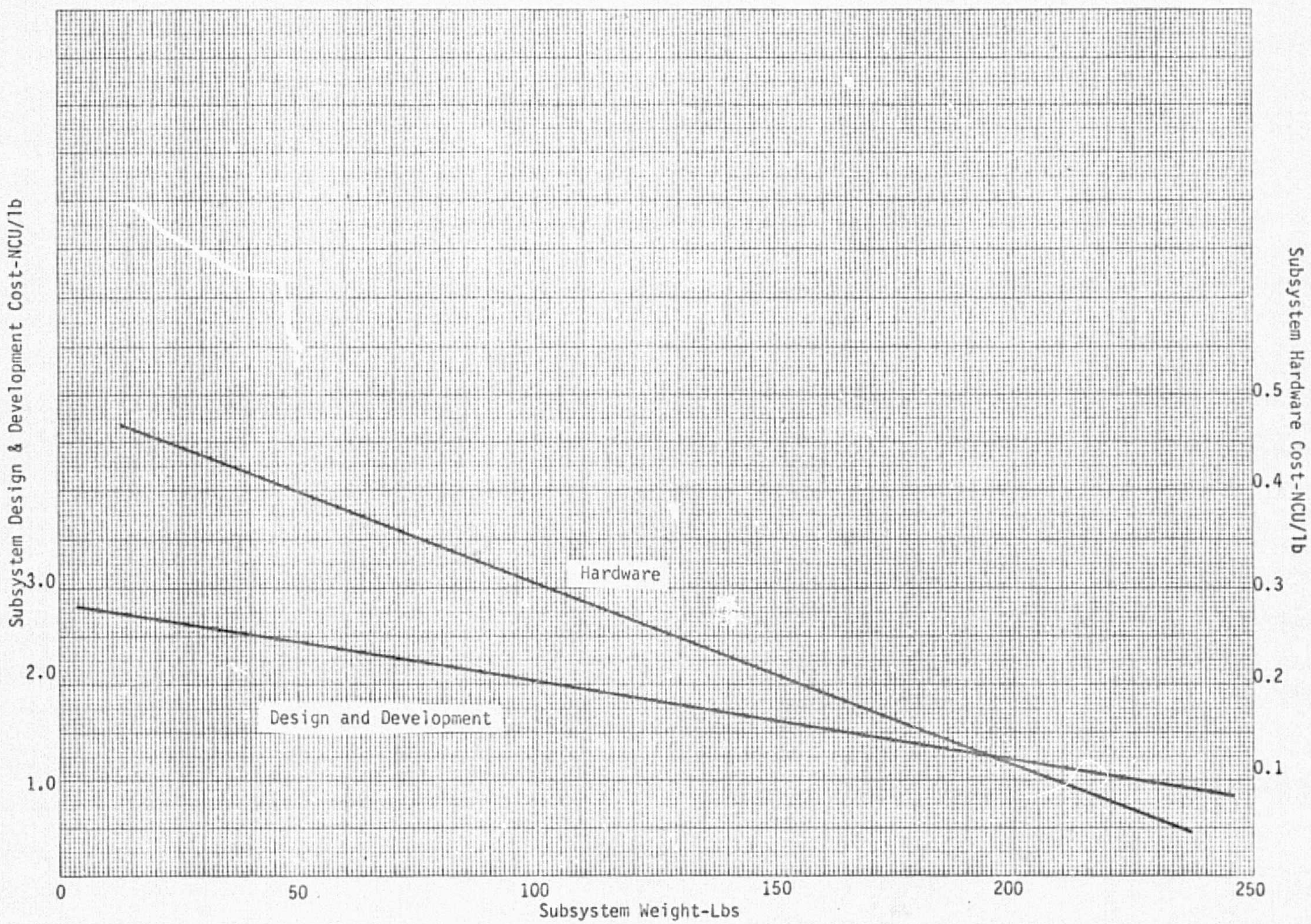

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EXHIBIT 15. SUBSYSTEM CER: STRUCTURE-III (PRESSURE STRUCTURE)

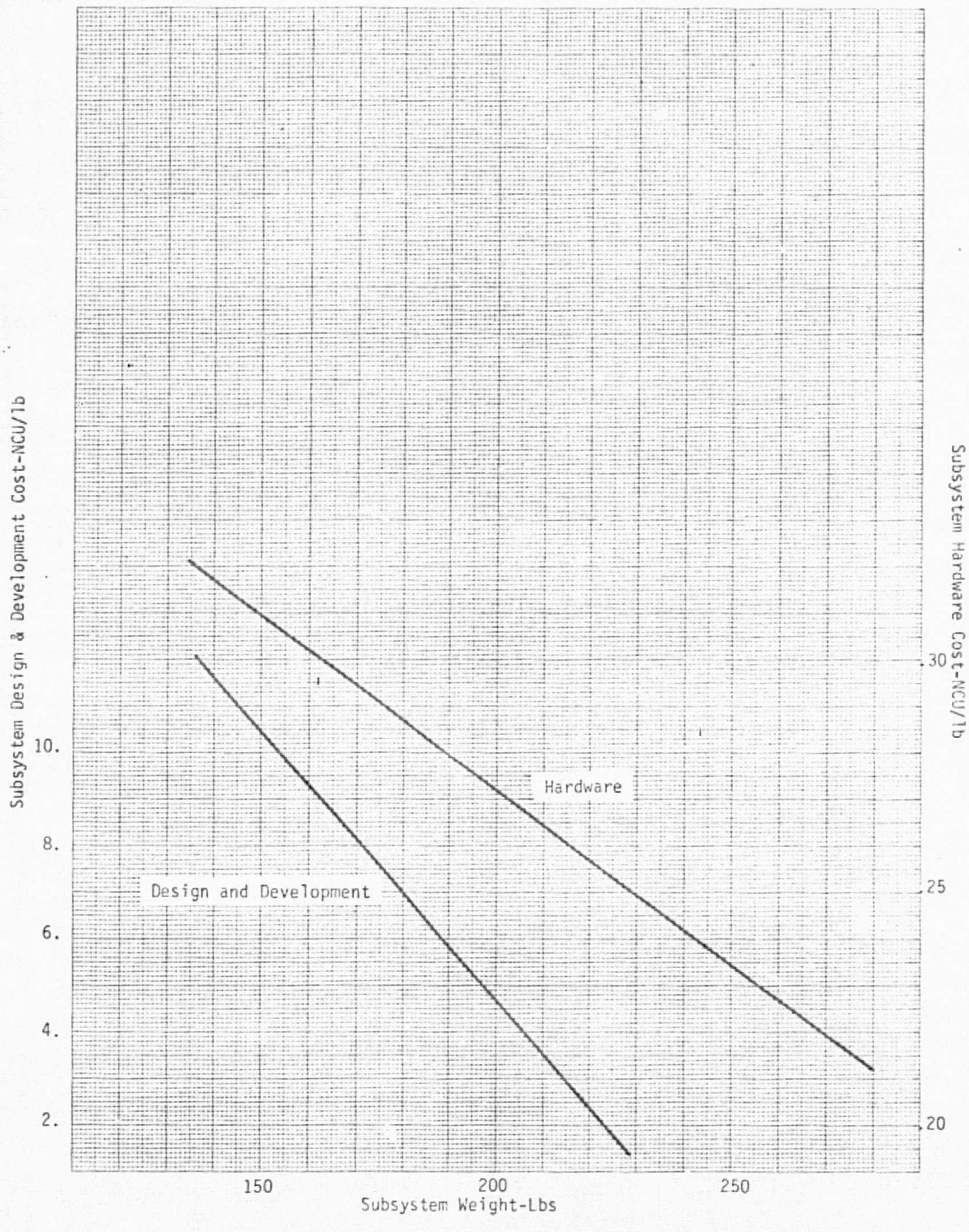

EXHIBIT 16. SUBSYSTEM CER: PROPULSION

Type	Thrust	D&D NCU/lb-Th	HW Cost NCU/lb-Th	Use - Comments
Hydrazine	50 lbs	1.711	.0309	Flyby-midcourse--single chamber only
Monomethyl/hypazine + Nitrogen Tetroxide	300 lbs	1.859	.0488	Orbital injection and midcourse corrections--single chamber only

EXHIBIT 17. SUBSYSTEM CER: GUIDANCE

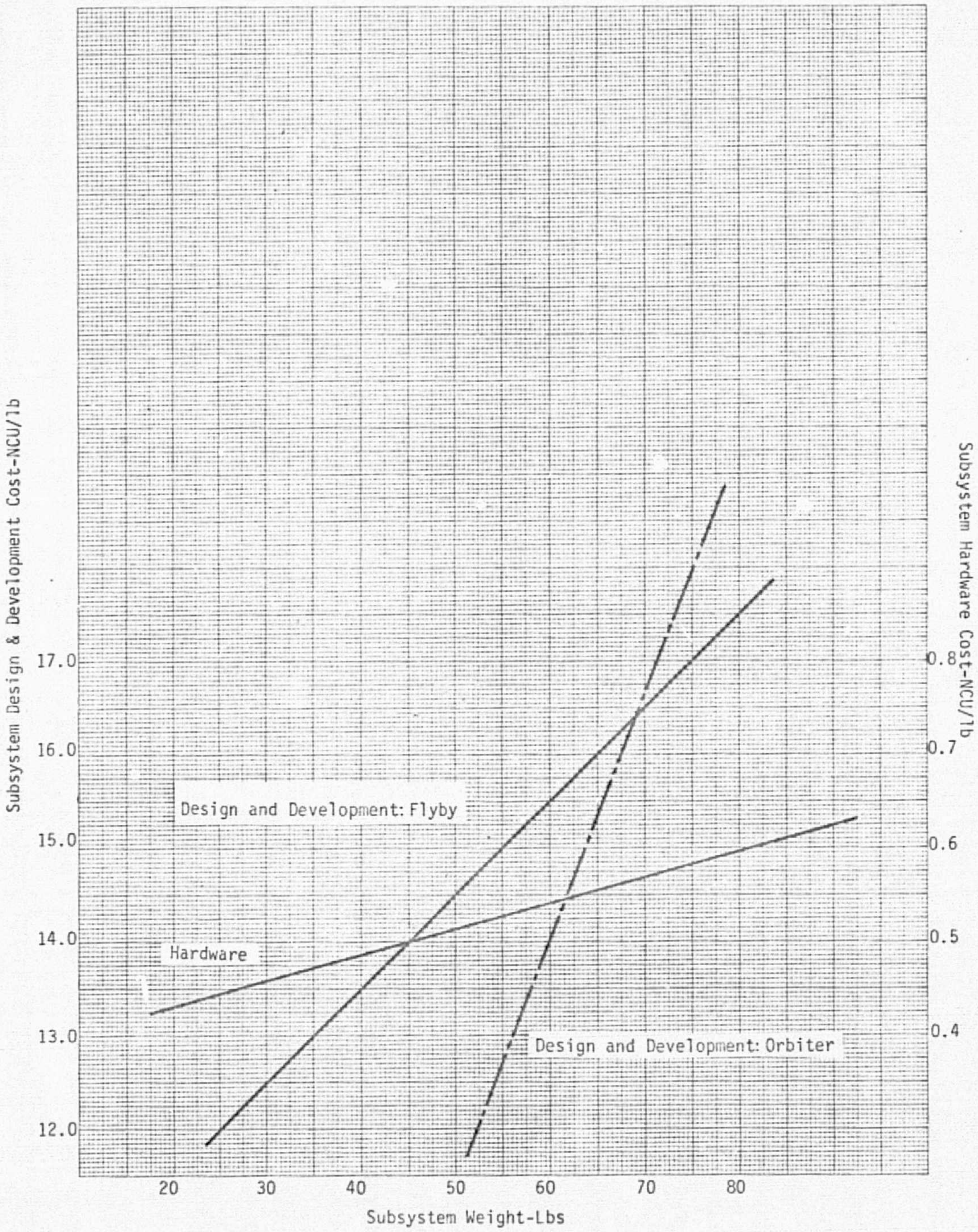

EXHIBIT 18. SUBSYSTEM CER: ATTITUDE CONTROL

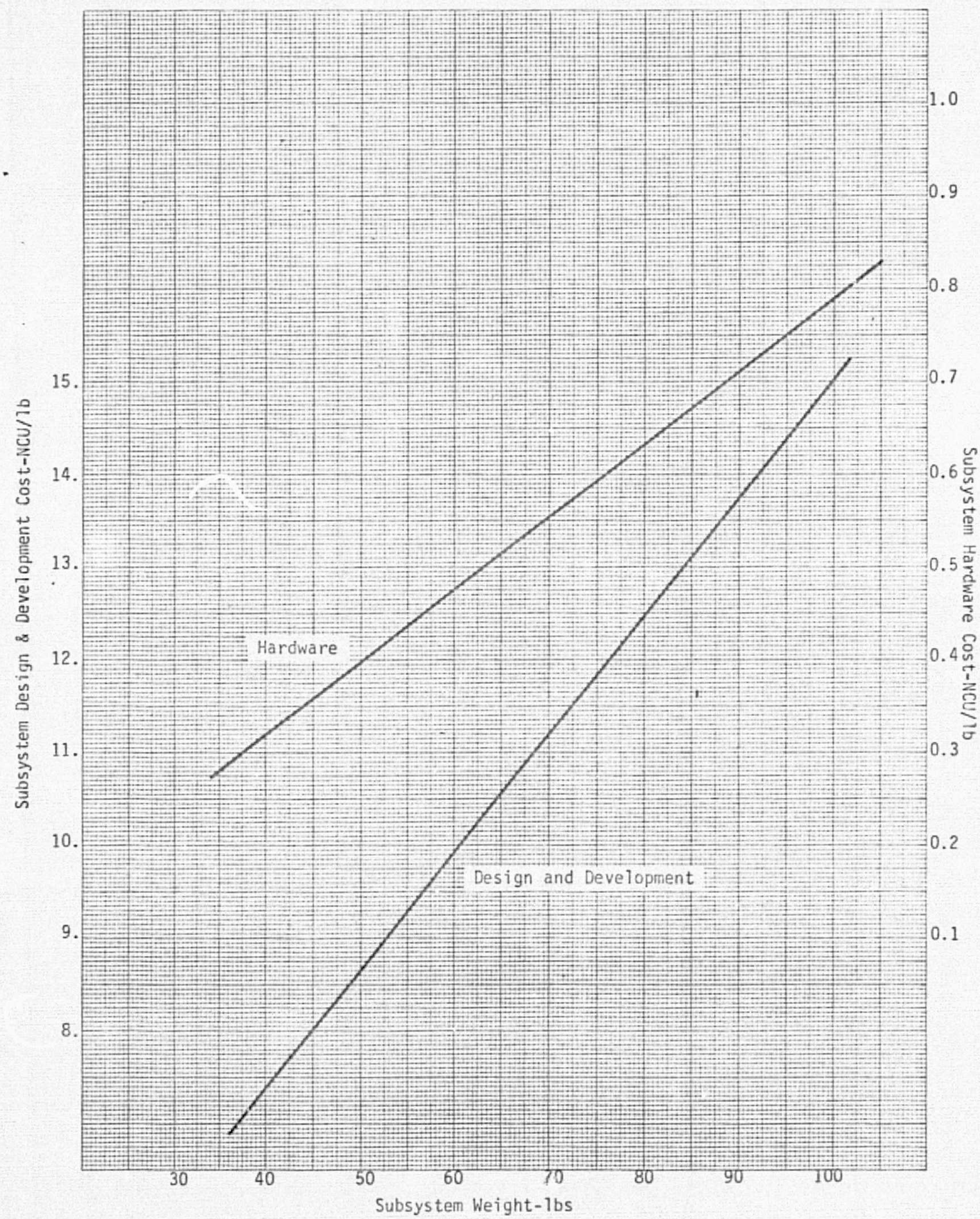

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EXHIBIT 19. SUBSYSTEM CER: COMMUNICATIONS

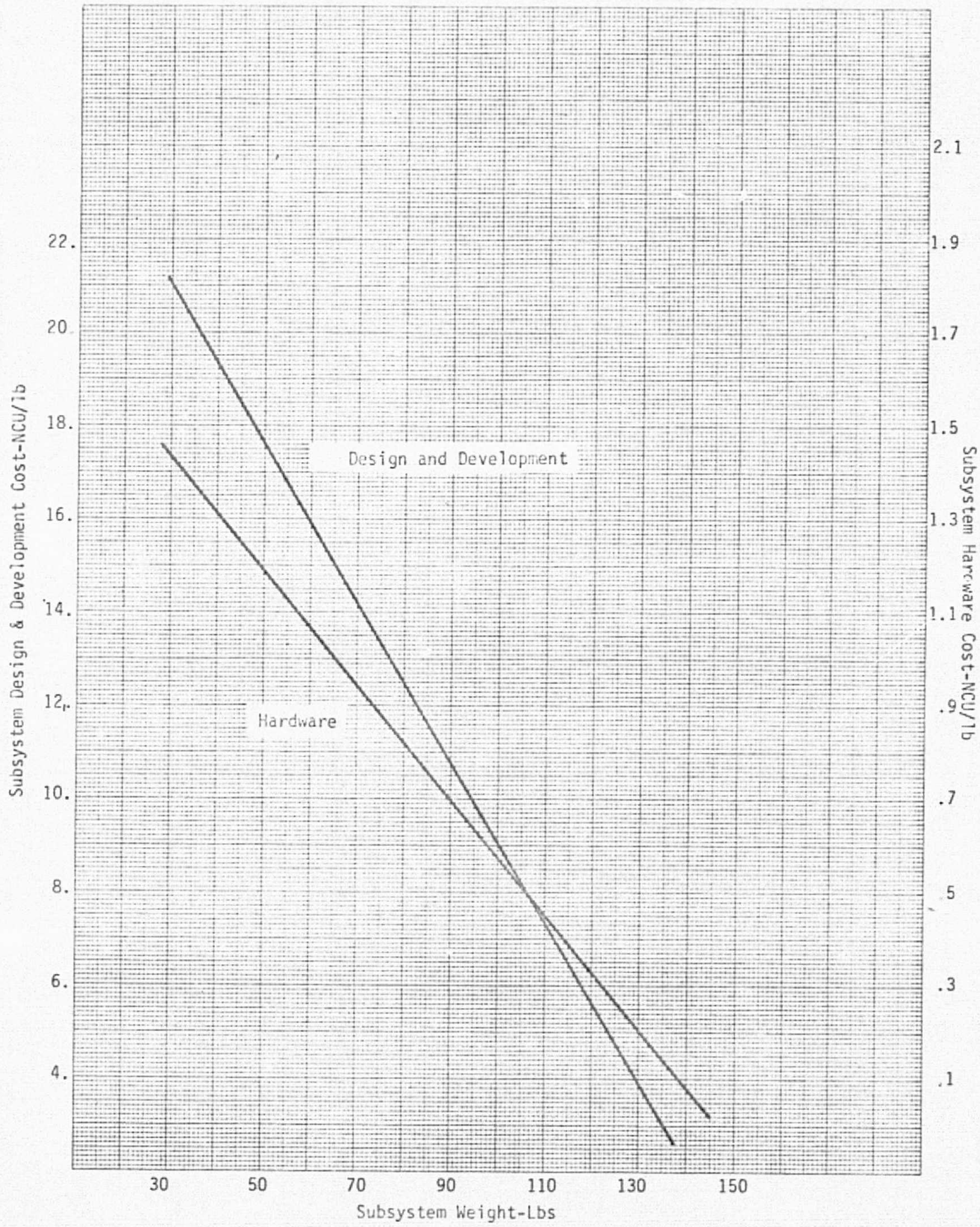

EXHIBIT 20. SUBSYSTEM CER: DATA HANDLING

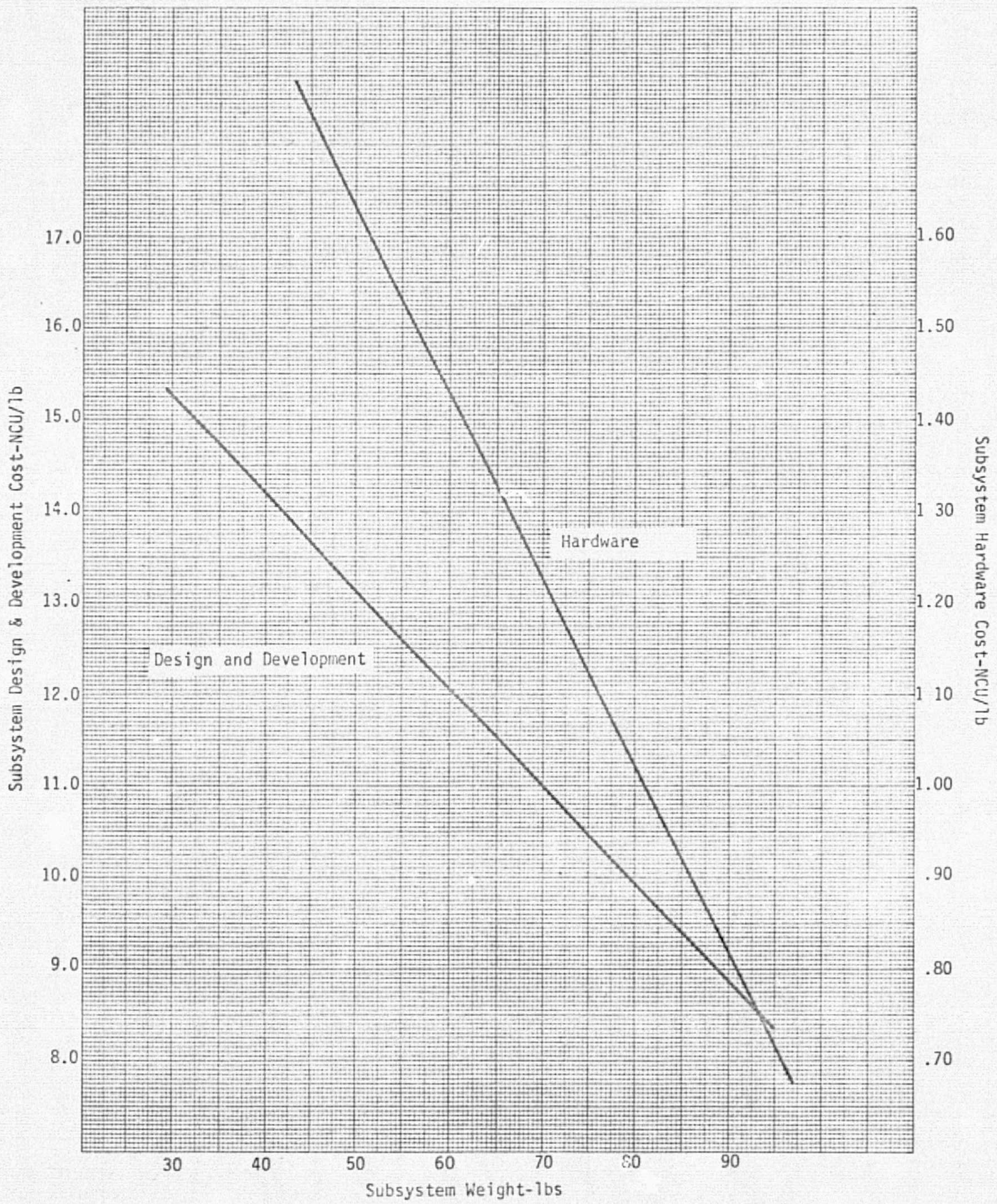

EXHIBIT 21. SUBSYSTEM CER: ELECTRIC POWER (SOLAR ARRAY SOURCE)

