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Manned Systems Utilization Analysis (Study 2.1)
Final Report

Volume II: Manned Systems Utilization

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THE AEROSPACE CORPORATION

Report No.
ATR-76(7361)-1, Vol II

MANNED SYSTEMS UTILIZATION ANALYSIS (STUDY 2.1)
FINAL REPORT

Volume II: Manned Systems Utilization

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FOREWORD

Study 2.1, Manned Systems Utilization Analysis, is a continuation of previous efforts directed at investigating new operational concepts for future space applications. This effort addresses the potential improvement in operational effectiveness that could be achieved by active manned maintenance of scientific instruments. Skylab/ATM (Apollo Telescope Mount) experience is employed as an historical foundation for what can be accomplished even when the instruments have not been designed for maintenance. Empirical relationships are developed to relate man's contribution to the success of the mission. This effort, coupled with associated contractor studies under NASA direction, point up the utility of man in space and emphasize the need to incorporate man's role into future space planning efforts.

This study was one of several tasks performed by The Aerospace Corporation under NASA Contract NASW-2727. This was a 12-month effort, initiated on 1 September 1974. The Technical Monitor was Mr. V. N. Huff, Code MT, at NASA Headquarters. Upon Mr. Huff's retirement in May 1975, the technical responsibility for this effort was assigned to Dr. J. W. Steincamp, MSFC, Code PD34. This volume is one of five that comprise the Final Report for Study 2.1. The five volumes are:

Volume I:	Executive Summary, ATR-76(7361)-1, Vol I
Volume II:	Manned Systems Utilization, ATR-76(7361)-1, Vol II
Volume III:	LOVES Computer Simulations, Results, and Analyses, ATR-76(7361)-1, Vol III
Volume IV:	Program Manual and Users Guide for the LOVES Computer Code, ATR-76(7361)-1, Vol IV (formerly ATR-74(7341)-6)
Volume V:	Program Listing for the LOVES Computer Code, ATR-76(7361)-1, Vol V (formerly ATR-74(7341)-7)

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1. INTRODUCTION

The Aerospace Corporation, under contract to NASA Headquarters, Office of Manned Space Flight, has continued to address new concepts that might enhance future space operations. The basic intent, in all cases, has been to examine various options that could reduce future expenditures without sacrificing scientific objectives. This drive toward improved efficiency of operations has continued to be the major motivation for assessing new system concepts and, in part, serves to emphasize the benefits of these new systems relative to the integrated space program planning efforts.

The Space Transportation System (STS) has substantially expanded these horizons of space operations and has exposed new fields of interest that heretofore have not been available for consideration. The capability to efficiently service and maintain automated payloads in orbit was thoroughly examined in the previous year's effort. The cost benefits over the eleven year period of 1980 through 1990 have been conservatively estimated to be over $300 million for geostationary operations alone. This concept, removing and replacing failed components, with the ability to also upgrade equipments in orbit, has a tremendous potential for enhancing future operations and should be exploited to the fullest extent.

Further consideration has led to the possibility of more comprehensive space maintenance operations employing man as the key ingredient to assure success of a mission. This is of particular interest in low-earth orbit where highly complex and costly scientific instruments are under consideration in current mission model projections. This class of payloads, in particular, stimulates interest because each tends to be unique in its application; therefore, there is no assured maturing process as with operational satellites. Yet, because of this uniqueness, it is imperative that a high level of availability be maintained along with the option to respond to transient phenomena as it occurs within the framework of steady state operations.

Without question, under the above conditions, the only way to achieve these goals is through active manned participation. This was repeatedly demonstrated, very dramatically, in the recent Skylab Program. As will be shown later in this report, without this active support and the ability to improvise, there is no doubt that many, if not all, of the ATM experiments would have fallen far short of their respective scientific objectives. However, this does not imply poor design, inadequate testing, or improper training, but merely reflects the very nature of extending the frontiers of scientific achievement.

Hindsight indicates that many of the anomalies could easily have been avoided with proper attention in the design and testing phases of the program. However, although the learning process suffers occasional setbacks, scientific and engineering disciplines do in fact make extensive use of this knowledge. But failures and anomalies will be ever present in these types of applications in particular, because of increasing complexity and the drive to attack new and unique regions of scientific advance. Under these circumstances, it is not possible with classical techniques to predict all failure paths. Even if it were, it is not feasible to design sufficient levels of redundancy or alternate paths to all elements of a given design to assure success of the operation.

Manned maintenance, with proper spares provisioning and a few basic tools, can provide that unique element which assures a high level of success for scientific missions. Arguments in the past in support of this position have been primarily subjective in nature with little experience for a foundation. The Skylab Program has changed this, and now thoughts are directed at the preferred level of interaction and methods to quantify these benefits relative to future space program options. This is the foundation for Study 2. 1, Manned Systems Utilization Analysis.

2. STUDY OBJECTIVES

It is a difficult task to quantify man's contribution to mission success but unless this can be done, it will not be possible to establish a consistent basis for evaluating man's role for the future. Other study efforts are addressing man's contribution to simplify payload designs by performing final assembly and erection of appendages after delivery to orbit. Still, others are investigating man's contribution toward assembly of large space structures, and what the total manned operational concept should encompass. All of these efforts join in attacking the question of man's contribution to future space operations. The total composite emphasizes the need for manned operations in every facet of the space program. This study emphasizes man's potential in the areas of maintenance and management of complex and unique scientific instruments.

The principal objective of this study is to develop basic data that demonstrates man's contribution to the achievement of scientific mission objectives. Emphasis has been placed on scientific missions, as opposed to routine operation of subsystem equipments, because of their unique character and relatively high potential for increased achievement. Historically speaking, one of man's principal roles has been the advancement and application of scientific achievement. This should also be true of his role in space, hence the need to quantify these benefits and to examine the basic character of the operations required to sustain these equipments. The Skylab ATM program is to serve as the foundation for this effort, hence the emphasis is on experience.

The second objective is to examine, in a theoretical sense, what could be expected in future applications of scientific instruments relative to the need for interactive manned support operations. This objective is to address the design impact, the inherent reliability characteristics, and the relative improvement in system availability that could be achieved by maintenance or repair actions. Tradeoffs are then to be made to assess the viability of manned support versus alternative measures for achieving a high level of mission success.

3. STUDY APPROACH

The tasks performed in this study effort have been directed along two parallel complementary paths. The first path researches the experience of various correlatable space programs and develops empirical techniques to associate the benefits of repair and management actions. The actions taken during the course of these programs are then examined in detail to establish man's contribution, either remotely or by active participation, to the task of achieving the original mission objectives. The results are then related to the possible further enhancement that could have been achieved had the instrument been designed for space maintenance.

The second path addresses the penalties in weight and volume associated with designing for space maintenance. This is achieved by reconfiguring a single instrument and then extrapolating the results to others. The estimated reliability characteristics are then examined to establish, in a theoretical sense, how space maintenance could enhance system availability.

Conclusions are then drawn relative to experience versus estimated repair actions to establish guidelines for future design efforts. The basic character of anomalies and failures are further considered relative to the ability to preclude their occurrence as future instruments become more complex and costly.

The S-056 X-ray Telescope, flown in the ATM on Skylab (Ref. 1) was selected as the basic instrument of interest. There is considerable experience at The Aerospace Corporation relative to solar physics, and one of the principal scientists associated with this program is currently employed in the Laboratory Division. In addition, Dr. E. Gibson, Scientist - Astronaut on Skylab IV, is also employed in the same division.

In addition, two earlier experiments were selected to develop a picture of the growth in instrument complexity. These were the OV1 USAF Satellite Program (Ref. 2) and the OSO-7 (Ref. 3), a Goddard Space Flight Center orbiting solar observatory. Each instrument was designed to record data in the X-ray region of the spectrum. Therefore, their results are correlatable in scientific value and as such provide a reasonable basis of comparison of automated versus man supported operations. The basic characteristics of each instrument are shown in Figure 3-1.

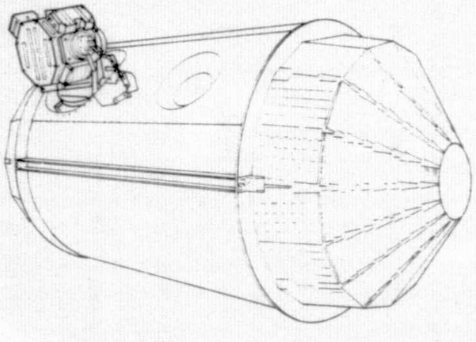
The S-056 X-ray Telescope experiment was developed to obtain and record data in the X-ray region of the spectrum. The experiment is designed to provide both X-ray filtergrams in five band widths from 5 to 33 angstroms and spectral data in two adjacent channels of 10 wavelength bands from 2.5 to 20 angstroms. The S-056 was launched on 14 May 1973.

The OSO-7 consists of four spectroheliographs and an X-ray polarimeter. It was designed to study solar radiation at selected wavelengths in the X-ray, and in extreme ultraviolet (EUV) ranges make observations at the H-alpha wavelength, and measure the degree of polarization of X-ray emissions. Only the grazing incidence telescope (X-ray and EUV spectroheliograph) was of interest because of its relationship to the S-056 ATM instrument. The OSO-7 was launched in 1971 and had an expected lifetime of 12 months.

The OV1 USAF satellite instrument was a relatively simple instrument designed to collect and record X-ray emissions. It was initially launched in 1966 (OV1-10) followed by a second flight in 1969 (OV1-17). It was designed for an operational lifetime of six months.

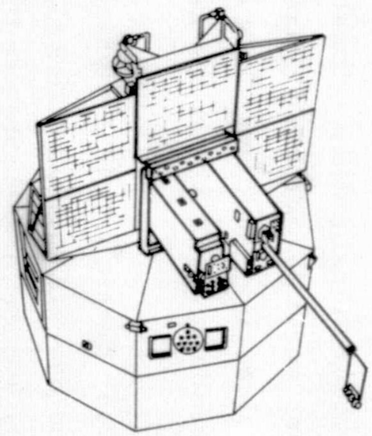
After developing the basic set of data, it was possible to expand the data search to include many of the remaining ATM experiments. The objective of this effort was the distribution or spread of the empirical data relative to that of the S-056 instrument. Although there is some variety in their scientific objectives, all of the ATM experiments were directed at solar physics and basically covered different spectral regions.

Empirical relationships were developed to express the complexity of the design concept relative to the effectiveness with which the equipment was maintained in operation. In this regard, remote response to an anomalous occurrence is also considered maintenance, as experienced on OSO-7. Relationships were also developed to express the benefits of improved management of the instruments resulting from manned interaction as opposed to pre-programmed activities.



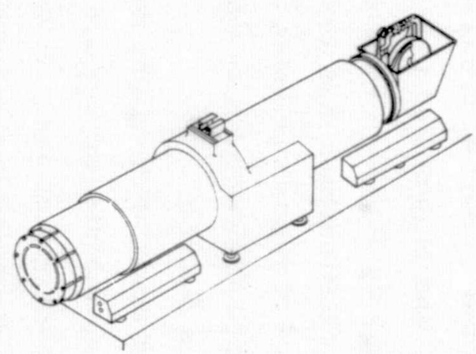
OV1-10, -17

Instrument type:	Crystal spectrometer, proportional counter
Area of sun covered:	Full disk
Resolution:	None (emission from whole sun)
Data format:	Spectral scans, total flux
Physical:	12 x 12 x 14 inch, 18 lbs
Mount:	Bi-axial sun centered pointer, 20 arc-sec stability



OSO-7

Instrument type:	Grating spectrometer, proportional counter, Hα, polarimeter
Area of sun covered:	Full disk in raster scan
Resolution:	10 x 20 arc-sec
Data format:	Spectral scans, total flux, Hα, polarization
Physical:	7 x 14 x 50 inch, 50 lbs
Mount:	Bi-axial raster, sun-centered pointer, 1 arc-sec stability



S-056

Instrument type:	Filtergraph, proportional counter
Area of sun covered:	Full disk
Resolution:	2 arc-sec in pictures, none for counter
Data format:	Photographs, total flux
Physical:	23 x 24 x 105 inch, 354 lbs

Figure 3-1. Basic Experiment Characteristics

The above effort involved a substantial amount of research into the basic instruments, how they were operated, and in detail what results were obtained. In addition, it also involved lengthy conferences with experts in the field of solar physics to establish basic relationships that would correlate the various experiments to a finite set of common variables. This included conferences outside of The Aerospace Corporation as well. The results of this effort are reported in Sections 5 and 6.

During this same period, a detailed study of the S-056 was performed relative to modifying the basic design to allow maintenance of all components that could represent a potential risk to mission operations. A search was performed to establish reliability characteristics and hence develop an overall system reliability for the S-056. Similar data was also developed for the OSO-7. It was not possible to develop an accurate reliability estimate, nor was this the major intent. It was, however, possible with the available data to estimate the overall reliability using engineering judgment. This data was then correlated with the design effort to assure accessibility to the weak elements.

As a result of this effort, it was then possible to investigate the remaining ATM experiments of interest and develop approximate weight penalties to allow access for servicing. These weight increments are then used in subsequent tradeoffs. The results of this effort are reported in Section 4 in order to provide a foundation of design information prior to discussing the Skylab experience presented in Sections 5 and 6. The tradeoffs are reported in Section 7.

4. DESIGN CONSIDERATIONS

4.1 OBJECTIVES

The S-056 X-ray telescope experiment was selected for an in depth assessment of the design impact associated with orbital maintenance. This was one of eight experiments incorporated into the Apollo Telescope Mount (ATM) attached to the Skylab. The S-056 experiment, shown schematically in Figure 4-1, incorporated two separate and independently operated instruments: the grazing incidence X-ray Telescope (X-RT) and the X-ray event analyzer (X-REA). The telescope provided x-ray filtergrams in five wavelength bands (5 to 33 Å) and one in the visible region (6378 Å). The x-ray event analyzer provided for spectral data in 10 wavelength bands (2.5 to 20 Å).

The objective of this portion of Study 2.1 was to examine the S-056 experiment packaging concept and reliability characteristics as a basis for reconfiguring the instrument for orbital maintenance. Specific ground rules were established for this effort consistent with rational engineering judgment. In this way, it was possible to establish the approximate impact, in terms of weight and volume, of designing for orbital maintenance. This impact is then used to assess the overall benefits of maintenance versus automated servicing or the incorporation of various levels of redundancy. In addition, it is of special interest to compare the predicted failure characteristics with those actually experienced in practice. This is a continual problem in any preliminary design and it is seldom possible to perform a post-operative analysis to determine the adequacy of the initial design effort.

The S-056 is considered to be reasonably representative of the type of instruments employed for scientific observations. Alignments are critical and thermal balance is essential. The instrument relies on the ATM for power, attitude stabilization, pointing, and to some extent thermal-protection. In the current design, access is limited to removal and replacement of film cassettes, and to the ATM solar shield door mechanism. Everything else is located within the ATM canister and, in its current configuration (Ref. 4), is

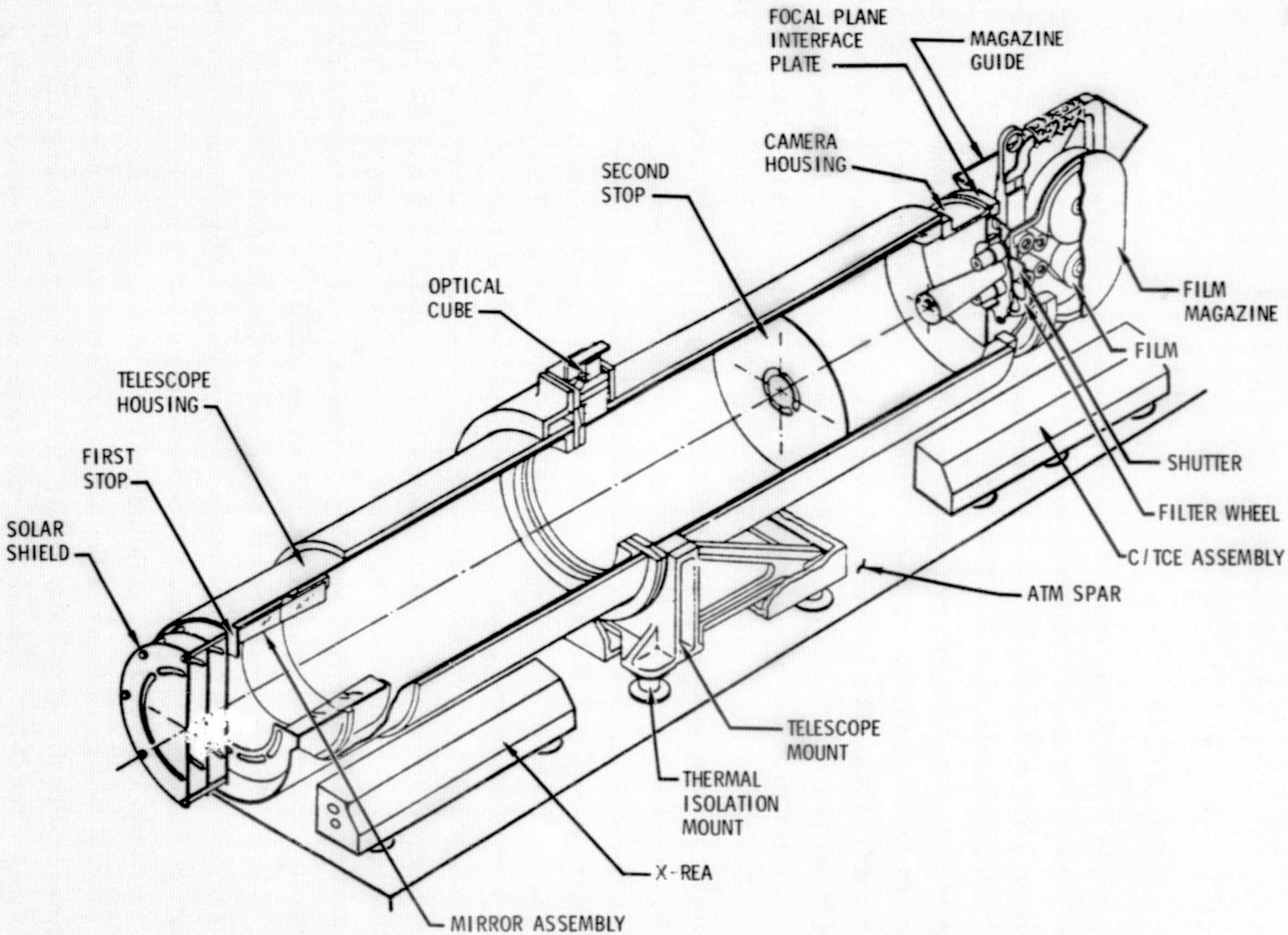


Figure 4-1. S056 X-Ray Telescope Configuration

inaccessible. The weight budget was established at 161 kg (354 lbs); however, the actual weight was estimated to be 133 kg (294 lbs).

4.2 DESIGN DESCRIPTION

The X-ray Telescope consists of two major assemblies: the telescope and camera assembly, and the camera/thermal control electronics assembly. The grazing-incidence mirrors, supporting tubes, centermount, and thermal control components are all parts of the telescope. The grazing-incidence optics provided an image of the sun to one of the six different filters of the film camera. Image quality of this type of focusing device is excellent on the optical axis, but is degraded with angular deviations from this axis. The optical alignment of the telescope was maintained to within ±1 arc-minute by the fine sun sensor of the ATM.

The film camera was designed to place the film plane coincident with the focal point and to alternately position six different filters ahead of the film plane. The camera mechanisms, housed within the telescope assembly, are shown schematically in Figure 4-2 to emphasize the important components. The film is contained within a replaceable magazine, retained at the camera interface plate by guides. The camera, consisting of the film magazine guide, the interface plate, the shutter and filter wheels, and associated drive mechanisms recorded the X-ray image on film along with ancillary data describing the conditions that existed at the time of exposure. A detail description of the camera mechanisms is shown in Figure 4-3. Particular attention should be given to this view because this is where the majority of moving parts are located. The film magazine is replaced after exposing approximately 6000 frames of 35mm, SO-212 black and white roll film. The drive mechanism for the film magazine is contained within the camera and projects through the faceplate.

The camera/thermal control electronics assembly was contained in a separate housing as previously shown in Figure 4-1. This assembly controls the operation of the electromechanical components within the camera and the operation of the telescope thermal control system (TCS). It consists

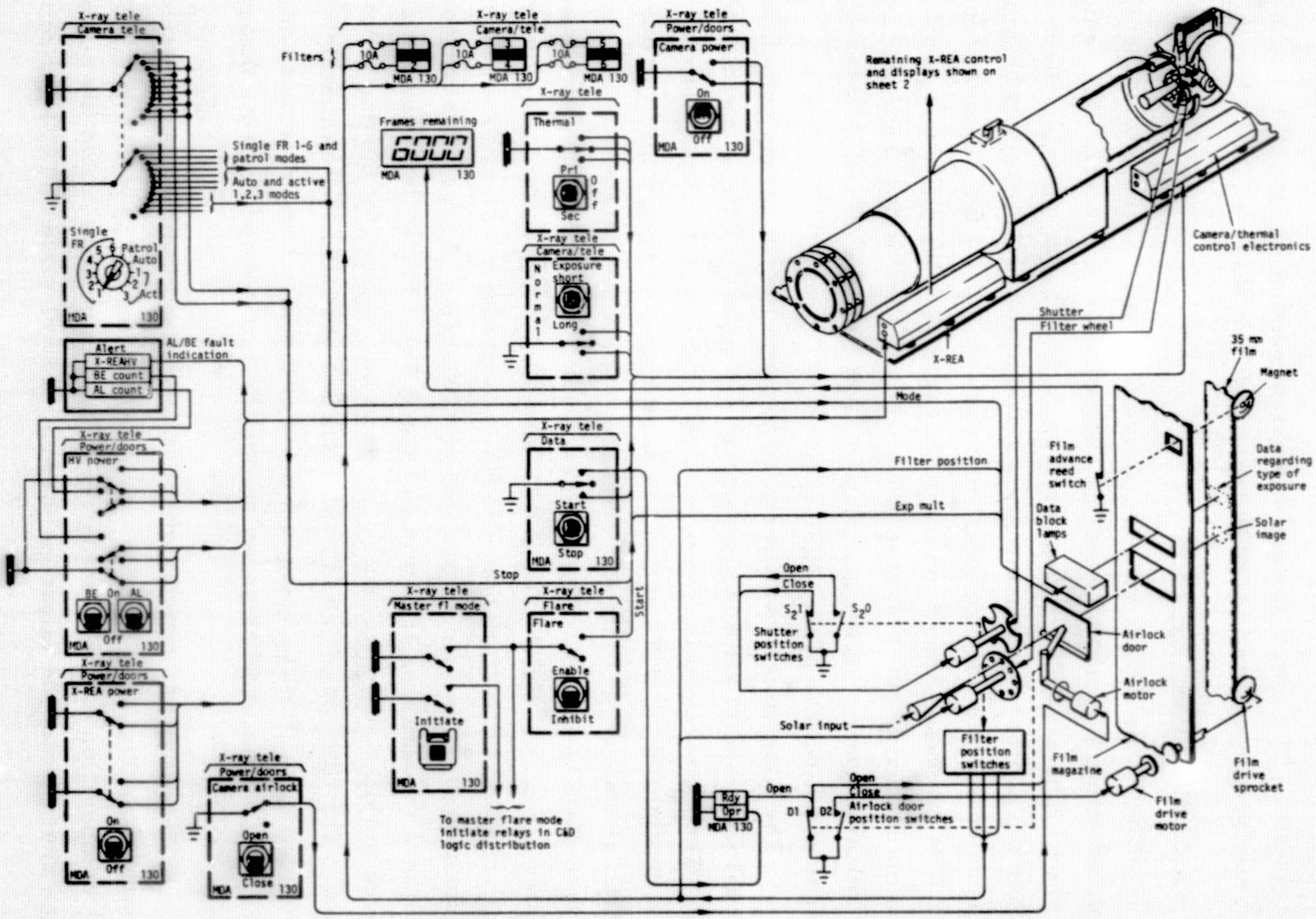


Figure 4-2. X-Ray Telescope Functional Schematic

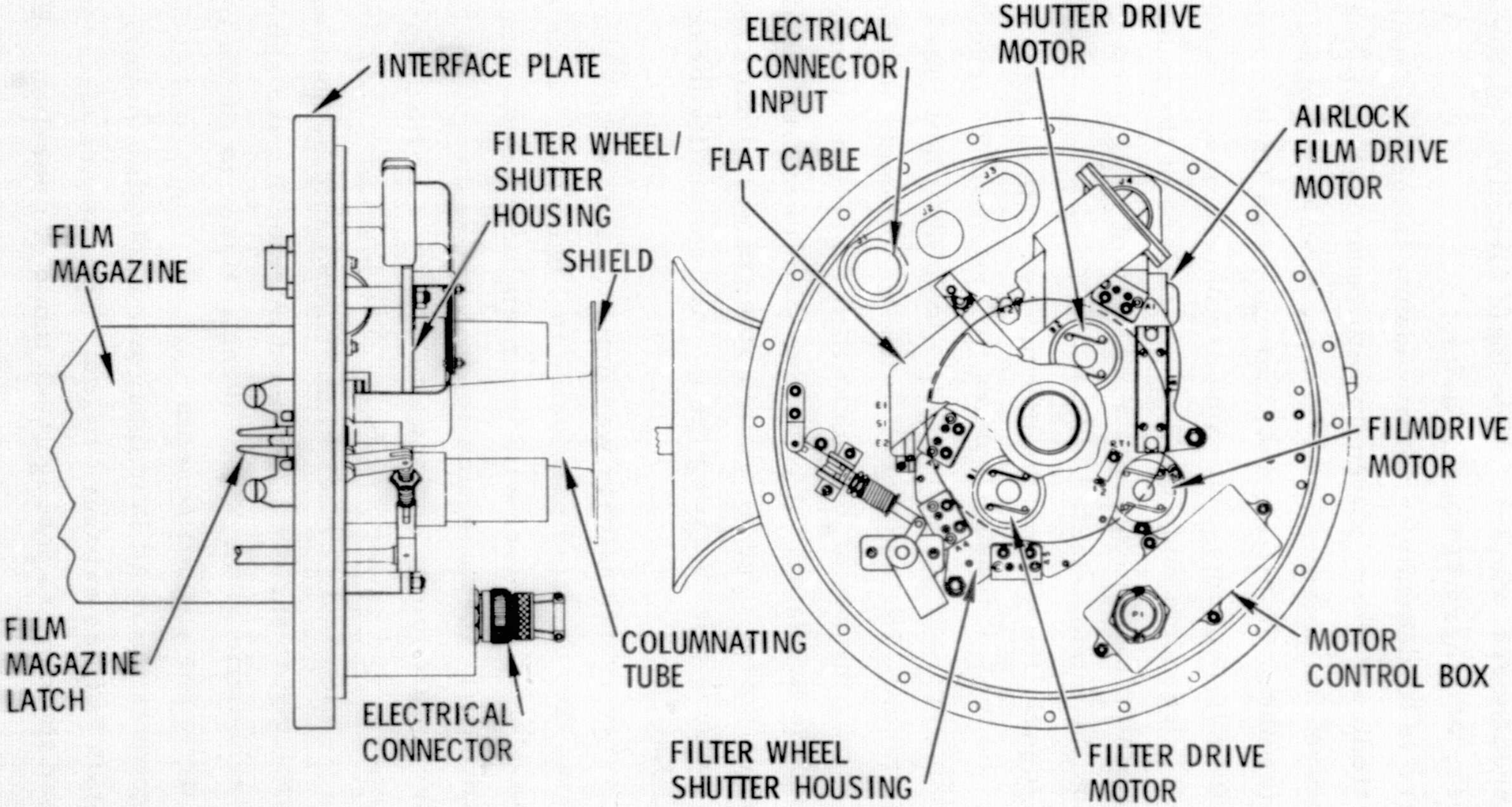


Figure 4-3. S-056 X-Ray Telescope Interface Plate/Shutter Assembly

of exposure sequencers, timers, mode logic circuitry, motor drive amplifiers, power supplies, and thermal control units.

There is fundamentally no redundancy in the electronics except for the TCS electronics that are paired up with redundant strip heaters, thermostats, and control thermistors. There are, however, manual back up operating modes (as shown in Figure 4-4) that can, to a limited extent, approximate the automatic sequencing of exposure operations. This limitation is, to some extent, dependent upon the mode of failure of the individual logic circuits. As an example, the exposure time control inhibits specific timers, depending upon the mode selected. A typical failure could prevent removal of the inhibit signal, thereby precluding the use of the timers in other modes. In this event, the loss of these exposure timers would be irreversible. However, if the exposure control merely fails to inhibit the timers, then extra exposures are taken. The additional film use, although substantial, can be compensated for by the use of additional film cassettes. Consequently, a workaround path is available. It is not possible to assess all of the potential workaround situations without a detailed study of each logic circuit. Therefore, for the purpose of estimating the overall reliability these alternate paths have been ignored.

The X-ray event analyzer was mounted adjacent to the telescope on the ATM spar as also depicted previously in Figure 4-1. It consisted of two gas filled proportional counters with thin metallic windows (one of beryllium and one of aluminum), aperture size control, pulse-height analyzers, digital-channel counters, rate meter and activity history recorder drive circuits, signal conditioners, and power supplies. The level of X-ray energy passing through either the aluminum or beryllium filter could be numerically and graphically displayed to the crew as an aid in selecting the camera modes of operation. A schematic of the X-ray event analyzer is shown in Figure 4-5 to emphasize its important components.

The camera operated in manual and automated modes, as mentioned earlier, to obtain various exposure times. The camera electronics automatically sequenced the camera through each mode of operation. Each mode of

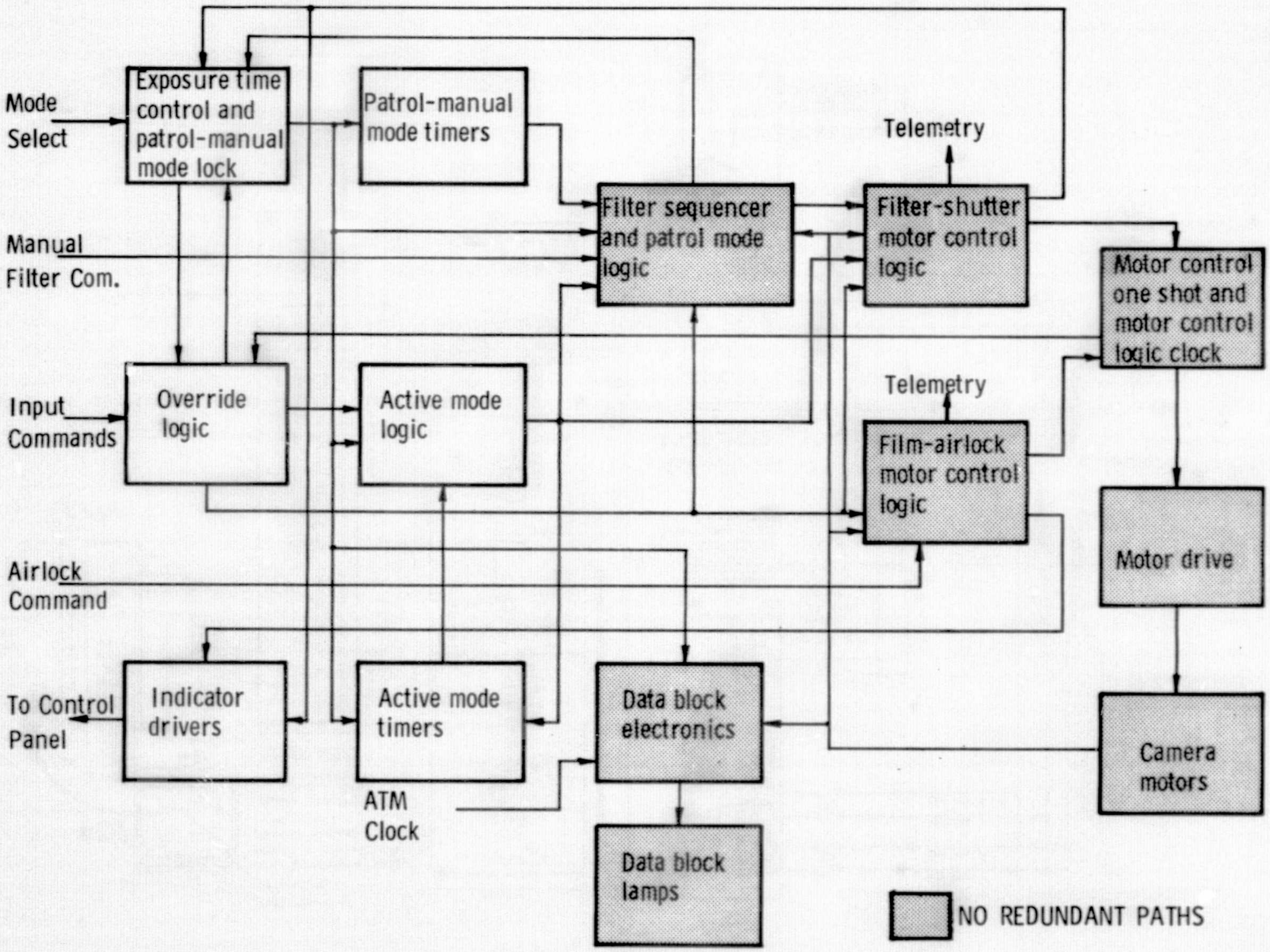


Figure 4-4. Functional Block Diagram of S-056 Camera Electronics

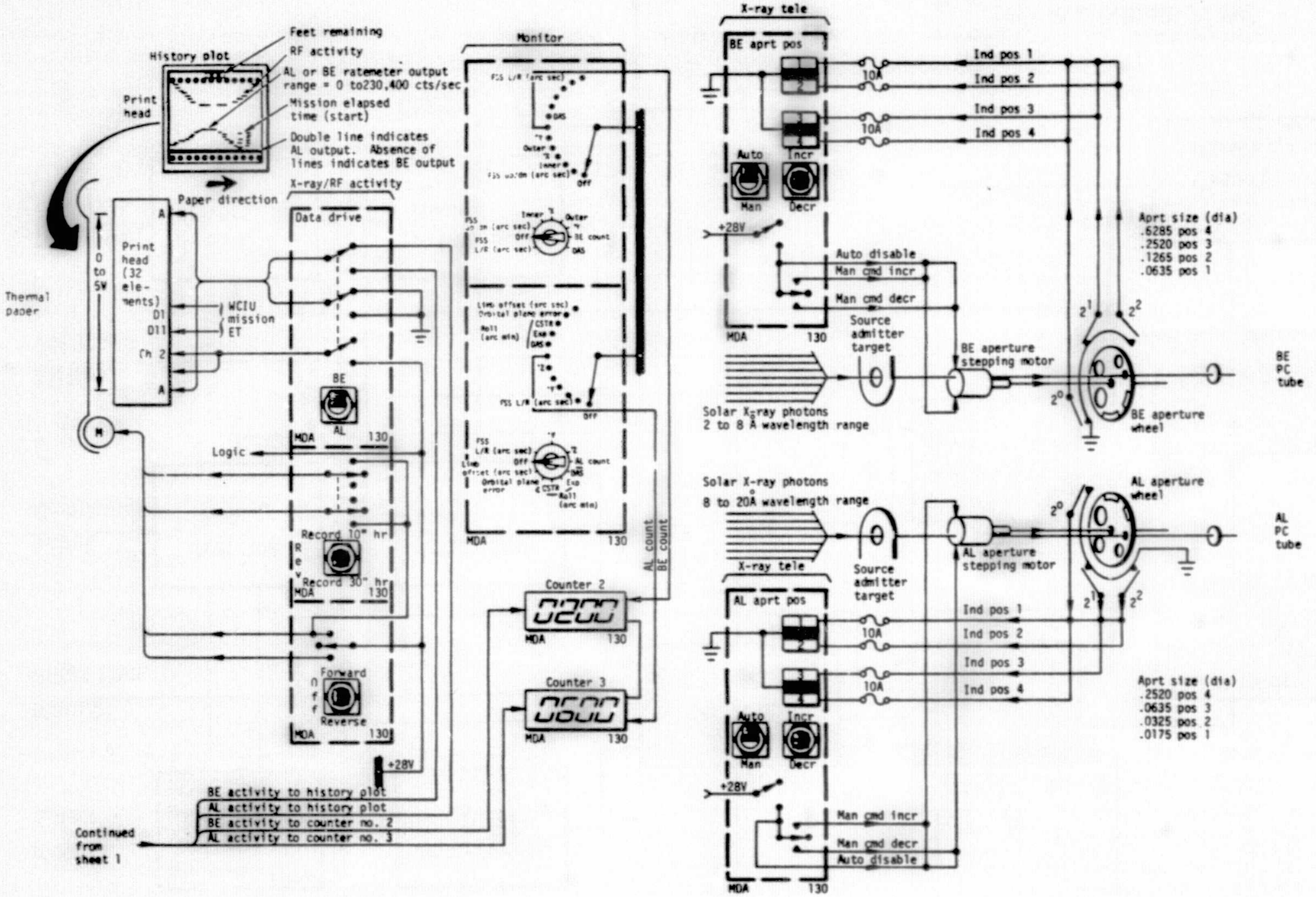


Figure 4-5. X-Ray Event Analyzer Functional Schematic

action included shutter open/close, filter movement, and film advance. The crew could lengthen or shorten the normal exposure time. The S-056 operated only in the manned mode; that is, a crewman was in attendance to establish and initiate the operational sequences. The crew functions, for reference purposes, are shown schematically in the figures previously discussed, Figures 4-2, 4-4, and 4-5, which represent the monitoring and control functions. As can be seen, in the present configuration, there is little fault isolation capability. The crew can monitor the filter position, but cannot recognize the loss of a filter; the crew can select various operating modes, but cannot determine if the exposure sequences or timers are functioning correctly.

