26821-H004-R0-00

Technical Report
for
Contract NAS 9-14264

Formulation of Detailed Consumables Management Models for the Development (Preoperational) Period of Advanced Space Transportation System

VOLUME III

STUDY OF CONSTRAINTS/LIMITATIONS FOR STS CONSUMABLES MANAGEMENT

November 1976

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PREFACE

Future manned space programs that will have increased launch frequencies and reusable systems require an implementation of new consumables and systems management techniques that will relieve both the operations support personnel and flight crew activities. These techniques must be developed for the optimum combination of an onboard and ground support consumables management system consistent with the goals of the program. Effective operational performance of the consumables management techniques of a total system requires that a very explicit definition of the time, place, and method of performance of each function be determined by trade studies to ascertain that the operational methods do, indeed, meet these goals. This requires that the complete consumables management cycle be considered by including the mission planning and scheduling functions, prelaunch activities, onboard mission functions, ground mission support functions, and postmission activities.

Formulation of models required for the mission planning and scheduling function and establishment of the relation of those models to prelaunch, onboard, ground support and postmission functions for the development phase of Space Transportation System (STS) was conducted under Contract NAS 9-14264 during the period 1 November 1975 to 31 October 1976. The preoperational Space Shuttle is used as the design baseline for the subject model formulations.

Analytical models were developed which consist of a Mission Planning Processor with appropriate consumables data base, a method of recognizing potential constraint violations in both the planning and flight operations functions, and a Flight Data File for storage/retrieval of information over an extended period which interfaces with a Flight Operations Processor for monitoring of the actual flights.

The Final Report for the Formulation of Detailed Consumables Management Models for the Development Period of Advanced Space Transportation Systems consists of an Executive Summary and five Technical Volumes. The Technical Volumes include information required for the implementation of a Consumables Management System. The individual volumes consist of:

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Volume I. Detailed Requirements for the Mission Planning Processor

Volume II. Consumables Data Base Workbook

Volume III. Study of Constraints/Limitations for STS Consumables Management

Volume IV. Flight Data File Contents

Volume V. Flight Operations Processor Requirements

Two additional documents were issued in the course of the contract execution. These reports support the development of the Consumables Management System. The reports are:

Study of Existing Analytical Models for STS Consumables Management, dated February 1976.

Documentation of Computer Routines Developed to Determine Cyclic Probability (CYCPRO) Trends of Shuttle Heater Usage, dated September 1976.

This volume of the technical report, Volume III, contains the constraints/limitations study for STS Consumables Management. The study identifies variables imposing constraints on the consumables-related subsystems and presents a method of determining constraint violations with the simplified consumables model in the Mission Planning Processor.

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1. INTRODUCTION AND SUMMARY

Past consumables constraint analysis methods and causes of constraint violations were reviewed. The Constraints and Limitations Section of the Shuttle Operational Data Book was reviewed to determine consumables-related constraints. The review indicated that the constraints that could be related directly to the consumables were identified in the Power Section.

A consumables model is the only method available for flagging times during a flight that consumables-related constraint violations will occur. With the advent of increased flight frequencies, a more efficient method of determining potential problem areas is desired. The method proposed for flagging consumables-related constraint violations that may occur is the scanning of the rate versus time profiles for those times during the flight when the rate violates the specified rate and time constraints. Since the power consumables are calculated using average power data, it is necessary to bias the specified constraint power values downward in accordance with the probability of cyclic components exceeding various power values for specified constraint times. The cyclic power data was analyzed and it was concluded that power constraint studies using a statistical bias could determine with confidence if a constraint violation would occur when large power consuming activities were scheduled. A method was developed for statistically determining the bias power values. However, since the Power subsystem is the only consumable-related subsystem that requires biasing, it is recommended that on future advance spacecraft the designers address the problem of constraint violations that can be caused by the large number of unscheduled cyclic power components operating simultaneously.

2. DISCUSSION

2.1 GENERAL

The purpose of this study was to develop consumable-related subsystem constraint criterion and data for use in constraint analyses by the Mission Planning Processor (MPP) presented in Volume I of the Final Report for the Formulation of Detailed Consumables Management Models for the Development Period of Advanced Space Transportation Systems.

2.2 CONSTRAINTS ANALYSIS

Constraints analysis determines if transient and/or short-term subsystem as well as steady-state design limits will be exceeded if the flight is performed as planned. Violation of these limits will cause degradation of subsystem performance or interference with nominal spacecraft operations. Constraints analyses should be performed during the intermediate planning phase of a flight when data of sufficient detail should be available to determine if any violations are likely to occur.

Traditionally, consumables analyses have identified flight times when consumables-related subsystems exceed subsystem- or spacecraft-imposed constraints and/or limitations. The following Shuttle Operational Data Book (SODB) spacecraft constraint and limitation definitions were utilized in this study. A spacecraft constraint is defined as a spacecraft-imposed limitation which, if exceeded, may result in degradation of subsystem performance or failure. An operational limitation is defined as that limit a flight planner should not exceed in order to avoid interference with nominal spacecraft operation. During the remainder of this report, constraints will be used to mean constraints and/or limitations.

There are cases where the sequence of scheduled activities cause some of the consumables-related subsystems to violate spacecraft-imposed constraints. It is required that these violations be flagged preflight so that activities can be rescheduled, contingency procedures developed and scheduled, or studies performed with detail subsystem models to prevent violations which could interrupt the planned activities of the flight.

2.3 PAST ANALYSES

Past analyses have been performed as a by-product of consumables analyses with detail subsystem models initialized at lift-off and exercised with standard time steps and/or timeline input of changes for the duration of the planned flight. This method of analysis results in extremely large numbers of solutions, computer run times, and volumes of printout to determine in many cases that constraints were violated at only a few time points. With the advent of increased flight frequencies, a more efficient method of determining potential problem areas is desired and solutions for these areas performed to determine if any steady-state or transient constraints will be violated.

2.4 REVIEW OF SHUTTLE CONSTRAINTS/LIMITATIONS

General

In order to determine the scope and nature of this effort, the constraints and limitations section of the SODB was reviewed to identify the constraints requiring consideration in the consumables model being developed for the advanced spacecraft Mission Planning Processor. To this end, the Propulsion, Power, and Environmental Control and Life Support Subsystem sections of the SODB (Reference 1) were reviewed.

Propulsion

Review of the Propulsion section (3.4.3) indicates that there are no constraints/limitations that can be directly related to the propulsion consumables. However, a consumables model can help by flagging simple limit check time constraints and scheduling conflicts.

Power

Review of the Power section (3.4.4) indicates that there are constraints/limitations that can be directly related to the power consumables. Specifically, these constraints are:

Constraint/Limitation	Rationale
3.4.4.1.2 Power Output - The fuel cell powerplant power output limits are as follows: a. 7 KW Continuous b. 10 KW 1 hour maximum c. 12 KW 15 minute maximum (every 3 hours)	Damage or deterioration may occur
3.4.4.1.3 Current Limits - The fuel cell powerplant limits are as follows: a. 545 AMPS 1 minute maximum (under 25 VDC)	Damage or deterioration may occur
3.4.4.1.4 System Power Output - Maximum system power output must not exceed 24 KW for more than 2 minutes	Exceeds the design capability of the ATCS
3.4.4.1.7 Power Output During Purge - Power output must not exceed 8 KW	FCP regulator may freeze