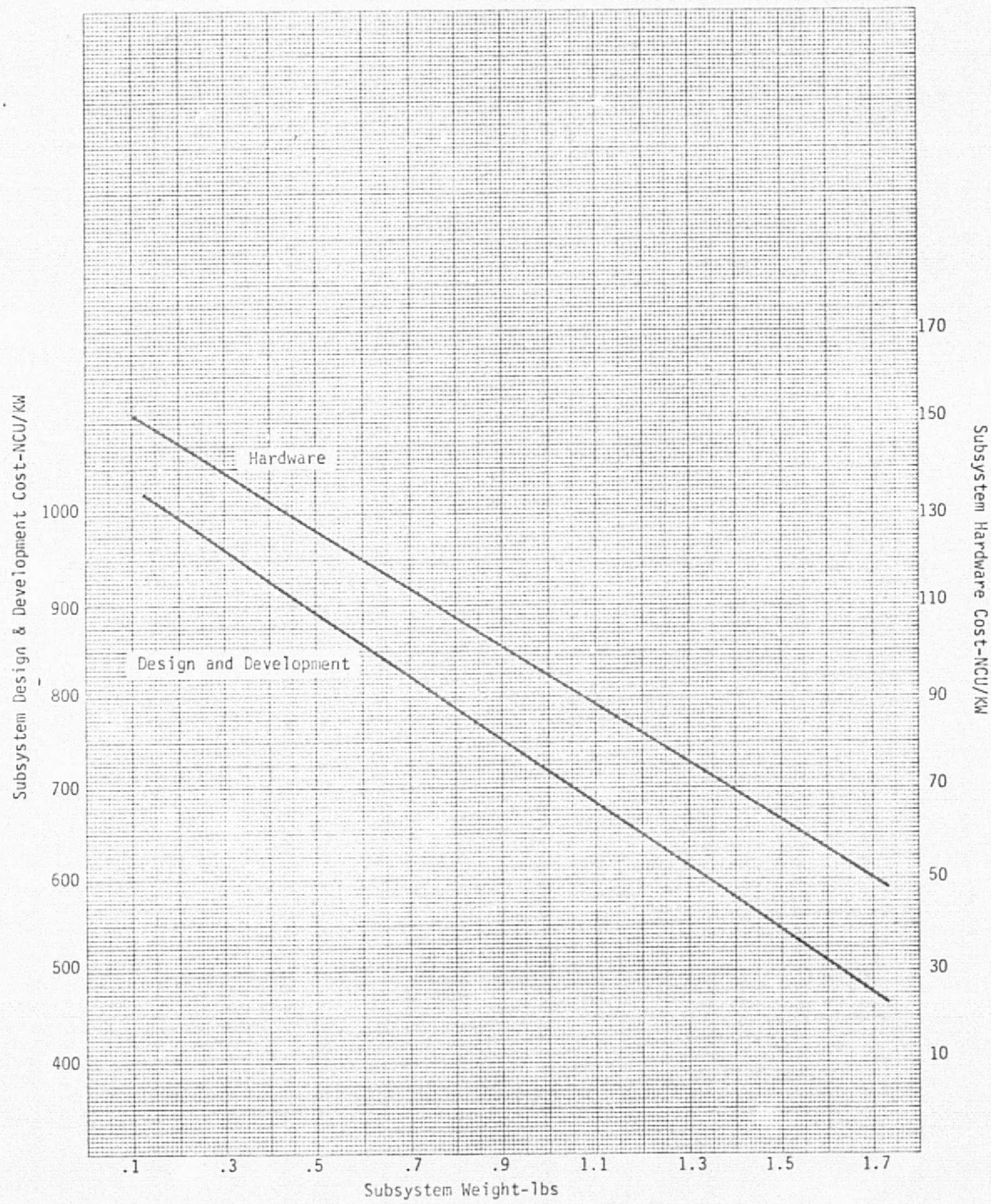

EXHIBIT 22. SUBSYSTEM CER: SCIENCE (SCAN PLATFORM & STRUCTURE MOUNTED)

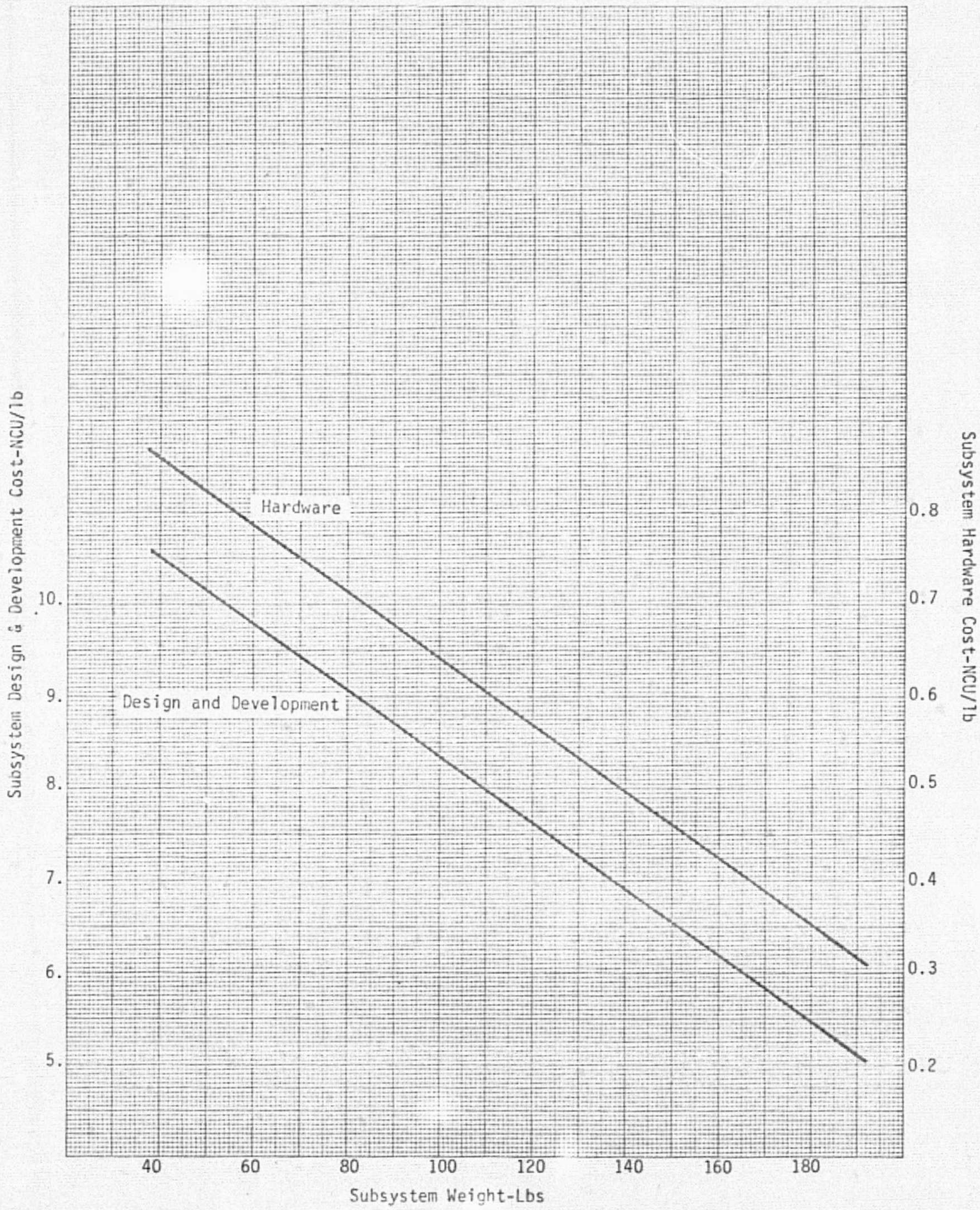

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EXHIBIT 23. PROGRAM COMPONENTS: PROGRAM MANAGEMENT

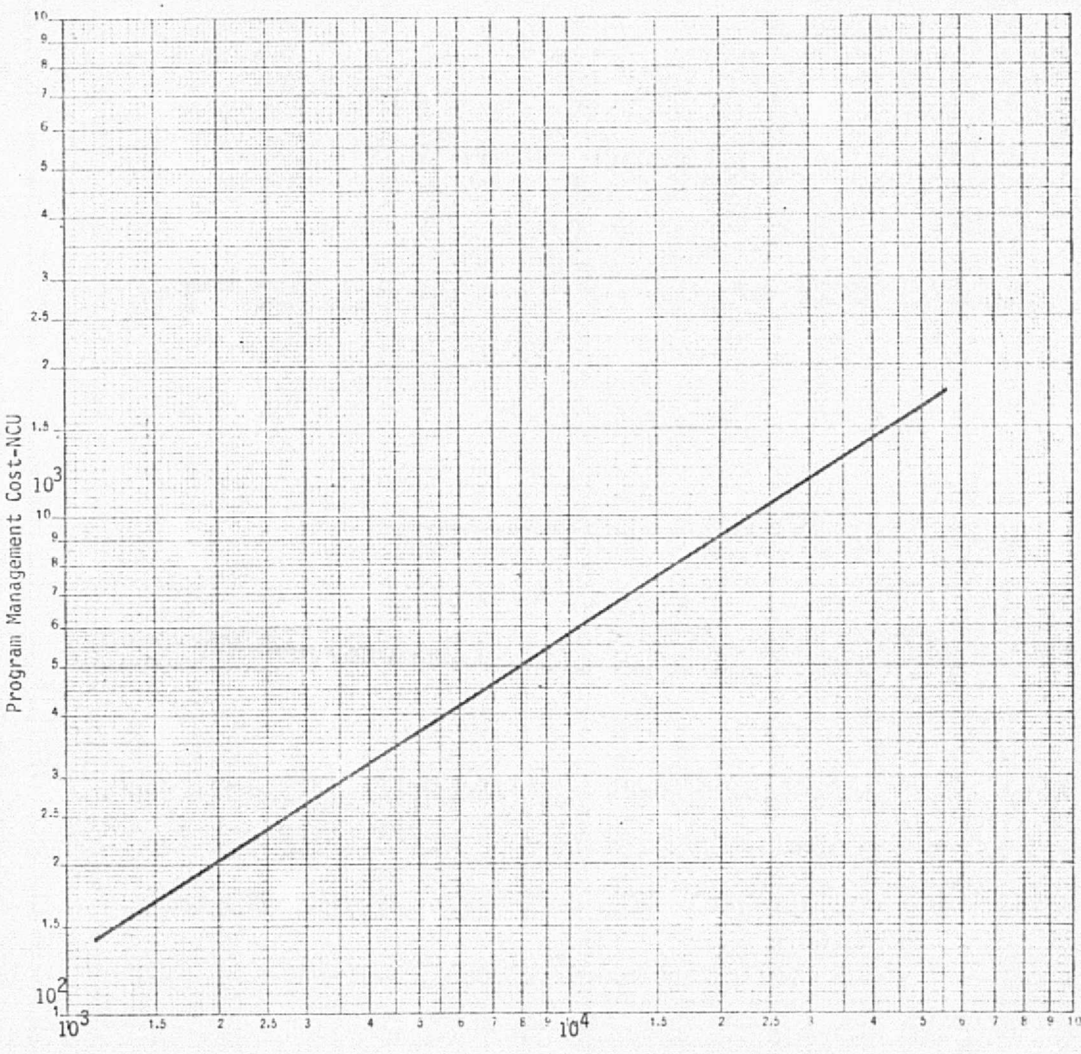


EXHIBIT 24. PROGRAM COMPONENTS: SYSTEM ANALYSIS & SYSTEM ENGINEERING

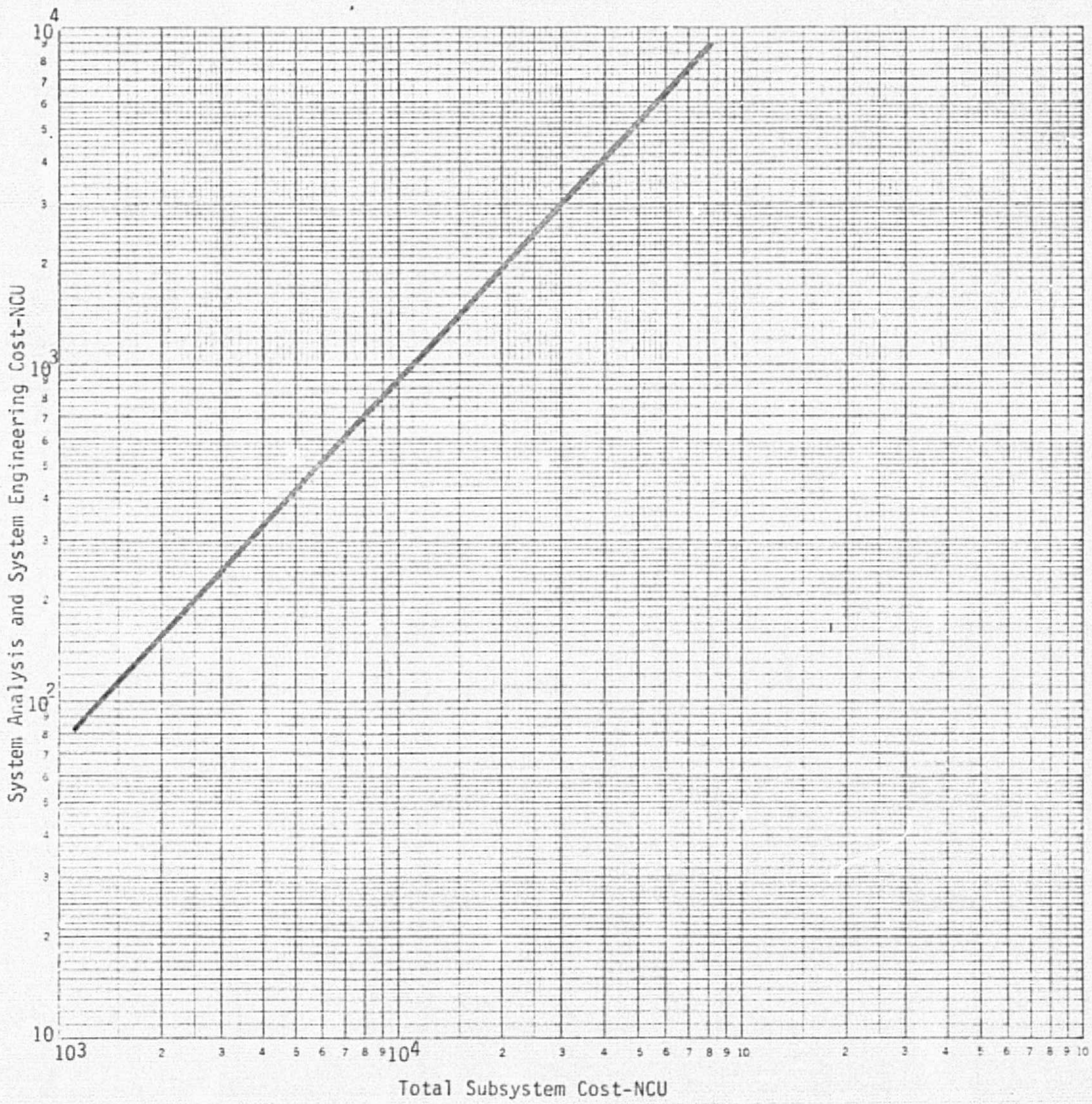


EXHIBIT 25. PROGRAM COMPONENTS: SYSTEM TEST

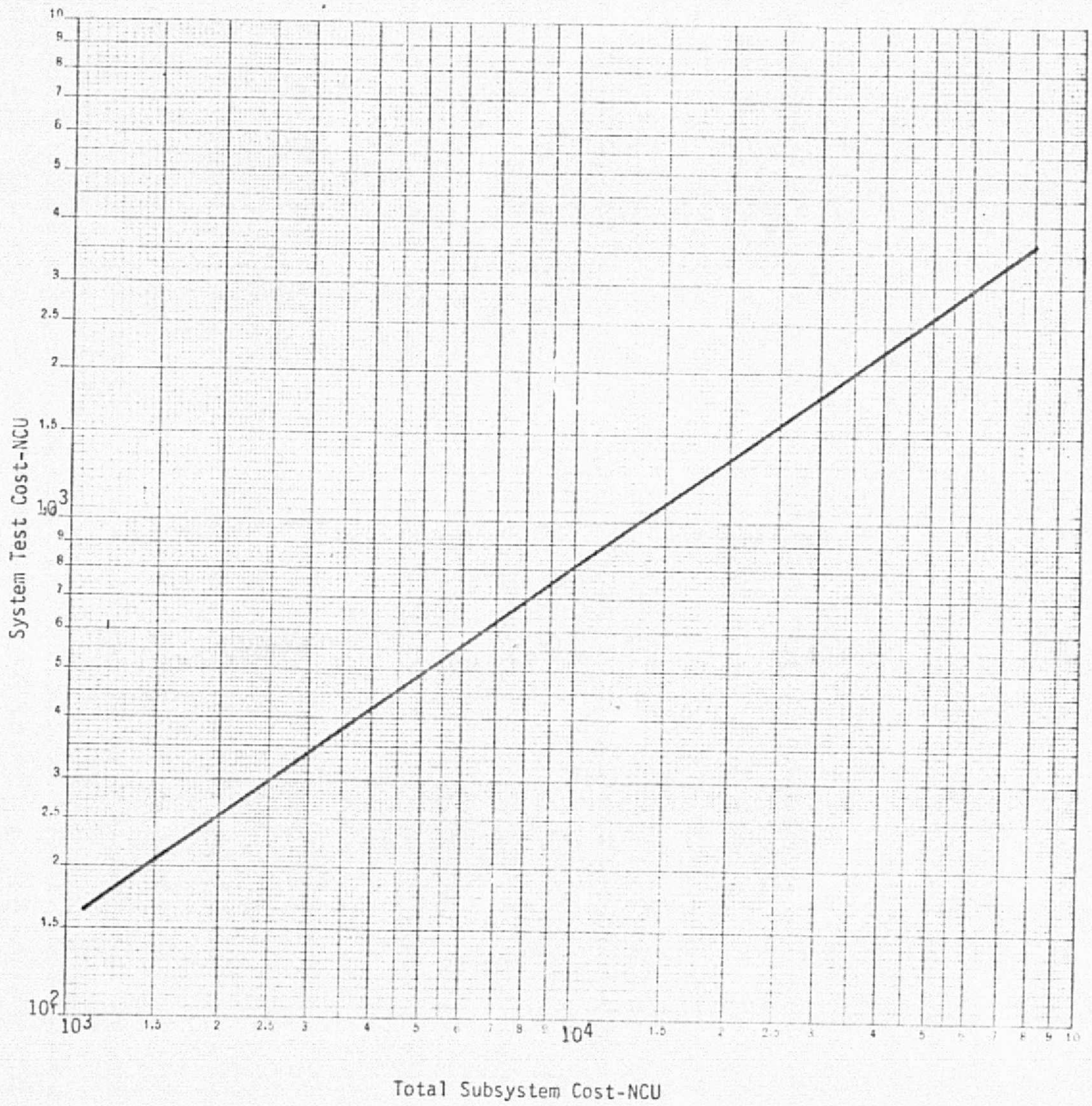


EXHIBIT 26. PROGRAM COMPONENTS: QUALITY ASSURANCE & RELIABILITY (QA&R)

