

CR-137854

ANALYSIS OF SPACECRAFT ANOMALIES

By Charles E. Bloomquist and Winifred C. Graham

March 1976

PRC R-1833

(NASA-CR-137854) ANALYSIS OF SPACECRAFT
ANOMALIES (PRC Systems Sciences Co., Los
Angeles) 145 p HC \$6.00 CSCI 22B

N76-22271

Unclas
G3/18 27404

Prepared under Contract No. NAS 2-9041

for

AMES RESEARCH CENTER

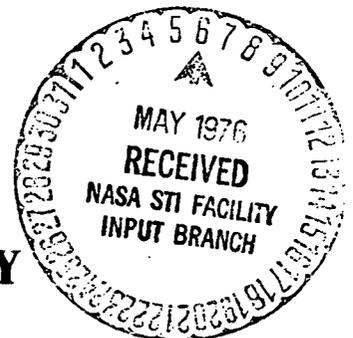
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION



PRC SYSTEMS SCIENCES COMPANY

A Company of Planning Research Corporation

1100 GLENDON AVENUE • LOS ANGELES, CALIFORNIA 90024 • (213) 473-1163



FOREWORD

This document presents the results of a study to determine empirically, from an analysis of the PRC Space Data Bank, if there are problem areas where in-space experimental or technological programs would contribute to the prevention of spacecraft anomalies, and to define these programs.

The study was performed in the 4-month period beginning 11 November 1975 by PRC Systems Sciences Company for The Ames Research Center under Contract NAS2-9041. Mr. F. F. DeMuth was the contract technical monitor.

ABSTRACT

The anomalies from 316 spacecraft covering the entire U.S. space program were analyzed to determine if there were any experimental or technological programs which could be implemented to remove the anomalies from future space activity. Thirty specific categories of anomalies were found to cover nearly 85 per cent of all observed anomalies. Thirteen experiments were defined to deal with 17 of these categories; nine additional experiments were identified to deal with other classes of observed and anticipated anomalies.

Preliminary analyses indicate that all 22 experimental programs are both technically feasible and economically viable.

OVERVIEW

The objective of the study described in this report was to determine empirically, from an analysis of the PRC Space Data Bank, if problem areas exist which could best be treated by in-space programs. These programs would be such that their results would contribute to the prevention of specific types of spacecraft anomalies or to the mitigation of their effects. Program implementation would utilize the capabilities of the Space Shuttle/Spacelab.

The PRC Space Data Bank, which provided the principal "input" to the study, was compiled through a series of studies, and contains performance information on 316 spacecraft from 43 U.S. space programs. Over the time period covered by the PRC Space Data Bank (1960 to 1975), these spacecraft have accumulated two million hours of on-orbit operation, and over 1,600 separate anomalies have been recorded during their operation.

In conducting the analysis for this study, two separate approaches were applied: (1) an anomaly-by-anomaly evaluation of the data base anomaly listings, and (2) a spacecraft-by-spacecraft evaluation of the data base engineering reports. Approach 1 was not especially fruitful in that very few single anomalies were found which could clearly be impacted by an in-space program. Approach 2, on the other hand, proved exceedingly fruitful.

This spacecraft-by-spacecraft evaluation revealed that a structure of 30 problem area categories clearly accommodates 50 percent of the anomalies. The anomalies essentially grouped themselves into these categories, and further, the classes of anomalies which constitute these categories are remarkably persistent over the entire duration of the U.S. space program.

Following the completion of the two types of evaluations, the results of both were merged, then considered from the standpoint of where in-space experimental programs appeared warranted. Twenty-two such program areas were defined, and a number of others were identified where ground-based programs appeared more promising.

A brief economic feasibility analysis was then conducted. This analysis, which was restricted to a level of detail sufficient for initial decision-making purposes, was based on the number of anomalies that can be expected on future spacecraft, and on varying efficiencies of the recommended experimental programs. The economic analysis indicated that the programs would be cost-effective even at efficiencies as low as 10 percent.

TABLE OF CONTENTS

	<u>Page</u>
FOREWORD	
ABSTRACT	
OVERVIEW	
I. INTRODUCTION AND SUMMARY	1
II. SPACE DATA BANK UPDATE	5
A. General Background	5
B. Update for This Study	6
III. ANALYSIS	9
A. Analysis Overview	9
B. Approach 1	10
C. Approach 2	11
D. Merging the Results of the Two Approaches	16
E. Problem Areas for Which No In-Space Program is Recommended	19
F. Observations	29
IV. RECOMMENDED EXPERIMENTAL AREAS	33
V. ECONOMIC FEASIBILITY	75
VI. CONCLUSIONS AND RECOMMENDATIONS	81
REFERENCES	83
APPENDIX A: PRC SPACE DATA BANK UPDATE	A-1

LIST OF EXHIBITS

	<u>Page</u>	
II-1	Spacecraft Included in Update for This Study	8
III-1	Catalog of Anomaly Assignments, Approach 1	12
III-2	Leading Problem Areas	14
III-3	Rank Order of Problem Areas	15
III-4	Anomaly Occurrence By Year of Launch	17
III-5	Anomaly Categories for Which No Experimental Programs are Proposed	18
III-6	Recommended Experimental Areas	20
IV-1	Gravity Gradient Stabilization Performance and Reliability Information Summary	49
V-1	Economic Viability of Recommended Experimental Programs	79

I. INTRODUCTION AND SUMMARY

The Space Shuttle/Spacelab will impact future unmanned space programs in several ways. Its implementation will effectively prevent the loss of payloads at launch, it will reduce the frequency of launch-induced anomalies, and it will provide a means of correcting postlaunch anomalies of individual spacecraft. The Space Shuttle/Spacelab will exert a significant influence on the prelaunch design, development, and test activities associated with unmanned spacecraft or other payloads. It may also contribute to the resolution of many previously observed spacecraft anomalies by providing the capability to implement space-oriented experimental and technology programs needed to resolve specific anomalies or problem areas.

The potential extent of this latter Space Shuttle/Spacelab impact is investigated in the study reported herein. The other mentioned ways that the Space Shuttle might influence unmanned space programs were investigated in a previous study, the results of which are reported in Reference 1. Both of these studies depend on an existing historical file of operational spacecraft reliability data referred to as the PRC Space Data Bank. This file contains data on the actual performance of over 300 spacecraft of the U.S. space program. Particular emphasis is given to the incidents of anomalistic behavior recorded against these spacecraft.

The overall objective of the study is to establish an empirically-based rationale for Space Shuttle/Spacelab service to future spacecraft systems. This service takes the form of applied research, technology evaluation and experimental programs that require the capabilities of the Space Shuttle/Spacelab for implementation. These programs are structured so that their results can be used in the prevention of specific anomalies and general problem areas in future spacecraft or at least to the mitigation of their effects.

Section II of this report contains a brief description of the PRC Space Data Bank; the limited extension of the data bank that was undertaken in this study is also discussed. The total data base includes information on the reliability of 316 spacecraft from 43 programs. These

spacecraft have accumulated over two million hours of on-orbit operation and over 1600 individual anomalies have been recorded during their operation. Information from six spacecraft (five programs) involving over 100,000 hours of spacecraft operation and 173 anomalies were added to the data bank during this study. A detailed compilation of the added data is presented in Appendix A.

Section III presents the analyses of the PRC Space Data Bank performed during this study. Each spacecraft anomaly was reevaluated using all available information and coded using two different approaches. In the first approach, each anomaly was considered individually and a judgment made as to whether there was a potential experimental or technology program, to be conducted in space, that could be used to prevent the anomaly or mitigate its effect in future space activities. For approximately 100 anomalies (6 percent), a positive judgment was made. The other anomalies were further separated into those for which such a program was judged to be unwarranted (39 percent) and those for which no determination could be made (55 percent). A more detailed assessment of the 100 anomalies reduced the number to 69 which could be treated by 18 experimental and technology evaluation programs.

In the second approach, thirty problem areas were refined from the data bank. These problem areas included over eighty percent of the anomalies analyzed. For this reason and because of the persistence of these problem areas over time, each was evaluated as to its potential for being resolved by an experimental or technology program conducted from the Space Shuttle. It was judged that seventeen of the thirty problem areas (covering about 50 percent of all anomalies) would benefit significantly from such a program.

Section IV identifies and outlines the main features of the proposed experimental and technology programs. Twenty-two programs are presented. Thirteen of these deal with the seventeen problem areas determined to be amenable to an in-space applied research program. Nine other experiments are proposed to deal with specific anomalies or particular facets of certain problem areas (such as lubrication, semiconductors, and radiation) or with equipments which have a special requirement for the space environment

(these include gravity gradient stabilization systems and heat pipes).

A crude economic evaluation of the twenty-two programs is presented in Section V. The factors involved in the evaluation are delineated and their treatment to arrive at a decision in each case is explained. All twenty-two programs are judged to be economically viable although some are more clearly viable than others.

Section VI contains the conclusions of the study and recommendations for further work. The study indicates that there are several persistent problem areas that could be removed from future spacecraft by application of the results of defined Space Shuttle system experimental and technology evaluation programs. These programs appear to be technically and economically feasible. It is recommended that additional data on past programs be assembled, that new lines of investigation opened up by the current study be pursued, and that the role of spacecraft reliability in the Shuttle era be analyzed using the observed experience of the data bank, projected missions, and considerations of the economic impact of differing levels of required reliability.

II. SPACE DATA BANK UPDATE

A. General Background

PRC has compiled, through a series of studies, considerable information regarding the on-orbit reliability of U.S. spacecraft. This information is referred to collectively as the PRC Space Data Bank. It consists of the following:

- o The published reports and papers describing data bank studies and results.
- o An unpublished file of engineering analysis reports (EARs), one for each spacecraft represented in the published portion of the data bank.
- o An organized collection of study notes, related reports, articles, clippings, bibliographies, and interview records.

The published portion of the data bank⁽¹⁾ now includes information on the reliability of 316 spacecraft from 43 programs. These spacecraft have accumulated 2 million hours of on-orbit operation, and over 1,600 separate anomalies have been recorded during their operation. The published reports and papers do not correlate specific anomalies with particular spacecraft; the EARs do.

The EARs are the basic data collection. They contain:

- o General descriptive and operational data on each spacecraft.
- o A detailed breakdown of the spacecraft assemblies, components, and piece-parts.
- o Operating (and dormant) time accumulated by each hardware element.
- o Descriptions of all anomalies and failures recorded against the spacecraft, together with information on the known or probable causes of many anomalies.
- o Background information regarding manufacture, test, and launch.

The information contained in each EAR, as summarized above, is organized into 3 categories, namely, (1) general information, (2) reliability data, and (3) development and prelaunch information. General information includes launch date, launch vehicle, launch site, intended mission, orbital parameters, spacecraft description, and a general performance assessment over the time period covered by the PRC Space Data Bank.

¹See references 1 through 13.

The reliability data elements, to the extent possible, break the spacecraft down into its major components (receivers, tape recorders, digital decoders, etc.), accumulate the survival hours in space for each, including length of time on standby and number of times cycled, list in a further breakdown the piece-parts in each component, and finally, provide a rather detailed description of each anomaly (failure or other non-nominal mission behavior) recorded during the mission.

Development and prelaunch information includes, as available, the prelaunch test and checkout routines and experience, and thumbnail descriptions of developmental testing, part selection procedures, and quality assurance provisions.

The PRC Space Data Bank has been built up through a variety of sponsors⁽¹⁾ and study objectives, and was accumulated in four stages. The first stage provided data through 1970. In the second stage, access to military program data was considerably reduced, also no data were actively sought for spacecraft with nominally short mission durations. The data quality in the second stage was greatly improved over that in the first stage for both NASA and the unrestricted military programs. The third and fourth stages were limited additions to the PRC Space Data Bank.

Typical of the 43 programs included in the PRC Space Data Bank are the Army-sponsored SECOR program with 14 spacecraft, the Navy SOLRAD program with 3 spacecraft, the Air Force Vela program with 10 spacecraft, and the NASA Gemini, Mariner, Nimbus, OGO, ATS, and Pioneer programs. In terms of chronology, the data base extends from Vanguard---the first U.S. satellite---to, with the update discussed below, a spacecraft launched as recently as May, 1974.

B. Update For This Study

While the published PRC Space Data Bank was considered to be adequate for purposes of this study, the desirability of extending the data base to include anomalies of a more recent vintage was also manifest. Therefore, data received too late for inclusion in the last published update were analyzed and included as part of the data base for this study. Since

(1) Sponsors include the General Electric Company (Apollo Support Department), the Navy Space Systems Activity, NASA headquarters, and Marshall Space Flight Center. In addition, substantial quantities of data were supplied without benefit of contract to the Goddard Space Flight Center, the General Accounting Office, and General Electric Company (Viking Project Support Services).

these data were so sparse, however, it was also decided to include readily available data from programs with established contacts and a record of cooperation. The overall results of this data base update are summarized in Exhibit II-1.

The information on SOLRAD 10 was chiefly that received too late for the last update, although specific anomaly data was obtained from the program office for this study. Practically all of the other update information, i.e., that for ATS-6, Landsat-1, Mariner 10, and Pioneers 10 and 11, was obtained during this study.

Since such large quantities of data were found to be available, and were received, some restrictions were necessary in order to deal effectively with them on this study. Hence, it was decided to analyze only anomaly data and the general descriptive and operational information on each of the 6 spacecraft included in the update. In other words, operating times, hardware breakdowns and configurations, and information on prelaunch activities were not considered. While these would be of interest in data bank analyses similar to those conducted in the past, they are not especially pertinent to the anomaly evaluation required on this study.

In this rather restricted update effort, 173 anomalies were found which, interestingly enough, do not appear to be significantly different from a random sample of anomalies from the previously published PRC Space Data Bank. Some anomalies that occurred as recently as the last quarter of 1975, for instance, bear a striking resemblance to some of those occurring in the early 1960's. Thus, in addition to increasing the anomaly data base by over 10%, the 173 anomalies added during this update indicate that the entire data base appears to be relatively homogeneous.

Appendix A contains the PRC Space Data Bank update for this study.

EXHIBIT II-1: SPACECRAFT INCLUDED IN UPDATE FOR THIS STUDY

<u>SPACECRAFT</u>	<u>LAUNCH DATE</u>	<u>ORBITAL HOURS</u>	<u>ANOMALIES</u>
ATS-6	May 1974	13,000	52
LANDSAT-1	July 1972	26,000	41
MARINER 10	November 1973	12,000	41
PIONEER 10	July 1972	30,000	14
PIONEER 11	April 1973	24,000	23
SOLRAD	July 1971	<u>3,000</u>	<u>2</u>
		108,000	173

III. ANALYSIS

A. Analysis Overview

The objective of the analysis conducted during this study was essentially the same as the overall study objective. This was to determine empirically, from an analysis of the PRC Space Data Bank, if problem areas exist which could best be treated by in-space programs. These programs would be such that their results would contribute to the prevention of specific types of spacecraft anomalies or to the mitigation of their effects. Program implementation would utilize the capabilities of the Space Shuttle/Spacelab.

In conducting the analysis, two separate approaches were applied: (1) an anomaly-by-anomaly evaluation of the data base, and (2) a spacecraft-by-spacecraft evaluation of the EAR's. Approach 1 was not especially fruitful in that very few single anomalies were found which could clearly be impacted by an in-space program. In other words, very few anomalies, when considered individually, cry-out "fix me." Approach 2, on the other hand, proved exceedingly fruitful.

This spacecraft-by-spacecraft evaluation revealed that a structure of 30 problem area categories clearly accommodates a large percentage of the anomalies. The anomalies essentially grouped themselves into these categories, and further, the classes of anomalies which constitute these categories are remarkably persistent over the entire duration of the U.S. space program.

Following the completion of the two types of evaluations, the results of both were merged, then considered from the standpoint of where in-space experimental programs appeared warranted. Twenty-two such program areas were defined, and a number of others were identified where ground-based programs appeared more promising.

In addition to the PRC Space Data Bank, two other principal types of "input" were utilized throughout the analysis. These can be summarized as follows: (1) the capabilities of the Space Shuttle System to accommodate payloads and the definition of the interfaces between payloads and

the Space Shuttle System taken from the Johnson Space Center publication JSC 07700, Volume XIV, Revision D, 26 November 1975, and (2) direction provided by the Ames Research Center and supplementary information consisting of attendance at the Office of Aeronautics and Space Technology Workshop Report to Universities, Industry and Other Government Agencies, as well as published literature on research applicable to on-orbit spacecraft reliability improvement.

In the following subsections, the various aspects of the analysis and its results are described in more detail. In addition, some observations made during the analysis, which are not especially related to the purposes of this study but may nevertheless be of interest, are presented.

B. Approach 1

As indicated above, Approach 1 consisted of examining the PRC Space Data Bank, including the update completed during this study, anomaly-by-anomaly. Each anomaly was considered in terms of its context of occurrence and the specific objectives of this study, and each was assigned to one of three categories. These categories were defined to reflect the reasonableness of eliminating a particular type of anomaly in the future by conducting an experimental or technology program based on Shuttle system capabilities. These three categories, then, are as follows:

- o Potential shuttle utilization
- o Not reasonable to utilize shuttle
- o Unable to determine

Typical anomalies assigned to the "potential Shuttle utilization" category include those caused by unpredictable space-environmental effects which could conceivably be better understood through in-space programs. Also included are anomalies stemming from hardware requirements that cannot be adequately evaluated under simulated conditions.

Typical anomalies assigned to the "not reasonable to utilize shuttle" category include all launch-induced problems as well as those related to early postlaunch events. The rationale here was that implementation of the Space Shuttle/Spacelab will effectively prevent the loss of payloads at launch, will reduce the frequency of launch-induced anomalies, and

will provide a means of correcting postlaunch anomalies of individual spacecraft.

The "unable to determine" category is self-explanatory. Typical anomalies assigned to it include those due to unknown causes and those where little information is available.

Of the 1,613 PRC Space Data Bank anomalies, 100, or just over 6 percent, were judged to be potentially amenable to treatment by a Space Shuttle System experimental or technology program. Since this is a rather trivial number, all anomaly assignments were further partitioned to see if any trends with calendar time would be evident. Exhibit III-1 presents the results of both this partitioning as well as the assignments of the three overall categories. From the distributions shown in this exhibit, it can be seen that no trends with calendar time are evident.

C. Approach 2

As indicated above, Approach 2 consisted of a spacecraft-by-spacecraft examination of the PRC Space Data Bank EAR's. Since the specific objectives of previous data base studies had never required such an examination, this is the first time that the anomalies have been analyzed on this basis. The fundamental aim of this analysis was to seek out any trends in anomaly occurrences which would indicate problem areas. It was initially felt that if such trends, and their associated problem areas, existed, they would become evident by systematic evaluations that considered such factors as type of spacecraft (e.g., 3-axis stabilized versus spin stabilized), the state-of-the-art during spacecraft development, similarity of anomalies experienced by the individual spacecraft within a program, and spacecraft complexity.

This initial premise, i.e., that there are trends in anomaly occurrences which indicate problem areas, was substantiated quite early in the Approach 2 analysis. In addition, two divergent lines of possible investigations became apparent. One of these lines, involving a systematic characterization of anomaly occurrences, was not pursued since it is not applicable to the study objective of defining in-space programs for preventing anomalies. It did result, however, in the observations reported in subsection III-F below. The other possible line of

EXHIBIT III-1 - CATALOG OF ANOMALY ASSIGNMENTS, APPROACH 1

DATA BASE PARTITION	NUMBER OF ANOMALIES	NUMBER OF SPACECRAFT	SHUTTLE UTILIZATION CATEGORIES (PERCENT)		
			POTENTIAL	NOT REASONABLE	UNABLE TO DETERMINE
≤1965	692	225	4.5	41.9	53.6
1966-1970	538	79	9.5	35.3	55.2
1971	210	6	3.3	36.2	60.5
≥1972	173	6	6.1	38.9	55.0
TOTAL	1613	316	6.2	38.6	55.2

investigation that became apparent deals with the clustering and persistence of certain problem areas.

When the anomalies were considered as described above, and also with a view to applying a space experimental or technology program to prevent future occurrences, they essentially grouped themselves into 30 categories. Two significant aspects are apparent from this: (1) the tightness of the clustering of anomalies, i.e., their similarity, and (2) the persistence of the anomalies from the earliest days of the space program to the present. This is illustrated by the fact that the 30 categories easily accommodate a large percentage of the data base anomalies.

During this Approach 2 analysis, approximately 1,000 anomalies were considered. Unsuccessful launches, anomalies from the manned space programs (Mercury and Gemini) and anomalies from the Agena program, which together total about 600 data base anomalies, were not specifically considered. The anomalies occurring on both the manned space programs and the Agena program are, in general, unique to the special requirements of those programs and therefore not especially pertinent to this study. These anomalies were, however, briefly surveyed and entered into the deliberations leading to the definition of candidate experimental or technology programs.

Of the approximately 1,000 anomalies considered, then, well over 80 percent fall into the 30 categories of leading problem areas. The remaining 15 or 16 percent of the anomalies are quite widely scattered. These leading problem areas are listed in Exhibit III-2.

Most of the anomalies were rather clearly associated with specific types of hardware items. These 16 categories are listed in the left column of Exhibit III-2. The middle column lists functions experiencing anomalous behavior which are rather difficult to tie to a specific piece of hardware. The right column lists three particularly common and widespread anomalies.

The rank order, by percentage, of these 30 problem area categories is shown in Exhibit III-3. Since approximately 1,000 anomalies, and also 150 spacecraft, are represented in the exhibit, the 12.3 percent of

EXHIBIT III-2 - LEADING PROBLEM AREAS

<u>EQUIPMENT</u>	<u>FUNCTIONS</u>	<u>OTHER</u>
BATTERIES	COMMAND & CONTROL	RFI/EMI
CAMERA EQUIPMENT	(TIMERS, SEQUENCERS)	SOLAR ARRAY DEGRADATION
DEPLOYABLE STRUCTURES	COMMAND & CONTROL	SPURIOUS COMMANDS
GYROSCOPES	(LOGIC)	
HORIZON SCANNERS	COMMAND & CONTROL	
REACTION WHEELS	(REGISTERS, MEMORIES)	
SCIENTIFIC INSTRUMENTS	COMMAND, RF-LOCK ON	
SOLAR ARRAYS	COMMAND, RF-OTHER	
(EXCEPT DEGRADATION)	POWER CONDITIONING	
SOLAR ARRAY DRIVES	PROPULSION (CHEMICAL)	
STAR TRACKERS	TELEMETRY ENCODING	
SUN SENSORS	TELEMETRY, RF	
TAPE RECORDERS	TELEMETRY SENSING	
WIDE-BAND RECEIVERS	THERMAL CONTROL	
WIDE-BAND TRANSMITTERS		
WIDE-BAND TRANSPONDERS		
WIDE-BAND, OTHER		

EXHIBIT III-3 - RANK ORDER OF PROBLEM AREAS

<u>AREA</u>	<u>PERCENTAGE</u>	<u>AREA</u>	<u>PERCENTAGE</u>
SCIENTIFIC INSTRUMENTS	12.3	TELEMETRY SENSING	2.7
TAPE RECORDERS	10.0	COMMAND, RF-LOCK-ON	2.5
CAMERA EQUIPMENT	7.3	COMMAND & CONTROL-MEMORIES	2.5
BATTERIES	5.5	REACTION WHEELS	2.3
RFI/EMI	5.3	WIDE-BAND, OTHER (1)	2.2
COMMAND & CONTROL-LOGIC	4.6	COMMAND, RF-OTHER (2)	1.7
POWER CONDITIONING	4.5	THERMAL CONTROL	1.7
TELEMETRY-RF	4.3	HORIZON SENSORS	1.5
SPURIOUS COMMANDS	4.1	SOLAR ARRAYS	1.4
STAR TRACKERS	3.7	DEPLOYABLE STRUCTURES	1.4
TELEMETRY ENCODING	3.5	GYROSCOPES	1.1
WIDE-BAND TRANSMITTERS	2.9	SOLAR ARRAY DEGRADATION	1.1
COMMAND & CONTROL-TIMERS	2.8	SOLAR ARRAY DRIVES	1.1
PROPULSION (CHEMICAL)	2.8	WIDE-BAND RECEIVERS	0.3
SUN SENSORS	2.7	WIDE-BAND TRANSPONDERS	0.2

NOTES: (1) Other than wide-band receivers, transmitters, and transponders.

(2) Other than command, RF-lock-on.

anomalies assigned to Scientific Instruments represents approximately 123 anomalies occurring in this category; furthermore, these 123 anomalies were observed on 150 spacecraft. The first five categories account for over 40 percent of the anomalies considered in the Approach 2 analysis, and over 1/3 of all anomalies including those unassigned to the 30 categories.

