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LANDSAT-D REFURBISHMENT STUDY

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SECTION 1. INTRODUCTION

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1.1 SCOPE

This report presents the results of a study to determine what would be necessary to refurbish the Landsat-D spacecraft after its recovery from orbit at the end of a 3-year mission in order to reuse the spacecraft on a second 3-year mission. A schedule of the time required for the refurbishment including the procurement cycle for long lead-time items is developed and a cost comparison made between refurbishment and the procurement of an entirely new Landsat-D spacecraft.

1.2 REPORT FORMAT

This report is broken down into seven sections. Section 1 establishes the ground rules, assumptions, and the approach taken for this study. A summary of the results is presented in section 2. The next two sections discuss the factors which were used to determine whether an item would require refurbishment or replacement, or could be reused as is. Section 3 discusses spacecraft reliability and on-orbit performance. Operational and environmental stress factors which could affect spacecraft performance are presented in section 4. A discussion of the designs and detailed refurbishment requirements for Landsat-D components is found in section 5. A refurbishment program implies a great deal of planning and preparation. These considerations are discussed in section 6. Finally, section 7 recommends areas which need to be addressed to effectively prepare for an era in which operations in space include refurbishing and reusing spacecraft as a routine procedure.

1.3 STUDY GROUND RULES

The Landsat-D Flight Segment satellite comprises an Instrument Module (IM) and a Multimission Modular Spacecraft (MMS). The IM consists of two instruments, the Thematic Mapper (TM) and the Multispectral Scanner (MSS); the Wideband Communications Subsystem (WCS); a solar array; and supporting structural, thermal and electrical equipment. The WCS is made up of a Wideband Module (WBM) and a deployable boom on which there is a radio frequency (RF) compartment and the Tracking and Data Relay Satellite (TDRS) antenna with its gimbal drive assembly. The Global Positioning System (GPS) antenna is also on this boom. The MMS includes the Modular Power Subsystem (MPS), the Modular Attitude Control Subsystem (MACS), the Command and Data Handling Module (C&DH), a Propulsion Module (PM), and the supporting structural assembly with its associated mechanical, thermal and electrical components. The structural assembly also includes the Signal Conditioning and Control Unit (SC&CU) which is attached to it. An exploded view of the spacecraft is shown in Figure 1-1.

The refurbished spacecraft is to be a duplicate of Landsat-D with the exception of the PM. The follow-on mission needs the larger PM-2, which has a greater fuel capacity than the PM-1A, for the transfers between its orbit and the Space Transportation System (STS) orbit at launch and recovery. Refurbishment will consist of doing whatever is necessary in the way of cleaning surfaces, making repairs, selectively replacing parts, or by substituting duplicate units to restore Landsat-D to a condition which will have adequate reliability and performance characteristics to complete a second mission.

It is assumed that the original Landsat-D mission will be launched by a Delta vehicle, operate for 3 years on-orbit, and then be recovered with the STS orbiter. The solar array and deployable boom will be jettisoned prior to de-orbiting. All operational and environmental factors associated with ground operations, the launch and the retrieval, de-orbit and landing phases will be within the design envelopes. It is known that certain STS orbiter operations could have damaging effects on Landsat-D. It is assumed that constraints will be imposed to prevent this, as long as it does not conflict with safe orbiter operations (refer to section 4.3). During on-orbit operations Landsat-D will have operated as expected which means that

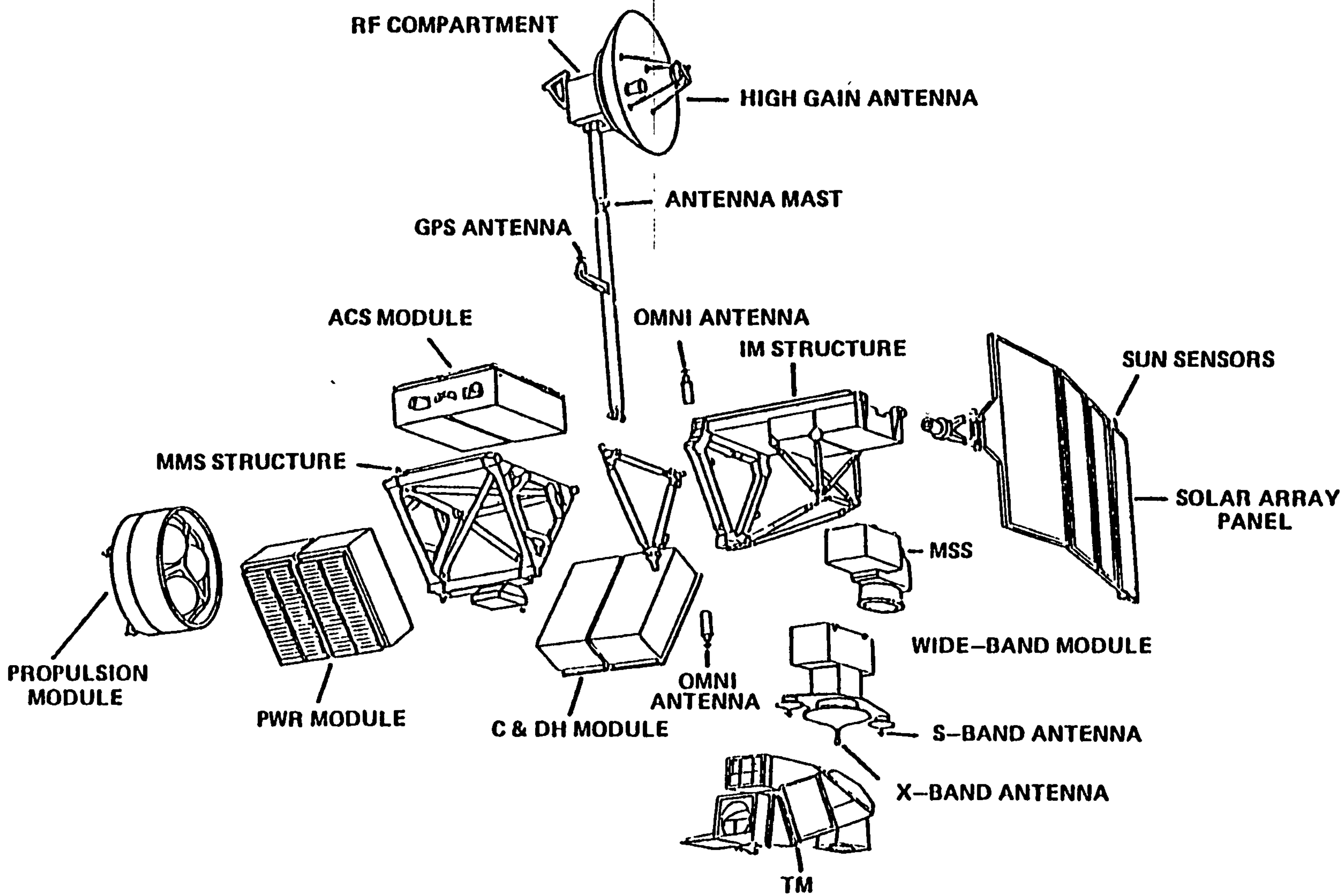

Figure 1-1. Modular Design of Landsat-D

no design errors will be uncovered, there will be no workmanship defects which cause unexpected failures, and no ground control errors will be made. This implies that redundant units will not be used during the flight operations, which is an assumption required to estimate operational life and switching frequencies.

The refurbishment plan presented in this study is success oriented. No provisions are made for the unavailability of manpower, facilities or test equipment. All schedule and procurement cycle information is based on that which is currently being experienced, not what may possibly be the case in the future.

1.4 APPROACH TO THE STUDY

This study was undertaken in two phases. The first phase was to determine what would most likely be the refurbishment required for Landsat-D. The second phase was to determine the schedule for this refurbishment and to estimate the costs involved. Long lead-time items were identified in order to properly schedule their procurement cycles.

To accomplish the first phase, a comprehensive list of all Landsat-D components was made. A component was considered to be any functional unit which could be viewed as an entity for the purposes of analysis, manufacturing, maintenance, testing or record keeping. The individual components were then screened to determine if they would probably require refurbishment or replacement to refly. Three factors were used for these screenings: the susceptibility of a component towards damage by the environment which occurs naturally in space and that which is induced by the launch and recovery vehicles; operational stresses which could affect component performance or increase the rate of failure; and on-orbit data from previous satellites which may indicate the likelihood of lower reliability and high failure rates. If any of these factors indicated that a component would not likely operate satisfactorily for two missions, that component was identified as a candidate for refurbishment or replacement. Details of these factors are discussed in sections 3 and 4.

Information used for these screenings came from many sources. Talks were held with Landsat-D and MMS personnel at the Goddard Space Flight Center (GSFC). Other scientists and engineers at GSFC supplied pertinent information based on their experiences with other programs or their familiarity with factors that would influence a refurbishment program. Personnel at Marshall Space Flight Center (MSFC) provided relevant information from the Skylab, Spacelab, and Space Telescope programs. Jet Propulsion Laboratory (JPL) personnel supplied information on their experiences with spacecraft reliability and on-orbit performance. Hughes Aircraft Company provided information on the two Landsat instruments, as did Fairchild Industries for the PM. The other Landsat-D contractors were not available. In addition to these private conversations, published data and documents were used as sources of information relevant to the study. These are referenced where appropriate in the report.

Having established the expected refurbishment requirements for the various Landsat-D components, the second phase involved integrating these individual requirements into a total refurbishment program which would include all events which would take place from the time Landsat-D is removed from the STS orbiter until it is shipped to the launch site for STS integration and relaunch. Using the work flow for the total program, the schedule for operations was estimated, as were the associated costs. These costs were then compared to those for building an entirely new Landsat for the follow-on mission. It was hoped that cost and schedule estimates would be provided by the contractors involved with the various Landsat-D modules, however, this turned out not to be the case. All OAO Corporation's (OAOCO) cost and schedule comparison are estimates based on a review of work breakdown structures and scheduling information which were made available through the GSFC Landsat and MMS project offices.

SECTION 2. RESULTS

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2.1 GENERAL

OAOCO recognizes that there are a multitude of opinions when it comes to estimating what will be necessary to refurbish a spacecraft for reflight. These range from doing little to the spacecraft to totally discarding it and using a new spacecraft. Costs, schedules, and other programatic considerations, including the amount of risk or level of reliability which is considered to be acceptable, will determine which approach should be taken. The refurbishment plan presented in this study is a conservative approach, emphasizing testing to assure reliability and minimize the risk of potential failures. If no weakness, degradation, or design feature could be readily identified which would indicate that a component would not operate satisfactorily during a second mission, that component was considered to be reusable. If conflicting or inconclusive data were available regarding the risk of reusing an item, refurbishment or replacement was generally considered necessary. Two other factors influenced the plan, particularly with regard to the extensive pre-refurbishment testing. First, Landsat-D was not originally conceived of as a reusable spacecraft to fly two 3-year missions, so its design goals will be exceeded. Second, Landsat-D will be the first spacecraft to be refurbished and flown on a second mission, so no prior experience is available for establishing refurbishment guidelines. A different approach may be taken in the future, after spacecraft are designed for reuse and more experience has been gained regarding refurbishment.

Although the initial phase of this study addressed the question of predetermining the candidates for replacement and refurbishment, it is obvious that the Landsat-D refurbishment program would not be based solely on what was presupposed to be needed, but rather on a systematic plan which would ascertain what refurbishment and replacement would actually be required. As a result, this study presents a total plan which provides for a systematic evaluation of the recovered spacecraft to establish the refurbishment needs. Also included is an estimation of these needs as would have been determined by this evaluation. These are discussed in detail in section 5. This does not preclude the fact that additional refurbishment requirements for supposedly good items may surface during the evaluation or that items which were believed to need refurbishment may prove to be reusable. Final determination cannot be made until the spacecraft has been returned from orbit.

2.2 LANDSAT-D REFURBISHMENT PLAN

First, prior to STS retrieval, Landsat-D should have an on-orbit performance check made, within the operational limits of the system. This will provide a baseline under true environmental conditions which cannot be achieved in an ambient functional test. Also, this provides a means for assessing the effects of retrieval and landing on the spacecraft. Data should also be taken during the landing to establish the actual levels of induced dynamic loads. These will be used to verify that no design limits were exceeded. Following retrieval and return to Earth, Landsat-D will be removed from the STS orbiter and shipped to the prime contractor for inspection, test, and disassembly. The initial visual inspection will be done to identify any physical damage which has occurred, including degradation of the thermal and optical surfaces by radiation, meteoroids, and visible contamination. An ambient function test of the spacecraft will be performed to permit the isolation of any suspected failures or areas of degraded performance. Data taken during flight operations should also be included in this assessment of performance.

The systems level post-retrieval verification testing having been performed, Landsat-D will be disassembled into the following functional modules and instruments: TM; MSS; WBM; the IM including its associated thermal, electrical and mechanical components; MPS; MACS; C&DH; PM; and the MMS structure with its electrical, thermal and mechanical components, including the SC&CU.

These modules will then be shipped to their respective vendors. Upon receiving his module or instrument, each vendor will perform an ambient functional test to further evaluate the performance characteristics of the returned equipment. He will then disassemble it to the component or subassembly level and return these to the appropriate vendors where each will undergo a bench acceptance test. A flow chart of this verification procedure is shown in Figure 2-1.

The information derived from this controlled disassembly and test sequence will be the basis for determining specific refurbishment requirements. Any unit which is shown to have failed, or to exhibit anomalous behavior, will be refurbished or replaced. If the tests show that there has been any degradation of functional performance beyond some predetermined acceptable limit, that item will also be refurbished or replaced. The same will be the case for items exhibiting visual degradation. As part of this assessment process, the induced landing loads and the on-orbit operational times will be evaluated. A loads analysis will be necessary for determining the former. Any unit which has exceeded its design loads, operating life, or operating cycles will be refurbished or replaced.

