NASA SP-6503

Introduction to the Derivation of Mission Requirements Profiles For System Elements

Written under contract by the
Planning Research Corporation for
the Reliability and Quality Assurance Office
NASA Headquarters

Scientific and Technical Information Division
OFFICE OF TECHNOLOGY UTILIZATION 1967
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D.C.

For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151 – Price $3.00

Foreword

The task of characterizing the problem to be solved (i.e., determining what must be accomplished, when, and under what set of difficulties) is basic to the proper planning of any function. In the case of the technical aspect of space system design, this characterization takes the form of a sequential description, or "profile," of mission requirements. Since the design of an overall system is a composite of the designs of its elements, requirements profiles are needed not only at the system level but also at lower assembly levels. The formulation of these profiles for lower level hardware elements involves a derivation process that uses the profile for the overall system as a starting point.

The existence of many examples of well-designed space system hardware is evidence that profile derivation, in some form, is being accomplished. However, the difficulties experienced in many programs in evolving an adequate design, particularly when the state of the art is not a problem, indicate that there is still room for improvement in:

(1) The ability to characterize the design challenge accurately
(2) The degree of technical discipline applied to the characterization task

NASA Reliability Publication NPC 250-1 entitled "Reliability Program Provisions for Space Systems Contractors" requires the contractor to develop before-the-fact design specifications for each item of hardware down to the component (black box) level. This requirement is a deliberate effort to foster a disciplined approach to timely identification of the requirements to be met by the design at all levels. The discipline involved here is the primary province of project management and the systems engineering function; however, it is one of the key cornerstones for the planning and achievement of reliability.

The systems approach has been recognized in concept and has been used for quite some time, although for the most part in rudimentary form. In recent years, however, this approach has evolved to a much higher degree of sophistication and is now being applied in a number of areas including overall mission planning, hardware design, and management of research and development (R & D) projects.

In the evolution of the systems approach, the tutorial literature has not kept pace in all areas with advances in the application of the concept. This is particularly true in the area of identifying detailed performance and environmental criteria at the component and subsystem levels, a task which is essential to development of thorough design specifications. The present publication on mission requirements profiles is intended to be of use in the identification of these detailed criteria. It presents (1) a basic methodology suitable for use in performing the derivation on a program-wide front and (2) a general guide to selection of analytical techniques useful in making such derivations in each of the functional subsystem areas covered.

This publication was developed under contract NASw-1032. Its authorship has been a combined effort led by Mr. H. S. Watson and participated in by Messrs. R. J. Mulvihill, M.D. Reed, and L. V. Klein, Miss W. C. Graham, and Mrs. H. M. Dye—all of Planning Research Corp.—and the effort has been guided and edited by Mr. D. S. Liberman of this office. In addition, many useful comments and suggestions from NASA field installations and program offices have contributed significantly in clarifying and improving the presentation of the material; this assistance is gratefully acknowledged.

As a technical aid, this publication is not intended to be mandatory. Rather it is hoped that the methods, procedures, and information presented will find use based on their merits. Although the experienced designer or project engineer may not find the logic presented herein to be new to him, it is felt that this publication can be helpful (1) in orienting new personnel to the use of a systems engineering approach to the design task and (2) as an information tool to assist NASA or other personnel in communicating with contractors about the design specification area.

John E. Condon, Director
Reliability and Quality Assurance
Office of Industry Affairs
NASA Headquarters

Contents

Summary

The present report describes a methodology for deriving the mission requirements profiles of the subsystem and lower level hardware elements from the system profile. This methodology consists of:

(1) Identification of the parameters that relate the functions and operations of the lower elements to each specific function and operation of the overall system
(2) Arrangement of the parameters in the order of their importance to that function and operation of the system (so that they can each be treated in accordance with the appropriate priority and allocation of resources)
(3) Resolution, through the selection and application of the most appropriate analytical or empirical techniques, of the influences of each parameter from the system level to the level of the element under consideration
(4) Compilation of the parameters and their influences derived in this manner into the mission requirements profile for the element in question

The appendices to this document are devoted to the presentation of supplementary data regarding parameters and analytical techniques necessary for the implementation of the methodology. These supplementary data, although incomplete in some respects, provide much basic information. The types of data necessary and the considerations involved are adequately indicated so the reader may add to the data provided from his own knowledge and from the literature.

CHAPTER 1

Introduction

DEFINITION

The term "mission requirements profile" identifies a time sequence description of the operational events required from prelaunch to mission completion in order to accomplish the objectives of a space mission. In practice, it may be quite difficult to present all the information implied by this definition in a single concise format. Instead, the most frequently used manner of presentation is a series of charts (frequently matrixes) which, as a composite, (a) show the mission characteristics and constraints and (b) identify and describe in mission sequence the pertinent environments and functions (and their parameter ranges) which describe the mission. The use of a requirements profile to characterize the design problem is not restricted to the system level. It is fully applicable also at the subsystem and component levels, and in principle it applies even to the level of individual parts.

RELATION TO SYSTEMS DEVELOPMENT AND PROJECT EXECUTION

In order to place the contents of this document in proper perspective, some discussion is helpful to show the relationship of this material to other descriptions of the systems engineering approach. In the application of this approach to the overall research and development (R & D) process for space and weapons systems, current literature (refs. 1 and 2) describes a series of cycles or phases which successively:

(1) Select a desired mission to satisfy certain policy objectives and identify a number of possible approaches for accomplishing the mission
(2) Determine the overall feasibility of conducting a project by use of any of the possible approaches
(3) Study and compare the feasible approaches to select one for further development
(4) Develop and define a basic system design and project plan to implement the approach selected
(5) Conduct detail design and hardware development, build and test the hardware, and finally conduct the mission

The method described in this document applies in general to phases 2 through 5 above but has its greatest utility in phases 3 and 4. This method follows the basic principles of identifying an objective, describing it in terms of functions and constraints, developing implementation approaches (concept of system elements) for the functions, and identifying and quantifying the environmental and performance parameters which are an important part of the criteria for design of these system elements.

PURPOSE AND APPROACH

This publication is concerned with the development of mission requirements profiles for subsystems and components from the profile of the overall system. In a sense this development is a derivation process; it takes into account the apportionment of system functions to subsystems and components, provides for the performance of auxiliary functions, and considers induced environments created by interactions between system elements and the physical positions of the elements within the overall assembly. The method described here for this derivation appears relatively straightforward. However, it must be borne in mind that in practice the derivation process must be repeated numerous times. First it is used to evaluate alternative design approaches and later, in an iterative fashion, it is used at successive times during the complete design cycle to redefine profiles for subsystems and components as trade-offs are made in parameter allocations and as new information is gained.

An example of a composite description of a system mission requirements profile for a very early stage of project evolution appears as tables 1, 2, and 3 in chapter 2.

The primary objective of this publication is to present a methodology for the derivation of the mission requirements profiles for subelements of the system and to provide guidance in the selection of analytical derivation techniques appropriate for the solution of specific problems under the constraints of budget, time, and required accuracy.[1] The methodology presented herein provides a logical procedure for asking questions that lead to the development of the required knowledge.

In view of the primary objective stated above, the scope of this effort was limited to consideration of unmanned space systems and to treatment of the portion of the mission following launch. For this reason much of the detailed information relating to specific subsystems could not be included. The methodology, however, is fully developed and sufficient subsystems are treated in varying levels of detail (according to the individual need relevant to the state of the art) to allow technical readers to make full use of this guideline.

Chapter 2 of this document discusses the content of a system mission requirements profile, chapter 3 describes the methodology for subelement profile derivation, and chapter 4 covers the way in which major parameters in the profile at the mission level relate to those at the system and subsystem levels. The appendices present some of the data necessary for the application of the methodology. Each appendix treats a different specific kind of subsystem.

---

[1] "Accuracy" as used here denotes that degree of faithfulness of representation of a parameter needed for the actual system being studied.

CHAPTER 2

System Mission Requirements Profile

The system mission requirements profile, from which the subelement profiles are to be derived, must define all the significant objectives and constraints that affect the mission. These are enumerated as follows:

(1) The mission objectives must state what, when, and where some function is to be accomplished.
(2) The mission constraints must describe and clearly define the conditions (including predetermined approaches) that affect the way in which the objectives are to be accomplished. These include such items as flight path to be followed, weight limitation, lifetimes, accuracy of position, choice of a particular launch vehicle, and spacecraft orientation.

The profile must also show in mission sequence the functions to be performed and the environments which will exist. Finally, all this information must be set forth in a documented, well-organized fashion to provide a useful working basis for all derivations. If the system mission requirements profile is not found in such a form, it will be necessary to construct one from the information that usually exists in a number of separate sources (e.g., basic customer project planning documents, specifications, contractual supplements, or study reports), since it is an essential prerequisite for the success of the remainder of the derivation effort.

It should be borne in mind that the length and degree of detail of a mission requirements profile increase markedly as the system evolution proceeds from the feasibility phase through concept selection and, finally, to design. An ideal profile illustration might be the requirements profile as it appears at the beginning of the design definition phase (phase 4 as given in the preceding chapter). However, such an illustration, which would be a small volume itself, cannot be practically included here (see, e.g., ref. 3). Instead, tables 1 to 3 illustrate a simplified form of the profile which might be used for one of the candidate approaches at the beginning of the single-approach selection phase (phase 3 as given in the preceding chapter) for a hypothetical solar-probe mission. Even for this purpose a true profile would be more detailed in stating the rationale underlying the prescribed constraints and functional requirements and in discussing various considerations affecting the design concept. Also, each of the major functions shown in table 3 would be broken down into as many subfunctions as practical. (However, for any functional requirements breakout made prior to configuration selection, care would be exercised to avoid the listing of subfunctions which place unnecessary constraints on configuration selection.)

Table 1.—Simplified Basic Mission Specification for a Hypothetical Solar Probe Mission

I. Mission Objectives:

The overall objective of the mission is to conduct a scientific exploration of the Sun and its atmosphere by means of a spacecraft on a trajectory approaching within 0.3 astronomical unit (AU) of the Sun. Specific objectives include measurements of solar wind, magnetic field, corona electron density, solar flares and cosmic rays. Priorities based on a concept of a minimum meaningful mission are expressed in terms of the following payload instrumentation:

Primary Instrumentation

- Magnetometer
- Plasma probe
- Charged particle telescope
- Neutron detector

Secondary Instrumentation

- VHF experiment (corona electron density)
- White-light corona meter
- Flare scanner

II. Predetermined Constraints:

A. Instrumentation Requirements:

1. The magnetometer will be of the triaxial-flux-gate type and must have a capability of measuring magnetic fields of 0 to 50 gamma with an accuracy of ±0.1 gamma. The sensors will be mounted on a boom of appropriate length.
2. The plasma probe will be similar to that used on Mariner II and be capable of measuring fluxes of particles in the 0.1- to 1.5-keV energy range in flux densities of 10^7 to 10^9 particles/cm^2 sec-steradian within 10-percent accuracy. The instrument must have a rotating mount to measure angular distribution of plasma.
3. The charged particle telescope (Explorer XII type) must measure fluxes of particles of 40 keV or greater energy in flux densities of 10^5 to 10^8 particles/cm^2 sec-steradian within 10-percent accuracy. It will also have a rotating mount to measure angular distribution of protons.
4. The VHF experiment will operate on the principle of Doppler shift caused by transmission through the Sun's corona. It must have a frequency stability of at least one part in 10^8.
5. The flare scanner will be mounted on a rotating platform (mechanical scanning) rotating at low velocity, and will be sensitive to X-rays of 1.0 to 0.1Å length.
6. The neutron detector will be of the "phoswich" type and will count neutrons in the 5- to 20-MeV energy range in densities ranging from less than 1 particle to 100 particles per second. It must be mounted on a boom and point continuously at the Sun.
7. The white-light corona meter must be capable of distinguishing brightnesses 10^{-13} times that of the solar disc and must be mounted on a rotating platform.

Table 1.—Simplified Basic Mission Specification for a Hypothetical Solar Probe Mission—Continued

B. Trajectory:

The spacecraft will be launched on a heliocentric orbit with a nominal perihelion of 0.3 AU.

C. Weight:

Launch capability and trajectory requirements limit spacecraft weight to 400 pounds.

D. Launch Vehicle:

Largest vehicle to be considered is the Atlas-Centaur-X259.

E. Launch Site:

Launch will take place from Cape Kennedy.

F. Launch Constraints:

1. Azimuth. Territorial overflight and tracking considerations require a launch azimuth between 75° and 110°. Exact azimuth will depend on time of launch and established orbit requirements.
2. Environments. The spacecraft and experimental payloads must be shock-temperature-radiation protected to withstand at least the launch and orbital environments shown in the phase/environment matrix.

G. Reliability:

Assuming proper orbit injection, the spacecraft, instrumentation, and primary experimental payload must perform satisfactorily for the first 6 months with a probability of 80 percent and for the following 6 months with a probability of 60 percent. The secondary experimental payload shall have as high a reliability as possible, but not at the expense of stated reliability levels for the primary payload.

H. Ground Equipment Location and Utilization:

The mission will use existing tracking and ground communications facilities. Initial deep space net (DSN) tracking will be accomplished from Johannesburg, South Africa. After the initial pass after launch, all DSN tracking and communications will be accomplished from Goldstone, California, using existing 85-foot antennas. Goldstone visibility of 8 hours per day, except when the spacecraft is obscured by the Sun, is sufficient.

I. Payload Utilization:

Communication equipment, spacecraft instrumentation, and experimental instrumentation will, for practical purposes, operate continuously throughout the mission, although capability for on-off command control from Earth will be required. In addition, attitude control, solar panel, and antenna pointing adjustments will occur periodically.

Table 1.—Simplified Basic Mission Specification for a
Hypothetical Solar Probe Mission—Concluded

J. Payload Positional Requirements:

The stabilization system must provide a pointing direction accurate within 0.1° of arc. This will suffice for telemetry and general payload. Special positional requirements for experiments are given in paragraph II-A previously in this table.

K. Security:

Since this is a basic research mission, security is not a significant problem.

L. Fidelity:

Fidelity requirements must be determined separately for each payload experiment.