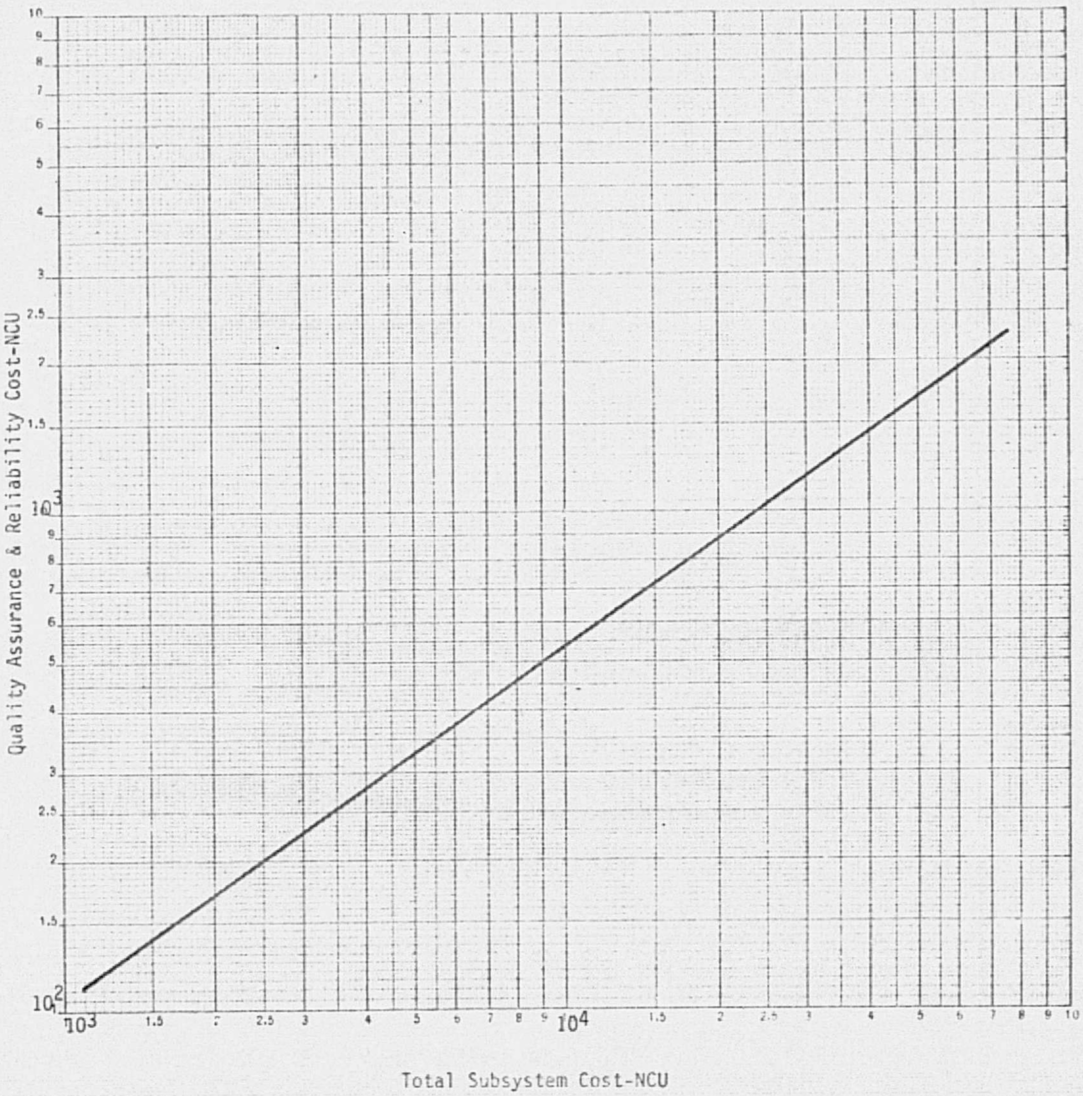


EXHIBIT 27. PROGRAM COMPONENTS: ASSEMBLY AND INTEGRATION

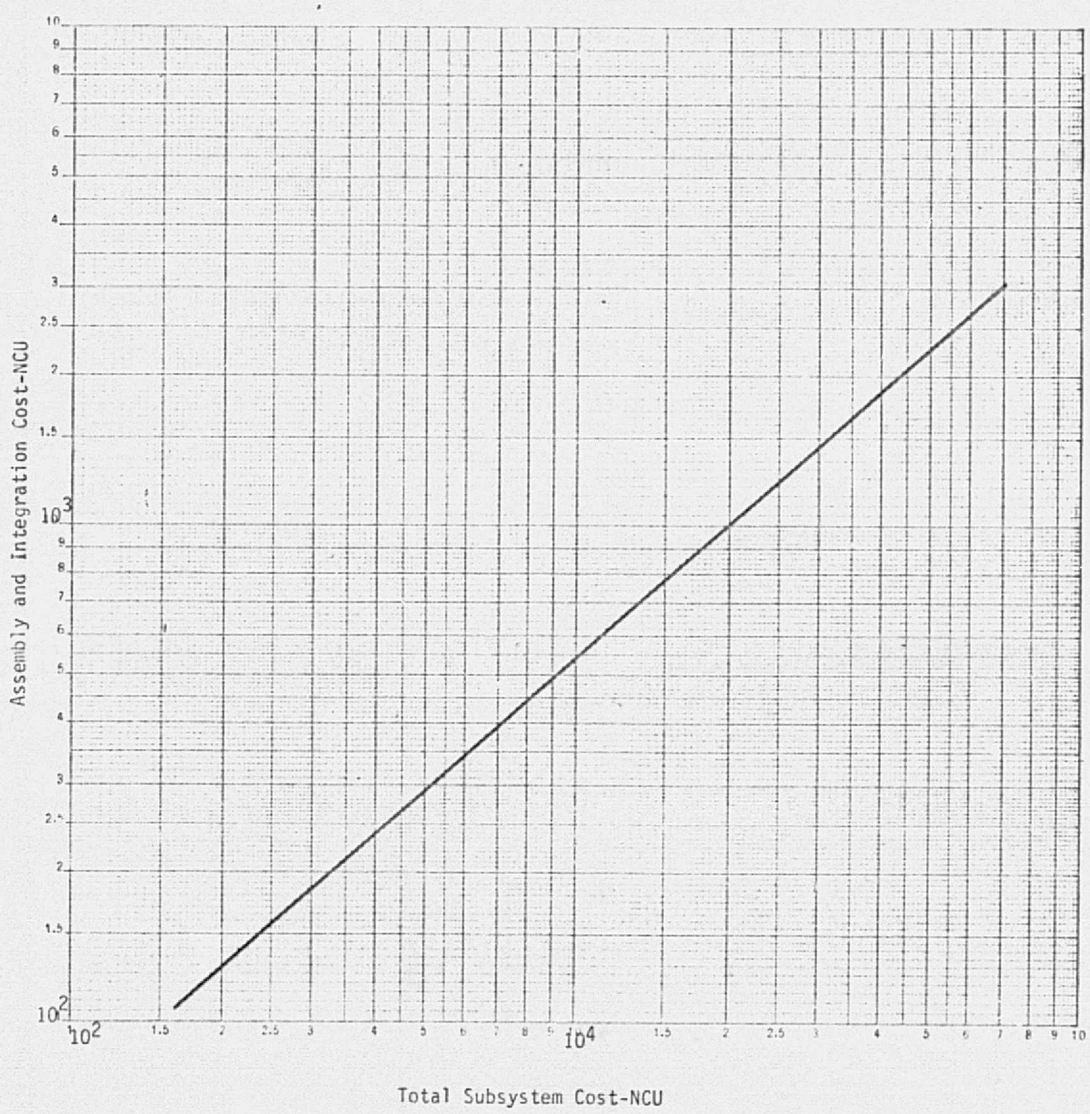
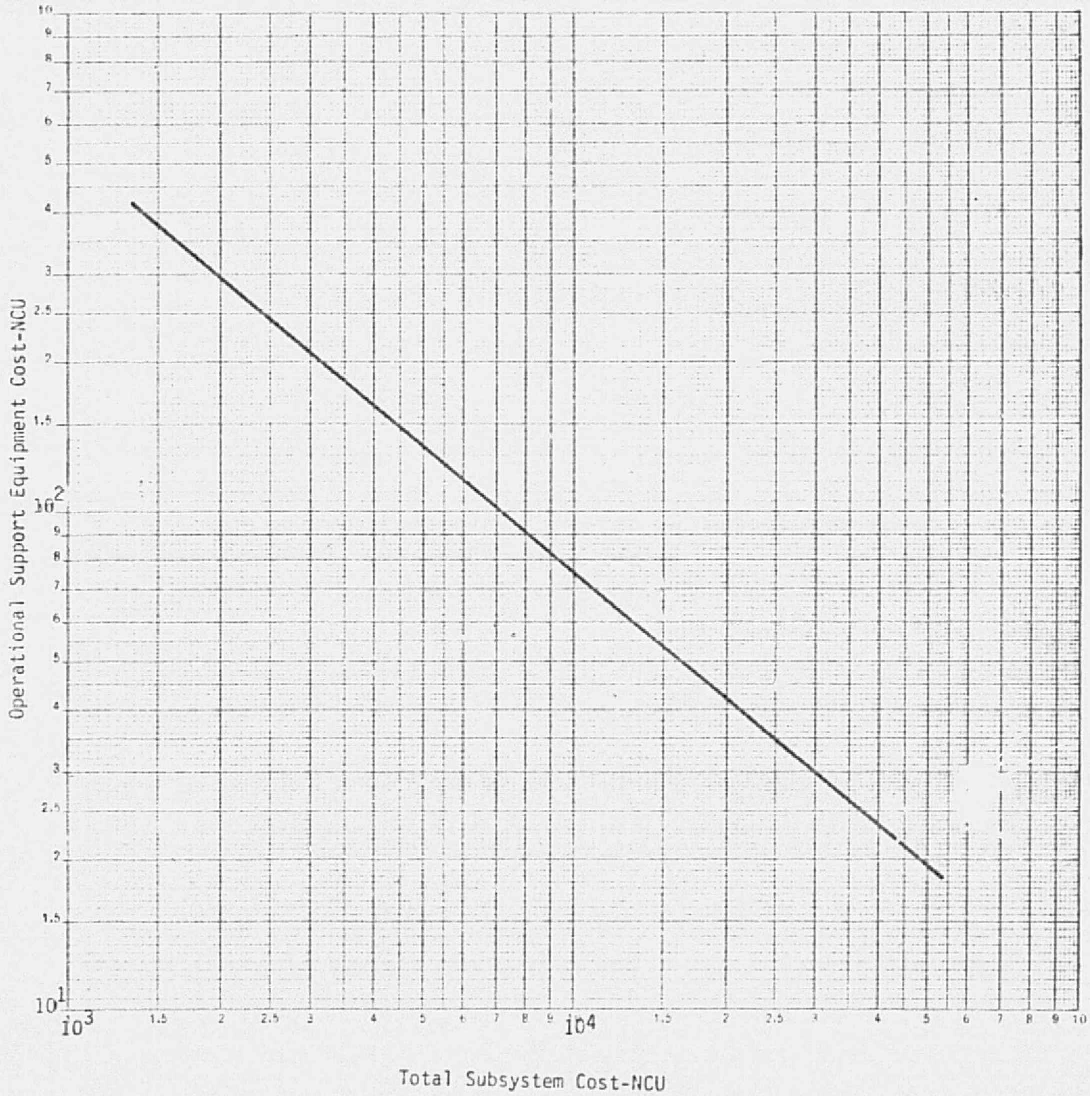


EXHIBIT 28. PROGRAM COMPONENTS: OPERATIONAL SUPPORT EQUIPMENT (OSE)



The inputs to the model are as follows:

1. The subsystems paramters of weight, power, thrust (P_{ss_i})
2. The Novelty Fraction for each subsystem (N_{F_i})
3. The number of Flight Articles (spacecraft to be assembled) (N_{FA})
4. The total number of units produced (N_p)
5. The total number of each pair of subsystems to be installed in three or more spacecraft, for all programs (P_{ij})

In the model there are M subsystems. For each subsystem, the total subsystem cost is composed of a Design, Development, and Type Approval Testing contribution (C_d) and a Hardware plus Flight Approval Testing contribution (C_h) . Thus, for the i th subsystem,

$$c_{di} = f_{di}\ (P_{ss_i}, N_{F_i}) + t_{a_i}\ (P_{ss_i}, N_{F_i}); \tag{1}$$

where $f_{di}\ (P_{ss_i}, N_{F_i})$ is the functional relation between the novelty, the parameter, and the NCU cost, for Design & Development and where $t_{a_i}\ (P_{ss_i}, N_{F_i})$ is the corresponding relation for Type Approval Testing. For the hardware there exists the relationship

$$c_{hi} = N_{FA}\left[g_i(P_{ss_i}) + t_{f_i}(P_{ss_i})\right] + N_T g_i(P_{ss_i}) \tag{2}$$

where $g_i(P_{ss_i})$ relates the subsystem parameter to the unit hardware cost, $t_{f_i}(P_{ss_i})$ relates the Flight Approval Testing cost to the parameter, and N_T is the number of type approval tests.

If the subsystem is a common one, i.e., is to be acquired from a production quantity, then the approach is somewhat similar. For each common subsystem all the acquisition NCU costs are put into $\overline{g}_i(P_{ss_i})$ by the following relationship:

$$\overline{g}_i\ (P_{SS_i}) = \frac{1}{N_{p_i}}\left[c_{di} + N_T g_i(P_{ss_i}) + N_{p_i} g_i(P_{ss_i}) F_{\ell}(N_{pi})\right] \quad , \tag{3}$$

where $F_{\ell}(N_{pi})$ is the learning factor and represents the fraction of the first unit cost which is the average unit cost of the whole production quantity. Each production unit must receive flight approval.

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To recapitulate, the subsystem total cost is given by either

$$\Gamma_i = c_{di} + c_{hi} \quad \text{(program specific subsystem--PS)} \qquad (4a)$$

or

$$\Gamma_i = N_{F_A} \left\{ \bar{g}_i(P_{ss_i}) + t_{f_i} (P_{ss_i}) \right\} \quad \text{(nonprogram specific subsystem--NPS)} \qquad (4b)$$

Then the Subsystems Total NCU cost to the program is

$$c_{T_{ss}} = \sum_{i=1}^{M} \Gamma_i \quad . \qquad (5)$$

In the model, there are L Program Components. Each cost associated with the Program Components is a single valued function of the total subsystem cost, $c_{T_{ss}}$. Thus, if the functions are represeted by $U_j (c_{T_{ss}})$, the contribution of the Program Components to the total NCU cost is given by

$$c_{pc} = \sum_{j=1}^{L} U_j (c_{T_{ss}}) \quad .$$

Then the total program NCU cost is,

$$c_p = c_{T_{ss}} + c_{p_c} \quad ,$$

$$c_p = \sum_{i=1}^{M} \Gamma_i + \sum_{j=1}^{L} U_j (c_{T_{ss}}) \quad . \qquad (7)$$

In the list of inputs, the total numbers of times each pair of similar (i.e., like hardware) subsystems will be assembled together must be specified; the p_{ij} for the i^{th} and j^{th} $(i, j = 1, \ldots, M)$ subsystems. Clearly, $p_{ij} = p_{ji}$. Corresponding to each p_{ij}, or p_{ji}, are numbers $\pi_{ij} = \pi_{ji}$ which represent the cumulative effects of learning due to the number of times each pair combination is co-assembled.

To estimate the savings from common assembly, the cost reduction factor

$$\sigma_i = \prod_{j=1}^{M} \pi_{ij} \leq 1 \tag{8}$$

is calculated. Then, the total subsystem cost is modified to a reduced value by computing

$$c'_{T_{ss}} = \sum_{i=1}^{M} \sigma_i \, \Gamma_i \leq c_{T_{ss}} \quad . \tag{9}$$

This new, Adjusted Subsystem Total NCU Cost is then used in computing the Program Component costs.

Hence, for the case of full commonality, relation (7), Total Program NCU Cost, is rewritten as

$$c'_p = \sum_{i=1}^{M} \Gamma_i \sum_{j=1}^{L} U_j (c'_{T_{ss}}) \quad . \tag{7a}$$

It should be noted that in (7a) the <u>cost</u> contribution of the subsystem is unchanged from before. That is (other than the effect of amortizing costs over the design and production of multiple quantities of units), commonality savings appear only at the system level program component costs.

2. Cost Estimating Relationships (CERs)

In this section, another component of the Model--the CERs--are presented. These CERs, Exhibits 13 through 28, relate a subsystem parameter to the cost expressed in NCUs. The subsystem parameters are usually weight with two exceptions, power for the electrical power subsystems and pounds-thrust for propulsion. Each CER sheet contains two curves, one for design/development and the other for hardware first unit NCU cost, with appropriate, different NCU cost scales. The range of the independent variables for each curve is extensive enough so as to include any feasible spacecraft which could be launched from the Shuttle. To use the CERs, first determine the appropriate value of the subsystem parameter and then derive the corresponding NCU value.

In developing these CERs, an extensive data base was collected, and analyzed and synthesized. (See Appendix A for a list of the data base.) Of the numerous reports, only several reports were considered to be directly applicable. The actual cost data shown in (A31) (current value money) was deemed the most reliable basic data available. Although the subsystem definitions in (A31) were not considered to be standard, these subsystem definitions contained the standard subsystems as subsets. Using the data contained in (A46, A47) it was possible to disaggregate the cost data in (A31) and to derive the approximate raw dollar costs of the design, development, and type approval testing and the total hardware cost for each standard subsystem for each of the programs of interest.

It should be noted that actual cost will implicitly include the effects of technological inheritance. Therefore, to translate "raw" actuals to that cost associated with doing the work with all new design and/or material means removing the effects of such inheritance. Again, the previous work in (A46, A47) proved invaluable. In each of these reports, the inheritance estimates for each subsystem had been included as a by-product; therefore, the raw data could be "disinherited" to approximately determine the quantities. From these two documents, the numbers of test and flight articles fabricated were obtained. Report (A31) uses only the number of flight articles actually launched in estimating hardware costs.

Emphasis has been placed upon developing a standard unit of cost which will be constant rather than requiring the application of inflation or deflation factors. The raw data on costs are in current value dollars of the year spent. For developing the Cost Estimating Relationships for design and development and for the hardware cost it was necessary to convert all costs to a common base year. This was done with the aid of the "Aerospace Inflation Factors" found in (A18). Consequently, in all of the CERs and other relationships, between value and hardware, cost is measured in a unit defined as the Normalized Cost Unit (NCU). Because of the normalizing to the NCU, old CERs and new CERs can be fully utilized, compared, and interchanged.

3. Commonality Evaluation Model Tables of Factors

In addition to the CERs other relationships were also developed and are required as an integral part of the Commonality Evaluation Model. This section presents these six relationships in a tabular format--Tables 3 through 8.

4. Commonality Evaluation Model Subsystem Cost Definitions

As used in the CEM, the subsystem cost has the following components: design/development, hardware first unit cost and testing costs. The testing costs are considered in two parts. The first testing part--type approval--is generally included in design/development cost while the second--flight approval--is categorized as a separate cost. The following subsections provide expanded definitions of selected terms associated with the CEM.

a. Design/Development

The design/development value corresponds to designing and developing the subsystem completely from scratch and so must be adjusted downwards for projects of "novelty fraction" less than 1.0.

b. Type Approval Testing Cost

In context of current CER development, it is important to realize that the costs of a subsystem include not only the direct design/development and hardware cost but also the costs of testing the

Table 3

NOVELTY FRACTION ASSIGNMENT FOR S/S DESIGN & DEVELOPMENT (N_F)

	Material and Fabrication Novelty				
	Previously Used Materials and Fabrication Technology	Minor Change in Materials Properties or in Fabrication Technology	Significant Change in Materials or in Fabrication Technology	Major Change in Fabrication or a Material with Little Experience in Spacecraft Usage	Completely New Materials and Fabrication Technology
Prior Design and Software	0.00	.25	.50	.75	1.00
Minor Design or Software Changes	.25	.40	.60	.80	1.00
Significant Changes to a Prior Design or Software	.5	.65	.80	.90	1.00
Major Change to an Old Design	.75	.80	.85	.95	1.00
Completely New Design and Software	1.00	1.00	1.00	1.00	1.00

Table 4

DESIGN/DEVELOPMENT REDUCTION FACTOR (F_D) AS A FUNCTION OF THE NOVELTY FRACTION (N_F)

N_F	F_D
1.0 - .75	1.00
.74 - .5	0.85
.49 - .3	0.7
.29 - .15	0.65
.14 - 0.0	0.5

Table 5

TYPE APPROVAL TESTING ARTICLES* (N_T)

Subsystem Name	Novelty Fraction (N_F) 1.0-0.75	0.74-0.5	0.49-0.3	0.29-0.15	.14-0.0
Struc I	3	3	2	2	1
Struc II	3	3	2	2	1
Struc III	3	3	2	2	1
Propulsion	3	2.5	2	1.5	1
Guidance	4	3	3	2.5	2
Attitude Control	4	3	3	2	1
Communications	4	3	3	2.5	2
Data Handling	4	3	3	2.5	2
Power (elect)	3	2.5	2	1.5	1
Science	4	3	3	2.5	1.5

* In Type Approval Testing each test requires that a prototype unit be made. Hence #Test - #Articles; = N_T - N_{TA} . None of the TA-Testing articles are used as Flight Articles; therefore, all of Flight Articles must be made separately after TA has been obtained.

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Table 6

PRODUCTION LEARNING COST REDUCTION FACTOR (F_2)

Number of Units	Cumulative Average Unit Cost Reduction Factor 90% Curve	85% Curve	80% Curve
1	1.00	1.00	1.00
2	0.950	0.925	0.900
3	0.922	0.883	0.846
4	0.903	0.855	0.810
5	0.888	0.834	0.783
6	0.876	0.817	0.762
7	0.866	0.803	0.744
8	0.857	0.791	0.729
9	0.850	0.780	0.716
10	0.843	0.771	0.705
11	0.837	0.763	0.695
12	0.832	0.755	0.685
13	0.827	0.748	0.677
14	0.823	0.742	0.670
15	0.818	0.736	0.663
16	0.815	0.731	0.656
17	0.811	0.726	0.650
18	0.807	0.721	0.645
19	0.804	0.717	0.639
20	0.801	0.713	0.634

Table 7

COMMONALITY INTERACTION COEFFICIENT LEVEL SELECTION (IN PERCENT)

	Subsystem Name	1 Structure I	2 Structure II	3 Structure III	4 Propulsion	5 Guidance	6 Attitude Control	7 Communications	8 Data Handling	9 Power (elect.)	10 Science
1	Structure I		80		70					70	
2	Structure II	80					80	80		80	70
3	Structure III										
4	Propulsion	70				60					
5	Guidance				60		60	70			
6	Attitude Control		80			60					60
7	Communications		80			70			60		60
8	Data Handling							60			60
9	Power (elect.)	70	80								60
10	Science		70				60	60	60	60	

Table 8

COMMONALITY INTERACTION COEFFICIENTS (π_{ij})

Number Common Pairs	80% Curve Coefficients	70% Curve Coefficients	60% Curve Coefficients
1	1.00	1.00	1.00
2	1.00	1.00	1.00
3	0.95	0.90	0.87
4	0.89	0.83	0.78
5	0.85	0.78	0.71
6	0.82	0.74	0.66
7	0.80	0.71	0.62
8	0.78	0.68	0.59
9	0.76	0.66	0.57
10	0.75	0.64	0.54

components to be sure they can survive the spacecraft environment. The testing of subsystems typically occurs in two stages. First, the component(s) are tested for "Type Approval," which means they can physically survive the space environment and still function; for a new component design it is usual for either three or four type approval tests to be conducted before approval is given.

c. Flight Approval Test Cost

After type approval has been obtained, the hardware flight articles can be produced. For each flight article there is further testing, although less severe, to be sure the produced items will also stand the environment. Those which pass this test are given Flight Approval and may be installed in the spacecraft. No matter how mature the design nor how often a similar, or even identical device, has been flown, it will always be required to pass the Flight Approval tests.

Aside from producing components on an as-required basis (Progress Specific--PS) for each spacecraft program or project as it evolves, there exists the possibility of acquiring components "off the shelf," from an inventory of standard-type components, or from a continuously operating production line. These subsystems or components are designated Non-Program Specific (NPS). The costs of such NPS components must be calculated differently from those which are custom made for a single program. The essential feature for NPS components, from the standpoint of this model, is the achievment of cost savings associated with extended, serial production. Although NPS reduces the design/development and type approval costs, flight approval test costs are not reduced through the use of Non-Program Specific components.

d. Novelty

The cost of design and development is split approximately 55 percent "true" design/development and approximately 45 percent testing, if the subsystem is being developed from scratch. In the case of novelty less than 1.0, the design development costs must be appropriately reduced by the estimating, for each subsystem separately, the amount of novelty in the new design. If a new material is to be used with an older design, "novelty fraction" = 1.0 ; and similarly if an old material is to be used with a new design. For intermediate values of novelty, Table 8 shows the appropriate relationship between "novelty fraction" and the design/development reduction factor.

e. Hardware First Unit Cost

The hardware value read from the CER is the true first unit cost for a subsystem manufactured to spacecraft standards, and needs no adjustment. For estimating the total hardware cost. it is first necessary to know the number of flight articles to be acquired. The number to be acquired is the number to be flown plus the number of fully assembled space spacecraft. The number of flight articles is in addition to the number of type approval test articles. Table 4 contains suggested values to be used for the additional numbers of hardware units required for testing as a function of novelty. The values provided are expected numbers based on the experience of several programs.

f. Non-Program Specific Hardware Costs

If NPS hardware is acquired, the model reflects amortized production unit cost for the full production run, and the spacecraft program is charged only unit acquisition cost and flight approval testing for the acquired hardware. In this mode, the model does not permit the assignment of design/development cost and its related type approval testing cost as a separate component.