This post-retrieval screening divides the components into three categories; those which can be reused, those which must be replaced, and those requiring some refurbishment. Whether it will be possible to refurbish a unit by selective parts replacement or be necessary to replace it with a totally new unit will depend on the extent of the damage and the practicality of doing selective replacement. All that will be required to prepare the reusable items for module or instrument integration is to clean the external surfaces to remove any possible contaminating residue. Any totally new unit being used as a replacement will have to complete the full

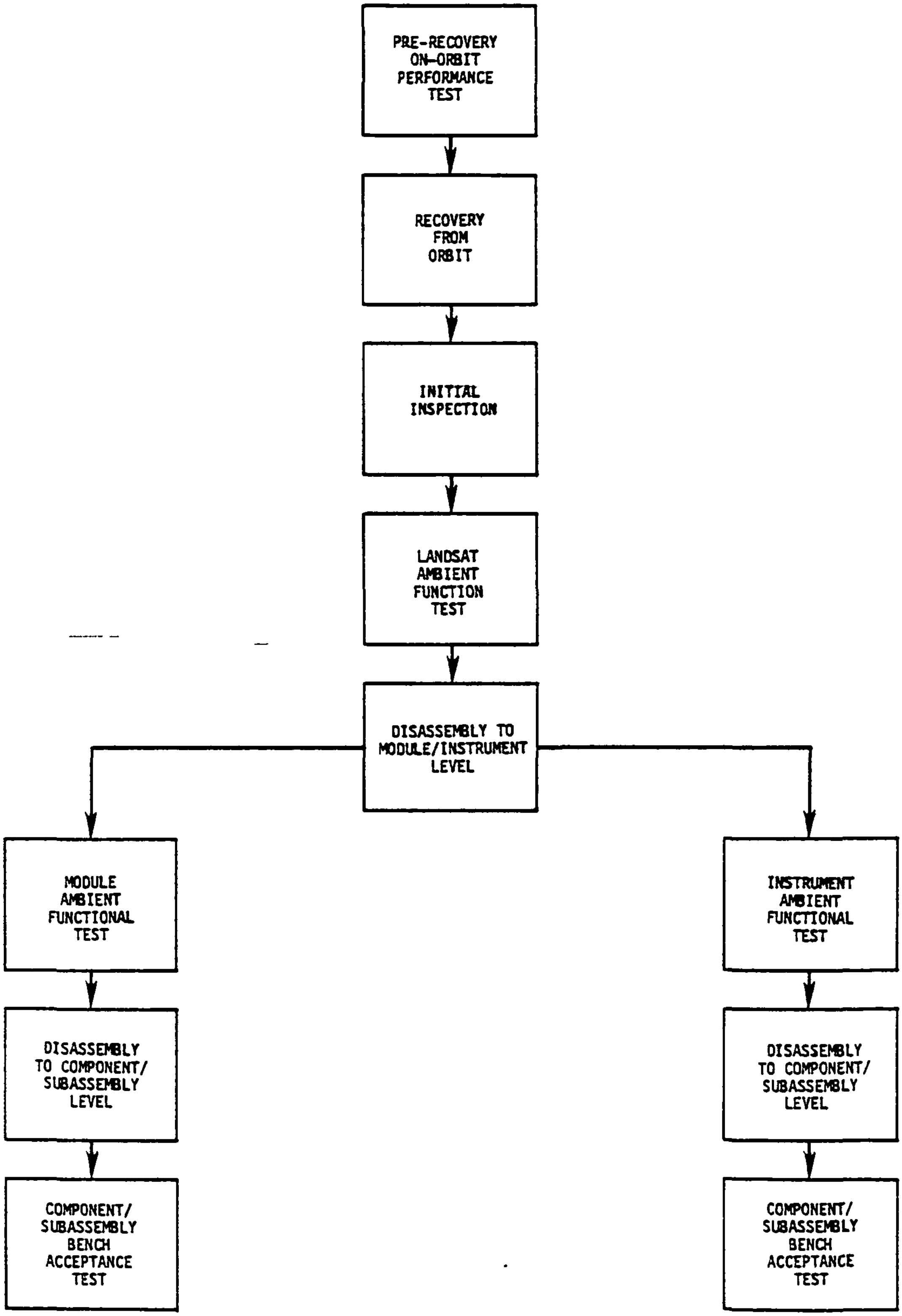

Figure 2-1. Landsat-D Post Mission Performance Evaluation

acceptance test cycle that the original unit had undergone before being considered ready for integration. Some original test cycles did not include shock or vibration exposures since they would be seen at a higher level of integration. For those cases, these tests must be included in the acceptance program for the replacement unit since the higher level retesting will not include them. Efforts to prepare those items requiring refurbishment for integration will include performing the rework, cleaning surfaces to remove contamination, and testing for readiness. The testing will consist of a bench acceptance test, a workmanship vibration test, and temperature cycling at ambient pressure, with functional tests being performed after each environmental exposure. If the rework involves only repainting or recoating a thermal or optical surface without any disassembly, no additional tests will be necessary.

As each component becomes ready for integration it will be sent to the appropriate module or instrument contractor. Integration will proceed at this level in the same manner as if a new module or instrument were being assembled. Once integrated, each module and instrument will undergo a modified test program consisting of an ambient functional test, a vibro-acoustic test and a thermal-vacuum test with functional checks performed at the end of each environmental exposure. The MMS modules will then be sent to the MMS contractor for integration, while the instruments and the WBM will go to the Landsat-D contractor for integration with the IM. Alignment and ambient functional tests will be done at the MMS and IM levels. The MMS will then be sent to the Landsat-D contractor where it will be mated to the IM, followed by alignment and an ambient functional test. The spacecraft will then have a vibro-acoustic test and a thermal-vacuum test performed, each followed by a post-environment functional test. Following satisfactory completion of this integration and test sequence, Landsat-D will be delivered for STS integration and relaunch. A flow chart of the integration and test procedures is shown in Figure 2-2.

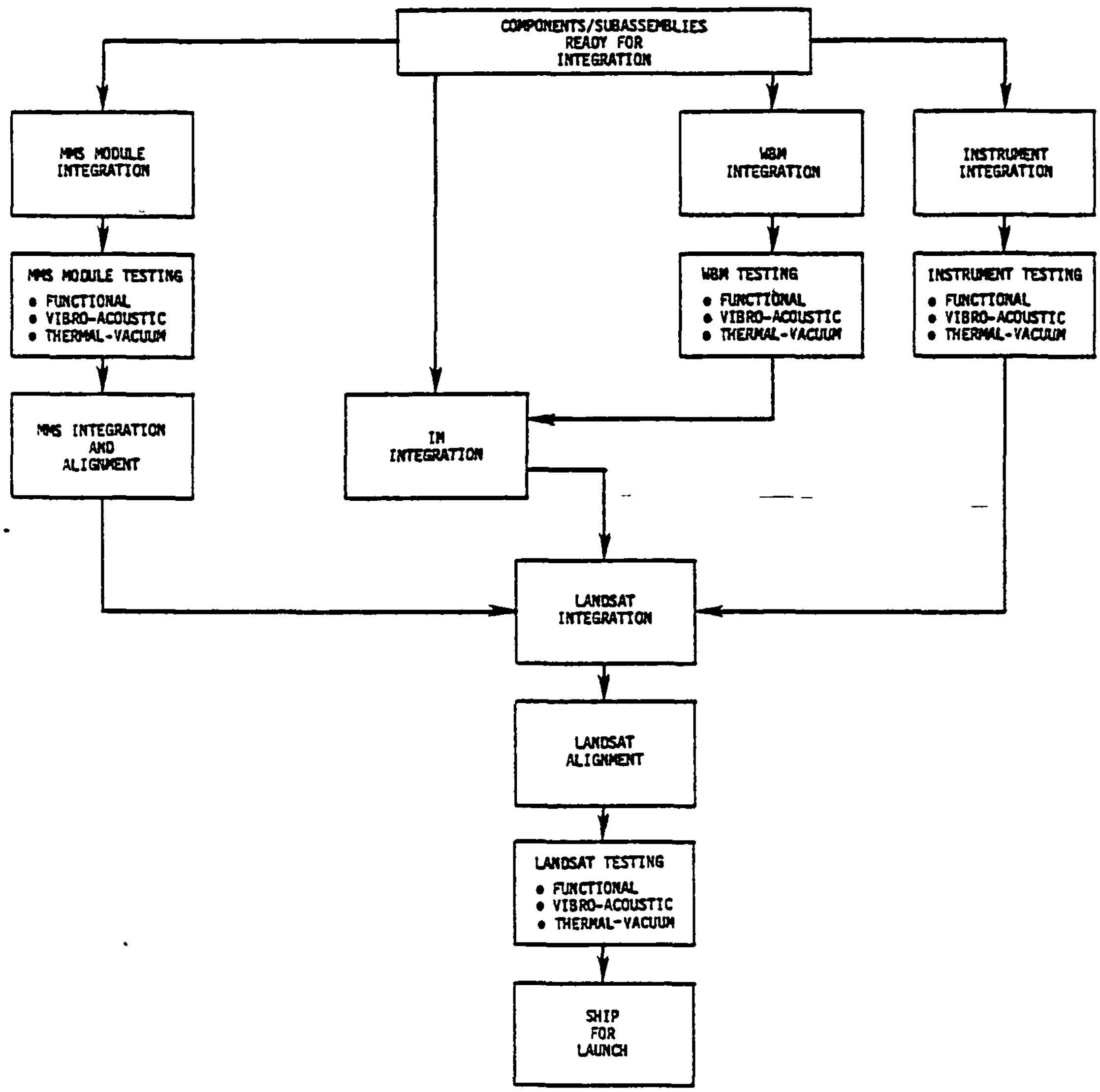

Figure 2-2. Refurbished Landsat Integration and Test Flow

The modified test program in this build-up is sufficient to verify the completeness and workmanship of the refurbishment without overstressing the components, many of which will have already experienced 3 successful years in orbit.

2.3 REFURBISHMENT SCHEDULE

The total time to complete the Landsat-D refurbishment is estimated to be 27 months, with the instruments and the narrowband tape recorder being the major items which determine the time for refurbishment. Even if new instruments were available for replacement at the time of retrieval, the refurbishment time would still be 27 months because the tape recorders delay the MMS integration. The initial inspection, testing and disassembly to the component and subassembly level involves about 3 months of effort, including the time to perform bench acceptance tests on the components and subassemblies. Even without any refurbishment requirements, disassembly to this level requires 17 months for re-integration and testing to have the spacecraft ready for relaunch. The schedule for the overall refurbishment program is shown in Figure 2-3. Figure 2-4 shows the schedule with no delays for rework. This schedule could be met with the procurement of selected spares for those items whose rework delays the integration.

The time required to integrate a module or instrument depends, in part, on when the individual components and subassemblies are available. For the most part, integration can start immediately after the bench acceptance testing because the majority of components will not require any rework. With proper planning, the replacements for those components which cannot be reused will have been procured and will be available for integration at that time. The rework of those components needing refurbishment can proceed in parallel which usually results in their being available before they are needed in the integration cycle. Tables 2-1 through 2-8 summarize the integration and test (I&T) information for the modules and the instruments. The information in these tables includes: the normal I&T time; the