The following ground rules were employed in consideration of reconfiguring the S-056 for on-orbit maintenance:

a. No attempt was made to improve upon the design or reflect later technologies. This could tend to mask the effects of redesigning for servicing.

b. Maintenance is restricted to removal and replacement of subassemblies, rather than repair of broken items.

c. EVA will be employed to remove complete assemblies, such as the camera housing, or electronics, only.

d. Disassembly of any subsystem will occur within the pressurized compartment in a shirt sleeve environment.

e. Repair procedures will be limited to those subassemblies that do not require auxiliary equipment for alignment or calibration.

f. All repair actions will be limited to simple movements (nut removal, pull connectors, etc.) to avoid the need for soldering, filing, or any other potentially hazardous operation.

4.3 DESIGN FOR REPAIR

Figure 4-6 indicates the areas considered as viable candidates for repair action. The remaining areas of the telescope assembly consist of static elements and are not amenable to repair. Although a failure may occur in the main structural body due, for instance, to thermal distortion, no reasonable repair action can be defined. It would therefore be necessary, in this instance, to abort the mission. Repair of the insulation cover or thermal standoffs may be possible if deemed necessary.

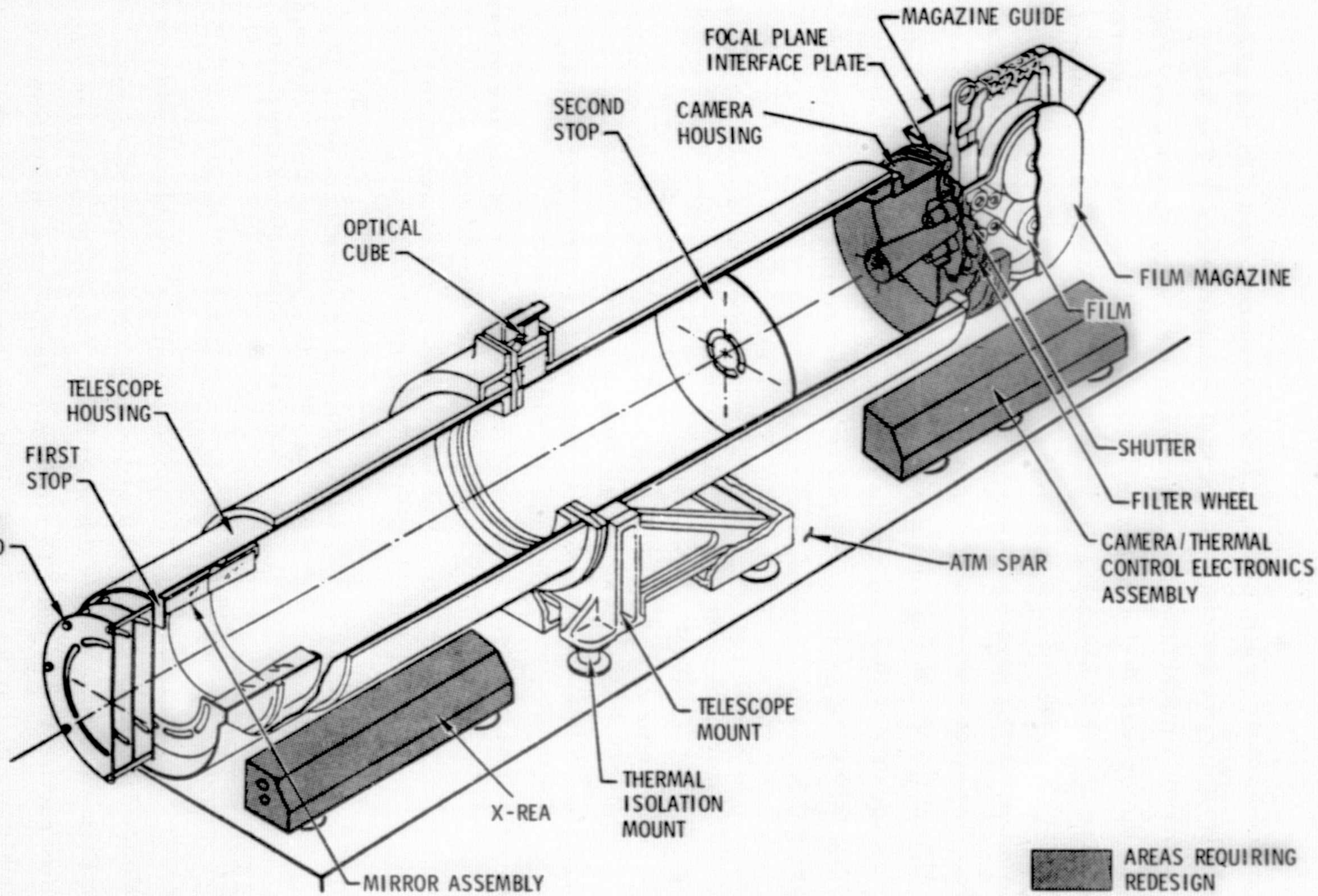


Figure 4-6. S-056 X-Ray Telescope Candidate Redesign Areas

The camera housing was redesigned to be removable by a suited crewman and returned to the crew compartment interior for repair. It was elected to retain the housing with the camera to serve as a protective enclosure during transport. The interface between this housing and the telescope aft tube consists of a V-band flange, so that the housing can be clamped to the tube rather than bolted. The camera housing and clamp design are shown in Figure 4-7. Sufficient accuracy at the machined faces is retained to meet all alignment requirements. The V-band can be removed by the single movement of an over-center latch. The release handle is held in place by a locking pin which can be removed by the crewman. The V-band will then move forward to leave the housing unobstructed for removal. The camera faceplate is bolted to the after interface of the housing. The housing is indexed to assure proper alignment.

This was a straightforward modification with a negligible weight impact. However, the application of electrical connectors posed a different situation. A single connector was desired to replace the existing four connectors. Also, a technique that provides positive alignment of the connectors during reinstallation was required, considering the limitations of a suited crewman in EVA. The redesigned connector arrangement is shown in Figure 4-8 and uses Deutsch rack and panel plugs held together by an external Acme thread connection. Alignment and guiding of the plugs as they are being engaged is achieved by the external case surrounding the connectors. The crewman in pressure suit has simply to rotate the single large ring to mate the connectors. The weight penalty is estimated to be 3.6 kg (8 lb).

The X-ray event analyzer and the electronic assembly are very similar in construction. Each consists of specific components that may need replacement during the course of the mission. The proportional counters are particularly susceptible as evidenced by the Skylab experience. Cut-away views of each assembly are shown in Figures 4-9 and 4-10. The electronic components (sequencers, power supplies) are mounted on printed circuit boards. As will be pointed out later, there are numerous single point failures existing in each of these assemblies. Therefore, it was elected to remove the assembly in toto to the crew compartment for repair procedures. The vast majority of items can be removed and replaced with ease under these conditions.

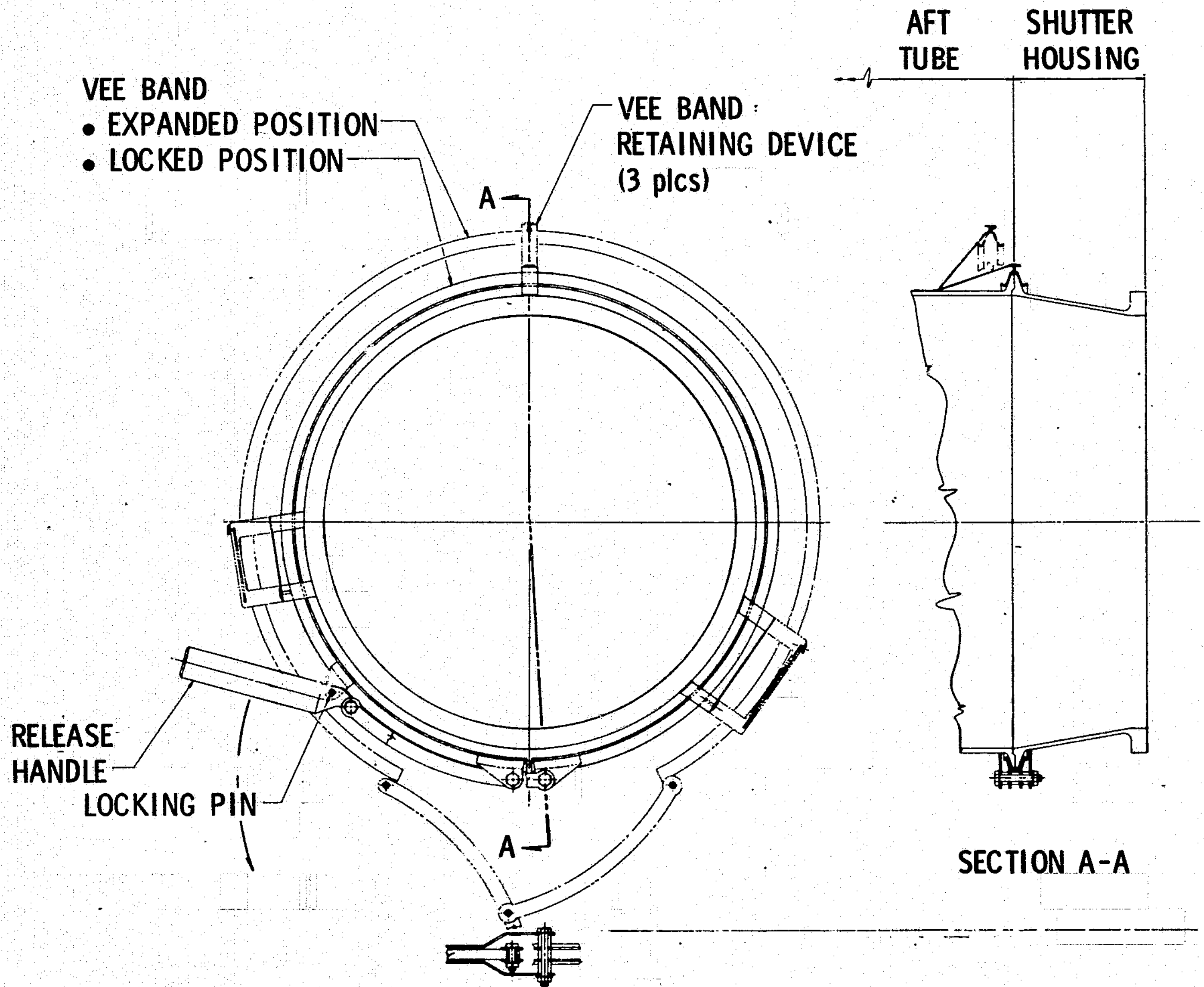


Figure 4-7. Shutter Housing/Aft Tube Interface Clamp

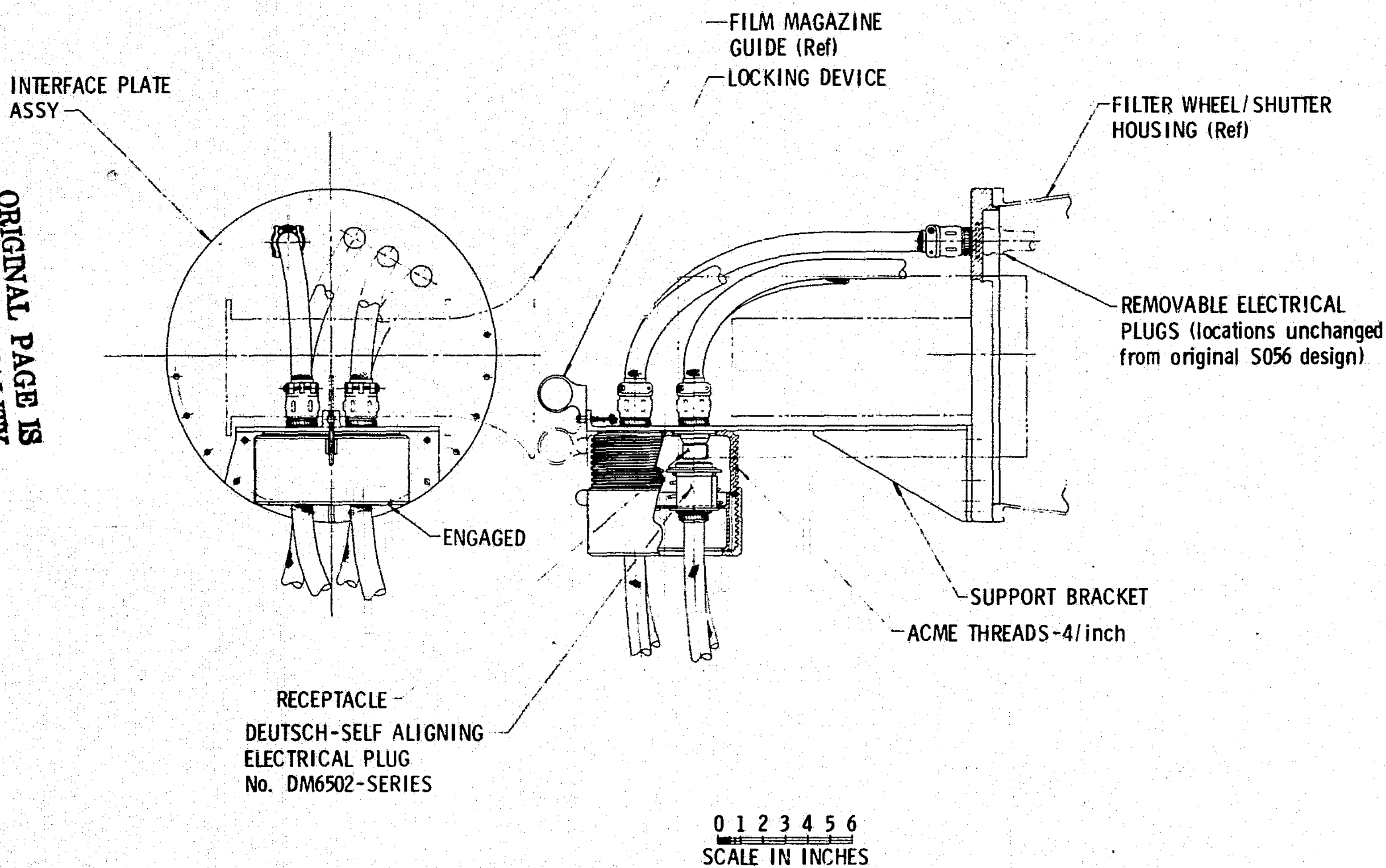


Figure 4-8. Redesigned Electrical Disconnect S-056 X-Ray Telescope

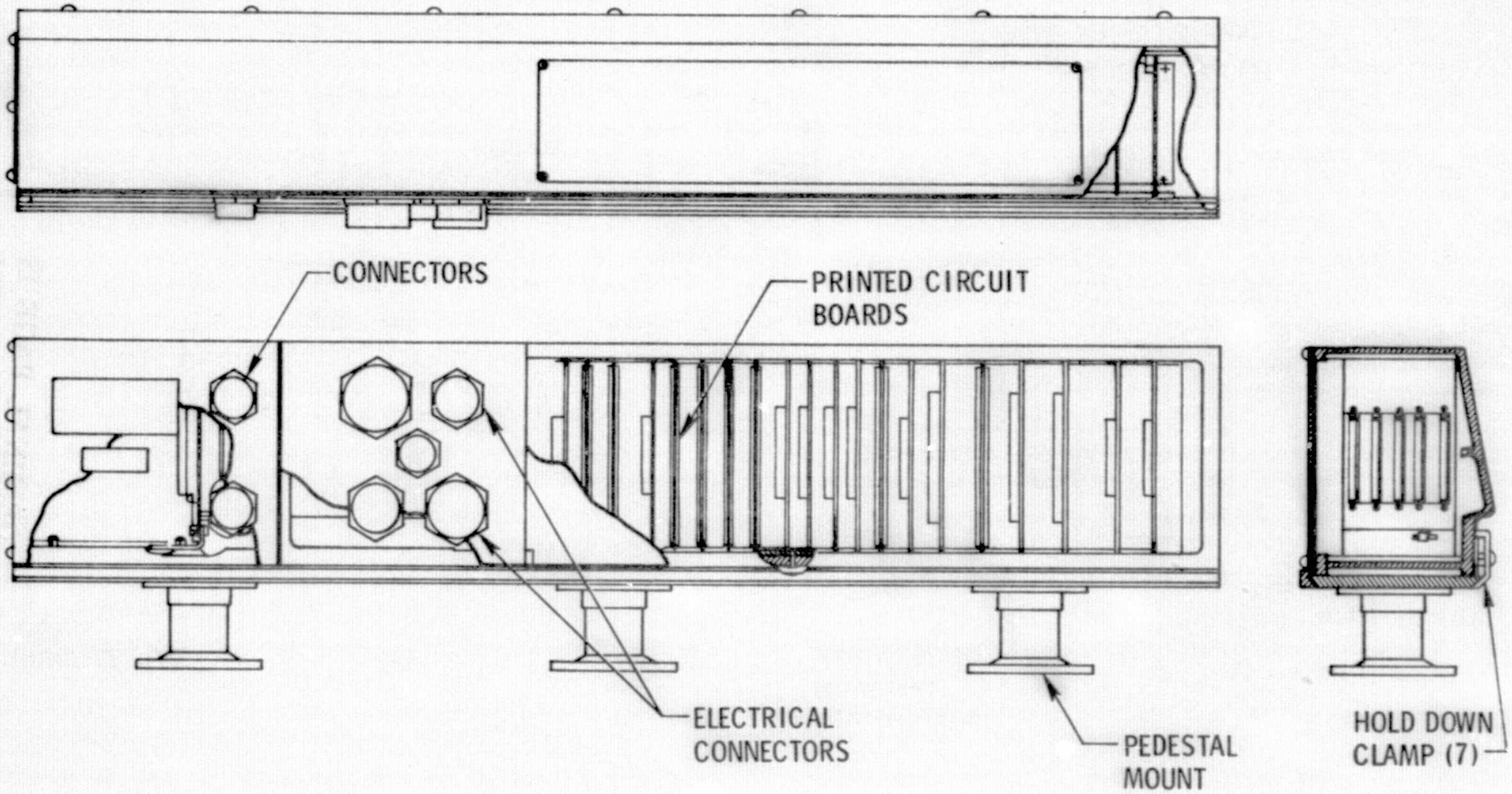


Figure 4-9. S-056 Camera Electronics Assembly

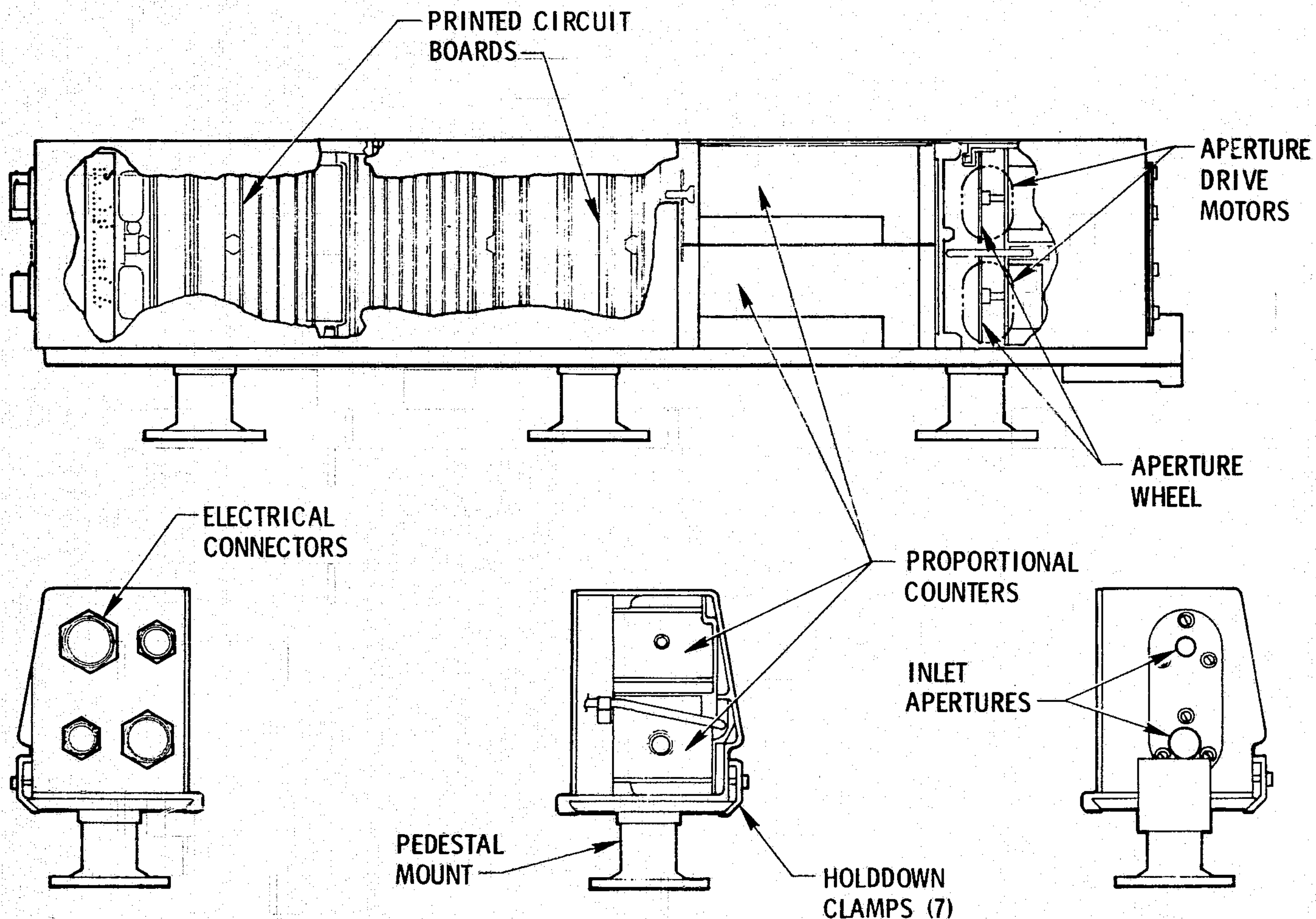


Figure 4-10. X-Ray Event Analyzer Assembly

Redesign of the assemblies is shown, typically in Figure 4-11. The large spin off connector has been incorporated without disturbing the basic design of the assembly. Hold-down clamps have been altered from 7 screws to an over center latch system with three latches and a tie bar. The crewman removes the assembly with a single motion. The weight impact for each assembly is approximately 2.7 kg (6 lb).

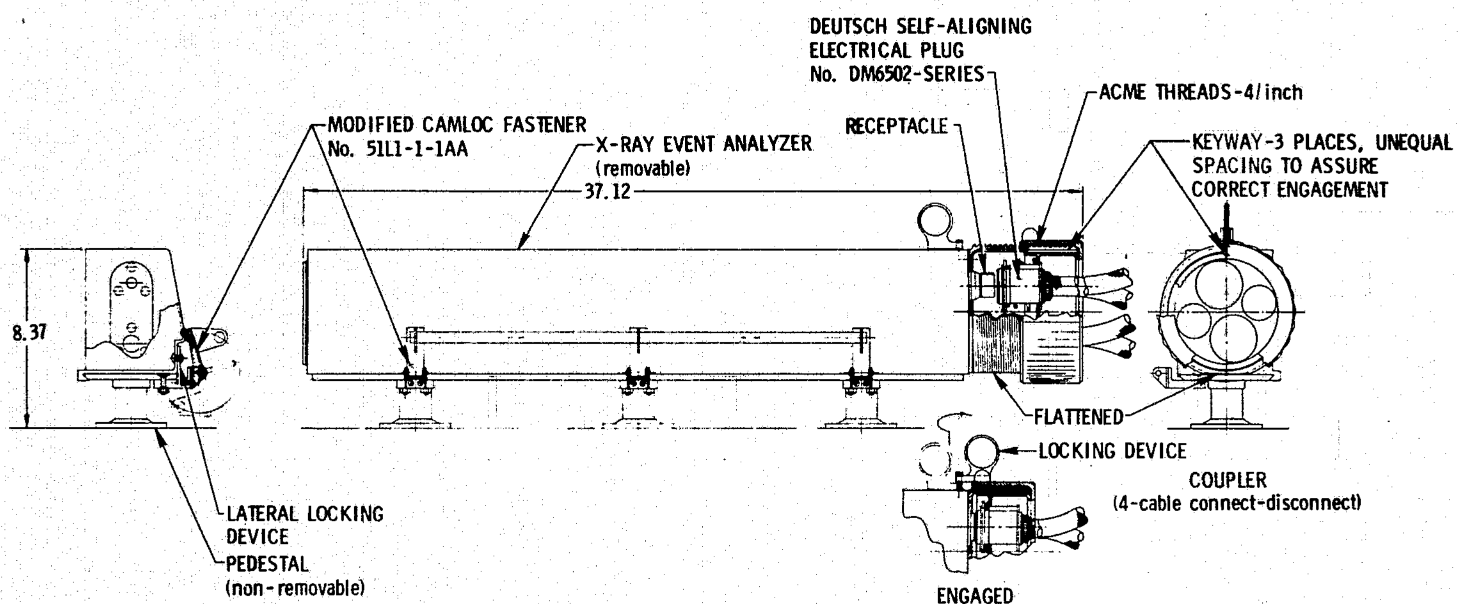
The total estimated weight impact is given in Table 4-1. This table summarizes the review made of each element considered as a candidate for repair action, outlining the disassembly procedure and associated design impact.

In summary, the design review indicated that with a minimum of redesign the S-056 experiment could be maintained in orbit with little training and simple tools. The weight impact was approximately 9 kg (20 lbs) for an original design weight of 133 kg (294 lbs), or seven percent.

The volume requirements were not defined other than to allow access to the major subassemblies for removal and replacement. The impact on overall volume requirements is difficult to assess because this parameter is very sensitive to the platform configuration, e.g., the ATM. The ATM canister imposed a severe penalty relative to access to the various instruments. However, had access been a requirement, it should have been possible to achieve without a severe design impact. In addition, the ATM went through several design evolutions in which operational requirements were altered. Therefore, it is probably not a good example to employ for assessing volumetric requirements or the impact of designing for accessibility. The Spacelab platforms may be more representative of future configurations in which access to all major subassemblies should be readily available.

4.4 RELIABILITY ASSESSMENT

A preliminary reliability assessment was also performed on the S-056 in support of the above design process. Reliability estimates are in general difficult to obtain on any system and are particularly so on "one of a kind" scientific equipment. Wherever possible, documented reliability analyses were employed. These were then supplemented by engineering judgment to arrive at a total system reliability estimate. The majority of



Note:
To be incorporated on S056
X-Ray event analyzer and
Camera Electronics Assembly

0 1 2 3 4 5 6
SCALE IN INCHES

Figure 4-11. Redesigned Latch Mechanism and Electrical Disconnect
S-056 X-Ray Event Analyzer

Table 4-1. S-056 Removable/Replaceable Components

ITEM	DISASSEMBLY PROCEDURE	REQ DESIGN CHANGE	Weight Impact Kg	Weight Impact lbs
Film Magazine	Grasp handle, activate latch and withdraw magazine	None	0	0
Shutter/Filter Mech. Housing	Disconnect Cables and release "V" band clamp	Redesigned for ease of remove/replace action	0.1	0.2
Interface Plate	Remove cap screws to remove from housing	Added bracket and over-size connector	3.6	8.0
Filter Wheel/ Shutter Assembly	Disconnect electrical leads, remove 3 hold down nuts	Electrical wiring disconnects	0	0
Filter Drive Motor	Unscrew Fasteners	None	0	0
Shutter Drive Motor	Unscrew Fasteners	None	0	0
Airlock Drive Motor	Disconnect linkage and unscrew fasteners	Add disconnects to electrical wiring	0	0
Film Drive Motor/Assy	Disconnect electrical leads and unscrew fasteners	Add disconnects to electrical wiring	0	0
Film Drive Motor	Unscrew flex coupling and remove motor	None	0	0
Motor Control Box	Remove 4 hold down screws	None	0	0
X-REA Assembly	Disconnect electrical cables and release latches	Redesigned connectors and hold down latches	2.7	6.0
Printed Circuit Boards	Remove Phillips Hd screws on side cover and remove	None	0	0
Be Analog Module	Disconnect electrical leads and remove 4 cap screws	None	0	0
Al Analog Module	Same as Be Module	None	0	0
Motor Drive Assembly	Disconnect wiring and lift out assembly	None	0	0
Camera Electronics Assembly	Disconnect cables and remove latches	Similar to X-REA assembly	2.7	6.0
Printed Circuit Boards	Remove side cover and lift out	None	0	0
	ESTIMATED TOTAL WEIGHT IMPACT		9.1	20.2

documented data are related to the X-ray event analyzer electronics unit (Ref. 5-10). However, even this falls short of a total subassembly, concentrating on a few discrete elements, such as power supplies and digital signal conditioners.

Except for the thermal control system, the S-056 X-ray telescope with the X-ray event analyzer is composed of a series of single string elements. The failure of any one element will, in general, preclude continued operation, or at best, will allow only limited data acquisition. Even where manual workarounds are provided, there is still a heavy dependence upon timers, logic circuits, and motor drive amplifiers that again are single string. Therefore, the approach taken was to block out the basic functions to the second and third levels, as shown by the example in Figure 4-12. Where formal reliability estimates could be obtained they were utilized. Judgment was then employed where these estimates were not available.

Although there are numerous single point failures in the electronics, this is not the principle area of concern. Generally electronic components are very reliable relative to electro-mechanical components, and it can be anticipated that this situation will continue to exist in the future. In addition, any argument developed here based upon the electronics would be open to question because redundancy is relatively easy to achieve even if initial reliability estimates were low. On the other hand, mechanical components have a relatively slow improvement rate primarily because of their unique applications and lack of extensive test data on a large population. Redundancy in mechanical systems is not easily achieved and, in fact, is seldom addressed. For the record, however, it is interesting to note the reliability characteristics of the various power supplies as summarized in Table 4-2. There are a minimum of 22 single point failures associated with the input stage of the various power supplies and from 26 to 67 single point failures on the output stage. Since each power supply performs a specific task, the loss of a single unit would be catastrophic.