M. Scanning Rates and Data Storage Capability:

Scanning rate will be determined by meaningful frequencies for obtaining data from each experiment. Data storage requirements will be dictated by (a) total bit requirements from this source and on-board functions monitoring, (b) Goldstone visibility periods, and (c) solar blackout of the spacecraft. A nominal storage capability of 100 days' accumulation of data will be provided.

N. Power Supply:

Payload experiments preclude use of nuclear power sources. Power capacities will be determined in tradeoff studies based on experiment requirements and considering other onboard functions and constraints.

Table 2.—Matrix of Environments and Mission Phases for a Hypothetical Solar Probe Mission

Item	Flight phase									
	Prelaunch		Initial ascent		Transsolar insertion	Solar orbit data acquisition				
	Event									
	Precount and countdown	Hold for launch window	Launch and stage I	Stage II	Stage III	Zone I collect data	Zone II collect data	Zone III (behind Sun) collect data	Zone IV collect data	Zone V collect data
Mission time event starts	...	...	0	5.9 min	9.2 min	2 hr	74 days	113 days	273 days	305 days
Duration of event	...	...	296 sec	200 sec	60 sec	74 days	39 days	160 days	32 days	74 days
Mean solar dist., AU	...	...	...	...	...	1.0 to 0.5	0.5 to 0.3 to 0.5	0.5 to 1.0 to 0.4	0.4 to 0.3 to 0.5	0.5 to 1.0
Mean Earth dist.	...	...	0 to 476,000 ft	584,000 to 550,000 ft	550,000 ft to insertion	10^{-4} to 0.5	0.5 to 1.5	1.5 to 2.0 to 1.4	1.4 to 0.6	0.6 to 0.2
Lateral shock (max) on payload, g in 10 ms	Free drop 1 in.	...	2.5	2.5	3.0	0	0	0	0	0
Ambient pressure, psia	14.7	14.7	14.7	0	0	0	0	0	0	0
Controlled temperature, °C	14° to 26°	14° to 26°	14° to 26°	14° to 26°	14° to 26°	14° to 26°	14° to 26°	14° to 26°	14° to 26°	14° to 26°
Acoustic, db	100	100	140	92	77	...	...	...	...	...
Vibration (payload) Sinusoidal, 20 to 2000 cps, g, rms	...	...	10	8	4	...	...	...	...	...
Vibration (payload) Random, 20 to 2000 cps, g^2/cps	...	...	0.15	0.15	0.10	...	...	...	...	...
Longitudinal load, g	0	0	6.9	2.3	23	...	...	...	...	...
Lateral load, g	0	0	0	0	8	0	0	0	0	0
Thermal radiation, BTU/hr-ft^2	...	...	...	540	540	0	0	0	0	0
Solar flare, protons	...	...	...	...	...	...	4930 max	...	4930 max	...
						Spectrum follows modified NASA A.R.C. model. Flux of protons exceeding 120 MeV energy is 10^9, and flux of those exceeding 0.75 MeV is 10^{13} particles/sq cm sec sr				
Solar wind, plasma flux, max	...	...	...	...	...	Flux of 1.2×10^8 particles/sq cm sec; velocity of 500 km/sec; energy of 0.5 to 1.0 keV				
Solar E-M radiation, X-ray through infrared	...	...	...	...	...	Maximum X-ray flux during flares follows modified Johnson spectrum. Max energy is 10^{11} keV/cm^2 sec keV for X-rays of energies up to 0.5 keV, and 10^2 keV/cm^2 sec keV for X-rays of *energies up to 200 keV*				
Pressure	...	...	...	...	...	Less than 10^{-10} mm of mercury				

Table 3.—Matrix of Functions and Mission Phases for Hypothetical Solar Probe Mission
[A, GSE; B, Atlas; C, Centaur; D, DSN; F, Solar Probe; G, Range Safety; H, X259]

Subsystem functions	Data for flight phase	Flight phase									
		Prelaunch		Initial ascent		Transsolar insertion	Solar orbit data acquisition[a]				
		Precount and countdown	Hold for launch window	Launch and stage I	Stage II	Stage III	Zone I collect data	Zone II collect data	Zone III collect data	Zone IV collect data	Zone V collect data
	Event										
	Mission time start	...	...	0	5.9 min	9.2 min	2 hr	74 days	113 days	273 days	305 days
	Duration of event	2 days	1 hr	296 sec	200 sec	60 sec	74 days	39 days	160 days	32 days	74 days
	Mean solar distance	...	...	...	...	...	1.0 to 0.5	0.5 to 0.3 to 0.5	0.5 to 1.0 to 0.4	0.4 to 0.3 to 0.5	0.5 to 1.0
	Mean Earth distance	...	...	0 to 476,000 ft	504,000 to 550,000 ft	550,000 ft to insertion	10^{-4} to 0.5	0.5 to 1.5	1.5 to 2.0 to 1.4	1.4 to 0.6	0.6 to 0.2
Navigation and guidance	Position references	A,C,D	A,C,D	A,C	A,C,D	A,D	D	D	D	D	D
	Time reference	A,C,D,F	C,D,F	A,D	A,D	D,F	D,F	D,F	D,F	D,F	D,F
	Sense attitude and give functional sequence commands	A,C,F	A,C,F	A,C,F	C,F	A,D,F	F	F	F	F	F
	Command control	A,D,F	A,D,F	A,C,F	A,C,F	D,F	D,F	D,F	D,F	D,F	D,F
Stabilization and control	Provide Earth and solar reference	A,C,D,F	A,C,D	C,D	C,D	F,D	D,F	D,F	D,F	D,F	D,F
	Determine and control attitude	A,B,C,F	A,B,C,F	B,C	C	...	F	F	F	F	F
Electrical power functions		A,B,C,F,H	A,B,C,F,G	B,C,F,H	C,F,H	F,H	F	F	F	F	F
Communications and telemetry	Tracking	A,B,C,D,F,G	A,B,C,D,F,G	A	A,D	D	D	D	D	D	D
	Data and command control links	A,B,C,D,F,G	A,B,C,D,F,G	A,B,C,F,G	A,C,F,G	C,D,F	D,F	D,F	D,F	D,F	D,F
Scientific experiments	Provide, operate, and sequence	A,D,F	A,D,F	F	F	F	F	F	F	F	F
	Emergency on-off control	A,D,F	A,D,F	A,F	A,F	D,F	D,F	D,F	D,F	D,F	D,F
Environmental control		A,B,C,F,H	A,B,C,F,H	B,C,F,H	C,F,H	F,H	F	F	F	F	F
Propulsion		A,B,C,H	A,B,C,H	B	C	H	...	...	...	...	...
Structure		A,B,C,F,H	A,B,C,F,H	B,C,F,H	C,F,H	F,H	F	F	F	F	F
Separation		A,B,C,F,H	A,B,C,F,H	B	C	F,H	...	...	...	...	...

[a] Critical functions on board monitored by DSIF throughout mission.

CHAPTER 3

Derivation Process for System Elements

REQUIREMENTS PROFILES FOR SUBSYSTEMS

In this document, the profile derivation methodology for system elements has been reduced to a 10-step process, as shown in figure 1. First the system mission objectives and constraints are translated into a set of descriptive parameters (step 1); these parameters are then described as a sequence of system-level functions and a sequence of environments under which they will occur (step 2). After a study of these functional and environmental sequences or "profiles," a conceptual system configuration study is made (step 3) to select the near-optimum subsystem types and interface arrangements.

Attention is then turned to the subsystems, and in step 4 the subsystem performance and environment parameters are related to those of the system. With the aid of a criticality matrix (step 5), parameter priorities are established so that time and funds can be more efficiently allocated.

The analysis technique that is most appropriate to the solution of the relationships between system and subsystem requirements is selected (step 6) and then applied (step 7) in order to resolve influence from system level to subsystem level. A grapic presentation (step 8) of the subsystem performance and environment profiles is then made.

The current state of the art is examined in step 9 to determine whether the approach results in an attainable system, and a projection of the state of the art is made. The last task (step 10) is to decide whether the derived subsystem profile represents a set of subsystem requirements which can be met with reasonable expectation. If the decision is affirmative the design specifications package can be prepared for the various subsystems by utilizing the results of step 8. If the decision is negative the configuration study of step 3 must be reevaluated, and the remaining steps must be repeated on the basis of a new configuration.

The derivation of profiles for components from those of their respective subsystems is performed in the same way as that described above for subsystem profiles (i.e., the subsystem now replaces the system and the component of interest replaces the subsystem). The following paragraphs discuss the steps in further detail.

STEP 1: IDENTIFICATION OF OVERALL MISSION AND SYSTEM REQUIREMENTS

The first concrete operation to be performed is the identification of the overall objectives and characteristics of the mission. Lists of typical mission characteristics (constraints and performance requirements) useful in describing the system level are herewith given.

Typical mission constraints are:

(1) Purpose
(2) Destination and path
(3) Location (launch site)
(4) Target launch date
(5) Reliability
(6) Configuration limitations

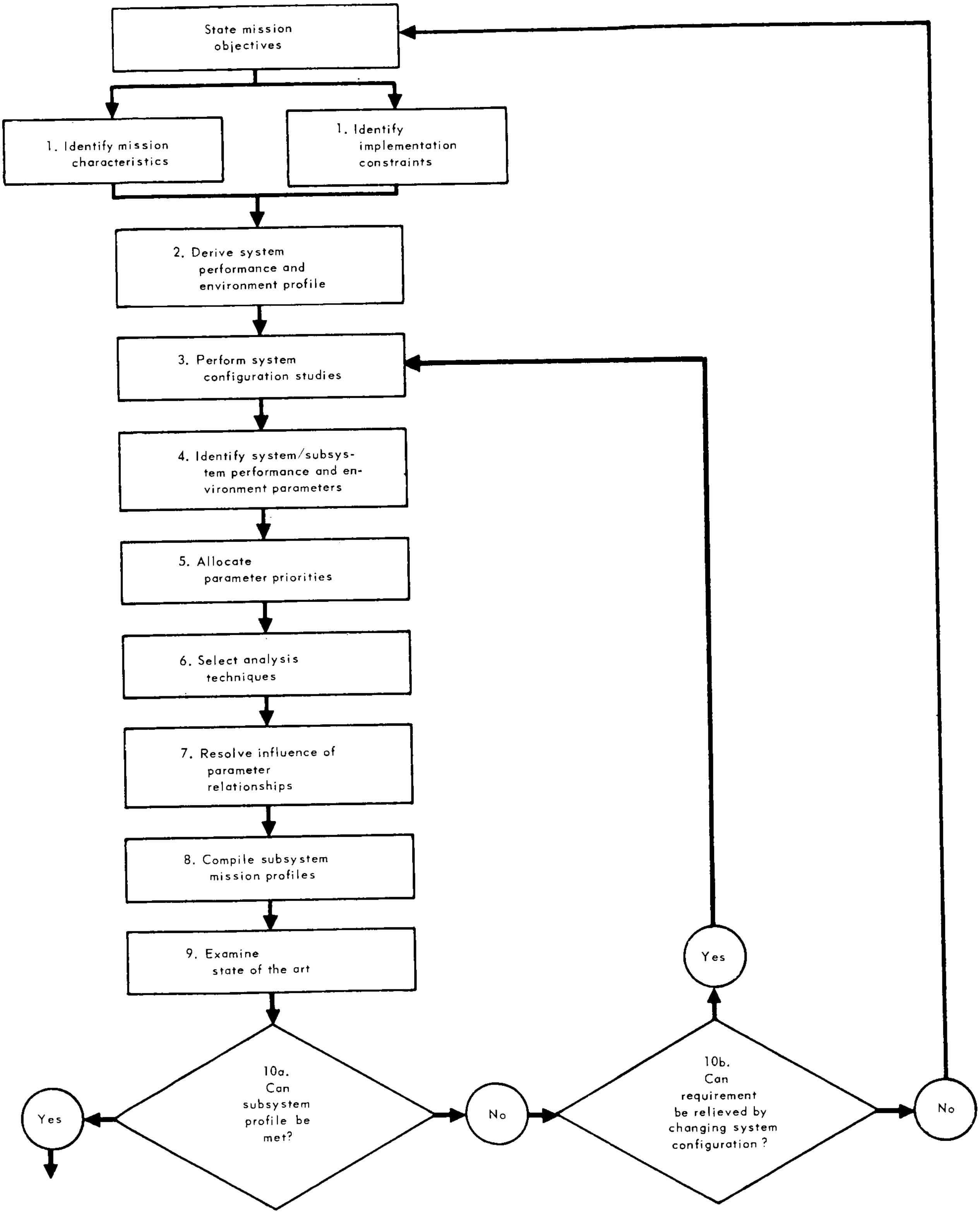


Figure 1.—Profile derivation flow diagram.

(7) Weight limitations
(8) Envelope limitations

Typical system performance parameters are:

(1) Trajectory
(2) Weight
(3) Envelope
(4) Payload utilization profile (what does what when)
(5) Support-equipment utilization profile (what does what when)
(6) Payload sensitivities (such as resolution required of sensors)
(7) Locations (ground-station locations, launch sites, etc.)
(8) Information rate
(9) Fidelity (accuracy of information transfer)
(10) Security
(11) Payload positional requirements (such as pointing accuracy)
(12) Payload dynamic limitations
(13) Reliability
(14) Storage requirements
(15) Configuration requirements

These lists are representative; not all these parameters will be applicable to any one system, and additional parameters may be necessary.

By defining the set and then quantitatively defining the time history of the values of the parameters, the system profile is described in a manner adapting it to analytical treatment (this is done in step 2). Sometimes the maximum or minimum values of the individual parameters are sufficient. The primary concern of the user is not to adhere strictly to a preconceived arbitrary list but to take sufficient time and apply sufficient study to the analysis of system mission requirements; this will ensure that the set of parameters selected describes the mission completely from the functional, environmental, and operational standpoints. "Parameter," as the reader will note, is used with a broader meaning in this publication than the usual one. Here "parameter" includes some nonquantitative items because many of these items act as parameters in the truest sense in the design process (e.g., type of power source and launch site).

STEP 2: DETERMINATION OF SYSTEM FUNCTIONAL AND ENVIRONMENTAL PROFILES

The second operation expresses the problem in terms of functional and environmental requirements. Functional requirements describe types and elements of work that must be accomplished by the operation of the equipment in order that the mission objectives will be realized. Environmental requirements are those conditions under which the equipment must be capable of operation in order to achieve the necessary performance.