The persistence of the anomalies, as indicated above, was noted by the fact that anomalies occurring on the more recently launched spacecraft are the same types as those on earlier spacecraft. In other words, even though advances in the state-of-the-art have occurred, they have not resulted in "new" or different types of anomalies. Exhibit III-4 depicts the occurrence of anomalies as a function of the year of spacecraft launch for five typical problem area categories. The persistence of anomalies in these categories, as in the other categories defined during the analysis, can be seen from this exhibit.

D. Merging the Results of the Two Approaches

After completing the analyses of Approaches 1 and 2, their results were evaluated in order to define experimental programs that could alleviate the observed problem areas. The general ground rules that were established for this experiment definition or selection process are as follows:

- o Potential for eliminating large numbers of anomalies
- o Requires the space environment for effective completion
- o High probability of useful results
- o Contribution to extended on-orbit life

A problem area was more likely to be selected as a candidate experiment as more of the ground rules were satisfied. However, some experiments were defined which are felt to be important even though they satisfy only one of the established ground rules.

For many high ranked problem area categories, a space conducted program was not considered to be worthwhile. These areas are listed in Exhibit III-5. The primary reason for failing to propose experimental

EXHIBIT III-4 - ANOMALY OCCURRENCE BY YEAR OF LAUNCH

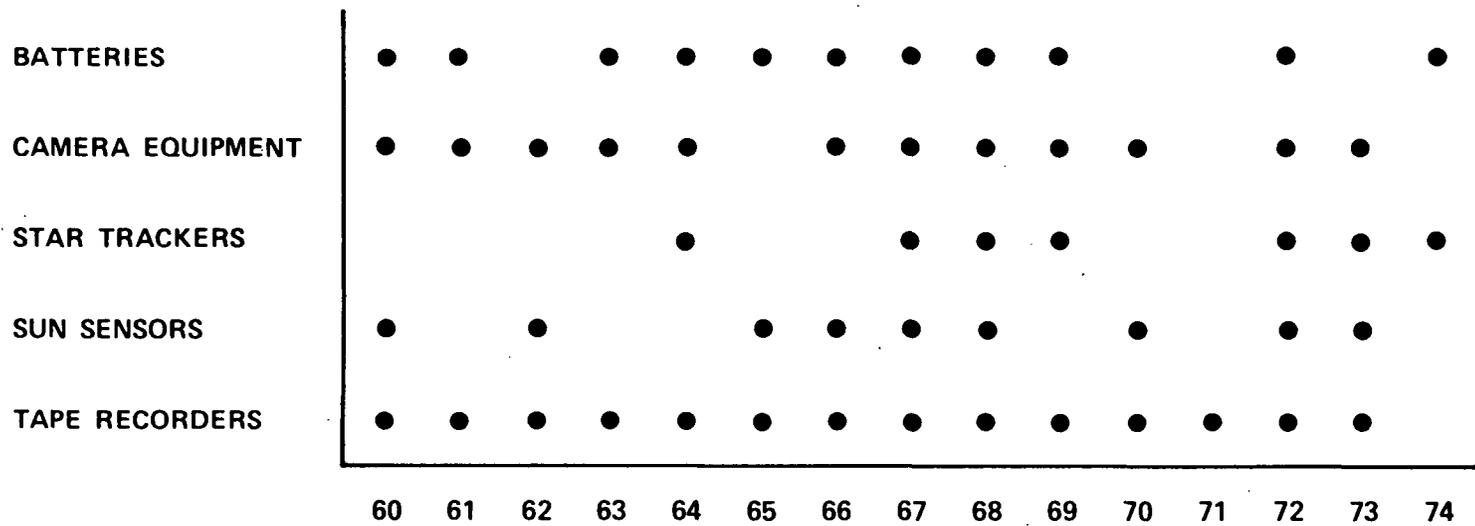


EXHIBIT III-5 - ANOMALY CATEGORIES FOR WHICH NO EXPERIMENTAL PROGRAMS ARE PROPOSED

DEPLOYABLE STRUCTURES
GYROSCOPES
POWER CONDITIONING
PROPULSION (CHEMICAL)
SCIENTIFIC INSTRUMENTS
SOLAR ARRAY DRIVES

TELEMETRY ENCODING
TELEMETRY-RF
TELEMETRY SENSING
WIDE-BAND RECEIVERS
WIDE-BAND TRANSMITTERS
WIDE-BAND TRANSPONDERS
WIDE-BAND, OTHER

programs in these areas is that it seems highly preferable to undertake programs utilizing only ground-based equipment and facilities first. A secondary reason is that many of these problems are highly design related and do not lend themselves to a common solution. Complete rationales are given in subsection III-E below on all these anomaly categories for which no in-space experimental programs are recommended.

For the other anomaly groups, or problem areas, identified through Approaches 1 and 2, 22 experimental programs were defined. Some of these deal with more than one problem area, or in other words, "merged" problem areas. All are considered to be technically feasible, all would contribute to the reliability of future spacecraft, and all require the space environment for successful conclusion. Generally, the recommended programs are a kind of space qualification which should provide the information necessary to upgrade specific equipment or function reliability.

These 22 recommended experimental areas, together with the number of observed anomalies covered by each, are listed in Exhibit III-6. Approximately 50 percent of all anomalies are impacted by these recommended programs. Section IV discusses each of these programs, including the rationales for their recommendation.

E. Problem Areas for Which No In-Space Program is Recommended

Of the 30 problem area categories defined through Approach 2 of the analysis, 13 do not appear to warrant an in-space experimental program. One of these, scientific instrument packages, while the highest ranking problem area, can be dismissed immediately. The types of equipment represented by this category cover a wide range, e.g., electron traps, spectrometers, and scintillation counters, and the hardware is often designed and built by universities on grant funds. Therefore, there does not appear to be a common solution for anomalies in this category. The remaining 12 problem area categories from Approach 2 as well as some anomaly groups identified in Approach 1 are discussed in the following 11 subsections.

EXHIBIT III-6 - RECOMMENDED EXPERIMENTAL AREAS

<u>EXPERIMENT</u>	<u>NUMBER OF ANOMALIES</u>	<u>EXPERIMENT</u>	<u>NUMBER OF ANOMALIES</u>
ANTENNAS	14	LUBRICANTS	6
ARRAY DEGRADATION	23	NUCLEAR POWER SUPPLIES	1
BATTERIES	52	RADIATION	8
CAMERA EQUIPMENT	69	REACTION WHEELS	22
COMPUTERS	93	RFI/EMI	50
DAY/NIGHT EFFECTS	9	SEMICONDUCTORS	10
EARTH EFFECTS	5	STAR TRACKERS	35
GRAVITY GRADIENT	13	SUN SENSORS	25
HEAT PIPES	1	TAPE RECORDERS	94
HORIZON SCANNERS	14	THERMAL CONTROL	16
ION ENGINES	3	UPLINK PROBLEMS	39

1. Deployable Structures

PRC originally felt that this might be an area where direct observations in the 0-g environment would prove beneficial. However, only 13 anomalies are chargeable to this deployable structures category, and they are all quite related to the specific spacecraft design. In other words, the anomalies are all a function of the particular design selected, and hence not amenable to any more generalized evaluation techniques.

2. Gyroscopes

The 11 gyro anomalies analyzed during this effort indicated no problem areas that would justify in-space evaluation. One aspect was noted however, which PRC feels is cause for concern, and this is the early wear-outs that were reported. Three of the gyro anomalies were attributed to wear-out, one after 37 days in orbit, one after 9 months, and the third after a more respectable 18 months. A fourth anomaly for which only limited information is available, may be a wear-out problem.

It is possible that improved lubricants, as discussed in Section IV, would increase gyro service life. Also, some of the other 11 anomalies involve noisy signals, a condition which could conceivably be related to lubrication. With the exception of the wear-out problems and the potential for improved lubricants, the data base offers no other background information of interest to this study.

3. Power Conditioning

With 42 anomalies charged to power conditioning, this category ranks as the sixth highest of all those established during this study. Judging from this record, it would seem that some kind of effort aimed at eliminating or precluding anomalies in this category would be desirable. It is not clear, however, that this effort should take place in space.

The equipment in this category includes regulators, battery chargers, inverters, converters, etc. At least three anomalies in such equipment have caused complete loss of a spacecraft, and several others have considerably reduced mission accomplishments. Many anomalies, however,

have involved noncatastrophic problems, many of which were possibly made less severe by redundancy although that was not evaluated during this study. It was noted during the analysis that postflight evaluations of manned spacecraft revealed several blown fusistors, possibly indicating problems in this area that were compensated for somehow.

The data base contains a considerable amount of information on the suspected or established causes of these power conditioning anomalies. They range from design inadequacies and manufacturing defects to unanticipated operating conditions. It appears that corrective actions for these can best be developed on the ground. The few causes that are related to the space environment or in-space operation appear to be best soluable by the more general efforts described in several of the recommended experimental programs. Thus, while PRC feels that some type of effort to deal with these numerous and potentially serious anomalies would be advantageous, it appears that specific, in-space programs can not be justified at this time.

4. Propulsion (Chemical)

A number of propulsion system anomalies were analyzed, but it was concluded none of them presented a clear-cut case for an in-space program. Before discussing the reason for this conclusion, the anomalies considered should be noted.

a. On three spacecraft in one program a decrease in predicted thrust was attributed to propellant degradation. On the first two spacecraft, this was thought due to the effects of vacuum and time, but on the third, it was apparently obvious that it was a vendor quality-control problem.

b. On one spacecraft and possibly another where it was not reported as an anomaly, there was a pressure increase in a hydrazine tank, which was attributed to incompatibility of the hydrazine and the decomposing bladder material (butyl rubber). The pressure increase over the total mission life (approximately 180 days) was reported to be 16 psi, and some of this was thought due to temperature.

c. Approximately half of the anomalies charged to the propulsion category involved leaks in regulators, valves, thrusters, and tanks. In the few cases where a cause was reported, these anomalies were attributed to worn valve seats, possible damage from asteroids, and damage induced by launch vibration.

d. Other propulsion anomalies include valve heater problems, thrust offset due to plume reflection, a nitrogen tank explosion, and "stuck" valves, plus some other rather trivial problems.

With respect to the anomalies considered and summarized above, the propellant degradation problem was solved, apparently by improved vendor quality control, and there are no other instances of it in the data bank. The bladder-hydrazine incompatibility is certainly something to be considered in future designs, especially for long-life spacecraft. But PRC feels that in-space testing and evaluation is not justified, first because there are other approaches that do not require a bladder, and second, because ground test programs should be able to isolate any inherent incompatibilities in a wide range of bladder materials in a far more cost effective manner.

While the leakage anomalies do comprise slightly over half of all those in the chemical propulsion category, the overall record in this area is outstanding if one considers the amount of operational, propulsion hardware that has not malfunctioned. PRC feels that the record clearly indicates that valves, thrusters, etc., can be designed and fabricated to yield a long, trouble-free life.

The other propulsion anomalies summarized above involve design problems for which solutions are now readily available.

5. Solar Array Drives

The situation with the solar array drive category is identical to that of deployable structures, as discussed in item "1" above. While it was originally thought that 0-g observations might prove beneficial, the 10 anomalies in this category are too design-specific to justify any generalized program.

6. Telemetry

The three anomaly categories in this overall group, together with the number of anomalies charged to them, are encoding (33 anomalies), sensors (25 anomalies) and RF equipment (40 anomalies). The encoding anomalies involve such things as sync errors, missing or garbled channels, incorrect commutator stepping, etc. These anomalies are all of the type one would expect from encoding equipment, and considering the amount of hardware required to implement encoding functions, the number of anomalies does not appear excessive. In general, they never resulted in serious mission consequences, in many cases due to redundant equipment or to the availability of other data channels which allowed any missing or lost data to be interpreted by other means. Based on these considerations, PRC does not feel that in-space experimentation with telemetry encoding equipment is worthwhile.

A similar situation exists for telemetry sensors (i.e., thermistors, pressure monitors, voltage and current monitoring devices, etc.). The number of anomalies is not excessive for the number of such sensors in the sample, and they never resulted in serious mission consequences.

The 40 anomalies charged to telemetry RF equipment seems excessive, especially since this equipment consists, for the most part, of reasonably straightforward VHF and UHF transmitters. It is not clear, however, that in-space experimentation with regard to this equipment is warranted.

Eight of the 40 anomalies involve failed or inoperative transmitters. For those cases where the PRC Space Data Bank contains information on the reasons for these failures, they are attributed to damage induced by launch shock, a degraded transistor, a failed coax switch, and in two cases, to a blown fuse. There are nine beacon transmitter problems, with five of them involving noisy transmissions. The data base contains no further useful information on these beacon anomalies.

SCO or VCO problems accounted for 11 more anomalies. Where the data bank contains background information, these problems are attributed to frequency drift and shifts to the lower band edge, and anomalous drop-outs.

Temperature problems are reported to have caused four anomalies-- a transmitter power amplifier failure due to overheating, a transmitter turn-on problem due to low temperature, a high transmitter temperature due to a base plate problem, and thermal action effecting the operation of a coax relay.

The remaining eight anomalies appear to be one-of-a-kind situations, such as a power monitoring detector malfunction due to a diode problem, the shifting of the center frequency of a telemetry transmitter, momentary transmission drop-outs, transmitter turn-on/turn-off delay problems, and general down link degradation and fading.

It appears to PRC that ground-based programs would be more cost-effective in resolving these telemetry-RF problems than in-space experimentation. The available information on anomaly causes does not indicate that environmental effects which cannot be simulated are involved. In the cases where no cause for the anomaly is given, several of the experiments recommended in Section IV, particularly the semiconductor, radiation and antenna ones, could possibly yield general results that would be applicable to telemetry RF equipment.

7. Wide Band Communications

This overall equipment group, which includes the anomaly categories of wide band transmitters, receivers, transponders, and "other" (such as synthesizers, feeds, etc., as well as interactions between equipments) is charged with 52 anomalies. Receiver and transponder problems account for only five of these anomalies, while problems in the "other" category account for 20, and transmitter problems to 27. Since many of the problems in the "other" and "transmitter" categories were found to be similar, they will be discussed together.

Of these 47 anomalies, three are directly related to antenna operations, six are RFI problems, and one involves an up-link problem; these three areas are covered in Section IV. The remainder of the anomalies, as discussed below, do not seem to offer possibilities for correction actions via in-space experimentation.

Fifteen more of the anomalies involve anomalous conditions with the down-link signal, such as loss-of or drops-in power, loss of carrier, power fluctuations, or loss of the down-link signal. The data base contains little information on the cause of these anomalies, so no conclusions can be drawn. Another anomaly appeared to be a link problem which was resolved on the ground.

Problems which seem to be a function of fabrication were noted in four instances. In these cases, the problems were attributed to a mechanical discontinuity, an intermittent open in a cable, a cabling impedance discontinuity, and poor contact between a tuning screw and its grounding point. Five anomalies involved early or late shutoff of transmitters or drivers. While it is possibly of academic interest that this type of anomaly occurred in dissimilar spacecraft, its frequency does not appear to warrant concern.

Oscillator frequency drift or instability accounts for four anomalies, with two being temperature related and another attributed to a condition explained only as "high voltage."

The remaining eight anomalies occurred to TWT's or TWT circuitry. For two of these, the information in the PRC Space Data Bank states only that the TWT's degraded, and in a third instance only that a TWT failed. Helix current was involved with two anomalies, in one case it was reported to be too high, and in another to be varying. Also, variations in TWT exciter drive was the attributed cause for another anomaly. In one case, the power output of a TWT amplifier dropped, but the data base does not indicate any suspected cause. Finally, RF power was reflected back into a TWT amplifier, resulting in erratic operation.

It is not clear to PRC that in-space experimentation would be cost-effective in eliminating or reducing the problems associated with TWT's. The state-of-the-art in this area is sufficiently advanced so that the design problems and requirements should be well known. This is borne out by the number of space communications systems utilizing TWT's that have exhibited excellent performance. But the fact remains that TWT's and their associated components do present design and fabrication problems, their high-voltage and alignment requirements being but two examples. For such reasons, some predict that solid state devices now

coming into application will phase-out TWT systems. These devices include Gunn diodes, gallium arsenide field effect transistors, IMPATT diodes, silicon Schottky-barrier varistors, and varactors. PRC feels that since such new devices will probably be widely used, it would be more practical to utilize funds for in-space experimentation in this area, as described under "Semiconductors" in Section IV.

8. Pyrotechnics

PRC considered anomalies in this area on the premise that the space environment could create conditions that would effect the firing probability. However, the PRC Space Data Bank reveals that no explosive-actuated function has ever failed to occur due to a pyrotechnic device anomaly. This is possibly because most pyrotechnic functions incorporate a high degree of redundancy, although this cannot be determined from the data base.

Based on this performance record, PRC feels in-space experiments with pyrotechnic devices are not necessary. On the possibility, however, that the anomalies associated with pyrotechnic devices might prove informative on future design efforts, they are summarized as follows:

a. Pyrotechnic debris caused a few problems, including shorting one antenna, and possibly degrading another, and clogging a porous plug.

b. In one case, a "sneak path" was set up by a shorted squib.

c. One explosive valve on an unmanned spacecraft did not fire. Postflight evaluation revealed that several pyrotechnic devices did not actuate on manned spacecraft.

9. Shrouds

PRC considered these because they are difficult, if not impossible, to fully evaluate via ground tests. The data base, however, contains only two shroud related problems, one a failure to eject which was corrected on subsequent flights by changing the shroud material from fiberglass to metal. The other involved explosive destruction of the

shroud honeycomb panels due to environmental effects during launch. This record indicates to PRC that techniques for designing and fabricating shrouds are well in hand.

10. Radiometers

The data base contains 31 identified radiometer problems; there are a few others where it is not clear that the anomaly is chargeable to a radiometer. Seven of these are attributed to interference, including mutual interference between a television camera system and a radiometer and between two radiometers, EMI from an antenna cooling fan, and interference during appendage slews. In three cases, a chopper motor or scanning motor failed, and two cases involved anomalous temperature increases. On a spacecraft which did not attain the desired orbit, there were problems with the mirror shields on two radiometers since they had been designed for a lower orbit. In three cases, the data base only contains reports that a radiometer failed.

The remaining 14 radiometer anomalies appear to be "one-of-a-kind" occurrences, involving data drop-outs due to faulty solder joints, sunlight entering an aperture due to spacecraft attitude, an obstructed "fov" due to baffle design, an incorrectly positioned shutter, a saturated output channel, and problems with a capacitor.

While this overall record indicates that radiometer reliability could certainly improved, none of the anomalies analyzed involves conditions for which in-space evaluation should be required. Hence, PRC feels that improvements in radiometer reliability can be achieved more cost-effectively during the design and fabrication stages.

11. Nonapplicable Environmental Effects

As indicated earlier, a major criterion for selecting candidate areas for in-space experimentation was that there be some factor involved that was not amenable to ground evaluation. Anomalies resulting from the effects of the space environment certainly meet this criterion. In analyzing this type of anomalies, PRC found groups for which space experimentation appears cost-effective; these are discussed

in Section IV of this report. There were, in addition, several environmentally-induced anomalies for which space-experimentation does not appear reasonable. These anomalies, as summarized below, were "one-of-a-kind" occurrences, and appear preventable by currently available design techniques.

a. On one spacecraft, the lens of a TV system were contaminated by the third stage rocket exhaust.

b. A spectrometer began degrading during launch, probably due to water condensation and icing.

c. For unknown reasons, the membrane of a micrometeorite detector was punctured.

F. Observations

During the course of this effort, a number of observations were made which, while not applicable to the objectives of this study, may nevertheless be useful. These observations resulted from the analysis of the data base EAR's and their only common denominator is that they stem from reported, anomalous spacecraft behavior. They have not been analyzed, and they are offered here simply as observations that might prove useful to pursue in future program planning and spacecraft design.

1. Similarities Within Programs

The PRC Space Data Bank contains EAR's on 43 space programs, and of these 19 represent programs with two or more similar, or in some cases, identical spacecraft. The similarities between reported anomalies for spacecraft within a program is striking. Of the 19 programs with similar spacecraft, the reported anomalies are quite repetitive within the spacecraft on nine programs. In fact, for the eight spacecraft on one program, the anomaly lists were virtually carbon copies. On six other programs, there were several repetitive anomalies within each program, although the repetition is not as great as on the nine programs indicated above. On only four programs were the anomalies on each spacecraft dissimilar.

2. Recurring Anomalies

Another type of repetition was noted, this time recurring anomalies of the same type on individual spacecraft. In some cases, the anomaly would first be intermittent, and later "fail solid."

3. Misunderstandings

Several anomalies were noted which seem to indicate a "communication gap" between designers and operations personnel, perhaps due to differences in the working vocabularies of these two groups. Most of the anomalies of this type were sequencing errors, e.g., commanding a certain function before other pre-requisite functions had been activated/deactivated. A good illustration of this type situation is that on one occasion, a star tracker "locked-out" and failed to respond to star acquisition commands because of a prior command sequence. On another occasion, high voltage was applied to three cameras too soon, which was attributed to the design being incorrect for the requisite operational sequences. Although it appears anomalies of this type never resulted in damage or irreversible actions, the situation clearly presents such a potential.

Two factors noted as associated with these kinds of anomalies, are (1) they occurred, as might be expected, on complex spacecraft, and (2) it may well be that terminology plays a role in creating them.

With regard to spacecraft complexity, the overall anomaly pattern of one of the most complex unmanned spacecraft ever launched, shows a "clustering" of anomalies of this type, which may be suggestive of a learning curve.

With respect to terminology, designers deal with a spacecraft in terms of equipment, and their terminology is very equipment-oriented. Operations personnel, on the other hand, deal with functions, and further, with their "access" to these functions via ground equipment. The data base EAR's contain both design and operational information, and in several cases there is such a considerable difference in the terminology that, except for the title, one would have difficulty establishing that it referred to the same spacecraft.

4. Anomaly Threshold Level

It would appear, on the basis of very casual observations, that there is a "threshold," or crossover point, in terms of the number and extent of anomalies which is dependent on the implementation approach at the system level. For instance, it appears that the anomalies of the simpler spacecraft are dominated by certain types of problems, such as experiment package or power supply malfunctions, and often, while there may be few anomalies, they are likely to be severe. As spacecraft complexity increases, and requires more equipment such as reaction wheels, star trackers, etc., it would appear that the anomalies become more dominated by attitude control system problems. The number of anomalies seems to crossover the threshold level to some increased magnitude, although many do not appear severe enough to jeopardize mission success.

IV. RECOMMENDED EXPERIMENTAL AREAS

In the 22 subsections below, each of the 22 recommended experimental areas is discussed. Each discussion includes a description of the problem area, the rationale for recommending in-space experimental and evaluation activities, and a brief discussion of a possible experimental approach. In addition, a brief literature search was conducted to survey the state-of-the-art and the results of this are also discussed. The objective of this necessarily limited survey was to determine (1) if new techniques now under development offered promising alternate approaches to problem areas, and (2) the extent of activity now underway to resolve problem areas with current technology.

1. Antennas

The data base contains 14 anomalies associated with antenna equipment; they can be summarized as follows:

- (1) Squib products shorted two antennas.
- (2) There were two cases when a temperature problem in the control electronics caused a mechanically despun antenna to be inoperable for long periods.
- (3) In another case, antenna signal strength dropped due to increased temperature in the antenna electronics.
- (4) Two anomalies involved cross-coupling between two antennas.
- (5) One deployable antenna did not deploy to its full length.
- (6) One long antenna was distorted due to a "thermal engine" effect.
- (7) The pattern of one antenna was distorted due to anomalous lobing.
- (8) The characteristics of one antenna changed, probably due to outgassing.

- (9) In two instances, a diplexer and switch operated only marginally due to inadequate interface design.
- (10) One antenna was shorted by a set of deployed spheres utilized in an experiment.

While these anomalies do not seem to indicate any consistent problem, they do point out the kinds of difficult-to-predict anomalies that can occur. PRC is aware, for instance, that the equipments associated with the mechanically-despun antenna anomalies received as detailed and thorough design and development analyses as is humanly possible. It is safe to assume that the problems that did occur could not have been envisioned beforehand, and thereby prevented.

PRC feels that a main reason for unforeseeable antenna problems lies in the difficult and complex testing requirements they pose. As pointed out in Reference 14, antenna characteristics are normally assumed to be completely described by the antenna radiation pattern, which is in turn a function of several complicated and independent variables. Measurement techniques usually consist of measuring antenna power variations as a function of only one variable at a time. In addition, as discussed in Reference 15, analysis of the mechanism of noise generation in an antenna is complicated and the mechanism itself is not well understood. Hence, in determining system signal-to-noise ratios, approximations of antenna noise are usually based on the concept of equivalent noise temperature. While many reasonably accurate equivalent noise temperatures are known, they too involve many variables such as background noise from the sun, moon, planets, etc., the effect of side and rear lobes, atmospheric conditions, and antenna "front end" characteristics.

