N72 29861

Repro Copy.

USE OF THE SPACE SHUTTLE TO AVOID SPACECRAFT ANOMALIES

PRC R-1467

3 May 1972

Prepared for

Space Shuttle Program Office
NASA Headquarters
Washington, D. C.
Under Contract NASW-2282

Charles E. Bloomquist
Project Manager

PRC SYSTEMS SCIENCES COMPANY

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

FOREWORD

This document presents the results of a study to assess the impact of the Space Shuttle on historical spacecraft had it been operational in the appropriate time frame, and to assess the impact it may have on the design, development, and test phases of future space programs.

The study was performed in the 6-month period beginning 3 November 1971 by PRC Systems Sciences Company for the Space Shuttle Program Office, Headquarters, National Aeronautics and Space Administration under Contract NAS W-2282. Mr. William F. Moore was the contract technical monitor.

The PRC/SSC study team members were E. E. Bean, C. E. Bloomquist, W. C. Graham, R. H. Kallmeyer, E. Kamiya, D. E. LaGrange, H. G. Mallean, and C. M. Robb. Data reduction assistance was provided by E. T. Rumble and E. M. Lucero. Production of the report was ably directed by D. H. O'Lear.

ABSTRACT

An existing data base covering 304 spacecraft of the U. S. Space program was analyzed to determine the effect on individual spacecraft failures and other anomalies that the Space Shuttle might have had if it had been operational throughout the period covered by the data. By combining the results of this analysis, information on the prelaunch activities of selected spacecraft programs, and Shuttle capabilities data, the potential impact of the Space Shuttle on future space programs was derived.

The Shuttle was found to be highly effective in the prevention or correction of spacecraft anomalies, with 887 of 1,230 anomalies analyzed being favorably impacted by full utilization of Shuttle capabilities. The Shuttle was also determined to have a far-reaching and favorable influence on the design, development, and test phases of future space programs. This is documented in 37 individual statements of impact.

TABLE OF CONTENTS

Page

ABSTRACT iii

I. INTRODUCTION 1

II. STUDY INPUTS 3

A. The PRC/SSC Space Data Bank 3

B. Shuttle Capabilities 11

III. SHUTTLE IMPACT ON PREVIOUS SPACECRAFT PERFORMANCE 13

A. Anomaly Classification 13

B. Spacecraft Availability Analysis 19

IV. SHUTTLE IMPACT ON FUTURE SPACE PROGRAMS . . . 35

A. Spacecraft Design, Development, and Test Experience 35

B. Statements of Impact 36

V. CONCLUSIONS 67

REFERENCES 69

APPENDIX A: SHUTTLE CAPABILITIES A-1

APPENDIX B: SPACECRAFT AVERAGE AVAILABILITY ANALYSIS B-1

LIST OF EXHIBITS

		Page
1.	Annual Distribution of U.S. Spacecraft Launches and Those in the PRC/SSC Space Data Bank Through 1970	5
2.	Tabulation of Spacecraft in PRC/SSC Space Data Bank	6
3.	Anomalous Behavior Description Card	9
4.	Frequency Distribution of Anomaly Occurrence Versus Time	12
5.	Shuttle Classification Codes	14
6.	Anomaly Classification Ground Rules	15
7.	Anomaly Distribution by Shuttle Impact	16
8.	Anomaly Distribution by Shuttle Impact and Mission Effect	20
9.	Anomaly History for Spacecraft 15b	21
10.	Instantaneous Availability for Spacecraft 15b Without Shuttle Utilization	23
11.	Instantaneous Availability for Spacecraft 15b Under Various Shuttle Utilizations	27
12.	Selected Sample of Space Programs	29
13.	Summary of Spacecraft Average Availability Analysis	32
14.	Average Spacecraft Availability Versus Launches per Spacecraft	33
15.	Instantaneous Availability Profiles for an Average Spacecraft	34
16.	Spacecraft Design, Development, Test, and Operation with Space Shuttle	37
17.	Anomaly Distribution Among Major Components and Equipment Types	39

I. INTRODUCTION

The Space Shuttle will impact future unmanned space programs in two ways. First, its implementation will 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. Second, it will exert an influence on the prelaunch design, development, and test activities or payloads.

The extent of this impact is investigated in the study reported herein by conjecturally superimposing Shuttle capabilities on an existing historical file of operational spacecraft reliability data. The historical file is the PRC/SSC Space Data Bank. It contains data on the actual performance of 304 spacecraft of the U.S. space program launched in the 1958 to 1970 time span. A record of prelaunch activities is also available in the Data Bank for many of these spacecraft.

Two broad objectives are defined for the study. The first is to show which of the 1,230 spacecraft anomalies recorded in the Data Bank could have been prevented or corrected had the Space Shuttle been available for use during the indicated time span, and to investigate the impact the Space Shuttle would have had on the associated spacecraft. The second objective is to identify specific changes which may be expected in future payload design, development, and test activities by hypothesizing full utilization of the Space Shuttle capabilities on programs documented in the PRC/SSC Space Data Bank.

A discussion of the two basic data sources for this study is presented in Section II of this report. The first is the data on the reliability aspects of operational spacecraft in the U.S. space program that is referred to herein as the PRC/SSC Space Data Bank or simply the Data Bank. A general description of the total Data Bank with emphasis on those portions particularly applicable to this study is given in subsection II.A. The second basic data source consists of reports and other documentation describing Space Shuttle capabilities and is discussed in subsection II.B. Appendix A contains an internally generated document that summarizes Shuttle capabilities as used for this study.

Section III addresses itself to the analyses of the Data Bank performed during this study. Each spacecraft anomaly was evaluated anew and coded in accordance with the potential impact the Space Shuttle would have had were it available. For this purpose 15 Space Shuttle impact codes were identified. Also, the spacecraft from a selected set of space programs were analyzed in detail to determine (1) individual and average spacecraft availability without the Shuttle and (2) the corresponding availabilities under the assumption of various Shuttle utilization profiles. Appendix B is a detailed summary of this analysis.

The potential impact of the Space Shuttle on the design, development, and test phases of a typical, future, unmanned spacecraft is treated in Section IV. A generalized flow diagram indicating spacecraft design, development, test, and operational activities, utilizing the Space Shuttle, was developed based on information from past spacecraft programs as contained in the Data Bank and future Space Shuttle capabilities as summarized in Appendix A. Thirty-seven statements of impact were then generated to indicate the specific influence of the Space Shuttle on these activities as applied to potential future programs. A rationale and supporting data from the Data Bank are included for each statement of impact.

Section V contains the conclusions of the study. The study clearly indicates that the Space Shuttle can have a very favorable effect both on the postlaunch availability of spacecraft through the prevention or alleviation of anomalistic behavior and on the prelaunch design, development, and test activities mainly through the increased range of choice opened to the designer by Shuttle System capabilities.

II. DATA SOURCES

This study, like most, relies heavily on previously accomplished work. Inputs to this study are of two kinds. One is the documentation of historical behavior and related information regarding spacecraft in the U. S. space program referred to collectively as the PRC/SSC Space Data Bank. The other includes various study reports and interim information that defines Space Shuttle capabilities. These two sources of data are discussed in the following subsections.

A. The PRC/SSC Space Data Bank

1. Introduction

Detailed information regarding the scope, generation and contents of the PRC/SSC Space Data Bank is available in a document[1] titled: "Reliability Data From In-Flight Spacecraft; 1958-1970." This document complements the results of a previous study to compile, interpret, and analyze reliability data on U. S. spacecraft. The earlier study, documented in Reference 2, was completed in March 1967. These two reports are the primary published documentation formulated from the Data Bank and contain much, but by no means all, of the collected data.

The Data Bank draws on two sources of information. The first is the open literature. Through the years a large number of reports and papers have been published documenting many aspects of a large number of space programs. The various space programs and their sponsoring agencies are (for the most part) identified in the open literature.

Sponsoring agencies of specific space programs responding to requests for specific data elements represent the second but most important source of information in the Data Bank. For each program included in the Data Bank, a request was made to the sponsoring agency for two major types of data: (1) an engineering report of the final design of the spacecraft, and (2) a flight analysis for individual spacecraft from which operating histories and all known anomalous behavior could be

[1] Reference 1.

obtained. Other types of information utilized in the Data Bank include reliability assessment reports, documents describing design, development, test, and prelaunch activities, and interviews with program management personnel. The scope of these studies precluded the analysis of raw telemetry reports or daily logs of the operational experience of spacecraft. Sources other than the cognizant program offices were not used, except to fill in gaps in the basic documentation. In the Data Bank all data elements are, of course, related to specific spacecraft or space programs. However, at the request of many program offices, published reports derived from the Data Bank may not relate specific anomalies or anomaly records to specific spacecraft. That procedure is followed in this report by identifying spacecraft, where necessary, by code number only.

2. Scope

The scope of the Data Bank is indicated in Exhibit 1. Overall, the Data Bank provides operational reliability data on approximately 40 percent of all U.S. spacecraft launches and attempted launches through 1970. As indicated earlier the Data Bank was accumulated in two stages. The first stage provided data through 1965, the second stage provided the data thereafter. In the second stage, access to military program data was considerably reduced and 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.

Exhibit 2 lists the programs included in the Data Bank together with the number of spacecraft sampled from each program. The sponsoring agency and the years in which launches occurred for each program are also included in this exhibit. Although the quantity and quality of the data received from each program varies widely, the Data Bank contains all readily available summary information.

3. Data Elements

For each spacecraft in the Data Bank, three categories of data are accumulated in standardized working papers referred to as

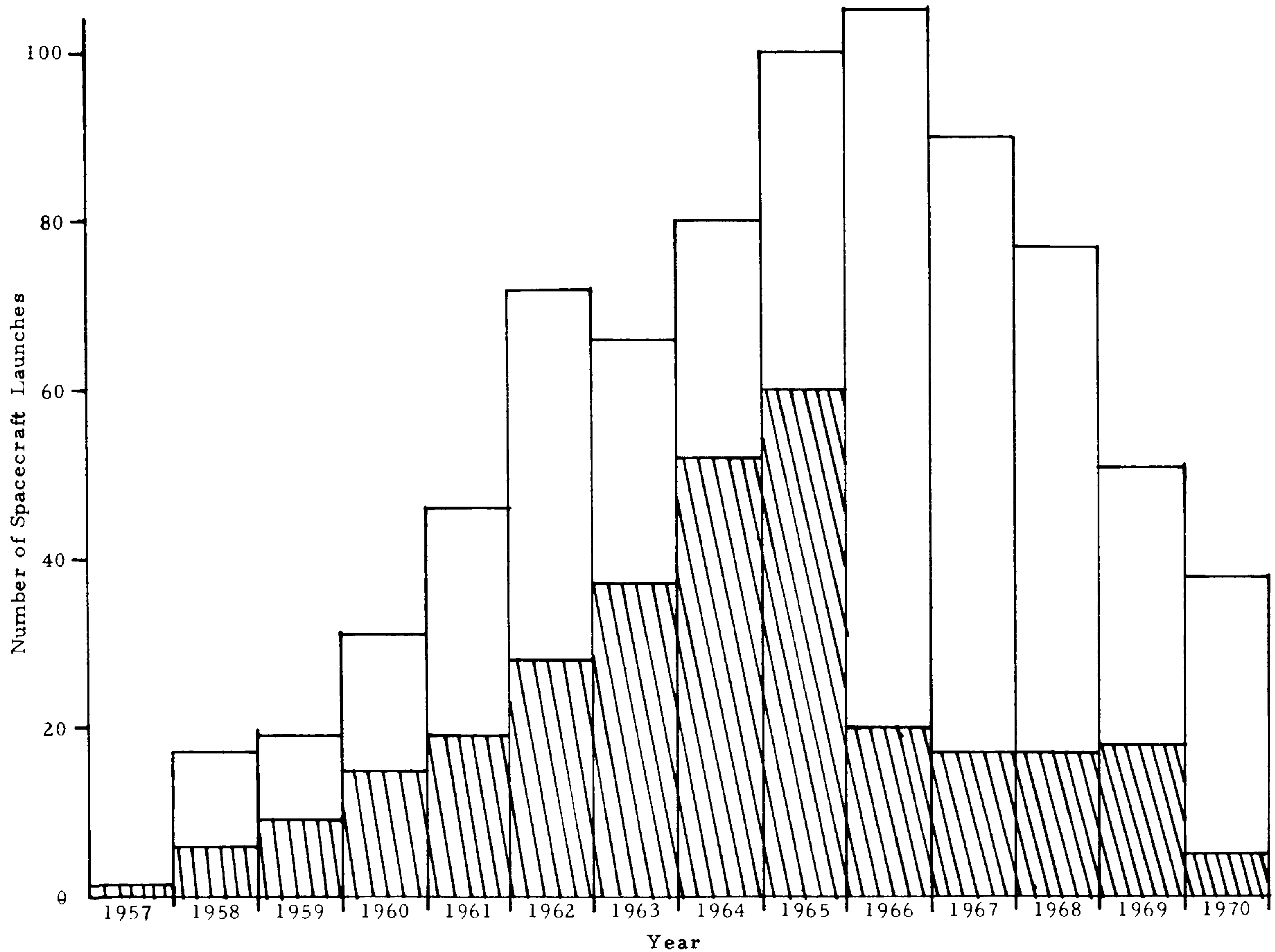


EXHIBIT 1 - ANNUAL DISTRIBUTION OF U.S. SPACECRAFT LAUNCHES AND THOSE IN THE PRC/SSC SPACE DATA BANK THROUGH 1970

EXHIBIT 2 - TABULATION OF SPACECRAFT IN PRC/SSC SPACE DATA BANK

Program	Agency	Launch Dates	Number of Spacecraft in Sample
Agena	Air Force	1959-1965	93
ANNA	Navy	1962	2
Ariel	NASA/UK	1962-1964	2
ATS	NASA	1966-1969	5
Courier	Army Signal Supply Agency	1960	2
Early Bird	COMSAT	1965	1
Echo	NASA	1964	1
Explorer 32	NASA	1966	1
Gemini	NASA	1964-1966	8
GEOS	NASA	1965-1968	2
IMP	NASA	1963-1967	6
Injun	NASA	1963-1964	3
Lofti	Navy	1961-1963	2
Mariner	NASA	1962-1967	7
Mercury-Atlas	NASA	1959-1963	25
Nimbus	NASA	1964-1970	5
OAO	NASA	1966-1970	3
OGO	NASA	1964-1969	6
Orbiting Vehicle			
OV1	Air Force	1965-1969	12
OV2	Air Force	1965	2
OV3	Air Force	1966-1967	6
OV4	Air Force	1966	2
OV5	Air Force	1967-1969	3
Oscar	Amateur Radio	1961-1966	4
OSO	NASA	1962-1969	8
Pioneer	NASA	1965-1969	5
RAE	NASA	1968	1
Ranger	NASA	1961-1965	9
Relay	NASA	1962	1
Secor	Army	1964-1970	14
Snapshot	AEC/Air Force	1965	1
Solrad	Navy	1960-1968	3
Syncom	NASA	1963-1964	3
Telstar	Bell Telephone Lab	1962-1963	2
TIROS	NASA	1960-1963	8
TOS	ESSA/NOAA	1966-1969	7
Traac	Navy	1961	1
Transit	Navy	1959-1966	17
Vanguard	NASA	1957-1959	11
Vela	Air Force	1963-1969	10

TOTALS
40 Programs
304 Spacecraft
Launch Dates: 1957-1970
1230 Anomalies

Engineering Analysis Reports (EARs). The three categories of information are (1) general data elements, (2) reliability data elements, and (3) development and prelaunch data elements. The general data elements include:

- Spacecraft launch date
- Launch vehicle
- Launch site
- Intended mission
- Initial orbital parameters
- General spacecraft description
- Performance record
- Number of hours on orbit covered by the Data Bank

The Data Bank was originally generated with the specific objective of collecting the reliability data elements. This initial objective was further constrained to collect those reliability data elements which would permit the calculation of on-orbit failure rates for piece parts. To achieve this objective each spacecraft was first defined in terms of its subsystems and major components. Typical major components are command receivers, telemetry transmitters, tape recorders, power converters, and horizon sensors. A space-environment operating profile of each component was then deduced from spacecraft operational records including the proportion of time in a standby condition, number of times cycled, and the occurrence time of component-related failures or other anomalies. A breakdown of the number of piece parts in each major component was determined. It was assumed that if the component was operable all of its constituent piece parts were also. If the component failed (ceased operating) all its piece parts were removed from the sample. The final tabulation for the reliability data element is the description of each anomaly (failure or any other nonnominal mission behavior) recorded during the time the spacecraft was under observation.

The spacecraft anomaly data and the development and prelaunch data elements are the portions of the Data Bank most immediately relevant to the study reported herein. Due to the objectives of the original data collection, little emphasis was placed on securing data elements on the prelaunch portions of a spacecraft's life cycle. The update of the Data Bank, reported in Reference 1, did not seek these elements and only incorporated them in the Data Bank if they were received together with information on the general or reliability data elements. Cooperation of the various space program offices, together with a number of independent reliability assessment contracts performed by PRC for programs in the Data Bank, results in a significant amount of prelaunch data even though it is much less systematic than the other data elements.

4. Spacecraft Anomalies

Since the anomalous behavior descriptions play such an important role in this study, a discussion of their content and derivation is in order. First, it must be emphasized that these anomalous incidents are those reported, either in the open literature or by the cognizant program office. Thus, there are certainly fewer anomalies recorded in the Data Bank than have actually occurred on the spacecraft. The reported anomalies are assumed, however, to be reasonably representative of all anomalies and especially the more significant ones.

There are 1,230 anomalies in the Data Bank. Summaries, reduced from detailed descriptions in the EARs, of 692 of these are contained in Reference 2; summary descriptions of 538 more recent anomalies are in Reference 1. The tabulations in these two references are taken directly from cards, one of which is prepared for each observed anomaly.

Exhibit 3 is a reproduction of one of these cards. The upper portion of the card contains coded information used in the analyses of References 1 and 2. The lower portion contains, from left to right, (1) an index number identifying the anomaly for a particular spacecraft, (2) the time of occurrence of the anomaly, and (3) an abbreviated description of the anomaly. The anomaly shown in Exhibit 3 was the first recorded against the particular spacecraft and occurred at some indeterminate time less than one day, denoted by epsilon. The normal entry in this position is the number of hours from launch to anomaly occurrence.

The number in the upper left hand corner of the card indicates the spacecraft program. The letter indicates the particular spacecraft in that program, in launch sequence. The number in the upper right hand

15 b 212

L L 4 d E N A 1

1 ϵ Proper attitude not established.
Inadequate design of horizon scanner.
Nearly catastrophic.

EXHIBIT 3 - ANOMALOUS BEHAVIOR DESCRIPTION CARD

corner is a card index number. The remaining codes are defined in detail in either Reference 1 or 2. Briefly, reading from left to right, they serve to define for sorting purposes: (1) whether the spacecraft is intended for a long or short duration mission, (2) whether the anomaly occurred in the launch or orbital phase of the mission, (3) the effect of the anomaly on mission objectives, (4) the subsystem in which the anomaly occurred, (5) whether it is primarily electrical or mechanical, (6) whether it represents a piece part failure, and (7) whether or not it has an assignable cause. The last code of the sequence associates the anomaly with a particular function of the subsystem in which it occurred.

The code describing the effect of the anomaly on mission objectives (third in the sequence) is used extensively in this study. The possible codes are the numbers 1 through 5, and the letter U. The letter U indicates an unreported effect on the mission.[1] The numbers index a percentage degradation in the capability of the spacecraft to perform its intended mission. The code is intended to be independent of time and other anomalies. That is, the code indicates the effect of the anomaly on a perfect spacecraft at time zero. The influence of redundancy or other backup is noted on the card in the narrative section. These codes are defined as follows:

Mission Effect Code	Percent Degradation
1	0 to 5
2	5 to 33
3	33 to 67
4	67 to 95
5	95 to 100

When assigning the code, reliance is placed on the evaluation of the effect by the program office tempered with independent determinations of number of experiments lost, decline in data quality or coverage, etc.

All 1,230 anomalies have been transferred to computer tape for ease in manipulation. A typical printout of the data lists all anomalies

[1]There were only two of these in the entire Data Bank.

by time of occurrence, a parameter of considerable interest to this study. Exhibit 4 graphically depicts the distribution of anomalies by occurrence time and shows that nearly half of all anomalies occur in the first week after launch. Further analysis of anomaly occurrence time and other aspects of the Data Bank is deferred to Section III.

B. Shuttle Capabilities

To determine the hypothetical impact of the Space Shuttle on the spacecraft on-orbit anomalies and on the design, development, and test activities of programs in the PRC/SSC Space Data Bank, it was necessary to outline in some detail the capabilities of the Shuttle System. This was done using as a starting point the Level I Space Shuttle Program Requirements Document controlled by the Space Shuttle Program at NASA Headquarters. The results, which remained fixed for the duration of this study, are presented in Appendix A. None of the recently reported changes to the Shuttle System are judged to have a significant impact on the conclusions of this study.

The general baseline Shuttle and Space Tug configurations used in this study were those defined in the Aerospace Corporation Integrated Operations/Payload/Fleet Analysis, Final Report, August 1971, Report Number ATR-72(7231)-1. The new concepts for spacecraft design, development, and test operations were evolved from preliminary work documented in the Lockheed Missiles and Space Corporation Final Report, Payload Effects Analysis Study, 30 June 1971, Report Number LMSC-A990556.

In Appendix A, as in the body of this report, the terms Space Shuttle, Shuttle System, Shuttle and Tug, Space Transportation System (STS), and Shuttle are all generally interchangeable, depending on the particular context for their exact meaning.

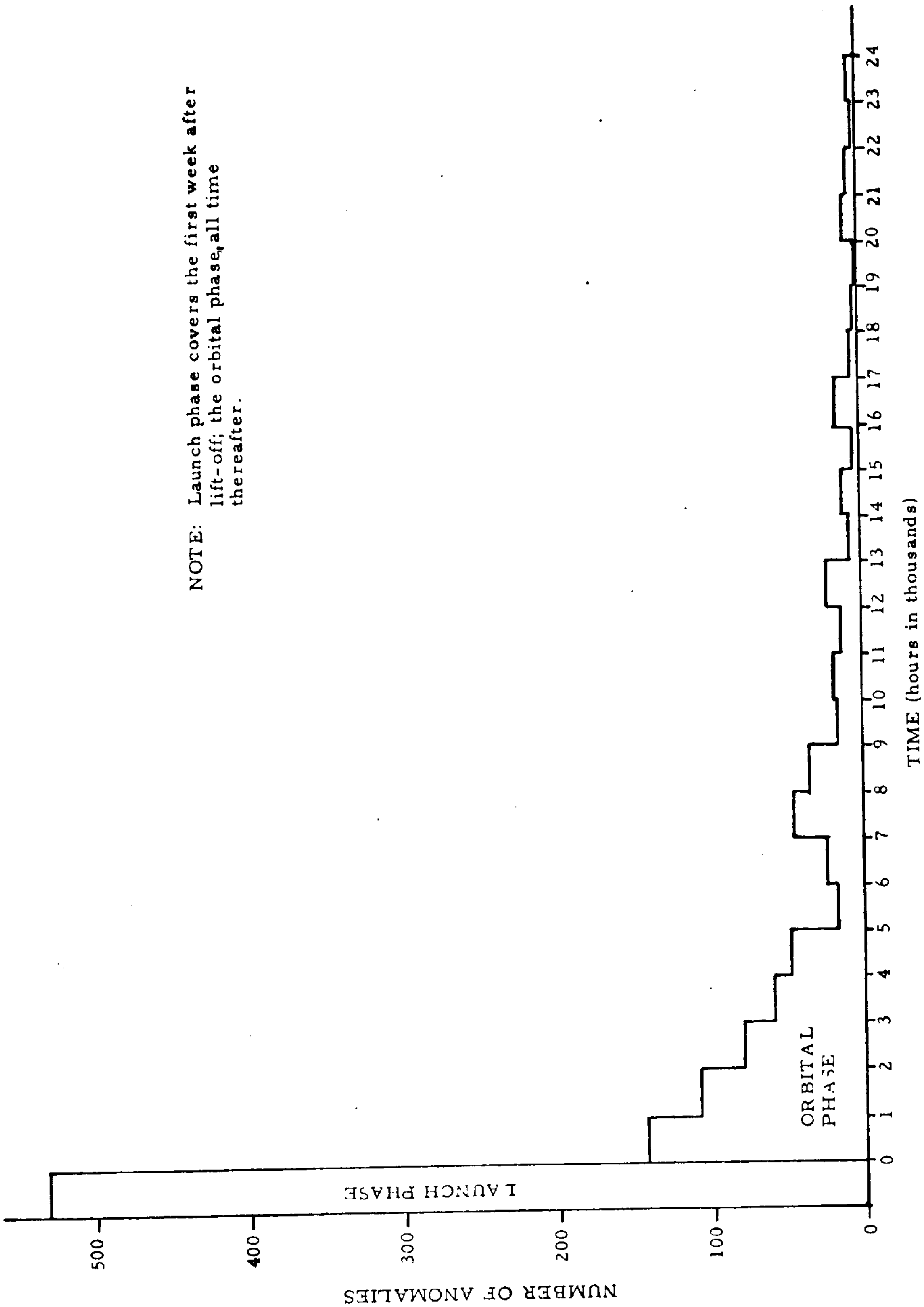


EXHIBIT 4 - FREQUENCY DISTRIBUTION OF ANOMALY OCCURRENCE VERSUS TIME

III. SHUTTLE IMPACT ON PREVIOUS SPACECRAFT PERFORMANCE

The investigations reported in this section of the report are concerned with determining the influence the Shuttle might have had on the spacecraft anomalies recorded in the Data Bank. Each anomaly is analyzed to determine if the Shuttle could be expected to have had any influence and, if so, what the general nature of that influence might have been. The Shuttle impact on individual spacecraft is also examined. These investigations are reported in the following two subsections. In both subsections it is assumed that the historical spacecraft are as specified in the Data Bank record except that they are Shuttle-compatible as described in Appendix A and that they are launched in an era of full Shuttle capability.

A. Anomaly Classification

As indicated in the previous section, there are 1230 spacecraft anomalies in the Data Bank. Classifying the anomalies for this study involves assigning to each anomaly a code which describes the impact that the Space Shuttle could have exerted on it. Fifteen codes were developed; they are listed and briefly defined in Exhibit 5. Exhibit 6 lists the more general ground rules used in classifying the anomalies and where others are needed, they are given in context.

Exhibit 7 illustrates the classification process and summarizes the results.

Of the 1230 anomalies, 19 were not applicable to nor consistent with shuttle missions; for instance, the anomalies associated with reentry, impact, and recovery of manned spacecraft obviously do not apply. These 19 anomalies were assigned Code A. Of the 1211 applicable anomalies, the descriptive data for 11 of them were insufficient to make any further judgment regarding Shuttle impact; these were assigned Code B.

