AEROSPACE REPORT NO.
ATR-76(7361)-1, VOL I

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Manned Systems Utilization Analysis (Study 2.1) Final Report

Volume I: Executive Summary

(NASA-CR-145899) MANNED SYSTEMS UTILIZATION ANALYSIS (STUDY 2.1). VOLUME 1: EXECUTIVE SUMMARY Final Report (Aerospace Corp., El Segundo, Calif.) 31 p HC $4.00 CSCL 22A

N76-13141

Unclas
G3/13 15043

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1 September 1975

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

Contract No. NASW-2727

Systems Engineering Operations
THE AEROSPACE CORPORATION

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

MANNED SYSTEMS UTILIZATION ANALYSIS (STUDY 2.1)
FINAL REPORT, Volume I: Executive Summary

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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 particular 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.

Although the principal interest has been devoted to man's role in the area of maintenance, there have been additional subtask efforts performed in response to direction from the NASA Technical Monitor. These subtasks have not been addressed in this summary report but have been documented and are listed below for reference purposes.

Space Servicing Pilot Program Study, ATR-75(7361)-1

Final Reports:

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)

The Technical Monitor of this 12-month effort was Mr. V. N. Huff, Code MT, at NASA Headquarters. Upon Mr. Huff's retirement in May 1975, the technical responsibility for Study 2.1 was assigned to Dr. J. W. Steincamp, Code PD 34, MSFC.

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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 a major motivation for assessing new system concepts, and serves to emphasize the benefits of these new systems relative to the integrated space program planning efforts.

The Skylab/ATM (Apollo Telescope Mount) experience has shown that active manned support, at least for complex scientific instruments, is vital for the achievement of mission objectives. Had this support not been available, many of the ATM instruments would have fallen far short of their scientific objectives. This does not imply poor design, inadequate testing, or improper training, but merely reflects the inherent nature of extending the frontiers of scientific achievements.

Manned maintenance, with proper spares provisioning and a few basic tools, can provide that unique element that 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 basis for Study 2.1, Manned Systems Utilization Analysis.

2. STUDY OBJECTIVES

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, thus the need to quantify these benefits and to examine the basic character of the operations required to sustain these benefits. The Skylab/ATM Program serves as the foundation for this effort; therefore, 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 addresses the design impact, the inherent reliability characteristics, and the relative improvement in system availability that could be achieved by maintenance or repair actions. Tradeoffs can then be made to assess the viability of manned support versus alternative measures for achieving a high level of mission success.

3. STUDY APPROACH

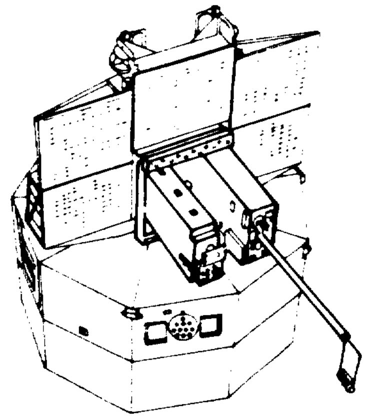
The tasks performed in this study have been directed along two parallel complimentary paths. The first path researches the experience of various correlatable space programs and develops empirical techniques to associate the benefits of repair and management actions. The actions taken during the course 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 alternate path addresses the design features in terms of weight, volume, and reliability associated with designing for space maintenance. This is achieved by reconfiguring the S-056 X-ray telescope for maintenance, and using this data to extrapolate to other ATM experiments. The estimated reliability characteristics are then examined to determine the benefits of repair operations, as well as, when redundancy versus repair should, in general, be employed.

The foundation for the research into anomalous occurrences was developed by examining the historical results of three similar experiment programs. These were the OVI series of automated spacecraft developed by the USAF SAMSO organization, the OSO-7 automated spacecraft developed by NASA, GSFC, and the Skylab S-056 X-ray telescope experiment in the ATM. The basic characteristics of each of these is given in Figure 3-1. Each program is similar in its objectives and represents increasing levels of complexity to accomplish the mission objectives. Each program has, as its basic objective, the gathering of solar X-ray spectral data. Each program had unique failure modes and in every case, to some degree, failed to accomplish the total mission objectives. The three programs also represent increasing levels of cost to obtain the desired scientific data.

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

After evaluating these three experiments, it was found desirable to expand the effort to include the remaining ATM experiments in the historical search for anomalous actions. Although not X-ray instruments, they were in all cases solar experiments representing the state of the art at the time, and having similarities in equipment design.

4. DESIGN CONSIDERATIONS

The S-056 X-ray Telescope shown in Figure 4-1, is considered to be reasonably representative of the type of instrument employed for scientific observations. Alignments are critical, and thermal balance is essential. The instrument relies on the ATM for power, stabilization, and other support functions. In the current configuration, access is limited to removal and replacement of film cassettes, and to the ATM solar shield door mechanisms. All other elements are contained within the ATM canister and are inaccessible. The weight budget was established at 161 kg (354 lbs); however, the actual weight was determined to be 133 kg (294 lbs).

The areas of interest, from a maintenance standpoint, are the camera mechanisms, the camera and thermal control system electronics, and the X-ray event analyzer (X-REA). The camera (shown in Figure 4-2) consists of shutter and filter wheels with stepping motors to drive them, a film drive mechanism, airlock door mechanism, and a data block to record reference data on the film. The camera electronics assembly is similar to the X-REA assembly and contains six power supplies, control circuitry, and the logic circuits to operate in several different modes. The X-REA (as shown in Figure 4-3) has two proportional counters, four power supplies, aperture control mechanisms, and various control and logic circuits. The only redundancy is limited to the thermal control system electronics.

There are over 500 single point failures in the input and output stages of the various power supplies alone. The loss of any one power supply will, as a minimum, result in a severe loss of data. In the majority of cases, complete loss of mission will occur. There are also numerous other single point failure situations (stepping motors, logic circuits, etc.) that would produce a similar result.