Based on both the complexity of dealing with all the variables pertinent to antenna performance, and on the unforeseeable types of anomalies that have occurred, PRC feels an in-space evaluation program via the Shuttle would be worthwhile. Especially significant results are anticipated in the area of new antenna approaches.

Antenna developments that can be expected in the coming decade include "printed antennas" for microwave applications, reflectors

fabricated with composite materials,¹ and generally larger antennas for deep space probes. Prototype testing of such systems via the Shuttle would provide realistic measures of their performance as pertinent variables fluctuated.

The antenna radiation patterns could be determined for various path lengths and elevation angles, and the effect of such atmospheric conditions as rain and snow could be monitored, as could the effects of lunar cycles, solar disturbances, and radio stars. In addition, such aspects as lobing and notching could be evaluated.

The mounting approach and location of the test antenna would depend on its size and type, but the Shuttle should be able to accommodate even large reflectors with no undue problems. PRC feels that if the performance evaluation approach does not also subject antenna materials to a complete "soak" in the space environment, additional steps should be taken, possibly via the LDEF, to determine the potential for outgassing, radiation damage, and bending or warping due to thermal stresses.

2. Array Degradation

The PRC Space Data Bank contains 23 solar array anomalies, with 10 of these being attributed to array degradation. An interesting aspect of these degradation anomalies is that they are fairly evenly distributed from 1962 to 1972. This spread, together with the reported type of radiation causing the degradation, where such information is available, is shown at the top of the following page.

Another interesting aspect is that on one spacecraft the degradation occurred within a few weeks after launch.

The other 13 "nondegradation" array anomalies cover a broad range. On one spacecraft, beryllium-copper busses failed-open under thermal stress, and three spacecraft had solar panel shorts, with one of these being a shorted string. On another spacecraft, one board of cells failed, but no further information is given. One spacecraft had a "sneak path"

¹See Aviation Week and Space Technology, January 26, 1976.

		<u>1962</u>	<u>1964</u>	<u>1965</u>	<u>1966</u>	<u>1967</u>	<u>1969</u>	<u>1972</u>
1.	No further information	x						
2.	High altitude nuclear detonation	x						
3.	No further information		x					
4.	No further information			x				
5.	Solar flare radiation			x				
6.	Solar particle damage			x				
7.	Ultraviolet radiation				x			
8.	Particle radiation, space heat and ultraviolet rays					x		
9.	No further information						x	
10.	Solar flares							x

in the array, and on another, the solar cell short circuit characteristics were high due to calibration via flight resistors that had not been altitude calibrated. For the other cases, no further information is given, including the one described rather cryptically as "solar panels failed sequentially as each faced the sun."

PRC feels that the "nondegradation" anomalies do not pose sufficient cause for concern to justify in-space evaluation. There is no consistent cause which could be dealt with, and they appear preventable by the proper design and development precautions. On the other hand, the degradation anomalies appear to warrant evaluation via the shuttle because of their persistence, and because the response of solar cells to space radiation can best be measured in space. Especially, new developments in solar cell technology such as "violet cells" and flexible arrays

could benefit from in-space evaluations that would improve degradation prediction capabilities.

The approaches for predicting array degradation are well understood, but this still does not eliminate problems and uncertainties. Reference 26, for instance, describes the environmental factors that effect solar panel output, and discusses in detail the uncertainties that are an integral part of the prediction process. The error analyses in particular are quite complex. Reference 17 discusses quite thoroughly the means of simulating the various environmental factors and the problems associated with this. The complexity of error analyses is again evident in this document as are the extensive facilities and equipments required for effective simulation.

Reference 18 reports on a study of radiation-hardened cells, and discusses tests conducted to evaluate various hardening approaches. Among other things, this report points out that the behavior of highly doped cells cannot be realistically extrapolated from that of lightly doped cells.

Except for some of the radiation-hardened cells discussed in Reference 18, the three references above deal with conventional array approaches. Even so, the processes involved in predicting degradation and designing and fabricating arrays that will produce the required power are time-consuming and costly. In addition, the special environments of interplanetary probes, as discussed in Reference 19, introduce other array considerations.

It appears to PRC that several approaches to evaluation via the Shuttle could result in less costly and time-consuming prediction activities as well as improved array performance. One promising, relatively simple Shuttle program could be to space calibrate enough cells of the required types to provide an ample supply of standard cells. As pointed out in Reference 17, the availability of standard cells, which are normally calibrated by balloon tests or high altitude flights, is often too limited for general use. As a result, secondary cells are calibrated from these primary ones for use as working standards. Cell calibration procedures via the Shuttle, it seems, could produce enough standard cells to satisfy the requirements of any program.

Another possibility for reducing the likelihood of array degradation would be to deploy test arrays in the LDEF to monitor their long-term response to radiation. The approach to this could be similar to that reported in Reference 61, where various types of cells, and approaches to soldering, coatings, cover slides, etc., were monitored on an ATS-5 experiment. It appears that such an evaluation would be particularly useful in such developmental areas as "violet cells" and flexible arrays. Reference 20 discusses both these approaches, and Reference 21 describes laboratory testing of "violet cells," the results of which are quite promising. Reference 22 discusses a flexible, roll-up solar array ("FRUSA") which was tested on a DoD spacecraft, with reportedly successful results.

To sum up, solar cell and array evaluations via the LDEF would provide several advantages over currently available evaluation approaches. The response to all forms of radiation could be monitored simultaneously, which is not possible in test facilities equipped to simulate only certain types of radiation. Retrieval of the cells would allow complete analysis of the mechanisms of degradation, thus enabling corrective actions to be established. Also, more readily usable and realistic degradation curves could be derived in order to eliminate some of the complex analytical procedures now required in the prediction process.

3. Batteries

Batteries, with a total of 52 anomalies, rank fourth highest among the problem area categories established during this study. Many of these anomalies involve complete battery failure, and at least eight spacecraft were rendered completely useless by battery anomalies, and several others were severely degraded. In addition, the PRC Space Data Bank contains two reports of batteries rupturing, and reports of a number of wear-out problems. Among the other battery anomalies, causes are attributed to insulation breakdown due to silver migration, cell leaks, cell shorts, cell reversals, and overheating and temperature problems. The earliest reported battery anomaly occurred on a spacecraft launched in 1960; the latest on one launched in 1974.

The problems associated with batteries are well known, but in some cases poorly understood. Reference 23, for instance, states that ground test programs have not demonstrated the state-of-the-art capability of a particular battery system, but rather the capability of a particular manufacturer to produce a particular lot of cells at a given time. This report goes on to state that on one program, the variations in cells from different lots required design changes in the battery chargers. It also points out, with respect to separator problems which are common to Ni-cad, silver zinc and silver cadmium batteries, that improvements are being made but no breakthroughs are in sight. Reference 24, a report on an accelerated testing program for space batteries, states that no such program existed before it, and that little was known about battery degradation processes.

On the other hand, Reference 25, a report on an evaluation program now entering its twelfth year, indicates that the program has solved the battery problems that occurred on several programs. Ni-cad, silver zinc, and silver cadmium cells have been evaluated with regard to such variables as types of separators, plates, seals, auxiliary electrodes, etc., and the reported results include data on which cells last longer, the best operational regimes, etc.

While PRC agrees that such evaluation programs contribute significantly to battery improvements, it still appears that two major overlapping problems remain unresolved. First, to be effective, the testing and evaluation programs must be quite complex and costly. Reference 24 provides an indication of this in the detailed models and analyses utilized in the accelerated testing program it discusses. Also, Reference 26, which describes testing of specific cells, reports on a wide range of leak tests, capacity tests, charge efficiency tests, etc. The requirement for complex and costly evaluation, it seems to PRC, presents difficult tradeoff choices in terms of how much testing to conduct at the upper, "generic approach" level, and how much at the more detailed level of specific cells for specific applications. In other words, testing and evaluations can be designed to effect general improvements in, say, Ni-cad batteries, or Ni-cad batteries with a certain type separator, or

they can be designed to eliminate observed deficiencies in batteries being utilized on a specific program.

The second problem referred to above involves new developments in battery technology. These include nickel-hydrogen batteries, batteries with integral heat pipes, and batteries capable of operating in the kilowatt range.¹ In addition to the problems and aspects common to the testing of any battery, these new developments will impose unique problems and requirements.

PRC feels that evaluations via the Shuttle would prove more effective and less costly in the final development stages of these new battery technologies than would ground testing. The batteries with heat pipes pose the same kinds of questions discussed in subsection 9, below, under "Heat Pipes," and their thermal control aspects should be evaluated in the same manner. In addition, the absence of convection in the space environment should allow more realistic appraisals of both the KW-range and the nickel hydrogen batteries' performance under thermal cycling and thermal extremes. Also the potential for condensation, outgassing or sublimation from cell electrodes could be determined. Such factors as these, which are more a function of the basic approach than of design and fabrication techniques, could be evaluated by placing test cells in the Shuttle payload bay. It appears that useful information could be obtained in this manner over five to ten missions.

Factors that are more a function of design and fabrication techniques would require longer duration testing, either via the LDEF or via deployed equipment packages. One advantage of this would be that charge/discharge cycles could be adjusted on subsequent revisits to provide information on optimum depth of discharge. Also eventual retrieval would allow an in-depth analysis of wear-out mechanisms.

¹Documents that PRC found useful on the state-of-the-art in these areas are as follows: Reference 20: Nickel hydrogen batteries; Reference 27: Nickel hydrogen batteries; Reference 28: Batteries with integral heat pipes; and Reference 29: Kilowatt batteries.

4. Camera Equipment

Camera equipment, with a total of 69 anomalies, ranks third highest of all problem area categories examined during this effort. These camera anomalies run the gamut from vidicon wear-out, shutter malfunctions, and contrast and synchronization problems to circuit failures or malfunctions. Vidicon wear-out or degradation due to age is often cited as the cause for the reported anomalies. An unusual aspect of this is the disparate times given. On one spacecraft, the wear-out times given for each of three vidicons are less than two months, approximately 3½ months, and 8 months. The less than two-month life is the shortest in the PRC Space Data Bank; the longest is approximately 27 months.

Many of the camera equipment anomalies considerably reduced a spacecraft's ability to fulfill its mission requirements, and in two reported cases caused loss of the mission. In one of these cases, camera anomalies resulted in discontinuing the use of a meteorological spacecraft; in the other, loss of the spacecraft was thought due to a momentary turn-on of a television system at critical pressure during boost, causing corona and arcing conditions.

The brief literature search conducted as a part of this effort turned up no papers or reports on the subject of TV system performance, reliability, life characteristics, or the present state-of-the-art. The information that was found, References 30, 31, and 32 discuss imaging approaches possible with charge-coupled devices (CCD's). While a CCD image sensor has been developed and employed in a miniature TV camera, it appears that much development remains to be done.

One area currently under development involves the number of defect-free, high density elements necessary for high resolution. A CCD chip providing high resolution could require a 500 by 500 matrix, which means about a quarter-million elements. Many predict that this will be within the state-of-the-art by the late 1970's or early 1980's.

Since CCD imaging approaches appear so promising for replacing other imaging approaches, it is recommended that they be evaluated via the Shuttle. They can be configured into an area sensor array or a linear sensor array, and electronic exposure control can eliminate mechanical shutters.

It is also recommended that the first stage of this Shuttle experiment consist of evaluating the inherent characteristics of CCD chips as discussed under Semiconductors, subsection 17, below. When it is evident that design and fabrication techniques for the chips are well-in-hand, the second stage could consist of evaluating complete camera systems. Characteristics which should be evaluated as particularly pertinent to the space environment include achieved resolution in-orbit, the effects of albedo and stray light, contrast control features, and the response to temperature extremes and solar heating. This second stage evaluation could probably be accomplished with test systems mounted in the Spacelab.

It is further recommended that the third, and final, stage of this experiment evaluate long-term operational characteristics and achieved life-time in space. This could be accomplished by deploying a test system and monitoring its performance via revisits, then eventually retrieving it for complete analysis on the ground.

5. Computers

While few spacecraft have yet carried programmable, general purpose computers, PRC feels that the LSI microprocessors now coming onto the market will make it hard to justify not using an on-board computer, even for small spacecraft, low-budget programs. Together with high density, light weight memories (see subsection 20, below), microprocessors can handle many functions now implemented by separate equipments for command and control, data formatting, sequencing, and attitude control.

Since so few spacecraft have utilized computers, the PRC Space Data Bank contains little information on their record. All the later manned spacecraft carried computers, and the PRC Space Data Bank contains one reported anomaly; PRC is also aware of another anomaly which is not covered in the PRC Space Data Bank reports. Even so, the flight durations of the manned spacecraft were too short to provide any insights on long-term computer operation, which will be required for long-life communications satellites and deep space probes.

A quite recently launched spacecraft has an on-board computer, and two anomalies have been charged to it. On another program, computers on two spacecraft failed, and an anomaly on each of two other spacecraft in that program may be computer malfunctions, although this is not clear. Another spacecraft included in the PRC Space Data Bank is known to have had a computer, and a "processor" anomaly is reported but it is not obvious that the processor and the computer are one and the same.

The present hardware area of command and control, including programmers, sequencers, controllers, etc., is most related to computers. They resemble each other in that both are generally implemented with digital logic, and on spacecraft they can be expected to perform the same functions.

The PRC Space Data Bank contains a significant amount of information on command and control. There are 43 reported logic problems and 26 reported timing and sequencing problems. This total of 69 anomalies ranks third highest along with camera equipment anomalies. In addition, there are 23 other anomalies associated with registers and memories and some of the 38 reported spurious command problems are undoubtedly due to logic malfunctions. While many of these problems have not had serious effects, a significant number have reduced mission effectiveness, and two have caused loss of the associated spacecraft.

PRC interprets this as indicating that the record for command and control leaves something to be desired. Further, it is not clear at this point that extensive implementation of command and control functions with microprocessors will improve this record in the near future. The in-space evaluation of microprocessors as semiconductor devices, as discussed in subsection 17, below, should be useful in eliminating inherent design and fabrication defects that are best detected in the space environment. Judging from the operational characteristics of ground-based computers as well as the PRC Space Data Bank anomaly record for on-board computers, however, problems are still likely to arise due to unanticipated interactions at the system level.

These types of problems arise because the conditions leading to such things as "logic races," sneak paths, and worst cause accumulations

of propagation delays cannot be adequately established under test conditions. In other words, computer testing programs can be written to evaluate all specific computer functions (e.g., "add," "multiply," "store," etc.), most functional combinations, and typical operational routines. It is never possible with test routines, though, to simulate all the stresses a computer will encounter in actual operation simply because the number of possible hardware operational states is virtually infinite.

PRC has found on other studies and in the brief literature search conducted during this study, that the subject of space-borne computer reliability usually emphasizes the need for fault-tolerant computers, and to a lesser degree, for reliable software, two aspects that are unquestionably important. However, the equally important need for operational integrity under hardware stresses resulting from program-commanded operational states does not seem to have been specifically addressed. The anomalies that would come under this heading are not "faults," in the sense that they could be mitigated or "worked around" by a fault tolerant system. They result from numerous interactions, including that of the operational environment as it pertains to data flow, computational load, etc.

PRC feels that the most feasible way that operational integrity can be assured is by evaluating performance under actual operating conditions. This allows unpredictable operating states to occur, and those resulting in anomalous behavior can be analyzed and corrective actions determined. Thus, evaluation via the Shuttle seems logical.

One approach to this experiment would be to combine the evaluation of spaceborne computers with that of some other device with a long-life requirement. The self-lubricated bearing evaluation, as discussed in subsection 12, below, seems an especially promising candidate if a rate-measuring package is used. The computer could accept rate inputs and perform any number of realistic computations without interfering with the operation of the rate-measuring package. Since revisits and retrieval would occur, a diagnostic display panel could be included so that computer anomalies could be readily analyzed and corrective actions could be incorporated without lengthy interruptions that would compromise long-term evaluation.

6. Day/Night Effects

The PRC Space Data Bank contains nine anomalies that occurred at or about the spacecraft day/night or night/day transition. These anomalies can be summarized as follows:

- (1) Data from a radiometer was degraded at the day/night and night/day transitions due to inadequate mirror shield design.
- (2) A radiometer experienced sunlight interference due to inadequate shielding design at the night/day transition.
- (3) A spacecraft exhibited roll and yaw perturbations after the night/day transition due to sun interference in the horizon scanner during attitude error corrections.
- (4) Sunlight reflections from the spacecraft structure caused ACS errors at the day/night transition.
- (5) The output of a solar array drive amplifier was excessively high as the spacecraft exited from the earth's umbra due to either a potentiometer malfunction, slip ring contamination, or shading effects.
- (6) An experiment package exhibited an irregular earth scan six to eight minutes after earth day, possibly due to thermal effects.
- (7) One spacecraft experienced boom flutter at sun rise, probably due to solar heating.
- (8) The output of a spacecraft rate measuring package was high near the day/night transition due to some unexplained energy input.
- (9) A power system day/night switch exhibited excessive switching.

PRC feels that the fact that nine such anomalies occurred indicates some degree of incomplete understanding of the effects of day/night

and night/day transitions. While the PRC Space Data Bank contains the likely causes of seven of these anomalies, it appears that the causal influences could not be foreseen and thereby mitigated during design and development. For instance, even if it were possible to simulate the full range of transition conditions, the testing costs would be prohibitive. Similarly, computerized analytical simulations could not be expected to include a sufficient number of parameters to fully evaluate transition effects.

PRC feels that in-space observations are required to provide a full understanding of these transition characteristics. Since the number of anomalies and their dates of occurrence indicates a persistent but not extensive problem, the effort associated with these observations need not be excessive. Its objective should be to collect an on-the-spot, annotated set of data covering from 20 to 50 transitions. While measurements of temperature variations, albedo from different sources, and fluctuations in energy inputs should be included in this data, PRC feels the direct observations and the capability to interpret transition effects as they are occurring offers the greatest potential for extending the understanding of this area.

7. Earth Effects

Many aspects of this recommended experiment are similar to those of the day/night transition experiment discussed in subsection 6, above. In this case, the data base contains five anomalies that were caused in some manner by effects of the earth on spacecraft equipment. These anomalies can be summarized as follows:

- (1) A power regulator failed to change modes due to the effect of the earth's penumbra on automatic transfer circuitry.
- (2) Television pictures were distorted due to modulation by the earth's field at spacecraft spin rates.
- (3) The sensitivity of an infrared interferometer decreased due to increased temperature of the optics housing, caused in turn by earth albedo entering the housing.

- (4) On a spacecraft equipped with TV cameras to monitor the behavior of a long boom, the lower boom tip targets could not be seen due to earth brightness.
- (5) On another spacecraft equipped with a camera for monitoring the behavior of small balls ejected from the spacecraft, the reflection of light from the surface of the earth masked the object ball.

As was the case with the day/night transition experiment, the number of the earth effects anomalies and their dates of occurrence indicate a persistent but not extensive problem stemming, it would appear, from a less than complete understanding of these effects. Again, the restrictions associated with test simulations or analytical models makes direct in-space observations the most promising approach for gaining new information. Except for the fact that anomalies 4 and 5 above are almost identical, the only common factor that appears consistently is the effect of the earth's albedo, including that of the penumbra. With respect to anomalies 4 and 5, approaches of the type reported in Reference 33 could possibly be applied to improve camera performance. This document, which recommends improvements for airborne TV cameras, ground telescope systems and air traffic control cameras, describes contrast enhancement of weak targets seen against a bright background.

However, while such anomalies as 4 and 5 could probably be dealt with on an individual basis, it appears to PRC that a more general approach that provided usable, background information would be more advantageous. A modest level-of-effort experiment to accumulate albedo data is recommended as a possible, generalized approach. This data would allow more precise design evaluations of a number of spacecraft equipment types. Via monitoring equipment carried as a Shuttle payload, such factors as background luminance and irradiance for various fields of view could be collected. To preclude the costly accumulation of vast amounts of difficult-to-analyze data, PRC feels the objective of this experiment must limit data collection to that pertinent to the proper operation of spacecraft equipment.

8. Gravity Gradient

PRC feels that the information in the PRC Space Data Bank on gravity gradient stabilization neither confirms nor denies the high reliability and successful performance expected of this approach. Exhibit IV-1 summarizes this information for the 17 spacecraft in the PRC Space Data Bank known to be gravity gradient stabilized. Another three spacecraft are not included in this record; they carried quite sophisticated subsystems for evaluating this stabilization approach in space, but launch vehicle problems on two of them and an early system malfunction on the third precluded informative evaluation efforts.

While the record indicates that gravity gradient systems have performed successfully, a number of anomalies have occurred and there has been only a limited number of spacecraft which have provided experience. Since gravity gradient stabilization is primarily a passive approach, it should offer benefits in reliability as well as economics over active stabilization approaches requiring such equipments as reaction wheels, attitude sensors, thrusters, etc. For applications where precise pointing is not required, PRC feels these benefits make gravity gradient stabilization logical choice. Applications that PRC foresees include spacecraft utilizing ranging techniques for marine navigation, those carrying experiment packages for monitoring such things as solar flare radiation levels or background noise at radio wavelengths, and, not inconceivably, for spacecraft carried "piggyback" to orbit other planets.

The problems of analyzing and qualifying gravity gradient systems on the ground are well known. In addition to the impossibility of simulating the 0-g environment, solar-thermal effects are difficult to reproduce, especially for configurations involving long booms. Computer simulations, while useful, become too complex to handle if they investigate more than three to five factors of interest, and even then require simplifying assumptions and empirical insights for their formulations. For instance, Reference 34 describes a computerized model for determining the influence of solar heating on the low frequency, dynamic stability of a gravity gradient spacecraft. While exercise of this model was able to explain the source of anomalous behavior in a Naval Research

EXHIBIT IV-1 - GRAVITY GRADIENT STABILIZATION PERFORMANCE AND
RELIABILITY INFORMATION SUMMARY

1. Two spacecraft stabilized upside down, one due to the jet effects of a subliming solid used as a release mechanism.
2. Excessive spin rate delayed G/G capture; the spacecraft attitude during this period caused the battery temperature to rise.
3. A de-spin mechanism did not function because the spacecraft spin rate was too low to cause release.
4. A G/G boom did not deploy fully.
5. On one spacecraft, 750' booms have been successfully deployed.
6. On one spacecraft:
 - o A marginal lock on gravity due to rod bending and twisting, with thermal bending being the driving force, caused the spacecraft to intermittently turn upside down, then right itself.
 - o Solar heating caused boom flutter at spacecraft sunrise.
 - o Erroneous equilibrium orientation occurred due to complex boom interactions.
7. One spacecraft never reached static equilibrium.
8. A prior experiment turn-on prevented boom deployment on the first attempt.
9. One spacecraft did not capture after boom deployment due to complex interactions.
10. A damper boom did not deploy due to a malfunction in a "stop device."
11. One spacecraft underwent continuing spin-up due to complex interactions.

Laboratories' spacecraft,¹ the model and its computer program are so extremely complex that only boom thermal bending could be considered. In fact, one of the recommendations of this referenced report concerns the need to obtain a much better physical understanding of the behavior of a boom exposed to solar heating, including the effects of sun-angle and the boom end conditions on actual thermal deflection.

From the preceding considerations, PRC feels that in-space experimentation via the Shuttle could provide useful information for the design of gravity gradient systems. This experimentation could include direct observation and measurement of boom behavior in response to such factors as:

- o Solar pressure
- o Magnetic torques
- o Eccentricity
- o Thermal profile, including sun angle
- o Vibration

In addition, absorbtivity, thermal lag, and hinge effects as well as interactions of many of these factors could be monitored.

PRC feels that the objective of this experimentation should be to provide an information baseline that would not otherwise be available. In other words, the experiment should provide information that will extend the capabilities of computerized simulations and provide the designer with empirical behavior data. One approach to the experiment would be to position a gravity gradient stabilized, boiler-plate structure via the Shuttle's Remote Manipulator System. Observations and monitoring could be accomplished in several ways. Motions recorded on video tape, with a known and manually established reference background, could be correlated with local measurements of magnetic field strength, sun angle, etc. Reference grids could be positioned via EVA, and strain gages, temperature monitors, etc., could be manually read and repositioned to gain more information on unusual occurrences.

PRC feels that possibly two of the most significant aspects of this experiment will be the opportunity to observe and monitor boom

¹This spacecraft is not included in the PRC Space Data Bank.

deployment and spacecraft capture, possibly on multiple occasions, and to retrieve the system for subsequent ground evaluation. Also, the opportunity to conduct the experiment at several altitudes and inclinations may prove to be of considerable value.

9. Heat Pipes

Since heat pipes have only recently begun to be used on spacecraft, the PRC Space Data Bank contains almost no information on them. The available data, which covers two spacecraft, is however quite interesting. On one spacecraft, it is reported that they worked quite well; on the other, heat pipes contributed to an anomaly that rendered the spacecraft virtually useless.

The anomalous situation involved an accumulation of worst-case effects which imparted torques that caused the spacecraft to spin stabilize end-over-end, thus severely restricting solar power availability, antenna coverage and experiment packages' fields-of-views. The torques responsible for this came from a number of sources, with one being generated by the fluid in the heat pipes.