This step involves two tasks:

(1) Construct the system function profile by showing on a time scale all the system-level functions that must be performed to accomplish the mission under conditions prescribed for the mission.
(2) Construct the system environment profile by showing on a time scale the significant properties of the surroundings (and their limits) which are likely to have an effect on the operation or survival of the equipment.

Some typical system functions are:

(1) Structural support
(2) Navigation and guidance
(3) Attitude control and stabilization
(4) Electric power
(5) Propulsion
(6) Communications and telemetry
(7) Command and sequencing
(8) Environmental control
(9) Scientific experiments (measurements and operations)

Some typical system environment parameters are:

(1) Pressure
(2) Temperature
(3) Thermal radiation
(4) Acceleration
(5) Ionizing radiation (gamma)
(6) Particulate radiation (protons, neutrons, nuclei)
(7) Gravity field
(8) Magnetic field
(9) Large particles (micrometeoroids)
(10) Humidity
(11) Atmosphere
(12) Vibration and acoustic noise
(13) Shock

It should be borne in mind that for any specific application these typical lists must be expanded as necessary to cover all significant parameters in order to specify completely the functions to be performed and the environment to be experienced by the system.

STEP 3: SYSTEM CONFIGURATION STUDIES

The determinations of the system functional profile and system environmental profile set the stage for a series of trade-off studies (including configuration studies) directed to arriving at a near-optimum selection of subsystem types and interface arrangements in order to meet overall system requirements. In the purest sense, this step is design rather than profile derivation. It must be performed as an integral part of the derivation process, however, because it is necessary before the profile derivation can be continued, and it can occur only after the completion of the first two steps.

The system configuration study consists basically of three tasks:

(1) Evaluate information from the system profile and the predetermined design constraints from the system profile
(2) Derive all feasible system-level subsystem characteristics, and determine possible technological methods and approaches to implementing subsystem functions
(3) Apply optimization techniques to select the most appropriate of these feasible items

In the second task above, several definitions are helpful. "System-level subsystem characteristics" designate those functions that exist within the bounds of a subsystem but either are system functions or are closely related to system functions. For instance, the power source (solar cells, fuel cells, isotopes, etc.) is a part of the power supply subsystem, but because of its effect on all other subsystems (weight, possible environment modification, power requirements, etc.) it must receive attention at the system level. Likewise, a transmission scheme is a part of the communications subsystem but must receive attention at the system level because of its relationship to information capacity and the spacecraft/ground station distance at any given time. "Technological methods" are possible physical approaches to performing some function. They might, for instance, specify that digital data from the spacecraft be pulse-code modulated for transmission or that three-axis stabilization be achieved with the use of infrared sensors.

Figure 2 is a flow diagram of a configuration study illustrating the interrelations of the three tasks, their major steps, and the typical decisions to be made regarding implementation of the system.

The system configuration study requires judgmentive scaling of previous craft, modification of previous equipment, etc. and is usually best performed by a team of preliminary designers and/or system engineers. Often it is actually accomplished in several steps with more than one team participating. This situation arises naturally during the R & D process, the iterative nature of which is discussed more fully in step 6.

STEP 4: IDENTIFICATION OF SYSTEM/SUBSYSTEM PERFORMANCE AND ENVIRONMENTAL PARAMETERS

It is now necessary to identify those specific parameters which relate the performance and environment criteria of each subsystem to the performance and environment requirements of the system (e.g., incident radiation environment, heat rejection from thermal-control subsystem, and heat flow between subsystems).

The necessity of identifying the major relating parameters at the system level before attempting to deduce the requirements at subsystem levels is axiomatic. Although the identity of the parameters of interest seems evident in many cases, the process of identification must be careful and complete; otherwise significant problems may appear during the development program that should have been eliminated in the system design phase. The following example illustrates this point.

> Example: Design a sounding vehicle for the purpose of near-source investigation of the variation of the spectral emittance of clouds with geographic location. Some of the requirements on various subsystems are fairly obvious, while others are not. For example, it is quite evident that the desired trajectory is one of the major parameters influencing the requirements on the propulsion subsystem. On the other hand, it is not nearly so apparent that the launch-site location is one of the system parameters placing major, and possibly governing, requirements upon the thermal-control subsystem. The reasons for such influence arise logically from the requirements of the mission. For near-source measurements of cloud properties, a sounding vehicle is a logical choice. Generally, the thermal-control problem is relatively mild for near-earth sounding vehicles because of the relatively short time durations of interest. In this particular case, however, the measurement of properties related to geographic location utilizing a sounding vehicle dictates that the launch sites encompass the extremes of earth thermal environments. Therefore, since the thermal-control subsystem must maintain the equipment within acceptable temperature limits for relatively long periods during prelaunch checkout and launch preparation, the launch-site locations may well be the governing factors in determining the requirements of the thermal-control subsystems.

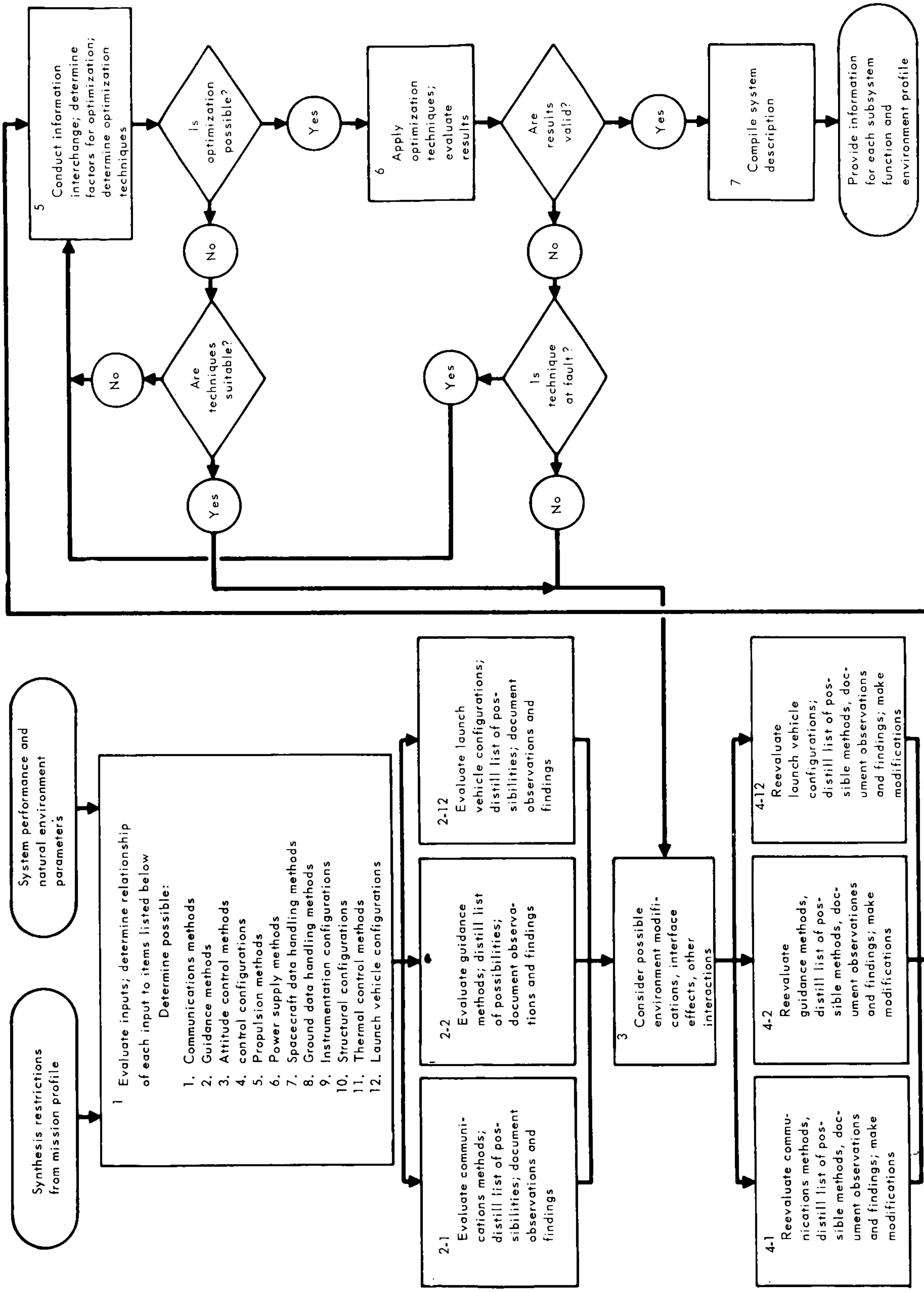


Figure 2. Flow diagram for optimization studies of system configuration.

Unfortunately, there exists no one simple method for relating the subsystem and system parameters that will insure that all the correct parameter identifications are made. However, a logical general approach to the problem is as follows:

(1) Each subsystem specialist compiles a list of the major performance and environmental parameters characteristic of his subsystem.
(2) Each of the parameters on these lists is then checked with each of the parameters on the system parameter list previously compiled.

This procedure will help to reveal any combinations that represent important relationships.

STEP 5: ALLOCATION OF PARAMETER PRIORITIES

Step 5 provides visible relative importance ratings for the problems to be resolved so that resources can be allocated in the most efficient manner. Although this may be considered a management concern, it is included as a step in the derivation of subsystem profiles because it is necessary for optimization, it is important for an organized and efficient approach to the derivation process, and it is essential for the creation of more reliable systems within the time and cost limitations.

The following method can be used to perform this step in a consistent and convenient manner. This method employs a criticality matrix, which is formed by listing all the subsystems involved in the system in rows (or columns) and defining the remaining dimension of the matrix, columns (or rows), by each of the performance and environment parameters from the system profiles. Each of the n-intersections of the matrix is then identified with an index number which indicates the criticality of each intersection relative to all the others. An example of such a criticality matrix is shown as table 4.

The criticality of a particular intersection is a function of two considerations:

(1) The importance to the success of the mission of attaining a high degree of accuracy in establishing the relationship between the subsystem and system parameters represented by that intersection. In each case, this must be determined by sound engineering judgment.
(2) The difficulty and complexity of deriving this relationship.[2]

The importance of the accuracy of the derived relationships and parameter values depends on the particular mission and system configuration involved. The accuracy required in the derivation of a particular subsystem parameter value relates directly to the accuracy required of the related system-level property in order to achieve the mission objectives. Other factors affecting the derivation accuracy required are the phase of project life and the step of the design process involved in the particular case. These are described on page 3 of this publication.

---

[2] The evaluation of the difficulty and relative costliness of the necessary analysis is covered in appendices A to E.

Table 4.—Example of Criticality Matrix[1]

Parameter / System	Payload positional requirements	Payload utilization profile	Envelope requirements	Reliability	Payload dynamic limitations		
Communications	7	10	2	5	1		
Power	1	7	3	6	1		
Structure	8	1	3	1	6		
Thermal	3	10	2	4	9		
Propulsion	7	1	3	2	5		
Guidance and control	6	2	3	4	5		

[1] Notes: (1) The index assigned to each intersection is based on the necessity (criticality) of establishing the relationship between the subsystem and the parameter and the difficulty expected in deriving the relationship. For example, the index assigned to the thermal/payload utilization profile intersection is considered critical for many satellites because accurate determinations are necessary, and complex thermal models and analyses are necessary to make the determinations. In the case of the thermal/envelope requirements intersection, however, less criticality is attached because the relationship is straightforward, and the determinations are simple, even though the requirement for compatibility is important.

(2) The index used in this matrix ranges from 1 (least critical) to 10 (most critical), but the index system may be of any form convenient and significant to the task manager.

STEP 6: SELECTION OF ANALYSIS TECHNIQUES

The objective of the selection of the analysis techniques is to select the least costly technique necessary to achieve the accuracy required for each development phase. In cases where the relationship between the system and subsystem requirements is simple and straightforward, it may be necessary to consider only one method of analysis, although usually it will be necessary to consider more than one. In any case, it is still necessary to decide whether to proceed with the immediate rough estimate or to spend additional time and effort to refine the estimate.

The decisions concerning the appropriate technique to use and the degree of refinement needed will be influenced by several factors.[3] The minimum factors for any case are:

(1) The need for accuracy in the solution of the relationship
(2) The time available for obtaining the answer
(3) The cost of analysis.

Although these factors were discussed in step 5, further comments concerning accuracy are appropriate here.

Two classes of problems are quite different in their accuracy requirements: First, those problems in which the objective is to determine whether a requirement at the subsystem level is significant (this class will normally not require an extremely high degree of accuracy) and second, those problems concerned with obtaining a numerical solution for further refinement of the design requirements (this class may require either high or low accuracy, the degree of accuracy depending on several factors as discussed below).

An example of the first class of problems might be the determination of whether a particular source of power can be used on a particular spacecraft. Moderate accuracy can be tolerated here because the object is to distinguish between relatively large increments of power requirement (whether on the order of 400 or 4000 watts will be required). In such cases efficiency dictates that the analytical technique chosen should not be more refined than is necessary.

For the second class of problems, the selection of an analytical technique that optimizes the trade-offs between required accuracy, analysis time, and analysis cost is far more complex. Here the accuracy required depends on the size and complexity of the system, the phase of development involved, the particular subsystem of concern, and the objectives of the mission. For example, the problem might be the selection of the technique of analysis to determine the allowable drift rate for the stabilization subsystem of an earth satellite whose mission is to produce moon photographs of a given resolution.

The effect of the development phase for which the profile derivation is being performed must be considered. The several phases that exist in the design and development process are given on page 3 of this publication. Attempts to provide high accuracy are usually neither necessary nor appropriate in the early phases. This situation exists because the whole development process is accomplished in a highly iterative manner, with each iteration bringing in more details as well as fixing more closely upon design, performance, and environmental characteristics. Table 5, which follows a hypothetical system as it progresses through the phases of design, development, and fabrication, shows some of these iterative steps.

---

[3] Appendices A through E, each describing a typical spacecraft subsystem, give further details for selecting analysis techniques for the parameters of each of these subsystems.