Of the remaining 1200 anomalies with sufficient descriptive data, 84 were judged to be preventable with Shuttle utilization. These anomalies are preventable because: 1) a unit-reliable shuttle would have prevented the 40 unsuccessful launches (Code C); 2) the launch environment of the Shuttle would have prevented the 29 anomalies induced by the more severe launch effects of conventional booster systems (Code D); and 3) the

EXHIBIT 5 - SHUTTLE CLASSIFICATION CODES

A. NOT APPLICABLE

- o Inconsistent with assumption of STS existence

B. UNKNOWN, INSUFFICIENT INFORMATION TO CATEGORIZE

C. UNSUCCESSFUL LAUNCHES

D. LAUNCH INDUCED

- o Anomaly induced by standard launch operations but not anticipated by shuttle launch operation

E. DESIGN INDUCED

- o Design shortcomings of a major component detectable during a shuttle test flight

F. STATUS QUO, RESOLVED

- o Anomaly was corrected or overridden by ground controls (not by switching to a redundant unit or capability)
- o Was compensated for by changing operational procedures, programs, etc.
- o Self-healed in short time (< shuttle launch reaction time ≈ 1 week)

G. MINOR, NO MISSION EFFECTS

- o Anomaly so lacking in adverse mission effect that repair would never be undertaken
- o Occurred only rarely causing little or no lasting effects

H. MINOR, CONDITIONALLY REPAIRABLE

- o Anomaly which would be repaired only if the shuttle were at the spacecraft for another reason

I. MINOR, CONDITIONALLY NONREPAIRABLE

- o Anomaly which could not be repaired even if the shuttle were at the spacecraft

J. MINOR, INSUFFICIENT DATA

- o Anomaly of known negligible effect which cannot be placed in Categories G, H, or I for lack of data in the space data bank

K. REPAIRABLE, SHUTTLE ONLY

- o Orbit ephemerides correction or reestablishment for low orbits
- o Spacecraft stabilization or orientation for low orbits
- o Module replacement, system adjustment, or calibration for low orbits

L. REPAIRABLE, SHUTTLE AND TUG

- o Module replacement, system adjustment, or calibration for high earth orbits

M. REPAIRABLE, TUG ONLY

- o Orbit ephemerides correction or reestablishment at high orbits
- o Spacecraft stabilization or orientation, at high orbits

N. GROUND REPAIRABLE ONLY

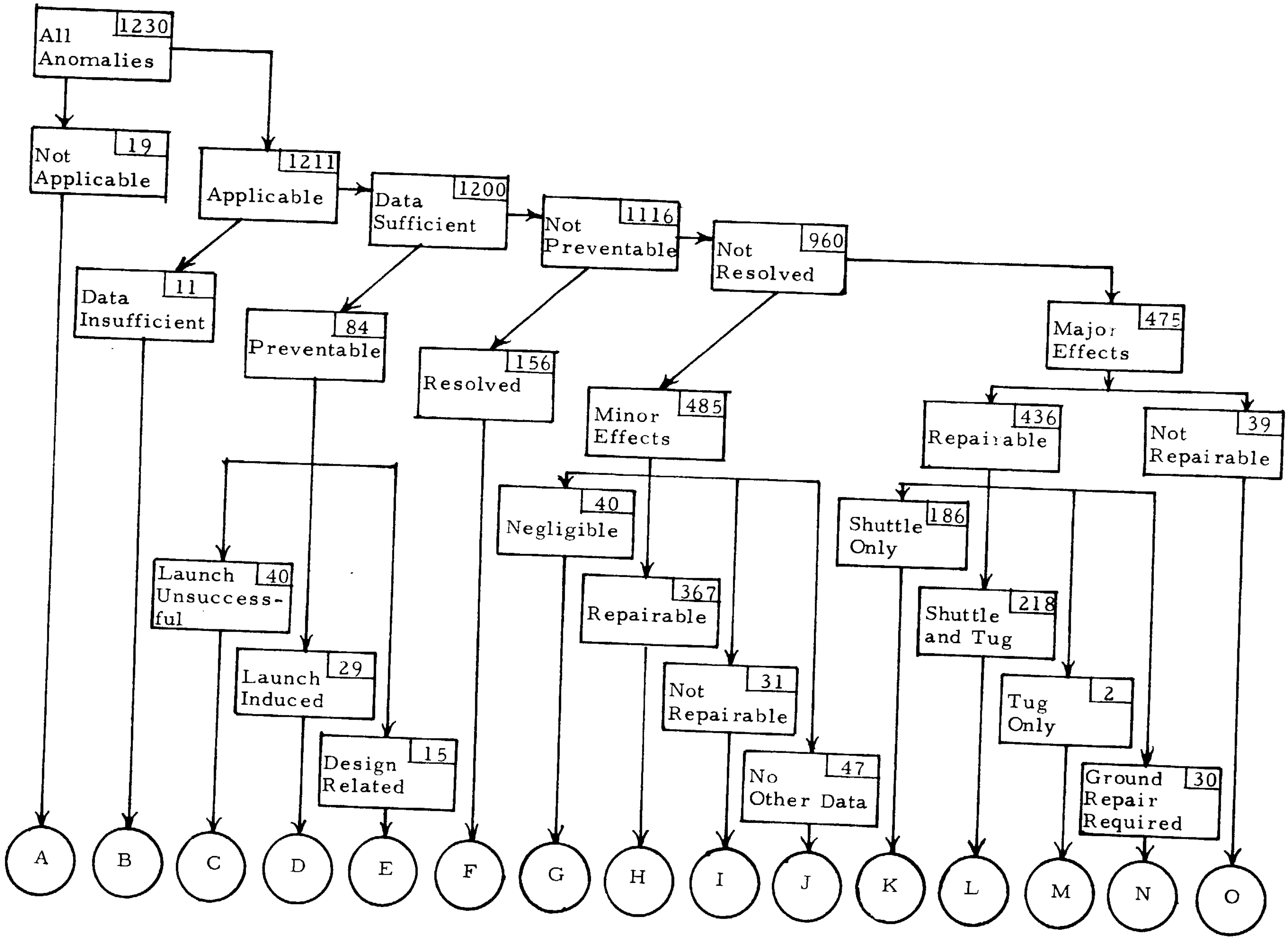
- o Design shortcoming not detectable during test flights and not repairable by shuttle
- o Detailed diagnosis not compatible with shuttle capabilities

O. NON-PREVENTABLE/NON-REPAIRABLE

- o Non-recoverable spacecraft (e.g., heliocentric orbits, lunar impact trajectories)

EXHIBIT 6 - ANOMALY CLASSIFICATION GROUND RULES

- The STS is assumed to be unit reliable.
- An STS is assumed to be available for tests, launch, or maintenance, as required.
- Anomalies whose mission effect code is 2 or greater will be repaired whenever the Shuttle classification code indicates that repair is possible.
- The STS will repair anomalies with mission effect Code 1 only if the Shuttle is at the spacecraft for another reason--launch or repair of a more severe anomaly.
- For Shuttle repair missions, the average time from anomaly occurrence to restoration is assumed to be one week (170 hours). This does not include mission effect Code 1 anomalies nor those occurring within an already-scheduled Shuttle mission as for launch or repair of another anomaly.
- Ground repair of anomalies is assumed to require three weeks (500 hours) from anomaly occurrence to restoration of the spacecraft on orbit.
- On-orbit repair time is assumed to be negligible with respect to arrival time (the time from anomaly occurrence to Shuttle/spacecraft contact) for all repairable spacecraft and anomalies.
- Spacecraft component design faults detectable in five days of space operation but not detectable in ground tests are assumed to be preventable via a Shuttle test prior to the spacecraft mission.
- On a spacecraft launch mission, a Shuttle is assumed to remain in position for repairs for 24 hours after spacecraft deployment and establishment of steady-state operation.



Shuttle Classification Codes

EXHIBIT 7 - ANOMALY DISTRIBUTION BY SHUTTLE IMPACT

use of the Shuttle for on-orbit testing would have prevented the 15 design-related anomalies that could have been detected only by on-orbit testing (Code E). A typical Code D anomaly is a pressure vessel leak due to excessive launch vibrations. Horizon sensor inaccuracies due to sensitivity to cold clouds and other gradients account for seven of the 15 Code E anomalies.

Of the remaining 1116 anomalies that were classified "Not Preventable," 156 were actually resolved during the spacecraft mission (Code F). That is, positive action from the ground was able to negate the effects of the anomaly, or the anomaly self-healed within a week with no lasting effects. Anomalies resolved by switching to a redundant unit or capability are not included in this category. An example of a Code F anomaly is the discovery that the slits of an aspect sensor are electrically reversed. This problem was resolved by software changes to correct the ground displays. The 960 anomalies that were not resolved were further categorized as those having minor mission effects and those with major effects. The minor and major effects are defined by the mission effect codes given in Section II, page 10.

The minor effect anomalies are defined as those with mission effect Code 1. Major effect anomalies are those with mission effect Codes 2 through 5. There is one exception to this definition. Any anomaly which was assigned Code 1 because a redundant capability was available is included in the major effect group rather than the minor effect group. As can be seen in Exhibit 7 there are 485 minor effect anomalies and 475 major effect anomalies.

The 485 minor effect anomalies are further divided into: 1) 40 anomalies so lacking in adverse effect that repair would never be undertaken (Code G), 2) 367 minor effect anomalies which could be repaired but whose repair would be undertaken only if the Shuttle were at or near the spacecraft for some other purpose (Code H), 3) 31 minor effect anomalies that could not be repaired even if a Shuttle were at the spacecraft (Code I), and 4) 47 minor effect anomalies where the data is inadequate to classify them in either of the preceding three codes (Code J). A typical Code G anomaly is the one reporting the condition that power delivered by a battery was two percent below the predicted minimum due mainly to estimating errors and changing mission requirements; no adverse mission effects were attributed to this condition. Intermittent telemetry monitors are common Code H anomalies. Excessive temperature in an experiment boom package caused by reflection from the solar arrays is a typical Code I anomaly; that is, it cannot be repaired on orbit but its mission effect is not severe enough to return the entire spacecraft to ground to rectify it.

The repairability of the 475 major effect anomalies was assessed. Thirty-nine were judged not repairable (Code O) and 436 were judged repairable. Code O anomalies are largely those from spacecraft in interplanetary orbits; catastrophic explosion of a system on an earth-orbital satellite is an anomaly also included in this category. For the purpose of evaluating the Shuttle utilization mode, the repairable anomalies were further categorized into: 1) 186 anomalies that could be repaired with a Shuttle only (Code K), 2) 218 anomalies that would also require a Tug to transport the spacecraft to the Shuttle for repairs (Code L), 3) 2 anomalies where the Tug would be able to effect repair without transporting the spacecraft to the Shuttle (Code M), and 4) 30 anomalies that could not be repaired on orbit and whose effect is sufficiently degrading to return the spacecraft to the ground for repairs (Code N). Code K anomalies are characteristic of spacecraft in low earth orbits; typical are tape recorder failures where it is assumed that the failed recorder is simply replaced with a like item. Code L anomalies are similar, but occur on spacecraft in synchronous or other high-energy earth orbits. The two Code M anomalies both involve non-nominal orbital parameters of high-energy earth orbital spacecraft. The parameters are assumed to be correctable with the Tug only; i.e., there is no necessity to return these spacecraft to the Shuttle. Excessive operating temperature due to inadequate spacecraft thermal design is an example of an anomaly which is assumed to be correctable only by returning the spacecraft to ground; i.e., a Code N anomaly. Many of the more serious radio frequency interference (RFI), microphonics, and parameter drift problems also fall in this category.

Thus, the categories that can be favorably impacted by Shuttle utilization are Codes C, D, and E, -- the preventable anomalies-- and Codes H, K, L, M, and N-- the repairable anomalies. There are 887 anomalies classified in these categories, representing about 72 percent of all anomalies reported in the Data Bank.

Exhibit 8 arrays all anomalies by the mission effect categories defined earlier and the Shuttle classification codes. Note that well over half the anomalies are mission effect Code 1 and therefore do not constitute a serious loss in mission capability. The anomalies bearing mission effect Code 2 (28 percent of the total) constitute at least a serious annoyance but cause considerably less than 50 percent mission degradation. That is, if 50 percent or more degradation in mission effectiveness were defined as a spacecraft failure, at least 85 percent of all anomalies definitely would not, by themselves, result in spacecraft failure. Thus, all mission effect Codes 3, 4, 5, and unknown anomalies and unsuccessful launches account for less than 15 percent of the anomalies in the Data Bank. Fifty-five of the Code 1 anomalies (4.5 percent) would have had a more severe mission effect except for the provision of redundancy.

Of the 57 essentially catastrophic anomalies (mission effect codes 4 and 5) nearly 80 percent (45 anomalies) could have been favorably affected by Shuttle utilization. Twelve (21 percent) could have been prevented and 33 (58 percent) could have been repaired. If unsuccessful launches are included as catastrophic spacecraft failures, then 88 percent of all spacecraft catastrophes could have been prevented or otherwise remedied by Shuttle utilization.

B. Spacecraft Availability Analysis

The preceding analysis is quite indicative of the potential usefulness of the Space Shuttle in the prevention and correction of spacecraft anomalies. In this subsection, the analysis is extended to assess the potential impact on individual spacecraft, taking into account both the occurrence times and cumulative effects of the various anomalies associated with a particular spacecraft.

1. Procedure

To illustrate the analysis procedure, consider the anomaly history of Spacecraft 15b in the Data Bank as shown in Exhibit 9. This spacecraft immediately after insertion into orbit suffered a highly detrimental design related anomaly (mission effect Code 4) which could have been prevented by prelaunch orbital testing on the Shuttle (Shuttle impact Code E). Another less severe anomaly (mission effect Code 2) occurred

EXHIBIT 8 - ANOMALY DISTRIBUTION BY SHUTTLE IMPACT AND MISSION EFFECT

SHUTTLE CLASSIFICATION CODES		MISSION EFFECT CODES 1: 0 to 5%	2: 5 to 33%	3: 33 to 67%	4: 67 to 95%	5: 95 to 100%	U: Unknown	Launch Unsuccessful	
A	Not Applicable	14	5	0	0	0	0	—	19
B	Data Insufficient	0	5	1	0	5	0	—	11
C	Launch Unsuccessful	—	—	—	—	—	—	40	40
D	Preventable, Launch Induced	8	7	3	3	8	0	—	29
E	Preventable, Design Related	6	7	1	1	0	0	—	15
F	Status Quo Resolved	137	19	0	0	0	0	—	156
G	Minor, No Mission Effect	40	—	—	—	—	—	—	40
H	Minor, Repairable	367	—	—	—	—	—	—	367
I	Minor, Not Repairable	31	—	—	—	—	—	—	31
J	Minor, Data Insufficient	47	—	—	—	—	—	—	47
K	Repairable, Shuttle Only	15	129	29	6	5	2	—	186
L	Repairable, Shuttle & Tug	39	131	29	6	13	0	—	218
M	Repairable, Tug Only	0	0	0	0	2	0	—	2
N	Ground Repair Required	0	20	9	0	1	0	—	30
O	Not Repairable	5	22	5	1	6	0	—	39
		709	345	77	17	40	2	40	1230

EXHIBIT 9 - ANOMALY HISTORY FOR SPACECRAFT 15b

Anomaly Sequence	Occurrence Time (Hours)	Mission Effect Code	Shuttle Impact Code
1	ϵ	4	E
2	ϵ	2	E
3	660	2	L
4	1,136	1	H
5	1,210	1	H
6	1,775	1	H
7	1,775	1	J
8	1,786	2	L
9	1,790	3	L
10	1,800	1	H
11	1,800	1	E
12	2,200	1	H
13	2,524	2	I
14	2,754	1	H
15	2,880	1	J
16	2,880	1	G
17	3,391	1	F
18	3,393	1	F
19	3,631	1	H
20	3,650	1	F
21	3,790	1	H
22	4,518	1	H
23	5,860	3	L
24	8,330	2	L
25	9,500	2	L
26	9,800	2	L
27	10,600	2	L
28	13,140	2	L
29	13,150	1	H
30	~	1	J
End of Data	14,144		

shortly thereafter, also design related and preventable using the Shuttle for orbital test. The third anomaly, at 660 hours, had a mission effect Code 2 and a Shuttle impact Code L, indicating a repairable anomaly requiring both the Shuttle and the Tug. The twenty-ninth anomaly is the last one for which a specific time of occurrence is available. The Exhibit 9 entry indicates that this anomaly occurred at 13,150 hours, had only a slight mission effect (Code 1), and would have been repairable if the Shuttle were at or near the spacecraft (Code H). Anomaly 30 was a report of spurious and ineffective commands occurring sporadically throughout the mission. Hence, no specific time of occurrence is given. The effect of the anomaly is slight in any event (Code 1) and there is not enough information reported about it to determine whether the anomaly would have been Shuttle-repairable or not (Code J). Operating data were accumulated on this spacecraft for 14,144 hours.

A profile of the instantaneous spacecraft availability versus time is shown in Exhibit 10. The instantaneous availability of the spacecraft is defined as that fraction of maximum spacecraft capability remaining at any given time. Each spacecraft is assumed to be launched with a perfect instantaneous availability (1.0) although, as in the case here, degradation from this value at time ϵ is graphically and practically indistinguishable from degradation at time 0. Degradation is assumed to cumulate in a multiplicative fashion. That is, defining instantaneous availability immediately after the nth anomaly as A_n and the degradation occurring due to the ith anomaly as D_i,

$$A_n = \prod_{i=1}^{n} (1 - D_i)$$

Degradation in spacecraft capability upon the occurrence of an anomaly is related to Exhibit 9 through the mission effect code using a specific and singular percentage degradation for each mission effect code as listed in the following tabulation.

Mission Effect Code	Degradation (Percent)
1	2.5
2	20
3	50
4	80
5	97.5

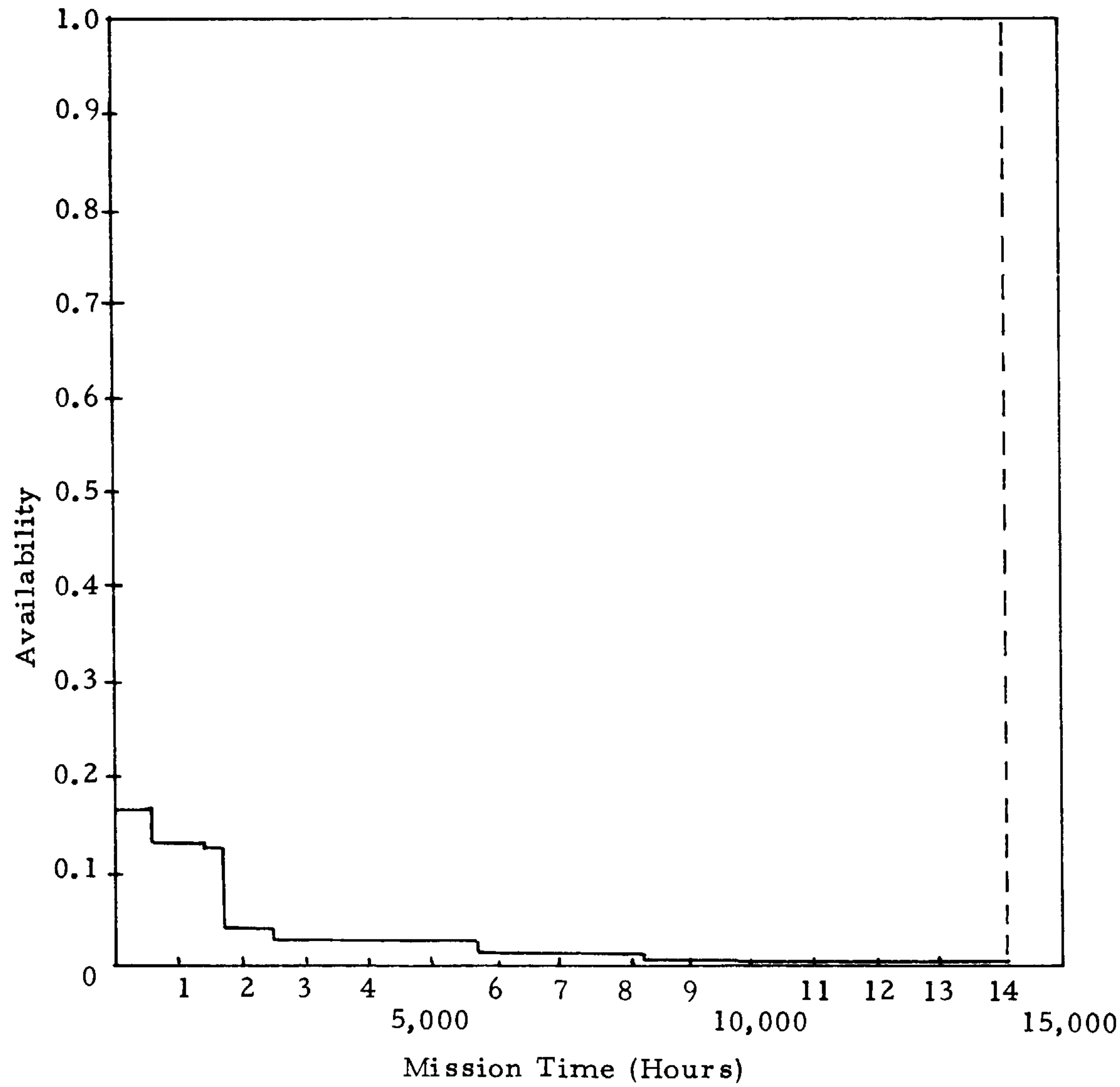


EXHIBIT 10 - INSTANTANEOUS AVAILABILITY FOR SPACECRAFT 15b WITHOUT SHUTTLE UTILIZATION

These values fall approximately at the midpoint of the ranges defined earlier and are used simply to make the analysis more tractable.

Thus, after the first anomaly the spacecraft is degraded to 20 percent of its nominal capability. After the second, which occurred at essentially the same time, instantaneous or point availability is further reduced to 16 percent.

$$A_2 = \prod_{i=1}^{2} (1-D_i)$$

$$=(1-0.80)(1-0.20)$$

$$=0.16$$

After the third anomaly, at 660 hours, the availability is further degraded to 12.8 percent and so on for the remainder of the anomalies. Anomaly 30 which has no specific time given is assumed to occur midway between launch and the time of anomaly 29; i.e., at 6575 hours. The scale of the curve in Exhibit 10 is such that it does not accurately portray each anomaly occurrence (end point availability is less than one-half of one percent) but it is generally indicative of the mathematical process described above. Furthermore, in spite of all the assumptions made and expedients taken, the curve is reasonably representative of actual spacecraft performance.

Spacecraft 15b was, in fact, turned off at 14,144 hours and no further attempt has been made to extract useful information from it. This profile of the availability history of Spacecraft 15b, while quite indicative of the performance of this spacecraft is not easily related to the performance of other spacecraft or to the performance of this spacecraft under the assumption of Space Shuttle utilization. A single numeric which satisfies the requirement of being easily comparable is the average availability. Average availability is determined by integrating the instantaneous availability curve (Exhibit 10, for example) from zero to mission end and dividing by the mission duration. This figure for Exhibit 10 is 0.035 or, expressed as a percentage, the average availability for Spacecraft 15b is 3.5 percent under actual historical conditions.

The potential impact of the Space Shuttle on Spacecraft 15b still remains to be determined. For this purpose, the following general assumptions with respect to Shuttle utilization are made.

1. The Space Shuttle can be fully utilized as described in the previous subsection dealing with anomalies. Repair missions, however, are undertaken only when the spacecraft accumulates a predetermined percentage of repairable degradation as defined above. The percentages selected for this analysis are 100, 80, 50, and 20. In terms of the instantaneous availability curve, a Shuttle repair mission is undertaken whenever availability falls below the value (1-D) where D is the repairable degradation. This term (1-D) is referred to herein as the availability threshold. Note that because of the defined relationship between degradation and mission effect codes, a zero percent availability threshold is never reached and, hence, no repair missions, subsequent to initial satellite launch, are ever undertaken in this case. All repair is assumed to be perfect, where possible.

2. All repairable anomalies occurring at an indicated time of ϵ or at a specific time less than 24 hours are repaired by the launching Shuttle before leaving the vicinity of the spacecraft.

3. All repairable anomalies occurring before 170 hours but after 24 hours are assumed to be repaired by the launching Shuttle if the mission effect of the anomaly is Code 2 or larger.

4. Any orbit repairable anomaly with mission effect greater than Code 1 which occurs too late for repair by the launching Shuttle will be repaired by another shuttle 170 hours from occurrence.

5. Any repairable spacecraft anomaly occurring within the 170 hours required for the orbit repair of another anomaly in that spacecraft will also be repaired during the Shuttle mission scheduled to repair the initial anomaly.

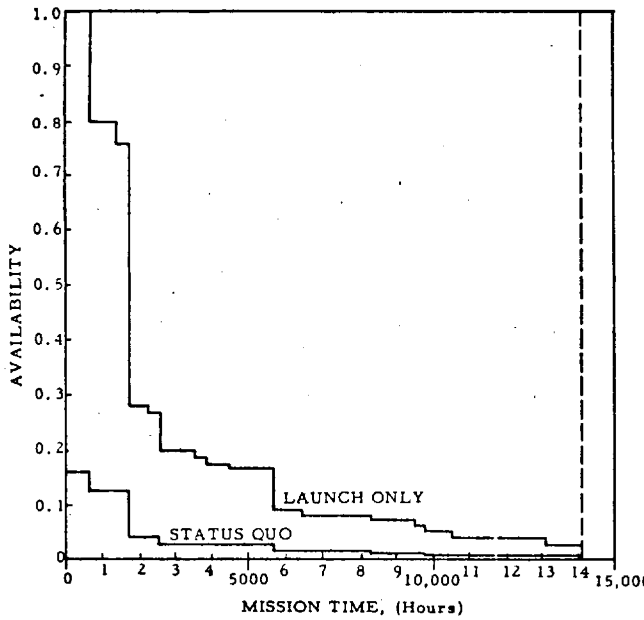
6. Any ground repairable anomaly is assumed to take the spacecraft out of commission for 500 hours before resuming operation. The times of occurrence of all subsequent anomalies for that spacecraft are adjusted accordingly. The only exception is when the spacecraft is recovered and returned to ground by the launching Shuttle, in which case the times of the subsequent anomalies remain unchanged. Two Shuttle missions are necessary for each ground repair incident; one to return the spacecraft to ground and another to relaunch it.

7. When the available data for a particular spacecraft ends with an anomaly no repair mission is undertaken. The average availability is unchanged by this assumption, but the number of repair missions required is reduced somewhat; i.e., if a final repair is made, an additional repair mission is required to achieve the same average availability.

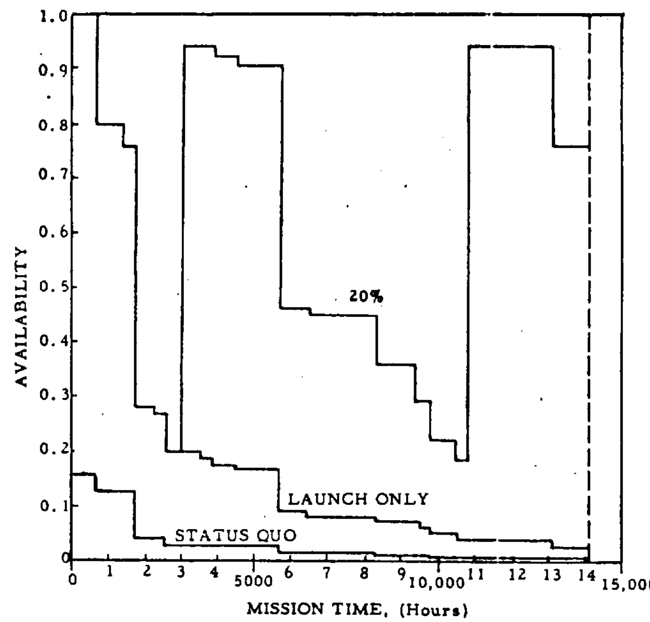
8. Some spacecraft anomalies as recorded in the Data Bank have no specific time associated with their occurrence. These anomalies are assumed to be evenly distributed within the interval from launch to last reported anomaly. When the number of anomalies with no time of occurrence is greater than four for a given spacecraft, they are aggregated into at most four groups for ease of handling. The combined effect of the anomalies integrated into a group is treated as an individual anomaly.

Exhibit 11a repeats the plot of the actual performance of Spacecraft 15b (referred to as status quo) and adds a curve representing the instantaneous availability over the same mission duration for the "launch only" or 0 percent availability threshold case. Note that the first two anomalies cause no degradation since they would have been prevented by Shuttle utilization. The first degradation in this curve occurs at 660 hours and then basically tracks the status quo curve but at a higher availability level. Integrating under this curve and normalizing indicates an average availability of 21.9 percent, a six-fold increase over the status quo case.

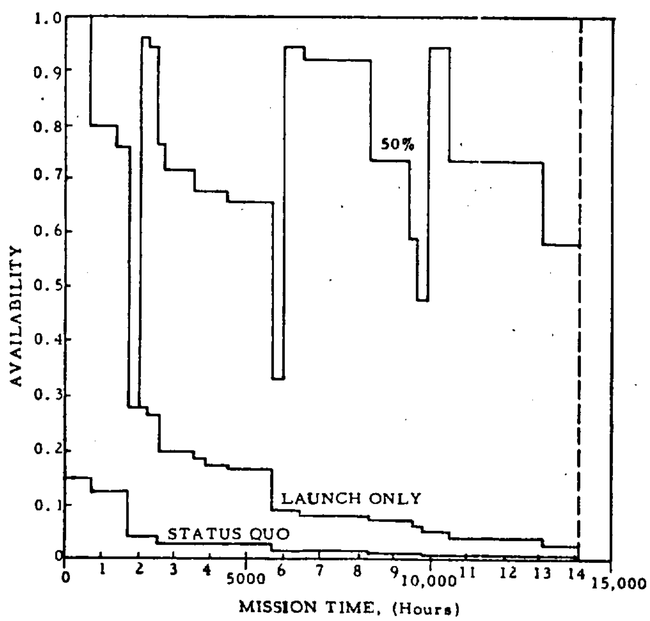
Exhibits 11b, 11c, and 11d add curves to the status quo and launch only cases which represent Shuttle utilization policies based on initiating a repair mission at a 20 percent availability threshold, respectively. Each increase in the instantaneous availability curve represents another Shuttle repair mission. In Exhibit 11b Shuttle repair missions occur at approximately 3000 and 11000 hours. Thus, three Shuttle missions are required for the case of a 20 percent spacecraft availability threshold: an initial mission to launch the spacecraft and two repair missions. The following tabulation summarizes the analysis of Spacecraft 15b.



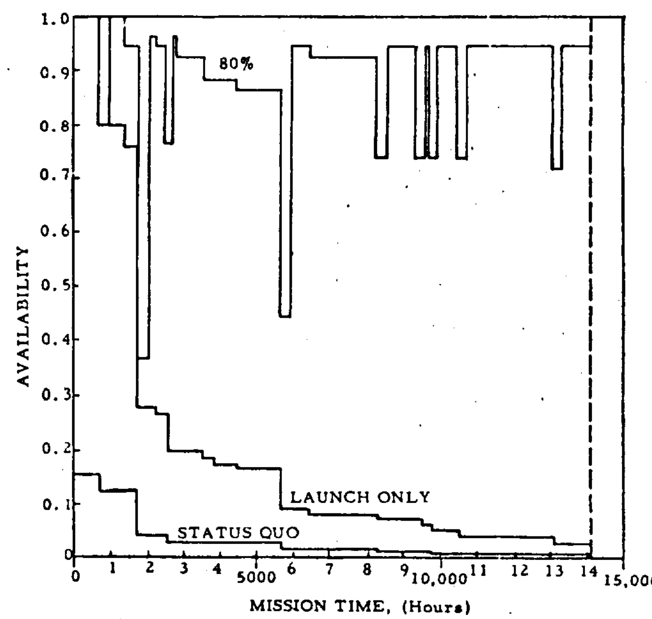
a. Shuttle Launch Only



b. Shuttle Revisit at a 20% Availability Threshold



c. Shuttle Revisit at a 50% Availability Threshold



d. Shuttle Revisit at an 80% Availability Threshold

EXHIBIT 11 - INSTANTANEOUS AVAILABILITY FOR SPACECRAFT 15b UNDER VARIOUS SHUTTLE UTILIZATIONS

Shuttle Utilization Policy	Average Availability (Percent)	No. of Missions Required
Status Quo	3.5	1
Launch Only	21.9	1
20% Availability Threshold	68.0	3
50% Availability Threshold	76.8	4
80% Availability Threshold	90.0	10

2. Application

Analyses entirely similar to that given above for Spacecraft 15b were performed for 104 spacecraft in the Data Bank. These spacecraft represent all those in the Data Bank from programs which 1) had reasonably long term earth orbital missions, 2) used unmanned spacecraft, and 3) had reasonably complete historical data. The programs used in the analysis, together with the number of spacecraft in each program, are listed in Exhibit 12. Appendix B gives a detailed summary of the availability analyses of these spacecraft.