PRC has not seen this heat pipe problem addressed, possible because it can be evaluated realistically only in a 0-g environment, and possibly because the potential torques are felt to be so low as to be of little concern. The concerns that are addressed include entrapment of gas bubbles within arteries, wicking action, and choice of fluids and materials.

Many currently feel that variable conductance heat pipes are the ultimate development for spacecraft thermal control. If heat pipes are to become widely used, PRC feels they should be evaluated via the Shuttle. The spacecraft with the torque problem was reasonably straightforward--it was conservatively designed, its basic subsystems utilized equipment types well within the state-of-the-art, and it underwent a thorough test program. If the magnitudes of the torques could have been predicted, it can be assumed that measures would have been taken to preclude the problem.

A possible approach to this recommended Shuttle experiment would be to combine a mounting that allowed freedom in all three axes with a package containing heat pipes and sensors. This could be extended via the Remote Manipulator Arm and the torques of the unrestrained package could be monitored. Arrangements could be provided for clamping the package in any axis, then measuring response during various Shuttle maneuvers. In addition, this experiment could provide information on the formation of gas bubbles and wicking action.

PRC feels a point is in order concerning the heat pipe approach selected for this experiment. Reference 35 describes a large, variable conductance heat pipe utilizing a transverse header and ammonia as a working fluid. This is reportedly a novel device that eliminates entrapment of gas bubbles. While this was the only report on the state-of-the-art and its advancement found during the brief literature search, doubtlessly other heat pipe approaches are under development. Since there are so many possible combinations of configuration, materials, working fluids, etc., it appears that the selection of a device, or devices, for evaluation should be based on the most promising approaches.

10. Horizon Scanners

The PRC Space Data Bank contains 14 anomalies associated with horizon scanner/earth sensors. One each of these anomalies is attributed to magnetized ball bearings, failure of a sensing head, low sensitivity, improper threshold, and a leak in a pressurized container. Two additional anomalies are attributed to inadequate design. The remaining seven, or half the anomalies, are due to sensing incorrect light sources. This has ranged from sun interference (four cases) to tracking cold clouds (two cases), to sensing Venus stray light (one case).

The potential for sensing incorrect light sources is well known, but since the data base reveals that anomalies of this type occurred on spacecraft launched from 1960 to 1972, it appears that problems remain to be solved. Since a number of approaches are possible for detecting the earth as a reference, the approaches for solving these problems can involve a number of choices. Reference 36, for instance, reports that

the CO₂ absorption band in the atmosphere is most suitable for accurate earth horizon detection. The reasons stated for this are that reflected sunlight hardly contributes to this band, canceling out day and night side differences in radiance; in addition, hot deserts or cold clouds do not effect earth signals in this band. For the application discussed in this report, the detector chosen was an immersed thermistor bolometer, although the author acknowledges that future horizon sensors will probably utilize pyroelectric detectors once they are space qualified.

Another approach, as discussed in Reference 37 utilizes an array of four fixed point, horizon trackers, each independently controlled by a thermocouple drive mechanism which centers the tracker's mirror on the horizon limb. Still another variation, as described in Reference 38, utilizes a radiometric approach with bolometers. It can be expected that other approaches using charge-coupled devices for infrared imaging, as mentioned in Reference 30, may become possible within this decade. Also research now being conducted on Josephson-junction devices for high speed computer logic (see Reference 30) may result in spin-offs that will allow their application as advanced infrared detectors.

While the various possible approaches, both current and future, involve many "approach-unique" aspects, they all share the common requirement to accurately distinguish some given earth characteristics and to ignore all others. Ground facilities are capable of simulating some earth characteristics, and of some potential interference sources. It is not possible, however, to simulate the complete, operational environment with its multitude of radiation sources at numerous levels, bandwidths, intensities, etc. Thus, PRC recommends a Shuttle program with the dual objective of obtaining information applicable in earth sensor design and of evaluating the performance of new sensor approaches.

Obtaining information for design use could be accomplished by measurements taken from the Shuttle payload bay. The specific information collected (i.e., the bandwidth, etc.) would depend on the earth sensing approach under consideration, but generally it would include

radiance profiles and data on such aspects as latitude-dependent factors, earth oblateness, and seasonal and diurnal effects.

Evaluating the performance of new sensor approaches could also be initially accomplished by test packages mounted in the payload bay, although evaluation of long-term performance would require utilization of the LDEF. The initial evaluation should monitor the test sensor's performance under a wide range of attitude conditions and seasonal and diurnal variations. The package used for the long-term evaluation could eventually be retrieved for a detailed analysis of any degradation incurred.

11. Ion Engines

The PRC Space Data Base contains information on only two spacecraft which are known to have carried ion engines. One spacecraft carried one engine, the other spacecraft carried two engines. None of the three ion engines could be used.

On the spacecraft with the one engine, interference with telemetry and attitude control resulted in the ion engine being shut-off and not used after only a few hours of operation. On the spacecraft with two engines, one engine operated successfully after initial turn-on, but then failed to turn-on on all subsequent attempts. The second engine experienced a similar turn-on failure, apparently on the first attempt.

This information in the PRC Space Data Bank indicating lack of in-space experience with ion engines coincides with that reported in Reference 39. This document reports that SERT-II¹ is the only spacecraft with an extensive thruster operational history. SERT-II carried two mercury-ion engines (the three in the PRC Space Data Bank are cesium engines), and according to Reference 39, one operated approximately 4,000 hours and then developed a short in the accelerator grids. The other operated about 2,000 hours before it incurred the same failure.

The most well known and wide spread concern regarding ion engines is the danger of thruster efflux deposits contaminating spacecraft surfaces. The above-referenced document, in fact, reported on a detailed

¹Not in the PRC Space Data Bank.

study of SERT-II flight thermal data to determine what, if any, contamination had occurred. The study found that only experimental solar cells mounted near the edge of the thruster exhaust had been contaminated.

Contamination can occur, however, and it is a function of spacecraft geometry, charge, shielding, etc. Reference 40, for instance, reports on a ground evaluation program that determined that almost any imaginable surface, coating, or lens material would be contaminated if exposed to the thrust products of a cesium engine.

Thus, while the potential for contamination certainly remains a valid concern, PRC feels that other aspects of ion engine operation should also receive attention. Neither the PRC Space Data Bank nor SERT-II's operational history provides any assurance that ion engines have yet reached the stage where reliable operation and a reasonably long service life can be achieved.

The difficulties associated with ground testing to determine the contamination potential have long been recognized. Large test chambers are required for even very basic, prototype units, and such factors as the interaction of the thruster beam and the chamber walls introduces uncertainty. Determining the other aspects of ion engine operation on the ground seems to PRC to be impossible.

The beam forming mechanisms and the ion generating devices, for instance, rely on a variety of material properties and operational-environmental conditions for their proper operation. Either alone or in combination, exposure to the space environment and the environment created by ion engine operation must certainly influence the long-term reliability of these equipment elements. It seems to PRC that these overall effects depend on the behavior of charged particles in 0-g and vacuum, and therefore require the space environment for proper evaluation. Since the propulsion characteristics of ion engines offer such promise for future spacecraft, one example being for stationkeeping on large communications satellites, PRC recommends experimentation via the Shuttle.

One approach to such experimentation would be to evaluate the long-term effects of the space environment on typical ion-engine components

via the LDEF. The objective of this experiment should be to determine whether any degradation occurs that would effect such aspects of ion engine performance as beam forming, ion generation, charged particle containment, etc.

Another approach would be to deploy an ion engine package via the Shuttle, then, with the Shuttle maintaining sufficient distance to preclude contamination, monitor and map the fields and particle tracks produced by thrusting. This would provide information for use in contamination studies, and thrust impulses large enough to cause navigation problems should not be required. If this were repeated over a number of Shuttle revisits, indications of long-term performance could be obtained. In any event, retrieving the engine package and evaluating it on the ground should provide valuable insights for designing engines with increased service lives.

12. Lubricants

The PRC Space Data Bank contains several anomalies attributed to lubrication problems, some of which are associated with equipment discussed elsewhere such as tape recorders and gimbaled equipment. Other anomalies caused by lubrication problems include a drive motor failure, gyro "wear-out" due to a frozen bearing, and erratic operation of a pitch flywheel, which eventually resulted in an emergency (see subsection 15, below).

In general, however, review of the data base indicates that the behavior of presently used lubricants in the space environment is reasonably well understood. Still, there is a widely recognized need for improved lubricants, especially in view of the long lives required of communications satellites and deep space probes. Self-lubricated bearings are receiving much attention, as are new compounds such as Teflon-thickened polysiloxane which are reported to have significantly increased mean-times-between failure.¹

¹See, for instance, Aviation Week and Space Technology, January 26, 1976.

Thus, based on the in-space anomalies that have occurred and on the fact that such effects as outgassing and composition changes due to the space environment cannot be adequately determined on the ground, PRC recommends that evaluations of new lubricants be conducted via the Shuttle. For new lubricating materials, samples placed in the LDEF and retrieved at intervals up to one year could be analyzed for composition changes, ionization due to radiation, impending structural instabilities, etc. For new lubricating approaches, such as self-lubricating bearings, active testing involving actual operation seems indicated. Since the data base reveals a number of gyro wear-out failures (see subsection III.E.2), it might be advantageous to "kill two birds with one stone" and deploy a simple rate measuring package utilizing self-lubricated bearings. Shuttle revisits for inspection and analysis could be conducted on a routine basis, with eventual retrieval for extensive evaluation on the ground.

13. Nuclear Power Supplies

Since nuclear power supplies have not been widely used on spacecraft, the PRC Space Data Bank contains little information on them. The information that is available, however, appears to PRC to be of some interest with regard to the objectives of this study.

Radioisotope power supplies (RIPS) are known to have been carried on spacecraft in four programs included in the PRC Space Data Bank. No anomalies are specifically attributed to these, but a power supply failure caused loss of one spacecraft on a program that utilized RIPS; it is not clear from the available information whether this power supply was a RIPS.

Another spacecraft carried a liquid sodium-potassium fission reactor, and it experienced one direct and one indirect anomaly. The direct anomaly, which was thought to be possibly due to deposition of outgassed materials on insulators, involved a decline in the resistance to ground of the thermoelectric converter. The indirect anomaly occurred when a voltage regulator failed, thereby placing the high reactor voltage on the main bus and causing the entire spacecraft to become inoperable. This anomaly occurred after 43 days in-orbit.

Whether nuclear power supplies will be used to any extent in the future appears open to question. Reference 20 reports that in the near future, their cost and attendant ground handling problems will probably restrict their use to special situations such as outer planet explorations. Another document surveyed during the literature search, which was a rather thinly disguised commercial for the manufacturer's product, claimed that RTG's (radioisotope thermoelectric generators) now offer many advantages for earth-orbit applications. Reference 41 objectively evaluates the status of RTG development and concludes that means will soon be available for producing a new generation of RTG's which will meet weight, performance, and reliability requirements.

PRC feels that if RTG's become a viable power supply alternative, in-space testing will be highly desirable. They pose the same, if not higher, potential for composition changes in materials as discussed in subsection 11, above, for ion engines, and, as with ion engines, this can greatly alter performance characteristics. In addition, their high power output at beginning-of-life requires "dumping" power initially, sizing the unit for adequate power at its decreased levels, and designing control circuitry capable of handling both the high initial power and the subsequent decreased levels.¹ Evaluating the performance of the control circuitry under actual operating conditions, possibly via the LDEF, would provide valuable information on long-term characteristics.

14. Radiation

The PRC Space Data Bank contains eight anomalies, in addition to array degradation as discussed in subsection 2, and the transistor problem discussed in subsection 17, which were attributed to the effects of radiation. These anomalies can be summarized as follows:

- (1) On two spacecraft in one program, a neon reference for an infrared interferometer degraded, with one attributed to high radiation exposure early in the mission, and the other to energetic particle

¹Reference 42 discusses the design of control circuitry for meeting these requirements.

bombardment. The high radiation exposure also caused degradation to an experiment package.

- (2) Two spacecraft on another program experienced shifts in spacecraft potential.
- (3) A Gieger-Mueller tube failed due to radiation damage.
- (4) An ultraviolet monitor package degraded due to radiation damage.
- (5) The power system of an interplanetary spacecraft exhibited anomalous fluctuations that were possibly due to Jovian radiation.

The extent of experimentation via the Shuttle that should be undertaken with respect to radiation and its effects, it appears, must be considered from two standpoints. These are (1) current knowledge of the space radiation environment and its effects on various materials, and (2) the areas in which Shuttle experimentation could most feasibly extend this knowledge.

Much is currently known about radiation and its effects on many presently available materials. Reference 43, for instance, examines the space radiation environment and its effects on the various components and materials utilized in multiplier phototubes. Except for this reference, however, the literature search conducted as part of this effort turned up no recent papers (i.e., the 1973-1975 time frame) of the type that would be applicable in designing radiation-tolerant equipment.

This lack of reported work may imply that no significant new information has become available since 1973; PRC is aware of a number of in-depth reports published in the late 1960's, and these may still be adequate.

With regard to how the Shuttle could most feasibly extend knowledge in this area, PRC feels the distinction between collecting radiation data for scientific purposes and for applications purposes should be noted. There will doubtlessly be many experiments on the Shuttle

program for collecting scientific information. PRC's experience has been, however, that this type of data is not easily interpreted by the engineer or technologist, and that often quite lengthy periods elapse before this information becomes available in a form usable for applications purposes by the technologist. Thus, Shuttle experiments set up specifically to collect data for applications purposes seems worthwhile.

It is not possible at this point to suggest implementations for these experiments. They would depend heavily on extending the current knowledge of radiation and its potential effects, and as indicated above, PRC could not determine the status of this information during this effort. It is certainly not feasible to attempt to collect data over the multitude of spectral bandwidths, field intensities and occurrence profiles that characterize space radiation. The selection of experiments would require careful analysis to select the most cost-effective of the many candidates.

One possibility, suggested by the anomalies cited above where on two occasions a shift in spacecraft potential occurred, concerns in-space research on spacecraft charging. This phenomenon, where an interaction between electric fields from the spacecraft and particle motion causes current to circulate through the spacecraft, can create spacecraft potentials as high as several kilovolts. Some feel that this is responsible for many spurious commands and other anomalies. References 44, 45, and 46 discuss spacecraft charging, the problems it poses, and the need for more information.

15. Reaction Wheels

The PRC Space Data Bank contains 22 anomalies associated with reaction wheels. On two spacecraft these resulted in severe attitude instabilities, which, in turn, required considerable expenditure of control gas for reacquisition under such emergency conditions as power limitations due to incorrect array orientation and improper antenna coverage. On another spacecraft, a momentum wheel anomaly caused complete loss of attitude control through a complex chain of events which began when a wheel control mag-amp shorted. On two other spacecraft, momentum wheel anomalies caused loss of pitch control.

For those cases where the data bank contains information as to the cause of the anomaly, bearing lubrication problems are reported in two cases, bearing temperature increases are reported in another two cases, and brush wear on motors in another two cases. In addition, five anomalies involve fluctuations in duty cycle, erratic wheel response, and motor voltage abnormalities for which no specific cause is given.

Improved lubricants, as discussed in subsection 12, would prevent some reaction wheel anomalies of the type contained in the data base. In addition to the two lubrication problems cited above, some bearing temperature problems as well as some other problems where no specific cause is given, may involve lubricant deficiencies. An interesting point, however, is that for at least half of the anomalies, the underlying causes either were not, or could not, be determined. For instance, two spacecraft developed a nutation due to some unspecified cause having to do with the combination of wheel response and "lunar conflict."

While some of the anomalies could undoubtedly have been prevented, PRC feels that unpredictable interactions will always be possible due to the difficulties in simulating realistic operational conditions. The problem lies, as PRC sees it, not so much in the performance of bearings and motors in 0-g--where they are subjected to less loading than on the ground--but rather in the combination of torques which must be reacted. The two cases of nutation resulting from the combination of wheel response and "lunar conflict" are examples of this.

Therefore, PRC feels that evaluation via the Shuttle of momentum wheel performance would be beneficial. This could be accomplished by deploying an instrumented test package which could be both observed and monitored automatically. Correlations between such factors as energy inputs and system performance could be determined directly, as could such aspects as response time, unloading characteristics, etc.

PRC feels that such evaluations will be especially desirable for new momentum wheel approaches. As discussed in References 47 and 48, magnetically suspended wheels now being developed utilize techniques that eliminate the power consumption problems of an all-electromagnetic

system. While Reference 47 reports that these wheel systems are immune to environmental effects, PRC feels that the response to operational combinations of torques remains an area to be investigated.

Another new momentum wheel approach, as discussed in Reference 49, utilizes hydrodynamic gas spin bearings that allow stopping and reversing without bearing touch-down. As opposed to magnetic suspension, this approach does require special considerations for testing in 1-g. Thus, this fact as well as the torque combination effect cited above, seems to PRC to warrant in-space evaluation.

16. RFI/EMI

The PRC Space Data Bank contains 50 anomalies attributed to interference. Slightly more than half of these are "nonequipment specific," i.e., the source of the interference could not be isolated to a specific equipment or the interference effected groups of equipments rather than some specific equipment. By the same token, slightly less than half the anomalies were "equipment-specific" in that either the interference source or its effect involved identified, specific equipment.

The nature of both categories of this interference runs the gamut from cross-talk, noise, RFI, and EMI to "glitches." Some examples include one complex communications spacecraft which experienced six persistent types of interference between the various equipments in its communications system. At least two of these have resulted in restricted operational regimes. On several spacecraft in one program, interference with various equipments occurred during ignition of thrusting devices. All of the spacecraft on this program were "noisy," or had other "noise" problems of some sort. The spacecraft on two other programs have similar records of persistent noise problems.

The 50 anomalies in this RFI/EMI category are surpassed by only four other anomaly categories established for this study effort. Yet the literature search conducted as a part of this effort, while necessarily brief, turned up no pertinent documents on this subject. There are several possible reasons for this apparent lack of interest.

The means for controlling or eliminating interference--i.e., grounding, shielding, filtering, etc.--are sufficiently well understood that they may be felt more fitting topics for textbooks than papers or reports. Beyond this, many interference characteristics are so dependent on a particular system configuration and its implementation that discussions of what worked well in one case might seemingly be of little interest in another. Also, PRC feels that many accept interference as a "fact of life," to be dealt with by adding a filter capacitor or increasing the size of a grounding system.

Based on the number of anomalies in the interference category, and, PRC feels, on the lack of attention, experimentation in this area is recommended. While it is obvious that many benefits could accrue from a ground-based program, problems with adequately simulating actual operational conditions are well known. Anechoic chambers, thermal-vacuum facilities, system test facilities, etc., all are capable of revealing a number of interference problems but, as the record indicates, not all of them.

The recommended in-space experimentation could be based on the objective of determining and cataloging the characteristics of various EMI/RFI suppression and protection approaches. The equipment could utilize noise generating devices, and the response of various combinations of approaches could be monitored. For instance, approaches under test could be sequentially modified with respect to such details as grounding bars vs. braids, different types of electrolytic capacitors, different shielding materials, etc., for a wide range of configurations. The test package could be deployed sufficiently distant from the Shuttle to guarantee that any interference noted resulted from operation of the test package or from environmental effects. With respect to this, information from Shuttle environmental monitoring devices would allow the data to be correlated with respect to such factors as solar field strength and radiation levels.

17. Semiconductors

Analysis of the PRC Space Data Bank reveals several semiconductor malfunctions which are indicative of an area that would probably

benefit from in-space evaluation. The anomalies associated with these malfunctions can be summarized as follows:

- (1) Space radiation damage to transistors, possibly ionization of the gases encapsulated in the transistors, caused complete failure of both command decoders on one spacecraft.
- (2) A high power regulator failed to turn-off on several occasions, in one instance discharging the battery and incapacitating the spacecraft. A dew point problem in a power transistor was possibly the cause of this anomaly.
- (3) On two spacecraft on one program, "purple plague" in integrated circuits caused loss of the computer portion of the command and control unit.
- (4) On one spacecraft, "ionic contamination" of integrated circuit chips caused loss of a telemetry channel. This anomaly was attributed to incomplete removal of the ammonia cleaning solution residue, thus creating polarity problems within the chip.

Of the anomalies summarized above, one occurred fairly early in the space era, one occurred quite recently (1975), with the others occurring in between. An especially interesting point is that with the possible exception of the transistor dew-point problem--for which the PRC Space Data Bank contains no further information--all the other anomalies involved semiconductors which did not have an extensive, in-space operational record but had undergone a thorough and detailed parts qualification program. While the causes of these anomalies could have been eliminated on the ground, they are the kind that are almost impossible to predict before actual operational data become available. With the rapid proliferation of new types of semiconductor devices, an experimental program to obtain such data on in-space device behavior would be highly desirable.

In addition to the accelerating trend toward LSI (Large Scale Integration) for digital applications, numerous new devices for communications and analog equipment are beginning to appear. These include

charge-coupled devices, gallium arsenide field effect transistors (GaAsFET's), varactors, IMPATT diodes, Gunn diodes and silicon Schottky barrier varistors. The fabrication of all these new devices is complicated by the resolution required (for instance, distances and line widths that are in microns) for the high packing densities.

This introduces many possibilities for potential operational problems of the types reflected by the above anomalies. From the choice of fabrication materials and techniques to the inability to separate "failure mode" from "failure mechanism," there are numerous ways in which unforeseeable device limitations can occur. While these can be corrected once they are understood, it has often been the case that long periods in an actual operational environment are required to provide the necessary information.

Thus, it is recommended that new semiconductor devices such as the ones mentioned above be operated in space for purposes of gaining advance information on their potential, inherent failure modes. These tests should be conducted as nearly as possible to duplicate operational use rate and length of service, factors which are difficult to duplicate on the ground. This should include powered operation and cycling.

One approach would be to place test circuits incorporating new devices in the LDEF, then retrieve these after various operational periods, e.g., one month, two months, six months, one year. These circuits could then be extensively inspected on the ground to detect impending problems or signs of aging or degradation, and to evaluate the adequacy of fabrication techniques. With such information available, any necessary corrective actions could be implemented in a more timely manner.

18. Star Trackers

The PRC Space Data Bank contains 35 anomalies associated with star trackers, the earliest occurring on a spacecraft launched in 1964, and the latest on one launched in 1974. The nature of these anomalies can be summarized as follows:

- (1) Twelve anomalies were attributed to mechanical problems, with "stuck gimballs" accounting for eight of

these, a "stuck" sun shutter, for two, a "stuck shutter" for another, and another reported as simply "mechanical hangup."

- (2) Three anomalies were attributed to improper calibration or calibration problems.
- (3) Degradation or aging are the reported causes of three anomalies, with one of these being loss of sensitivity due to aging, another gain degradation, and the third degradation because the unit had earlier been pushed beyond its design limits.
- (4) For six anomalies, little detailed information is given except for statements such as "lost star during slews," failed to acquire guide star," drop in reference voltage," "light leak through shutter," and "noise bursts from tracker caused it to become unusable."
- (5) The remaining 11 anomalies involve tracking anomalies and the capability of the tracker to remain locked-on to the proper star. On three occasions, a tracker locked-on to the wrong star, in one case due to the scintillation from high energy particle radiation and albedo saturation recovery effects. Bright particles, whose sources ranged from dust particles from the spacecraft to sun reflections, caused four anomalies. In one case, a star tracker acquired earth stray light, in another a tracker "fov" was occulted by an unknown object. The micropulses within each star pulse caused improper operation of the star-advance function in one tracker, and another anomaly involved tracking jitter on bright stars.

From the above anomaly summaries, it can be seen that the majority of the star tracker anomalies are about equally divided between mechanical problems and tracking problems involving imaging performance. While PRC

feels these problems must have been recognized, neither the extent of the recognition nor the corrective actions being taken was evident from the literature search. In the three most applicable documents found, Reference 50 discusses a tracker that uses V-slits and measures the crossing time of the trailing edge of each star against a time reference source. It is reported that this approach prevents acquisition of star clusters and sensing of the moon or sun. Reference 51 describes a star sensor for spacecraft with low spin rates which utilizes N-shaped slits to produce a photomultiplier tube output of three equal pulses for a given star. The amplitudes of these signals are indicative of the star's visual magnitude, and it is reported that a star catalog will be compiled which tabulates the sensor's response to each star. Reference 52 discusses a rather radical departure from conventional star tracking techniques in that it considers interferometric star tracking. This paper reports the advantages of this approach and acknowledges that many problems remain to be solved.

It seems to PRC that the ultimate objective in star tracker technology would be to develop approaches that precluded both mechanical and imaging problems. While this does not appear feasible within the current state-of-the-art, innovative approaches utilizing holographic techniques, semiconductor imaging with something like charge-coupled devices, interferometry, etc., offer possibilities.