Table 5.—Iterative Steps in Design and Development of a Hypothetical Space System[a, b]
[Subscripts on step numbers indicate iterative repetition of a step; e.g.,
2_1 means first repetition of step 2]

1. Mission is conceived.

2. Mission objectives are defined.

3. Mission requirements profile is derived and; a profile results which obviously cannot be achieved with the launch vehicles available.

2_1. Mission objectives are redefined to relieve the launch vehicle requirements.

3_1. New mission requirements profile is derived.

4. Requirements profile, including the launch vehicle constraints, is defined.

5. The request for proposal (RFP) is prepared for a space vehicle to fulfill the mission profile utilizing the designated launch vehicle and the existing ground facilities except for peculiar ground support equipment (GSE) which must interface with the existing facilities. First-cut system specifications are included.

6. Proposals are prepared by five potential contractors, each including a second-cut determination of system requirements, a first-cut system configuration, and a first-cut derivation of subsystem performance and environmental requirements. Three of the proposals (those presenting the best thought out design approaches) note that significant state-of-the-art advances are required in the guidance and control subsystem.

3_2. Mission requirements profile derivation is reviewed by NASA and modified to relax the guidance and control requirements.

4_1. Requirements profile definition is modified.

5_1. RFP is modified so that the system specification reflects the changes. Proposal revisions to incorporate the changes are requested.

6_1. Proposal revisions are prepared by the potential contractors.

7. The proposals are evaluated by NASA, and two study contractors are chosen for predefinition studies.

8. During the predefinition phase each of the study contractors make a third-cut determination of system requirements, a second-cut determination of system configuration, and a subsystem configuration study.

9. Studies are evaluated, and system contractor (one or more) selected by NASA initiates the definition phase. Definition phase includes a fourth-cut derivation of system requirements, a third-cut system configuration, a third-cut subsystem requirements derivation, and a second-cut subsystem configuration. First-cut component requirements derivations may be included.

10. During the succeeding phase, the contractor performs component design studies, may revise the subsystem configurations and component requirement derivations, and completes the design and fabrication of the system equipment.

[a] This particular example does not use phase project planning.

[b] This hypothetical case by no means exhausts the iterative possibilities encompassed within the design & development process. It does point out the necessity of initiating a system concept with fairly loosely derived requirements and proceeding in iterative steps toward more and more accurately derived requirements as lower and lower levels of system elements and design details are treated. The application of the proper talents, ranging from system analysts to detail designers, thus occurs at the most suitable levels.

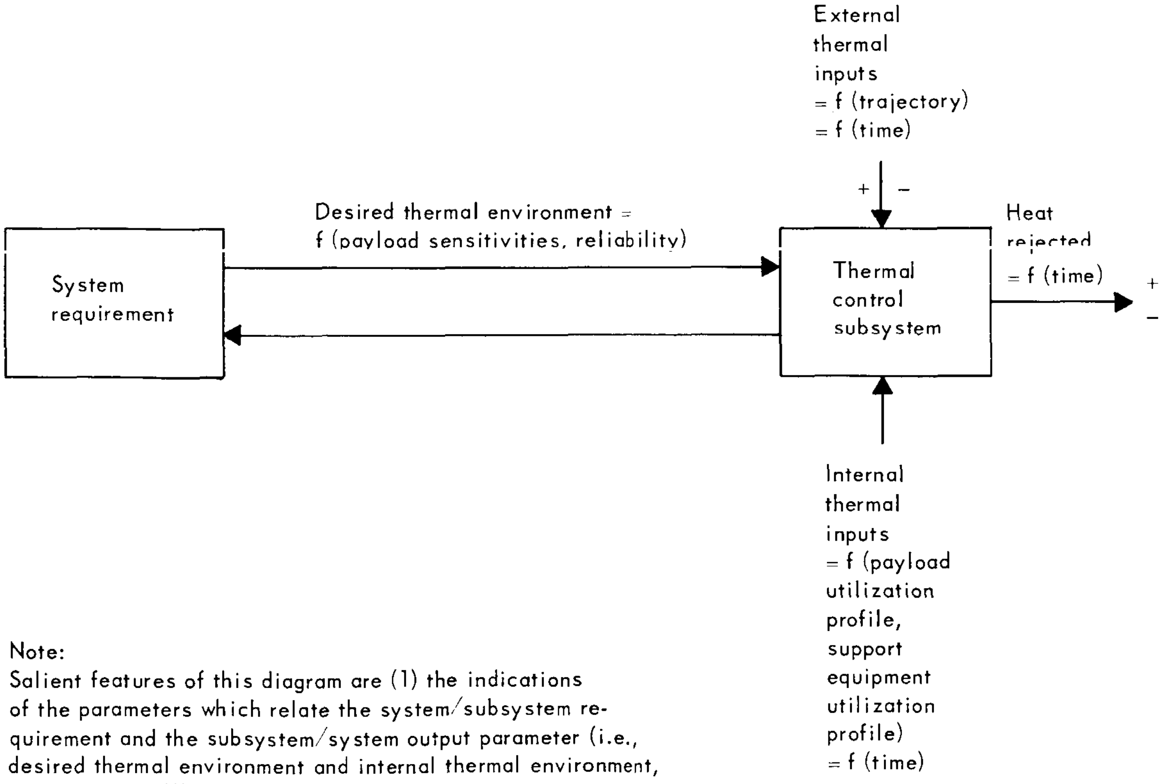
STEP 7: RESOLUTION OF INFLUENCE FROM SYSTEM LEVEL TO SUBSYSTEM LEVEL

This step involves three tasks:

(1) Ascertain that all the necessary inputs from system level considerations are available and correct.

(2) Model the relationship in block-diagram form for each subsystem. The model should include (a) all the significant system parameters affecting the relationships between the system and the subsystem, (b) output parameters affecting the performance of the system and of other subsystems (interface considerations), and (c) the significant subsystem input parameters, which may in some cases be identical to the system parameters involved and may depend heavily on the relationship of other subsystems to the subsystem of interest. Relationships should be defined in terms of system parameters wherever possible. Figure 3 is a diagram of this type for a thermal-control system.

(3) Apply the analytical technique selected in step 6 in order to resolve the influence of the system requirement parameter on the output parameters of the subsystem. The solution obtained defines the requirements placed upon the subsystem by virtue of the system requirements as a function of time (i.e., the mission profile).



Note:
Salient features of this diagram are (1) the indications of the parameters which relate the system/subsystem requirement and the subsystem/system output parameter (i.e., desired thermal environment and internal thermal environment, respectively, (2) the significant subsystem input parameters, and (3) the remaining subsystem output parameter.

Figure 3.—Block diagram of thermal control system/subsystem parameter relationship. "Function of" is denoted by f.

STEP 8: COMPILATION OF SUBSYSTEM PERFORMANCE AND ENVIRONMENTAL PROFILE

The performance and environmental requirements of the system which were resolved to the subsystem level in the preceding step are now to be compiled into a useful and easily understood presentation format. The clearest presentation format for the subsystem mission requirements profile is the graphic one, which should be utilized whenever possible.

For graphic presentation the choice of coordinates is simple, since the common denominator relating all the parameters of interest is mission time, and the value or levels of the parameters are the dependent variables. Such a profile shows the major performance conditions that must be achieved, the major environment conditions to which the subsystem will be subjected, and the points at which changes occur in the mission-time domain. Figure 4 is an example of a subsystem mission profile presentation for the thermal-control subsystem. The determination of the tolerance limits may be approached in a number of different ways, which range from engineering judgment estimates to Monte Carlo simulation error analysis. A brief general treatment of this area of analysis appears in the next chapter of this publication. For other subsystems, or even for other thermal-control subsystems, other environmental inputs, such as vibration and radiation, should be shown.

This method of compiling and presenting the subsystem mission profile creates a totally descriptive picture of the subsystem design requirements and is also a convenient form from which to prepare specifications. Often a specification can be significantly improved by including its mission profile directly in the specification as the performance requirement definition.

STEP 9: EXAMINATION OF STATE OF THE ART

The state-of-the-art capability for each subsystem of concern must be examined to form a basis for determining whether the approach taken thus far will result in an attainable hardware system or is beyond "real world" design capability. Effort is concentrated almost entirely on the characteristic performance and environmental parameters identified as being of major importance to this particular mission.

An examination of the present state-of-the-art capability for each subsystem may take many forms, such as consulting a knowledgeable subsystem specialist, reviewing current literature in the field, or appraising recent systems of a similar nature. Since the main purpose is assessment of the present state of the art for each subsystem in preparation for step 10, a significant expenditure of time or effort is generally unneccessary.

STEP 10: DETERMINATION OF ABILITY TO MEET SUBSYSTEM PROFILE

A determination must be made of the possibility of achieving the subsystem requirements dictated by the subsystem mission requirements profile within the present projected state of the art. This assessment, which depends heavily on engineering judgment, is of singular importance, since it may carry far-reaching implications.[4]

Two activities are involved in this step. First, a decision must be made on the extent of projection of the state of the art that can be reasonably expected for the subsystem design area in question. Unless the system is to be composed of available hardware (which is an unusual situation where space systems are concerned), some projection of the state of the art is necessary. It is generally the tendency to be overly optimistic in this projection, and a word of

---

[4] In the case of missions involving rare opportunities (because of celestial factors), misjudgement of the state of the art can result in abandonment of an opportunity after a large proportion of the costs have been expended.

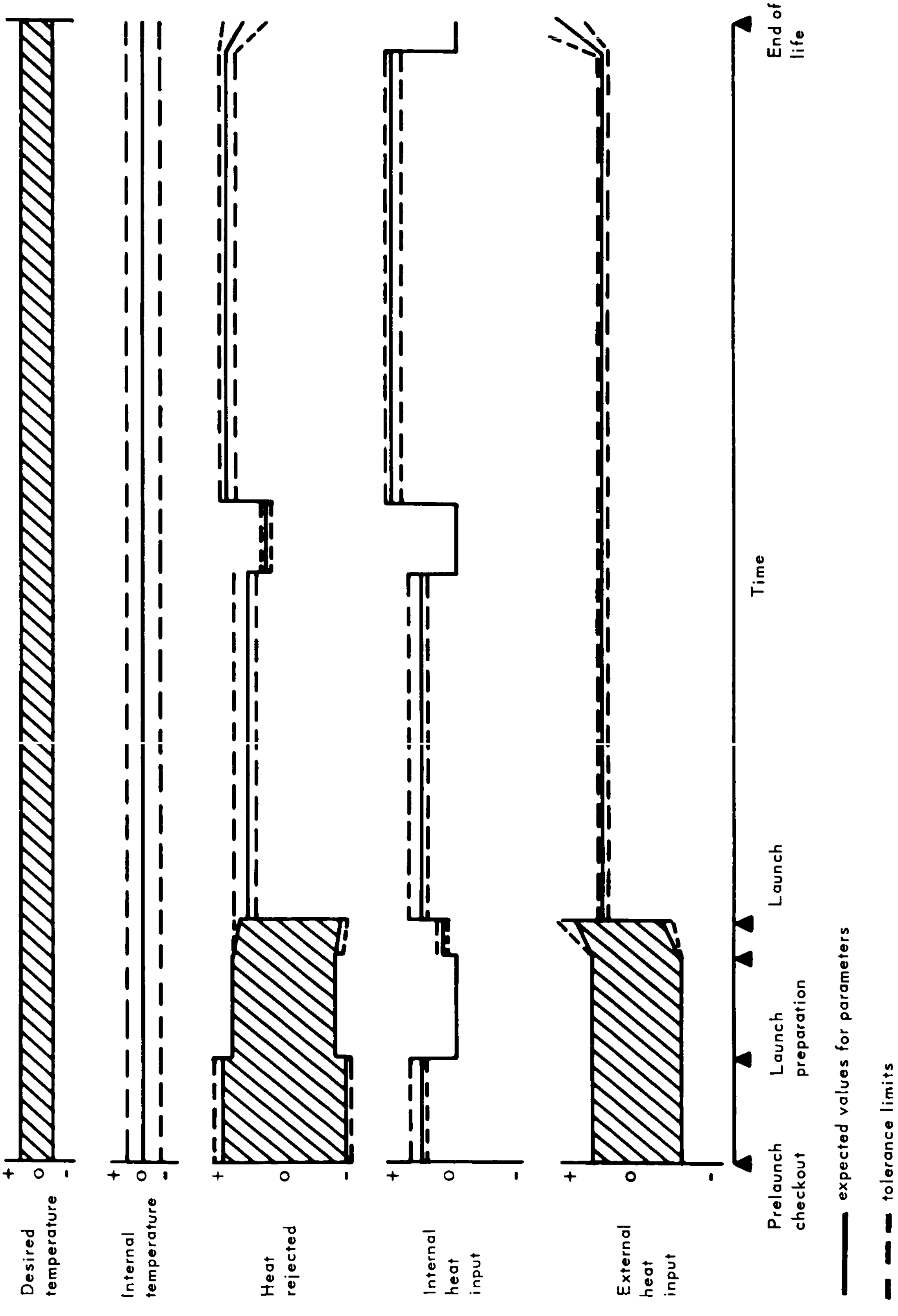


Figure 4. —Thermal-control subsystem mission profile.

caution is appropriate. Projections should be based on the trend over the past few years, except in fields where major breakthroughs have occurred. Although it is almost inevitable that additional breakthroughs will come in various fields at some time in the future, it will usually be disastrous to system planning to depend on their occurrence during any specific period.

The state-of-the-art projection should be bounded by tolerance limits. The upper tolerance, however, is of no interest. It is too risky to depend upon capability based on a projected state of the art above the nominal. The lower tolerance limit in the projection should be based on the increase that is expected to take place through normal evolution without any really significant technological advances.

Second, a decision should be made whether the subsystem profile represents a set of subsystem requirements that can be met with a reasonable expectation in light of the profile projection reached above. If it is decided that the requirements cannot be met, then the profile derivation process must revert back to the system configuration study (step 3) to determine if a more promising system configuration can be made for accomplishing the mission. If this decision is negative, the mission profile itself and the mission objectives must be reviewed and modified. If it is decided that the requirements can be met, the design specification packages for subsystems can now be prepared.