In Appendix B, each spacecraft is listed by an index number, together with the length of time that the spacecraft was under observation as recorded in the Data Bank. If the spacecraft requires only a Shuttle (no Tug) for launch or revisit its index number is annotated with an asterisk. The average availability and required number of Shuttle System visits (expendable launch vehicle for the status quo case) are tabulated for each spacecraft. These numbers are derived as illustrated in the preceding example. For the status quo case, A is defined to be the average availability and N the number of expendable launch vehicles. N is at most one for each spacecraft but may assume fractional values of the form 1/n when n spacecraft are carried into orbit by the same vehicle. The Vela spacecraft, for example, are launched in pairs; hence, these spacecraft are each assigned one-half a launch vehicle.

EXHIBIT 12 - SELECTED SAMPLE OF SPACE PROGRAMS

Program	No. of Spacecraft
Ariel	2
ATS	5
Courier	2
Early Bird	1
Explorer 32	1
GEOS	2
Nimbus	5
OAO	3
OGO	6
OVI	12
OV2	2
OV3	6
OSO	8
RAE	1
Relay	1
Secor	14
Solrad	3
Syncom	3
Telstar	2
Tiros	8
TOS	7
Vela	10
	104

The Shuttle Systems required are tabulated as N_1, which represents the number of Shuttle System missions required in the "baseline" situation. That is, each Shuttle System is assumed to launch the same number of spacecraft as its expendable counterpart and each on-orbit repair is assumed to require one Shuttle System mission. Ground repair requires an additional mission. N_1 is given for the Shuttle launch-only case (zero percent availability threshold) and for the availability thresholds of 20, 50, and 80 percent. Average spacecraft availability, again denoted as A, is also given for each of the four thresholds.

The final entry for each spacecraft in the tabulation of Appendix B is denoted N_2 and represents the number of Shuttle System missions required when multiple missions are considered. Multiple missions are defined herein as a single Shuttle System performing two (or more) of the baseline missions. Multiple missions are assumed to occur whenever two (or more) baseline missions have launch dates in the same one week period and the ephemerides of the two (or more) spacecraft are compatible with the altitude and plane change capabilities of the Shuttle and Tug as given in Appendix A. Multiple missions are entered in separate rows of the Appendix B tabulation and indicate that a Shuttle and Tug are nearly always required for multiple missions even if the Shuttle alone is capable of performing the baseline missions. By entering the multiple missions separately, the value of N_2 for a particular spacecraft sometimes becomes zero and simply indicates that the required baseline mission has been subsumed in a multiple mission.

There are three classes of spacecraft missions included in Appendix B. First, and most numerous (81 of the 104 missions), are successfully launched spacecraft which experience one or more anomalies and operate for their indicated length of time. The second class consists of those spacecraft which were unsuccessfully launched (17 of the 104 missions). Finally, there are six spacecraft which were successfully launched, but which have no recorded anomalies in the Data Bank. The average availability of the last class is, of course, always 100 percent. For the unsuccessful launches, average availability is zero for the status quo case and 100 percent (for essentially zero time) for all Shuttle utilization cases. The first class of spacecraft has an average availability depending on its anomaly record and the Shuttle utilization case considered.

Exhibit 13 has been constructed to summarize the analyses reported in Appendix B. Averages for all the parameters discussed above are included for each of the three classes of spacecraft, for all successfully launched spacecraft, and for all 104 spacecraft analyzed.

An even more abbreviated summary of this analysis is presented in graphical form in Exhibit 14. The largest gain in average availability is achieved by using the Space Shuttle as a launch vehicle. However, average availabilities on the order of 95 percent can be obtained by dedicating as few as two Shuttle system launches per spacecraft mission; i.e., one launching Shuttle and one revisit, taking advantage of multiple mission capabilities. Exhibit 15 gives the instantaneous availability profile of an "average" spacecraft both for the status quo case and for the various Shuttle utilizations.

The preceding analysis is conservative on at least two counts. First, it only considers the increase in availability over the observed length of the mission. It is clear, however, that a Shuttle assisted mission could be much longer in most cases even without additional Shuttle flights. For example, Spacecraft 15b is essentially "dead" at 14,000 hours in the status quo situation, whereas at a 20 percent availability launch threshold the availability at 14,000 hours is over 75 percent. The extended time to degrade to zero from this point has not been considered in this analysis at all. The second point of conservatism lies in the assumption that the same anomalies occur at the same time in each situation. Shuttle repair of an early anomaly might, however, exercise a favorable influence on subsequent anomalies by lengthening their time to occurrence, preventing them altogether, or more likely, changing their occurrence time, nature, and specific effects. Repair of earlier anomalies should in no case accelerate the occurrence rate of subsequent anomalies or increase their inherent degradation potential.

	Number of Spacecraft	Average Mission Duration (hours)	Status Quo		Availability Threshold for Shuttle Launch											
					0% (Launch Only)			20%			50%			80%		
			$A^{(1)}$	$N^{(2)}$	A	$N_1^{(3)}$	$N_2^{(4)}$	A	N_1	N_2	A	N_1	N_2	A	N_1	N_2
All S/C Missions	104	11,200	49.3	0.87	74.3	0.88	0.83	78.9	1.08	1.06	88.1	1.49	1.27	94.7	2.47	2.07
Successful Launches	87	13,400	59.0	0.88	69.3	0.89	0.87	74.8	1.13	1.15	85.9	1.63	1.43	93.7	2.80	2.39
o Incurring Anomalies	81	13,400	55.9	0.88	67.1	0.89	0.87	72.9	1.15	1.18	84.8	1.68	1.48	93.2	2.94	2.51
o Incurring No Anomalies	6	13,000	100	0.83	100	0.83	0.83	100	0.83	0.83	100	0.83	0.83	100	0.83	0.75
Unsuccessful Launches	17	0	0	0.80	100	0.80	0.63	100	0.80	0.57	100	0.80	0.45	100	0.80	0.45

Notes: (1) A is the sum of all spacecraft average availabilities divided by the number of spacecraft considered.

(2) N is the total number of expendable boosters required divided by the number of spacecraft launched.

(3) N_1 is the number of Shuttle Systems required per spacecraft for the baseline situation in which no missions are combined.

(4) N_2 is the number of Shuttle Systems required per spacecraft for the multiple mission situation in which all possible missions are combined without changing original launch dates or spacecraft ephemerides.

EXHIBIT 13 - SUMMARY OF SPACECRAFT AVERAGE AVAILABILITY ANALYSIS

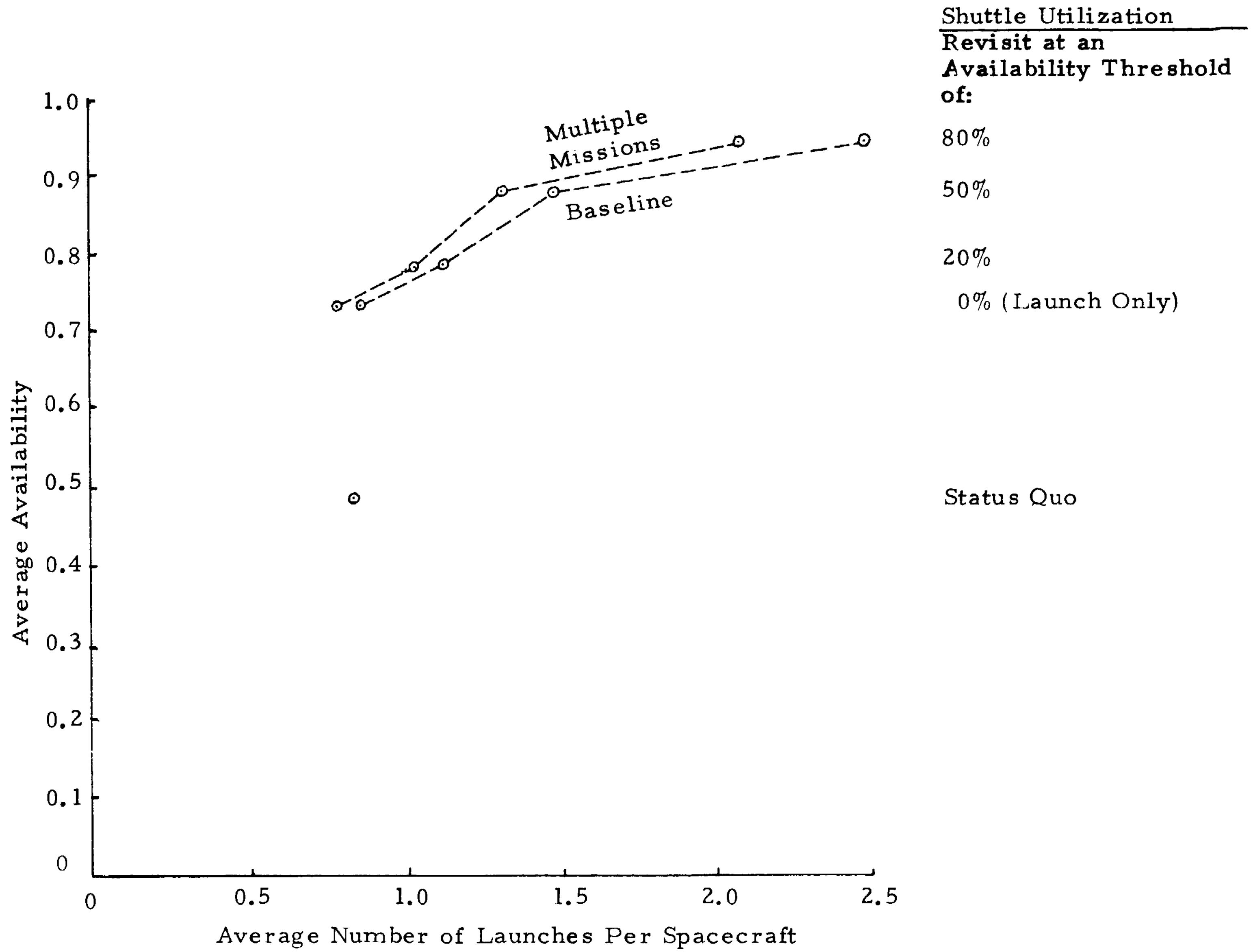


EXHIBIT 14 - AVERAGE SPACECRAFT AVAILABILITY VERSUS LAUNCHES PER SPACECRAFT

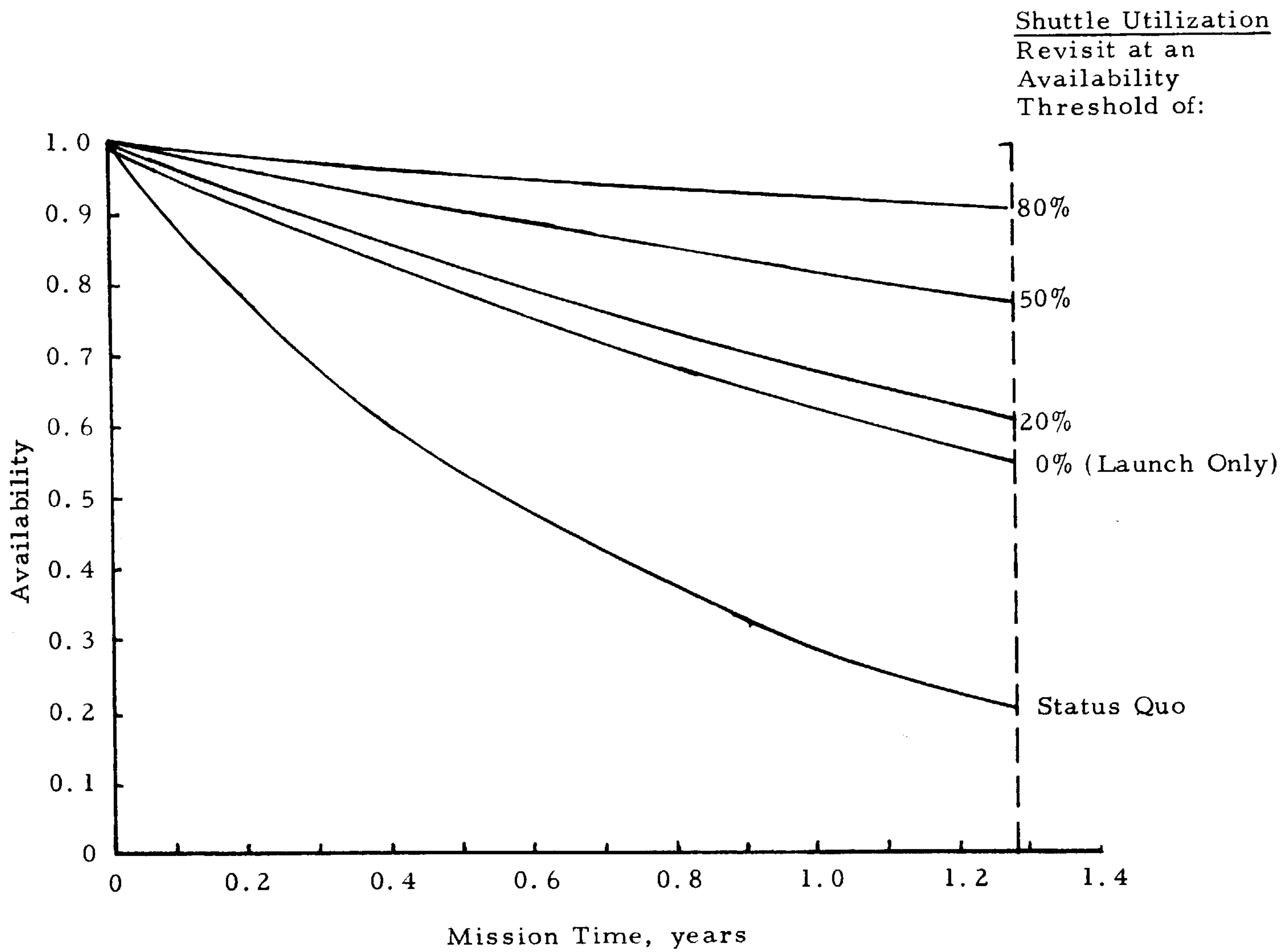


EXHIBIT 15 - INSTANTANEOUS AVAILABILITY PROFILES FOR AN AVERAGE SPACECRAFT

IV. SHUTTLE IMPACT ON FUTURE SPACE PROGRAMS

The potential impact of the Shuttle System on future spacecraft design, development, and test programs is presented in this section in the form of Statements of Impact (SOIs). The SOIs illustrate the potential effect of the Shuttle in modifying existing program approaches and procedures to achieve greater overall effectiveness at lower cost. The emphasis in this presentation is on effectiveness rather than cost. Both factors, however, are treated only in a qualitative sense.

The starting point for this effort was a survey of the design, development, and test activities of previous space programs as documented in the PRC/SSC Space Data Bank. Special attention was devoted to problems encountered in the completion of these previous programs to determine areas most susceptible to improvement through Shuttle utilization. Three programs were studied in some detail to assure that all factors were considered. The following two subsections discuss this survey of previous space program experience and the generation of the Statements of Impact.

A. Spacecraft Design, Development, and Test Experience

Three programs, the Nimbus, the Orbiting Geophysical Observatory (OGO), and the Applications Technology Satellite (ATS) were reviewed in detail to gain insight into the historical problems encountered in the design, development, and test activities of typical large unmanned spacecraft programs. Particular aspects of other unmanned spacecraft programs were also studied. Typical of these were the antenna tests for the Radio Astronomy Explorer, the development and test of various subsystems of the Mariner series of spacecraft, and the shroud ejection tests of the Orbiting Astronomical Observatory. The results of these investigations are reflected in the rationale for each SOI as presented in subsection B, below.

In reviewing these programs, it was concluded that had they been performed in the Shuttle era, on spacecraft of contemporary design, most ground development and test efforts would have remained the same with a few notable exceptions. The principal exceptions are those development and test activities which could be more effectively performed in an orbital environment, particularly those which are difficult, expensive, or impossible to conduct within the constraints of the present ground facilities. Examples are qualification and acceptance tests in orbital environments rather than in thermal-vacuum chambers, evaluation of advanced state-of-the-art components under actual operational conditions, and electromagnetic propagation experiments. In most cases, tests at the integrated spacecraft level are more advantageously replaced with on-orbit Shuttle tests than are part, subassembly, and assembly level tests.

For spacecraft redesigned to take advantage of Shuttle capabilities, further alterations could be made in current space program test requirements. The alleviation of payload weight and size constraints together with Shuttle availability would result in high reliability through the use of redundancy and lower part stresses. Better maintainability and repairability through modularization would allow less sophisticated mechanical and electronic designs to be used and would result in more commonality with other spacecraft. These factors would, in turn, give a high degree of confidence in component flight readiness with a significant reduction in part and subassembly ground tests.

B. Statements of Impact

The studies described in subsection A above, together with the Shuttle Capabilities Document (Appendix A), were used to formulate a generalized flow diagram of the design, development, test, checkout, and operations of a typical spacecraft using Shuttle System capabilities. This flow diagram is presented in Exhibit 16. The first nine boxes, through that labeled spacecraft launch, are representative of current space programs. The five added boxes represent capabilities made possible only with the utilization of a Shuttle System. The nonrectangular boxes (also designated by a Roman numeral) indicate those stages in the overall space program development which might be expedited by Space Shuttle flights. The Statements of Impact (SOIs) presented below are organized into eight categories corresponding to the eight Shuttle assisted

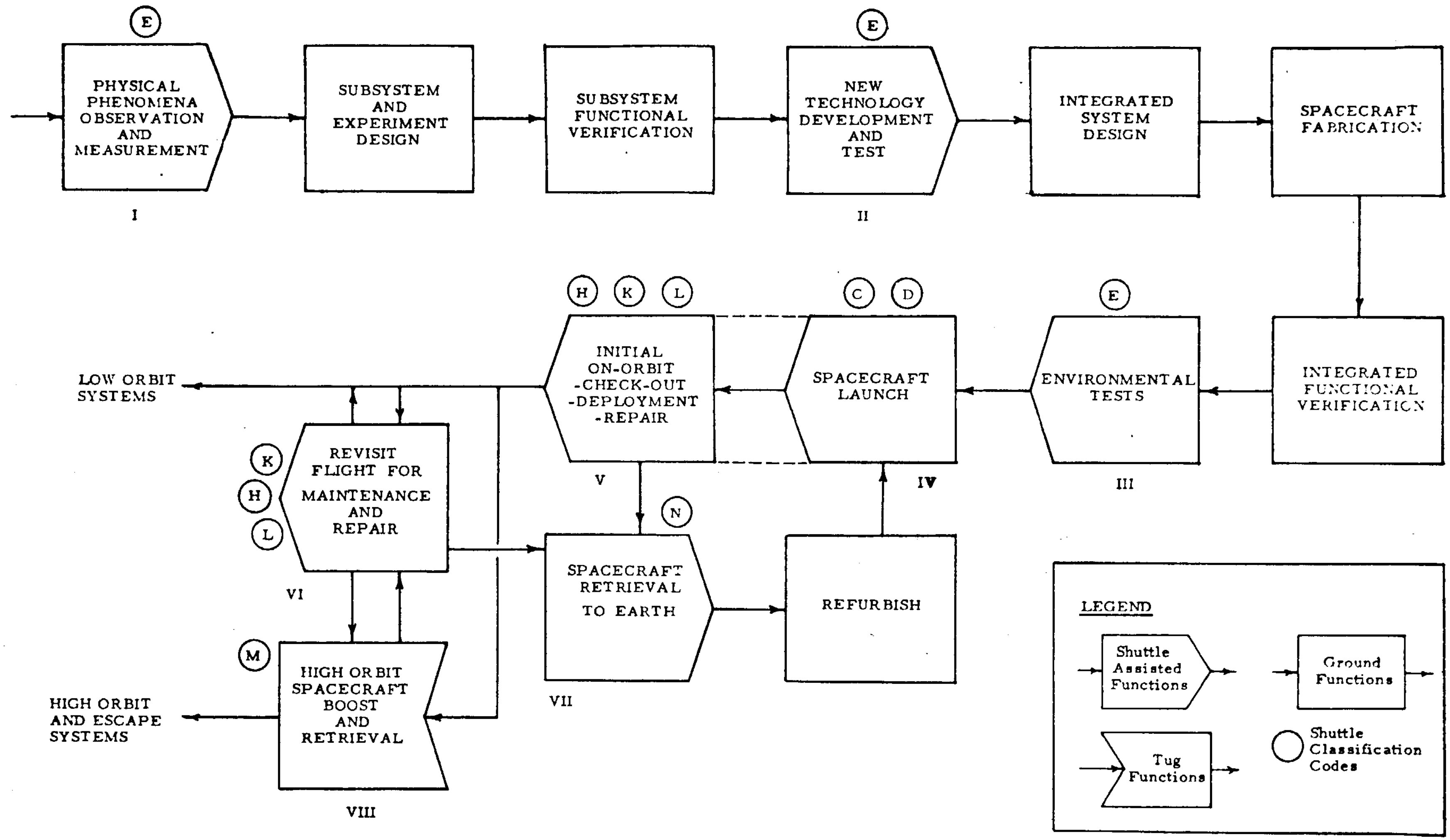


EXHIBIT 16 - SPACECRAFT DESIGN, DEVELOPMENT, TEST, AND OPERATION WITH SPACE SHUTTLE

functions. The Shuttle impacts all activities in the program of course and, although not shown in Exhibit 16, there are information feedback loops which carry the products of Shuttle utilization to the appropriate ground based design or planning function.

Of the eight Shuttle assisted functions, only I and II are not related to a completed (or nearly completed) spacecraft. Function I implies the use of the Shuttle to determine the value of physical phenomena as measured from space, which are needed to design a long term, unmanned satellite. If achievement of space program goals requires the development of new technology devices, these can be proven in space prior to their integration in an entire spacecraft through the Function II applications of the Space Shuttle. Function III is primarily envisioned as use of the Space Shuttle to replace awkward space simulation tests such as the commonly required thermal-vacuum tests. Major subsystems might also be tested in this way. If an entire system is tested and found to be successful, it may be started on its mission without returning it to the ground.

Functions IV and V cover the nominal launch mission, including spacecraft checkout, deployment, and initial repair as required. The two blocks are connected with dashed lines to indicate that, although they define separate functions, they are usually conducted together using the same Shuttle mission. Boxes VI and VII cover the on-orbit repair and retrieval functions capable with the Space Shuttle. Box VIII indicates the addition of Tug capabilities to all other Shuttle functions if required.

The circled letters in Exhibit 16 are Shuttle classification codes indicating anomalies which could have been prevented or repaired by using the Shuttle for a particular function. These are used in conjunction with the various Shuttle capabilities to generate and support the various Statements of Impact. An example is the tabulation of Exhibit 17. Of the 1190 anomalies occurring on successfully launched spacecraft, 320 were associated with malfunctions of major components. The other anomalies represent system, subsystem, interface, or other problems not related to a specific major component. Two tabulations are shown in the

EXHIBIT 17 - ANOMALY DISTRIBUTION AMONG MAJOR COMPONENTS AND EQUIPMENT TYPES

Major Components	Number of Anomalies	Percent
Tape Recorders	65	20
Batteries	47	15
Experiments	43	14
Attitude Sensors	30	9
Transmitters	23	7
T.V. Cameras	18	6
Converter-Inverters	14	4
Receivers	13	4
Probes-Monitors and Detectors	13	4
Motor Controls, Etc.	9	3
TM Encoders-Decoders	9	3
Miscellaneous	36	11
	320	100

Equipment Type	Number of Anomalies	Percent
Basic Electronics	144	45
Energy Sources	52	16
Experiments	43	14
Mission Sensors	31	10
Attitude Control	30	9
Non-Electronics	20	6
	320	100

exhibit, one classifies the major component anomalies by general equipment type, and the other by specific components.

The following subsections contain expanded descriptions of Shuttle Impact Categories I through VIII. Supplementing the category descriptions are (1) a list of components, subsystems, or tests which are potentially impacted by the particular Shuttle function and (2) several Statements of Shuttle Impact (SOIs) that together with the rationale and supporting data, serve as vehicles for presenting specific ideas on the design, development, and testing of Shuttle compatible spacecraft and potential changes in the management of space programs.

1. Category I: Physical Phenomena - Observation and Measurement

The Shuttle experiment packages carried on the planned sortie missions will provide means for precisely measuring and evaluating the physical characteristics of earth and space as seen from orbit. Data from these missions will enhance the design of subsystems and experiments such as:

- Star trackers
- Solar arrays
- Horizon scanners
- Infrared, visible and ultraviolet photography
- Photometry
- Spectography
- Radiometry
- Antennas (patterns and propagation)
- Electromagnetic and particle radiation
- Laser communications (atmospheric propagation)

SOI s 1 through 3 have been generated in this category. These are presented and discussed in the following paragraphs.

a. <u>SOI 1: For some space program objectives, automated spacecraft will be completely eliminated.</u>

Many short duration space experiments can be conducted within the time frame of a Shuttle sortie mission. Sufficient data can be taken during this period so that a dedicated spacecraft launch might be eliminated. For example, the biological experiments conducted in low earth orbit during the Bio Sat program could have been conducted more effectively on the Space Shuttle, where first hand examination of the specimens would have been possible.

Other specific functions which could be performed on a Shuttle Sortie mission, thereby eliminating the need for an automated spacecraft, include:

- o Laser communications experiments
- o Photographic missions for specific areas of interest
- o Observations of solar eclipses and other transient phenomena

Spacecraft launches in the Data Bank that could have been replaced by Space Shuttle sortie missions include some of the Orbiting Vehicle series devoted primarily to short term data gathering functions and a large proportion of the 93 Agena spacecraft.

b. <u>SOI 2: Spacecraft design problems will be eased and anomalies prevented by utilizing Shuttle observations of astronomical phenomena.</u>

Selected phenomena can be observed on the earth and in space during Shuttle sortie missions. These data can then be utilized in the analysis and development of new technology sensors. For example, selected parameters of the ocean might be measured from the Shuttle to assist in the development of oceanographic sensors to be placed on automated spacecraft.

At least 25 anomalies in the Data Bank might have been prevented had Shuttle observations of various astronomical and geophysical phenomena been available. Most of these are related to horizon sensor designs requiring earth infrared models or solar array degradation caused by the several components of solar radiation.

c. SOI 3: The sensitivity, resolution, and accuracy of earth and astronomical observation sensors will be verified.

It is difficult, if not impossible, to properly simulate the conditions under which such instruments as spectrometers, photometers, and radiometers will be gathering data. On previous programs, the tests failed to predict many of the problems encountered with the quality of sensor outputs. Shuttle testing of these devices will not only reveal problem areas but also provide information required for design parameters. Designing for a wide input range, simply because no previous direct observations have been made on the input characteristics, leads to over-complexity and hence decreased reliability.

Attitude sensors alone accounted for 30 of the major component anomalies (nearly 10 percent of the total) listed in Exhibit 17. The majority of the anomalies associated with experiments, mission sensors, and attitude control equipment types are also sensor problems. These equipment types account for nearly one-third of all major component anomalies.

2. Category II: New Technology - Development and Test

Another use of the Shuttle sortie mission is to conduct tests on advanced state-of-the-art experiments and subsystem designs that are potentially affected by the space environment or which observe and/or use physical phenomena that can only be accurately duplicated in orbit. The advantage of the Shuttle test lies in verifying the performance and realized potential of the equipment prior to integration into the spacecraft subsystem. Typical tests are to determine:

- Angular resolution and discrimination characteristics of star trackers and horizon scanners
- Actual effects of solar heating on sensitive assemblies (e.g., solar panels)
- Realized resolution of photographic experiments
- Assembly performance in thermal-vacuum conditions
- Sensitivity and accuracy of spectrometers, photometers, radiometers and other designs

SOIs 4 through 7 have been generated in this category. These are presented and discussed below.

a. <u>SOI 4: The elapsed time from concept formulation to final design of new technology components will be significantly reduced.</u>

Using the Shuttle system capabilities, new components and sensors can be developed and subsequently tested prior to being used operationally in an automated spacecraft, thereby reducing overall development time. For example, the Shuttle would have been instrumental in the development of the horizon sensor. At least six anomalies can be identified in the Data Bank which could have been prevented by verifying the design on the Shuttle prior to use.

Other component anomalies of this type include (1) the failure of an infrared interferometer spectrometer caused by the earth albedo entering the optics housing and thereby raising the temperature of the unit to intolerable levels, (2) the loss of a millimeter wave experiment for six months while outgassing in the area of the multipactor was completed, and (3) an inoperable filter wedge spectrometer caused by an ice deposit on the cooled detector.

Without the Shuttle, each of these anomalies and approximately six others required feedback from orbital operation to perfect their design. With the Shuttle this time lag could be eliminated and many of the usual ground test procedures could also be eliminated or at least considerably streamlined.

b. <u>SOI 5: Routine Shuttle testing of spacecraft components prior to spacecraft integration is not warranted for components within the state-of-the-art.</u>

Only a small fraction of the anomalies in the Data Bank could have been prevented by component testing on the Space Shuttle, and most of these involved experimental components. For components that are within the state-of-the-art, the record indicates that shuttle testing is unnecessary in terms of both the anomaly occurrence frequency and the mission effect.

The Data Bank contains data on 4000 to 5000 major components, the vast majority of them being well within the state-of-the-art.

Only 16 anomalies, however, were judged to be preventable by component testing on the Space Shuttle. Of these 16 anomalies, 13 were associated with experimental components. Only 2 of the anomalies had a mission effect greater than Code 2 (both on developmental horizon sensors) and only 3 of the anomalies occurred after May 1966.

c. SOI 6: Antennas will be realistically tested and actual antenna radiation patterns will be obtained by orbital evaluations instead of simulations.

Antenna radiation patterns, both satellite-to-satellite and satellite-to-ground, can be determined without the interference or reflections that occur even in the purest ground-based anechoic chambers. Also, ground-based atmospheric and ionospheric simulations cannot accurately duplicate the normal spacecraft operational conditions.

Though no serious antenna performance problems have been encountered in the past, a number of minor problems directly and indirectly related to antenna propagation and interference might have been avoided had new antenna deployment and positioning schemes been evaluated on a Shuttle sortie mission.

d. SOI 7: New approaches to spacecraft stabilization or new applications of existing types of stabilization mechanisms to uniquely configured spacecraft will be evaluated under orbital conditions.