Considering the two types of problems separately, improved lubricants, as discussed in subsection 12, could possibly eliminate some mechanical problems. For eliminating imaging problems, an approach that should be feasible within the next few years would utilize a microprocessor and semiconductor memory for handling star-mapping algorithms. This would, in essence, involve "voting logic" in that multiple sensor heads, which need not have high accuracy requirements, could provide information on constellations or groups of stars. In other words, this approach would derive reference information, for instance, from the Big Dipper, instead of simply Polaris.

PRC feels that all efforts toward star tracker improvement will require evaluation via the Shuttle. For improvements that are feasible

within the current state-of-the-art, information on star characteristics taken outside the earth's atmosphere will be invaluable. This information can be obtained from instruments mounted in the Shuttle payload bay for measuring spectral characteristics. In addition, specific trackers can be evaluated and calibrated in-orbit.

For improvements not currently within the state-of-the-art, it can be expected that the Shuttle will play a vital role in prototype development. In-orbit bench-tests, prototype qualification tests, etc., can be conducted via the Shuttle under actual operational conditions which are difficult and costly to simulate.

19. Sun Sensors

The PRC Space Data Bank contains 25 sun sensor and solar aspect detector anomalies. These can be summarized as follows:

- (1) Five were due to human error, with two of these involving wiring errors, one an incorrect gain setting, one a manufacturing defect, and one incomplete testing.
- (2) No information beyond such statements as "malfunctioned" or "failed" is given for six anomalies.
- (3) Three anomalies were attributed to detector failures.
- (4) A thermal problem caused one anomaly.
- (5) Four anomalies involved "double sun pulses," "premature sun pulses" and "extra sun pulses."
- (6) Earth albedo and earth stray light were responsible for two anomalies.
- (7) Radiation damage, and particularly ultraviolet radiation, was responsible for four anomalies.

While the anomalies summarized above reveal no consistent trends, PRC feels two underlying factors are exhibited. First, sun sensor and even solar aspect sensors are the least complex of the attitude reference sensors in that detecting the sun presents few problems. PRC feels that for this reason they probably receive less attention during design and fabrication (as evidenced in particular by item 1 above) than the more

complex sensors. Second, they possess several features that make realistic test conditions difficult to simulate. This stems from three requirements that their detectors must meet, namely, they must be able to withstand the radiation environment, they must reject luminance from sources other than the sun, and they must have the capability of producing "nonconfusing" sun signals. The anomalies summarized in items 5, 6, and 7, above, are indicative of problems that can arise due to these three requirements.

While the possibility of such problems is undoubtedly recognized, the literature search conducted during this study turned up nothing related to them. PRC feels that the anomaly record indicates that this apparent lack of attention is not justified. Sun sensor performance, particularly with regard to the three requirements cited above, should be more thoroughly investigated. Since it is difficult to simulate operational conditions realistically, PRC recommends that this be done via the Shuttle.

One approach to this could utilize coarse and fine sun sensors as well as solar aspect sensors mounted in the payload bay. Their performance could then be monitored under a wide range of Shuttle orientations to provide such information as response characteristics under varying angles of incidence, the effect of seasonal or diurnal variations, and the capacity to discriminate between solar radiation and other sources of radiance. These evaluations could be performed for a number of radiation-protection approaches which would utilize cover slides of several different materials and thicknesses. To evaluate the potential for radiation damage more extensively, test units could be placed in the LDEF.

20. Tape Recorders

The PRC Space Data Bank contains 94 tape recorder anomalies, making them second only to scientific experiment packages in number of anomalies, and also the most anomaly-prone specific type of equipment. These tape recorder anomalies have run the gamut from broken or degraded tapes, failed tape drive motors, capstans and drive units, to problems, malfunctions and failures in read/write circuitry.

The problems associated with tape recorders are well known. A joint AF/NASA Tape Recorder Action Committee (TRAP) was formed in early 1972 as a result of the interest that had been aroused as to the questionable performance of tape recorders. Reference 53 describes this committee and its findings and recommendations, including recommendations for improvements in both hardware and management functions.

During the course of this study, PRC briefly evaluated three papers on tape recorder state-of-the-art. Reference 54, which is a good tutorial paper on high data-rate tape recorders, summarily admits that there are reliability problems but concludes that they can be overcome. Reference 55 and 56 describe possible improvements in the mechanical portions of tape recorders, and report that they would eliminate many potential failure mechanisms.

PRC is not inclined to agree that tape recorder reliability can be substantially improved nor that the improvements being recommended will eliminate the most troublesome areas. In ground computer installations, magnetic tape units require rigorous preventative maintenance programs, including lubricating, alignment, etc., and even then they are among the most troublesome equipments in the system. For space applications, it is difficult to imagine that long-life requirements can be met.

PRC feels that alternate memory approaches offer the ultimate solution, but currently these still pose problems. Based on the record revealed by the PRC Space Data Bank, alternate memory approaches experienced 23 anomalies. It is not always clear what types of memories these were but it can be determined that at least two of these anomalies involved ferrite core memories.

A basic problem with alternate memory approaches in the past has been weight restrictions. In the typical range of 10^5 to 10^{10} bits needed for spacecraft data storage, the tape recorder has so far been the only approach that could meet weight requirements. New developments in large-scale integration, bubble memories, charge-coupled devices, and several other approaches can be expected to change this situation.

Reference 57 describes a 0.5 megabit memory utilizing new ferrite core techniques which was developed in Germany for the Helios space probe.

Reference 58 discusses current trends in semiconductor memories, as do References 30 and 31. Packing densities for currently available commercial devices are about 4K bits per chip, except for charge-coupled devices where densities of 16 kilobits per chip are reported. One hundred to 400 kilobit bubble memory chips have been built, and a 100 megabit one is apparently being evaluated, but intensive funding is reported needed for effective development and fabrication programs. Still further downstream are optical data storage utilizing holography, as described in Reference 59, and electron beam/CRT approaches, as mentioned in Reference 58. Both these approaches are reported to be capable of storing millions of bits.

For any of these devices that appear feasible alternatives to tape recorder storage, PRC recommends, a three-phase program via the Shuttle similar to the one recommended for computers (subsection 5, above). The first phase should consist of evaluating the individual devices as semiconductors, as discussed in subsection 17. The second stage should consist of in-space evaluation of a complete system, with emphasis on interface stresses. That is, the system should be exercised with maximum input and output data rates to evaluate stability, error rate, response to worst case addressing patterns (which PRC expects to be a critical area), and interactions at the memory/RF interfaces under actual operating conditions that can be expected to include fading and distortion.

Following this, the recommended third phase would be deployment of a test package, with revisits and eventual retrieval to evaluate long-term performance.

21. Thermal Control

While the PRC Space Data Bank contains 16 anomalies related to thermal control, most of them appear to have been preventable by techniques that were within the state-of-the-art at the time the effected spacecraft were designed. Of these 16 anomalies, only four occurred to individual spacecraft without some form of repetition within a program. That is, two spacecraft on one program each had a thermal anomaly, four spacecraft on another program had one each, and so on for a total of 12 anomalies. Almost all 16 anomalies involve temperature

increases, high rates of temperature rise and excessive temperatures. In one case, "hazardous spacecraft overheating" is reported, but most of the anomalies did not jeopardize mission success.

Thus, in general, PRC feels the PRC Space Data Bank indicates that thermal control design and implementation approaches are well in-hand. Thermal coatings as well as materials such as aluminized mylar and kapton are readily available and their properties appear to be well understood. Two of the thermal anomalies, however, suggest that in some cases in-space evaluation would be justified.

One of these two anomalies involves the flaking and outgassing of a black coating, the other a sooner-than-predicted degradation of thermal paints. For these two anomalies, it was reasonably clear that the cause was the space environment; this may also be true for some of the other anomalies where causes either were not or could not be determined.

Based on the performance record of thermal control and the fact that space environmental factors can cause degradation, PRC recommends in-space evaluation for any thermal material or coating which is a departure from those that are currently well understood. Reference 60, for instance, describes a new laminated coating that absorbs particulate radiation at one laminar level and solar radiation at another. PRC feels that in-space evaluation for such new approaches as this would provide useful data that could not otherwise be obtained.

One approach to this experiment would be to place test patches on the LDEF, then retrieve and analyze them on the ground to determine the extent of degradation. An extension of this "passive" approach to the experiment would be to incorporate sensors beneath the test patches to allow the monitoring of temperature data. This "active" approach could be taken if either the nature of the material or coating was a radical departure from that now available, or if the results from a passive experiment indicated that more extensive information was required.

22. Uplink Problems

The PRC Space Data Bank contains 39 anomalies related to problems with the command uplink. The reports on 25 of these anomalies describe only symptoms, such as "drop-outs," "lost lock," "spacecraft could not be contacted," and "commands not executed on first transmission." In one case, failure of the command system to lock-on to the incoming signal caused loss of the spacecraft. In several cases, the ability to contact the spacecraft was lost for unknown reasons, then after periods ranging from several days to over a month, the spacecraft again responded properly--for equally unknown reasons. All command systems in the data base utilize redundant receivers, so it can be assumed that the mechanisms causing such problems effected all of the spacecraft's receivers.

For the other 14 anomalies, more detailed information is available. Two of these involve degraded receiver sensitivity, one a failed calibration oscillator, and one a failed receiver. Two anomalies were due to the RF signal saturating the receiver, and in one case the receiver locked-on to the payload clock. In one case, the receiver confirm signal shifted frequency, and in another a receiver shifted frequency. The remaining five anomalies involve interference of various types.

In addition to the 39 anomalies related specifically to uplink problems, there are 38 more "situations" involving spurious commands. The word "situation" is emphasized here to distinguish between a condition where spurious commands occur, and the actual number of spurious commands. On one spacecraft for instance, one spurious command situation is recorded in the data base, but it encompasses over 50 spurious commands.

For most spurious command situations, little or no information is available beyond that they somehow occurred. Several spacecraft constantly performed some decoded action on commands intended for other spacecraft, but the mechanism causing this as well as the other spurious command situations is usually not known. It is reasonable to assume that uplink problems play some role, but other factors are also undoubtedly involved.

PRC feels that an in-space investigation into this entire uplink problem area is warranted. Little is presently known concerning the causes for these problems, primarily because diagnosis on the ground is restricted due to lack of information on the conditions existing at the receiver. Hence, PRC feels that the objective of the recommended investigation should be to collect and catalog data that will provide a better understanding of the nature of the problems. Since the problems are currently so poorly understood, further study would be required to determine the most promising investigation approach.

V. ECONOMIC FEASIBILITY

The effort conducted to analyze the economic feasibility of the recommended experimental programs was restricted to a level of detail sufficient for initial decision-making purposes. The 22 experimental areas were assumed to constitute a single reliability improvement program, then evaluated to determine if, and under what conditions, this single program would be cost effective. The unknowns involved are too great at this point to attempt any analysis of individual experiment areas or to undertake a more sophisticated cost-benefit analysis.

The time frame of this analysis is the Shuttle era defined herein to extend from about 1981 to the year 2000. It is assumed that the proposed experimental program is accomplished very early in the Shuttle era and that subsequent spacecraft benefit from the results of the experimental program by immediately incorporating all indicated changes. Moderate departures from this assumption are covered in the analysis by the range established for the number of spacecraft launched in the Shuttle era.

A rather large number of mission models have been postulated for the Shuttle era; for this exercise a range of from 20 to 40 satellites per year is assumed. This is close to most mission models and is intended to represent those space missions in the Shuttle era which are similar to those contained in the PRC Space Data Bank. Thus, over the Shuttle era, it is assumed that there will be 400-800 unmanned, individual spacecraft missions.

For the missions of the type considered to be most likely; i.e., relatively long-term, relatively complex spacecraft, the PRC Space Data Bank indicates an average occurrence of about 7.5 anomalies per spacecraft mission. If those anomalies associated with launch and the first 120 hours of spacecraft life are eliminated, there yet remain six anomalies per spacecraft over the average spacecraft life.¹

This translates immediately, of course, into 2400 to 4800 anomalies to be anticipated from unmanned spacecraft in the Shuttle era if the proposed experimental program is not implemented. This assumes that the

¹This data was developed from the analyses presented in Reference 1, where the operational life cycle of over 100 spacecraft of the type under consideration were developed in detail.

frequency and types of anomalies which occur in the future are predicted by those that have occurred in the past, an assumption which is borne out by the analysis of Section III.

The cost of these anomalies is taken to be the sum of the cost of lost data and the cost of added activities incurred as a result of their occurrence. From Reference 1 (page B-8), the average availability of successfully launched spacecraft with Shuttle assistance for the first five days is 69.3 percent. This corresponds to a data loss of 30.7 percent. Without further Shuttle assistance, this would be the percentage of data expected to be lost from the projected missions. The average total cost of the spacecraft missions considered is about $\$58 \times 10^6$. Adding $\$5.25 \times 10^6$ (one-half the cost of a single Shuttle mission) for launch costs gives a total of $\$63.25 \times 10^6$ per spacecraft mission. The cost of lost data then, is in the range:

$$\begin{aligned} 400 \times \$63.25 \times 10^6 \times 0.307 &= \$7.77 \times 10^9 \\ 800 \times \$63.25 \times 10^6 \times 0.307 &= 15.5 \times 10^9 \end{aligned}$$

This assumes equal weight of spacecraft data early and late in the mission and no escalation in average spacecraft cost. The assumption of equal weight is reasonable as most Shuttle era missions can be characterized that way (e.g., communications and meteorological satellites rather than experimental spacecraft). It is highly unlikely that there will be no escalation in spacecraft cost, but the result of making this assumption is conservative, i.e., it results in lower anomaly costs than would otherwise be the case.

The cost of added activities is estimated by assuming no additional Shuttle assistance to anomalous spacecraft, i.e., no repair missions.¹ The activities then are essentially those which occur now. Program offices investigate and document the anomaly and establish procedures to reduce its effect. The cost of this activity is assumed to be 10 percent of all the operational costs which in turn are approximately 10 percent of total spacecraft costs.² This figure then, is in the range:

¹ While repair missions are quite likely in at least some cases, analysis of its economic impact is beyond the scope of this effort.

² Aerospace Report No. ATR-72(723)-1, Integrated Operations/Payloads/Fleet Analysis Final Report, Volume III: System Costs, August 1971, page 3-257; also Mathematica Incorporated, Economic Analysis of New Space Transportation Systems, May 1971, page 6-3.

$$400 \times \$63.25 \times 10^6 \times 0.10 \times 0.10 = \$2.53 \times 10^8$$

$$800 \times \$63.25 \times 10^6 \times 0.10 \times 0.10 = \$5.06 \times 10^8$$

Total anomaly costs, assuming only a Shuttle launch and initial checkout then, are $\$8.0 \times 10^9$ for a 400 spacecraft Shuttle era and $\$16 \times 10^9$ for an 800 mission period. When the anticipated number of anomalies is considered, this makes the cost per anomaly $\$3.33 \times 10^6$.

The cost of the proposed experimental program is the cost of the experimental hardware, its operation, and analysis of the results, plus the cost of Shuttle/Spacelab/LDEF support. For the first cost category, each experimental program is assumed to cost about as much as an Explorer-class satellite, or 15 million dollars per experiment. This cost includes the experiment's own data handling, power supply for LDEF experiments, power conditioning for Spacelab experiments, data analysis and operation. Shuttle support cost is estimated under the assumption that the entire experimental program could be carried out on three dedicated and appropriately time-phased Shuttle missions. This is probably not optimum from a scheduling viewpoint nor is it necessary. It does, however, provide a means for roughly estimating Shuttle support costs. To these two costs, 10 percent is added for integration, LDEF usage, and miscellaneous costs. The total experimental program cost then, is given by:

$$1.10 \left[3(\$10.5 \times 10^6) + 22(\$15 \times 10^6) \right] = \$3.98 \times 10^8$$

The savings to be anticipated from implementation of the program are a function of the number of anomalies prevented. Since, as indicated in Section IV, only 50 percent of the anomalies are being treated by this program, that is the maximum proportion of anomalies which could be eliminated. The number of anomalies to be eliminated is given by:

$$.5N \times E \text{ or,}$$

$$\frac{N}{2} \times E$$

where N = total number of anomalies anticipated without the experimental program, and

E = efficiency of the experimental program.

An E of 90 percent means that 90 percent of the anomalies investigated by the experimental program will be eliminated from future spacecraft.

Under two assumptions of anomalies anticipated without the experimental program and three levels of experimental program efficiency, the following array of anomalies eliminated may be generated:

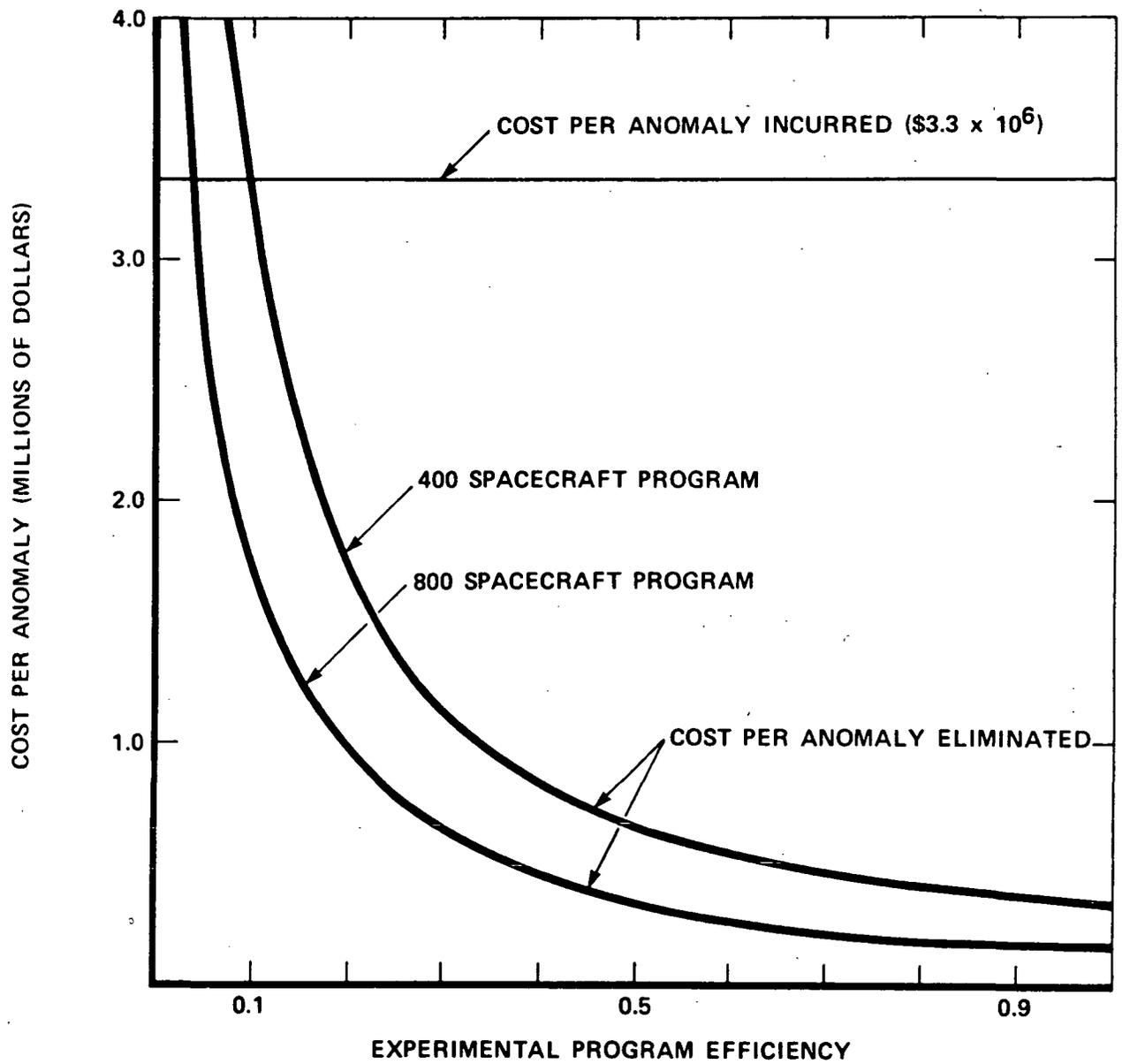
E	N	
	2400	4800
0.10	120	240
0.50	600	1,200
0.90	1,080	2,160

Program costs per anomaly prevented are shown in the following array:

E	N	
	2400	4800
.10	$\$3.32 \times 10^6$	$\$1.66 \times 10^6$
.50	$\$0.66 \times 10^6$	$\$0.33 \times 10^6$
.90	$\$0.37 \times 10^6$	$\$0.18 \times 10^6$
100	$\$0.33 \times 10^6$	$\$0.17 \times 10^6$

The impact of the experimental program is shown graphically in Exhibit V-1. Without the program, there will be six anomalies per spacecraft, on the average, each of which will cost about \$3.3 million. This is represented by the horizontal line in Exhibit V-1. Implementation of the experimental program will result in the elimination of a certain number of anomalies from the Shuttle era spacecraft, depending on the number of spacecraft and the efficiency of the experimental program. From the tabulation above, which shows anomalies eliminated for two assumptions of program size and three levels of experimental program efficiency, it can be seen that the larger the space program or the more efficient the experimental program, the less the cost per anomaly eliminated. This is

EXHIBIT V-1 - ECONOMIC VIABILITY OF RECOMMENDED EXPERIMENTAL PROGRAMS



represented by the two curves in Exhibit V-1. The program is justified wherever the horizontal line exceeds the curved line, i.e., for any efficiency greater than 10 percent for a 400 spacecraft program, and any experimental program efficiency greater than five percent for an 800-spacecraft program.

VI. CONCLUSIONS AND RECOMMENDATIONS

During this study, the anomalies contained in the PRC Space Data Bank were evaluated via two approaches: (1) an anomaly by anomaly evaluation; and (2) a spacecraft by spacecraft evaluation. The first approach was not especially fruitful in that very few individual anomalies were found which could specifically be impacted by an in-space program. The second approach, however, was exceedingly fruitful in a number of ways.

In terms of the objectives of this study, two major conclusions were obvious from the approach two analysis, i.e., (1) a large percentage of the PRC Space Data Bank anomalies fall into 30 clearly defined problem areas; and (2) these problem areas are persistent; each contains relatively evenly distributed anomalies from the earliest spacecraft launches to the most recent. The merging of the results of the approach one and two analyses and the subsequent economic feasibility analysis led to the recommendation of 22 in-space experimental programs. These programs, which are both technically feasible and economically viable, involve in-space applied research or technology evaluations, and could prevent a significant number of anomalies on future spacecraft. These programs could be carried out early in the Shuttle era to the distinct advantage of all space vehicles, especially long-life, unmanned spacecraft. Reliability requirements for these spacecraft are expected to become more severe in the future in order that more complex, and worthwhile, missions may be accomplished.

Since all previous PRC Space Data Bank studies have had other specific objectives, this is the first study that has considered the anomalies on a spacecraft by spacecraft basis. Hence, some features of spacecraft reliability that had been suspected before but which were unsupported by an explicit data analysis were noted. In addition to the clustering of anomalies into the 30 problem area categories and their persistence, as indicated above, this includes several other types of anomaly trends. For instance, the analysis strongly suggests that particular types of spacecraft will have a characteristic type of "anomaly profile."

It is almost inevitable that in a study of this type, some major recommendations will be for more study, and PRC feels that the anomaly trends observed during this study deserve more in-depth analysis. Specifically, those that were not pursued since they were not pertinent to this study should be examined more quantitatively. Also, the problem areas identified in this study should be defined in the kind of detail that is readily usable during design considerations. For such purposes, it would be desirable to assemble additional data on past spacecraft, then, using the observed experience of the data bank, analyze the role of spacecraft reliability in the Shuttle era. PRC believes that such an approach could provide valuable information on the economic impact of differing levels of required reliability.

Since this report has dealt at length with spacecraft anomalies, PRC feels that a point is in order to prevent misinterpretation. While numerous anomalies have occurred, and while some of them have been quite serious, the overall success of the U.S. space program is unquestionable. This fact was borne out in this study as it has been in previous data bank studies. Nevertheless, even trivial anomalies have an economic impact, and all have the potential for reducing mission effectiveness. It is from this viewpoint, PRC believes, that feasible programs for preventing anomalies should be based.

