A STUDY OF LOW COST APPROACHES TO SCIENTIFIC EXPERIMENT IMPLEMENTATION FOR SHUTTLE LAUNCHED AND SERVICED AUTOMATED SPACECRAFT

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17 OCTOBER 1975

FINAL REPORT

Prepared for

National Aeronautics and Space Administration Headquarters
Washington D.C. 20546

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SUMMARY

Scope

This study has been primarily directed at determining the cost reductions that can be obtained in experiment instrumentation by the use of standardized electronics and by the relaxation of instrument reliability requirements. We have limited our considerations to instrumentation for scientific and developmental applications payloads to be flown on Shuttle launched and serviced automated spacecraft.

We have examined two aspects of instrument development which are relevant to cost reduction by standardization. In the experiment system design portion of the study, we have assessed the feasibility of using standardized equipment for experiment instrumentation and have developed a system design approach that most effectively incorporates standardized equipment. The work in the area of electronic packaging was directed at determining the level and form of modularization that is appropriate for the standardized equipment.

We have also examined the mission assurance aspects of instrument development to determine the cost reductions that might be derived from the relaxation of reliability requirements and to formulate a systematic approach to the optimization of mission assurance cost reductions.

In the final phase of the study, we have applied the results of our analyses in these three areas to a representative model HEAO payload in order to provide a concrete example of the cost reductions that can be achieved by a standardized approach to the instrument electronics.

Experiment System Design

The instrumentation requirements of 29 scientific payloads and 11 applications payloads intended for flight on automated spacecraft in the Shuttle era were analyzed. Extensive commonality was found in the various electronic subsystems required to support the sensor subsystems. It was immediately evident that the power conditioning subsystem and the engineering data processing subsystem, as well as many portions of the command and control subsystem, could readily be implemented with standard functional

elements. Analysis of the payload science data processing requirements revealed that ten types of sensors were widely used and that six basic types of standard functional elements could process the sensor output data. The net conclusion was that a reasonably limited family of standard functional elements could satisfy the requirements of a broad range of payloads.

Two alternative system design approaches for a multi-instrument payload using standard functional elements were developed and evaluated. In the first approach, each support subsystem was implemented as an assembly of standard modules satisfying the instrument requirements, and one such assembly was dedicated to each instrument. The second approach considered the sharing between instruments (i.e., centralization) of common support functions in an attempt to increase the efficiency of hardware utilization. In all cases, the limited increase in efficiency achieved was not worth the penalty paid in terms of increased system complexity and interdependence of the instruments. In considering the integrated assemblage of support subsystems dedicated to each instrument, an interesting approach was formulated which significantly increases system flexibility with an integrated command and data processing subsystem under the control of a microprocessor.

Finally, an estimate of the potential cost impact of standardization was made. The results show that the instrument electronics costs can be reduced to about fifteen percent of the cost of the current custom-built, one-time development with production quantities as low as ten units. The cost estimate demonstrated that the cost benefits of standardization result primarily from the amortization of nonrecurrent development costs and are relatively insensitive to recurring production unit costs.

Standardized Modular Packaging

As a starting point, we reviewed five widely-used, standard, modular packaging systems for ground-based laboratory, military and avionic equipment: NIM and CAMAC modules; Navy Standard Hardware Program (SHP) modules; Navy Quick Easy Design (QED) modules, and Air Transport Radio (ATR) enclosures. We have also examined a TRW-developed aerospace standard module, the TRW Slice.

Three of these packaging methods (NIM-CAMAC, QED, and TRW Slice) are modularized at a level that is appropriate for the standard functional elements identified in our experiment system design work. A comparative evaluation of these three approaches was made with respect to suitability for use in a conventional automated spacecraft environment.

NIM-CAMAC modules are designed for laboratory use and would require conversion to conduction cooling and relatively simple structural changes to withstand Shuttle launch vibration.

QED modules are also convection cooled in normal use. In addition, because they are intended primarily for packaging digital circuit functions, modifications are probably required to satisfactorily package low-level analog circuitry.

Since it was developed for this environment, the TRW Slice module is excellent in all areas except ease of replaceability and maintainability.

Our conclusion is that an approach similar to the Slice concept would be very well suited for packaging standard modular instrument electronics. If easy replaceability and maintainability were to become a dominant consideration, an alternative concept derived from NIM-CAMAC and Slice, is suggested.

Mission Assurance

In principle, an optimum instrument reliability can be determined by a trade-off between instrument development cost and operational cost. To perform this trade-off, the dependence of both development cost and operational cost on instrument reliability must be known. In this study, we were primarily concerned with developing an approach to determining the development cost/reliability relationship.

As a first step, typical instrument development activities were analyzed from a mission assurance viewpoint to establish a baseline program representative of current practices. Although directly-identified mission assurance functions typically account for only 18 percent of the instrument development cost, it was determined that the cost of mission assurance activities performed by all program organizational elements amounts to nearly 50 percent of the total development cost. An analysis of instrument in-flight failure data indicated that the reliability of an instrument developed in accordance with the baseline program is about 0.93.

Before turning to the question of cost/reliability relationships, a number of suggestions for improving the efficiency of current mission assurance procedures were formulated. The cost savings that would result by adopting these suggestions was estimated to be on the order of 12 percent of the total development cost.

Next, an interesting approach to determining the relationship between cost and instrument reliability was developed. Since actual implementation of the approach was beyond the scope of this study, a simple, general cost/reliability relationship was used to estimate the magnitude of the cost reductions that might possibly be derived from reduction of instrument reliability requirements. This exercise demonstrated that instrument reliability levels are not currently in the range in which mission assurance activities seriously escalate program costs. As a conse- the estimated cost reduction possible by relaxation of reliability requirements is no greater than about 20 percent.

In considering the impact of standard modules on mission assurance, we came to the conclusion that instrument reliability should be slightly improved due to the growth of reliability with operating experience.

Finally, the question of total cost/reliability optimization was briefly examined. A simple model of the relationship between operational cost and instrument reliability was used to demonstrate the process. It was shown that because of the accompanying rise in operational costs, reduction of reliability from the current value of 0.93 to an optimum value would only yield a reduction in total program cost of about 10 percent.

Model HEAO Payload

The recommended approaches developed in the three study areas were applied to a model payload to assess the potential cost savings for a specific case. The model payload consisted of four of the 14 instruments originally selected by NASA for Missions A and B of the High-Energy Astronomy Observatory (HEAO).

It was found that all of the electronics required for the model payload could be implemented in modular form with the exception of a very limited amount of sensor-specific signal conditioning circuitry associated with proportional chambers. Of these modules, 80 percent were high-usage standard types that would be broadly applicable to a wide variety of payloads from many disciplines. Low-usage standard modules with more limited applicability satisfied 9 percent of the payload requirements, and custom-built modules accounted for the remaining 11 percent. For the individual instruments, the applicability of standard modules (high- and low-usage combined) ranged from 79 percent to 98 percent.

The cost of providing the electronic equipment for the model payload was evaluated for a conventional approach to instrument development and for three cases involving a standardized approach. The electronics cost using a conventional approach was estimated to be $11.1 million. In the first case involving a standardized approach, taking advantage of only the commonality of requirements among the four instruments on this single payload, the cost would be $6.0 million. The second and third cases assumed that the nonrecurrent design and development cost of the standard modules were borne by a previous payload. If only the modules required for the model payload were then produced in a single production run, the cost would be $3.3 million. In the case where standardization has become widespread and modules are being produced in larger production runs, the electronics cost for the model payload would be $3.1 million. Clearly, the most significant cost saving is that achieved by taking advantage of the commonality of requirements that exists among the instruments of an individual payload. Of course, the savings increase if the modules are applicable to additional payloads beyond the first.

To estimate the potential cost reduction on a broader scale than a single payload, the results quoted above were applied to a HEAO program consisting of four missions. This hypothetical example approximates the HEAO Block II series of missions. Utilizing current practices, the total cost of the electronics for all four mission payloads would be $44.4 million. Using standard modules,for the instruments, this cost would drop to $15.5 million, a net reduction of about $30.0 million or 65 percent.

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1. INTRODUCTION

1.1 STUDY BACKGROUND

1.1.1 Current Costs of Experiments

Today the cost of experiments making up the payload for an automated scientific spacecraft typically runs into the tens of millions of dollars. The cost of each experiment varies greatly depending on the mission, but experiments costing several million dollars each are the rule and experiments which cost over 10 million dollars are not uncommon. Roughly one-third to one-half of the total experiment cost goes into the development of the flight instrumentation or hardware used to perform the experiment. The trend in experiment hardware costs has certainly been toward increasing cost, primarily due to the increased complexity of the instrumentation required to perform more sophisticated investigations. In spite of this inevitable trend toward increased complexity, there are several other aspects of experiment implementation currently contributing to the high cost of hardware, that are not inevitable.

Each instrument is almost always custom designed for each mission. The principal reasons for custom design are the constraints of minimized weight, power, and size, as well as the frequent use of new and highly developmental instrumentation. It is true, however, that while there is considerable commonality between experiments, or with previously designed hardware, little advantage is taken of this commonality.

In addition, the close integration of the instrument package typically used to minimize weight and size makes changes to the system relatively expensive. The highly developmental portions of the instrument (usually the primary sensors) are, and should be, subject to change. Today this frequently results in costly major instrument redesign efforts during development or even after flight hardware fabrication is underway.

Finally, the current requirement for high reliability (i.e., high confidence in the successful operation of the instrument) adds significantly to the experiment hardware costs, both in terms of the mission assurance procedures adopted to achieve the reliability and in terms of additional units built for qualification and as spare or backup instruments.

Several approaches are currently being pursued to hold down experiment hardware costs in the face of budgetary constraints. The number of units built during experiment development is reduced by combining qualification and spare units or by using the same unit for qualification and flight. A second approach is to use previously developed instruments to perform experiments on new missions. This method is difficult to implement because of the strong pressure to use the latest technical advances in order to perform the best experiment possible.

1.1.2 Impact of Space Shuttle

A primary reason for the development of the Space Shuttle was to reduce the costs of space operations in general. The advent of the Space Shuttle certainly will have a significant impact on the cost of the type of mission we are concerned with in this study; namely, automated, free-flying, scientific spacecraft that use the Shuttle as a launch vehicle, for on-orbit servicing or maintenance, and for retrieval and return to the earth. The most obvious impact on total program costs is the reduction in launch costs. The factors that may have the greatest impact on experiment hardware costs are the relaxation of weight, power, and size constraints afforded by the Shuttle capabilities and the relaxation of reliability requirements due to the ability to retrieve, repair or reuse experiment equipment.

The general problem or challenge is to determine how to best exploit the capabilities provided by the Shuttle to reduce overall experiment costs. The particular aspect of this problem addressed in this study is how to reduce experiment hardware costs.

1.1.3 Possible Approaches to Experiment Hardware Cost Reduction

The most obvious possibility for experiment hardware cost reduction is the utilization of standardized equipment. The reduction of costs associated with standardization through the elimination of the continually recurring design, development, and qualification of new hardware is well recognized. The movement toward standardization of spacecraft systems is already well underway. A comparable trend in spaceflight experiment implementation has barely begun. Many people believe that the inherent developmental nature of experiment instrumentation rules out or at least severely limits the applicability of standardized equipment. Experience with ground-based laboratory experiments has shown that standardized equipment can be used without placing undue restrictions on the application of technological advances.

The feasibility of using standardized equipment to implement scientific instrumentation depends critically upon the extend to which the instrument system can be broken into functional modules at least some of which find broad or common application. Those elements that are widely used can be standardized without unduly limiting the flexibility to incorporate new developments or modify and upgrade the system.

This modularization of the instrumentation usually carries the penalty of increased size, weight, and to a lesser extent, power. This penalty is usually not significant in ground-based instrumentation but it has been considered prohibitive for spaceflight instrumentation. The relaxation of the weight, size, and power constraints afforded by the Shuttle should significantly increase the opportunity to use standard, modular instrumentation.

As previously noted, the ability provided by the Shuttle to replace or repair equipment that has failed makes it possible to consider the acceptance of increased equipment failure rates. The corresponding reduction in reliability requirements should be convertible into experiment hardware cost reductions since high reliability is believed to be one of the important cost drivers of current spaceflight hardware. The problem is to determine the most cost-effective way to capitalize on the reduced reliability requirements.

Another possible approach that has been suggested is to use the increased weight and size made possible by the Shuttle to reduce the environmental levels to which spaceflight equipment is exposed and thereby reduce the cost of producing the hardware. This is an interesting approach that is being studied by General Electric for NASA/GSFC. In most respects, it is complementary to the approaches considered in this study. A combination of all three concepts may produce the maximum cost reduction for experiment hardware.

1.2 STUDY SCOPE AND OBJECTIVES

1.2.1 Scope

The scope of this study is concentrated on several specific areas of the overall problem of experiment cost reduction in the Shuttle era which our experience with experiment hardware development for automated spacecraft indicated were subject to possible cost reductions.

We have directed our attention primarily to instrumentation development for scientific experiments flown on Shuttle-launched and serviced, automated spacecraft (e.g., low earth-orbital missions such as HEAO, SMM, etc.). This class of missions constitutes an important part of NASA's overall program, particularly in the scientific disciplines of astronomy, high-energy astrophysics, solar physics, atmospheric and space physics, both in terms of scientific priority and costs. The approaches to instrumentation development considered in the study also are directly relevant to certain types of applications missions in the disciplines of earth observations and earth and ocean physics.

In our view, the type of experiment instrumentation on which the impact of the Shuttle could be most significant is electronic hardware. This is because the use of standardized modular equipment and the acceptance of increased equipment failure rates, discussed as possible approaches to hardware cost reduction in Section 1.1.3, are most appropriate to electronic equipment. It should also be noted that the electronic subsystems constitute a significant fraction of the experiment costs since the cost of this type of equipment typically represents about 40 percent of the total experiment hardware development costs.

The specific areas or aspects of the experiment instrumentation development process that we have concentrated on in this study are:

Experiment System Design - The work in this area was directed at first to examining the feasibility of incorporating standardized, modular electronic equipment into instrumentation for a broad range of science and applications experiments and then at developing experiment electronic system designs that maximize the applicability of standardized, modular equipment.

Standardized Modular Electronic Packaging - The work in this area was directed at first determining the level and form of modularization that would be most effective in optimizing the utilization of standardized equipment and then at developing an electronic packaging approach or concept that is suitable for the automated spacecraft environment.

Mission Assurance - The work in this area was directed at determining what reductions in costs associated with mission assurance activities are possible with the acceptance of reduced reliability requirements and the increased use of standardized equipment and at establishing a methodology for determining the most cost-effective reliability requirements and mission assurance approach for the instruments in the Shuttle era.

In order to provide a specific example of the system concepts, packaging techniques, and mission assurance approaches developed in our study, we proposed to use a High Energy Astronomy Observatory (HEAO) as a model payload. The so-called Block II versions of this automated spacecraft are representative in size, weight, subsystems and mission of the scientific spacecraft to be launched and serviced by Shuttle. Further, experiments for both of the original HEAO A & B missions had been selected and conceptually defined prior to the suspension and subsequent redefinition of the HEAO program. These experiments are still quite representative of the type being considered for HEAO Block II. In the final phase of this study we analyzed a model payload consisting of four of these experiments (BGR-5, BCR-5, AGR-4 and BXR-2). We believe the results of that analysis, particularly with respect to the potential cost savings derived from a standardized approach to the experiment electronic instrumentation, provide a significant input that should be considered in HEAO Block II planning.

1.2.2 Impact on Other Experiment Costs

It is not our intent to imply that the areas addressed in this study are the only places to reduce experiment costs. We are certainly aware that the total problem of experiment cost reduction requires attention to all phases of an experiment; i.e., experiment definition, experiment integration into a payload, experiment operations, and data analysis and interpretation, as well as instrumentation development. Significant cost reductions should be possible in areas other than instrumentation development. Regardless of other factors that may affect experiment costs, it is possible to identify some of the beneficial effects that the use of standardized, modular electronic equipment could have on other elements of the total experiment program.

Once the use of standard modules has been established, the process of experiment definition should be changed in a way analogous to what has happened in ground-based experiments in fields where standardized equipment is used. Experimenters tend to design their experiments around the existent standardized equipment to the maximum extent possible and are free to devote a larger portion of their attention to the innovative and developmental portions of the instrumentation.

In addition, if the standardized equipment approach used for spaceflight experiments has a ground-based functional counterpart, the usual evolutionary process of experiment development, moving from laboratory testing and functional verification through developmental stages such as balloon-borne experiments and development flights to full-fledged spaceflight experiments, should be simplified because redesign and development of the entire apparatus will not be required at each step.

Experiment integration should be facilitated because the electrical interfaces will have been essentially standardized and well-understood. The standardization of the experiment electronics will complement the standardization of the associated spacecraft subsystems. The range of experiment interface requirements with which the spacecraft will have to deal will be reduced.

Standardization of the experiment electronics, particularly in the data processing and control functions, can be accompanied by a corresponding standardization of the experiment software. The same types of advantages in terms of reduced development effort, interchangeability, etc., can apply. Again, experience with ground-based experiments has demonstrated this effect. The reduction of the experiment software development effort should have a beneficial influence on experiment operations costs, especially when on-board computer-controlled data processing and experiment control is used.

1.2.3 Applicability to Other Mission Types

We also realize that the advent of the Space Shuttle will have significant cost impact on other types of missions, in particular, the sortie mode of operation. However, we believe that the impact on sortie-mode experiments is more universally recognized and consequently felt than concentration on experiments for Shuttle-launched and serviced automated spacecraft missions could possibly contribute in a more unique way. On the other hand, the low-cost approaches investigated in this study are not limited strictly to automated spacecraft missions. The methods used in performing the study and many of the results are applicable to other types of missions.

In the case of automated spacecraft for which the Shuttle serves only as a launch vehicle (e.g., planetary missions), the current constraints on weight, size, and power will continue to be operative. Thus, only some of the concepts considered here will be appropriate. In particular, the experiment electronic systems analysis directed at maximizing the common use of functional elements among experiments making up the payload will be applicable and the electronic design and development effort could be reduced even though standardized modular packaging may not be feasible.

For sortie missions, there will be many functional requirements on experiment instrumentation that will be shared with equipment flown on automated spacecraft. A higher premium will be placed on the flexibility to easily reconfigure or modify instrumentation. This argues even more strongly for a modular approach. The differences in requirements are mainly a question of the degree of relaxation of weight, size and power constraints, reliability requirements, etc. These differences would primarily influence the area of electronic packaging techniques. Even so, it would be very desirable to take as common an approach as possible to the use of standardized, modular equipment in order to extend the range of applicable missions.

Finally, since the objective of the mission assurance work is the development of methods to determine an optimum mission assurance program for a particular set of requirements, the techniques developed will be applicable to all of the mission types, although the particular results would probably differ for each mission type.

2. EXPERIMENT SYSTEM DESIGN

2.1 INTRODUCTION

Standardization of common support subsystem functions could significantly reduce the present high development and hardware costs of scientific payloads. In spite of the high degree of commonality of these support functions in instrument systems, standardization in spaceflight scientific instruments is practically nonexistent. The primary reasons have been the diversity of sources of instruments and the need to wring the maximum performance out of the limited available weight, volume, and power. The larger payload capacity of the Space Shuttle will relax the instrument weight and volume constraints and, hence, remove one of the prime deterents to standardization. Also important is the fact that standardization, and in addition modularization, of experiment equipment will be mandatory if we are to repair, refurbish, and modify payloads economically. Past designs of scientific instruments did not generally lend themselves to easy disassembly or expansion.

The extent of cost savings obtained by such an approach, however, greatly depends on the degree of standardization and the system architecture of the payload. It is clear that custom-designed payloads are costly. On the other hand, a highly standardized, general-purpose system that could accommodate a wide variety of instruments might also become more costly because of the compromises involved for each individual system. For Shuttle, we believe the most cost-effective system will fall between these two extremes.

The experiment system design study had five major objectives:

- Determine the extent of commonality of support subsystem requirements for instruments that will be used in the Shuttle era.
- Assess the feasibility of satisfying these requirements with standard functional elements.
- Develop alternative instrument system design concepts incorporating standardized functions.
- Evaluate these concepts and identify the preferred system architecture.

- Determine the cost savings arising from the use of standard functional elements.

The study results for the first two objectives are presented in Section 2.2. A widely diversified set of Shuttle era payloads, representative of a number of science and applications disciplines, was selected for analysis of requirements. The types of sensors appropriate for use in these payloads were identified and the requirements associated with those sensors were analyzed to assess the extent of commonality. The types of standard functional elements that would satisfy these common requirements were identified and their applicability was determined.

The study results for the third and fourth objectives are presented in Section 2.3. Two new system architectures were developed for comparison with the conventional approach now used. In evaluating these system concepts, the following general system requirements were considered:

- accommodating a wide variety of instruments without compromising the scientific objectives,
- maximizing the use of standard modules,
- providing simple flexible machanical and electrical interfaces,
- using the hardware efficiently,
- expanding and reconfiguring the system without extensive redesign.

One of the new system architectures was found to provide significant advantages over the conventional approach and the other new system concept in almost all respects.

The study results for the final objective are presented in Section 2.4. It was found that the utilization of standard functional elements rather than the present practice of using new designs for each instrument represents a very sizable potential cost saving. The magnitude of this saving is demonstrated in Section 5.3 for the four instruments of the HEAO model payload.

2.2 EXPERIMENT INSTRUMENTATION REQUIREMENTS

Almost all scientific instruments consist of one or more sensor subsystems and several electronic support subsystems. A functional block diagram of a typical instrument system is shown in Figure 2-1. The sensor subsystem, which includes the sensors and their signal conditioning electronics, is configured to satisfy the scientific objectives of a particular experiment. In general, that configuration is unique to the specific type of experiment.

The functions provided by the support subsystems in Figure 2-1 are generally required in any instrument regardless of the specific scientific objectives of the experiment. These four subsystems have a great deal of commonality from instrument to instrument, which will be demonstrated in the following sections.

2.2.1 Science Data Processing

The science data processing support subsystem acquires analog or digital data from the sensor subsystem and processes that data into an appropriate format and sequence for transmission to the spacecraft telemetry system. These general requirements for data conversion, temporary data storage and data formatting usually exist in every experiment.

Of the four types of support subsystems, the science data subsystem potentially has the widest variety of requirements imposed on it and accounts for a large fraction of the instrument system. Although it has received little previous attention from the standpoint of standardization, the results of this study show that great potential exists for cost saving through standardization of this support subsystem as well as the other three.

In order to assess the degree of commonality that exists in the science data processing requirements of a wide variety of instruments, a representative set of 40 payloads was selected from the July 1974 edition of "Summarized NASA Payload Descriptions - Automated Payloads Level A Data." The specific payloads selected are listed by discipline in Table 2-1. In the case of the four scientific disciplines, all payloads listed in the reference were included. For the two applications disciplines, all developmental payloads were included except for Minilageos which is a completely

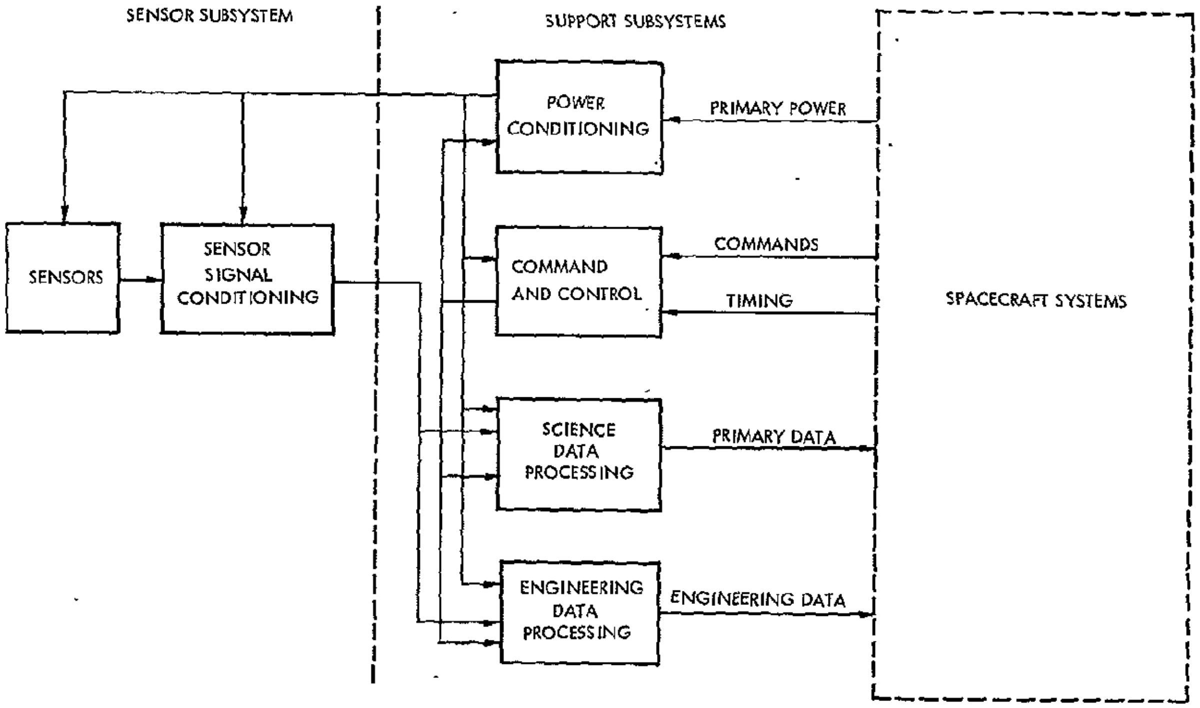

Figure 2-1. Typical Instrument System

Table 2-1. Disciplines and Payloads Studied

ASTRONOMY:	Large Space Telescope	1.5 m IR Telescope
	Extra Coronal Lyman Alpha Explorer	UV Survey Telescope
	Cosmic Background Explorer	1.0 m UV-Optical Telescope
	Advanced Radio Astronomy Explorer	Large Radio Observatory Array
	3m Ambient Temperature IR Telescope	30 m IR Interferometer
HIGH ENERGY ASTROPHYSICS:		
	Large X-Ray Telescope Facility	Extended X-Ray Survey
	High Latitude Cosmic Ray Survey	Small High Energy Observatory
	Large High Energy Observatory A	Large High Energy Observatory B
	Large High Energy Observatory C	Large High Energy Observatory D
	Cosmic Ray Laboratory	
SOLAR PHYSICS:		
	Large Solar Observatory	Solar Maximum Mission
ATMOSPHERIC AND SPACE PHYSICS:		
	Upper Atmosphere Explorer	Medium Altitude Explorer
	High Altitude Explorer	Earth Orbit Gravity and Relativity Satellite
	Environment Perturbation Satellite A	Solar Gravity and Relativity Satellite
	Environment Perturbation Satellite B	Heliocentric and Interstellar Spacecraft
EARTH OBSERVATIONS:		
	Advanced Synchronous Meteorological Satellite	Earth Observatory Satellite
	Synchronous Earth Observatory Satellite	Special Purpose Applications Explorer
	TIROS 'O'	
EARTH AND OCEAN PHYSICS:		
	GEOPAUSE	Vector Magnetometer Satellite
	Gravity Gradiometer	Magnetic Field Monitor Satellite.
	GRAVSAT	SEASAT B

passive laser retroreflector target. These developmental type applications payloads were included because of their similarity to the scientific payloads. Since both utilize some of the same types of sensors, commonality of support subsystem requirements was anticipated. Also, unlike the operational models, the developmental payloads in these applications disciplines are one-of-a-kind like the scientific payloads and, thus, similar hardware implementation techniques are applicable. Scientific payloads of the lunar and planetary type were not considered because their resource budget and reliability requirements are potentially different from scientific payloads launched and serviced by the Shuttle and Tug in earth orbits.

In addition to the primary reference, two other major references were used to identify the types of sensor subsystems required to achieve the mission objectives of the 40 payloads. These were the July 1974 edition of "Summarized NASA Payload Descriptions - Automated Payloads Level B Data," and the May 1973 "Final Report of the Space Shuttle Payload Planning Working Groups." Information was also gathered from many other sources on instrument payloads used to carry out similar missions. The sources included NASA reports, scientific journals, and conversations with TRW scientists. Analysis of this information showed that ten basic sensor types would be used in large numbers to satisfy the objectives for the 40 payloads. These basic types are listed in Table 2-2 along with a few specific examples of each type. This list of basic types is not inclusive, of course, but does encompass a substantial number of widely used sensors.

The applicability of these ten sensor types to the 40 payloads is shown in Figure 2-2. Each entry in the figure indicates that a particular sensor type would be used as part of that payload. It should be noted that these are only potential applications since they are based on mission concepts in many cases. Because of this, a quantitative assessment of the number of sensors of each type used on each payload was not attempted. In most cases, a large number of sensors is used in each payload. For example, a high-energy astrophysics payload typically consists of a single instrument that may use more than 50 electron-multiplier-type sensors and more than 30 large-area spatial-type sensors. Alternatively, a solar physics payload may include a large number of instruments, each of which may use several different sensors. In these ways, each sensor type in Figure 2-2 is extensively utilized by many of the indicated payloads.

Table 2-2. Sensor Subsystem Types

- Electron Multiplier
    - photomultiplier tube
    - channel multiplier
    - single anode microchannel plate
- Solid State
    - silicon radiation detector
    - germanium radiation detector
- Micro Channel Plate Spatial
    - multiple discrete anode
    - self scan IC anode array
    - resistive anode
- Large Area Spatial
    - spark chamber
    - multi-wire proportional chamber
    - drift chamber
- Target-Electron Beam Spatial
    - vidicon
    - SEC vidicon
    - EBS vidicon
    - return beam vidicon
- IR
    - photoconductive
    - bolometric
- Magnetometer
    - fluxgate
    - rubidium vapor
- Accelerometer
    - electrostatic proof mass
- RF Receiver
    - VLF spectrum analyzer
    - HF spectrum analyzer
- Current Collector
    - mass spectrometer readout
    - Langmuir probe
    - retarding potential analyzer
    - ion pressure gauge

	ASTRONOMY										HIGH ENERGY ASTROPHYSICS									SOLAR PHYSICS		ATMOSPHERIC AND SPACE PHYSICS								EARTH OBSERVATIONS					EARTH AND OCEAN PHYSICS						TOTAL
	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	1	2	1	2	3	4	5	6	7	8	1	2	3	4	5	1	2	3	4	5	6	40
ELECTRON MULTIPLIER	●	●							●				●		●	●	●		●	●	●	●	●			●		●	●	●	●	●	●	●							20
SOLID STATE																				●			●	●		●		●	●	●				●							8
MICRO CHANNEL PLATE SPATIAL	●	●							●											●	●																				5
LARGE AREA SPATIAL											●	●		●	●	●	●	●	●	●																					9
TARGET-ELECTRON BEAM SPATIAL	●	●							●			●								●	●																				6
I R			●			●	●			●																			●	●	●	●	●	●						●	11
MAGNETOMETER																						●	●	●					●	●								●	●		7
ACCELEROMETER																						●					●										●				3
R F RECEIVER				●	●																	●		●		●															5
CURRENT COLLECTOR																						●	●	●		●															4

Figure 2-2. Sensor Subsystem Payload Applicability

Four of the payloads have no identified sensor requirements among the ten types. For example, the gravity gradiometer (earth and ocean physics payload 2) as presently envisioned might use strain transducers. However, even though these transducers do not fit any of the ten sensor types, their data processing requirements are similar to several of the types that produce information in the form of DC voltage levels.

Investigation of the data processing requirements for the ten sensor types showed that, with appropriate signal conditioning electronics, the information output would assume one of four forms. These forms are illustrated in Figure 2-3. Six types of data processing elements typically associated with these four signal forms are also identified in the figure.

The digital pulse is a standardized logic pulse with a known temporal relationship to the occurrence of a sensor event. This type of signal is usually produced by a discriminator connected to a sensor that observes discrete events occurring at random intervals. The temporal information contained in the signal is used explicitly by event identification logic and by time encoders in processing data for individual events. A scaler uses the temporal information indirectly since it typically determines the total number of events that have occurred within a given time interval. The interface of the data processing elements with the sensor subsystem usually includes specification of the digital logic family used (which, in turn, identifies the signal characteristics), the average and instantaneous maximum pulse rate, the pulse width, and the precision of the timing information.

The analog pulse has a peak voltage proportional to the magnitude of the parameter measured by the sensor during the occurrence of an individual event. This type of signal is usually produced by an amplifier connected to the sensor and is processed by a pulse amplitude analog-to-digital converter (ADC). A common implementation of this type of ADC consists of a sample and hold, to stretch the peak amplitude, followed by a voltage level ADC. The interface specifications usually include the amplitude limits (which also define the dynamic range), the average and instantaneous maximum pulse rates, the pulse shape time constants, and the precision with which the amplitude must be digitized.

- DIGITAL PULSE
    - SCALER
    - EVENT LOGIC
    - TIME ENCODER
- ANALOG PULSE
    - PULSE AMPLITUDE ADC
- VOLTAGE LEVEL
    - VOLTAGE LEVEL ADC
- VOLTAGE RAMP
    - $^{DV}/_{DT}$ TO DIGITAL CONVERTER

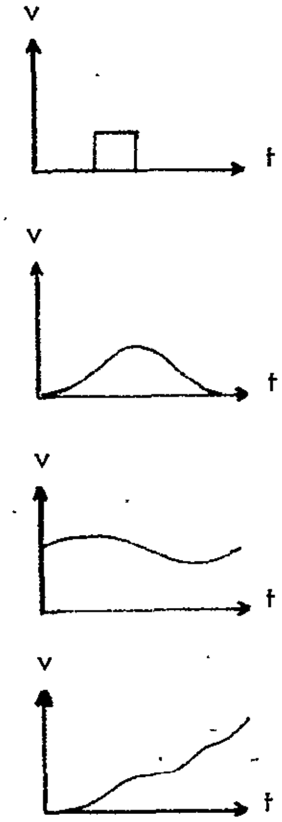

Figure 2-3. Sensor Output Forms and Data Processing Elements

The voltage level is proportional to the magnitude of a parameter measured by a sensor on a continuous basis. It is usually produced by an amplifier connected to the sensor and is processed by a voltage level ADC. The interface specifications include the voltage limits, the period for sampling the signal, the duration of the sampling interval, and the required digitizing precision.

The voltage ramp has a time rate of voltage change (dV/dt) proportional to the magnitude of a parameter measured by a sensor. This type of signal is encountered considerably less often than the other three types. It is produced, for example, by an integrating electrometer connected to a current collector. Processing of this signal requires a dV/dt-to-digital converter, and the interface specifications typically include voltage limits, dV/dt limits, and the digitizing precision required.

The applicability of the six types of data processing elements considered above to the ten basic sensor types considered earlier is shown in Figure 2-4. Note that if the voltage level ADC is used with a sample-and-hold to satisfy the pulse amplitude ADC requirements this basic ADC is universally applicable to all ten sensor types. At the other extreme, the dV/dt-to-digital converter has very limited applicability.

In order to demonstrate the extensive commonality of data processing requirements, the applicability of these six processing elements to the 40 payloads is shown in Figure 2-5. This matrix is not simply a folding together of the two previous applicability matrices but considers other sensors in addition to the ten basic types. For example, the voltage level ADC is used with the strain transducers for the gravity gradiometer. Another interesting feature of this matrix is the uniformity of distribution. The ordering of the elements along the axes of Figure 2-2 was selected to demonstrate the somewhat systematic correlation of sensors with disciplines by means of an enhanced diagonal distribution. A similar correlation is even more evident in Figure 2-4. In spite of these two previous correlation effects, the applicability of the basic science data processing subsystem elements to the 40 missions is generally uniform and very widespread. The only exception to this, again, is the dV/dt-to-digital converter which clearly represents a second tier of utilization relative to the other five types of processing elements.