Redesign of the S-056 assumes accessibility to the subassemblies of interest. The basic procedure is to redesign latches and connectors to allow removal of the three subassemblies of interest to the Skylab pres-

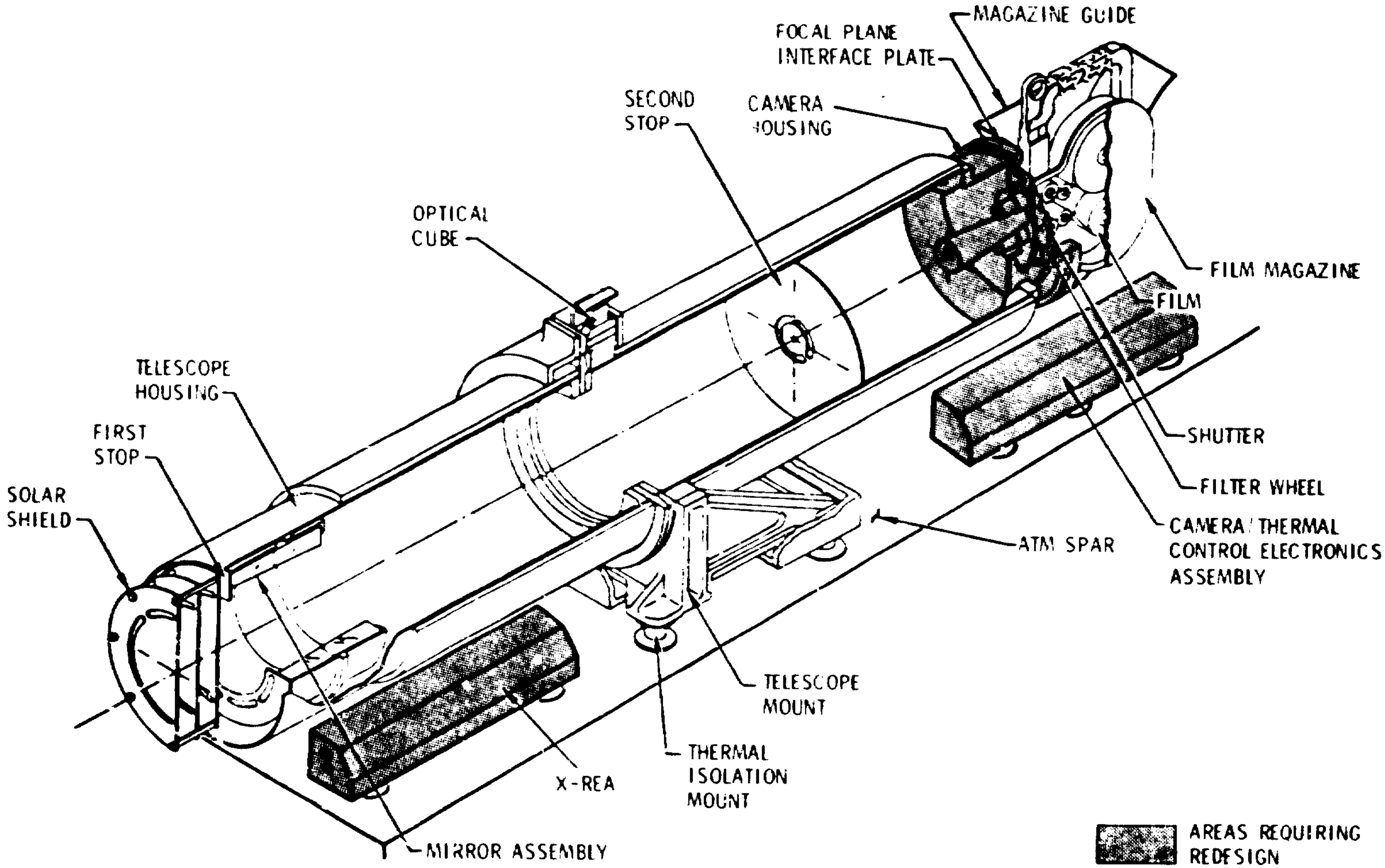


Figure 4-1. S-056 X-Ray Telescope Candidate Redesign Areas

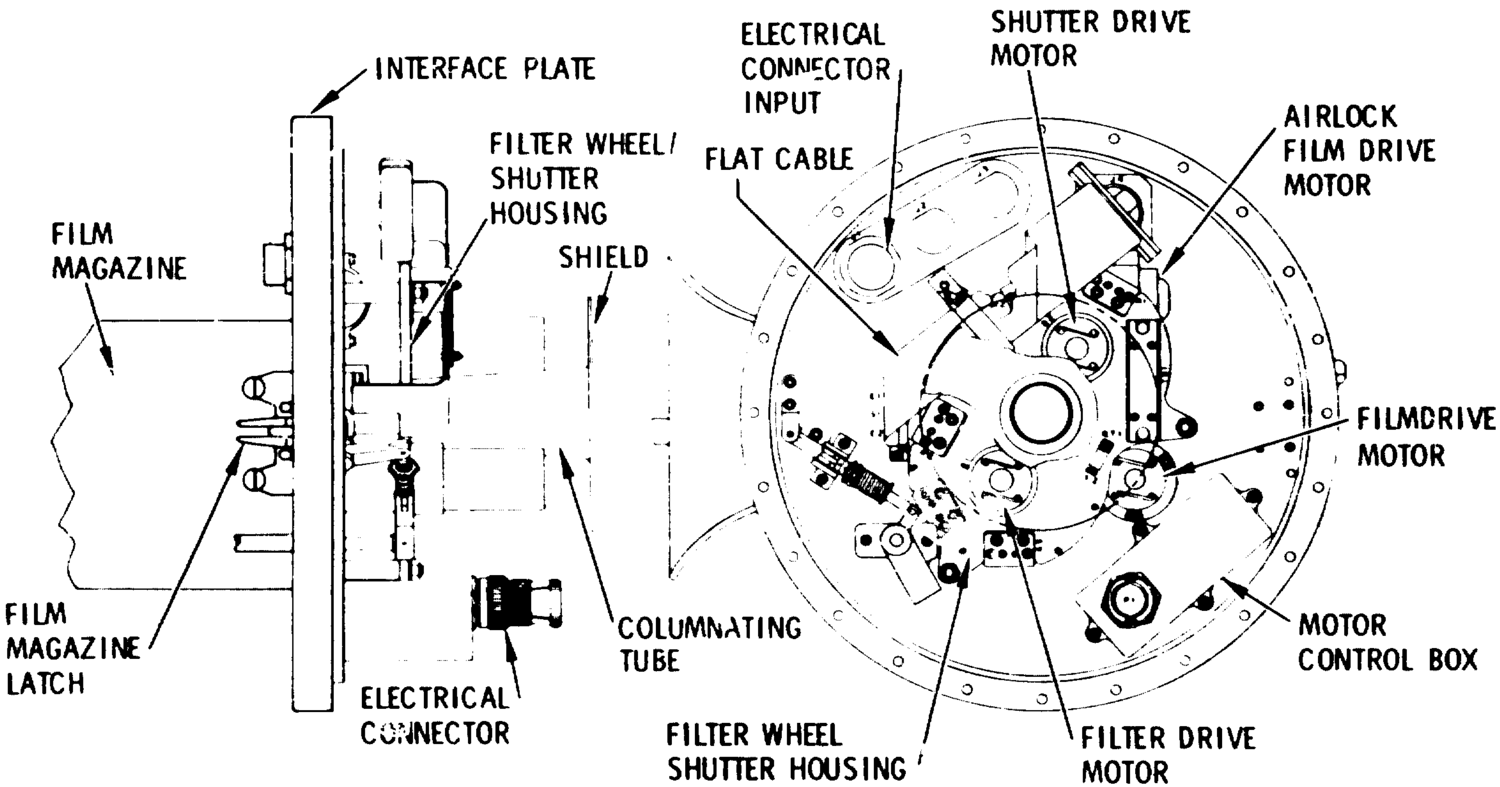


Figure 4-2. S-056 X-Ray Telescope Interface Plate/Shutter Assembly

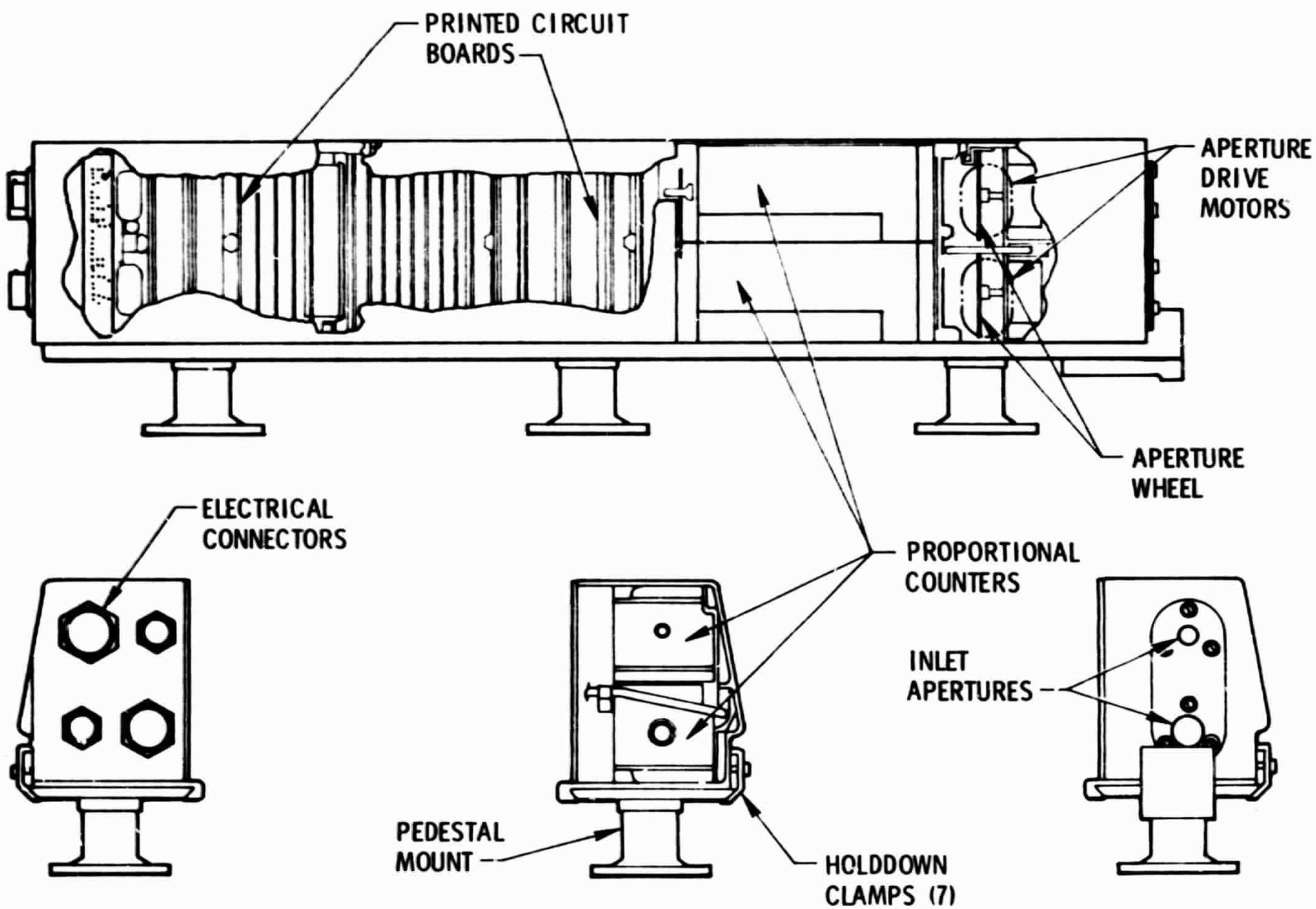


Figure 4-3. X-Ray Event Analyzer Assembly

surized compartment. An examination of design details indicates that commonality exists among the various components within these subassemblies, and that replacement operations are relatively simple. Therefore, a failed component (stepper motor, printed circuit board, etc.) could be replaced without difficulty and the subassembly reinstalled on the telescope. The weight penalty for redesign of latches and connectors was estimated to be 9 kg (20 lbs), or approximately 7 percent. This value will be employed later in tradeoffs with redundancy of components.

Reliability information on the S-056 is limited to power supplies and a few active electronic circuits. However, it is possible, through experience with other sensor systems, to estimate the overall system reliability based upon typical equipment failure rates. As mentioned previously, redundancy is limited to the thermal control system, consequently this item has been removed from consideration, and all remaining components treated in a single string manner.

In summary, based upon available information, the probability that the entire S-056 experiment will operate successfully for the defined 112-day mission has been estimated to be approximately 22 percent. This is not inconsistent with other space programs of similar design and therefore can be accepted as a representative value. Consideration of this level of reliability emphasizes the benefits associated with the repair actions performed by the crew in that it can be reasonably anticipated that data acquisition would have been severely curtailed without their assistance. However, the estimated reliability characteristics have a more important application in developing the desired level of on-orbit repair as discussed in Section 6.