Such stabilization devices as gravity gradient systems, magnetic torquers, and nutation dampers can be satisfactorily tested only in orbit. The need for such testing is obvious if the devices utilize a new design. It is also needed if an existing stabilization device is incorporated into a new spacecraft, since each satellite has a unique mass distribution which creates unique problems. Due to the physical nature of the forces involved and the difficulty of suspending a satellite without friction, accurate simulation of orbital conditions is impossible.

Unpredictable precessions, wobbles, and other instabilities have been observed on previous programs. Thus, an effective approach would be to evaluate stabilization system operation in conjunction with other orbital performance and environmental tests.

Several programs incorporating new designs and approaches for attitude stabilization have experienced serious failures. At least three spacecraft in the Data Bank suffered a 33 to 67 percent mission loss due to poor attitude control as a result of oscillations in the veristat booms and disruption of the gravity gradient system by aerodynamic drag and solar pressure effects.

3. Category III: Orbital Environmental Tests

The Shuttle provides an opportunity to conduct qualification and acceptance tests on integrated prototype spacecraft in a fully deployed mode under true operating conditions. A spacecraft, upon successfully completing this test, can then serve as the first operating model in the flight program. Failed spacecraft would be returned to earth for failure evaluation and hardware or procedure redesign. This type of test would be particularly effective on complex, high-cost programs. It would partially or entirely replace the following simulations and environmental tests.

- o Thermal-vacuum chamber test -- especially solar simulations, liquid N_2 heat sink simulations, and air-bearing attitude control and stabilization tests.
- o Separation system tests
- o Solar array and boom deployment tests
- o Anechoic chamber tests
- o Pyrotechnic demonstration tests
- o Integrated system EMI tests

SOIs 8 through 12 are presented and discussed below:

a. <u>SOI 8: Thermal-vacuum testing of spacecraft will be eliminated or replaced by testing on a Shuttle sortie mission.</u>

Thermal-vacuum testing on the ground of large spacecraft or spacecraft with complex deployable members requires extensive equipment and complicated procedures. Even then, an adequate simulation of the actual space environment is rarely achieved. Both of these difficulties are readily overcome by testing the integrated spacecraft on a Shuttle sortie mission.

The following items, chosen from the Data Bank, are indicative of the residual problems associated with current thermal-vacuum testing:

- There are many spacecraft with extremely long appendages (booms or antennas) for which existing thermal-vacuum facilities are generally inadequate to conduct an integrated spacecraft test in the fully deployed mode. Therefore, all aspects of the spacecraft design cannot be evaluated even under simulated conditions.
- On one such spacecraft a boom deployment failure occurred due to cable insulation stiffened by low orbital temperatures. The ground testing of this deployment was inadequate because of unrealistic simulations imposed by the size limitations of readily available thermal-vacuum chambers.
- At least four programs in the Data Bank have suffered mission degradation averaging nearly 50 percent due to thermal design deficiencies remaining after the conduct of thermal-vacuum tests.

b. <u>SOI 9: Attitude control and stabilization subsystem designs will be verified during orbital qualification tests on a Shuttle sortie mission.</u>

Comprehensive tests of the attitude control and stabilization (ACS) subsystems on various spacecraft programs have proved to be very difficult since an accurate simulation of the conditions of space is not possible. Most of these tests are conducted in conjunction with thermal-vacuum chamber tests on the prototype-model spacecraft.

Thermal-vacuum tests of ACS subsystems can be improved by orbital qualification tests in at least the following areas:

- o Providing real targets for star, solar, and horizon sensors. Simulated targets for star and solar sensors and particularly for horizon sensors are rarely satisfactory and often result in erroneous sensor inputs. A number of operational and test failures have occurred because of this problem.
- o Maintaining a vacuum environment. With thrusters operating, true vacuum conditions cannot be maintained in a thermal-vacuum chamber (37 anomalies - 25 percent of those on the ACS were related to thruster operation).
- o Providing actual spacecraft mass effects. Thermal-vacuum chamber size constraints usually do not permit complete boom deployment and therefore bending moments, true mass, and moments of inertia are not adequately simulated. This is especially true of spacecraft with long booms such as those of the Orbiting Geophysical Observatory spacecraft.
- o Investigating solar radiation pressure and aerodynamic force effects on the stability and attitude control of low perigee orbit spacecraft. This can only be done in space. Three anomalies of this type were found in the Data Bank resulting in 33 to 67 percent mission loss.
- o Eliminating the need for air bearing suspension systems. These systems are essential for ground tests, are difficult to set up, and tend to introduce errors. In one program the position and rate tracking system used with the air bearing suspension system was too complex to implement and was never successfully exercised.

c. <u>SOI 10: Component interactions and interface characteristics that cannot be determined with ground testing procedures will be evaluated in an orbital qualification test.</u>

A number of operational problems have arisen in past programs due to the impossibility of accurately simulating all operational and environmental conditions. Typical areas where simulation is difficult, if not impossible, include artificial horizons, dynamic booster/spacecraft interface, zero- g deployments, pyrotechnic actuations, etc. Also, it is difficult to duplicate all operating modes for a realistic test of a complex control system, such as one utilizing an on-board computer. The most effective means to reduce the problems stemming from such unpredictable factors is orbital qualification of a totally integrated system.

The Data Bank indicates that approximately 25 percent of the problems in space vehicles were related to the lack of relevant system tests.

One experiment failed due to overheating when an outgassing shroud caused changes in the properties of the spacecraft thermal coating.

OAO-B failed to achieve orbit when a dynamically untested latch failed and prevented nose fairing jettison.

Reference 4, a study of 88 launches in 3 launch vehicle programs, indicates that 25 flight failures were encountered. Of those, "three were attributed to personnel error and the remaining 22 were the result of an anomalous operation of a deficient or defective component that, once it had been assembled in or attached to the completed vehicle, allowed for no testing technique that would provide for malfunction detection." Reference 4 concludes:

> "Thus, the most frequent real cause of flight failure is the malfunctioning, inoperability, or structural separation of a piece of basically mechanical hardware that does not lend itself reasonably, or, in most cases at all, to systems testing."

d. <u>SOI 11: On programs involving several identical spacecraft, orbital testing will be a very effective and economical means of qualifying the subsystems.</u>

Integrated qualification tests in the launch and orbital environment would exercise the spacecraft subsystems and their interfaces under conditions that are difficult to simulate on the ground. On programs involving several spacecraft, this would be economical in that individual sybsystems testing would be reduced. Also. design deficiencies could be discovered before equipment fabrication or subsequent missions had progressed far enough to make rework costly.

e. <u>SOI 12: Testing for overstress conditions will be difficult on a Shuttle sortie mission.</u>

In general, testing for overstress conditions will have to be carried out at ground facilities since development tests utilizing the Shuttle are limited to the normal, orbital environmental exposures. Some exceptions to this might be:

- o Overstress launch acoustic conditions could be created by a shuttle launch with reduced acoustic insulation in the payload bay.
- o Low temperature overstress could be simulated by operating the test spacecraft in the shadow of the Shuttle.

4. <u>Category IV: Shuttle Payload Launch Capability</u>

The capability of the Shuttle to launch much larger and heavier payloads than are common in the Data Bank with relatively milder environmental stresses has many design and cost implications.

Five areas of spacecraft design in which the Shuttle would have the greatest impact are listed below. The pre-Shuttle implementation in most of these areas was not possible due to the relatively limited payload capability of the expendable boosters then available. For each of these design areas, a number of potential benefits are listed which might be expected from full Shuttle utilization.

1) <u>Subsystem and Component Standardization and Modularization</u>

- o Greatly reduced design verification and environmental testing
- o Higher reliability
- o Lower cost per spacecraft
- o Spacecraft-to-spacecraft interchangeability
- o Cluster satellite concepts possible
- o Ease of maintenance and repair
- o Fewer wearout problems
- o Fewer integrated system tests

2) <u>More Subsystem and Component Redundancy</u>

- o Reduced reliability testing
- o Lower parts burn-in requirements
- o Lower component reliability requirements
- o Improved reliability
- o Fewer Shuttle repair missions required

3) <u>Overdesign and Increased Safety Factors</u>

- o Wider parameter margins
- o Lower parts burn-in requirements
- o Reduced subsystem reliability testing
- o Increased component reliability
- o Better experiment isolation
- o Better EMI control
- o Better thermal control
- o More effective radiation shielding possible

4) <u>Built-in Test Capability</u>

- o Less prelaunch testing required
- o Less Shuttle test equipment required
- o Fewer telemetry channels used for diagnosis
- o Easier on-orbit repair

5) <u>Increased Spacecraft Performance</u>

- o Larger propellant capability for orbit modification
- o Larger nuclear power supplies
- o Larger stationkeeping potential
- o Larger and more effective radio telescopes
- o Added capabilities for interplanetary missions

The largest number of SOIs for any of the eight categories occur here. There are 12 Statements of Impact, numbered 13 through 24. These are presented and discussed below:

a. <u>SOI 13: The physical spacecraft envelope will be less restricted, thereby allowing more conservative techniques to be applied at the lower design levels to reduce the possibility of failures.</u>

Shuttle launched spacecraft can be designed with packaging techniques that are far less dominated by volume and weight considerations.

This should result in:

- More conservative circuit assembly methods utilizing more effective potting and more rigid mounting. This should, in turn, lead to a reduction in corona problems, vibration induced failures, and internal shorts and opens.
- The use of more conservative part stresses through the use of physically larger components.
- The use of heavier heat sinks for more effective component cooling and better reliability.

b. SOI 14: Much more redundancy will be possible, thereby significantly enhancing reliability.

In the past, weight restrictions have often been the deciding factor in whether redundancy should be incorporated. With the increased capacity of the Shuttle, redundancy based on reliability considerations alone can be provided in both mechanical and electronic subsystems.

c. SOI 15: More effective techniques for suppression and control of electromagnetic interference will be available, thus reducing design and test efforts and yielding performance benefits.

In the Shuttle programs, weight and envelope tradeoffs against the control of EMI need no longer be seriously considered. The ample payload and volume capacity of the Shuttle allows increased use of:

- Shielded cables in areas of possible interference
- Shielding cans around transformers, relays, motors and other EMI producers
- Heavier shielding in critical areas where light shielding is now employed
- Specialized packaging for improved electromagnetic compatibility of components that are highly sensitive to interference
- Designs which are not EMI sensitive
- Large ground busses

Seventy-six anomalies in the Data Bank are directly attributed to EMI/RFI causes. EMI was a source of performance degradation for 60 of the 304 spacecraft in the entire Data Bank.

d. SOI 16: Locations for sensitive experiments will be optimized for isolation and maximum data gathering capability.

Magnetic and electromagnetic interference and compatibility problems have occurred in nearly all complex spacecraft such as those from the Nimbus, Orbiting Geophysical Observatory (OGO), and Mariner programs.

With the increased size, weight, and deployment capabilities of the Shuttle, each sensitive or noisy experiment can be positively shielded and mounted separately on a boom sufficiently long for proper isolation. Where questionable, the degree of shielding and boom length required can be determined by Shuttle test.

Typical of on-orbit problems is the fact that on one spacecraft the full capability of a very sensitive search coil magnetometer could not be realized because of magnetic interference. This interference occurred due to the proximity of magnetic sources. Among these sources were magnetized components, radiated fields in current carrying wires, and malfunctions in experiments.

To automatically deploy many isolated experiments is quite expensive, especially in terms of reliability. Also it is very difficult to conduct a realistic and adequate test of a spacecraft on the ground in the properly deployed configuration. Extensive OGO tests at the quiet magnetic facility near Malibu, California, were unable to prevent later orbital problems, evidenced by the fact that on all OGO's it has been necessary to alternately cycle some experiments to reduce as much as possible their interference with one another.

e. SOI 17: Spacecraft performance will be greatly enhanced due to improvements that can be achieved in thermal control.

In the past, thermal control limitations have placed restrictions on the designs of other subsystems and poor thermal characteristics have caused operational failures. With the Shuttle launch capability, a wider, more flexible selection of thermal control designs and techniques will be available. The use of more and larger radiators and coolant systems, elaborate control mechanisms such as shutters, and increased insulation will allow much more precise thermal control of the primary spacecraft subsystems as well as isolating them so that they are more independent of each other.

The Data Bank reveals that nine percent of the successfully launched spacecraft have experienced anomalies correctable by better thermal control. Thirteen percent of these spacecraft experienced a mission degradation in excess of thirty-three percent.

One spacecraft, for example, lost all data storage capability due to thermal problems after 720 hours of operation and another suffered severe degradation due to a final amplifier overheating which caused the telemetry transmitter to fail.

f. SOI 18: Nuclear power systems will become feasible, resulting in larger power capacity and longer missions.

Several problems which currently dominate the nuclear power supply field will be alleviated by the Shuttle. The launch capacity will allow the use of heavy shielding and the boost vehicle reliability will assure safe injection. If desired, the power supply can be deployed a large distance away from the spacecraft to avoid any nuclear effects on the subsystems.

This is especially significant for interplanetary missions, since the ultimate success of such exploration depends largely on the development of reliable power sources other than solar/battery systems. For less far-ranging missions, the increase in available power will allow less sophisticated and therefore lower-cost, more reliable designs.

For example, larger safety factors and design margins can be employed, more redundancy can be incorporated, and better thermal control can be achieved.

g. <u>SOI 19: Extensive self-check and built-in test capabilities will be incorporated in spacecraft designs.</u>

With the easing of weight and size constraints, more of the payload can be devoted to spacecraft self-check and built-in test capability. This can be accomplished through the use of an on-board computer which would also be able to automatically sense failing conditions and switch to redundant circuits.

This system should reduce the number of telemetry and data handling circuits required which, in the past, were responsible for 34 percent of all satellite anomalies. It should, in turn, reduce ground station requirements, and facilitate circuit trouble-shooting and "work-around" solutions to the problems not automatically solved on-board.

h. <u>SOI 20: Vulnerability to nuclear radiation will be more easily reduced to tolerable levels.</u>

With only limited weight and envelope constraints, nuclear hardening and shielding is more easily effected. For example, specially hardened components can be selected without considering their weight and volume impact; more and heavier shielding, commensurate with the equipment sensitivity and vulnerability can be employed.

i. <u>SOI 21: Use of standardized subsystems will greatly reduce spacecraft testing requirements and increase spacecraft reliability.</u>

The standardization of spacecraft subsystems as proposed by the Lockheed Low Cost Payload Study (Reference 5) will substantially reduce the subsystem and component environmental tests, design verification tests, and integrated functional verification tests, which currently occupy a large proportion of an overall spacecraft development program.

Standardized subsystems also promise to yield substantial benefits by avoiding spacecraft anomalies attributed to all kinds of design deficiencies. The Data Bank attributes 65 percent of all anomalies with an assignable cause to design deficiencies (Reference 1, page 45). Since 80 percent of these anomalies occurred in subsystems which could be standardized, it follows that fully 50 percent of all anomalies could eventually be avoided by correcting design deficiencies in early models of standardized subsystems. This goal could be approached more rapidly through wider use of the standardized subsystems.

j. <u>SOI 22: Spacecraft structural dynamic simulation and testing will be virtually eliminated</u>.

The support structure for a Shuttle-launched spacecraft may be designed with a wider margin of safety in bending moments, rigidity, etc., due to the relaxation of weight constraints made possible by utilizing the Shuttle System. These increased safety factors will allow the spacecraft to easily withstand acceleration, vibration, and acoustic forces far larger than those that will be experienced in the relatively mild launch environment of the Shuttle or Tug. Optimizing the designs with structural dynamic simulations and tests will therefore not be required.

k. <u>SOI 23: Full scale simulator-type testing to launch environments will be replaced by lower-level testing to the Shuttle environment, thus eliminating the need for large simulators.</u>

Launch phase simulators are constructed to provide full scale, combined environmental testing for the launch environments of acceleration, acoustic loading, three degree-of-freedom vibration, and vacuum. In the Shuttle era, the following three factors will result in elimination or reduction of these simulator testing requirements.

- o It will not be practical or necessary to build the very large simulators needed to contain and test the large spacecraft of this period. Should a launch induced failure occur, spacecraft retrieval would be more practical.

- o For small spacecraft, limited launch phase simulator tests will still be necessary, since it would probably be cheaper to run limited tests than to retrieve a failed spacecraft for a rerun. The tests would provide assurance that no launch-induced failure would cause loss of the spacecraft prior to the environmental tests or loss of a spacecraft launch on a regular mission without environmental tests.
- o The generally milder Shuttle environments will allow a significant reduction in simulator testing requirements, particularly in the areas of acceleration and vibration (lower overall levels combined with better adapters).

In applicable cases, consistent with the three factors above, launch phase simulator tests can be replaced by the actual Shuttle launch environment experienced by the spacecraft during placement for orbital environments or qualification testing.

1. <u>SOI 24: Large scale acoustic tests on full size spacecraft models will be eliminated.</u>

Current programs require acoustic environmental tests to experimentally determine the magnitude and spectra of the spacecraft vibrational response. Extensive tests were conducted on the Orbiting Geophysical Observatory (OGO) program to determine the acoustic response of the spacecraft and to verify shroud transmission loss characteristics. On OGO, these tests were conducted using the thermal structures wind tunnel at Langley Research Center.

With the Shuttle system, the acoustic tests can be eliminated for the following reasons:

- o The acoustic environment produced by the Shuttle launch vehicle with most proposed configurations will be milder than the acoustic environment produced by standard launch vehicles.

- The spacecraft structure can be produced with minimal acoustic sensitivity due to the reduced launch weight constraints provided by the Shuttle.
- The Shuttle Orbiter payload bay can be acoustically isolated, if necessary for a particular spacecraft, with a relatively small weight penalty.

5. Category V: Initial On-Orbit Checkout, Deployment and Repair

The spacecraft designs possible with the large payload capabilities of the Shuttle, together with its ability to accompany a spacecraft for a period of time after orbital insertion, allow a complete post-launch checkout prior to release with solitary orbit. Any anomaly resulting from the launch and release environments would be repaired on-orbit or, if this is not feasible, the spacecraft can be returned to earth for refurbishment. Manual assistance in deployment of experiments, long booms, solar paddles, etc., is also possible in this mode.

Some impacts on present spacecraft designs, tests, and procedures by this Shuttle utilization are:

- Reduced deployment mechanism tests
- Increased deployment reliability
- Better experiment EMI control (using very long booms)
- Better ACS performance (using more rigid booms)
- Larger radio telescope possible
- Reduced subsystem testing
- Reduced part burn-in requirements
- Solution for very prevalent early failures

SOIs 25 through 28 for this category are presented and discussed below.

a. SOI 25: Separation subsystem design and testing programs will be greatly simplified.

Standardized Shuttle adapter mounts for docking and retrieval will obviate the need for the development tests usually required for each type of spacecraft. In one program, for example, a special separation mock-up was fabricated to evaluate the dynamic separation of the spacecraft from the adapter and to verify proper shroud clearance. Actually, two series of tests, several years apart, were necessary to complete this evaluation.

OAO-B is only one of a number of spacecraft that failed to achieve orbit due to failure to jettison the nose cone. This failure occurred in spite of an extensive test program to assure that the separation subsystem would function properly. The entire background surrounding this particular anomaly which tends to support this SOI is contained in: Final Report of Investigations Conducted By the OAO-B Launch Vehicle Review Board, Lewis Research Center, NASA, 8 June 1971.

b. SOI 26: Design and test efforts associated with complicated, automatic deployment mechanisms will be greatly reduced and more dependable deployment methods will be achieved.

Many low orbit spacecraft have long booms for experiments, gravity gradient systems, and antennas. In addition, nearly every spacecraft program requires some deployable elements such as solar arrays, sensor platforms, etc. The Shuttle makes it possible to either 1) accomplish the complete, required deployment manually, 2) perform some portion of the deployment sequence manually, or 3) provide a standby service to manually assist in automatic deployments if needed. For low orbit spacecraft, this would eliminate the necessity for redundant and complicated automatic deployment mechanisms which are subject to failure, and would reduce the necessity for such mechanisms on spacecraft in high energy orbits. In addition, it would greatly reduce the design and test burden associated with these devices.

There are six anomalies in the Data Bank associated with deployable structures. The most severe of these resulted in serious mission degradation when experiment booms did not completely deploy precluding attitude control and stabilization and a concomittant loss of power.

c. SOI 27: Extensive component burn-in programs can be reduced to minimal levels.

Several aspects of the Shuttle program on spacecraft reliability combine to reduce the need for extensive component burn-in programs. The liberalized launch weight and size constraints will allow specified reliability to be achieved more effectively by redundancy. Also, the use of the Shuttle for on-orbit repair, refurbishment, or retrieval will contribute to the operational reliability. Such factors as these imply that more cost-effective designs can be achieved by the use of standard parts that undergo the more economical lot burn-in procedures.

d. SOI 28: More sophisticated and reliable radio-telescope arrays will be possible due to the elimination of present deployment test and construction problems.

A number of current problems limit the expansion of orbiting radio astronomy observatories. Some of these problems are:

- o Large boom-arrays must be deployed with automatic mechanisms that have a relatively high failure rate.
- o Actual operating conditions, i.e., weightlessness and vacuum, cannot be simulated in ground testing.
- o Systems with tubular, extendable elements must be tested for straightness to assure a tip deflection within the specified limits. This is a formidable task for very long (up to 1000 feet) arrays.
- o Thermal gradients from solar radiation can cause long, lightweight booms to bend.
- o Critical portions of the system, such as the dispenser mechanism, cannot be made redundant.

With the availability of the Shuttle, these problems can be overcome and larger, more sophisticated radio-telescope arrays can be deployed in space. Specifically, the Shuttle can serve in the development and implementation of such systems in the following ways:

- o It can test concepts of automatic and manual deployment on sortie missions.

- It can verify accepted deployment schemes, the straightness of extended elements, etc.
- It can carry larger (and redundant if necessary) dispenser mechanisms to deploy tubular, extendable elements of a larger diameter and heavier material. This would reduce tip deflection and alleviate the thermal gradient problem on increasingly longer booms.
- It can repair a system that has not deployed properly or utilize a manual, backup mode to accomplish deployment.
- It can retrieve a system for rework if deployment cannot be accomplished or if boom straightness or tip deflection are not within the specified range.
- It opens the way to design approaches not previously considered.

6. Category VI: Revisit Flight for Maintenance and Repair

In the event of spacecraft damage, wearout, or failure, the Shuttle is capable of returning for on-orbit repair. This capability would extend spacecraft design life by replacement of worn-out components and replenishment of depleted propellants in addition to the impacts related in Category V.

SOIs 29 through 32 for this category are presented and discussed in the following paragraphs.

a. SOI 29: Spacecraft design will be modularized.

Most of the standard subsystems and major components will be modularized and removable without requiring calibration, for ease of replacement on-orbit. Priority will be given to modularizing failure-prone subsystems and components.

Ninety-two percent of the major nonpreventable anomalies (436 of 475) are repairable utilizing Shuttle system capabilities. Of these 436 anomalies, modularization would expedite repair in over half of the cases.

If the priority for modularization is based on failure susceptibility, the Data Bank indicates the following should receive early consideration:

Subsystems	Components	Component Category
Telemetry and data handling	Tape recorders	Electronics
Payload subsystems	Batteries	Energy sources
Timing and command	Experiments	Experiments
	Attitude sensors	Mission sensors
	Transmitters	Attitude control
	TV cameras	

Exhibit 17 and Reference 1 provide a more detailed and quantitative assessment of the relative frequency of component and subsystem anomalies.

b. SOI 30: Significant cost benefits will accrue from repair or retrieval of spacecraft that incur early failures.

The Shuttle enables on-orbit escort of a spacecraft for as long as seven days after the initial deployment. Since a significant number of anomalies have occurred during this initial period in the past, the ability to effect repairs from the Shuttle, especially by modular remove-and-replace techniques, will assure a greater chance of successful, long-term, spacecraft operation. Irrepairable spacecraft will be retrieved for earth refurbishment if it appears to be cost effective.

Of the 57 unmanned spacecraft under the management of GSFC in the 1960 to 1970 timeframe (Reference 6), 58 percent of the failures experienced during the first month of flight occurred on the first day and 76 percent occurred in the first week. The 45 first-day failures involved 30 of the spacecraft. Only 22 spacecraft survived the first day without any type of malfunction. Seven percent of the first-day malfunctions were catastrophic (greater than 90 percent loss) to the mission and 52 percent were catastrophic to the component involved.

The sample of 104 spacecraft selected for availability analysis in Section III. B included 17 unsuccessful launches and 40 other spacecraft that incurred significant anomalies within the first week of launch. Using cost estimates provided by The Aerospace Corporation, the total first-article cost of the unsuccessfully launched spacecraft is approximately \$150 million. Multiplying the first-article cost of each of the other 40 spacecraft by its first week mission degradation and summing the products indicates a loss of another \$176 million. For the selected sample, this amounts to a potential savings of over \$3 million per spacecraft launch, due solely to the repair and retrieval capability of the Space Shuttle as applied to anomalies occurring in the first week.

c. SOI 31: The Shuttle capability of replacing spacecraft battery modules will prolong the life of many spacecraft and prevent mission degradation on others due to battery wearout.

If spacecraft battery modules, which preferably would contain the charge and discharge control circuitry, were easily replaceable on-orbit, many failures would be prevented. Battery failure usually has a significant to catastrophic impact on system operation, which is especially important in view of the fact that batteries have a low shelf and cycle life, and relatively low reliability. Also, failures in solar arrays, charge control, and command and control assemblies, which create life-degrading over/under charge conditions, frequently cause a secondary failure of a battery. In addition to reliability risks such as these, the data bank indicates many more problems would have occurred due to battery degradation and wearout had the spacecraft not failed for other reasons. This implies that the availability of Shuttle maintenance and repair will cause battery problems to become increasingly significant.

Fifteen percent of the spacecraft in the Data Bank (47 of 304) experienced battery anomalies. Thirteen percent of all battery anomalies caused the total loss of the spacecraft. Four percent permitted sunlight operation only using the solar panels. Twenty-one percent of the anomalies caused a mission degradation of 33 to 67 percent. The remainder caused an average degradation of 21 percent.

d. <u>SOI 32: Spacecraft expendables can be replenished on a routine basis.</u>

Many programs could have been extended had the Shuttle been available to replenish depleted propellant. Mission degradation could have been prevented in other cases when restricted operating modes became necessary to conserve a prematurely dwindling propellant supply. Also, with the Shuttle replenishment capability, fuel cells, which have had limited application due to their voracious appetite for fuels, might see wider use. In addition to being attractive for systems requiring large quantities of electrical power, the cryogenic hydrogen-oxygen could be used as a propellant and the water by-products could be used as an evaporative cooling agent.

The Data Bank indicates that 33 anomalies of ACS subsystems were related to or caused by the excessive loss of propellants and pressurizing expendibles. The average mission degradation for these anomalies was 21 percent. Three of the anomalies caused an 80 percent average loss in spacecraft capability.

7. <u>Category VII: Spacecraft Retrieval and Return to Earth</u>

Even more fundamental than the Shuttle capability for spacecraft on-orbit repair is the capability for retrieval of spacecraft or portions thereof and returning them to earth.

Impacts in this area include:

- o Refurbishment of orbit-unrepairable spacecraft
- o Analysis of long-term space environment effects on materials and assemblies
- o Retrieval of photographs and other permanent records
- o Retrieval of defunct spacecraft for analysis

SOIs 33 and 34 for this category are presented and discussed below.

a. <u>SOI 33: Orbital failure mechanisms and reactions due to the space environment will be studied by retrieval of long-term spacecraft after their mission is completed.</u>

Retrieval on a space-available basis of spacecraft which have orbited over an extended period and which are no longer being used can yield important data in such areas as:

1) Micrometeorite erosion of lenses, mirrors, solar cell glass cover plates, etc.
2) Solar radiation degradation of thermal reflective surfaces, solar cells, sun sensors, etc.

The recovery of Surveyor components by the Apollo crew yielded valuable data on the space environmental effects on hardware and on solar and cosmic phenomenon.

Anomalies resulting from material and component degradations due to particulate and electromagnetic effects might have been prevented had recovery of some early failure samples for study been possible. Programs suffering from this type of anomaly include GEOS, Nimbus, OGO, OSCAR, OSO, OV1, Pioneer, Relay, Transit, and Telstar. The average degradation for the anomalies occurring on these spacecraft was about 32 percent.

b. <u>SOI 34: Materials will be placed in orbit for prolonged periods and then retrieved to determine their reaction to the space environment.</u>

Several failures and performance deficiencies on past programs have been attributed to the failure of materials to perform as predicted in the space environment. Typical problems have involved changes in the reflectivity of thermal coatings, degradation of solar cell output, micrometeorite erosion of lenses, vacuum welding, evaporation of bearing lubricants, etc. Such space-induced failures can be reduced by orbiting test vehicles carrying a wide assortment of new materials that have possible spacecraft applications. These experimental assortments could be designed to simulate their anticipated application and, in cases where a catastrophic failure is possible (for instance, bearing lubrication), they could be monitored to establish their MTTF.

8. Category VIII: High Orbit Boost and Retrieval

With the Tug, Shuttle capabilities are extended to high orbit and deep space.

Impacts of the Tug on future space programs are very similar to those of the Shuttle in Categories IV, V, VI, and VII as applied to spacecraft with orbits beyond Shuttle capabilities.

SOIs 35, 36, and 37 for this category are presented and discussed below.

a. SOI 35: High altitude spacecraft will be injected into designated orbits with high reliability.

The Tug, a well designed and tested boost vehicle, standardized for all high altitude injection missions, will be at least as reliable as currently used boost vehicles for high orbit injection and positioning and will have the added advantage of transferring to high orbit only those spacecraft checked out at a low orbit and found to be space worthy.

b. SOI 36: High-orbit spacecraft will be repositioned.

Spacecraft in circular orbits above the Shuttle zone and those in highly elliptical orbits can be repositioned or restabilized by the Space Tug. This could be required as a result of a failure in the spacecraft propellant system, or as part of the design in cases such as synchronous, communications satellites that must be periodically restationed.

In the Data Bank sample of 104 spacecraft, two were found to be amenable to restoration of 100 percent capability by stabilization and reorientation using the Space Tug.