	SCALER	EVENT LOGIC	TIME ENCODER	PULSE AMPLITUDE ADC	VOLTAGE LEVEL ADC	DV/DT TO DIGITAL CONVERTER
ELECTRON MULTIPLIER	●	●	●	●		
SOLID STATE	●	●		●		
MICRO CHANNEL PLATE SPATIAL	●		●	●		
LARGE AREA SPATIAL			●	●		
TARGET – ELECTRON BEAM SPATIAL					●	
I R					●	
MAGNETOMETER					●	
ACCELEROMETER					●	
R F RECEIVER					●	
CURRENT COLLECTOR					●	●

Figure 2-4. Data Processing Element Applicability to Sensor Subsystems

	ASTRONOMY										HIGH ENERGY ASTROPHYSICS									SOLAR PHYSICS		ATMOSPHERIC AND SPACE PHYSICS								EARTH OBSERVATIONS					EARTH AND OCEAN PHYSICS						TOTAL
	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	1	2	1	2	3	4	5	6	7	8	1	2	3	4	5	1	2	3	4	5	6	40
SCALER	●	●							●				●		●	●	●		●	●	●		●	●		●		●	●	●				●							17
EVENT LOGIC													●		●	●	●		●	●			●	●		●		●	●	●				●							13
TIME ENCODER	●	●							●		●	●	●	●	●	●	●	●	●	●																					13
PULSE AMPLITUDE ADC	●	●							●			●	●		●	●	●		●	●	●		●	●		●		●	●	●				●							18
VOLTAGE LEVEL ADC	●	●	●	●	●	●	●		●	●										●	●	●	●	●		●	●		●	●	●	●	●	●		●	●	●	●	●	27
$^{DV}/_{DT}$ TO DIGITAL CONVERTER																						●	●	●		●															4

Figure 2-5. Sensor Data Processing Element Payload Applicability

2.2.2 Engineering Data Processing

The engineering data processing subsystem monitors the status of the various nonscientific system parameters such as supply voltages, temperatures, and pressures at various parts of the experiment. It also provides information on the operating mode of the instrument and sensor performance data.

To investigate the commonality of requirements for this support subsystem, three specific types of engineering data were considered. Status flags are used to either identify the operating mode of the instrument, if it is controlled by adaptive on-board logic that can undergo real-time configuration changes, or to verify the mode if it is under ground control by command inputs. These status flags are, therefore, typically associated with the command and control functions and can be appropriately provided as a part of that support subsystem in most cases.

Sensor counting rate data are used to assess sensor performance and state-of-health. This information is frequently used as an aid in adjusting sensor high-voltage power supplies during flight. The counting rate data are generally indistinguishable from science data and can be readily processed with the same scaler functions as the science data.

Analog data are used to provide supply voltage and temperature information as well as measurements of other parameters. These types of data are frequently processed by a standard approach in present systems. An example of this is the use of voltage dividers multiplexed within the instrument and interfaced to a spacecraft analog housekeeping channel with a single ADC shared by several instruments. Again, this type of data processing is indistinguishable from science data processing in many cases.

2.2.3 Command and Control

The command and control support subsystem accepts commands and timing signals from the spacecraft and stores, decodes, and distributes them, in the appropriate sequence, to the various instrument subsystems. A large number of command and control functions are used to control the instrument support functions such as adjusting and turning on and off the supply voltages.

Five specific command and control functions were considered in the investigation of commonality of requirements for this subsystem:

- establishment of operating mode of the instrument,
- control of sensor power supply voltages,
- establishment of frequency and phase relationship of the instrument clocks,
- determination of telemetry format,
- performance of calibration and test functions.

Although very little commonality of requirements exists among these five types of functions, it was found that the range of requirements for the first three types are narrow enough to make standardization of those types straightforward.

The operating mode of the instrument can be established by a standard functional element that receives commands from the spacecraft, decodes the commands and establishes the appropriate state on a set of control lines, and provides serial digital commands to other functional elements with built-in decoding capability. The sensor power supply voltages can be controlled by standard digital-to-analog converters driven by outputs from the same standard functional element that establishes the operating mode. The internal instrument clocks can be derived from spacecraft clocks or independent oscillators by standard functional elements using programmable counters.

For the last two types of command and control functions, broad applicability of a standard functional element would require a more sophisticated device, probably based on a read-only memory, that could be programmed to fit the specific requirements of each instrument. This capability would then allow complex telemetry formats to be established and also provide complex calibration and test function sequences.

2.2.4 Power Conditioning

The power conditioning support subsystem generates the various supply voltages required in the instrument from the primary power source provided by the spacecraft. Every instrument usually requires one or more low-voltage supplies for the electronic support functions and the sensor signal conditioning electronics. High-voltage supplies are frequently required to operate the sensors. Commonality of the requirements for this subsystem was found to exist in each of three categories; analog electronics power supply, digital electronics power supply, and sensor high-voltage power supplies.

Analog circuitry makes extensive use of standard integrated circuit (IC) analog devices (operational amplifiers and comparators for example). In addition, circuitry built from discrete parts usually has voltage requirements that are compatible with the IC devices. These devices are usually operated from positive and negative supplies of equal magnitude, typically ranging from ±10 volts to ±15 volts. In general, the lower voltages are chosen to reduce power consumption while ±15 volts provide improved performance and, in fact, are usually the voltages at which the electrical parameters of the IC's have been specified by the manufacturers. If power consumption constraints are relaxed, standardizing the analog power supply at ±15 volts will allow maximum flexibility for use of the analog circuitry.

Three families of IC digital logic are found in significant numbers of applications. These families appear to occupy optimum positions at the present time in a trade-off of power and operating speed. From a power consumption and heat dissipation standpoint, the lowest power devices that meet the speed requirements in a given application are preferred. This occasionally leads to the use of two or more logic families in a single instrument in order to minimize power and waste heat. In standard usage, the three families have different voltage requirements. In order of increasing speed and power consumption, the families and their typical power supply voltages are: 1) complementary metal-oxide-semiconductor (CMOS), +10 volts; 2) transistor-transistor logic (TTL), +5 volts; and 3) emitter-coupled logic (ECL), -5.2 volts. In general, standardized power supplies providing these three voltages would satisfy the large majority of requirements for digital circuitry.

Although sensors, as a whole, have a wide range of high-voltage supply requirements, the most frequently used types fall into four reasonably narrow voltage ranges. The bias voltage requirements of solid-state sensors can be satisfied by a standard supply covering the range up to 1 kV. Most electron multiplier requirements can be satisfied by a standard supply operating in the 1 to 3 kV range. A standard supply covering 3 to 6 kV could be used for large-area spatial proportional chambers and a 6 to 10 kV supply for vidicon-type sensors. In general, each of these supplies should be programmable by command to allow the sensor performance to be optimized during flight.

2.2.5 Applicability of Standard Functional Elements

The investigation of typical requirements for the four support subsystems showed that a large degree of commonality exists. This commonality spans a wide variety of sensor subsystems in frequent use by both scientific and applications disciplines. A substantial fraction of the requirements for each subsystem could be satisfied by a reasonably small number of standard functional elements.

In the science data processing support subsystem, five of the six types of functional elements investigated satisfy most requirements of ten frequently used types of sensors as well as other less frequently used types. A small family of standard data processing functional elements of these types would have broad applicability throughout the range of payloads and disciplines investigated.

The requirements for the engineering data processing support subsystem have a significant degree of commonality with the science data subsystem and, in fact, the same set of standard functional elements suggested for science data processing would also be widely applicable for engineering data processing. In taking advantage of this great degree of commonality, these two subsystems do not need to be separately identifiable and, in fact, can be merged into a single data processing support subsystem.

Command and control requirements can generally be satisfied by a very limited number of standard functional elements that interface with the spacecraft and distribute the commands to the standard functional elements of the other subsystems. Because of the number of interactions between the command and control subsystem and the data processing subsystem, it is also reasonable to consider merging those functions into a single standardized instrument command and data handling support subsystem.

In all cases, because of its specialized nature and lack of commonality with the other subsystems, the power conditioning support subsystem would remain separately identifiable. The requirements for this subsystem can, in general, be satisfied by a single standard type of analog electronics supply, three types of digital electronics supplies, and four types of high-voltage supplies.

2.3 SYSTEM DESIGNS FOR EXPERIMENT INSTRUMENTATION

Our analysis of experiment instrumentation requirements in the previous section has demonstrated that extensive commonality of support subsystem requirements exists and that it should be feasible to satisfy these requirements with standard functional elements. In this section we turn to the question of how to organize the overall payload system that provides the various support functions to each instrument in the most cost-effective way. In addressing this question we have drawn upon system concepts emphasizing standardization that are currently used in ground and aircraft-based systems and, in a more limited way, in spacecraft systems.

Our primary premise or guideline is that the approach that maximizes the use of standard functional elements will minimize the instrument cost. On the other hand, there are a number of other considerations that may run counter to the objective of maximal standardization. These factors, which must also be used as criteria in the evaluation of different system design approaches, are the requirements for:

- accommodating a wide variety of instruments,
- minimizing detrimental interactions between instruments such as failure propagations,
- providing simple flexible interfaces,
- maintaining flexibility to modify or change any instrument with minimal impact on the spacecraft or the other instruments,
- efficient use of hardware.

As we see in the next section, it is relatively easy to demonstrate the cost advantages of standardization.

It is much more difficult, if not impossible, to quantitatively assess the cost impact of the other factors. Therefore, we have had to rely to a large extent on our qualitative judgment to arrive at conclusions regarding the optimum approach.

2.3.1 General System Design Approach

The general approach that we have taken to develop alternative system design concepts and to evaluate their relative merits consists of the following. Starting from the current method of implementing a particular support subsystem, we have constructed a system design concept which uses standard functional elements in a rather straightforward way to satisfy the functional subsystem requirements as well as the general criteria listed in the preceding section. This concept generally amounts to dedicating an assembly of standard functional elements or modules to each instrument. Each assembly has the necessary flexibility while providing simple interfaces with the spacecraft and its particular instrument. This concept naturally minimizes the interaction between instruments. The potential shortcoming of this concept is that it may not be an efficient use of hardware, due either to the presence of excess, unused capability or to a duplication of common overhead functions.

The next step in the process is to construct a system design which tries to minimize inefficient use of hardware by centralizing and sharing the common functions. This concept necessarily increases the interaction between instruments. The evaluation of this system design relative to the first system design approach then involves a tradeoff between the increased efficiency achieved and the increased interdependence of the individual instruments.

In the following subsections we describe the results of this type of analysis for each of the instrument support subsystems identified in Section 2.2. As discussed in Section 2.2.5, the requirements for the engineering data processing subsystem are really indistinguishable from those of the science data processing subsystem. Consequently, we have merged them into a single data processing subsystem here. Finally, in the last subsection we consider a system design concept which integrates the data processing functions and the command and control functions into a single subsystem under the control of a microprocessor.

2.3.2 Power Conditioning Subsystem

The two basic functions of the power conditioning subsystem are:

the conditioning of the power input from the spacecraft, and the generation of the instrument supply voltages.

The input power conditioning requirements are common to each instrument and are dictated by the nature of the spacecraft power system. In some cases, they are implemented within the spacecraft systems and are not included in the instrument system. Usually, the following functions are required:

- Instrument power switching controlled by spacecraft command.
- Isolation of instrument loads from the spacecraft power bus.
- Protection of the primary power bus from instrument overload conditions.
- Filtering of the input power lines.

Typical instrument power requirements were discussed in section 2.2.4. Generally, the following types of supplies are required:

- Fixed low-voltage supplies.
- Programmable and/or fixed high-voltage supplies.

The block diagram of a typical instrument power conditioning subsystem is shown in Figure 2-6. It must be pointed out that in a custom-designed system it is not always possible to make such a clear cut separation of the various functions, as shown in Figure 2-6, since a group of components may perform more than one function in order to minimize the hardware.

The input power conditioning functions are the same for each instrument with the exception of their power handling capacity, which is determined by the power consumption of the particular instrument.

There is considerably more instrument-to-instrument variation in the low and high voltage supply area, since the supply voltages and their power capacity is usually tailored to each specific instrument requirement. However, standardization of the instrument supply voltages, as it has been demonstrated in Section 2.2.4 is feasible without significant effect upon the instrument performance.

The functional block diagram of a typical instrument power conditioning subsystem utilizing standard functional elements is shown

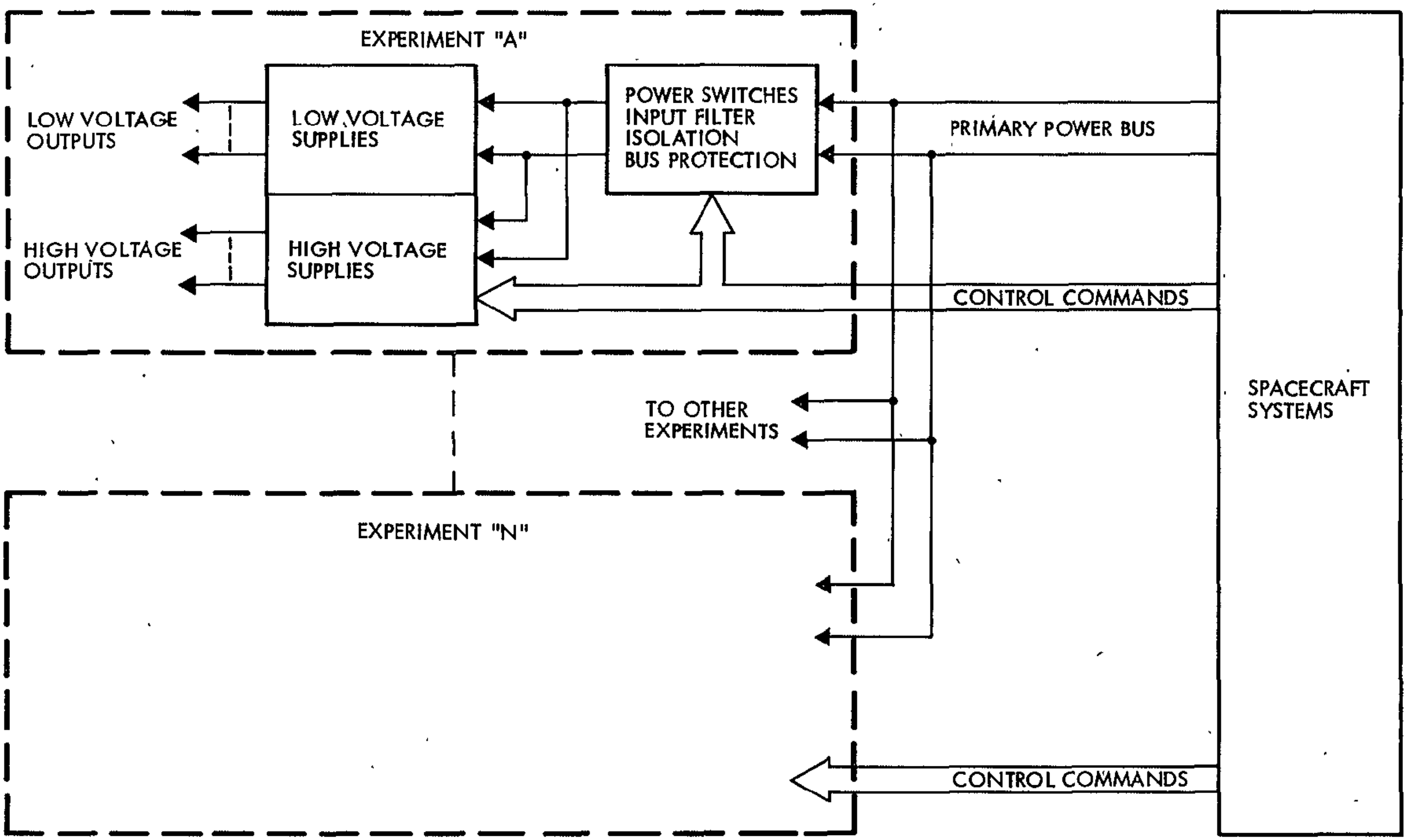

Figure 2-6. Custom-Designed Power Conditioning Subsystem

in Figure 2-7. In this organization, each instrument is provided with a dedicated set of standard input power conditioning, low and high voltage modules. The type, number, and power rating of the modules is selected to satisfy the requirements of the particular instrument. This approach satisfies the established system requirements with the exception that the capabilities of the standard subsystems may not be fully utilized by each instrument.

A subsystem organization which would provide a more efficient use of the hardware is shown in Figure 2-8. In this approach the power conditioning functions are provided by a centralized power conditioning subsystem shared by all the instruments. Sharing of the same modules, however, is not practical in most cases because of the requirements for independent instrument power control, isolation, and overload protection, and the possibility of fault propagation.

If individual modules are assigned to each instrument, this system is merely a combination of individual experiment power conditioning systems at the same physical location and would only complicate the system wiring. We conclude, therefore, that the dedicated subsystem organization, shown in Figure 2-7, is a better approach, although it may be less efficient.

2.3.3 Command and Control Subsystem

As discussed in Section 2.2.3, instrument operation is generally controlled by spacecraft commands. The instrument command and control subsystem receives, decodes and distributes these commands to the appropriate instrument subsystem. The following command and control functions that were identified as amenable to standardization will be considered here:

- Establish the operating mode of the instrument and initiate operating sequences.
- Control instrument power supply voltages.

In addition to the specialized command functions identified in Section 2.2.3, some instruments require commands for operating mode

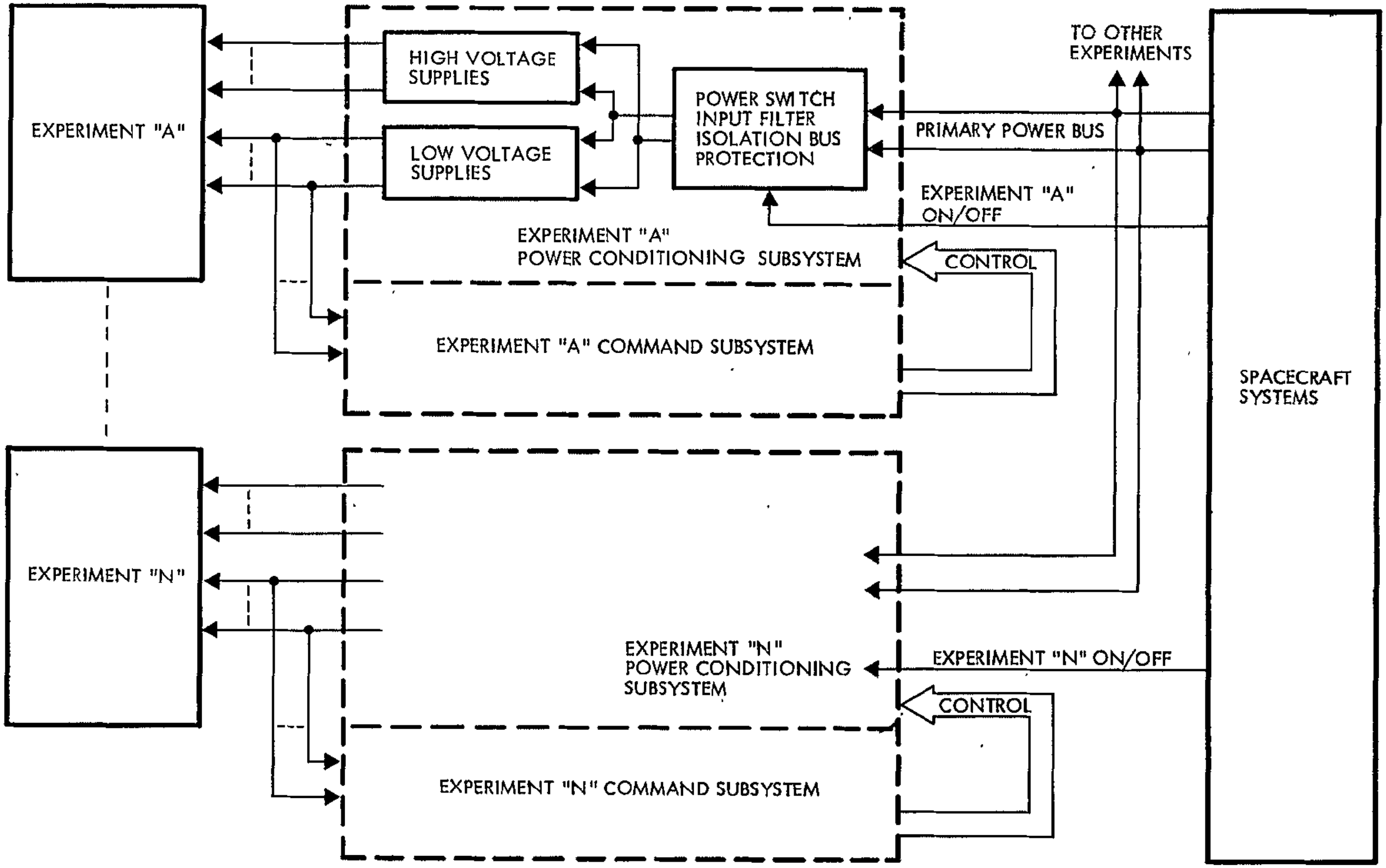

Figure 2-7. Power Conditioning Subsystem Implemented with Dedicated Standard Modules

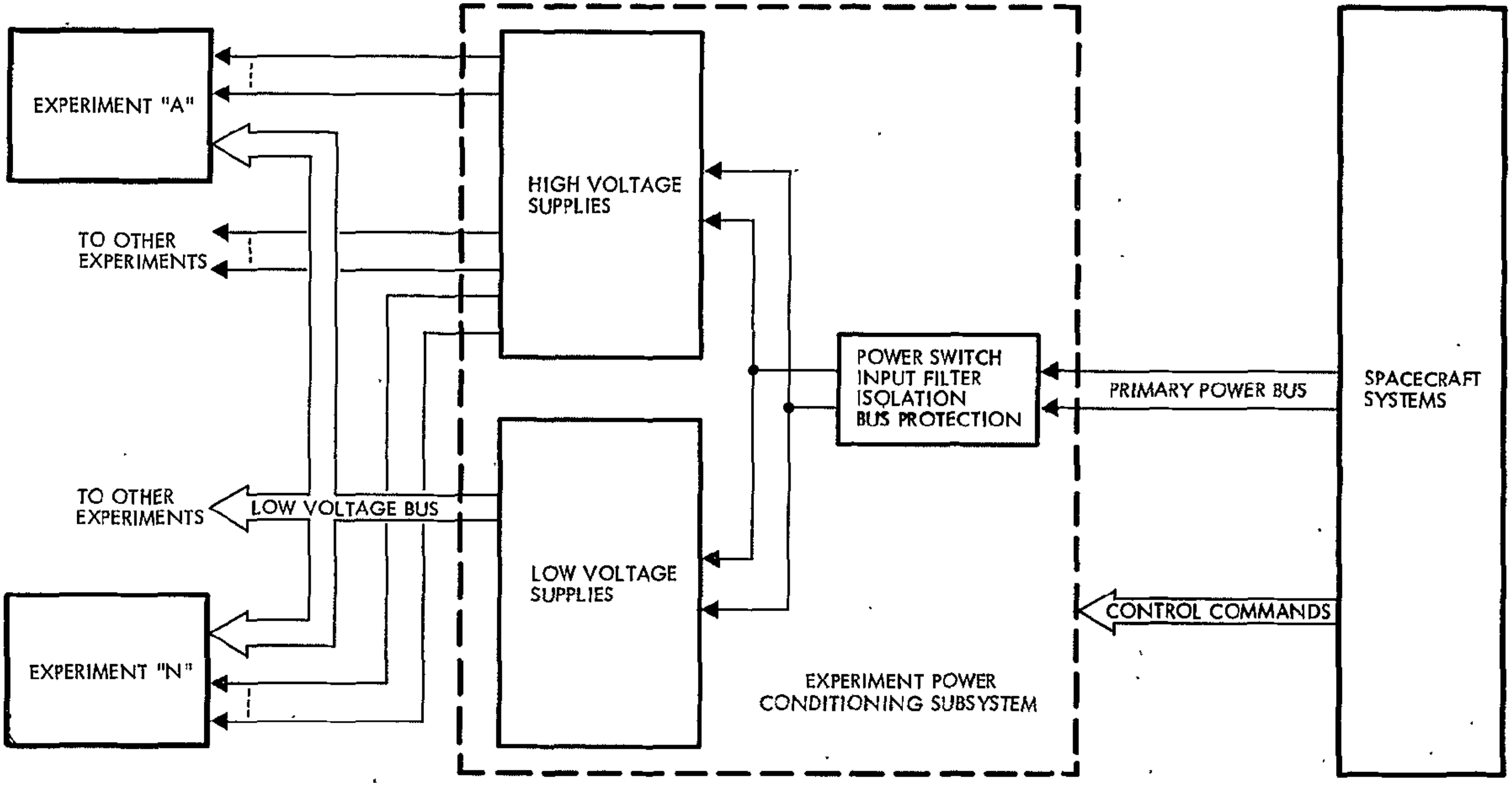

Figure 2-8. Power Conditioning Subsystem Implemented with Centralized Standard Modules

changes and/or initiation of certain operating sequences as a result of an instrument event or condition. These types of commands are in most cases stored or pre-wired within the instrument. Since they are usually closely related to the data acquisition functions it is appropriate to treat them as part of the data processing subsystem.

The block diagram of a typical instrument command and control subsystem is shown in Figure 2-9. The spacecraft commands are transmitted to the instrument either as discrete (pulse or bilevel) and/or as a serial word. The command registers hold the instrument control lines in the commanded state. Discrete commands are used as direct controls. Serial commands are decoded either as digital controls and/or converted into analog controls by digital-to-analog conveters. The number of control lines, command registers and D to A converters is dictated by the requirements of a particular experiment.

An instrument command and control subsystem implemented with standard functional elements is shown in Figure 2-10. This subsystem organization dedicates a standard command register, decoder and D to A modules to each instrument. Since serial commands are easily decodable into discrete control lines, we have eliminated the discrete command lines between the spacecraft and the instruments. This approach would simplify the spacecraft-to-instrument wiring.

Figure 2-11 shows a centralized instrument command and control subsystem shared by all instruments. The centralized subsystem shown uses a single serial command link to the spacecraft and distributes the commands to the appropriate instrument command registers by decoding the instrument address included in the command word. The potential advantage of the centralized approach is that only a single decoder is required. The simplification in the spacecraft interface is really artificial since the dedicated subsystems could share a common command bus that also carried the instrument address.

At this point, there is no overriding reason for selecting one approach over the other and the choice will be deferred to section 2.3.5 where we will consider the integration of the command subsystem with the data processing subsystem.

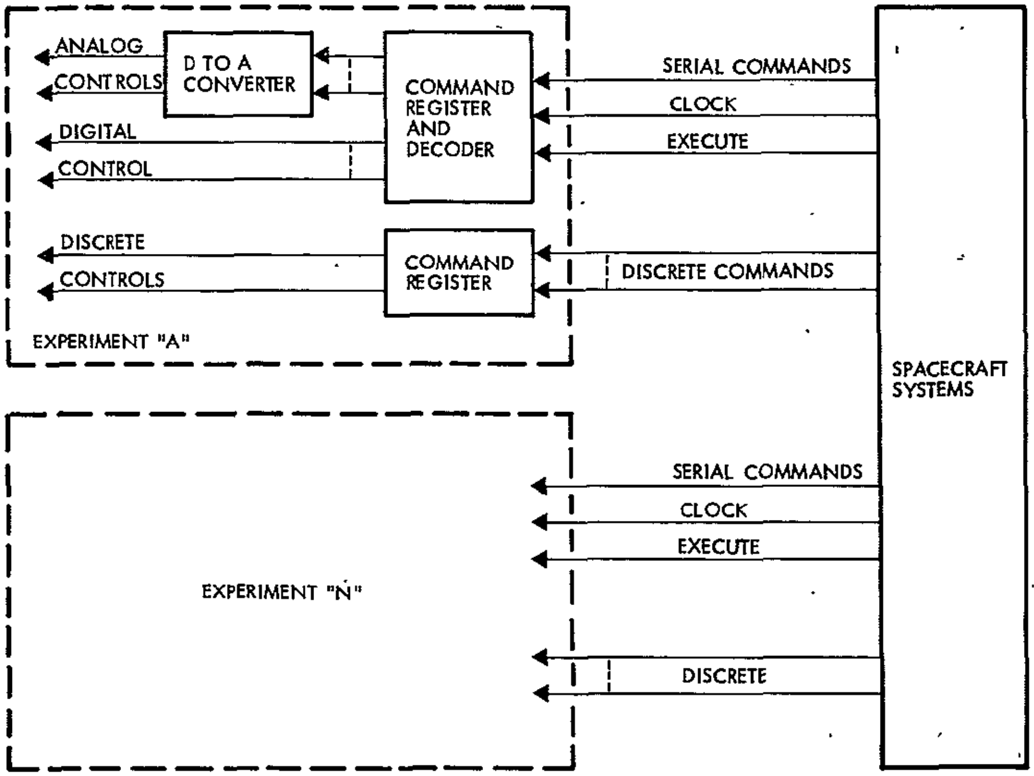

Figure 2-9. Custom-Designed Command and Control Subsystem

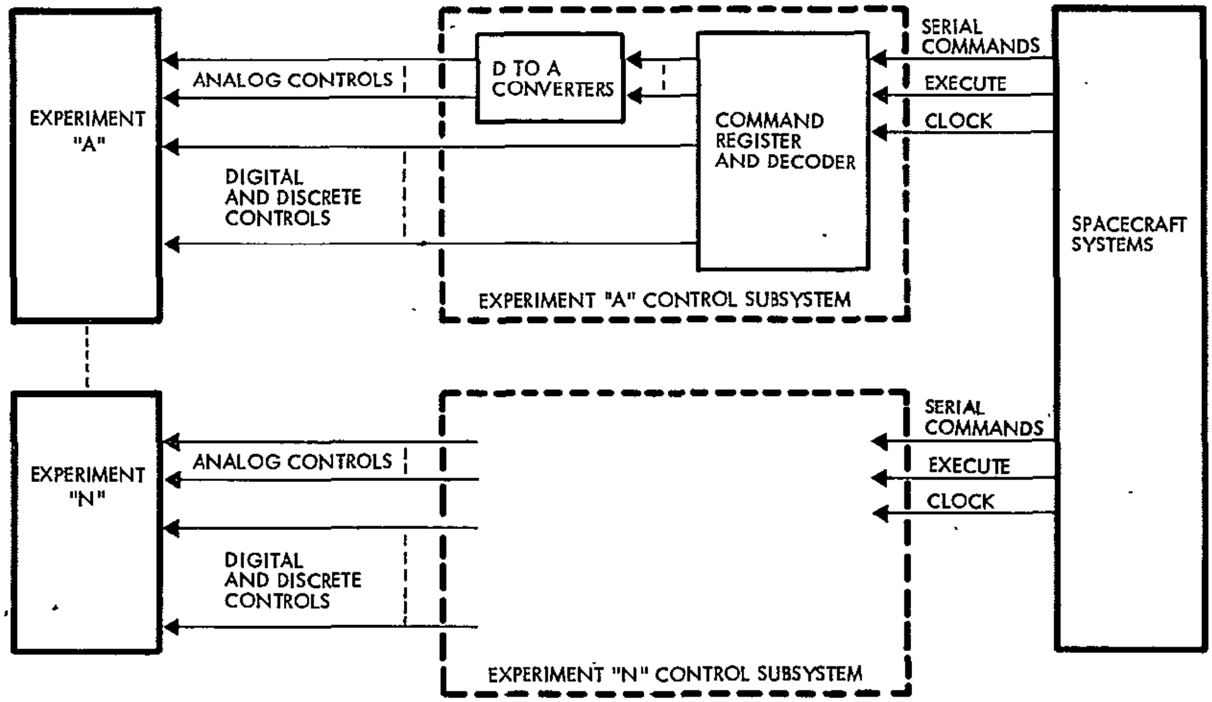

Figure 2-10. Command and Control Subsystem Implemented with Dedicated Standard Modules

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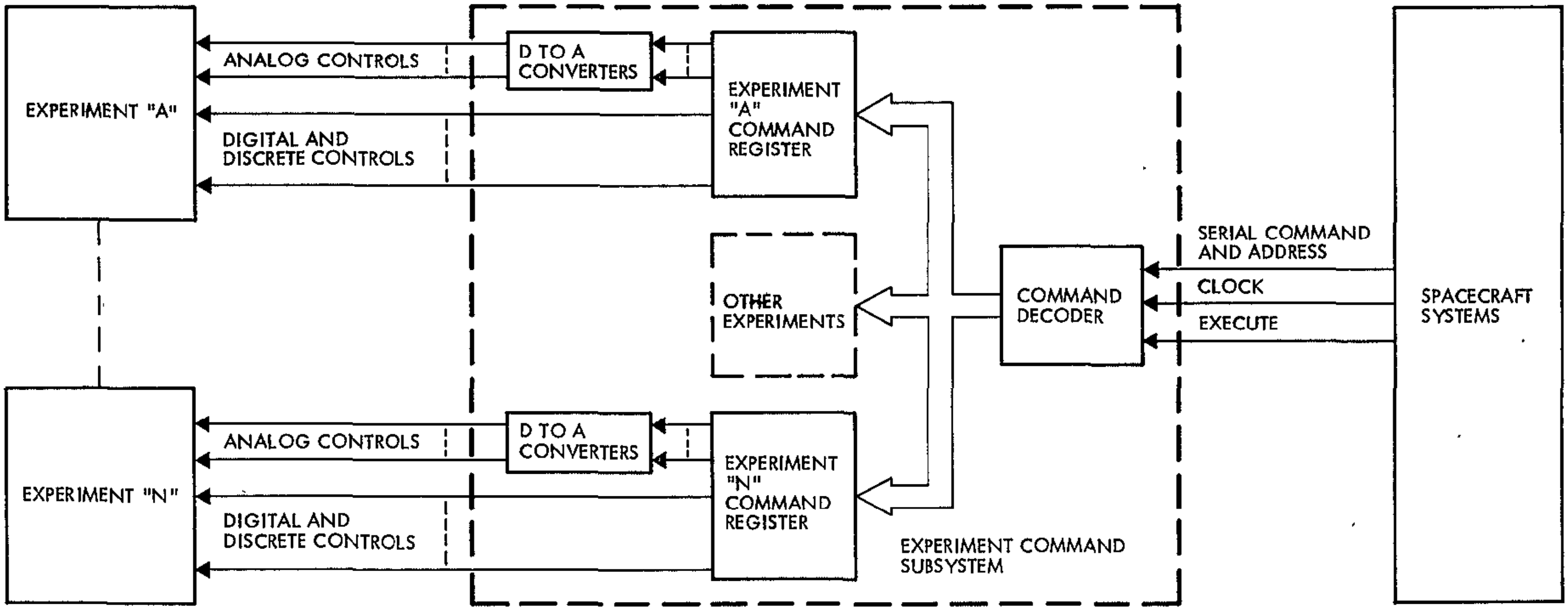

Figure 2-11. Command and Control Subsystem Implemented with Centralized Standard Modules

2.3.4 Data Processing Subsystem

The data processing subsystem collects data from the instrument sensors and subsystems and processes the collected data into a suitable format for delivery to the spacecraft telemetry system. In some cases the data may also be utilized in the internal operation of the instrument. The functional requirements of the data processing subsystem are the following:

- Sampling the various sources of instrument data.
- Conditioning of the acquired data into a suitable form for processing.
- Processing and formatting the data.
- Provide temporary data storage.
- Control and timing of the data flow.

A typical instrument data processing subsystem is shown in Figure 2-12. In most instruments the data processing subsystem has to process both digital and analog data from several sensors and subsystems. The various data sources are sampled by multiplexing them into one or more data processing channels. Digital data may be serial, parallel, or discrete (bilevel or pulse) signals. These data forms are usually converted into a single format (parallel or serial) which is compatible with the organization of the system. Analog data is converted by analog to digital converters and processed in digital form. In most instruments the analog engineering data is transmitted in analog form and the conversion is performed in the spacecraft system.

The sampling of the various data sources via the multiplexers is controlled by the sequencer. The sampling sequence may be fixed or variable according to the operating mode of the instrument, and controlled by wired logic, internally stored or spacecraft commands or, in some cases, by instrument events and conditions. Instrument event sequences are initiated by interrupts from the appropriate instrument subsystem. The sequencer timing is controlled by internal clocks or by spacecraft system clocks.