Gathering what information is available results in the expected failure rates shown in Table 4-3 for the X-ray event analyzer and the X-ray telescope assemblies, exclusive of the thermal control systems. The incandescent lamps and stepper motors were particularly suspect. There are 44 lamps

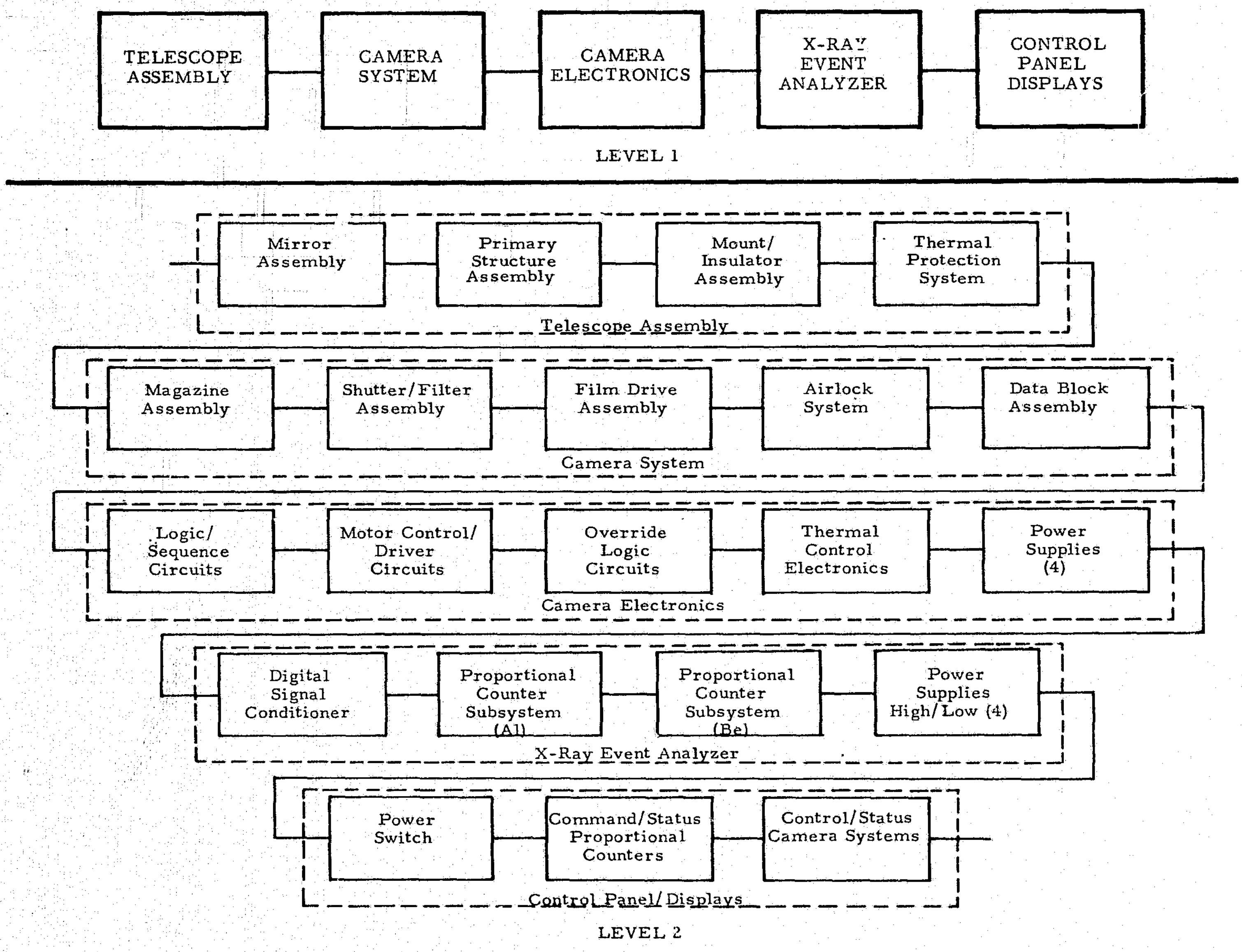


Figure 4-12. Functional Block Diagram of S-056 Experiment

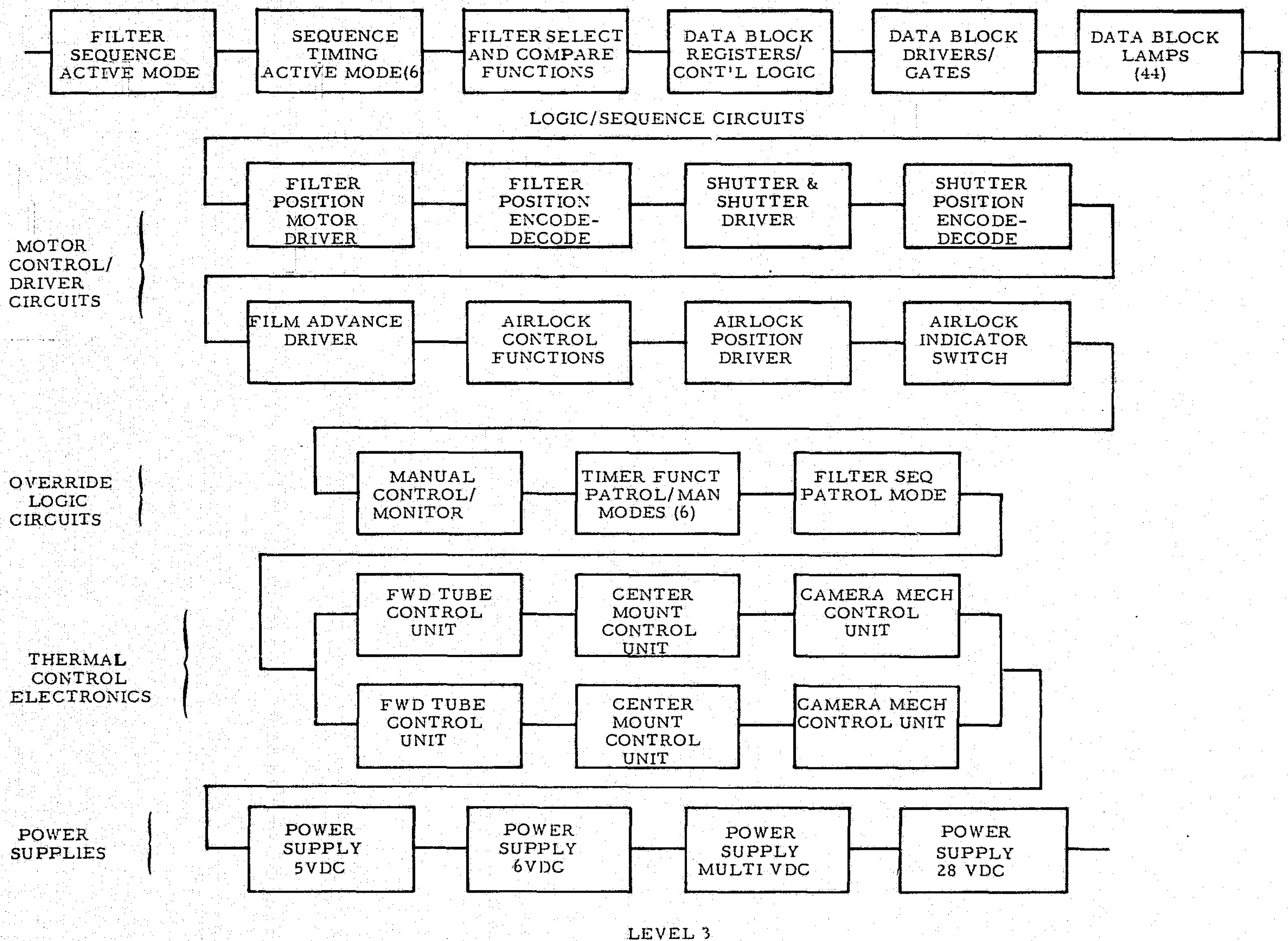


Figure 4-12. Functional Block Diagram of S-056 Experiment (Continued)

Table 4-2. S-056 Power Supply Reliability Characteristics

Experiment	Power Supply	Reliability*	Single Pt. Failures	
			Input	Output
X-Ray Telescope	20 Volts	0.9990	25	28
	-5, +3.1, +7.0, +1.9	0.9986	22	60
	6 Volts	0.9989	25	31
X-Rea	High Voltage (2)	0.9983	43	67
	+5 Volts	0.9990	25	31
	+12 Volts	0.9989	25	26
	-6 Volts	0.9990	25	31
	±12, +28, +29	0.9984	22	42

*Period of Performance

- 2-56 Day Periods
- Conditional Upon Insertion
- All Parts Derated (No Redundancy)

that provide a digitalized set of data on each frame. The loss of a lamp is equivalent to the loss of a digit in an eleven-bit binary word that could present difficulty in reconstructing the record after operation. Since there is no way to monitor these lamps, it would be difficult to determine when the sequence was interrupted thereby allowing some other form of record keeping to be instituted. It may be possible to lose one or two lamps and still be able to reconstruct the records; it appears unreasonable to expect a reconstruction of the record if more than two lamps are lost. Consequently, the system reliability has been estimated on the basis of 42 of 44 lamps being operational. This creates a substantial impact on the reliability estimate. The results for various mission durations are shown in Table 4-4. The nominal mission was originally specified as 112 days, although the instrument in fact operated longer than this.

Table 4-3. S-056 Expected Failure Rates

Subassembly	Failures per 10^6 Hrs*
X-Ray Event Analyzer	
Digital Signal Conditioner	22.05
Al Pulse Processor	1.42
Be Pulse Processor	1.82
Power Supplies	5.48
X-Ray Telescope	
Camera/Thermal Control Electronics	30.77
Incandescent Lamps (per cycle)**	1.0
Stepper Motors (per cycle)***	0.33

*Operational Duty Cycle = 0.625 of Orbit Period

**Based upon 4 magazines of film @ 7200 frames each

***Six motors with total number of steps approximately 4.9×10^5

The data block lamps have, in this example, a predominate effect on the reliability estimate. A new design, instigated with current technologies, would probably use light emitting diodes (LEDs) or some alternate more reliable approach. This would have a substantial impact on the reliability estimate. Also, further investigation has indicated the stepper motors may have a lower failure rate than estimated, although substantiating test results are not available. Consequently, these values of reliability might be considered very conservative if not for other extenuating factors.

The reliability of the proportional counters (2) in the X-ray event analyzer is not available, but these components are well known for their wear out characteristics. The incoming photons impart energy to ionize the gas in the proportional counters. After receiving a high but finite number (approximately 10^9) of photons, the characteristics of the proportional counter change in an unpredictable manner, causing a baseline reference shift. In addition, there are no data relative to mechanical problems, similar to those that

Table 4-4. S-056 Estimated Reliability

Subsystem	Mission Duration, Days		
	30	112	360
Camera/TC Electronics	0.986	0.95	0.846
Data Block			
44 Lamps Required	0.712	0.282	0.017
42 Lamps Required	0.995	0.865	0.227
Stepper Motors	0.957	0.850	0.592
X-Rea	0.986	0.950	0.846
Mission Reliability			
44 of 44 Lamps	0.663	0.22	0.01
42 of 44 Lamps	0.926	0.66	0.10

occurred in practice as discussed in Section 5. Therefore, these and other factors reinforce the position that the low reliability estimate is not unrealistic for systems of this complexity. More depth is desirable but for the present, these estimates will have to be employed and later (Section 7) treated as a variable.

In summary, the probability that the S-056 experiment will operate successfully for the defined 112-day mission has been estimated to be approximately 22 percent. As a point of reference, this is not inconsistent with USAF satellite programs designed during the same time frame. The satellites are, in general, designed for a two-year life, but there are also several redundant paths. Consequently, even though the S-056 flight experience was considerably better than this, (as discussed in Section 5) this value (22%) is not considered unrealistic as a point of reference. It is also interesting to note that the majority of problems that did occur with the ATM instruments would not have been exposed in a classical reliability analysis anyway.

Improvements can be expected in the future, but three factors mitigate against a significant increase in reliability. The system complexity will inherently increase, the equipment will continue to push the forefront of technology on sensors, and the operating time on orbit will be extended. Hence, although electronics and other components can be expected to improve in reliability, single string failures will continue to be in abundance and the overall system reliability should not be expected to exceed 50 percent at best.

Therefore, it should be the general practice in the future to design for access to mechanical subassemblies, in particular, and electronic subassemblies in general. Where access to electronics is not possible, redundancy or alternate paths should be employed. Also, a very important factor is commonality of components to ease replacement and spares provisioning. There are, for example, six stepper motors in the S-056 experiment. Three are identical in the telescope assembly and two are identical in the event analyzer. Each steps through a specified number of degrees upon command. The drive amplifiers are also very similar. It should be possible to make these components interchangeable so that a single spare could be employed in several areas. The same is true of power supplies. The number of different power supplies (8) should be reduced and commonality of units or P.C. boards should be employed. These would not have imposed any severe constraints on the S-056 but since maintenance was not an objective, there was little incentive for commonality.

Finally, in consideration of future applications, there is a school of thought with experience behind it that emphasizes that failures are seldom random but instead represent design or manufacturing deficiencies. We learn from these failure occurrences, but the challenge of new designs appears to always harbor this basic characteristic. Therefore, the risk associated with unique, immature systems is inherently high, independent of reliability estimates. Until the system can be brought to maturity, it is only prudent to retain the option to service the system by removing and replacing failed subsystems. The penalty incurred in the design process should be easily offset by the extended life and availability of the system, if in fact repair is required.

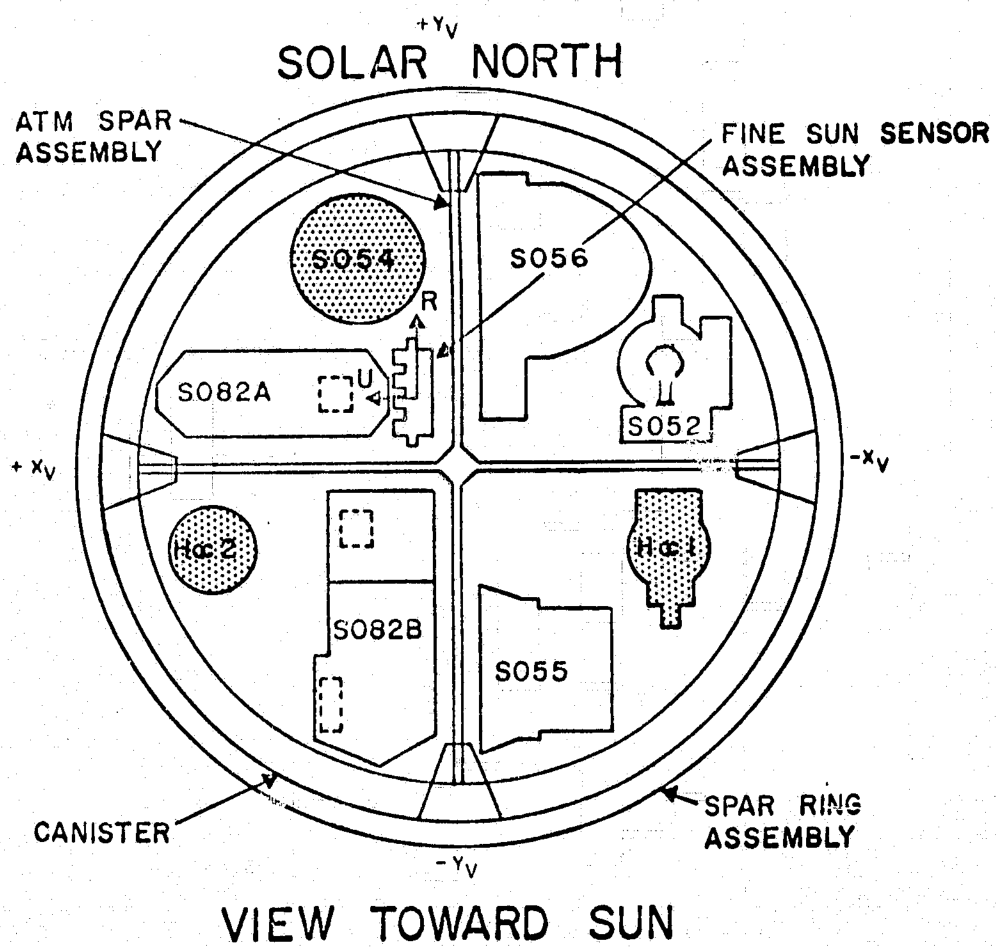
4.5 APPLICATION TO OTHER ATM EXPERIMENTS

In order to reinforce the results obtained from the S-056 analysis, the effort was directed to analyze four additional ATM experiments. Detail design drawings were obtained from Ball Brothers Research Corporation (Ref. 11 -14). Figure 4-13 lists the experiments examined, and shows their general placement within the ATM cannister. The maintainability impact assessment was performed without the benefit of a redesign of each instrument. Rather, the design was examined in depth and subassemblies or components were identified that could be considered likely to require replacement. An estimate of the weight impact was then performed based on the knowledge gained from the S-056 effort.

An example of this is given in Figure 4-14, showing an exploded view of the S-082B Spectrograph and XUV Monitor. Each subassembly was assessed relative to alignment tolerances, access for replacement, and cable routing. Consideration was also given to maintaining the continuity of the thermal control system, including removal of thermal control panels. The results were tabulated, similar to Table 4-1 for the S-056, and are presented in Appendix 1. The respective weight impact for each instrument is provided in Table 4-5. The weight impacts are considerably higher than for the S-056 due primarily to more electronic subassemblies, each requiring a latch mechanism, handle, and electrical connector housing. The weight changes are considered to be

Table 4-5. Weight Impact for Servicing

Experiment	Initial Wt., kg	Weight Increment, kg	Percent Change, %
S-056	133	9	7
S-052	145	38	26
S-055	159	47	29
S-082A	136	29	21
S-082B	192	70	36



- S-052 White Light Coronograph
- S-055 UV Scanning Polychromator - Spectroheliometer
- S-082A XUV Coronal Spectroheliograph
- S-082B Spectrograph and XUV Monitor

Figure 4-13. Arrangement of ATM Experiments

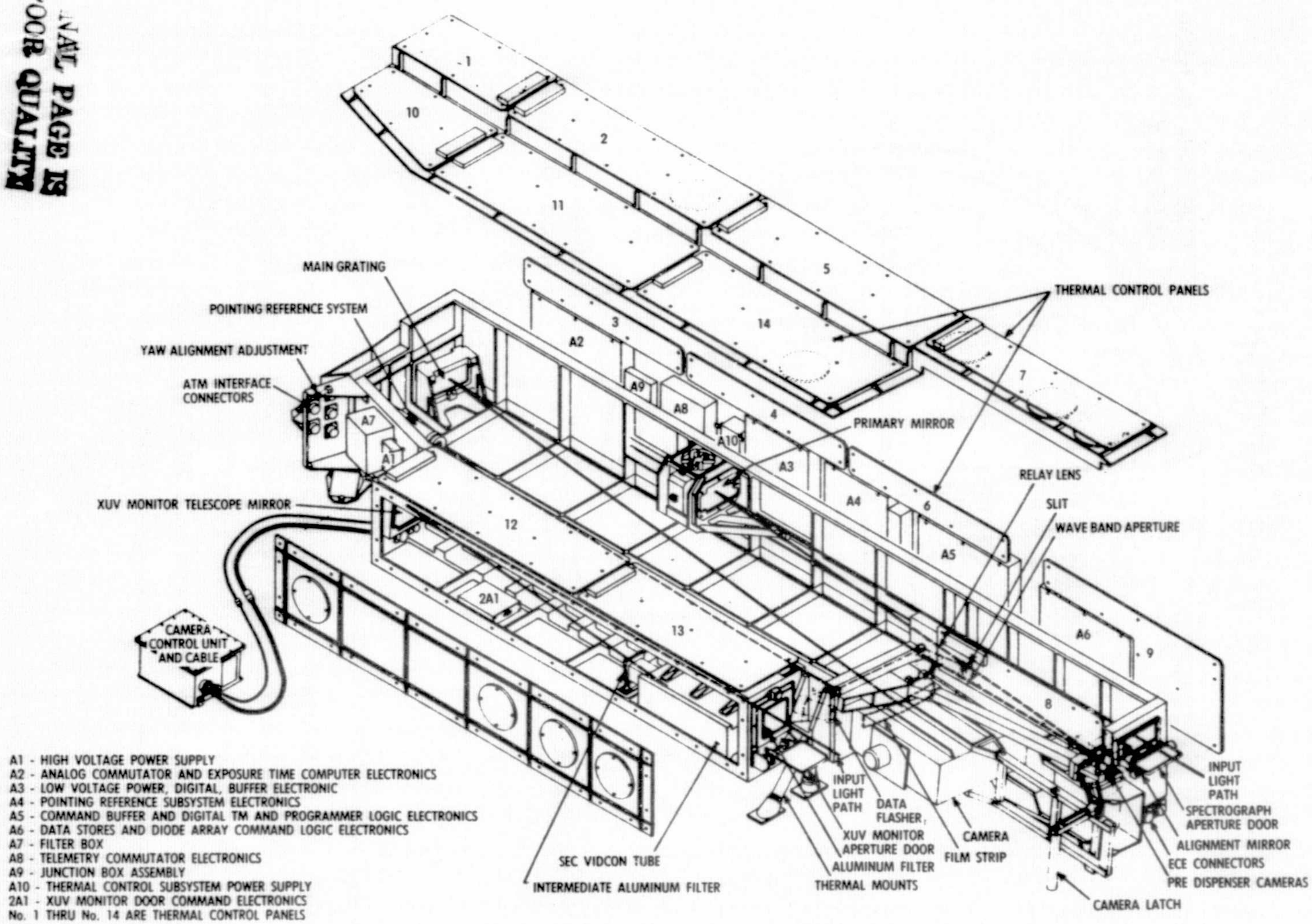


Figure 4-14. Spectograph and XUV Monitor Experiment S082B

extremely conservative since repackaging could probably be used to reduce the number of connectors. The weight impact varies from 21 to 36 percent as compared with 7 percent for the S-056.

In general, the volume changes were trivial for the instrument itself, but access would be required beyond that provided in the ATM.

These results emphasize the need for care in configuring an instrument for maintenance. It would be difficult to justify a 36 percent increase in weight unless a thorough reliability analysis could substantiate this as the only means of achieving a high availability. It has been estimated, however, that these values could be reduced by proper design to approximately one-half of the quoted values, or approximately 15 percent. For example, many of the electronic components can be packaged together; reducing the attachment, handle, and connector weights. This incremental weight increase will undoubtedly pay off in terms of increased reliability as opposed to use of redundancy as shown later in Section 7.

5. MAINTENANCE ASSESSMENT

5.1 SELECTION OF INSTRUMENTS

The previous sections have provided the general description of the three candidate payloads of interest, with emphasis on the S-056 X-ray telescope. This section addresses the actual anomaly experience and relates corrective action possibilities to the failure occurrences. As will be pointed out later, the majority of anomalies that occurred in practice were not identifiable through classical reliability analysis.

The purpose of this effort was to relate the failure occurrences with the respective actions taken and relate these in a quantifiable manner relative to the basic characteristics of the equipment. This serves two purposes: an assessment of the fundamental character of these types of instruments relative to mission objectives, and as a source for improving failure assessment techniques, as shown in Section 7. Emphasis has been placed on the role man played, either remotely or by direct action, in maintaining an operational status even after repeated failure occurrences. This involved detailed discussions with the Principal Investigators and Skylab crew members, as well as, a review of Skylab experience (Ref. 15-17).

The basis for evaluation of manned maintenance capability used in this study is a comparison of three representative space-based experiments with various degrees of manned involvement. The three experiments selected, as described in Section 3, were widely different in the degree of operational maintenance possible, but were very similar in function and purpose such that common criteria could be developed for forming a rational judgment. These criteria resulted in definitions, discussed in detail below, that permitted a numerical comparison of the experiments in terms of "complexity of operations" and "maintenance effectiveness." Although the following definitions are necessarily arbitrary, they are sufficiently objective to provide a consistent method of comparing instruments and evaluating performance. The methods developed for this study are unique for the instruments used; a similar approach, using different parameters, may be of value when evaluating other systems.

Selection of the instruments evaluated was made to ensure that they were similar but employed significantly different degrees of manned support. The choice was restricted by requiring that one of them was flown on Skylab and employed manned maintenance. Three categories of maintenance were used in the selection: 1) automatic or nearly automatic systems with no maintenance possible except for switching operations; 2) semi-automatic with manned operation via telemetry; and 3) semi-automatic with direct manned support and partial maintenance in orbit. As previously mentioned the examples selected for these categories were the OV1-10, -17, OSO-7 and the S-056 on the Skylab/ATM. The X-ray experiments on OV1-10 and OV1-17 were spectrometers that measured the spectral flux from the whole sun in the soft X-ray region of about 7-30Å. The OSO-7 experiment was a scanning spectrometer that obtained spectral scans of selected areas in the 2-40Å interval. The S-056 experiment obtained X-ray pictures of the whole sun in the 3-30Å band.

The approach taken in this effort was to break down the two major parameters, Maintenance Effectiveness and Complexity, into sub-elements that could be related to the actual design of the instrument and its operational experience. Judgment was required in several instances, but wherever possible, the parameters relate to measurable items. These parameters are then quantified and summed to obtain a graphic relationship of man's contribution to the success of the mission. These results are then extrapolated to examine what further improvement, if any, could have been realized had the equipment been designed for maintenance. This provides a basis for interpreting experienced failures relative to predicted failures and aids the subsequent tradeoffs presented in Section 7.

5.2 MAINTENANCE EFFECTIVENESS DEFINITIONS

The parameters that were used to define maintenance effectiveness are:

1. Period of Operation (P_o). The length of time the experiment operated and obtained some useful data. By normalizing to the expected lifetime, P_o, equal weight is given to operations of fixed duration such as the ATM and of unspecified duration such as the OSO. This does not limit the value of the period of operation that can be extended by maintenance.

2. Quality of Data (Q_L). Maintenance can obviously affect quality of the data and hence the effectiveness of the experiment. The parameter has been assessed on a scale of 0 - 4 as follows: (0) no usable data were obtained, (1) important parts of the experiment failed and did not obtain any data, or most of the data were inferior or missing, (2) part of the data are of inferior quality which would compromise the scientific objectives and limit its usefulness, (3) data are of excellent quality but incomplete because of malfunctions that occurred in operation, (4) data are excellent in every respect and all data planned were obtained so that scientific objectives could be realized.

3. Quantity of Data (Q_N). The total quantity of data obtained by the instruments expressed in bits. For analog data or film in the form of pictures, this is the bits obtained from conversion to digital format. This number is weighted by some scale factor or normalized to a similar data base, Q_{N_o}.

4. Number of Repairs Made (N_R). Repairs made to the instruments by operational or program procedures through telemetry commands or by manned maintenance. Each repair is counted, even if recurrent, but a weighting factor is applied that estimates the importance of the repair relative to the total function of the instrument. Maximum value for a repair is 1.0 if the instrument were totally inoperative before the repair was made and fully operable afterward.

5. Redundancy (R). Back-up or alternate parts or systems that were used during operations to replace a component that failed. A repair made by redundancy is counted only once and a weighting factor is applied that estimates the importance of the repair relative to the total function of the instrument. Maximum value is 1.0 as in parameter 4 above.

6. Operational Manpower (O_M). The manpower required to operate the experiment averaged over an extended period in units of man-months/month. This indicates the average number of personnel necessary to perform observations with the instrument including the fraction of support personnel who contribute to the observations.

The use of these parameters in defining maintenance effectiveness is based on the following relationship

$$M_E = \frac{(P/P_o) + Q_L \left[Ln\left(Q_N/Q_{N_o} \right) \right] + \left[1 + \Sigma F(N_R) \right] + \left[1 + \Sigma H(R) \right]}{O_M + (T_R/P)} \qquad (1)$$

where the symbols are defined above and T_R is the training, in man-months, required to operate the experiment, as defined in Section 5.3, paragraph 4. The terms of equation (1) have been made dimensionless by normalization to appropriate factors. In addition, the quantity of data, Q_N, has been weighted by the logarithm to base e of the ratio Q_N/Q_{N_o} where Q_{N_o} is the total data in bits obtained by the OV1-10 satellite. This choice for the data quantity parameter is based on the estimate that the value of data to the scientific objectives decreases with increasing volume. This quantity weighting factor will be different for each type of experiment on test, and will depend on use of the data in analysis. For communications instruments, for example, each data bit is equally valuable and no weighting would be given. For scientific and technical instruments, however, value of the data will depend on both quantity and epock for time dependent investigations. Repeated observations of equal quality will not increase their value in satisfying program objectives and will diminish overall effectiveness by recording unused data. For the solar experiments evaluated in this study, the estimate by the Principal Investigators and knowledgeable scientists working with the data was that the value would decrease exponentially beyond some lower bound. Values of maintenance effectiveness, M_E, for the OV1-10, OV1-17, OSO-7 and S-056 X-ray experiments are given in Table 5-1.

Table 5-1. Maintenance Effectiveness Factor, M_E

Parameter	Payloads			
	OV1-10	OV1-17	OSO-7	S-056
1) Period of Operation (P/P_o)	7.2/6 = 1.2	0.5/6 = 0.08	29/12 = 2.4	9/8.2 = 1.1
2) Quality of Data (Q_L)	2	1	2	3
3) Quantity of Data (Q_N)	10^{7*}	5.5×10^6	5.04×10^9	5.57×10^{11}
4) Number of Repairs (N_R)	0.5	0	0.9	3
5) Redundancy (R)	1	1	4	6
6) Operational Manpower (O_M)	1	1	4	6
7) Training (T_R)	0.25	0.25	4	6
M_E	3.59	1.43	4.29	6.13

*Reference Value of Q_{N_o}

The value of effectiveness of maintenance derived from equation (1), in addition to being somewhat arbitrary, is not sufficient to characterize these experiments because of the differing degrees of manned operations and instrument complexity. As indicated above, these experiments can be put in three categories determined by the degree of manned maintenance: 1) automated with manned operation limited to switching control and no maintenance or repair; 2) automated but with complete manned operational control via telemetry, and with possible maintenance and repair through switching and redundancy; and 3) semi-automated with complete manned operational control and with limited manned maintenance and repair. Because of the significant differences in instrument operations and complexity between these experiments, additional parameters were defined to characterize maintenance and operations complexity.

5.3 INSTRUMENT COMPLEXITY DEFINITIONS

The parameters developed for this were:

1. Number of Components, (N_C). The number of subsystems of the experiment that were separately packaged. Various items with different functions but enclosed in one box are counted only once. External support systems, mountings or monitoring equipment are not counted as a component of the experiment.
2. Number of Modes (N_M). The number of operating modes that the instrument is designed to provide. These modes may be automatic, semi-automatic or manual provided that they can be achieved without permanent changes in planned instrument operations, and can be used repeatedly. Calibration or test modes used to evaluate instrument performance are not counted as part of the number of operating modes.
3. Number of Instructions (N_I). Total number of operating instructions that can be given to the instrument in making observations. This includes switching between modes of operation as well as for calibration and test. Switching and sequencing done by the instrument during a standard mode of operation are not counted as instructions. Each external switching that changes the operating characteristics of the instrument is counted as an instruction if it is used individually to control the instrument. If it is part of a sequence of switching to achieve a change, individual switches are not counted separately.
4. Training Required (T_R). Training, in man-months, required to instruct a qualified person to use the instrument effectively for routine operations. It is presumed that the individual has prior experience in working with space-flight experiments and is knowledgeable about terminology and technology associated with the instrument. Training of manpower required to operate telemetry, communications, data recording, and related support operations are not counted as part of this category.

5. Automation (A). The number of steps in the instrument operations that provide for automatic switching or sequencing to accommodate observational changes or malfunction. This function is for responding to unscheduled changes in routine operations that are usually associated with instrument logic functions, such as, gain changes, and data rate. It also includes transfer to alternate modes of operation or switching in parallel or back-up subsystems in the event of failure.

6. Data Rate (D_R). The data rate of the instrument in bits per second averaged over the lifetime of operation. For analog data, conversion to digital data is required to determine the bit rate. Data on film are determined by computing the bits required to digitize the image frame with a microdensitometer used for data reduction and counting the number of frames obtained. Resolution of the densitometer should equal the resolution in the image.

7. Design Constraints (D_C). Limitations placed on the instrument design such as configuration, size, and weight, in order to conform to requirements of the satellite. This parameter has an arbitrary scale of 1 - 5 with increasing number corresponding to greater limitations. Estimate of this factor is based on comparison with other flight instruments and the investigators estimates of design constraints.

8. Instrument Requirements (I_R). Complexity of the instrument with regard to its function and operation. Examples of these are unpointed, spin stabilized, pointed and stabilized, scanned, time and space correlated with other instruments on the satellite or ground, and instrument type, e.g., optical, radio, and charged particle. The scale of this parameter is 1 to 5 with increasing number corresponding to greater requirements. Estimate of the value is based on comparison with other instruments.

9. Instrument Objectives (I_O). The number of scientific and technical objectives of the instrument measured by the different types of data collected. Each type of data obtained is counted even if it came from the same source, i.e., solar, stellar, and atmospheric.

Values of these complexity parameters for the OV1-10, OV1-17, OSO-7 and S-056 are given in Table 5-2. The complexity, C, is computed from a linear sum of the parameters defined above with certain weighting factors assigned to prevent any single factor from being dominant. Although this weighting is necessarily arbitrary, it is consistent. The value of C is given by

$$C = N_C + N_M/I_O + N_I/10 + T_R + A + \text{Log}_{10}\, D_R/D_{R_o} + D_C + I_R \qquad (2)$$

and is listed in Table 5-2 for the four instruments evaluated.