REFERENCES

1. Bloomquist, Charles E., Use of the Space Shuttle to Avoid Spacecraft Anomalies, PRC R-1467, PRC Systems Sciences Company, May 1972
2. Bean, E. E., and C. E. Bloomquist, Study of Reliability Data From In-Flight Spacecraft, PRC R-948, Planning Research Corporation, March 1967, (NASA CR-84628, Accession No. X67=17000)
3. Bean, Eloise E., and Charles E. Bloomquist, "Reliability Data from In-Flight Spacecraft," Proceedings, 1968 Annual Symposium on Reliability, Boston, Massachusetts, January 1968
4. Bloomquist, Charles E., Jerome A. Joseph, and Abraham Leventhal, "Spacecraft Failure Rates--Where Are We?" Proceedings, 1969 Annual Symposium on Reliability, Chicago, Illinois, January 1969
5. Bean, E. E., and C. E. Bloomquist, An Investigation of On/Off Effects on Equipment Operating in Space, PRC R-1293, Planning Research Corporation, October 1969
6. Bean, E. E., and C. E. Bloomquist, The Effects of Ground Storage, Space Dormancy, Standby Operation, and On/Off Cycling on Satellite Electronics, PRC R-1435, Planning Research Corporation, May 1970
7. Bean, E. E., and C. E. Bloomquist, Reliability Analysis and Synthesis, PRC D-1799, Planning Research Corporation, October 1970
8. Bean, E. E., and C. E. Bloomquist, Reliability Data From In-Flight Spacecraft; 1958-1970, PRC R-1453, Planning Research Corporation, November 1971 (AD889943L)
9. Bean, E. E., and C. E. Bloomquist, A Standardized Approach for the Evaluation of Spacecraft Reliability, PRC D-1814, Planning Research Corporation, 30 November 1971
10. Bean, E. E., and C. E. Bloomquist, Addendum to Reliability Data From In-Flight Spacecraft; 1958-1970, PRC D-1864, PRC Systems Sciences Company, November 1972 (AD906048L)
11. Bean, E. E., and C. E. Bloomquist, Some Reliability Information on Spacecraft Batteries and Slip Rings, PRC D-1865, Planning Research Corporation, 30 November 1972
12. Bean, Eloise E., Charles E. Bloomquist, and Jay Finkelstein, "More Reliability Data From In-Flight Spacecraft," Proceedings of 1973 Annual Reliability and Maintainability Symposium, Philadelphia, Pennsylvania, January 1973

13. Bloomquist, Charles E., Some Reliability Information on Vidicon Tubes and Tube Assemblies, PRC D-1865V, Planning Research Corporation, 12 April 1974
14. Cofer, Jr., J. W., Recording of Dynamic Antenna Radiation Patterns, IEEE Transactions on Antennas and Propagation, Vol. AP-21, July 1973 (A73-35699)
15. Sanyal, G. S., Noise Considerations in Space Communication Antennas, Journal of the Institution of Telecommunication Engineers, Vol. 18, Spetember 1972 (A73-20228)
16. Anspaugh, Bruce, Uncertainties in Predicting Solar Panel Power Output, JPL Technical Memorandum 33-673, April 15, 1974, NASA CR-138455 (N74-22710)
17. Carter, Jr., J. R., and H. Y Tada, Solar Cell Radiation Handbook, TRW #21945-6001-RU-00, 28 June 1973. NASA CR-133738 (N73-30055)
18. Berman, P. A., "Study of Interaction Among Silicon, Lithium, Oxygen, and Radiation-Induced Defects for Radiation-Hardened Solar Cells," JPL Quarterly Technical Review, Vol. 3, No. 1, April 1973. NASA CR 135529 (N73-32836 through N73-32841)
19. Goldsmith, J. V., and L. D. Runkle, "The Performance of Solar Arrays in Deep Space," Proceedings of International Congress on the Sun in the Service of Man, Paris, France, July 2-6, 1973 (A74-24931)
20. Stofel, E., "Spacecraft-Electrical Power," Proceedings of EASCON '73: Electronics and Aerospace Systems Convention, Washington, D.C., September 17-19, 1973 (A74-12201)
21. Arndt, R. A., "Effects of Radiation on the Violet Solar Cell," COMSAT Physics Laboratory, Clarksburg, Maryland, COMSAT Technical Review, Vol. 4, Spring 1974 (A74-32908)
22. Massie, Jowell D., "The Flexible Solar Array--A Spacecraft Electrical Power Source Technology Option," Proceedings of 7th Inter-society Energy Conversion Engineering Conference, San Diego, California, September 25-29, 1972 (A73-22790)
23. Ford, Floyd E., et al, Progress in Electrochemical Storage for Battery Systems, NASA TM X-66129, September 1972 (N73-13049)
24. McCallum, J., R. E. Thomas, and J. H. Waite, Accelerated Testing of Space Batteries, NASA SP-323, 1973 (N73-21958)
25. Harkness, J. D., Evaluation Program for Secondary Spacecraft Cells, Eleventh Annual Report of Cycle Life Test, NASA CR-142374, January 1975 (N75-19822)

26. Harkness, J. D., Evaluation Program for Secondary Spacecraft Cells: Initial Evaluation Tests of General Electric Co. 6.0 Ampere-Hour Nickel-Cadmium Spacecraft Cells With Auxiliary Electrodes for the Atmospheric Explorer Satellite C and D, January 2, 1974, AD771 993 (N74-18734)
27. Klein, M., and B. S. Baker, Nickel-Hydrogen Battery System, Proceedings of 9th Intersociety Energy Conversion Engineering Conference, San Francisco, California, August 26-30, 1974 (A75-10492)
28. Coggi, J. V., "Heat Pipe Thermal Control of Spacecraft Batteries," Proceedings of 5th Intersociety Energy Conversion Engineering Conference, Las Vegas, Nevada, September 21-25, 1970 (A73-25992)
29. Kerr, R. L., and D. N. Stager, "Kilowatt Battery Systems," Proceedings of 7th Intersociety Energy Conversion Engineering Conference, San Diego, California, September 25-29, 1972 (A73-22756)
30. Allen, Roger, Technology Forecasting V: Components, IEEE Spectrum, April 1975
31. Allen, Roger, Circuit/System Building Blocks, IEEE Spectrum, January 1975
32. Fairchild Camera and Instrument Corporation., Charge Coupled Device Image Sensor Study; Final Report, NASA CR-136937, February 1974, (N74-17168)
33. Abell, Gurdon R., and George Philippou, Improved Acquisition of Targets Seen Against the Daylight Sky, (A74-32267), Optical Engineering, March/April 1974
34. Goldman, Robert L., Instability of a Gravity Gradient Satellite Due to Thermal Distortion, Final Report. NASA CR-2516 (N75-19331), March 1975
35. Grumman Aerospace Corporation, Large Variable Conductance Heat Pipe, Final Report: Transverse Header, NASA CR-120640, 1975. (N75-18514)
36. Van Dijk, P., "Infra-red Detection for Satellite Attitude Sensing: The ANS Horizon Sensor," Proceedings of 1st European Electro-optics Markets and Technology Conference, Geneva, Switzerland, September 13-15, 1972 (A73-32853)
37. Simcox, D. G., et al, "An Attitude Determination Experiment for Evaluation of In-Flight Performance of Two New Spacecraft Attitude Sensors," Proceedings of American Institute of Aeronautics and Astronautics, Mechanics and Control of Flight Conference, Anaheim, California, August 5-9, 1974, Paper 74-892, (A74-37873)

38. Barnes Engineering Company, Accurate, Reliable Prototype Earth Horizon Sensor Head, NASA CR-132267, May 1973 (N73-32334)
39. Stevens, John N., Determination of the Extent of Ion Thruster Efflux Deposition on Spacecraft Surfaces from the SERT-II Flight Thermal Data, NASA TM X-71642 (N75-14829), 1975
40. Kemp, R. F., D. F. Hall, and E. E. Luedke, Electrostatic Propulsion Beam Divergence Effects on Spacecraft Surfaces, Volume III, Final Report. TRW No. 11985-6003-RU-00 (N74-17510), 15 September 1973
41. Goldenberg, N., "RTG Technology Development--Where We Are/Where We Are Going," Proceedings of 9th Intersociety Energy Conversion Engineering Conference, San Francisco, California, August 26-30, 1974 (A75-10496)
42. Gillis, Joseph A., A Power Conditioning System for Radioisotope Thermoelectric Generator Energy Sources, Goddard Space Flight Center X-711-74-164, June 1974. NASA TM X-70678 (N74-28106)
43. Johnson, Jr., S. M., "Radiation Effects on Multiplier Phototubes," Proceedings of 19th Nuclear Science Symposium, Miami, Florida, December 6-8, 1972; IEEE Transactions on Nuclear Science, Vol. NS-20, February 1973 (A73-25960)
44. Inouye, G. T., Spacecraft Charging Model, "Journal of Spacecraft and Rockets, Volume 12, Number 10, October 1975.
45. McPherson, D. A., et al, Spacecraft Charging at High Altitudes: SCATHA Satellite Program, "Journal of Spacecraft and Rockets, Volume 12, Number 10, October 1975
46. Domitz, Stanley, and Normal T. Grier, The Interaction of Spacecraft High Voltage Power Systems with the Space Plasma Environment, NASA TM-X-71554, June 1974 (N74-27390)
47. Henrikson, C. H., et al, "Magnetically Suspended Momentum Wheels for Spacecraft Stabilization," Proceedings of 12th American Institute of Aeronautics and Astronautics Aerospace Sciences Meeting, Washington, D.C., January 30-February 1, 1974 (A74-18786)
48. Sabnis, A. V., et al, "Magnetically Suspended Large Momentum Wheels," Proceedings of American Institute of Aeronautics and Astronautics, Mechanics and Control of Flight Conference, Anaheim, California, August 5-9, 1974 (A74-37880)
49. Gates, R. L., and S. C. Wright, "A Dual-Spin Gas-Bearing Reaction Wheel," Proceedings of American Institute of Aeronautics and Astronautics, Guidance and Control Conference, Key Biscayne, Florida, August 20-22, 1973 (A73-38841)

50. Gutshall, R. L., et al, Star Scanner, Patent Application, NASA-Case GSC-11569-1, Filed 29 September 1972 (N73-11404)
51. Schenkel, F. W., and A. Finkel, "Star Sensor/Mapper for the Small Astronomy Satellites," Proceedings of the Seminar-in-Depth, Instrumentation in Astronomy, Tucson, Arizona, March 13-15, 1972 (A73-21773)
52. De Cov, A. B., Interferometric Star Tracking, Applied Optics, Vol. 13, February 1974 (A74-19533)
53. Report of the Tape Recorder Action Plan Committee, March 21, 1972, N73-15225
54. Thompson, C. R., and J. M. Hayes, "High-Data Rate, Spacecraft Tape Recorders," Proceedings of 1972 National Telecommunications Conference, Houston, Texas, December 1972 (A73-14383)
55. Hoffman, J. K., "Magnetic Tape Transport for High Reliability in Space," Proceedings of Management and Design of Long-Life Systems Symposium, Denver, Colorado, April 24-26, 1973 (A75-16619)
56. Eshleman, R. L., et al, Feasibility Model of a High Reliability Five-Year Tape Transport, ITT Technical Report, Volume II, October 1973, NASA CR-132898 (N74-14895)
57. Florancic, M., and H. Reiner, Megabit Memory for Helios Space Probe, "Electrical Communication," Vol. 49, Number 3, 1974 (A75-10057)
58. Allen, Roger, Semiconductor Memories, IEEE Spectrum, August 1975
59. Friedrich, O. M., and A. A. Dougal, "Optical Data Storage and Data Processing, and Holography in Aerospace and Electronic Instrumentation," Proceedings of 25th Annual Southwestern Conference and Exhibition, Houston, Texas, April 4-6, 1973 (A73-35382)
60. Slemp, Wayne S., Particulate and Solar Radiation Stable Coating for Spacecraft, Patent Application, NASA Case LAR-10805-1, December 1973 (N74-16246)
61. Anspaugh, B. E., ATS-5 Solar Cell Experiment Results After One Year in Synchronous Orbit, JPL Technical Memorandum 33-522, January 1, 1972. NASA-CR-125061 (N72-14030)

APPENDIX A PRC SPACE DATA BANK UPDATE

I. SCOPE

The most recent update of the PRC Space Data Bank¹ incorporated all operational reliability data from inflight spacecraft received by PRC through the middle of calendar year 1972 with a few minor exceptions noted in the report. The published data,^{1,2,3} together with supporting source documents and working papers form the PRC Space Data Bank.

While the PRC Space Data Bank is considered to be adequate for the purposes of this study, the desirability of extending the data base is manifest. Thus, the excluded data from the last update have been analyzed and included as part of the data base for this study. Since these data are so sparse, however, it was also decided to include readily available data from programs with established contacts and a record of cooperation. This has been done.

The programs mentioned in the most recent Space Data Bank publication include PIONEER, MARINER, ERTS (LANDSAT), and SOLRAD. Programs from which additional data were sought are PIONEER, MARINER, ERTS (LANDSAT), and ATS. The general results are given in Sections II through VI of this appendix and a composite anomaly listing is given in Section VII.

It should be made clear that there are strong indications of ample data available from other sources and more information could have been

¹ Bean, E. E., and C.E. Bloomquist, Addendum to Reliability Data From In-Flight Spacecraft; 1958-1970, PRC D-1864, PRC Systems Sciences Company, November 1972 (AD906048L)

² Bean, E.E., and C.E. Bloomquist, Reliability Data From In-Flight Spacecraft; 1958-1970, PRC R-1453, Planning Research Corporation, November 1971 (AD889943L)

³ Bean, E.E., and C.E. Bloomquist, Study of Reliability Data From In-Flight Spacecraft, PRC R-948, Planning Research Corporation, March 1967, (NASA CR-84628, Accession No. X67-17000)

derived from the programs mentioned. However, due to budget and schedule constraints, update efforts were limited to the programs listed and, furthermore, only data regarding anomalies were considered.

In this very restricted effort, 173 anomalies were found which, interestingly enough, do not appear to be significantly different from a random sample of anomalies from the published PRC Space Data Bank. Thus, not only is the anomaly data base increased by about 10 percent with anomalies occurring more recently than those in the most recent publication, but the entire data base appears to be relatively homogeneous.

II. SOLRAD

The Naval Research Laboratory's SOLRAD (Solar Radiation) program consists of eight successful satellites launched to make continuous measurement of the sun's emission in the x-ray band. The PRC Space Data Bank currently contains data on SOLRAD's 1, 8, and 9. No additional data have been received on SOLRAD's 1 through 8. Data received but not included in the PRC Space Data Bank publications indicate that SOLRAD 9 operated an additional 10 months with no additional anomalies. Hence, this satellite is not considered any further in this update.

SOLRAD 10 was not previously considered. Rather extensive data on the configuration and intended mission of this satellite have been received but essentially nothing on its operation. It was successfully launched and operated for some indeterminate period of time; two experiment failures were noted in the available documentation. Table I (General Data Elements) of the PRC Space Data Bank standard engineering analysis report (EAR)¹ is included here as Exhibit A1. The anomalous behavior descriptions (Table IV of the EAR) are incorporated into Exhibit A7 at the end of this appendix.

The significance of this satellite program update for the current study is minimal; it is included for completeness rather than its contribution. Additional data are surely available but the effort needed to acquire such data was judged to be too great to be borne by this study project.

References

1. Horan, Donald M. and Robert W. Kreplin, The SOLRAD 10 Satellite, Explorer 44, 1971-058A, NRL Report 7408, Naval Research Laboratory, July 12, 1972
2. NASA Press Kit, NRL/NASA SOLRAD 10 (C), Release No. 71-115, National Aeronautics and Space Administration, July 2, 1971

¹ Bean, E.E., and C.E. Bloomquist, Reliability Data From In-Flight Spacecraft; 1958-1970, PRC R-1453, Planning Research Corporation, November 1971 (AD889943L), Appendix B, Section II fully describes the engineering analysis report which is generated for each spacecraft in the Space Data Bank.

Mission; SOLRAD 10

Launch Vehicle: Scout B

Launch Date: 8 July 1971

Orbit Parameters: 51.0° inclination, 620 kilometer
(340 nautical mile) apogee, 430
kilometer (235 nautical mile)
perigee, 95.3 minute period.

Mission Objectives: To make continuous measurements of
the sun's emission in the x-ray band.

Performance Evaluation: None specifically available. It was
successfully launched and apparently
operated for a number of months. Two
experiment failures were noted within
four months which implies that the
other 12 operated successfully for at
least that period.

Sponsoring Agency: Naval Research Laboratory.

III. ATS

The spacecraft of the Applications Technology Satellite program are designed to carry as a payload, a group of technological and scientific experiments. The experiments can be divided into five groups according to experimental emphasis: (1) communications, (2) meteorology, (3) spacecraft stabilization, (4) other technological experiments, and (5) environmental measurement. The spacecraft are large and complex, and are usually placed in stationary orbits. Six ATS spacecraft have been launched to date. ATS-1 through 5 are included in the PRC Space Data Bank publications.

No additional data of any significance to this study have been obtained on the first five spacecraft. A wealth of data has been obtained for ATS-6, however, none of which was previously included in the data bank.

ATS-F before its launch, this sixth spacecraft in the ATS series carries a number of applications experiments. It is stationed in synchronous orbit and contains a wide range of communications equipment that can be command-configured in numerous ways to assess techniques for aircraft tracking, spacecraft tracking, television relay and so forth. A unique feature of ATS-6 is its 30-foot, space deployable, parabolic reflector antenna. To conduct its various experiments, the spacecraft must maintain high-precision, three-axis stabilization (to 0.1 degree). In addition to its experimental communication equipment, other experiments include an ion engine, interferometer, environmental measurements package, and a radiometer.

The spacecraft was launched 30 May 1974, and as of 8 December 1975 was still operable. A number of anomalies have occurred but they have not jeopardized mission success. Many of the anomalies are due to operational problems stemming from the complexity of the spacecraft.

General data elements are given in Exhibit A2, and anomalous behavior descriptions are compiled in Exhibit A7.

References

1. Various flight anomaly reports, summaries, and other interoffice communications supplied by Ken Kissin of Goddard Space Flight Center, 5 December 1975 (retained in the ATS-6 EAR).
2. Final Report for ATS F & G Independent Reliability Assessment, R-1818, PRC Systems Sciences Company, May 1974.

Mission: ATS-6 (ATS-F)

Launch Vehicle: Titan III-C

Launch Date: 30 May 1974

Orbit Parameters: 42,160 kilometer synchronous orbit; spacecraft can be restationed and has been.

Mission Objectives: To demonstrate the feasibility of long duration, precision pointing, three-axis stabilized flight at synchronous altitude for various applications and scientific payloads. A successful flight of a minimum of two years duration is required.

Performance Evaluation: The spacecraft has been generally successful in spite of a number of anomalies but still has about 6 months of operation to go to be called an unqualified success.

Sponsoring Agency/
Prime Contractor: Goddard Space Flight Center/Fairchild-Hiller.

IV. ERTS (LANDSAT)

The ERTS, or as it is now called, the LANDSAT program, is a follow-on to the NIMBUS program. Four NIMBUS meteorological satellites were orbited to develop the capability incorporated into ERTS-1 (now LANDSAT-1). The ERTS program objective was to demonstrate the capability and usefulness of remote sensing of conditions on the earth's surface on a global scale and on a repetitive basis. Specifically, the ERTS program determined what data can be gathered by unmanned spacecraft, how this data can be interpreted and applied to a diversity of endeavors, and how the information yield can be of economic or social value to commercial, scientific, and government interests. The spacecraft weighs nearly 900 kilograms (2000 pounds) with over 200 kilograms (440 pounds) devoted to sensors, communications, and related electronics equipment.

The earlier NIMBUS spacecraft are included in the PRC Space Data Bank and no new information was acquired in this update. ERTS-1 (LANDSAT-1) information was acquired and the general data elements are included in Exhibit A3. Anomalous behavior descriptions are compiled in Exhibit A7. Preliminary information was received on LANDSAT-2 but was not analyzed due to a lack of operating time on the spacecraft and the occurrence of significant anomalies coupled with a lack of resources and time in this study project.

While ERTS-1 was highly successful, there were quite a few anomalies, and in several cases they could have considerably reduced mission success had it not been for redundancy and a good bit of luck. The early loss of the return beam vidicon (one of 2 prime sensors) was mitigated by the fact that the multispectral scanner (MSS) was collecting far better data than expected. This piece of "luck" resulted in the MSS carrying out all ERTS objectives. Redundant units switched include the s-band transmitter, the rate measuring package, and the narrow band tape recorder.

References

1. ERTS-1 Flight Evaluation Reports: 735D4224, 27 February 1973; 735D4260, 10 August 1973; 735D4274, 28 November 1973; 745D4205, 26 February 1974; 745D4217, 18 May 1974; 745D4236, 15 August 1974; 745D4255, 31 December 1974; prepared by General Electric ERTS Operations Control Center for the Goddard Space Flight Center.

2. LANDSAT-1 Flight Evaluation Report, 755D4222, 30 April 1975, prepared by General Electric LANDSAT Operations Control Center for the Goddard Space Flight Center.

3. LANDSAT-1 and LANDSAT-2 Evaluation Report, 755DS4228, 15 August 1975, prepared by General Electric LANDSAT Operations Control Center for the Goddard Space Flight Center.

Mission: ERTS-1 (LANDSAT-1)

Launch Vehicle: Delta 900

Launch Date: 23 July 1972

Orbit Parameters: Near-polar, 900 kilometer (500 nautical mile) circular orbit

Mission Objectives: To demonstrate the usefulness of remote sensing of conditions on the Earth's surface on a global scale and on a repetitive basis

Performance Evaluation: Data returned has surpassed all expectations, both in volume and quality. Some equipment problems have been encountered but mission objectives were met.

Sponsoring Agency/
Prime Contractor: Goddard Space Flight Center/General Electric

EXHIBIT A3 - General Data Elements for ERTS-1 (LANDSAT-1)

V. PIONEER

Three generations of Pioneer missions have thus far provided information from interplanetary space. The first five Pioneer space probes were launched on a variety of missions ranging from lunar to deep space exploration; the first was launched in 1958 and the last in 1960. Due to sparsity of data none of these spacecraft are included in the PRC Space Data Bank.

The second generation of Pioneers all orbit the Sun and are designed to return data on fields and particles of the solar wind and plasma particles originating from the Sun and the galaxy. In addition they map the magnetic field of outer space. This generation includes Pioneers 6 through 9 and one unsuccessful launch (Pioneer E). Data are included in the PRC Space Data Bank on these spacecraft. Launch dates range from December 1965 through August 1969; Data Bank coverage currently extends through 15 September 1970. While ample evidence has been received of continued operation of these spacecraft very little is available regarding anomalous behavior. Some of this is due to the minimal Deep Space Network (DSN) coverage resulting from the DSN response to more pressing needs including Pioneers 10 and 11. Evidence has been received of successful operation of all four spacecraft for at least two years beyond that recorded in the published PRC Space Data Bank and in December 1975, Pioneer 6 completed ten years in orbit with all subsystems except the magnetometer operating well. However, since no further significant anomaly data are available no further effort to update the data bank with respect to these spacecraft has been made.

Pioneers 10 and 11 constitute the third generation. The objectives of these spacecraft are to conduct exploratory investigations beyond the orbit of Mars of the interplanetary medium, the nature of the asteroid belt and the environmental and atmospheric characteristics of the planet Jupiter. Pioneer 10 was launched 2 March 1972 and Pioneer 11 was launched 5 April 1973. Both spacecraft have encountered Jupiter and continue to operate on extended missions, Pioneer 10 to eventually leave the solar

system and Pioneer 11 to encounter Saturn. The previously published PRC Space Data Bank contains no data on these spacecraft. Exhibits A4 and A5 provide the general data elements for Pioneers 10 and 11. Exhibit 7 compiles the anomalous behavior descriptions for both spacecraft.

References

1. Letter PAS-2-59(244-8) from Charles F. Hall, Pioneer Project Manager to Eloise E. Bean, Planning Research Corporation, dated 13 October 1972.
2. Pioneer Document P-201, Pioneer F/G Technical Plan, 30 June 1970.
3. "Anomalies Packages for Pioneers 10 and 11" transmitted by letter RQ:244-5/191-75 from F. F. DeMuth, Ames Research Center to C. E. Bloomquist, PRC Systems Sciences Company, dated 4 December 1975.

Mission: Pioneer 10

Launch Vehicle: Atlas SLV-3C/Centaur D/TE-364-4

Launch Date: March 3, 1972 (01:49 GMT)

Orbit Parameters: Jupiter Flyby
1st Midcourse maneuver day 6
2nd Midcourse maneuver day 21
Jupiter encounter - 12/3/73

Mission Objectives: 1) To conduct exploratory investigations beyond the orbit of Mars, 2) to investigate the nature of the asteroid belt, and 3) to investigate the environmental and atmospheric characteristics of Jupiter.

Performance Evaluation: Highly successful.

Sponsoring Agency: Ames Research Center

Mission: Pioneer 11 (G)

Launch Vehicle: Atlas Centaur TE 364-4

Launch Date: April 6, 1973 (02:11 GMT)

Orbit Parameters: Jupiter Flyby
1) Transit thru asteroid belt:
~9/10/73 - 10/10/73
2) Passed bow shock of Jupiter
without incident: 11/26/74
3) Jupiter encounter phase:
2/25/74 - 1/3/75
4) Periapsis: 12/3/74

Mission Objectives: 1) To conduct exploratory
investigations beyond the
orbit of Mars, 2) to
investigate the environmental
and atmospheric characteristics
of Jupiter.