In the ATS F & G Program, the satellite is required to be repositioned from over the Americas to over India to implement one experiment. This requires a large payload penalty in propellant and several months in transit time. Restationing tasks such as this could be more effectively executed by the Tug.

c. <u>SOI 37: High orbit spacecraft will be returned for repair and refurbishment in the event of failure.</u>

Spacecraft in circular orbits above the Shuttle zone and those in highly elliptical orbits can be returned to useful life through repair by the Shuttle or ground refurbishment using the Space Tug for orbital transportation.

The Data Bank indicates that 220 anomalies could be repaired only with the availability of the Space Tug. Fifteen of these failures (7 percent) were catastrophic and 6 (3 percent) were very serious (67 to 95 percent loss). The remaining 199 resulted in an average mission loss of 20 percent.

V. CONCLUSIONS

In this study, the reliability history of the U. S. space program has been examined in detail while considering the question: "What if the Space Shuttle had been operational in the 1958-1970 time period?"

In answering this question it was assumed that Shuttle capabilities were as defined in late 1971 and that all spacecraft considered were Shuttle-compatible with respect to repair and retrieval. These assumptions are completely defined in Appendix A of this report. Recent modifications to these assumptions are not reflected in Appendix A, since they do not influence the results of this study in any significant way. The reliability history of the U. S. space program in the 1958-1970 time period was assumed to be adequately reflected in the PRC/SSC Space Data Bank, which is discussed in Section II.

The study was treated in two parts. The first part, covered in Section III, analyzed the potential effect of the Shuttle on the anomalistic behavior of orbital spacecraft. The second part, covered in Section IV, investigated the influence of Shuttle capabilities on future unmanned spacecraft design, development, and test programs. In both parts, only the technical influence of Shuttle utilization was considered; cost tradeoffs were not within the scope of this study.

From Section III it may be concluded that the Space Shuttle would be highly effective in correcting or preventing spacecraft anomalies of the type occurring in the 1958-1970 time period. Nearly three-fourths of all observed anomalies would be favorably affected by Space Shuttle utilization. An even higher proportion of early or severe anomalies would be amenable to Shuttle utilization.

The average availability (proportion of nominal spacecraft capability that is realized) is increased 50 percent by simply replacing the expendable boosters with Space Shuttle launches and providing initial on-orbit checkout and repair capability. Average spacecraft availability can be increased to nearly 95 percent by dedicating, on the average, one Shuttle repair mission per year.

As discussed in Section IV, the impact of the Space Shuttle on future programs will be extremely far-reaching and favorable. Removal of constraints imposed by expendable boosters on spacecraft volume and weight appears to be the largest single contributing factor. This factor has major implications for the spacecraft design, permitting as it does the use of:

- Larger safety margins
- Increased redundancy
- Standardized modules
- Standardized subsystems

These design changes, in turn, permit a much reduced testing program. Standardization in particular, once implemented, should rapidly obviate the need for all but the most routine checkout of standard modules because early feedback from space operation could be used to remedy inherent design or procedural deficiencies.

Testing state-of-the-art components or entire spacecraft in the actual space environment by means of the Space Shuttle would also eliminate or reduce the extent of many of the awkward and unsatisfactory ground tests and simulations currently required.

The repair and retrieval capability of the Space Shuttle exercises its principal influence by maintaining operable spacecraft on-orbit, but also tends to reduce testing requirements, simplify designs, and shorten the development period of individual space programs.

REFERENCES

1. Planning Research Corporation, PRC R-1453, Reliability Data From In-Flight Spacecraft; 1958-1970, E. E. Bean and C. E. Bloomquist, 30 November 1971. (Unclassified) (AD889943L)

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

3. OMSF, Space Shuttle Program, "Space Shuttle Program Requirements Document, Level I; Section: Shuttle/Payload Interface," undated.

4. Carnahan, Charles E., "An Investigation of the Adequacy of Aerospace Vehicle Testing," Journal of Spacecraft, Vol. 7, No. 9, September 1970, pp. 1143-1144.

5. Lockheed Missiles and Space Company, LMSC-D154696, Design Guide for Low-Cost Standardized Payloads, 10 March 1972.

6. National Aeronautics and Space Administration, NASA TN D-6474, A Study of First-Day Space Malfunctions, A. R. Timmins and R. E. Heuser, September 1971.

APPENDIX A

SHUTTLE CAPABILITIES

TABLE OF CONTENTS

Page

I. SCOPE A-1

II. SHUTTLE REQUIREMENTS AND CAPABILITIES A-2

A. Configuration A-2

B. Shuttle Performance A-9

C. Reliability A-27

D. Payload Environments A-28

III. SHUTTLE-COMPATIBLE SPACECRAFT CONCEPTS. . . . A-30

A. Spacecraft Design A-30

B. Spacecraft Checkout and Test A-33

C. Spacecraft Repair and Refurbishment A-34

REFERENCES A-39

APPENDIX A SHUTTLE CAPABILITIES

I. SCOPE

The intention of this summary is to provide the general requirements and capabilities of the Shuttle Orbiter (Earth to Orbit Shuttle (EOS)) and the Space Tug (Orbit to Orbit Shuttle (OOS)) to be utilized as a baseline for the PRC/SSC study, PRC D-1813, "Use of the Space Shuttle to Avoid Spacecraft Anomalies," dated 24 November 1971, as defined in the Study Plan. These capabilities are presented in terms of Shuttle and Tug performance for payload orbit injection, maneuvering and retrieval.

The approach to the design and configuration concepts of spacecraft built to be compatible with the proposed Shuttle Systems are also described. The data for this summary are principally derived or inferred from the references listed.

II. SHUTTLE REQUIREMENTS AND CAPABILITIES

The general baseline configuration assumed for this study is the McDonnell Douglas Aircraft Corporation (MDAC) two-stage fully reusable launch vehicle with a high cross range (HCR) delta wing orbiter similar to the configuration used in the analyses of the Aerospace Corporation (References 1-5).

The Shuttle Booster is an LO_2/LH_2 powered unit of 30 x 10^6 Newtons (6.6 x 10^6) lbs.) of sea level thrust with turbofan jet engines for flyback and go-around capabilities.

The Shuttle Orbiter is a double delta wing configuration powered with rocket engines to supply the ascent thrust to orbit and with an optional turbofan Air Breathing Entry System (ABES) weighing 9,230 kg (20,300 lbs.) employed for powered landing and go-around capability. The ABES is used when the Shuttle Orbiter is configured for transporting passengers to and from orbit and should otherwise be assumed to be removed. Orbiter entry heat protection is provided by reusable metallic heat shields using titanium, nickel, cobalt, and columbium materials, with carbon-carbon for leading edges.

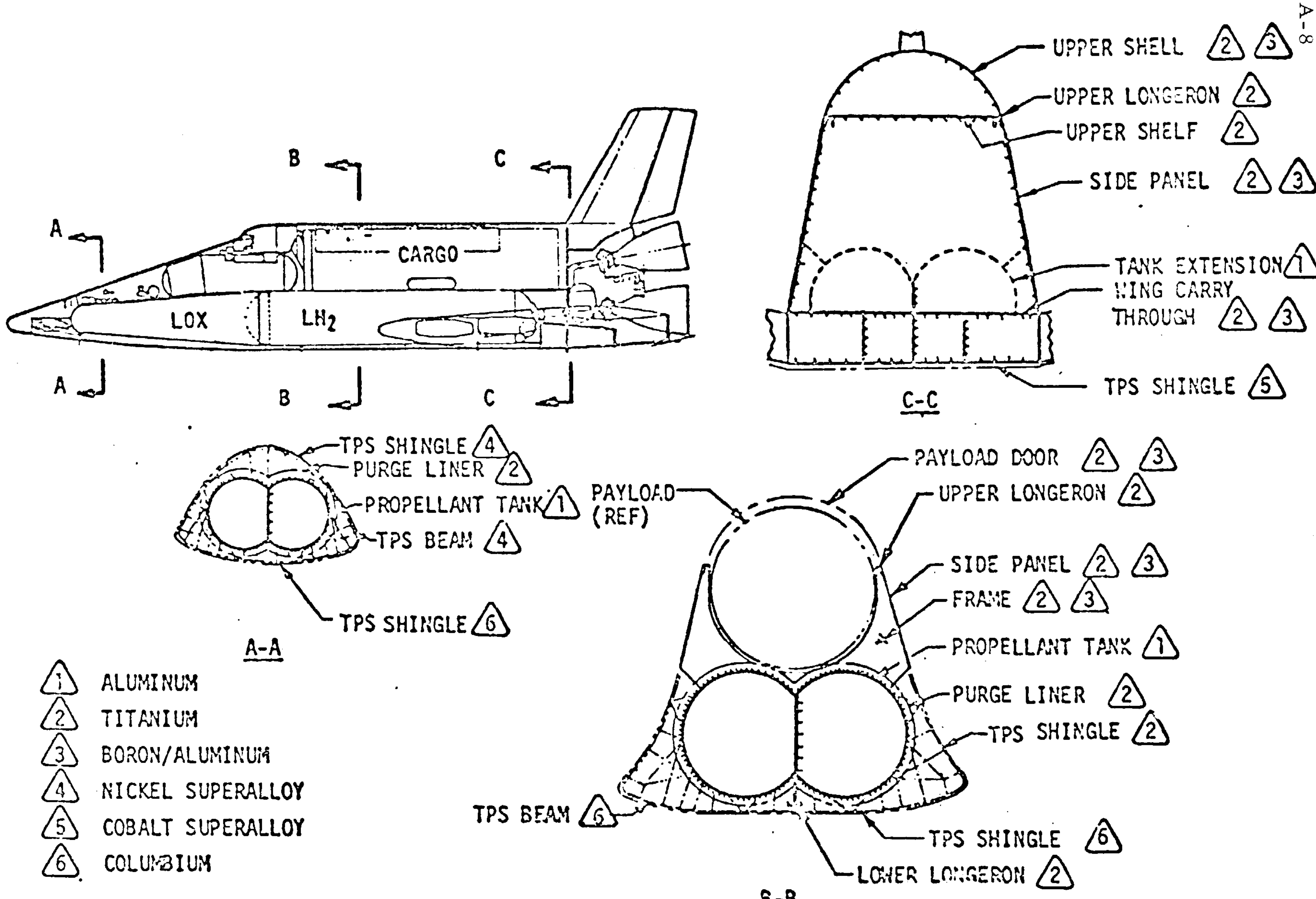
The Space Tug, as a reusable single stage, functions in conjunction with the orbiter to extend its payload-altitude capability. It is designed to furnish spacecraft ascent, retrieval, and positioning capability above that obtainable with the Shuttle Orbiter.

A. Configuration

The configuration of principle interest to this study is the mechanical, structural and crew interfaces with the payload.

1. Shuttle Mechanical/Structural Configuration

The mechanical/structural interface includes the payload bay structure, payload deployment/retrieval mechanisms, and payload support structure. The orbiter structure in the vicinity of the payload bay is shown in Figure 1. The payload is contained within the structure.



Reference 4, page 4-139

FIGURE 1 - DELTA WING ORBITER FUSELAGE STRUCTURAL DEFINITION

There is no separate container/compartment that defines the payload bay. A preliminary design of the MDAC baseline payload deployment and docking mechanism is shown in Figure 2. The payload is stowed as shown and deployed 90 degrees out of the cargo bay for subsequent payload release, recapture, and/or docking to orbiting space stations or other Shuttle orbiters. The flexible tunnel shown allows transfer of personnel from the orbiter to the payload in either the stowed or deployed positions without interrupting the tunnel pressure seal.

The payload release and docking mechanism is shown in Figure 3. This system consists of a square docking frame supported on eight extendable shock attenuators. The attenuators/actuators are extended and retracted. by redundant nitrogen sources. They are capable of retracting payloads (after docking capture) to engage structural latches for subsequent pressurized crew/cargo transfer and payload stowage in the cargo bay for payload return to earth.

The crew is carried in the forward compartment in a shirt sleeve environment. From 6 to 12 passengers can be contained in a special shirt sleeve environment module carried in the payload bay.

2. Shuttle Payload Bay

The nominal Shuttle payload bay is sized to accommodate a payload with envelope dimensions 4.57 m (15 feet) in diameter and 18.29 m (60 feet) in length for a minimum clear volume of 283 m^3 (10,000 ft^3). The clear volume is defined as that space envelope required to accommodate the above-mentioned payload envelope, allowing for payload and Shuttle deflection and movement for any combination of temperature and load conditions during any flight, pre-flight, or post-flight phase of operation. Additional space is provided for the payload support/attachment structure and the deployment/retrieval mechanisms and for nominal clearance of the payload envelope within the orbiter structure. 28VDC and all phase 400 Hz AC power is supplied from the standardized junction boxes. Standardized fluid interfaces are provided for propellants and for cryogenic and pressurized gasses.

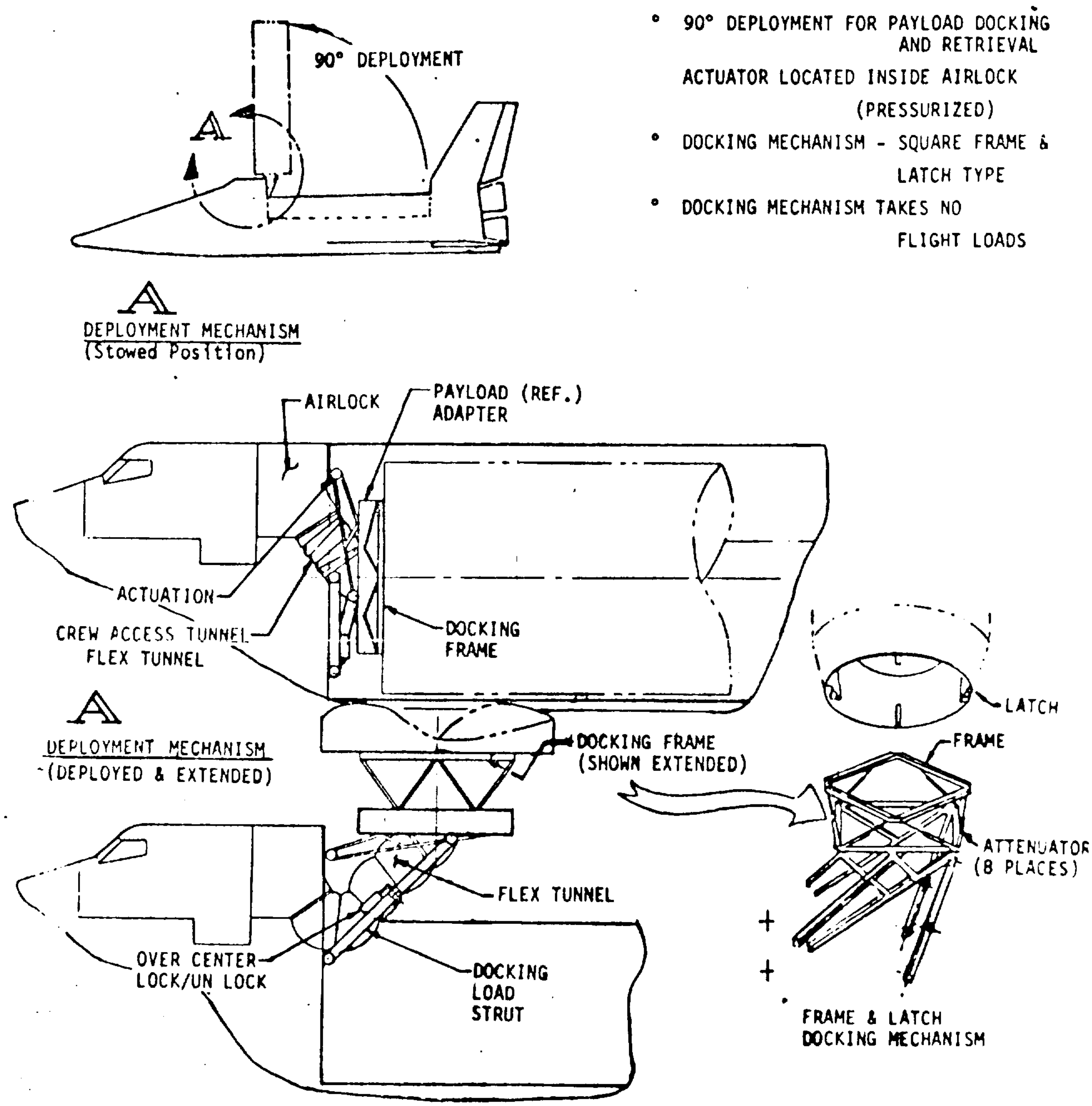


FIGURE 2 - PAYLOAD DEPLOYMENT AND DOCKING MECHANISM
(Reference 4, page 4-173)

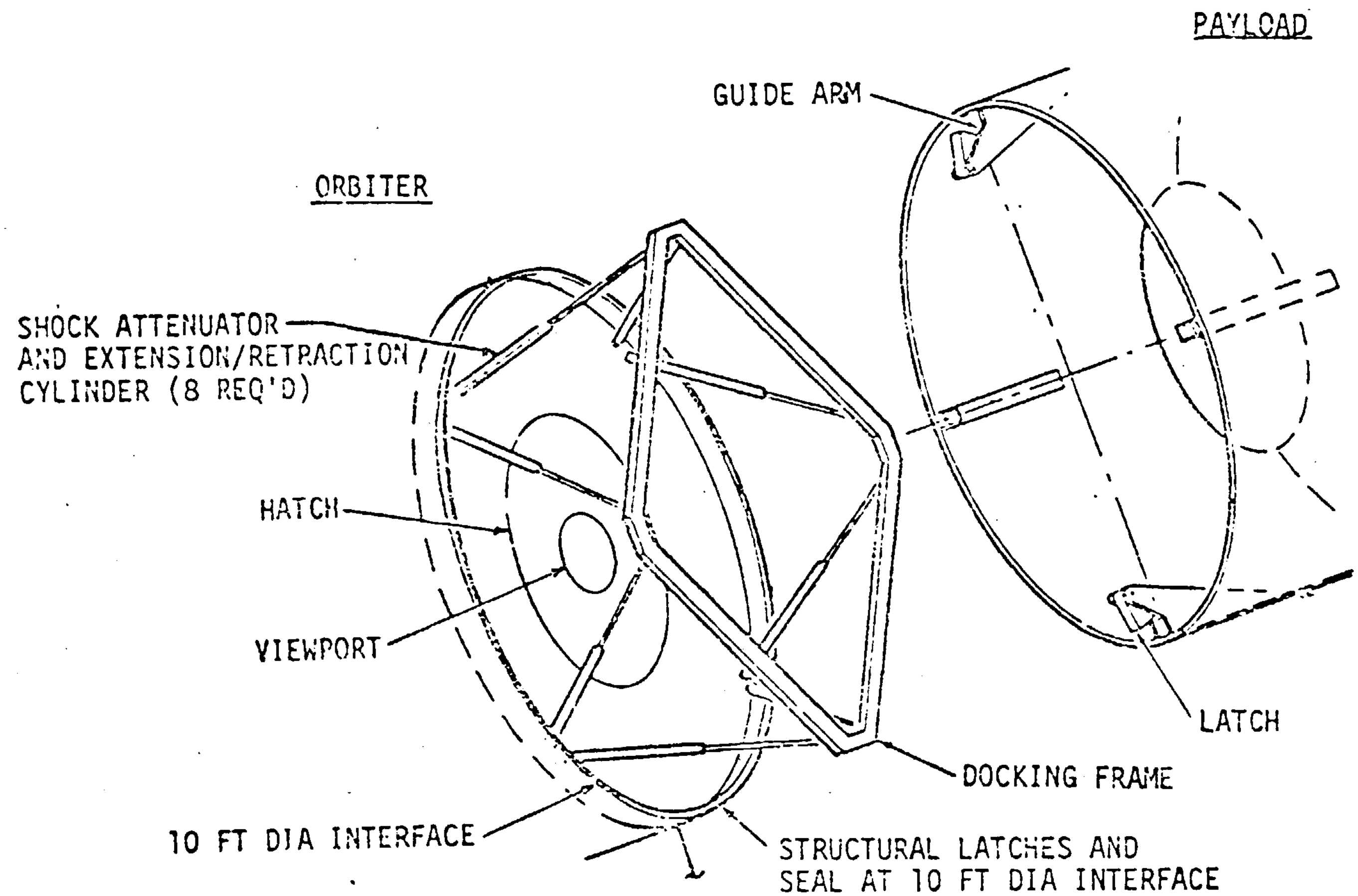


FIGURE 3 - DOCKING SYSTEM--BASELINE MISSION (Reference 4, page 4-174)

3. Payload Configuration Constraints

Payloads will be equal to or less than 4.57 m (15 feet) in diameter and 18.29 m (60 feet) in length including handling rings, attachment fittings for the deployment mechanism and docking, cargo bay storage fittings and spares. The standardized deployment mechanism(s) and tie points are charged to the orbiter and shall not occupy the clear volume. Deployment clearance will be provided by the orbiter. Limited transfer of cargo, however, is possible through the personnel transfer hatch which is 0.76 meters (30 inches) in diameter. In general, payloads are loaded prior to moving the orbiter to the launch pad but will be accessible on the pad. Payload elements containing hazardous material have self-contained protective devices or provisions against all hazards. Provision for purging, conditioning, and venting the payload bay for all mission phases are provided in the vehicle design.

Payload weight constraints can be determined by calculations from data in the following sections.

4. Shuttle Manned Experiments

NASA has tentatively defined two possible manned "sortie" missions which are briefly defined. The first category includes the manned experiment modules, and the second category includes the pallet type modules which are generally unmanned (with the exception of the orbiter astronauts and technicians). The manned experiment modules consist of a spherical shaped crew quarters, that always remains in the Shuttle, and a pressurized cylindrical shaped experiment compartment that can be rotated 90 degrees to enable its extension into free space from the Shuttle cargo compartment. Figure 4 presents a typical manned experiment module configuration. The same basic module can be utilized to house different experiments, and thus reduce the number of basic modules that must be provided to conduct the planned sortie mission model. The average sortie mission will carry four to six principal researchers into orbit for about five days. The planned operation of these manned experiment module sorties will be similar to the Convair 990 program now being conducted at Ames Research Center.

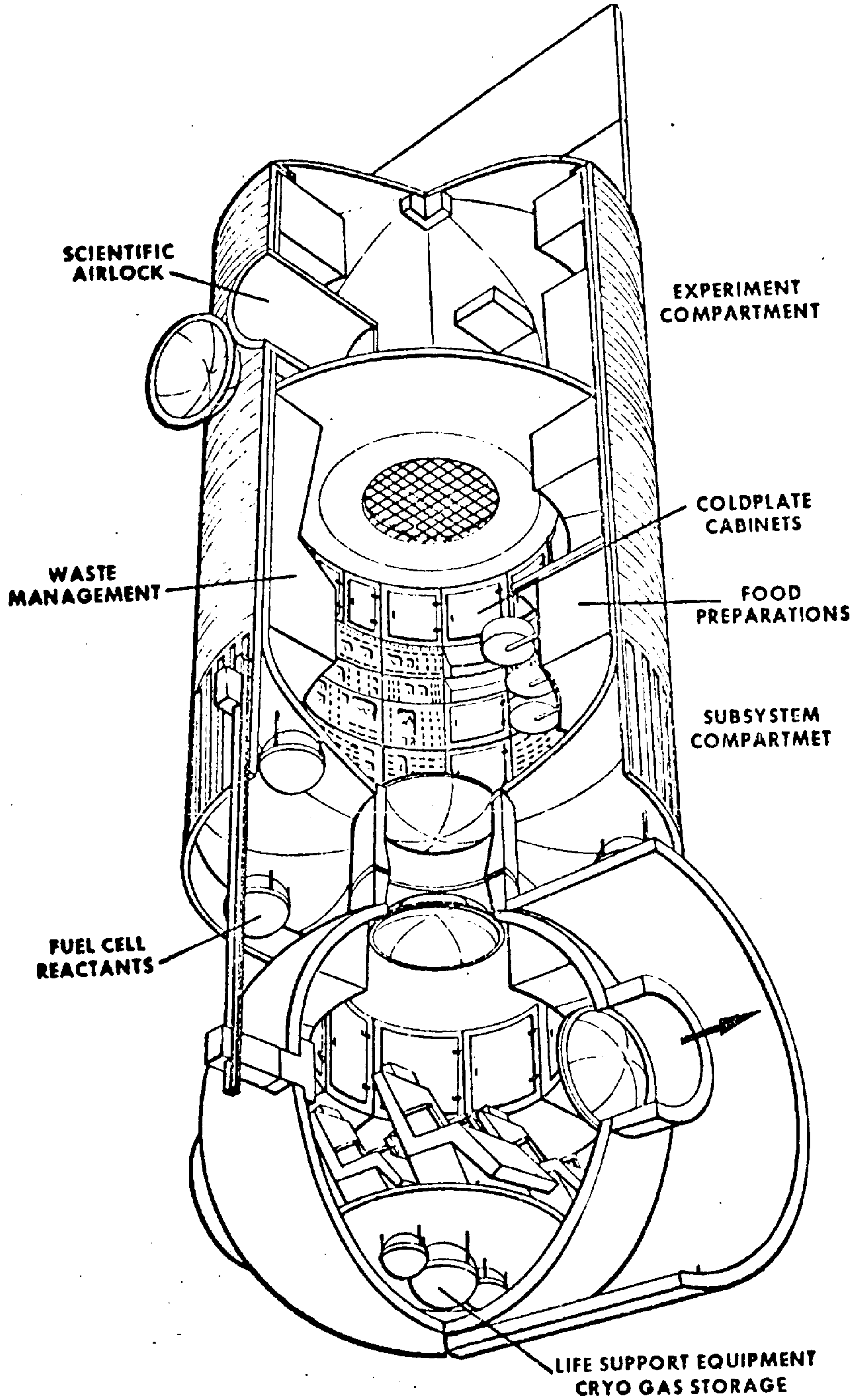


FIGURE 4 - MANNED EXPERIMENT (Reference 5, page 2-144)

The pallet type modules consist of an air lock and experiment support structure. The experiment support structure can be rotated 90 degrees to facilitate equipment viewing or thermal requirements in space. The air lock will be used to house mission-unique monitoring equipment and may require ingress/egress capability into the cargo bay by a suited astronaut. The missions will generally be from 2 to 5 days in duration. The pallet-type module is much simpler than the manned experiment module (which utilizes a pressurized container to house most of the man-operated experiments), and will therefore be developed first in the evolution of the sortie modules. Other experiment packages and concepts are described in more detail in Section 5 of the LMSC Report (Reference 6).

5. Space Tug Mechanical/Structural Configuration

The most likely Tug configuration to be selected is the reusable single-stage unmanned concept. This will be used as a baseline. It is 4.57 m in diameter and 10.67 m in length (15 x 35 feet), fueled with LH_2/LO_2 and weighing approximately 31750 kg (70,000/lbs) fueled and 3175 kg (7,000 lbs) empty. It is designed to fit snugly in the orbiter payload bay with volume left for spares, test equipments, etc. It is reusable for ten flights before reconditioning is necessary and can remain quiescent in orbit for 180 days. The standardized docking mechanism in the Tug is assumed to be similar to that proposed by LMSC for the SEO (Synchronous Equatorial Orbiter) spacecraft as shown in Figures 5 and 6. This system would likely function with four passive reflectors mounted on the ring face to supply transponding to rendezvous and alignment sensors through transmitters on the Tug. The maneuvers would be coordinated from the Shuttle Orbiter or earth stations.[1]

B. Shuttle Performance

The data in this section are presented in two parts. The data for the Orbiter capabilities are first, followed by data for the Tug capabilities.

[1] See Section 8.3, Reference 6, for more detail.