Table 5-2. Complexity Factor, C

Parameters	Payloads			
	OV1-10	OV1-17	OSO-7	S-056
Number of Components (N_C)	2	3	7	6
Number of Modes (N_M)	1	2	6	11
Number of Instructions (N_I)	1	2	34	46
Training Required (T_R)	0.25	0.25	4	6
Automation (A)	1	1	0	1
Data Rate (D_R)	25	2.0×10^2	2.0×10^2	3.7×10^4
Design Constraints (D_C)	2	2	3	4
Instrument Requirements (I_R)	2	2	2	3
Number of Objectives (I_O)	1	1	2	2
C	8.35	11.4	23.3	33.3

These results are shown in Figure 5-1 where they are plotted as instrument complexity versus maintenance effectiveness. A trend line drawn through the OV1-10, OSO-7 and S-056 points shows a significant increase in M_E associated with the greater involvement of man in the maintenance of these instruments. OV1-17, which was considered a failure in terms of meeting scientific objectives, is well below this curve.

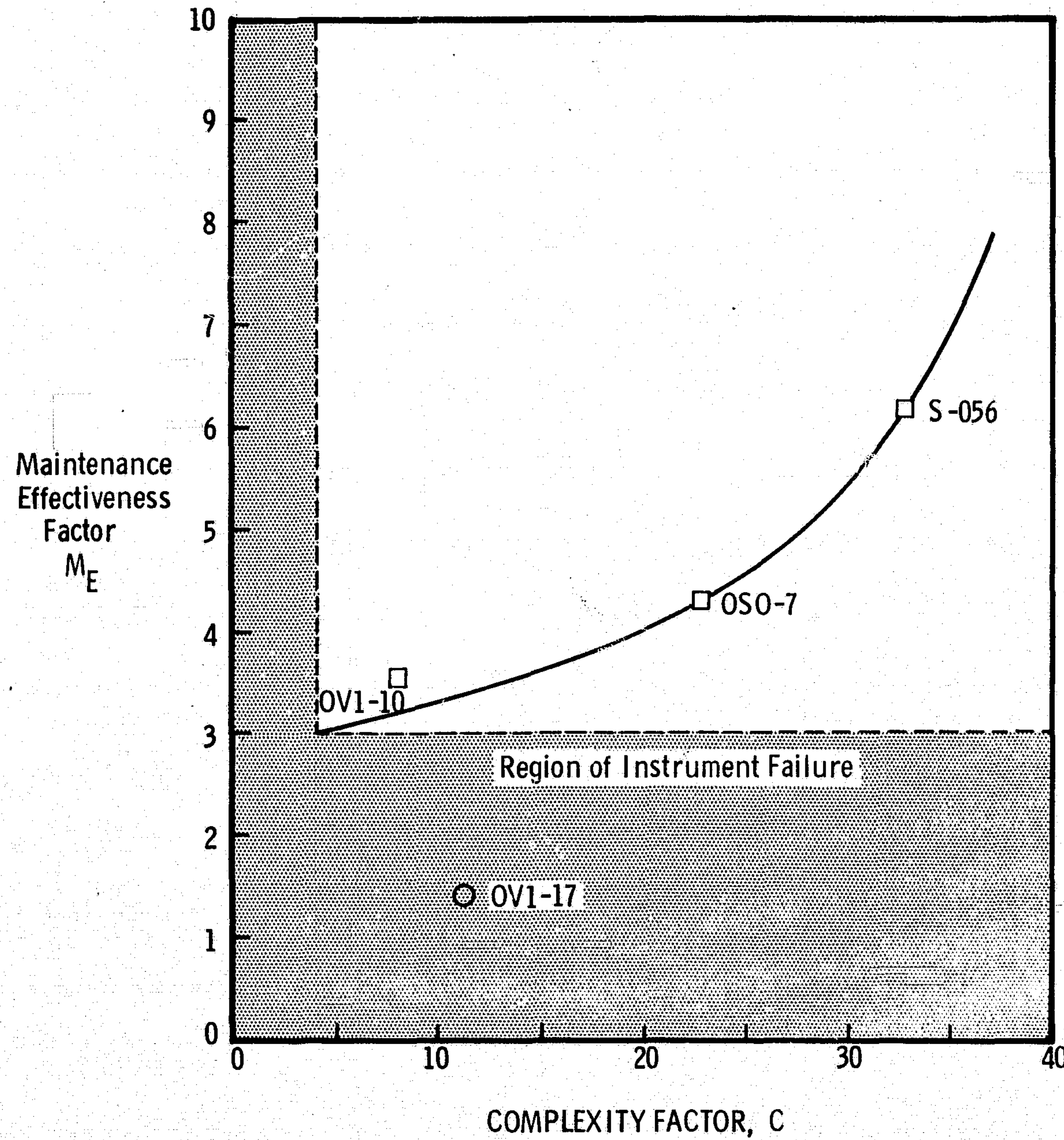


Figure 5-1. Instrument Complexity versus Maintenance Effectiveness

Based on the analysis, minimum values of C and M_E can be established for instruments that are launched successfully and that function properly during part of their designed lifetime. For complexity, this value is 4 representing the lower bound to the parameters that define C in Equation (2). For maintenance effectiveness, this minimum value is about 3 for an instrument that functioned properly during its planned lifetime and required no maintenance actions. These minimum values of M_E and C are also shown in Figure 5-1. The region below M_E equal 3 represents instrument failure and includes OV1-17.

To provide additional data for evaluating the manned contribution to maintenance and determining consistency of the model, other experiments on the ATM were analyzed using the definitions given above and Equations (1) and (2). Results of this analysis are given in Table 5-3 for the six additional experiments of ATM. These values show typical experimental dispersion for data obtained by instruments with similar purposes but dissimilar methods of operation. Except for the S-082B experiment, both the complexity, C, and the maintenance effectiveness, M_E, parameters for these experiments are consistent. The significant factor in the S-082B was the relatively small amount of data it obtained which resulted in a lower value for M_E.

Plots of these parameters versus maintenance effectiveness and complexity are given in Figures 5-2 and 5-3. Each of the parameters of M_E and six of C are shown in the Figures. Data points taken from Tables 5-1, 5-2, and 5-3 are indicated in the plots by the following symbols: + for the ATM experiments, and O for the OV1-10, 17, OSO-7 and S-056. The solid line is drawn to show trends for the data points and is based on a curve of best fit. These plots are useful in postulating such values for other instruments.

Figures 5-2 and 5-3 indicate that use of the analysis developed in this study for a narrow range of instruments used for solar X-ray observations can be extended to include other types of related instruments. The trends shown by the data are significantly more consistent than typical scatter

Table 5-3. Complexity and Maintenance Values for the Scientific Instruments on the Skylab ATM

PARAMETERS	PAYLOADS					
	S-052	S-054	S-055A	S-056	S-082A	S-082B
COMPLEXITY						
1) No. of Major Components	6	8	4	6	4	5
2) No. of Modes	5	4	4	11	4	4
3) No. of Instructions	29	24	19	46	21	31
4) Training Required	4	6	6	6	12	12
5) Automation	1	0	0	1	0	0
6) Data Rate	2.90×10^3	2.37×10^4	2.40×10^3	3.70×10^4	1.67×10^4	50
7) Design Constraints	4	4	4	4	4	4
8) Instrument Req'ts.	3	2	2	3	2	2
9) No. of Objectives	1	1	1	2	1	2
Complexity Factor C	28.0	29.4	23.9	33.3	30.9	28.4
EFFECTIVENESS OF MAINTENANCE						
1) Period of Operation	1.1	1.1	1.1	1.1	1.1	1.1
2) Quality of Data	3.5	4	4	3	4	3.5
3) Quantity of Data	6.86×10^{10}	5.31×10^{11}	3.18×10^{10}	5.57×10^{11}	3.75×10^{11}	1.12×10^9
4) No. of Repairs Made	4	4	1	3	3	2
5) Redundancy	1	0	9	2	1	1
6) Operational Manpower	5	5	7	6	5	5
Maint. Eff. Factor M_E	7.17	8.93	5.91	6.13	7.78	3.57

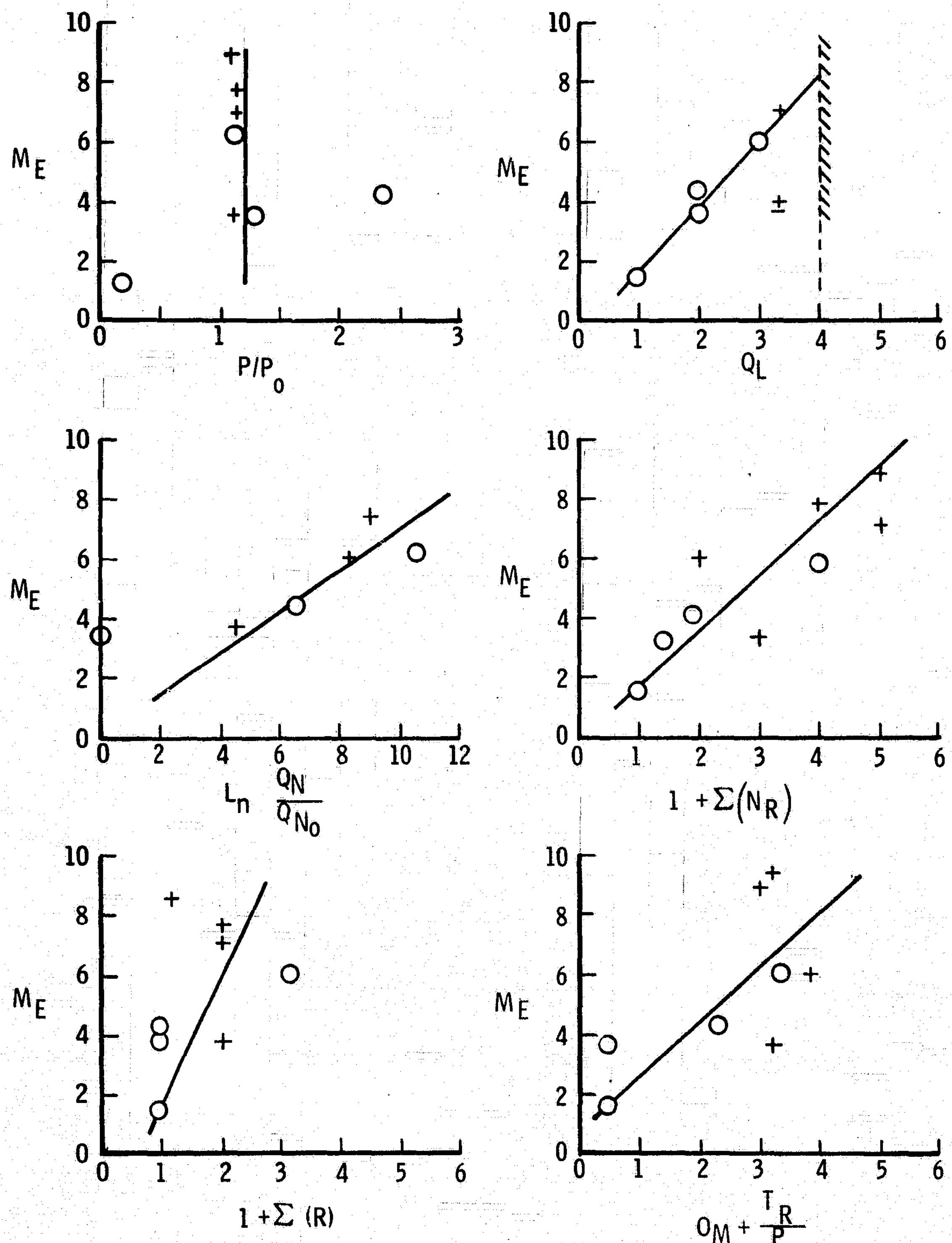


Figure 5-2. Manned Maintenance Effectiveness Parameters for Selected Experiments

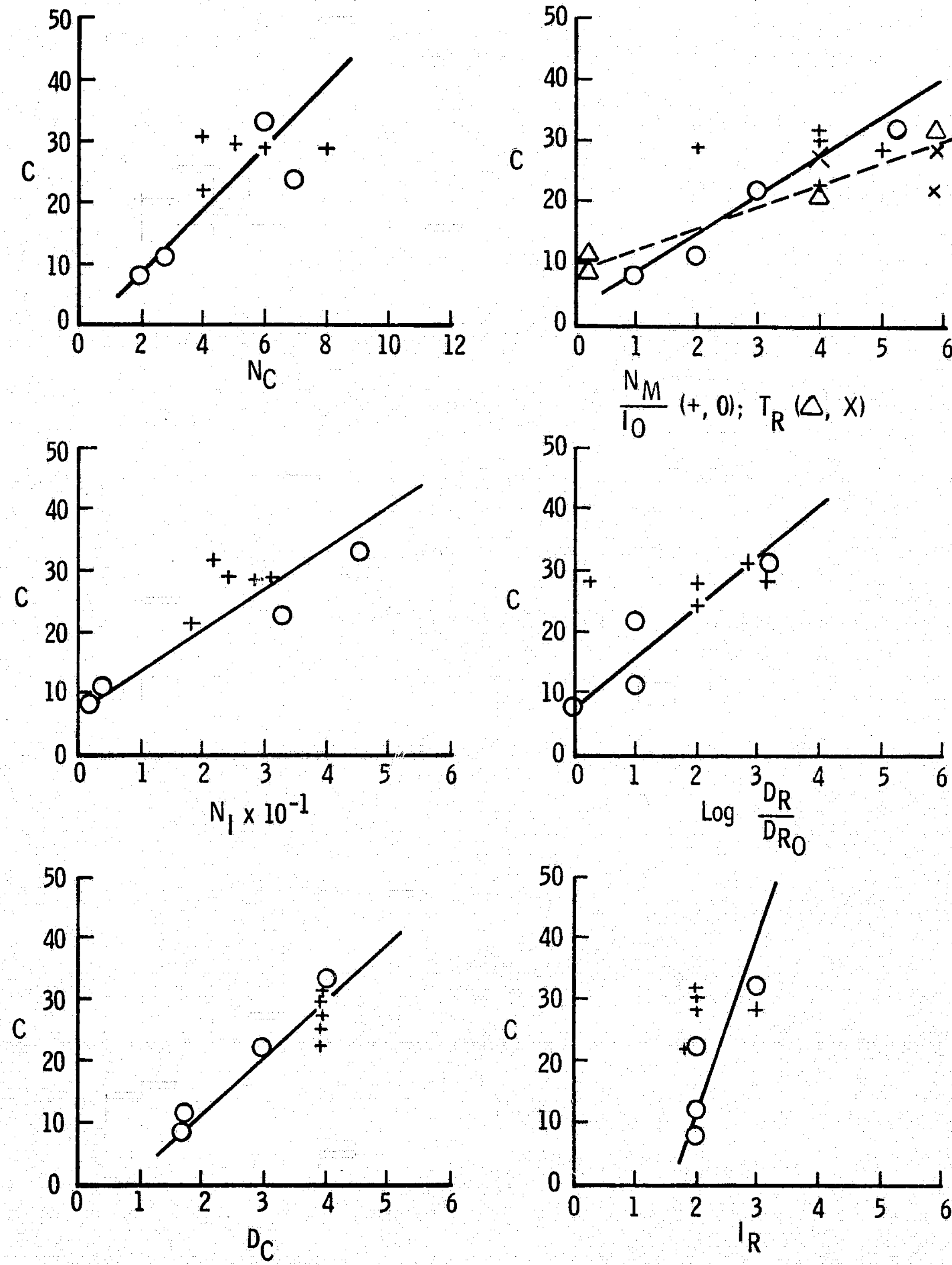


Figure 5-3. Complexity Parameters for Selected Experiments

diagrams of random statistical data. Since all of the points are fit approximately by a slope-intercept line, this indicates a linear relationship between M_E and the maintenance parameters, and C and the complexity parameters. This result is consistent with the assumptions of Equations (1) and (2) that the weighting factors used would give a linear response to the parameters.

5.4 MANNED CONTRIBUTIONS TO MAINTENANCE

In using these results to evaluate the effectiveness of manned maintenance, it is essential to examine the failure histories of the experiments that significantly affected performance and data. Typical failures for the four X-ray type instruments are shown in Table 5-4. Each of these failures resulted in significant degradation of the instrument and required maintenance (where possible) or alteration of the operational mode to minimize loss of data. For each failure, manned maintenance was attempted and every option exercised to correct the problem or to minimize the impact on instrument operation and scientific objectives. The effect of these failures was incorporated into the analysis in estimating the contribution of manned maintenance.

Figure 5-4 is a plot of the complexity for the experiments studied versus the effectiveness of maintenance. Values for the plotted points of the Figure are given in Tables 5-1, 5-2 and 5-3 with the inclusion of failure effects listed in Table 5-4. The open square points show the true values of C and M_E experienced by the three classes of X-ray experiments and the solid curve shows the trend line for these types of experiments.

The solid lines for M_E equal 3 and C equal 4 represent minimum values as explained above. Based on the definitions developed in this study and Equation (2), instrument systems with complexity less than 4 would be marginal or incomplete. Likewise, such a system with maintenance effectiveness less than 3 would be considered as a failure. Thus OV1-10, OSO-7, and S-056 would all have failed without manned maintenance to correct malfunctions early in the flights. OV1-17 could not be repaired and is classed as a failure.

Table 5-4. Histories of Typical Failures of Solar X-ray Experiments

I. OV1-10

1. R. F. interference caused pointer malfunction. Delayed turning on pointer until end of R. F. operations
2. Tape recorder failed after 7 mos

II. OV1-17

1. Scan motor malfunction after 6 1/2 days
2. Gravity gradient stabilizer failed after 7 days
3. Proportional counter turned off after 32 days

III. OSO-7

1. Placed in orbit with sensors oriented 180° from desired. Satellite was stabilized with proper pointing by ground command - occurred within first few days
2. Lost 1st MEM (Magnetic Electron Multiplier) at 6 mos
3. Lost 2nd MEM at 14 mos
4. Lost 3rd MEM at 24 mos
5. Tape recorder failed after 29 mos

IV. S-056

1. Camera cut-off 14 days - restarted by Astronauts
2. Door failed to open 23 days - opened using 2 motors
3. Door failed to open 90 days - required EVA to open
4. Filter #3 failed during middle of SL-3
5. Shut down at about 9 mos

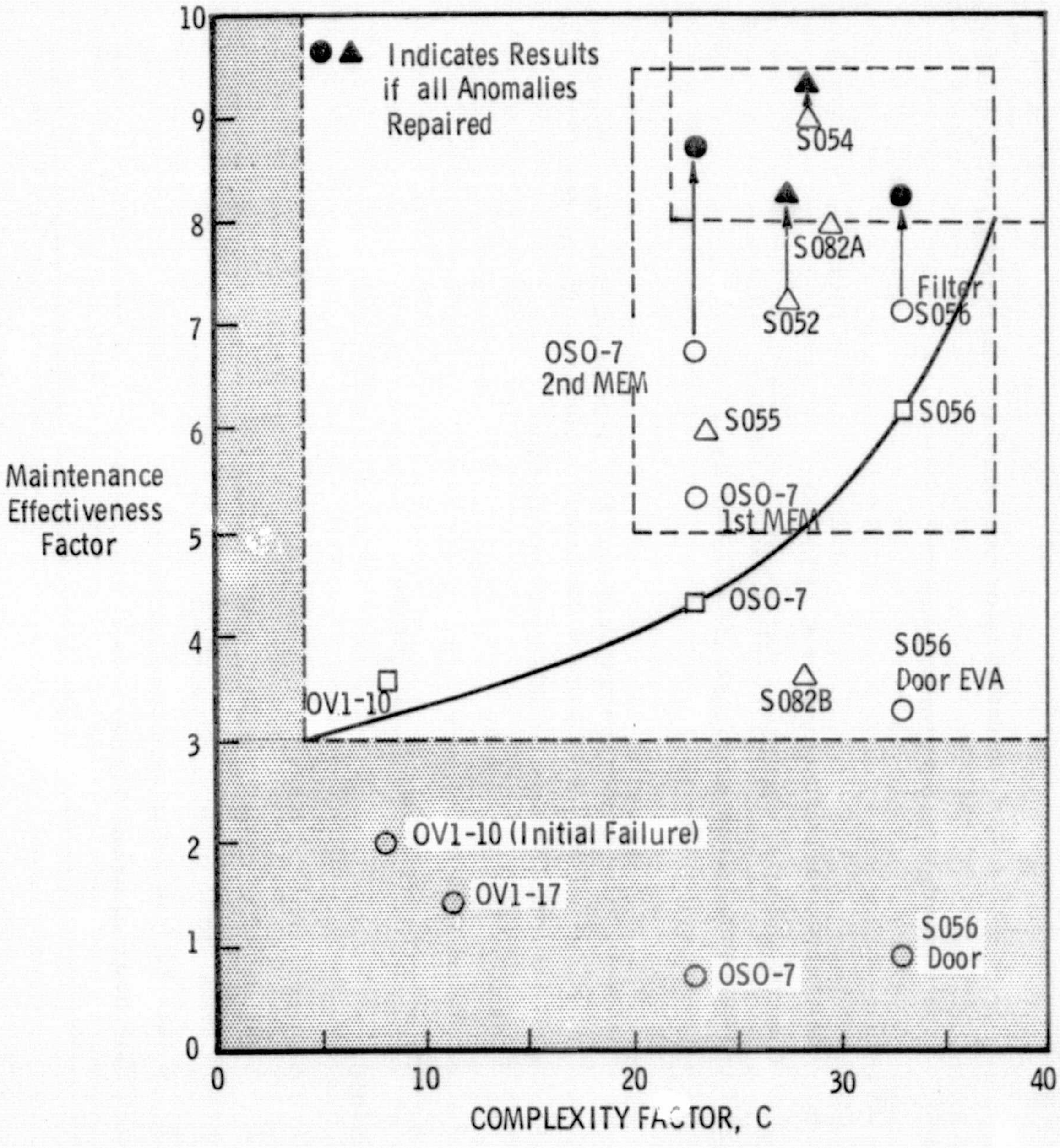


Figure 5-4. Effectiveness of Maintenance versus Complexity

The additional points in Figure 5-4 are for computed values of M_E that would have occurred if maintenance were different from that achieved. In the absence of any maintenance, all of the X-ray instruments would have been below M_E equal 3, hence, failures. These are the open circles in the shaded region of the figure near M_E equal 1. For the S-056, repair of the shutter door resulted in increasing M_E to the intermediate value of about 3 and a second repair increased it to its final value of 6.1. The real values for M_E resulting from actual maintenance are shown by the open square points, that lie on or near the solid trend line curve. Values of M_E for hypothetical maintenance for OSO-7 and S-056 are shown by the circular points above the trend line. For OSO-7, two repairs to the magnetic electron multipliers (MEM) are shown and for the S-056, a filter repair is shown. If 100 percent maintenance had been achieved, the solid circle point would have occurred. Data for the S-055, S-082B, S-052 and S-054 experiments on ATM are also included and indicated by the triangle points.

The values of the maintenance effectiveness parameters used in Figure 5-2 for the OSO-7 and S-056 are listed in Tables 5-5 and 5-6. The column labeled reference condition is for the actual case. For the OV1-10, the reference condition was equal to the 100% maintenance case since failure occurred after the nominal lifetime. Results for these three instruments showing the effectiveness of maintenance based on the data of Tables 5-5 and 5-6 are plotted in histogram format in Figure 5-5. This figure clearly shows the marked improvement achieved by manned maintenance and the potential for increasing effectiveness by complete maintenance and repair. None of these instruments was fully man maintained and, except for minimal redundancy, no repair was possible for a failed part. However, the maintenance available was adequate to ensure that the OV1-10, the OSO-7, and the S-056 were successful to varying degrees. Had this maintenance not been available, all instruments would have failed before obtaining any significant data.

Table 5-5. Effectiveness of Maintenance for the OSO-7 X-ray Experiment

		LAUNCH FAILURE	REFERENCE CONDITION	1st MEM REPAIR	2nd MEM REPAIR	3rd MEM REPAIR
1.	PERIOD OF OPERATION	0	29/12 = 2.4	2.4	2.4	2.4
2.	QUALITY OF DATA	0	2	2.5	3	4
3.	QUANTITY OF DATA	0	5.04×10^9	67/44(1)	82/44(1)	87/44(1)
4.	NO. REPAIRS MADE	0	0.9	1.9	2.9	3.9
5.	REDUNDANCY	0	0	0	0	0
6.	OPERATIONAL MANPOWER	4	4	4	4	4
	M_E	0.50	4.29	5.33	6.72	8.68

(1) FACTOR USED TO RATIO QUANTITY OF DATA IN BASELINE

Table 5-6. Effectiveness of Maintenance for the S056 X-ray Experiment

		23-DAY DOOR FAILURE	DOOR FAIL EVA	REFERENCE CONDITION	FILTER REPAIR	USE ALL FILM
1.	PERIOD OF OPERATION	0.091	0.366	9/8.2 = 1.1	1.1	1.1
2.	QUALITY OF DATA	1	2	3	3.5	4
3.	QUANTITY OF DATA	0.75/9(1)	3/9(1)	5.57×10^{11}	1(1)	1.32(1)
4.	NO. REPAIRS MADE	0	2	3	4	5
5.	REDUNDANCY	2	2	2	2	2
6.	OPERATIONAL MANPOWER	6	6	6	6	6
	M_E	0.90	3.25	6.13	7.10	8.24

(1) FACTOR USED TO RATIO QUANTITY OF DATA IN BASELINE

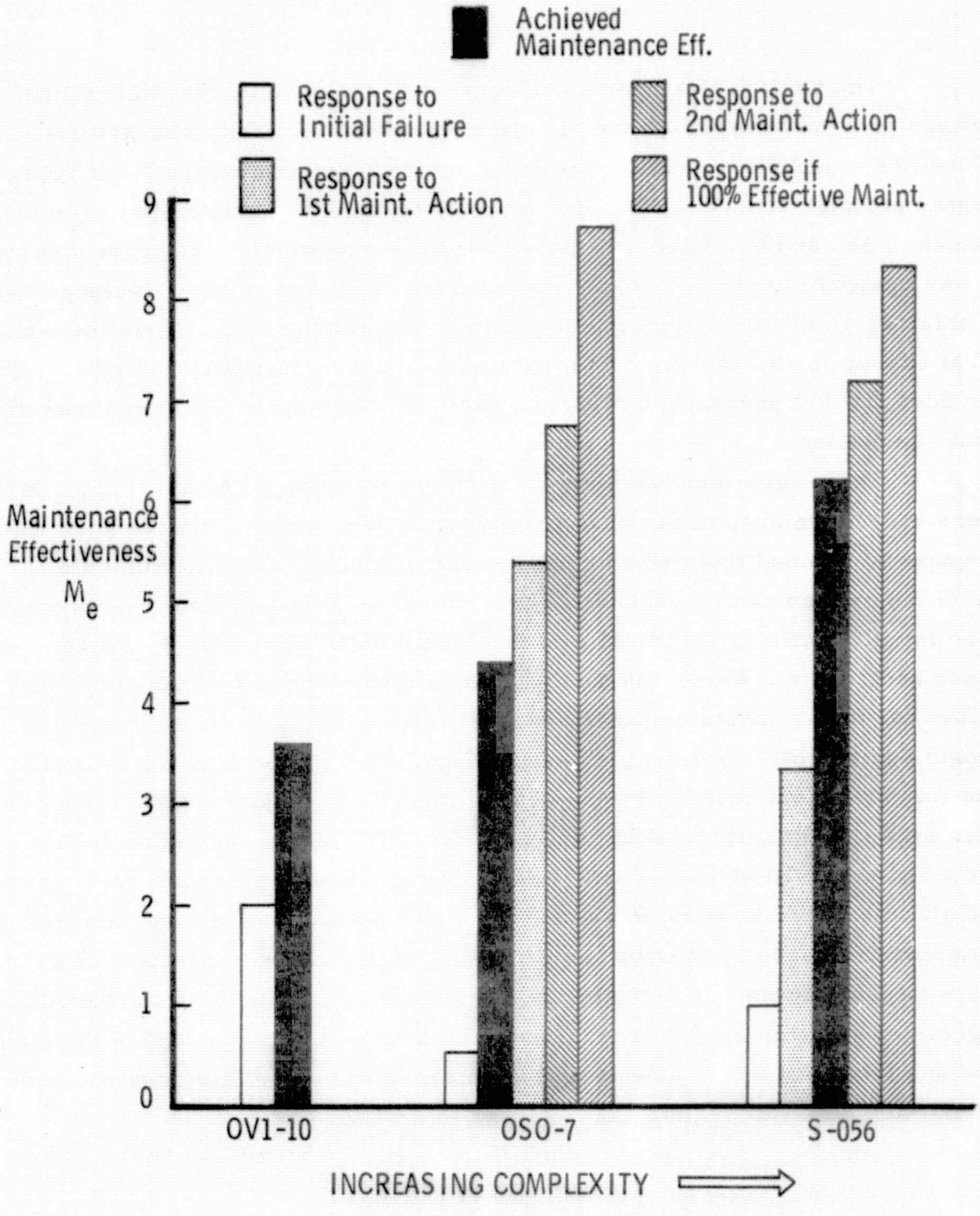


Figure 5-5. Maintenance Effectiveness for Three Types of X-ray Instruments

The rectangular region of Figure 5-4 enclosed by the dashed line defines an area of maintenance effectiveness and complexity characteristic of limited manned maintenance realized by the ATM experiments. It represents the range of levels achieved in the instruments evaluated based on actual values of M_E and C. Experiment S-082B falls outside of this region; however, it was designed for limited data, and consequently, lower M_E. Included also in this region are the hypothetical points of M_E for the OSO-7, and the other ATM experiments, had complete maintenance and repair been provided. This includes the 100 percent maintenance case for perfect operation and maximum data acquisition.

This region indicates the consistency of these ATM instrument parameters and the validity of the analytical method developed to measure the effectiveness of manned maintenance for a class of space-based instruments. Since the method can be generalized, it should be applicable to other systems used for scientific or technical measurements with partial manned maintenance and repair. Results of this study can also be used to define boundary values for future instrument systems that utilize man fully to maintain and repair equipment. This can be seen in Figure 5-4 by the upper part of the plot for the region bounded by the dashed lines at M_E equal 8 and C equal 22. This area includes the hypothetical points of 100% maintenance and repair if parts and capabilities had been available to repair or replace any failed part and all data possible were obtained. This defines an area of ideal manned maintenance that fully utilizes the capability of man in the operation of a space-based system. It is to this region that future manned space-based experiments should be directed in order to achieve the highest level of scientific and technical effectiveness and to optimize the value of a program based on cost and effort to realize these goals.

6. MANAGEMENT CAPABILITY

6.1 BACKGROUND

Since the contribution of man to the operation of any scientific or technical instrument system extends beyond repair and maintenance, study of his contributions to management was also included. The purpose of this part of the study was to identify the functions of management in instrument operations, and to evaluate the unique contributions of man for a space-based system. This included a wide variety of levels of manned involvement in management from simple switching functions to hands-on operation.

The method of evaluating management effectiveness developed for this study is similar to that used for maintenance as described in Section 5. Parameters adopted for the management evaluation are based on discussions with several of the Principal Investigators of the ATM experiments and ground-based research groups who supported the Skylab missions as well as one scientist-astronaut. From these discussions, six parameters were selected that best define the unique contribution of man to the management of space-based experiments.

6.2 MANAGEMENT EFFECTIVENESS DEFINITIONS

The parameters used to define management effectiveness are:

1. Availability of Management (A_M). The fraction of total time that manned attendance is available to supervise and operate an instrument. This does not require continuous attention to the details of operation but availability of man and access to the instrument when necessary. The number of individuals who participate in management of the experiment and operate equipment is not a factor of this parameter. Alternate methods of remote operation are not included in determining A_M.
2. Schedule Changes (S_C). The number of times per day that the operations crew instigated a change in the regularly scheduled observing or operating program to obtain other data. Such changes are made because of new information obtained from real-time observations that occurred after the daily planning meeting. This information is developed from the space-based

instruments and not from ground-based support observations. Each change in observing is counted if it is not to return to the regularly scheduled program.

3. Planning Observations (P_O). The number of observations made by the instruments per day and used for planning the daily observing program. These observations may be either in real or post-time and used later. However, to be counted an observation must be used for planning even if not for the next day. Observations that were made but not used are counted if they were intended for use in planning.

4. Instrument Changes (I_C). The number of times per day that changes in instrument operating mode were made to accommodate the observing program. This includes the regularly scheduled program as well as the unscheduled changes included in category 2 above. Routine mode changes associated with a particular type of observation are not counted separately. Repair or maintenance changes are not counted in this category.

5. Real-Time Observations (O_B). The number of observations made per day in real-time for technical or scientific purposes. These observations are separate from those made in support of planning observations in category 3 above. Duration of these observations may be limited to telemetry passes over a ground station and restricted to part of the complete instrument system provided that they are examined by the operation's staff.

6. Data Quality Increase (D_Q). The incremental change in the quality of data resulting from manned management of the experiments. This is based on an estimate by the experimenter of data quality enhancement. Quality includes all factors that contribute to realizing the scientific objectives from data obtained with the instrument. The scale of data quality is defined in Section 5.2, second paragraph.