REQUIREMENTS PROFILES FOR COMPONENTS

Once the mission profiles for the subsystems have been derived, the mission profile for each component can be derived from that of its parent subsystem by using the same 10-step procedure as that described above.

CHAPTER 4

Profile Relationships

The present section discusses relationships that exist between mission and system parameters and the fundamental principles which underlie them. References are provided for additional details concerning most of the relationships. The references list is not exhaustive but contains representative samples to direct the reader conveniently to pertinent areas of literature.

MISSION/SYSTEM RELATIONSHIPS

The relationships between the mission and the system required to perform the mission are philosophically quite straightforward. They can be represented as cause and effect relationships, with the mission objectives representing the effects and the system parameter requirements representing the causes. The relationships between cause and effect, however, are not always amenable to straightforward mathematical description. For this reason, the derivation process at the mission/system level, and in some cases at lower levels, is sometimes better pursued through knowledgeable estimation and extrapolations from recent experience, rather than through pure mathematical analysis. It should be noted here, however, that approaching a difficult derivation analytically is far better than applying experience which is not truly appropriate. Table 6 shows the major parameter relationships between mission and system, that is, the cases where important cause and effect relationships definitely exist. In the development of the mission profile at every level, it is desirable to quantify as many of these relationships as possible as early in the derivation process as possible. Those which cannot be practicably quantified at any phase of the effort or hardware level must be handled qualitatively, of course, but effort should be exercised to keep this group to a minimum. However, regardless of state of quantification, it is essential to define all the parameter sets to the greatest extent possible at each level.

The following subsections present discussions and some references related to the determination of the relationships that influence the major system parameters.

PAYLOAD SENSITIVITIES

The payload of a space vehicle may be scientific experiments, communication relay equipment, or whatever relates directly to the primary purpose of the mission. The necessary payload sensitivities can be determined from the physical laws governing the phenomena to be investigated and the definition of the accuracy necessary to achieve the mission purpose. Also, there usually will be a relationship between sensitivity and the distance of the payload from the source of the phenomena. See references 4 and 5.

PAYLOAD UTILIZATION

The payload utilization profile is a function of the times during the mission the payload is brought into a position appropriate for the detection of the phenomena of interest. It may also relate to the proximity (or visibility) to ground stations (communications and command considerations).

Table 6.—Mission/System Parameter Interaction Matrix

Mission parameter System parameter	Purpose	Destination	Ground locations	Target date	Configuration	Weight	Envelope	Reliability
Payload sensitivities	X	X						
Payload utilization	X	X	X					
Support equipment utilization	X	X	X					
Information rate	X	X	X					
Fidelity	X							
Security	X	X	X					
Payload positional requirements	X							
Payload dynamic limitations	X							
Trajectory	X	X	X		X	X	X	
Weight					X	X		
Envelope					X		X	
Ground element location	X	X	X					
Storage requirements	X	X	X	X				
Reliability	X	X		X				X
Configuration constraints	X			X	X			
Natural environment		X	X					

SUPPORT EQUIPMENT UTILIZATION

Support equipment is that equipment which operates in support of the space vehicle payload, such as power supplies or thermal-control equipment in some cases. Support equipment utilization profiles are generally a function of the payload utilization profile and the trajectory. The relationships with the trajectory depend primarily on maneuver requirements and proximity to ground stations.

INFORMATION RATE

The basic information rate results from the range and the precision desired in the measurement of the phenomena of interest and from the amount of engineering necessary for operation and performance assessment. These considerations depend on the mission purpose. See references 6 and 7.

FIDELITY

The fidelity required is simply the accuracy and precision necessary to the accomplishment of the mission purpose. Fidelity requirements apply primarily to instrumentation and are expressed in terms of the resolution of optical, photographic, or television payload elements and in terms of the precision and accuracy of measuring payload elements. See references 4, 5, 8, and 9.

SECURITY

The need for security may or may not exist in the space missions of interest. In cases where it does exist, it usually relates to the communications channels and is influenced primarily by the trajectory (a function of destination) and the ground-station locations. Command addresses often play an important role in maintaining secure control of the space vehicles.

PAYLOAD POSITIONAL REQUIREMENTS

Primary requirements for payload positioning at this level relate to definition of the necessary pointing directions required for the various payload sensors. The pointing directions are determined by the purpose of the mission.

PAYLOAD DYNAMIC LIMITATIONS

Limitations on angular velocity or angular acceleration may be important for some payload sensors, particularly for photographic and optical type sensors in general. The relationships are straightforward and can be found in many physics and dynamics texts.

TRAJECTORY

The mission definition of the destination automatically gives rise to the selection of a trajectory. The trajectory usually will be selected to minimize either energy requirements or flight time to the destination; in some cases a compromise between the two may be desired. The science of orbit and trajectory computation has been refined to a sophisticated point and many sources of reference exist. Preliminary determinations involve reasonable hand calculation, while more exact determinations involve computer and computations. See current periodicals and references 10 to 12.

WEIGHT

The weight of the flight system is usually determined by mission requirements, launch vehicles available, destination, and possible landing requirements. The maximum allowable weight is often specified as a predetermined mission constraint.

ENVELOPE

As with weight, the envelope is usually determined by the launch vehicles available and aerodynamic considerations during launch. The maximum allowable envelope is often specified as a predetermined mission constraint.

GROUND ELEMENT LOCATIONS

In the purest sense, the purpose and destination of the mission should dictate the locations of launch facility, tracking stations, and communications stations. However, in practice the locations of these facilities are usually fixed. Therefore, the sequencing of critical events in the mission profile must be adjusted to make the most advantageous use of these fixed locations (by selecting those most favorably located to give the desired coverage) and the functional capabilities of the existing stations. See references 10 to 12.

STORAGE REQUIREMENTS

The necessity for significant periods of inactive storage on earth, in orbit, or on a celestial body other than earth may exist for certain missions. Such requirements are a direct function of the purpose of the mission and the range of time involved in the total mission.

RELIABILITY

Required reliability is usually specified for the system in the mission profile. This reliability is a function of the purpose of the mission (its importance), the destination (difficulty of attempting the mission several times rather than a very few times), and the target date for the mission (advance in state of the art).

CONFIGURATION CONSTRAINTS

The constraints placed on the configuration are influenced by the launch vehicles available (envelope), the purpose, and the target date for the mission. The purpose of the mission dictates the view areas for sensors and in some cases dictates that provision be made for specific sensors at significant distances from the flight system to reduce interference that unavoidably exists near the bulk of the flight system. The mission target date may be influential in restricting various types of power conversion, control actuation, etc., because of the state-of-the-art situation.

NATURAL ENVIRONMENT

The natural environment is related directly to the destination and trajectory of the system. The known existing natural environments are well documented, and the system's exposure to them over mission time and trajectory is examined so that cumulative exposures (sum or integral) and extremes can be recorded. For those missions involving unknown environments such as planetary atmospheres, due allowances must be made (and identified as estimates) in the environment profile. See references 4 and 11 to 13.

TOLERANCE AND ERROR ANALYSIS

The problem of determining allowable tolerances or errors from nominal performances is closely related to the derivation of performance requirements and may be of major concern in any profile derivation problem. The allowable tolerance for a performance-related parameter is the allowable change in performance divided by the extent of change in performance with change in parameter.

Three determinations are necessary in this problem:

(1) The allowable change in performance

(2) The extent of change in performance with changes in each performance-related parameter
(3) The cumulative effect and interrelationship of all the parameter changes taking place simultaneously

The first determination relates back to the mission profile. The allowable change in a system parameter (or parameters) is governed by the performance (achieved value) of that parameter necessary to accomplish the purpose of the mission. Often at this level the determination must depend on engineering judgment or past experience. In some cases, however, the physical laws involved will allow the determination; for example, if a mission is to photograph an area on the moon's surface from a distance of 1,000 nautical miles and the photographs are to show surface irregularities with maximum dimensions of no less than 50 feet, the physical laws of optics and geometry will allow the determination of the performance variation allowable in pointing direction of the optical components.

The second element of the problem is affected by whether the performance of concern is steady state or dynamic. For instance, in the above example the next level is the determination of the allowable tolerances on the accuracy and drift rate of the attitude control and stabilization subsystem. The determination of the applicable tolerances may require significantly different approaches for steady-state performance (i.e., constant perturbing forces) than for dynamic performance (i.e., time varying perturbations).

STEADY-STATE PERFORMANCE

In cases where algebraic equations relating performance to the parameters are available, steady-state performance variations can be determined by taking partial derivatives analytically or by taking finite differences. For steady-state analysis, linear approximations of the actual performance to parameter-relating functions (which may be nonlinear) are usually sufficient.

DYNAMIC PERFORMANCE

Dynamic performance variations introduce another factor. For dynamic inputs, most systems have errors that are functions of the values of the system parameters. A so-called "dynamic partial," Δ overshoot/Δ parameter (where Δ indicates change), of performance versus parameter change can be obtained by using nominal and off-nominal values for the system parameters to compare system dynamic responses. This determination is often made through simulation, by using either computations or empirical tests. For most systems which contain nonlinearities, the Δ overshoot/Δ parameter gradient will not be uniform over wide ranges of operating conditions. It is therefore necessary to determine the range of validity for the "dynamic partial" before applying it to wide deviations of operating conditions.

RANDOM PARAMETER ERRORS

The errors in parameter values of interest in many practical cases are independent of one another and their variations are random in nature. In this particular case, the combined effect of the errors on the overall system can be estimated by the square root of the sum of their squares; i.e.,

$$\text{Random system error} = \left[\sum_1^n (\text{Individual random parameter errors})^2\right]^{1/2}$$

In the situation where the effect on performance is linearly related to the parameter errors, the performance error can be determined in like manner. In cases where the relationship is not linear, more complex relations apply.

SYSTEMATIC AND RANDOM ERRORS

Systematic error, which may be involved in situations where nonlinearities exist, cannot be combined with random errors on the same basis as that on which only random errors are combined. In many cases, knowledge of the existence of systematic error allows it to be eliminated. Where this is not feasible, systematic and random errors can be satisfactorily combined to a first-order approximation by separating the two types, combining the random errors, and combining the systematic errors algebraically, i.e.,

$$(\text{Net systematic error}) = \sum \begin{pmatrix} \text{Individual systematic errors} \\ \text{including effects of signs of} \\ \text{errors} \end{pmatrix}$$

The total resultant system error then is

$$\left[(\text{Net systematic error})^2 + (\text{Net random error})^2\right]^{1/2}$$

SIMULATION

Monte Carlo simulation techniques are often used to evaluate complicated tolerance relationships. This method obtains approximate evaluations of mathematical expressions which consist of one or more probability distribution functions; it uses random sampling to play a game with a man-made simulation model, and the experiment is repeated to obtain average results. Very complex problems can be handled with the Monte Carlo simulation coupled with digital computers. See references 14 to 18.

SYSTEM/SUBSYSTEM RELATIONSHIPS

The foregoing portions of this publication have described the basic approach to the derivation of mission requirements profiles and the governing relationships between the mission and system levels. As the process proceeds to the subsystem and lower levels, the derivation of parameters becomes more exacting and requires more intensive knowledge of the many and varied specific subsystem and component technologies involved.

Since the primary objective of this publication is to describe and discuss the general method for profile derivations, it is not practical here to attempt to provide detailed treatment of all types of subsystems. However, to compliment the description of method and to illustrate the considerations involved in the relationships between the system and subsystem levels, six different kinds of subsystems are treated in some detail in appendices A through E. The selection of subsystem examples has been made primarily from the unmanned spacecraft area (spacecraft and ground equipment). However, an attempt has been made to orient the discussions within each appendix in as general a manner as possible so that they can also serve as selective illustrations for subsystem relationships on manned spacecraft or launch vehicles. Experimental payload must be identified and considered as one or more subsystems during the derivation process.

Of the examples provided in the appendices, not all are treated in the same depth. The more straightforward system areas for which the analytical study techniques are most widely recognized are treated in the least depth, while the more difficult subsystems are treated more intensively and appear first. Those treated in least depth appear toward the end of the appendices.

In each appendix, the information presented centers around the relationship between the system level and the particular subsystem being treated. The relationships of parameters between these levels are discussed, and, where applicable, the mathematical relationships are given. The techniques of analysis for solution of the relationships are described, their relative accuracies are noted, and the relative effort required for their application is discussed. Representative references and subsystem parameter lists are included.

References

1. Anon.: Systems Management. Air Force Systems Command Manual AFSCM 375-5, Systems Engineering Management Procedures, U.S. Air Force, March 10, 1966.

2. Thome, P. G.; and Willard, R. G.: The Systems Approach—A Unified Concept of Planning. Aerospace Management, Gen. Elec. Co., Vol. 1, No. 3, Fall/Winter, 1966, pp. 25-44.

3. Anon.: Elements of Design Review for Space Systems. NASA SP-6502, 1967.

4. LeGalley, D. P.; and Rosen, A.: Space Physics. John Wiley & Sons, Inc., 1964.

5. Berkner, L. V.; and Odishaw, H.: Science in Space. McGraw-Hill Book Co., Inc., 1961.

6. Gruen, H.; and Olevsky, B.: Increasing Information Transfer. Space/Aeron., Feb. 1965.

7. Raisbeck, G.: Information Theory. M.I.T. Press, 1964.

8. Select Committee on Astronautics and Space Exploration: Space Handbook: Astronautics and Its Applications. G.P.O. (Washington, D. C.), 1961.

9. Leary, F.: Television from Space. Space/Aeron. Mar. 1964.

10. Koelle, H. H.; et al.: Handbook of Astronautical Engineering. McGraw-Hill Book Co., Inc., 1961.

11. Anon.: Orbital Flight Handbook. NASA SP-33, 1963.

12. Anon.: Lunar Flight Handbook. NASA SP-34, 1963.

13. Johnson, Francis S., ed.: Satellite Environment Handbook. Second ed., Stanford Univ. Press (Stanford, Calif.), 1965.

14. Chestnut, H.: Systems Engineering Tools. John Wiley & Sons, Inc., 1965.

15. Moon, W. D.: Predicting System Checkout Error. Electro-Technology, Jan. 1964.

16. Shinners, S. M.: Control System Design. John Wiley & Sons, Inc., 1964.

17. Haddad, R. A.; and Truxal, J. G.: Sensitivity and Stability in Multiloop Systems. Fifth JACC (Stanford, Calif.), IEEE, June 1964.