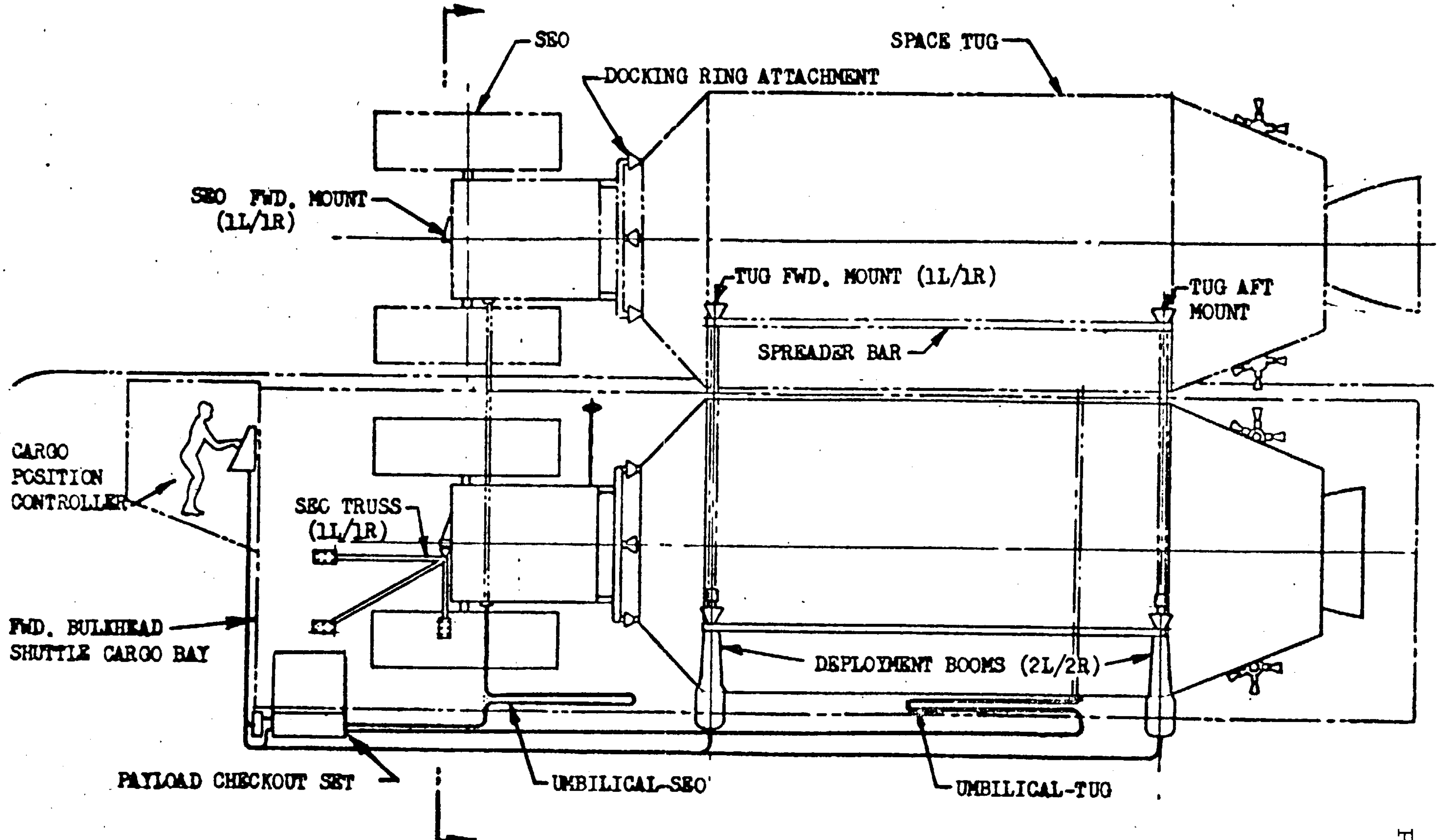
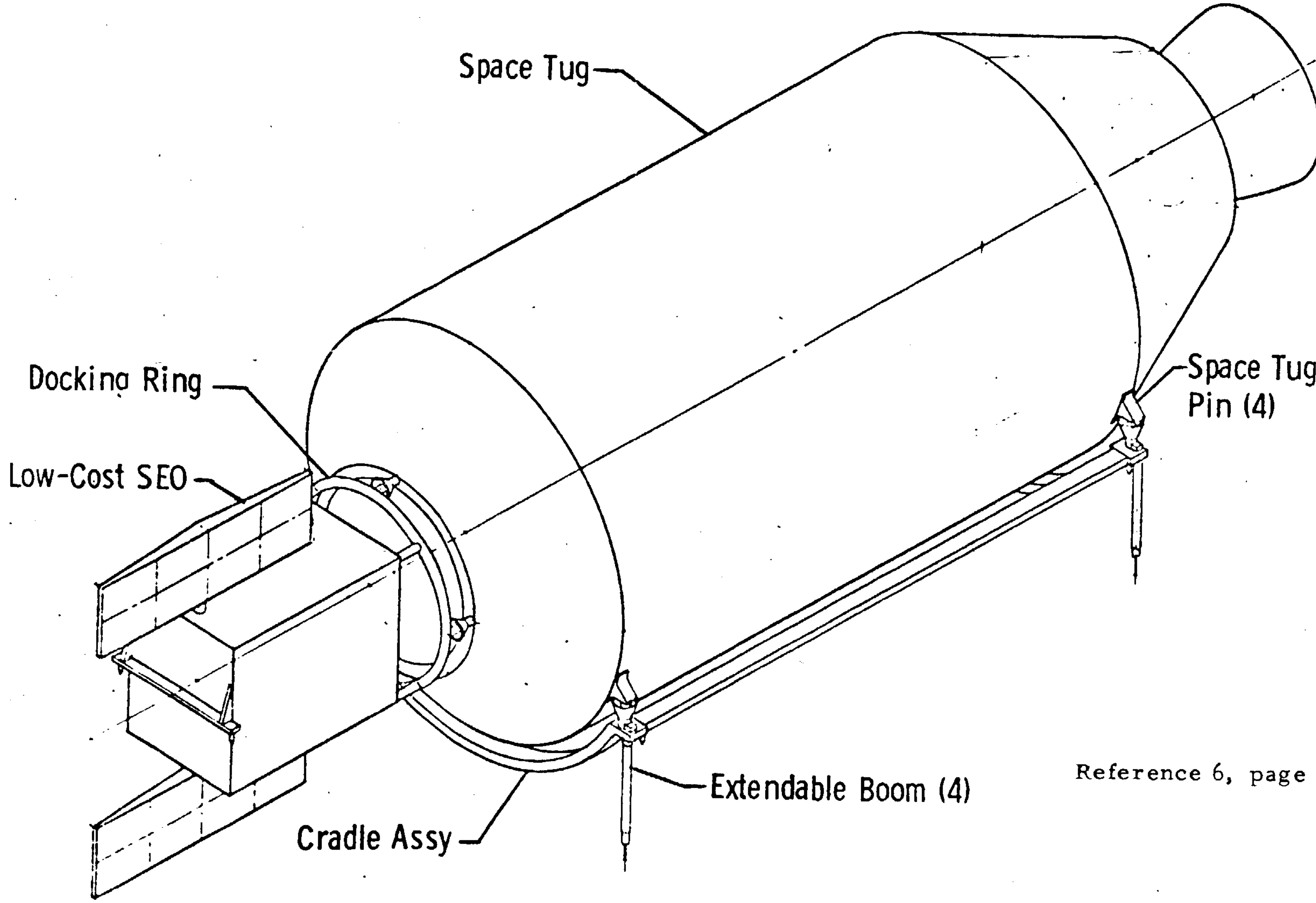


FIGURE 5 - SHUTTLE INSTALLATION OF SEO AND SPACE TUG (Reference 6, page 2-54)



Reference 6, page 2-55

FIGURE 6 - SEO/TUG EXTENDED POSITION FOR DEPLOYMENT/RETRIEVAL

1. Shuttle Orbiter General Performance

The STS[1] will have the availability of four Booster Stages, two at the Eastern Test Range (ETR) and two at the Western Test Range (WTR). Five Orbiters will be available, three at ETR and two at WTR. The turn-around time for landing to launch readiness will be less than 2 weeks with a launch rate varying between 25 and 75 per year. The Shuttle has an all-azimuth launch capability. Figures 7 and 8 show the azimuths available from each test range.

The system is designed with nominal safety factors (1.4) to place 29,480 kg (65,000 lbs) of payload into a 28.5-degree inclination low orbit design mission and to return 18,150 kg (40,000 lbs).

The basic system shall be capable of seven days of self-sustaining lifetime from liftoff to landing. Orbiter systems shall be qualified for 30 days of on-orbit operation, with the mass of expendables above the 7-day requirement charged against the payload. The orbiter Attitude Control System (ACS) is accurate to $\pm 1^{o}$ with a stabilization rate of 0.3^{o} per sec.

2. Shuttle Orbiter Maneuvering Capability

The orbiter is initially injected into an insertion orbit of 93 x 185 km (50 x 100 n. mi.) and then thrust into the desired orbit with the Orbital Maneuvering System (OMS). There are three reference mission orbits which serve here to bracket the nominal capabilities of the shuttle.

Inclination	Circular Altitude	Payload
28.5^{o}	185 x 500 Km (100 x 270 n. mi.)	79,480 kg (65,000 lbs)
55^{o}	185 x 500 Km	23,590 kg (52,000 lbs)
90^{o}	185 x 500 Km	12,700 kg (28,000 lbs)

[1]Space Transportation System.

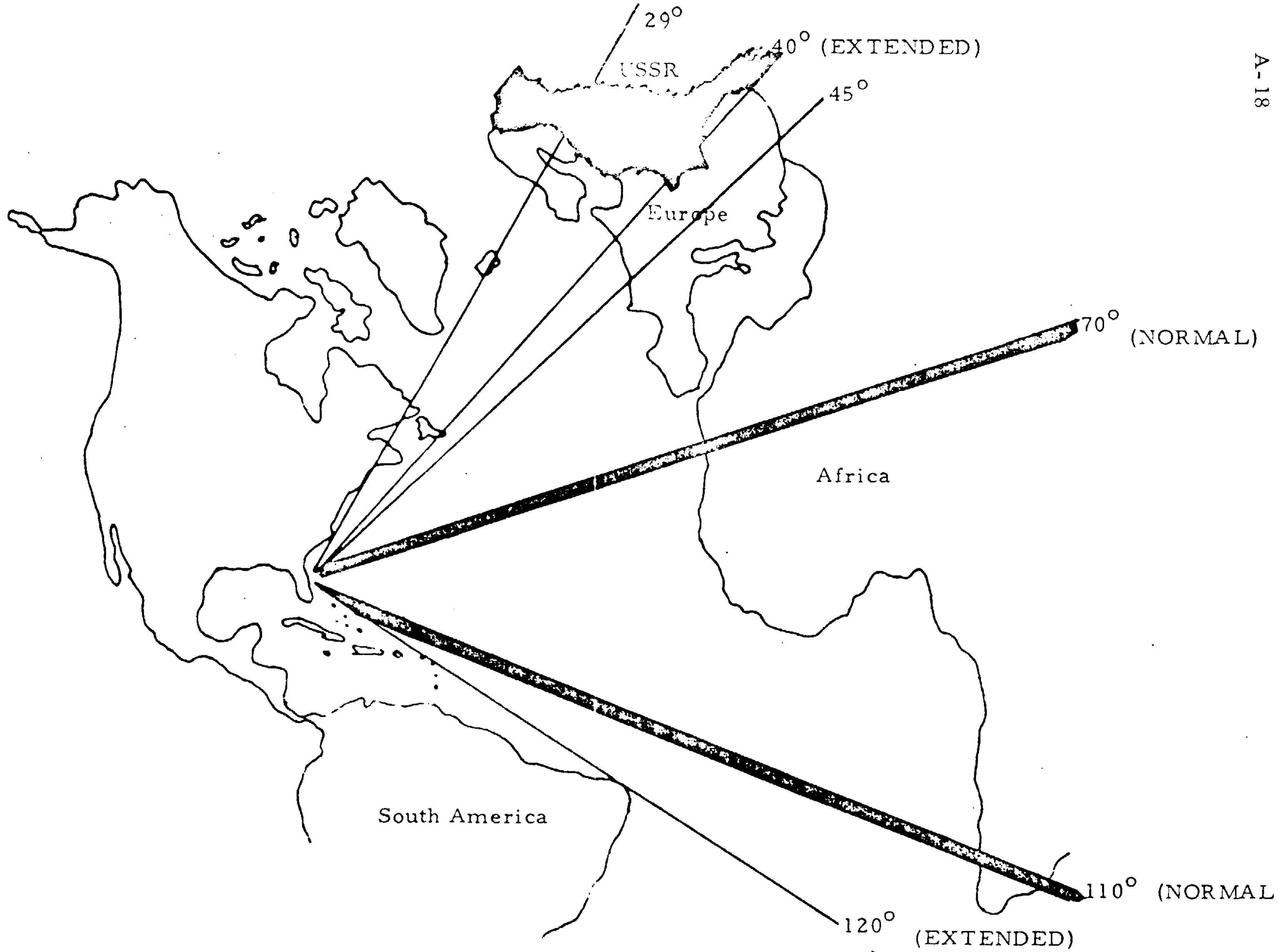


FIGURE 7 - CURRENT VEHICLE LAUNCH AZIMUTH--ETR (Reference 5, page 4-35)

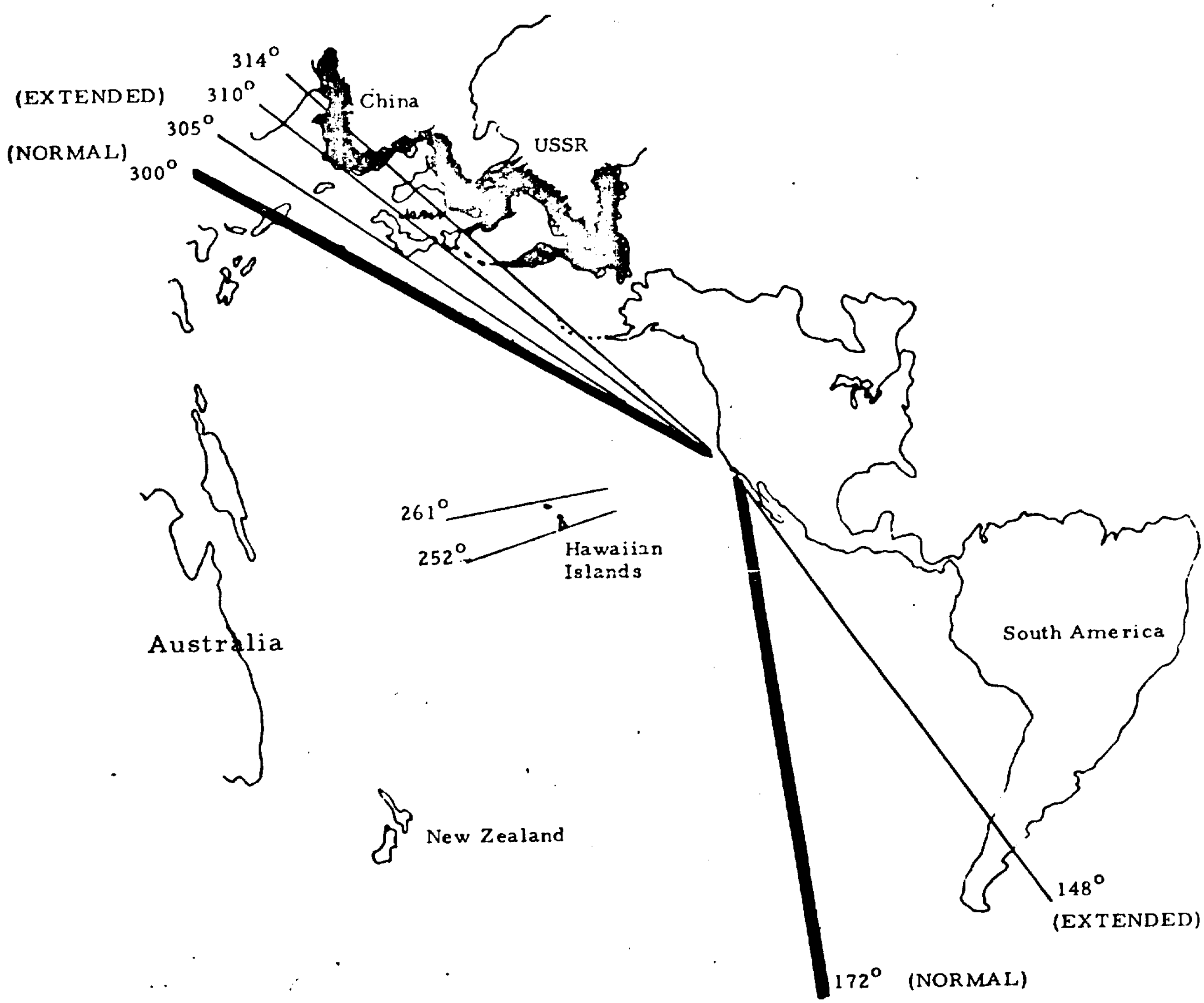


FIGURE 8 - CURRENT VEHICLE LAUNCH AZIMUTHS--WTR
(Reference 5, Page 4-36)

The values here and those in the following figures are based on (1) a High Cross Range (HCR) orbiter configuration that has a reentry glide range of 2,040 km (1,100 n. mi.), (2) retention of an abort capability, (3) removal of the ABES (with the ABES used, subtract 9,230 kg from the allowable payload weight), and (4) fuel allowances allocated for rendezvous and docking maneuvers and for other contingencies. Under these conditions the Orbiter has the nominal ΔV capability at orbit injection of 460 m/sec (1,500 ft/sec). It is planned that the OMS propellant tanks may be sized to provide a total ΔV as large as 610 m/sec (2,000 ft/sec) which yields the maximum payload-altitude capability.

The nominal gross and maximum gross payload capabilities for any launch inclination are provided in Figure 9. The nominal rather than the maximum impulses should be used in calculations unless otherwise stated. Figure 10 provides similar Orbiter gross payload capabilities as a function of inclination and circular orbit altitudes without ABES. Any payload/orbit/inclination combination of which the Shuttle Orbiter is capable can be extrapolated from these figures. For purposes of this study, 900 km (485 n. mi.) is considered the maximum altitude for the Shuttle Orbiter. In order to utilize these figures properly, net payload weights must be converted to gross payloads weights to account for adapters, handling and mounting fixtures, and spares. Figure 11 provides an estimate, as a function of net Shuttle payload weight, of the payload adapter weight, spares weight (assumed to be 0.7 times the net payload weight), and the combination of these to provide the gross payload weight. With spares, the gross weight is approximately twice the net weight. Elliptical orbits must be converted to circular energy equivalents. Figure 12 provides those conversions for low earth-Shuttle orbits. For calculations of higher orbits see Figures 13, 14, and 15 in the section on Tug performance.

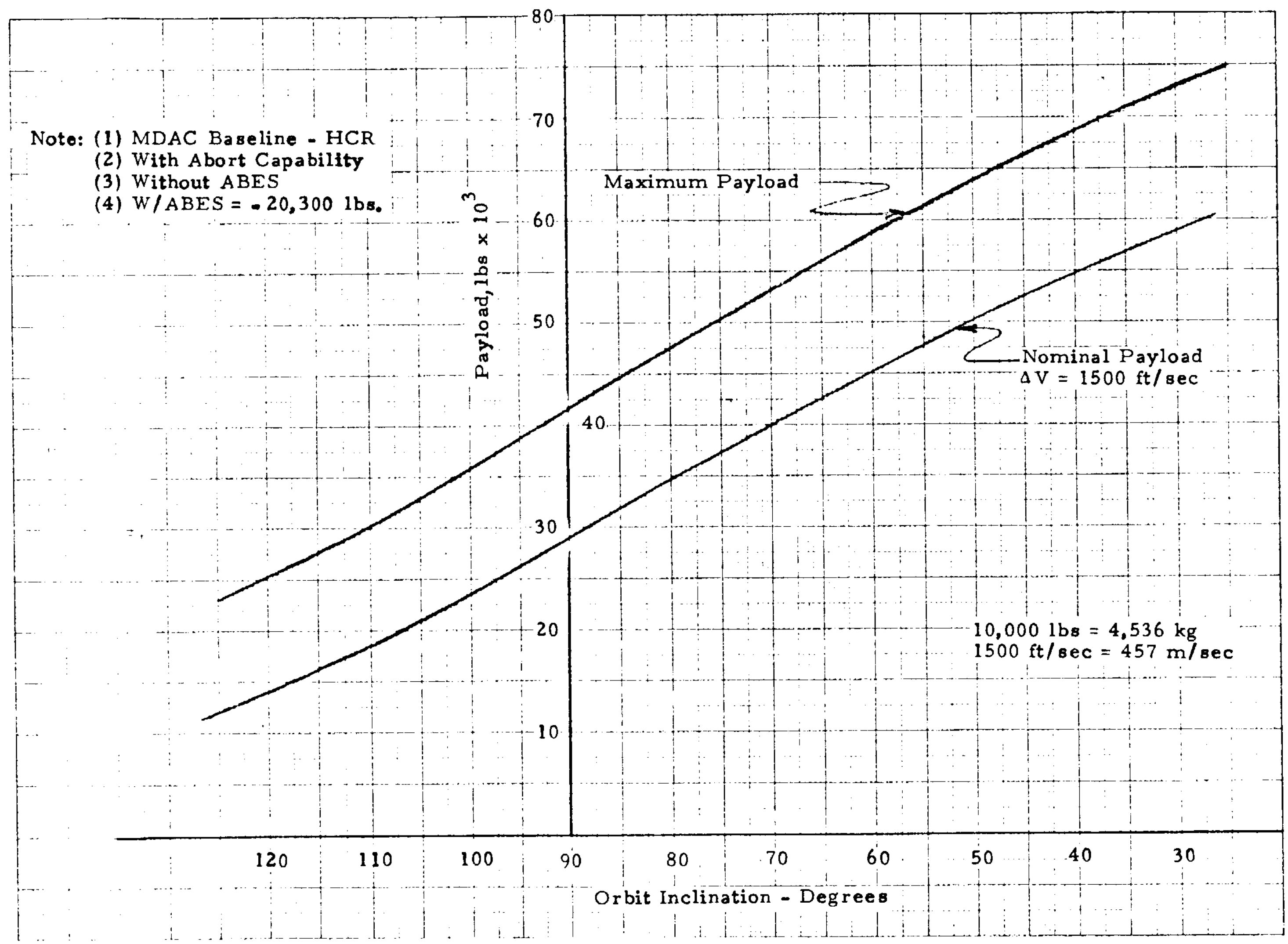


FIGURE 9 - SHUTTLE PERFORMANCE CAPABILITY--PAYLOAD VERSUS INCLINATION
(Reference 4, page 4-140 modified with NASA data and for ABES out)

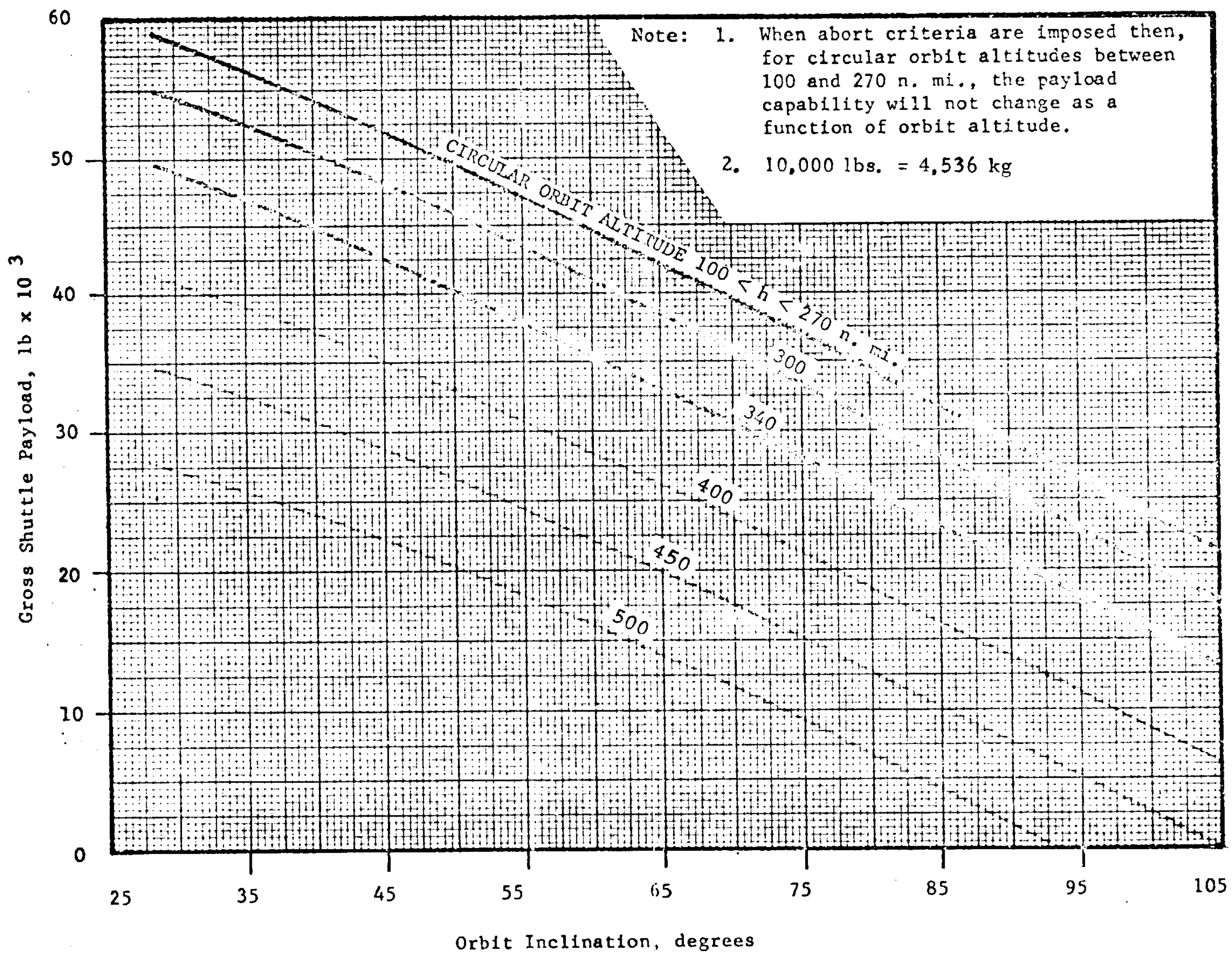


FIGURE 10 - MAXIMUM PERFORMANCE SPACE SHUTTLE PAYLOAD CAPABILITY (ORBITER AIR-BREATHING ENGINES OUT) (Reference 7, page IV-C-14 with altitudes extended)

10,000 lbs = 4,536 kg

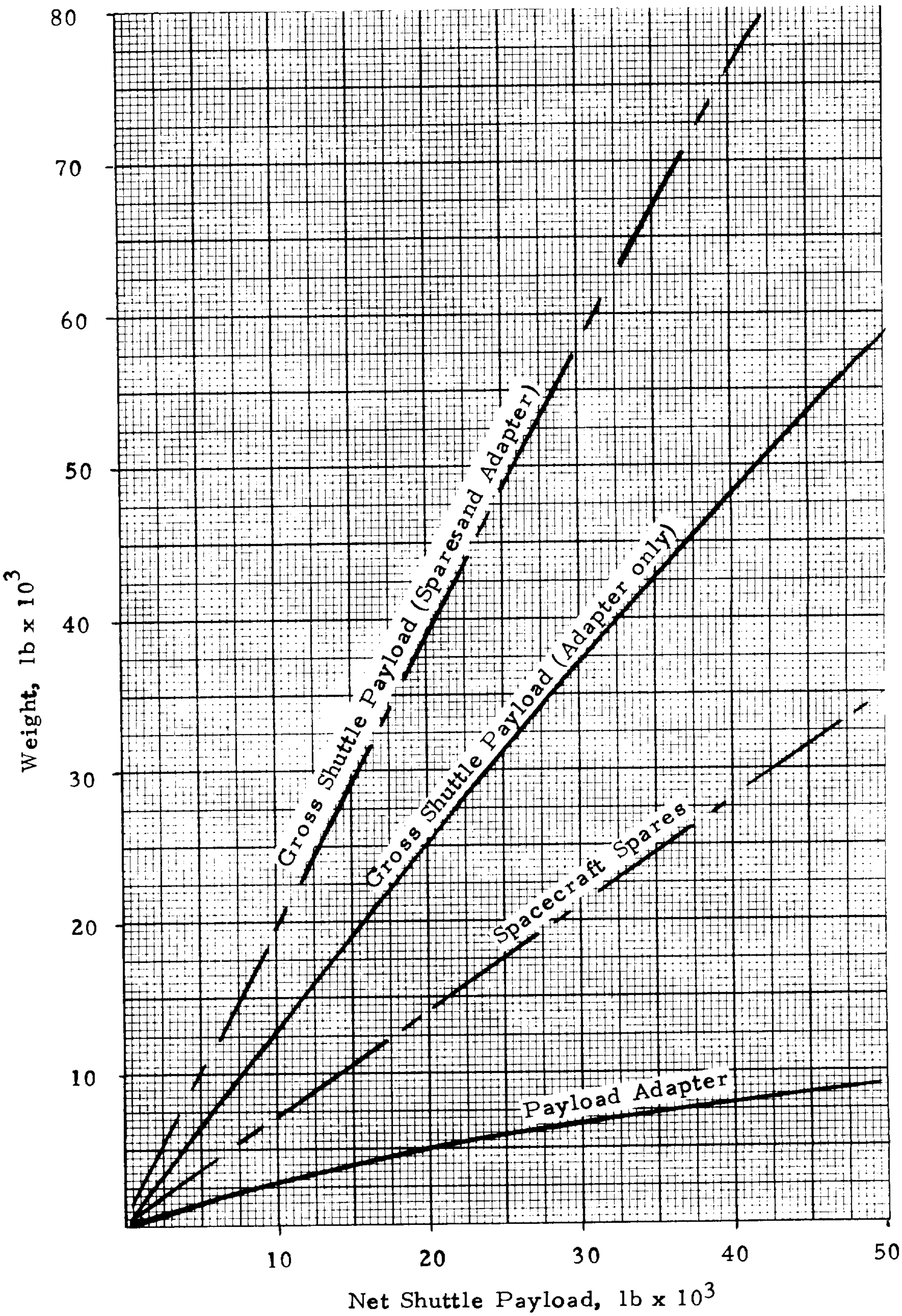


FIGURE 11 - SHUTTLE PAYLOAD, ADAPTER AND SPARES WEIGHTS
(Derived from Reference 7, page IV-C-12)