Environmental Control and Life Support

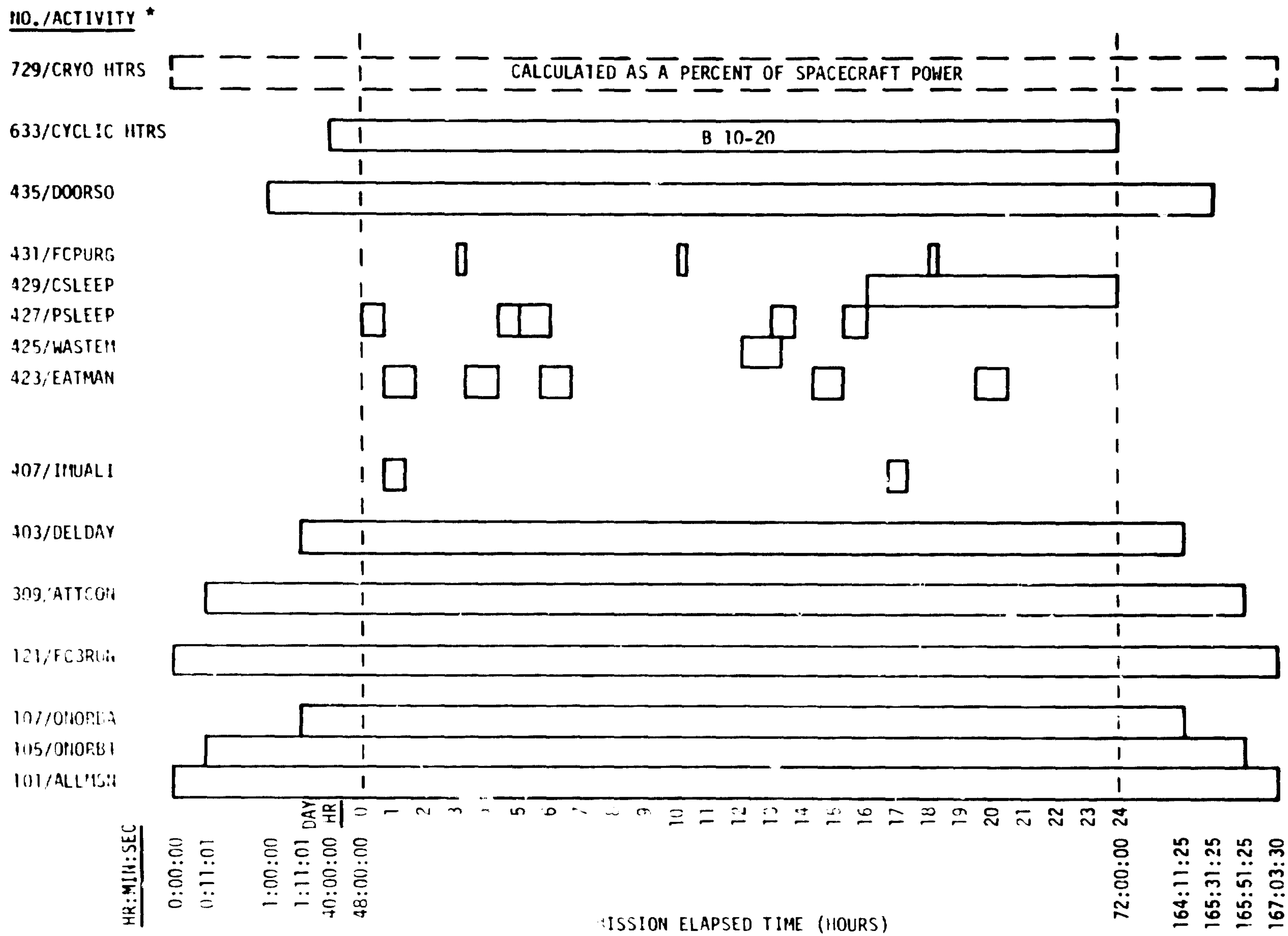
Review of the Environmental Control and Life Support section (3.4.6) indicates that there are no constraints/limitations that can be directly related to the Environmental Control and Life Support consumables. However, it is known that the subsystem has a maximum rate (106 KBTU/HR) at which it can reject heat without causing some of the listed constraints/limitations to be violated. Since the rate of heat generated is a function of the power required to support the electrical equipment, the number of crewmen, the vehicle attitude, and the Beta angle at the time the mission is flown, the total amount of heat requiring rejection can be determined premission and flagged if it violates the capability of the subsystem so that the extent of the violation can be analyzed. However, this violation may be preceded by violating a Power section constraint/limitation (3.4.4.1.4) and is not something the planner would know at the time the mission is planned unless a power consumables analysis of the mission was performed.

2.5 ANALYSIS OF SHUTTLE CONSTRAINTS/LIMITATIONS

In the previous section, the SODB was reviewed to determine the constraints impacting the consumables subsystems. Constraints impacting the consumables-related subsystems were identified in the Power section for the FCPS. A consumables model is the only method available for flagging times during the flight that violations of the FCPS subsystem capacity constraints will occur. This is because there are many ongoing activities that have been scheduled as well as nonschedulable cyclic components that operate concurrently with payload support, crew, and Orbiter activities. Individually, none of these activities will violate the capacity of the FCPS subsystem.

Shuttle power data available as of May 5, 1976 (Reference 8) was analyzed to determine the likelihood that scheduled activities requiring power would exceed the consumable-related constraints listed in the Power section (3.4.4) of the SODB. Since the constraints are based on power values exceeding specified time durations, the 1, 15, and 60 minute, as well as continuous specified time durations, were considered in this analysis. To analyze the referenced data, the scheduled activities between 48 and 72 hours of the Life Science flight are presented in Figure 1 and indicate that some activities can be grouped together for analyses while others should be analyzed separately. Since Figure 1 only presents a typical day from one type of mission, additional activities were included in the analysis to cover the broad spectrum of missions that the MPP must consider. The data for these activities were obtained from Reference 8. For the purpose of this report, the following grouping of activities was utilized:

1) Activities that were ON continuously from orbit insertion to deorbit preparation.
2) Activities that are normally not performed simultaneously.
3) Activities that may be performed simultaneously.
4) Cyclic heaters that are a function of spacecraft attitude and Beta.
5) Cyclic heaters that are a function of the quantity remaining in their tanks and as a result varies with the mission elapsed time.
6) Large cyclic components such as the hydraulic circulation pumps.



* ACTIVITY ACRONYMS ARE EXPLAINED IN APPENDIX A

Figure 1. Activity Schedule for Typical Day of Life Science Flight

Activities that were ON continuously from orbit insertion to deorbit preparation are presented in Table 1. Since the source data contained average data, it indicates that details are not available or cannot be predicted accurately at this stage in development. In order to determine peak powers and time durations, duty cycles specified were applied to time periods available or best time period estimates. The duty cycle of a component is the ratio of the component's on time and period. The results are shown in Table 1. Analyses of the profile indicate the likelihood of obtaining the following peak powers for the specified constraint times:

- 1 MINUTE - 13797 WATTS
- 15 MINUTES - 13797 WATTS
- 60 MINUTES - 13356 WATTS
- CONTINUOUS - 9349 WATTS

Activities that are normally not performed simultaneously are presented in Table 2. Since Figure 1 only contains one of these types of activities (407/IMUALI), all of the activities of this type were analyzed and the worst case selected for inclusion in the peak power determination. These activities normally fall into the Orbital Phase category specified in the MPP. An Orbital Phase is defined as being "...unique to a mission and, in general, items from this set cannot be performed simultaneously."* The operating times and power values were obtained from Reference 8. The following peak powers for the specified constraint times are likely to occur:

- 1 MINUTE - 5420 WATTS
- 15 MINUTES - 4959 WATTS
- 60 MINUTES - 0 WATTS
- CONTINUOUS - 0 WATTS

Activities that may be performed simultaneously are presented in Table 3. These activities normally fall into the Orbital Activities category specified in the MPP. An Orbital Activity is defined as being a "...cyclic type of operation which may vary in magnitude and location with respect to the profile, but are, in general, operationally required on all flights."* The

*Page 5, Reference 3

Table 1. Activities ON Continuously from Orbit Insertion to Deorbit Preparation

TIME		ACTIVITIES/NUMBER						
HR:MIN	HR	ALLMSN 101	ONOBR1 105	ONORBA 107	FC3RUN 121	DELDAY 403	DOORSO 435	Total
		POWER (WATTS)						
:00	.00	5165	3338	2290	207	1247	1550	13797
:24	.40	5165	2992	2290	207	1247	1550	13451
:50	.84	5123	2992	2290	207	1247	1550	13409
:57	.96	5070	2992	2990	207	1247	1550	13356
1:12	1.20	5070	2854	2145	207	1247	1550	13073
2:38	2.64	5070	2719	2145	207	1247	1550	12938
4:05	4.08	5070	2649	2145	207	1247	1550	12868
4:48	4.80	4866	1587	2077	207	1243	1550	11530
5:46	5.76	4866	807	2077	207	1243	1550	10750
6:00	6.00	4866	807	2077	207	1108	1550	10615
6:15	6.24	4866	507	2077	207	1108	1550	10315
7:54	7.92	4866	138	2077	207	1108	1550	9946
8:09	8.16	4686	138	2077	207	1108	1550	9766
12:00	12.00	4686	138	2077	207	691	1550	9349

Table 2. Orbital Phase Peak Power Values

MPP NUMBER	ACTIVITY NAME	ACTIVITY NUMBER	POWER (WATTS) 1 MINUTE	15 MINUTES	60 MINUTES	CONTINUOUS
1	ORBOMS	301	4380	1581	0	1297
2	AUTRCS	303/307	2574	2456	0	0
3	ATTCON	309	784	0	0	0
4	RENDEZ	409	948	948	0	0
5	STAKEP	405	1002	818	0	0
6	DOCKIN	411	2145	1361	0	0
7	UNDOCK	413	2145	1361	0	0
8	PTC	NONE	-	-	-	-
9	ANYEVA	417/419	854	816	0	0
10	ANYIVA	415	198	60	0	0
11	PAYDEP	451/453	5420	4959	0	0
12	IMUALI	407	594	594	0	0

Table 3. Orbital Activity Peak Power Values

MPP NUMBER	ACTIVITY NAME	ACTIVITY NUMBER	POWER (WATTS) 1 MINUTE	15 MINUTES	60 MINUTES	CONTINUOUS
1	DOORSO/C	435/437	3972	1600	1600	1600
2	PAYLOAD	NONE				
3	COMPUTER	NONE				
4	CREW TV	421	198	198	0	0
5	DNLK	NONE				
6	UPLK	NONE				
7	FCPURG	431	137	0	0	0
8	EATMAN	423	1173	768	547	0
9	CSLEEP	429	38	38	0	0
10	WASTEM	425	312	158	0	0
11	A[illegible]	NONE				
12	CO_2	NONE				

operating times and power values were obtained from Reference 8. Analyses of the Life Science flight indicate that the following activities will be scheduled concurrently and produce the indicated powers for the specified constraint times:

ACTIVITY→	435/437	423	421
• 1 MINUTE	3972	1173	198 WATTS
• 15 MINUTES	1600	768	198 WATTS
• 60 MINUTES	1600	547	0 WATTS
• CONTINUOUS	1600	0	0 WATTS