18. Tacher, K. D.: The Art of Simulation. D. Van Nostrand Co., Inc., 1963.

PRECEDING PAGE BLANK NOT FILMED.

APPENDIX A

Power

SYSTEM RELATIONSHIPS

The power subsystem furnishes the electrical power required by all other subsystems and experiments. A checklist for the power subsystem appears as table A1. Relationships important for the power subsystem can be grouped into four categories: Source, load, time, and configuration.

SOURCE RELATIONSHIPS

Since electrical energy must be converted from some other type of energy, the source of this other energy and the conversion method must be considered. Certain sources dictate particular conversion methods, which may limit the power output available and/or the useful lifetime of the subsystem.

The two types of conversion methods are defined below.

Direct Methods of Conversion

Direct methods are those which convert source energy to electrical energy with no intermediate conversions. Examples include solar photovoltaic (e.g., solar cells), thermoelectric (e.g., thermocouples), and electrochemical (e.g., batteries) methods. Generally, these methods are power limited.

Indirect Methods of Conversion

Indirect methods are those which convert heat energy to mechanical energy and then to electrical energy. This conversion can be based on various thermodynamic cycles (e.g., Rankine, Stirling, Brayton). Generally, these methods are weight and/or cost limited.

LOAD RELATIONSHIPS

Load relationships are concerned with the overall requirements of the individual loads that must be satisfied. Of primary concern are the total power output capability required of the subsystem, the number and types of individual outputs required, and the relationships of the peak and average power demands. These overall requirements can greatly influence the subsystem configuration. As an example, the requirements may dictate the use of individual regulators or inverters in preference to central ones.

TIME RELATIONSHIPS

Time relationships fall into two categories that may be termed "preparation time" and "recovery time."

The preparation time includes such things as the initial warmup or startup period required for the heat source in an indirect conversion system or the time it takes an engine to come up to speed; it also includes dormant and standby periods. The recovery time refers to the period required by a device to return to its normal operating conditions during and after some interruption; it includes use periods. The charge time of a battery falls into both of these categories because it requires both an initial charge period (preparation time) and recharging after some given amount of use (recovery time).

CONFIGURATION RELATIONSHIPS

Configuration relationships involve the major configuration differences that exist, depending on whether a power subsystem is classed as a power supply or as a power plant. One way of distinguishing the difference is by size. A power supply can provide power in the watt range or, at most, up to a few kilowatts. A power plant, however, usually provides power in the kilowatt and megawatt ranges. Another way of distinguishing the difference is to note that subsystems that utilize indirect conversion methods are normally classified as power plants; indirect methods usually involve a sizable complex of hardware, which is justifiable for a spacecraft only if a large power output is required.

The size, weight, and complexity factors for power subsystems do not relate linearly with power output. For typical power supplies, these factors, per unit power output, rapidly tend to become unreasonable as the output approaches and exceeds the 1-kilowatt range. For power plants, on the other hand, the same factors, per unit power output, tend to be excessive in the low-kilowatt range, but become more reasonable (on a basis of per unit power output) at higher outputs. These relationships may create significant problems in terms of the influence of system configuration choice. The problems are likely to be especially acute in the "grey area" of power output requirement, where neither type of power subsystem represents a clearly superior approach.

SUBSYSTEM PARAMETERS

Table A2 is a list of subsystem parameters and related system parameters. Very few parameters are involved at this level because a power subsystem configuration depends more on the state of the art than on the solution of mathematical parametric relationships. There are few practical power conversion methods available at the present time (i.e., solar cells, batteries, fuel cells) and relatively few on the horizon (i.e., nuclear methods); thus, the parameters given in table A2 provide sufficient information for this limited choice. The subsystem design is not a simple task, but the major portion of the effort is in configuration and provision of specifications for design at the lower levels.

ANALYSIS TECHNIQUES

No single analysis technique (such as the root-locus method used in control subystems) is consistently applied to power subsystems. Rather, a wide variety of numerical and algebraic procedures is used under different circumstances.

Table A3 presents possible types of analyses and pertinent information applicable to both power supply and power-plant design. Past experience indicates that the analyses required for power-supply design are generally simple and can often be handled manually. (See refs. A1 to A21.)

Since power-plant design for space vehicles has not yet reached an advanced state of practice, extrapolation from other areas must be used. Fortunately, several of these other areas (e.g., shipboard power plants and power-plant systems for aircraft) are well enough established for these extrapolations to be realistic.

REFERENCES

A1. Anon.: Space Batteries. Technology Handbook. NASA SP-5004, 1964.

A2. Szego, George; and Cohn, Ernest: Fuel Cells for Aerospace Application. Astronaut. Aerospace Eng., May 1963.

A3. Spindler, William: An Analysis of Power Distribution Relative to the Design of High-Energy Density Batteries. NOL Corona, July 15, 1961. (Available from CFSTI as AD 260002.)

A4. Cambria, J. L.; and Schuk, N. F.: Design Parameters for Thermoelectric Generators.

A5. Ray, K. A.: Design Parameters for Photovoltaic Power Conversion in Space.

A6. Hrycak, P.; and Unger, B. A.: General Criteria for Solar Simulation and Model Testing Rept. R-58, Planning Res. Corp.

A7. Duane, J. T.: Dynamic Converters for Aerospace Use.

A8. Taylor, J. E.; Cummings, R. L.; and Landers, R. R.: Reliability of Space Power Plants.

A9. Sherfey, Joseph M.; and Johannsen, Klaus: Reliability and Redundancy Considerations in Selecting Spacecraft Batteries. NASA TN D-1452, 1962.

A10. Rajnikant; Thakkar, B.; Hughes, Roy C.: Maximizing Reliability with Respect to Weight. IEEE Trans. on Aerospace, vol. 2, no. 2, Apr. 1964. (Also Rept. R-46, Planning Res. Corp.)

A11. Anon.: Analog Study of Naval Shipboard Power System. Vol. 1: Short Time Transients. Vol. 2: Long Time Transients. Vol. 3: Additional Studies. Gen. Elect. Co., Dec. 1962. (Available from CFSTI as AD 61504, AD 61505 and AD 61506.)

A12. Ralston, A.; and Wilfe, H. S.: Mathematical Methods for Digital Computers. John Wiley & Sons, Inc., 1960.

A13. Mackey, D. B.: Space Radiator Analysis and Design.

A14. Aukerman, L. W.: Proton and Electron Damage to Solar Cells. Batelle Memorial Inst., Apr. 1, 1962. (Available from CFSTI as AD 274954.)

A15. Cochran, D. L.; and Friedman, S. T.: Preliminary Shield Design for Nuclear-Electric Space Power Plants.

A16. Schipper, Leon: Weight Optimization of a Solar or Nuclear Mechanical Conversion System. Aeron. Accessories Lab., WADC, June 1959. (Available from CFSTI as AD 231289.)

A17. Shair, R. C.: Primary and Secondary Electrochemical Cells for Space Vehicle Power Supplies. Gulton Ind., Oct. 1963.

A18. Koerner, Terry W.: Statis Power Conversion For Spacecraft. Astron. Aerospace Eng., May 1963.

A19. Osmim, Wm. G.: Space Nuclear Power: SNAP-50/SPUR. Space Aeron., Rept. R-108, Planning Res. Corp., Dec. 1964.

A20. Beale, Robert J.: Nuclear-Electric Spacecraft Concepts for Unmanned Planetary Exploration. IRE Trans. on Space Electronics and Telem. Rept. R-134, Planning Res. Corp., June 1962.

A21. Adler, Ernst: Power Supplies. Electromech. Des., Aug. 1965.

Table A1.—Power Checklist

1. Configuration
    - a. Source, solar (photovoltaic or thermionic), battery, fuel cells, nuclear fission, isotopes, engine/generator, furnished by power service (ground only), or some combination of sources
    - b. Central or individual regulators, converters, inverters, and number of each (if any) required
    - c. Source connection method and failure protection
    - d. Backup or alternate emergency source
    - e. Starting method
    - f. Power requirements of other subsystems
    - g. Attitude control requirements

2. Time considerations
    - a. Required mission life
    - b. Stand or storage time; may cause special charging of batteries to be required
    - c. Preparation time; includes prelaunch charging, warmup time, and time required to come up to speed (engine generator sources only)
    - d. Cycle life or duty cycle, on-time/off-time and its effects on charging requirements and power consumption
    - e. Lightness/darkness time required to determine solar cell configuration
    - f. Switching time required to bring in alternate source
    - g. Power use-time profile
    - h. Recovery time

3.1 Output parameters (ac or dc)
- a. Number of outputs required
- b. Regulation, static and dynamic

3.2 Output parameters (dc only)
- a. Polarity, positive or negative
- b. Nominal voltage level and tolerance
- c. Ripple, millivolts peak-to-peak of ac component impressed on dc level
- d. Transients or spikes, millivolts peak-to-peak impressed on dc level
- e. Power required of each output, watts, watt hours, amperes, ampere hours

3.3 Output parameters (ac only)
- a. Voltage outputs, average, peak-to-peak, rms
- b. Frequency, cps
- c. Phases, 1φ, 3φ, special
- d. Power factor
- e. Power, watts, watt hours, amperes, ampere hours, volt-amperes, average and peak
- f. Wave shape, sinusoidal, square, saw tooth
- g. Distortion
- h. Harmonics
- i. Spikes and transients

Table A1.—Power Checklist—Continued

4. Input parameters
    - a. Light incidence on solar cells
    - b. Power, watts, Btu, hp
    - c. Type of fuel(s)
    - d. Environmental radiation, type and amount

5. Subsystem internal parameters and considerations
    - a. Allowable battery discharge depth
    - b. Discharge rate
    - c. Discharge capacity
    - d. Excessive discharge protection
    - e. Battery charging capacity
    - f. Battery charging rate
    - g. Excessive charge protection
    - h. Charge-discharge efficiency
    - i. Marginal testing capability
    - j. Battery dark time load, watts, watt hours, amperes, ampere-hours
    - k. Insulation resistance, ohms, between output terminals
    - l. Individual battery capacity and output, volts, amperes, ampere-hours, watts, watt-hours
    - m. Solar cell output, volts/cm^2 and capacity
    - n. Efficiency of converters (percent)
    - o. Efficiency of inverters (percent)
    - p. Efficiency of regulators (percent)
    - q. Overall power supply efficiency (percent)
    - r. Remote sensing
    - s. Short circuit protection
    - t. Surge protection
    - u. Stability
    - v. Overshoot
    - w. Transient response of regulators, inverters, converters, charging circuits
    - x. Temperature coefficient
    - y. Thermal control requirements

6. Typical equipment found in subsystem
    - a. Solar cells
    - b. Batteries
    - c. Nuclear power generators
    - d. Fuel cells
    - e. Reflecting mirrors
    - f. Converters
    - g. Inverters
    - h. Regulators
    - i. Switchgear and circuit protections
    - j. Cables and connectors

Table A1.—Power Checklist—Concluded

7. Subsystem parameters and performance factors that can affect devices external to subsystem
    a. Effects of age; pressure, gravity, and temperature on battery or fuel cells (leakage, outgassing, generation of byproducts); control, containment, or minimization of these effects; mass change of cells due to leakage, evaporation, outgassing
    b. Turn-on/turn-off transients
    c. Fuel storage method

8. Effects of other subsystems on power subsystem
    a. Checkout and instrumentation requirements
    b. Umbilicals and external power systems
    c. Balance of external loads

Table A2.—Power Subsystem/System Relationships

Subsystem parameter	Related system parameter	Relationship
	Output	
Power	Payload utilization profile Support equipment utilization profile	Evaluation of these profiles allows the determination of the power consumption at various phases of the mission. Peak and average requirements can be predicted and the range of voltages that will be required can be estimated.
Accuracy	Payload sensitivities	This is a qualitative rather than quantitative evaluation in that the required accuracy range is determined in test.
	Input	
Source energy available	Trajectory	The required subsystem lifetime and available external energy sources (e.g., solar energy) can be evaluated.
Weight	Weight	This evaluation should determine what restrictions are imposed.
Envelope	Envelope	Same as above.

Table A3.—Power Subsystem Analyses

Type (1)	Factors determined	Information derived	Complexity	Reference
Load	Size, location and time/use profile of loads	Total capacity requirements of subsystem	Simple manual process for small subsystems. May require digital computer for large subsystems with complex duty cycles.	
Source (usually associated with direct energy conversion)	Amount of energy available for conversion (e.g., solar energy profile)	Configuration and sizes required of conversion equipment to supply load (e.g., solar cell array and battery arrangement)	Possibly the most complex analysis required for a small subsystem. Requires digital computer in many cases.	A1 to A6
Thermodynamic (associated with indirect energy conversion)	Thermodynamic cycle (e.g., Carnot, Brayton, etc.), maximum thermal efficiency	Operating characteristics, such as power output vs. fuel consumption, required fuel capacity	Can be done manually but digital computer required if optimization techniques applied.	A7
Reliability	Effects of failures, probability of success	Where redundancy or more reliable design should be incoporated	Usually done manually, although digital computer techniques have been applied in some cases.	A8 to A10
Network	Effects of switching transients and overloads	Proper locations and sizes of protective devices, distribution configuration for balanced system	Usually only given consideration for large subsystems. Best results obtained from network simulation on analog computer or special purpose network analyzer. Digital computers have been used but are not as adaptable to problem.	A11, A12
Thermal	Heat produced or required, cooling requirements	Radiator or heat exchanger characteristics, insulation requirements, heat sink or source capacity	Simple manual process for small subsystems since a large portion of the analysis is done for the space craft thermal control subsystem. For large power plants requires sophisticated digital computer techniques or analog simulation.	A13
Radiation	Effects of external radiation and/or amount and type of radiation generated within subsystem	Shielding requirements, safety precautions	Can become very complex even for small systems. For nuclear power plants requires very sophisticated digital computer techniques.	A14
Weight	Weight characteristics (i.e., mass of subassemblies and specific weights	Trade-off possibilities between weight and power, reliability or lifetime Weight reduction possibilities by using other materials or components	Because of inherent weight problems with power equipment for the foreseeable future, this is a very critical area. Analysis can become very complex even for small subsystems because of the trade-offs involved with other subsystems. For large systems, optimization techniques utilizing digital computers are required.	A10, A15

[1] These types of analysis are applicable at various levels of design. A load analysis, perhaps of a very coarse nature, is required in going from the system to the subsystem level. Within the subsystem level a more refined load analysis is required. Again, in going from the subsystem level to the component level, a load analysis is required, with its complexity depending on configuration and size.