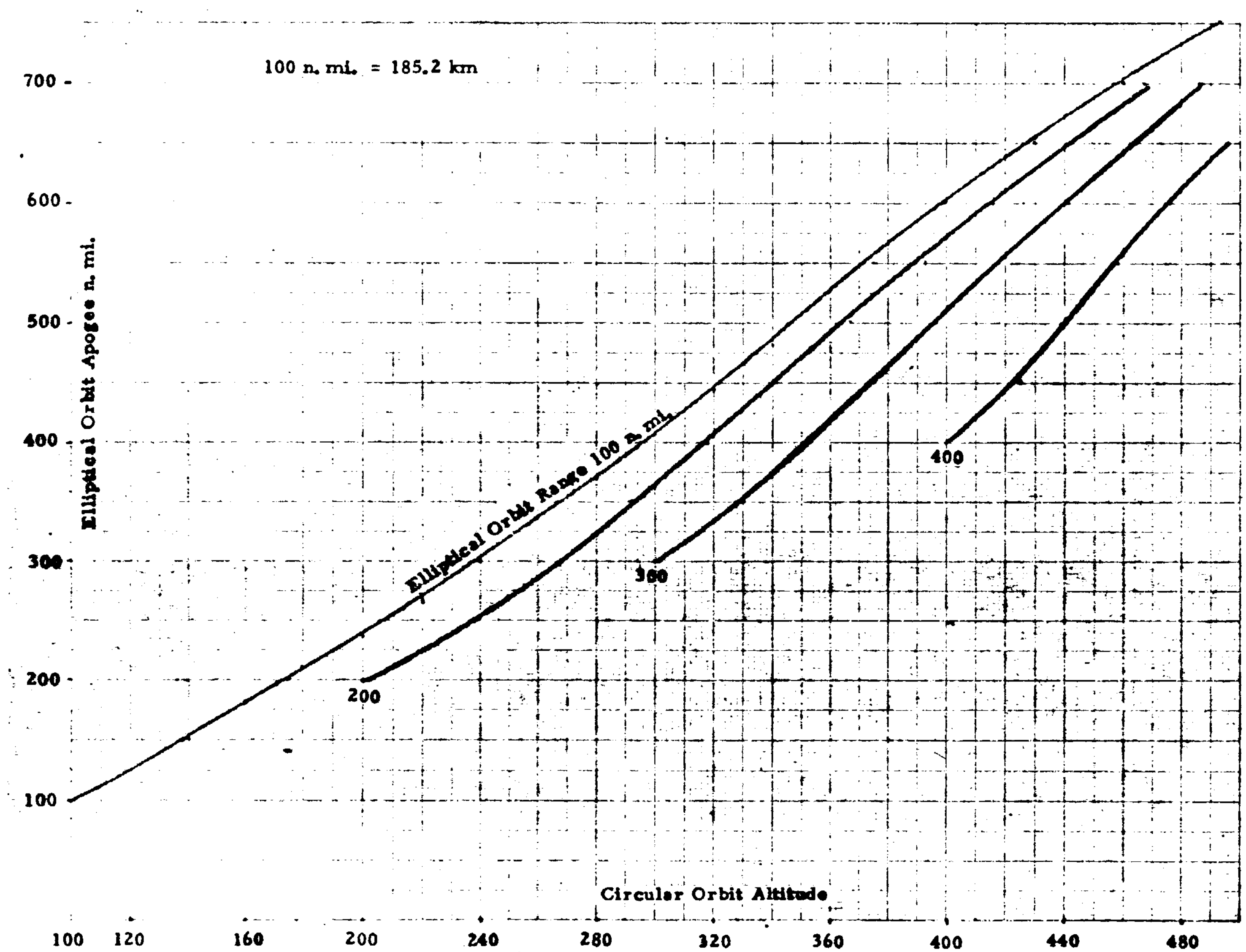


FIGURE 12 - EQUIVALENT ENERGY CIRCULAR AND ELLIPTICAL ORBITS FOR SHUTTLE MISSIONS (Reference 9, page IV-C-15 with perigee altitudes extended)

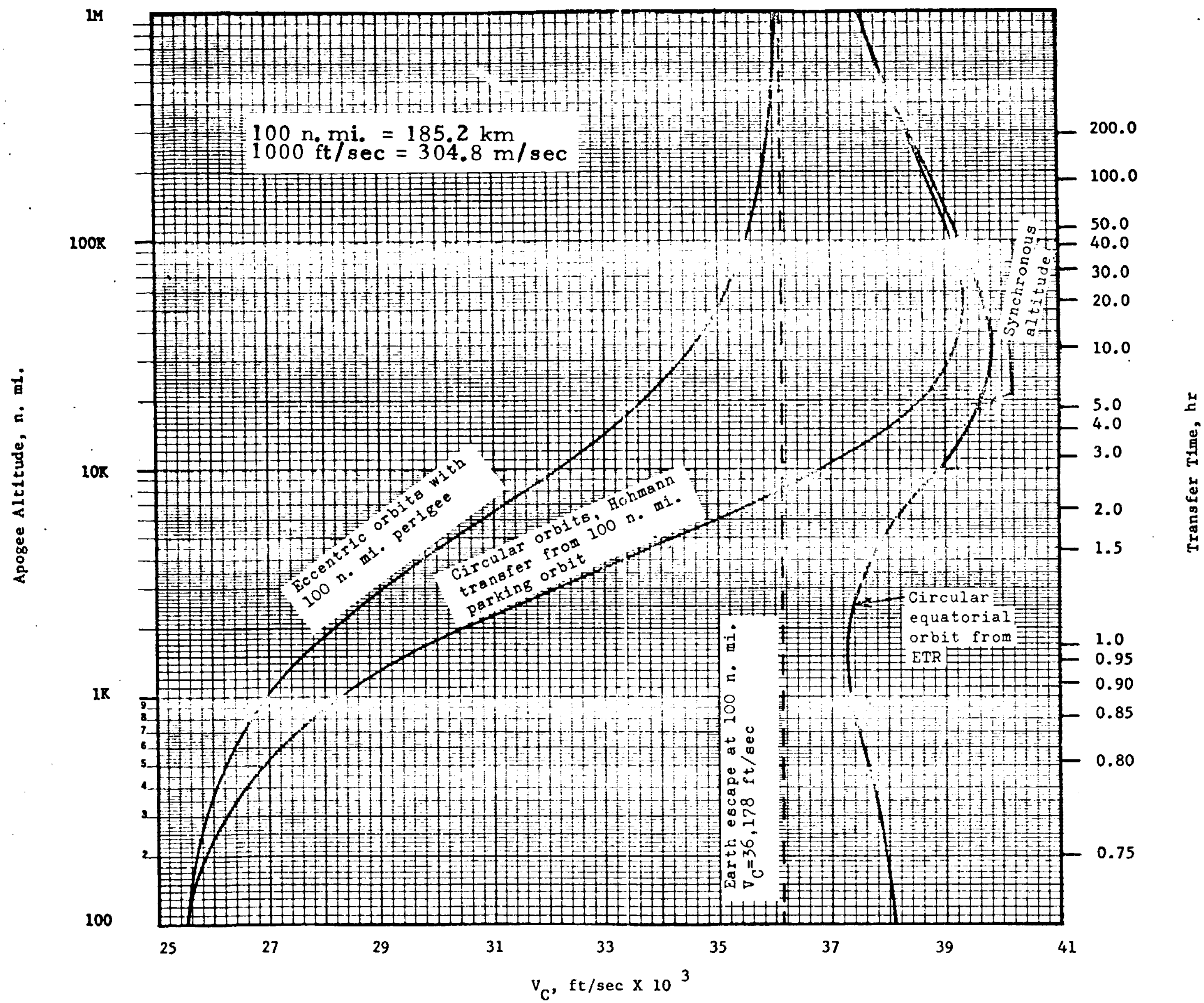


FIGURE 13 - VELOCITY REQUIRED FOR EARTH ORBITS (Reference 7, Page II-42)

100 n. mi. = 185.2 km
1000 ft/sec = 304.8 m/sec

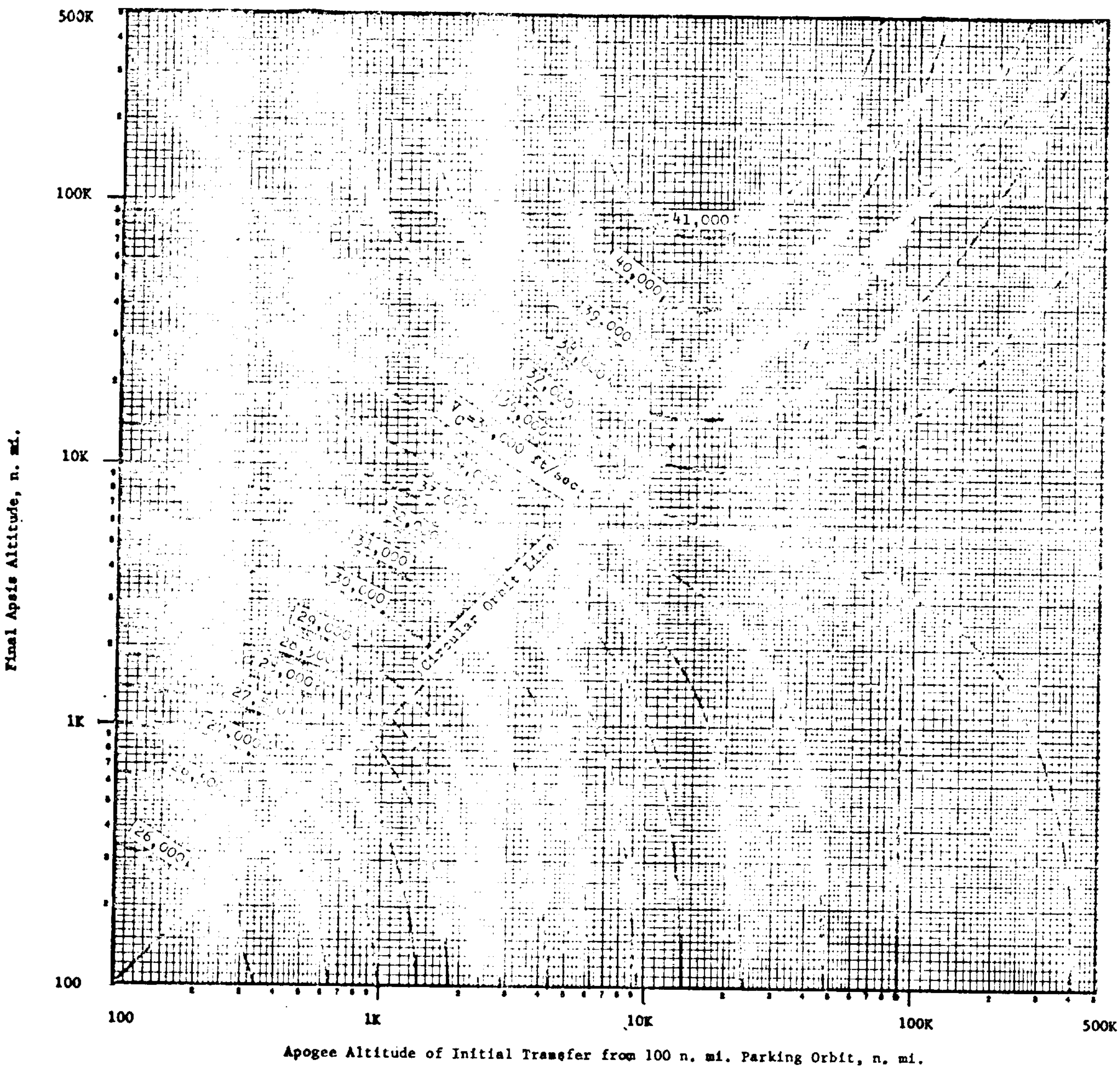


FIGURE 14 - TOTAL V_C REQUIREMENTS ASSUMING TWO-IMPULSE TRANSFER FROM 100 N. MI. ORBIT (Reference 7, Page II-43)

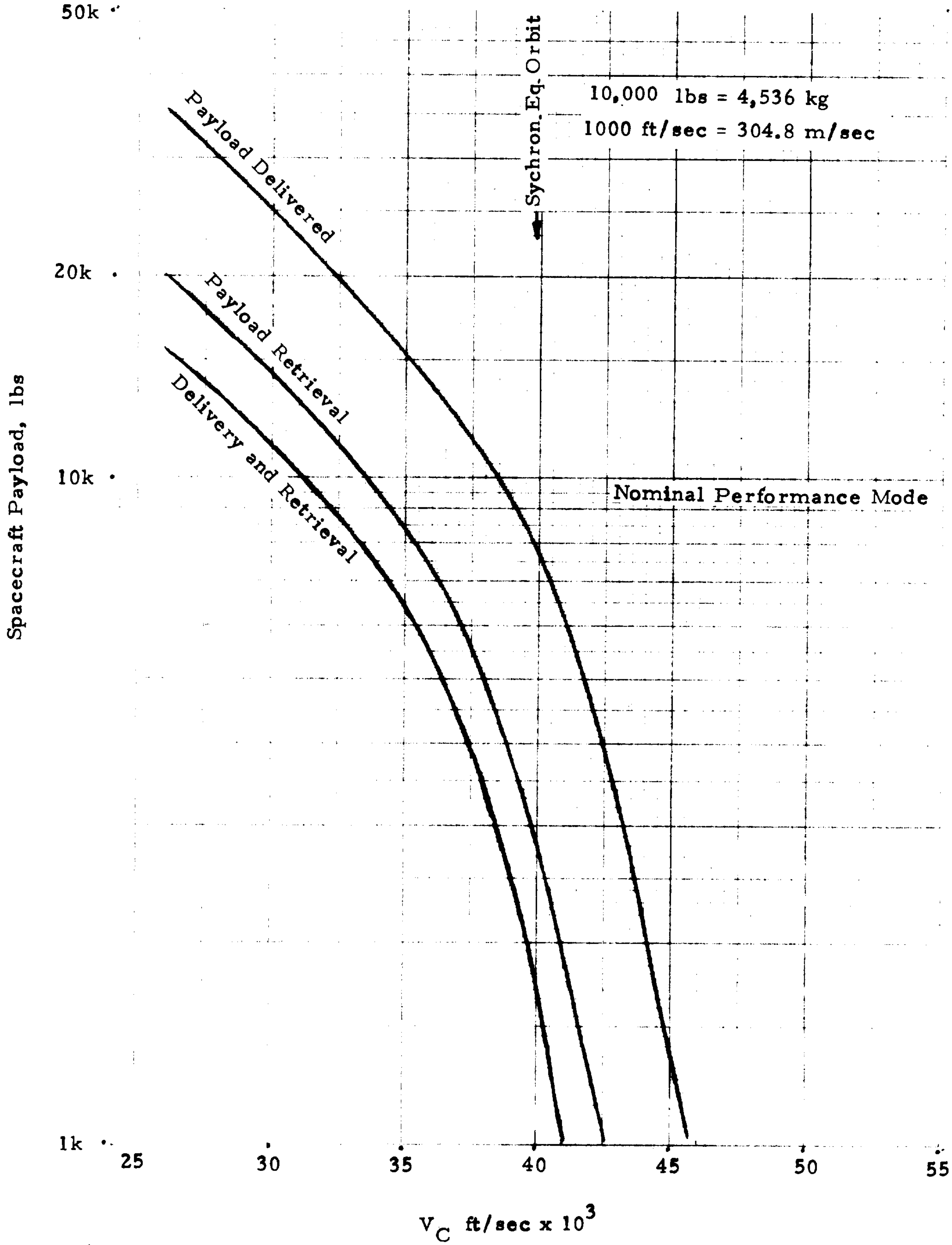


FIGURE 15 - TUG SINGLE STAGE PERFORMANCE (From Reference 4, Page 5-16)

Problem: Consider a 100 x 400 n. mi.[1] elliptical orbit for a net payload of 15,000 lbs launched at a 90-degree inclination with spares. Is this within the shuttle orbiter capability?

Solution: From Figure 11 the gross payload with spares is found to be 29,000 lbs (13,150 kg). The elliptical orbit is converted with Figure 12 to a 300-n. mi. (555 km) equivalent-energy circular orbit. From Figure 10 it can be seen that in a 300 n. mi. (555 km) circular orbit at an inclination of 90 degrees, the shuttle is capable of a gross payload of 25,000 lbs (11,340 kg) which is below the calculated gross. The mission must therefore be conducted with the Tug or more likely be considered without carrying most of the spares, since the spares cannot be used with the Tug anyway. Figure 11 reveals that approximately 6,000 lbs (2,722 kg) of spares can be carried in the Shuttle mode.

3. Space Tug (OOS) Performance and Orbit Maneuvering Capability

If mission requirements exceed Shuttle-only capabilities, or if the mission destination lies outside the shuttle operating regime, then a shuttle upper stage would be required to complete the mission. In this case, the net Shuttle payload would consist of a "package" that would include the user's payload (spacecraft or cargo), a spacecraft/ upper stage adapter, a shuttle upper stage, and whatever payload service equipment that might be required. As delineated in Figure 11, the gross shuttle payload would be the sum of the net Shuttle payload weight and the shuttle adapter weight (spares are not considered for the Tug).

For Shuttle/Shuttle upper stage missions (both earth orbit and earth escape), it has been assumed that the Shuttle Orbiter would be

[1] U. S. units facilitate use of the figures which were not converted to international units for this report.

injected into a 93 x 185 km (50 x 100 n. mi.) elliptical orbit (reference injection orbit); that the Orbiter would then transfer to an appropriate parking orbit; and, finally, that the Shuttle upper stage would deliver the user's payload from the parking orbit to the final orbit or space destination. All maneuvers would be coplanar if the final orbit inclination is greater than 28.5 degrees. Otherwise, the Shuttle parking orbit inclination would be 28.5 degrees and the required plane change would be accomplished by means of the shuttle upper stage. The single stage Tug (as differentiated from the expendable solid or liquid upper stage, the OOS-nuclear stage, the tandem reusable/expendable upper stages, etc.) considered here has a geosynchronous equatorial orbit capability as follows:

Payload delivery only, 3,720 kg (8,200 lbs)

Payload retrieval only, 1,315 kg (2,900 lbs)

Payload delivery and retrieval, 9.0 kg (2,000 lbs)

Payload delivery (expending stage), 9,030 kg (19,900 lbs)

For orbits other than geosynchronous, the payload capabilities of the Tug can be calculated using the data in Figures 13 through 16.

Figure 13 depicts the velocity required for earth orbits. The circular orbit characteristic velocities (V_C) assume a Hohmann transfer from the reference 185 km (100 n. mi.) initial parking orbit. The curves for circular and eccentric orbits in Figure 13 are not related to any particular launch site. However, the curve for circular equatorial orbits from ETR shows the characteristic velocity requirements to establish a circular orbit with zero-degree inclination after launching due east from ETR. The calculation is based on the plane change being optimally divided between the two impulses of a Hohmann transfer. Synchronous altitude is indicated on this curve.

More general earth orbital data are contained in Figure 14, where the total characteristic velocity (V_C) requirements for orbits of arbitrary perigee and apogee are shown. The velocity contours of Figure 14 are based on the assumption of a transfer orbit with perigee at 185 km (100 n. mi.) and apogee as shown along the abscissa, followed by a second

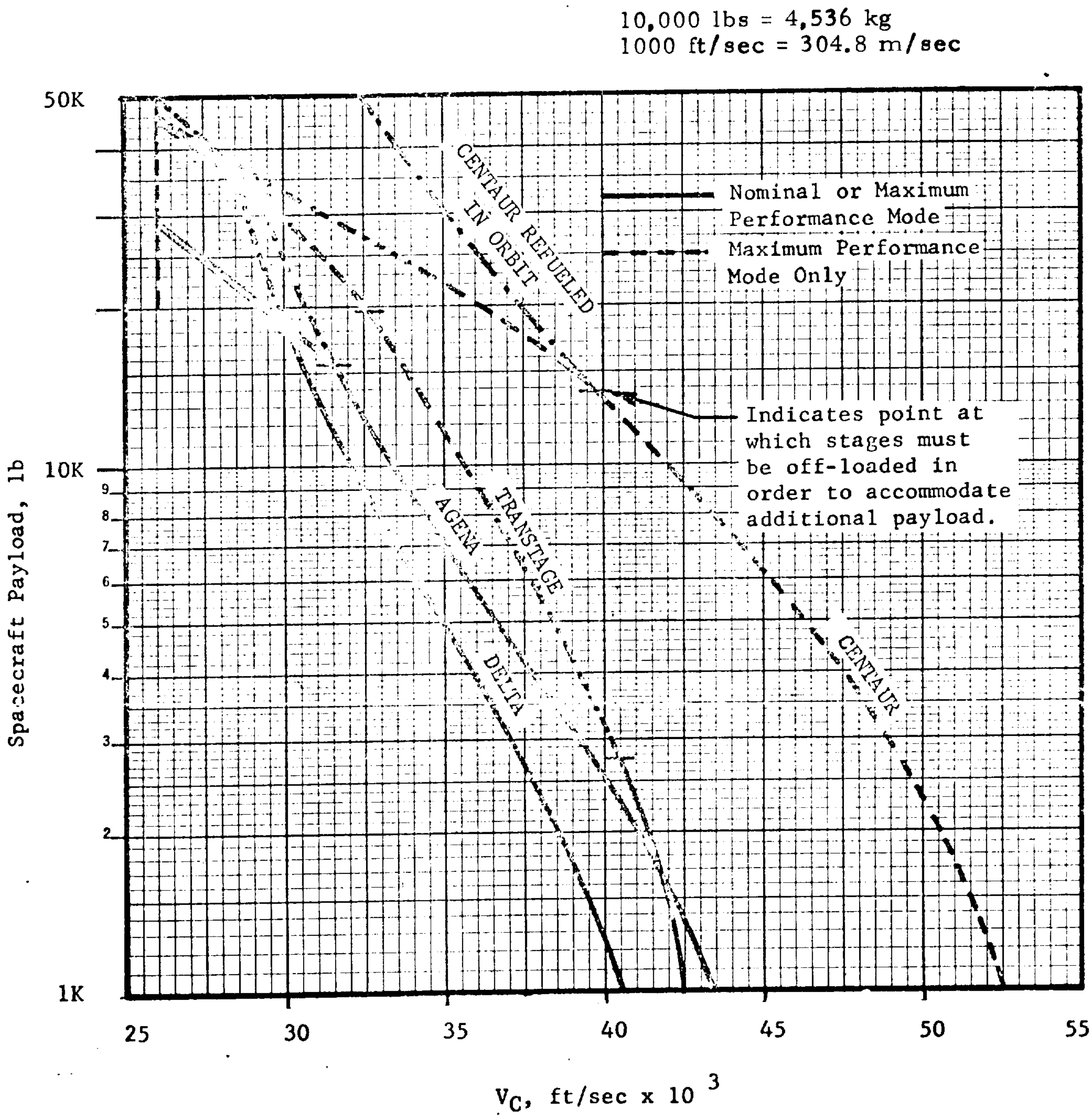


FIGURE 16 - SHUTTLE/LIQUID PROPELLANT UPPER STAGE PERFORMANCE (Reference 7, page IV-C-17)

impulse to raise perigee or, if sufficiently large, to establish a new apogee with the apogee of the transfer orbit becoming the perigee of the final orbit. The more efficient maneuver involves establishing the transfer orbit with apogee being the final apogee value, while using the second impulse to establish a new perigee, rather than transferring first to the new perigee and then raising the apogee. The difference between the two techniques is significant only for very high-energy orbits. The coast time in the initial transfer orbit may be limited by system considerations. The coast time from 185 km (100 n. mi.) to any transfer apogee may be estimated from Figure 13.

The total characteristic velocity shown in Figure 14 includes the velocity impulse required at the apogee of the initial transfer orbit. V_C in these figures is the arithmetic sum of all velocity increments required to perform a given mission. When V_C of an orbit has been determined from Figures 13 and 14, Figure 15 can be used to establish the payload capabilities of the single-stage Tug for the delivery, retrieval, or the delivery and retrieval modes. Figure 16 provides the means for calculating payloads for the expendable upper stages. The expendable upper stage has been considered as an interim propulsion vehicle used in the Tug flight regime until the single-stage reusable Tug is developed. These stages should not be considered unless they are the only means of achieving the required payload/orbit capability (e. g., maximum performance Centaur).

An example of calculations for verifying the adequate capacity of a single-stage Tug vehicle is shown below:

Problem: Retrieve a 6,000 lb spacecraft from a 100 x 10,000 n. mi. elliptical orbit without a coplanar orbit change.

Solution: For the special case of 100 n. mi. (185 km) perigee, Figure 13 yields a V_C of 32,200 ft/sec (9,755 m/sec). From Figure 15 this V_C is within the single-stage Shuttle retrieval capability for a 6,000 lb (2,720 kg) payload.

Problem: Deliver a 5,000 lb payload to a 4,000 n. mi. x 50,000 n. mi. elliptical orbit with the Tug.

Solution: From Figure 14 the altitude of initial transfer becomes the perigee of 4,000 n. mi. (7,410 km). On the ordinate the 50,000 n. mi. (92,650 km) final apsis requires a 39,000 ft/sec (11,890 m/sec) characteristic velocity. Figure 15 reveals that this is within the nominal delivery capabilities of the single-stage Tug.

Problem: Deliver a 10,000 lb spacecraft to synchronous equatorial orbit by means of a shuttle upper-stage launch from ETR.

Solution: From Figure 13 the required characteristic mission velocity (V_C) is 39,600 ft/sec (12,070 m/sec). From Figure 15 the required velocity exceeds the capability of the single-stage Tug for the required payload. From Figure 16, the required characteristic velocity could be provided at the required payload using the shuttle in the maximum performance mode in conjunction with the Centaur upper stage. The coplanar change required for this maneuver is accounted for in Figure 13.

The use of the figures in these examples is restricted to an initial Earth orbit of 185 km (100 n. mi.) with no plane change required after the launch ascent. If these restrictions are violated, the general method of calculating earth orbital transfers should be as specified in Section II of Reference 7.

C. Reliability

For purposes of this study the STS can be considered a very reliable system. The probabilities of success estimated for the various system components over the life of the program are as follows:

Component	Failure Extent	Reliability
STS (Booster & Orbiter)	Catastrophic	.9999
STS	Intact Abort	.995
Expendable Booster[1]	Catastrophic	.97 (Avg)
Space Tug (Reusable)	Catastrophic	.99
Space Tug	Intact Abort	.99

D. Payload Environments

The STS is expected to provide very mild environments for the payloads. The data available at this time[2] are general.

1. Vibration

The latest data, which place the Shuttle launch/ascent and reentry loads at 3g maximum, provide a potentially softer payload ride on the Shuttle than on the new low-cost expendable launch vehicles. However, payloads mounted flexibly on the Shuttle structure or suspended cantilever-style from a support platform (like the payloads historically mounted atop a booster vehicle) will probably be exposed to load-amplifications which will approach those experienced with the expendable launch vehicles. The maximum value experienced should be less than 0.02 g^2/Hz from 50 to 2,000 Hz.

2. Acoustic

Maximum acoustic levels are 159 db overall sound pressure level (OASPL).

3. Acceleration

Maximum acceleration is 3g for the launch ascent, translation and reentry regimes.

4. Shock

The payload experiences maximum shock on landing, which is:

[1]May be used early in the program as an interim booster.

[2]Reference 4 Section 4, and Reference 6.

1.5g for 200 ms
1.25g for 150 ms
1.0g for 100 ms
0.75g for 50 ms

4. Pressure

The rate of pressure change on the payload for ascent and descent is:

Ascent 1.013×10^5 N/M^2 (14.7 psi) to 0 in 120 sec
Descent 0 to 1.013×10^5 N/M^2 in 1600 sec

5. Temperature

The temperatures of the orbiter vehicle internal structure and surfaces in the vicinity of the payload will remain within the following ranges:

	Maximum	Minimum
Prelaunch	322^oK ($+120^oF$)	200^oK (-100^oF)
Launch & Ascent	390^oK ($+150^oF$)	200^oK
On-Orbit (doors closed)	390^oK	200^oK
Entry	390^oK	200^oK
Post Landing	390^oK	200^oK

During on-orbit operation with the payload bay doors open, the payload thermal environment is dependent upon the payload thermal control provisions and the orientation of the payload bay opening with respect to the sun.

III. SHUTTLE-COMPATIBLE SPACECRAFT CONCEPTS

The logical consequences of a low-cost, high-capacity STS is that it allows modularized spacecraft of increased weight and volume to be constructed at a reduced cost with improved reliability, maintainability, and repair aspects.

A. Spacecraft Design

The following is a summary of the low-cost payload design philosophy proposed by LMSC for spacecraft compatible with the STS and utilizing its distinct advantages. These design guidelines will, for purposes of this study, be assumed to be the approach used to engineer the spacecraft which will be operational in the Shuttle flight period from 1979 to 1990. Greater details of these concepts may be obtained from Sections 2 and 5 of Reference 6 or from Reference 8.

1. Design Guidelines

The following are the assumed general guidelines that payload system designers will implement in the design of low-cost payload systems compatible with the STS.

a. System Design Guidelines

- Standardize unmanned payload subsystems
- Standard experiment interfaces
- Utilize minimum quantity of multi-mission standard spacecraft
- Standardize unmanned payload checkout equipment--for ground and in-orbit usage
- Select a simple spacecraft configuration, taking full advantage of the payload weight and volume capability of the Space Shuttle.
- Select the simplest systems that will meet specification requirements to reduce design, analysis, fabrication, and testing efforts.

- o Establish reliability goals based on the in-orbit checkout capability of the Space Shuttle
- o Limit equipment redundancies and backup operating modes to those actually required by reliability goals
- o Avoid state-of-the-art developments that are not proven in hardware usage
- o Minimize command and data requirements

b. <u>Subsystem Design Guidelines</u>

- o Select a simple spacecraft configuration that requires only a simple structure
- o Provide volume for low-density equipment installations to simplify installation design and to ensure complete accessibility of equipment
- o Use high factors of safety (three or greater) for sizing structural elements to reduce design and analysis efforts and to reduce or eliminate static load testing
- o Do not use beryllium, composite materials, or other high-cost materials
- o Eliminate deployment mechanisms whenever the launch vehicle payload envelope permits fixed installation of solar panels, antennas, sensors and other equipment
- o Avoid sophistication and miniaturization of mechanisms

c. <u>Experiment Subsystems</u>

- o Select simple experiment package configurations, taking full advantage of the greater payload capability
- o When experiment thermal control requirements differ significantly from other spacecraft subsystem requirements, isolate the experiment to

simplify thermal control of both the experiment and the spacecraft

- Design for in-orbit maintenance of experiment installation by modularization of equipment
- Design low-density experiment installations with provisions for additions or changes to experiment equipment
- Avoid mechanisms that are not self-supporting in 1g
- Design low-density electronic packages to reduce design, development, and manufacturing costs
- Eliminate in-flight adjustments
- Avoid miniaturization for weight and volume reduction

d. <u>Stabilization and Control Subsystems</u>

- Do not overspecify component performance requirements
- Limit back-up operating modes and equipment redundancies to those specifically required by reliability goals
- Simplify equipment design by taking full advantage of the greater weight and volume capability afforded
- Tradeoff the use of a general-purpose computer for stabilization, control and data processing functions against alternate mechanizations
- Increase the volume of electronic equipment (x2 or more) to reduce packaging density, thus reducing design, manufacturing, and inspection costs
- Reduce stress on parts and/or use larger, higher-rated parts, in circuit design, thereby increasing confidence in performance, and reducing testing costs

- o Minimize command and data requirements
- o Design for in-orbit maintenance by modularization

e. Communication, Data Processing, and Instrumentation (CDPI) Subsystems

- o Use the guidelines recommended for the Stabilization and Control Subsystems
- o Standardize CDPI equipment for spacecraft commonality

f. Electrical Power Subsystem

- o Standardize battery size for commonality
- o Design to facilitate battery replacement in orbit
- o Standardize and use low-density packaging techniques for the regulation and control of electrical power
- o Relax weight and volume constraints on solar arrays for simpler design, lower stress factors, and less costly solar cells

g. Attitude Control Subsystem

- o Relax weight and volume constraints to achieve simplicity commensurate with high-reliability and long life

h. Environmental Control Subsystems

- o Reduce complexity by isolating the areas requiring special thermal control and through the increased use of insulation

B. Spacecraft Checkout and Test

A phased spacecraft checkout approach was developed by LMSC for the STS, so that a series of verifications using the same checkout tests could be performed on a payload.[1] There are seven phases associated with this checkout test plan.