C. Learning Curve Approach for Common Pairs Development

1. Definition of Common Pair Interactions

Common pair commonality occurs if the same subsystems are to be paired in two or more programs or projects. For instance, if the same Guidance subsystem and Attitude Control subsystem are to be used together in three different projects, then common pair commonality exists with regard to that combination or pair of subsystems. Additional savings will accrue due to that commonality application.

The first step in the development of the approach to incorporating the cost reduction due to common pair commonality was to qualitatively define the interactions between various pairs of common subsystems. This was accomplished by constructing a matrix of the subsystems and assigning rankings related to the potential cost reduction impact of each of the pair intersections.

The cost reduction impact of a pair is determined by the amount and complexity of the interaction between them. If there is no interaction or only negligible interaction, the potential for cost reduction through multiple interfacings of that pair is negligible. If the interaction is very intimate and complex, the opportunity to reduce the cost of interfacing that pair through a learning process is large.

A four-level qualitative ranking index was used. Level one represents the most intimate and complex interactions. Level two represents an intermediate range. Level three represents a lesser but still significant interaction. A blank intersection represents negligible interactions. The matrix is shown in Exhibit 29.

2. Approach

The development of the learning curve technique used to derive the adjustment factors for adjusted subsystems costs, and thereby, the reduction in the Program Components costs where common pairs are involved, began with a simple hypothesis based upon experience and observation.

Essentially, the hypothesis states that management and integration functions become progressively simpler and more efficient, similar to manufacturing tasks, when identical items are brought together repeatedly, even in different systems. This effect can be observed in the production of aircraft and, perhaps most graphically, in ships. Interestingly enough, it can also be observed in the integration of common software subroutines and logic into complex computer programs.

A further observation indicates that the rate of increase in efficiency of the management and integration functions is somewhat proportional to the complexity of the interface between the pairs of items.

Exhibit 29

MAJOR FUNCTION COMMONALITY INTERACTION FACTORS

	Structure I	Strucutre II	Structure III	Propulsion	Guidance	Attitude Control	Communications	Data Handling	Power (elect.)	Science
Structure I		3		2					2	
Structure II	3					3	3		3	2
Structure III										
Propulsion	2				1					
Guidance				1		1	2			
Attitude Control		3			1					1
Communications		3			2			1		1
Data Handling							1			1
Power (elect.)	2	3								1
Science		2				1	1	1	1	

Value: 1 = Highest Interaction
2 = Mid Interaction
3 = Lowest Interaction

Little of this improvement (an insignificant amount, if any) could come from the kind of learning of manual tasks represented by the learning curves applied in manufacturing operations. Observations, however, indicated that the patterns followed were somewhat similar to the typical learning curve shape. Considering the fact that the manual task learning curves almost always apply to a single organization, whereas the observed improvements in management and integration sometimes apply to different organizations and even to different end systems, transferable learning has to be involved.

This conclusion leads to the realization that the underlying causal factor is better documentation. Where items are intentionally developed to be applied more than once, in more than one system, and, perhaps, by more than one organization, a significant effort is committed to the developing of comprehensive, accurate documentation which defines the properties of the interfaces. This includes, for example, the methods of checkout and the interface wiring diagrams. This realization prompted a literature search to determine if similar observations had been made elsewhere.

The only evidence that the learning theory for "knowledge work" (as contrasted with that for manual tasks) was being pursued was found in the field of computer programming. The data indicate a situation quite similar to the hypotheses proposed above.[1] In some cases, the documentation is replaced by interteam communication. Although a direct comparative analogy cannot be drawn at this time, the findings in the programming field appear consistent with the concept of "transferable knowledge learning."

In order to apply this concept to the impact of common pairs on Program Component Costs, it was necessary to establish the "slopes" of the learning curves to be used, as well as the start and the end points.

a. "Slopes"

The 80 percent learning curve is usually considered, and fairly well demonstrated, to be about the best that is normally achieved

[1] Documents 49, 50, 51, and 52 in Appendix A.

in complex aircraft manufacturing operations. Since this represents improvements (or learning) in primarily manual operations, it was reasoned that this "slope" or rate of learning effect should be at least equalled by "transferable knowledge learning" which occurs principally through documentation rather than through conditioning by repetition. This assumption could not be verified directly by historical data since this type of commonality application has not yet occurred in significant portions of unmanned space systems. Reviews of cost data from some previous space projects that involved a very high order of inheritance in some subsystems, however, revealed cost deltas that lend support to the 80 percent "slope" selection. The use of an 80 percent learning curve to establish the reduction factor for determining adjusted subsystem cost was accepted for application to the least complex common pair interactions.

More complex common pair interactions were judged to benefit at a faster rate from "transferable knowledge learning" since the more complex the interaction is, the greater is the amount of information about the interface that can be transferred through documentation. Based on this reasoning, 70 percent and 60 percent learning curves were tried for the intermediate and most complex interactions, respectively. Program component costs were computed using these curves for some typical subsystem costs and common pair combinations. The results were satisfying because they produced approximately the cost savings that our judgment and experience had led us to anticipate for the test cases. Following this exercise, 70 percent and 60 percent curves were selected for the intermediate and most complex interactions, respectively.

b. Starting Points

It was considered inappropriate to start the learning curve at the first unit since, for most unmanned space projects, the first two or three units are essentially prototypes. Therefore, the correcting and updating of documentation would not really provide significant learning for the second unit. Based on these considerations, the second unit was selected for the starting points of the learning curves.

c. End Points

Since the basic assumption underyling the application of the "transferable knowledge learning" technique is that the bulk of the learning comes through the preparation, correcting, and upgrading of documentation about the properties of the interfaces, it is also necessary to recognize that this process does not continue indefinitely.

In manufacturing operations, where the learning applies primarily to manual tasks, the process continues as long as the manufacturing goes on and the curves flatten out to a slowly changing asymptote. In the situation at hand, however, the cutoff comes fairly early because the increase in the amount of information transferable through documentation will be truncated after a relatively small number of units. The number of units selected for truncation of the learning curves is ten. Few cases are likely to occur where the documentation will continue to be improved after ten units have been produced.

3. Learning Curve Computation

The tabulated values for the learning curves used in the model were calculated by first calculating the unit learning curves for each of the selected slopes. Next the cumulative average values for the first three units were calculated for each of the three curves. From these calculated cumulative average values, the "slopes" or exponents for the cumulative average curves could be determined. The first ten values were then computed for each of the three cumulative average curves. These values are shown in Table 7.

D. Conclusions and Recommendations

1. Conclusions

When used in accordance with the instructions provided, the Commonality Evaluation Model provides a good comparative evaluation of the costs of unmanned planetary space projects involving various amounts and kinds of commonality among their elements.

Application of the model is straightforward and is easily exercised by manual operations. It is equally well suited to automated computation and can be programmed for small computers with a minimum of difficulty.

The Commonality Evaluation Model was developed for a specific set of space projects. The model could be extended to other classes of space projects with appropriate modification of the CERs and the model-specific factors.

The utilizing and realization of cost in a Normalized Cost Unit, rather than using "then" or real year dollars, eliminates the necessity for inflation/deflation correction and eases the interpretation of results.

A generalized relationship was not developed, within the scope of this effort, that related changes in operational phase costs to increased commonality within the constraints of the existing CERs. The impact of these savings is provided for within the framework of the model.

2. Recommendations

Increased hardware and software commonality constitutes an effective method of lowering the costs of unmanned interplanetary space projects. The Commonality Evaluation Model should be used to make comparative evaluations of various commonality approaches.

Further development of the Commonality Evaluation Model is possible and should be undertaken. The model should first be extended to incorporate the impact of various management modes because the impact of management modes and commonality can be either mutually reinforcing or dissipative in various combinations. Sufficient data to allow this extension is in existence and should be exploited.

The model should also be extended by the development of new CERs to allow comparative analysis at lower levels of breakdown for the hardware elements. This would also allow the structure to be extended to more closely approach the new fraemwork and structure also developed during this effort.

V. NEW TECHNOLOGY

No reportable items of new technology were identified during the implementation of this study contract.

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APPENDIX A

DATA BASE DOCUMENTS

A. Documents containing useful information:

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COMMONALITY EVALUATION MODEL HANDBOOK

APPENDIX B, P21-R-001

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II. GENERAL

The unit of cost used in the Commonality Evaluation Model (CEM) is a normalized value called the Normalized Cost Unit (NCU). All of the cost estimating relationships (CERs) and other relationships are expressed in terms of the NCU. Therefore, attempts to use this model to predict actual dollar costs of spacecraft hardware or programs will not produce meaningful results.

The CEM is limited to the pre-launch phases of the unmanned spacecraft program. Table 1 presents the reference order of the functional subsystems treated by the CEM. Table 2 presents, in order, the Program component or system level costs implemented in the CEM.

Several terms or concepts used in conjunction with the CEM require brief explanation. These terms are Novelty Fraction, quality procurement, and commonality.

A particular device or design is "technically mature" when it is similar to a recent predecessor in both design and materials of construction. In this CEM, the degree of technological maturity of the system is represented by a "Novelty Fraction." Novelty fraction values fall into the range of 1.0 to 0.0, where 1.0 is equivalent to a new design and/or materials and 0.0 is equivalent to a tried design and previously used materials.

The costs of quantity procurement (non-program specific) equipment are calculated differently from those made for a single program (program specific). Section III describes this procedure which permits realization of the cost savings associated with serial production. It is recognized that the first user of a quantity-procured item generally absorbs the design and development costs. However, in order to provide meaningful commonality comparisons, the design and development costs are prorated among the total units produced.

For purposes of the CEM, commonality is defined as follows: major components of the spacecraft subsystems are common to a series of programs or projects, or a program with a significant number of spacecraft has one or more components common to each spacecraft.

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TABLE 1

COMMONALITY EVALUATION MODEL SUBSYSTEMS

1. Structure I (fixed, immovable mechanical structure and supporting members of the spacecraft

2. Structure II (mechanical devices, hinges, springs, dampers, rotating joints, pin-pullers, etc.)

3. Structure III (pressurized structure, typically cold gas vessels and rocket fuel and oxidizer tankage)

4. Propulsion (specify kind, may be ion-drive, chemical rockets, or solar sails)

5. Guidance (includes star trackers, sun sensors, and the Central Computer and Sequencer, if any, in the spacecraft)

6. Attitude Control (includes the roll, pitch, and yaw sensors, the means for rotating the spacecraft about its axes, and any expendable stores associated with such control)

7. Communications (includes the on-board radio systems from the modulators to the antennae for X-mitters and the antennae to the demodulators for the receivers; it will include any special power conditioning which is used by the radios exclusively)

8. Data Handling (includes all data collection and on board data storage devices and all encoding and pre-modulation modification of the on-board generated data stream)

9. Power (includes the power generation, solar cell or other, and all conditioning for the spacecraft power service, but not any dedicated power conditioning associated with a particular instrument or subsystem)

10. Science (includes all scientific instruments on board the spacecraft; <u>does not</u> include supporting structure or scan platforms unless a <u>functional</u> part of the instrument, not just supports or pointing aids)

TABLE 2

COMMONALITY EVALUATION MODEL
PROGRAM LEVEL COMPONENTS

1. Program Management (all the costs of administering the spacecraft program which are program specific)

2. Systems Analysis and Systems Engineering (the costs usually paid for the systems level technical effort in design and in such areas as the engineering part of systems integration)

3. Systems Test (the costs of all systems level testing of the assembled spacecraft, but not of any single subsystem or component)

4. Quality Assurance and Reliability (the costs of all the system level QA&R effort, but, again, not that of any component)

5. Assembly and Integration (the costs of assembling the subsystems and integrating them into a functioning spacecraft, exclusive of testing)

6. Operational Support Equipment (the necessary test and checkout equipment for the spacecraft at the system level; subsystem OSE is a part of the cost of subsystem hardware)

III. MODEL USE

This section contains the details of the Commonality Evaluation Model implementation and use. All required CERs are contained in either Appendix A (subsystem CERs) or Appendix C (program-level component CERs). The required tables are located in Appendix B and suggested computational forms are in Appendix D.

To exercise the CEM, a relatively straightforward approach has been implemented. The approach basically determines the NCU cost of design/development, hardware production, and all testing for each subsystem. The sum of these NCU costs determines the cost associated with the hardware portion of the program cost. The program-level component NCU costs are determined as a function of hardware component NCU cost. The sum of the two components is the program NCU cost.

When components or subsystems are utilized which do not have to be redesigned or where the hardware cost is to be prorated among several programs or projects, a modification of the basic approach is required. This reduces not only the hardware component cost but also reduces the program-level component.

Sub-section A then describes the basic process, a process which is similar to that employed by the current JPL cost model. Sub-sections B and C describe the methodology employed to determine cost reductions due to commonality, while Sub-section D describes the methodology for determining program-level component costs. Sub-sections E and F briefly discuss the completion of the calculations and our approach to comparing among several alternative cases.

A. Subsystems Costs

A set of CERs relate subsystem parameters to cost expressed in NCUs. Each CER Exhibit contains two curves--one for design/development and another for hardware first unit cost. To determine the subsystem cost use Form 2 and determine the appropriate subsystem parameter value. Then, using the appropriate CER, determine the corresponding NCU value.

The design/development CER values correspond to new design and its development for a subsystem. Therefore, the CER value is adjusted downward for subsystems with novelty fractions less than 1.0. The subsystem hardware value read from the CER is the first true unit NCU cost for a subsystem manufactured to spacecraft standards.

The cost of design/development is split approximately 55 percent "true" design/development and 45 percent testing for a new design subsystem being developed. To reduce design/development costs for novelty values less than 1.0, estimate the amount of novelty in the new design for each subsystem separately. New material with an old design or old material with a new design are equivalent to a Novelty Fraction of 1.0. Table B-1 presents an array for determining the appropriate Novelty Fraction. Table B-2 presents the relationships between novelty and the design/development reduction factor. After reducing the CER values of the component subsystem costs, total them to determine the design/development contribution to the total spacecraft program cost.

Hardware cost estimates are dependent upon the quantity of spacecraft to be flown. Table B-3 contains suggested values to be used for the additional numbers of hardware units required for testing as a function of the Novelty Fraction. Hardware costs are computed using Form 3.

B. Common Subsystem Component Costs

Computing the cost of a common component subsystem for a single spacecraft program or project (i.e., one of the alternative cases) utilizes a different procedure.

For each subsystem it is necessary to estimate or know the total planned number of production sets. Use the appropriate subsystem parameter and determine the CER costs as before. A Novelty Fraction of 1.0 is recommended; i.e., a full testing program is contemplated.

Enter the CER and quantity to be produced on Form 1. Obtain the number of test articles from Table B-3. The total subsystem production run cost is obtained by summing the design/development, type approval testing, hardware, test hardware, and the production NCU cost of the required number of subsystems. Cost advantages of production line savings are calculated from Table B-4. Obtain the fraction of first unit cost applicable to the selected production quantity. Multiply the total number produced by the first unit cost and by the appropriate reduction factor. To this total, add the design/development costs and divide by the total quantity produced. This quotient is the amortized per unit cost to the spacecraft program and should be entered in the hardware unit cost column on Form 3.

C. Total Subsystem Cost Adjustment for Commonality

If a number of previous occurrences of spacecraft with common subsystems have successfully passed through all the program phases, using these subsystems will result in a commonality cost savings.

To compute a lower or Adjusted Subsystem Total Cost (ASSTC) to reflect such usage, use Form 4, part A and B. Enter on part A the number of times a given pair of subsystems is common to a spacecraft (i.e., all the spacecraft on which it is, was, or will be used). Using these numbers, use Table B-5, for the percent interaction of each pair of subsystems given, enter Table B-6 and determine the savings allowed for each interaction. If the Table B-5 interaction value is not specified, use the value of unity (1.0) for Table B-6. Enter the Table B-6 values in the appropriate interaction intersections on part B of Form 4 in columns 1 through 10. Each interaction factor is entered in two places for each pair of subsystems. If there is no interaction, or the value of the interaction in Table B-5 is zero or not specified, unity (1.0) is assumed; however, for convenience, these have been pre-printed on Form 4, part B.

When all the interaction pair values have been entered on part B, the row products of columns 1 through 10 are computed to develop a Commonality Factor. Each subsystem cost is multiplied by this commonality factor to determine an adjusted subsystem NCU cost.

The sum of all the adjusted subsystem costs is the Adjusted Subsystem Total NCU Cost (ASSTC).

D. Program-Level Component Costs

Program-Level Component costs utilize the system level cost categories defined in Section II. Form 5 will be used for the computation.

CERs are provided for each of the program component of costs, where the independent variable is either the Subsystem Total NCU Cost or the Adjusted Subsystem Total NCU Cost.

With the appropriate value of either the SSTC or ASSTC, use the CERs to find the proper values to enter on to Form 5.

For program-level component costs, there is no adjustment other than the SSTC adjustment to ASSTC to account for the due to common subsystems savings.

E. Spacecraft Total Pre-Launch Costs

Sum all of the entries on Form 5. Use the unadjusted value of SSTC for the hardware component share of the program.

F. Comparisons

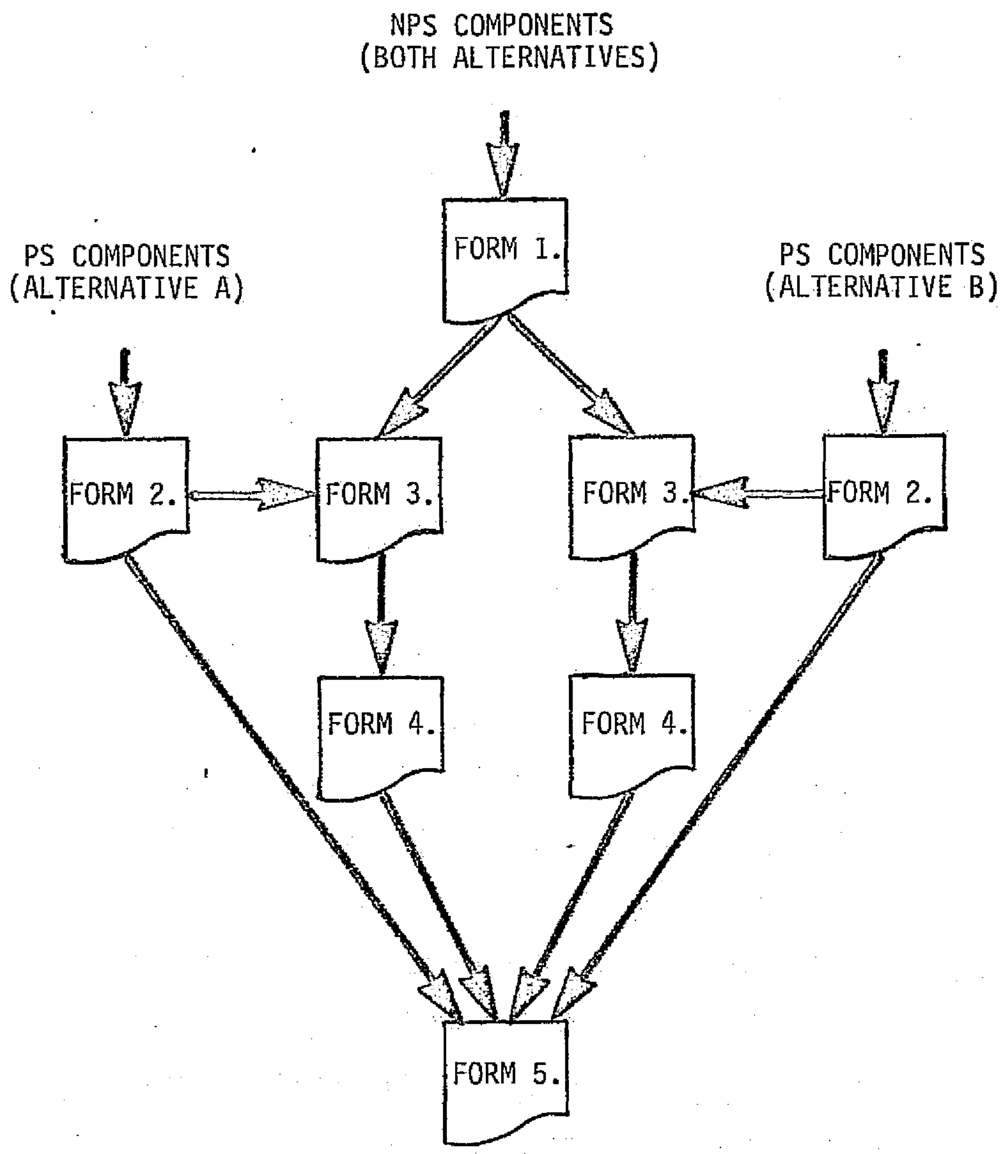
If it is desired to make comparisons between alternatives, each alternative must have a set of calculations.

G. Flow Chart

Exhibit 1 depicts the computational process utilizing the forms contained in Appendix D. The diagram, for simplicity, shows a comparison involving two alternative cases.

Planning Systems and Sciences

EXHIBIT 1 - COMPUTATION FLOW CHART



IV. EXAMPLES

The purpose of this section is to demonstrate the principles and uses of the model. The example is divided into three applications, progressing from familiar ground through full utilization of all the model features. The first application demonstrates the CEM in a mode which essentially emulates the current JPL Cost Model. The second application extends the first by employing the concept of Novelty Fraction and illustrating the computation of system cost with a portion of a subsystem made up of non-program specific components. In a like manner, the third application extends the second by illustrating the cost effects of common pair assembly and several quantity-procured subsystems, and, in particular, illustrates the computation and application of the adjusted total subsystem cost.

With this purpose in mind, the three applications of one example are included only for illustration purposes to demonstrate the straightforward, step-wise design of the CEM.

These three applications, neither singularly nor collectively, exhaust the versatility of this Model. They are intended to introduce the user to the main features. Application 2 demonstrates the CEM's flexibility.

A. Overview

Of the three applications, the first primarily assumes the project contains all new design with the usual number of interplanetary scientific mission flight articles - three.

The second application demonstrates the concept and use of the Novelty Fraction as well as illustrating the flexibility of the Model. That is, the informal expansion beyond the formal methodology is demonstrated by assuming that half the communications subsystem is to be non-program specific, while the remainder is program specific, i.e., made specifically for this spacecraft project.

The last application exercises all of the features of the Model. Four subsystems are non-program specified and a significant number of subsystem common pairs will be utilized. This application demonstrates the methodology utilized to account for savings attributable to commonality.

B. Model Preparation

In order to exercise the CEM for the stated applications, two additional items are required. These two items are the input parameters and the computation forms. Table 3 contains the input parameters for the example. Shown below is an enumeration of the forms required for each application. Sample forms are contained in Appendices B-D.

Form	Application 1	Application 2	Application 3
1		X	X
2	X	X	X
3	X	X	X
4 Part A			X
4 Part B			X
5	X	X	X

As an aid to the user, Table 4 contains the nomenclature used throughout the various computation forms.

For ease of computation, it is suggested that the first computational form to be completed is Form 1, followed by 2 and then 3. Following the completion of Form 3, complete Form 4, Parts A and B, in sequence. Form 5 is the recap form which contains all of the various subtotal data as well as the comparison data.