APPENDIX B

Communications and Data Handling

SYSTEM RELATIONSHIPS

The communications subsystem transmits and receives information (e.g., by voice, video, or digital code) between remote points. The information content (data, commands, etc.) is related to the state of knowledge (ability to interpret signals) of the receiver.

Communication proceeds by the modulation of an energy flux. Because of interference from the Earth's atmosphere, only certain wavelengths propagate freely in space. These are primarily the ones from about 3 meters to 3 centimeters, certain infrared bands, and the visible optical region.

A one-way link in a communication system consists of a transmitter, a propagating medium, and a receiver. The communications subsystem may be a network of such links or of two-way links, in which information flows in opposite directions through a pair of one-way links. The subsystem may also contain repeaters which retransmit received data. Delays may occur when data are recorded and stored for a time before transmission, when data are generated faster than they can be transmitted, or when data are codified for transmission.

The two unavoidable limitations in deep-space communications are (1) the total energy required by the transmitter and (2) the delay that occurs when signal waves travel great distances in space. This delay may amount to several minutes and thus restrict conversation and remote-control operation.

Table B1 lists communications and data-handling parameters that relate to the system parameters.

PARAMETER RELATIONSHIPS

The following paragraphs present a broad discussion of the interrelationships between the input/output parameters (see table B1) and the internal parameters of the subsystem (see table B2).

Capacity is the maximum rate at which information (in either analog or codified form) may be transmitted through a communication link. In the analog case, capacity is specified in terms of bandwidth, as in a speech link; in digital links, capacity is specified in terms of symbols per second or bits per second. Capacity is not always the same as the data rate, however, because redundant symbols with no message value may be present. Similarly, an analog link, such as wideband frequency modulation, may utilize much greater bandwidth in transmission than in the output message.

Fidelity is the accuracy of the received message as compared with the source message. The fidelity of the received message is often improved by redundancy. In a digital link, the error rate (the proportion of incorrect symbols in a message) is a good measure of fidelity. The fundamental limitation on fidelity is universal noise, which is significant at points where message energy level is low. The critical parameter is the signal-to-noise ratio, the ratio of message (signal) energy to noise energy. For analog links, the output signal-to-noise ratio is a good measure of fidelity.

Distortion may cause a link to depart from a true analog, even when noise is small. Distortion arises from natural effects in propagating media and from equipment. Digital systems suffer from distortion because of propagation effects that cause errors when separate symbols overlap in reception.

Another limitation on fidelity is interference, which is signal energy from other artificial sources. Crosstalk interference occurs when a link having a number of simultaneous operations interferes with itself.

Signal energy is smallest at the input to the receiver, and it is at this point that the signal-to-noise ratio is determined. The total noise flux is the flux due to all sources, for example:

(1) Atmospheric noise
(2) Galactic noise
(3) Solar noise
(4) Plasma noise
(5) Man-made noise
(6) Receiver noise

Signal energy is maximized by employing a large receiving aperture (area) oriented perpendicularly to the direction of the signal flux, so that the receiver collects energy from the direction of the transmitter.

Directivity is a function of aperture and wavelength. The contribution of noise flux from other directions is reduced. The total noise flux varies with the parameters of bandwidth, location, wavelength, directivity, and angle. With a given fidelity, the required minimum signal flux follows from the required minimum signal-to-noise ratio.

The transmitter directs radiation toward the receiver by the use of directivity. The required effective radiated power is related to the transmitting directivity and the minimum signal flux by the path loss. The path loss depends on transmitting directivity and angle, receiving directivity and angle, wavelength, range, and location, as well as on environmental factors such as:

(1) Atmospheric losses
(2) Plasma losses
(3) Scattering losses
(4) Rotation of polarization
(5) Multipath interference

The required transmitter power and efficiency may lead to requirements for cooling capacity that have a significant effect on the vehicle's weight and envelope. Efficiency will be found to depend on wavelength relative to the state of the art in transmitters. Large apertures will also have a significant effect on weight and envelope.

Because the range and angle of a space link vary, it is necessary to track one or both endpoints. The range rate determines the apparent wavelength due to Doppler effect. Before communication begins, highly directive apertures must be brought into alinement, and receivers must be tuned to the appropriate wavelengths.

The total message delay depends on coding delay, storage delay, propagation delay, and acquisition delay. By the use of sufficiently elaborate error-correction coding, it is theoretically possible to communicate with good fidelity in the presence of noise. Delays caused by coding are called "coding delay." Ordinary data systems must usually store data before transmission, and thus storage delay arises. Signals spanning great distances in space will incur appreciable propagation delay. Finally, before a link can be used it must be free from maintenance shutdowns, the apertures must be brought into alinement, exact angles and range rates must be established, and adjustment must be made for variable factors such as Doppler wavelength shift; this delay is acquisition delay.

Coverage refers to the fraction of time the endpoints of a communication link are in contact. The coverage depends on location, maximum range, angular limits, angle rate, and range-rate limits, if applicable.

Security is the relative freedom from loss due to active or passive intervention by undesired parties in a communication link. Security depends primarily on coverage and also on directivity and minimum signal flux. Link capacity, fidelity, delay, and coverage depend on security.

Duty cycle is the relative proportion of time that a link is in operation. Generally speaking, performance in terms of other parameters increases as duty cycle increases. In some cases, however, security and reliability decrease with duty cycle.

ANALYSIS TECHNIQUES

Table B3 presents the various types of analysis procedures used in deriving the communications and data-handling subsystem requirements at the subsystem and lower levels. Tables B4, B5, and B6 present the relationship categories applicable to the various parameters. Table B7 is a communications and data-handling checklist. References B1 to B92 contain background material on this subject.

REFERENCES

GENERAL SYSTEM ANALYSIS AND SYSTEM ENGINEERING

B1. Hall, Arthur D.: A Methodology for Systems Engineering. D. Van Nostrand Co., Inc., 1962.

B2. Morse, P. M.; and Kimball, G. E.: Methods of Operations Research. John Wiley & Sons, Inc., 1951.

B3. Churchman, C. W.; Ackoff, R. L.; and Arnoff, E. L.: Introduction to Operations Research. John Wiley & Sons, Inc., 1957.

B4. Flagel, C. D.; Huggins, W. H.; and Roy, R. H., eds.: Operations Research and Systems Engineering. Johns Hopkins Univ. Press (Baltimore, Md.), 1960.

B5. Freeman, R. J.: A Generalized PERT. Operations Res., vol. 8, 1960, p. 281.

B6. Fu, Y.: Applications of Linear Graph Theory to Probabilistic Communications Networks. Univ. of Ill. Circuit Theory Group, Office Sci. Res. (Available from CFSTI as AD 271973.)

B7. Kiene, R. C.: Mathematical Formalisms of Command, Control, and Communication Systems. Military Products Group, Minneapolis-Honeywell Regulator Co. (Available from CFSTI as AD 278211 and RADC as TDR 62-328.)

B8. Merrill, G., ed.: Principles of Guided Missile Design, Operations Research, Armament, Launching. D. Van Nostrand Co., Inc., 1956.

B9. Anon.: Investigation of Model Techniques. USAEPG-SIG 940-43R1, U. S. Army Electronic Proving Ground, July 1961. (Available from CFSTI as AD-275549.)

B10. Anon.: Notes on System Theory. Vol. 5. Electronics Res. Lab. Rept. ERL 64-8 (Nonr 222 (53) AFAFOSR 139-63), Univ. Calif. (Berkeley), Apr. 1964. (Available from CFSTI as AD 601993.)

B11. Bellman, R.; Kagiwada, H.; and Kalaba, R.: A Computational Procedure for Optimal Systems Design and Utilization. RM-3174-PR, The RAND Corp., June, 1962. (Available from CFSTI as AD 276534.)

B12. Rechtin, Eberhardt: Basic Constraints of Space Communications Systems. Space Communications, A. V. Balakrishnan, ed., McGraw-Hill Book Co., Inc., 1963, pp. 4-29.

B13. Nichols, Myron H.; and Rauch, Lawrence L.: Radio Telemetry. John Wiley & Sons, Inc., 1957.

B14. Lutz, S. G.: Earth-Space Telecommunication of the Future. U.S. Air Force Association's Sixteenth Annual Conv. (Las Vegas, Nev.), 1962.

B15. Mueller, George E.: A Pragmatic Approach to Space Communication. Proc. IRE, vol. 48, no. 4, Apr. 1960, pp. 557-566.

B16. Brockman, M. H.; Buchanan, H. R.; Choate, R. L.; and Malling, L. R.: Extra-Terrestrial Radio Tracking and Communication. Proc. IRE, vol. 48, no. 4, Apr. 1960, pp. 643-654.

B17. Dimond, Robert H.: Interplanetary Telemetering. Proc. IRE, vol. 48, no. 4, Apr. 1960, pp. 679-684.

B18. Mueller, G. E.; and Taber, J. E.: An Interplanetary Communication System. IRE WESCON Conv. Record, Aug. 1959.

COMMUNICATION THEORY

B19. Shannon, C. E.: The Mathematical Theory of Communication. Univ. of Ill. Press (Urbana, Ill.), 1949.

B20. Black, H. S.: Modulation Theory. D. Van Nostrand Co., Inc., 1953.

B21. Goldman, S.: Information Theory. Prentice-Hall, Inc., 1953.

B22. Sanders, R. W.: Communication Efficiency Comparison of Several Communication Systems. Proc. IRE, vol. 48, no. 4, Apr. 1960, pp. 575-588.

B23. Weaver, C. S.: A Comparison of Several Types of Modulation. IRE Trans. on Communications Systems, Mar. 1962.

B24. Viterbi, Andrew: Classification and Evaluation of Coherent Synchronous Sampled-Data Telemetry Systems. Jet Propulsion Lab., June 15, 1961. (Available from CFSTI as AD 260585.)

B25. Florman, E. F.; and Tary, J. J.: Required Signal-To-Noise Ratios, RF Signal Power, and Bandwidth for Multichannel Radio Communications Systems. Nat. Bur. Standards, Jan. 6, 1962. (Available from CFSTI as AD 288285.)

B26. Sampson, W. F.: Maximum Utilization of Narrow-Band Data Links for Interplanetary Communications. Proc. IRE, vol. 48, no. 4, Apr. 1960, pp. 589-593.

B27. Ratz, Alfred G.: Telemetry Bandwidth Compression Using Airborne Spectrum Analyzers. Proc. IRE, vol. 48, no. 4, Apr. 1960, pp. 694-702.

B28. Ellis, D. H.; and Walter, J. M., Jr.: An Analog and Digital Airborne Data Acquisition System. Proc. IRE, vol. 48, no. 4, Apr. 1960, pp. 713-724.

B29. Williams, E. W., Jr.: Space Telemetry Systems. Proc. IRE, vol. 48, no. 4, Apr. 1960, pp. 679-684.

B30. Schneebaum, M. I.; and Stampfl, R. A.: Data Storage for Meteorological Satellites. Astronaut. Aerospace Eng., vol. 1, no. 3, Apr. 1963, pp. 48-51.

B31. Rochelle, R. W.: Signal-to-Noise Considerations for a Space Telemetry System. Proc. IRE, vol. 48, no. 4, Apr. 1960, pp. 691-693.

B32. Gruen, Harold; and Olevsky, Benjamin: Increasing Information Transfer. Space/Aeron., vol. 43, no. 2, Feb. 1965, pp. 40-43.

B33. Lehan, F. W.; and Parks, R. J.: Optimum Demodulation. IRE Conv. Record, pt. 8, PGIT, Mar. 1953, pp. 101-103.

B34. Elliott, E. O.: Estimates of Error Rates for Codes on Burst-Noise Channels. Bell System Tech. J., vol. 42, no. 5, Sept. 1963, pp. 1977-1997.

B35. Develet, Jean A., Jr.: Modulation Considerations for the Transmission of Real-Time Space Television. Aerospace Corp., May 31, 1963. (Available from CFSTI as AD 406315.)

B36. Anon.: Design of Bandlimited Signals for Binary Communication Using Simple Correlation Detection. Rept. No. AFCRL-64-289, Office of Aerospace Res., Cambridge Res. Lab., U.S. Air Force, Feb. 1964. (Available from CFSTI as AD 602712.)

B37. Gerks, I. H.: Analysis of Distortion Resulting From Two-Path Propagation. Proc. Inst. Radio Eng., vol. 37, Nov. 1949, pp. 1272-1277.

B38. Develet, J. A., Jr.: Minimum Power Analogue Communication. Aerospace Corp., May 15, 1963. (Available from CFSTI as AD 437203 and from SSD as TDR 63-111.)

SECURITY

B39. Shannon, C. E.: Communication Theory of Secrecy Systems. Bell System Tech. J., vol. 28, Oct. 1949, pp. 656-715.

B40. Dresher, M.: Games of Strategy. Prentice-Hall, Inc., 1961.

B41. Braverman, D. J.: A Discussion of Spread Spectrum Composite Codes. Communications Systems Tech. Rept. No. 3, Aerospace Corp., Dec. 1, 1963. (Available from CFSTI as AD 425862.)

B42. Yates, F. F.: AGC Versus Limiting in a Communication Satellite. TOR-269(4111)-12, Aerospace Corp., May 6, 1964.

NOISE AND INTERFERENCE

B43. Hogg, D. C.; and Mumford, W. W.: The Effective Noise Temperature of the Sky. Microwave J., vol. 3, Mar. 1960, pp. 80-84.

B44. Smith, Alex G.: Extraterrestrial Noise as a Factor in Space Communications. Proc. IRE, vol. 48, no. 4, Apr. 1960, pp. 593-599.

B45. Bennett, W. R.: Electrical Noise. McGraw-Hill Book Co., Inc., 1960.

B46. Hogg, D. C.: Effective Antenna Temperatures Due to Oxygen and Water Vapor in the Atmosphere. J. Appl. Phys., vol. 30, no. 9, Sept. 1959.