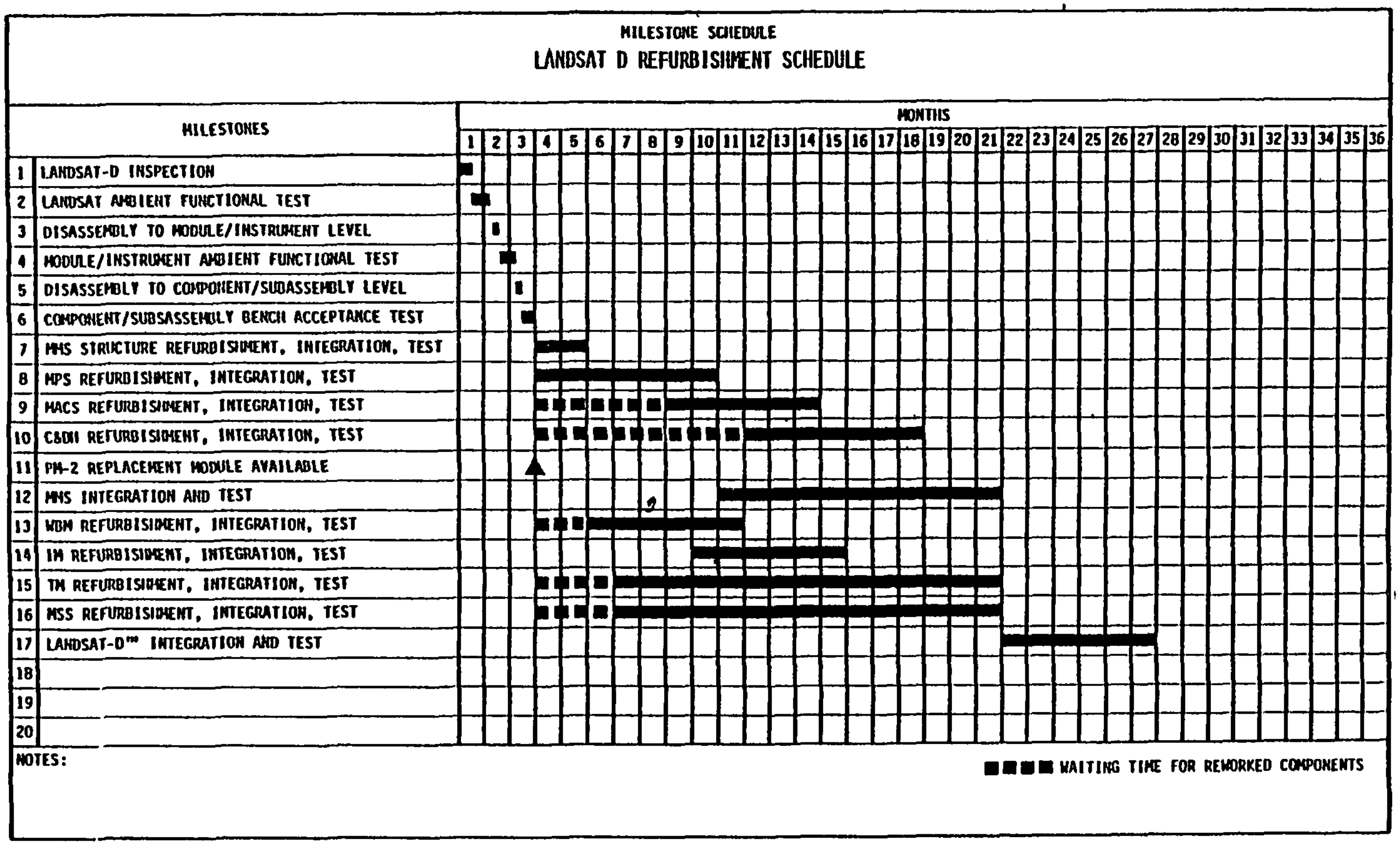

Figure 2-3. Landsat-D Refurbishment Schedule

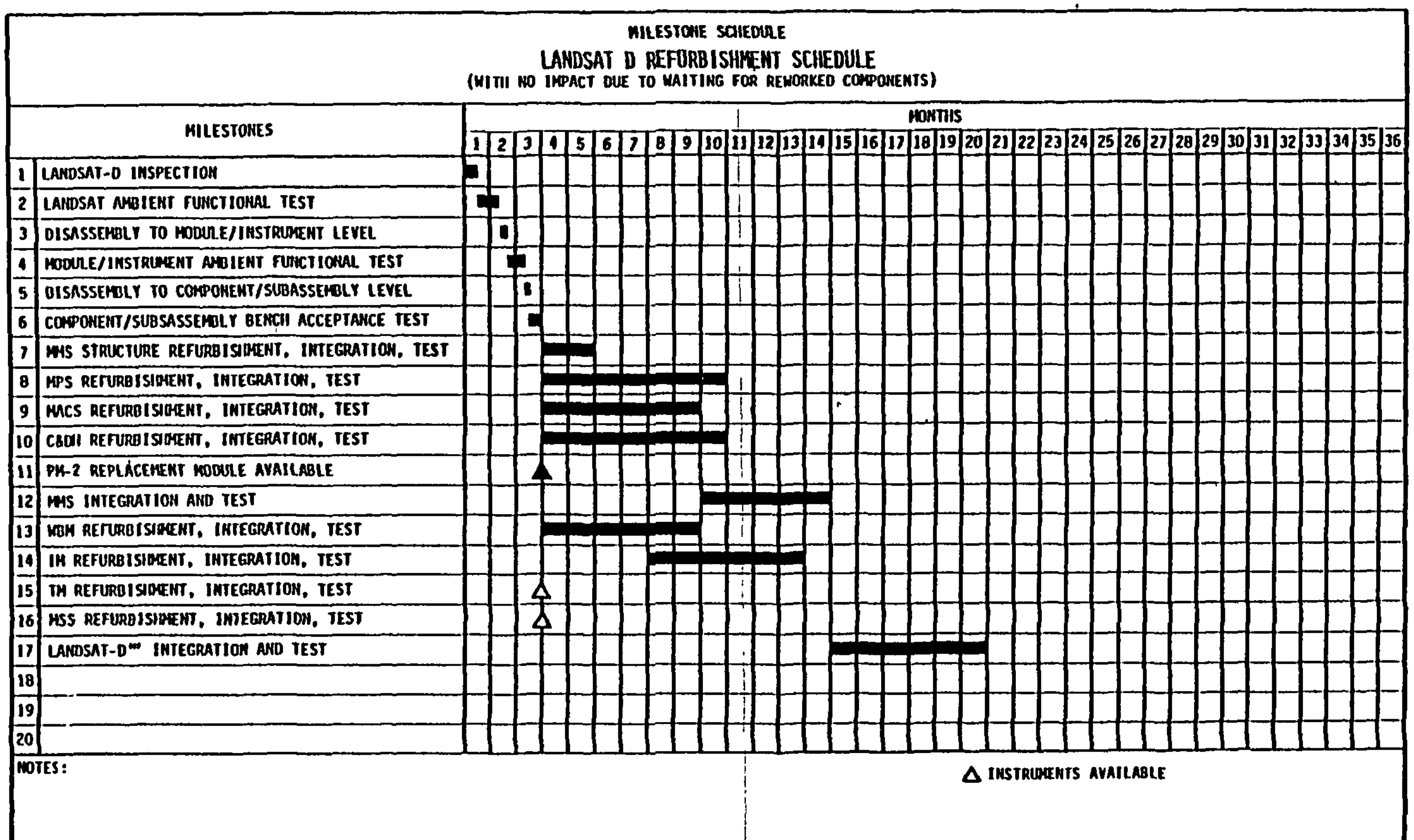

Figure 2-4. Landsat-D Refurbishment Schedule With No Rework Impact

Table 2-1. IM Refurbishment Schedule

INTEGRATION AND TEST TIME

Normal Integration and Test Time	6 Months
Integration and Test Time as Impacted by Refurbishment Work	8 Months

REWORK SCHEDULE

Component	Rework Time (Months)	Refurbishment Impact
Direct Access S-band Transmitter	2	No
Power Distribution Unit	2	Yes
Payload Correction Data Multiplexer	2	No
Solar Array Drive/Power Transfer Assembly	1	No
Boom Release/Deploy/Jettison Assembly	1	No

PRE-REFURBISHMENT PROCUREMENTS

Component/Special Part	Procurement Time (Months)
RF Boom Assembly/GPS Antenna	22
Solar Array	12
Solar Array Drive Motor/Bearings/Slip Rings	6
Angular Displacement Sensor	6
RF, Power Transistors	RA
CMOS Devices	RA
Wiring	RA
Insulation	RA

Table 2-2. MSS Refurbishment Schedule

INTEGRATION AND TEST TIME

Normal Integration and Test Time	15 Months
Integration and Test Time as Impacted by Refurbishment Work	18 Months

REWORK SCHEDULE

Component	Rework Time (Months)	Refurbishment Impact
Telescope	3	Yes
Detectors	3	Yes
Shutter Assembly	1	Yes
Calibration Source	1	No
Scan Mirror Assembly	3	No
Scan Monitor	3	No
Electronics	3	No

PRE-REFURBISHMENT PROCUREMENTS

Component/Special Part	Procurement Time (Months)
Laser Diodes	9
Shutter Motor	3
Bumpers/Dampers	1
Photodiodes	RA
Power Transistors	RA
Flex Pivots	RA
Insulation	RA

RA - readily available

Table 2-3. TM Refurbishment Schedule

INTEGRATION AND TEST TIME

Normal Integration and Test Time	15 Months
Integration and Test Time as Impacted by Refurbishment Work	18 Months

REWORK SCHEDULE

Component	Rework Time (Months)	Refurbishment Impact
Telescope	3	Yes
Scan Mirror Assembly	3	No
Focal Plane Bulkhead Assembly	3	Yes
Radiative Cooler	1	No
Scan Mirror Electronics	2	No
Multiplexer	2	No

PRE-REFURBISHMENT PROCUREMENTS

Component/Special Part	Procurement Time (Months)
Prime Focal Plane Detectors	12
Cooled Focal Plane Detectors	12
Light Emitting Diodes	9
Calibration Shutter Assembly	6
Specular Reflector	6
Bumpers	1
Lamps	RA
Photodiodes	RA
Microprocessor, RAM Chips	RA
Flex Pivots	RA
Insulation	RA

RA - readily available

Table 2-4. WBM REFURBISHMENT SCHEDULE

INTEGRATION AND TEST TIME

Normal Integration and Test Time	6 Months
Integration and Test Time as Impacted by Refurbishment Work	8 Months

REWORK SCHEDULE

Component	Rework Time (Months)	Refurbishment Impact
Power Converter and Switching Unit	2	Yes
Antennas	1	No

PRE-REFURBISHMENT PROCUREMENTS

Component/Special Part	Procurement Time (Months)
X-Band Traveling Wave Tube Amplifier (TWTA)	18
Power Transistors	RA
Thermal Coatings	RA
Insulation	RA

RA - readily available

Table 2-5. MMS Structure Refurbishment Schedule

INTEGRATION AND TEST TIME

Normal Integration and Test Time	2 Months
Integration and Test Time as Impacted by Refurbishment Work	2 Months

REWORK SCHEDULE

Component	Rework Time (Months)	Refurbishment Impact
SC&CU	1	No

PRE-REFURBISHMENT PROCUREMENTS

Component/Special Part	Procurement Time (Months)
Insulation	RA
Pyro Devices, Fusistors	RA

RA - readily available

Table 2-6. MPS REFURBISHMENT SCHEDULE

INTEGRATION AND TEST TIME

Normal Integration and Test Time	7 Months
Integration and Test Time as Impacted by Refurbishment Work	7 Months

REWORK SCHEDULE

Component	Rework Time (Months)	Refurbishment Impact
None	None	None

PRE-REFURBISHMENT PROCUREMENTS

Component/Special Part	Procurement Time (Months)
Batteries	15
Insulation	RA

RA - readily available

Table 2-7. MACS REFURBISHMENT SCHEDULE

INTEGRATION AND TEST TIME

Normal Integration and Test Time	6 Months
Integration and Test Time as Impacted by Refurbishment Work	11 Months

REWORK SCHEDULE

Component	Rework Time (Months)	Refurbishment Impact
Star Trackers	1	No
Inertial Reference Unit (IRU)	6	Yes
Horizon Scanner	3	No
Reaction Wheels	6	Yes

PRE-REFURBISHMENT PROCUREMENTS

Component/Special Part	Procurement Time (Months)
Bearings - Reaction Wheels	17
Bearings - Horizon Scanner	9
Coarse Sun Sensors	3
Insulation	RA
Gyros - IRU	RA

RA - readily available

Table 2-8. C&DH Refurbishment Schedule

INTEGRATION AND TEST TIME

Normal Integration and Test Time	7 Months
Integration and Test Time as Impacted by Refurbishment Work	15 Months

REWORK SCHEDULE

Component	Rework Time (Months)	Refurbishment Impact
S-band Transponder	1	No
Tape Recorders	12	Yes

PRE-REFURBISHMENT PROCUREMENTS

Component/Special Part	Procurement Time (Months)
Tape Recorder Mechanical Parts	RA
Microprocessor Chips	RA
Insulation	RA

RA - readily available

I&T time which results from waiting for components to have their rework completed; a listing of the times required to rework and test the components needing refurbishment, with a notation as to the possibility of impacting the integration time; and a list of all replacement components and special order parts which must be procured before the integration and rework can begin, with estimates of their procurement times. The procurement time for the PM-2 which replaces the PM-1A is approximately 24 months assuming it is a follow-on to a previously funded development program.

2.4 COST COMPARISON FOR REFURBISHMENT

The costs for refurbishment were estimated from the cost segments for the Landsat-D program and judging which ones and what portion of each would apply. Since specific information was not made available, all costs are presented on a comparative basis. Several major procurements comprise the Landsat-D program. The prime contractor has the responsibility for the IM and the overall integration and test of the spacecraft. The instruments are being supplied to the prime contractor as Government Furnished Equipment (GFE). Likewise the MMS is GFE. The most practical approach is to compare the cost for each of the major procurements: IM, TM, MSS, and MMS.

For each of these major procurements there are several costing segments which should have about the same cost for either a refurbishment program or a new procurement program. The first is the project management which, for this study, includes the reliability and quality assurance support. It does not appear that there should be any substantial difference in this requirement for either program. The second is the I&T segment, including the necessary ground support equipment. Since, with either program, integration starts from the same level of disassembly, these costs should be the same. The few differences in the acceptance test requirements should not result in any major difference in the costs. Neither a refurbishment program nor a new procurement program should include any systems analysis, engineering test or design costs since both will be duplicating an existing, proven design. The refurbishment program has one cost segment which does not occur with a new procurement; those costs associated with determining the refurbishment requirements. This involves developing procedures for the extensive testing and controlled disassembly following the recovery from orbit. Engineering analysis is needed to establish the criteria which will determine if refurbishment or replacement is required. It also includes the evaluation of the on-orbit performance data for Landsat-D.

The final costing segment includes the procurement and fabrication of the components and subassemblies for module and instrument integration. These costs should be substantially different for the two programs, with refurbishment being the less costly because of the number of items which are likely to be reused. Obviously, these costs are zero for a reusable component. For those components for which some rework is needed the costs will generally be considerably less than the costs of new components, depending, of course, on the amount of rework required. Finally, the cost would be the same to either program for any new component.

The overall cost difference for refurbishing Landsat-D rather than procuring a new spacecraft is the total of the savings realized by all the major procurements by reusing or reworking a component as opposed to buying a new component, less the added costs associated with the post-recovery testing and disassembly. OAOCO estimates that refurbishment can save approximately 25 percent of the cost of a new instrument for both the TM and the MSS. Likewise, refurbishing the IM will save approximately 25 percent of the cost of a new IM procurement assuming either program includes the overall integration and testing of the spacecraft. The cost for refurbishment includes estimates for the engineering and test support needed for the post-flight evaluation process. Without these evaluation costs, refurbishment would be closer to 65 percent of the cost of a new procurement. These comparisons are based on the TM, MSS, and IM contractor costs for the various work breakdown segments, as submitted to the GSFC Landsat-D project office. A refurbished MMS is estimated to cost approximately 30 percent of the cost of a new one. This number is based on information supplied by the GSFC project office.

SECTION 3. ON-ORBIT RELIABILITY STUDIES

SECTION 3. ON-ORBIT RELIABILITY STUDIES

3.1 GENERAL

To gain insight about which components of Landsat-D may have a propensity towards on-orbit failures, performance data from previous space programs were examined. Several studies compiled and analyzed data from a large number of spacecraft to develop reliability models and estimate failure rates. TRW investigated the orbital experience for 42 of their spacecraft (References 1 and 2). Timmons and Norris did the same for 57 Goddard Space Flight Center spacecraft (References 3 and 4). Planning Research Corporation (PRC) analyzed the operational data for 350 spacecraft from 52 U.S. space programs (Reference 5). Performance data for specific programs were examined. These were usually a tabulation of observed phenomenon with no general conclusions regarding on-orbit reliability. The data from some of these programs are relevant in that they are from the same or similar components as will fly on Landsat-D or they are indicative of environmental effects which will apply to Landsat-D.

3.2 RELIABILITY MODELS

The most basic reliability notion associated with a piece-part is the failure rate of that part. This represents the percentage of the part's population which will fail in a given time interval. Historically, reliability models assume a constant failure rate, independent of the age of the part. In reality, the failure rate may vary with time. Quite often, a plot of the failure rate versus time for a large population results in a "bathtub" curve, with a rapidly decreasing rate at first, a constant rate middle section and an increasing rate at the end. Different failure mechanisms seem to apply in each region. Weak parts will fail quickly giving an initially high rate but as they are weeded out of the population the rate decreases. The constant rate region represents the random failures which will occur. (Following initial screening and "burn-in" to get rid of weak parts, space parts are expected to exhibit this kind of behavior.) The increasing rate at the end is indicative of a wear-out mechanism as parts reach their nominal end of life.

Three different models can be used to represent the various regions of the "bathtub" curve. Early life failures or "infant mortality" can be described with a Weibull distribution which has a decreasing failure rate with time. The simple exponential distribution with its constant failure rate applies to the middle region. This constant rate (λ) yields the familiar exponential formula for reliability (R) as a function of time (T) of $R = \exp(-\lambda T)$. A normal or Gaussian distribution about a mean which corresponds to the nominal end of life describes the wearout failures.

The TRW studies show that spacecraft parts do not exhibit a constant failure rate but rather show a decreasing rate with time. Timmons and Norris made the same observation in their study. Both studies conclude that the constant failure rate assumption of the exponential distribution is in error for the average piece-part, the level at which this assumption is usually made. Figure 3-1, which is from Reference 2, clearly shows the difference between an exponential fit and a Weibull fit for an observed failure rate distribution.