The amount and type of processing performed on the raw instrument data is usually determined by the amount of data generated and by the data handling capacity of the spacecraft telemetry system available to the particular instrument. When the instrument data rate is compatible

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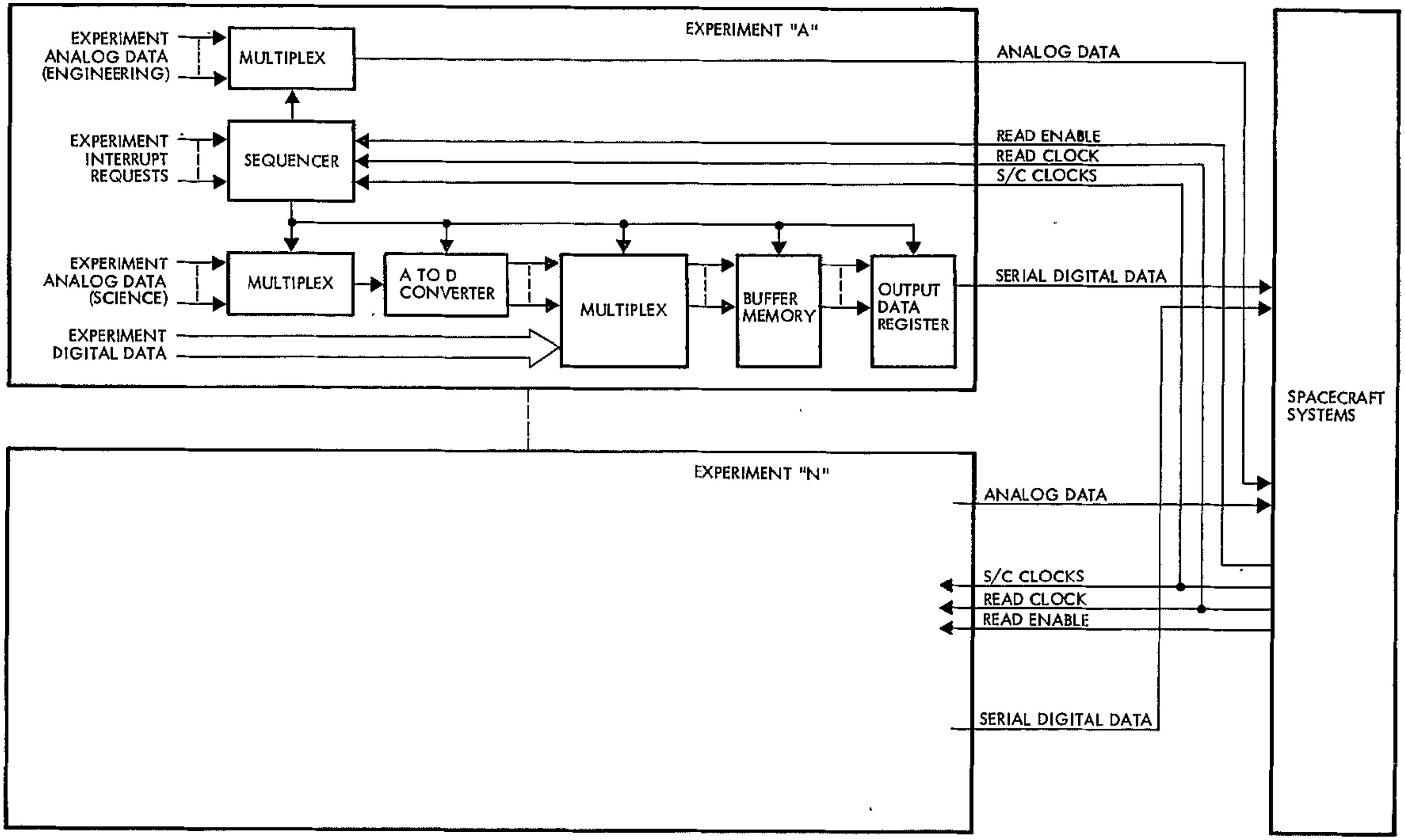

Figure 2-12. Custom-Designed Data Processing Subsystem

with the available telemetry capacity, the processing consists of only formatting the data for subsequent transmission to the telemetry system. If the instrument data rate is higher than the available telemetry capacity, then various types of processing techniques are used to preserve as much critical data as possible. Selecting data by priorities or data compression are two of the techniques employed.

In addition to processing telemetry data, processing may also be required for data used in the operation of the instrument. Temporary storage of the data for further processing and during periods when the telemetry system is not available is provided in a buffer memory. The output-data register facilitates synchronization of the instrument data transfer to the telemetry sampling rate.

An instrument data processing subsystem implemented with standard functional elements is shown in Figure 2-13. As discussed in Section 2.3.1, the science and engineering data processing functions are handled by the same subsystem.

In this organization a set of standard functional modules are provided for each instrument. The multiplexing, analog to digital converter, buffer memory and output register functions differ only in their data handling capacity from instrument to instrument. Consequently, it is straight forward to implement these functions with standard modules. The sequencer requirements, however, are more unique to a particular instrument in most cases. Therefore, a standard configuration must have a great deal of flexibility and include most of the required functions. The capabilities of such a system, however, may not be fully utilized by all the instruments.

A centralized system organization which could provide the required functions more efficiently is shown in Figure 2-14. This system is basically a general purpose data acquisition system controlled by a central computer. This data processing subsystem is shared by all instruments. With this system organization the instrument to instrument variations could be handled by computer software. This would result in more efficient hardware utilization. On the other hand, processing data from a large

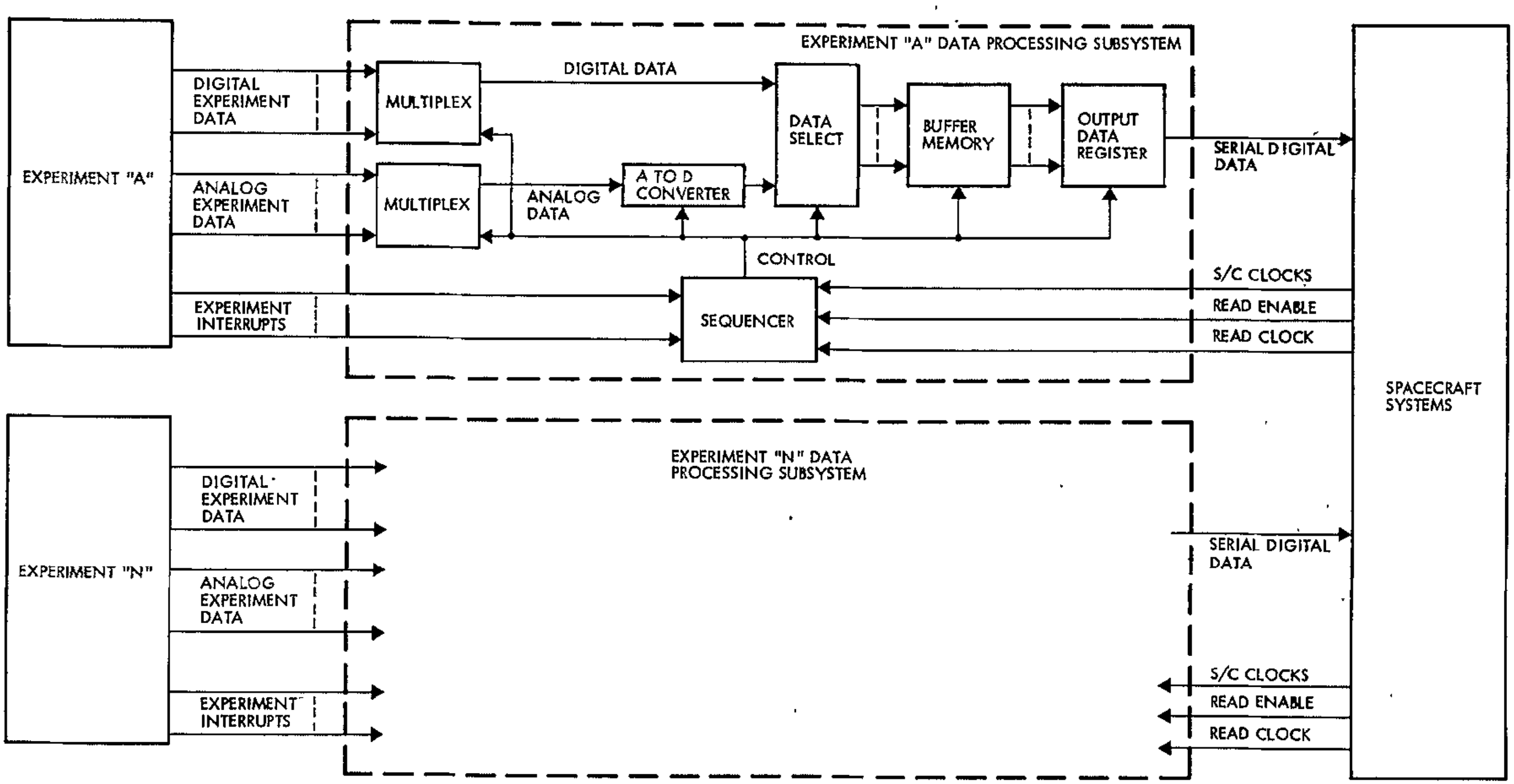

Figure 2-13. Data Processing Subsystem Implemented with Dedicated Standard Modules

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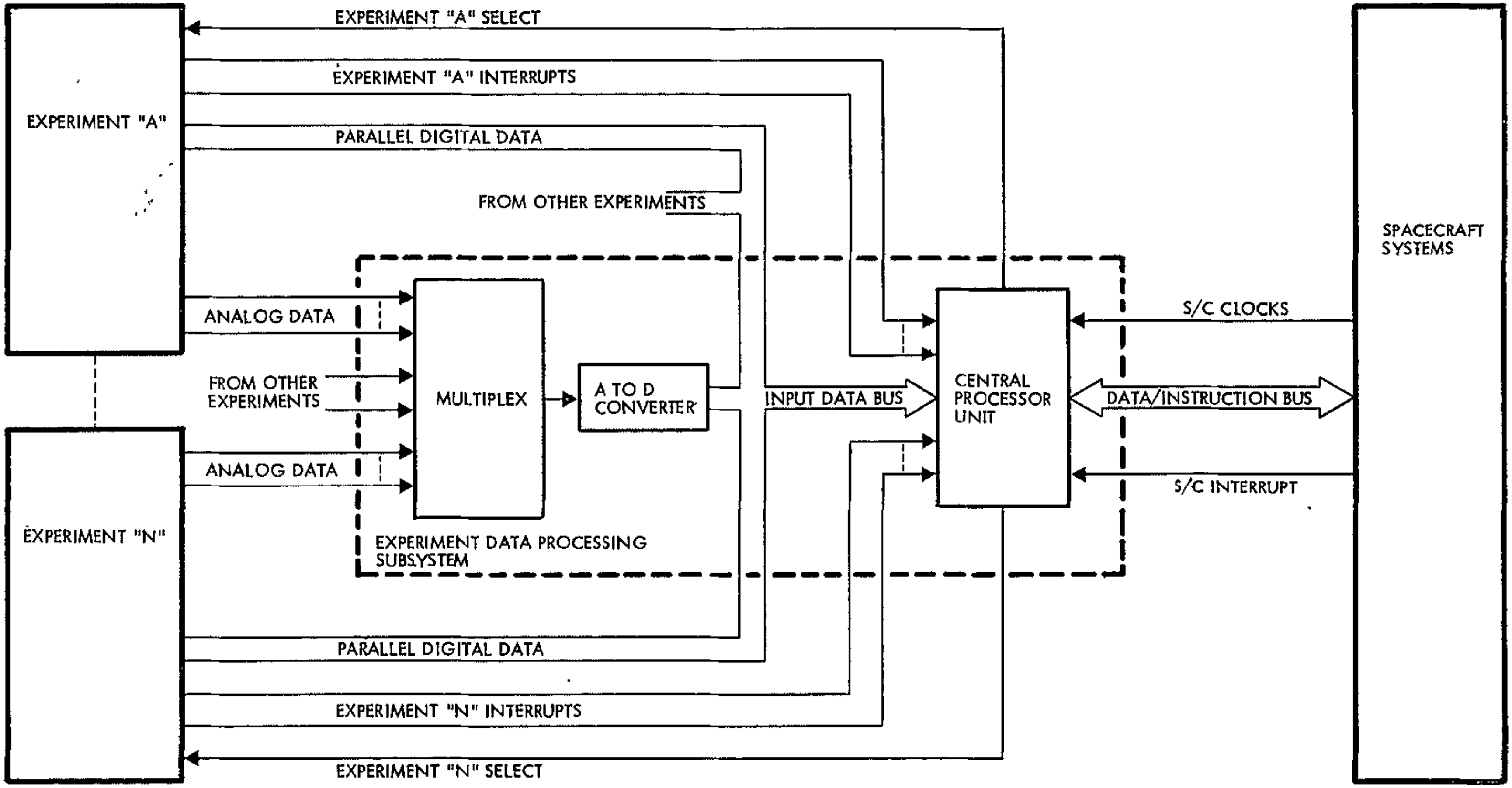

Figure 2-14. Data Processing Subsystem Implemented with Centralized Standard Modules

number of data sources in real time might require a highly sophisticated and high-speed computer system. In addition, with such an approach, each instrument would require a complex set of electrical ground-support equipment to fully simulate its spacecraft interface. Finally, the possibility of fault propagation and the complexity of system wiring could significantly compromise the reliable operation of the instruments.

In our opinion, the instrument dedicated system, shown in Figure 2-13 is a better approach considering the risks inherent in the centralized system.

2.3.5 Recommended System Designs

In the previous sections we evaluated the relative advantages and disadvantages of alternative system design concepts for implementing the instrument power conditioning, command and control, and data processing subsystems with standard functional elements. Two basic concepts were considered for each of the subsystems. One of these is the implementation of the particular subsystem with an assembly of standard functions dedicated to one instrument. The other approach combines the subsystems into a centralized system made up of standard modules and shared by all of the individual experiments. For the power conditioning and data processing subsystems the dedicated subsystem approach appears to be the best solution. For the command and control subsystem we did not have sufficient evidence to make a clear cut choice. However, as we discussed in section 2.3.3, there are command and control functions which are closely related to the data processing functions. To provide the option for exploiting the potential advantages of this commonality we have chosen the dedicated approach for the command and control subsystem.

Figure 2-15 shows the selected subsystems integrated into a total instrument support system. This system approach facilitates the implementation of the support system requirements with standard functions without compromising the flexibility required to accommodate a wide variety of instruments. This system also provides simple interfaces to the instrument as well as the spacecraft subsystems and minimizes the interaction between experiments.

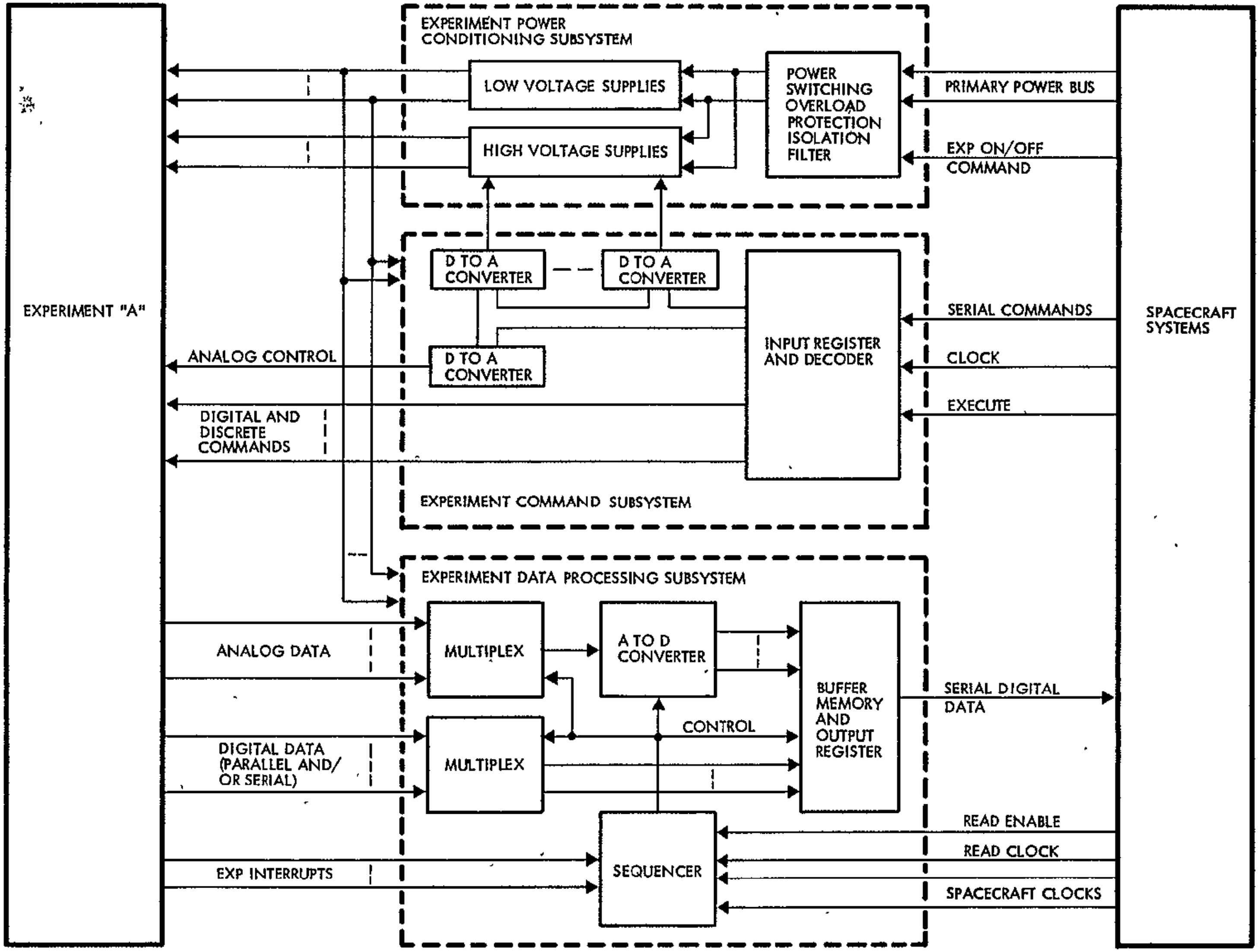

Figure 2-15. Instrument Implemented with Dedicated Standard Support Subsystems

This approach looks even more attractive considering the latest developments in microprocessor technology. Using a microprocessor to implement the data processing and control functions would greatly reduce the hardware requirements and provide added capabilities to the system.

A typical implementation of the instrument support subsystems utilizing a microprocessor is shown in Figure 2-16. This approach combines the command and data processing subsystem functions into a single subsystem controlled by a microprocessor. It provides the advantages of computer control without centralizing the instrument subsystems. The simplicity and economics of the microprocessor hardware would justify the use of this versatile system for each instrument even if the particular instrument did not require the full capabilities of such an approach.

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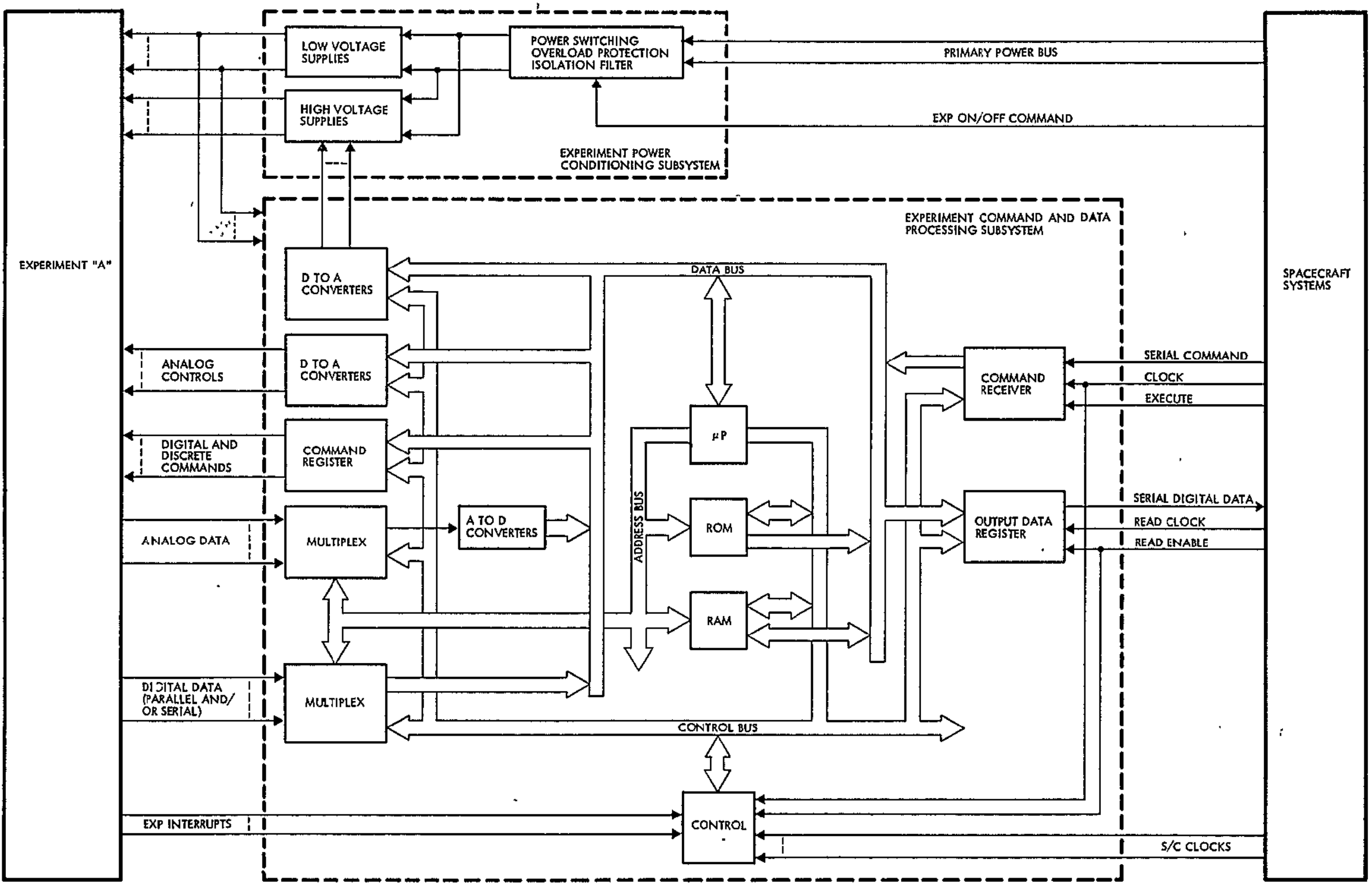

Figure 2-16. Instrument Implemented with Dedicated, Microprocessor-Controlled, Command and Data Processing Subsystem

2.4 COST SAVINGS BY USE OF STANDARD FUNCTIONAL ELEMENTS

To get a more quantitative idea of the cost impact of standardization, in this section we will use a cost model for quantity production of electronic equipment that is applicable to the type of instrument standard functional elements under consideration. The results will be presented in terms of production unit costs relative to the total cost of the first production unit. These results will then be used in a simple example that illustrates the potential instrument cost reduction due to standardization. In Section 4.5, after a more detailed picture of instrumentation costs has been built up, the initial design and development costs (in absolute terms) for a representative standard module will be estimated. The results from the present section and those from Section 4.5 will be combined and applied to the specific example of the HEAO model payload in Section 5.3.

2.4.1 Unit Costs for Standard Modules

Our cost model assumes that the standard modules will be designed and developed using procedures that are quite similar to those for current spaceflight hardware and that the production program will be geared to limited-quantity production on the order of 10 to 100 units. A review of costs from representative types of programs indicates that the recurrent cost of the first production unit constitutes about 5 percent of the initial development cost. The recurrent costs for subsequent production units are based on a 90 percent learning curve which we feel is reasonable for this type of production.

The results derived from the model are shown in Figure 2-17 which gives three different unit costs as a function of the number of units produced. Curve A is the recurrent cost of producing the n^{th} unit. Curve B is the cumulative average cost of the n^{th} unit; i.e., the average recurrent cost of producing the first through n^{th} units. Curve C is the cumulative average unit cost including all development and nonrecurrent costs. Since the cost of the first unit on Curve C is a reasonable representation of the cost of a flight unit produced in the current manner, the curves have been normalized to 1.0 for that point.

Figure 2-17 demonstrates directly the cost benefits of the quantity production that would apply for standard modules. If development costs can

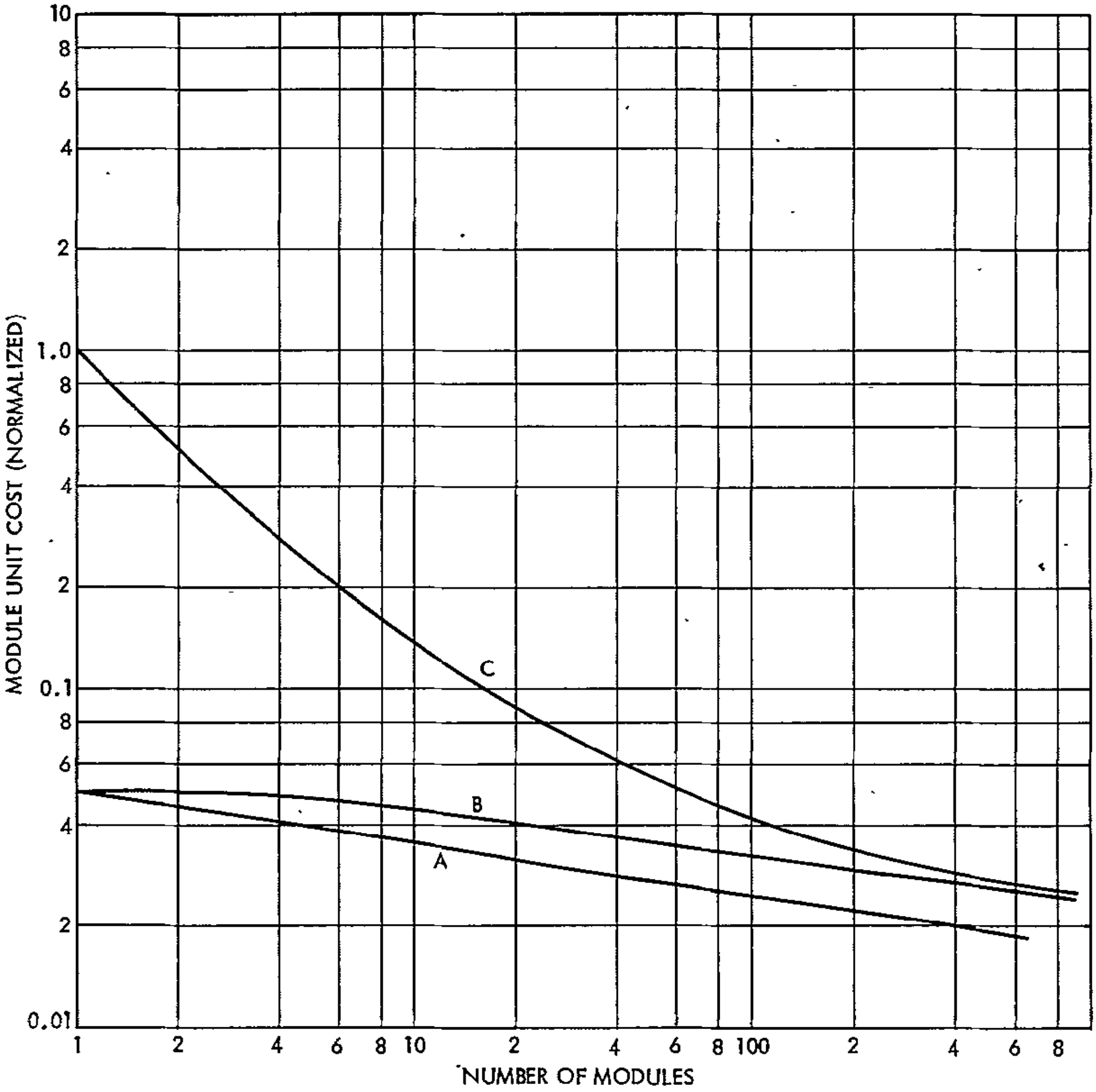

Figure 2-17. Relative Unit Costs of Standard Modules versus Quantity Produced

be amortized over a production run of even as low as 10 units, the average unit cost is reduced to 13.5 percent. At 50 units, the cost is down to 5.5 percent. It is clear that the bulk of the cost reduction results from the amortization of the development costs and is relatively insensitive to the unit production costs. If we doubled the unit production cost, the 13.5 percent would change to 18 percent.

2.4.2 Potential Instrument Cost Reduction by Standardization

The results from the previous section were used to estimate what might be considered as the upper limit on the reduction of overall experiment instrumentation cost. If we take the current typical value of 40 percent as the fraction of the instrument costs going to the electronic systems and optimistically assume that all of the electronics can be implemented with standard functional elements, we come to the following conclusion: if the development costs of the standardized functions can be amortized over even a relatively low number of units such as 10, the overall instrument costs will be reduced by about 35 percent compared to the ultimate limit of about 38 percent.

3. STANDARDIZED MODULAR PACKAGING

3.1 INTRODUCTION

3.1.1 Current Spacecraft Experiment Electronics Packaging

Today, experiment electronic equipment is custom packaged for each mission. Due to weight and volume restrictions, this equipment is frequently very densely packaged into oddly-shaped envelopes. Little advantage is taken of previously designed hardware and even where nearly identical experiments are to be flown, redesign is often necessary because of different envelope assignments. Repair is usually expensive and little flexibility exists for modification or expansion. Refurbishment or reuse is normally not a requirement. Further, to meet the stringent weight and volume constraints, the experimenter is often forced into expensive packaging techniques (e.g., intricate machining and plating, difficult thermal and structural designs, etc.).

3.1.2 Impact of Shuttle on Packaging Techniques

The capability of Shuttle to inexpensively launch larger automated spacecraft will result in a relaxation of weight, volume, and power constraints, thus making feasible the use of standardized and modularized packaging. Potentially, the most significant cost savings that can be realized by adopting a standard system of modularized equipment packaging, results from the use of common designs for standard experiment functions in a variety of experiments; i.e., minimizing custom packaging design and development.

Further, Shuttle retrieval and on-orbit maintanance of automated spacecraft should allow the refurbishment and reuse of the hardware for the same or different experiments providing significant "economies of multiple use" that have not been possible in the past. To accomplish experiment refurbishment and reuse in a cost-effective manner, the equipment will need to be readily replaceable, maintainable, and accommodate experiment modification. The obvious mechanism to provide these characteristics is the modularization and standardization of experiment equipment.

Finally, the relaxation of weight and volume constraints, in itself, will lead to some cost saving resulting from a reduction in packaging design complexity.

3.1.3 Modularization

Modularization is the packaging of the experiment equipment in units that correspond to system functional elements in such a way that the units can be easily removed, replaced, and reconfigured. Modular functional elements are readily replaceable units, preferably plug-in with blind mating connectors, guides, and hold-down hardware that facilitate installation and removal. In order to be easily maintained, the individual modular elements should have well-defined functional characteristics that facilitate troubleshooting and allow the use of automated test sets. Modular elements provide enhanced accessibility for servicing. Individual modular elements have well-defined interface characteristics to allow easy reconfiguration of system functions and the characteristics of the functions should be reasonably general to allow application flexibility.

For discussion purposes, it is convenient to define four levels of experiment equipment modularization:

- Level 1 - Major System Level; total instrument electronics package
- Level 2 - Instrument Subsystem Equipment; for example, the instrument data processing subsystem or the power conditioning subsystem
- Level 3 - High-Level Instrument Functions normally contained on a single PC board; for example, amplifiers, power supplies, analog to digital converters
- Level 4 - Individual Components or Simple Circuits; small PC card

An objective of this study was to determine the level and form in which the modularization should be accomplished in order to optimize the implementation of experiment instrumentation. In this regard, the differences between spacecraft subsystems and experiment instrumentation are significant. For example, experiment instrumentation will almost always be more subject to change than the spacecraft subsystems - both during development and from flight to flight. Therefore, greater emphasis should be placed on flexibility in the modularization of experiment equipment as opposed to spacecraft equipment. Further, the functional level chosen for modularization should readily accommodate technological advances in component usage.

3.1.4 Standardization

Standardization refers to a packaging system that will reduce the high development and hardware costs of instrument modules and not become overly restrictive. Standardization is mandatory if we are to repair, refurbish, and modify payloads economically.

The benefits that can result from standardization of experiment equipment include a greatly reduced and concentrated instrument design and development in the critical nonstandard areas (usually the sensor subsystem). Standardization also permits a significantly reduced test effort because fewer parts of an experiment require qualification and multiple usage of standardized test equipment, software, and procedures is facilitated. Cost estimating techniques and reliability and quality assurance efforts are streamlined. Finally, logistics requirements are eased due to volume procurement and the reduced requirement for numerous types of spares.

Balanced against all of these advantages is the inherent danger of loss of flexibility in adopting a standard. If the standards cannot accommodate the vast majority of potential users, the standards will either not be used or important considerations, such as experiment science, will be compromised. Therefore, it becomes extremely critical to select the appropriate level of standardization sufficient to realize the potential benefits without becoming overly restrictive.

3.1.5 Task Objectives and Scope

This task defines a standard system of modules for packaging experiment electronic equipment. This definition consists of recommendations with respect to what areas should be standardized and to what extent they should be standardized. General recommendations are presented as to specific packaging design approaches that seem most appropriate and the impact on weight, volume, and cost of experiment equipment. The areas with which we are primarily concerned include:

- Module Size: Module size considerations include determination of the smallest functional element, the lowest replacement level, and the smallest testable unit.

- Growth: The study provides guidelines for standard package envelope growth patterns and how system growth can be accommodated; i.e., the ability to expand the system so that it provides more power, signal lines, memory size, etc.

- Electrical Interfaces and Interconnections: Methods of electrical interconnection were studied to determine a flexible system that could be optimized around the new experiment system architectures.

- Mounting Configurations and Mechanical Interfaces: Recommended methods of mounting were examined for the different sizes and designs to meet the dynamic, thermal, and EMC requirements.

3.1.6 Study Task Approach

The packaging study task proceeded as follows: We compiled and reviewed a variety of standard module packaging methods to determine their general characteristics and to assess the feasibility of adopting approaches or features for packaging experiment functional elements. We reviewed current spaceflight packaging methods and trends to establish experiment packaging requirements. We examined, in detail, promising standard module packaging approaches and performed comparative evaluations of their relative merits for the various instrument system concepts. Packaging requirements considered in these evaluations included:

- Modular Design Level: to provide maximum cost savings by reducing instrument design and development activities

- Launch Environment: primarily the ability of the equipment to withstand the structural vibration and acoustic noise at launch

- Thermal Environment: use in automated spacecraft requires that electronic equipment be conduction cooled

- EMC: the ability of the external case to protect against outside EMC interference and the internal protection afforded between circuits by the packaging concept

- Modularity: the number of high-level functions that can be accommodated by a single module

- Maintainability: the ease of access to the equipment for repair and servicing

- Flexibility for System Expansion and Modification: includes interchangeability as well as incurred overhead penalties

- Ground Handling: primary emphasis on suceptibility to damage during normal manufacture and test activities

- Producibility: referring to manufacturability and ease of assembly and test

3.2 REVIEW OF EXISTING PACKAGING TECHNIQUES

In our review of current modular packaging practices we examined widely used laboratory, military and avionic techniques and the TRW "Slice" approach for aerospace application. The review included NIM-CAMAC modules, Navy SHP and QED modules and ATR enclosures as well as the TRW Slice. A brief description of each of these is presented in the following sections.

3.2.1 NIM-CAMAC Modules

NIM and CAMAC modular equipment is presently in widespread use throughout the United States and Europe for laboratory applications and the use of CAMAC for industrial process control is growing rapidly. Because of this broad user acceptance, the equipment is manufactured and competitively marketed by numerous commercial suppliers. Although these two complementary standards for modular equipment differ in several details, we have considered them together because they use essentially common packaging approaches.

Background and Description - The NIM (Nuclear Instrument Modules) standard* was developed by an AEC sponsored committee with the objective of providing a means for laboratories to obtain a low-cost, off-the-shelf, set of interchangeable electronic modules reducing the need for expensive custom-built experiment equipment. The standards define mechanical and power supply interface characteristics of the modules and their associated support structure (NIM bin) which provides for rack mounting and power supply interconnections. They do not define any required signal processing standards, although suggestions to enhance commonality are provided.

The bin will accomodate 12 single width modules, each 34.92 mm wide. Modules can be built in any multiple of the basic single width with double, triple and quad width modules being commonly used. These modules can be installed in a bin in any combination of widths equivalent to a total of 12 single widths or less.

The modules have a standard depth of 254 mm and the only height in common use is 222.24 mm although the standard provides for an

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*Standard Nuclear Instrument Modules, TID-20893(Rev. 4), USAEC, 1974 alternative height of 133.34 mm. Two bins are defined, one for each of the standard module heights (again, in current practice, only the taller bin is readily available). Both bins mount in EIA standard 482.6 mm (19 inch) electronic racks.