Cyclic heaters that are a function of spacecraft attitude and Beta are baselined in the MPP as an average value for all attitudes and Beta. However, for constraint analysis, the magnitude of peak powers and time durations are required. Since there are 54 activities in the data base to represent the nine spacecraft attitudes for Beta angles between 0 and 90 degrees, two additional activities with Beta angles between 10 and 20 degrees were selected for comparison with activity 633 to determine the worst case for inclusion in the peak power determination. Therefore, the period and duty cycle of the components of several activities were used to calculate power versus time profiles. These profiles are shown in Table 4. Analyses of the profiles to determine magnitude of peak power for the specified constraint times indicate the likelihood of obtaining the following values during a consumables analysis:

- 1 MINUTE - 7929 WATTS
- 15 MINUTES - 5134 WATTS
- 60 MINUTES - 350 WATTS
- CONTINUOUS - 260 WATTS

Cyclic heaters that are a function of the quantity remaining in their tanks, and as a result vary with the mission elapsed time, are shown in Figure 1 as a dotted line because the cryogenic heaters were not scheduled in the Life Science flight but calculated as a percent of the power that the spacecraft must support. Since peak powers and their duration times are required for constraint analysis, activity 729 from the electrical power consumables data base (Reference 13) was chosen to be representative of this

Table 4. Profiles of Cyclic Heaters That Are a Function of Attitude and Beta

ACTIVITY 603	
TIME (MINUTES)	POWER (WATTS)
.0	7879
2.3	7829
2.9	7809
3.8	7509
4.0	7486
4.1	6766
4.5	6716
4.6	6044
4.7	5931
5.5	5837
5.6	5774
6.1	5464
6.2	5164
6.6	5117
6.7	4817
6.9	4517
8.2	4490
8.3	4458
11.6	4314
12.4	4304
14.9	2704
15.7	2614
17.4	2448
22.6	848
26.2	768
29.2	752
29.8	782
37.5	476
37.9	410
40.9	260
90.0=.0	7879

ACTIVITY 633	
TIME (MINUTES)	POWER (WATTS)
.0	7684
.4	7384
.5	6784
1.9	6064
2.1	6044
2.5	5744
3.2	5721
3.7	5411
3.8	5349
4.1	5223
4.4	5192
4.5	5129
5.6	4829
5.8	4519
6.3	4519
6.4	4472
7.7	4413
8.7	4269
10.1	4259
12.0	2659
14.0	2493
14.5	893
21.3	877
21.7	797
25.8	627
31.2	582
34.7	467
35.4	410
40.0	260
90.0=.0	7684

ACTIVITY 701	
TIME (MINUTES)	POWER (WATTS)
.0	7929
1.4	7629
1.5	7329
1.9	7029
3.8	7006
4.5	6944
4.6	6634
5.0	6508
5.2	6477
5.3	6414
5.4	6383
5.5	6363
6.3	6347
6.7	6047
6.9	5737
9.1	5678
9.7	5378
10.8	5234
13.7	5184
13.8	5134
17.1	4968
18.2	4868
22.9	1668
26.8	1658
27.2	1578
28.1	1408
29.7	688
37.3	573
37.4	516
54.1	366
59.3	350
63.4	260
90.0=.0	7929

time period during the Life Science flight. The period and duty cycles of the components were used to calculate a power versus time profile. The profile is shown in Table 5. Analyses of the profile indicate the likelihood of obtaining the following peak powers for the specified constraint times:

- 1 MINUTE - 2853 WATTS
- 15 MINUTES - 2853 WATTS
- 60 MINUTES - 0 WATTS
- CONTINUOUS - 0 WATTS

Table 5. Profiles of Cyclic Heaters That Are a Function of Quantity Remaining

ACTIVITY 729	
TIME (MINUTES)	POWER (WATTS)
.0	2853
27.0	495
41.0	0
180.0	2853

Large cycle components such as the hydraulic circulation pumps fall into a special category. They are sequenced such that they will not operate simultaneously. These cyclic components are baselined in the MPP as an average for all attitudes and Beta. However, for constraint analysis, the magnitude of peak powers and time durations are required. Therefore, the period and duty cycle of the components of several activities were used to calculate power versus time profiles. These profiles are shown in Table 6. Analyses of the profiles to determine magnitudes of peak power for the specified constraint times indicate the likelihood of obtaining the following values during a consumables analyses:

- 1 MINUTE - 1944 WATTS
- 15 MINUTES - 1944 WATTS
- 60 MINUTES - 0 WATTS
- CONTINUOUS - 0 WATTS

Table 6. Profiles of Large Cyclic Components That Are a Function of Attitude and Beta

ACTIVITY 603		ACTIVITY 633		ACTIVITY 701	
TIME (MINUTES)	POWER (WATTS)	TIME (MINUTES)	POWER (WATTS)	TIME (MINUTES)	POWER (WATTS)
.0	1944	.0	1944	.0	1944
11.3	0	6.3	0	16.5	0
30.0	1944	30.0	1944	30.0	1944
41.3	0	36.3	0	46.5	0
60.0	1944	60.0	1944	60.0	1944
71.3	0	66.3	0	76.5	0

2.6 RESULTS OF SHUTTLE CONSTRAINTS/LIMITATIONS ANALYSIS

Shuttle power data, available as of May 6, 1976, was analyzed to determine the likelihood that peak power and time durations of groups of scheduled activities requiring power would exceed the consumables-related constraints listed in the Power section of the SODB and are presented in Table 7. These are tabulated as a function of the specified time constraints in the Power section of the SODB. For each specified time constraint, the peak power values were totaled and compared to the total capabilities of a two-fuel cell, on-orbit configuration. Analyses of Table 7 indicate the scheduled activities resulted in power values of sufficient time duration capable of violating two of the four time constraints specified for a two-fuel cell Orbiter configuration during on-orbit operations when one fuel cell is dedicated to the payload.

Table 7. Peak Power Determination

SOURCE	DESCRIPTION	ACTIVITY NUMBER	POWER (WATTS) 1 MINUTE	15 MINUTES	60 MINUTES	CONTINUOUS
Table 1	Activities ON Continuously		13797	13797	13356	9349
Table 2	Orbital Phase	451/453	5420	4959	0	0
Table 3	Orbital Activities	435/437	3972	1600	1600	1600
		423	1173	768	547	0
		421	198	198	0	0
Table 4	Cyclic Heaters That Are A Function of Attitude and Beta	701	7929	5134	350	260
Table 5	Cyclic Heaters That Are A Function of Quantity Remaining	729	2853	2853	0	0
Table 6	Large Cyclic Component That is A Function of Attitude and Beta	701	1944	1944	0	0
	Subtotal		37286	31253	15853	11209
	Distribution Loss (2.5 Percent)		932	781	396	280
	Total		38218	32034	16249	11489
	Constraint (2 Fuel Cells)		27000	24000	20000	14000
	Margin		-11218	- 8034	+ 3751	+ 2511
	Percent Margin		-46	-33	+19	+18

Power constraints will generally be violated when peak demands occur. Past experience indicates that peak demands occur during ascent and descent when most systems are powered up for burns, and during on-orbit operations when large power-consuming experiments are initiated. In order to complete the flight objectives, the systems are designed to handle the large power levels of scheduled activities. The constraint violation generally occurs when nonscheduled cyclic heaters and components, that cannot be predicted accurately during preflight planning, cycle ON requiring large amounts of power.

During ascent and descent this problem is minimized by preconditioning, deactivating non-critical cyclic components, and using three instead of two fuel cells to support the power demands. This leaves the on-orbit operations period with a problem of flagging power constraint violations that could disrupt the planned objectives of the flight. The procedure used to eliminate violations that may occur during real-time flight operations is to inhibit the cyclic component until the peak power demand of the activity ends and reactivate the cyclic component so that the scheduled activity can be accomplished.

As a result of the above analysis, the remainder of this study is directed to the development of a criterion, data, and a method to flag power constraint violations in the advance spacecraft Mission Planning Processor.

2.7 PROPOSED METHOD OF FLAGGING CONSTRAINT VIOLATIONS

The method proposed for flagging consumables-related constraint violations that may occur during preflight planning is the scanning of rate versus time profiles for those times during the flight when rate levels violate the specified rate and time constraints. If no violations are flagged, the maximum rate and time duration for each specified constraint should be output to determine relative safety margins. By using this method, it minimizes the number of solutions, computer run times, and the amount of printout.

However, the simplified power consumables model utilizes the average power of cyclic components in generating the power rate versus time profile. Scanning this rate versus time profile for values exceeding specified constraint rates will not yield realistic results unless the specified constraint rates are biased downward in accordance with the probability of cyclic components exceeding various rates for specified constraint times. The philosophy of biasing the specified constraint power rate downward is discussed in the next section.

2.8 PHILOSOPHY OF BIASING POWER CONSTRAINT VALUES

The philosophy of biasing the specified constraint power values downward in accordance with the probability of cyclic components exceeding various power values for specified constraint times is discussed below. The probability of all of the cyclic components operating simultaneously with a scheduled activity requiring a large amount of power is extrememly small. Therefore, the following considerations were made in defining the bias power value: 1) The value should be less than the maximum value for simultaneous operation of all cyclic heaters and components and greater than the average value; 2) the value must enable the planner to schedule activities requiring large amounts of power for short periods of time with confidence that a constraint violation will not occur as long as the power value containing the average cyclic power is less than the biased constraint power value.

Computer routines were designed and built (Reference 12) to develop the power constraint violation criterion and determine the statistical trend of the power data for cyclic components on any spacecraft for the Mission Planning Processor. These routines use the component's cyclic characteristics (period, percent ON time during period, power value when ON, first start time, and last stop time) to calculate the maximum possible power, expected average power, the total power at any time during the evaluation interval, the probability that the cyclic power will exceed a specified power value for a specified time, the number of times that the cyclic power changed value during specified ranges, and the average power during the evaluation interval. Cyclic components are defined as any component turned ON and OFF automatically (i.e., not scheduled), be it by a computer, thermstat, pressure switch, etc.