TRW hypothesized a "weak sister" theory to account for this decreasing failure. In essence, a spacecraft starts off with a mixture of two populations, one composed of good parts and one of weak parts, or "weak sisters". This population of weak parts may arise from workmanship or manufacturing defects. The initially high failure rate is due to the "weak sisters". As these parts fail they leave the spacecraft operating with strong components. TRW presents a good deal of evidence supporting this theory. The observed performances from other programs also seem to support it. (It should be noted that the "burn-in" and the testing done before launch weeds

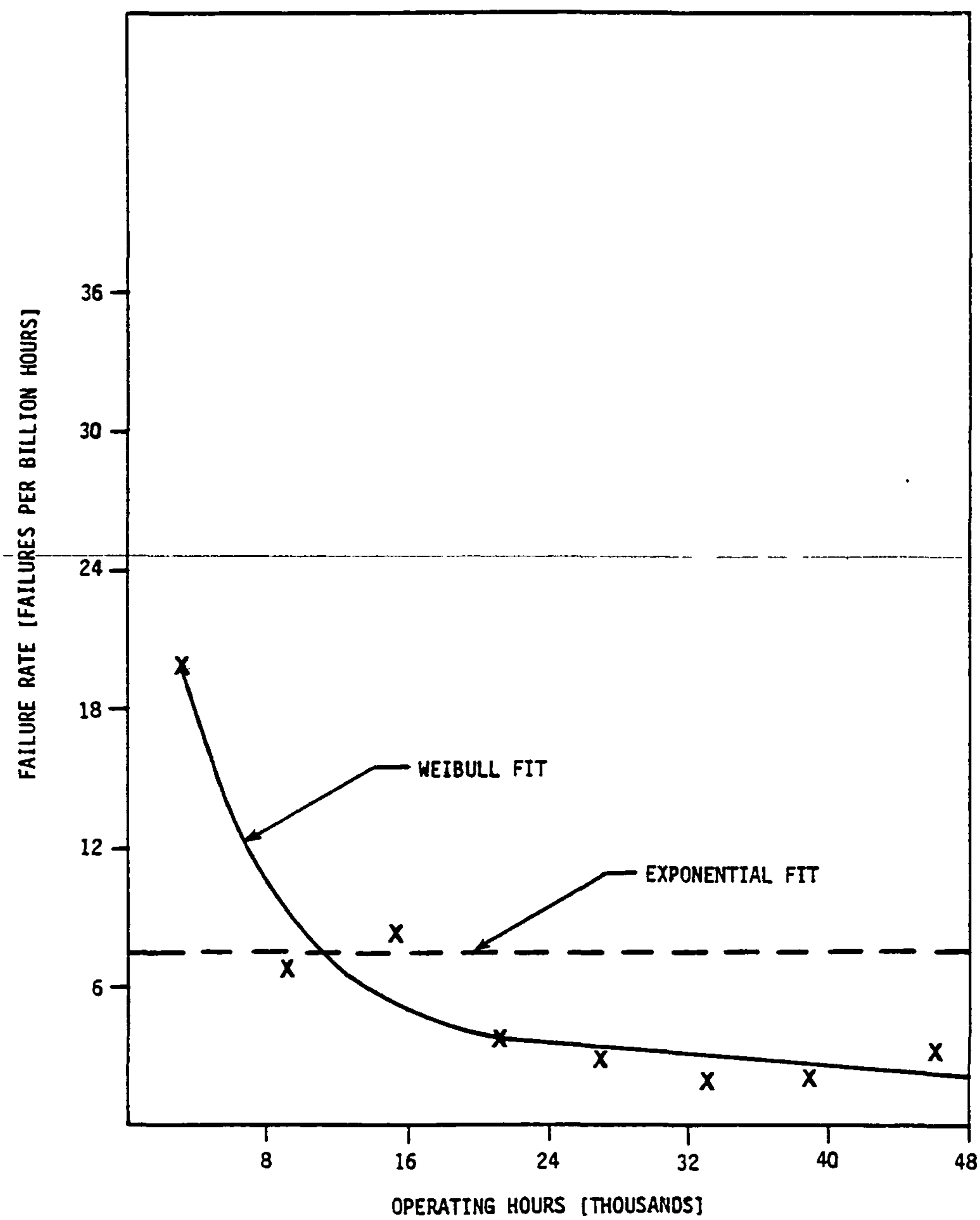

Figure 3-1. Failure Rate Distribution of TRW Piece-Parts

out many of the "weak sisters" thus reducing the potential for early on-orbit failures.)

The PRC study tabulates the estimated failure rates for various spacecraft components based on their in-flight performance; however, a constant failure rate was assumed. The assumption that piece-parts exhibit a constant failure rate means that the reliability models for components will be described by an exponential distribution since the component reliability is proportional to the product of the piece-part reliabilities. This, then, implies that components will have a constant failure rate. The data bases for the TRW and the Norris and Timmons studies are both subsets of the PRC data base giving a good indication that a decreasing failure rate should also apply for the PRC data. As can be seen in Figure 3-1, an exponential fit underestimates the initial failure rate, but as operating time increases it predicts a higher rate than observed. Using the PRC data to estimate component reliability for long term operations is most likely conservative.

Table 3-1 lists spacecraft components in order of decreasing estimated failure rates as determined from the PRC study. The list in Table 3-2 includes components for which there are no failures in the PRC data base, but for which a 90 percent confidence upper bound for the failure rate was calculated from the accumulated survival times on-orbit (Reference 6). The 90 percent confidence upper and lower bounds were also calculated for those components for which an estimated failure rate was determined. The components in Table 3-2 are listed in order of decreasing value for the 90 percent confidence upper bound. The estimated failure rate can be used to determine the probability of survival (reliability) as a function of time using the formula $R = \exp(-\lambda T)$. A failure rate of 2.0 per 10^6 hours gives a probability of 0.9 for surviving 6 years on-orbit.

None of these studies showed any evidence of an increasing failure rate indicative of a wear-out failure mechanism. One reason for this is those components which have a known wear-out mechanism are generally designed with

Table 3-1. Components Ranked by Estimated Failure Rate

Components	$\hat{\lambda}$
Star Trackers	57.0
Magnetic Tape Units	24.0
Radiometers	11.0
Video Transmitters	9.2
Reaction Wheel	5.3
Vidicon Cameras	5.1
Wideband Transmitters	5.0
S-band Transmitters	4.4
Telemetry Encoders	3.2
Control Gas Assemblies	3.1
Special Purpose Transmitters	2.8
Timers and Clocks	2.6
Magnetometers	2.6
Transponders	2.5
Computers	2.3
Other Transmitters	2.3
Magnetic Sensing Devices	1.9
Command Distribution Units	1.8
Gyros	1.7
Accelerometers	1.6
Battery Pack	1.3
Signal Conditioners	1.2
Sun Sensors	1.2
Receivers	0.86
DC/DC Converters	0.84
Voltage Regulators	0.75
Data Handling Units	0.59

$\hat{\lambda}$ = Estimated failure rate per 10^6 hours.

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Table 3-2. Components Ranked by Upper Bound on Estimated Failure Rate

Components	$\hat{\lambda}_1$	$\hat{\lambda}$	$\hat{\lambda}_2$
Fuel Cell Modules	0.0		3700
Compressors and Pumps	0.0		587
Heat Exchangers	0.0		410
FM Transmitters	0.0		190
Heat Pipes	0.0		128
Gyro Assembly Units	0.0		85
Star Trackers	39.0	57.0	81
Magnetic Tape Units	18.0	24.0	30
Doppler Transmitters	0.0		30
Video Transmitters	2.5	9.2	24
Gear Trains	0.0		22
Radiometers	6.1	11.0	18
Subcarrier Oscillators	0.0		18
Demodulators	0.0		16
Wideband Transmitters	1.4	5.0	14
Horizon Sensors	0.14	2.9	14
Special Purpose Transmitters	0.14	2.8	13
S-band Transmitters	1.2	4.4	11
Reaction Wheels	2.1	5.3	11
Computers	0.012	2.3	11
Vidicon Cameras	2.2	5.1	10
Control Gas Assemblies	0.55	3.1	9.7
Magnetic Sensing Devices	0.097	1.0	9.7
Infrared Scanners	0.0		8.6
Magnetometers	0.46	2.6	8.1

= Estimated failure rate per 10^6 hours

$\hat{\lambda}_1$ = 90% confidence lower bound of estimated failure rate

$\hat{\lambda}_2$ = 90% confidence upper bound of estimated failure rate

Table 3-2. Components Ranked by Upper Bound on Estimated Failure Rate (cont.)

Components	λ_1	$\hat{\lambda}$	$\hat{\lambda}_2$
Transponders	0.45	2.5	8.0
Accelerometers	0.0		7.7
Memory Units	0.0		7.5
Accumulators	0.0		7.4
Sequencers	0.0		6.4
Earth Sensor Assemblies	0.0		6.1
Phase Modulators	0.0		5.9
Signal Conditioners	0.0		5.8
Telemetry Encoders	1.6	3.2	5.8
Filter Network	0.0		5.6
Command Distribution Units	0.31	1.8	5.6
Gyros	0.29	1.7	5.2
Tracking Transmitters	0.0		4.7
Louver Assemblies	0.0		4.6
Power Amplifiers	0.0		4.6
Timers and Clocks	1.4	2.6	4.4
Control Switching Assemblies	0.0		4.0
Pneumatic Assemblies	0.0		3.9
Beacon Transmitters	0.0		3.7
Other Transmitters	1.4	2.3	3.6
Sun Senors	0.33	1.2	3.2
Undervoltage Detectors/ Control Circuits	0.0		3.0
Power Distribution Units	0.0		2.9
Diplexers	0.0		2.9

$\hat{\lambda}$ = Estimated failure rate per 10^6 hours

$\hat{\lambda}_1$ = 90% confidence lower bound of estimated failure rate

$\hat{\lambda}_2$ = 90% confidence upper bound of estimated failure rate

Table 3-1. Components Ranked by Estimated Failure Rate (cont.)

Components	$\hat{\lambda}$
Pressure Regulators	0.40
Oscillators	0.36
Command Decoders	0.26
Heaters	0.23
Battery Charge/Discharge Control Circuits	0.23
Amplifiers	0.12

$\hat{\lambda}$ = Estimated failure rate per 10^6 hours.

Table 3-2. Components Ranked by Upper Bound on Estimated Failure Rate (cont.)

Components	$\hat{\lambda}_1$	$\hat{\lambda}$	$\hat{\lambda}_2$
Battery Packs	0.62	1.3	2.3
Bolometer Assemblies	0.0		2.3
Commutators	0.0		2.3
DC/AC Inverters	0.0		2.3
DC/DC Converters	0.23	0.84	2.2
Programmers	0.0		2.1
Voltage Controller Oscillators	0.0		2.1
Pressure Regulators	0.021	0.40	1.9
Receivers	0.34	0.86	2.8
Oscillators	0.019	0.36	1.7
Voltage Regulators	0.30	0.75	1.6
Valves	0.0		1.5
Command Decoders	0.014	0.26	1.3
A/D, D/A Converters	0.0		1.2
Battery Change/Discharge Control Circuits	0.012	0.23	1.1
Heaters	0.012	0.23	1.1
Electrical Motors	0.0		0.95
Amplifiers	0.0063	0.12	0.58
Antenna Assemblies	0.0		0.28
Nutation Dampers	0.0		0.01

= Estimated failure rate per 10^6 hours

$_1$ = 90% confidence lower bound of estimated failure rate

$_2$ = 90% confidence upper bound of estimated failure rate enough margin to far exceed the expected life of the spacecraft. Spacecraft operations are usually terminated before these types of failures occur. Operations may be terminated due to programatic considerations, such as the launch of a follow-on spacecraft or the closing of the ground station, or because a single failure may be so disruptive to normal operations that the spacecraft is retired.

3.3 RELEVANT EXPERIENCES OF OTHER PROGRAMS

Many of the components which comprise the MMS are similar to those flown on previous GSFC missions, including several long-life spacecraft such as ATS-6 and OAO-3. This indicates there should be a reasonable expectation for long life for MMS. Further evidence of this is provided by the Solar Maximum Mission (SMM) which uses a MMS. SMM was launched on February 14, 1980 and, to date, there has been no MMS failure, although a transient bit flip data anomaly has occurred several times. It has been surmised that this anomaly is caused by radiation in the South Atlantic Anomaly. The Landsat-D MMS will be fitted with a less sensitive component.

The Landsat program has flown an MSS instrument on Landsat-1, -2 and -3 with great success (Reference 7). The Landsat-1 MSS had three of the four data bands operational when the spacecraft was turned off after 5 1/2 years. A power supply failure, which occurred after more than 4 1/2 years, was responsible for the loss of the fourth band. The Landsat-2 MSS was operating without problems after about 4 1/2 years when it was shut off. Recently it was reactivated and has been operational for an additional half year. On Landsat-3, the cooled IR detector channel has failed, but this band is not included on the Landsat-D instrument. MSS continues to operate satisfactorily on Landsat-3 after more than 2 years.

A report was made of the Skylab reactivation activities from March 1978 until reentry on July 11, 1979 (Reference 8). Reactivation occurred more than 4 years after it had been powered down at the end of its original mission. Assessments were made of the condition of all systems which were operated during this reactivation. System degradation was determined to be minimal with the performance exceeding all expectations. Of particular relevance to Landsat-D was the airlock module power control groups which had regulators of similar design to the Power Regulator Unit in the MPS. These regulators experienced no failures. The control moment gyros exhibited some bearing problems, both during the original mission and the reactivation. It was determined that retainer instability aggravated by low temperatures, temperature gradients and marginal lubrication was the probable cause. The drive electronics associated with these units had no problems. Whether this problem applies to Landsat-D is uncertain, but it highlights a potential problem area.

During the original Skylab mission, an experiment was conducted to collect micrometeoroids (Reference 9). Although there were considerable impacts, all were caused by very small particles; one of the largest impact craters observed was only about 50 μm in diameter. The only evidence of penetration was in the thin film collectors. The collectors facing away from the Sun had more impacts than those facing the Sun; however since the solar arrays always faced the Sun, there was no surface which continually viewed the Earth to assess the shielding effect of the Earth.