TABLE 3

EXAMPLE INPUT PARAMETERS

Parameter / Application / Subsystem Name		Units	Parametric Value	Novelty Fraction			Learning Saving Curve		Number Production Articles	
			All	1	2	3	2	3	2	3
1.	Structure I	lbs	200	1.0	.5	.3				
2.	Structure II	lbs	30	1.0	.5	.3				
3.	Structure III	lbs	150	1.0	0	0				
4.	Propulsion	lbs-T	50	1.0	0	0				
5.	Guidance*	lbs	50	1.0	.7	1.0		.85		10
6.	Attitude Control	lbs	70	1.0	.7	1.0		.85		10
7.	Communications	lbs	100**	1.0	1.0	1.0	.85	.80	10	15
8.	Data Handling	lbs	10	1.0	.8	1.0		.90		20
9.	Power (elect)	KW @ 1 AU	.8	1.0	0	0				
10.	Science	lbs	100	1.0	1.0	1.0				

Pairwise installation count for construction of Application 3, Form 4-part A

$P_{5,6} = 5$; $P_{5,7} = 7$; $P_{5,8} = 7$; $P_{6,7} = 5$, $P_{6,8} = 5$, $P_{7,8} = 7$; all others =3

*Guidance - Mission Fly By

** For Application 2, the 100 lbs is divided 50 lbs for non program specific and 50 lbs of program specific communications.

TABLE 4

NOMENCLATURE USED ON THE COMPUTATION FORMS

F_D	Design/Development Reduction Factor
F_L	Production Learning Cost Reduction Factor
N_F	Novelty Fraction
N_{FA}	Number of Flight Articles
N_T	Number of Type Approval Tests
N_{TA}	Number of Type Approval Test Articles
π_{ij}	Commonality Interaction Coefficient

C. Application 1

The spacecraft is defined by the parametric entries in columns 1 of the Forms 2 and 3. Using the Subsystem parameters, 2-1 and 3-1, determine the appropriate NCU values from the CERs and fill in columns 2 on Forms 2 and 3. The application program starts with all new design; therefore set N_F to unity for all subsystems (2-3). Consulting Table B-3, find the number of Tests and Test Articles required. Enter N_T into 2-5 and N_{TA} into 3-4. The last input required is the number of Flight Articles - (3-5) - 3 - the usual number for an interplanetary scientific mission. The computation proceeds as indicated in the column headings of Forms 2 and 3. Since this is an entirely new spacecraft, no savings due to learning are appropriate.

The Subsystem Total Cost (SSTC) is calculated on Form 3. The Program Component costs can be read from each appropriate CER and entered in the appropriate places in Form 5 (shown in E of this section).

PROGRAM SPECIFIC SUBSYSTEM DESIGN/DEVELOPMENT NCU COSTS

APPLICATION 1 — FORM 2

	①		②	③	④	⑤	⑥	⑦	⑧
	PARAMETER VALUE		DES/DEV CER VALUE	NOVELTY FRACTION	DES/DEV REDUCTION FACTOR	NUMBER OF TYPE APPROVAL TESTS	DES/DEV NCU COST	TEST NCU COST	SUBSYSTEM DES/DEV NCU COST
SYMBOL SOURCE	INPUT		CER	N_F INPUT	F_D TABLE B-2	N_T TABLE B-3	.55 x ① x ② x④	.09 x ① x ② x⑤	⑥ + ⑦
SUBSYSTEM NAME	PS	NPS							
STRUCTURE I	200		2.53	1.00	1.00	3	278.30	136.62	414.92
STRUCTURE II	30		2.7	1.00	1.00	3	44.55	21.87	66.42
STRUCTURE III	150		10.5	1.00	1.00	3	866.25	425.25	1,291.50
PROPULSION	50		1.711	1.00	1.00	3	47.05	23.10	70.15
GUIDANCE	50		14.5	1.00	1.00	4	398.75	261.00	659.75
ATTITUDE CONTROL	70		11.2	1.00	1.00	4	431.20	282.24	713.44
COMMUNICATIONS	100		9.1	1.00	1.00	4	500.50	327.60	828.10
DATA HANDLING	60		12.5	1.00	1.00	4	412.50	260.28	672.78
POWER	0.8		785	1.00	1.00	3	345.40	169.56	514.96
SCIENCE	100		8.3	1.00	1.00	4	456.50	298.80	755.30
SUBTOTALS							3,781.00	2,206.32	
SUBSYSTEM DESIGN/DEVELOPMENT NCU COST (SSD/DC)									5,987.32

SUBSYSTEM HARDWARE COSTS

APPLICATION 1 | FORM 3

	① Parameter Value		② Hardware Unit Cost CER Value	③ Hardware Unit Cost		④ Number of Test Articles	⑤ Number of Flight Articles	⑥ Subsystem Hardware NCU Cost	⑦ Flight Article Test Cost	⑧ Hardware NCU Cost
Symbol Source	Input		CER	① x ② Form 1		N_{TA} Table B-3	N_{FA} Input	(④ + ⑤) x ③	.09 x .5 x (2-①) x (2-②)	⑥+⑦
Subsystem Name	PS	NPS		PS	NPS					
Structure I	200		.254	50.80		3	3	304.80	136.62	441.42
Structure II	30		.43	12.90		3	3	77.40	21.87	99.27
Structure III	150		.31	46.50		3	3	279.00	425.25	7[illegible]4.25
Propulsion	50		.0309	1.55		3	3	9.27	23.10	32.37
Guidance	50		.51	25.50		4	3	178.50	195.75	374.25
Attitude Control	70		.56	39.20		4	3	274.40	211.68	486.08
Communications	100		.57	57.00		4	3	399.00	245.70	644.70
Data Handling	60		1.43	85.80		4	3	600.60	202.50	803.10
Power	0.8		107	85.60		3	3	513.60	169.56	683.16
Science	100		.645	64.50		4	3	451.50	224.10	675.60
Subtotals								3,088.07	1,856.13	
Subsystem hardware NCU cost (SSHWC)										4,944.20

D. Application 2

To illustrate the concept and use of Novelty Fraction, this application assumes half the Communications subsystem is to be common, and the other half made specially for this spacecraft program. Consequently, the appropriate entries are made on Form 1, as indicated, using half the weight of the whole Communications subsystem as the subsystem parameter value; the other half of the subsystem is calculated using the usual methods on Form 2 and Form 3. Notice that on Form 3, where the total hardware cost is obtained (column 3), it is necessary to total the two subsystem component costs together to derive the subsystem unit hardware cost. When the Flight Approval Test cost is calculated, the total subsystem weight must be used, not the half weight for the calculation on Form 2. From then on the calculation proceeds as before.

Application 2 shows one of the many ways the Model can be expanded beyond the formal methodology which has been developed.

NON PROGRAM SPECIFIC SUBSYSTEM NCU ACQUISITION COSTS

APPLICATION 2 — FORM 1

	①	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩	⑪	⑫	⑬
	PARAMETER VALUE	DES/DEV CER VALUE	NOVELTY FRACTION	DES/DEV REDUCTION FACTOR	NUMBER OF TYPE APPR TESTS	DES/DEV NCU COST	TEST NCU COST	HARDWARE UNIT COST CER VALUE	FIRST UNIT COST	NUMBER OF UNITS PRODUCED	LEARNING SAVING FACTOR	LEARNING CURVE RED FACTOR	AMORTIZED UNIT ACQ NCU COST
SYMBOL SOURCE	INPUT NPS	CER	N_F INPUT	F_D TABLE B-2	N_T TABLE B-3	.5 x ① x ② x ④	.09 x ① x ② x ⑤	CER	① x ⑧	INPUT	INPUT	F_L TABLE 4	[⑥ + ⑦ + (⑤ x ⑨) + (⑨ x ⑩ x ⑫)] / ⑩
SUBSYSTEM													
STRUCT I			1.0	1.0									
STRUCT II			1.0	1.0									
STRUCT III			1.0	1.0									
PROPUL			1.0	1.0									
GUIDANCE			1.0	1.0									
ATT CTRL			1.0	1.0									
COMM	50	17.6	1.0	1.0	4	484.0	316.3	1.18	59	10	.85	.771	149.17
DATA HAND			1.0	1.0									
POWER			1.0	1.0									
SCIENCE			1.0	1.0									

NOTE: USE THIS CALCULATION WHEN THE NUMBER OF FLIGHT ARTICLES TO BE PRODUCED IS 3 OR MORE.

PROGRAM SPECIFIC SUBSYSTEM DESIGN/DEVELOPMENT NCU COSTS

APPLICATION 2

FORM 2

	①		②	③	④	⑤	⑥	⑦	⑧
	PARAMETER VALUE		DES/DEV CER VALUE	NOVELTY FRACTION	DES/DEV REDUCTION FACTOR	NUMBER OF TYPE APPROVAL TESTS	DES/DEV NCU COST	TEST NCU COST	SUBSYSTEM DES/DEV NCU COST
SYMBOL SOURCE	INPUT		CER	N_F INPUT	F_D TABLE B-2	N_T TABLE B-3	.55 x ① x ② x④	.09 x① x ② x⑤	⑥ + ⑦
SUBSYSTEM NAME	PS	NPS							
STRUCTURE I	200		2.53	.5	.85	3	236.56	136.62	373.18
STRUCTURE II	30		7.7	.5	.85	3	107.99	62.37	170.36
STRUCTURE III	150		10.5	0	.5	1	433.13	141.75	574.88
PROPULSION	50		1.711	0	.5	1	23.53	7.70	31.23
GUIDANCE	50		14.5	.7	.85	3	338.94	195.75	534.69
ATTITUDE CONTROL	70		11.2	.7	.85	3	366.52	211.68	578.20
COMMUNICATIONS	50	50	9.1	1.0	1.0	4	250.25	163.8	414.05
DATA HANDLING	60		12.5	.8	1.0	4	412.50	270.00	682.50
POWER	0.8		785	0	.5	1	172.70	56.52	229.22
SCIENCE	100		8.3	1.0	1.0	4	456.50	298.8	755.3
SUBTOTALS							2,798.62	1,544.99	
SUBSYSTEM DESIGN/DEVELOPMENT NCU COST (SSD/DC)									4,343.61

SUBSYSTEM HARDWARE COSTS

APPLICATION 2 FORM 3

	①		②	③		④	⑤	⑥	⑦	⑧
	Parameter Value		Hardware Unit Cost CER Value	Hardware Unit Cost		Number of Test Articles	Number of Flight Articles	Subsystem Hardware NCU Cost	Flight Article Test Cost	Hardware NCU Cost
Symbol Source	Input		CER	① x ② Form 1		N_{TA} Table B-3	N_{FA} Input	(④ + ⑤) x ③	.09 x .5 x (2-①) x (2-②)	⑥+⑦
Subsystem Name	PS	NPS		PS	NPS					
Structure I	200		.254	50.8		3	3	304.8	136.62	441.42
Structure II	30		.43	12.9		3	3	77.4	62.37	139.77
Structure III	150		.31	46.5		1	3	186	425.25	611.25
Propulsion	50		.0309	1.545		1	3	6.18	23.10	29.28
Guidance	50		.51	25.5		3	3	153	195.75	348.75
Attitude Control	70		.56	39.2		3	3	235.2	211.68	446.88
Communications	50		.57	28.50		4	3	199.5	122.85	322.35
		50			149.17		3	447.51	122.85	570.36
Data Handling	60		1.43	85.8		4	3	600.6	202.5	803.10
Power	.8		107	85.6		1	3	342.4	169.56	511.96
Science	100		.645	64.5		4	3	451.5	224.1	675.60
Subtotals								3,004.09	1,896.63	
Subsystem hardware NCU cost (SSHWC)										4,900.72

E. Application 3

In this last application, the major, new and unique features of the model are utilized. Assume that four subsystems--guidance, attitude control, communications, and data handling--are to be procured in a large enough quantity to qualify as a production-type or non-program specific purchase and that a significant number of pairs will be installed in the spacecraft. Consequently, the savings attributable to this "mass" production are computed by using the two-part Form 4. Form 4 is utilized after Forms 1, 2, and 3 have been completed.

With Form 4, first fill out Part A which determines the total number of assembled spacecraft from all programs which will share the pairs of subsystems. This is a symmetrical array; therefore only one entry for each pair is made. For example, guidance and data handling are paired 7 times (an input parameter from Table 3).

Part B of Form 4 is used to translate the Commonality Interaction coefficients into remaining value parameters through the use of Tables B-5 and B-6.

For example, Structure I is paired with Structure II a total of three times. Using Table B-5, the number of pairs (3) and the 80% column yield a value of 0.95 which is entered in two places on Part B, the intersection of Structure I and Structure II, and the intersection of Structure II and I. As currently implemented, some interactions either never occur, or if they do, the interaction is negligible. These have been blanked out on Part A and set to unity on Part B.

Part B is completed by entering the product of each row from Columns 1 to 10 in Column 11, entering the appropriate values in Column 12 and completing the Column 14 instructions. Totaling Column 14 provides the Adjusted Subsystem Total NCU Cost (ASSTC).

In Application 2, the Subsystem Total NCU Cost was utilized as the input parameter to determine the various program component elements. Application 2 did not utilize the saving for pair-wise commonality. To utilize the savings for pair-wise commonality, the Adjusted Subsystem Total NCU Cost is utilized as the input parameter. The appropriate values are then entered onto Form 5.

NON PROGRAM SPECIFIC SUBSYSTEM NCU ACQUISITION COSTS

APPLICATION 3 FORM 1

	①	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩	⑪	⑫	⑬
	PARAMETER VALUE	DES/DEV CER VALUE	NOVELTY FRACTION	DES/DEV REDUCTION FACTOR	NUMBER OF TYPE APPR TESTS	DES/DEV NCU COST	TEST NCU COST	HARDWARE UNIT COST CER VALUE	FIRST UNIT COST	NUMBER OF UNITS PRODUCED	LEARNING SAVING FACTOR	LEARNING CURVE RED FACTOR	AMORTIZED UNIT ACQ NCU COST
SYMBOL			N_F	F_D	N_T							F_L	
SOURCE	INPUT NPS	CER	INPUT	TABLE B-2	TABLE B-3	.5 x① x②x④	.09 x① x②x⑤	CER	①x⑧	INPUT	INPUT	TABLE 4	(⑥ + ⑦ + (⑤ x ⑨) + (⑨ x ⑩ x ⑫)) / ⑩
SUBSYSTEM													
STRUCT I			1.0	1.0									
STRUCT II			1.0	1.0									
STRUCT III			1.0	1.0									
PROPUL			1.0	1.0									
GUIDANCE	50	14.5	1.0	1.0	4	398.75	261.00	.51	25.50	10	.85	.771	95.84
ATT CTRL	70	11.2	1.0	1.0	4	431.20	282.24	.56	39.20	10	.85	.771	117.23
COMM	100	9.1	1.0	1.0	4	500.50	327.60	.57	57.00	15	.80	.663	108.20
DATA HAND	60	12.5	1.0	1.0	4	412.50	270.00	1.43	85.80	20	.90	.801	120.01
POWER			1.0	1.0									
SCIENCE			1.0	1.0									

NOTE: USE THIS CALCULATION WHEN THE NUMBER OF FLIGHT ARTICLES TO BE PRODUCED IS 3 OR MORE.

PROGRAM SPECIFIC SUBSYSTEM DESIGN/DEVELOPMENT NCU COSTS

APPLICATION 3 | FORM 7

	①		②	③	④	⑤	⑥	⑦	⑧
	Parameter Value		Des/Dev CER Value	Novelty Fraction	Des/Dev Reduction Factor	Number of Type Approval Tests	Des/Dev NCU Cost	Test NCU Cost	Subsystem Des/Dev NCU Cost
Symbol Source	Input		CER	N_F Input	F_D Table B-2	N_T Table B-3	.55 x ① x ② x④	.09 x① x ② x⑤	⑥ + ⑦
Subsystem Name	PS	NPS							
Structure I	200		2.53	.3	.7	2	194.81	91.08	285.89
Structure II	30		2.7	.5	.85	3	37.87	21.87	59.74
Structure III	150		10.5	0	.50	1	433.13	141.75	574.88
Propulsion	50		1.711	0	.50	1	23.53	7.70	31.23
Guidance	0	50	14.5						
Attitude Control	0	70	11.2						
Communications	0	100	9.1						
Data Handling	0	60	12.5						
Power	.8		785	0	.5	1	172.70	56.52	229.22
Science	100		8.3	1.0	1.0	4	456.50	298.80	755.30
Subtotals							1,318.54	617.72	
Subsystem Design/Development NCU Cost (SSD/DC)									1,936.26

SUBSYSTEM HARDWARE COSTS

APPLICATION 3 — FORM 3

	① Parameter Value		② Hardware Unit Cost CER Value	③ Hardware Unit Cost		④ Number of Test Articles	⑤ Number of Flight Articles	⑥ Subsystem Hardware NCU Cost	⑦ Flight Article Test Cost	⑧ Hardware NCU Cost
Symbol Source	Input		CER	① x ② Form 1		N_{TA} Table B-3	N_{FA} Input	(④ + ⑤) x ③	.09 x .5 x (2-①) x (2-②)	⑥+⑦
Subsystem Name	PS	NPS		PS	NPS					
Structure I	200		.254	50.80		2	3	254.00	136.62	390.62
Structure II	30		.43	12.90		3	3	77.40	21.87	99.27
Structure III	150		.31	46.50		1	3	186.00	425.25	611.25
Propulsion	50		.0309	1.545		1	3	6.18	23.10	29.28
Guidance		50			95.84		3	287.52	195.75	483.27
Attitude Control		70			117.23		3	351.69	211.68	563.37
Communications		100			108.20		3	324.60	245.70	570.30
Data Handling		60			120.01		3	360.03	202.50	562.53
Power	.8		107	85.60		1	3	342.40	169.56	511.96
Science	100		.645	64.50		4	3	451.50	224.10	675.60
Subtotals								2,641.32	1,856.13	
Subsystem hardware NCU cost (SSHWC)										4,497.45

ADJUSTED SUBSYSTEM NCU COSTS

FORM 4 PART A

	SUBSYSTEM NAME	1 STRUCTURE I	2 STRUCTURE II	3 STRUCTURE III	4 PROPULSION	5 GUIDANCE	6 ATTITUDE CONTROL	7 COMMUNICATIONS	8 DATA HANDLING	9 POWER	10 SCIENCE
1	STRUCTURE I	0	3	3	3	3	3	3	3	3	3
2	STRUCTURE II		0	3	3	3	3	3	3	3	3
3	STRUCTURE III			0	3	3	3	3	3	3	3
4	PROPULSION				0	3	3	3	3	3	3
5	GUIDANCE					0	5	7	7	3	3
6	ATTITUDE CONTROL						0	5	5	3	3
7	COMMUNICATIONS							0	7	3	3
8	DATA HANDLING								0	3	3
9	POWER									0	3
10	SCIENCE										0

AT EACH EMPTY INTERSECTION ENTER THE TOTAL NUMBER OF ASSEMBLED SPACECRAFT FROM ALL PROGRAMS WHICH WILL SHARE THE TWO OR PAIRED SUBSYSTEMS: ONE ENTRY FOR EACH SUBSYSTEM PAIR.

ADJUSTED SUBSYSTEM NCU COSTS

FORM 4 PART B

	① STR I	② STR II	③ STR III	④ PROPUL	⑤ GUIDANCE	⑥ ATT CTRL	⑦ COMM	⑧ DATA HD	⑨ POWER	⑩ SCIENCE	⑪ SUBSYSTEM INTERACTION PRODUCT	⑫ SUBSYSTEM DES/DEV NCU COST	⑬ HARDWARE NCU COST	⑭ ADJUSTED SUBSYSTEM NCU COST
SOURCE	TABLE B-6										ROW PROD	2-⑧	3-⑧	⑪ x (⑫ + ⑬)
STR I		.95		.9					.9		.76950	285.83	390.62	520.57
STR II	.95					.95	.95		.95	.9	.73306	59.74	99.27	116.56
STR III											1.0	574.88	611.25	1,186.13
PROPUL	.9				.87						.7830	31.23	29.28	47.38
GUIDANCE				.87		.71	.71				.43857		483.27	211.95
ATT CTRL		.95			.71					.87	.58682		563.37	330.60
COMM		.95			.71			.62		.87	.36383		570.30	207.49
DATA HD							.62			.87	.53940		562.53	303.43
POWER	.9	.95								.87	.74385	229.22	511.96	551.33
SCIENCE		.9				.87	.87	.87	.87		.51561	755.30	675.60	737.79

ADJUSTED SUBSYSTEM TOTAL NCU COST (ASSTC) 4,213.23

F. Application Comparison

In the three applications, various costs associated with either the hardware or program component cost were either determined directly from the CERs--program component cost--or determined through a process requiring the use of the calculation forms. In this section, the completed Form 5 is presented with the appropriate entry for each component of the cost. In the lower portion of that form is an example of how comparisons can be expressed. As shown, Application 1 was considered to be the base line. The relative NCU cost between each of the remaining applications and the base line are indicated. As expected, the use of increasing amounts of commonality significantly reduced the program NCU cost.