Since the cyclic components will be influenced by random variables within their environment, options are available to randomly bias the components first start time within ±.5 hours, change all components' period to a fixed value, and make repeated runs over the evaluation interval with start times being randomly biased to obtain data for parametric analyses of the probability of violating time constraints for various power values. By handling cyclic components in this manner, peaks will be obtained which are representative of what the thermostatically-controlled components and heaters will produce.

For the purpose of determining the probability that the cyclic power will exceed a specified value for a specified time duration, the time duration (t) that the power was above the specified power value for the specified time duration was determined over an observation period of time (T). The probability that the cyclic power will exceed a specified value for a specified time duration is approximately t/T. This formulation is extracted from Pages 211-212 of Reference 11.

2.9 DETERMINATION AND ANALYSIS OF CYCLIC POWER TREND DATA

The cyclic Shuttle heater data in Appendix B of Reference 6 was utilized as typical input data to determine the trend of the cyclic power data. The trend of the cyclic power as a function of probability of exceeding specified power values for the various constraint times specified in the SODB was determined using

1) Worst case heater duty cycles for the attitudes indicated, and
2) Specified duty cycles for the +ZLV, +XVV attitude for three different Beta ranges.

The results of the output data were plotted to show the trend of that data.

Figure 2 presents the probability of various power values violating a 1-minute constraint time for various spacecraft attitudes when worst case heater duty cycles are used. This data represents the results of making 20 repeated runs over a 10-hour evaluation interval with start time of 56 cyclic components being randomly biased at the beginning of each repeated run.

Figures 3, 4 and 5 present the probability of various power values violating 1-, 15- and 60-minute constraint times, respectively, for the +ZLV, +XVV attitude using specified heater duty cycles for three different Beta ranges. Also included for comparison purposes are the results of using worst case heater duty cycles for this attitude. This data represents the results of making 40 repeated runs over a 10-hour evaluation interval with start times of 54 cyclic components being randomly biased at the beginning of each repeated run.

Analysis of Figure 2 indicates that the probability of the cyclic power exceeding a specified power for a specified constraint time decreases exponentially as the specified power approaches the maximum possible power. If an infinite number of cases were run, these curves would tend to smooth out. The trend of the data is illustrated by the fact that the data from the other attitudes follows the same characteristics. The probability ratio also decreases as the expected average power value decreases.

Figures 3, 4, and 5 also exhibit the same trends discussed above. In addition, the probability of obtaining cyclic power values that will exceed a specified power value decreases as the constraint time increases. This is illustrated in Figure 5 by the fact that the probability of obtaining a cyclic power value for 60 minutes for two of the three Beta ranges was nil and was subsequently lower in progressing from Figure 3 to 4 to 5.

Figure 3 is used to illustrate a method whereby the trend data can be used to determine a power value for biasing the specified constraint power when the average cyclic power value for the +ZLV, +XVV attitude and Beta

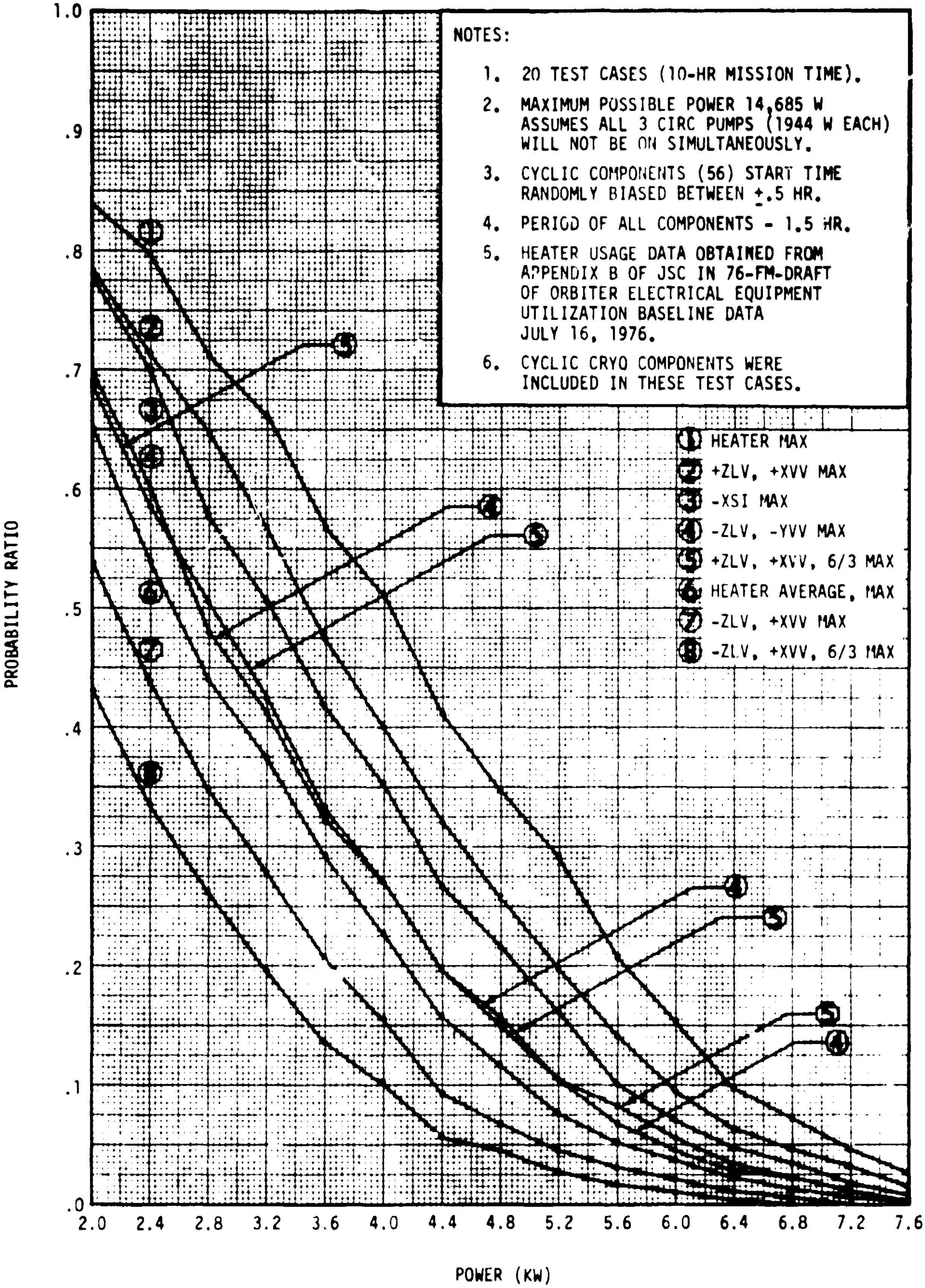


Figure 2. Probability of Violating 1-Minute Constraint for Various Power Values and Attitudes