Parts of the Surveyor III spacecraft were brought back from the Moon by the Apollo XII astronauts, providing the first opportunity to test for the long term effects of space on an actual piece of hardware. These parts had been on the Moon for 2 1/2 years prior to recovery. Results of engineering tests showed the parts withstood the environment exceedingly well (Reference 10). Although changes occurred in the properties of some materials, no change was found which would have prevented any part from performing its task. The major effect was the discoloration of the surfaces, much of this due to the solar radiation. Of importance were those effects which were expected but not observed. No cold welding of mechanisms was seen, nor was any significant pitting by micrometeoroids seen, although some impacts were noted. Degradation of the electrical properties of the wiring harness did not occur. Also there was no loss of adhesion or cohesion of the inorganic paints. Some "mud-cracking" was seen but this was due to a mismatch in the thermal expansion properties of the paint and the fiberglass substrate. This problem was manifest because of the wide temperature extremes experienced between the lunar day and lunar night. This temperature cycling also changed the hardness of the aluminum alloys.

3.4 RELIABILITY CONCLUSIONS

All data seems to indicate that space hardware is quite reliable and capable of operating for many years in the space environment, provided there is no failure in the early days of the mission. The exceptions to this are those components for which there is a known degradation or wear-out mechanism. This being the case, the candidates for refurbishment should generally be those which do have a predictable finite life because of wearout or degradation. Components which are operating properly after recovery have passed the "infant mortality" period. The first Landsat-D mission could be considered as an extended "burn-in" which has weeded out the so called "weak sisters", leaving only highly reliable, long life components.

SECTION 4. ENVIRONMENT AND OPERATIONAL CONSIDERATIONS

SECTION 4. ENVIRONMENT AND OPERATIONAL CONSIDERATIONS

4.1 GENERAL

The lifetime and performance characteristics of systems operating in space can be greatly affected by the various stresses they may experience. These stresses can be due to the natural environment of space itself, or the environment imposed by the launch and recovery vehicles, or normal operations of the components themselves.

4.2 SPACE ENVIRONMENT FACTORS

Four factors of the natural space environment influence spacecraft performance: the vacuum of space, penetrating radiation, non-penetrating radiation and meteoriods (Reference 11).

The extremely low pressure in space enhances the evaporation of the volatile components of materials, which causes two effects. One is a change in the properties of the material. The other is to provide a source of contamination which affects optical and thermal control surfaces, particularly cooled surfaces which will readily absorb contaminants and gases. By selecting materials with very low outgassing properties these problems can be minimized. Furthermore, proper design and operational practices can be used to prevent contamination of critical surfaces. Both of these measures are being observed on the Landsat-D program. In the case of lubricants, it is not always possible to have a low outgassing material and still provide the properties needed to meet the mechanical requirements. In addition, the heat generated by the mechanical processes accelerates the breakdown and evaporation of the lubricant. Proper sealing reduces, but does not totally eliminate, this loss of lubricant. It is generally felt that lubricants have a finite operating life.

The natural penetrating radiation environment consists of energetic particles, both charged and neutral, as well as high-energy electromagnetic radiation. This environment has a damaging effect on semiconductor devices used in spacecraft electronics. It may also cause a darkening effect on certain doped glasses used in optical systems, change the optical properties of thermal control surfaces, and affect solar cells. From the standpoint of damage, the charged particles are most important because of their relatively high intensities and damage coefficients, and then only electrons and protons exist in sufficient numbers to be of interest. In assessing the susceptibility to radiation damage it is convenient to convert the incident radiation on a material to the energy deposited per unit mass, or dose.

Various semiconductor technologies have differing total dose tolerance levels, with bipolar devices being generally more tolerant than Complementary Metal Oxide Semiconductor (CMOS) devices (Reference 12). Determining the radiation dose a particular device will encounter is not any easy matter. There are strong spatial and temporal dependences which must be considered, as well as the effects of shielding due to surrounding space craft components and structure. An estimate of the expected radiation dose as a function of the shield thickness was made for the Landsat-D mission (Reference 13). Figure 4-1 is adapted from that study and shows that doses will be low enough that almost all materials and devices being used on Landsat-D will not be damaged sufficiently to cause malfunction or failure during a 6-year mission. The expected worst case dose for any 2-year MMS mission is shown for comparison. Specific exceptions will be addressed in section 5.

Non-penetrating radiation consists of that portion of the solar spectrum with wavelengths between 0.01 and 15 , solar radiation reflected off the Earth (albedo) and the emitted infrared radiation from the Earth. The amount of this radiation absorbed by exposed surfaces and the radiation characteristics of these surfaces affect the overall temperatures of the

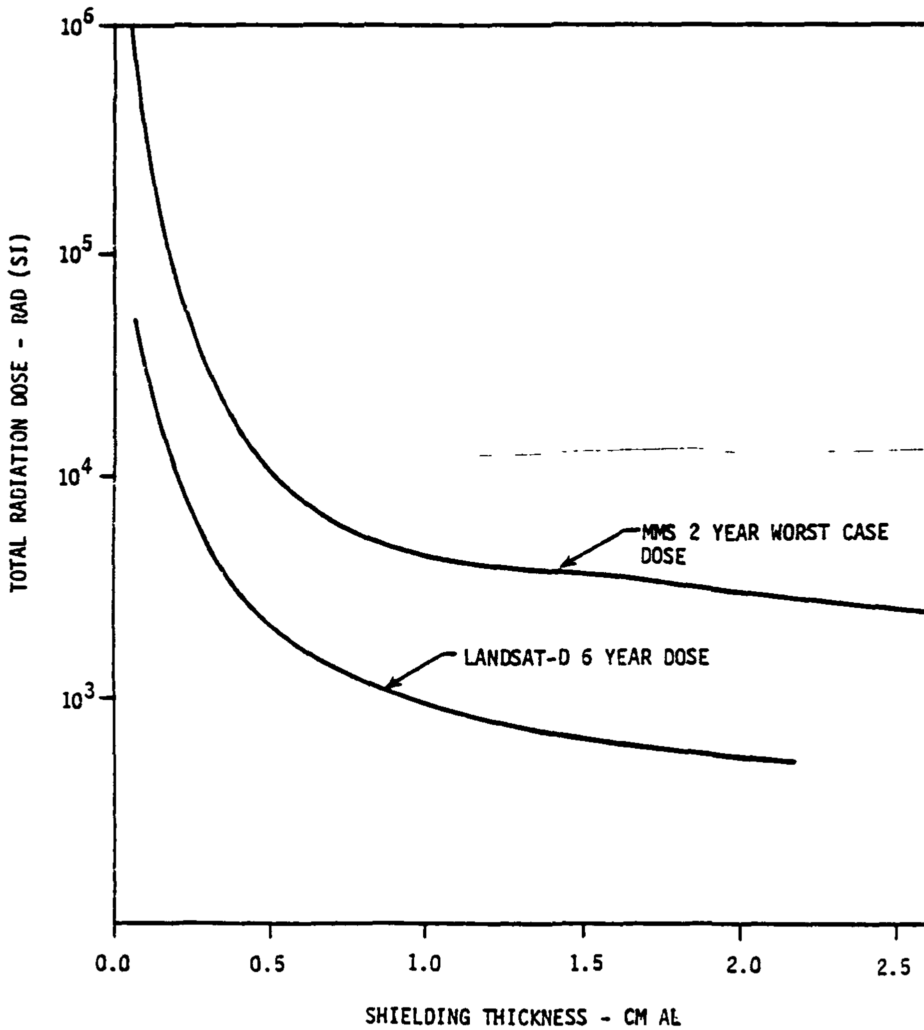

Figure 4-1. Total Radiation Dose Versus Shielding Thickness

spacecraft and the intensities entering an experiment aperture. The materials on these surfaces are carefully selected to have properties which will assure proper operation in space. Unfortunately, the ultraviolet (UV) radiation can alter the optical properties of these surface coatings causing a change in the performance characteristics. Spacecraft are designed with enough margin to allow for the degradation expected over some finite period of time. Beyond this time, UV damage may preclude acceptable performance for exposed optical and thermal coatings.

Experiments have been flown to determine the nature of the meteoroid environment in the Earth's vicinity and to estimate the extent of damage they could do (Reference 14). The results show that there is a very low flux for larger meteoroids but that micrometeoroids ($<10^{-6}$ gm) exist in a fairly large number (see Figure 4-2). The impingement of these micrometeoroids causes surface erosion, cratering and spalling, but they will only penetrate very thin materials such as the outer layer of Multi-Layer Insulation (MLI). There is a very low probability of penetrating thicker surfaces (see Figure 4-3) or of a damaging hit by a large meteoroid. The impact damage caused by micrometeoroids will cause a gradual change in the optical and thermal properties of the exposed spacecraft surfaces.

4.3 LAUNCH AND RECOVERY STRESSES

The vehicles used to launch, and in the case of Landsat-D, recover a spacecraft can impose environments which could damage the spacecraft systems unless they were designed to withstand their effects. Landsat-D is to be launched on a Delta vehicle whose launch environment is fairly well known. The expected environment of the STS orbiter has been described but will not be known with any certainty until after the orbital flight test series. Until then, only the information in the Interface Control Document (ICD) (Reference 15), which hopefully encompasses the full range of possible conditions, and analyses of the effects the environment may have on the payloads are available to assess the STS impact.

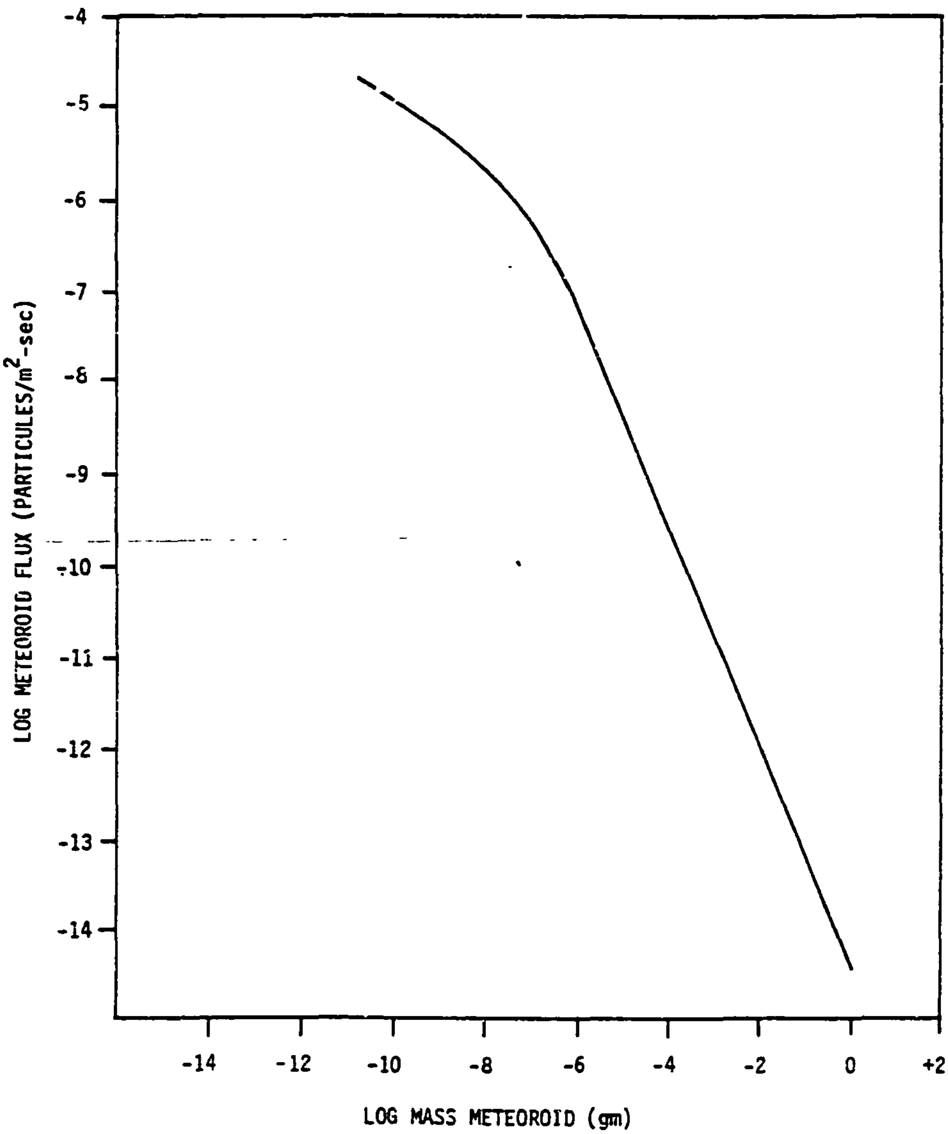

Figure 4-2. Annual Meteoroid Flux as a Function of Mass (at 1 AU)

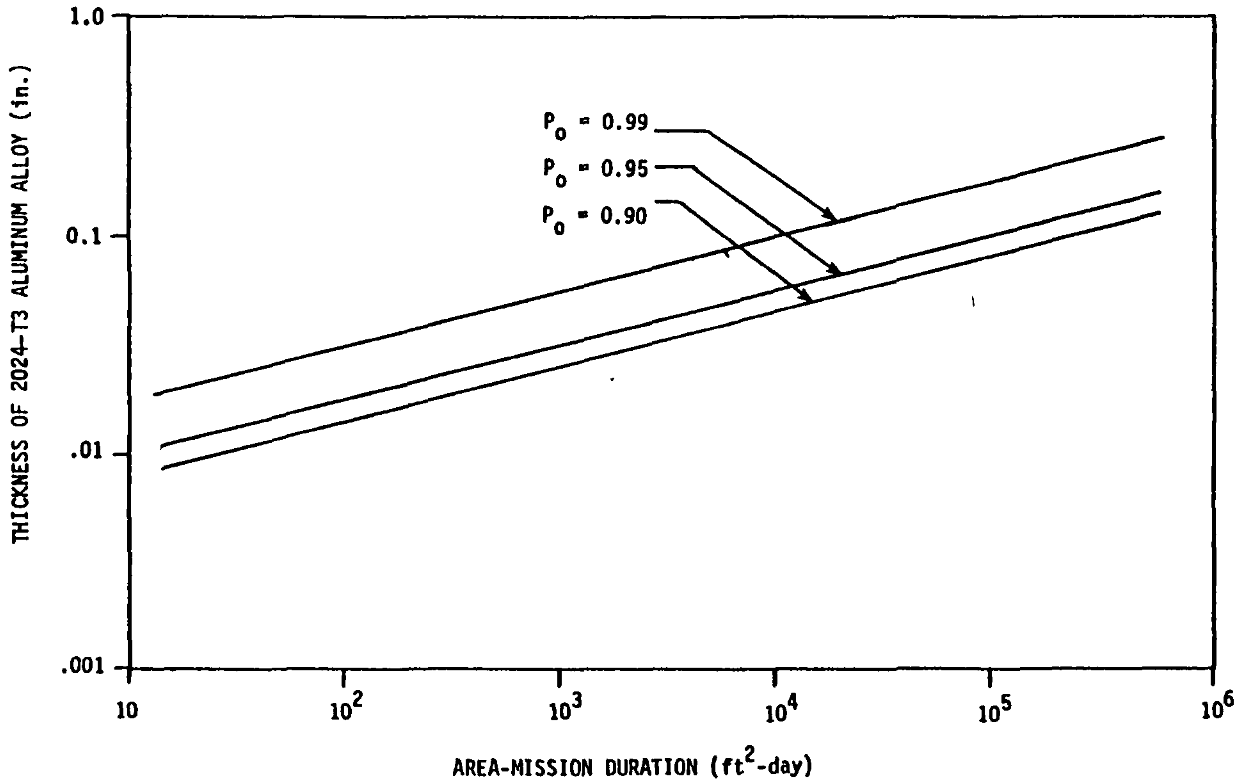

Figure 4-3. Probability (P_o) of No Meteoroid Penetrations Through a Single Sheet of 2024-T3 Aluminum Alloy (at 1 AU)

The static, vibration, and acoustic loads to which all Landsat-D modules, except the MSS are being designed to encompass the expected Delta and STS values, including the STS emergency landing loads. Heaters are being provided to keep the non-operating spacecraft from getting too cold once it has been recovered. With these exceptions, no other aspects of the STS environment have been considered in the design. Several of these could possibly damage the spacecraft. The STS ICD (Reference 15) specifies electromagnetic field intensities at certain locations in the payload bay from the Ku- and S-band transmitters which exceed the design level of 5 volts/meter for the spacecraft. Reduced levels can be achieved by procedural controls but this may reduce communication coverage.