TOTAL PROGRAM NCU COSTS

FORM 5

I. PROGRAM NCU COST	SOURCE	APPLICATION 1	APPLICATION 2	APPLICATION 3	APPLICATION 4
A. HARDWARE COMPONENT					
1. SSD/DC	FORM 2	5,987.32	4,343.61	1,936.26	
2. SSHWC	FORM 3	4,944.20	4,900.72	4,497.45	
3. TOTAL HARDWARE COMPONENT		10,931.72	9,244.33	6,433.7	
ASSTC	FORM 4	N/A	N/A	4,213.23	
B. PROGRAM LEVEL COMPONENT					
1. PROGRAM MANAGEMENT	CER	620.0	550.0	330.0	
2. SYS ANALYSIS & SYS ENGR	CER	1,000.0	800	360.0	
3. SYSTEM TEST	CER	860.0	760	440.0	
4. QUAL ASSUR & RELIABILITY	CER	570	500	295.0	
5. ASSEMBLY & INTEGRATION	CER	590	500	250.0	
6. OPERATIONAL SUP EQUIP	CER	70	82	160.0	
7. TOTAL PROGRAM LEVEL COMP		3,710.00	3,192	1,835.00	
C. TOTAL PROGRAM NCU COST (TPC)		14,641.72	12,436.33	8,268.7	

II. COMPARISON BETWEEN PROGRAMS

A. BASELINE NCU COST (BC) 14,641.72

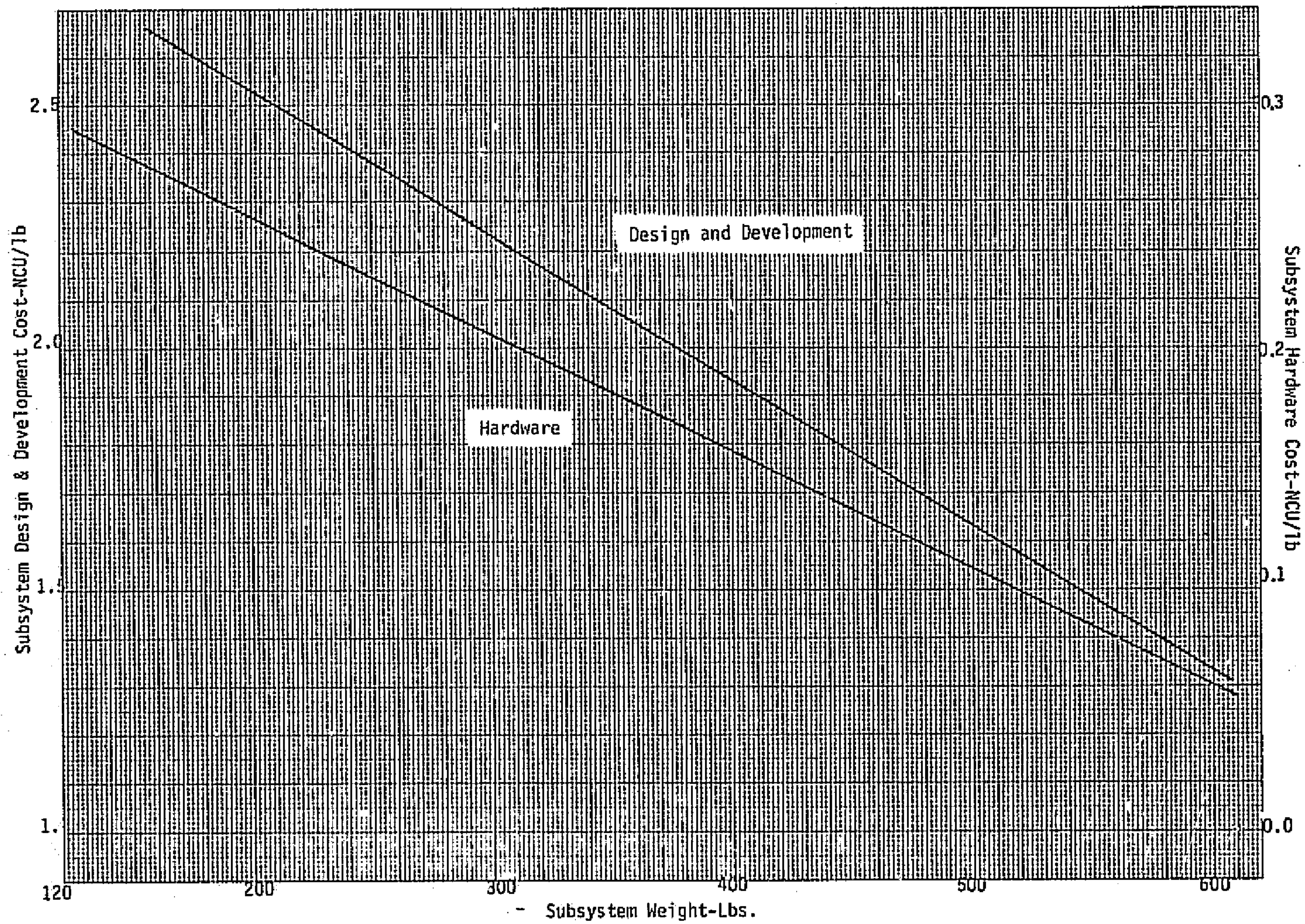
B. PERCENT SAVINGS IN TOTAL PROGRAM OR PROJECT COST ATTRIBUTABLE TO COMMONALITY $\left(\frac{BC-TPC}{BC} X100\right)$

	Application 1	Application 2	Application 3	Application 4
Percent savings	0	15	44	

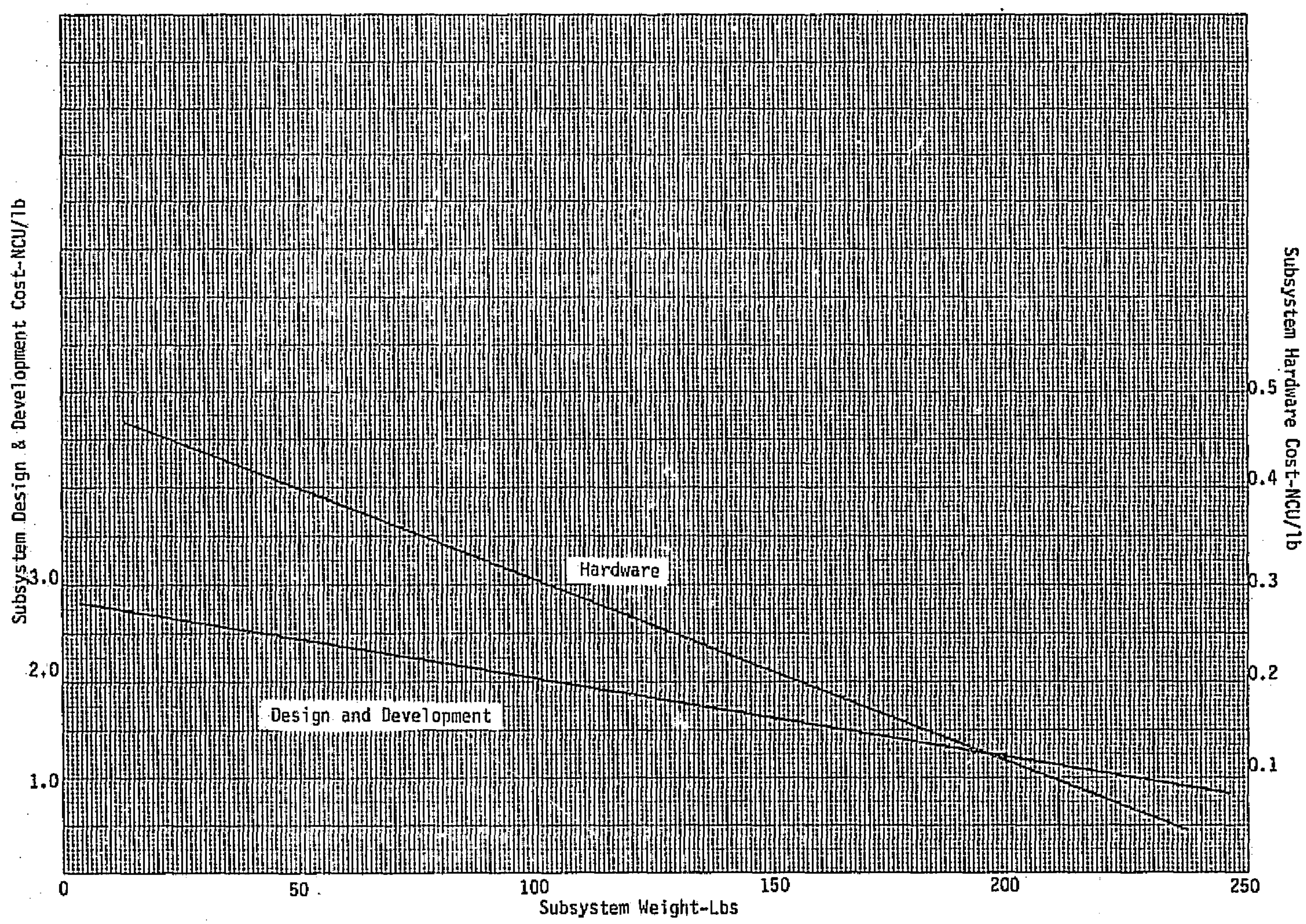
APPENDIX A

CERs FOR EACH COMMONALITY EVALUATION MODEL SUBSYSTEM

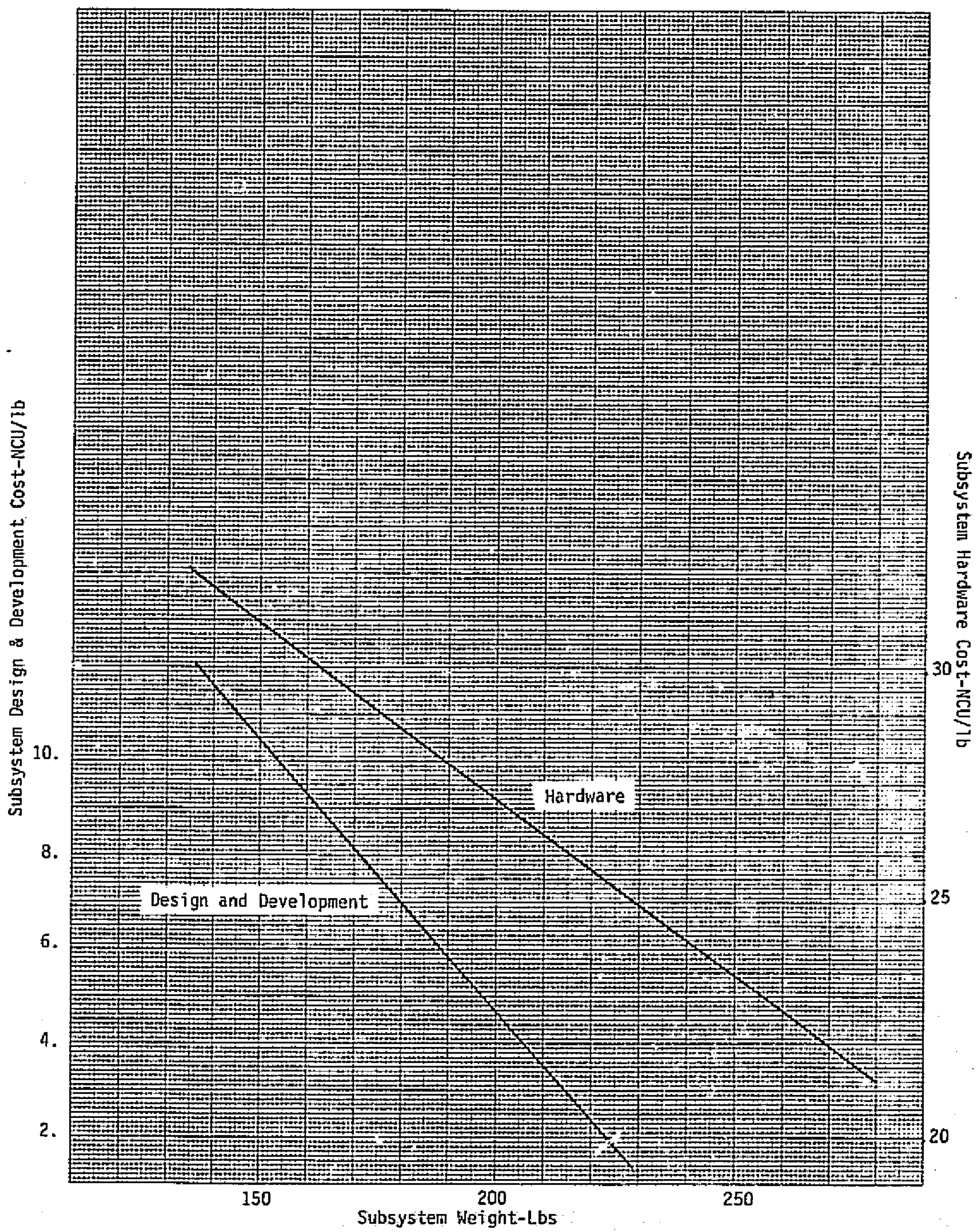
A-1. SUBSYSTEM CER: STRUCTURE-I (FIXED STRUCTURE)



A-2. SUBSYSTEM CER: STRUCTURE-II (MECHANICAL DEVICES)



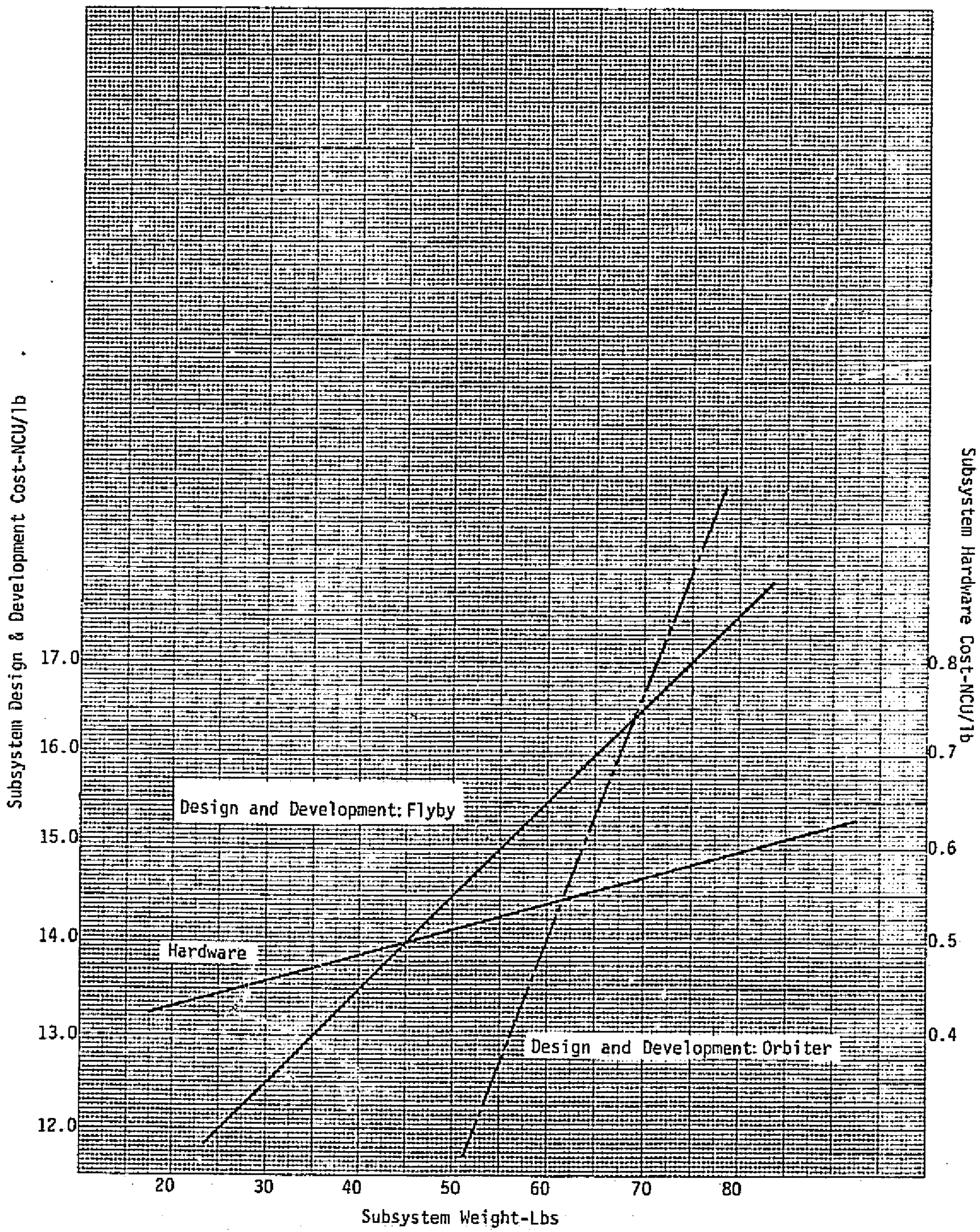
A-3. SUBSYSTEM CER: STRUCTURE-III (PRESSURE STRUCTURE)



A-4. SUBSYSTEM CER: PROPULSION

Type	Thrust	D&D NCU/lb-Th	HW Cost NCU/lb-Th	Use - Comments
Hydrazine	50 lbs	1.711	.0309	Flyby-midcourse--single chamber only
Monomethyl/hypazine + Nitrogen Tetroxide	300 lbs	1.859	.0488	Orbital injection and midcourse corrections--single chamber only

A-5. SUBSYSTEM CER: GUIDANCE



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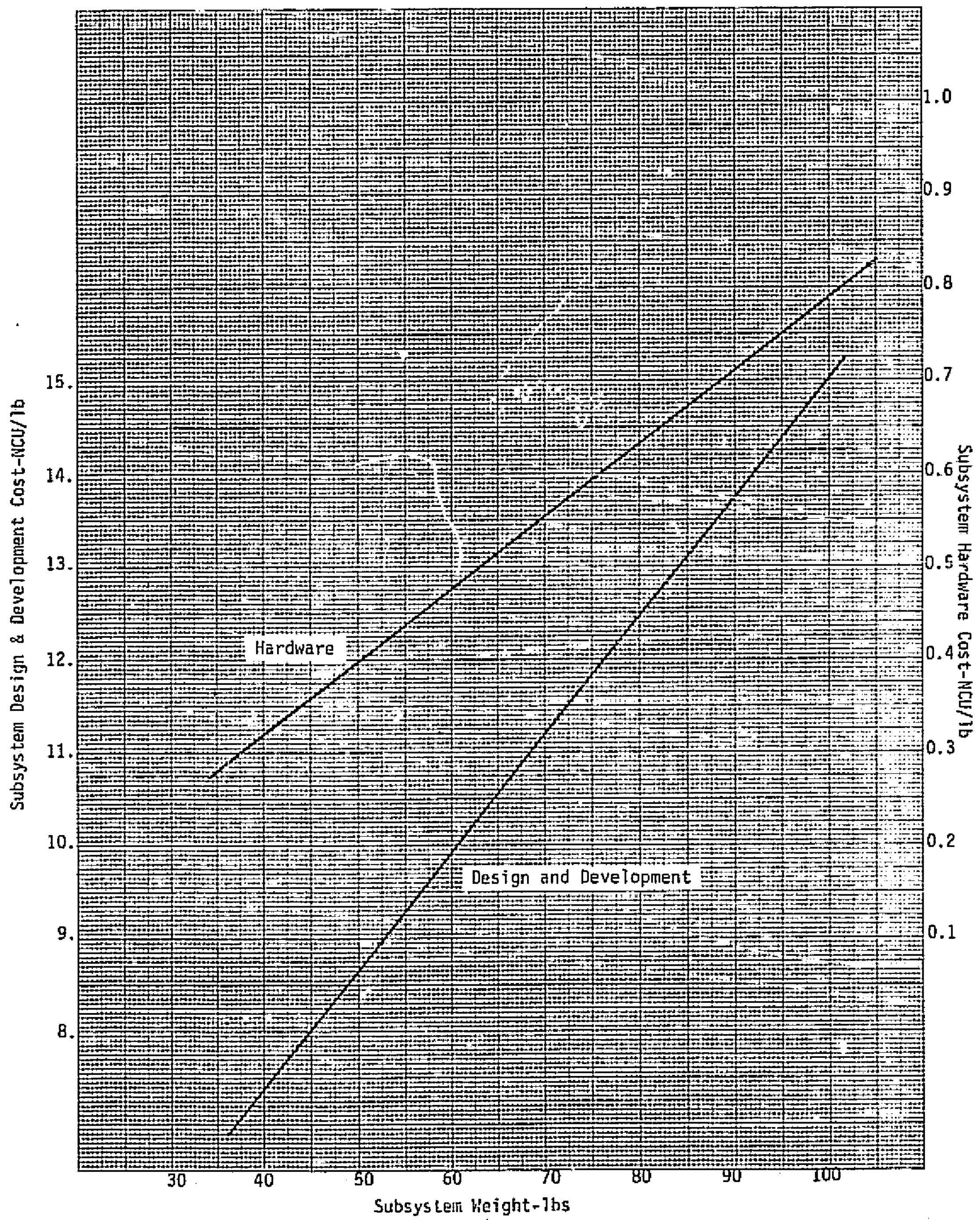
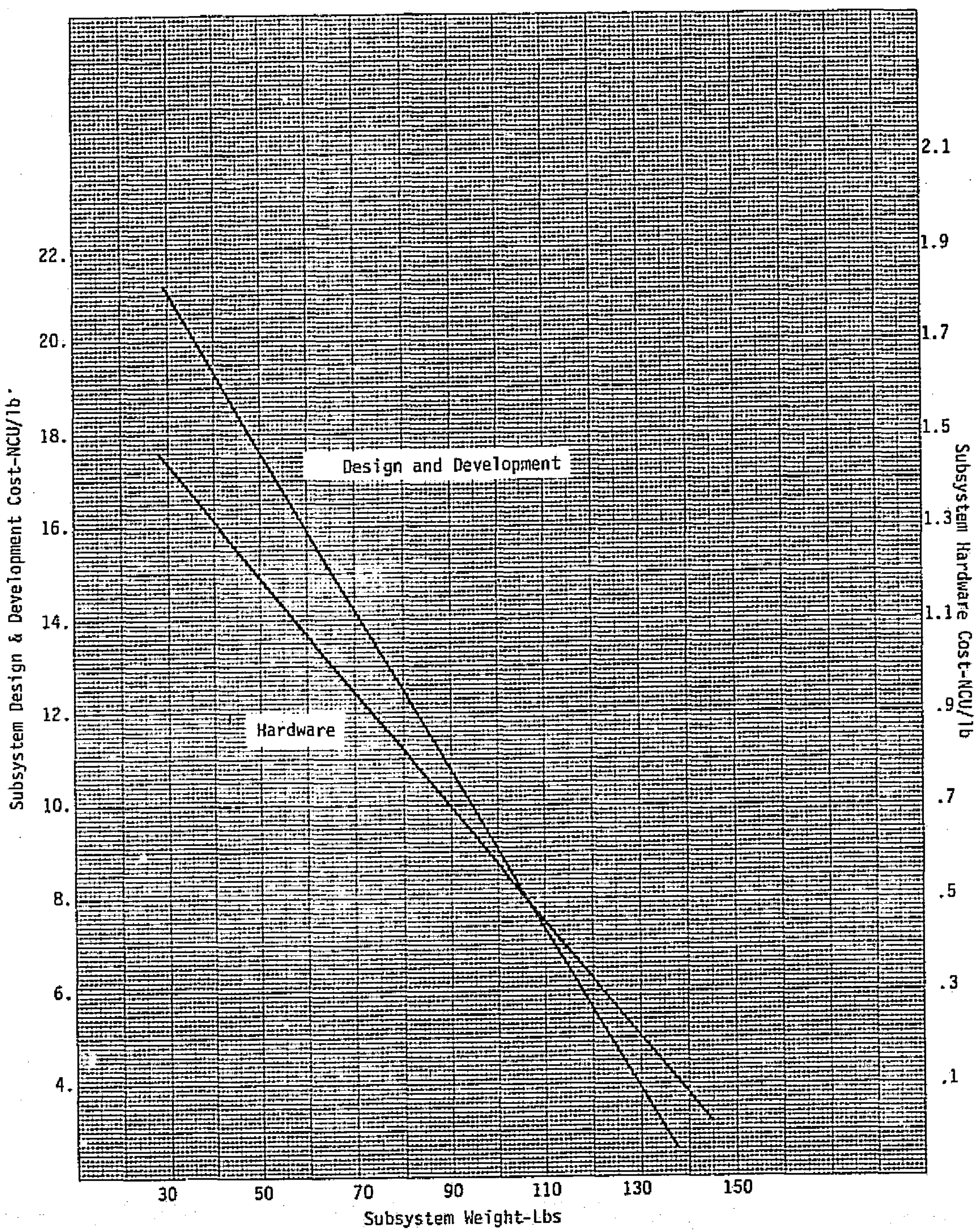
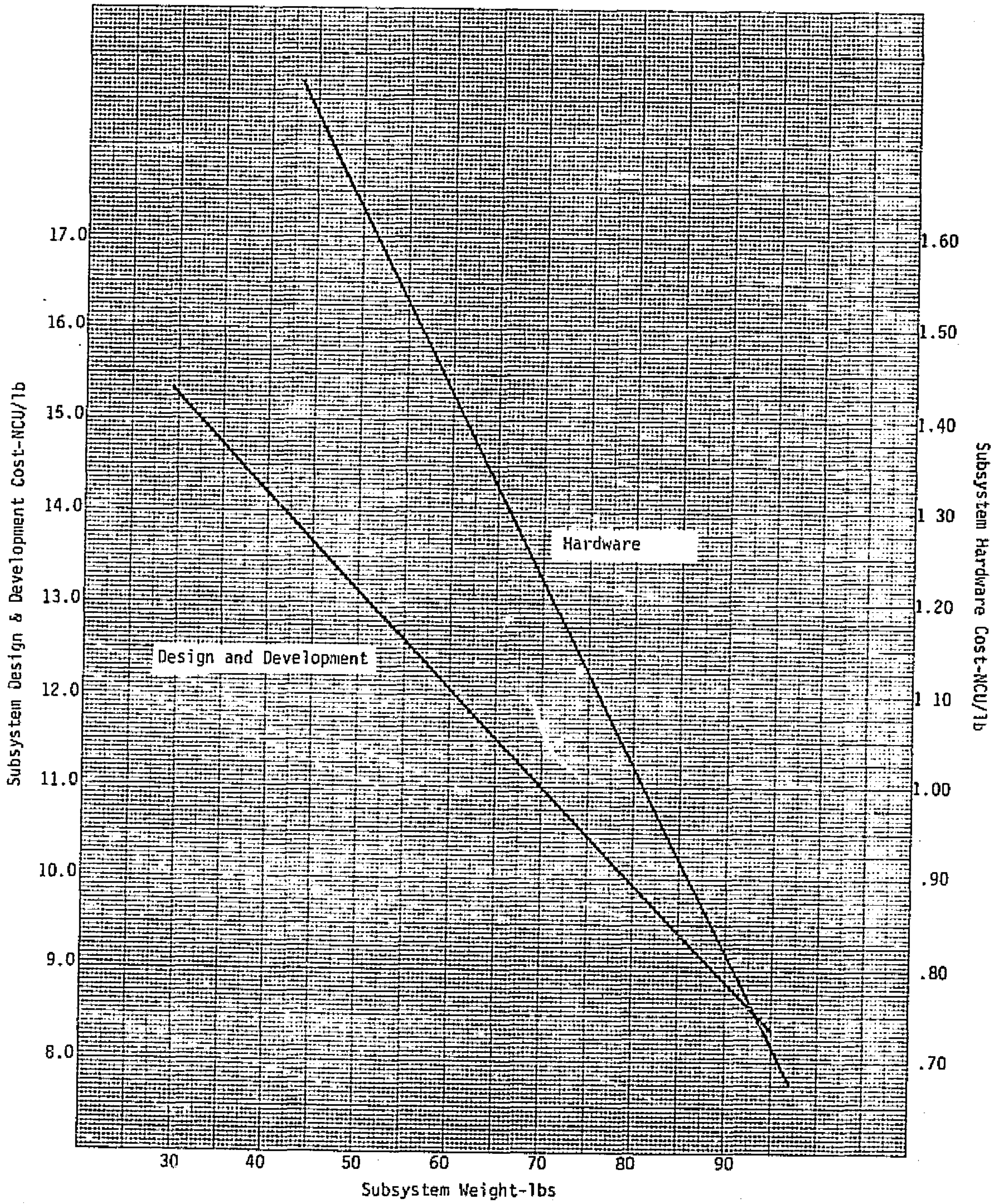
A-6. SUBSYSTEM CER: ATTITUDE CONTROL