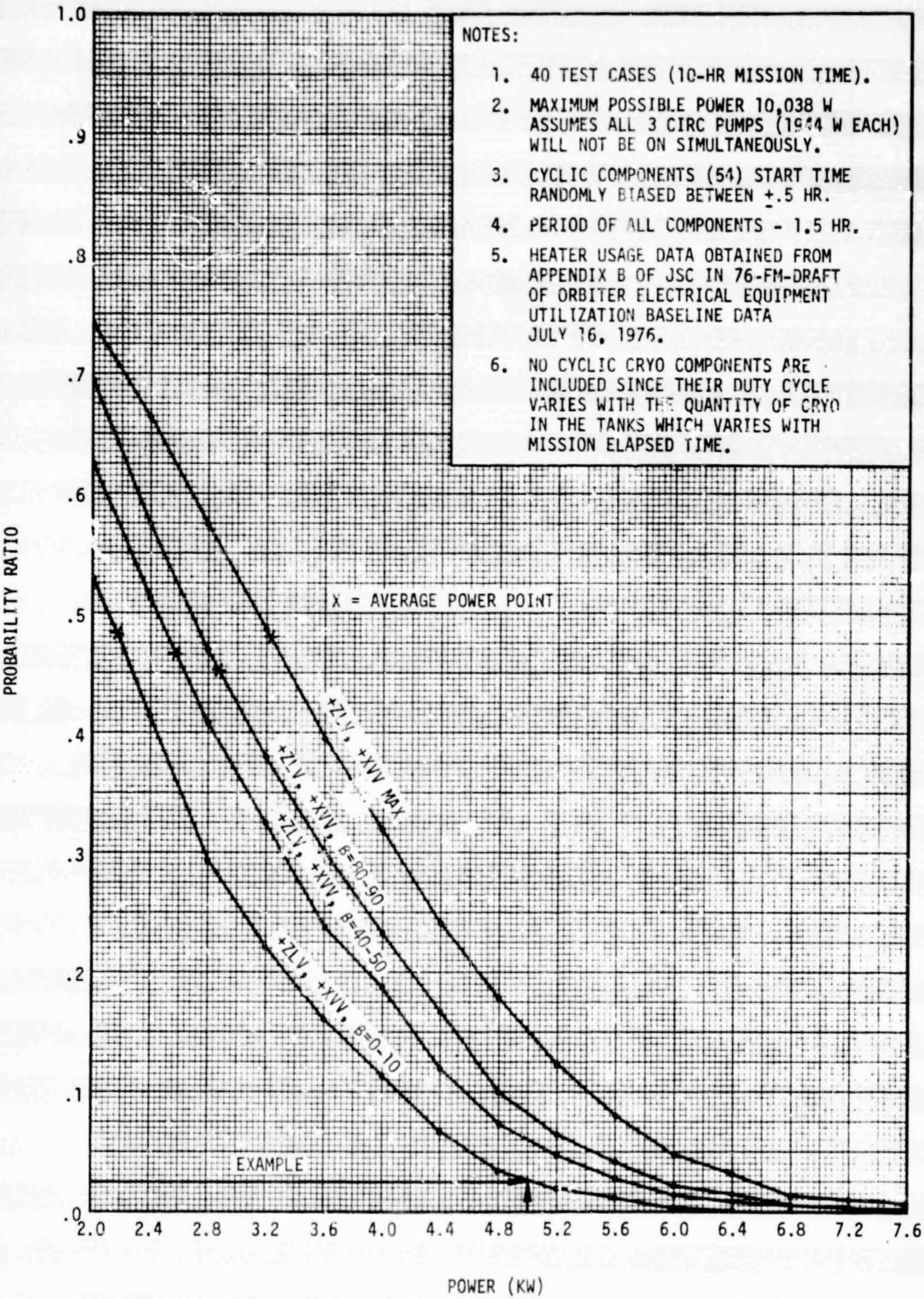


Figure 3. Probability of Violating 1-Minute Constraint for Various Power Values of +ZLV, +XVV Attitude at Various Beta Angles

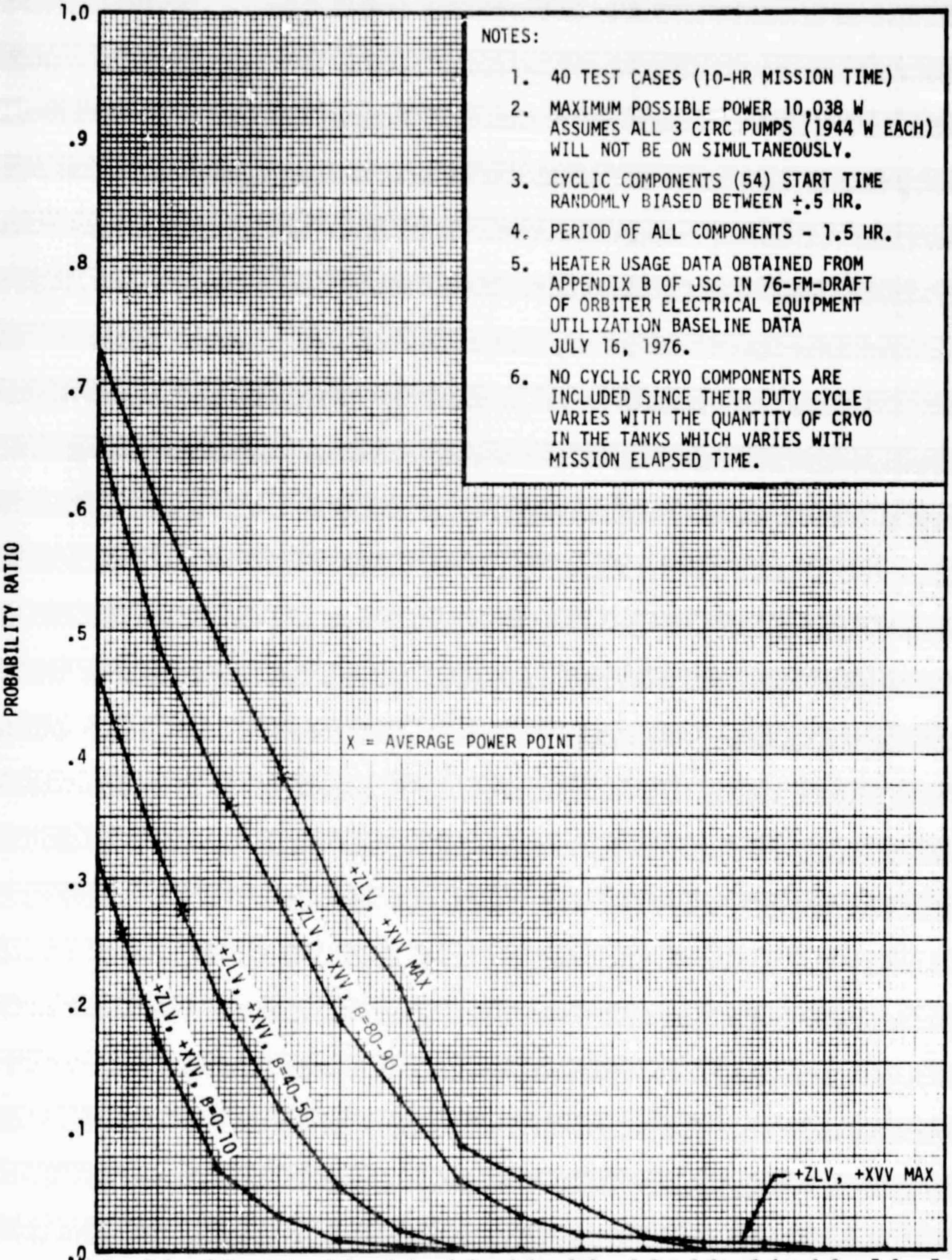


Figure 4. Probability of Violating 15-Minute Constraint for Various Power Values of +ZLV, +XVV Attitude at Various Beta Angles

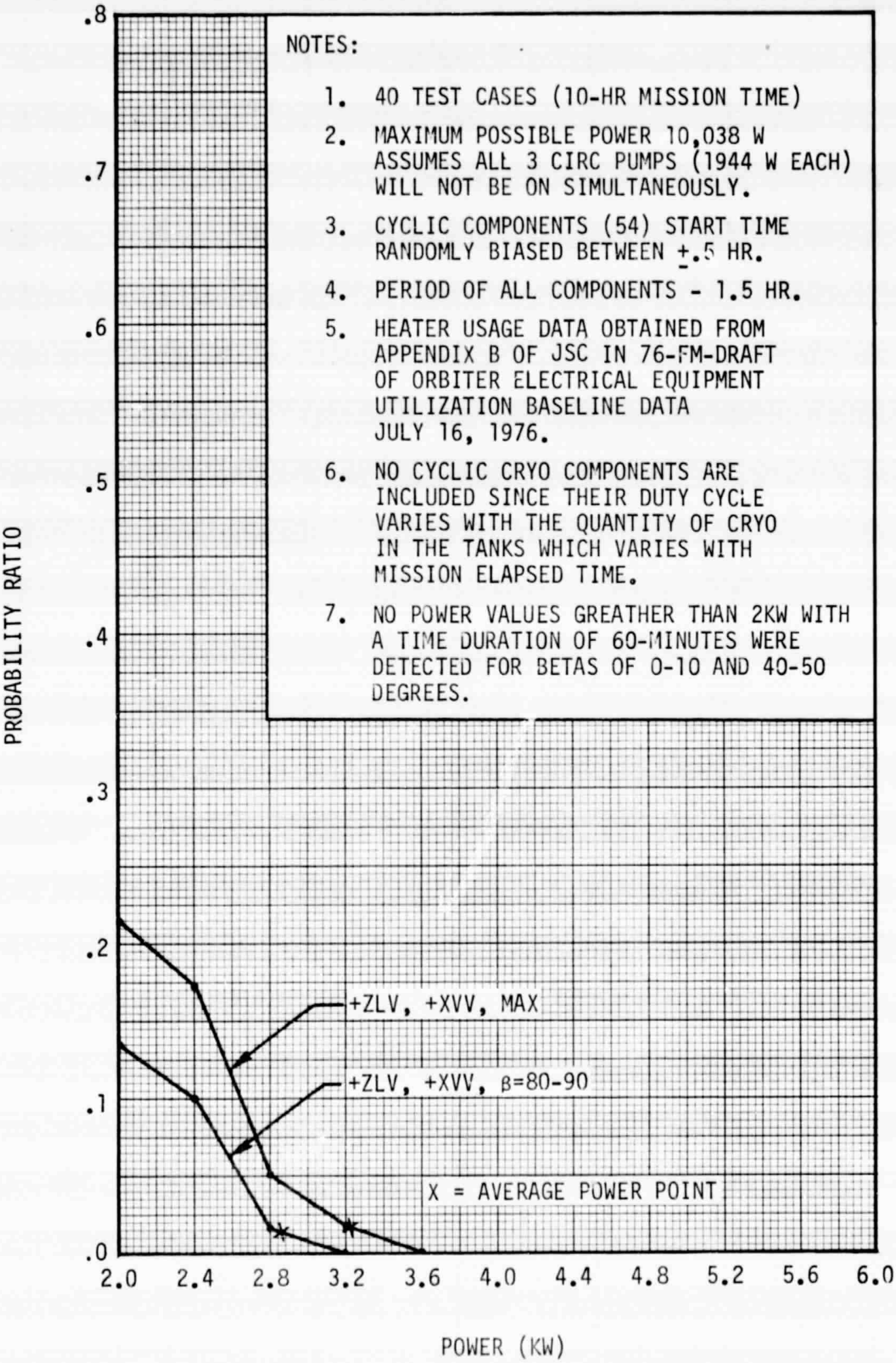


Figure 5. Probability of Violating 60-Minute Constraint for Various Power Values of +ZLV, +XVV Attitude at Various Beta Angles

between 0-10 degrees is used in computing the power rate versus time profile. It is desired that the bias value

1) be less than the maximum value for simultaneous operation of all cyclic heaters and components and greater than the average value, and

2) must enable the planner to schedule periods of time with confidence that a constraint violation will not occur as long as the power value containing the average cyclic power is less than the biased constraint power value.