Performance Evaluation: Highly successful.

Sponsoring Agency: Ames Research Center

VI. MARINER

The ten spacecraft of the JPL Mariner series (with the exception of three launch failures) have all been quite successful and have contributed a great deal of highly significant data toward the understanding of our solar system. There have been four successful missions to Mars, two to Venus, and the highly productive Mariner Venus/Mercury launched in 1973, also referred to as Mariner 10. Mariners 1 through 7 are included in the PRC Space Data Bank publications. There are no further data from these spacecraft and no details on the Mariner 8 launch failure or the Mars orbiter, Mariner 9. Data on Mariner 10, however, are available from Reference 1 and are incorporated in this update.

The spacecraft design was derived from the JPL Mariner series, with some new subsystems and special modifications added as required by its sunward trajectory. The spacecraft's TV cameras took the first pictures of both Venus and Mercury. The mission was the first multiplanet mission and the first to use a gravity-assist technique.

The Mariner 10 scientific instrument complement was selected with the primary objective of conducting an exploratory investigation of Mercury. A brief description of the experiments follows:

- (1) A dual fluxgate magnetometer, mounted on a 6-m boom, measured magnetic fields.
- (2) A plasma science instrument measured energy and directional spectra of solar wind protons and electrons.
- (3) A charged-particle telescope measured high-energy ions and electrons.
- (4) Two extreme ultraviolet spectrometers (occultation spectrometer and airglow spectrometer) measured pressure and composition of the Hermian atmosphere.
- (5) A body-mounted infrared radiometer measured surface thermal properties.
- (6) Television cameras provided high-resolution imaging at long slant range.

The spacecraft was launched 3 November 1973 and operated in space continuously for over 16 months, including two complete orbits of the sun and three encounters with Mercury. Mariner 10 used the last of its attitude control gas supply at approximately 11:25 GMT on March 24, 1975, and the spacecraft transmitter was turned off for the last time.

General data elements are given in Exhibit A6 and the anomalous behavior descriptions are incorporated in Exhibit A7.

Reference

1. Paul, Floyd A., A Study of Mariner 10 Flight Experiences and Some Flight Piece Part Failure Rate Computations, Technical Memorandum 33-759, Jet Propulsion Laboratory, January 15, 1976.

Mission: Mariner 10 (Mariner Venus/Mercury 1973)

Launch Vehicle: Atlas/Centaur

Launch Date: 3 November 1973

Orbital Parameters: Venus flyby using a gravity assist into a solar orbit encounter with Mercury

Mission Objectives:

- 1) To conduct exploratory investigations of the planet Mercury's environment, atmosphere, surface, and body characteristics during the 1973 Mercury opportunity.
- 2) To obtain environmental and atmospheric data from Venus during the flyby of Venus, to perform interplanetary experiments while the spacecraft is enroute from Earth to Mercury, and to obtain experience with a dual-planet, gravity-assist mission.

Performance Evaluation: The spacecraft was highly successful in spite of a number of anomalies and fully achieved both mission objectives.

Sponsoring Agency/Prime Contractor: Jet Propulsion Laboratory/Boeing Aerospace Company

VII.. ANOMALY LISTING

The 173 anomalies experienced by the six spacecraft included in this update of the PRC Space Data Bank are listed in the following pages as Exhibit A7. While PRC usually codes anomalies in order of time-of-occurrence for published data base material, this coding was not necessary for the analyses conducted during this study and would have been a superfluous step. Therefore, the anomalies listed in Exhibit A7 have simply been randomized in a manner that masks the identity of the spacecraft.

Identification	Time to Failure	Consequences	Comments
1. TV heaters failed to cycle through positions. Most likely cause is leakage path from heater circuit-rw dc power line to chassis biasing off FDS MOSFETs that control TV optics heater. Optics heater came on 1-17-74 when direct command DC-64 sent.	€	Functional redundancy provided "work-around."	PFR5001.
2. MAG temperature at -54°C (-66°F), 11.1°C (20°F) lower than predicted. Heater function verified by manual command. Not a thermal anomaly; interpretation problem.	€	No effect on mission.	PFR5002. MAG=Magnetometer.
3. Comstor B, cell 12 verified with a 256 second change in the required execute time.	Orbit 583	Has occurred 13 times; each time a second try verified correctly.	Cause unknown, see item #87.
4. Orbit adjust subsystem firing gave 60% of computed thrust.	Orbit 38	Trivial; has been fired 5 times and all longer burns produced very near computed thrust.	
5. Power output of the "A" S-band xmitter has dropped to 0.6 watts (was 1.6 watts at launch).	Orbit 2600 (began at orbit 808)	Insignificant, system performance still exceeds link margin requirements. If decline continues, would eventually have to use other xmitter.	See item #89, #147.

EXHIBIT A7 - ANOMALOUS BEHAVIOR DESCRIPTIONS

Identification	Time to Failure	Consequences	Comments
6. Missing thruster pulses as indicated by TLM.	During 1st 6 days	No effect. 33 out of 192 pulse counts were missed during initial reorientation, conscans, and the first midcourse maneuver. Doppler measurements of s/c response to thrusting commands indicate that the pulses were not actually missed.	Thrusters were precession pair #2. Anomaly attributed to erratic thruster pressure switch, which is used only for assessment of firing, not for control.
7. Separation switch started sequencer 99 seconds early.	Post injection	Switch was apparently activated during or at end of 3rd stage burn, rather than at separation. No adverse effect because sequencer time margins were designed to be great enough to accommodate such an event.	Some references say 90 seconds early; apparently a typo. The sequencer is the CDU sequencer.
8. Battery temp. 13 ^o F higher than expected.	Day 1	No effect, s/c put in more thermally benign attitude for several weeks.	Attributed to lapse in testing procedure.
9. RGA #1 roll gyro null high during initial earth acquisition.	Day 13	RGA #1 roll gyro null error is -0.15 ^o /sec; RGA #2 used to complete initial earth acquisition and subsequent acquisitions.	FAR 102 Component anomaly.
10. Solar array shunt tap voltage high.	Day 14	Shunt tap voltage indicates high only at certain times during summer solstice. No other indications of anomalous behavior of array or power conditioning system have been observed.	FAR 401 and 402 Not verified.
11. Daily transient in DOC pitch attitude command.	Day 15	Problem due to programming error; was eliminated by re-programming DOC in flight.	FAR 105
12. Noise cross-coupling in L-band PLACE.	Day 19	Not considered flight anomaly: condition was noted and accepted prior to launch. No significant impact on operations.	FAR 302 Communications problem.

EXHIBIT A7 - (Continued)

Identification	Time to Failure	Consequences	Comments
13. One of two identical, independent ionization chambers sensitive to the 8 to 16 Angstrom band of the x-ray spectrum ceased its detection function for an unknown cause.	(Within two months of launch)	None, due to redundancy.	Identical to similar chamber on previous spacecraft which continued to operate 48 months after launch. Reference 1, Page 7.
14. Lyman-Alpha Flare Detector failed.	(Within one month of launch)	Loss of anticipated data.	Reference 1, Page 8.
15. IPP solar diffuser was ~65% as bright as the calibration lamp.	Day 335	Apparently the diffuser results are nominal but this could have some impact on measurements near a 10° sun-look angle.	Solar diffuser 1st looked at on day 335, thus revealing this and anomaly #65.
16. Sensitivity of the 4 IPP channeltron detectors not well balanced.	Assumed subsequent to day 335	Apparently not significant. Channel 2 (Red?) about twice as sensitive as channel 1 (blue?), depending somewhat on color and polarization of object being observed. For Mode 4 images of Jupiter, red signal will be twice the blue signal, precluding use of the automatic gain decrement function for maintaining optimum gain settings.	

EXHIBIT A7 - (Continued)

Identification	Time to Failure	Consequences	Comments
17. C-band xmitter power drop.	Day 4	Minimized/eliminated by use of the 6db attenuator in the driver ckt. w/ no adverse effects on s/c or experiment operations.	Periodically observed by ground stations. (FAR #301) component anomaly.
18. Occasional loss of YIRU Rate Bias.	Day 8	Would effect yaw control accuracy in offset pointing maneuvers; however, YIRU is in stand-by back-up mode and PSA is used for yaw control.	FAR 103 Component anomaly.
19. EME-U. of N. Hamp. exp. failure (and others).	Day 9	Initial turn-on of the U. of N. Hamp. exp. caused permanent malfunction in the 64 level word #189; affected all EME housekeeping data.	FAR 710, Refers to FAR 710-A-G for other EME anomalies; not clear that PRC has those FAR's. GFE experiment anomaly.
20. MMW 20 GHz H1 TWTA failure.	Day 13	All attempts to turn on the millimeter wave 20 GHz horn-TWTA in flight have failed. The 2nd 20 GHz TWTA operates properly.	FAR 709 GFE experiment anomaly.
21. Inteferometer IFZ operates intermittently.	Day 13	IF-2 initially operated intermittently, subsequently failed. F-1 channel can be used for interferometer operations.	FAR 101 Component anomaly.
22. PSE scan package temperature 5.5°C (10°F) below specification limit. PSE temperature was low because PSE not on early in mission and combination of supplemental heater size, test errors, and lower unregulated dc supply voltage. No corrective action.		No effect on mission.	PFR5003. PSE=Plasma Science Experiment.

EXHIBIT A7 - (Continued)

Identification	Time to Failure	Consequences	Comments
23. Power transient in WB Video Tape Recorder #2.	Orbit 148	Disabled the unit-used 2nd unit.	Attributed to short between T2 transformer taps in WBVTR dc-dc converter.
24. Return Beam Vidicon failed to respond to "off" command.	Orbit 196	RBV commanded "off" by alternate commands. Since then, mission has been performed with the Multi-Spectral Scanner.	Problem believed to be associated with relay system that feeds power to the RBV.
25. Array degradation slightly higher than projected.	During 1st 3 months	Insignificant, power requirements can be met.	Possibility of degradation due to solar flares.
26. Battery temperature spread increased.	During 1st 3 months	Insignificant, battery performance good. Spread apparently later returned to nominal.	
27. Perturbations due to sun glint in the IR horizon scanners.	During 1st 3 months	Not disruptive enough to necessitate single scanner mode.	
28. More thruster spin coupling than expected.	?	No significant mission effect. Apparently due to 1 thruster having $\sim 1.5^\circ$ offset in its thrust axis.	Similar occurrence on subsequent spacecraft leads to conclusion that plume reflection is responsible, a design error.
29. Thruster temperature sensor erratic.	Day 1	Problem apparently in sensor, so no mission effect.	

EXHIBIT A7 - (Continued)

Identification	Time to Failure	Consequences	Comments
30. Synthesizer interferes with RFI experiment.	Day 19	Not considered flight anomaly since condition was known before launch. RFI experiment detects synthesizer output; problem avoided by turning synthesizer off during RFI experiment operations.	FAR 303 Communications problem.
31. C-band ECH/PFF receive coupling.	Day 20	Isolation between the Earth Coverage Horn and the Prime Focus Feed, provided by C-band receive switch, less than anticipated. Additional isolation when req'd. (such as when receiving on ECH while pointing to transmitting station) is provided by PFF polarization switch.	FAR 304 Communications problem.
32. HET negative power spikes.	Day 20	Not considered flight anomaly as condition could not be verified between Rosman and IDA. No subsequent power drops observed.	FAR 702 Not verified.
33. TWT amplifier showed erratic drops in output power of several db, lasting for several hours.	Day 37	Redundant unit switched-in.	No further information given.
34. Imaging photopolarimeter (IPP) calibration lamp values low by ~10%.	Day 2	Not significant; due to pressure change on the high voltage power supply (was Mode 3 calibration lamp).	It is not clear how many of these IPP anomalies (i.e., #15, #16, #34, #35, #63, #64, #65) are cause and effect. They appear very related.
35. IPP Aperture anomalies in a few rolls of data.	~ Day 60 to Day 150	Not significant; The "phosphor source" position came into place once every few hundred rolls of Mode 3 data. Occurred during the summer of '73, with no subsequent reoccurrence.	

EXHIBIT A7 - (Continued)

Identification	Time to Failure	Consequences	Comments
36. Tracker temperature below specification limit of -6.6°C (20°F). Tracker temperature was low because it dissipates less power when star is acquired than in viewing dark field.		No performance effect, temperature only 1.1°C (2°F) below limit.	PFR5004. Star tracker anomaly.
37. Tracker failed to acquire Vega in brightness gate 2. Vega acquisition missed due to desensitization of tracker by exposure to Earth. Recovery completed within 24 h and is operating satisfactorily.		No effect on mission.	PFR5005. Star tracker anomaly.
38. Solar Array A5 temp. sensor failure.	Day 22	Sensor failed-open; has not impacted flight operations.	FAR 403 Component anomaly.
39. Noisy video pictures on HET.	Day 22	Not considered flight anomaly; due to polarity reversal in HET ground antenna feeds. Performance excellent after field re-work.	FAR 701 Ground problem.
40. Erroneous DOC PSA roll off-set command.	Day 23	Problem could not be duplicated, nor has it recurred.	FAR 106 Not verified.
41. L-Band negative power spikes.	Day 23	Not considered flight anomaly; due to ground station adjustments.	FAR 305 Ground problem.
42. L-Band transmitter noise in absence of an up-link carrier.	Day 29	Not considered flight anomaly; condition known and accepted prior to launch. No significant effect on operations.	FAR 306 Communications problem.

EXHIBIT A7 - (Continued)

Identification	Time to Failure	Consequences	Comments
43. MSS - steady decrease of the calibration-wedge levels in Bands 1 and 2.	Thru 1st 1200 orbits	Not significant. Trend has been reversed to a slight rise.	These cal-wedges used to compute signal to noise ratios.
44. Data collection system experienced several periods of external interference and one 9-day period of fewer than expected messages received.	During 1st 3 months	Insignificant, always returned to normal.	Possibly due to external interference.
45. ACS gating frequency greater than expected.	During 1st 3 months.	Insignificant, later leveled off and only 60% of impulse available at launch has been used.	Long term correlation with seasons and β angle, and short term correlation with payload operation. Phenomenon being studied.
46. Camera temperatures exceeded lower specification limit of -15°C (5°F), due to TV heaters not functioning. TV heaters came on 1-12-74 and camera temperatures returned to normal.	Day 2	Caused by anomaly #1. Apparently no mission effect.	PFR5006.
47. Scanning electrostatic analyzer (SEA) ion and electron counts too low. Possible failure modes were: (1) SEA aperture door failed to open, (2) SEA analyzer plates damaged during launch, and (3) component or solder failure in SEA electronics. Cause unknown.	Day 3	Cited as "significant problem" - not clear what this implies.	PFR5007. Experiment package anomaly (PSE).

EXHIBIT A7 - (Continued)

Identification	Time to Failure	Consequences	Comments
48. Incorrect scan clock and cone commands reversed scan platform operations program (SPOP). All CC-6 coded commands to be run through SPOP and command generation.	€	A systems problem; apparently no effect on mission.	PFR5008.
49. Scanning electron spectrometer (SES) channel A has 1881 counts added to all data. Problem had cleared when channel A checked on 12-20-73. SES is sensitive to 2.4-kHz rise time and may have cleared due to slight change in rise time.	Day 9	No effect on mission.	PFR5009. Experiment package anomaly (PSE).
50. Ion Engine #2 Turn-on failure.	Day 50	After highly successful operation following initial turn-on, engine failed to turn-on, or, turned off automatically on all subsequent attempts.	FAR 707 GFE experiment anomaly.
51. Solar Array A3 Temp. sensor failure.	Day 60	Same type failure as #38.	FAR 404 Component anomaly.
52. SPS-2 Primary Valve heaters not functioning.	Day 62	Heaters inoperative due to ckt. malfunction; back-up heaters now used.	FAR 001 Component anomaly.
53. L-band/C-band cross talk.	Day 63	During C x L and L x C PLACE test, modulation observed on C-band downlink in the absence of an uplink L-band signal due to noise in the system. Not considered flight anomaly. See item #12.	FAR 310 Communications problem.

EXHIBIT A7 - (Continued)

Identification	Time to Failure	Consequences	Comments
54. Radiometer (VHRR) turn-on failure.	Day 29	Initially, the VHRR scan start was intermittent and tended not to start at housing temps. below 20° c. On 8/15/74, chopper motor failed; exp. has not operated since then.	FAR 703 GFE experiment anomaly.
55. C-band oscillations.	Day 33	Not a flight anomaly: due to faulty ground instrumentation.	FAR 307 Ground problem.
56. ACS loss of control using C-band monopulse as roll/pitch sensor.	Day 43	Due to procedural difficulties; subsequent operations on C-band monopulse were satisfactory.	FAR 107 Ground problem.
57. Radio beacon interferes w/ S and C return link for T and DR Exp.	Day 47	Problem avoided operationally by turning off Radio Beacon during T and DRE (Tracking and Data Relay Exp.) operations involving s-band x c-band link.	FAR 308 Communications problem.
58. Slight increase in yaw motor drive duty cycle.	Orbit 1870	Lasted for several days - minor. Settled back near Orbit 3500	} Being investigated; anomalies still occur occasionally for short periods (thru orbit 7651). The one in pitch became more sustained. ~ 12/20/73.
59. Small excursion of roll drive duty cycle.	Orbit 1890	Minor-returned to normal after several orbits.	
60. Pitch drive duty cycle increased sharply.	Orbit 2150	Returned to normal after 15 orbits;	
61. WPA #1 came on with lowered power output.	Orbit 1890	Had been off since orbit 196; when turned on again, its power was down by 0.3db. Finally increased so that after 200 orbits was back to post-launch value. WPA 2 has remained essentially constant.	
62. Thermal anomaly of right fwd. sun sensor.	Orbit 4	No further information given except temperature high.	

EXHIBIT A7 - (Continued)

Identification	Time to Failure	Consequences	Comments
63. Occasional uncommanded gain decrements in the IPP.	Over the 1st year of operation.	Not significant. They appear unpredictably once every few hours, mostly at the high gains. Apparently a disabling command is available to by-pass this fault during Jupiter fly-by.	
64. IPP channeltrons show a momentary surge in sensitivity at the instant of a gain increment.	Over the 1st year of operation	Not significant. Causes elevated signal levels for ~0.5 seconds (i.e., in 3 sectors of Mode 3 data).	
65. 2 IPP channeltron outputs dropped to zero for several seconds shortly after a gain decrement command.	Day 335	Not significant. Occurred only once (in channels 2 and 3). Reason unknown.	
66. Bright particle caused loss of Canopus lock. Particle tracked in plus direction and lost. Roll search to Canopus inhibited by setting of roll search inhibit logic in the attitude control electronics. Corrective action is to send DC-21 to allow roll search.	Day 10	No mission effect.	PFR5010.
67. Attitude control N ₂ gas usage higher than expected. 9.07 g/day (20 mlb/day) initial estimate was based on insufficient data. Cruise usage was actually about 4.54 g/day (10 mlb/day) per prelaunch predicts.	Day 17	No mission effect.	PFR5011.

EXHIBIT A7 - (Continued)

Identification	Time to Failure	Consequences	Comments
68. Camera A cathode current low at turn-on. Degradation probably due to leaving TVS power on due to TV heaters not coming on. Diagnostic tests run and vidicon beams off in Earth-Venus cruise. TVS power off in Mercury cruise.	Day 13	Caused by anomaly #1; apparently no mission effect:	PFR5012.
69. Solar Paddle temp. excursions greater than expected.	Orbit 4	No further details available.	
70. Slow leak in FWD IR scanner pressure.	~Orbit 3660 (4/8/73)	Not expected to interfere with normal operations.	Leak rate is very slow.
71. Same as #90, except left cosine pot.	~Orbit 4250 (5/20/73)	Same as #90.	
72. RMP output several times its normal value to several minutes near the s/c day-night transition.	Orbit 7210	Caused by unexplained energy input; signal returned to normal by Orbit 7235. Apparently occurred with both RMP 1 and 2.	RMP= Rate Measuring Package.

EXHIBIT A7 - (Continued)

Identification	Time to Failure	Consequences	Comments
73. Slow battery discharge when it is supposed to be floating.	Day 31	No effect since alternate modes of operation maintain battery in charged condition. Attributed to design error.	The relation between these is not clear. The ref. for anomaly #74 says the discharge current while floating was really 0 (telemetry said 0.245 Amp), and goes on to describe analysis leading to conclusion of failed cell. Also concludes that battery thermal history not responsible for failure.
74. Failed battery cell (short circuited).	Day 75 to Day 102	First referred to as battery voltage anomaly, then analytically diagnosed as battery cell progressively failing-short. No effect, since battery could perform its function even with 2 failed cells.	
75. One sun sensor channel has double sun pulse.	Day 52	Occurs over a very limited combination of sun-angles and sun distance. No effect on mission-there is redundant unit.	No further information given.
76. Star sensor misses more star pulses than it should.	~ Day 60	Attributed to calibration procedure error. Problem can be overcome by using sun sensor instead of the non-redundant star sensor.	
77. FDS power-on-reset (POR) when gyros turned on by command 7M1, pre-roll control maneuver. Another POR on day 341. Probable causes are random combination of normal 2.4-kHz bus dip at gyro turn-on and converted common mode noise in FDS. Precautions and contingencies now used.	Day 18	Functional redundancy provided "work around," would have otherwise been serious.	PFR5013. FDS=Flight Data System.
78. No platform telemetry response to 2 of 8 CC-6 commands. Reference anomaly #105 for corrective action.	Day 23	Anomaly in Articulation and Pointing System; apparently no mission effect.	PFR5014.

EXHIBIT A7 - (Continued)

Identification	Time to Failure	Consequences	Comments
79. RTG boom deployment incomplete.	Post-launch	Spin rate changes indicated that one pair of RTG booms stopped deploying when only partially deployed. Full deployment occurred spontaneously 6 hours later before any corrective actions were attempted.	
80. Power Subsystem Anomaly.	Post-launch	Apparently, no mission effect. First revealed by a telemetry measurement of relative power system performance - some kind of figure-of-merit indication that considers bus current and RPG current. Other telemetry data later revealed similar condition, viz, that power margin was lower than predicted.	One would have to know the s/c intimately to be able to interpret the reports on this.
81. More thruster spin coupling than expected.	Post-launch	Also occurred on previous spacecraft. No significant effect. Plume reflection (a design error) causes an offset of $\sim 1.5^\circ$ in 1 thruster axis.	
82. C-band downlink power drop-out during SAPPAC/ Interferometer test.	Day 82	Due to saturation of the RFI transponder by interferometer c-band up-link (Rosman pointing) which suppressed the signal being monitored by the ground station. Attributed to procedural error.	FAR 315 Communications problem.
83. Battery temperatures higher than desired.	Day 126	Batt. temps 31°C during winter solstice. Condition avoided operationally by use at c/60 charge rate, reduction of shunt dissipation, and restriction of Millimeter Wave and S/C pointing for 2 hours/night during winter solstice.	FAR 601 Note: Charged to thermal control subsystem.
84. EME-UCSD experiment scanning sensor head mechanically bound.	Day 128	Experiment is 40% inoperative.	FAR 711 GPE experiment anomaly.
85. HET-2 driver turn-off intermittent.	Day 132	Driver off-relay tends to hang-up in "on" position. Problem avoided operationally by disconnecting the up-converter, then turning off the HET xmitter to turn HET off.	FAR 316 Component anomaly.

EXHIBIT A7 - (Continued)

Identification	Time to Failure	Consequences	Comments
86. Abnormally high minor frame sync error counts in WBVTR-1 data.	Orbit 3463	Operations continue on restricted sections of the tape, and error counts have greatly diminished.	Returned to normal by orbit 4650, possibly due to tape damage; later experienced anomaly several more times. See item #146.
87. Comstor B-cell 12 - See #3.	~ Orbit 4523	Problem has now occurred on 23 occasions; use of cell for active commands discontinued.	
88. Integrated ckt. chip in TMP failed.	Orbit 4396	A telemetry channel disabled; s/c operation not effected.	
89. Decreasing power output from the "A" s-band xmitter (See items #5 and #147).	Orbit 3574	Output power now 0.29 watts. Still adequate to perform required functions.	Showed decreasing decline from orbits 5100 to 6370.
90. ACS - right cosine pot has developed consistent signal deviation at s/c - midnight.	Sometime between Orbits 3810 and 5100	Degrades signal output but does not interfere with s/c operation.	Part of SAD; attributed to internal debris.
91. X-Band Transmitter (XTX) output power drop from 96 to 90 data numbers (DN). Several 6 DN changes in XTX output level seen since launch, during S/C maneuver with XTX case temperature of 10 ^o --15.5 ^o C (50 ^o --60 ^o F). XTX output is now 1.5 dB above requirement. 6 DN= 0.3 dB. Satisfactory above 15.5 ^o C (60 ^o F).	Day 34	Apparently no mission effect.	PFR5015.