5. MAINTENANCE ASSESSMENT

The basis for evaluating manned maintenance capabilities is a comparison of the three representative space-based experiments as described in Section 3. The three experiments differ widely in the degree of operational maintenance that can be performed, but are very similar in function and purpose. In this way, common criteria could be developed for assessing the relative improvement in mission success as a function of maintenance actions. This criteria was based upon two fundamental parameters, an estimate of the relative design complexity, and the maintenance effectiveness that was, or could have been, performed. Although the development of this criteria is arbitrary, the various parameters employed are sufficiently objective to provide a consistent means of comparing instruments and evaluating performance.

The design complexity factor relates to such parameters as number of operating modes, number of major subsystems or components, and the degree that operational sequences are automated. The maintenance effectiveness factor relates to the degree that the instrument performed over the period of interest, incorporating repair actions as necessary to achieve mission objectives. In a simplified sense, this represents the effectiveness with which the desired quality and quantity of scientific data is obtained. It is, therefore, judged that increased complexity can be tolerated if the effectiveness of maintaining the instrument shows a like or better improvement. The final assessment is derived by considering a value function that relates the effectiveness of gathering data to the cost of the instrument involved. In effect, the increased cost of relatively complex instruments can only be rationalized if a substantial improvement in data acquisition is realized.

This effort required extensive research into the instrument characteristics, as well as, to anomalies that occurred in operation. On initial contact, most Principal Investigators felt they obtained more than adequate data from the experiment of interest. However, in each case, failures did occur, and a loss of some data did result. Consequently, although compromises may have been acceptable in practice, the initial mission objectives were not achieved. Therefore, the results presented here represent relative trends rather than upper bounds on the value of maintenance. Further repair action might have been possible (if it had been required), but to the extent repair action did occur, it is represented in the comparison shown in Figure 5-1. Repair action, in this context, can be either by remote command or by a crewman in space. In either case, it represents a conscious effort to correct some unplanned anomalous occurrence.

There is a region of exclusion shown in Figure 5-1, indicating early failure conditions. If, for instance, a failure occurs and maintenance could not be performed, it would lie in this region. As maintenance actions are employed, the point of reference will rise representing the effectiveness of the maintenance that was performed. No maintenance action was possible on the OV1-17 payload; consequently, it falls within this zone of exclusion. If repair actions could not have been performed on the remaining instruments, they also would remain in this same zone.

However, repair was performed and the relative effectiveness is shown for the three reference payloads of interest, the OV1-10, OSO-7, and the S-056. The OV1-10 had a telemetry sequence interference problem that was compensated for by altering uplink commands. The OSO-7 was oriented incorrectly and only partial data was obtained. Through a series of command actions, it was possible to correct this, to a large extent, providing a substantial improvement in data acquisition over that of the OV1-10. Further improvement could have been realized if the magnetic electron multipliers (MEMs) could have been replaced.

The S-056 suffered a problem within the first two weeks of operation. High friction loads on the film drive mechanism caused a system shutdown. By repeated sequencing, the crew was able to reactivate the experiment. Subsequent aperture door problems also had to be faced. The

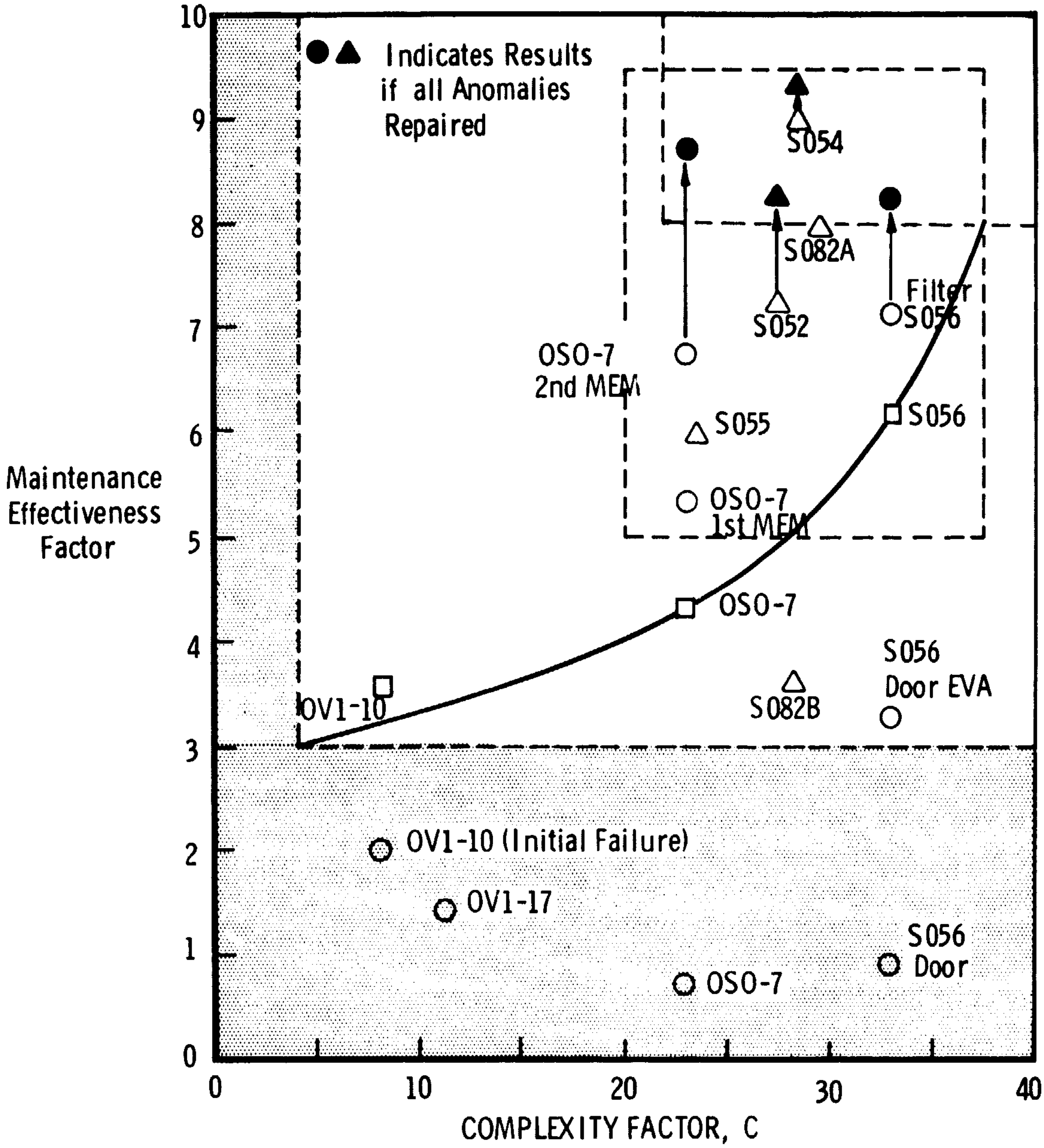


Figure 5-1. Effectiveness of Maintenance versus Complexity

influence of these actions, relative to the previous experiments, was to place the S-056 in a position to retrieve substantially more scientific information than previously obtained. Without the crew action, it is anticipated that the mission objectives would have been compromised to the extent that the S-056 would have produced less usable data than the OSO-7, but at a substantial increase in cost. The remaining ATM experiments show similar trends as discussed in Volume II of this report.