A probability ratio of .025 was chosen so that the chance of obtaining a cyclic power value greater than the bias value would be very small. From Figure 3, the .025 probability ratio for Beta between 0-10 degrees yields a bias value of 5.00 KW. This also satisfies the requirement that the bias be less than the 10.04 KW maximum value for simultaneous operation of all cyclic components and heaters and greater than the 2.16 KW average value.

A two-fuel cell on-orbit configuration has a 1-minute specified constraint power value of 27.00 KW. Biasing the specified constraint power downward with the 5.00 KW bias value would result in a biased constraint power value of 22.00 KW. Therefore, if the Orbiter power rate versus time profile containing the average cyclic power does not exceed the biased constraint power value of 22.00 KW for the 1-minute specified constraint time, there is a 97.5-percent probability that a constraint violation will not occur for the planned profile. Biases for the power values for the other constraint times can be similarly determined.

2.10 MODIFICATION OF MPP EPS CONSUMABLES RATES AND CONSTRAINTS

Since the Mission Planning Processor has baselined an average cyclic power for all flights, this average value must be modified to obtain a reasonably accurate consumables value and for use in constraint analyses. This modification should take into account spacecraft attitude, Beta angle, and mission elapsed time.

The OFT consumables analyses data (Reference 10) was analyzed to determine the magnitude of the cryogenic consumables required by the cyclic heaters and components on a typical day. The results are shown in Table 8. On an average, the cyclic heaters and components required approximately

Table 8. OFT EPS Consumables Tradeoff and Comparison Study

Mission	Energy-KWH					HTR Ratio	
	Total	Total-DFI	Basic Day	HTR	DFI	Total	Total-DFI
2	368.3	306.1	251.5	54.6	62.2	.148	.178
3	374.2	313.0	252.1	60.9	61.2	.163	.195
4	404.6	343.5	262.9	80.6	61.1	.199	.235
5	384.8	323.5	267.6	55.9	61.3	.145	.173
6 (AS)	419.5	358.8	280.5	78.3	60.7	.187	.218
6 (CS)	407.2	346.2	267.5	78.7	61.0	.193	.227
TOTAL	2358.6	1991.1	1582.1	409.0	367.5	1.035	1.226
AVERAGE	393.1	331.9	267.7	68.2	61.3	.173	.204
DISPERSION						±.027	±.031

AS - Alternate Sleep
CS - Concurrent Sleep

17.3 ± 2.7 percent of the cryogenic consumables required to support the Orbiter power requirements on a typical day when DFI was used. During the operational era when the DFI is not required, the cyclic heaters and components will require approximately 20.4 ± 3.1 percent of the cryogenic consumables for a typical day.

Figure 6 illustrates the average cyclic power as a function of spacecraft attitude, Beta angle and mission elapsed time (MET). The average power of the cyclic heaters and components that have been modeled by the spacecraft's prime contractor in thermal models as a function of attitude and Beta vary between 2940 and 1220 watts. During the course of a 160-hour mission, the average cryogenic heater power will vary between 840 and 220 watts. These values will increase with the number of kits added and the method of utilization. These large variations in average cyclic power requires that the average cyclic power b˙selined in the MMP be modified to obtain a reasonably accurate consumables value and for use in constraint analyses. This can be accomplished using the following variables and equations to modify referenced variables in the MPP (Reference 4) which determine the values for calculating EPS consumables rates and constraint violations.

Total Power Determination

$$TP = RATE(EPS)^{*} + DCP \tag{1}$$

where TP = Total Power - Watts (1)**
RATE(EPS) = Rate vs Time for EPS Consumable - Watts (3)
DCP = Delta Cyclic Power - Watts (2)

Delta Cyclic Power Determination

$$DCP = ACPV - AHPB \tag{2}$$

where ACPV = Average Cyclic Power Value - Watts (5)
AHPB = Average Heater Power Baselined - Watts (input)

* Page A-94 of Reference 4.
**(1) indicates the equation in which the variable is calculated (typical).

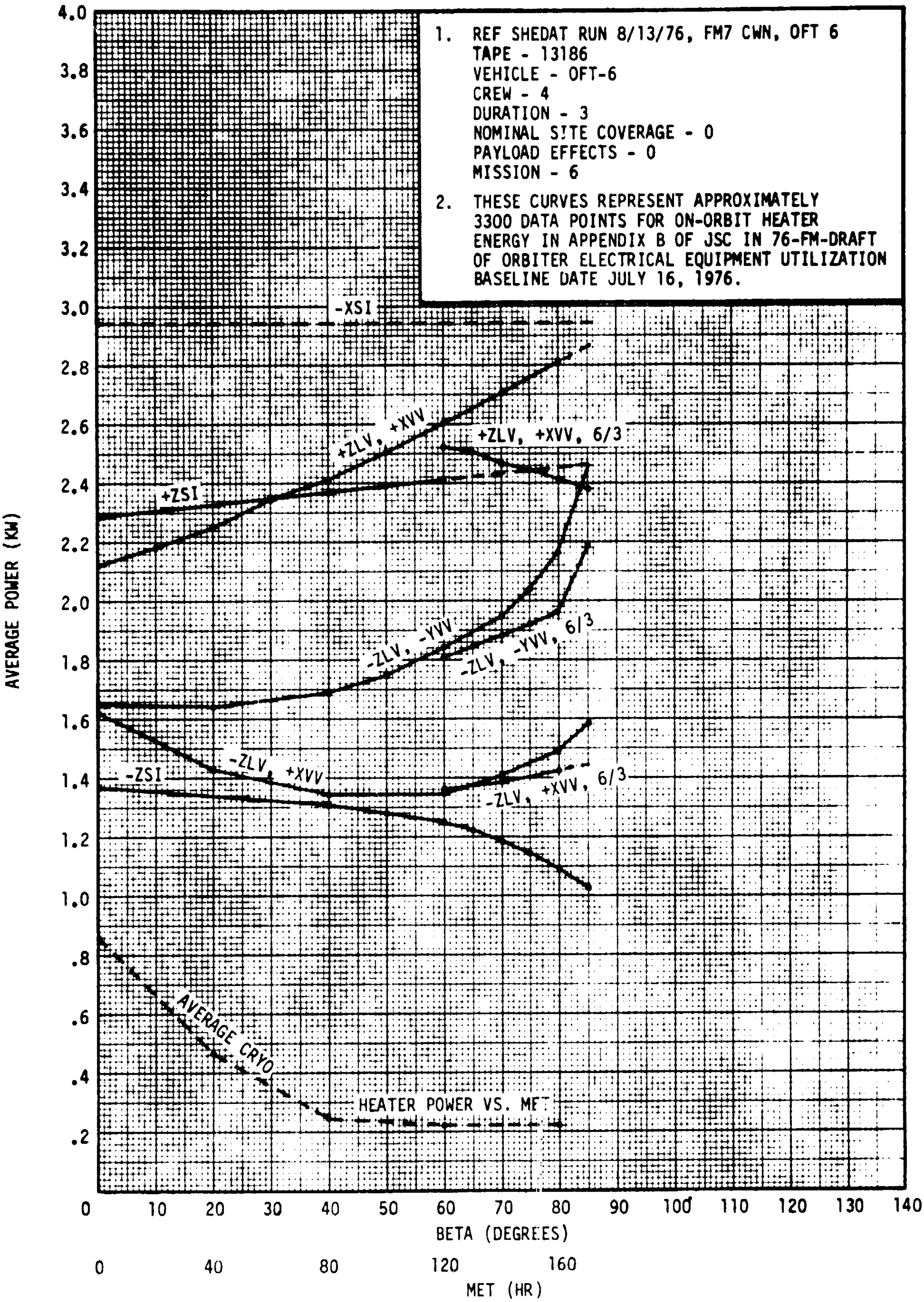


Figure 6. Average Heater Power Versus Beta and MET

Rate vs Time for EPS Consumables Determination

$$RATE(EPS) = BLP + \sum_{I=1}^{N} A(I) \tag{3}$$

where BLP = Baseline Power - Watts (input)
A(I) = Activity Power - Watts (input)
N = Number of Activities

Specified Constraint Power Determination

$$SCP(I) = RLIM(EPS,I)^{*} - CPBV(I) \tag{4}$$

where SCP(I) = Specified Constraint Power for Constraint I - Watts (4)
RLIM(EPS,I) = Rate Limit Power Value for Constraint I - Before Biasing - Watts (input)
CPBV(I) = Constraint Power Bias Value for Constraint I - Watts (6)

Average Cyclic Power Value Determination

$$ACPV = AHP + ACP \tag{5}$$

where ACPV = Average Cyclic Power Value - Watts (5)
AHP = Average Heater Power - Watts (7)
ACP = Average Cryo Power - Watts (8)

Constraint Power Bias Value Determination

$$CPBV(I) = HPB(I) + CPB(I) - ACPV \tag{6}$$

where CPBV(I) = Constraint Power Bias Value for Constraint I - Watts (6)
HPB(I) = Heater Power Bias for Constraint I - Watts (9)
CPB(I) = Cryo Power Bias for Constraint I - Watts (10)
ACPV = Average Cyclic Power Value - Watts (5)

*Page A-49 of Reference 4.