The ESONE committee of European laboratories issued the CAMAC modular instrumentation standards in 1969. These standards were subsequently adopted by the AEC NIM committee*

In addition to mechanical and power supply interface characteristics, the CAMAC standard defines the characteristics of digital data transfer between modules and with a centralized data processing system. Also incorporated in the standards are the details for a crate that provides for rack mounting and data bus and power connections for up to 23 modules and a control unit.

A typical CAMAC module is shown in Figure 3-1 and a crate with an integral power supply and a full complement of modules is shown in Figure 3-2. The single width module is the same height as the tall NIM module (222.24 mm) and half of its width (17.46 mm). The depth of a CAMAC module is 304.80 mm. Again, the modules can be built in any multiple of the single width although triple widths and wider are rarely used. A single width module accomodates a single board with soldered-in integrated circuits. A double width module accomodates either two such boards or one board with wire-wrap type integrated circuit sockets.

In practice, the common usage of NIM and CAMAC is complementary. CAMAC is used almost exclusively for data acquisition functions while NIM is typically used for analog signal conditioning functions.

Summary of Major Characteristics

- Candidate packaging concept
- Level 3 module
- Widely used in ground based laboratories

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*CAMAC - A modular Instrumentation System for Data Handling, TID-25875, USAEC, 1972

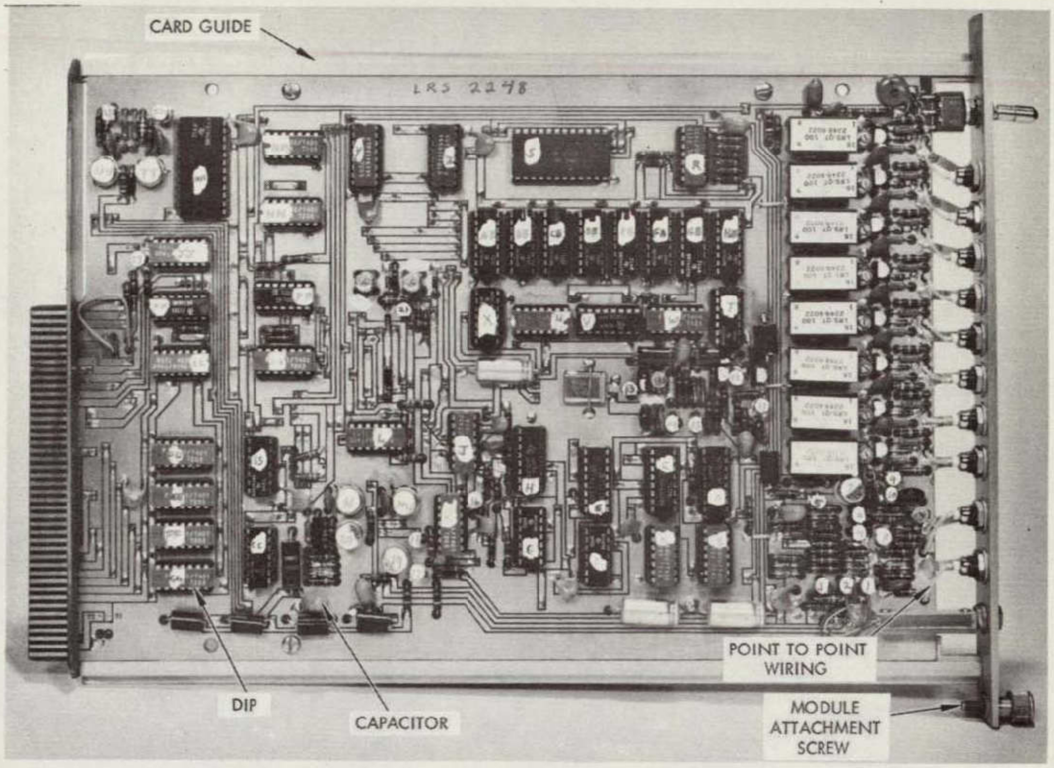

Figure 3-1. A Typical CAMAC Module

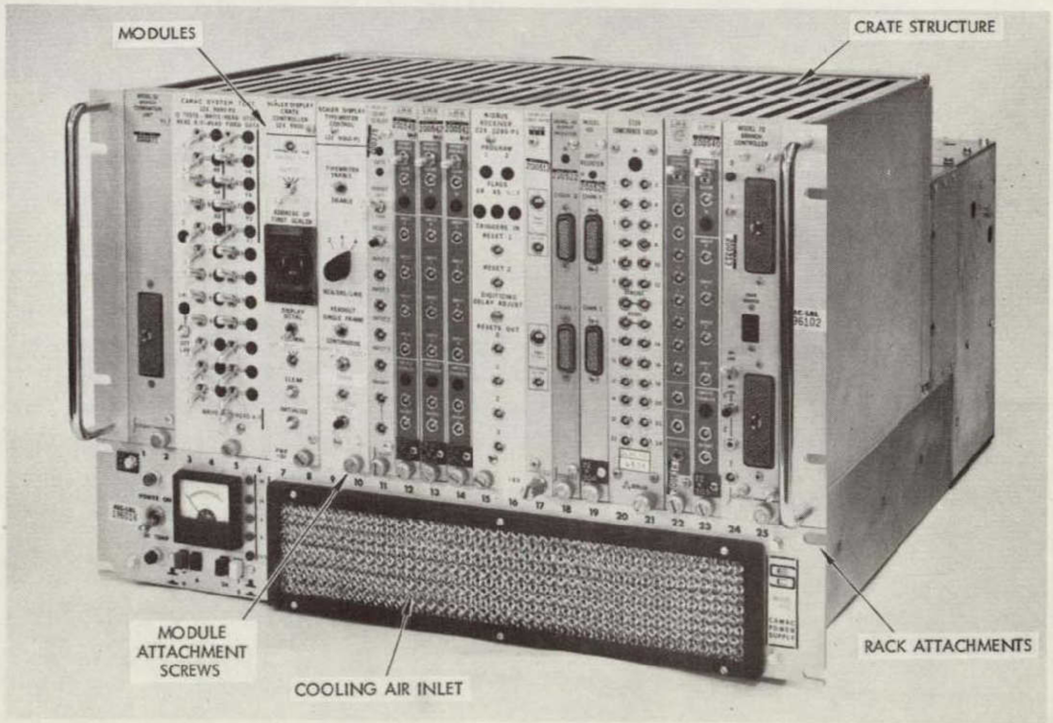

Figure 3-2. A Typical CAMAC Crate with Modules

- Convection cooled and, therefore, would require modification for use in conventional automated spacecraft
- Large catalog of level 3 functions exist

3.2.2 Navy SHP Module

Background and Description - SHP modules*, manufactured by several military equipment supliers, are a family of electronic plug-in, throw-away-upon-failure modules used in a variety of military electronic systems. The SHP module is a combination of a specific functional printed circuit board and several basic components (frame/heat sink, keying pins, and 40-pin I/O connector).

The Navy emphasizes that Standard Hardware Program (SHP) modules have been successfully employed in over 40 separate military electronic systems. Some of the more significant SHP module systems are:

- Mk 88 (Poseidon) Fire Control System,
- Mk 113 Mod 9 Torpedo Fire Control System,
- AN/BQQ-5 Sonar System,
- AN/BQR-21 (Dimus) Sonar System,
- AN/BQS-13 Sonar System,
- Submarine Acoustic Warfare System (SAWS).

These considerations led to the development of a basic module increment with overall dimensions of 66.55 mm in width, 49.53 mm in height, and 7.62 mm in thickness (Figure 3-3). There are also provisions for multiple growth SHP module increments for use in the development of modules of multiple span and thickness. Modules can be increased in span by increments of 76.20 mm as illustrated in Figure 3-3, and in thickness by increments of 7.62 mm.

Figure 3-4 identifies the component parts of a typical 1A-size module. The parts are as follows:

- Fin Structure - The fin serves as the identification marking surface, extraction interface, and as a means of heat dissipation. Cooling is by means of free- or forced-convection.

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*NAVELEX 0101-073, Standard Hardware Program Module Descriptions

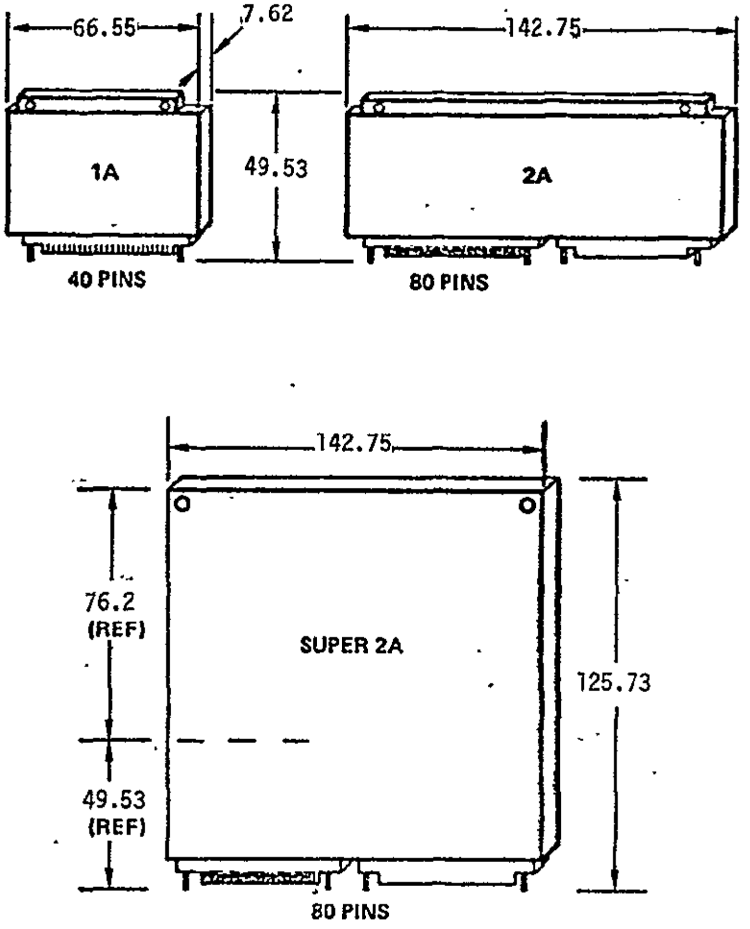

Figure 3-3. SHP Type 1A and 2A Modules and QED Type Super 2A Module

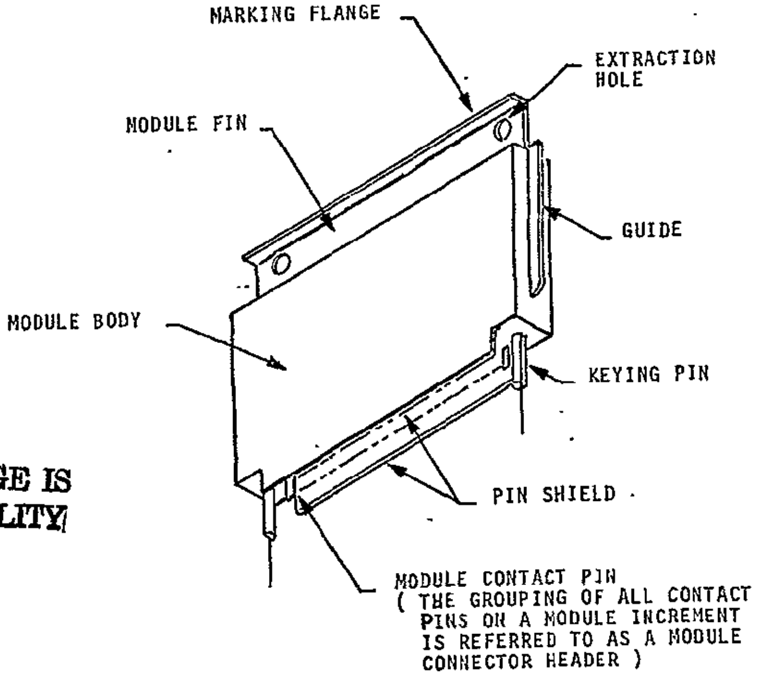

Figure 3-4. SHP Module Component Parts

- Guides - The guides at each end of the module span aid in the alignment of the module in the card cage and assist in the proper mating of the module contacts and mounting structure connector.
- Contact Pins - The portion of each of the male contacts protruding from the header surface is configuratively controlled by the SHP to insure the proper engagement of the SHP module and its interface mounting structure. The contacts are arranged in two rows of 20 contacts each on a 2.54 mm grid system to form module-connector increments. Each module increment may have a maximum of 40 contacts or a minimum of 20 contacts per module.
- Key Pins - Two keying pins serve to insure the proper mating of the SHP module to its appropriate interface connector. Each SHP module type is assigned a three-letter key code which identifies and establishes the configuration and rotational postions of the two uniquely configured keying pins. SHP modules having the same key code are both mechanically and electrically interchangeable.
- Pin Shields - The pin shields function as a protective cover for the module contacts and a marking and identification surface.

Summary of Major Characteristics

- Level 4 module
- Convection cooled and, therefore, would require modification for use in conventional automated spacecraft
- History of use by the Navy in submarine and surface-ship electronic equipment
- Large catalog of low-level functions exists
- Usage generates as much as 6:1 and 4:1 increase in volume and weight, respectively, over custom-designed systems due to level 4 modularization
- Small discrete component module is pin limited and, hence, unable to accomodate LSI/MSI components

3.2.3 Navy QED Modules

Background and Description - The Naval Electronics Laboratory Center in San Diego, California, is presently developing a series of electronic modules called Quick Easy Design (QED)*. These Modules, which are not available as yet, are being developed primarily because of the

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*Technical Report 1904,2175 Program: Quick and Easy Design (QED) of Systems Through High-Level Functional Modularity inability of the SHP modules to accept LSI/MSI components. QED modules are patterned after the SHP 2A module except that they are taller by 76.2 mm (Super 2A in Figure 3-3) and contain high-level functions (Level 3).

These modules are designed to be readily expanded and assembled into Level 2 functions with significantly less detailed design, interface hardware, and control circuitry than would be required for designing directly from Level 4 components.

The following are the mechanical packaging constraints that have been placed on the QED modules:

- The functions shall be partitioned at a level suitable for implementation with existing state-of-the-art LSI technology and packing (for example, no more than 80 pins).
- Module implementation at the breadboard level must be pin-for-pin compatible with the package to be used for the QED production model of the system.
- Standard pin assignment for power, ground, and certain common signals will be used throughout the QED module family.
- The overall system package must be compatible with existing standard rack size limitations and power usage of Navy systems.

The basic component in the QED project is the super 2A card. This card is an extended height version of the SHP 2A module with a span of 142.75 mm, thickness of 7.62 mm and height of 125.73 mm. The super 2A card has a total of 80 contacts in the form of two 40-pin SHP connectors mounted at the bottom. Each card has two extraction holes at the top which may be used with an extraction tool to pull the cards from their mounting structure.

Summary of Major Characteristics

- Candidate packaging concept
- Level 3 module
- Typically convection cooled, conduction cooling modification possible

- Primarily used for digital circuitry
- Due to its rugged design, the module is probably suitable for automated spacecraft use with minor modifications
- Accepts LSI/MSI components

3.2.4 Air Transport Radio (ATR) Enclosures

Background and Description - The Air Transport Radio Equipment Case and Racking program* is basically a mechanical module standardization program. Its aim is to dimensionally control the sizes of mechanical enclosures and associated isolation mounting assemblies to house avionics electronic equipment for aircraft and helicopters. The standardization program came about through a cooperative effort between United Air Lines and Aeronautical Radio, Inc. (ARINC) in 1940. As a result of their efforts, a specification was prepared to standardize cases for airborne electronic equipment which was then being designed for use in the Douglas Commercial Four Aircraft (DC-4). This specification for ATR cases and racks was later revised, updated and published as ARINC Specification 404. The ATR cases and racking system is currently used in both commercial and military avionics equipment, and is also found in some ground electronic equipment installations, surface vehicles, and ships.

Figure 3-5 describes the dimensions of the standard ATR case sizes.

Summary of Major Characteristics

- Level 2 module
- Widely used for avionics by both military and commercial organizations since 1940
- Convection cooled (modification to conduction cooling is possible)
- Internal packaging design for electronic functions not specified
- Rugged construction suitable for automated spacecraft

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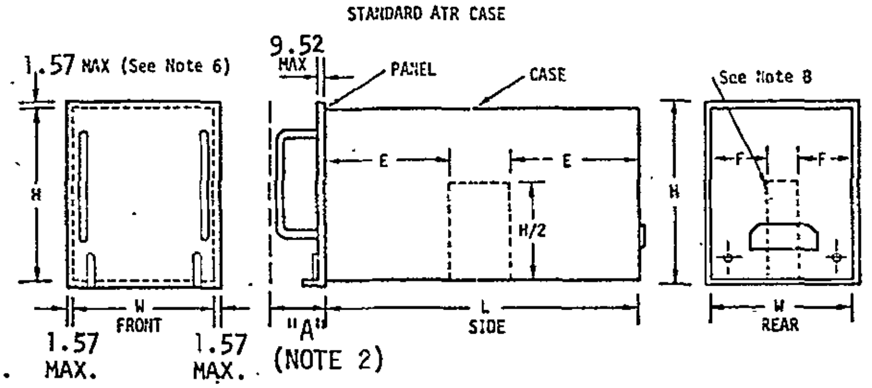
*ARINC Specification 404



Case Size	Approx. Volume cu. cm.	(W) Width ±.78	(L) Length Max.	(H) Height Max.	F	E	Wt. Range kgm.
Short 1/4 ATR	3531	57.15	319.07	193.68	19.05	133.35	15-26
Long 1/4 ATR	5499	57.15	496.87	193.68	19.05	207.96	17-66
Short 3/8 ATR	5587	90.42	319.07	193.68	31.75	133.35	11-33
Long 3/8 ATR	8701	90.42	496.87	193.68	31.75	207.96	26-77
Short 1/2 ATR	7651	123.82	319.07	193.68	50.80	133.35	17-39
Long 1/2 ATR	11915	123.82	496.87	193.68	50.80	207.96	39-88
Short 3/4 ATR	11772	190.50	319.07	193.68	76.20	133.35	22-66
Long 3/4 ATR	18332	190.50	496.87	193.68	76.20	207.96	44-99
Short 1 ATR	15893	257.18	319.07	193.68	107.95	133.35	39-88
Long 1 ATR	24749	257.18	496.87	193.68	107.95	207.96	55-132

NOTES:

1. All Dimensions include finish and are in millimeters.
2. Front panel forward projection including handles and antenna connectors shall not exceed dim. "A" max. from rear face of front panel. (ARINC #404, A = 66.67 mm; MIL-C-172, MS91403, A - 98.42 mm).
3. Bottom Projections are not permitted beyond panel.
4. Side face projections shall not be used below 19.05 mm above base. Projections must not exceed 1.78 mm max. and shall have round edges.
5. Back Projections shall not be used below 88.90 mm above base. Projections must not exceed 1.78 mm max. and shall have rounded edges.
6. Front Panel - use of a full front panel is optional. Use of the 1.59 mm max. front panel top and side projections is optional.
7. Panel thickness - Max. thickness shall not exceed 9.52 mm. Preferred thickness 1.57 mm, 3.18 mm.
8. Center of gravity for cases used with class A mounting base shall fall within dotted lines. The weight of the connections and 30.5 cm of attached cabling is considered for c.g. location.

Figure 3-5. ATR Case Specifications

3.2.5 TRW "Slice" Modular Concept

Background and Description - The TRW "Slice" is an internally developed modular semistandardized packaging concept* which has been used on Pioneer, HEAO, FLTSATCOM and other recent automated spacecraft programs. This modular packaging method makes possible the development of the various portions of the electronics assembly separately as the circuit design for individual functions becomes established.

Each module is in the form of a complete cross-sectional "slice", incorporating its own housing, structural integrity, circuit board mounting, interconnection wiring, thermal transfer paths, and usually, its own external connectors (see Figure 3-6). The modules are capable of being designed, built, and tested as individual units. By maintaining standard size and mating requirements for all modules, it is possible upon completion of all units to fit the slices together to provide a complete, well-designed, spaceworthy electronics assembly. Since each slice has its own housing, it is not necessary to provide another box to enclose the entire assembly. The modules are specifically designed for conduction cooling.

Nominal external dimensions are 15.2 cm by 17.8 cm with a nominal thickness dimension of 2.5 cm. All dimensions, however, may be varied. The external design of most slices is fairly similar. Internal structure of the module slice is varied to provide mounting flanges for circuit boards and compartmentalization for electro-magnetic interference shielding. In some instances, closely fitted metallic covers are provided for a full shielding enclosure of internal compartments containing radio frequency or noise generating circuits.

Each slice housing thus serves a threefold purpose as basic structure for the assembly, a chassis for mounting circuit boards and parts, and shielding for electro-magnetic interference protection.

The slice module concept allows a considerable degree of flexibility in design. If, in the integration of the spacecraft electronics,

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*Electronic Packaging and Production, Vol. 9, No. 10, Page 29, October 1969

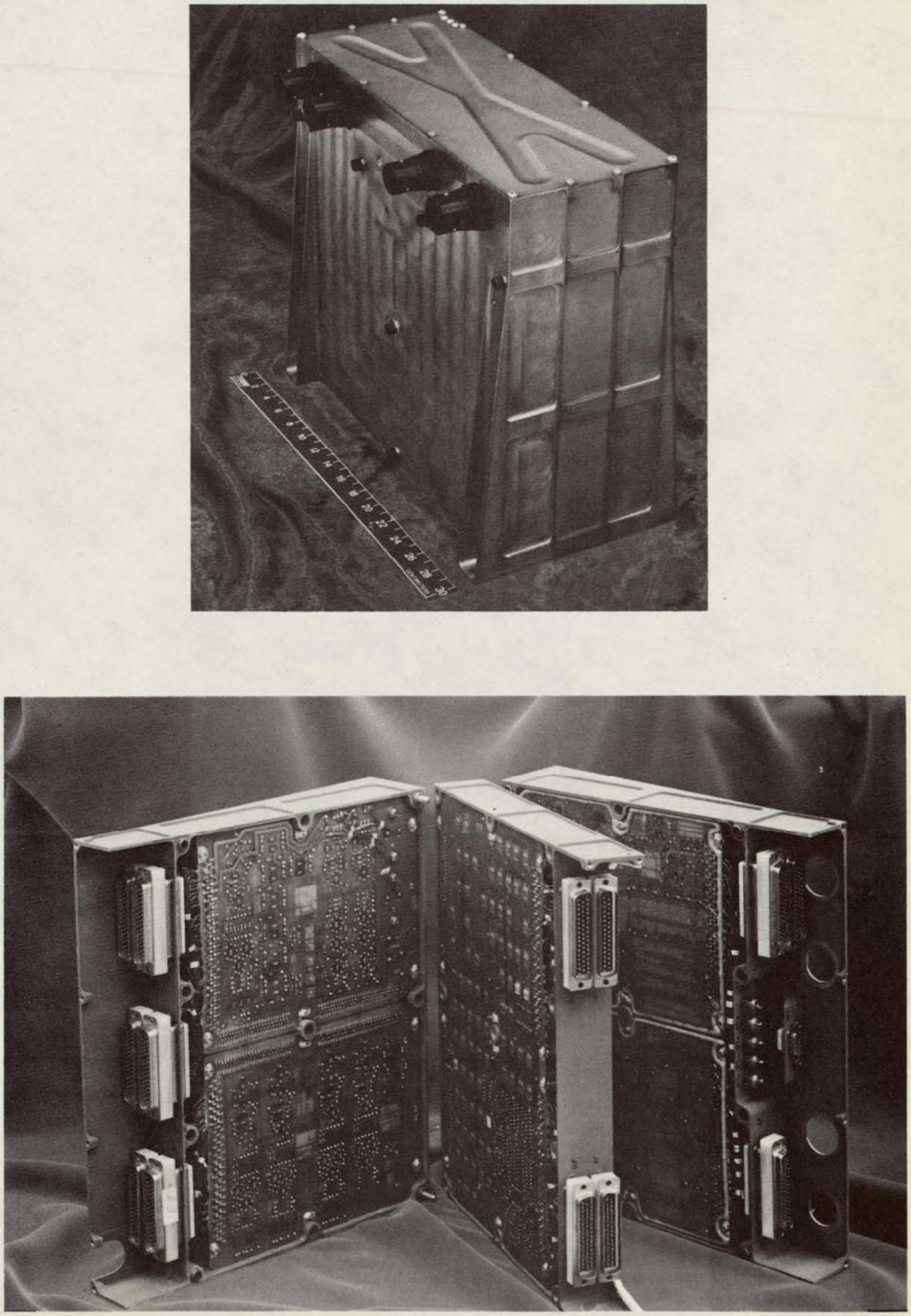

Figure 3-6. TRW Slice Modular Packaging for Spaceflight Electronics

it becomes necessary to add additional circuitry, this is easily accomplished simply by designing and inserting another slice module. Since such design changes occur routinely, rather than rarely, it is important that it not be necessary to redesign the entire structure. Other variations in design are also possible.

Summary of Major Characteristics

- Candidate packaging concept
- Can be implemented at Level 2 or 3
- Conduction cooled
- History of use in automated spacecraft
- Suited for conversion into a low-cost, ruggedized, NIM-CAMAC type, high-level functional module

3.3 INSTRUMENT PACKAGING CONCEPT

We have examined in detail each of the packaging concepts described in the previous section for characteristics that could be utilized in packaging experiment electronics. The functional elements defined for commonality in Section 2 correspond to Level 3 modularization. Three Level 3 packaging approaches were examined, NIM/CAMAC, QED Modules and the Slice Modules. In the following section, we summarize our comparison of the characteristics of the three approaches for adaptability to automated spacecraft usage. Following this comparison, a suggested concept suitable for use in conventional automated spacecraft environment is presented in Section 3.3.2.

3.3.1 Comparison of Alternative Packaging Characteristics

Launch Environment

NIM/CAMAC - This equipment is designed for use in ground-based laboratory environments. We believe that with relatively simple structural modifications, the equipment could withstand the launch vibration environment.

QED/ATR - This module has been ruggedized to meet Navy shipboard vibration and shock environment but because of its mounting characteristics, it may be susceptible to high-frequency vibration failures.

SLICE - The Slice is specifically designed for spacecraft environment and of the three approaches reviewed, the slice is clearly superior with regard to structural integrity.

Thermal Environment

NIM/CAMAC - This equipment is designed to operate in a laboratory environment and is cooled by forced convection which is not available in conventional automated spacecraft. Redesign would be required for modification to conduction cooling.

QED/ATR - Heat sinks are available for conducting heat away from the electronic components but the basic module design relies on convection cooling.

SLICE - The Slice is specifically designed as space equipment and conduction cooling capability is good. Some relaxation in weight requirements on the units would, in turn, reduce thermal resistance and permit a reduction in critical thermal analysis and design costs.

EMC-External

NIM/CAMAC - The equipment is not well protected against external EMC interference due to the large cooling holes in the module structure.

QED/ATR - The Navy QED module is housed in a fully covered ATR case, which provides good EMC protection.

SLICE - The Slice, in its enclosed assembly, is also completely protected from any external EMC interference but needs close machining tolerances to achieve the best protection.

EMC-Internal

NIM/CAMAC - In NIM/CAMAC equipment, internal protection from EMC interference is good because of the flow of the circuits and the separate locations of the low-level and digital input/output connectors.

QED/ATR - Internal EMC protection is only fair because input and output connectors are located in the same area of the module.

SLICE - The low-level and digital circuits together with their connectors are separated resulting in good internal EMC protection.

Modularity - Number of Level 3 Functions/Module

NIM/CAMAC - Equipment is typically designed with multiple Level 3 functions.

QED/ATR - QED modules would normally provide a single Level 3 function.

SLICE - Multiple Level 3 functions can be provided.

Level 2 Integration - Maintainability

NIM/CAMAC - Maintainability is good. The module is easily removed from its rack. Covers can readily be removed providing unrestricted access to the printed circuit boards.

QED/ATR - QED modules are also easily maintained.

SLICE - The Slice is more difficult to maintain because of time required to disassemble

Flexibility for System Modification and Interchangeability

NIM/CAMAC - The system is extremely flexible and facilitates interchangeability due to its standard interfaces. The system carries with it an overhead penalty in excess volume associated with unused module spaces.

QED/ATR - With a properly designed standard interface, the QED modules could provide flexibility for modification. These modules like the NIM/CAMAC modules have a significant overhead associated with them.

SLICE - Modification of the Slice is simply a matter of disassembly and replacement of a function with a modified Slice. Hence, overhead penalties can be minimized.

Module Ground Handling

NIM/CAMAC - NIM/CAMAC is an enclosed module used in the laboratory - readily handled, shipped, etc.

QED/ATR - The QED module by itself has poor resistance to damage since it does not have the protection of module covers or siderails.

SLICE - The printed circuit board is exposed when a slice is separated from its assembly.

Producibility

NIM/CAMAC - Excellent producibility; PC board is easily assembled by several screws to module frame and accessible from both sides of module.

QED/ATR - Also has excellent producibility; easily assembled into case.

SLICE - Module frames must be machined to close tolerances.

3.3.2 Recommended Packaging Concept for Standard Modular Electronics

After reviewing and comparing the three Level 3 standard modules for desirable features and characteristics, it is our recommendation that an approach similar to the TRW Slice concept be utilized for standard modules to package instrument electronics.

Among advantages offered, this packaging design:

- provides accessibility to the printed circuit boards and their components,
- permits the design and fabrication of each chassis assembly through final test without depending upon other circuits or changes elsewhere in the unit,
- provides for system growth of the unit by adding additional slices without complete redesign,
- permits removal and replacement of individual slices without rewiring if component failures occur during test,
- standardizes packaging techniques and reduces costs in the design and manufacturing phases of each instrument project,
- provides lightweight assemblies sufficiently rigid to withstand the vibration environment of spacecraft,
- provides adequate electromagnetic compatibility and thermal management.

If replaceability and maintainability become a major consideration, a concept similar to that illustrated in Figure 3-7 could be adopted at the penalty of greater weight and volume than the Slice. Fundamentally, this packaging approach is a ruggedized conduction-cooled version of ground-based laboratory modules.

The printed circuit board is mounted to a unitized structural frame which, in turn, is mounted in a module mounting rack along with similar modules that make up the electronic system. The rack is customized to accommodate all of the required modules for a particular instrument without leaving unused module space.

The module frame has good rigidity; is easily mounted or removed from the rack and provides a good heat conduction path. A module would normally consist of a single printed circuit board, however, larger modules

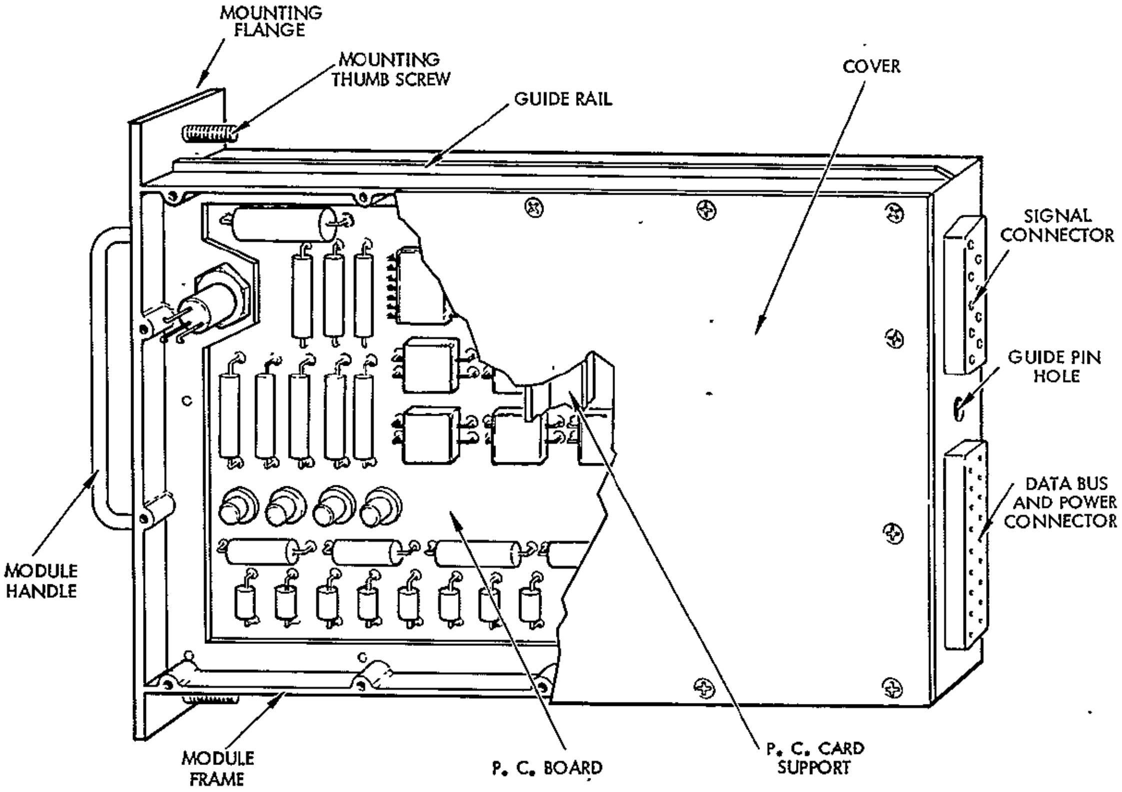

Figure 3-7. Ruggedized, Conduction-Cooled Packaging Concept Derived from NIM/CAMAC

could be provided to contain multiple printed circuit boards if desired. The printed circuit boards, along with their associated heat sinks, are mounted to the frame by standard mounting screws.

Attachment of the module to the mounting rack is accomplished by the guide pin at the rear of the module and the two mounting thumb screws on the front panel, one on each flange. The guide pin acts as a locator for connector engagement and also provides structural support in shear assuring that no forces are applied directly to the connectors.

Guide rails on the top and bottom of the module frame and the mounting rack permit easy assembly of the modules into the mounting rack and direct the module to the respective guide pin for connector engagement.

The module covers protect the unit from damage during handling, shipping, and storage and also provide EMC integrity. The printed circuit board can be attached to a rib on the inside of the cover to prevent excessive board deflection.

4. MISSION ASSURANCE

4.1 INTRODUCTION

It is generally recognized that the capability to retrieve, repair and reuse spaceflight equipment to be offered by the Shuttle should make the acceptance of increased equipment failure rates feasible. Since a significant fraction of spaceflight hardware costs are currently expended in performing mission assurance activities to attain high equipment reliability, it follows that a relaxation of the requirement for high reliability should be convertible into cost savings. Before proceeding into a description of the specifics of our work in the mission assurance area of the study, we will state the problem in slightly more quantitative terms.

4.1.1 Cost/Reliability Tradeoff

The performance measures of mission assurance are cost and reliability (i.e., the probability that the equipment will successfully function as specified for the duration of the mission). From a hardware point of view, the total cost of performing a mission can be regarded as the sum of the instrument development cost and the operational cost of flying the instrument. The qualitative relationship between instrument development cost and instrument reliability is well known. The development cost increases as the reliability increases towards 1.0 due to the increasing amount of effort required to attain the reliability. On the other hand, if we define the operational cost as the cost required to successfully perform the mission, the operational cost increases as the reliability decreases due to the added number of flights required on the average to achieve success. Because of the opposing relationships between these two components of the total cost and reliability, there is a minimum in the relationship between total mission cost and reliability. These qualitative relationships are depicted graphically in Figure 4-1.

The current situation with relatively expensive, nonrecoverable launch vehicles is represented by the dashed curves. Because of the high operational cost of failures, the optimum (i.e., minimum cost) point corresponds to a relatively high value of instrument reliability.