Figure 5-1 clearly shows the marked improvement achieved by manned maintenance and the potential for increasing effectiveness by complete maintenance and repair. This would be the upper right hand region of the figure, indicating a 100 percent effectiveness. This is the region where future instruments should fall if they are to show improvement over the S-056. These results indicate that to reach this region will require more extensive involvement of man in a repair role supporting a design that is space maintainable.

Active management of experiment operations by the crew was also examined in a similar manner. Management considerations include such parameters as: the ability to alter the sequence of operations, implementation of real time operations, and the potential to improve the quality of the data obtained by virtue of man's presence. These results also indicate that involvement of man in day-to-day operations substantially improves the overall operational effectiveness. Since scientific investigation often relies on being able to respond to unusual occurrences, these results can be interpreted as showing that a significant improvement in achieving mission objectives can be realized with increased manned involvement.

The trends that result from examining this historical data indicate that future instruments will inherently become more complex. As such, it is important to recognize that proper involvement of man in maintenance and management roles is a key factor to assure increased scientific achievement commensurate with the increased cost of doing business.

6. 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.

6.1 APPLICATION OF VALUE ASSESSMENT

Results of this study show a marked improvement in operational effectiveness with increasing involvement of man. The Skylab/ATM was the most advanced system to date in terms of manned utilization. Unfortunately, most of the instruments were not designed for maintenance and repair, and many of the operations were sufficiently automated so that only monitoring was available. Even so, this resulted in a significant improvement in performance over other unmanned instruments with remote monitoring and control. However, the performance improvement must be evaluated in light of the additional cost for the instrument. This becomes the basis of a value assessment; performance divided by instrument cost.

The measure of performance selected for this assessment is the amount of data obtained over the defined operational period. This is, in effect, a measure of the availability of the instrument; a high availability inherently results in a large quantity of data. Quantity of data can be measured in several ways, such as, number of images obtained, but for this case, it is defined as the estimated data bits obtained, as employed in defining the maintenance factor M_E. The quantity of data thus obtained is divided by the cost of the instrument. Since this number is, in general, quite large, it has been normalized to some extent by nondimensionalizing and taking the logarithm to the base 10. A further adjustment is made to account for the variation in quality of the data, recognizing that larger instruments, although they may cost more, often provide improved resolution.

The resulting formula is given as:

$$\text{Value Function} = Q_L \log_{10}\left(\frac{Q_N}{M}\right)$$

where Q_L = Quality of data

Q_N = Quantity of data (Bits)

M = Cost of instrument (Dollars)

The cost of the OV1-10, OSO-7, and S-056 experiments was estimated to be 1, 4, and 6 million dollars respectively. The estimated value functions were then found to be 2, 6, and 15. Consequently, the relative return on investment shows a substantial improvement with increased manned involvement despite the increased instrument cost.

The basic character of this trend is the point of importance rather than the computed values. It is estimated that in practice the scientific value of data decreases somewhat exponentially after some period of operation. That is to say that after some undefined point in time, more and more of the acquired data becomes repetitious. There is, of course, always the chance that some new phenomenon will develop hence, the desire to continue operation for as long a period as possible. Consequently, the quantity of data employed for this assessment is not considered to be an absolute parameter, but rather an indicator of the operational performance or availability of the instrument in question.

The following conclusions can be drawn from this assessment. As the complexity of an instrument is increased, there will be an associated cost increase, but the trend today is, with minimal manned involvement, that this cost increase will provide a substantial improvement in performance. Also, the point of man's involvement is very crucial. It appears highly unlikely that a similar cost increase for an automated program would generate a sufficient increase in performance to show a value improvement over past efforts. In fact, if man (either remotely or directly) had not been involved with the OSO-7 and the S-056, the results would have been of less value than the simplified OV1-10 experiment, although the costs were substantially higher.

Finally, the ultimate in manned involvement will only be achieved when man can function in space with the same degree of freedom he realizes with terrestrial observatories. Many functions are necessarily automated, but a small crew of men can maintain, operate, reprogram, and analyze the observational programs to maximize scientific achievement. This same concept must eventually evolve in space to maximize the scientific achievement that can be realized in this environment. The trend toward increased complexity is obvious. It is also obvious from historical comparisons that active manned participation is a necessity to achieve a level of performance that justifies the increasing cost of scientific programs. The next question arising is what level of maintenance should be programmed. This is addressed in the next section

6.2 APPLICATION OF MAINTENANCE TRADEOFFS

The S-056 X-ray telescope is employed for the following tradeoffs because it is representative of scientific instruments, unique in its design concept as opposed to mature operational systems. A simplified fault tree is developed to demonstrate failure paths that could lead to loss of the instrument. The failures are considered sufficiently complete to form a set of conditions representing the unreliability of the instrument. These component failures are then ordered such that the benefit of repair action can be assessed relative to the overall system availability.

A further tradeoff is performed to assess the value of component redundancy as opposed to component repair. This tradeoff includes the initial penalty associated with designing for repair operations, but also takes advantage of the commonality of components. The results are limited to the availability of reliability data, but are considered to be reasonably representative of the trends that would be experienced with equipment similar to the S-056 X-ray telescope.