Average Heater Power Determination

The average heater power is determined from a data array containing average heater power as a function of Beta for various spacecraft attitudes using straight line interpolation. This array is defined as follows:

AHPA(I,J) = Average Heater Power Array

where I = number of points for each J

J = 1,n (average heater power values corresponding to n various spacecraft attitudes - Watts)

n+1 (corresponding Beta angle values - degrees)

The Beta portion of the array is indexed until a value of Beta is located that is greater than or equal to the value of Beta input. The value of the index (H) and index minus one (L) are used to obtain corresponding Beta and average heater power values for the specified input spacecraft attitude. The average heater power can be determined utilizing the following equation:

$$AHP = PH - [(PH-PL)*(BH-B)/(BH-BL)] \quad (7)$$

where AHP = Average Heater Power - Watts (7)
PH = Power value in data array corresponding to index H - Watts
PL = Power value in data array corresponding to index L - Watts
BH = Beta value in data array greater than or equal to input Beta - degrees
BL = Beta value in data array less than input Beta - degrees
B = Beta value input - degrees

Average Cryo Power Determination

The average cryo power is determined from a data array containing average cryo power as a function of mission elapsed time using straight line interpolation. This array is defined as follows:

ACPA(I,J) = Average Cryo Power Array

where I = number of points for each J

J=1 (Cryo Power Value - Watts)

2 (Mission Elapsed Time value - hours)

The mission elapsed time (MET) portion of the array is indexed until a value of MET is located that is greater than or equal to the value of MET input. The value of the index (H) and index minus one (L) are used to obtain corresponding MET and average cryo power values for the specified input MET. The average cryo power can be determined utilizing the following equation:

$$ACP = PH - [(PH-PL)*(TH-MET)/(TH-TL)] \tag{8}$$

where ACP = Average Cryo Power - Watts
PH = Power value in data array corresponding to index H - Watts
PL = Power value in data array corresponding to index L - Watts
TH = MET value in data array corresponding to index H - hours
TL = MET value in data array corresponding to index L - hours
MET = Mission Elapsed Time input - hours

Heater Power Bias Determination

The heater power bias is determined from a data array containing heater power bias values as a function of Beta for various spacecraft attitudes and constraint times using straight line interpolation. This array is defined as follows:

HPBA(I,J) = Heater Power Bias Array

where I = Number of points for each J

J = 1,n (attitude bias power values corresponding to n various spacecraft attitudes for Constraint time I - Watts)

n+1,2n (attitude bias power values corresponding to n various spacecraft attitudes for Constraint time I+1 - Watts)

⋮

(I-1)n+1,In (attitude bias power values corresponding to n various spacecraft attitudes for Constraint time I last - Watts)

In+1 (corresponding Beta angle values - degrees)

The Beta portion of the array is indexed until a value of Beta is located that is greater than or equal to the value of Beta input. The value of the index (H) and index minus one (L) is used to obtain corresponding Beta values and modified by the input spacecraft attitude to determine the corresponding heater power bias values for each constraint time specified. The heater power bias for each constraint time can be determined utilizing the following equation:

$$HPB(I) = CBPH(I) - \left\{[CBPH(I)-CBPL(I)]*[CBBH-B]/[CBBH-CBBL]\right\} \qquad (9)$$

where HPB(I) = Heater Power Bias for Constraint time I - Watts
CBPH(I)= Constraint Bias Power value in data array corresponding to index H - Watts
CBPL(I)= Constraint Bias Power value in data array corresponding to index L - Watts
CBBH = Constraint Bias Beta value in data array corresponding to index H - degrees
CBBL = Constraint Bias Beta value in data array corresponding to index L - degrees
B = Beta value input - degrees

Cryo Power Bias Determination

The cryo power bias is determined from a data array containing cryo power bias values as a function of mission elapsed time for various constraint times. This array is defined as follows:

CBA(I,J) = Cryo Bias Array

where I = number of points for each J

J = 1,n (Cryo bias power values for various constraint times - Watts)

n+1 (Mission elapsed time - hours)

Since the biases are step functions, the mission elapsed time (MET) portion of the array is indexed until a value of MET is located that is greater than the value of MET input. The value of the index minus one defines the point number (I) corresponding to the cryo power bias values for the various constraint times (J). Therefore, the cryo power bias for each constraint time can be determined utilizing the following equation:

$$CPB(I) = CBA(I,J) \tag{10}$$

where CPB(I) = Cryo Power Bias for constraint time J - Watts
CBA(I,J) = Cryo Bias Array value for point I and constraint time J - Watts

Figure 6 illustrates the Shuttle's average heater power as a function of Beta and mission elapsed time. This figure represents approximately 3300 primary data points contained in Appendix B of Reference 6 for 140 heater identification numbers of which approximately one-half are activated during on-orbit operations and the other half are redundant backup units. From an electrical energy point of view, this data can be represented by 60 points that yield a value that is within 2 percent of the value that would be obtained from the referenced data for various attitudes (9) and Betas (0-90 degrees). Due to the variations in the data, it is easier to maintain and use in this form than in a curve fit form. The value for a specified Beta is determined by straight line interpolation between data points.

Figure 7 illustrates heater bias as a function of Beta angle for various constraint times and spacecraft attitudes. The data for the 1 minute +ZLV, +XVV curve was obtained from Figure 3 for the .025 probability ratio.

Figure 8 illustrates the cryo heater bias as a step function of mission elapsed time for various constraint times.