EXHIBIT A7 - (Continued)

Identification	Time to Failure	Consequences	Comments
92. Increase in spin period (decrease in spin rate) due to thruster leaks.	Day 160	Not sufficient to impact mission. Occurred following a despin maneuver, when slow but continuous spin rate decrease persisted over next 7 days, resulting in accumulated decrease of 0.1% in spin rate. Due to small leak in despin thruster, but leaks also detected in precession pair #2 (thruster 1 and 4) over the next several weeks.	Occurred during Asteroid belt transit.
93. Degradation in thrust levels for all axial thrusters in the precession duty cycle mode.	Subsequent to day 160	Apparently due to leaks described in item #92, but also pressure drops in propellant supply from such things as restricted filters. Decrease in isp not significant.	This is reported separately, but is apparently related to item #92 above. Condition noted during Asteroid Belt transit.
94. Ion Engine #1 Turn-on failure.	Day 146	Same type failure at item #50.	FAR 706 GFE experiment anomaly.
95. C-band pre amp #1 gain loss.	Day 171	Not a flight anomaly; due to inaccuracy in calibration curve. Subsequent tests verified proper operation and provided data for improving calibration curve.	FAR 317 Ground problem.
96. DACU #1 format anomaly.	Day 183	DACU #1 tends to skip even words and repeat odd words when commanded to dwell on odd channels, or, upon turn-on after being off for an extended period of time. Problem diagnosed as due to Ionic contamination of address line of DACU #1 Read Only Memory. Operational procedures now restrict dwell operations to DACU #2 only.	FAR 201 Component anomaly, due to improper cleaning after ammonia cleaning process. Ammonia residue altered chip's characteristics, which show up under certain conditions.

EXHIBIT A7 - (Continued)

Identification	Time to Failure	Consequences	Comments
97. C-band ECH/PPF receive coupling.	Day 64	Same as item #31.	FAR 309 Communications problem.
98. HET video cross talk.	Day 68	Observed during c-band x c/HET 2 and s-band x HET-1 when both HET's were on 52. Crosstalk eliminated by using 51. Possibly due to insufficient selectivity at ground station.	FAR 311 Communications problem.
99. HET audio cross talk .	Day 71	Not a flight anomaly; due to ground equipment.	FAR 312 Ground problem.
100. Synthesizer frequency drift.	Day 82	Original report in error; subsequent tests showed synthesizer operation to be well within spec.	FAR 313 Ground problem.
101. No output from #2 UHF xmitter.	Day 82	Not a flight anomaly; due to incorrect command sequence (regulator had not been turned on).	FAR 314 Ground problem.
102. MAG flipper failed to complete stroke. Flipper continued incomplete strokes until 2-21-74 when cable warming to -26.1°C (-15°F) allowed complete stroke.	Day 3	Work-around procedure used to ensure adequate power for flips.	PFR5016. MAG=magnetometer.
103. Tracker failed to acquire Canopus six times. Low temperature, prolonged darkness exposure in roll control maneuver and gate calibration accuracy caused marginal acquisition conditions.	Day 34	Use gate G-2 for future acquisitions after prolonged dark condition.	PFR5017.

EXHIBIT A7 - (Continued)

Identification	Time to Failure	Consequences	Comments
104. Abnormal backlash in cone slews at 160 deg. Reference anomaly #105 for corrective action.	Day 42	Anomaly in Articulation and Pointing System. See anomaly #105.	PFR5018.
105. Scan cone slew sluggish from 150 to 179 deg.	Day 45	Cone limits established.	PFR5019.
106. High-gain antenna (HGA) drive changed from 84 to 85 DN. Low-gain antenna (LGA) drive changed from 0 to 9 DN. Fault in hybrid cavity or in S-band radiating cavities. 11 state changes occurred before final cure on 3-4-74. Check design and fabrication cleanliness on future projects.	Day 52	Cited as "significant problem" - not clear what this implies.	PFR5020.
107. Extra sun pulses from sun sensor.	Day 190	No mission effect. 16 extra sun pulses occurred in the span of 2 s/c revolutions. Comet Kohoutek was too distant to trigger sensor. Also, asteroids which could have caused this would have had to be in the large charted group and near the s/c, which was not the case.	Occurred during Asteroid Belt transit.
108. Small thruster leaks detected by small changes in s/c spin rate.	Day 325 to day 637 (Encounter)	During encounter period, leaks would start after a precession maneuver and continue to next precession maneuver. Leaks were small enough that there was no detectable pressure drop.	Possibly the same leaks that developed earlier (See #93), but this is not indicated in the available data.
109. False count in thruster #2.	Day 607	Counter register for thruster #2 jumped a count during periapsis. Reason unknown since ACS was deactivated and no thruster pulse could have occurred.	

EXHIBIT A7 - (Continued)

Identification	Time to Failure	Consequences	Comments
110. Stored commands blocked by real time sequences which overlap in time.	Sometime between Orbits 6371 and 7651	Happens occasionally.	
111. Left and right SAD occasionally have ripple voltages on their drive mechanisms.	11/13/73	Insignificant - returned to normal.	Attributed to wobble gear wear-in.
112. WBVTR-1 had high headwheel current during re-wind.	Orbit 6865	Apparently only happened once; established policy that re-wind could be performed only when in gnd. station contact.	Attributed to a slip in the count-down chain delivering 2 phase power to the headwheel motor.
113. WBVTR-1 tape unit pressure drop.	Orbit 6560	Due to defect in pressure instrumentation which causes drop in telemetry indication. Returns to normal.	
114. Power Subsystem went from main to standby chain. Probably due to shorted Dickson 1N3892 diode in the main booster/regulator. Modify in-flight sequences to minimize Power Subsystem stresses.	Day 67	Switched to block redundancy; would otherwise have been catastrophic to mission.	PFR5021.

EXHIBIT A7 - (Continued)

Identification	Time to Failure	Consequences	Comments
115. Multiple pulses from sun sensor B.	Day 365	Unexplained, single occurrence. Sun sensor A utilized during remainder of encounter period.	
116. Star tracker lock found to have jumped from Canopus to Aldebaren.	Day 613	Tracker had not been in use when this was detected. Attributed to tracker's susceptibility to scintillation from the high energy particle radiation environment and to albedo saturation recovery effects.	
117. Degradation in star sensor gain.	From day 450 to day 604	Determined by observations of degenerate progression in the detection probability of the star Vega. Subsequent to encounter, Vega could not be detected. Canopus detection unaffected.	
118. RFI Transponder turn-off when certain HET cmds issued.	Day 186	Apparently reported due to a misinterpretation. S/C designed to have RFI transponder turn-off under these command conditions.	FAR 708 Communications problem.
119. PSA-2 tracks bright particle.	Day 15	Polaris Sensor #2 tracking of particles occurs only occasionally and has not yet effected system operation significantly. Can cause minor disturbance in yaw axis, but DOC will automatically select the YIRU, which is always on, and closed loop control will be maintained.	FAR 104 Possibly due to either 1) sun reflections getting into the Image dissecting tube, or, 2) sun reflections off particles.
120. UHF xmit: #1 High Temp.	Day 217	With no uplink signal, temp was 37.8 ^o c. After uplink turn-on, temp increased to 44 ^o c and xmitter was turned off. Related to starting base plate temp and was determined that 10-13 ^o c temp rises could be expected.	FAR 318

EXHIBIT A7 - (Continued)

Identification	Time to Failure	Consequences	Comments
121. HGA dish stopped before reaching stop position. Curled HGA cabling wrapped around the HGA boom.	Day 63	HGA dish position limits set to avoid problem and incremental commands used near limits.	PFR5022. HGA=High Gain Antenna.
122. DSS stuck in parking window when commanded low-rate playback. Relative humidity in DSS may be 57% to 80%, causing excess catalyst A in magnetic heads to come out, reacting with oxide coating and causing sticking.	Day 68	Tape recorder anomaly; corrective action was to park on window and exit with high torque.	PFR5023. DSS=Data Storage System.
123. Automatic (non-intended) switching from star sensor to sun sensor.	~ Day 60	Problem can be overcome by using sun sensor instead of star sensor.	No further information given.
124. Star advance feature of cmd.340 does not work.	~Day 350	Problem can be overcome by transmitting a special command sequence to acquire Canopus.	Attributed to the micro-pulses within each star pulse; for advance feature to work, each star must have <u>only</u> 1 pulse. This feature allows lock to be broken on unwanted star in order to acquire Canopus.
125. Sun sensor issued a premature sun pulse.	Day 555	Occurred once at considerably smaller sun aspect angle than "double pulse" anomaly (See #75). No significant consequences resulted.	

EXHIBIT A7 - (Continued)

Identification	Time to Failure	Consequence	Comments
126. L-band xmitter #1, intermittent power output.	Day 219	Communication subsystem was configured in unusual arrangement to serve as a DC load. Problem attributed to excessive loading on IF-2 output. Subsequent tests under more standard conditions reveal no problems.	FAR 319
127. PSA-2 failed to respond to acquisition commands.	Day 242	Subsequent investigation revealed the PSA was functioning properly for the cmd. sequence it had received (i.e., it was supposed to "lock-out" with that sequence).	FAR 108
128. TWTA #1 RF power low.	Day 259	Attributed to too much power going into ground antenna inadvertently, thus blocking receiver.	FAR 320 Ground problem.
129. High-rate roll gyro oscillations and high gas use. Roll gyro had steady 3.62-Hz oscillation. Extensive tests and analysis indicate most likely cause is exciting seventh S/C structural mode. Use solar sailing to minimize gas use.	Day 88	Functional redundancy provided "work-around"- would otherwise have been catastrophic to mission.	PFR5024.
130. DSS tape stuck at left end of tape. Not in parking window.	Day 98	See anomaly #122.	PFR5025.

EXHIBIT A7 - (Continued)

Identification	Time to Failure	Consequences	Comments
131. Roll wheel anomaly.	Day 392	Instability developed in roll axis subsequent to anticipated perturbations due to Moon transiting the Earth Sensor Roll Scan. Jet control was necessary to correct instability. Anomaly attributed to problem in the pulse modulator lag amp. and/or its compensation circuitry. Special DOC programming for mixed operations with wheels and roll jet is planned as corrective action.	FAR 110 Component problem. Apparently quite a serious problem.
132. A2 South Array temp. sensor failure.	Day 410	Same type failure as #38. Third of this type. No serious effect reported, but calibration curves for temp. sensors have been changed.	FAR 406 Component problem.
133. Several scientific instruments experienced increased temperatures.	Day 607	Occurred at periapsis, and returned to nominal afterwards. Believed due to Jupiter's infrared radiation through instrument apertures.	Increases not large enough to cause damage.
134. Several telemetered power system parameters varied slightly during encounter.	Day 325 to day 607 (During encounter)	Not significant, returned to normal after periapsis. Possibly due to combined effects of magnetic, thermal and radiation environments encountered at that mission phase.	No correlation found to link this with radiation effects on germanium transistors.
135. Gradual increase in TWT helix current.	Day 607	Not significant. Cause unknown. No changes in power output, cathode current, or ref. voltages were observed.	

EXHIBIT A7 - (Continued)

Identification	Time to Failure	Consequences	Comments
136. Solar panel tilted to 50 deg. Temperature over 115°C (239°F). Specification limit of 115°C (239°F) applies to cell surface. Temperature transducer on opposite side. Peak cell temperature was 133.3°C (272°F) and average was 126.1°C (259°F). Flight acceptance temperature is 120°C (248°F).	Day 119	Apparently no mission effect.	PFR5026.
137. A430 high shunt tap voltage.	Day 310	Shunt tap voltage was 24.5, versus 23.1 to 20.5 for other taps. Evaluation indicated that no array degradation occurred. Similar problems have occurred on A419 shunt tap. Possible cause is change in solar cell impedance during peak temp. periods. Anomaly did not impact flight operations.	FAR 405 Component problem.
138. ESA roll scan frozen.	Day 336	During offset pointing maneuver, ESA anomaly caused complicated chain reaction, including the S/C Z-axis being driven off the Earth and the sensor sun-avoidance ckt. to operate at the extreme pitch angles which existed. The combination of S/C attitude and sun elevation which can cause this are rare and predictable, thus operational policies can prevent future occurrences of this type anomaly.	FAR 109 Component problem. Apparently quite a serious problem.

EXHIBIT A7 - (Continued)

Identification	Time to Failure	Consequences	Comments
139. Stellar reference system sending jumbled messages to Earth.	Day 12	Alternate approaches possible.	Reported in 3/15/72 Space Daily - no other information given, and not mentioned in reports available from ARC.
140. Mysterious change in axis of rotation.	Day 1050	Change causes s/c to point away from the Earth $1/12^{\circ}$ each day. Reason for change unknown, could be slight malfunction or planetary force not known about. No danger to s/c. Checks ruled out the possibilities of slight leak, interference from interstellar dust and magnetic field distortions.	Reported in June 15, 1975 L.A. Times. Attributed later to star tracker locking on wrong star.
141. On panel tilt to 76 deg. current differential between panels increased. Probably a partial failure in section 1 of -X panel. Cause unknown.	Day 126	Cited as "significant problem" - not clear what this implies. Switched to block redundancy.	PFR5027.
142. Airglow (AG) high-voltage power turned off in playback. Similar problem occurred in subsystem tests on both UVS AG units (Reference prelaunch PFRs 5802 and 5805), but no occurrence in system tests.	Day 127	Commands will be sent during Mercury encounter to reset UVS AG if off at the time of UVS AG state change. No significant change in DSS drive volts or power telemetry.	PFR5028. Experiment package anomaly. UVS=Ultraviolet Spectrometer.

EXHIBIT A7 - (Continued)

Identification	Time to Failure	Consequences	Comments
143. Engine catalyst bed resistance decrease after post-trajectory correction maneuver (TCM). Drop after TCM 1 was 16% and after TCM 2 was 12%. 1% = 0.09% in delta velocity.	Day 128	Catalyst bed resistance stabilized after TCM 3. Flight impulse errors less than 1/4 of specification.	PFR5029. Anomaly in hydrazine propulsion system.
144. HGA boom temperature exceeded specification limit of 90°C (194°F). Cause is unknown. No corrective action.	Day 133	Charged to thermal control; apparently no mission effect.	PFR 5030.
145. Pitch flywheel exhibited a 2 minute halt.	Orbit 8040	Occurred during a sun transient when wheel was changing directions.	Average wheel speed was increased to obtain a better lubrication condition.
146. WBVTR-1 not used because of high error counts - same problem as Item #86.	Orbit 8612	Unit not usable from orbit 8612 to 8845. Usage will be limited to tape footages requiring no more than 5 minutes.	Also experienced high head wheel current - see item #112. Note: has not been used since Orbit 9881.
147. The "A" s-band xmitter power finally dropped too low (see items #5 & #89).	Orbit 10,068	Power output finally declined to 0.14 watts with noticeable loss in coverage. Operation switched to "B" unit.	
148a. Pitch CCW motor driver duty cycle rose ~15%.	From Orbit 9290 to 9340	Returned to normal after each occurrence.	Postulated that anomaly is connected with lubrication.
148b. Duty cycle rose ~26%.	From Orbit 9887-9910		
148c. Occurred 6 more times	From Orbits 10,183 to 11,466		

EXHIBIT A7 - (Continued)

Identification	Time to Failure	Consequences	Comments
149. Spurious commands; over 50 have been executed, beginning early in the mission and continuing thru June '75 (date of latest available data).		This has never created mission problems since the falsely executed commands have always been reversible by ground commands.	This situation has been intensively studied and the reason for the spurious commands is still not known. The latest available report postulates that the Asteroid/Meteoroid detector package may be causing the problem, but this was still under study.
		<u>Status Changes due to False Commands:</u>	
	Day 20	ARC-Rt Bank CCM from 1 to 2 (An exp. pkg.?)	
	4/26/73		
	Day 70	+Y line heater on (propellant line heater)	
	6/15/73		
	Day 85	ARC - Rt Bank CCM from 1 to 5	
	6/30/73		
	Day 101	ARC - Sector Integ. period from 1 to 8	
	7/16/73		
	Day 106	+Y and -Y line heaters on	
	7/21/73		
	Day 150	ARC - Left bank CCM from 1 to 3	
	9/3/73		
	Day 172	ARC - Left bank CCM from 1 to 5	
	9/25/73		
	Day 182	+Y and -Y line heaters on	
	10/5/73		
	Day 183	-Y line heater on	
	10/6/73		
	Day 184	CDU Sequencer enabled	
	10/7/73		
	Day 304	ARC - Rt. bank CCM from 1 and 2	
	2/4/74		
	Day 349	ARC - Left bank CCM from 1 to 3	
	3/21/74		
	Day 360	ARC High voltage limit switched off	
	4/1/74		
			Asteroid belt transit.

EXHIBIT A7 - (Continued)

Identification	Time to Failure	Consequences	Comments
Spurious commands (Continued)	Day 382 4/23/74	+Y and -Y line heaters on	
	Day 429 6/9/74	ARC - Sector Integ. period from 1 to 8	
	Day 440 6/20/74	ARC - Rt. Bank CCM from 1 to 3	
	Day 465 7/15/74	ARC In-flight calibration on	
	Day 541 9/29/74	ARC Data source MFM from 4 to 3	
	Day 606 12/2/74	Antenna feed offset on, +Y and -Y line heaters heaters on	
	Day 607 12/3/74	Numerous changes in scientific Inst. pkgs.	Periapsis - these possibly due to Jupiter's radiation.
	Day 624 12/20/74	+Y line heater on	
	Day 679 2/13/75	1) CDU sequencer enabled, 2) +Y and -Y line heaters on, 3) cmd processor changed from unit B to A, 4) at least 1 cmd. register appeared selected for cmd loading 5) HVM inst. changed from narrow to wideband.	When the sequencer enabled, several ordnance functions automatically switched from safe to arm. These functions were for deployments, so presumably the squibs had all been fired.
	Day 702 3/8/75	1) +Y and -Y line heaters on, 2) cmd processor switched from unit B to A.	
	Day 703 3/9/75	+Y and -Y line heaters on	
	Day 722 3/28/75	-Y line heater on	
	Day 723 3/29/75	1) CDU sequencer enabled, 2) +Y and -Y line heaters on, 3) cmd processor changed from unit A to B, 4) cmd register 5 selected for loading, 5) HVM inst. changed from Auto to Manual ranging.	
	Day 725 3/31/75	ARC - Left Bank CCM from 3 to 7	

EXHIBIT A7 - (Continued)

Identification	Time to Failure	Consequences	Comments
Spurious commands (Continued)	Day 729 4/4/75	+Y and -Y line heaters on	
	Day 734 4/9/75	1) CDU sequencer enabled, 2) cmd processor changed from unit B to A, and 3) TPP inst. high voltage on.	The first time the IPP inst. has gotten in on the act.
	Day 736 4/11/75	1) CDU sequencer enabled, 2) +Y and -Y line heaters on, 3) cmd processor changed from unit B to A, 4) HVM inst. changed from Auto to Manual ranging, 5) AMD instrument changed from narrow to wideband, 6) AMD inst. changed from high to normal threshold, 7) precession pairs changed from 1 and 3 to 2 and 4.	First time for the precession pairs.
	Day 737 4/12/75	1) CDU sequencer enabled twice, 2) +Y and -Y line heaters on, 3) AMD inst. changed from high to normal threshold, 4) HVM inst. changed from auto to manual ranging.	
	Day 779 5/24/75	More of the now familiar pattern of line heaters, CDU sequencer, etc., changes. No "new" types reported.	
	Day 780 5/25/75		
	Day 799 6/13/75		1) CDU sequencer on, and 2) -Y line heater on
Day 800	1) CDU sequencer on, and 2) +Y and -Y line heater on		

EXHIBIT A7 - (Continued)

Identification	Time to Failure	Consequences	Comments
150. Pitch flywheel stopped for 8 hours.	From 11,125 to 11,130	Has been kept close to 0-speed ever since using pitch control.	Created emergency; large quantity of control gas used to re-acquire normal attitude, solar paddles lost sun track, etc.
151. Switched from RMP-B to RMP-A.	Orbit 11,257	Precautionary measure after B unit began showing current variations.	
152. PCM regulators switched from unit 1 to unit 2 without command.	Orbit 10,910	Switched back without commands on orbit 11,035.	Believed due to VHF input signal transients.
153. Data collection subsystem shut-off.	Orbit 12,690	Not an anomaly; subsequent spacecraft assumed this function.	
154. NBTR-B became noisy and was turned off.	Orbit 13,015	Unit A still available.	Approaching wear-out of tape.
155. Spacecraft drawing 87 watts added power; TV heaters off. Prime suspected cause is booster regulator in the power conditioning equipment. Other symptoms include: DSS drive toggles on/off, no response to DC-43 and 47, X-band spikes, +4 V TV power dropped 4 DN, S/C bus temperature up and RFS frequency change.	Day 137	Switched to block redundancy, array was able to support unplanned load, thus preventing mission failure.	PPR5031.
156. X-Band Transmitter (XTX) output dropped from 81 to 3 DN. Possibly due to loss of voltage regulation in chopper transformer circuit. Carrier can be recovered by turning XTX power off and then back on.	Day 137	Functional redundancy provided "work-around."	PPR5032.

Identification	Time to Failure	Consequences	Comments
157. No response to DC-43 (switch traveling-wave tube to low power). Switches probably have component failure or circuit degradation. No more DC-42's or 43's will be sent.	Day 138	Functional redundancy provided "work-around."	PFR5033.
158. Analog engineering data from FDS analog/digital converter 2 went to 127 DN. Appears to be due to isolated part failure in FDS.	Day 154	Switched to block redundancy; probably would otherwise have caused loss of extended mission.	PFR5034; FDS=Flight Data System.
159. DACU #1 frame sync error.	Day 434	Word 0 Frame sync errors occur in frames 11 and 15 permanently, and frames 0,1,2,3, 7,8 and 9 intermittently. Possibly caused by change in threshold voltage due to ionic contamination of ROM (see #96) ground software changed to ignore these sync errors.	FAR 202 Component problem. See #96. Same anomaly, different symptom.
160. DACU #1 frame sync error.	Day 452	Frame sync pattern for word 2, frame 15 intermittently reads octal "000" instead of "006." No impact because frame 15 masked due to #159 above.	FAR 203 Component problem.
161. EME-UCLA Magnetometer Y-axis failure.	Day 466	Attributed to open winding in y-axis offset coil, possibly caused by temperature extremes during eclipse season.	FAR 710F GFE Experiment problem.

EXHIBIT A7 - (Continued)

Identification	Time to Failure	Consequences	Comments
162. Canopus tracker lost Canopus lock due to bright particle tracking. Remain in cruise mode to minimize oscillations.	Day 295	Apparently no mission effect.	PFR5038.
163. Canopus tracker lost lock, storm of bright particles. Same analysis and closure action as anomaly #162.	Day 296	Apparently no mission effect.	PFR5039.
164. Lost Canopus acquisition due to bright particles. Maintain roll drift mode until Mercury encounter III.	Day 326	Apparently no mission effect.	PFR5040.
165. Yaw position exceeds limit, switch amplifier did not fire. Exact cause not determined.	Day 379	Cited as "significant problem" - not clear what this implies.	PFR5041.
166. Load sharing of battery #6 decreased and batt. over-charged.	Orbit 13,300	Battery was turned off for a restoration cycle; will be turned on again after it has discharged back to normal.	
167. S/c clock consistently loses time.	Throughout	Is periodically reset via ground command.	
168. Solar array current drops.	Orbit 13,000	No effect on mission; current drops 500-600 ma for 1 to 14 minutes early in the day, then returns to normal.	

EXHIBIT A7 - (Continued)

Identification	Time to Failure	Consequences	Comments
169. MMW 30 GHz H2 failure.	Day 508	The high voltage tripped off each time the HV cmd sent. Filament comes on but HV command shuts down tube. Permanent failure.	FAR 711 GFE Experiment problem. (See item #20.)
170. PSA failure.	Day 509	Simultaneous bursts of noise noted on both PSA and ESA outputs, when PSA turned off, ESA noise cleared up. Spontaneous resets of PSA adaptive gate step also noted. (No further details given.)	FAR 111 Component problem.
171. +X solar panel current increase when tilted away from Sun. Data analysis reveals all responses normal.	Day 167	Apparently no mission effect.	PFR5035.
172. PSE SES electron multiplier count rate decreasing. Normal wearout. No corrective action except turn-off until Mercury encounter II. Predictable event.	Day 259	Apparently no mission effect.	PFR5036. Experiment package anomaly. PSE=Plasma Science Experiment.
173. DSS appears jammed approximately 21.3 m (70 ft) from right end of tape. Probably caused by head-to-tape weld causing the tape to loop and jam.	Day 279	Tape recorder anomaly; turned off subsystem.	PFR5037. DSS=Data Storage System.

EXHIBIT A7 - (Continued)