Values obtained for these parameters for the OV1-10, OSO-7, and S-056 are listed in Table 6-1 with the value of M_A, the management effectiveness value. The definition of M_A developed for this study is given by

$$M_A = A_M + S_C + P_O + I_C + O_B + D_Q \quad (3)$$

Table 6-1. Management Effectiveness Parameters for X-Ray Experiments Evaluated

	SYMBOL	OV1-10	OSO-7	S056
1. AVAILABILITY OF MANAGEMENT	A_M	0.1	0.2	1.0
2. SCHEDULE CHANGES	S_C	0.1	0.5	0.5
3. PLANNING OBSERVATIONS	P_O	0	2.0	2.0
4. INSTRUMENT CHANGES	I_C	0	1.0	5.0
5. REAL-TIME OBSERVATIONS	O_B	1.0	2.0	1.0
6. DATA QUALITY INCREASE	D_Q	0	0	1.0
M_A		1.2	5.7	10.5
NOTE: VALUES ARE GIVEN ON A PER DAY BASIS				

where the terms of Equation (3) are defined by 1 through 6 above and no weighting has been assigned any of the parameters. Plots of each of these parameters for the X-ray experiments versus M_A are given in Figure 6-1. Because of the limited number of examples studied, trend lines have not been included, as for maintenance parameters. It is evident that the management parameters may not lead to a linear trend line, since program and mission objectives will determine the degree of manned management at the experiment level in flight. The principal purpose of these plots is to indicate variations in the individual parameters for a program and instruments that can be used as guidelines in improving performance. The shaded, horizontal lines, in Figure 6-1, represent upper bounds for the trend lines.

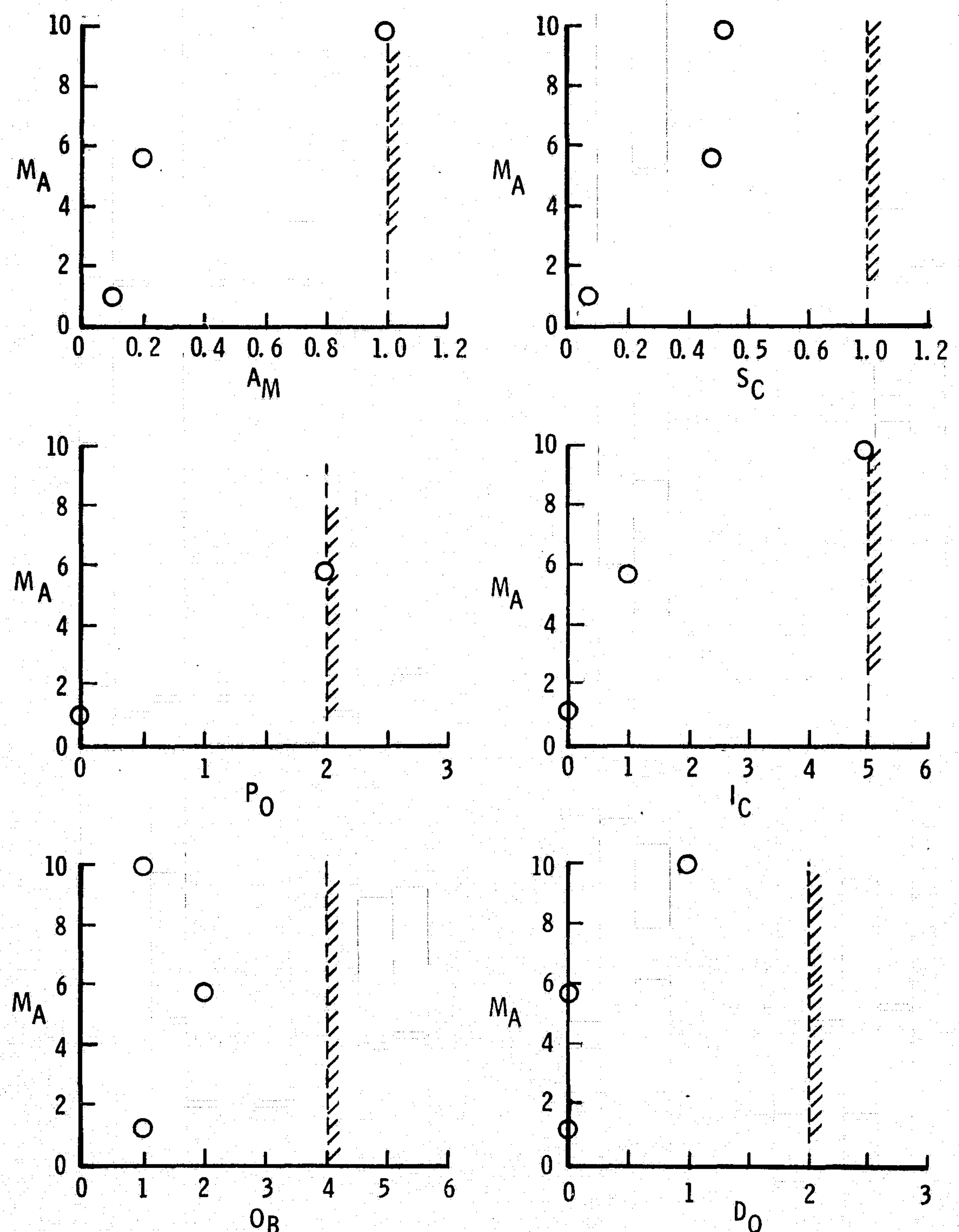


Figure 6-1. Management Effectiveness Parameters for the Three X-Ray Experiments Studied

6.3 MANNED CONTRIBUTION TO MANAGEMENT

A plot of the management effectiveness parameter, M_A, for the OV1-10, OSO-7, and S-056 versus the complexity for these experiments is shown in Figure 6-2. There is a marked increase in M_A associated with the increasing participation of man in the management of the experiments. Based on the definition of M_A from Equation (3), this result might have been expected; however, the benefits to the program from increased management effectiveness can be objectively assessed in evaluating both the numerical estimate and the scientific accomplishments. In the latter category particularly, the results indicate significant improvement with increasing manned management.

This is verified by the ATM experience, that showed increased reliance upon onboard management as the mission progressed.

The management function, like the maintenance function, can certainly be increased significantly by mission planning and instrument designs that utilize man effectively. To do this, it is necessary to examine critically how man can function in an optimum way in experiment operations, and to develop a program with man as an integral factor and not as a spectator or casual participant. Increased system complexity is inherent in the development of new scientific instruments.

The need to improve management effectiveness as instrument complexity increases is apparent from the trend line presented in Figure 6-2. Special efforts must therefore be employed to exploit man's capability to assure that the trend toward more effective operations is maintained. In the limit, man should have the same freedom of management authority in space as with existing ground-based observations.

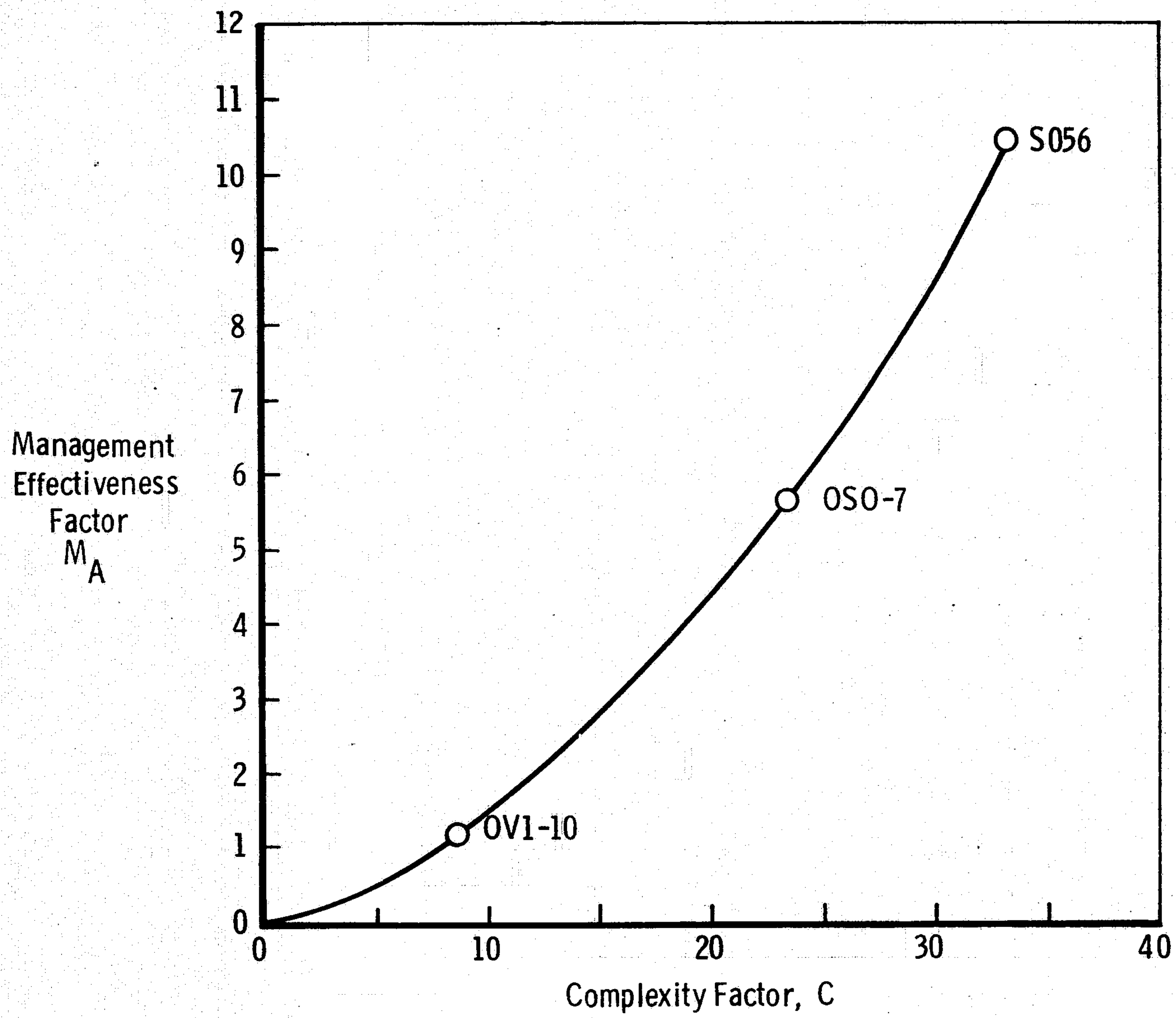


Figure 6-2. Management Effectiveness Factor versus Complexity for the Three X-Ray Experiments Studied

7. APPLICATION TO FUTURE PROGRAMS

The assessment of past programs, such as, the Skylab/ATM experiments, provides valuable insight when considering future program applications. This background has been employed in two ways: to establish trends that show a value improvement with the introduction of manned support, and to assist in the definition of typical repair actions that would improve the probability of achieving a high system availability. Both of these approaches are presented in this section, each having its own merits relative to the value of man in the role of orbital maintenance.

7.1 EXTRAPOLATION OF HISTORICAL RESULTS

Results of this study to evaluate the effectiveness of man in management and maintenance, as discussed in Sections 5 and 6, show a marked improvement in both areas with increasing involvement of man. Based on the analysis developed here, i.e., to represent the results as a plot of the effectiveness of man versus instrument complexity, this improvement can be quantified and used to evaluate other systems and to provide guidelines for future programs such as the STS. The consistency of these numerical representations for a small sample of similar instruments is particularly encouraging for extrapolation to more complex instruments that utilize man even more effectively. This latter possibility is particularly significant, since none of the examples used in this study critically tested the full potential of man in conducting space-based investigations.

The Skylab/ATM was the most advanced system to date in terms of manned utilization. However, most of the instruments were not designed for maintenance and repair, and many of the operations were sufficiently automatic that only monitoring was required. This resulted in significant improvement in performance over other unmanned instruments with remote monitoring but was substantially less than could be achieved. For the ATM instruments, that could be compared with the OSO, the principal achievement was in simplifying the operating controls by modifying telemetry and command with the addition of manual switches. No advances were made in operations or maintenance. Diagnosis of failures and repairs for the ATM were similar to OSO except for simple mechanical adjustments, such as, opening a jammed door. No provision was made for replacing damaged or failed parts, except for the cameras that were changed during EVA.

An estimate of the additional gain in performance of the ATM for the case of ideal maintenance, shown in Figure 5-4, indicates an upper bound on effectiveness of manned utilization for typical ATM instruments. Although there is dispersion in the values of the effectiveness parameters between the various ATM instruments, the consistency is sufficiently high to warrant extrapolation to future systems that could incorporate manned operation. Future concepts should, in general, provide a substantial improvement in performance with an inherent increase in complexity. This relationship should follow the trend line of Figure 5-4. However, a necessary condition for this to occur is the development of improved maintenance methods, including diagnostic and testing techniques. Such techniques are routine in ground-based systems where high availability is desired. Their inclusion in space-based systems can provide the capability necessary to maintain highly complex instruments and with an M_E greater than eight as shown in the upper part of Figure 5-4

7.1.1 Empirical Value Function

A crucial factor in determining the level of performance is the cost to achieve it. Unless the value of a program, measured in terms of results obtained per unit of cost is optimum, alternate methods should be evaluated. The difficulty in defining a value function is estimating what factors can be counted as results and what weighting is assigned. For similar instruments, such as those evaluated in this study, any consistent method can be used since the analysis is based on nearly identical results.

The method adopted for this study is based on quantity and quality of data as the principal product of the experiment with the cost of the instrument, excluding vehicle launch costs, as the normalizing factor. The use of these parameters in defining value is based on the assumption that a program was successful if the instruments obtained all of the data desired and the quality was high. Total data obtained in bits as defined in Section 5.2 were used for quantity. As in Section 5, a weighting factor of $\log_{10}$ was adopted to limit the scale of data quantity which varies greatly. Further, as discussed in Section 5, the value of data to the scientific and technical objectives of a program will decline with volume. The exact formula for weighting the data quantity factor will depend on the instrument and program objectives. For the instruments evaluated in this study, either a $\log_{10}$ or Ln_e appears appropriate. Quality of data is equally critical to success of the program and, regardless of volume, will limit the ability of an instrument to satisfy objectives. The scale of quality is 0-4 as previously discussed. The numerical value of the value function is defined by:

$$\text{Value Function,} \qquad V = Q_L \log_{10} \left(\frac{Q_N}{M}\right) \tag{4}$$

where Q_L is the quality of data, Q_N is the quantity of data and M is the cost of the experiment in dollars. Values of Q_L and Q_N were defined in Section 5 and are tabulated in Table 5-1.

Values of V determined by Equation (4) for the OV1-10, OSO-7 and S-056 are shown in Figure 7-1. These are plotted versus the complexity for each of these experiments as was done for M_E and M_A. The trend line that is drawn through the points shows a strong increase in value function for increasing use of manned operations in maintenance and management. These results clearly demonstrate the advantages of manned operation based on the parameters of data quantity and quality in satisfying the technical and scientific objectives of the programs.

The increase in value function for these experiments is particularly significant, since the cost of the experiments increased also. These cost increases, however, were less than the much greater increase in the

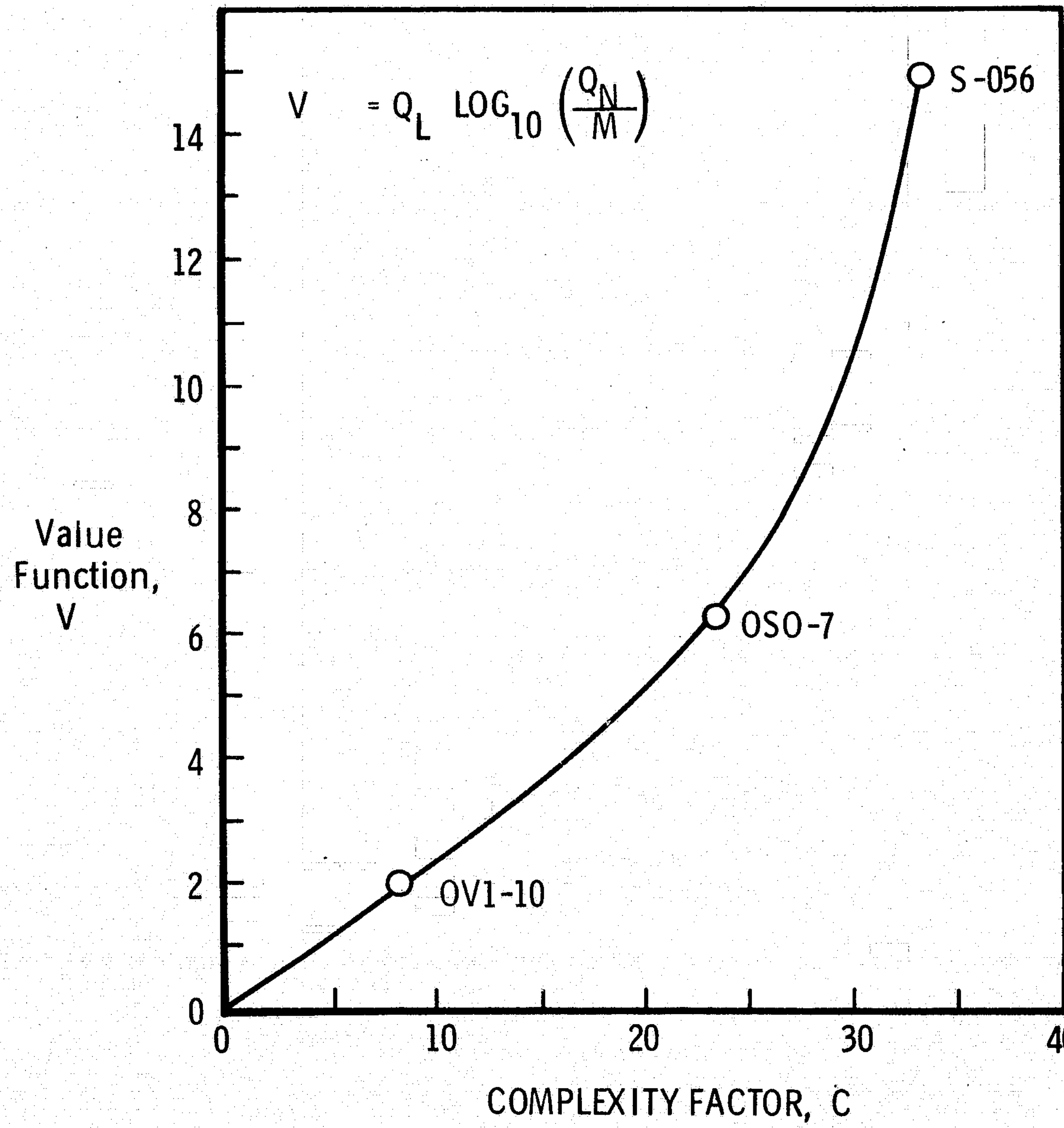


Figure 7-1. Relative Value of X-Ray Experiment Operations

scientific objectives realized by quantity and quality of data. For other payloads with different objectives, the value function must be determined from other parameters. In the future, costs can be expected to continue to increase, and it will be necessary to develop methods of increasing the return from instruments to keep the value function from declining. This can occur if an optimum system can be developed that increases the management and maintenance parameters as instrument complexity continues to increase.

The trend line in Figure 7-1 indicates that with increasing complexity greater value can be expected. This has obvious limitations since the instrument complexity cannot be increased indefinitely for a fixed level of manpower. Examples of sophisticated ground-based systems can provide guidelines for evaluating optimum space-based systems that extend the value function without reducing success by excessive complexity. A study to define possible operational methods for manned maintenance and management could provide detailed data to estimate the complexity and value function for systems beyond the ATM.

7.2 MAINTENANCE REPAIR TRADEOFFS

The review of the Skylab experience as discussed in Sections 5 and 6, and the redesign effort of Section 4 have provided the necessary background to allow assessment of the overall reliability characteristics relative to the benefits of space maintenance. These benefits can then be compared to alternative measures of achieving proposed mission objectives that may evolve in the future.

The results apply specifically to scientific equipment, similar to the S-056 X-ray telescope, that consist of unique concepts as opposed to mature operational systems, such as communication satellites. In addition, because these types of instruments represent an extension of the Principal Investigator's Laboratory, it should be recognized that it is difficult to obtain valid reliability data relative to the sensor portions of the instrument. And, as the experience of the ATM experiments prove, few of the failure occurrences would have been exposed by a classical reliability analysis anyway. This merely emphasizes the need to improve and augment these analytical techniques because hindsight has shown that with little impact on the original designs, the vast majority of anomalies that did occur could have been easily eliminated had they been considered. Also the reliability of electronic components has improved to the extent that remaining problem areas usually relate to mechanical and electro-mechanical elements that are not readily made redundant.

Consequently, an alternate approach has been employed to arrive at quantitative values that demonstrate the basic characteristics common to these types of equipment. This approach employs a simplified Fault Tree with a supporting failure assessment to demonstrate the basic character of the S-056 instrument and relates this to the ability to meet the desired mission availability. Availability, in this context relates to the ratio of the time the instrument is operational relative to the planned operational period. It is assumed that the quality and quantity of desired scientific data is obtained under these conditions.

The S-056 Fault Tree is developed to the basic element block, indicating typical failures that could be employed to develop the Tree further. The top event is "Failure to Achieve Scientific Objectives" as shown in Figure 7-2. In following this Tree, it should be remembered that all possible failures are not identified, only those that contribute to the top event. Also, no account of failures induced by interface support equipment has been considered, such as ATM power failures; the interest here is limited to the S-056.

There are two reasons why mission objectives may be compromised: failures occur that are not detected and, therefore, stimulate no action during equipment operation; and failures that are detected, but for one reason or another cannot be corrected. All occurrences can be grouped into these two categories. Further, the principal interest lies in the area of incidents requiring repair action rather than consideration of why the repair was not performed. If a new design were being developed, this latter point would be

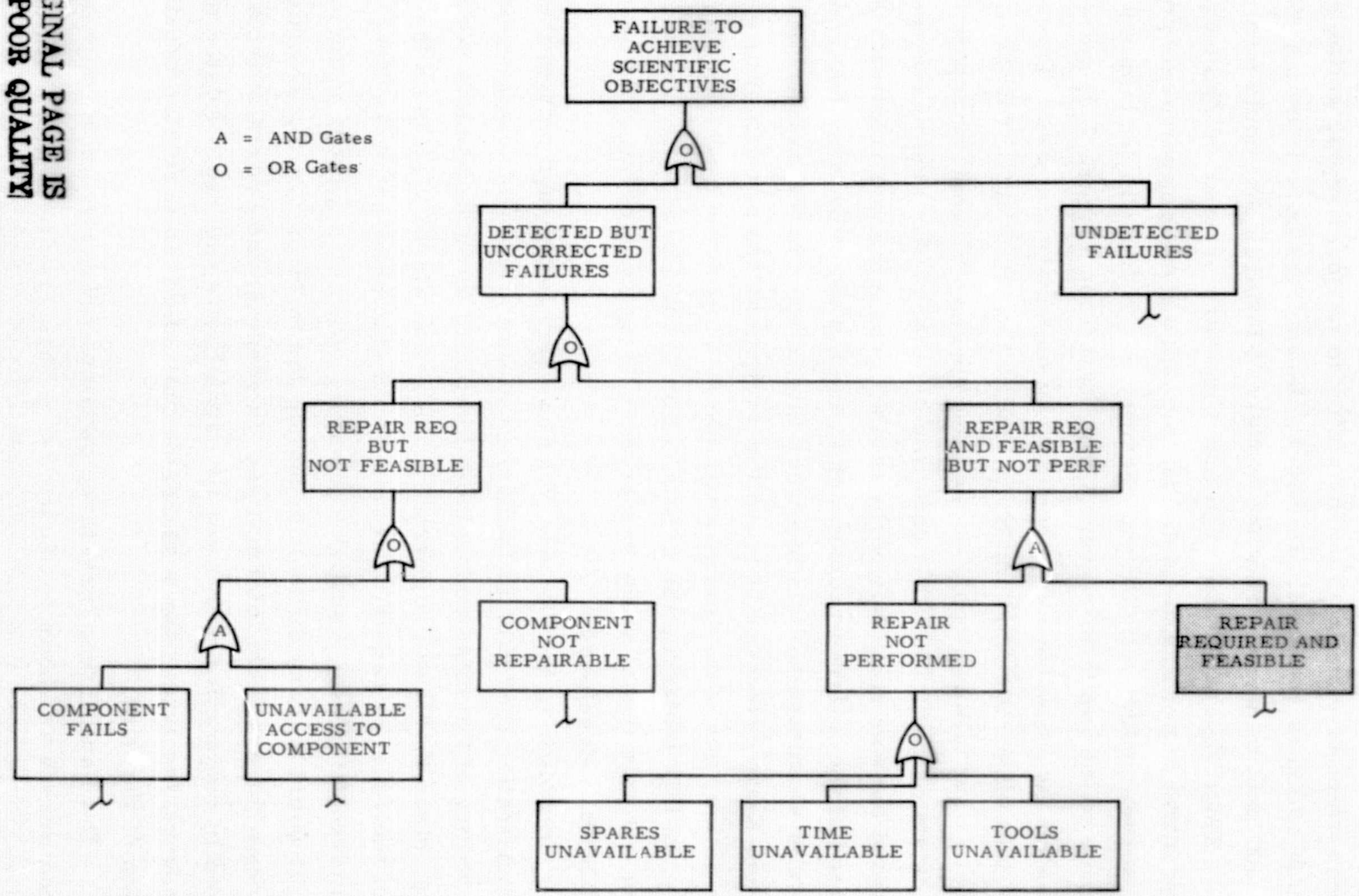


Figure 7-2. S-056 X-Ray Telescope Fault Tree

very important as it reflects on the ability to perform repair action given that such action is required. However, the interest here is on the "Repair Required" path to demonstrate the variety of failures that could occur.

This "inverse" thought process is characteristic of Fault Trees in that the intent is not to establish how to ensure a system performs correctly as in "success path" reliability diagrams, but rather which elements could contribute to the top failure event. The first Tree (Figure 7-2) merely establishes the organization to be followed on subsequent Fault Trees to assure that all events and conditions lead to the top event. The Tree then considers what failures could occur, irrespective of whether repair capability exists or not. The AND gate implies that repair could have been performed but was not. Normally an AND gate implies a relatively low likelihood of the failures propagating to the top event because two conditions must exist simultaneously. However, this is rare in the case of the existing S-056 X-ray telescope because the equipment was not designed for repair action, nor were spares available to support such action. Consequently, in this instance, the repair action branch is of little interest, pointing out only that if a new design were being considered, this branch should be fully developed.

In addition, the "Repair Not Feasible" is pursued only to the point of demonstrating that certain failures of major structural items would also cause failure of the mission but their likelihood of occurrence is very low. Finally, since there was no formal monitor and alarm system on the S-056, most of the failures requiring repair would also show up on the Tree of unmonitored failures. Although anomalies would be apparent on the control panel, it would be very difficult to isolate the failures for repair action based upon the available information. In general, the degree of isolation required in conjunction with a repair capability is inversely related to the repair level; the larger the replaceable unit, the less precision required in isolation of the fault.

The Fault Tree, therefore, develops primarily on the repair required branch as shown in Figure 7-3. This Tree provides a view of those

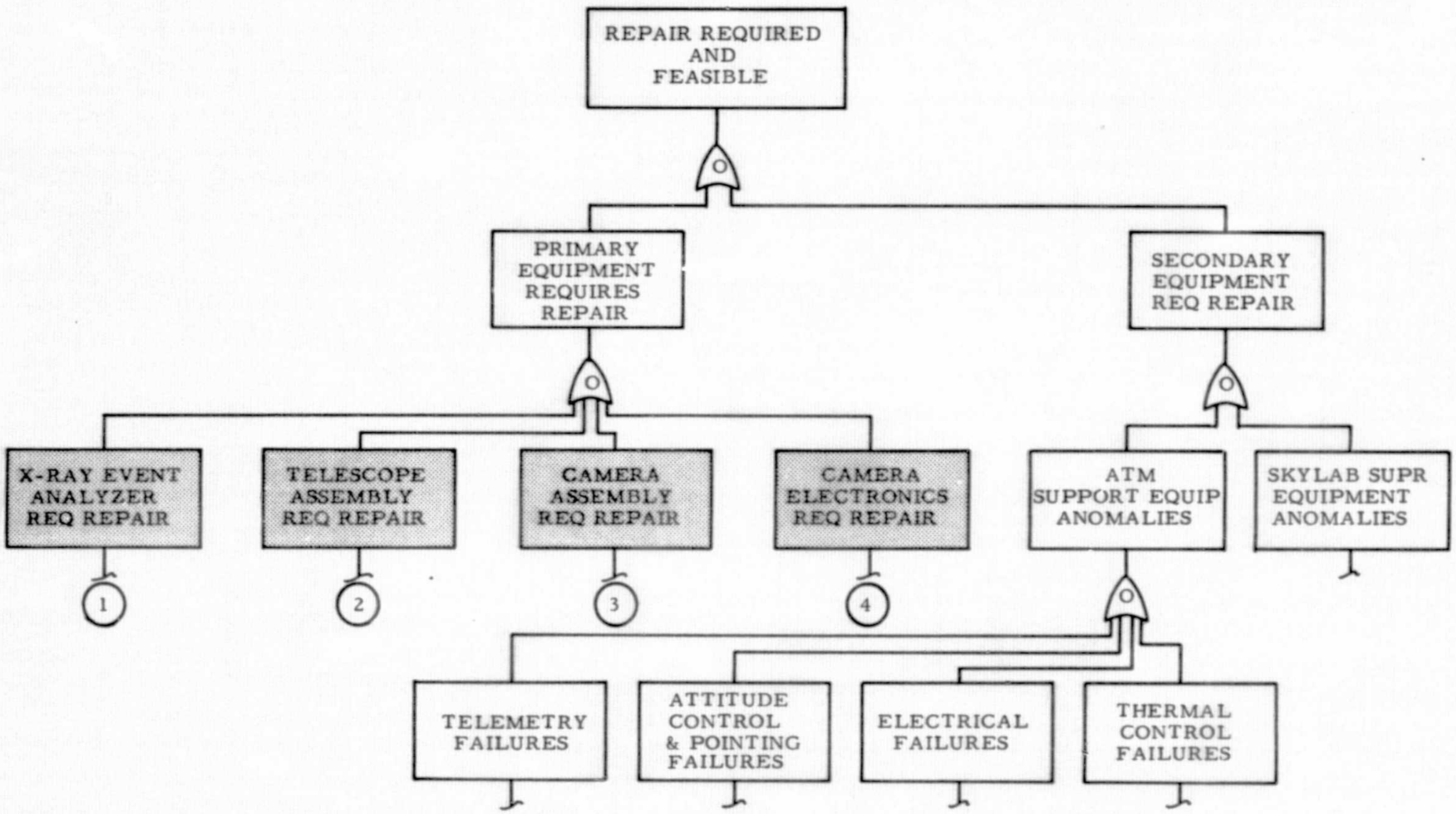


Figure 7-3. S-056 Second Level Fault Tree

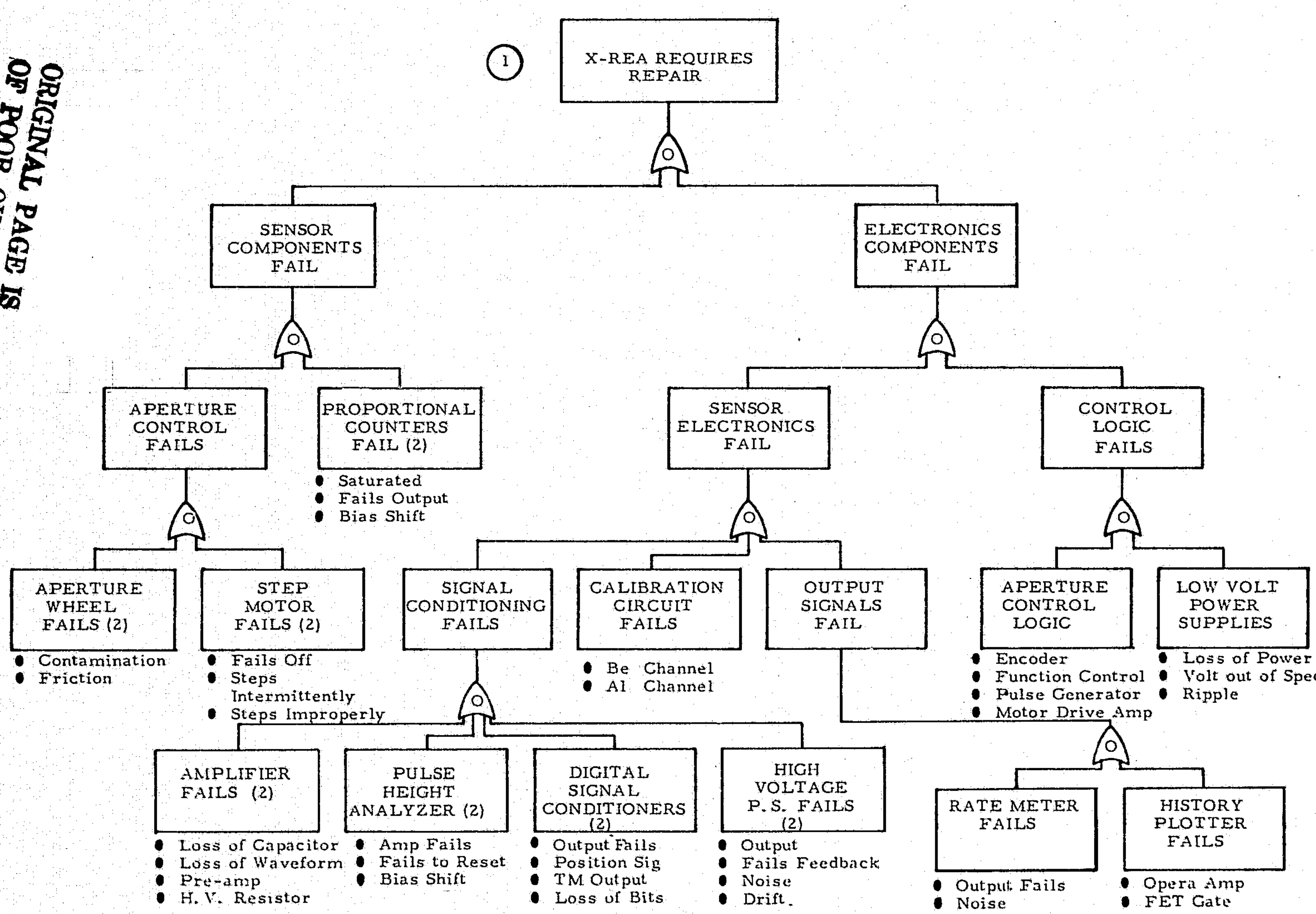


Figure 7-3. S-056 Second Level Fault Tree (Continued)