While protection is being provided for a cold environment during recovery, the STS orbiter could have an attitude which could possibly allow the spacecraft to overheat due to specular reflections of sunlight off the orbiter's radiators or by solar energy entrapment between the spacecraft and the payload bay liner. More critical is the possiblity that the attitude will allow sunlight to enter unprotected apertures. With no power applied, the star trackers' protective shutters remain open. Serious damage could be done if a tracker were allowed to continually look at the Sun. Likewise, sunlight continually shining into the Thematic Mapper (TM) or MSS would be concentrated at the prime focus and could burn critical surfaces. The firing of the STS thrusters or the dumping of wastes could cause a contamination problem if the plume or the waste products could impinge on the spacecraft surfaces. Simple operational constraints on the STS attitude and control, and on overboard dumps could preclude these problems. It is prudent to assume that the necessary controls will be imposed to prevent damage to the spacecraft.

During reentry and for the first 15 minutes after touchdown (at which time the air condition system becomes operational) there will be very hot temperatures within the payload bay. Repressurization is accomplished by opening vents and drawing external air into the bay. The air will be filtered but not to the level of the clean-room conditions seen by Landsat prior to launch. The air will not be dehumidified. This combination of hot, humid air, and the potential of contamination from the air and the hot STS surfaces can have a very serious effect on the spacecraft, particularly on the optical instruments. The temperatures most likely will not present a problem. The MMS has been tested in a thermal environment simulating this reentry soakback (Reference 16). An analysis has also shown that for instruments and modules as heavy as those on Landsat-D, the thermal mass will prevent them from increasing greatly in temperature (Reference 17). Figure 4-4, reproduced from that reference, shows the expected temperature increase during reentry and landing for a 500-pound mass MSS module in the payload bay, both with and without the air conditioning purge. For this study, the purge was initiated 30 minutes after touchdown, not the 15 minutes which is now expected. Contamination and humidity conditions are speculative until measurements are made during STS flights. Analysis has shown that, under certain conditions, condensation can take place on surfaces as warm as 79°F (26°C) at touchdown (Reference 18). Figure 4-5 shows payload temperatures relative to the dewpoint temperature for a warm, humid day with the payload at 70°F (21°C) at the start of descent. No analysis has been done to determine the temperature of Landsat following recovery and preparation for the de-orbit nor whether these hot, humid conditions would apply for a West Coast landing. As an estimate, one can expect all surfaces of Landsat-D to encounter warm, humid, contaminated air at touchdown, with the possibility of moisture condensing on some surfaces.

Although the Landsat-D is being designed to loads which included the expected STS launch conditions, the question of fatigue has not been addressed. If, in the course of the test programs and the two launches, a sufficient number of high stress cycles occur in structural members, fatigue failures may occur. Rough estimates were made which indicate that with the margins in the design keeping the stresses well below yield limits, and with the relatively short durations over which the loads are applied, this will not

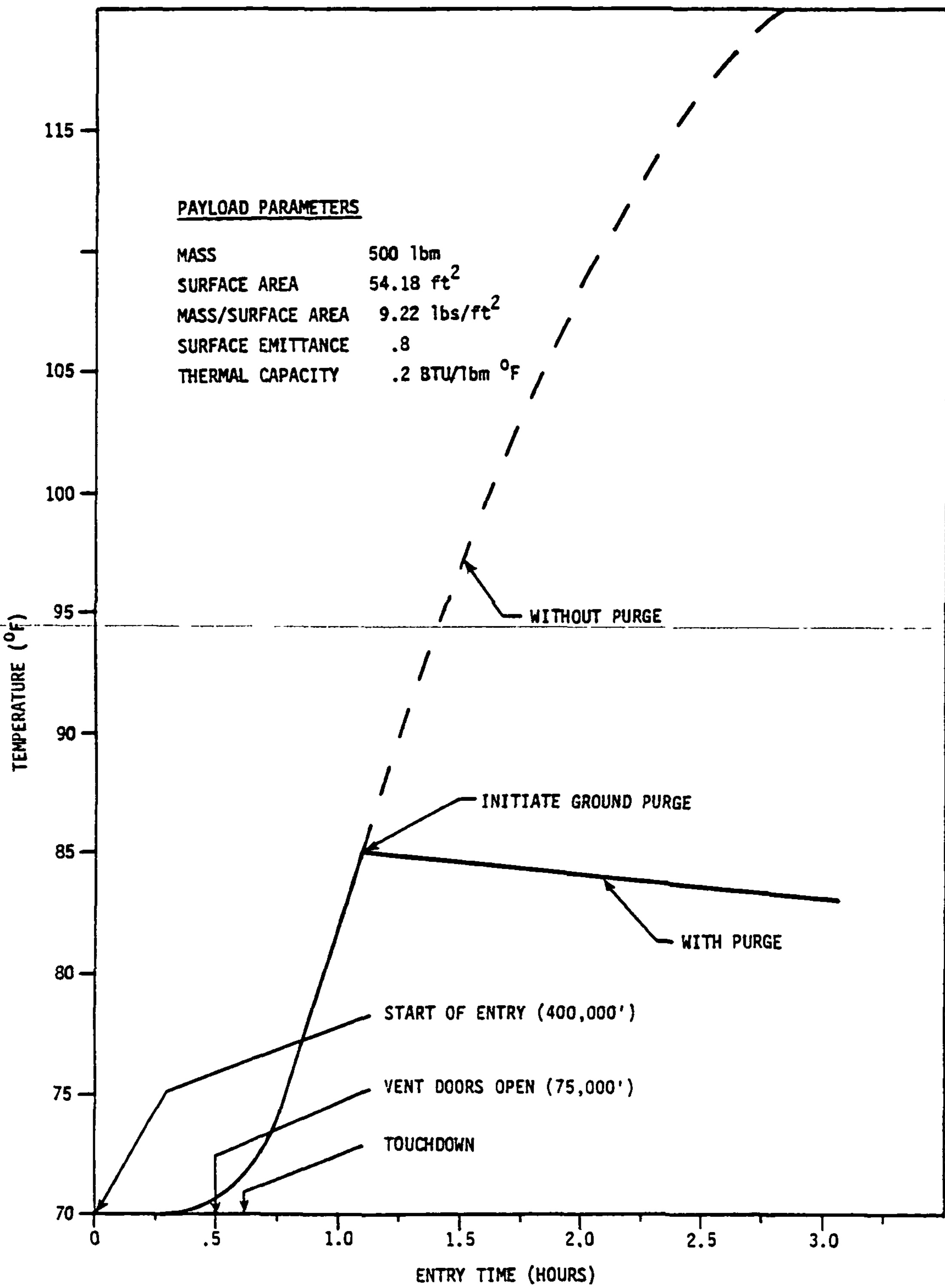

Figure 4-4. STS Payload Reentry Temperature Profile

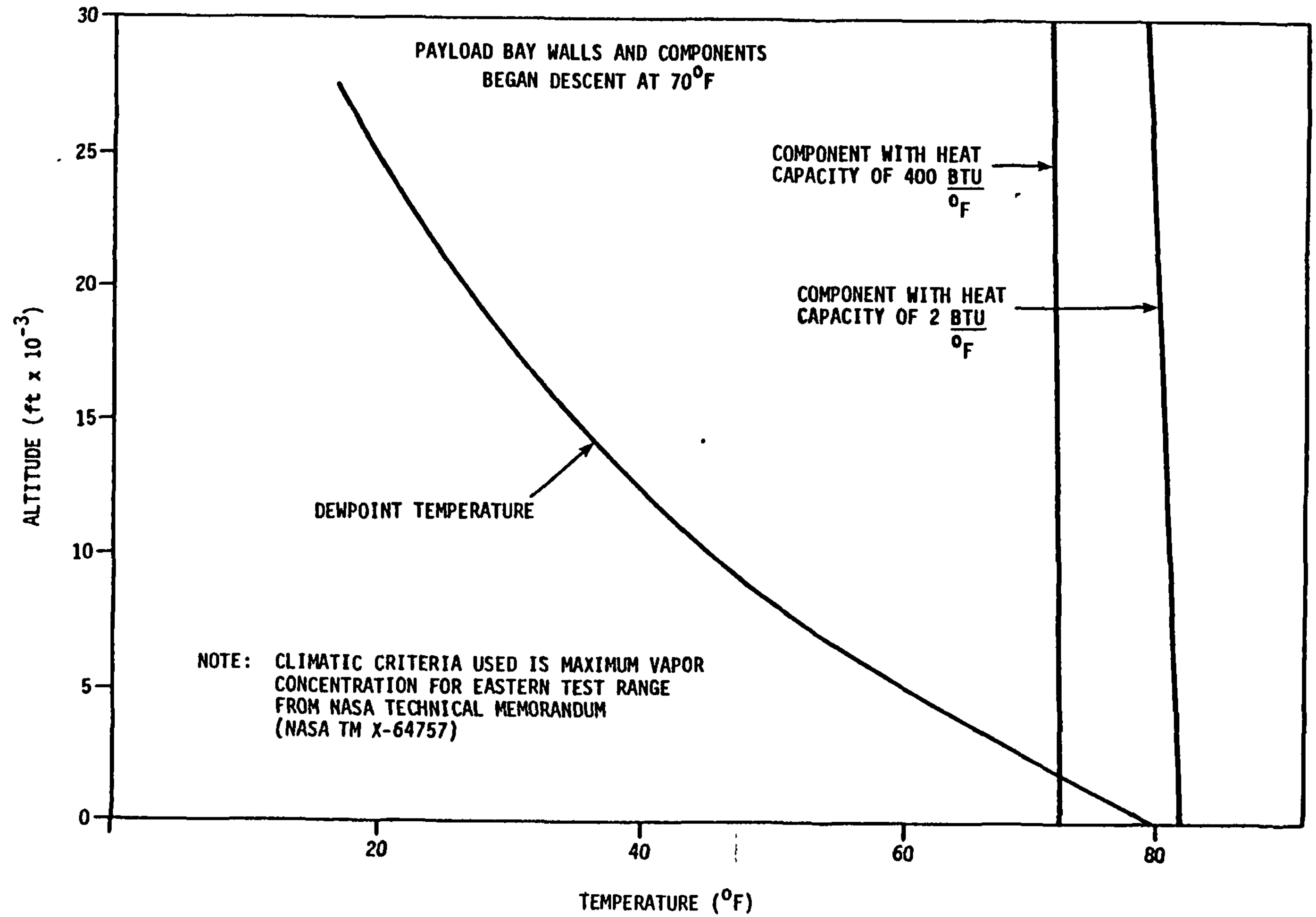

Figure 4-5. Component Temperature Relative to the Dewpoint Temperature

be a problem, provided excessive vibration testing is not done between launches.

4.4 OPERATIONAL FACTORS

Under normal operations, certain components experience stress by the very nature of their design. These stresses eventually lead to failure, causing these components to exhibit a wear-out characteristic. A specific design life is usually associated with such components. Any moving device falls into this category due to the wear caused by friction. The loss and breakdown of lubricant mention in section 4.2 contributes to this phenomenon. Other mechanical assemblies undergo cyclic stresses. If, for a given level of the stress, the number of cycles is great enough, fatigue failure will occur. The expected operational profiles of these devices are carefully considered in order to design them to last the mission with a reasonable amount of margin. To use them past their design life invites failure.

Electrical parts can also experience operational stresses, particularly high power and high voltage devices. High power devices usually generate a great deal of heat and, unless they have an adequate thermal coupling to a radiator or cooling device, the heat shortens their life. High voltages can cause a gradual deterioration of material properties which results in impedance changes which affect performance characteristics. In order to assure long life, most of these devices are operated below their ratings so they will not be overstressed. Likewise the thermal design is carefully thought out to prevent overheating. Devices which are operated near limits of their rating and which may possibly operate at quite warm termperatures may not have sufficient life for reuse on a second mission. The same is true for items which go through extremely wide temperature variations due to on and off cycling.

Degradation of performance characteristics is another operational phenomenon which needs to be considered. This differs from the above in that it does not necessarily mean a shortened life due to the failure of a part but does reduce the capability of the spacecraft to perform its mission. This degradation is not the same as that due to the natural environment of space. Devices which exhibit this kind of behavior include Photomultiplier Tubes (PMT), photodiodes, batteries, and possibly solar cells, although, with the latter, this may be due solely to radiation and meteoroid damage. Spacecraft gyros can also show degraded performance, manifest as increased "R term" drift and output noise.