Figure 6-1 provides a sample of one of the fault trees developed for the S-056. This is one of four trees that identify typical

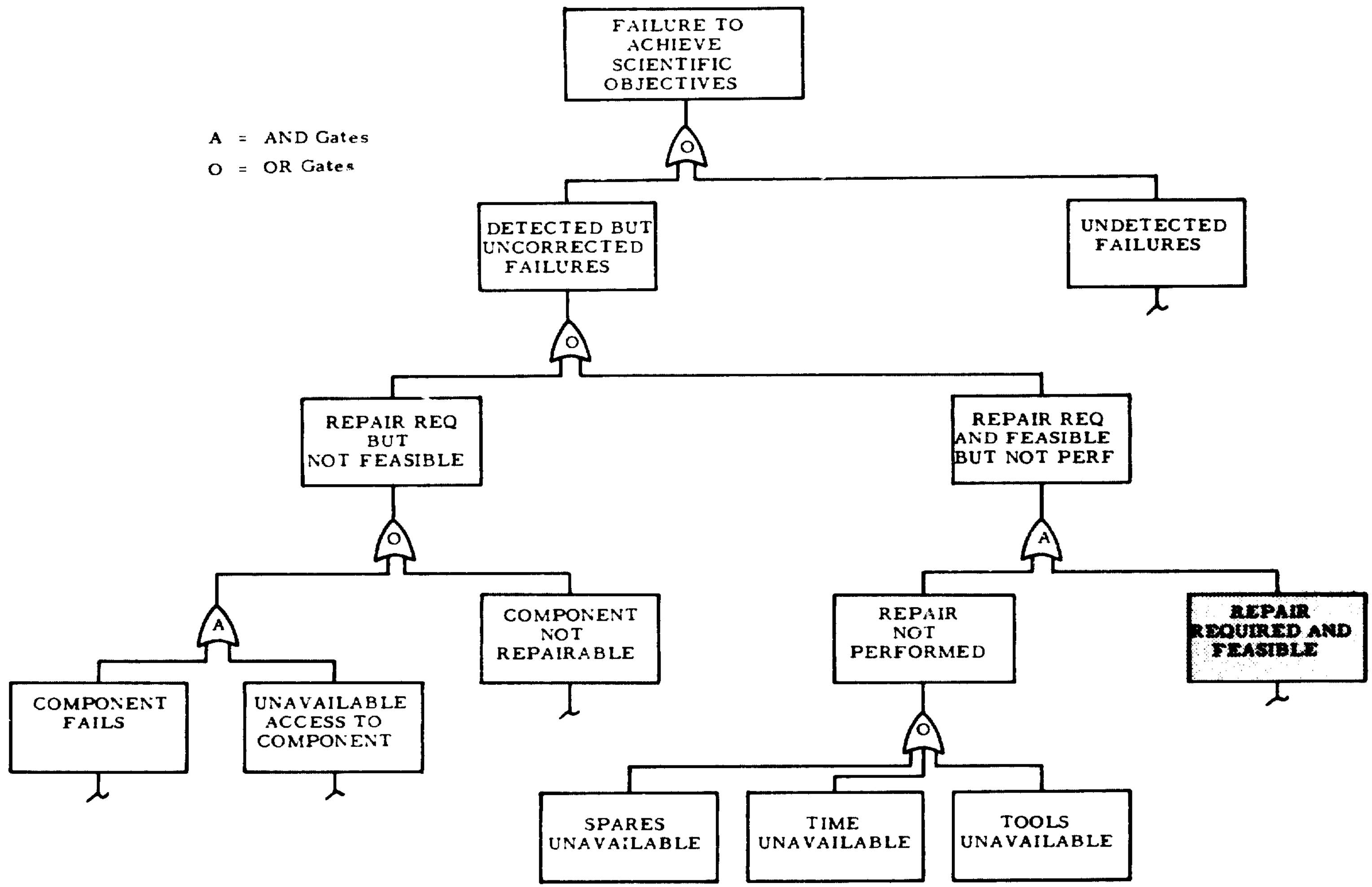


Figure 6-1. S-056 Second Level Fault Tree

failures at the black box level. These component failures have then been assigned a relative likelihood of occurrence factor (RLOO) that in effect orders the components relative to the total composite of predicted failures. Although this cannot incorporate all possible failures, (as with a comprehensive study) the sample is sufficiently large to be representative. This, therefore, leads to the histogram shown in Figure 6-2.

This histogram can be integrated to derive the incremental benefits of component repair relative to decreasing the unreliability of the total system. In addition, the histogram can be arbitrarily varied to represent both optimistic and pessimistic distributions, thereby providing reasonable bounds on the expected benefits of repair. The integrated effect is shown in Figure 6-3. The reference distribution, which is considered most realistic, shows a substantial improvement in availability even for low values of repair. This catches the majority of weak items in the reliability string. After this point (approximately 25%), the rate of return diminishes, but is still sufficiently rewarding to be of value.

The shaded region of Figure 6-3 indicates the area of interest for these types of instruments. The inherent nature of these designs will probably preclude availabilities above 90 percent, but certainly with the cost involved, a value above 70 percent is desirable. To reach this region with the reference distribution requires access (and spares) for approximately 70 percent of the components in the sample. By examining the detail fault tree, it will be noticed that there is a good deal of commonality among the components. Also, it should be recognized that with little modification, all are accessible for repair. Consequently, a 70 percent repair capability does not appear unrealistic.

If, however, a pessimistic distribution were assumed (a high percentage of components have a high likelihood of occurrence), the influence of repair is even more dramatic. This is to be expected, and shows that conservatism can be employed in the reliability estimates without decreasing the system availability, provided a repair compatibility exists. Repair may never be required, but designing with this in mind