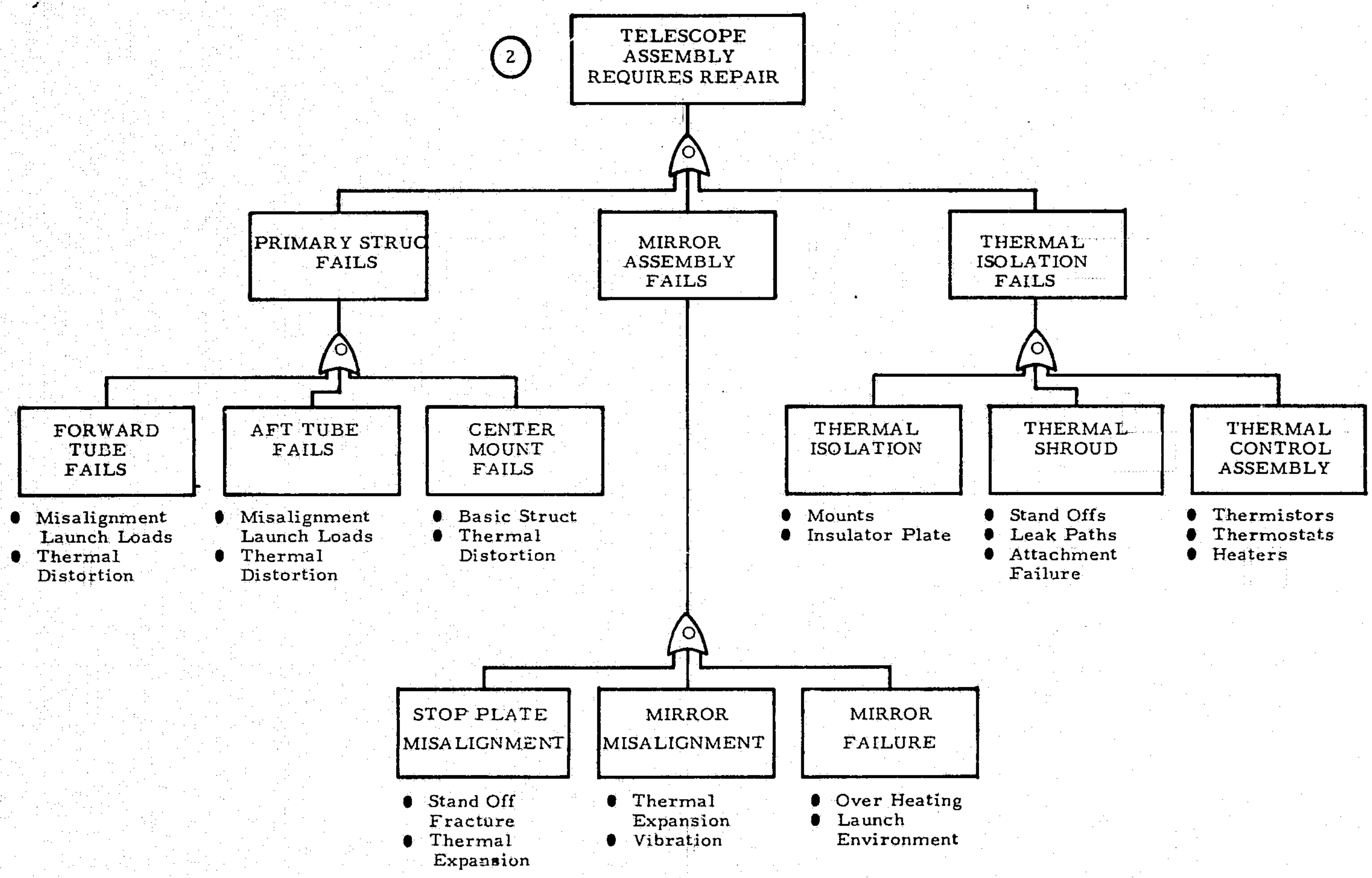


Figure 7-3. S-056 Second Level Fault Tree (Continued)

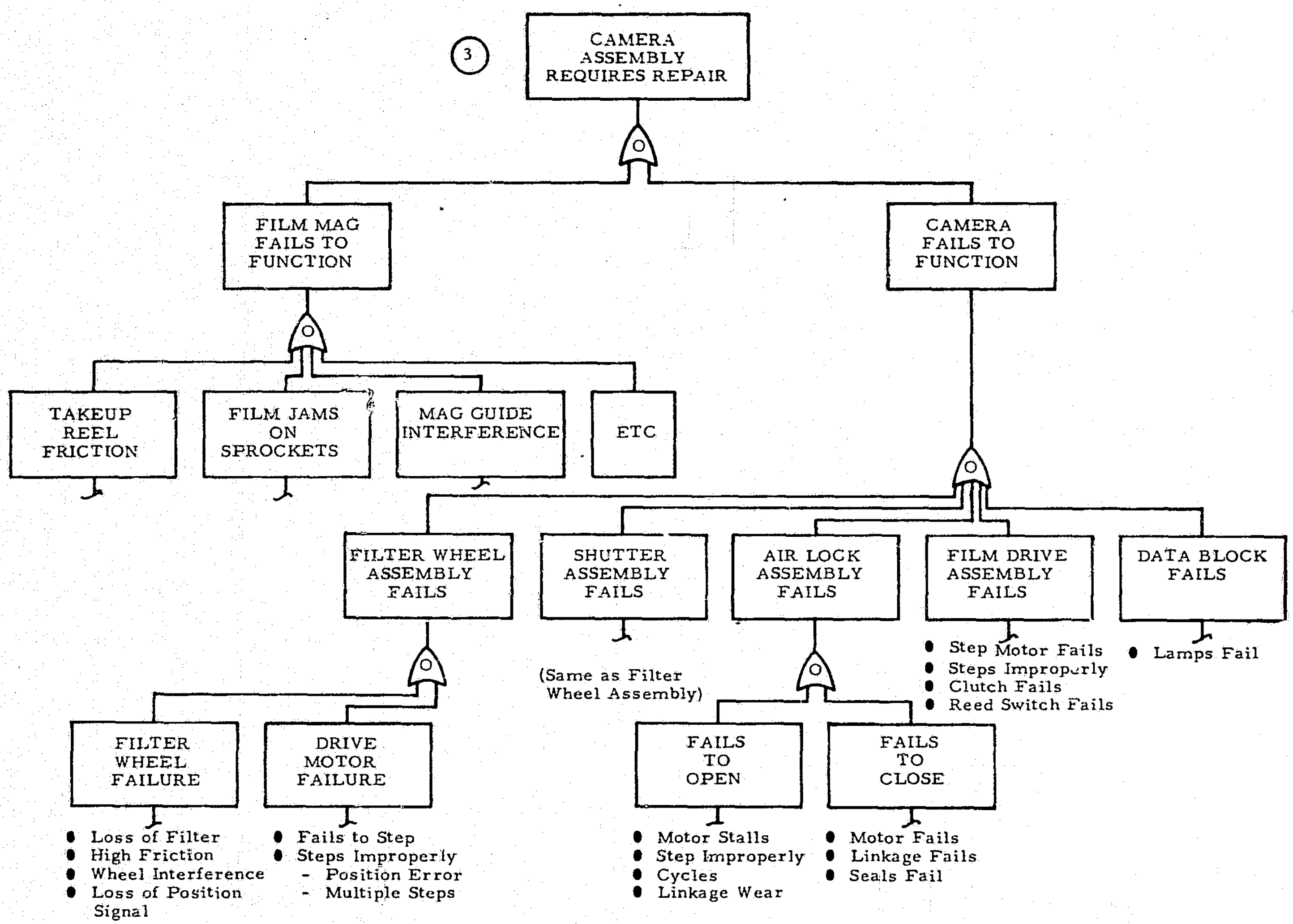


Figure 7-3. S-056 Second Level Fault Tree (Continued)

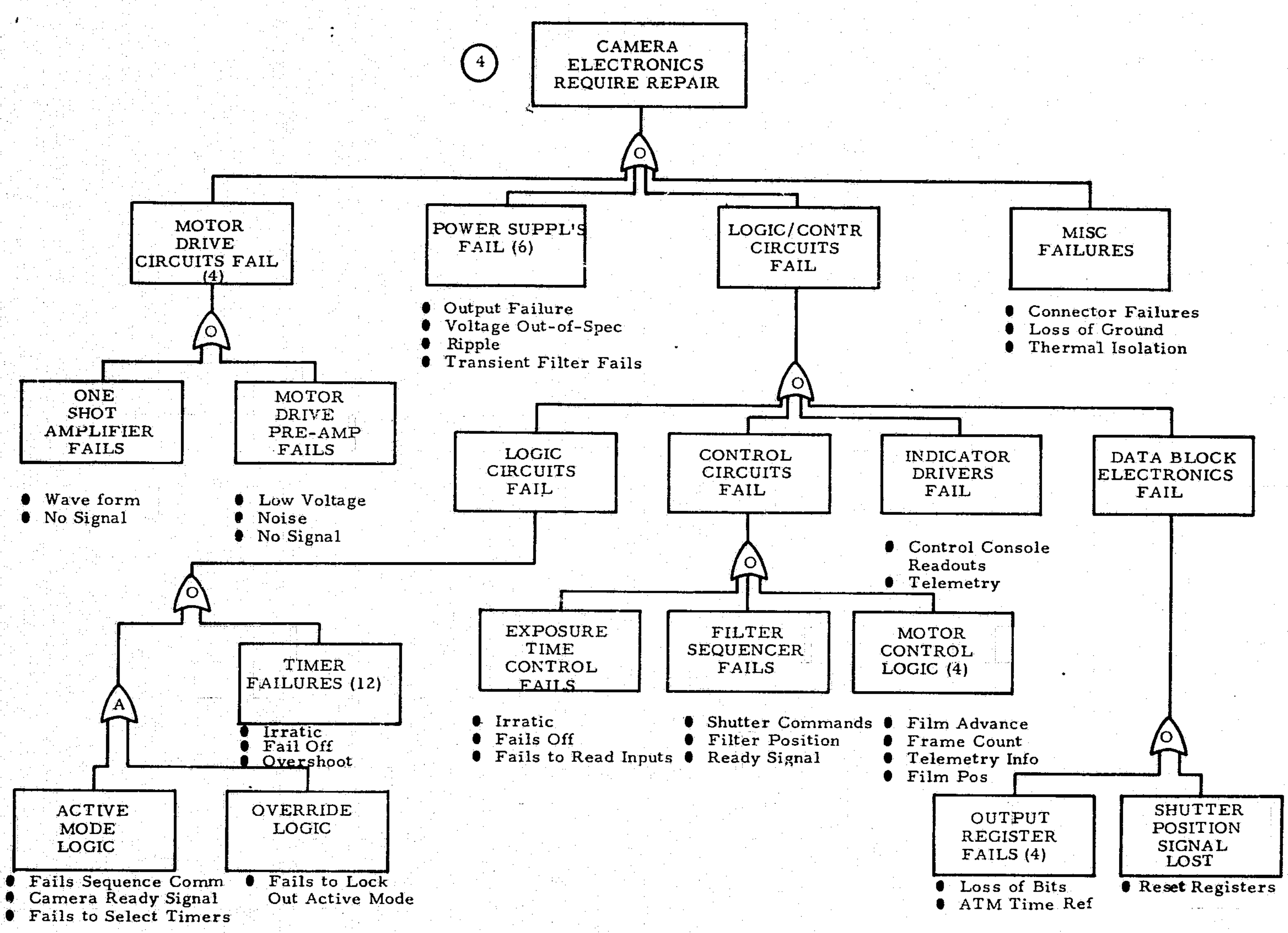


Figure 7-3. S-056 Second Level Fault Tree (Continued)

items that, if not repaired, could lead to failure of the mission. It should be recognized that in the classical reliability sense, many of these conditions are not quantifiable in terms of failure rates or failures per cycle. These are instead, problem areas that typically occur with complex scientific space instruments. As such, the Tree provides a road map of potential problem areas that should be closely scrutinized during the design and testing periods. In the case of the S-056, many of the items on the Tree represent hindsight, having the benefit of post flight assessments. However, experience has shown that the elements of the Tree, although not extended in depth, are representative of problem areas that should be observed in future design efforts both for Spacelab and free flying instruments.

The Tree does serve another purpose: quantifying the effect of various anomalies. If this were a preliminary design effort, expected failures would be estimated for each block on the Tree and the Tree could be used to aid in achieving a balanced design. Where valid information exists, it is also possible, through Boolean algebra, to estimate the probability of occurrence of the top event. However, even with the lack of definitive information and with engineering judgment, the Tree can be very useful to demonstrate the influence of repair capability to preclude the top event from occurring. This is accomplished in the following manner. Each of the items on the Tree can be represented as contributing to the total unreliability of the S-056. As presented in Section 4, the overall reliability of the S-056 is estimated to be approximately 22 percent. This, of course, relies heavily on experience because it is not possible to perform an indepth analysis, but it is felt to be realistic and representative of these types of instruments. Therefore, all of the elements represented on the Fault Tree must compose the total unreliability of the system, or a probability of failure of 78 percent. The question then is the distribution of the failures, and how this distribution influences the ability of repair actions to maintain the instrument.

The elements of the Tree are tabulated into a failure characteristic table as shown in Table 7-1. This is only a sample to demonstrate the

Table 7-1. Sample of Failure Characteristics

INSTRUMENT S-056 X-RAY TELESCOPE PAGE 3 of 11

Sub-Assembly	Component	Failure Modes	RLOC*	Single Point Failure	Repair Poss	Repair Action
CAMERA ASSEMBLY	Film Magazine	● Drive fails to engage ● Film take-up fails due to high load ● Film becomes brittle ● Idler sprocket drag ● Latching pawl fails to engage ● Latching pawl fails to disengage	6	Yes	Yes	Crew remove and replace film magazine assembly. If repeated action fails to remove magazine, terminate mission
	Filter Wheel	● Loss of filter material ● Step motor fails off ● Step motor steps improperly ● Filter wheel jams	5	Yes	Yes	Stepper motor and filter wheel are replaceable by manned action - manual adjustment of guides possible with proper tool
	Rotary Disc Shutter	● Motor fails off ● Motor steps improperly ● Shutter guide friction	5	Yes	Yes	Remove and replace shutter wheel or motor or shim to reduce shutter guide friction
	Film Drive Assembly	● Motor fails off ● Motor steps improperly ● Motor stalls	6	Yes	Yes	Remove/replace motor
		● Clutch fails to engage properly			Condl	Drive linkage in camera housing is adjustable - film magazine is not. Replace film magazine

*RLOO = Relative Likelihood of Occurrence

application. The complete table is provided in Appendix B. This table relates each subsystem element to a Relative Likelihood of Occurrence (RLOO), ranging from zero to ten. The value of this action is to provide a point of reference that represents a "best judgment" of the weak points of the design. This distribution will subsequently be altered to assess the sensitivity of the assumed values for the relative failure relationships.

There are 49 elements tabulated in Appendix B having a RLOO between 1 and 10, (those elements with a RLOO of less 1 have been eliminated from consideration). These elements were used to develop the histogram shown in Figure 7-4. Although the distribution is skewed, it is felt to be representative of the S-056 X-ray telescope. If repair is to be employed, consideration should be given first to components with a high RLOO. Thus, this histogram provides an insight into spares provisioning and where emphasis should be placed on design modifications.

Figure 7-4 can be integrated to develop the expected repair potential as shown in Figure 7-5. This indicates that a 20 percent repair capability can easily accommodate a large portion of the expected failure occurrences (40 percent). Beyond this, the rate of return on repair actions diminishes, and to expect to compensate for all possible failures appears unrealistic. The question of just how much repair is desirable is answered by examining the basic reliability of the instrument relative to the desired availability.

Figure 7-6 takes the initial reliability estimate and indicates for the expected failure distribution how much repair should be incorporated to achieve a reasonable system availability. The availability in this instance is defined as the ratio of time the system was operational to planned operational period. The desired availability for these types of instruments is estimated to lie between 70 and 90 percent. Since these types of instruments are generally one-of-a-kind, usually very complex in design and having special requirements for unique sensors, it is unrealistic to expect availabilities above 90 percent. With this goal in mind, it is seen that a 40 percent repair capability can be expected to substantially improve the

S-056 X-RAY TELESCOPE

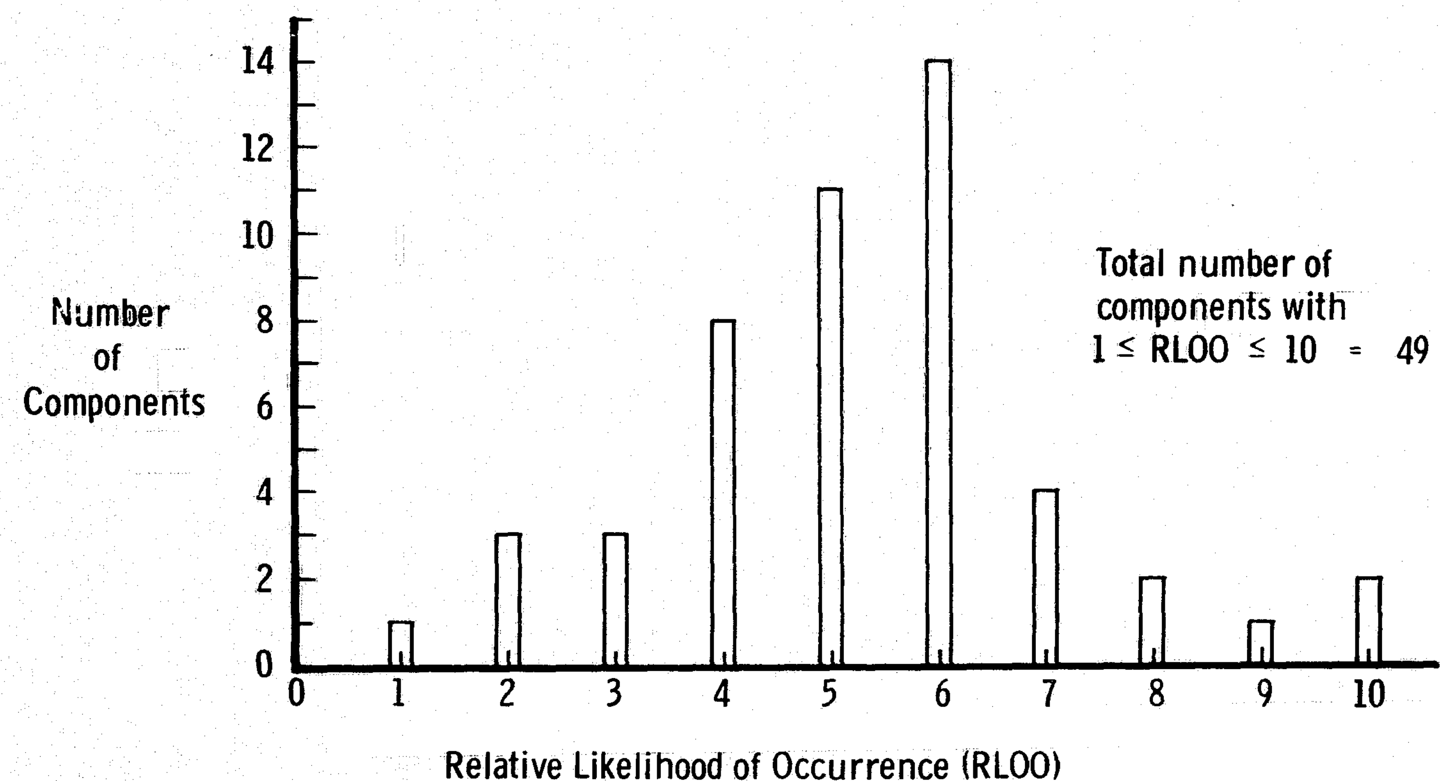


Figure 7-4. Histogram of Component Reliability Characteristics

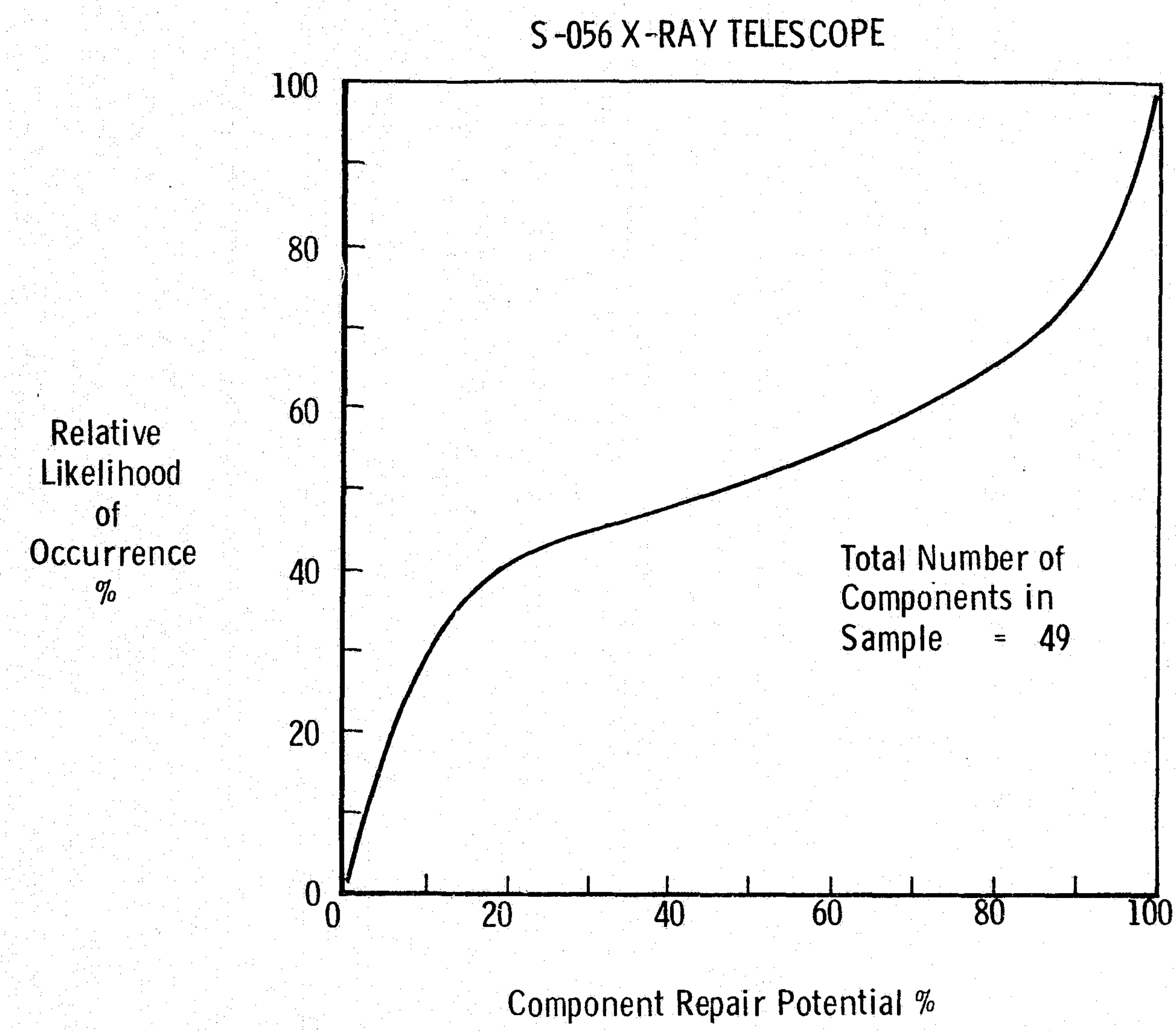


Figure 7-5. Expected Repair Potential

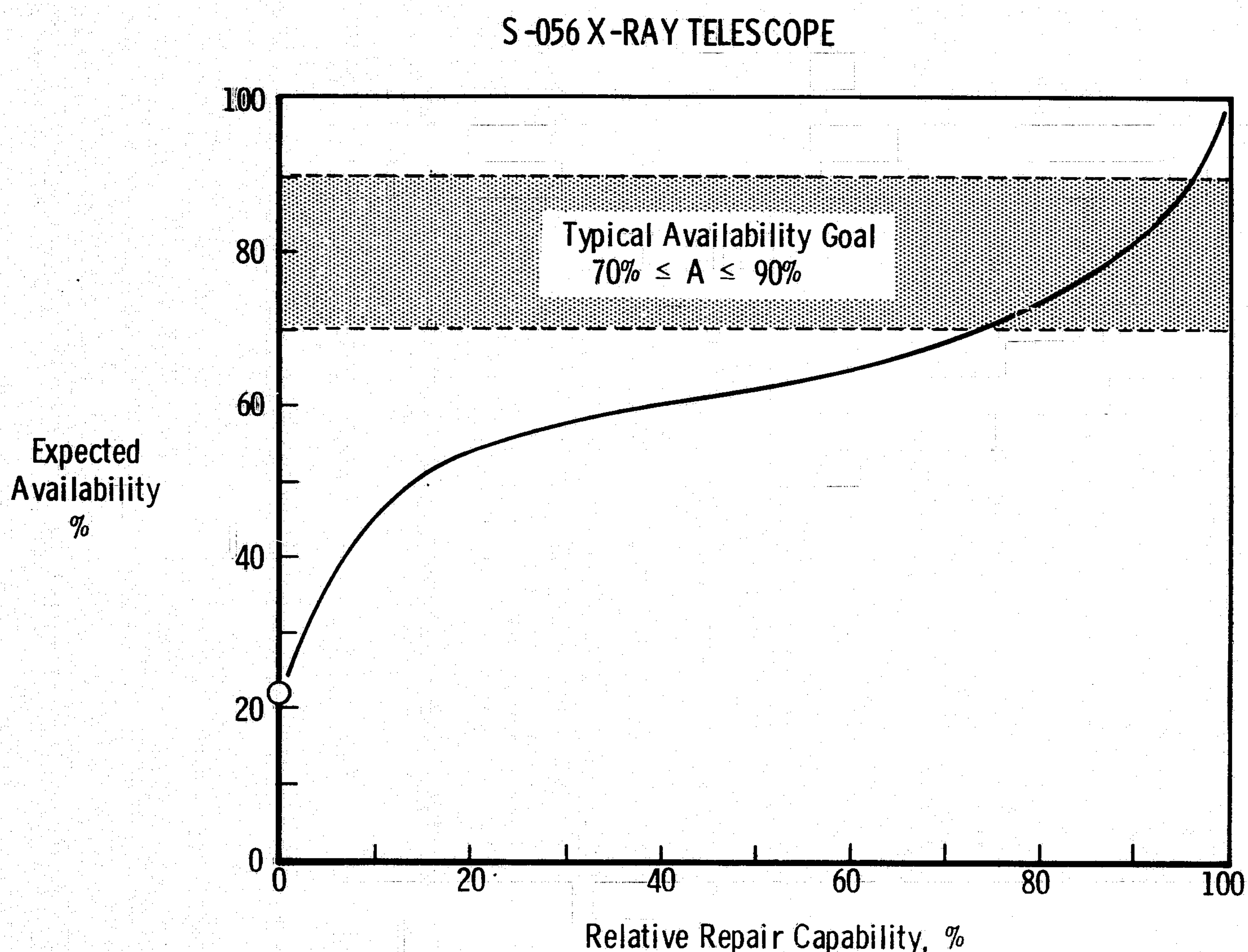


Figure 7-6. S-056 Availability versus Relative Repair Capability

expected availability from 22 percent to over 60 percent. However, the relative repair capability must be increased to approximately 75 percent to achieve the desired availability.

It is unrealistic to consider a 100 percent repair capability, if for no other reason than that of isolating all failure conditions such that the proper repair action could be performed. All possible failures are not incorporated into the assumed failure distribution, but the sample is sufficiently broad to be representative of the failure characteristics and the influence of repair actions. A more thorough "failure modes and effects analysis" would probably uncover more component failure paths but should not appreciably alter the shape of the curve, in Figure 7-5.

For this set of conditions, repair proves to be very attractive and a great deal of commonality of components exists in the design of the S-056 X-ray telescope, thereby minimizing spares provisions. However, it is always advisable to examine alternate failure distributions to determine the sensitivity of the conclusions to the initial conditions. This is done by referring to Figure 7-7. This figure shows typical distributions that could occur as a result of changes in the component reliability assessment. If the estimated component reliability were improved, the histogram would be skewed to the left. This indicates that very few of the components have a high RLOO. If the component reliability is reduced, the curve is skewed to the right with a high percentage of the components having a potentially high RLOO. The curves have been constrained to all contain the same number of components to provide a consistent comparison with the reference case.

These distributions have then been integrated to provide an indication of component repair potential, as shown in Figure 7-8. If the components are estimated to have a relatively high likelihood of failure, it is very apparent that even a low repair capability provides substantial benefits. However, if the reliability distribution were to improve, the "value of repair" is diminished unless a very high level of maintenance can be achieved.

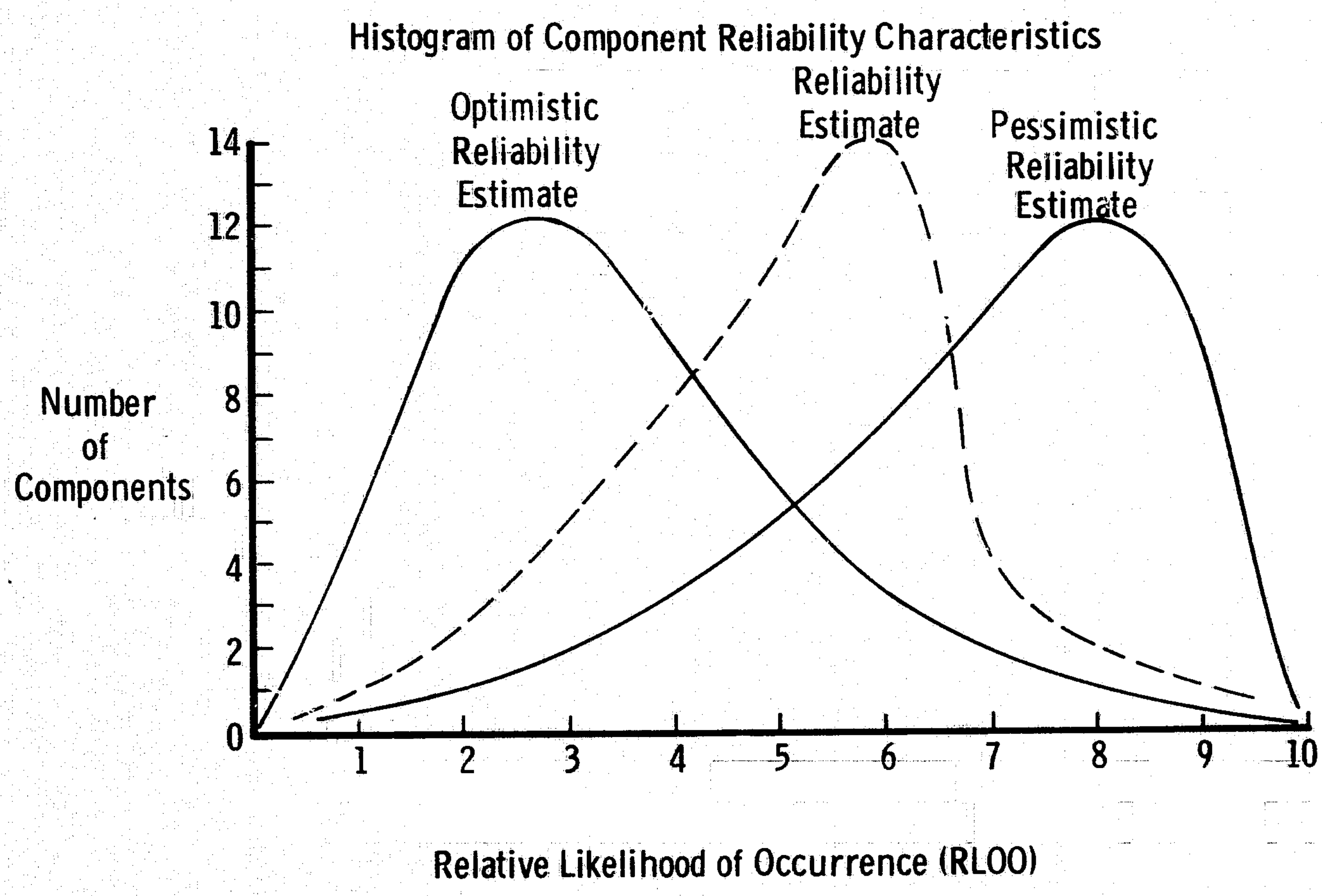


Figure 7-7. Variation of Estimated Component Reliability Characteristics

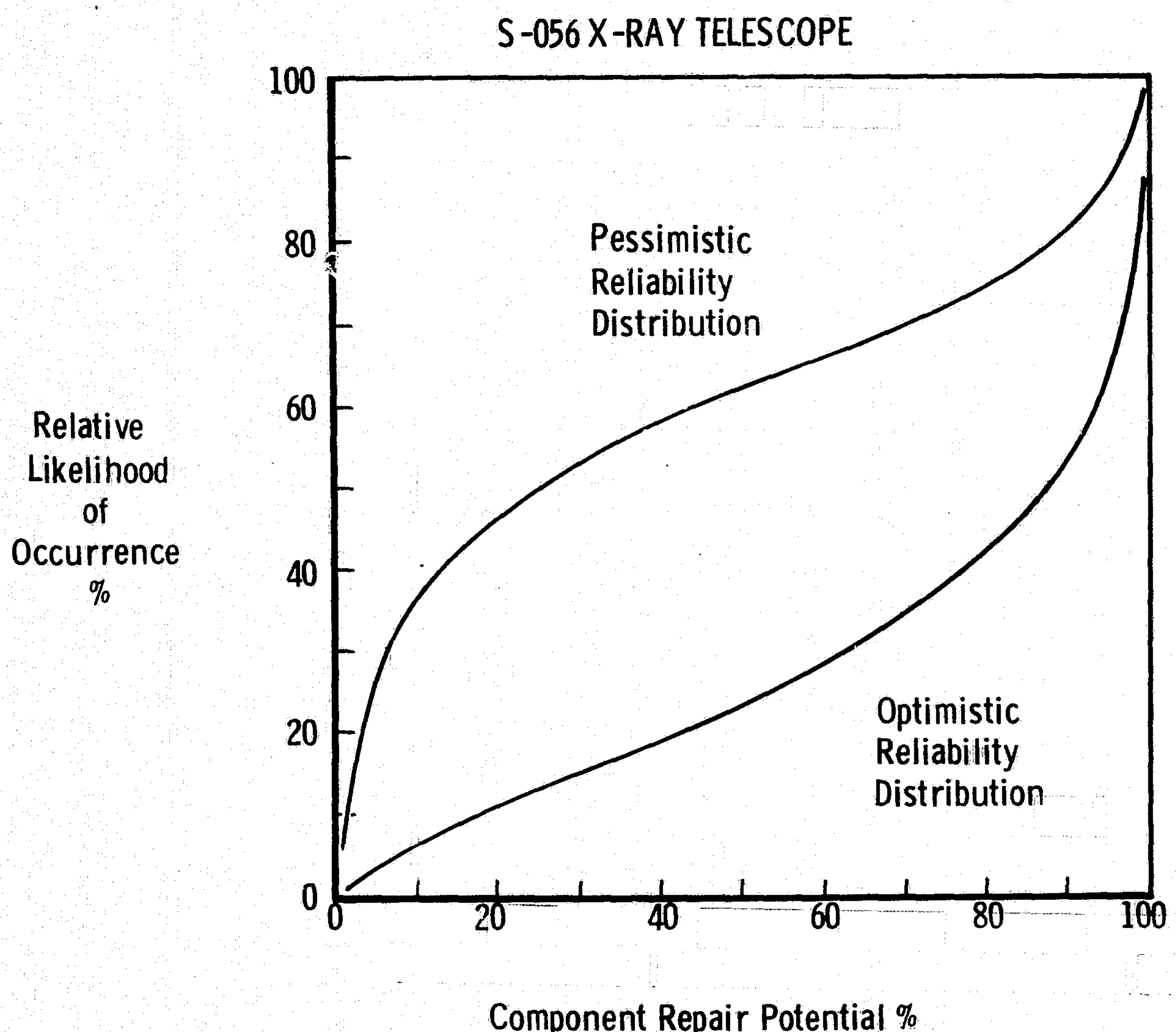


Figure 7-8. Alternate Component Repair Characteristics

These two curves, therefore, provide a reasonable bounds of influence of repair action on maintaining an operating system.