By necessity, spacecraft designs include enough margin to account for some degraded performance and still permit normal operations. In addition, calibration sources are usually included with instruments that use photosensitive devices as sensors to adjust for the shift in the output characteristics. Unless there is a distinct threshold beyond which the component ceases to function it is difficult to know what amount of degradation is acceptable before a component must be replaced. Batteries and solar arrays either have enough capacity to support normal spacecraft operations or they don't, so their thresholds are readily discernable. Gyro performance is usually specified in terms of acceptable spacecraft pointing and stability requirements. If the drift rates and noise level will not allow these requirements to be met, refurbishment will be required. The calibration procedures allow a great deal of change in the output of the photosensitive devices before the resolution becomes unacceptable. On Landsat-1 and -2, the MSS sensors still had adequate margin after more than 5 years of operations (Reference 7). The degradation rates for the output indicated they would still be acceptable for at least another year.

4.5 SUMMARY OF STRESS FACTORS

It is fairly certain that all exposed thermal and optical surfaces will not be reusable due to UV, radiation and meteoroid damage, and the potential of contamination on landing. Contamination and the potential of condensation means that all optical components will be in need of cleaning. The humidity also will affect aluminized MLI and make it unusable. Any device which will have its design life exceeded during the second mission will be replaced or refurbished. This will also be the case for any mechanical assembly which will see a considerable number of high stress cycles. Any electronic parts and semiconductors which are not tolerant to relatively low radiation doses will be replaced. High power and high voltage devices which operate at or near their rated levels, those which operate at high temperatures and those which are repeatedly stressed by extreme temperature cycling will also be replaced. Finally, those devices whose projected rates of degradation show that they most likey would not meet their functional requirements during the second mission will be replaced.

SECTION 5. LANDSAT-D REFURBISHMENT REQUIREMENTS

SECTION 5. LANDSAT-D REFURBISHMENT REQUIREMENTS

5.1 GENERAL

The following section, although not intended to be a complete systems description, presents the salient design features of Landsat-D components which were found to be relevant to the refurbishment plan. The details of the refurbishment plan are given in Tables 5-1 through 5-8 at the end of this section. The components of each instrument, module and subsystem are listed with recommended refurbishment activities and a brief statement of the reasons each component would require refurbishment.

The pre-refurbishment testing and the reverification testing are described in section 2.2. The following refurbishment actions presume the results of the pre-refurbishment tests.

5.2 INSTRUMENT MODULE

The Landsat-D Instrument Module here refers to all equipment other than the MMS. The instruments and the wideband module are discussed in the following paragraphs. The solar array and the boom with the TDRS antenna, RF compartment and gimbal drive assembly are to be jettisoned according to our baseline scenario, therefore complete replacement of these components is required.

Most of the IM electronics considered here (which does not include the instruments or wideband electronics) are considered to be reusable without refurbishment for the second mission. Exceptions would include the Direct Access S-band Transmitters' output devices, the high power semiconductors and switches in the power supplies, and the Payload Correction Data Multiplexer which contains commercial grade CMOS devices. The Solar Array Drive and Power Transfer Assembly will experience cyclic mechanical wear, so the motor, bearings, and slip ring assembly are considered to require replacement. Pyrotechnic devices and initiators obviously cannot be used more than once. All thermal blankets and coatings will be replaced due to contamination and degradation of UV and micrometeorites.

Little detailed design information or reliability data were available for the angular displacement sensor, so its refurbishment requirements are to be determined. Considering the nature of its function, one may suppose it to be sensitive to wear and, because it has moving parts experiencing cyclic stress, to require replacement.

5.2.1 MULTISPECTRAL SCANNER

The Landsat-D MSS is similar to those flown on earlier Landsat missions, but without the cooled IR detectors which were added to Landsat-3. The orbiting instruments have shown surprisingly long life: MSS-1 did have a power supply failure for one of the bands after more than 5 years; MSS-2 is still working well after reactivation and 5 years of accumulated operation; MSS-3 is showing some scan line problems, but still functioning after 2 years (except for the cooled IR band detectors). The MMS was included in the Landsat-D without any extensive redesign. It was not designed for the STS environment, although the assumption is made that it is compatible with the environment. The design technology for MSS is now a decade old and spares for the instrument and supporting equipment are not readily available.

The instrument Earth-viewing aperture is open to the environment. The internal surfaces of the instrument are exposed to sources of contamination during STS retrieval and landing, so all optical surfaces are considered to require cleaning. Since MSS components are not easily accessible, this implies major disassembly of the instrument. Mechanical wear on the shutter assembly motor also necessitates disassembly.

The silver-coated scan mirror and telescope optics, although not as critical as those on the TM, could suffer chemical degradation extensive enough to require stripping and replacing the surface coatings. The degradation is not well understood, but it is considered likely to occur.

The PMT detectors have shown good performance on all previous Landsat missions; the 5-year performance data indicates that, although the PMT's do show a decrease in output with time, the level of degradation does not seriously affect the instrument's performance, particularly because of the calibration capabilities. The photodiode detectors show a greater level of change in their output. Although their performance after 5 years is within the calibration capabilities of the instruments, they should probably be replaced because of the reduced margin.

The motor of the shutter assembly and the scan mirror bumpers, flex pivots, and dampers will experience continuous or repeated mechanical stress and wear and should be replaced.

The shutter wheel position monitor and the scan monitor use laser diodes whose life is not expected to last two missions. The calibration lamp and scan mirror optical switch lamps have tungsten filaments which are judged to need replacement. Similarly, the phototransitors and photodiode detectors corresponding to the above light sources are also considered to need replacement. Other optical surfaces in these light paths must be cleaned.

In the electronics, the high voltage and main power relays are highly stressed and cycled repeatedly, and should be replaced. Switching transistors in the main power supply are operated near their limits and are therefore not considered reliable enough for two missions. The PMT high voltage power supplies, which are potted assemblies, will be replaced.

5.2.2 THEMATIC MAPPER

The TM, a new design, is a significant extension of capability beyond MSS concepts. It has solid state detectors with IR detectors attached to a radiative cooler and incorporates a scan line corrector. The TM has greater spatial resolution and radiometric precision than MSS, and has greater size, weight, and power requirements. It is designed for Delta or STS launch and retrieval, but not necessarily reuse after retrieval.

The TM is open to the environment through the Earth-viewing aperture and is susceptible to contamination during STS retrieval and landing. This contamination may include humidity which can affect optical surfaces and exposed electronics components. Any effect on the graphite epoxy structure should be negligible. The TM should be disassembled and cleaned.

The stray light specification puts stringent requirements on the silver-coated optical surfaces in the primary light path. These surfaces can suffer chemical degradation. Humidity seems to aggravate the degradations, which can continue to spread under protective coatings. Therefore, the scan mirror, primary and secondary mirrors in the telescope, and the two surfaces in the scan line corrector will all need to be stripped and recoated.

The stresses and wear due to the repeated cycling of the scan mirror assembly will require that the striker plates will need refinishing and the bumpers and flex pivots will need to be replaced. Likewise, the prime calibration shutter assembly will be replaced, but the scan line corrector flex pivots are not stressed sufficiently to warrant replacement.

Ancillary optical components used for the scan angle monitor and the calibration assembly are not expected to serve two missions. These bonded assemblies include laser diodes, photodiode detectors, and calibration lamps and should be replaced. All associated optical surfaces will be cleaned. The relay optics between the prime focal plane and the cooled focal plane will also require disassembly and cleaning.

At the prime focal plane, the entire detector assembly including filters, silicon detectors, Field Effect Transistors (FET) preamplifiers and hybrid amplifiers, is recommended for replacement. The detectors may have degraded, the other components will be contaminated, and the unprotected electronics will be susceptible to moisture and "purple plague," an unexplained change which can occur to the bond between a wire·lead and a semiconductor device which weakens the bond. The entire cooled focal plane assembly will also be replaced, since the exotic IR detector lifetimes are uncertain, unsealed electronics components are susceptible to humidity, and the connecting conductors are extremely delicate (8000 Angstroms thick). At the radiative cooler, the specular reflector and multilayer insulation will be replaced due to degradation by contamination and humidity. The cooler door will be used little, so the mechanisn will not suffer appreciable wear.

In the TM electronics, the scan mirror electronics includes a microprocessor and a random access memory that are susceptible to radiation and will be replaced. In the electronics module and the multiplexer, the high power semiconductors that are operated near their limits, should be replaced.

5.2.3 WIDEBAND MODULE

The WBM consists of RF electronics and supporting power circuitry, thermal control, and structure. These components are presumed to have adequate reliability for retrieval, relaunch, and a second mission, except for the X-band TWTA, and the high power and high voltage semiconductors in the power supplies which will be replaced. The surfaces of the X-and S-band antennas will be repainted and thermal coatings and blankets will be replaced.

5.3 MULTIMISSION MODULAR SPACECRAFT

The MMS, intended for use in a variety of missions, is designed for a more severe environment than that expected for the Landsat-D mission. It is designed for Delta or STS launch, STS servicing on-orbit by module replacement, and STS retrieval.

The first MMS launched was part of the SMM Observatory. The Landsat-D version differs in size of batteries, inclusion of a PM a different transition adapter structure, and a few other improvements. The SMM MMS has been operating well within the expected limits and has had no early failures. This indicates good design and workmanship and a high probability of long life.

The structural framework of the MMS and the module structures designs are considered to be adequate for the expected loads. The transition adapter and the PM mounting brackets, although having smaller design margins than the other structures, should also be able to withstand these loads. The electrical harness, connectors, Remote Interface Unit (RIU), SC&CU, louvers, and thermal sensors are not expected to require rework. The thermal blankets and coatings will all be replaced due to surface degradation.

5.3.1 MODULAR POWER SUBSYSTEM

The MPS for Landsat-D contains two 50-ampere-hour batteries, and these are considered to need replacement due to chemical degradation after regular charge/discharge use during the mission.

The Power Regulator Unit, a modification of the design used in the Skylab Airlock with good performance, has six power modules operating in parallel. Two parallel 30-ampere transistors share a 18-ampere load in each module. Baseplate temperature in the SMM unit varied from 12 to 22 degrees C, well below the 50 degrees acceptance limit.

The Power Control Unit relays will rarely be switched during the mission. This unit also contains fuses and magnetic current sensors. The Bus Protection Assembly contains few power electronics.

The MPS electronics is all Transistor-Transistor Logic (TTL); there are no CMOS or radiation sensitive components. Thermostat elements are operated below rated current and the rate of cyclic operation experienced on SMM is low, so it is not expected that the rated number of cycles would be exceeded after two Landsat-D missions.

5.3.2 MODULAR ATTITUDE CONTROL SUBSYSTEM

The MACS module includes components which will experience mechanical wear and which will be refurbished to ensure good performance. No long-term operation data is available for these units. The Reaction Wheel bearings and the bearings in the Horizon Scanner, will be replaced and relubricated. The Inertial Reference Unit (IRU) gyros will also be replaced.

The optical components will only require cleaning of external surfaces. The star trackers will have a quartz shield over the lens for radiation protection. The PMT's have a sensitivity margin of approximately 0.7 stellar magnitude. They will see only low level light and will operate in the nano-ampere range, so they are not being severely stressed and should have a long life. The Sun shutter will rarely be used. The Landsat-D mission unique Horizon Scanner has optics and detectors similar to long-life versions on earlier Landsat and Nimbus spacecraft. The Fine Sun Sensor is similar to the long life unit on OAO, which had good performance.

The Magnetometer design has been widely used in spacecraft with good reliability. The Magnetic Torquers are very simple, and will operate at low power.

The Power Conditioning Unit relays will be rarely used. The Attitude Control Electronics wheel drivers will switch about 90W to the wheels, but have been operating at low temperatures on SMM.

The star tracker electronics and IRU electronics have components which are exceptions to the MMS radiation tolerance specification; however, their shielding is judged to be adequate for exposure to two Landsat-D missions.

5.3.3 COMMUNICATIONS AND DATA HANDLING SUBSYSTEM MODULE

The MMS C&DH module electronic components generally do not require refurbishment. The transponder, however, is an exception since it contains a radiation sensitive CMOS microprocessor; an RCA 1802. The Standard Telemetry and Command Components (STACC) Central Unit, which experienced transient data anamolies on SMM, will be modified for Landsat-D. The sensitive component, a random-access memory chip, will be replaced by a less sensitive component which should have no problems for two Landsat-D missions.

The S-band transmitter solid-state components are operating with cool temperatures on SMM, and should therefore have good reliability. The RF switches will be infrequently used.

The Tape Recorders are expected to show mechanical wear and will thus need extensive mechanical rework. They also contain radiation sensitive CMOS microprocessors which need to be replaced.

5.3.4 PROPULSION MODULE

The MMS PM for Landsat-D, PM-1A, is a modification of PM-1 and includes an extra tank to increase fuel capacity to permit transfer from the Landsat orbit to the STS orbit for recovery.

The follow-on Landsat mission requires enough fuel to transfer it from the STS orbit to its orbit at launch, as well as to return it to the STS orbit for recovery. The PM-1A does not have the capacity to do this so the PM-2, with its even greater fuel capacity, will be needed. This means there are no refurbishment requirements for the Landsat-D PM-1A.

Table 5-1. Refurbishment Requirements Instrument Module

COMPONENT	REFURBISHMENT ACTION	REASONS
1. Solar Array	Replace entire assembly	Jettisoned
2. TDRS Antennas, RF Compartment, Gimbal Drive Assembly, GPS Antenna, GPS Preamplifier, Antenna Boom	Replace entire assembly	Jettisoned
3. Angular Displacement Sensor	Replace assembly	Friction wear; delicate device
4. PCD Multiplexer	Replace CMOS devices	Radiation dose exceeds tolerance
5. Data Processing Unit	Leave as is	
6. Direct Access S-band Transmitters	Replace RF output transistors	High power, low reliability
7. Remote Interface Units	Leave as is	
8. RF Combiner	Leave as is	
9. S-band Omni Antennas	Leave as is	
10. GPS Electronics	Leave as is	
11. Power Distribution Unit	Replace high power semiconductors and switches	High power stresses

Table 5-1. Refurbishment Requirements Instrument Module (cont.)