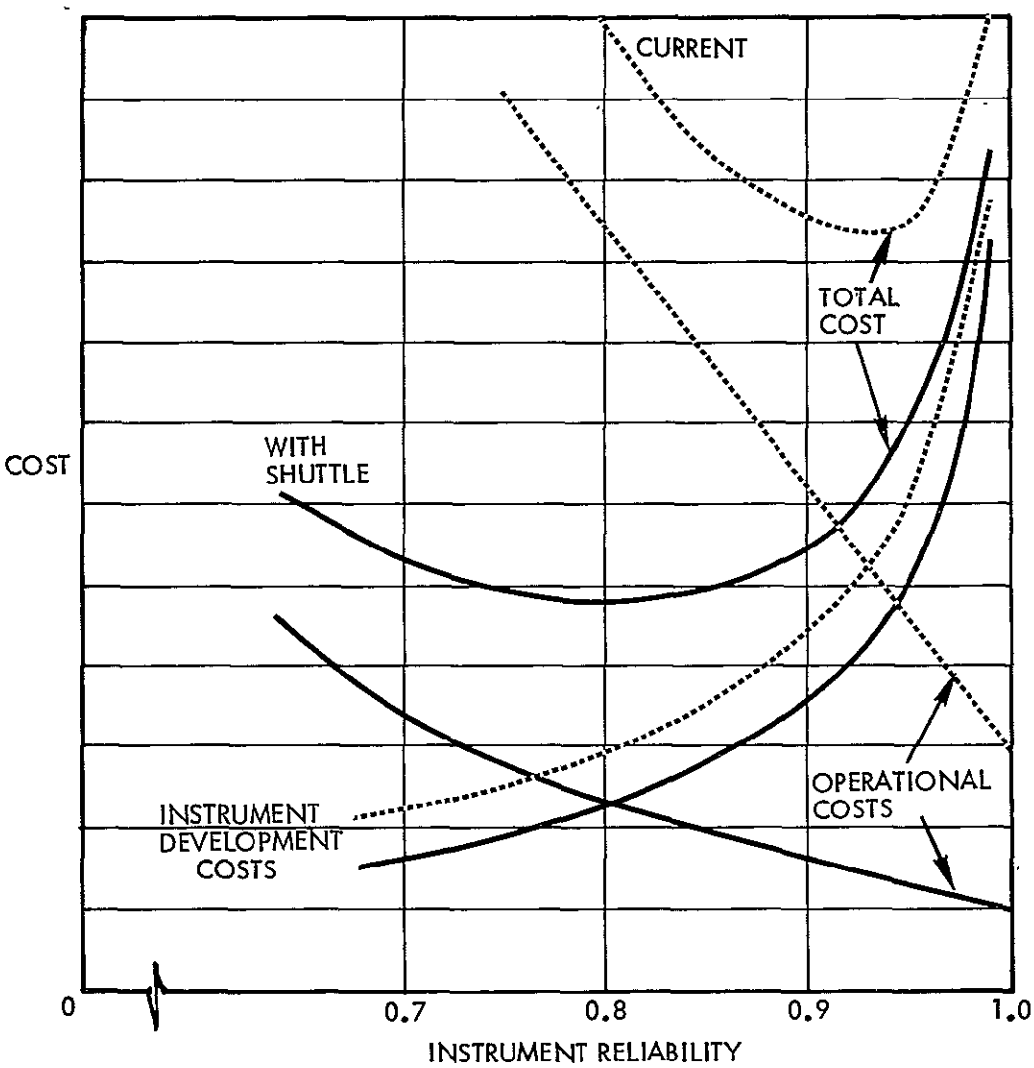

Figure 4-1. Graphical Representation of the Mission Assurance Cost Optimization Problem

The situation with the Shuttle is shown by the solid curves. The primary impact of the Shuttle will be to very significantly reduce the operational cost due to both reduced launch costs and the ability to retrieve, repair and reuse a failed instrument. As we have seen, instrument development cost reductions that can be attributed to the Shuttle are also possible. The net result is to move the optimum point to both lower cost and lower reliability.

4.1.2 Mission Assurance Study Scope

From a mission assurance standpoint, then, the problem of cost optimization over the entire mission amounts to a tradeoff between instrument development cost and operational cost. In order to perform this tradeoff, the quantitative relationship between reliability and both development and operational costs must be known. Unfortunately neither relationship is known today. The determination of the dependence of operational cost on instrument reliability is, in principle, a straight forward problem. The difficulty at the present time lies in the lack of definition of much of the requisite input data such as Shuttle operational costs.

The determination of the relationship between instrument development cost and instrument reliability presents a much more fundamental problem on which we have concentrated our attention in this study.

As a first step in an effort to develop a systematic approach to this problem, we have structured the tasks performed in a typical, or baseline, instrument development program in a way that is intended to clarify their relationship to the instrument reliability. We have also determined the distribution of program costs within this task structure as well as the overall instrument reliability produced by the baseline program.

The next step, which is beyond the scope of the present study, would involve establishing quantitative relationships between the level of effort devoted to any particular task and the instrument reliability. If this difficult step could be accomplished, a mathematical model could be constructed which would predict instrument reliability as a function of the level of mission assurance effort and therefore could be used to optimize the mission assurance program.

To assess the possible return that could be expected from the development of such a model, we have used a general cost/reliability relationship to estimate the cost reductions that could result from reducing instrument reliability requirements.

Although it was not our intent to complete the development of this approach within the scope of this study, the analysis performed provided a framework in which several possible approaches to mission assurance cost reduction could be evaluated. The results were also incorporated into a simplified model of total mission cost optimization which was used to give a more quantitative feeling for the tradeoff shown in Figure 4-1 between development cost and operational cost.

4.1.3 Mission Assurance Cost Reduction Approaches

The approaches to mission assurance cost reduction that were examined in the study are illustrated graphically in Figure 4-2. Starting from the baseline program, represented by Point A in the figure, a number of suggestions for improving the efficiency of current mission assurance procedures were developed. Adoption of these suggestions is depicted as a move from Point A to Point B since they are not expected to significantly reduce the instrument reliability. Cost reduction by reducing the required instrument reliability would involve moving along the cost/reliability curve from Point A to Point C. As discussed in the preceding section, a simple cost/reliability relationship was used to estimate the effect on instrument cost.

In Section 2.4, we saw that a significant cost reduction is possible by the use of standard modular electronics. This can be represented by a move from Point A to a reduced cost baseline at Point D. As will be discussed in Section 4.5, the incorporation of standard modules can be expected to result in an increase in instrument reliability. Finally, the composite effect of adopting standardization and reducing instrument reliability is represented by the move from Point A to Point E.

An extensive survey of the pertinent literature was performed in the course of the mission assurance analyses. A bibliography is included as an appendix to this report. The references cited in this section are found in the bibliography.

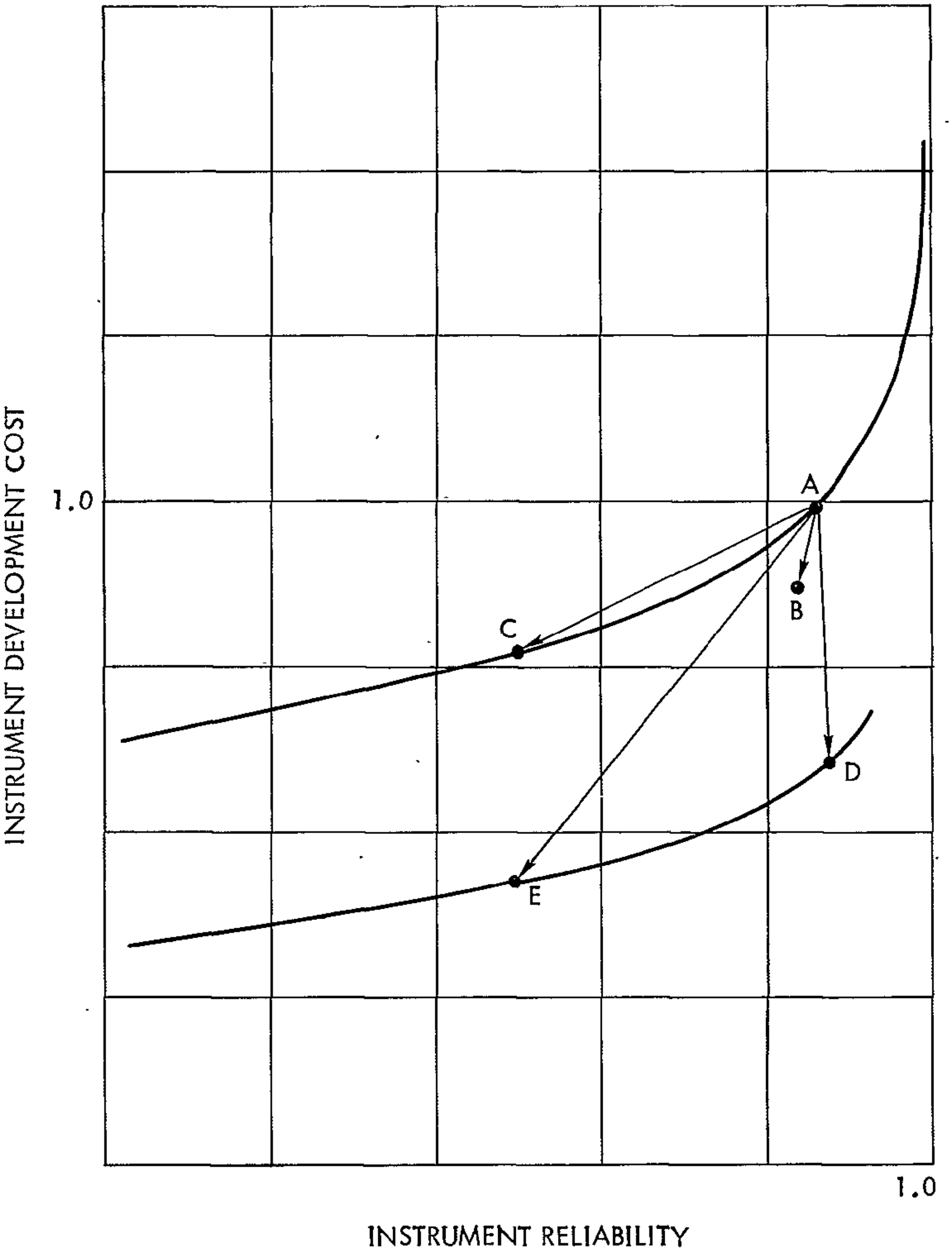

Figure 4-2. Possible Approaches to Mission Assurance Cost Reduction

4.2 BASELINE INSTRUMENT DEVELOPMENT PROGRAM

As a baseline or starting point for our analyses of instrument mission assurance, we developed a detailed definition of a spaceflight instrument development program as typically carried out today. The baseline instrument program to which it applies is visualized as a development program for a nonrecoverable spaceflight instrument using current design, reliability and management practices. Since it is to serve as a reference for new candidate approaches, the mission assurance program is assumed to be conventional rather than innovative in character. High-reliability parts are used; however, there is little redundancy and no reliability demonstration. The instrument is assumed to employ weight critical and precision manufacturing techniques and be primarily electronic in nature with few moving parts.

The program organization and functional task descriptions have been structured to provide visibility of the mission assurance aspects of the program and the distribution of program costs among the various tasks has been established. Finally, an analysis of in-flight failure data was performed to determine a typical instrument reliability that can be expected to result from such a program.

4.2.1 Functional Elements and Organization

All firms producing equipment have mission assurance functions embedded in their organizational structure in some form. Large aerospace organizations typically show specific areas devoted exclusively to mission assurance in their structure. At TRW this portion of the organization is called product assurance. Although nomenclature as well as structure varies somewhat among organizations, the major functional elements correspond to those shown in Figure 4-3, which is the organizational structure assumed for the purposes of this study.

Regardless of nomenclature or organizational structure, mission assurance effort is expended by other functional areas such as manufacturing and engineering. Thus, it is essential to recognize that the product assurance organization and the mission assurance effort or tasks are not the same. More specifically, the relative amount of mission assurance activity performed by the various major functional elements is indicated by the shaded

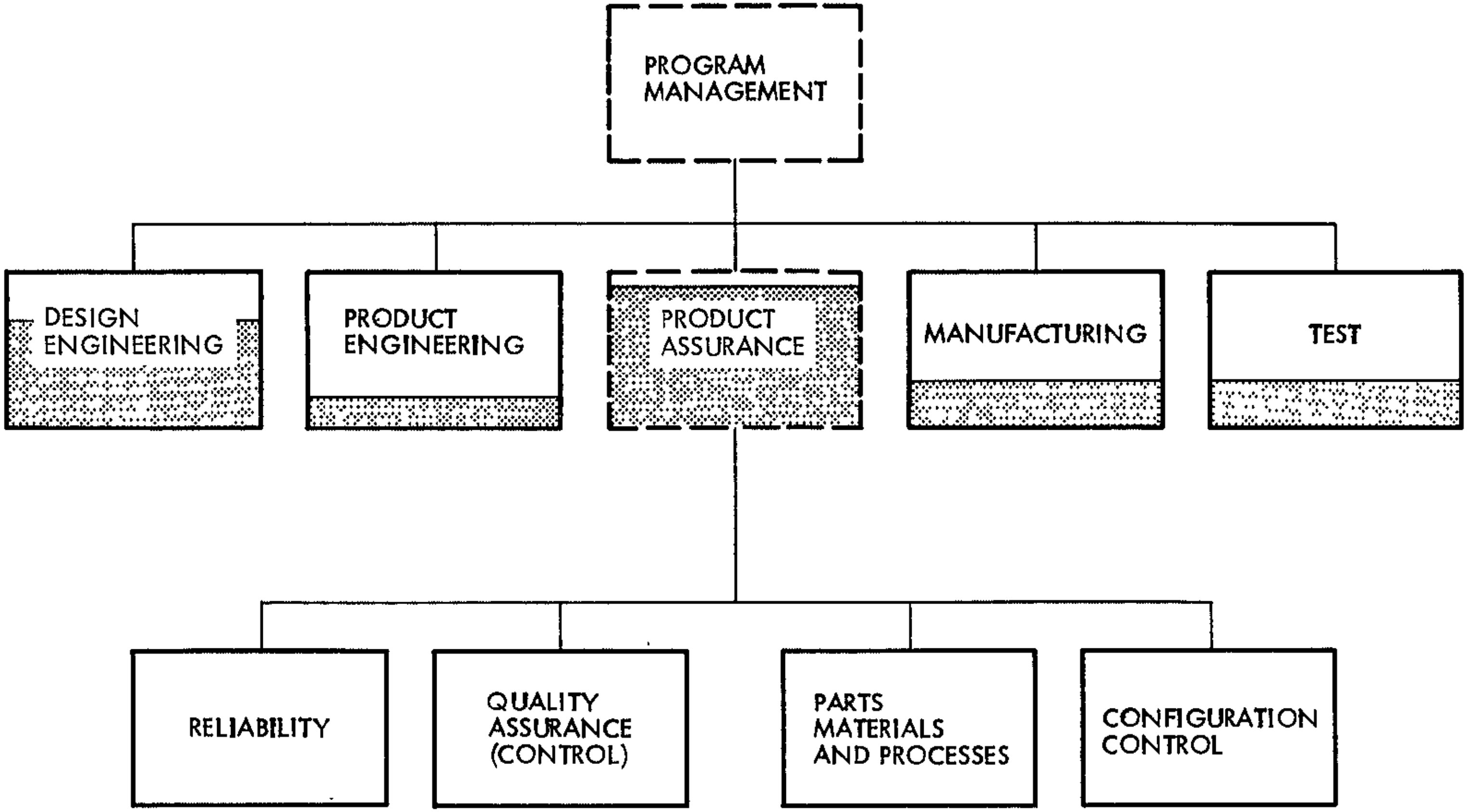

Figure 4-3. Baseline Program Organization

areas in Figure 4-3. As we will see in the discussion to follow, a considerable fraction of the design engineering effort is related to mission assurance as well as smaller fractions of product engineering, manufacturing and test.

Program management will not be explicitly included in task and cost analyses. We assume that it is spread proportionally through the other functions as is usually the case. Also, configuration control will not be directly addressed because the effort and costs expended over and above the functions provided by product engineering are typically quite small.

A functional flow diagram of the instrument development process, viewed from the perspective of mission assurance, is shown in Figure 4-4. The diagram depicts the mission assurance activities performed by the various functional elements and the essential interfaces or interactions between the functional elements.

We have defined mission assurance activities in the following context. The primary effort by engineering, manufacturing and test (which we consider as not directly concerned with instrument reliability, per se) involves the design and production of an instrument that meets the specified functional requirements. A number of failure mechanisms or weaknesses that would lead to future failures inevitably enter into the design and the hardware. The mission assurance activities essentially consist of a series of preventive and corrective screens, generally in the form of analyses, reviews, inspections and tests, that are set up to identify and eliminate the failure mechanisms. Conceptually, there is a correlation between the level of effort (and hence, the cost) of these screening activities and the reliability of the instrument produced. We have attempted to structure our description of the baseline mission assurance program in a way to facilitate the examination of this correlation.

The diagram is largely self-explanatory but two or three features warrant comment. The principal interface of reliability is with design engineering. In fact, within many organizations reliability is considered part of engineering. The principal interface of quality is with manufacturing and test via its role in planning, inspection and test monitoring. The principal failure prevention tasks performed by each functional element are indicated in the upper sections of the blocks on the left, and the

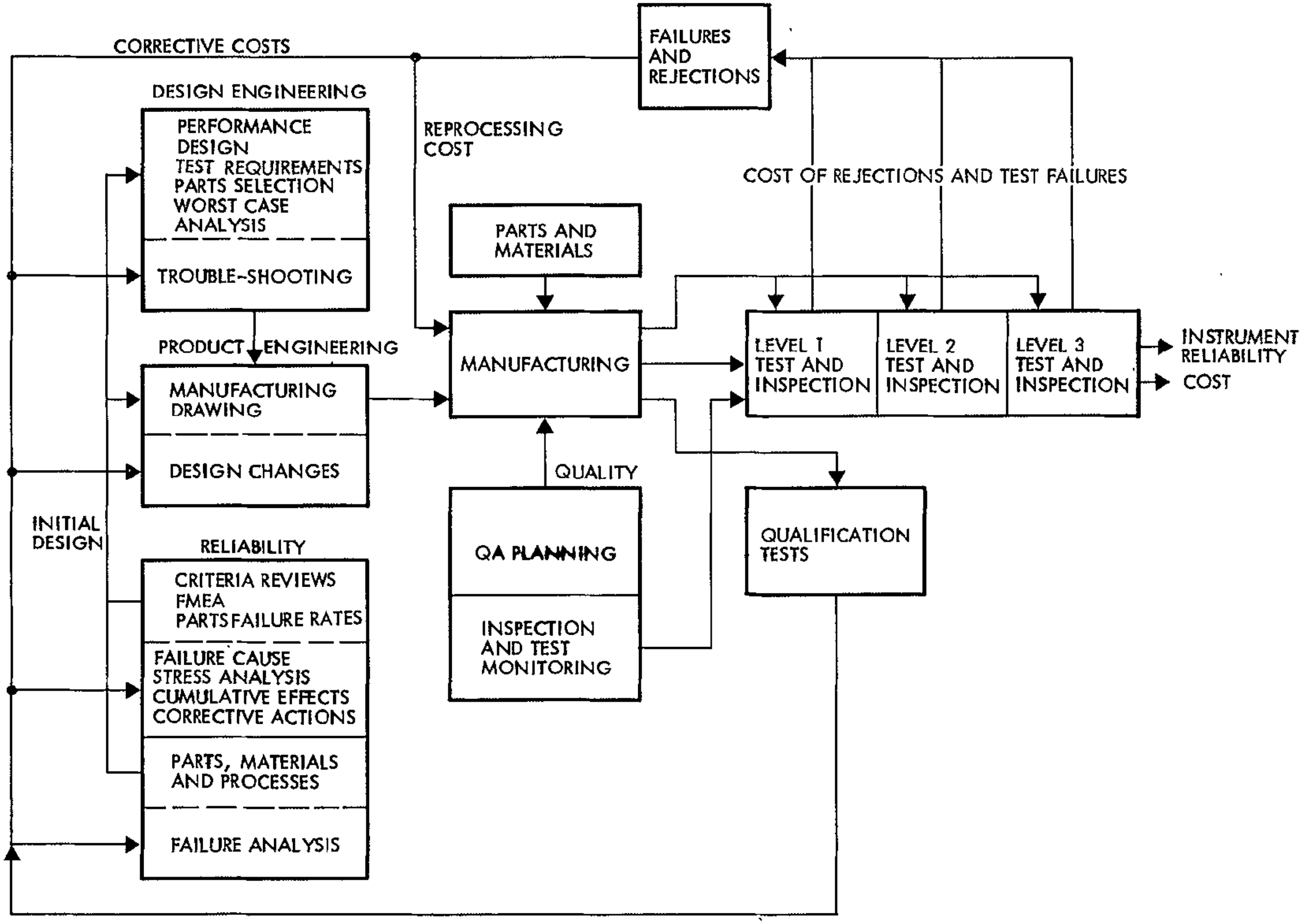

Figure 4-4. Mission Assurance Flow Diagram

corrective activites in the lower sections. The corrective actions arise from test or inspection rejections, failures, or anomalies, and typically involve high costs. The majority of the costs of a rejection arise not from rework or repair, but from the systematic troubleshooting and meticulous failure analysis procedures required to determine the disposition and corrective action necessary.

4.2.2 Task Definition

The breakdown of the overall program into elements that can be meaningfully related to mission assurance activities was handled in the following way. First, the activity under each functional element was divided into tasks. The breakdown we have adopted is tabulated in Table 4-1.

As a next step, the fraction or percentage of the total effort devoted to each task was estimated for each functional element. These estimates are typical values based on our current experience with instrument development programs.

Next, an estimate was made of the relative amounts of mission assurance activity and nonreliability-related activity in each task. Again, there is subjective judgment involved in the estimates, but they are believed to be representative of current practice.

Finally, the mission assurance activity was divided into design (or preventive) screening effort and product (or corrective) screening effort.

The results of this process are shown in Table 4-2. The percentage breakdowns within each of the seven functional elements are given in the PERCENT OF EFFORT column and the percentage breakdowns of each task are given in the DESIGN SCREENING, PRODUCT SCREENING and NONRELIABILITY EFFORT columns.

Test is one area which deserves comment. In our definition of test, we include the actual conducting of the test and the building of special test equipment. However, design engineering prepares the test requirements as well as analyzes the results and quality monitors the test. Therefore, the bulk of the mission assurance activity connected with testing is not actually performed by the test functional element.

Table 4-1. Baseline Program Tasks

Functional Element	Tasks
Design Engineering	Requirements Analysis
	Preliminary Design and Definition
	Special Component Development
	Worst-Case Analysis
	Breadboard Construction and Test
	Design Reviews
	Acceptance Test Requirements
	Qualification Test Requirements and Analysis
	Test Support
	Troubleshooting and Failure Support
Product Engineering	Design Calculations
	Layout and Engineering Coordination
	Prepare and Check Drawings
	Factory Support and Changes
Reliability	Guidelines and Criteria Preparation
	Reliability Analysis and Reviews
	Acceptance and Qualification Requirements and Data Review
	Reliability Prediction
	Failure Modes and Effects Analysis
	Failure Reporting, Disposition and Corrective Action
Parts, Materials, and Processes	Parts Program Planning
	Parts Selection
	Parts Application Review
	Materials Review
	Procurement Support
	Procedure Review
	Failure Analysis Support
Quality Assurance	Quality Planning
	Quality Sustaining Engineering
	Receiving Inspection
	Process Monitoring and Product Inspection
	Test Monitoring
Manufacturing	Planning and Control
	Purchased Parts and Materials
	Assembly
	Supervision and Training
Test (conducting)	Build Test Equipment
	Factory Test Procedure Preparation
	Conduct Tests
	Support Troubleshooting and Test Changes

Table 4-2. Baseline Program Task/Cost Array

DATA FILE: STANDAT	PERCENT OF EFFORT	DESIGN SCREENING	PERCENT OF PROGRAM $	PRODUCT SCREENING	PERCENT OF PROGRAM $	NON.REL. EFFORT	PERCENT OF PROGRAM $
A. DESIGN ENGINEERING							
A1 REQUIREMENTS ANALYSIS	4.00	10.00	.11	.00	.00	90.00	.99
A2 PRELIMINARY DESIGN AND DESIGN DEFINITION: PARTS, CIRCUIT, PACKAGE	19.00	20.00	1.03	10.00	.51	70.00	3.59
A3 SPECIAL COMPONENT DEVELOPMENT	20.00	15.00	.81	15.00	.81	70.00	3.78
A4 WORST CASE ANALYSIS	5.00	100.00	1.35	.00	.00	.00	.00
A5 BREADBOARD CONST. AND TEST	5.00	50.00	.68	5.00	.07	45.00	.61
A6 DESIGN REVIEWS	4.00	50.00	.54	5.00	.05	45.00	.49
A7 ACCEPTANCE TEST REQUIREMENTS	8.00	15.00	.32	85.00	1.84	.00	.00
A9 QUALIFICATION TEST REQUIREMENT AND ANALYSIS	10.00	100.00	2.70	.00	.00	.00	.00
A9 TEST SUPPORT	14.00	25.00	.95	55.00	2.08	20.00	.76
A10 TROUBLESHOOTING AND FAILURE SUPPORT	11.00	50.00	1.49	50.00	1.49	.00	.00
SUB-TOTALS	100.00	.00	9.96	.00	6.84	.00	10.19
B. PRODUCT ENGINEERING							
B1 PERFORM DESIGN CALCULATIONS	10.00	50.00	.60	.00	.00	50.00	.60
B2 LAYOUT AND ENGINEERING COORD.	15.00	20.00	.54	.00	.00	70.00	1.26
B3 PREPARE AND CHECK DRAWINGS	55.00	.00	.00	10.00	.66	90.00	5.94
B4 FACTORY SUPPORT AND CHANGES	20.00	5.00	.12	5.00	.12	90.00	2.16
SUB-TOTALS	100.00	.00	1.26	.00	.78	.00	9.96
C. RELIABILITY							
C1 PREPARE GUIDELINES & CRITERIA	8.00	75.00	.24	25.00	.08	.00	.00
C2 PERFORM RELIABILITY ANALYSIS AND REVIEW: PARTS;CIRCUITS, PACKAGE	17.00	90.00	.54	10.00	.07	10.00	.07
C3 REVIEW ACCEPTANCE AND QUAL. TEST REQUIREMENTS AND DATA	12.00	50.00	.36	50.00	.36	.00	.00
C4 RELIABILITY PREDICTION	22.00	30.00	.26	70.00	.62	.00	.00
C5 FAILURE MODES AND EFFECTS	12.00	55.00	.26	25.00	.12	20.00	.10
C6 FAILURE REPORTING,DISPOSITION AND CORRECTIVE ACTION	23.00	65.00	.60	35.00	.32	.00	.00
SUB-TOTALS	100.00	.00	2.27	.00	1.57	.00	.16
D. PARTS,MATERIALS AND PROCESSES							
D1 PARTS PROGRAM PLANNING	7.00	45.00	.14	45.00	.14	10.00	.03
D2 PARTS SELECTION	13.00	100.00	.59	.00	.00	.00	.00
D3 PARTS APPLICATION REVIEW	18.00	80.00	.65	20.00	.16	.00	.00
D4 MATERIALS PEVIEW (DRAWINGS)	15.00	80.00	.54	20.00	.14	.00	.00
D5 PROCEDURE REVIEW AND MODIFICATION	10.00	.00	.00	100.00	.45	.00	.00
D6 PROCUREMENT SUPPORT	12.00	30.00	.16	30.00	.16	40.00	.22
D7 FAILURE ANALYSIS SUPPORT	25.00	80.00	.90	20.00	.23	.00	.00
SUB-TOTALS	100.00	.00	2.98	.00	1.28	.00	.25
E. QUALITY ASSURANCE							
E1 QUALITY PLANNING	18.00	10.00	.17	60.00	1.02	30.00	.51
E2 QUALITY SUSTAINING ENGINEERING	15.00	15.00	.21	70.00	1.00	15.00	.21
E3 RECEIVING INSPECTION	8.00	.00	.00	80.00	.61	20.00	.15
E4 PROCESS MONITORING AND PRODUCT INSPECTION	35.00	15.00	.50	85.00	2.83	.00	.00
E5 TEST MONITORING	24.00	25.00	.57	75.00	1.71	.00	.00
SUB-TOTALS	100.00	.00	1.45	.00	7.17	.00	.98
F. MANUFACTURING							
F1. PLANNING AND CONTPOL	22.00	.00	.00	20.00	1.28	80.00	5.10
F2 PURCHASED PARTS & MATERIAL	8.00	10.00	.23	10.00	.23	80.00	1.86
F3 ASSEMBLY	60.00	10.00	1.74	10.00	1.74	80.00	13.92
F4 SUPERVISION AND TRAINING	10.00	10.00	.29	45.00	1.31	45.00	1.31
SUB-TOTALS	100.00	.00	2.26	.00	4.55	.00	22.19
G. TEST (CONDUCTING)							
G1 BUILD TEST EQUIPMENT	20.00	15.00	.42	25.00	.70	60.00	1.68
G2 PREPARE FACTORY TEST PROCEDURES	15.00	5.00	.11	60.00	1.26	35.00	.74
G3 CONDUCT TESTS	45.00	.00	.00	20.00	1.26	80.00	5.04
G4 SUPPORT TROUBLESHOOTING AND TEST CHANGES	20.00	10.00	.28	10.00	.28	80.00	2.24
SUB-TOTALS	100.00	.00	.81	.00	3.50	.00	9.70

SUMMARY ARRAY

A. DESIGN ENGINEERING	27.00	.00	9.96	.00	6.84	.00	10.19
B. PRODUCT ENGINEERING	12.00	.00	1.26	.00	.78	.00	9.96
C. RELIABILITY	4.00	.00	2.27	.00	1.57	.00	.16
D. PARTS,MATERIALS AND PROCESSES	4.50	.00	2.98	.00	1.28	.00	.25
E. QUALITY ASSURANCE	9.50	.00	1.45	.00	7.17	.00	.88
F. MANUFACTURING	29.00	.00	2.26	.00	4.55	.00	22.19
G. TEST (CONDUCTING)	14.00	.00	.81	.00	3.50	.00	9.70
TOTAL	100.00	.00	20.99	.00	25.69	.00	53.32

TOTAL: 100.00%   EXPERIMENT COST: $4,000,000   COST DELTA: $-
TOTAL MISSION RELIABILITY COSTS: $1,367,090 (46.7%)
PRODUCT ASSURANCE COSTS: $668,390 (16.7%)

We certainly recognize that this task breakdown is somewhat a matter of subjective definitions and choices. In many cases, the allocation is quite clear (e.g., worst-case analysis). In others (e.g., breadboard construction and test), the design screening, product screening, and nonreliability efforts are unavoidably intertwined and estimates cannot be considered to be precise. However, we believe that many of the possible biases are minimized by the process of breaking down the program into small manageable elements and somewhat independently examining each element.

Up to this point in the process, no effort has been made to determine the relative allocation of effort or costs between the main functional elements. We turn to that question in the next section.

4.2.3 Cost Distribution

A number of instrument development programs carried out by TRW were examined to establish the relative allocation of costs between the major functional elements. The program costs ranged in value from a few million dollars to about 50 million dollars. In addition, data on cost allocations within major subsystems on large spacecraft programs were examined. The mission assurance literature review also provided cost-related data, primarily typical ratios between mission assurance functions and other costs (e.g., References 16 and 19).

Our analysis of this composite of information led to the following allocation of costs as representative of the baseline instrument program.

Design Engineering	27.0%
Product Engineering	12.0%
Reliability	4.0%
Parts, Materials, and Processes	4.5%
Quality Assurance	9.5%
Manufacturing	29.0%
Test (conducting)	14.0%

The array shown in Table 4-2 was set up in a computer program to accept this cost allocation information as input and distributes the costs throughout the task structure. The results are shown in the PERCENT OF PROGRAM $ columns and in the SUMMARY ARRAY at the bottom of the table. An absolute-dollar program cost is also input. Four million dollars was used as a typical figure, but this information is not significant to our discussion here.

The most significant points should be noted. Although 18 percent of the program costs go to the directly-identified mission assurance organization (reliability; parts, materials, and processes; and quality assurance), 47 percent, or nearly one-half of the program costs, go to mission assurance activities. As could be reasonably expected, the bulk of the mission assurance effort outside of the directly-identified mission assurance areas (17 percent) is expended by design engineering. The division between design screening (i.e., preventative) effort and product screening (i.e., corrective) effort is about equal with a slightly larger share going to product screening.

4.2.4 Baseline Experiment Reliability

An analysis was made of spacecraft and experiment in-flight failures and their causes. The purpose of this analysis was both to develop a credible reliability value from actual field experience to assign to the baseline experiment and to determine the basic causes of flight failures.

In-Flight Failure Analysis - The Planning Research Corporation studies on reliability data for in-flight spacecraft (References 5 and 32) were deemed to contain the most applicable and definitive data readily available and these references constitute the principal data source for the analysis. The referenced studies are based on raw data concerning anomalies and failures in U. S. spacecraft and experiments during the 1958 to 1966 and the 1966 to 1970 periods. The documents contain both partially identified raw data and several statistical analyses of the data.

Even though the referenced study is of high quality, because of the nature of the data available, considerable interpretation and some adjustment was necessary. Our analysis was performed as follows:

- The referenced documents were reviewed for content and identification of applicable portions.
- The raw data, consisting of spacecraft and experiment anomalies occurring during the mission, were reviewed briefly, item by item, to determine the sample sizes and types of failures. Failure causes were compiled in categories related to the division of mission assurance activities defined in the previous section.
- The failure data compilations were reviewed, the portions applicable to the experiment instrumentation were identified, and the reliabilities were computed.

In order to maximize the data base, our initial analysis considered all anomalies causing a non-negligible effect in the 1966-1970 time period. Both spacecraft system failures and experiment failures were analyzed. The causes are divided into primary categories based upon the type of corrective action that would have been required to eliminate the problem had it been detected prior to launch. The results of this analysis are presented in the left-hand column of Table 4-3.

The categories used are failures due to: design error, manufacturing error, and operational error. Design errors and manufacturing errors are the types, respectively, that should be removed by the design screening and product screening mission assurance activities. Operational errors, such as the application of stresses outside of the design limits, are not under the control of mission assurance.

The first run through the raw data suggested that there might be enough reasonably clear and assignable experiment failures to base the analysis on such data alone. Consequently, a second run was made through the raw data using sharper criteria. Only the apparent experiment failures were used and more of the doubtful cases were assigned as uncertain. The results are given in the right-hand column of Table 4-3.

Assuming that the uncertain cases fall proportionately into the other categories, we see that the failures are about equally divided between design errors and manufacturing errors with possibly a slight excess of manufacturing errors. This correlates well with the division of effort between design screening and product screening in the baseline mission assurance program (Table 4-2) and indicates that the relative division of effort is about correct.

<u>Baseline Instrument Reliability</u> - To determine a reasonable value for experiment instrumentation reliability, only a portion of the data were included. Obviously, only experiment equipment failures were considered and amongst these, only those severe enough to clearly cause loss of the experiment were included. Table 4-4 summarizes the appropriate failure data and the one-year reliabilities computed from it.

Several factors were considered in going from these results to a reliability value corresponding to the baseline instrument program carried out today.

Table 4-3. In-Flight Failure Causes

	1966-70-Period Data	
	Spacecraft and Experiments	Experiments Only
Total Anomalies	545	99
Failure Category		
Design Error	27%	29%
Manufacturing Error	37%	28%
Operational Error	11%	7%
Uncertain	25%	36%

Table 4-4. Experiment Instrumentation Mission Reliability

	Number of Experiments	Cumulative Time (Hours)	Number of Failures	Reliability (One-Year)
1958-1966 Period	149	8.03×10^5	14	87.2%
Study with Statistical Adjustments by PRC	149		$15/10^6$ hr	87.8%
90% Confidence Limit (Upper)	149		$15/10^6$ hr	93.3%
90% Confidence Limit (Lower)	149		$15/10^6$ hr	81.9%
1966-1970 Period	196	2.32×10^6	21	92.4%
1958-1970 Period	345	3.12×10^6	35	90.8%

- The programs on which these results are based were generally at high funding levels and included substantial parts and reliability programs.

- A well-managed instrument development program started today would depend somewhat on the high parts reliability and reliability techniques attained in the past.

- Since a fraction of the parts are always newly developed and other delearning forces at work, not all the reliability attainments of the past are automatically retained.

- Due to certain biases in the data (Reference 5, pp 23 and 79), the failure rates on which the reliability estimates are based are more likely to be low than high, especially in the 1966 to 1970 sample.

- There was an apparent reliability growtn of five percentage points between the median years of 1963 and 1968, and it can be argued that reliability know-how in general has improved and spread since 1968 but probably not at the same rate.

While the factors listed tend to be compensating, we believe the growth and learning factors are more significant. We have, therefore, taken a reliability value of 0.93 as representative of today's instruments.