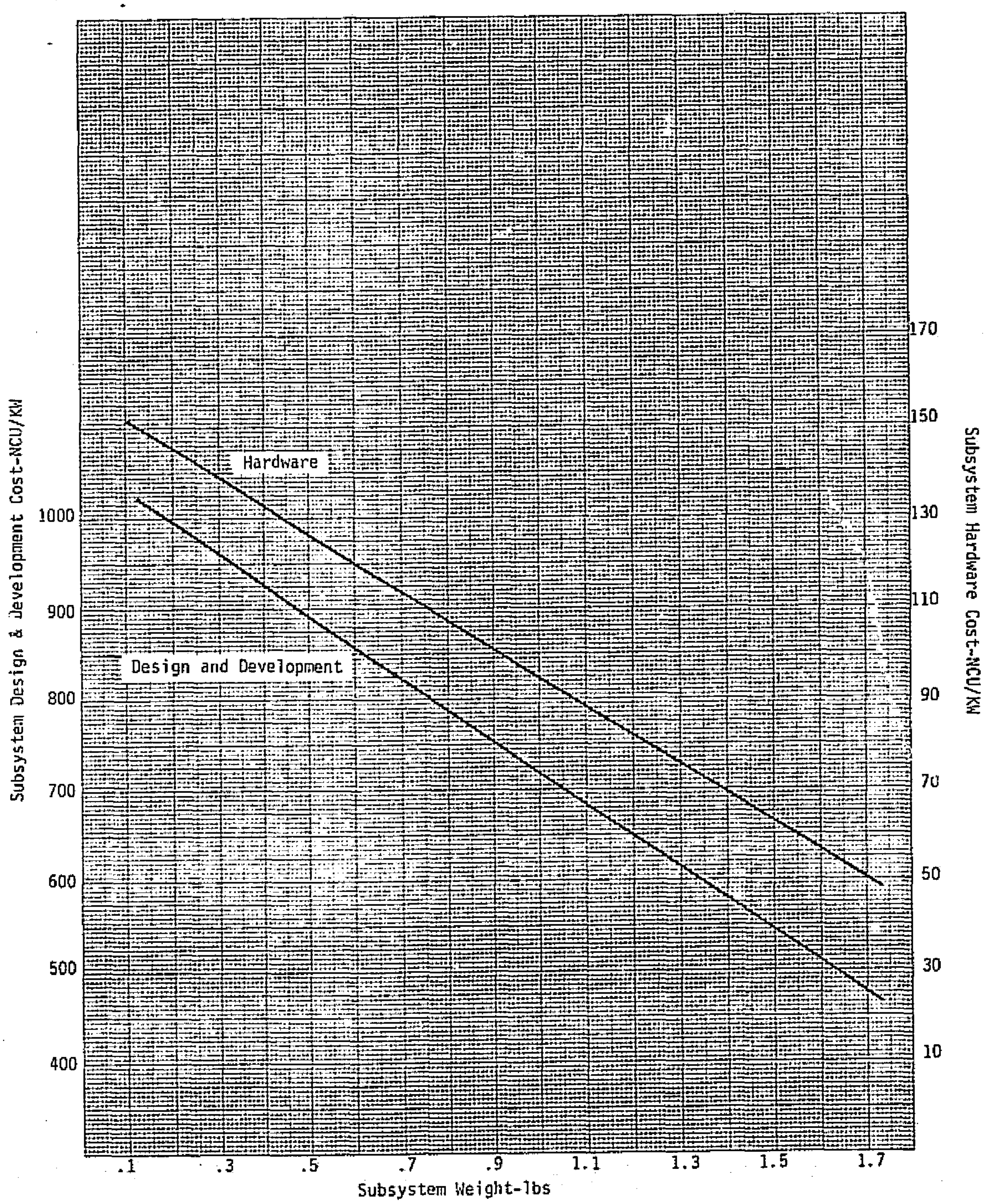
A-7. SUBSYSTEM CER: COMMUNICATIONS



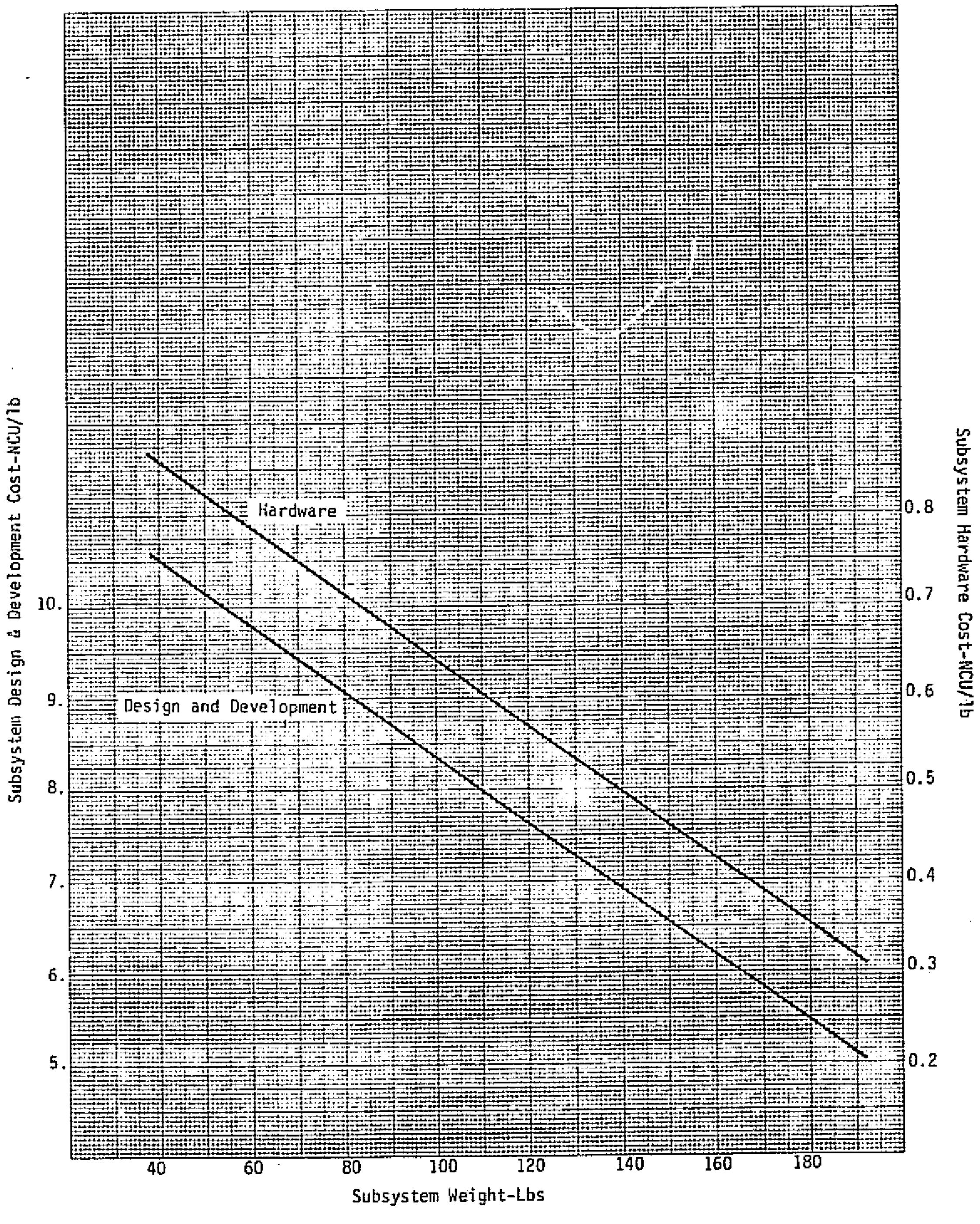
A-8. SUBSYSTEM CER: DATA HANDLING



A-9. SUBSYSTEM CER: ELECTRIC POWER (SOLAR ARRAY SOURCE)



A-10. SUBSYSTEM CER: SCIENCE (SCAN PLATFORM & STRUCTURE MOUNTED)



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APPENDIX B

PERTINENT TABLES FOR THE COMMONALITY EVALUATION MODEL

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APPENDIX B

Table B-1

NOVELTY FRACTION ASSIGNMENT FOR S/S DESIGN & DEVELOPMENT (N_F)

	Material and Fabrication Novelty				
	Previously Used Materials and Fabrication Technology	Minor Change in Materials Properties or in Fabrication Technology	Significant Change in Materials or in Fabrication Technology	Major Change in Fabrication or a Material with Little Experience in Spacecraft Usage	Completely New Materials and Fabrication Technology
Prior Design and Software	0.00	.25	.50	.75	1.00
Minor Design or Software Changes	.25	.40	.60	.80	1.00
Significant Changes to a Prior Design or Software	.5	.65	.80	.90	1.00
Major Change to an Old Design	.75	.80	.85	.95	1.00
Completely New Design and Software	1.00	1.00	1.00	1.00	1.00

Table B-2

DESIGN/DEVELOPMENT REDUCTION FACTOR (F_D) AS A FUNCTION OF THE NOVELTY FRACTION (N_F)

N_F	F_D
1.0 - .75	1.00
.74 - .5	0.85
.49 - .3	0.7
.29 - .15	0.65
.14 - 0.0	0.5

Table B-3

TYPE APPROVAL TESTING ARTICLES* (N_T)

Subsystem Name	Novelty Fraction (N_F) 1.0-0.75	0.74-0.5	0.49-0.3	0.29-0.15	.14-0.0
Struc I	3	3	2	2	1
Struc II	3	3	2	2	1
Struc III	3	3	2	2	1
Propulsion	3	2.5	2	1.5	1
Guidance	4	3	3	2.5	2
Attitude Control	4	3	3	2	1
Communications	4	3	3	2.5	2
Data Handling	4	3	3	2.5	2
Power (elect)	3	2.5	2	1.5	1
Science	4	3	3	2.5	1.5

* In Type Approval Testing each test requires that a prototype unit be made. Hence #Test - #Articles; = N_T - N_{TA} . None of the TA-Testing articles are used as Flight Articles; therefore, all of Flight Articles must be made separately after TA has been obtained.

Table B-4

PRODUCTION LEARNING COST REDUCTION FACTOR (F_2)

Number of Units	Cumulative Average Unit Cost Reduction Factor 90% Curve	85% Curve	80% Curve
1	1.00	1.00	1.00
2	0.950	0.925	0.900
3	0.922	0.883	0.846
4	0.903	0.855	0.810
5	0.888	0.834	0.783
6	0.876	0.817	0.762
7	0.866	0.803	0.744
8	0.857	0.791	0.729
9	0.850	0.780	0.716
10	0.843	0.771	0.705
11	0.837	0.763	0.695
12	0.832	0.755	0.685
13	0.827	0.748	0.677
14	0.823	0.742	0.670
15	0.818	0.736	0.663
16	0.815	0.731	0.656
17	0.811	0.726	0.650
18	0.807	0.721	0.645
19	0.804	0.717	0.639
20	0.801	0.713	0.634

Table B-5

COMMONALITY INTERACTION COEFFICIENT LEVEL SELECTION (IN PERCENT)

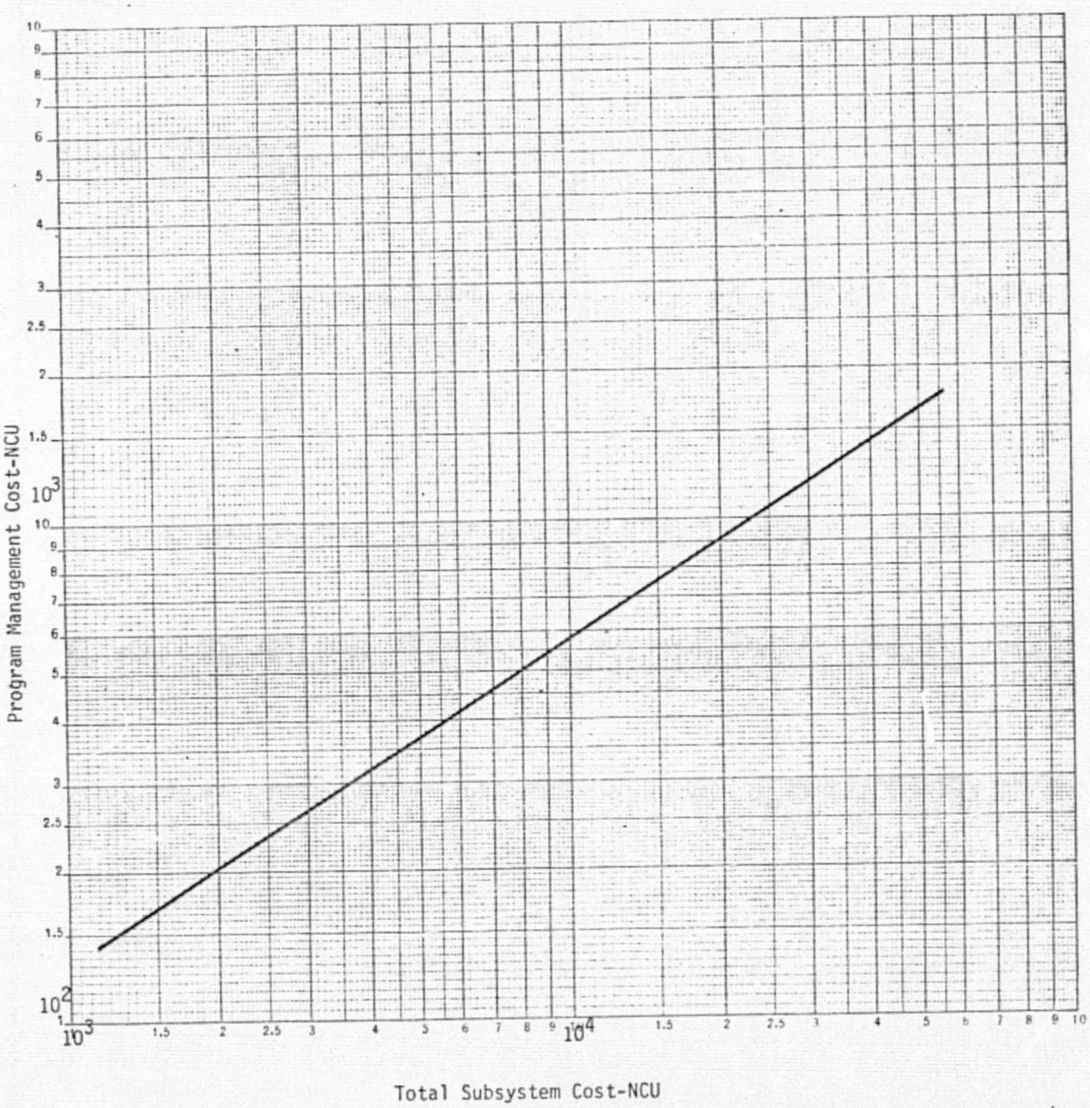
	Subsystem Name	1 Structure I	2 Structure II	3 Structure III	4 Propulsion	5 Guidance	6 Attitude Control	7 Communications	8 Data Handling	9 Power (elect.)	10 Science
1	Structure I		80		70					70	
2	Structure II	80					80	80		80	70
3	Structure III										
4	Propulsion	70				60					
5	Guidance				60		60	70			
6	Attitude Control		80			60					60
7	Communications		80			70			60		60
8	Data Handling							60			60
9	Power (elect.)	70	80								60
10	Science		70				60	60	60	60	

Table B-6

COMMONALITY INTERACTION COEFFICIENTS (π_{ij})

Number Common Pairs	80% Curve Coefficients	70% Curve Coefficients	60% Curve Coefficients
1	1.00	1.00	1.00
2	1.00	1.00	1.00
3	0.95	0.90	0.87
4	0.89	0.83	0.78
5	0.85	0.78	0.71
6	0.82	0.74	0.66
7	0.80	0.71	0.62
8	0.78	0.68	0.59
9	0.76	0.66	0.57
10	0.75	0.64	0.54

EXHIBIT C-1. PROGRAM COMPONENTS: PROGRAM MANAGEMENT



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APPENDIX C

CERs FOR EACH COMMONALITY EVALUATION MODEL PROGRAM COMPONENT

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EXHIBIT C-2. PROGRAM COMPONENTS: SYSTEM ANALYSIS & SYSTEM ENGINEERING