S-056 X-RAY TELESCOPE

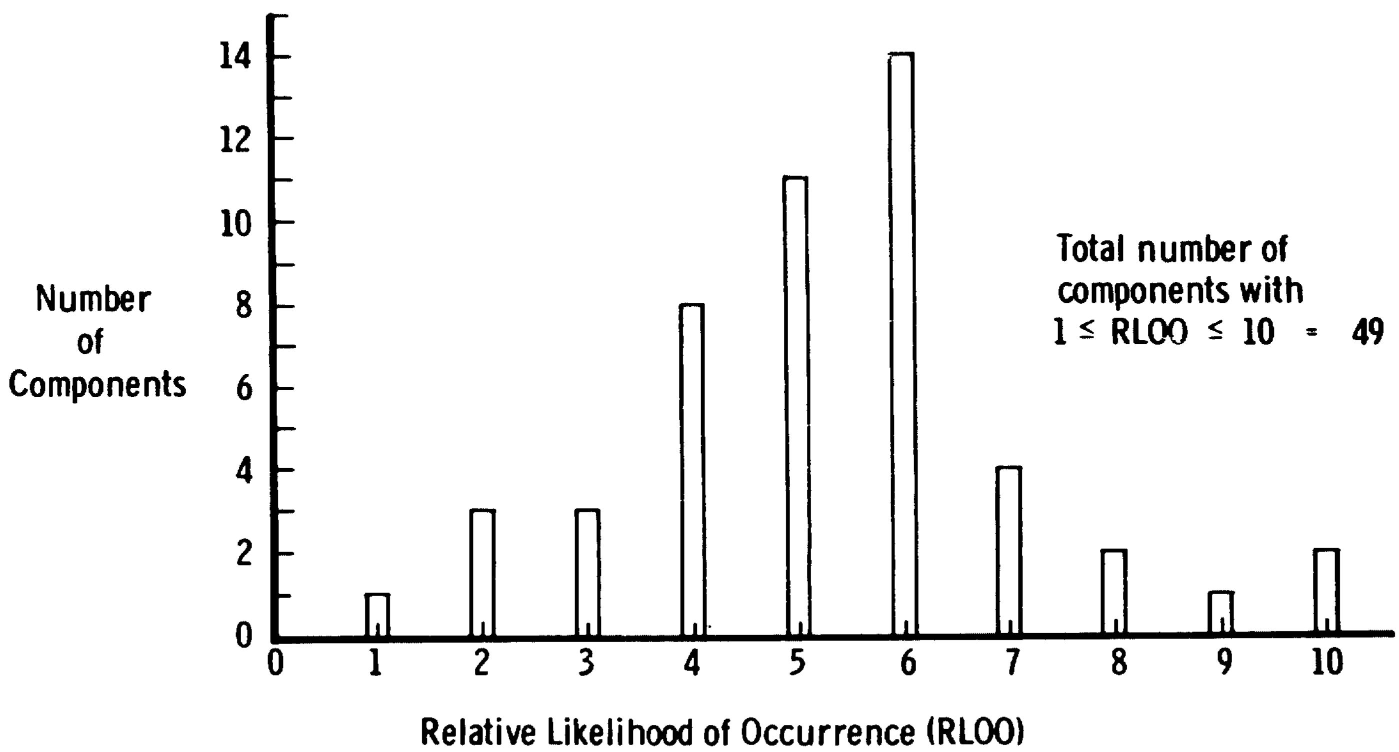


Figure 6-2. Histogram of Component Reliability Characteristics

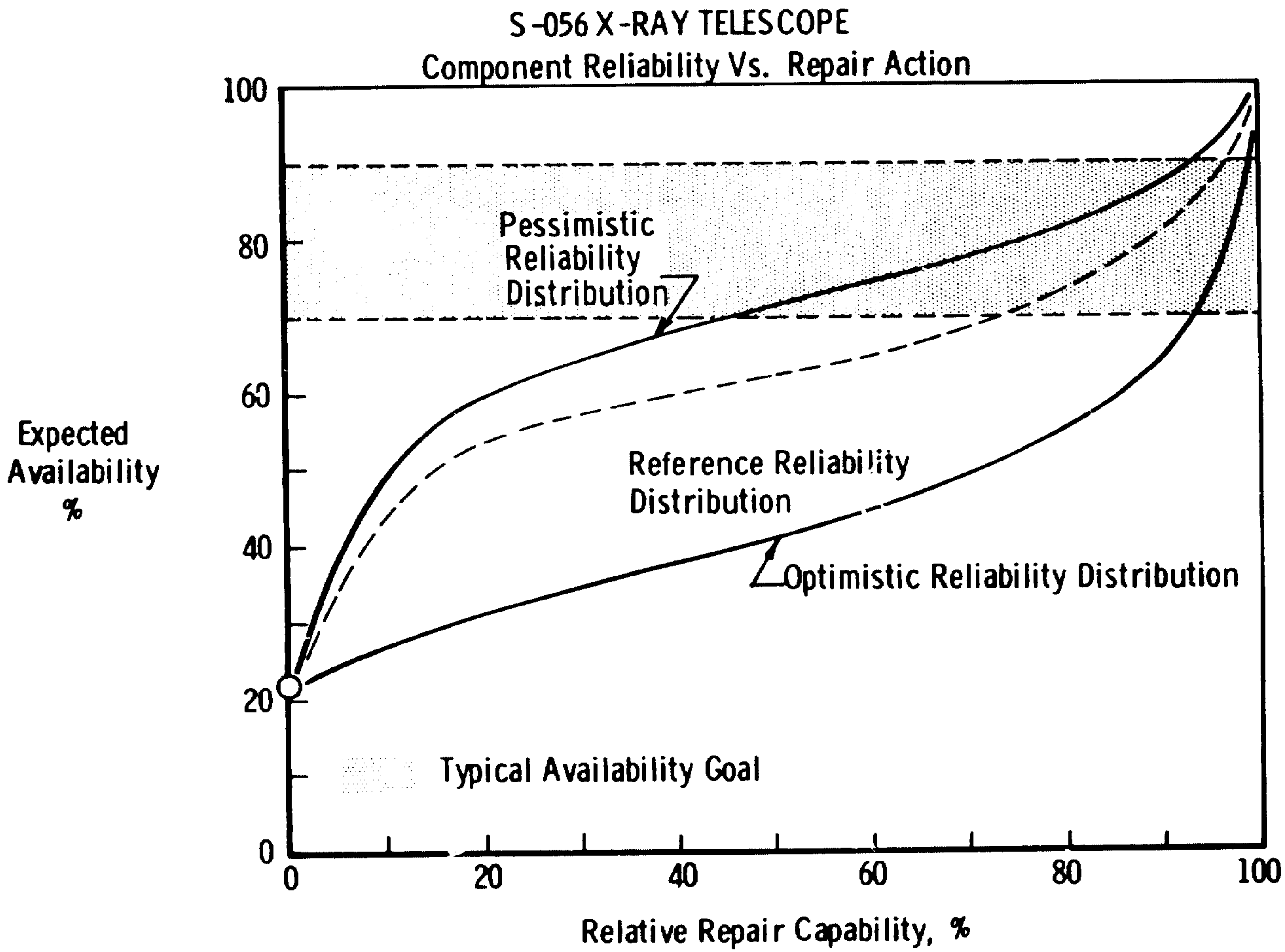


Figure 6-3. Rational Bounds of S-056 Repair Capability

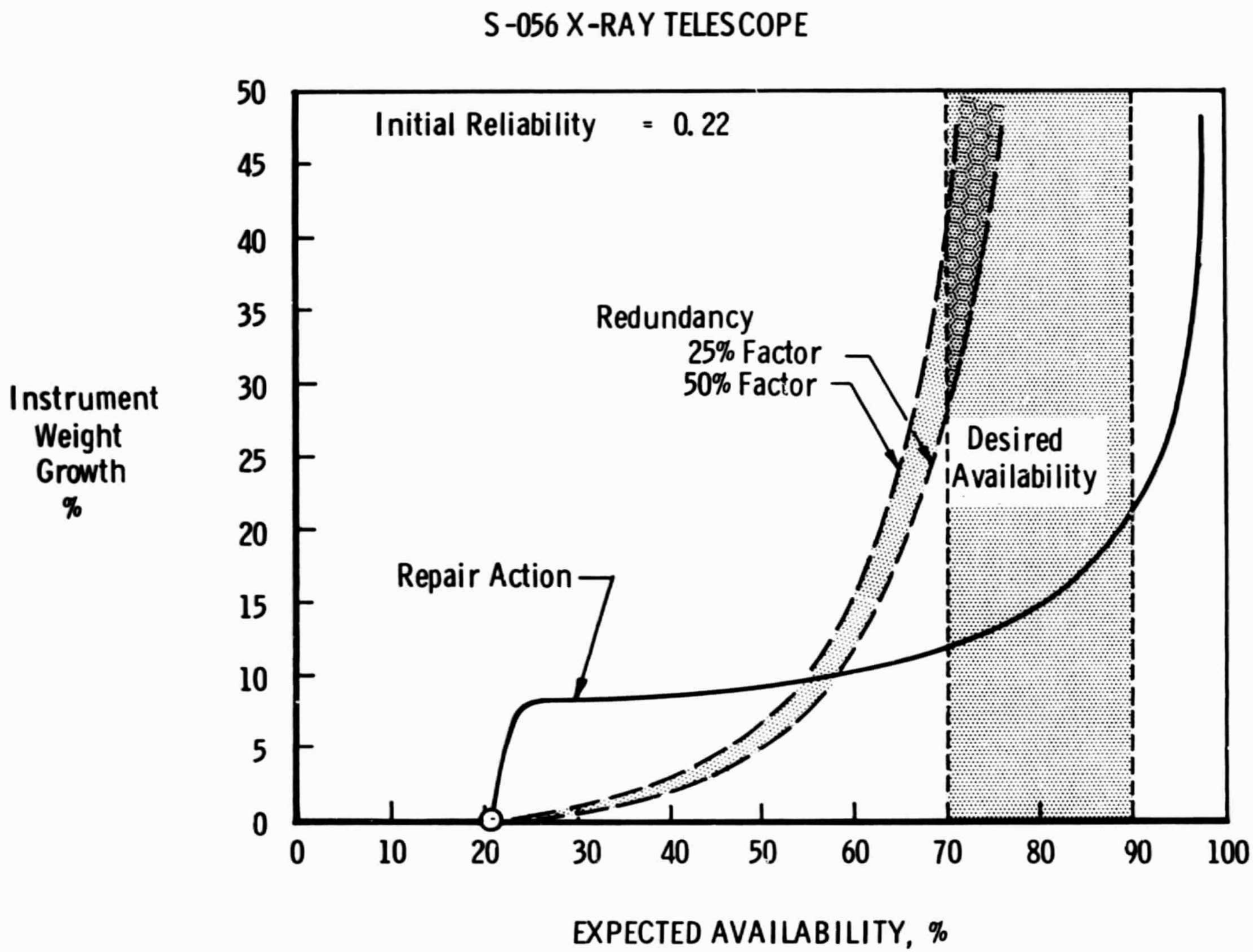


Figure 6-4. Redundancy versus Repair for S-056 (Initial Rel. = 0.22)

enhances the confidence that mission objectives can be achieved. If, on the other hand, the components are assumed to be highly reliable, the value of repair is diminished because any one component contributes only a small portion to the total reliability. Experience indicates this is unrealistic, but it serves to define a region of interest relative to the influence of performing repair operations.

The general character of the curves of Figure 6-3 shows the importance of incorporating the option to perform repair operations. It should further be pointed out that this figure only deals with currently identifiable failure events. The Skylab results prove that many anomalies are not predictable. They would not necessarily show up in a classical reliability analysis and they may not be obvious on a fault tree assessment. This is all the more reason to provide the repair option. Designing the capability to perform repair on known problem areas often will also provide access to repair unknown problems, or at least to develop effective work arounds. This approach is found to be considerably more effective than judicious use of redundancy as discussed next.

Redundancy is often employed as a means of increasing the reliability of a system. This is particularly true for avionic subassemblies. However, the reliability estimate for the S-056 shows the avionic subsystem to be considerably more reliable than other components. Consequently, the addition of a redundant set does not provide any substantial improvement in system reliability. It is therefore important to optimize the addition of redundant components relative to their incremental weight increase. The associated reliability improvement is shown in Figure 6-4. This curve shows that the knee of the curve occurs at an expected reliability of 55 percent. Increasing redundancy beyond this point generates a severe weight penalty. Scale factors have been employed, as shown in Figure 6-4, to reflect the additional weight of brackets, connectors, etc., that occur when a redundant component is employed.