Figure 7-9 shows this effect relative to achieving the desired availability. This shows that a repair capability, somewhere between 40 and 95 percent, would be desirable to achieve the preferred level of availability. Repair, in either extreme, still provides a substantial benefit. However, improved system reliability (S-506) may also provide benefits equal to that of active repair. Consequently, it is of interest to determine the influence of adding redundant components to the S-056 relative to the influence this will have on system availability.

In general, the first area considered for redundancy is the avionics. The S-056 avionics package performs all automated sequencing, contains all timers, all power supplies, and the thermal control system electronics. There are numerous single point failures in this design. As previously pointed out, each power supply contains from 20 to 60 single point failures. The loss of any of the power supplies will cause termination of the mission. Therefore, it is reasonable to expect a substantial improvement by use of redundant electronics. The overall reliability estimate for the S-056 as a function of data acquisition (operating period) is shown in Figure 7-10. This curve utilizes component failure data wherever possible, but as pointed out in Section 4, it is not possible to establish an accurate reliability estimate. Nor is it felt necessary, because experience has shown that the majority of failures occurred in electro-mechanical systems for which no reliability estimates exist. Consequently, this curve is reasonably representative of the S-056 X-ray telescope. The probability of acquiring all data is 22 percent. In practice, it is estimated that the S-056 actually acquired approximately 75 percent of its planned data but this did in fact require manned action as pointed out in Section 5.

If the avionics package is made totally redundant, the system reliability will improve to about 26 percent. The ability to gather data early in the program is enhanced; however, over the total period, the

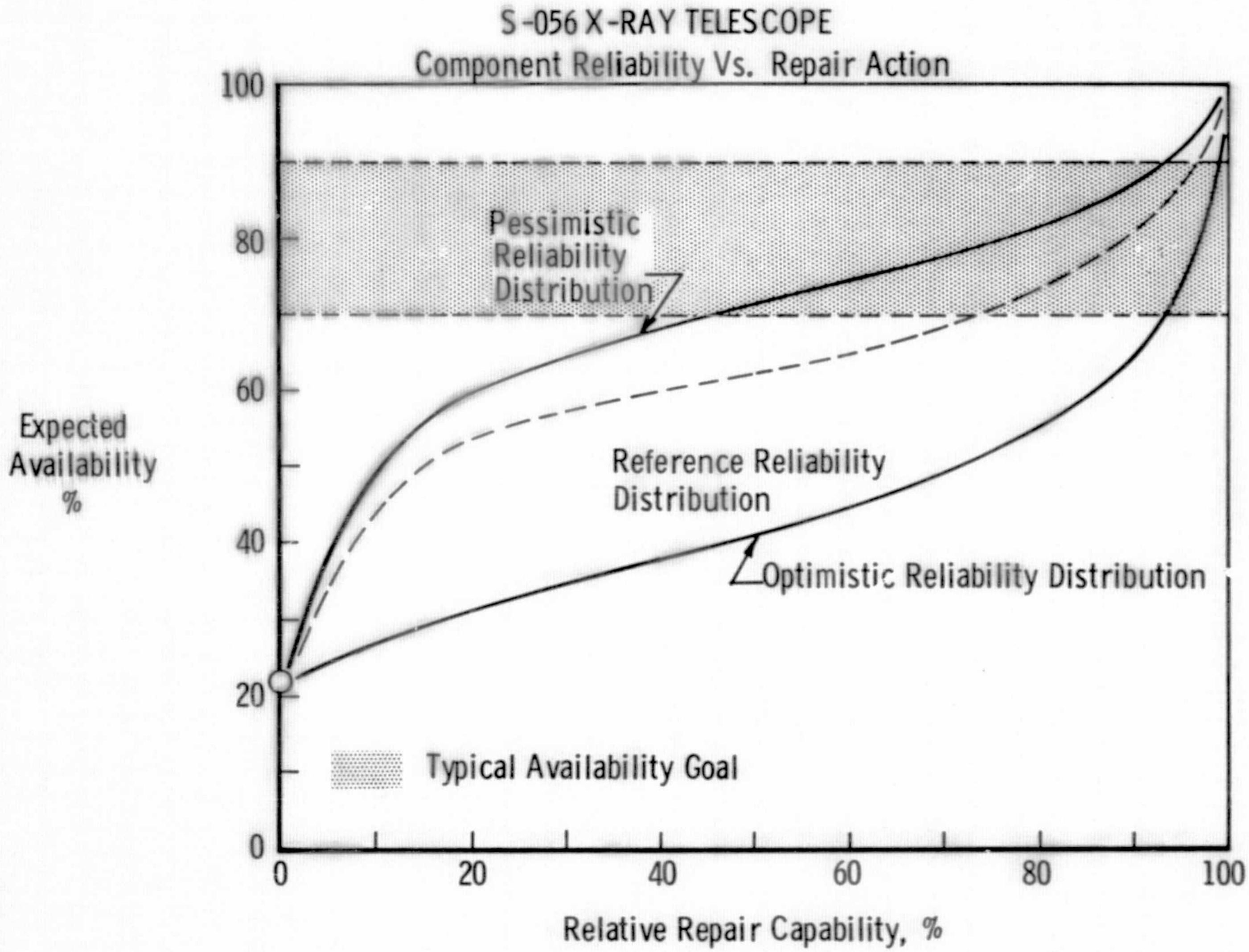


Figure 7-9. Rational Bounds of S-056 Repair Capability

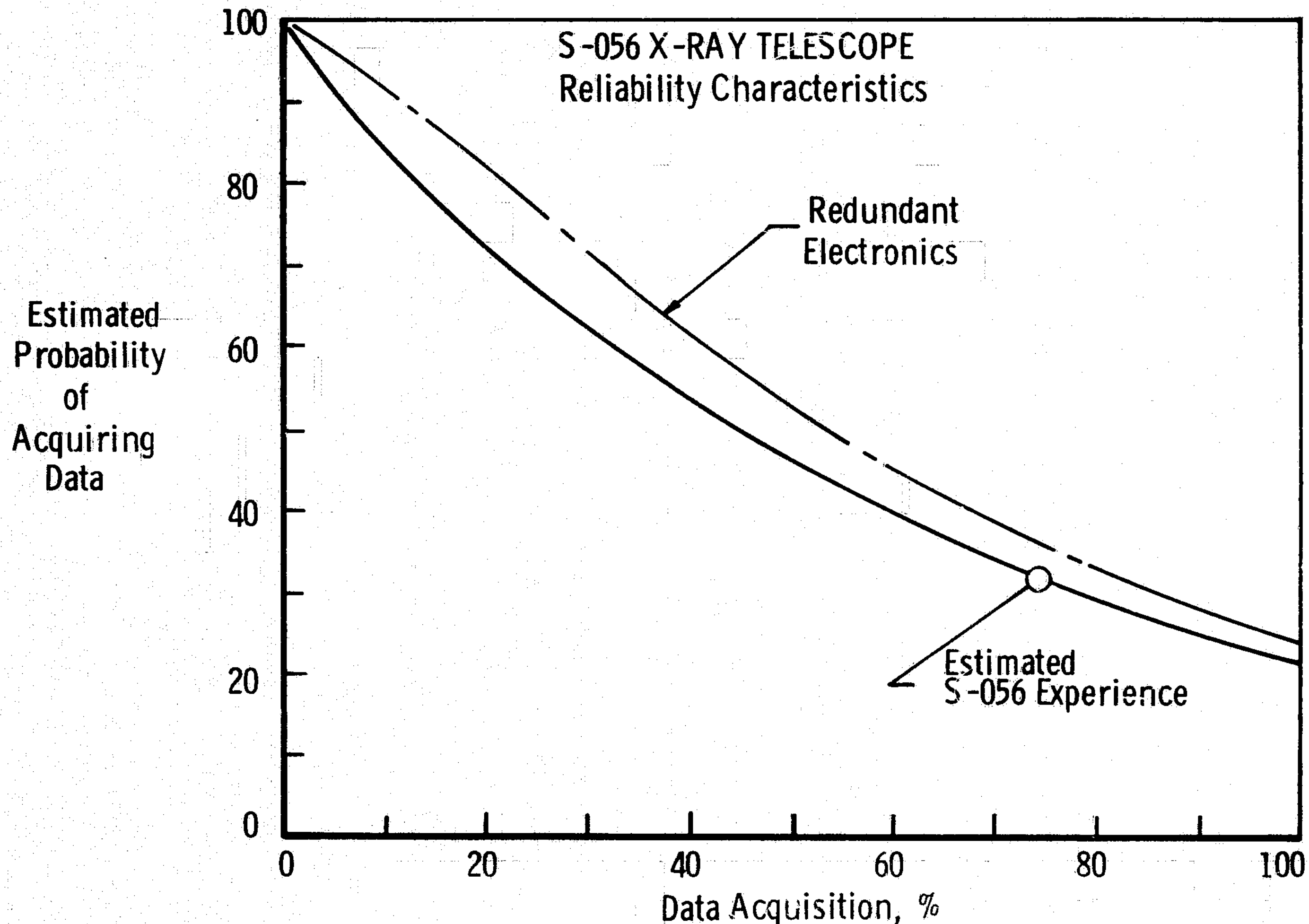


Figure 7-10. S-056 Estimated Reliability Function

improvement would be considered negligible. As more redundancy is incorporated, the overall reliability will improve, but at a substantial weight penalty. Optimization of this process will be addressed later, but first consider the influence of the initial reliability on the value of repair.

Since the initial value of the S-056 estimated reliability of 22 percent could not include all factors (for lack of definition) it is of interest to see what influence a higher reliability would have on repair actions, assuming it could be achieved. A system reliability of 60 percent was selected as a point of reference, representing a substantial improvement over what was estimated as the true reliability of the S-056. A value above this is questionable, because it is not obvious how redundancy would be incorporated into the mechanical components (air lock door and motor, film drive, etc.).

Figure 7-11 provides an estimate of the influence of repair if the initial reliability were 60 percent. The distribution of failures remains the same as before, but the higher reliability reduces the influence of repair capability. The benefits of repair are still very noticeable, but the incremental improvement has obviously been depressed. If the component failure distribution follows the high reliability curve, an extensive repair capability would be required before any substantial improvement could be realized. Hence, over a wide range of initial system reliabilities, it can be seen that repair actions can make a substantial contribution to the overall mission. The question now is how to set a value on these contributions, such that a valid conclusion can be drawn.

This has been accomplished by relating the weight penalty for repair, or for redundancy, to the expected availability. Since the S-056 is the only instrument for which reliability estimates exist, it is employed in this tradeoff. First, consider redundancy as a means of improving reliability. By taking a ratio of the incremental reliability to incremental weight of a component, it is possible to optimize the selection of redundant components to minimize weight. Also, in adding a redundant component there are additional weight factors to cover such items as connectors, brackets, etc.

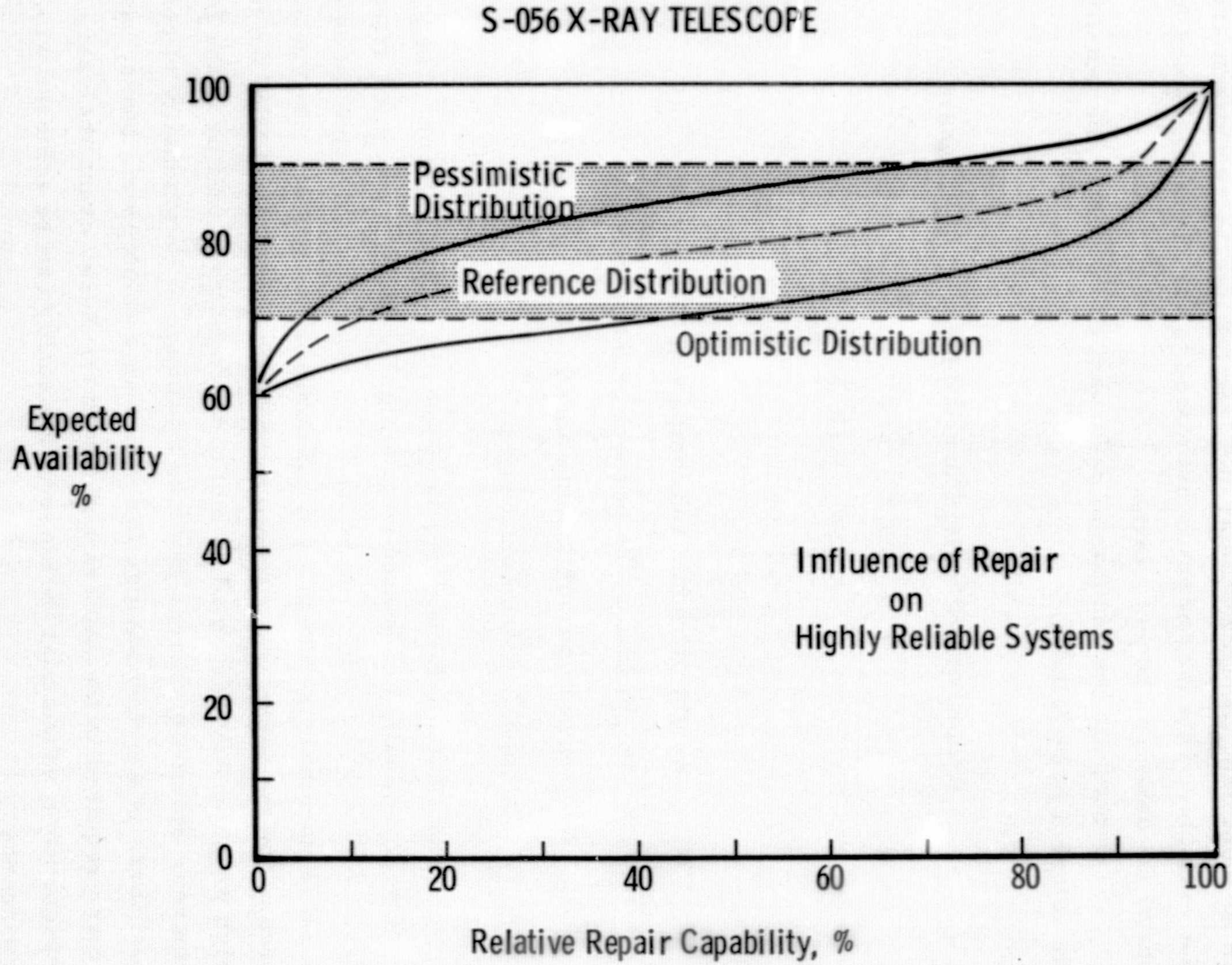


Figure 7-11. Influence of Initial Reliability Estimate on Repair Capability

This therefore becomes the penalty function; the weight increase as a function of improved availability. Although the weight of a given component can be identified, the incremental increase for interfaces must be treated as a variable. This increment is estimated to vary between 25 and 50 percent of the basic component weight.

Hence, for the addition of redundant components, the penalty function selected is as follows:

$$\text{Redundancy Penalty Function P. F.} = \frac{\Delta W}{W_T}, \text{ where}$$

$$\Delta W = (1+K)\, NW_C$$

Where

W_C = weight of redundant component

K = weight factor, 25 percent or 50 percent

N = number of components added

W_T = initial instrument weight

The situation for repair, however, is quite different. There is an initial weight penalty associated with designing an instrument for repair in space. Although the values expressed in Section 4 are considered conservative, it is nonetheless necessary to account for this effect. The incremental increase for the S-056 is estimated to be 9.1 kg, or 7 percent of the original design weight. Any additional weight to be considered will be in the form of spares. However, spares can take advantage of commonality of components; there is a weight savings for such items as stepper motors, where four are required in the camera and two in the X-ray event analyzer. Consequently a substantial increase in reliability can be achieved with only a few spares.

The penalty function selected for repair action is therefore:

$$\text{Repair Penalty Function P. F.} = \frac{\Delta W}{W_T}, \text{ where}$$

$$\Delta W = W_C + K_1 N\, W_C + K_2\, W_T$$

Where

W_C = weight of spare component

K_1 = weight factor associated with spares storage (5%)

N = number of spare components

K_2 = weight factor imposed on initial design for repairability (7%)

W_T = initial weight of instrument

The value function then becomes the ratio of the incremental weight growth to the initial design weight of the instrument (133 kg) as the availability is increased. For all practical purposes, this is the relative cost impact of doing business.

The advantage of repair over redundancy is dramatically shown in Figure 7-12. The weight growth is shown as a function of the expected availability of the instrument. The initial weight impact to design for repair is indicated by the step function of the repair curve. However, after this point, the system availability can be substantially improved with very little weight growth, capitalizing on the commonality of spare items. The desired range of availability (70 to 90%) can easily be attained with the knee of the curve at approximately 85 percent.

The result of added redundancy is also dramatic. Although there may be an initial weight penalty for mounting supports, additional cold plates, etc., it was not possible to devote any design effort to this definition.

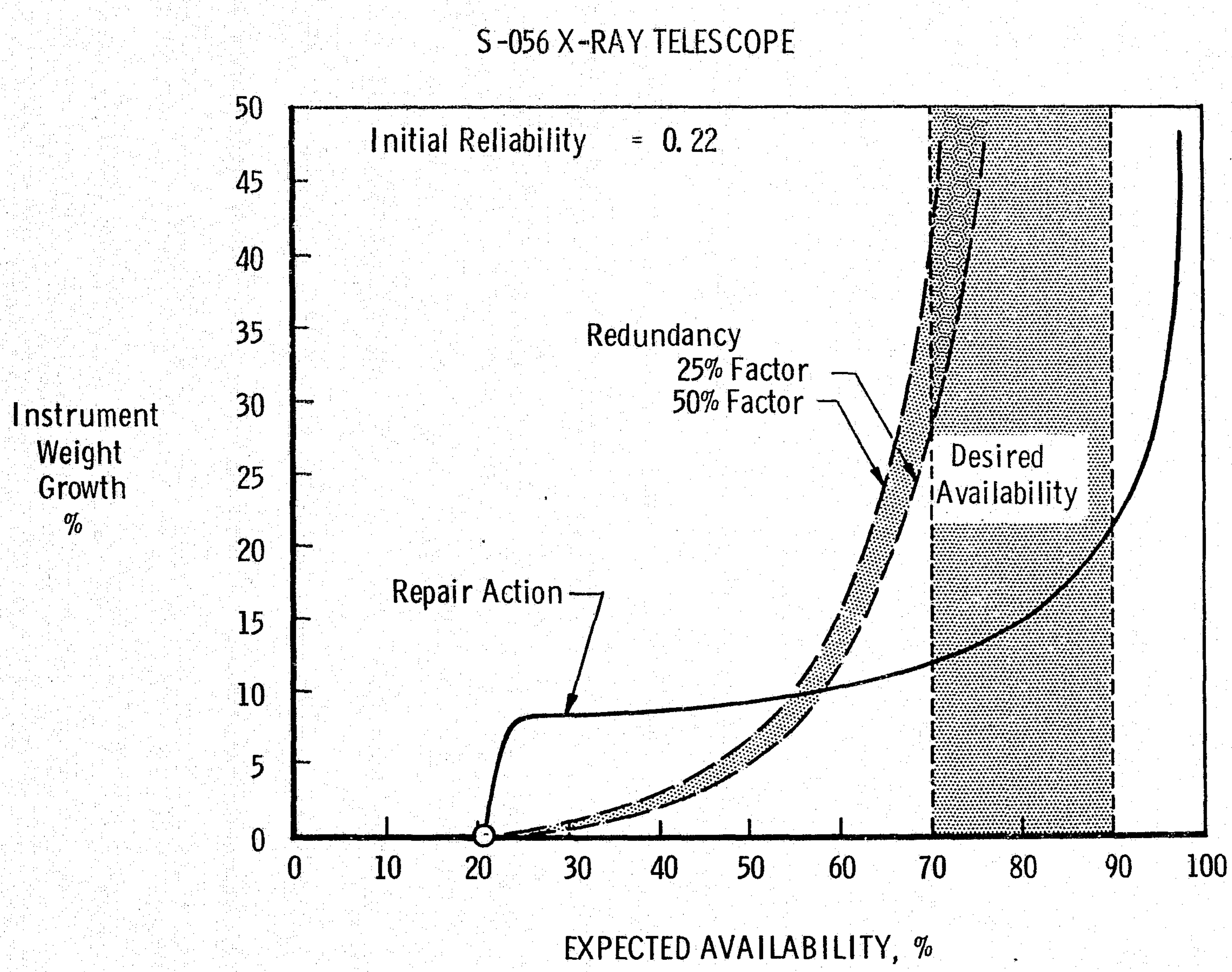


Figure 7-12. Redundancy versus Repair for S-056 (Initial Rel. = 0.22)

Consequently, the initial weight impact of designing for redundancy has been neglected. The optimum level of redundancy will provide approximately 55 percent availability, which also happens to be near the cross over point with repair actions. It is obvious that a severe weight penalty would be incurred if component redundancy were employed to achieve an availability of 70 percent or greater.

These results are, of course, sensitive to the initial reliability estimate, as discussed previously. Consequently, this trend was also examined for a higher level of initial reliability. The results are shown in Figure 7-13. Repair actions would provide a higher confidence of achieving the desired availability because of the associated slope of the curve; however, the initial weight penalty is, in this case, a serious detriment. The redundancy curve shows a substantial benefit over repair since only a small improvement in reliability is necessary, although the total weight savings in practice would be less than 6 kg. In this case, repair action would be highly beneficial if an availability above 90 percent were desired.

Although repair actions appear favorable for availabilities above 90 percent, it is difficult to draw any conclusions in this area. The S-056, as pointed out previously, should not be expected to operate in this range. If required, the basic design would probably change dramatically and an entirely new analysis would have to be performed. Even so, the option for repair, particularly on mechanical systems with little reliability experience, can be a valuable asset, especially if the inherent reliability is relatively low.

In summary, it is important to note the general character of the two curves involved. After the initial weight penalty, the repair curve is relatively flat, independent of the assumed initial system reliability. This is to be expected and emphasizes that although the initial level may vary, the slope of the curve is not sensitive to the component reliability estimates, provided commonality of spares can be achieved. However, the redundancy curve is very sensitive to the component reliability estimates and therefore reduces the confidence in this approach to achieve the desired availability.

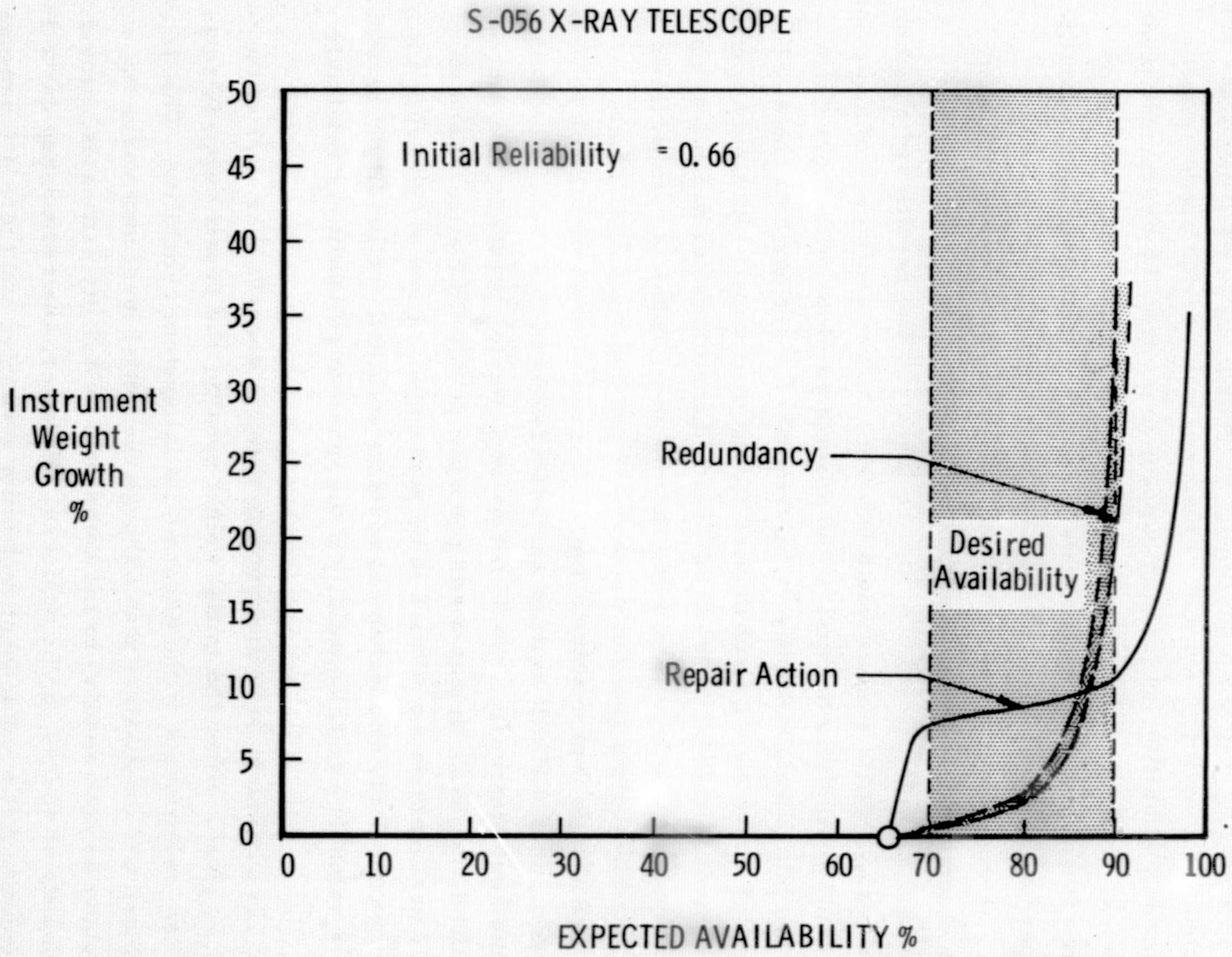


Figure 7-13. Redundancy versus Repair for S-056 (Initial Rel. = 0.66)

It should also be recognized that all components have not been incorporated into this analysis. The data employed is felt to be representative, but items such as the X-ray Event Analyzer Aluminum and Beryllium proportional counters, have definite wear out characteristics as a function of their exposure. The exposure time is not predictable, and consequently could not be included in the analysis, but experience indicates that several spares should be provided because they have a high relative likelihood of failure occurrences. In this case, adding multiple redundant components could produce a severe design penalty. The redundant component must be shielded until required and then calibrated against the counter to be replaced. Also, a mechanism would be required to align the component with the aperture opening. Redundancy for the aperture drive motors would produce even more complexity. Consequently, although the curves of Figures 7-12, and 7-13 are only approximate, it is the considered judgment that they are representative of what can be expected for the S-056 and similar scientific instruments.

As discussed previously in Section 4 (Table 4-5, p. 4-26), the weight penalty associated with the remaining ATM instruments is considerably higher than for the S-056, from 7 to 37 percent. These values would have a substantial impact on the weight increments needed to achieve the desired availability. However, the weights are considered to be highly conservative and are primarily related to the existing packaging concept of components on the instruments. The addition of redundant components would also be expected to generate a severe weight penalty because of the uniqueness of each design. Grating mirror torque motors could be replaced but could not easily be made redundant. Vidicons could be replaced but again, redundancy would be highly questionable. Hence, the items that could be made redundant tend to be limited to the avionics, which inherently are very reliable anyway. Consequently, it is felt that the conclusions drawn for the S-056 are also applicable to the remaining ATM experiments because they all fall within a class of scientific instruments developed for specific tasks, and, therefore, unique in design and application of sensors.

8. SUMMARY AND CONCLUSIONS

The arguments for the use of man are both subjective and objective. The crew, without question, contributed significantly to the success of the Skylab ATM experiments. Even under unexpected, improvised conditions, it was still possible to be effective. Had it been otherwise, the scientific achievements would have been severely hampered. Contemplating these achievements leads to the consideration of what might have been achieved had the experiments been designed for repair action. It also leads to consideration of what additional failures might have arisen that would have reinforced the need for direct manned intervention. It is a difficult question to answer because of so many uncertainties. This Study has attempted to rationalize and quantify some of the uncertainties to the extent that man's contribution could be assessed versus alternative concepts.

In summary, it should be remembered that instruments of the type flown on the ATM are relatively complex, unique in their application, and often employ new sensor techniques. Consequently, if the system performs well, as did many of the Skylab experiments, it should be recognized that this is not necessarily the basic nature of this equipment. In general, the equipment should be expected to be less reliable than operational satellites employing sensors with a relatively long history of development. This unreliability is often difficult to assess, emphasizing the need to retain all possible options to maintain an operational system. Thorough ground testing is extremely important, but history has shown that even this may fail to expose all weak points of a given design. Hence, the interest concentrates in quantifying the benefits of repair and examining the basic character of scientific equipment to develop guidelines for future developments. The fundamental question remains of how to achieve the highest return of scientific data at the lowest possible cost.

The Skylab experience demonstrated that, even with careful design and extensive ground testing, active manned support greatly enhanced the scientific achievements of the ATM experiments. If the extent of astronaut capabilities had been fully anticipated in design and mission planning, a significantly further enhancement would have been realized through repair and experiment management operations.

Going beyond this is speculation; however, the results of this effort show that using a rational approach to redesign, with reasonable reliability estimates, orbital maintenance is probably the most realistic means of achieving a high system availability. A capability to maintain approximately 40 percent of the more significant subassemblies is estimated to be a lower bound. A more desirable figure of 60 to 70 percent maintainability is preferred to assure an availability in the 70 to 90 percent region. The results of this Study indicate that these levels of maintenance can be attained with a minimal impact on the instrument design. As an example, the S-056 X-ray telescope would experience a weight growth of less than 7 percent. The remaining instruments are estimated to show a higher penalty but the analysis was not as extensive as with the S-056 and it appears reasonable to expect a weight growth of no more than 15 percent.

There are two ways that manned maintenance can be implemented. If the total system of experiments is sufficiently large, the crew can reside within the observatory, providing support to a broad set of applications. This provides continual coverage and would inherently provide the highest level of availability. Crew or scientist rotation could occur on a three-month cycle at which time replenishment of spares could be achieved. This is one concept. The alternative is to provide routine maintenance of a free flying observatory based upon telemetry data. Hard copy data could be retrieved and all anomalies corrected. If a serious failure occurs, support could be provided on any scheduled Shuttle flight with the capability for a revisit to the observatory orbit. The availability in this instance would be reduced over active support but even this allows a great deal of flexibility in dealing with unpredictable problems associated with design deficiencies.