---

[1] For more detail see Reference 6, sections 2 and 8.

EXHIBIT 17 - ANOMALY DISTRIBUTION AMONG MAJOR COMPONENTS AND EQUIPMENT TYPES

Major Components	Number of Anomalies	Percent	Equipment Type	Number of Anomalies	Percent
Tape Recorders	65	20	Basic Electronics	144	45
Batteries	47	15	Energy Sources	52	16
Experiments	43	14	Experiments	43	14
Attitude Sensors	30	9	Mission Sensors	31	10
Transmitters	23	7	Attitude Control	30	9
T.V. Cameras	18	6	Non-Electronics	20	6
Converter-Inverters	14	4		320	100
Receivers	13	4			
Probes-Monitors and Detectors	13	4			
Motor Controls, Etc.	9	3			
TM Encoders-Decoders	9	3			
Miscellaneous	36	11			
	320	100			

exhibit, one classifies the major component anomalies by general equipment type, and the other by specific components.

The following subsections contain expanded descriptions of Shuttle Impact Categories I through VIII. Supplementing the category descriptions are (1) a list of components, subsystems, or tests which are potentially impacted by the particular Shuttle function and (2) several Statements of Shuttle Impact (SOIs) that together with the rationale and supporting data, serve as vehicles for presenting specific ideas on the design, development, and testing of Shuttle compatible spacecraft and potential changes in the management of space programs.

I. Category I: Physical Phenomena - Observation and Measurement

The Shuttle experiment packages carried on the planned sortie missions will provide means for precisely measuring and evaluating the physical characteristics of earth and space as seen from orbit. Data from these missions will enhance the design of subsystems and experiments such as:

- o Star trackers
- o Solar arrays
- o Horizon scanners
- o Infrared, visible and ultraviolet photography
- o Photometry
- o Spectography
- o Radiometry
- o Antennas (patterns and propagation)
- o Electromagnetic and particle radiation
- o Laser communications (atmospheric propagation)

On a synchronous equatorial orbit payload (e.g., SEO)[1], it is not practical to perform repair only when a random catastrophic failure occurs. Rather a payload replacement will be performed and the failed SEO will be returned to Earth for refurbishment. The statistical probability of occurrence of random failures on the SEO has been assumed to average a 2-year time period.

2. Refurbishment of Payloads (with the OAO and SEO used as examples)

a. OAO Refurbishment in Orbit

It is planned to periodically (at the end of each 1-year operating period, or as varied by actual failure experience) launch a Shuttle with a set of replacement modules. The OAO would be retrieved by the Shuttle in low earth orbit and all modules replaced while the OAO is tethered to the Shuttle on the extended deployment/retrieval gear or within the Shuttle cargo bay. The new modules would be installed in the OAO by: (1) the Shuttle crew members working in EVA or non-pressurized IVA; (2) telefactor robots remotely controlled from the Shuttle crew compartment; (3) automated devices; or (4) combinations of these. Figure 17 shows four possible modes.

The Shuttle will return the failed or spent modules to earth for refurbishment.

b. SEO Refurbishment

It is planned to periodically (at the end of each 2-year operating period, or as varied by actual failure experience) launch a replacement SEO with a Shuttle/Tug. The failed or spent SEO would be returned to Earth for refurbishment. The low-cost SEO will accommodate refurbishment on orbit but because the Tug must be returned to earth for propellant refill in the mode assumed, the SEO is returned to

---

[1] SEO (Synchronous Equatorial Orbiter) Wt 494 kg (1,090 lbs)

earth for refurbishment. For this operation, a ready-to-launch replacement SEO must be available on the ground at all times.

The first, second, and third of a set of four SEO's must be refurbished and ready for relaunch within 60 days (to match the average launch cycle time of 60 days between launches). Refurbishment of the SEO will comprise replacement of the equipment modules and re-checkout of each SEO. Because of the longer time-span required for module-level refurbishment, two sets of modules should be held in standby; this allows approximately four months for turnaround time for refurbishment of a set of modules.

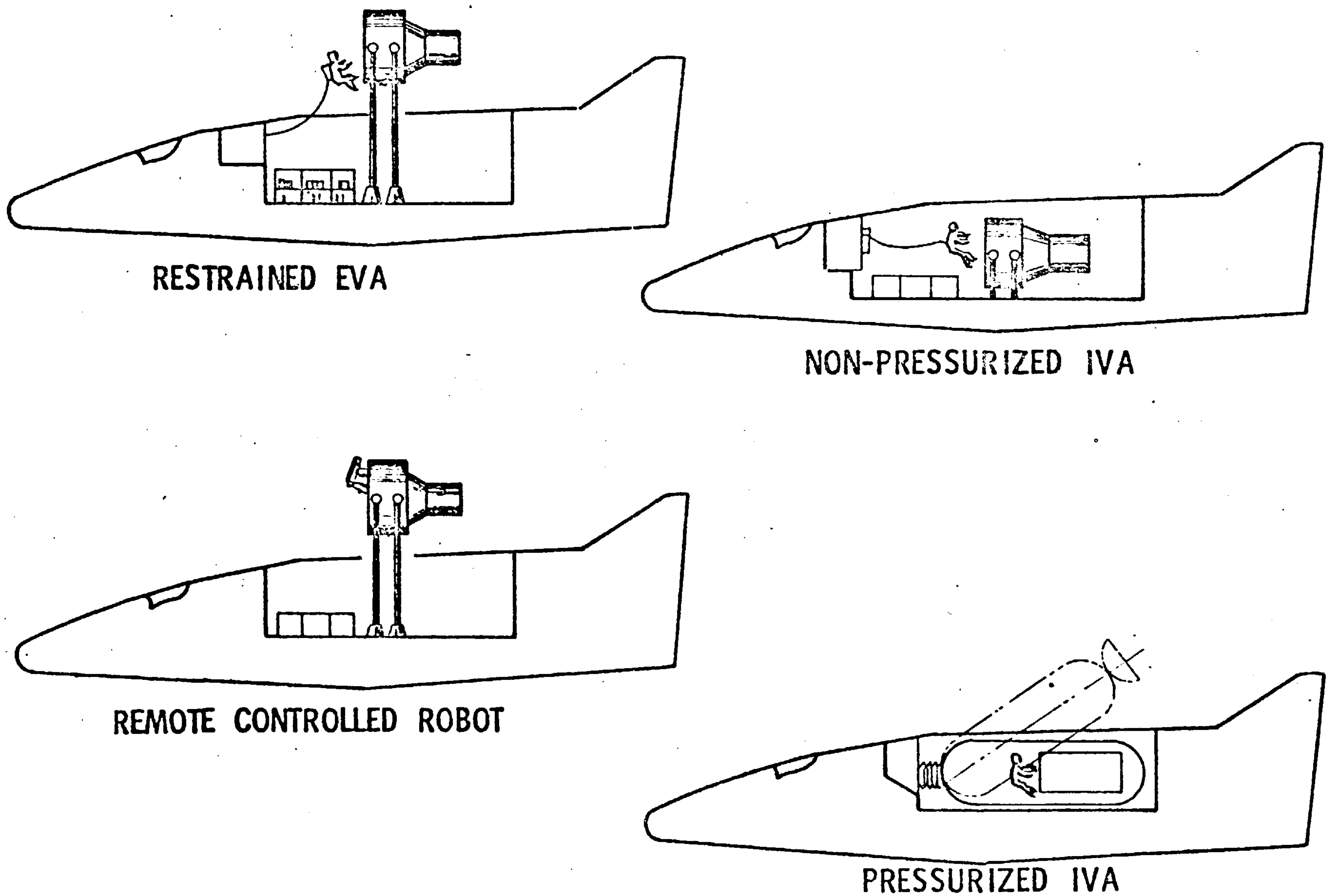


FIGURE 17 - IN-ORBIT REPAIR/REFURBISHMENT CONCEPTS (Reference 6, page 8-49)

REFERENCES

1. The Aerospace Corp., STS Cost Methodology, Volume I, Earth Orbital Shuttle Cost Methodology, August 1970, Report Number TOR-0059(6759-04)-1

2. The Aerospace Corp., STS Cost Methodology, Volume II, Orbit-to-Orbit Shuttle Cost Methodology, August 1970, Report Number TOR-0059(6759-04)-1

3. The Aerospace Corp., Integrated Operations/Payloads/Fleet Analysis, Final Report, Volume II, August 1971, Report Number ATR-72-(7231)-1

4. The Aerospace Corp., Integrated Operations/Payloads/Fleet Analysis, Final Report, Volume IV, August 1971, Report Number ATR-72(7231)-1

5. The Aerospace Corp., Integrated Operations/Payloads/Fleet Analysis, Final Report, Volume V., August 1971, Report Number ATR-72-(7231)-1

6. Lockheed Missiles and Space Company, Final Report Payloads Effects Analysis Study, June 1971, Report Number LMSC A990556

7. NASA, Launch Vehicle Estimating Factors for Use in Space Mission Planning, January 1971, Report Number NHB 7100.5

8. LMSC, Design Handbook for Low-Cost Space Shuttle Payloads, 7 June 1971, Report Number A-990558

APPENDIX B

SPACECRAFT AVERAGE AVAILABILITY ANALYSIS

APPENDIX B

SPACECRAFT AVERAGE AVAILABILITY ANALYSIS

Spacecraft Index No.(1)	Mission Duration (hours)	Status Quo		Availability Threshold for Shuttle Launch: 0% (Launch Only)			20%			50%			80%		
		A(2)	N(3)	A	N_1(4)	N_2(5)	A	N_1	N_2	A	N_1	N_2	A	N_1	N_2
1b	17,500	14.5	1	14.5	1	1	74.2	2	2	98.5	3	3	98.6	4	3
2a*	22,727	11.3	1	14.1	1	1	74.8	3	1	87.0	5	0	96.8	12	6
2b*	17,952	79.0	1	79.0	1	0	79.0	1	1	79.0	1	0	96.0	2	1
3a	5,448	86.9	1	86.9	1	1	86.9	1	0	86.9	1	0	96.9	2	1
3b	29,088	81.0	1	81.0	1	1	81.0	1	1	81.0	1	1	99.9	2	2
4	9,000	45.1	1	56.5	1	1	56.5	1	0	75.4	2	0	91.4	4	2
6a*	ε	0	1	100	1	1	100	1	1	100	1	1	100	1	1
6b*	4,780	71.0	1	72.8	1	1	72.8	1	1	90.6	2	2	95.7	4	3
7a*	3,300	35.6	1	45.7	1	1	73.7	2	1	93.9	3	2	96.4	3	2
7b*	9,000	13.5	1	16.9	1	1	84.6	3	3	84.6	3	3	98.1	4	4
7c*	5,500	53.9	1	53.9	1	1	53.9	1	1	64.8	3	3	82.5	7	6
7d*	6,200	19.8	1	20.3	1	1	53.6	3	2	80.2	4	2	89.2	7	5
7e*	8,600	18.5	1	37.0	1	1	52.0	2	2	96.4	3	1	96.4	3	1
7f*	9,300	48.4	1	49.6	1	1	49.6	1	1	96.2	2	2	96.8	4	3
7g*	23,000	36.4	1	36.4	1	1	45.5	2	1	94.4	3	2	95.2	5	4
7h*	17,500	45.3	1	58.1	1	1	58.1	1	1	83.4	2	2	98.8	5	4
8a*	616	70.7	1	70.7	1	1	70.7	1	1	66.6	2	2	69.6	3	3
8b	23,400	13.8	1	14.2	1	1	53.7	2	2	79.6	4	1	85.4	6	2
8d	2,160	32.9	1/2	53.6	1/2	1/2	53.6	1/2	1/2	53.6	1/2	1/2	86.0	2-1/2	1-1/2
8e	1,670	76.7	1	95.8	1	1	95.8	1	1	95.8	1	1	95.8	1	1
9a*	7,248	100	1	100	1	1	100	1	0	100	1	0	100	1	0
9b*	17,376	37.6	1	37.6	1	1	37.6	1	0	85.2	3	2	96.7	5	3
9c*	11,870	61.0	1	76.1	1	1	76.1	1	1	76.3	1	1	99.4	3	1

Notes:
(1) Those spacecraft index numbers bearing an asterisk require only a Shuttle; all others require both a Shuttle and Tug for launch or repair missions.
(2) A is average spacecraft availability in percent.
(3) N is the number of launches required per spacecraft. Fractional entries indicate 2 or more payloads launched from the same vehicle.
(4) N_1 indicates the number of Shuttle or Shuttle/Tug launches per spacecraft where no missions are combined.
(5) N_2 indicates the number of Shuttle or Shuttle/Tug launches per spacecraft where all possible missions are combined without changing original launch dates or orbital parameters.

APPENDIX B (Continued)

SPACECRAFT AVERAGE AVAILABILITY ANALYSIS

Spacecraft Index No. [1]	Mission Duration (hours)	Status Quo		Availability Threshold for Shuttle Launch											
				0% (Launch Only)			20%			50%			80%		
		A [2]	N [3]	A	N_1 [4]	N_2 [5]	A	N_1	N_2	A	N_1	N_2	A	N_1	N_2
10a	9,340	42.7	1	53.4	1	1	53.4	1	1	79.8	3	3	91.9	5	5
10b	14,568	37.7	1	52.4	1	1	52.4	1	1	41.8	2	2	96.9	4	4
15a	40,560	14.9	1	74.5	1	1	74.5	1	1	74.5	1	1	90.9	2	2
15b	14,144	3.5	1	21.9	1	1	68.0	3	3	76.8	4	3	90.0	10	6
15c	39,300	30.2	1	30.2	1	0	37.8	2	2	72.2	3	2	99.1	5	4
15d*	22,920	45.0	1	56.3	1	1	70.3	2	2	75.9	4	2	95.9	4	2
15e	24,000	73.5	1	73.5	1	1	92.0	2	2	92.0	2	2	92.0	2	2
15f*	13,000	65.0	1	65.0	1	1	65.0	1	1	72.4	2	2	74.2	3	2
17a	20,184	100	1	100	1	1	100	1	1	100	1	1	100	1	1
17b	20,232	100	1	100	1	0	100	1	0	100	1	0	100	1	0
17d	ε	0	1	100	1	1	100	1	1	100	1	1	100	1	1
17e	4,850	20.0	1	100	1	1	100	1	1	100	1	1	100	1	1
17g	3,220	80.0	1	100	1	1	100	1	1	100	1	1	100	1	1
17h	ε	0	1	100	1	0	100	1	0	100	1	0	100	1	1
19a	ε	0	1	0	1	1	0	1	1	0	1	1	0	1	1
19b	8,760	80.0	1	100	1	1	100	1	1	100	1	1	100	1	1
22a*	3,040	29.9	1	29.9	1	1	55.2	2	2	88.2	4	4	88.2	4	4
22c*	11,520	61.5	1	79.0	1	1	79.0	1	1	79.0	1	1	98.0	2	2
22e*	20,250	59.5	1	74.4	1	1	74.4	1	1	74.4	1	1	95.0	4	3
22f*	22,630	35.2	1	35.2	1	1	35.2	1	1	86.4	2	2	91.7	4	3
22g*	6,574	93.3	1	93.3	1	1	93.3	1	1	93.3	1	1	93.3	1	0
22h*	3,160	94.5	1	99.3	1	1	99.3	1	1	99.3	1	1	99.3	1	1

Notes:
(1) Those spacecraft index numbers bearing an asterisk require only a Shuttle; all others require both a Shuttle and Tug for launch or repair missions.
(2) A is average spacecraft availability in percent.
(3) N is the number of launches required per spacecraft. Fractional entries indicate 2 or more payloads launched from the same vehicle.
(4) N_1 indicates the number of Shuttle or Shuttle/Tug launches per spacecraft where no missions are combined.
(5) N_2 indicates the number of Shuttle or Shuttle/Tug launches per spacecraft where all possible missions are combined without changing original launch dates or orbital parameters.

APPENDIX B (Continued)

SPACECRAFT AVERAGE AVAILABILITY ANALYSIS

Spacecraft Index No.(1)	Mission Duration (hours)	Status Quo		Availability Threshold for Shuttle Launch											
				0% (Launch Only)			20%			50%			80%		
		A(2)	N(3)	A	N_1(4)	N_2(5)	A	N_1	N_2	A	N_1	N_2	A	N_1	N_2
26a	21,888	69.8	1/2	69.8	1/2	1/2	69.8	1/2	1/2	69.8	1/2	1/2	94.6	2-1/2	2-1/2
26b	21,888	82.1	1/2	84.2	1/2	1/2	84.2	1/2	1/2	84.2	1/2	1/2	98.8	1-1/2	1-1/2
26c	15,288	79.5	1/2	79.5	1/2	1/2	79.5	1/2	1/2	79.5	1/2	1/2	98.0	1-1/2	1-1/2
26d	15,288	96.5	1/2	96.5	1/2	1/2	96.5	1/2	1/2	96.5	1/2	1/2	96.5	1/2	1/2
26e	6,480	69.9	1/2	87.4	1/2	1/2	87.4	1/2	1/2	87.4	1/2	1/2	98.8	1-1/2	1-1/2
26f	6,480	95.7	1/2	95.7	1/2	1/2	95.7	1/2	1/2	95.7	1/2	1/2	95.7	1/2	1/2
26g	14,904	91.6	1/2	96.1	1/2	1/2	96.1	1/2	1/2	96.1	1/2	1/2	96.1	1/2	1/2
26h	14,904	95.8	1/2	95.8	1/2	1/2	95.8	1/2	1/2	95.8	1/2	1/2	95.8	1/2	1/2
26i	8,760	97.2	1/2	98.8	1/2	1/2	98.8	1/2	1/2	98.8	1/2	1/2	98.8	1/2	1/2
26j	8,760	98.0	1/2	98.0	1/2	1/2	98.0	1/2	1/2	98.0	1/2	1/2	98.0	1/2	1/2
27a	4,944	75.8	1	75.8	1	1	75.8	1	1	86.8	2	2	96.7	4	4
28a	9,823	62.9	1/3	62.9	1/3	1/3	62.9	1/3	1/3	98.9	1-1/3	1-1/3	98.9	1-1/3	1-1/3
33a	7,200	38.9	1	48.6	1	1	64.9	3	3	71.6	2	2	88.4	8	7
34a	19,518	56.5	1	72.5	1	1	72.5	1	1	72.5	1	1	95.7	3	3
35a	6,300	37.8	1	37.8	1	1	68.1	3	3	78.6	4	4	93.4	6	5
35b	7,400	43.1	1	67.4	1	1	67.4	1	1	67.4	1	1	94.8	4	1
35c	8,760	94.3	1/2	94.3	1/2	1/2	94.3	1/2	1/2	94.3	1/2	1/2	94.3	1/2	1/2
35d	144	52.8	1/2	60.5	1/2	1/2	60.5	1/2	1/2	60.5	1/2	1/2	60.5	1/2	1/2
35e	2,856	39.8	1/2	51.0	1/2	1/2	51.0	1/2	1/2	71.5	2-1/2	2-1/2	80.1	4-1/2	3-1/2
35g	8,450	35.5	1/3	36.4	1-1/3	1-1/3	36.4	1-1/3	1-1/3	72.9	2-1/3	2-1/3	94.1	3-1/3	2-1/3
35h	7,300	51.6	1/3	64.5	1/3	1/3	64.5	1/3	1/3	98.6	1-1/3	1-1/3	98.6	1-1/3	1/3
35i	8,030	80.0	1/3	100	1/3	1/3	100	1/3	1/3	100	1/3	1/3	100	1/3	1/3

Notes:
(1) Those spacecraft index numbers bearing an asterisk require only a Shuttle; all others require both a Shuttle and Tug for launch or repair missions.
(2) A is average spacecraft availability in percent.
(3) N is the number of launches required per spacecraft. Fractional entries indicate 2 or more payloads launched from the same vehicle.
(4) N_1 indicates the number of Shuttle or Shuttle/Tug launches per spacecraft where no missions are combined.
(5) N_2 indicates the number of Shuttle or Shuttle/Tug launches per spacecraft where all possible missions are combined without changing original launch dates or orbital parameters.

APPENDIX B (Continued)

SPACECRAFT AVERAGE AVAILABILITY ANALYSIS

Spacecraft Index No. (1)	Mission Duration (hours)	Status Quo A (2)	Status Quo N (3)	0% (Launch Only) A	0% N_1 (4)	0% N_2 (5)	20% A	20% N_1	20% N_2	50% A	50% N_1	50% N_2	80% A	80% N_1	80% N_2
				Availability Threshold for Shuttle Launch											
37a	41,136	62.8	1	64.4	1	1	64.4	1	1	93.3	2	2	99.6	4	1
37b	32,208	52.3	1	53.6	1	1	53.6	1	1	94.9	2	2	94.9	2	2
37c	34,248	41.4	1	51.8	1	1	51.8	1	1	94.8	2	0	99.6	3	0
37d	35,568	53.0	1	53.0	1	0	53.0	1	0	94.1	2	1	99.7	3	2
40a	37,671	69.0	1	69.0	1	1	69.0	1	1	69.0	1	1	99.8	3	3
40c	29,510	28.5	1	44.5	1	1	44.5	1	1	88.0	2	0	99.3	7	5
40e	12,134	74.0	1	95.0	1	1	95.0	1	1	95.0	1	1	96.9	2	1
41a	24,736	62.5	1	78.1	1	1	78.1	1	1	78.1	1	1	79.7	2	1
41b	19,156	57.6	1	57.6	1	0	57.6	1	0	71.3	2	0	77.8	3	0
41c	11,202	68.0	1	85.0	1	1	85.0	1	1	85.0	1	1	92.7	2	1
41d	13,880	62.3	1	62.3	1	1	62.3	1	1	62.3	1	0	91.4	3	1
41e	9,915	82.6	1	82.6	1	1	82.6	1	1	82.6	1	1	97.7	3	2
41f	3,183	52.6	1	52.6	1	0	52.6	1	0	78.9	2	1	94.8	4	2
41g	263	99.2	1	99.2	1	1	99.2	1	1	99.2	2	1	99.2	1	0
UNSUCCESSFUL LAUNCHES															
1a		0	1	100	1	1	100	1	1	100	1	1	100	1	1
6c*		0	1	100	1	1	100	1	1	100	1	1	100	1	1
8c		0	1/2	100	1/2	1/2	100	1/2	1/2	100	1/2	1/2	100	1/2	1/2
17c		0	1	100	1	0	100	1	0	100	1	0	100	1	0
17f		0	1	100	1	1	100	1	1	100	1	0	100	1	0
17j		0	1/2	100	1/2	1/2	100	1/2	1/2	100	1/2	1/2	100	1/2	1/2

Notes:
(1) Those spacecraft index numbers bearing an asterisk require only a Shuttle; all others require both a Shuttle and Tug for launch or repair missions.
(2) A is average spacecraft availability in percent.
(3) N is the number of launches required per spacecraft. Fractional entries indicate 2 or more payloads launched from the same vehicle.
(4) N_1 indicates the number of Shuttle or Shuttle/Tug launches per spacecraft where no missions are combined.
(5) N_2 indicates the number of Shuttle or Shuttle/Tug launches per spacecraft where all possible missions are combined without changing original launch dates or orbital parameters.

APPENDIX B (Continued)

SPACECRAFT AVERAGE AVAILABILITY ANALYSIS

Spacecraft Index No.(1)	Mission Duration (hours)	Status Quo		Availability Threshold for Shuttle Launch: 0% (Launch Only)			20%			50%			80%		
		A(2)	N(3)	A	N_1(4)	N_2(5)	A	N_1	N_2	A	N_1	N_2	A	N_1	N_2
17k		0	1/2	100	1/2	0	100	1/2	0	100	1/2	0	100	1/2	0
17l		0	1/2	100	1/2	0	100	1/2	0	100	1/2	0	100	1/2	0
22b*		0	1	100	1	0	100	1	0	100	1	0	100	1	0
22d*		0	1	100	1	1	100	1	1	100	1	1	100	1	1
28b		0	1/3	100	1/3	1/3	100	1/3	1/3	100	1/3	1/3	100	1/3	1/3
28c		0	1/3	100	1/3	1/3	100	1/3	1/3	100	1/3	1/3	100	1/3	1/3
36a		0	1	100	1	1	100	1	0	100	1	0	100	1	0
36b		0	1	100	1	1	100	1	1	100	1	1	100	1	1
37e		0	1	100	1	1	100	1	1	100	1	1	100	1	1
40b		0	1	100	1	1	100	1	1	100	1	1	100	1	1
40d		0	1	100	1	1	100	1	1	100	1	0	100	1	0
SPACECRAFT WITH NO ANOMALIES															
17i	31,000	100	1	100	1	1	100	1	1	100	1	1	100	1	1
17m	15,384	100	1/2	100	1/2	1/2	100	1/2	1/2	100	1/2	1/2	100	1/2	0
17n	6,770	100	1	100	1	1	100	1	1	100	1	1	100	1	1
19c	13,272	100	1	100	1	1	100	1	1	100	1	1	100	1	1
35f	936	100	1/2	100	1/2	1/2	100	1/2	1/2	100	1/2	1/2	100	1/2	1/2
37f	11,040	100	1	100	1	1	100	1	1	100	1	1	100	1	1

Notes:

(1) Those spacecraft index numbers bearing an asterisk require only a Shuttle; all others require both a Shuttle and Tug for launch or repair missions.

(2) A is average spacecraft availability in percent.

(3) N is the number of launches required per spacecraft. Fractional entries indicate 2 or more payloads launched from the same vehicle.

(4) N_1 indicates the number of Shuttle or Shuttle/Tug launches per spacecraft where no missions are combined.

(5) N_2 indicates the number of Shuttle or Shuttle/Tug launches per spacecraft where all possible missions are combined without changing original launch dates or orbital parameters.

APPENDIX B (Continued)

SPACECRAFT AVERAGE AVAILABILITY ANALYSIS

Spacecraft Index No. (1)	Mission Duration (hours)	Status Quo		Availability Threshold for Shuttle Launch: 0% (Launch Only)			20%			50%			80%		
		$A^{(2)}$	$N^{(3)}$	A	$N_1^{(4)}$	$N_2^{(5)}$	A	N_1	N_2	A	N_1	N_2	A	N_1	N_2
TOTALS:															
All S/C Missions	1,164,000		90		91	86		112	110		155	132		257	215-1/2
Successfully Launched	1,164,000		76-1/3		77-1/3	75-1/3		98-1/3	100-1/3		141-1/3	124-1/3		243-1/3	207-5/6
o Incurring Anomalies	1,086,000		71-1/3		72-1/3	70-1/3		93-1/3	95-1/3		136-1/3	119-1/3		238-1/3	203-1/3
o Incurring No Anomalies	78,000		5		5	5		5	5		5	5		5	4-1/2
Unsuccessfully Launched	0		13-2/3		13-2/3	10-2/3		13-2/3	9-2/3		13-2/3	7-2/3		13-2/3	7-2/3
Shuttles and Tugs					64	61		74	79		97	90		162	148-1/2
Shuttle Only					27	25		38	31		58	42		95	67
Baseline Missions			90		91	81		112	94		155	113		257	178-1/2
Shuttles and Tugs					64	54		74	64		97	72		162	112-1/2
Shuttles Only					27	27		38	30		58	41		95	66
Multiple Missions						5			16			19			37
Shuttles and Tugs						5			15			18			36
Shuttles Only						0			1			1			1

Notes:
(1) Those spacecraft index numbers bearing an asterisk require only a Shuttle; all others require both a Shuttle and Tug for launch or repair missions.
(2) A is average spacecraft availability in percent.
(3) N is the number of launches required per spacecraft. Fractional entries indicate 2 or more payloads launched from the same vehicle.
(4) N_1 indicates the number of Shuttle or Shuttle/Tug launches per spacecraft where no missions are combined.
(5) N_2 indicates the number of Shuttle or Shuttle/Tug launches per spacecraft where all possible missions are combined without changing original launch dates or orbital parameters.

APPENDIX B (Continued)

SPACECRAFT AVERAGE AVAILABILITY ANALYSIS

Spacecraft Index No.(1)	Mission Duration (hours)	Status Quo		Availability Threshold for Shuttle Launch: 0% (Launch Only)			20%			50%			80%		
		A(2)	N(3)	A	N_1(4)	N_2(5)	A	N_1	N_2	A	N_1	N_2	A	N_1	N_2
AVERAGES:															
All S/C Missions	11,200	49.3	0.87	74.3	0.88	0.83	78.9	1.08	1.06	88.1	1.49	1.27	94.7	2.47	2.07
Successfully Launched	13,400	59.0	0.88	69.3	0.89	0.87	74.8	1.13	1.15	85.9	1.63	1.43	93.7	2.80	2.39
o Incurring Anomalies	13,400	55.9	0.88	67.1	0.89	0.87	72.9	1.15	1.18	84.8	1.68	1.48	93.2	2.94	2.51
o Incurring No Anomalies	13,000	100	0.83	100	0.83	0.83	100	0.83	0.83	100	0.83	0.83	100	0.83	0.75
Unsuccessfully Launched	0	0	0.80	100	0.80	0.63	100	0.80	0.57	100	0.80	0.45	100	0.80	0.45

Notes:
(1) Those spacecraft index numbers bearing an asterisk require only a Shuttle; all others require both a Shuttle and Tug for launch or repair missions.
(2) A is average spacecraft availability in percent.
(3) N is the number of launches required per spacecraft. Fractional entries indicate 2 or more payloads launched from the same vehicle.
(4) N_1 indicates the number of Shuttle or Shuttle/Tug launches per spacecraft where no missions are combined.
(5) N_2 indicates the number of Shuttle or Shuttle/Tug launches per spacecraft where all possible missions are combined without changing original launch dates or orbital parameters.