4.3 MISSION ASSURANCE COST REDUCTION APPROACHES

The approaches to mission assurance cost reduction we have considered fall into two general categories. First, there are a number of suggested changes to conventional mission assurance procedures that would lead to improved efficiency; i.e., accomplishing the same end result with less expenditure of effort. We believe that instrument reliability would be, at most, only slightly reduced by adopting these changes. These cost reduction concepts have been derived by a critical examination of the baseline mission assurance program defined in the previous section. They are generally applicable to any instrument development program and are not dependent on any new capability offered by the Shuttle.

After discussing the improved efficiency recommendations, we will turn to the topic of cost saving by reduction of instrument reliability, or as the concept is frequently referred to, by increased risk acceptance.

4.3.1 Improved Mission Assurance Efficiency

The approach taken to identifying potential cost savings was to carefully examine each of the mission assurance functions or tasks defined in Section 4.2.2 and qualitatively judge their cost-effectiveness in the sense of identifying those mission assurance tasks that on the one hand can be most readily reduced without an obvious decrease in reliability, and on the other, those which might well be retained or extended because of their favorable reliability-cost characteristic. As we have seen, considerable mission assurance effort is expended by a number of organizations and this opened a third possibility - savings by improved integration of effort such as combining, or jointly performing, similar tasks. Some general conclusions that resulted from the critical examination of mission assurance functions are summarized in the following paragraphs.

Mission Assurance Concept - An increase in efficiency can result from what we call the mission assurance concept. This is more applicable to large organizations since small organizations tend, by their nature, to follow the concept.

In this concept, one individual from the product assurance organization acts as a full-time, working Mission Assurance Manager and performs duties in all of the mission assurance areas, calling upon other individuals for major tasks or problems. Maintaining familiarity with all aspects of the program, including the various subtle interactions, he is in a position to solve most minor problems and to identify the pertinent requirements for specialized assistance.

Parts Management and Reliability Estimations - A more efficient and versatile parts management and reliability estimation approach than that common today exists which we believe meets the needs of a typical instrument development program. In this approach, the parts list, which is normally prepared by design engineering, often aided by parts specialists or reliability, would be computerized. Because the parts list must be developed and updated in any event, a flexible computer listing method is cost effective for mechanical reasons alone.

In addition to the usual parts technical description consisting of type, manufacturer, quantity, and cost; additional data would be included. These would include failure rate, circuit location, and where applicable, weight and volume. The computer program would be arranged to edit, sort, and print by order of any of these characteristics.

Parts failure rate data often tends to be of questionable accuracy. On low-cost programs, however, they do provide a method for indicating to skilled reliability personnel what the general reliability limits are and a basis for deciding which parts should receive priority in reliability improvement or cost reduction.

Design Reviews - Formal design reviews involving large diverse groups attempting to enter into detail seldom cover the territory required in an efficient manner. A systematic sequence of two- or three-man reviews in an informal atmosphere would be much more effective. Review results should be reported by exception instead of requiring voluminous data packages.

Test Methods - It has been demonstrated (References 15, 29, 30 and 32) that comprehensive tests at marginal conditions can reveal incipient failures. Efficient testing is probably the function deserving the most attention in order to preserve reliability while reducing mission assurance costs.

The implementation of such tests in practice either requires, or is facilitated by, the use of rapid computer-controlled programmable test equipment. The initial cost of such equipment with the characteristics required is high, but once placed in use has several advantages over more conventional test programs in addition to improved product screening. Elimination of test accidents and automated test documentation are examples.

Inspection Procedures - There is an opportunity, in a low-cost approach, to simplify or eliminate certain inspection and quality assurance requirements, which have developed on programs where the required reliability was exceedingly high. Some examples are:

- When a single part is changed on a flight assembly or a repair is made, the entire unit is usually reinspected. If the repair is made immediately under inspection surveillance, only the immediate area of the repair need be reinspected. While assembly tests and final system tests should be required, intermediate tests need not be repeated if the assembly has already passed.
- Inspection should be performed at the last opportunity possible. The equipment design should provide for maximum inspection visibility.
- The practice of eliminating inspections and test stations where rejections reach a low value should be instituted.
- Time consuming effort required for complete traceability can be reduced or eliminated. The practice of recording and maintaining records of parts location on circuit boards should be eliminated on a low-cost program.

In order to assess the cost reductions that could be realized by implementing these concepts, their effect on each of the program tasks listed in Table 4-1 was estimated. In the following paragraphs, their effects are tabulated according to the different functional areas of the program.

Design Engineering

- Effort required to develop and maintain parts list reduced.
- Worst-case analysis combined with informal design review.
- "Test point" selection rationale improved.
- Qualification test requirements to be performed by reliability.
- Troubleshooting and failure support time reduced by rapid automated test program and implemented by improved test methods/points.

Reliability

- As first task in the program, before design is started, reliability guidelines and criteria are to be jointly prepared with design engineering, thus having maximum impact on design.
- Combine reliability analysis and review with worst-case analysis and informal design reviews with design engineers.
- Employ automatic test and printout to minimize failure support time.
- Streamline failure modes and effects analysis by making it primarily an interface effects review.
- Review selected computerized parts list runs which contain failure rates to determine instrument reliability and possible redundancy.

Parts Materials and Processes

- Prepare, update, and maintain parts list jointly with design engineering. Failure rates, derating levels, and parts locations are included.
- Use known parts, appropriate screening, and derating to confine procurement support to special cases.
- Eliminate routine materials usage drawing review. An initial materials review and selection is made and documented. Mission Assurance Manager reviews the drawings in any event and brings problems to the attention of Parts, Materials, and Processes.

Quality Assurance

- Reduce test monitoring by sharing and delegating responsibility amongst manufacturing and test personnel and through use of automatic printouts of test procedures and results. Inspector is not required to confirm or enter readings.
- Reduce parts traceability requirements. Assembler is not required to enter parts serial number and location.
- Inspect at highest level of assembly possible.
- Eliminate reinspection of entire hardware unit after repair.

Manufacturing

- Employ improved, automated tests at highest feasible level of assembly to reduce time lost to in-process and acceptance tests.

C.2

Test

- Use programmable digital automatic test equipment with full printout capability.

The estimated relative reductions in the mission assurance task efforts were entered into the cost/task array developed in Section 4.2 and the net effect on the baseline program was calculated. The results are presented in Table 4-5. The program cost reduction amounts to 12.6 percent. We believe that this represents the magnitude of the cost reduction that can be achieved by increased mission assurance efficiency without a significant effect on the instrument reliability.

4.3.2 Increased Risk Acceptance

It is generally recognized that the Space Transportation System's capability to retrieve payloads from earth orbit makes it possible to consider flying lower-reliability equipment. As discussed briefly in Section 4.1, the question that immediately arises when considering instrument cost reduction by relaxing reliability requirements is what is the relationship between instrument cost and instrument reliability. Unfortunately, the question connot be answered currently in anything approaching an analytical way. We have attempted to structure our analysis of the baseline instument development program so that it would facilitate study of the cost/reliability relationship. The next section describes the results of our attempt to develop a systematic approach to the problem.

Table 4-5. Increased Efficiency Program Task/Cost Array

DATA FILE: STANDAT2	PERCENT OF EFFORT	DESIGN SCREENING	PERCENT OF PROGRAM $	PRODUCT SCREENING	PERCENT OF PROGRAM $	NON.REL. EFFORT	PERCENT OF PROGRAM $
A. DESIGN ENGINEERING							
A1 REQUIREMENTS ANALYSIS	4.00	10.00	.11	.00	.00	90.00	.97
A2 PRELIMINARY DESIGN AND DESIGN DEFINITION: PARTS, CIRCUIT, PACKAGE	18.00	16.00	.78	10.00	.49	74.00	3.60
A3 SPECIAL COMPONENT DEVELOPMENT	20.00	15.00	.81	15.00	.81	70.00	3.78
A4 WORST CASE ANALYSIS	3.00	100.00	.81	.00	.00	.00	.00
A5 BREADBOARD CONST. AND TEST	5.00	50.00	.68	5.00	.07	45.00	.61
A6 DESIGN REVIEWS	4.00	50.00	.54	5.00	.05	45.00	.49
A7 ACCEPTANCE TEST REQUIREMENTS	6.00	15.00	.24	85.00	1.38	.00	.00
A8 QUALIFICATION TEST REQUIREMENT AND ANALYSIS	5.00	100.00	1.35	.00	.00	.00	.00
A9 TEST SUPPORT	14.00	25.00	.95	55.00	2.08	20.00	.76
A10 TROUBLESHOOTING AND FAILURE SUPPORT	9.00	50.00	1.22	50.00	1.22	.00	.00
SUB-TOTALS	89.00	.00	7.47	.00	6.09	.00	10.20
B. PRODUCT ENGINEERING							
B1 PERFORM DESIGN CALCULATIONS	10.00	50.00	.60	.00	.00	50.00	.60
B2 LAYOUT AND ENGINEERING COORD.	15.00	30.00	.54	.00	.00	70.00	1.26
B3 PREPARE AND CHECK DRAWINGS	55.00	.00	.00	10.00	.66	90.00	5.94
B4 FACTORY SUPPORT AND CHANGES	15.00	.00	.00	.00	.00	100.00	1.80
SUB-TOTALS	95.00	.00	1.14	.00	.66	.00	9.60
C. RELIABILITY							
C1 PREPARE GUIDELINES & CRITERIA	6.00	75.00	.18	25.00	.06	.00	.00
C2 PERFORM RELIABILITY ANALYSIS AND REVIEW: PARTS.CIRCUITS, PACKAGE	12.00	76.00	.36	10.00	.05	14.00	.07
C3 REVIEW ACCEPTANCE AND QUAL. TEST REQUIREMENTS AND DATA	15.00	50.00	.30	50.00	.30	.00	.00
C4 RELIABILITY PREDICTION	15.00	30.00	.18	70.00	.42	.00	.00
C5 FAILURE MODES AND EFFECTS	9.00	51.00	.18	22.00	.08	27.00	.10
C6 FAILURE REPORTING,DISPOSITION AND CORRECTIVE ACTION	17.00	65.00	.44	35.00	.24	.00	.00
SUB-TOTALS	74.00	.00	1.65	.00	1.15	.00	.16
D. PARTS,MATERIALS AND PROCESSES							
D1 PARTS PROGRAM PLANNING	5.00	43.00	.10	43.00	.10	14.00	.03
D2 PARTS SELECTION	6.00	100.00	.27	.00	.00	.00	.00
D3 PARTS APPLICATION REVIEW	14.00	80.00	.50	20.00	.13	.00	.00
D4 MATERIALS REVIEW (DRAWINGS)	8.00	80.00	.29	20.00	.07	.00	.00
D5 PROCEDURE REVIEW AND MODIFICATION	10.00	.00	.00	100.00	.45	.00	.00
D6 PROCUREMENT SUPPORT	9.00	23.00	.09	23.00	.09	54.00	.22
D7 FAILURE ANALYSIS SUPPORT	25.00	80.00	.90	20.00	.23	.00	.00
SUB-TOTALS	77.00	.00	2.15	.00	1.06	.00	.25
E. QUALITY ASSURANCE							
E1 QUALITY PLANNING	18.00	10.00	.17	60.00	1.03	30.00	.51
E2 QUALITY SUSTAINING ENGINEERING	15.00	15.00	.21	70.00	1.00	15.00	.21
E3 RECEIVING INSPECTION	5.00	.00	.00	68.00	.32	32.00	.15
E4 PROCESS MONITORING AND PRODUCT INSPECTION	25.00	15.00	.36	85.00	2.02	.00	.00
E5 TEST MONITORING	18.00	25.00	.43	75.00	1.28	.00	.00
SUB-TOTALS	81.00	.00	1.17	.00	5.65	.00	.88
F. MANUFACTURING							
F1. PLANNING AND CONTROL	20.00	.00	.00	12.00	.70	88.00	5.10
F2 PURCHASED PARTS & MATERIAL	5.00	.00	.00	.00	.00	100.00	1.45
F3 ASSEMBLY	58.00	7.00	1.18	10.00	1.68	83.00	13.96
F4 SUPERVISION AND TRAINING	7.00	6.00	.12	30.00	.61	64.00	1.30
SUB-TOTALS	90.00	.00	1.30	.00	2.99	.00	21.81
G. TEST (CONDUCTING)							
G1 BUILD TEST EQUIPMENT	20.00	15.00	.42	25.00	.70	60.00	1.68
G2 PREPARE FACTORY TEST PROCEDURES	13.00	5.00	.09	55.00	1.00	40.00	.73
G3 CONDUCT TESTS	39.00	.00	.00	5.00	.27	95.00	5.05
G4 SUPPORT TROUBLESHOOTING AND TEST CHANGES	15.00	.00	.00	.00	.00	100.00	2.10
SUB-TOTALS	86.00	.00	.51	.00	1.97	.00	9.56

SUMMARY ARRAY

A. DESIGN ENGINEERING	23.76	.00	7.47	.00	6.09	.00	10.20
B. PRODUCT ENGINEERING	11.40	.00	1.14	.00	.66	.00	9.60
C. RELIABILITY	2.96	.00	1.65	.00	1.15	.00	.16
D. PARTS,MATERIALS AND PROCESSES	3.47	.00	2.15	.00	1.06	.00	.25
E. QUALITY ASSURANCE	7.70	.00	1.17	.00	5.65	.00	.88
F. MANUFACTURING	26.10	.00	1.30	.00	2.99	.00	21.81
G. TEST (CONDUCTING)	12.04	.00	.51	.00	1.97	.00	9.56
TOTAL	87.42	.00	15.39	.00	19.56	.00	52.47

TOTAL: 87.42% EXPERIMENT COST: $4,000,000 COST DELTA: $-503,200
TOTAL MISSION RELIABILITY COSTS: $1,398,118 (35.0%)
PRODUCT ASSURANCE COSTS: $513,066 (12.8%)

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4.4 COST/RELIABILITY RELATIONSHIPS

As stated in Section 4.1.1, a possible approach to determining the relationship between instrument reliability and mission assurance costs is to split the problem into three steps. The first step would be to determine the relationship between mission assurance costs and mission assurance tasks or procedures. The task/cost matrix described in Section 4.2.1 has been set up as the mechanism for that portion of the analysis. The second step in this approach would be to determine the relationship between equipment reliability and mission assurance tasks. The final step would be to combine the results of the first two steps into reliability versus mission assurance cost. The second step of determining reliability versus mission assurance tasks, which we refer to as the reliability estimation problem, is far and away the most difficult step in the sequence.

4.4.1 Reliability Estimation Problem

The conventional method of estimating reliability consists of summing failure rates of the component parts of a unit to arrive at the reliability. This process is a part of the problem but obviously what we are referring to as reliability estimation is a much broader and more complex topic. Conventional methods of reliability estimation cannot be expected to predict instrument in-flight reliability accurately. Inaccuracies enter in several ways, but most important, the conventional estimates are based only on parts failures. Because of their developmental nature, instruments exhibit a high level of failures due to design errors. Reliability predictions should be made by methods able to estimate and control the failures actually experienced.

The approach we envision would be to start with a breakdown of the mission assurance activities, such as that used in the task/cost array, and to determine the relationship between the level of effort devoted to a particular task and the resultant effect on the instrument reliability. The objective would be to develop a quantitative relationship. In order to reasonably do this, it would be necessary to separately consider both the design screening and product screening portions of the activity as well as the differences between the various hardware elements making up the instrument.

A qualitative idea of the types of relationships that would be developed is shown in Figure 4-5. These examples also illustrate the fact that the effect of additional effort can vary widely for the different tasks. In general, there will be threshold effects and saturation effects pertaining to each task. For example, if a worst-case analysis is performed by the designer, there is little benefit if he then performs it a second time. The results/effort curve, therefore, would look like Curve A in Figure 4-5a. If a second individual performs the same task, he may see new problems and change design parameters in a few cases resulting in Curve B in the figure, which rises a little and then again saturates. On the other hand, tests, as long as they are conducted, tend to screen out problems and, in this case, the saturation curve would drop off more slowly as in Figure 4-5b.

The scale factors are clearly different in the saturation curves of the various tasks since the effect on reliability as well as the natural efficiency with which the task can be performed will vary. There is also the further complication of interactions among the tasks. For example, if only a cursory test were performed on one circuit board which could fail the experiment, the performance of a comprehensive test on another would lose some of its value.

While this type of approach to reliability estimation is obviously rather formidable, we do feel that it is feasible to set up a mathematical formulation of the problem that could form the basis for a computer model that could produce reliability estimates built up from the individual task/reliability relationships. The validity of the model would depend heavily on the accuracy of the individual relationships. Unfortunately these must be derived for the most part from the somewhat subjective judgments of experienced personnel. Actual data would be very difficult to obtain because records are seldom kept at the level of detail we are considering here. Also, there are few, if any, cases where the effect of the level of effort in one particular task can be isolated.

The desirability of proceeding on to actually construct a quantitative methodology for reliability estimation depends on the potential payoff involved. In order to estimate the magnitude of the cost reductions

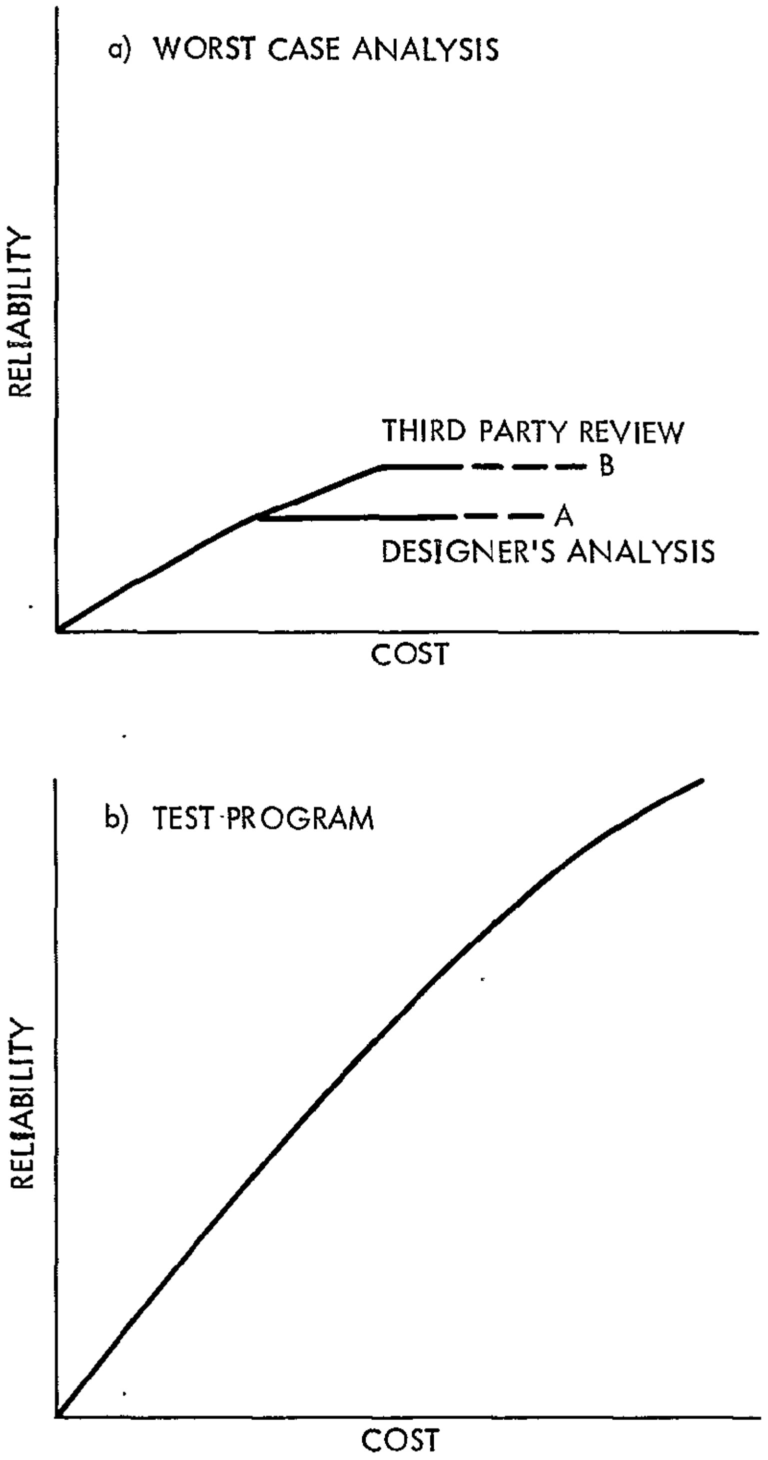

Figure 4-5. Qualitative Cost/Reliability Relationships

that can be expected from the acceptance of reduced instrument reliability, we have used a simplified overall cost/reliability relationship.

4.4.2 Simplified Cost/Reliability Relationship

The derivation of the simplified cost/reliability relationship we will use starts from the basic assumption that the efficiency with which potential failures are removed from a hardware item by the performance of a mission assurance activity is proportional to the number of potential failures in the system. Namely,

$$d\lambda/dC = -a\lambda$$

where λ is the failure rate, C is the cost of the mission assurance effort (assumed to be proportional to the level of effort), and a is the proportionality constant. This leads directly to:

$$\lambda(C) = \lambda_0 e^{-aC},$$

where λ_0 is the initial failure rate of the equipment before mission assurance efforts are expended. This general relationship between failure rates and mission assurance costs agrees with the consensus of other studies and analyses described in the literature that was reviewed as part of the overall mission assurance task (see, for example, References 1, 18, and 28).

Using the relationship between reliability and failure rate,

$$R = e^{-\lambda t},$$

where t is the mission duration, we obtain the following relationship between mission assurance cost and reliability:

$$C = -\frac{1}{a} \ln\left[\frac{\ln R}{\ln R_0}\right].$$

The baseline program analysis in Section 4.2 arrived at the conclusion that the mission assurance related costs account for about 50 percent of the total instrumentation costs and that the corresponding baseline reliability was 0.93. This information, along with one additional input, allows us to formulate a simplified overall cost/reliability relationship for experiment instrumentation produced in accordance with the baseline program. The additional input required is a value for R_0, the reliability of the equipment that would result from a program in which only the non-reliability-related effort was performed. In other words, no design or product screening effort was expended. Our subjective judgment is that R_o would be about 0.02. Since the value of R_o is certainly debatable, we will treat R_o as a parameter and assume it lies someplace between 0.02 and 0.40.

The resulting cost/reliability relationship, if we normalize costs to unity for the baseline program total instrumentation cost, is:

$$C(R) = 0.5 \frac{\ln\left(\frac{\ln R_o}{\ln R}\right)}{\ln\left(\frac{\ln R_o}{\ln .93}\right)} + 0.5$$

This relationship is plotted in Figure 4-6. As indicated, the limiting curves correspond to $R_o = 0.02$ and 0.40.

Some conclusions can immediately be drawn. The instrument costs are a relatively insensitive function of reliability until the reliability gets very close to 1.0. The typical current experiment instrumentation reliabilities of about 0.93 are not in the range where costs are being severely escalated by mission assurance activities. Consequently, the cost reductions that can be expected by the acceptance of reduced reliability are not very dramatic. We will return to this point in Section 4.6.2 in the context of the overall program costs and pursue it further.

In the context of the present section, we can arrive at the preliminary conclusion that the direct return, in terms of experiment hardware development cost reduction, to be expected from a detailed development of a quantitative approach to the reliability estimation problem is low enough to make the required effort questionable. On the other hand, the problem of cost optimization of mission assurance activities is certainly of general interest and the potential cost benefits in a broader context would probably be significant. To our knowledge, while the type of approach to the problem we have described has been suggested by others (Reference 42), no one has actually developed the concept.

Our derivation of the simplified cost/reliability relationship provides a framework for the more detailed approach discussed in Section 4.4.1. The overall relationship between failure rate and level-of-effort

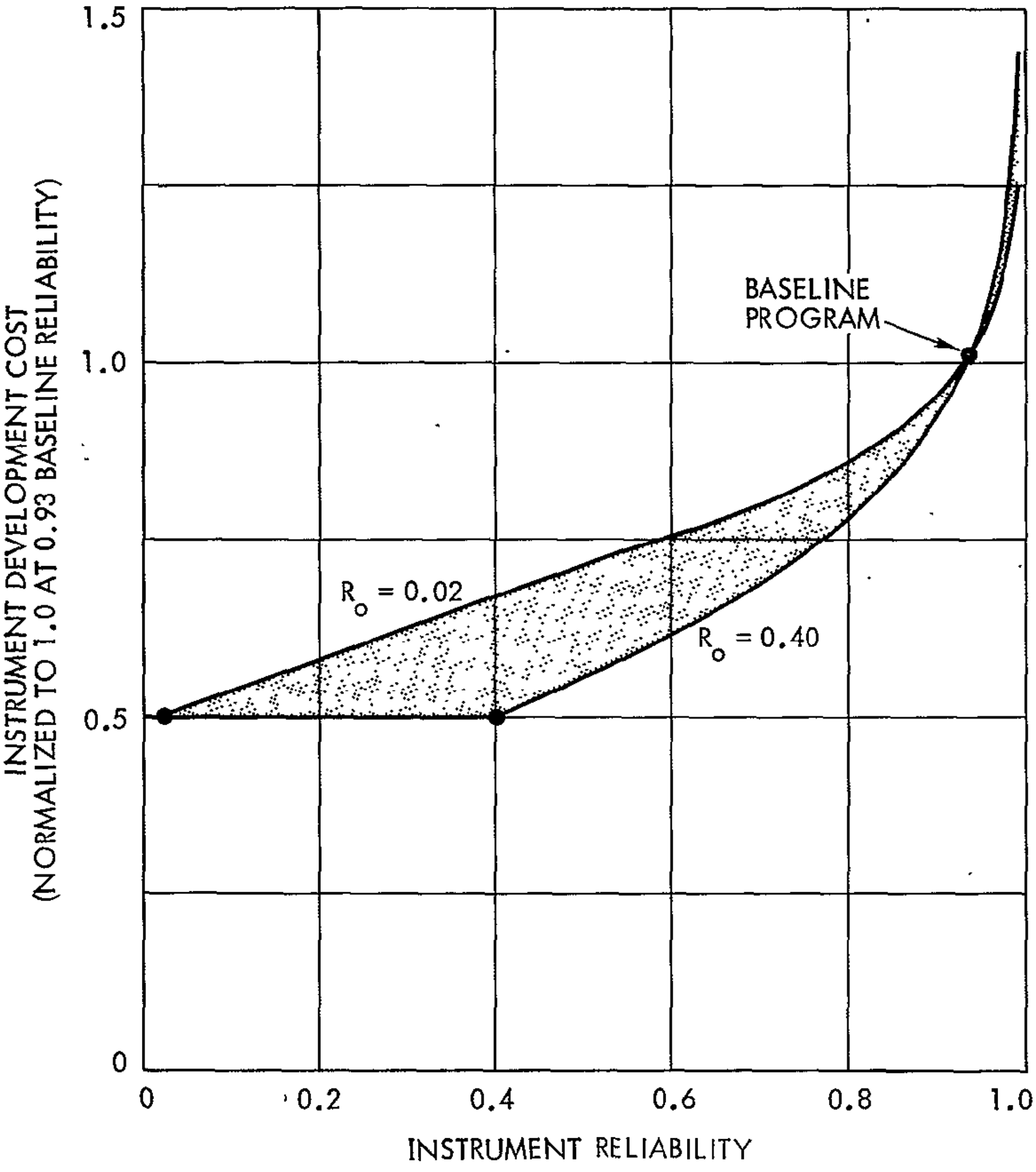

Figure 4-6. Simplified Instrument Cost/Reliability Relationship

that formed our starting point is also a good starting point for the analysis of the effectiveness of individual mission assurance tasks. The saturation effects discussed are built into the relationship and threshold effects can easily be incorporated. The first order step for each task would be the determination of the proportionality constants, a, for the individual tasks. The problem of combining the results for each task into an overall system reliability estimate is a somewhat straightforward mathematical chore that would certainly be manageable with the aid of a computer.

Finally, let us make sure one point is clear. We are not suggesting that cost reduction by accepting reduced instrument reliability be ignored. Whatever cost reductions can be achieved, should be. We are questioning the relative cost effectiveness of attempting a systematic optimization as opposed to a more subjective empirical approach.

4.5 IMPACT OF STANDARD MODULES

As indicated in Section 2.4, the cost impact of using standard modules in experiment instrumentation could, in principal, be a cost reduction approaching nearly 40 percent. In this section, we will consider how the incorporation of standard modules will influence the mission assurance aspects of the program.

In the general discussion of our approach to the topic of mission assurance in Section 4.1, we indicated in Figure 4-2 that the cost reduction due to standardization would possibly be accompanied by a slight increase in the instrument reliability. This belief is based on the well-established phenomenon of reliability growth. Experience with good quality avionics equipment demonstrates that failure rates decrease as approximately the square root of the operating (or test) time for a wide range of equipment. Therefore, as their cumulative operating time grows, the reliability of the standard modules should increase without an increase in mission assurance expenditures; or, alternatively, the mission assurance effort needed to maintain the same reliability could be decreased.

In the following we will examine more closely the effect of standardization on the instrument reliability and also estimate the expected reliability of a representative standard module. In addition, we will use the results of the instrument development cost analysis, described in Section 4.2, to estimate the development cost of the representative standard module. This information will enable us to convert the unit costs in Figure 2-17 to absolute dollars, and the results will be used in Section 5.3. Finally, we will discuss recommendations for a mission assurance approach that is appropriate to standard modules.

Throughout these discussions, we will assume that the representative standard module is a moderately complex unit consisting of a printed circuit board containing about 100 electronic parts and packaged in a standard enclosure of the type described in Section 3.3.

4.5.1 Effect on System Reliability

The instrument system reliability is the product of the reliabilities of the component elements and, barring redundancy, cannot exceed the lowest reliability in the system. From a mission assurance point of view, the instrument can be clearly divided into the standardized portions and the developmental or experiment-unique portions. As already indicated, we believe that as the cumulative operating experience with standard modules increases, the typical module reliability will grow, eventually to the point where the likelihood of module failure will be small compared to that for the developmental parts of the instrument. In this circumstance, the overall instrument reliability will be controlled or determined by the mission assurance approach which is adopted for the developmental equipment.

The standard modules will enter into the system reliability in a way somewhat analogous to electronic parts. Reliability estimation for the standard modules should evolve toward the current situation for electronic parts as failure rate data is accumulated. Granted, the same problems associated with questionable accuracy or applicability will be present, but the situation will be much more clear cut than that prevailing for the developmental equipment.

4.5.2 Standard Module Reliability Estimate

The reliability of individual standard modules will depend upon a number of factors including the quantities produced, the program continuity, and the quality and depth of the test programs. Obviously, the complexity of the module and the quality level of the parts are also important factors. Despite the uncertainties, a more or less conventional reliability estimate has been made for the representative standard module by estimating the parts failure rates and computing the one-year reliability. The results are shown in Table 4-6.

The failure rates were primarily taken from the Minuteman preferred parts list but were adjusted upward based on other sources. The rates actually used average about double the Minuteman rates and represent a moderately high, but not unreasonable, level. These rates also take into account a low level of design error failures. The reliability value obtained of 0.991 is intended as a best estimate of the minimum expected reliability resulting from a 50-module program using high-reliability, screened parts with occasional educated cost compromises in the case of a few proven parts.

Table 4-6. Failure Rate and Reliability Estimate for Standard Module

Part	Quantity	Failure Rate (x 10^{-9}/hr)	Total Failure Rate
Transistor, Low-Power	5	8	40
Op Amp	2	40	80
I. C.	34	20	680
Capacitors	26	4	104
Resistors	24	1	24
Inductor	2	10	20
Connectors	5	20	100
			λ = 1048
			$R_{1\ yr}$ = .991

Table 4-7. Estimated Standard Module Development Cost

Function	Cost	Percent of Program
Design Engineering	27,500	22
Product Engineering	12,500	10
Reliability	6,250	5
Parts, Materials and Processes	8,750	7
Quality Assurance	12,500	10
Manufacturing (Inc. Parts)	48,750	39
Test Conducting	8,750	7
Total Development Program	$125,000	100

4.5.3 Standard Module Development Cost Estimate

In order to estimate the cost of a representative standard module development program, we started with the baseline cost data for typical development programs discussed in Section 4.2.2. Since the development program for standard modules would have a somewhat different orientation and set of requirements than a one-time instrument development program, a number of adjustments had to be made to the baseline data.

For example, a higher percentage of nonrecurrent engineering, mission assurance, and manufacturing effort would be spent to reduce recurrent costs in the production phase. The cost of parts would become a larger percentage of the total and, while the use of commercial-grade parts becomes feasible, their decreased reliability must be compensated with more attention to derating, screening, and life-test programs. More consideration must also be given to the types of tools and fixtures and to production line planning and layout. Better tools, fixtures, and automated test equipment, and more production line stations improve unit efficiency, but also involve higher nonrecurrent costs.

The program functional tasks listed in Table 4-1 were carefully reviewed with these factors in mind and the relative allocation of effort was adjusted to correspond to the standard module development process. The absolute cost scale was set by using the estimated absolute cost of those tasks which have well-established cost estimating relationships in terms of the parameters of the representative standard module. Table 4-7 gives the development program cost estimate that results from the process and Table 4-8 shows the relative allocation of program costs in the cost/task array format previously developed. Although the relative allocation of effort differs from that in a one-time development program, the total development program cost is not significantly different from that for a comparable spaceflight unit developed for one-time use. Also, the development cost would vary somewhat for each particular module. We believe that our cost estimate represents a good average value.