The same figure shows the influence of performing maintenance, including the weight of spares provisioning. The initial weight increase is associated with designing for maintenance, that is, a 7 percent penalty. After this, however, large increases in reliability can be achieved with minor weight increases. This occurs because of the commonality of components. A single spare component (stepper motors) may be employed in one of several applications. The knee of this curve lies at 85 percent reliability, considerably beyond what could be achieved by redundancy. Although initially redundancy would be favored, the crossover occurs at about 55 percent. This is not considered to be an acceptable level; hence, repairability is the favored approach.

These results are sensitive to the equipment selected for examination. It is anticipated that this general characteristic will be true for all scientific instruments similar to the S-056 X-ray telescope. If the initial reliability were considerably higher, such as for COMSATs, the characteristics could change substantially. Therefore, at least for scientific instruments, the option to perform manned maintenance appears to be the most efficient means of achieving mission objectives.

7. SUMMARY AND CONCLUSIONS

The arguments for 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 curtailed. Contemplating these achievements leads to the consideration of what might have been accomplished 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 those uncertainties to the extent that man's contribution could be assessed versus alternative concepts.

The results of this effort show that orbital maintenance is probably the most realistic means of achieving high system availabilities for scientific instruments. A capability to maintain approximately 40 percent of the more significant subassemblies and components is estimated to be a lower bound. A 70 percent repair capability is preferred to assure achieving high availabilities. These levels of maintenance are found to have a minimal impact on the instrument design, with an associated weight increase of less than 7 percent.

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 and efficiency should be a sufficient incentive. The important point is to continue to keep the objective in mind and direct efforts toward it.