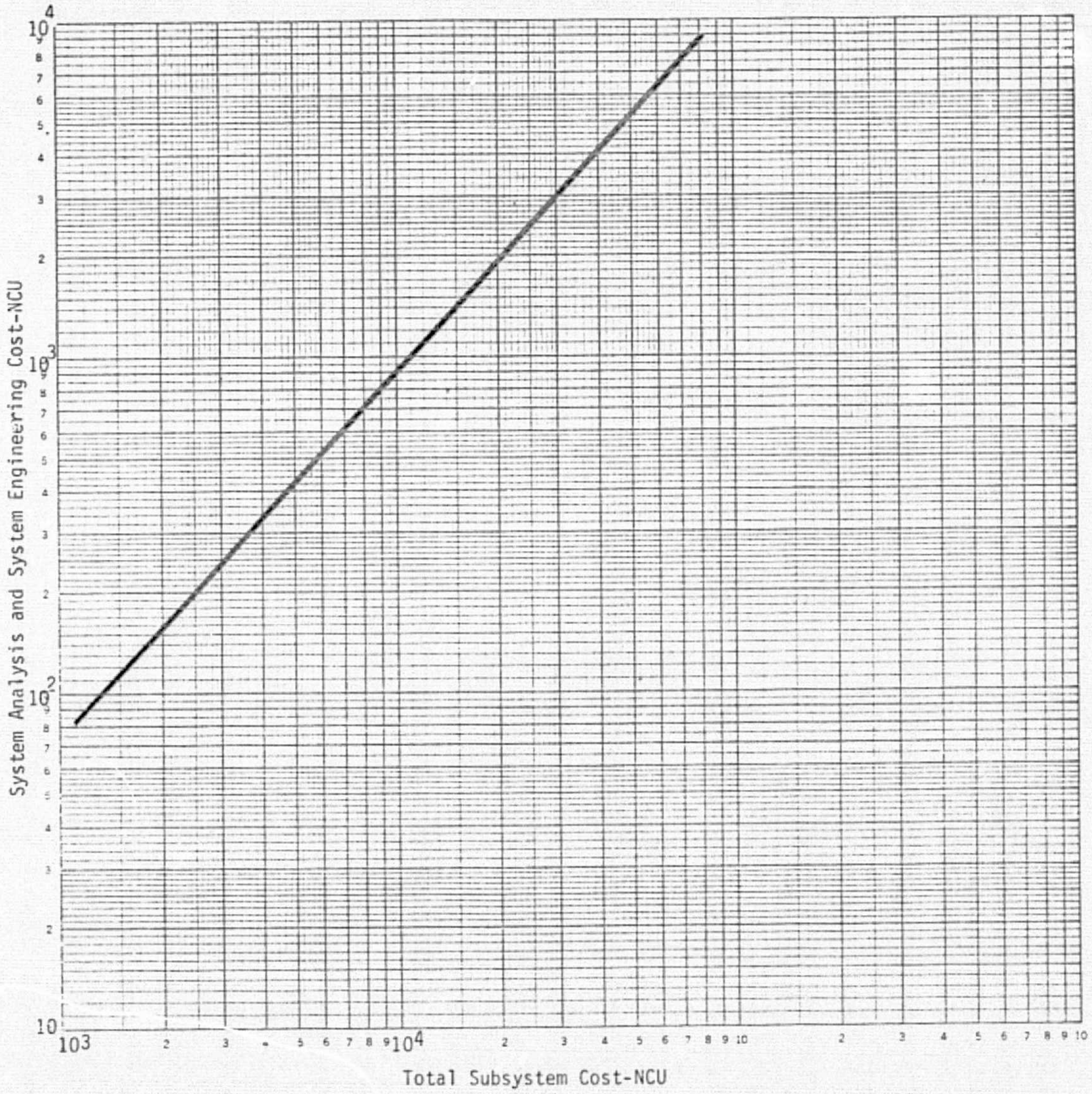

EXHIBIT C-3. PROGRAM COMPONENTS: SYSTEM TEST

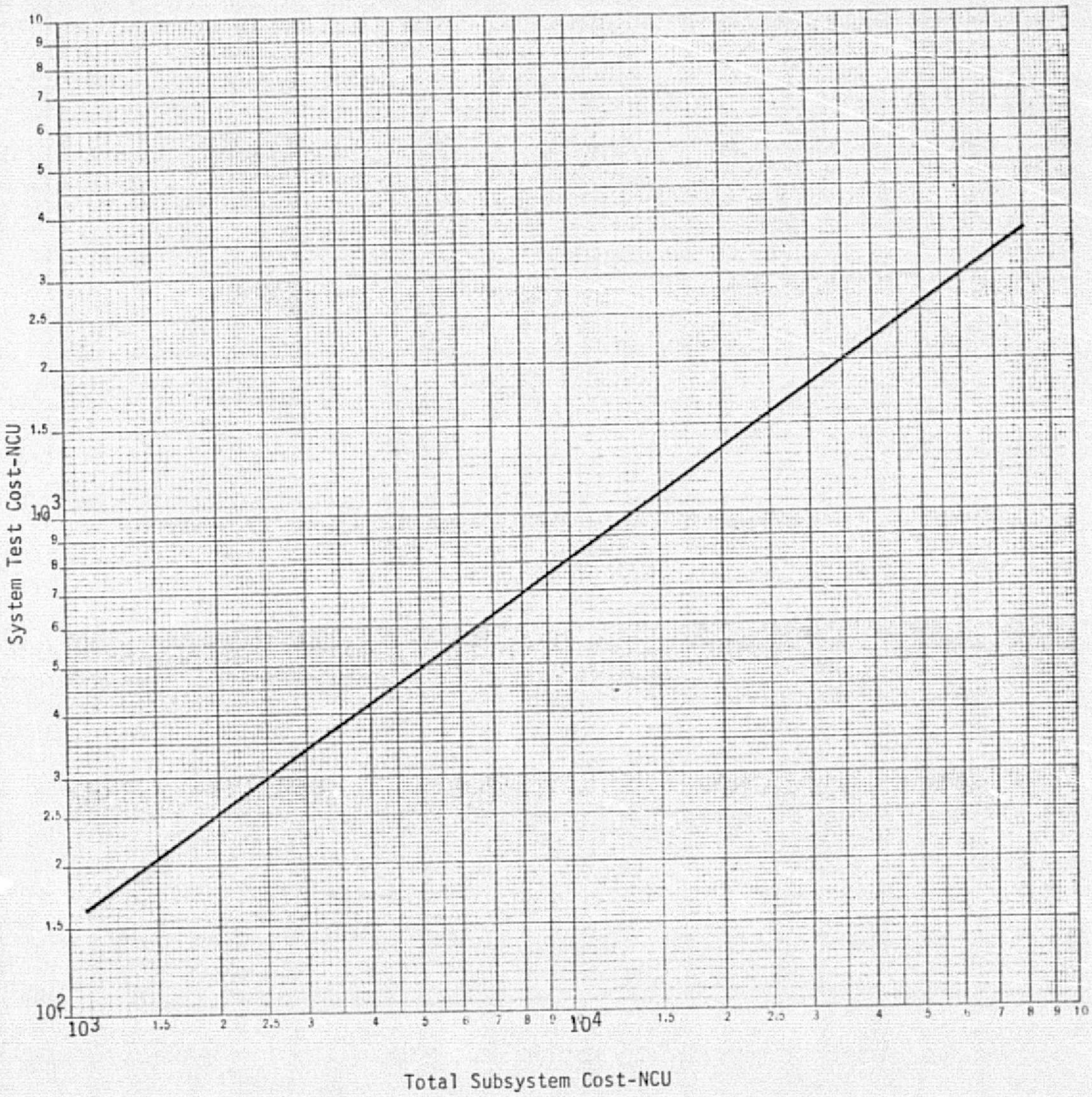

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EXHIBIT C-4. PROGRAM COMPONENTS: QUALITY ASSURANCE & RELIABILITY (QA&R)

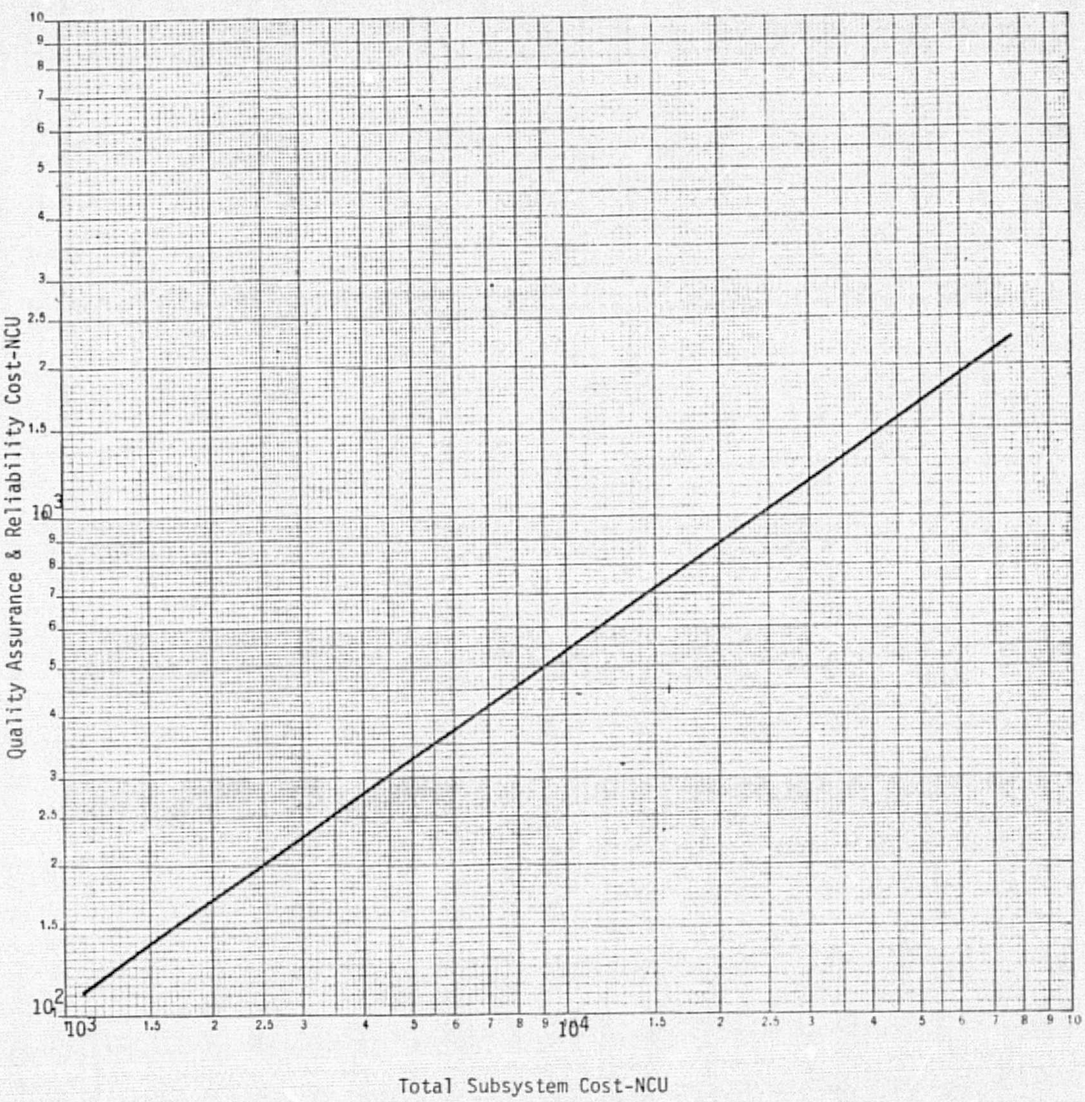


EXHIBIT C-5. PROGRAM COMPONENTS: ASSEMBLY AND INTEGRATION

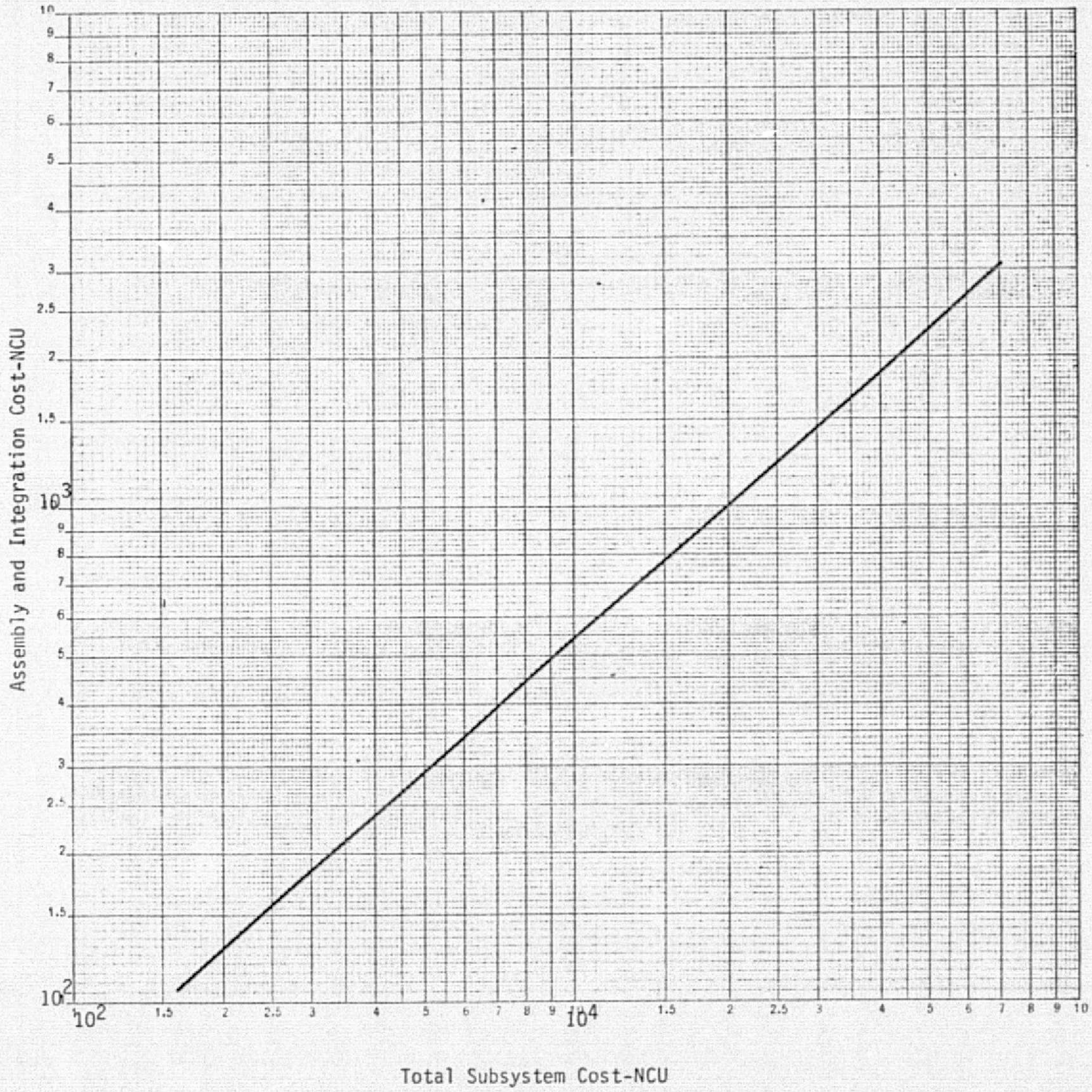
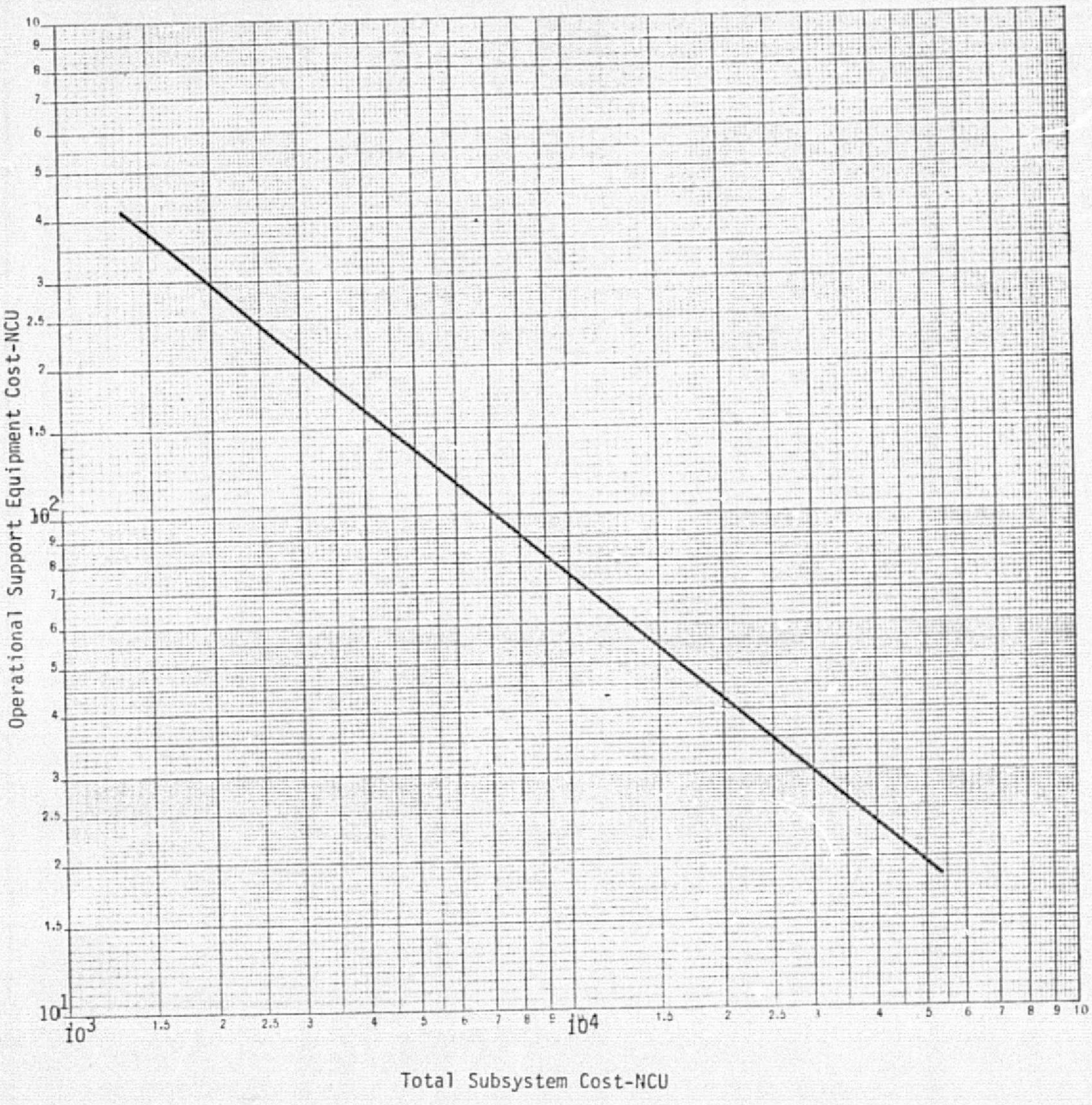


EXHIBIT C-6. PROGRAM COMPONENTS: OPERATIONAL SUPPORT EQUIPMENT (OSE)



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APPENDIX D

COMPUTATIONAL FORMS

NON PROGRAM SPECIFIC SUBSYSTEM NCU ACQUISITION COSTS

FORM 1

	①	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩	⑪	⑫	⑬
	PARAMETER VALUE	DES/DEV CER VALUE	NOVELTY FRACTION	DES/DEV REDUCTION FACTOR	NUMBER OF TYPE APPR TESTS	DES/DEV NCU COST	TEST NCU COST	HARDWARE UNIT COST CER VALUE	FIRST UNIT COST	NUMBER OF UNITS PRODUCED	LEARNING SAVING FACTOR	LEARNING CURVE RED FACTOR	AMORTIZED UNIT ACQ NCU COST
SYMBOL			N_F	F_D	N_T							F_L	
SOURCE	INPUT NPS	CER	INPUT	TABLE B-2	TABLE B-3	.5 x① x②x④	.09 x① x②x⑤	CER	①x⑧	INPUT	INPUT	TABLE 4	[⑥ + ⑦ + (⑤ x ⑨) + (⑨ x ⑩ x ⑫)] / ⑩
SUBSYSTEM													
STRUCT I													
STRUCT II													
STRUCT III													
PROPUL													
GUIDANCE													
ATT CTRL													
COMM													
DATA HAND													
POWER													
SCIENCE													

NOTE: USE THIS CALCULATION WHEN THE NUMBER OF FLIGHT ARTICLES TO BE PRODUCED IS 3 OR MORE.

PROGRAM SPECIFIC SUBSYSTEM DESIGN/DEVELOPMENT NCU COSTS

FORM 2

	① Parameter Value		② Des/Dev CER Value	③ Novelty Fraction	④ Des/Dev Reduction Factor	⑤ Number of Type Approval Tests	⑥ Des/Dev NCU Cost	⑦ Test NCU Cost	⑧ Subsystem Des/Dev NCU Cost
Symbol Source	Input		CER	N_F Input	F_D Table B-2	N_T Table B-3	.55 x ① x ② x④	.09 x① x ② x⑤	⑥ + ⑦
Subsystem Name	PS	NPS							
Structure I									
Structure II									
Structure III									
Propulsion									
Guidance									
Attitude Control									
Communications									
Data Handling									
Power									
Science									
Subtotals									

Subsystem Design/Development NCU Cost (SSD/DC)

SUBSYSTEM HARDWARE COSTS

FORM 3

	① Parameter Value		② Hardware Unit Cost CER Value	③ Hardware Unit Cost		④ Number of Test Articles	⑤ Number of Flight Articles	⑥ Subsystem Hardware NCU Cost	⑦ Flight Article Test Cost	⑧ Hardware NCU Cost
Symbol						N_{TA}	N_{FA}			
Source	Input		CER	① x ② Form 1		Table B-3	Input	(④ + ⑤) x ③	.09 x .5 x (2-①) x (2-②)	⑥+⑦
Subsystem Name	PS	NPS		PS	NPS					
Structure I										
Structure II										
Structure III										
Propulsion										
Guidance										
Attitude Control										
Communications										
Data Handling										
Power										
Science										
Subtotals										

Subsystem hardware NCU cost (SSHWC)

ADJUSTED SUBSYSTEM NCU COSTS

FORM 4 PART A

	SUBSYSTEM NAME	1 STRUCTURE I	2 STRUCTURE II	3 STRUCTURE III	4 PROPULSION	5 GUIDANCE	6 ATTITUDE CONTROL	7 COMMUNICATIONS	8 DATA HANDLING	9 POWER	10 SCIENCE
1	STRUCTURE I	0									
2	STRUCTURE II		0								
3	STRUCTURE III			0							
4	PROPULSION				0						
5	GUIDANCE					0					
6	ATTITUDE CONTROL						0				
7	COMMUNICATIONS							0			
8	DATA HANDLING								0		
9	POWER									0	
10	SCIENCE										0

AT EACH EMPTY INTERSECTION ENTER THE TOTAL NUMBER OF ASSEMBLED SPACECRAFT FROM ALL PROGRAMS WHICH WILL SHARE THE TWO OR PAIRED SUBSYSTEMS: ONE ENTRY FOR EACH SUBSYSTEM PAIR.

ADJUSTED SUBSYSTEM NCU COSTS

FORM 4 PART B

	(1) STR I	(2) STR II	(3) STR III	(4) PROPUL	(5) GUIDANCE	(6) ATT CTRL	(7) COMM	(8) DATA HD	(9) POWER	(10) SCIENCE	(11) SUBSYSTEM INTERACTION PRODUCT	(12) SUBSYSTEM DES/DEV NCU COST	(13) HARDWARE NCU COST	(14) ADJUSTED SUBSYSTEM NCU COST
SOURCE	TABLE B-6										ROW PROD	2-(8)	3-(8)	(11) x ((12) + (13))
STR I		___		___					___		___	___	___	___
STR II	___					___	___		___	___	___	___	___	___
STR III											___	___	___	___
PROPUL	___				___						___	___	___	___
GUIDANCE				___		___	___				___	___	___	___
ATT CTRL		___			___					___	___	___	___	___
COMM		___			___			___		___	___	___	___	___
DATA HD							___			___	___	___	___	___
POWER	___	___								___	___	___	___	___
SCIENCE		___				___	___	___	___		___	___	___	___

ADJUSTED SUBSYSTEM TOTAL NCU COST (ASSTC) [ ]

TOTAL PROGRAM NCU COSTS

Form 5

I. Program NCU Cost	Source	Application 1	Application 2	Application 3	Application 4
A. Hardware Component					
1. SSD/DC	Form 2	____	____	____	____
2. SSHWC	Form 3	____	____	____	____
3. Total Hardware Component		____	____	____	____
ASSTC	Form 4	☐	☐	☐	☐
B. Program Level Component					
1. Program Management	CER	____	____	____	____
2. Sys Analysis & Sys Engr	CER	____	____	____	____
3. System Test	CER	____	____	____	____
4. Qual Assur & Reliability	CER	____	____	____	____
5. Assembly & Integration	CER	____	____	____	____
6. Operational Sup Equip	CER	____	____	____	____
7. Total Program Level Comp		____	____	____	____
C. Total Program NCU Cost (TPC)		☐	☐	☐	☐

II. Comparison Between Programs

A. Baseline NCU Cost (BC) ____

B. Percent Savings in Total Program or Project Cost Attributable to Commonality $\left(\frac{BC-TPC}{BC} \times 100\right)$ ____ ____ ____ ____