4.5.4 Standard Module Mission Assurance Approach

By virtue of the fact that the cost of the standard modules should become a small fraction of the instrument costs, reduction of the mission assurance effort or acceptance of reduced reliabilities will not produce

Table 4-8. Stadard Module Program Task/Cost Array

DATA FILE: MODDAT5	PERCENT OF EFFORT	DESIGN SCREENING	PERCENT OF PROGRAM $	PRODUCT SCREENING	PERCENT OF PROGRAM $	NON.REL. EFFORT	PERCENT OF PROGRAM $
A. DESIGN ENGINEERING							
A1 REQUIREMENTS ANALYSIS	3.00	25.00	.17	.00	.00	75.00	.50
A2 DESIGN DEFINITION: PARTS, CIRCUIT, MODULE	20.00	35.00	1.54	.00	.00	65.00	2.86
A3 SPECIAL COMPONENT DEVELOPMENT	.00	35.00	.00	.00	.00	65.00	.00
A4 WORST CASE ANALYSIS	10.00	100.00	2.20	.00	.00	.00	.00
A5 BREADBOARD CONST. AND TEST	20.00	50.00	2.20	.00	.00	50.00	2.20
A6 DESIGN REVIEWS	8.00	50.00	.88	.00	.00	50.00	.88
A7 ACCEPTANCE TEST REQUIREMENTS	5.00	15.00	.17	85.00	.94	.00	.00
A8 QUALIFICATION TEST REQUIREMENT AND ANALYSIS.	19.00	100.00	4.18	.00	.00	.00	.00
A9 TEST SUPPORT	5.00	55.00	.61	25.00	.28	20.00	.22
A10 TROUBLESHOOTING AND FAILURE SUPPORT	10.00	40.00	.88	40.00	.88	20.00	.44
SUB-TOTALS	100.00	.00	12.82	.00	2.09	.00	7.10
B. PRODUCT ENGINEERING							
B1 PERFORM DESIGN CALCULATIONS	.00	50.00	.00	.00	.00	50.00	.00
B2 LAYOUT AND ENGINEERING COORD.	25.00	30.00	.75	.00	.00	70.00	1.75
B3 PREPAPE AND CHECK DRAWINGS	60.00	.00	.00	10.00	.60	90.00	5.40
B4 FACTORY SUPPORT AND CHANGES	15.00	30.00	.45	5.00	.08	65.00	.98
SUB-TOTALS	100.00	.00	1.20	.00	.67	.00	8.13
C. RELIABILITY							
C1 PREPARE GUIDELINES & CRITERIA	5.00	80.00	.20	20.00	.05	.00	.00
C2 RELIABILITY ANALYSIS & REVIEW PARTS,CIRCUITS, MODULE	25.00	90.00	1.13	.00	.00	10.00	.13
C3 REVIEW ACCEPTANCE AND QUAL. TEST REQUIREMENTS AND DATA	15.00	50.00	.38	50.00	.38	.00	.00
C4 RELIABILITY PREDICTION	25.00	100.00	1.25	.00	.00	.00	.00
C5 FAILURE MODES AND EFFECTS	5.00	55.00	.14	25.00	.06	20.00	.05
C6 FAILURE REPORTING,DISPOSITION AND CORRECTIVE ACTION	25.00	90.00	1.13	10.00	.13	.00	.00
SUB-TOTALS	100.00	.00	4.21	.00	.61	.00	.18
D. PARTS,MATERIALS AND PROCESSES							
D1 PARTS PROGRAM PLANNING	5.00	45.00	.16	45.00	.16	10.00	.04
D2 PARTS SELECTION	15.00	100.00	1.05	.00	.00	.00	.00
D3 PARTS APPLICATION REVIEW	15.00	90.00	.95	10.00	.11	.00	.00
D4 MATERIALS REVIEW (DRAWINGS)	10.00	100.00	.70	.00	.00	.00	.00
D5 PROCEDURE REVIEW AND MODIFICATION	15.00	100.00	1.05	.00	.00	.00	.00
D6 PROCUREMENT SUPPORT	20.00	35.00	.49	35.00	.49	30.00	.42
D7 FAILURE ANALYSIS SUPPORT	20.00	80.00	1.12	20.00	.28	.00	.00
SUB-TOTALS	100.00	.00	5.51	.00	1.03	.00	.46
E. QUALITY ASSURANCE							
E1 QUALITY PLANNING	30.00	10.00	.30	60.00	1.80	30.00	.90
E2 QUALITY SUSTAINING ENGINEERING	10.00	15.00	.15	70.00	.70	15.00	.15
E3 PECEIVING INSPECTION	30.00	10.00	.30	80.00	2.40	10.00	.30
E4 PROCESS MONITORING AND PRODUCT INSPECTION	5.00	15.00	.08	85.00	.43	.00	.00
E5 TEST MONITORING	25.00	75.00	1.88	25.00	.63	.00	.00
SUB-TOTALS	100.00	.00	2.70	.00	5.95	.00	1.35
F. MANUFACTURING							
F1. PLANNING AND CONTROL	15.00	.00	.00	20.00	1.17	80.00	4.68
F2 PURCHASED PARTS & MATERIAL	30.00	10.00	1.17	10.00	1.17	80.00	9.36
F3 ASSEMBLY AND TEST	30.00	10.00	1.17	10.00	1.17	80.00	9.36
F4 SUPERVISION AND TRAINING	3.00	5.00	.16	45.00	1.40	50.00	1.56
F5 TOOLS AND FIXTURES	15.00	.00	.00	20.00	1.17	80.00	4.68
F6 MECHANICAL FABRICATION	2.00	5.00	.04	15.00	.12	80.00	.62
SUP-TOTALS	100.00	.00	2.54	.00	6.20	.00	30.26
G. TEST (CONDUCTING)							
G1 BUILD TEST EQUIPMENT	80.00	15.00	.84	25.00	1.40	60.00	3.36
G2 PREPARE FACTORY TEST PROCEDURES	.00	5.00	.00	60.00	.00	35.00	.00
G3 CONDUCT TESTS	10.00	15.00	.11	10.00	.07	75.00	.53
G4 SUPPORT TROUBLESHOOTING AND TEST CHANGES	10.00	15.00	.11	10.00	.07	75.00	.53
SUB-TOTALS	100.00	.00	1.05	.00	1.54	.00	4.41

SUMMARY ARRAY

A. DESIGN ENGINEERING	22.00	.00	12.82	.00	2.09	.00	7.10
B. PRODUCT ENGINEERING	10.00	.00	1.20	.00	.67	.00	9.13
C. RELIABILITY	5.00	.00	4.21	.00	.61	.00	.18
D. PARTS,MATERIALS AND PROCESSES	7.00	.00	5.51	.00	1.03	.00	.46
E. QUALITY ASSURANCE	10.00	.00	2.70	.00	5.95	.00	1.35
F. MANUFACTURING	39.00	.00	2.54	.00	6.20	.00	30.26
G. TEST (CONDUCTING)	7.00	.00	1.05	.00	1.54	.00	4.41
TOTAL	100.00	.00	30.03	.00	19.10	.00	51.67

TOTAL: 100.00%   EXPERIMENT COST: $125,000   COST DELTA:
TOTAL MISSION ASSURANCE COSTS: $60,158 (48.1%)
PRODUCT ASSURANCE COSTS: $25,025 (20.0%)

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significant reductions in the overall program costs. On the other hand, because of the availability of relatively simple, well-defined, economical units in reasonably large numbers, the standard module development and production program offers a good trial vehicle for mission assurance cost reduction approaches. The development and production program will involve continuity and careful planning which will provide better visibility, predictability, control and measurability than the experiment-unique portions of the instrument.

Most of the mission assurance cost reduction approaches in the increased efficiency category (Section 4.3.1) are definitely applicable to a standard module program. Some of them, such as the suggestions regarding automated-test methods, are especially appropriate to standard modules. Other cost savings areas particularly applicable to standard modules include the following.

Parts - Production parts cost will be a large percentage of unit production cost. A good balance between very-high-cost parts and screening programs, and low-cost parts with low reliability and production recycle costs is a key factor. The balance can be achieved by:

- selecting parts with a good production history, proven record, or an existing low-cost manufacturer's screening program;
- use of derating at the expense of more parts where stress factors can be reduced - also protective parts;
- a selective nonrecurrent parts test and qualification program as a part of the module qualification program.

Test - The emphasis should be on maximum screening efficiency. The qualification program during the development phase should be used to establish the criteria. Therefore, we recommend:

- a module qualification program including performance under maximum permissible conditions, selective tests to destruction, active-life tests, data gathering concerning performance thresholds under degraded input and reduced-power conditions for normal units;
- an economical 100 percent module acceptance test including performance thresholds under conditions of reduced power and degraded inputs, a modest active-life test, performance monitoring under light vibration, and internal performance

monitoring at circuit points where degradation may be detected early. (The purpose of threshold tests, etc., is not to demonstrate the ability of the modules to operate under conditions that are not a part of the operational requirements, but to detect incipient failures.)

Inspection - The module design should be geared for efficient inspection. Additional recommendations are:

- minimal step-by-step visual inspection - units inspected once in detail;
- design configuration and test sequencing to be such that damage after inspection is precluded;
- manufacturing repair and recycle to be performed under selective inspection to avoid need for complete reinspection.

Documentation - Record keeping should be reduced to a minimum consistent with data-gathering requirements and geared to manufacturer's normal practices.

- minimal traceability - by lot or batch as appropriate with the emphasis on parts and materials selection and partial module requalification in case of significant changes;
- simplified recording of cause and corrective action of all failures;
- serialized, dated, data sheet showing acceptance test results - copy to accompany module.

4.6 LIFE-CYCLE COST OPTIMIZATION

Our approach to cost optimization over the complete life cycle of an experiment was briefly described in Section 4.1. The total cost is the sum of the instrumentation development costs and the experiment operational costs. Since instrument development costs increase as a function of instrument reliability while operational costs decrease as a function of reliability, the optimization consists of a tradeoff between these two components of the total cost as a function of instrument reliability to establish the minimum total cost.

The principal effort in this study and the discussion up to this point has dealt with the instrumentation development cost/reliability relationships. That analysis covers the portion of the total life cycle up to the delivery of experiment flight hardware for integration with the spacecraft. The next step in the process would involve the determination of operational costs as a function of instrument reliability. As a beginning step, within the scope of the present study, we have performed a preliminary investigation of the problem of operational cost determination.

4.6.1 Operational Costs

The operational phase of the experiment life cycle can be divided into ground operations and flight operations. The prelaunch phase of ground operations includes integration of the individual experiments making up the payload with the spacecraft, integration of this payload with the Shuttle Orbiter, integration of the Orbiter into the complete Shuttle System and the subsequent operations leading up to launch. Flight operations include launch, on-orbit checkout of the payload prior to deployment, deployment of the payload, experiment operations in orbit, retrieval of the payload for either on-orbit maintenance or return to the ground, and return and landing of the Orbiter. Post-launch ground operations include payload removal from the Orbiter, payload disassembly, and instrument repair, refurbishment, modification or disassembly as appropriate.

The primary dependence of operational costs on instrument reliability is fairly obvious. The cost of performing a single operational cycle includes many elements that are independent of instrument reliability and, in general, will be relatively insensitive to instrument reliability. The instrument reliability enters the picture principally by determining the number of times the operational cycle must be performed in order to successfully perform the experiment. Therefore, in first order, the problem of determining operational costs as a function of instrument reliability amounts to determining the cost of an operational cycle and determining the number of cycles as a function of instrument reliability.

The determination of the cost of a single operational cycle would, in principle, involve the straightforward buildup of the costs of all of the elements involved in the process. The main difficulty at the present time is the lack of detailed definition of the tasks, equipment, facilities and cost accounting procedures that will be involved. The cost of a single cycle will depend, to a certain extent, on the instrument reliability because equipment failures during the prelaunch phase of ground operations will cause additional costs for repair or replacement, retest, and delays. The quantity of spare equipment needed to minimize delays due to failures also depends on the instrument reliability.

A detailed analysis of operational costs is far beyond the scope of this study. It is an extremely important topic which should receive careful attention because of the very significant impact that operational costs will have on total program costs. Our objective in the present work is to determine the dominant sensitivity of program costs to instrument reliability and to assess the magnitude of the cost savings that could be achieved by the acceptance of reduced instrument reliability requirements. In order to do this, we have constructed a simplified mission cost model to provide an example of the optimization process and illustrate the potential cost reductions that could be obtained.

4.6.2 Simplified Mission Cost Optimization

The simple model we will use includes the dominant effect of instrument reliability on operational costs and neglects a host of secondary effects. The concept of operations addressed in this model is one in which an experiment of a particular type is flown and if it fails to complete the mission, is returned, recycled, and flown again. This process is repeated, if required, not necessarily until the experiment succeeds, but until its success ratio, achieved through multiple flights, equals the single-flight success ratio of a higher reliability baseline experiment. This definition of success provides a fair comparison with the current situation where an experiment is flown once whether it succeeds or not. The total cost of performing the experiment once is its acquisition cost, C_a, plus the cost of a single flight, C_f. If it has to be flown more than once, the single-flight costs must be multiplied by the number of flights, N, to obtain the total operational costs.

For the instrument acquisition cost dependence on reliability, we will use the simplified cost/reliability relationship derived in Section 4.4.2 (Figure 4-6). Any dependence of the single-flight operational cost on the instrument reliability is neglected and, therefore, the total operational cost is simply NC_f where only N depends on the reliability. Since C_f is not known, it will be treated as a variable parameter.

The method of calculating the expected number of flights, N, can bedeveloped by the following line of reasoning. Assume that, in principle, one-hundred different experiments are to be flown, and that each instrument has a reliability, r, of .60, for example. After each instrument has been flown once (i.e., one-hundred experiment flights), 60 will have made their measurements and need not be flown again, but 40 will require at least a second flight. At the conclusion of the second round of flights, another 24 will have succeeded and only 16 will require a third flight. At this point we have made 140 flights to achieve 84 successes or an average of 1.67 flights per success. Also, in that number of flights, 84 of the 100 experiments have succeeded, giving a group success ratio of .84. It can be seen that at any point in the sequence of flights the number of experiments successful will be .60 of the number of flights, and that, in general, N, the expected or average number of flights required by each experiment to achieve success will be N = 1/R. However, we are only requiring a success ratio equivalent to that for the baseline comparison instruments with a reliability of R_b. Thus, R_b/R is the average number of flights required for a success ratio equivalent to the baseline instrument.

In this simplified model, then, the mission cost is given by:

$$C_m = C_a(R) + \frac{R_b}{R} C_f.$$

Dividing by $C_a(R_b)$ and using the cost/reliability relationship from Section 4.4.2 for $C_a(R)$ gives:

$$\frac{C_m(R)}{C_a(R_b)} = 0.5 \frac{\ln \frac{\ln R_o}{\ln R}}{\ln \frac{\ln R_o}{\ln R_b}} + 0.5 + \frac{R_b}{R} \cdot \frac{C_f}{C_a(R_b)} .$$

This relationship is plotted in Figure 4-7 for $R_b = 0.93$, $R_o = 0.02$, and a range of values for $C_f/C_a(R_b)$.

Although this simple model neglects a large number of factors, the results can be used to demonstrate several points. The current ratio of flight costs to instrument development costs is typically 0.93. Therefore, point A in Figure 4-7 represents the current situation. We see immediately that the current reliability is close to optimum.

The expectation that the cost of performing an operational cycle will be less than the initial development cost of the experiment payload forms the basis for the belief that payload retrieval and reflight will be cost effective. If we assume that the advent of the Shuttle is successful in reducing flight costs by a factor of 4 and experiment instrumentation development is not changed, the situation would be represented by point B. The reduction in overall mission cost would be about 40 percent. The optimum instrument reliability would be about 0.7 and a further cost reduction could be achieved by reducing the instrument reliability from 0.93 to 0.7, as represented by moving from point B to point C in Figure 4-7. However, the cost reduction will only amount to about an additional 10 percent.

The cost savings ratio that results from the equivalent to moving from point B to point C (i.e., due to increased risk acceptance) is shown as a function of the ratio of the flight cost to the instrument cost (i.e., C_f/C_a) in Figure 4-8. Both the fractional reduction in mission cost and instrument cost are shown. As previously noted in Section 4.4.2, the cost reductions that can be derived by reducing instrument reliability are not dramatic. We now see that when the increased operational costs associated with the reduced reliability are taken into account, the cost reduction is even less significant.

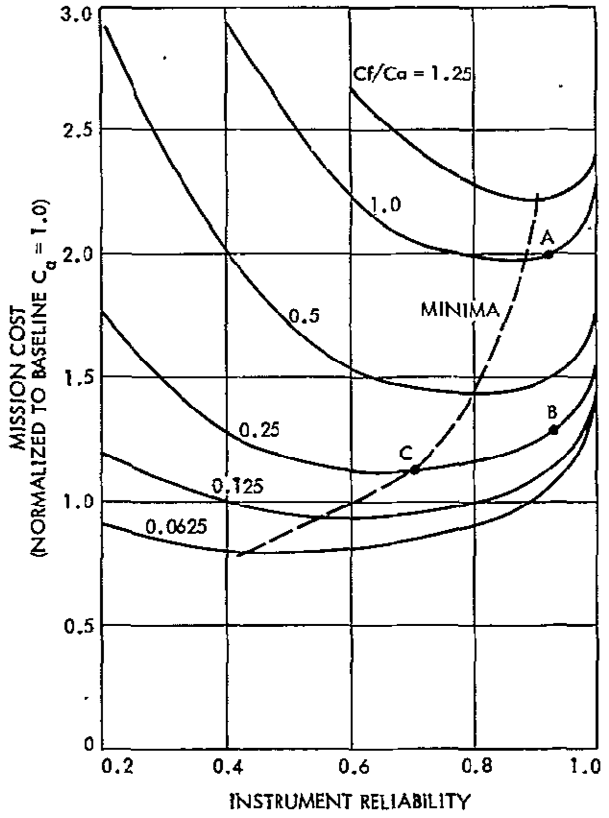

Figure 4-7. Mission Cost versus Instrument Reliability

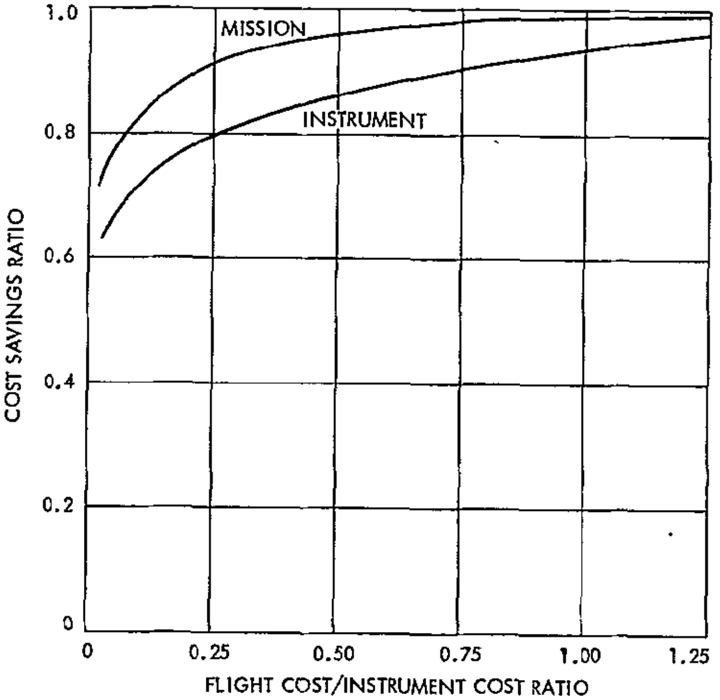

Figure 4-8. Mission and Instrument Cost Savings Ratios

5. APPLICATION TO HEAO MODEL EXPERIMENT PAYLOAD

5.1 MODEL PAYLOAD DEFINITION

To demonstrate specific applicability of the approaches recommended in Sections 2, 3, and 4, we have selected a model payload consisting of four scientific instruments. These instruments are among the 14 (including alternates) originally selected by NASA for Missions A and B of the High-Energy Astronomy Observatory (HEAO). We have chosen instruments that are representative of four HEAO subdisciplines: X-rays, cosmic rays, and low and high-energy gamma rays. The instruments are: BGR-4, High-Energy Gamma Ray Telescope; BCR-5, Superconducting Magnetic Spectrometer; AGR-4, MeV Range Gamma Ray Telescope; and BXR-2, Bragg Crystal X-Ray Spectrometer. In addition to forming a model payload that is broadly representative of high-energy astrophysics instrumentation, we have selected, in each category, the instrument for which we have the best understanding of requirements.

The model payload experiments utilize two basic sensor types: scintillators viewed by photomultiplier tubes and multiwire proportional chambers. These belong to the electron multiplier and large area spatial sensor categories (see Section 2.2) respectively. Figure 2-2 shows that these two categories dominate high-energy astrophysics instrumentation and, hence, our model payload is highly representative in that respect. In addition, the electron multiplier devices and associated support subsystem elements are widely used by four other disciplines. Large area spatial detectors are also used in solar physics instrumentation.

Photomultiplier tubes do not generally require specialized sensor signal conditioning electronics. Therefore, in our model payload, all photomultiplier tube signals are processed directly by standard modules. Conversely, multiwire proportional chambers typically require special preamplifiers mounted in close proximity to the signal source. Therefore, in our model payload, we assume that all proportional chamber signals are suitably conditioned in the sensor subsystems before being connected to standard modules.

In the preliminary designs of the HEAO instruments, various degrees of redundancy were incorporated. To avoid additional complexity in the block diagrams for the model payload, we have typically eliminated any explicit redundancy such as duplication of circuit functions. The number of additional modules required to provide redundancy at specific points can be easily assessed from the block diagrams.

In order to enhance commonality among the four instruments, a single approach has been adopted to satisfy each function that is required by more than one instrument. For example, the same pulse shape analysis approach, utilizing several standard modules, is used in all four instruments, and the same delay line readout approach, again utilizing several standard modules, is used in BGR-4 and BCR-5. Common approaches such as these would be taken by experimenters beginning to design new instruments based on existing standard modules, and, in general, will not compromise required instrument performance.

5.2 INSTRUMENT IMPLEMENTATION WITH STANDARD MODULES

All functional requirements for support subsystems for the model payload instruments can be satisfied by 23 standard modules and four types of custom-built modules. These modules are listed in Table 5-1. The first two columns of the table provide a qualitative assessment of the frequency of use of each standard module. The high-usage modules are typically used in conjunction with high-usage sensors or provide commonly required processing functions. The low-usage modules are typically associated with less widely-used sensors (e.g., gas supply controller for proportional chambers) or provide less commonly required processing functions (difference amplifier). The third column of the table identifies those modules that perform instrument specific functions and, in general, must be custom designed on an individual basis.

The number of identical functional elements that can be placed in a single modular package of the type recommended in Section 3 is given in the fourth column of the table. This number is based on an estimate of circuit complexity and number of external connections required per functional element. An amplifier, for example, typically has very few external connections but requires a significant printed circuit board area for proper layout and adequate room for installing selectable components to adjust the amplifier characteristics. Conversely, a logic OR is a very simple circuit but, typically, must provide a large number of input connections.

The amplifiers and discriminators included in the tabulation of data processing modules are actually sensor signal conditioning elements rather than support subsystem elements. Although the assessment of commonality of requirements in Section 2.2 considered only support subsystem elements, the broad applicability of the ten sensor types to many disciplines and a large number of payloads was a clear indication that very good potential also exists for the use of standard functional elements in the signal conditioning subsystem. In fact, the nine signal conditioning modules listed in Table 5-1 were found to be applicable in a standard form to the HEAO model payload and six of these appear to have broad applicability (high-usage) beyond the model payload.

Table 5-1. Module Descriptions

	High Usage	Low Usage	Custom	Functional Elements Per Module
DATA PROCESSING MODULES				
Shaping Amplifier	●			4
Stretcher Amplifier	●			4
Compression Amplifier	●			4
Summing Amplifier	●			2
Difference Amplifier		●		4
Sample and Hold	●			8
Discriminator	●			8
Programmable Discriminator		●		4
Zero Crossing Discriminator	●			8
Pulse Sequence Discriminator		●		4
Time Encoder	●			4
Scaler	●			16
Logic OR		●		2
Multiplexer	●			1
ADC	●			1
Memory	●			1
Programmable Attenuator			●	1
COMMAND AND CONTROL MODULES				
Gas Supply Controller		●		4
Position Encoder		●		4
Test Pulser	●			1
Data Sequencer			●	1
Command Interface	●			1
Special Device Controller			●	4
Event Logic			●	1
POWER CONDITIONING MODULES				
Low-Voltage Power Supply	●			1
High-Voltage Power Supply	●			1
Power Interface	●			1

Sections 5.2.1 through 5.2.4 describe the implementation of each experiment using the 27 modules. For clarity, the block diagrams in those sections include only the configuration of modules that is instrument dependent. Several modules (multiplexer, ADC, memory, data sequencer and command interface) are used in the standard configuration shown in Figure 2-15 for all four instruments. Although they are not shown on the block diagrams for the individual instruments, these modules are included in the tabulations of module requirements. The test pulsers are also used in a standard way and are tabulated but not shown on the block diagrams. The power conditioning modules are not shown on the block diagrams and have not been tabulated. The power interface and the low voltage power supplies are used in a standard way for all four instruments. The number of high voltage power supplies was not determined because of the lack of a sufficiently definitive criterion for the number of sensors to be operated by each supply.

A brief description of each of the 23 standard modules and the four types of custom modules is provided in the following paragraphs.

Shaping Amplifier. This general purpose amplifier provides selectable gain and integration and differentiation time constants for shaping and amplifying individual input pulses. The gain and time constants are varied by changing a few components attached to printed circuit board stakes.

Stretcher Amplifier. This amplifier is generally used to process photomultiplier tube signals produced by plastic scintillators. It produces an output pulse with a fixed decay constant and an amplitude proportional to the integrated charge contained in a single fast input pulse. The gain and decay constant are varied by changing components.

Compression Amplifier. This amplifier is generally used to process wide dynamic range signals. It provides logarithmic compression of the input signal to allow the amplitude to be digitized with an error that is independent of the signal magnitude.

Summing Amplifier. This amplifier provides unity gain amplitude summing for up to ten analog input signals.

Difference Amplifier. This amplifier provides a unity gain output that is equal to the difference in amplitude of two analog input signals.

Sample and Hold. This unit detects the peak amplitude of an input pulse and provides an output that maintains the peak amplitude for a preset length of time or until an earlier external reset pulse is supplied. The preset duration is selected by changing components.

Discriminator. This general purpose discriminator produces a fixed duration logic pulse each time an input pulse crosses a preset threshold in the direction of increasing amplitude. The threshold and logic pulse duration are selected by changing components. Updating or nonupdating mode for subsequent input pulses occurring during a logic pulse output can be selected by changing a printed circuit board jumper. The duty cycle for nonupdating mode is 100%.

Programmable Discriminator. This unit is the same as the general purpose discriminator except the threshold can be varied by means of a serial digital command input.

Zero-Crossing Discriminator. This unit produces a fixed duration logic pulse each time an input pulse exceeds a threshold and subsequently crosses the zero voltage level in a negative going direction. The logic pulse duration and updating or nonupdating mode are selected by component and jumper changes.

Pulse Sequence Discriminator. This unit accepts logic pulses at inputs A and B and produces a fixed-duration logic pulse output if the leading edge of the pulse at input A preceeds the leading edge of the pulse at input B. Two operating modes are available. In one mode the occurrence of a pulse at input B will inhibit the unit for a preset time interval. In the other mode an enable window is supplied by the event logic.

Time Encoder. This unit accepts two logic pulses as inputs and provides a serial digital word whose value is proportional to the length of the time interval between the leading edges of the pulses.

Scaler. This unit counts input logic pulses and provides the number of pulses as a serial digital word. The count is reset to zero when the data are read out. The counter will latch at its maximum value to indicate an overflow condition.

Logic OR. This unit accepts up to ten logic pulse inputs and provides a single output that is a logical OR of the inputs.

Multiplexer. This general purpose multiplexer accepts up to 16 inputs of analog or digital data and connects them, one at a time, to a single output. A control address from the data sequencer selects the input to be used.

Analog-to-Digital Converter. This is a general purpose 12-bit successive approximation ADC which accepts either DC levels or sample and hold output pulses for amplitude digitizing. It is generally used in conjunction with a multiplexer to select the analog input source.

Memory. This unit provides data buffering for instruments that produce data on a random event basis rather than periodically. It includes a data selector controlled by the data sequencer to select the input data source and an output data register to interface with the spacecraft.

Programmable Attenuator. This is a custom-built module that processes ten channels of analog data. It provides individual attenuation factors, selectable by command inputs, for each channel.

Gas Supply Controller. This is a feedback control unit that accepts an analog input from a pressure transducer and controls a gas supply valve to maintain a selected pressure. The pressure value to be maintained is supplied to the unit as a serial digital command.

Position Encoder. This unit is an up-down counter for use with incremental position transducers that can be either rotary or linear devices. It accepts two logic signals from the transducer and counts up or down depending on the direction of motion indicated by the phase relationship of the signals. It provides a serial digital output without destroying the contents of the up-down counter. Overflow indicators are provided for both directions of motion.

Test Pulser. This general purpose pulser provides pulses with preset amplitude and shape. It includes a 32-channel output demultiplexer to route the pulses. The routing is controlled by command inputs and the pulse amplitude and shape are varied by changing components.

Data Sequencer. This is a custom-built module that controls the operation of the multiplexers, the ADC and the memory. It is hardwired with the proper operational program for each instrument.

Command Interface. This general purpose unit interfaces with the spacecraft and decodes and distributes commands within the instrument. It provides discrete ON/OFF controls and serial digital commands. It can be used in conjunction with digital-to-analog converters to provide analog control levels.

Special Device Controller. These are custom-built modules which perform control functions within the instruments. There are four types required for the HEAO model payload: an X-ray tube controller, a radioactive source position controller, a crystal position controller and a magnet power supply controller. With the exception of the X-ray tube controller, these are all feedback control units with control parameter values supplied as serial digital commands. The X-ray tube controller executes commands directly.

Event Logic. Rather than provide a modular set of standard logic functions that would be used to configure the event logic for each instrument, a single custom-built module is used for this purpose. The large number of interconnections typically required between individual logic functions would greatly limit the number of functions per module. This would lead to very significant weight and volume penalties if standard modules were used for the event logic.

Low-Voltage Power Supply. This unit does not necessarily use the same packaging as the data processing and command and control modules. There is a family of supplies, all providing the same set of standard voltages but with varying power handling capabilities. A single supply with the appropriate rating is used for each instrument.

High-Voltage Power Supply. This unit has its own packaging suitable for mounting in close proximity to the sensor subsystems. There is a family of supplies, providing several ranges of high voltage. Each unit has a variable output within its voltage range, controlled by a serial digital command.

Power Interface. This is a general purpose unit, used one per instrument to interface with the spacecraft primary power and provide the instrument power ON/OFF, input filtering, isolation and bus protection functions.

5.2.1 High-Energy Gamma-Ray Telescope (BGR-4)

Sensors. The High-Energy Gamma-Ray Telescope uses the six sensor assemblies listed in Table 5-2. The anticoincidence dome is a single large plastic scintillator that covers the entire viewing aperture of the instrument. It is used to reject all observed events associated with incident charged particles. The dome is viewed by 24 photomultiplier tubes uniformly distributed around the skirt. In the original instrument these tubes are divided into two interleaved groups with separate electronic subsystems for redundancy. To simplify our illustration we will consider only a single group of 24 tubes.

The two scintillator tile arrays are used to define the aperture of the instrument and to identify the direction of the incident particles passing through the aperture. Each array consists of nine individual tiles of plastic scintillator arranged in a three by three matrix. Each of the 18 tiles is individually viewed by a photomultiplier tube attached by means of a plastic strip light guide. Of the 81 possible coincidence pairs between the two arrays, 49 are selected to define the instrument aperture. These 49 pairs are grouped to identify nine different look directions relative to the axis of the instrument and hence provide low resolution directional information. In addition, a time-of-flight measurement between the upper and lower arrays is used to determine the direction in which an incident gamma-ray produced electromagnetic shower is moving through the aperture of the instrument.

The two stacks of position sensitive detectors are used to provide high resolution directional information. The upper stack includes 21 sensor modules, each with x-y coordinate readout and one module with u-v coordinate readout (oriented at 45° with respect to the x-y coordinates to eliminate double track ambiguities). The lower stack includes 17 x-y modules and one u-v module. Thin metal plates are interleaved between the modules to induce electron-position pair-production by incident gamma-rays, thus producing electromagnetic showers containing charged particles more

Table 5-2. Model Payload Sensors

BGR-4 Sensor Assemblies

Anticoincidence Dome with Photomultiplier Tubes
Scintillator Tile Arrays (2) with Photomultiplier Tubes
Position Sensitive Detector Stacks (2) with Delay Lines and Preamplifiers
Total Absorption Shower Counter with Photomultiplier Tubes

BCR-5 Sensor Assemblies

Trigger Detectors (2) with Photomultiplier Tubes
Position Sensitive Detectors (8) with Delay Lines and Preamplifiers
Total Absorption Shower Counter with Photomultiplier Tubes

AGR-4 Sensor Assemblies

Anticoincidence Detector with Photomultiplier Tubes
Phoswich Detectors (7) with Photomultiplier Tubes
Exterior Shields (6) with Photomultiplier Tubes
Interior Shields (2) with Photomultiplier Tubes

BXR-2 Sensor Assemblies

Low Energy Spectrometer Position Sensitive Detector (8) with Preamplifiers
High Energy Spectrometer Position Sensitive Detector (8) with Preamplifiers

readily detected by the various sensors. The upper tile array is located below the upper position sensitive detector stack and thus detects the presence of electromagnetic showers originating in the stack. The original instrument used multiwire spark chambers with individual wire readout of position information. Multiwire proportional chambers with either individual wire readout or delay line readout are now widely used in ground-based instrumentation for high energy gamma-ray investigations. To enhance commonality with other high energy astronomy instruments, we have used multi-wire proportional chambers with delay line readout for BGR-4 in our model payload.

The total absorption shower counter (TASC) is a single large NaI (Tℓ) scintillator viewed by twelve photomultiplier tubes through a light diffusion box. This configuration is designed to distribute the signal from each event over all tubes in a reasonably uniform fashion to eliminate position dependence of the response. The total signal from the twelve tubes is collected and processed as a single high resolution measurement of the energy deposited in the scintillator by the gamma-ray produced electromagnetic showers.

Instrument Electronics. The electronic block diagrams for BGR-4 are shown in Figure 5-1. Table 5-3 summarizes the module requirements. The first column tabulates the numbers of each type of functional element required to implement the instrument electronic system. The second column tabulates the numbers of modules required taking into account the number of functional elements per module given in Table 5-1. Finally, the last column gives the excess or unused module fractions that constitute the modularization overhead.

The anticoincidence dome subsystem consists of two functional elements. The anode signals from all 24 tubes are combined and connected to a single discriminator. The discriminator output logic pulse is used as an anticoincidence signal by the event logic to reject events produced by incident charged particles. The discriminator output also provides counting rate data used to monitor tube performance and adjust the high voltage.

The scintillator array subsystem consists of 60 functional elements of six types. The anode signal from each photomultiplier tube is connected to an individual discriminator whose output logic pulse is used for three

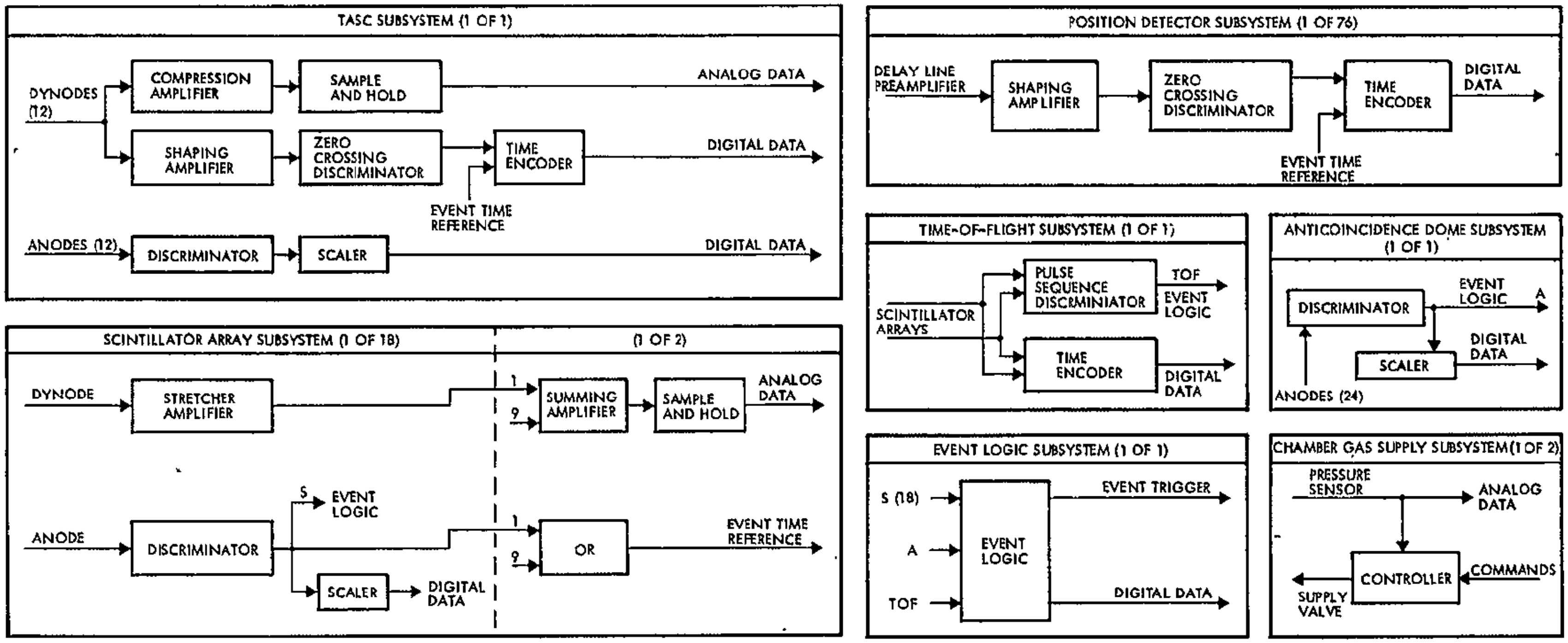

Figure 5-1. High Energy Gamma-Ray Telescope (BGR-4)

Table 5-3. BGR-4 Module Requirements

	Functional Elements	Modules	Excess Modules
DATA PROCESSING MODULES			
Shaping Amplifier	77	20	3/4
Stretcher Amplifier	18	5	2/4
Compression Amplifier	1	1	3/4
Summing Amplifier	2	1	
Difference Amplifier			
Sample and Hold	3	1	1/8
Discriminator	20	3	4/8
Programmable Distriminator			
Zero Crossing Discriminator	77	10	3/8
Pulse Sequence Discriminator	1	1	3/4
Time Encoder	78	20	2/4
Scaler	20	2	12/16
Logic OR	2	1	
Multiplexer	7	7	
ADC	1	1	
Memory	1	1	
Programmable Attenuator			
COMMAND AND CONTROL MODULES			
Gas Supply Controller	2	1	2/4
Position Encoder			
Test Pulser	2	2	
Data Sequencer	1	1	
Command Interface	1	1	
Special Device Controller			
Event Logic	1	1	
HIGH USAGE	308 (98%)	75 (94%)	4.25
LOW USAGE	5 (1.5%)	3 (3.5%)	1.25
CUSTOM	2 (0.5%)	2 (2.5%)	0
TOTAL	315	80	5.5

purposes. Each output is separately connected to one input of a nine-by-nine coincidence matrix in the event logic for use in determining the low resolution angle of incidence for each event. The nine outputs from each array (upper and lower) are also combined in a pair of logic OR's to provide the inputs for the time-of-flight subsystem. Finally, each output provides counting rate data. A dynode signal from each tube is connected to an individual stretcher amplifier for analog processing. The outputs of the amplifiers for the nine tiles in each array are combined in a pair of summing amplifiers to provide an analog pulse whose amplitude is proportional to the equivalent number of minimum ionizing singly charged particles contained in the electromagnetic showers passing through the arrays. The peak amplitude of each pulse is preserved in a sample and hold for processing by a multiplexer-ADC combination. A test pulser is used to drive light emitting diodes attached to each photomultiplier tube. This test function is used to verify proper operation of the event logic and calibrate the time-of-flight measurement for each pair of upper and lower tubes.