COMPONENT	REFURBISHMENT ACTION	REASONS
12. Solar Array Release/Deploy/ Jettison Assembly	Leave as is	
13. Solar Array Drive and Power Transfer Assembly	Replace motor, slip ring assembly, bearings	Friction wear
14. Boom Antenna Release/Deploy/ Jettison Assembly	Replace guillotined launch-lock pyro wires	Cut by boom jettison operation
15. Cable Harness and Connectors	Leave as is	
16. Pyro Devices and Pyros	Replace	Single use items
17. Heaters	Leave as is	
18. Thermostats and Thermal Sensors	Leave as is	
19. Thermal Blankets and Coatings	Replace	UV, micrometeoroid damage, Shuttle landing contamination and humidity
20. Structure	Leave as is	

Table 5-2. Refurbishment Requirements Multispectral Scanner

COMPONENT	REFURBISHMENT ACTION	REASONS
1. Telescope and Optics	Strip and recoat optical surfaces	Shuttle landing contamination and humidity, chemical degradation
2. Detectors	Replace silicon photodiodes Clean optical surfaces	Degraded performance Contamination
3. Shutter Assembly	Replace motor	Friction wear, loss of lubrication
	Clean optical surfaces	Shuttle landing contamination
	Replace laser diodes	Operational stress, life less than 6 years
4. Calibration Components	Clean optical surfaces Replace lamp assembly	Contamination Filament wearout
5. Scan Mirror Assembly	Strip and recoat mirror	Chemical degradation, Shuttle landing contamination
	Replace bumpers, dampers, flex pivots	Cyclic stress
	Replace optical switch lamps	Filament wearout
	Replace phototransistors	Degraded performance
	Clean switch optics	Contamination

Table 5-2. Refurbishment Requirements Multispectral Scanner (cont.)

COMPONENT	REFURBISHMENT ACTION	REASONS
6. Scan monitor	Replace laser diodes	Operational stress, life less than 6 years
	Clean optics	Contamination
7. Electronics	Replace high voltage and main power relays	Cyclic voltage and power stresses
	Replace switching transistors in main supply	Stressed near rated limits
	Replace high voltage PMT supplies	Voltage stress
8. Multiplexer	Use as is	

Table 5-3. Refurbishment Requirements Thematic Mapper

COMPONENT	REFURBISHMENT ACTION	REASONS
1. Scan Mirror Assembly	Strip and recoat scan mirror	Mirror degradation, Shuttle landing contamination
	Repolish striker plate	Cyclic impact wear
	Replace bumpers, flex pivots Replace LED's, photodiodes	Cyclic stresses Degraded performance
2. Telescope Assembly	Strip and recoat primary and secondary	Mirror degradation, Shuttle landing contamination
	Clean telescope	Shuttle landing contamination
3. Prime Focal Plane Bulkhead Assembly	Strip and recoat scan line corrector mirrors	Mirror degradation, contamination
	Replace entire detector assembly (filters, detectors, FET preamplifiers, hybrid amplifiers)	Contamination, humidity in unsealed electronics
	Replace entire prime calibration shutter assembly	Cyclic stress
	Replace calibration lamps	Filament wearout
4. Relay Optics Assembly	Clean optics	Shuttle landing contamination

Table 5-3. Refurbishment Requirements Thematic Mapper (cont.)

COMPONENT	REFURBISHMENT ACTION	REASONS
5. Cooled Focal Plane Assembly	Replace entire assembly	Detector life uncertainty, fragile structures, humidity in unsealed electronics
6. Radiative Cooler	Replace specular reflector	Micrometeoroid damage, contamination
	Replace MLI	Shuttle landing humidity, contamination
7. Electronics Module	Leave as is	
8. Scan Mirror Electronics	Replace microprocessor and RAM	Low radiation tolerance
9. Multiplexer	Replace highpower semiconductors	High power stress
10. Relay Optics Focusing Assemblies	Leave as is	

Table 5-4. Refurbishment Requirements Wideband Module

COMPONENT	REFURBISHMENT ACTION	REASONS
1. Digital Switching Unit	Leave as is	
2. DQPSK Modulator and Frequency Source	Leave as is	
3. UQPSK Modulator and Frequency Source	Leave as is	
4. X-band Upconverter	Leave as is	
5. X-band TWTA	Replace	High voltage and thermal stresses, cathode depletion, low reliability
6. X-band Low Pass Filter	Leave as is	
7. Autotrack Receiver	Leave as is	
8. Gimbal Drive Electronics	Leave as is	
9. Power Converter and Switching Unit	Replace high voltage and higher power semiconductors	High voltage and power stress
10. Bus Protection Assembly	Leave as is	
11. Coax Switches and Circulators	Leave as is	
12. X- and S-band Antennas	Repaint	UV damage

Table 5-4. Refurbishment Requirements Wideband Module (cont.)

COMPONENT	REFURBISHMENT ACTION	REASONS
13. Heaters and Thermostats	Leave as is	

Table 5-5. Refurbishment Requirements MMS Structural, Electrical, and Thermal Components

COMPONENT	REFURBISHMENT ACTION	REASONS
1. Module Support Structure	Leave as is	
2. Transition Adapter	Leave as is	
3. Module Structure	Leave as is	
4. PM Mounting Brackets	Leave as is	
5. Signal Control and Conditioning Unit	Replace associated pyro devices and pyros Replace safe/arm plug fusistors	Single use items High current operation
6. MMS Cable Harness and Connectors	Leave as is	
7. All RIUs	Leave as is	
8. MMS Heaters	Leave as is	
9. MMS Thermostats and Thermal Sensors	Leave as is	
10. MMS MLI and Thermal Coatings	Replace	UV, micrometeoroid damage, Shuttle landing contamination and humidity

Table 5-6. Refurbishment Requirements Modular Power Subsystem

COMPONENT	REFURBISHMENT ACTION	REASONS
1. Batteries	Replace	Chemical degradation, thermal and current stress
2. Power Regulator Unit	Leave as is	
3. Signal Conditioning Assembly	Leave as is	
4. Bus Protection Assembly	Leave as is	
5. Power Control Unit	Leave as is	

Table 5-7. Refurbishment Requirement Modular Attitude Control Subsystem

COMPONENT	REFURBISHMENT ACTION	REASONS
1. Fixed Head Star Tracker	Clean anti-reflection coatings, lens, lens shield	Shuttle landing contamination
2. Magnetometers	Leave as is	
3. Inertial Reference Units	Replace gyros	Friction wear
4. Fine Sun Sensors	Clean photocells	Shuttle landing contamination
5. Horizon Scanner	Clean lens	Shuttle landing comtamination
	Replace bearings, relubricate	Friction wear
6. Magnetic Torquers	Leave as is	
7. Reaction Wheels	Replace bearings, relubricate	Friction wear
8. Attitude Control Electronics	Leave as is	
9. Power Conditioning Unit	Leave as is	
10. Coarse Sun Sensors	Replace	Jettisoned
11. Bright Object Sensor	Clean photocells	Shuttle landing contamination
12. Heat Pipe	Leave as is	

Table 5-8. Refurbishment Requirements Communications and Data Handling Subsystem Module

COMPONENT	REFURBISHMENT ACTION	REASONS
1. STACC Central Unit	Leave as is	
2. On-Board Computer	Leave as is	
3. STACC STINT	Leave as is	
4. Pre-Modulation Processor	Leave as is	
5. S-band Transponder	Replace microprocessor	Radiation dose exceeds tolerance
6. RF Switches	Leave as is	
7. Tape Recorders	Replace tape, heads, guides, reel brakes, springs and motors	Friction wear, low reliability, cyclic stresses
	Replace microprocessor	Radiation dose exceeds tolerance
8. Power Conditioning Unit	Leave as is	
9. Diplexer	Leave as is	

SECTION 6. IMPLICATIONS OF THE REFURBISHMENT PLAN

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The refurbishment plan as presented in this report does not address the programatic aspects. Implementation of the plan will not be easy and will, most likely, require as much project planning and management support as the procurement of any new spacecraft. Careful coordination will be needed with all the appropriate contractors to ensure that each will be prepared to receive his equipment, proceed directly with the required testing and rework and return it within a given period of time. Preparation will have to be made months in advance of the return of Landsat-D. Procedures must be written to cover the inspection, disassembly and testing of the spacecraft. All necessary ground support and test equipment must be made ready. The scheduling of test facilities, work areas and manpower must be done to avoid potential conflicts. Adequate funding must be provided to do this preparatory work.

This plan is based on testing to determine the actual rework which will be required to refly Landsat-D. It will, therefore, be necessary to have established what information will have to be obtained from the testing and the criteria for determining if replacement or rework will be required. In many cases the criteria can be the values listed in the original procurement specification. For components exhibiting a known degradation phenomenon, an acceptable level, as well as a rate, of degradation will have to be specified, to assure adequate margins for the second mission. Comparisons will have to be made with pre-flight test data to try to uncover any insidious trends which may portend a premature failure. This implies thorough documentation and preservation of the pre-flight data, including the specific test input conditions.

Flight operations will play an important part in establishing the refurbishment requirements. Accurate logs which include the hours of operations, any switching done between units and other events which may affect the operational lifetime of components will have to be kept. As mentioned previously, it will be necessary to know the rates associated with degradation processes. Careful monitoring of flight performance characteristics will be required to supply this information. Procedures will have been established so that, in the event of an on-orbit failure, the proper action will be taken to ensure that the requirements for replacing or reworking the failed part, including the initiation of any special procurements, will be included in the refurbishment planning.

It will also be necessary to know that the design loads are not exceeded during the recovery and de-orbiting phases, particularly during the landing. Planning will have to be done to either include the instrumentation on the spacecraft itself or on the flight support equipment which will restrain Landsat-D during recovery.

As was stated in the ground rules, the refurbishment plan is success-oriented. No contingency has been included for unforseen events. With proper preparation, the availability of equipment, facilities, and personnel should not be a problem. Long lead-time procurements have been identified for those components which will most likely require total replacement or replacement of selected parts. There is, however, the possibility that the initial inspection and testing will uncover other components which will require some level of refurbishment and that replacement parts may not be readily available or may be totally unavailable. This problem may also arise if an on-orbit failure occurs shortly before the planned recovery. Such an occurrence could completely disrupt the refurbishment cycle. The impact of this on the turnaround time for refurbishing Landsat-D could be minimized by developing a selective or "precautionary" spares program but this is not included in the plan as presented.

Obsolescence is another issue which is not being considered with this refurbishment plan. The MSS on Landsat-D is using designs and technology which are close to a decade old. Consider, for example, the multiplexer. Although in all likelihood it will be reflyable, if some refurbishment were needed, a decision would have to be made whether to repair the old, obsolete unit or to upgrade the MSS with a newer technology multiplexer. Since some parts may no longer be available, the decision may be forced to update the multiplexer, which could present problems with the Landsat data interface. The PMT's are another example. These are costly, long lead items whose functions can be duplicated with solid state devices which do not need the associated high voltage power supplies. If the PMT's were to require replacement, it might make sense to use photodiodes instead. Fortunately, the reliability of the MSS PMT's and multiplexer appear to be good enough to allow reflight without replacement. The test equipment needed to support the MSS refurbishment test program could present a problem though. It, too, is obsolete and certain replacement parts are no longer available. The assumption is made that it will be operational when needed.

Finally, a refurbishment plan assumes that some acceptable level of reliability and performance can be defined. If the program is to work without having excessive replacements which will drive up the costs, a certain amount of risk, somewhat greater than that for a new satellite, must be taken by the responsible government agency. This can be done by clearly establishing the testing requirements and criteria used to determine the need for refurbishment or replacement so that nobody's judgement, particularly the contractor's, can be questioned in the event a reused component fails or does not perform satisfactorily during the second mission. Unless this is done, most contractors will be reluctant to do anything except fly a totally new component.

SECTION 7. RECOMMENDATIONS

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Many of the Landsat-D refurbishment requirements are to be established by comparing the results from post-recovery tests with those from the pre-flight tests. Some of this pre-flight testing is currently underway at the vendors. If these data are not properly preserved and the procedures well documented, they may not be available at the time of refurbishment. Also, at this time, certain procurements are being made for flight parts which may also be needed for the refurbishment. If adequate spares are planned now, the possibility of them not being available later is removed. It therefore appears that some of the preparation for refurbishment should begin now. Since these preparations involve coordination between many contractors, it is recommended that one contractor be selected to be responsible for developing the detailed refurbishment program. This contractor should have the responsibility of establishing the requirements for support from all the associated Landsat-D contractors so that proper planning and adequate funding will be forthcoming.

A second recommendation is that this study be extended, with additional funding being made available to the individual contractors to review their designs, evaluate the potential needs for refurbishment, and supply the detailed cost and schedules data involved. This means that policies must be established regarding the expected performance requirements for a refurbished spacecraft. This is needed for the vendors to respond with the necessary test criteria for determining the refurbishment needs.

This study indicates that a great deal of the refurbishment needs, particularly with the instruments, is due to the contamination and humidity which will occur during landing. It is strongly recommended that some sort of system be designed to protect Landsat-D from these effects.

Another observation made during this study was that the refurbishment planning for Landsat-D was complicated by the fact that Landsat-D was not designed for 6 years of operation nor was it designed with refurbishment in mind. Many questions arose as to whether a component would be good for the two missions, so extensive testing seemed necessary to establish the refurbishment needs. In certain areas a great deal of disassembly is required to get to parts requiring rework. All of this adds time and cost to the refurbishment. It is therefore recommended that, in the future, if a spacecraft is to be reused, the following design considerations be made: most components should be designed for long life with adequate margin to exceed the expected overall lifetime; those components which cannot be designed for long life should be considered expendable and be easily accessible for replacement; and a modular design should be incorporated to allow the replacement of the expendable components with the minimum impact on the other components or system. Such a design would expedite the refurbishment process.

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LIST OF ACRONYMS

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ATS	Applications Technology Satellite
AU	Astronomical Unit
C&DH	Command and Data Handling Module
CMOS	Complementary Metal Oxide Semiconductor
DQPSK	Differential Quadrature Phase Shift Key
FET	Field Effect Transistor
GFE	Government Furnished Equipment
GSFC	Goddard Space Flight Center
GPS	Global Positioning System
I&T	Integration and Test
ICD	Interface Control Document
IR	Infrared
IM	Instrument Module
JPL	Jet Propulsion Laboratory
LED	Light Emitting Diode
MSFC	Marshall Space Flight Center
MACS	Modular Attitude Control Subsystem
MPS	Modular Power Subsystem
MLI	Multi-Layer Insulation
MMS	Multimission Modular Spacecraft
MSS	Multispectral Scanner
OAO	Orbiting Astronomical Satellite

OAOCO	OAO Corporation
PMT	Photomultiplier Tube
PRC	Planning Research Corporation
PM	Propulsion Module
RF	Radio Frequency
RAM	Random Access Memory
RIU	Remote Interface Unit
SC&CU	Signal Conditioning and Control Unit
SMM	Solar Maximum Mission
STS	Space Transportation System
STINT	Standard Interface
STACC	Standard Telemetry and Command Components
TDRS	Telemetry Data Relay Satellite
TTL	Transistor - Transistor Logic
TWTA	Traveling Wave Tube Amplifier
UV	Ultraviolet
UQPSK	Unbalanced Quadrature Phase Shift Key
WBM	Wideband Module
WCS	Wideband Communication Subsystem

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