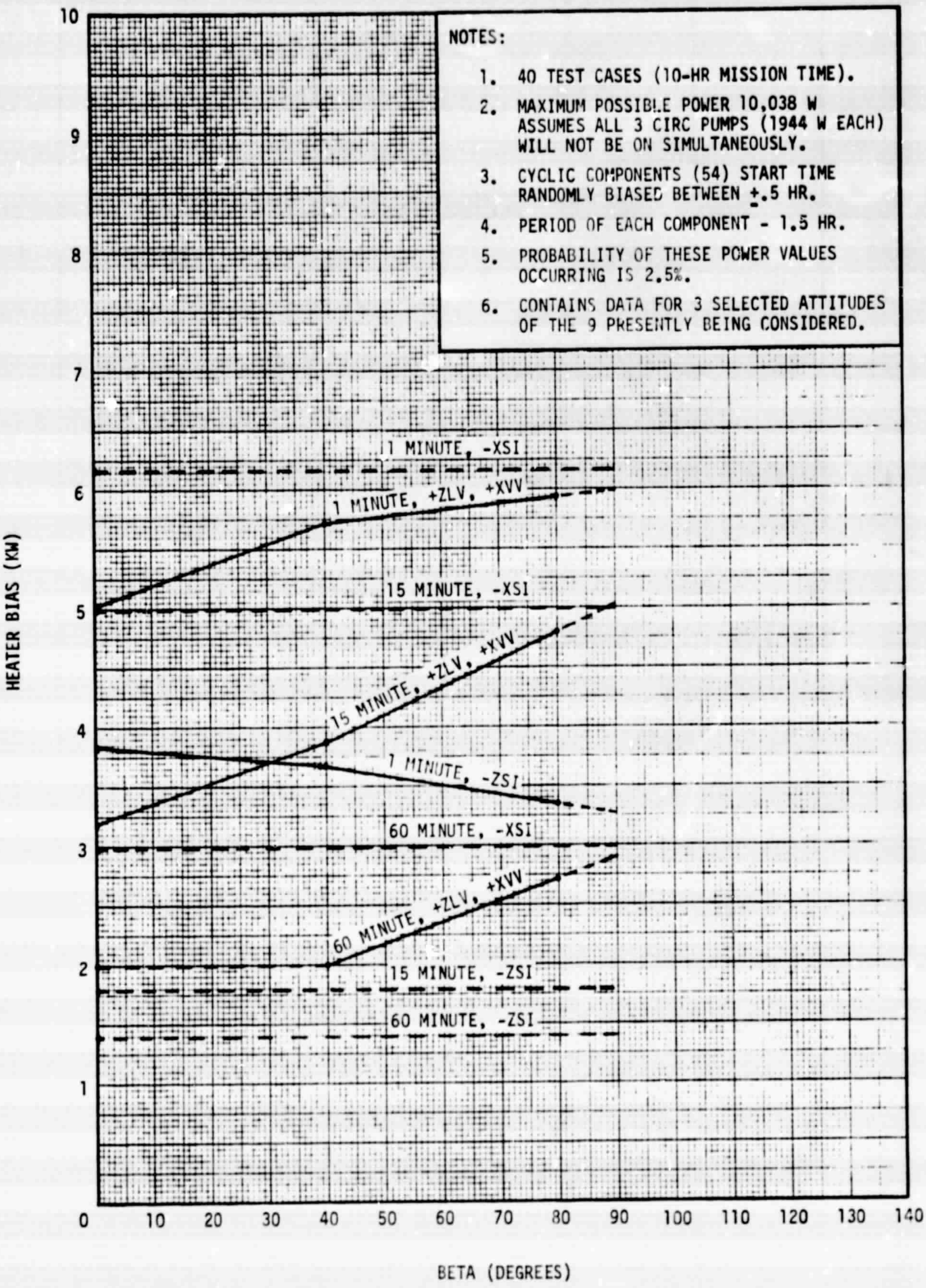


Figure 7. Heater Bias Versus Beta for Various Constraint Times

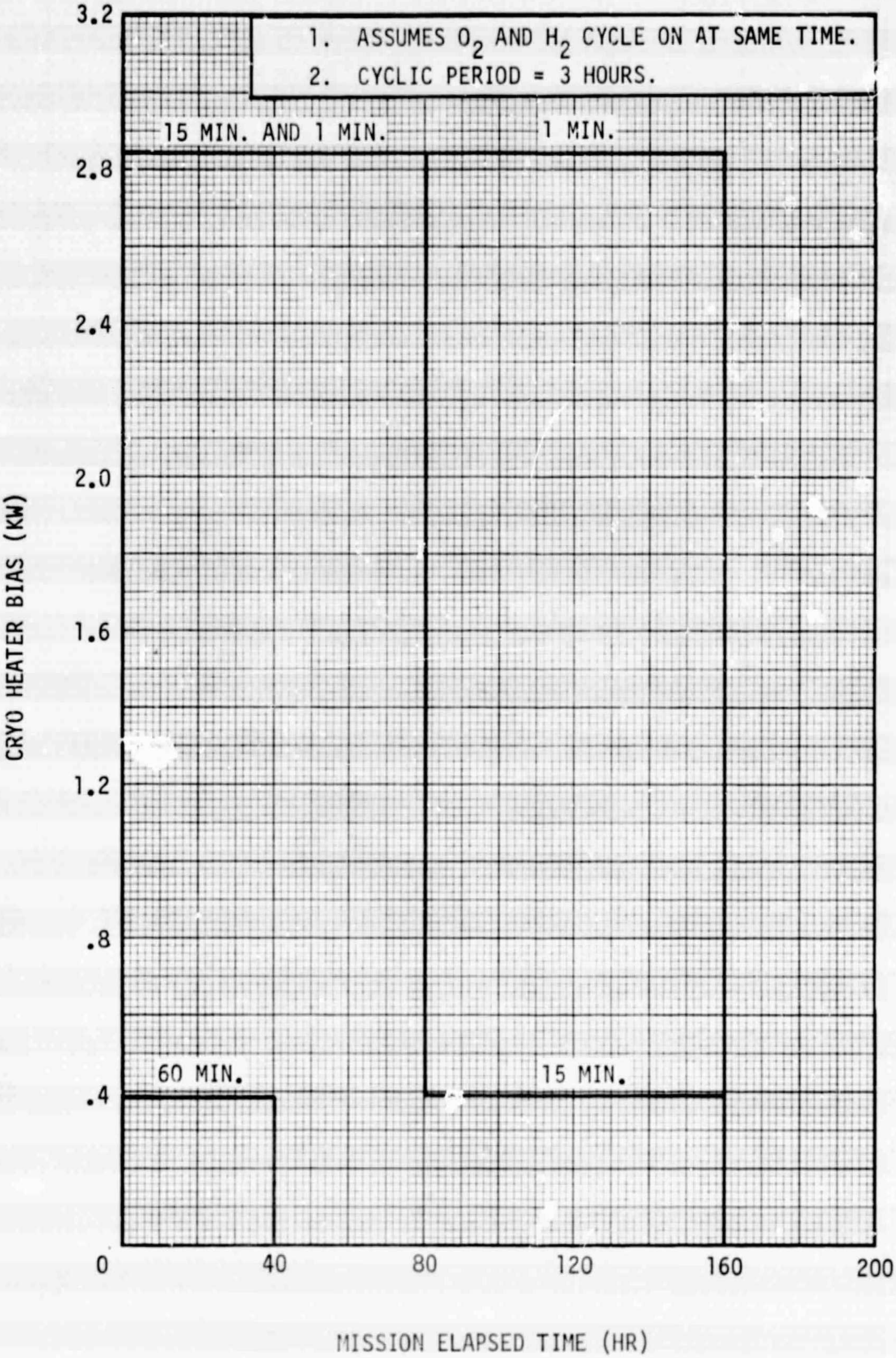


Figure 8. Cryo Heater Bias Versus Mission Time for Various Constraint Times

3. CONCLUSIONS

Present spacecraft design and planning procedures require a method to flag constraints imposed on the capacity of a subsystem when many scheduled ongoing activities operate concurrently with payload support, crew, and Orbiter activities as well as nonschedulable cyclic heaters and components. Individually, none of these activities will violate the capacity of the subsystem. This method must minimize the number of solutions, computer run times, amount of printout, and enable the planner to schedule activities, as in the case of the Electrical Power Subsystem, requiring large amounts of power for short periods of time with confidence that a constraint violation will not occur.

Analyses of the constraints imposed on consumables-related subsystems indicate this can be accomplished with simple limit checks on consumable rates and time durations. In the case of the EPS, statistical analyses of the cyclic power data resulting from nonschedulable cyclic components can be applied to the specified constraints which will allow utilization of the simple limit check on all subsystem constraints to be performed with confidence that a constraint violation will not occur. Therefore, the desired objectives of minimizing the number of solutions, computer run times, and amount of printout can also be realized.

4. RECOMMENDATIONS

On advanced spacecraft, the designers should address the problem of constraints violations that can be caused by unscheduled cyclic loads operating. On the Shuttle spacecraft these loads have been representing approximately 20 percent of the electrical load plus the capability of causing large transient power values in the range of 10-15 KW. This trend is expected to continue on future spacecraft.

Design alternatives that should be considered are narrowing the dead-band and incorporating logic in the heater circuits that will allow activities requiring large amounts of power for up to 15 minutes to inhibit non-critical heaters for this time period without causing detriment to the safety of the crew or spacecraft.

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*Not referred to in this volume.

APPENDIX A

SYMBOLS

A	Activity
ACP	Average Cryo Power
ACPA	Average Cryo Power Array
ACPV	Average Cyclic Power Value
AHP	Average Heater Power
AHPA	Average Heater Power Array
AHPB	Average Heater Power Baselined
ALLMSM	Mission Common
AMPS	Amperes
ANYEVA	Any Extra Vehicular Activity
ANYIVA	Any Intra Vehicular Activity
APU	Auxiliary Power Unit
AS	Alternate Sleep
ATCS	Active Thermal Control Subsystem
ATTCON	Attitude Control
AUTRCS	Automatic RCS Maneuver
B	Beta
β	Beta
BH	Beta High Index Value
BL	Beta Low Index Value
BLP	Baseline Power
CBA	Cryo Bias Array
CBBH	Constraint Bias Beta High Index Value
CBBL	Constraint Bias Beta Low Index Value
CBPH	Constraint Bias Power High Index Value
CBPL	Constraint Bias Power Low Index Value
CIRC	Circulation
CO_2	Carbon Dioxide
CPB	Cryo Power Bias
CPBV	Constraint Power Bias Value
CRYO	Cryogenics
CS	Concurrent Sleep

CSLEEP	Crew Sleep
CYCPRO	Cyclic Probability
DCP	Delta Cyclic Power
DELDAY	Delta Day
DFI	Development Flight Instrumentation
DNLK	Downlink
DOORSC	Payload Bay Doors Closed
DOORSO	Payload Bay Doors Opened
DOCKIN	Docking
EATMAN	Food Prep/Eat
ECLSS	Environmental Control and Life Support Subsystem
EPS	Electrical Power Subsystem
FC3RUN	Fuel Cell 3 On-Line
FCP	Fuel Cell Powerplant
FCPS	Fuel Cell Powerplant Subsystem
FCPURG	Fuel Cell Purge
FEAR	Fortran Environmental Analysis Routines
G -	None
H_2	Hydrogen
H	High Index Number
HPB	Heater Power Bias
HPBA	Heater Power Bias Array
HR	Hour
HTR	Heater
I	Indexing Variable
IMUALI	IMU Alignment
J	Indexing Variable
KBTU	Thousand British Thermal Units
KW	Thousand Watts
KWH	Thousand Watt Hours
L	Low Index Number

MAX	Maximum
MET	Mission Elapsed Time
MIN	Minutes
MPP	Mission Planning Processor
N	Number of Activities
O_2	Oxygen
OFT	Orbital Flight Test
ONORB1	Orbit Common 1 (Insertion-Deorbit)
ONORBA	Orbital Common A (On-Orbit Checkout-Deorbit Preparation)
OROMS	Orbital OMS Maneuver
PAYDEP	Payload Deploy
PH	Power High Index Value
PL	Power Low Index Value
PSLEEP	Pre/Post Sleep
PTC	Passive Thermal Control
Q -	None
RATE	Rate Versus Time for EPS Consumable
RENDEZ	Rendezvous
RLIM	Rate Limit Value
SCP	Specified Constraint Power
SEC	Second
SEPS	Shuttle Electrical Power Subsystem
SHEER	Shuttle Electrical and Environmental Requirements Program
SODB	Shuttle Operational Data Book
STAKEP	Station Keeping
STS	Space Transportation System
t	Time Duration
T	Time of Observation
TH	Time High Index Value
TL	Time Low Index Value
TP	Total Power
TV	Television

UNDOCK	Undocking
UPLK	Uplink
VDC	Volts Direct Current
W	Watts
WASTEM	Waste Management
-XSI	Minus X-Axis of Spacecraft, Solar Inertial
+XVV	Plus X-Axis of Spacecraft Along the Velocity Vector
-YVV	Minus Y-Axis of Spacecraft Along the Velocity Vector
+ZLV	Plus Z-Axis of Spacecraft, Local Vertical
-ZLV	Minus Z-Axis of Spacecraft, Local Vertical
+ZSI	Plus Z-Axis of Spacecraft, Solar Inertial
-ZSI	Minus Z-Axis of Spacecraft, Solar Inertial