The position detector subsystem consists of 228 functional elements of three types. Each of the 38 multiwire proportional chambers has a pair of delay lines attached to its two orthogonal cathode wire planes. The output signal from each delay line is processed by a shaping amplifier and a zero-crossing discriminator. The resulting logic pulse is one input to a time encoder. A signal derived from the trigger detectors provides a time reference logic pulse for the other input to the time encoder. The elapsed time between the reference pulse and the delay line output is the transit time through the delay line. This transit time is proportional to the position of the event along that coordinate of the chamber and the digital outputs of the time encoders which represent those positions are supplied to a multiplexer.

The TASC subsystem consists of seven functional elements. The anode signals from all twelve photomultiplier tubes are combined and fed to a discriminator which provides counting rate data. Dynode signals from the tubes are combined and used for two purposes. They are fed to a compression amplifier and sample and hold to provide a measurement of the pulse amplitude which is proportional to the energy deposited in the TASC by an event.

The combined dynode signals are also fed to a pulse shape analyzer consisting of a shaping amplifier, a zero-crossing discriminator and a time encoder. The pulse shape must be representative of an electron shower in the TASC for the event to be considered valid. The dynode pulse amplitude and pulse shape information are supplied to a multiplexer. A test pulser provides inputs to each amplifier and a light emitting diode mounted in the TASC light diffusion box. The test signals are used to check relative responses of the tubes and the analog electronics. A special event logic mode is used to select minimum ionizing charged particle events that provide an absolute calibration of the TASC response.

The time-of-flight subsystem consists of two functional elements. The inputs from the two scintillator tile array logic OR's are fed to both elements in parallel. The pulse sequence discriminator provides a real-time indication of particle transit direction to the event logic while the time encoder provides a digitized measurement to a multiplexer. The on-board determination is conservatively set to include a portion of the "wrong way" events in the data set and the time encoder value is used for a later offline rejection of those events during ground analysis.

The chamber gas supply subsystem consists of two gas supply controllers. The individual proportional chambers that form each of the stacks (upper and lower) are coupled as a single gas volume within that stack and one of the controllers is used for each stack.

The event logic subsystem consists of the custom-built event logic module. It accepts inputs from the 18 scintillator tiles, the tile array pulse sequence discriminator and the discriminator for the anticoincidence dome. A nine-by-nine coincidence matrix with 49 matrix points implemented is used to identify events originating from acceptable look-directions. Automatic suppression is provided for high rates of events due to earth albedo gamma-rays appearing in one or more of the look directions as the instrument performs an all-sky survey. The matrix output combined with the time-of-flight pulse sequence valid signal and the absence of an anticoincidence signal produces the event trigger. The event logic also provides scaled coincidence counting rates as digital data.

5.2.2 Superconducting Magnetic Spectrometer (BCR-5)

Sensors. The Superconducting Magnetic Spectrometer uses the eleven sensor assemblies listed in Table 5-2. The two trigger detectors are used to define the aperture of the instrument and to measure the charge and direction of the incident particle passing through the aperture. Each counter is formed from a large curved sheet of plastic scintillator viewed by two pairs of photomultiplier tubes located on opposite sides of the sheet. The tubes are coupled to the scintillator by plastic strip light guides. A coincidence between the trigger detectors is used as an indication of a possible valid event and a time-of-flight measurement between them is used to determine the direction in which an incident particle is moving through the aperture of the instrument. A pulse height analysis of the scintillator output is used to determine the charge of the particle.

The eight position sensitive detectors, grouped as four pairs, are used to measure the curvature of the trajectory of the charged particle through the instrument's magnetic field. This curvature allows the momentum of charged particles to be determined when the particle's electric charge is known. Multiwire proportional chambers with delay line readout are used for these detectors. Each of the eight detectors provides a readout in two orthogonal axes. The pairing of detectors provides improved track position resolution.

The total absorption shower counter (TASC) is built in a sandwich configuration with alternating layers of scintillator and metallic sheets. The top two scintillator layers are CsI (Na) while the remaining eight layers are plastic scintillator. Each layer is viewed by two pairs of photomultiplier tubes mounted on opposite sides of the TASC. Observation of a characteristic electromagnetic shower developing in the TASC is used to distinguish incident electromagnetic particles from hadronic particles.

Instrument Electronics. The electronic block diagrams for BCR-5 are shown in Figure 5-2. Table 5-4 summarizes the module requirements. The trigger detector subsystem consists of 40 functional elements of seven types. The anode signal from each photomultiplier tube is connected to an individual discriminator. The discriminator outputs corresponding to the four tubes on a single detector are combined in a logic OR that

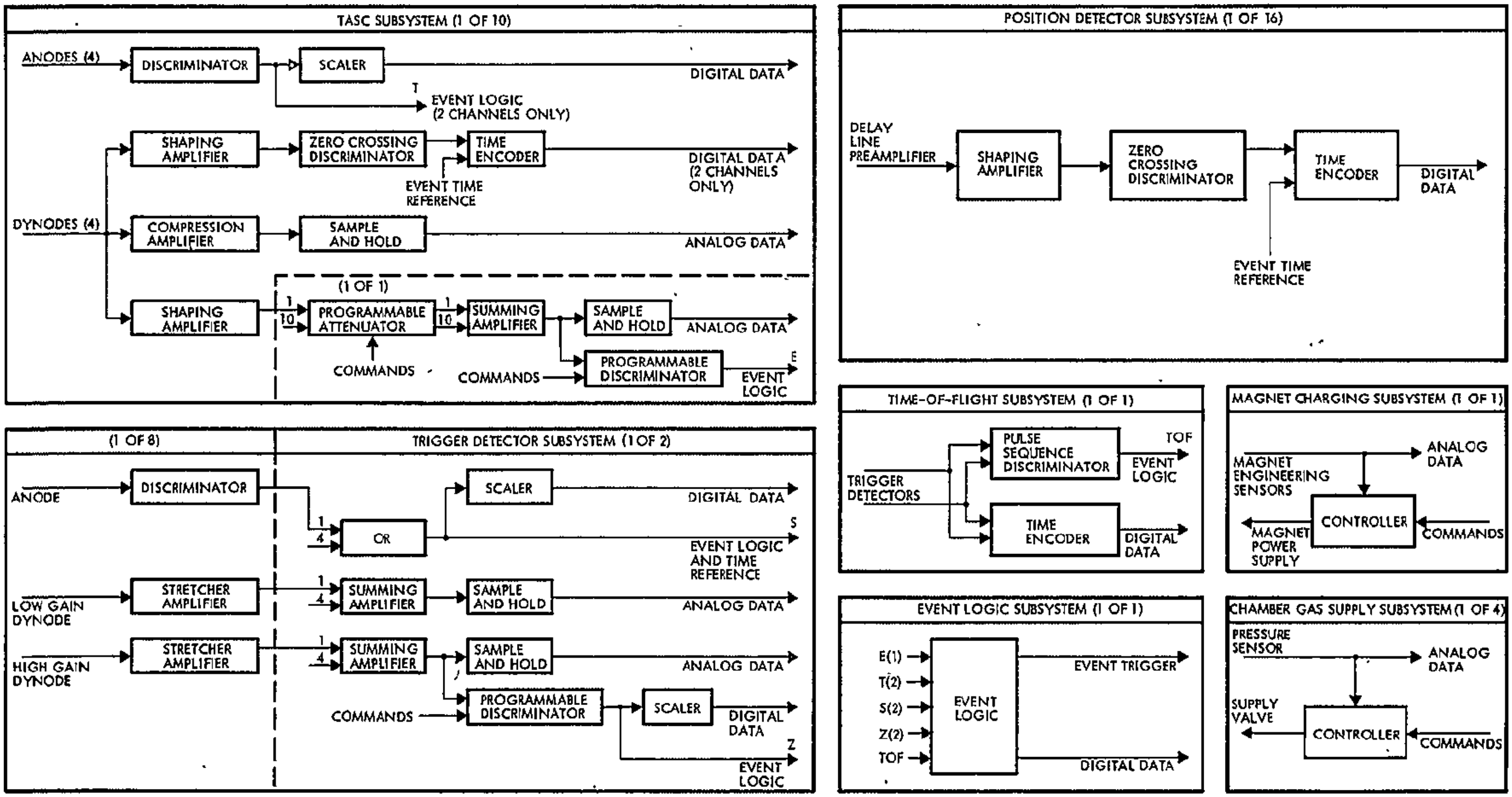

Figure 5-2. Superconducting Magnetic Spectrometer (BCR-5)

Table 5-4. BCR-5 Module Requirements

	Functional Elements	Modules	Excess Modules
DATA PROCESSING MODULES			
Shaping Amplifier	28	7	
Stretcher Amplifier	16	4	
Compression Amplifier	10	3	2/4
Summing Amplifier	5	3	1/2
Difference Amplifier			
Sample and Hold	15	2	1/4
Discriminator	18	3	6/8
Programmable Discriminator	3	1	1/4
Zero Crossing Discriminator	18	3	6/8
Pulse Sequence Discriminator	1	1	3/4
Time Encoder	19	5	1/4
Scaler	14	1	2/16
Logic OR	2	1	
Multiplexer	3	3	
ADC	2	2	
Memory	1	1	
Programmable Attenuator	1	1	
COMMAND AND CONTROL MODULES			
Gas Supply Controller	4	1	
Position Encoder			
Test Pulser	2	2	
Data Sequencer	1	1	
Command Interface	1	1	
Special Device Controller	1	1	
Event Logic	1	1	
HIGH USAGE	152 (91.5%)	40 (83%)	3.125
LOW USAGE	10 (6%)	4 (8.5%)	1.0
CUSTOM	4 (2.5%)	4 (8.5%)	0
TOTAL	166	48	4.125

provides inputs to the event logic and the time-of-flight subsystems. The output of the OR also provides counting rate data to a scaler. A signal from a low-gain dynode of each tube is connected to an individual stretcher amplifier for analog processing. The outputs of the amplifiers for the four tubes on each detector are combined in a summing amplifier followed by a sample and hold to provide an analog signal to be pulse height analyzed. Signals from a high-gain dynode of each tube are similarly processed. In this latter case, the summing amplifier output is fed to a programmable discriminator. The discriminator output is used by the event logic as an on-board indication of event type for a priority selection of data to be read out. The discriminator threshold is adjustable to change the trigger detector energy deposition required for this event selection criterion. The discriminator output also provides counting rate data to a scaler.

The position detector subsystem consists of 48 functional elements of three types. Each of the eight multiwire proportional chambers has a pair of delay lines attached to its two orthogonal cathode wire planes. The output signal from each delay line is processed in the same way as described for BGR-4 in Section 5.2.1.

The TASC subsystem consists of 60 functional elements of ten types. The anode signals from the four photomultiplier tubes viewing each of the ten scintillator subassemblies are combined and fed to a discriminator. The logic pulse output provides counting rate data to a scaler. In addition, for two of the subassemblies, the discriminator outputs are connected to the event logic to indicate the presence of an event in the TASC. Dynode signals from the four tubes are similarly combined and fed to amplifiers. The primary pulse amplitude data for each of the ten scintillator layers is processed by a compression amplifier and a sample and hold. A shaping amplifier also processes the combined dynode signal for each of the ten layers and a programmable attenuator is used with a summing amplifier to combine the signals with variable mixing ratios. This combined signal is fed to a sample and hold for pulse height analysis and also to a programmable discriminator for use by the event logic. A pulse shape measurement is performed for the two CsI (Na) layers by another shaping amplifier, a zero-crossing discriminator and a time encoder. The event time reference for this measurement is obtained from the trigger detector above the TASC. The results of the latter two types of on-board processing are used for a real-time separation of electromagnetic particles and hadrons by their characteristic signatures in the TASC.

The time-of-flight subsystem consists of two functional elements. The inputs from the two trigger detector logic OR's are fed to both elements in parallel. The pulse sequence discriminator provides a real-time indication of particle transit direction to the event logic while the time encoder provides a digitized measurement to a multiplexer.

The chamber gas supply subsystem consists of four gas supply controllers. The pair of proportional chambers in each of the subassemblies are coupled to form a single gas volume and one controller is used for each pair.

The magnet charging subsystem consists of a custom-built magnet power supply controller. This controller monitors various magnet parameters by analog inputs from engineering sensors and adjusts the power supply accordingly during the charging of the magnet. The time profile of the charging process is provided by command inputs to the controller.

The event logic subsystem consists of the custom-built event logic module. It accepts logic signals derived from the trigger detectors and the TASC and identifies events for telemetry readout on a priority basis so that data for less frequent, more interesting, types of events can replace data waiting to be read out for other types of events.

5.2.3 MeV Range Gamma-Ray Telescope (AGR-4)

Sensors. The MeV Range Gamma-Ray Telescope uses the 16 sensor assemblies listed in Table 5-2. The anticoincidence detector is a single sheet of plastic scintillator that covers the viewing apertures of all seven primary sensors. This scintillator is viewed by a pair of photomultiplier tubes and is used to reject all observed events associated with incident charged particles.

The phoswich detector assembly is comprised of the seven primary sensors. Each phoswich assembly consists of a NaI(Tℓ) scintillator optically coupled through a CsI(Tℓ) scintillator to a single photomultiplier tube. This pair of scintillators is selected because of the difference in characteristic decay time constant of their light outputs. Since the energy deposition of gamma rays of interest entering through the viewing aperture takes place entirely in the NaI(Tℓ), the resulting pulse for a good event will have a characteristic NaI(Tℓ) decay constant. If a longer decay constant produced by the CsI(Tℓ) is observed, the event is rejected. The CsI(Tℓ) thus serves as an antocoincidence detector to reject events incident on the back of the sensor assembly.

The shield subsystem consists of eight CsI(Na) scintillators which surround the primary sensors and are used to veto events entering from the sides. To minimize the amount of shield scintillator required, the primary sensors are arranged circularly, one in the center with the six others around it. The cylindrical shield around the central sensor is split axially into two halves. These halves are used both as shields and as sensors to identify the products of pair production taking place in the central phoswich sensor. The shields for the outer phoswich sensors are cylindrical sections that surround each sensor and mate with the central shield assembly.

Instrument Electronics. The electronic block diagrams for AGR-4 are shown in Figure 5-3. Table 5-5 summarizes the module requirements. The anticoincidence subsystem consists of two functional elements. The anode signals from both photomultiplier tubes are combined and connected to a single discriminator. The discriminator output logic pulse is used as an anticoincidence signal by the event logic to reject events produced by incident charged particles. The discriminator output also provides counting rate data used to monitor tube performance and adjust the high voltage.

The phoswich detector subsystem consists of 56 functional elements of six types. The signals from each of the seven photomultiplier tubes are individually processed. The anode signal is fed to a discriminator which provides counting rate data and an event time reference for use in the pulse shape determination. The dynode signal is processed by a pair of shaping amplifiers. One provides the correct pulse shape for a sample and hold whose output is used for pulse height analysis. The other prepares the pulse for shape analysis with a zero-crossing discriminator and pulse sequence discriminator. The result of this analysis is used by the event

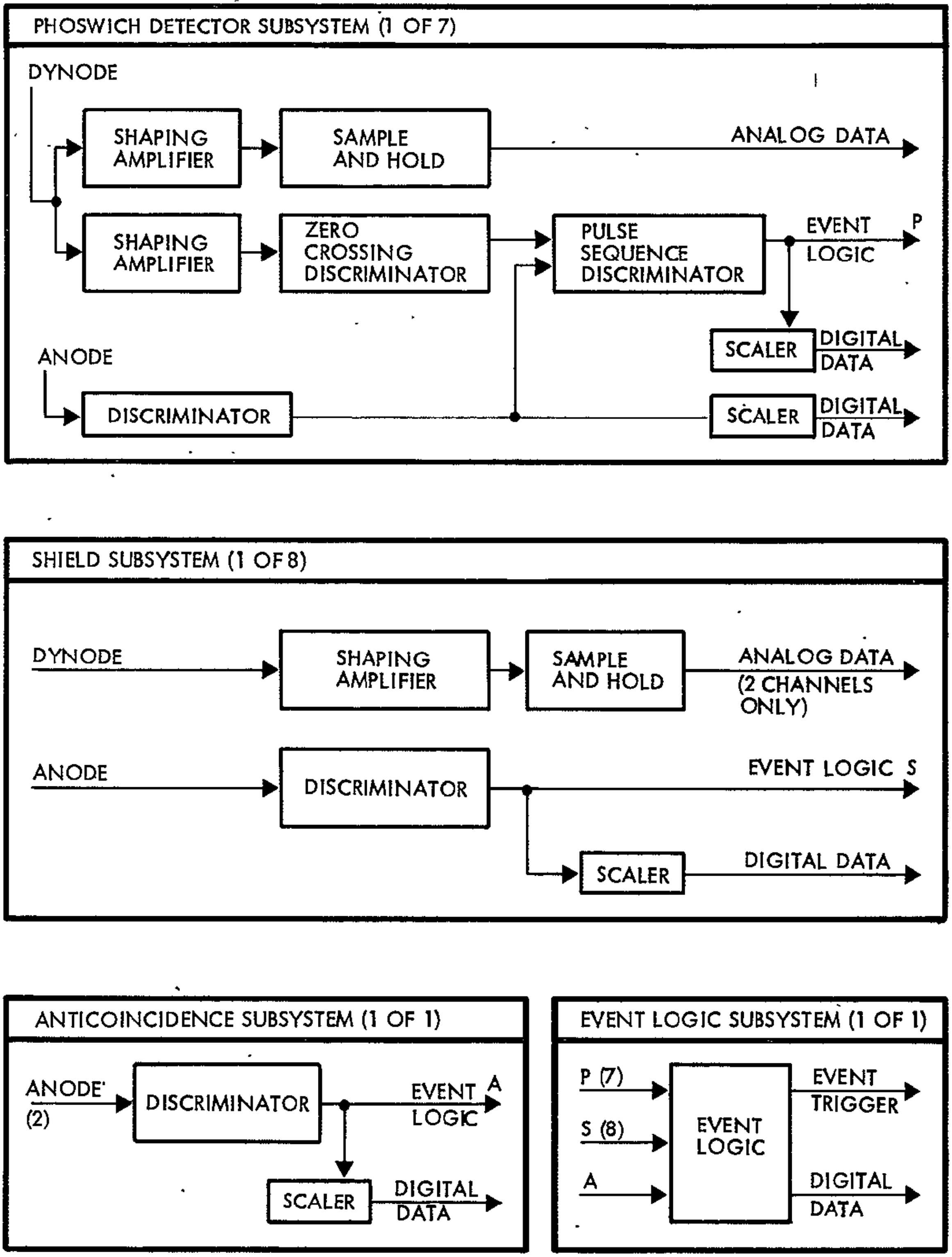

Figure 5-3. MeV-Range Gamma-Ray Telescope (AGR-4)

Table 5-5. AGR-4 Module Requirements

	Functional Elements	Modules	Excess Modules
DATA PROCESSING MODULES			
Shaping Amplifier	16	4	
Stretcher Amplifier			
Compression Amplifier			
Summing Amplifier			
Difference Amplifier			
Sample and Hold	9	2	7/8
Discriminator	16	2	
Programmable Discriminator			
Zero-Crossing Discriminator	7	1	1/8
Pulse Sequence Discriminator	7	2	1/4
Time Encoder			
Scaler	23	2	9/16
Logic OR			
Multiplexer	2	2	
ADC	1	1	
Memory	1	1	
Programmable Attenuator			
COMMAND AND CONTROL MODULES			
Gas Supply Controller			
Position Encoder			
Test Pulser	1	1	
Data Sequencer	1	1	
Command Interface	1	1	
Special Device Controller			
Event Logic	1	1	
HIGH USAGE	77 (89.5%)	17 (81%)	1.56
LOW USAGE	7 (8%)	2 (9.5%)	0.25
CUSTOM	2 (2.5%)	2 (9.5%)	0
TOTAL	86	21	1.81

logic to identify valid events contained completely within the NaI(Tℓ) portion of the phoswich sensor. The counting rate of events satisfying the pulse shape analysis are scaled for digital readout.

The shield subsystem consists of 20 functional elements of four types. The photomultiplier tube anode signals from each shield segment are fed to a discriminator that provides counting rate data and an anti-coincidence signal to the event logic. In addition, a shaping amplifier and sample and hold are used to prepare a dynode signal from each inner shield half cylinder for pulse height analysis. This data is used in identifying pair production events occurring in the central phoswich sensor.

The event logic subsystem consists of the custom built event logic module. It accepts logic signals from the various sensor subsystems and identifies valid events. A valid event requires the correct pulse shape in one of the phoswich sensors and no signals from either the anticoincidence detector or the two shields in contact with that phoswich sensor. The exception to this is the pair production mode that requires a valid pulse shape in the central phoswich sensor and a signal from both central shield halves.

5.2.4 Bragg Crystal X-Ray Telescope (BXR-2)

Sensors. The Bragg crystal X-ray telescope uses the 16 sensor assemblies listed in Table 5-2. The eight low-energy spectrometer (LES) position sensitive detectors are multiwire proportional chambers with readout for anode wires and cathode wires. The cathode wires are transverse to the plane of the spectral dispersion produced by the instrument's low-energy crystal and therefore provide spectral data. The anode wires are used to identify either narrow or wide field-of-view through the instrument's low-energy collimators.

The eight high-energy spectrometer (HES) position sensitive detectors are multiwire proportional chambers of a different configuration, with only anode wire readout. The anode wires in each detector are classified in two groups; one group consists of four primary sensor wires and the other group consists of twelve guard wires used to define the chamber entrance aperture.

Preamplification of the signals is provided for both types of proportional chambers by specialized signal conditioning electronics mounted in close proximity to the chambers. In general, these preamplifiers would not be suitable for construction in the form of the standard hardware discussed in Section 3.

Instrument Electronics. The electronic block diagrams for BXR-2 are shown in Figure 5-4. Table 5-6 summarizes the module requirements. The LES anode subsystem for each of the eight detectors consists of 11 functional elements of eight types. Separate discriminators are used to derive logic signals from the preamplifier signals for the guard anodes, the pair of wide-field anodes and the single narrow field anode. These signals are used by the event logic to identify the valid events. A summing amplifier combines the signals from the preamplifiers for the wide and narrow field anodes and provides the net signal to a sample and hold for pulse height analysis. Pulse shape analysis is also performed on the net signal by a shaping amplifier, a discriminator and a zero-crossing discriminator. A pulse sequence discriminator is used for a real-time indication of pulse shape for use by the event logic and a time encoder digitizes the information for ground analysis.

The LES cathode subsystem for each of the eight detectors consists of ten functional elements of four types. The two sets of cathode wires in each detector are connected to individual resistive strings to permit event position readout along that axis of the proportional chamber. Summing and difference amplifiers are used to form the signal combinations (A+B) and (A-B) for both resistive strings where A is the signal at one end of each string and B the signal at the other end. Sample and holds are used to process the combined signals for pulse height analysis. Taking the ratio (A-B)/(A+B) during ground based data analysis provides the event position information. Discriminators are used for the (A+B) signals from both cathode strings and indicate to the event logic (part of the LES anode subsystem) which set of LES cathode wires participated in each event.

The HES subsystem uses 13 functional elements of eight types to process the signals from each of the eight HES proportional chambers. The signal processing approach is identical to that used for the LES anode

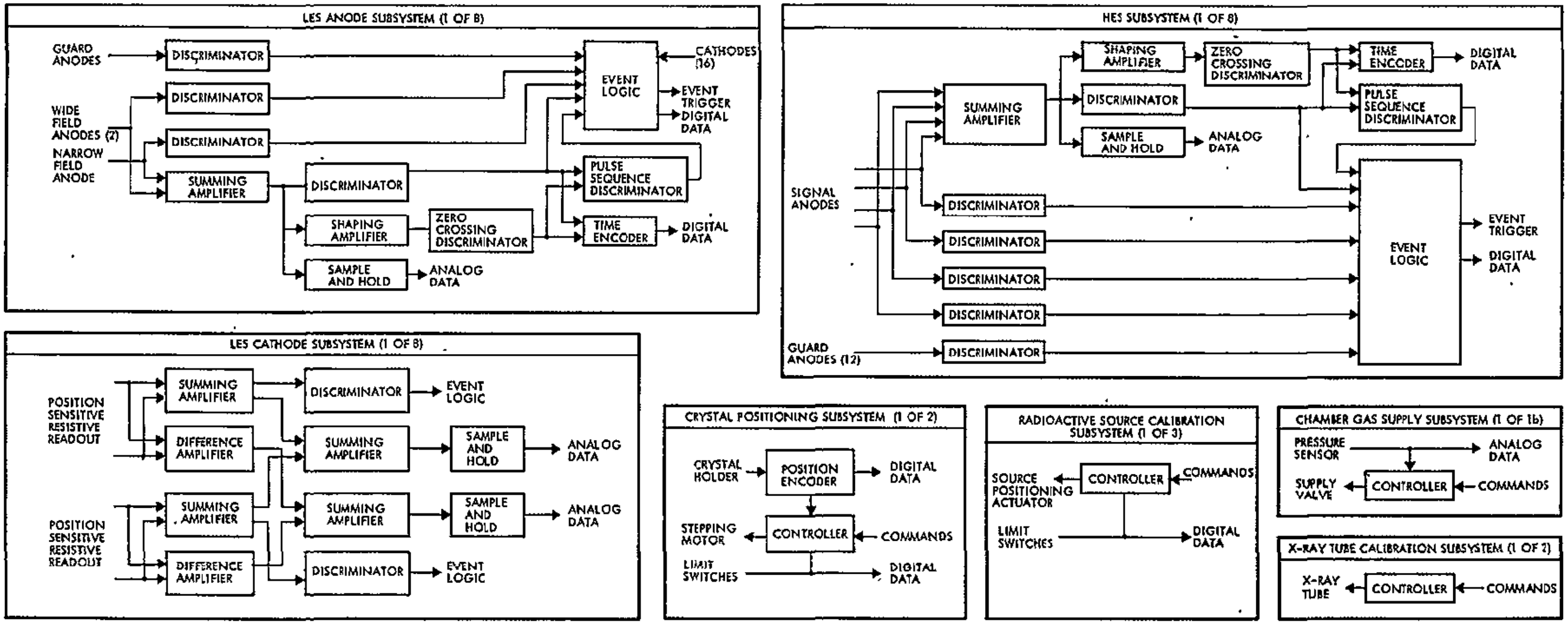

Figure 5-4. Bragg Crystal X-Ray Spectrometer (BXR-2)

Table 5-6. BXR-2 MODULE REQUIREMENTS

	Functional Elements	Modules	Excess Modules
DATA PROCESSING MODULES			
Shaping Amplifier	16	4	
Stretcher Amplifier			
Compression Amplifier			
Summing Amplifier	48	24	
Difference Amplifier	16	4	
Sample and Hold	32	4	
Discriminator	96	12	
Programmable Discriminator			
Zero-Crossing Discriminator	16	2	
Pulse Sequence Discriminator	16	4	
Time Encoder	16	4	
Scaler			
Logic OR			
Multiplexer	6	6	
ADC	3	3	
Memory	1	1	
Programmable Attenuator			
COMMAND AND CONTROL MODULES			
Gas Supply Controller	16	4	
Position Encoder	2	1	
Test Pulser			
Data Sequencer	1	1	
Command Interface	1	1	
Special Device Controller	7	3	
Event Logic	16	16	
HIGH USAGE	235 (76%)	61 (65%)	0
LOW USAGE	50 (16%)	13 (14%)	0
CUSTOM	24 (8%)	20 (21%)	0
TOTAL	309	94	0

wires, except in this case there are four individual signal anodes in each chamber. No cathode data processing is used for the high energy spectrometer chambers.

The chamber gas supply subsystem uses the same approach as the BGR-4 and BCR-5 gas supply subsystems. A separate controller is used for each of the 16 proportional chambers. The crystal positioning subsystem uses a custom built controller for the crystal drive in combination with a position encoder to determine the crystal position. The two calibration subsystems each use special purpose custom built controllers to position the radioactive sources and operate the X-ray tubes.

5.3 EVALUATION OF MODEL PAYLOAD IMPLEMENTATION

5.3.1 Performance

We strongly believe that the implementation of the model HEAO payload instruments developed in the preceding section would not compromise the functional performance of the instruments. Obviously, this is a somewhat subjective judgment on our part that can only be substantiated by a much more detailed analysis of the experiment requirements supported by more definitive specification of the standardized modules. At the level of analysis used in this study, all required instrument functions are provided by the implementation using standard modular electronics. The question that could still conceivably be argued is how well the requirements are satisfied.

With respect to other performance criteria, such as weight, size, reliability, etc., we have not attempted any quantitative evaluation. As has been previously discussed in Section 3.3, there will certainly be an increase in the weight and size required for the electronic instrumentation due to the modular packaging approach. For the type of instruments in the model payload at least, we do not believe the increase would represent a very significant fraction of the total instrument weight or size. In a somewhat related regard, we can see from the information given in Tables 5-3 through 5-6 that another potential penalty of the standard modular approach is not serious. The total excess or unused module overhead for the four instruments amounts to less than 5 percent.

The impact on the instrument reliability of using standard modules has been discussed in Section 4.5. The introduction of standardization can be expected to improve instrument reliabilities because recurring production and operating experience with the same units will be accompanied by reliability growth. However, as noted, the system reliability will always be controlled or limited by the reliability of the developmental elements of the system. The mission assurance cost reductions that can be realized from either improved efficiency or increased risk acceptance will certainly be applicable to the model payload.

5.3.2 Cost

With the more specific or concrete results from Section 5.2 available, we are in a position to proceed on a more quantitative evaluation of

Table 5-7. Model Payload Module Requirements

	BGR-4	BCR-5	AGR-4	BXR-2	TOTAL
DATA PROCESSING MODULES					
Shaping Amplifier	20	7	4	4	35
Stretcher Amplifier	5	4			9
Compression Amplifier	1	3			4
Summing Amplifier	1	3		24	28
Difference Amplifier				4	4
Sample and Hold	1	2	2	4	9
Discriminator	3	3	2	12	20
Programmable Discriminator		1			1
Zero-Crossing Discriminator	10	3	1	2	16
Pulse Sequence Discriminator	1	1	2	4	8
Time Encoder	20	5		4	29
Scaler	2	1	2		5
Logic OR	1	1			2
Multiplexer	7	3	2	6	18
ADC	1	2	1	3	7
Memory	1	1	1	1	4
Programmable Attenuator		1			1
COMMAND AND CONTROL MODULES					
Gas Supply Controller	1	1		4	6
Position Encoder				1	1
Test Pulser	2	2	1		5
Data Sequencer	1	1	1	1	4
Command Interface	1	1	1	1	4
Special Device Controller		1		3	4
Event Logic	1	1	1	16	19
HIGH USAGE	75	40	17	61	193 (79.5%)
LOW USAGE	3	4	2	13	22 (9%)
CUSTOM	2	4	2	20	28 (11.5%)
TOTAL	80	48	21	94	243

the cost impact of standardization. The results of Section 5.2 are summarized in Table 5-7. The module usage for each instrument in the model payload is given as well as the cumulative total usage for the entire payload. For the same reasons discussed in Section 5.2, the power conditioning subsystem module requirements have not been tabulated and power supply costs have not been explicitly included in the evaluation. Inclusion of the power conditioning subsystem would increase the cost savings resulting from standardization because of the high degree of commonality applicable for that portion of the electronic systems.

For the cost evaluation, we have made use of the general relationships between module unit costs and production numbers developed in Section 2.4 as well as the representative module design, development, and qualification cost estimate developed in Section 4.5. The costs of the electronic modules listed in Table 5-7 were estimated with four different sets of assumptions. The results are presented in Table 5-8.

Our cost estimate for what is labelled as the conventional approach was based on the following assumptions: each type of module used in each instrument was independently designed and developed for each instrument, and the quantity produced was the number required for each instrument. This is a reasonable representation of current practices. It may even be slightly optimistic because it assumes that advantage will be taken of standardization within each instrument. The total cost for the payload is simply the sum of the costs for each instrument.

Our cost estimate for what is labelled as Case 1 under standardized approach was based on the following assumptions: a common design and developement was performed for each type of standard module used in the payload and the quantity produced was the number required for the entire payload. The custom modules were treated exactly as in the conventional approach. This case is a reasonable representation of the situation in which a common supplier developed and produced the standard modules required for the entire payload and the total development costs were borne by this payload. This might correspond to the situation for the first payload to use the standardized approach. We see that the projected cost savings for this case, in which we have taken advantage of standardization within only one payload, amounts to about 5 million dollars or 46 percent of the cost of the conventional approach.

Table 5-8. Model Payload Cost Comparison

	Costs (Million $)			
	Standard Modules			
Conventional Approach	High Usage	Low Usage	Custom Modules	Totals
BGR-4	2.287	0.399	0.266	2.952
BCR-5	2.069	0.532	0.532	3.133
AGR-4	1.385	0.140	0.266	1.791
BXR-2	1.708	0.613	0.900	3.221
Totals	7.449	1.684	1.964	11.097
Standardized Approach				
Case 1.	3.076	0.924	1.964	5.964
Case 2.	1.182	0.158	1.964	3.304
Case 3.	1.023	0.117	1.964	3.104

For Case 2, we have assumed that the design and development costs of the standard modules have already been paid for and the modules were procured for a unit cost equal to the average production cost for the quantity required. Again, the conventional approach was assumed for the custom modules. This case might correspond roughly to the situation for the second payload to adopt the standardized approach. The cost savings compared to the conventional approach now amount to almost 8 million dollars or 70 percent of the conventional cost.

Finally, in Case 3, we have assumed that the usage of standard modules has become reasonably widespread and that the standard modules were procured for the average unit cost of the n^{th} module. We have taken n to be 50 for the high-usage modules and 15 for the low-usage modules. As can be seen, the additional cost reduction is slight since most of the cost advantage has already been realized.

As a final hypothetical example, we can include both mission assurance cost reductions and cost reductions arising from standardization for a payload operating in the era when both approaches are presumed to be well-established practices. If we assume that the electronics hardware costs constitute today's typical 40 percent of the total experiment instrumentation costs with a conventional approach, the standardization will reduce the instrument cost by 29 percent. If we further assume that the operational costs per mission are 15 million dollars, the ratio of the operational cost per flight to the instrument costs is 0.75. The results in Section 4.6 indicate that the optimum instrument reliability in this situation would be about 0.85. The estimated mission assurance cost reduction corresponding to reducing the instrument reliability to this level would be about 12 percent. When combined with the cost reduction due to standardization, we get a total reduction in the instrument cost of 37 percent. Reduction of the instrument reliability would be accompanied by an average increase in operational costs of about 10 percent. When these effects are all combined, the total mission cost (instrument plus operational costs) is reduced by 21 percent. In absolute terms, this amounts to a cost savings of 9 million dollars for the mission, 8 million of which is due to standardization of the instrument electronics.

In order to estimate the cost reduction that could be expected due to implementation with standard modular electronics on a slightly broader scale than a single payload, the results in Table 5-8 were applied to a simple example that approximates the situation for the HEAO Block II series of missions. Assuming the HEAO Block II program will consist of four payloads, each of which corresponds to our model HEAO payload, the cost of the electronics in the instruments would be 44.4 million dollars (4 x 11.1) with a conventional approach. For the case of a standardized approach to the program, Case 1 represents the first mission, Case 2 the second, and Case 3 the third and fourth. In this approximation, the instrument electronics cost for the program is 15.5 million dollars for a net reduction of about 30 million dollars or 65 percent. Admittedly, the instruments for each payload would be different, but the standard modules required would be very close to the same as for the model payload.

APPENDIX

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