A further alternative, aside from automated space servicing, is to increase the levels of redundancy to achieve the desired levels of availability. Although feasible, the results of this effort indicate that for these types of systems, redundancy is not as cost-effective as manned maintenance relative to the payload weight to orbit. The weight to orbit to achieve a similar level of availability can be a factor of two to ten times higher for redundancy versus spares provisioning. Even with the payload margins afforded by the Shuttle, these factors cannot be ignored. In addition, the sensitivity of the weight growth for redundancy is such that the optimum design, relative to improved reliability, falls far below the desired availability region. On the other hand, the optimum point on the repair curve lies near the upper value of the desired availability (90%).

These characteristics appear to be fundamental, relative to the assessment of man's utility. This is not to say a high level of reliability is not required or that redundancy and manned maintenance are incompatible. As the complexity of experiments increase (with associated cost increases), it is ever more important to adhere to rigid design and test procedures. Where redundancy can be employed without a severe penalty, it should be. Alternate work around paths should also be employed. However, the inherent character of scientific equipments will necessarily have non-redundant electromechanical devices, tight alignment tolerances, and complex sequences of operations. There may also be problems generated by support systems that require alteration of the basic configuration. This type of flexibility can only be achieved by direct manned participation

One final note deserves mention, even though it was not addressed in the Study effort. On any launch to orbit, there is some probability that the instrument will not function as desired. Historical data (Refs. 18-19) indicate that approximately 60 percent of the spacecraft launched through 1972 had some type of anomaly existing immediately after insertion. Approximately 65 percent of these represent a significant loss to the payload. This value drops to 40 percent when redundancy is employed but still represents a substantial loss of capability and risk to mission objectives. If the payload were associated with a manned observatory, it is reasonable to expect that repair operations could correct a very large percentage of these anomalies. Since spares would already be provided for subsequent operation on orbit, there should be no additional weight impact. Consequently, manned maintenance, in this role, could be expected to substantially reduce the number of Shuttle re-flights required to establish payloads in orbit. Even for unmanned payloads, spares provisioning should not represent more than a 10 to 15 percent weight penalty provided man can be utilized to perform the repair.

The following guidelines are therefore recommended for future programs to utilize the unique capabilities that man's presence offers to the successful operation of any payload, and particularly to long-lived scientific experiments.

a. Design

1. Repair capability should be provided at the subassembly level for at least 60 percent of items performing an active function during instrument operations.
2. The fundamental repair mode should be to remove/replace the subassembly, or remove to the pressurized compartment for repair and diagnosis.
3. Guide pins should be provided for all subassemblies requiring critical alignments.
4. Electrical connectors should be grouped to minimize disconnect actions and be compatible with pressure suit operations. All connectors should be self-aligning and polarized.
5. Accessibility should be provided without visual obstructions for pressure suit operation to remove and replace subassemblies.
6. Reliability standards should not be compromised because of the availability of manned maintenance. Redundancy should be employed wherever feasible up to the point that the reliability tradeoff is favorable.

7. Commonalty of components should be employed to the greatest extent possible to reduce the spares provisioning requirements.

8. Repair actions should be concentrated on mechanical and electro-mechanical equipment where redundancy is restricted.

9. Repair of electronic equipment should not be precluded even if redundancy is provided, using plug-in modules where possible.

10. Visibility should be provided to assure unobstructed removal and replacement of components or modules. Means should be provided for positive guidance of modules during remove/replace actions.

11. All subassemblies should have handle and tether provisions and tethers should be attachable prior to removal from the instrument.

12. One way, non-reversable erection devices, such as Electro-Explosive Devices (EEDs), should be eliminated due to the lack of a repair compatibility if failure occurs.

b. Operations

1. Operational timelines should be flexible enough to accommodate, on the average, one unscheduled repair action each day. Skylab experience indicated that one repair action every two days was required which impacted the normal work routines.

2. Instruments and subassemblies should have positive identification, expecially where commonality is employed, employing for example, color coding of components.

3. Instrument power should not be required to support removal and replacement of items, such as, solenoid actuated hold down latches, power actuated or restrained doors.

4. Adequate lighting should be provided to allow unrestricted maintenance.

5. Repair actions should be accomplished by simple crew motions when operating EVA. Disassembly of components, or modules should be relegated to a pressurized, shirtsleeve environment. Requirements for recalibration of equipment should be minimized.

6. All remove/replace operations should be compatible with a one-man operation. Remove/replace timelines should be minimized.

7. Instrument operations should not preclude changes in basic programming to allow management for targets of opportunity.

8. Reprogrammable sequences of operation are preferred rather than hardwired sequences.

9. The capability to do a failure search to isolate failures to a replaceable unit should be provided.

10. Attachment devices should be clearly visible to preclude removal of more than one subassembly at a time or damage to non-removable components.

11. No special maintenance training should be required other than familiarity with the instruments.

This Study has only touched on a small part of man's utility in space. It hopes to join with other efforts to surface the benefits, limitations and possible hazards of such actions. Further work is needed, leading to test programs and flight operations to prove this utility. There are bounds to man's activity for maintenance, at least in the near term. It is unrealistic to expect him to assemble complex, intricate components requiring special tooling and training. This will come eventually, but the present need is to maintain the operational status of equipment to maximize its value and to preclude having to repeat the experiment at a later time. This presents a new challenge to the designer, but improved performance should be a sufficient incentive to accept this challenge. The important point is to continue to keep the objective in mind and direct efforts toward it.

REFERENCES

1. Skylab Operations Handbook, NASA, Manned Spacecraft Center Houston, Texas (March 1972).

2. W. T. Chater, Solar Pointing Control OV1 Report, TR-1001(9260-02)-1, The Aerospace Corp., El Segundo, Ca. (May 1967).

3. EUV and X-ray Spectroheliograph for OSO-H, D/N 71SD4268, Final Report, General Electric Company, Space Division, Valley Forge, Pa. (January 1972).

4. MSFC Skylab Apollo Telescope Mount, NASA TM X-64811, NASA, Marshall Space Flight Center, Huntsville, Ala. (28 June 1974).

5. Critical Design Review for GSFC X-ray Telescope, ATM Experiment S-056, NASA, Marshall Space Flight Center, Huntsville, Ala. (30 January 1968).

6. Reliability Analysis of ATM Experiment S-056 Digital Signal Conditioner, prepared for NASA, MSFC, by Federal Electric Computer Applications Corp., Huntsville, Ala., Contract NAS8-20412 (AS-X-23-68) (15 April 1968).

7. Reliability Analysis of ATM Experiment S-056 Pulse Processors, Contract NAS8-20412 (AS-S-33-68), Prepared for NASA, MSFC, by Federal Electric Corp., Huntsville, Ala. (27 May 1968).

8. Reliability Analysis of Experiment S-056 (+12.0 VDC Power Supply), Contract NAS8-20412 (AS-S-202-67), Prepared for NASA, MSFC, by Federal Electric Corp., Huntsville, Ala. (27 October 1967).

9. Reliability Analysis of Experiment S-056 (Power Supplies), Contract NAS8-20412 (AS-S-187-67), Prepared for NASA by Federal Electric Corp., Huntsville, Ala. (27 September 1967).

10. Summary Report Reliability Analysis of ATM Experiment S-056 Power Supplies, Contract NAS8-20412 (AS-S-19-68), Prepared for NASA, MSFC, by Federal Electric Corp., Huntsville, Ala. (22 March 1968).

11. Inputs to Skylab Design Certification Review Report, Vol. III, ATM S052 White Light Coronograph, TN 72-13, Ball Brothers Research Corp., Boulder, Colo. (14 July 1972).

12. Inputs to Skylab Design Certification Review Report, ACO/ATM Instrument S055A, TN72-12, Ball Brothers Research Corp., Boulder, Colo. (17 July 1972).

13. Inputs to Skylab Design Certification Review Report, NRL/ATM Experiment S082A, 620-158, Ball Brothers Research Corp., Boulder, Colo. (20 September 1972).

14. Inputs to Skylab Design Certification Review Report, NRL/ATM Experiment S082B, 620-163, Ball Brothers Research Corp., Boulder, Colo. (20 September 1972).

15. MSFC Skylab Apollo Telescope Mount Experiment Systems Mission Evaluation, TM X-64821, NASA, Marshall Space Flight Center, Huntsville, Ala. (June 1974).

16. MSFC Skylab Apollo Telescope Mount Summary Mission Report, NASA TM X-64815, NASA, Marshall Space Flight Center, Huntsville, Ala. (28 June 1974).

17. Inflight Maintenance as a Viable Program Element, NASA Skylab Experience Bulletin No. 5, NASA, Manned Spacecraft Center, Houston, Texas (September 1974).

18. A. R. Timmins and R. E. Heuser, A Study of First-Day Space Malfunctions, NASA TN D-6474, Goddard Space Flight Center, Greenbelt, Md. (September 1971).

19. A. R. Timmins, A Study of First-Month Space Malfunctions, NASA TN D-7750, Goddard Space Flight Center, Greenbelt, Md. (October 1974).

Appendix A

Survey of ATM Experiments - Candidate Items for Removal/Replacement

S-052 White Light Coronograph
S-055 UV Scanning Polychromator
S-082A XUV Coronal Spectrohelliograph
S-082B Spectrograph

CANDIDATE ITEMS FOR REMOVAL/REPLACEMENT

INSTRUMENT: S052 WHITE LIGHT CORONAGRAPH

ITEM	FUNCTION	MODS REQUIRED FOR REMOVAL/REPLACEMENT	MODS REQUIRED FOR REPAIR	BBRC CRIT. NO.	EST. WT. IMPACT Kg	NOTES
Optics Housing Cover and TCS Panels	Provides closure for housing. Active TCS panels maintain constant temperature	Replace attachment screws with latch mechanism and hinge.	None. Cover hinged for access to components.	---	3.6	
TV Camera	Provides visual image to astronaut monitor.	Replace attachment screws with latch. Redesign electrical disconnect. Add alignment pins.	Not repairable.	---	4.5	
Film Camera Assy.	Provides photographic record of coronal image, calibration pattern and other data.	None; camera already designed to be removable.	No repair should be attempted on camera due to danger of exposing film.	606	0	Replacement cameras provided.
TV Monitor Mirror Motor	Rotates TV image mirror into optic axis.	Replace electrical disconnect for EVA. Add alignment pins. Replace attach screws with latch. Redesign clevis pin attachment with latch pin design for EVA removal.	Add electrical disconnect between motor and mechanism assy.	66	2.7	Redundant motor provided.
Polaroid Wheel Motor	Rotates 3 Polaroid filters to provide polarization data of corona.	Replace 4 base attach screws with latch. Replace electrical disconnect for EVA.	Add electrical disconnect for wiring between motor and mechanism assy.	66	1.8	
Internal Occulting Disk Motor	Drives occulting disk.	Same as above. Also, add alignment pins to assy base.	Same as above.	326	1.8 (both items)	Assy has 2 motors. Failure restricts disk motion.
Internal Occulting Disk Mechanism	Provides internal optical alignment capability to system.			114		

INSTRUMENT: S052 WHITE LIGHT CORONAGRAPH (CONT'D)

ITEM	FUNCTION	MODS REQUIRED FOR REMOVAL/REPLACEMENT	MODS REQUIRED FOR REPAIR	BBRC CRIT. NO.	EST. WT. IMPACT Kg	NOTES
Main Electronics Box Cover	Provides closure for case electronics.	Replace attachment screws with latch mechanism and hinge.	None. Cover hinged for access.	---	4.5	
Power Supply	Provides regulated power to the instrument.	Replace base attachment screw with latch mechanism Replace electrical disconnect for EVA.	Not repairable. See notes	2747	2.7	Welded module construction. Replace box.
J-Box	Serves as distribution point for power.	Same as above.	Same as above.	---	2.7	Redundant standby box.
TCS Filter Box	Signal bias for thermal control.	Same as above.	Same as above.	---	2.7	
DC/DC Converter	Supplies power to thermal controllers, temp. monitor, etc.	Same as above.	Same as above.	---	2.7	Redundant standby convert
Motor Drive Box	Provides matrix drive logic.	Same as above.	Same as above.	---	2.7	
Camera Programmer	Automatic sequencing and timing function for camera	Same as above.	Same as above.	986	2.7	Redundant programmer & diode matrix in same box.
Camera Diode Matrix	Encodes film exposure data.	Same as above.	Same as above.	455		
Pointing Error Electronics	Provides error signal discriminator for experimental equipment.	Same as above.	Same as above.	338	2.7	Error electronics digitizer in same box.
Pointing Error Digitizer	Digitizes error signal.	Same as above.	Same as above.	116		

Estimated Weight Increase 38 Kg

CANDIDATE ITEMS FOR REMOVAL/REPLACEMENT

INSTRUMENT: S055 UV SCANNING POLYCHROMATOR - SPECTROHELIOMETER

ITEM	FUNCTION	MODS REQUIRED FOR REMOVAL/REPLACEMENT	MODS REQUIRED FOR REPAIR	BBRC CRIT. NO.	EST. WT. IMPACT Kg	NOTES
Top Cover and Thermal Control System	Provides closure for case. Active TCS maintains constant temperature.	Gover hinged with shear tie and latch system. Heater panel wiring rerouted.	None. Cover and TCS panels are not to be completely removed or repaired.	---	11.3	Remove cover for access.
Primary Mirror	Reflects entrant radiation to spectrometer entrance slit. Pivots to provide raster or line scan.	Recommend no modifications. Extensive redesign required.	Recommend redesign. Removal/replacement of torque motors of present design too difficult.	1459	---	Torque motors are integral part of mirror assy.
Difraction Grating (Motor Drive)	Difracts the light from entrance slit to seven detectors. Motor positions grating upon command.	Redesign to relocate stepper motor, gear box and cam to allow removal without disturbing grating.	Replace motor, gear box and cam as a unit. Redesign of grating drive required.	---	6.8	Replacement of motor is desirable.
Detector Mount Assy	Seven detectors measure the intensity of light difracted by the grating.	Replace bolts at Spectrometer I/F with a latch/guide pin system. Add electrical disconnects.	Add electrical disconnects to each detector to allow replacement.	---	6.8	
Data Handling Electronic Assy	Counts and conditions pulses from detectors for presentation to telemetry.	Replace hold down screws with latch system. Replace electrical connector with a quick disconnect.	Entire box must be replaced. If repair is required, box must be redesigned to P.C. boards	3145	2.7	Assumes welded module construction.
Raster Control Electronics	Programs primary mirror for various operating modes and stowed position.	Same as above.	Same as above.	2240	2.7	
Logic Interface and Motor Pulse Counter Electronics	Provides motor pulses for different modes of operation Supplies grating position information.	Same as above.	Same as above.	1069	2.7	
High Voltage Power Supply	Supplies voltage to the detectors.	Same as above.	Same as above.	687	2.7	

INSTRUMENT:S055 UV SCANNING POLYCHROMATOR -SPECTROHELIOMETER Page 2 of 2

ITEM	FUNCTION	MODS REQUIRED FOR REMOVAL/REPLACEMENT	MODS REQUIRED FOR REPAIR	BBRC CRIT. NO.	EST. WT. IMPACT Kg	NOTES
Low Voltage Power Supply	Supplies power for electronics operation.	Replace hold down screws with latch system. Replace electrical connector with quick disconnect.	Entire box must be replaced. If repair is required, box must be redesigned to use P.C. boards.	578	2.7	Assumes welded module construction
Power J-Box	Serves as distribution point for Power, Command signals and S/C interface.	Same as above.	Same as above.	351	2.7	
Data Handling Intensity Display	Presents data to control panel for monitor and positioning of selected line of spectrum.	Same as above.	Same as above.	315	2.7	
Controller	Regulates temperature of heater panels.	Same as above.	Same as above.	303	2.7	
			Estimated Weight Increase		46.5	

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CANDIDATE ITEMS FOR REMOVAL/REPLACEMENT

INSTRUMENT: S082A XUV CORONAL SPECTROHELIOGRAPH

ITEM	FUNCTION	MODS REQUIRED FOR REMOVAL/REPLACEMENT	MODS REQUIRED FOR REPAIR	BBRC CRIT. NO.	EST. WT. IMPACT Kg	NOTES
Aperture Door	Prevents entry of light and contaminant particles to optical system when not in use.	Replace 4 screws with latch mechanism. Add electrical disconnect EVA.	Add electrical disconnect to leads for motor replacement.	469	2.7	
Grating Assembly and Cam Assembly	Allows selection of one of two wave lengths to be directed to camera. Cam assembly positions the grating.	Cam assembly/stepper motor to be removed. Replace hold down with alignment pins and latching system. Replace electrical connector.	Add electrical disconnects to motor leads.	2.6	4.5	Grating assy is separate from cam assy.
Short Wave Length Rejection Mirror	Rejects zero order white light from the grating when grating is in the short wave length position.	Replace hold down with alignment pins and latching system. Replace electrical connector.	Add electrical disconnects to motor leads.	229	4.5	
Instrument Electronics	Provides power for door, camera, grating, etc.	Replace hold down with latching system. Replace five connectors with ones capable of being removed during EVA.	No repair possible with construction employed.	From 3596 - 207 See Notes	2.7	Criticality varies with components.
TCS Electronics	Controls heater panels	Same as above.	Same as above.	---	2.7	
Film Camera Assembly	Provides photographic record of XUV and time record.	None; the camera is already designed to be removable.	No repair should be attempted on the camera. See notes of S082B.	5.3	0	
Top Cover and Thermal Control System	Provides closure for case. Active TCS maintains constant temperature within case.	Cover (approx. 9 ft x 2 ft) hold down bolts (≈70) replaced by hinge, shear tie and latch system. Heater panel wiring rerouted to hinged side.	None. Cover and TCS panels are not to be removed completely or repaired.	---	11.3	Remove cover for access to components
			Estimated Weight Increase		28.4	

CANDIDATE ITEMS FOR REMOVAL/REPLACEMENT

INSTRUMENT: S082B SPECTROGRAPH & S082B XUV MONITOR

ITEM	FUNCTION	MODS REQUIRED FOR REMOVAL/REPLACEMENT	MODS REQUIRED FOR REPAIR	BBRC CRIT. NO.	EST. WT. IMPACT Kg	NOTES
Spectograph Aperture Door	Prevents entry of light and contamination when instrument not in use.	Replace hold downs with latch mechanism. Replace electrical connector.	Add electrical disconnects in motor leads for replacement of motor.	7	2.7	
Primary Mirror Torque Motor	Moves mirror $\pm$ 35 arc secs about center.	Removal of top cover and TCS panels reqd. Entire mirror assy must be removed. Add electrical disconnects and alignment pins.	Redesign so rotor/stator can be removed as a unit. Present rotor can not be removed.	0.4	---	Suggest no redesign.
Predisperser Drive Motor	Rotates drum which holds long and short wave length gratings through 180°.	Removal of top cover and TCS panels reqd. Entire Predisperser Assy should be removed. Precision alignment pins reqd.	Add electrical disconnects to motor wires.	47	4.5	
Film Camera Assembly	Provides photographic record of XUV with time record.	None; camera is already removable.	No repair should be attempted on the camera.	606	0	
Pointing Reference System	Optical system and electronics to provide control of instrument pointing. Presents TV image to crew.	Removal of top cover and TCS panels reqd. Replace electrical connectors with disconnects for EVA. Replace hold down bolts with guide pins for alignment.	No repair to be attempted. Replace Image Disector Tube and electronics module as single unit.	4083 (IDT & Video Preamp)	2.7	

INSTRUMENT: S082B SPECTROGRAPH & S082B XUV MONITOR (CONT'D) Page 2 of 3

ITEM	FUNCTION	MODS REQUIRED FOR REMOVAL/REPLACEMENT	MODS REQUIRED FOR REPAIR	BBRC CRIT. NO.	EST. WT. IMPACT Kg	NOTES
Top Cover and Thermal Control System	Cover provides structural closure for case. Active TCS maintains constant temperature within case.	Cover (approximately 9 ft x 2 ft) hold down bolts (≈67) should be replaced by a hinge and latch system. All wiring rerouted.	None. Cover and TCS panels are not to be removed completely or repaired.	---	11.3	Removal required to gain access.
High Voltage Power Supply	General: The electronics control the application of power, the operation of doors, etc	Replace hold down screws with latch system. Replace electrical connector with quick disconnect.	No repair possible with welded module construction employed. Entire box replaced.	1673	2.7	Fabrication of all elect. boxes identical.
Analog Commutator and Exposure Time Computer Electronics	See above.	Same as above.	Same as above.	862	2.7	
Low Voltage Power Supply. Digital and Buffer Electronics	See above.	Same as above.	Same as above.	3461 599 476	2.7	(L. V. P. S.) (Digital Elect.) (Buffer Elect.)
Pointing Reference Subsystem Electronics	See above.	Same as above.	Same as above.		2.7	
Command Buffer and Digital TM & Programmer Logic Elect.	See above.	Same as above.	Same as above.	864 1314	2.7	(Command Buffer & Digital TM) (Prog. Logic)
Data Stores and Diode Array Command Elect.	See above.	Same as above.	Same as above.		2.7	
Filter Box	See above.	Same as above.	Same as above.		2.7	

INSTRUMENT: S082B SPECTOGRAPH & S082B XUV MONITOR (CONT'D)

ITEM	FUNCTION	MODS REQUIRED FOR REMOVAL/REPLACEMENT	MODS REQUIRED FOR REPAIR	BBRC CRIT. NO.	EST. WT. IMPACT Kg	NOTES
Telemetry Comutator Electronics	See preceding page	See preceding page	See preceding page	---	2.7	
Junction Box Assembly	General: The electronics control the application of power, the operation of doors, etc.	Replace hold down screws and standoffs with latch system. Replace connector with a quick disconnect.	No repair possible with welded module construction employed. Entire box must be replaced.	---	2.7	
Thermal Control Subsystem Power Supply	See above.	Same as above.	Same as above.	---	2.7	
XUV Monitor Aperture Door	Prevents entry of light and contamination when not in use.	Replace screws holding the assembly to the case with a quick release latch mechanism. Replace electrical connector.	Add electrical disconnects to motor leads.	7	2.7	
SEC Vidicon Tube	Provides a real time image of the solar disk in the XUV band between 170Å and 550Å.	Replace 6 mounting screws with latch assembly and guide pins for alignment. Provide electrical disconnect.	None.	---	4.5	
Camera Control Unit	Provides power, control and telemetry to/from the video camera.	Provide latching system and electrical disconnect.	None.	---	2.7	
XUV Monitor Door Command Elect.	Provides commands for door open and close.	Provide latching system and electrical disconnect.	Same as other elect. boxes.	131	2.7	
XUV Monitor Case	Closes off side of case.	Replace hold down screws with quick release latch sys	None.	---	9.00	

Estimated Weight Increase	69.8

Appendix B

Component Failure Assessment, S-056
X-Ray Telescope

INSTRUMENT S-056 X-RAY TELESCOPE

Sub-Assembly	Component	Failure Modes	RLOO*	Single Point Failure	Repair Poss	Repair Action
TELESCOPE ASSEMBLY	Mirror Assembly - Front Aperture Stop Plate - Mirrors & - Mirror Cell	● Misalignment of stop plate relative to mirror - Due to thermal distortion - Failure of thermal standoff ● Mirror Failure - Temp rise above 90°F due to loss of thermal protection	< 1	Yes	No	Alternate activity schedule to reduce heating - otherwise terminate mission
	Forward Tube	● Thermal distortion in excess of 7 sec	< 1	Yes	No	Alternate activity schedule. Some degradation can be tolerated; otherwise terminate mission.
	Aft Tube	● Thermal distortion	< 1	Yes	No	Same as forward tube
	Mounting Plate	● Structural Failure (titanium)	< 1	Yes	No	Terminate Mission
	Insulator Plate	● Thermal leak path	< 1	Yes	No	Alternate activity schedule; otherwise terminate mission
	Optical Cube Assembly	● Non-functional (for initial alignment only)	< 1	N/A	No	No impact

*RLOO = Relative Likelihood of Occurrence

INSTRUMENT S-056 X-RAY TELESCOPE

Sub-Assembly	Component	Failure Modes	RLOO*	Single Point Failure	Repair Poss	Repair Action
TELESCOPE ASSEMBLY (Cont.)	Thermal Shroud	• Failure of standoff leaf springs • Failure of mylar retainer - results in loss of insulation	< 1	No	Yes	Alternate schedule of activities with proper access insulation can be repaired/replaced by manned action (clamps or tape)
	Solar Shield	• Thermal distortion due to failure of thermal standoffs (results in loss of resolution)	< 1	Yes	No	Alternate activity schedule; otherwise terminate mission
	Thermal Isolation Mount	• Thermal shorts due to epoxy fracture	< 1	Yes	No	Minor distortion of focal plane can be accepted - alternate activities; otherwise, terminate mission
	Center Mount	• Loss of thermal isolation causing misalignment with ATM spar	< 1	Yes	No	Same as above
	Thermal Control Assembly	• Thermistors • Thermostats • Strip Heaters • Resistors	3	No	Yes	All active elements are redundant; however, parts remove/replace could be performed (treat as RLOO of 1 because of redundancy)

*RLOO = Relative Likelihood of Occurrence

Sub-Assembly	Component	Failure Modes	RLOO*	Single Point Failure	Repair Poss	Repair Action
CAMERA ASSEMBLY	Film Magazine	• Drive fails to engage • Film take-up fails due to high load • Film becomes brittle • Idler sprocket drag • Latching pawl fails to engage • Latching pawl fails to disengage	6	Yes	Yes	Crew remove and replace film magazine assembly. If repeated action fails to remove magazine, terminate mission
	Filter Wheel	• Loss of filter material • Step motor fails off • Step motor steps improperly • Filter wheel jams	5	Yes	Yes	Stepper motor and filter wheel are replaceable by manned action - manual adjustment of guides possible with proper tool
	Rotary Disc Shutter	• Motor fails off • Motor steps improperly • Shutter guide friction	5	Yes	Yes	Remove and replace shutter wheel or motor or shim to reduce shutter guide friction
	Film Drive Assembly	• Motor fails off • Motor steps improperly • Motor stalls	6	Yes	Yes	Remove/replace motor
		• Clutch fails to engage properly			Condl	Drive linkage in camera housing is adjustable - film magazine is not. Replace film magazine

*RLOO = Relative Likelihood of Occurrence

Sub-Assembly	Component	Failure Modes	RLOO*	Single Point Failure	Repair Poss	Repair Action
CAMERA ASSEMBLY (Cont.)	Data Block	● Multiple failure of incandescent lamps (44 req)	9	Yes	Yes	Remove and replace entire data block
	Film Magazine Guide	● Interference with film magazine	2	Yes	Yes	Reset guides with alignment tool or remove and replace guides (after removing interface plate)
	Airlock System	● Drive motor stalls or fails off ● Linkage wears preventing seal ● Linkage freezes ● Drive motor improper response to step command ● Damaged O-ring seal	4	Yes	Yes	Remove/replace motor - free linkage. Manually open if necessary. Replace seal
CAMERA ELECTRONIC	Exposure Timer Control	● Irratic time sequences ● Timer fails off/on ● No output ● Fails to read inputs thereby locking up sequence	4	No	Yes	Remove/replace P. C. boards in electronics package. Verify cable/connector continuity. Operate manually

*RLOO = Relative Likelihood of Occurrence

Sub-Assembly	Component	Failure Modes	RLOO*	Single Point Failure	Repair Poss	Repair Action
CAMERA ELECTRONIC (Cont.)	Timers (12)	• No output-fails to expose film • Extended duration over exposes film • Irratic outputs disrupts delays between exposures • Automated sequences unuseable	4	No	Yes	Remove/replace P.C. boards in electronics package. Verify cable/connector continuity. Note: Manual override provided for auto sequences and exposure times can be manually controlled (RLOO is low because of backup; otherwise, would be higher) (Low RLOO due to backups)
	Filter Sequencer (Motor drive amp.)	• Fails to issue shutter open and/or close commands • Fails to issue filter position command • Fails to issue ready signal for next command	3	No	Yes	Remove/replace P.C. boards. Verify cable/connector continuity. Note: Crew or ground command inputs to filter position.
	Filter/ Shutter Motor Control Logic	• Fails to read filter/ shutter position signals • Fails to issue drive signal • Fails to issueTM position info. • Fails to issue signal for film advance	5	Yes	Yes	Remove/replace P.C. boards. Verify cable/connector continuity

*RLOO = Relative Likelihood of Occurrence

INSTRUMENT S-056 X-RAY TELESCOPE

Sub-Assembly	Component	Failure Modes	RLOO*	Single Point Failure	Repair Poss	Repair Action
CAMERA ELECTRONICS (Cont.)	Film/Airlock Motor Control Logic	● Fails to advance film ● Fails to open/close airlock ● Fails to issue frame count ● Fails to issue TM position info. ● Fails to verify film advance position ● Irratic film advance action - 1/2 or multiple frames	5	Yes	Yes	Remove/replace P. C. boards for logic control. Verify cable/connect continuity. Magnetic Reed switch failure within film magazine can be corrected by changing magazine only - Failure on interface plate side is non-repairable as currently designed
	Motor Control One-shot Amplifier	● Fails to issue one-shot pulse ● Issues improper pulse - Low voltage - Wrong width	4 (4)**	Yes	Yes	Remove/replace P. C. board
	Data Block Electronics	● Fails to read ATM clock ● Fails to read shutter position ● Flip-flops fail to reset	3	Yes	Yes	Remove/replace P. C.board

*RLOO = Relative Likelihood of Occurrence
**( ) = Number of Like Elements

INSTRUMENT S-056 X-RAY TELESCOPE

Sub-Assembly	Component	Failure Modes	RLOO*	Single Point Failure	Repair Poss	Repair Action
CAMERA ELECTRONICS (Contd.)	Active Mode Logic/ Sequencer	● Fails to select proper timers ● Fails to generate sequence commands - Timers - Filter Position - Shutter Times ● Fails to issue camera ready signal	4	No	Yes	Remove/replace P.C. boards. Override commands are available in many cases providing substantial backup
	Override Logic	● Fails to initiate electronic circuits ● Fails to initiate start signal ● Fails to issue stop signal	6	No	Yes	Remove/replace P.C. boards. Operate in auto mode only
	Indicator Drivers	● Fails to provide signals to control console - Operate - Ready - Filter Pos. - Frames	5	Yes	Yes	Remove/replace P.C. boards Partial backup provided with TM
	Transient Filter	● Fails to protect low voltage power supply	3	Yes	Yes	Remove/replace P.C. boards with filter assembly

*RLOO = Relative Likelihood of Occurrence

INSTRUMENT S-056 X-RAY TELESCOPE

Sub-Assembly	Component	Failure Modes	RLOO*	Single Point Failure	Repair Poss	Repair Action
CAMERA ELECTRONICS (Contd.)	Power Supplies +3 Volt +5 Volt +6 Volt +7 Volt + 19 Volt + 20 Volt - 5 Volt	• Fails with no output • Fails with output out-of-spec • Fails with excessive voltage • Fails with ripple	6(7)	Yes	Yes	Remove/replace P. C. boards Multiple single point failures. Each power supply represents a single point failure.
X-RAY EVENT ANALYZER	Proportional Counters Al Be	• Failure of output • Saturation of pulse count with bias shift	10(2)	Yes	Yes	Remove/replace - recalibrate Two counters involved
	Aperture Control - Encoder - Function Controller - Pulse Generator	• Fails to read inputs • Fails to issue output pulses • Fails to inhibit aperture position	7(2)	Yes	Yes	Manual override available. Encoders can be removed and replaced if necessary
	Aperture Motor Drive and Motors	• Capacitor Failure (no pulse output) • Low pulse output • Failure of step motor	5(2)	Yes	Yes	Remove/replace P. C. boards One aperture motor for each proportional counter.

*RLOO = Relative Likelihood of Occurrence

Sub-Assembly	Component	Failure Modes	RLOO*	Single Point Failure	Repair Poss	Repair Action
X-RAY EVENT ANALYZER (Contd.)	Amplifier	● Output failure - Loss of Capacitor - Loss of Waveform - Loss of Gain Preamp - H. V. Resistor	2 (2)	Yes	Yes	Remove/replace P.C. boards, etc.
	Calibrator Be Al	● Failure to issue part or all calibration pulses for either channel ● Improper pulse height for calibration	5	Yes	Yes	Remove/replace P.C. boards
	Differential Pulse Height Analyzer (DHA) - Voltage Comparitors - One-shot Multivibrators - Flip-Flops	● Fails output - Amplifier fails - Failure to reset flip-flops - Bias voltage shift	5 (2)	Yes	Yes	Remove/replace P.C. boards

*RLOO = Relative Likelihood of Occurrence

INSTRUMENT S-056 X-RAY TELESCOPE

Sub-Assembly	Component	Failure Modes	RLOO*	Single Point Failure	Repair Poss	Repair Action
X-RAY EVENT ANALYZER (Contd.)	Digital Signal Conditioner 10-14 Bit Counters	● Fails to read out registers ● Fails to issue aperture position signal ● Loss of TM output register ● Intermittent loss of bits	8 (2)	Yes	Yes	Remove/replace
	Ratemeter & Activity History Plotter	● Failure of output ● Saturation of output ● Failure of input to plotter - Ops Amps - Voltage Compare - FET gate	5	Yes	Yes	Remove/replace circuit
	High Voltage Power Supplies Al Be	● Fails output ● Fails feedback ● Excessive noise ● Excessive drift	7 (2)	Yes	Yes	Remove/replace either or both power supplies

*RLOO = Relative Likelihood of Occurrence

Sub-Assembly	Component	Failure Modes	RLOO*	Single Point Failure	Repair Poss	Repair Action
X-RAY EVENT ANALYZER (Cont.)	Low Voltage Power Supplies (4 Modules) + 5 volt + 12 volts - 6 volt ± 12 volt + 28 volt + 29 volt	• Fails to no output • Output out of spec • Excessive voltage • Excessive ripple	6 (4)		Yes	Remove/replace - multiple single point failures

*RLOO = Relative Likelihood of Occurrence