B47. Hogg, D. C.; and Semplak, R. A.: The Effect of Rain on the Noise Level of a Microwave Receiving System. Proc. IRE, vol. 48, no. 12, Dec. 1960, pp. 2024-2025.

B48. Hansen, R. C.: Low Noise Antennas. Microwave J., vol. 2, June 1959, pp. 19-24.

B49. Ko, H. C.: The Distribution of Cosmic Radio Background Radiation. Proc. IRE, vol. 46, no. 1, Jan. 1958, pp. 208-215.

B50. Mayer, C. H.; McCullough, T. P.; and Sloanaker, R. M.: Measurements of Planetary Radiation at Centimeter Wavelengths. Proc. IRE, vol. 46, no. 1, Jan. 1958, pp. 260-266.

B51. Ogburn, O. H.; Donaldson, E. E., Jr.; Spence, P. T.; and Stuckey, C. W.: Electronic Equipment Interference Characteristics—Communication Type. Ga. Inst. Tech., Nov. 15, 1963-Feb. 15, 1964. (Available from CFSTI as AD 439503.)

B52. White, D. R. J.; and James, W. G.: Digital Computer Simulation for Prediction and Analysis of Electromagnetic Interference. IRE Trans. on Communications Systems, June 1961, pp. 148-159.

PROPAGATION

B53. Vogelman, Joseph H.: Propagation and Communications Problems in Space. Proc. IRE, vol. 48, no. 4, Apr. 1960, pp. 567-569.

B54. Tischer, F. J.: Propagation-Doppler Effect in Space Communications. Proc. IRE, vol. 48, no. 4, Apr. 1960, pp. 570-574.

B55. Tolbert, C. W.; and Straiton, A. W.: An Analysis of Recent Measurements of the Atmospheric Absorption of Millimetric Radio Waves. Proc. IRE, vol. 49, Mar. 1961, pp. 649-650.

B56. Millman, G. H.: Atmospheric Effects on VHF and UHF Propagation. Proc. IRE, vol. 46, Aug. 1958, pp. 1492-1501.

B57. Hutchinson, H. P.; and Arendt, P. R.: Ionosopheric Scintillations of Satellite Signals. Proc. IRE, vol. 48, no. 4, Apr. 1960, pp. 670-671.

B58. Dirsa, Edward F.: The Telemetry and Communication Problem of Re-Entrant Space Vehicles. Proc. IRE, vol. 48, no. 4, Apr. 1960, pp 703-712.

B59. Ratcliffe, J. A., ed.: Physics of the Upper Atmosphere. Academic Press, Inc. (New York), 1960.

B60. Bridge, H. S.; Dilworth, C.; Rossi, B.; Scherb, F.; and Lyon, E. F.: An Instrument for the Investigation of Interplantary Plasma. J. Geophys. Res., vol. 65, 1960, pp. 3053 ff.

B61. Gorgolowski, S.; and Hewish, A.: The Structure of the Solar Corona During 1959 June. Observatory, vol. 80, 1960, p. 99.

B62. Raymond, J.: Characteristics of Radio Tropospheric Scatter. Commun. Systems Tech. Rept. no. 6, TOR-269 (4304)-3, Aerospace Corp.

B63. Anon.: Scatter Communication Models for Space Vehicles. USCEE Rept. No. 104, Elec. Eng. Dept., Univ. Southern Calif., Jan. 1964. (Available from SSD as TDR-64-5.)

B64. Meyers, S. T.: Nonlinearity of Frequency Modulation Radio Systems Due to Multipath Propagation. Proc. IRE, vol. 34, 1946, pp. 256-265.

B65. Taylor, T. T.: Design of Circular Apertures for Narrow Beamwidth and Low Sidelobes. IRE Trans. on Antennas and Propagation, vol. AP-8, no. 1, Jan. 1960.

B66. Sletten, C. J.: Modern Antennas for Space Communications. Electromagnetic Radiation Lab., AFCRL, Feb. 1963. (Available from CFSTI as AD 403987.)

B67. Drane, C. J., Jr.: Phase-Modulated Antennas. AFCRC TR 59-138, Air Force Cambridge Res. Center, 1959. (Available from CFSTI as AD 215374.)

B68. Anon.: Time Domain Antenna Techniques — Technical Note. TM-686, Hughes Aircraft Co., June 1961. (Available from CFSTI as AD 264019 and from RADC as TN-61-145.)

B69. Potter, P. D.: Antennas. Space Communications, A. V. Balakrishnan, ed., McGraw-Hill Book Co., Inc., 1963, pp. 143-177.

B70. Kay, Alan F.: Application of Fresnel Zone Theory to Microwave Antenna Design. SR No. 3 (AF 19(604)-8057), TRG, Inc., Nov. 15, 1962. (Available from CFSTI as AD 296973 and AFCRL-62-950.)

TRACKING

B71. Potter, Norman S.: The Optimization of Astronautical Vehicle Detection Systems Through the Application of Search Theory. Proc. IRE, vol. 48, no. 4, Apr. 1960, pp. 541-553.

B72. Weiffenbach, George C.: Measurement of the Doppler Shift of Radio Transmissions from Satellites. Proc. IRE, vol. 48, no. 4, Apr. 1960, pp. 750-753.

B73. Anderson, R. F.: Study and Investigation of Acquisition and Tracking of Optical Communications Systems. Eng. Rept. No. 4 (AF 33(616)8392) and Rept. No. 9036-4, Philco Corp., May 31, 1962. (Available from CFSTI as AD 276564.)

B74. Gilchriest, C. E.: Application of the Phase-Locked Loop to Telemetry as a Discriminator or Tracking Filter. Trans. IRE on Telemetry and Remote Control, vol. TRC-4, June, 1958, pp. 20-35.

B75. Richter, H. L.; and Stevens, R.: The Elements of a Deep-Space Tracking System: The Tracking of Pioneer IV. External Publ. 685, Jet Propulsion Lab., Aug. 13, 1959.

SPACE COMMUNICATION TECHNIQUES

B76. Gatland, K. W., ed.: Telecommunication Satellites. Prentice-Hall, Inc., 1964.

B77. Lewis, Thomas B.: Primary Processor and Data Storage Equipment for the Orbiting Astronomical Observatory. IEEE Trans. on Electronic Computers, Dec. 1963.

B78. Martin, B. D.: A Coherent Minimum-Power Lunary Probe Telemetry System. External Publ. 610, rev. 1, Jet Propulsion Lab., Aug. 12, 1959.

B79. Kierner, Frederick A.: A Digital Command System for Satellites. NASA TN D-1076, 1962.

B80. Best, G. C.: Completely Automatic Weight-Minimization Method for High-Speed Digital Computers. J. Aircraft, vol. 1, no. 3, May-June 1964, pp. 129-133. (Available from CFSTI as A64-21028.)

B81. Wolf, E.: Ultraviolet Transmitter Design and Development Program. (Available from CFSTI as AD 283588.)

B82. Eden, D. D.: Solid State Techniques for Modulation and Demodulation of Optical Waves. Quart. Prog. Rept. No. 1 (DA-36-039-AMC-03250(E)), Tex. Instr., Inc., Sept. 30, 1963. (Available from CFSTI as AD 427740.)

B83. Eden, D. D.: Solid State Techniques for Modulation and Demodulation of Optical Waves. Quart. Prog. Rept. No. 2 (DA-36-039-AMC-03250(E)), Tex. Instr., Inc., Dec. 30, 1963. (Available from CFSTI as AD 600419.)

B84. Eden, D. D.: Solid State Techniques for Modulation and Demodulation of Optical Waves. Quart. Prog. Rept. No. 4 (DA-36-039-AMC-03250(E)), Tex. Instr., Inc., June 30, 1964. (Available from CFSTI as AD 453341.)

B85. Anon.: Study and Investigation of Millimeter and Submillimeter Receiver Techniques. Quart. Rept. No. 1 (AF 30(602)2456, Proj. 4505), Elect. Eng. Res. Lab., Univ. Ill., July 15, 1962. (Available from CFSTI as AD 284562.)

B86. Hazel, W. C.: Satellite Control Facility: Design Criteria; Expanding the Telemetry Demultiplexing Capabilities of the Remote Station Digital-Storage-Type Decommutation Equipment. Rept. No. TOR-269 (r110-01)-58, Aerospace Corp.

B87. Jenness, James R., Jr.: Radiative Cooling of Satellite-Borne Electronic Components. Proc. IRE, vol. 48, no. 4, Apr. 1960, pp. 641-642.

B88. Riblet, Henry B.: A Broad-Band Spherical Satellite Antenna. Proc. IRE, vol. 48, no. 4, Apr. 1960, pp. 631-635.

RELIABILITY

B89. Lloyd, David D.; and Lipow, Myron: Reliability: Management, Methods, and Mathematics. Prentice-Hall, Inc., 1962.

B90. Luebbert, W. F.: Achieving Operational Effectiveness and Reliability with Unreliable Components and Equipment. IRE Conv. Record, pt. VI, Mar. 1965, pp. 41-49.

B91. Lloyd, D. K.: Multienvironmental Life Testing of Parts and Components in Rockets and Guided Missiles by Statistical Design. IRE Trans. Reliability and Quality Control, Dec. 1958.

B92. Anon.: Design Techniques for Long-Term Reliability of Aerospace Electronic Communication Equipment. Contract AF33 657 9147, Bendix Radio Div., Bendix Corp., Dec. 1963. (Available from CFSTI as AD 429882.)

Table B1.—Communications Subsystem Input/Output Parameters

Parameter
1. Capacity
2. Fidelity
3. Delay
4. Transmission frequency
5. Coverage
6. Security
7. Duty cycle
8. Power
9. Reliability
10. Weight
11. Envelope

Table B2.—Internal Parameters of Communications Subsystem

Parameter
1. Wavelength
2. Bandwidth
3. Data rate
4. Signal-to-noise ratio
5. Distortion
6. Error rate
7. Storage delay
8. Coding delay
9. Propagation delay
10. Acquisition delay
11. Location
12. Range
13. Range rate
14. Angle
15. Angle rate
16. Aperture
17. Directivity
18. Noise flux
19. Signal flux
20. Path loss
21. Effective radiated power
22. Efficiency
23. Polarization

Table B3.—Analysis Procedures

Type of analysis	Factors determined	Parameters derived	Required input data	Complexity level	References
1. Operations analysis, systems analysis, and systems engineering a. Problem definition b. Value analysis c. System synthesis d. Network flow analysis e. Mathematical programming f. Queueing theory g. Reliability theory h. Information theory i. Human engineering	Communication subsystem requirements, type and number of links	All input/output parameters of each one-way communication link, i.e., capacity, fidelity, delay, coverage, security, duty cycle, power, reliability, weight, and envelope.	Mission profile, environmental profile, basic constraints	High	B1 to B18
2. Information-theoretic analysis a. Communication efficiency b. Modulation theory c. Error detection d. Error correction	Modulation and coding method, measures of capacity, fidelity, delay	Signal-to-noise ratio, bandwidth, data rate, error rate, coding delay, distortion, storage delay	Capacity, fidelity, delay, duty cycle	Moderate	B19 to B38
3. Security analysis (if applicable) a. Communication theory b. Theory of secrecy systems c. Games of strategy d. Political analysis	Effect of jamming and eavesdropping, coding requirements, coverage modifications, chances of loss	Security	Political and legal data, coverage, signal flux, duty cycle, message delay	High	B39 to B42

Table B3.—Analysis Procedures—Continued

Type of analysis	Factors determined	Parameters derived	Required input data	Complexity level	References
e. Criminal analysis f. Jamming and out-jamming					
4. Noise analysis a. Internal noise b. Cosmic noise c. Solar noise d. Terrestrial noise e. Man-made noise f. Interfering services (RFI)	Effects of all noise sources on total detected noise energy at various times	Noise flux, wavelength, location, angle, and directivity	Empirical data on all noise sources	Moderate	B43 to B52
5. Propagation analysis a. Atmospheric absorption b. Ionospheric absorption c. Free space absorption d. Reentry absorption e. Exhaust absorption f. Scattering g. Refraction h. Dispersion i. Rotation of polarization j. Transverse Doppler effect k. Medium turbulence l. Electromagnetic theory m. Optics n. Antennas	Relation of wavelength range, angle, modulation methods, and directivity on path loss, distortion, tracking errors, etc., due to effects at left; find optimum wavelengths and maximum directivity	Path loss, directivity, coverage, aperture, effective radiated power polarization, wavelength, propagation delay, signal flux	Empirical data on atmosphere, ionosphere, Sun's corona, free space plasma, etc., with respect to location, wavelength, time, and propagation	Moderate	B53 to B70

Table B3.—Analysis Procedures—Concluded

Type of analysis	Factors determined	Parameters derived	Required input data	Complexity level	References
6. Tracking analysis a. Angular tracking b. Doppler tracking c. Trajectory analysis d. Orbital mechanics e. Control system analysis f. Search theory	Spacecraft attitude control interface, tracking accuracy, aperture steering requirements, search patterns, effects on weight and envelope, trajectory data and computation requirements	Acquisition delay, envelope, weight	Trajectory refraction error directivity	High	B71 to B75
7. Design study a. Transmitters b. Receivers c. Antennas d. Optics e. Data processing f. Data storage g. Input/output equipment	Parameters of existing equipment, state-of-the-art, feasibility, cost, materials, mechanical support, and interface data	Efficiency, power, envelope, weight	Wavelength, bandwidth, data rate, storage delay, coding delay, acquisition delay, aperture, directivity, effective radiated power, duty cycle	Moderate	B76 to B88
8. Reliability analysis a. Prediction b. Testing c. Design for reliability d. Operational reliability	Effectiveness prediction, design factors for reliability, lifetime, part selection, test policies, operating procedures	Reliability	Tentative design, duty cycle, environmental data, power, efficiency, test data	Moderate	B89 to B92

Table B4.—Parameters Related Linearly

Parameters
1. Capacity — bandwidth
2. Capacity — data rate
3. Delay — propagation delay
4. Propagation delay — range
5. Duty cycle — power
6. Bandwidth — data rate
7. Total noise flux — bandwidth (usually)
8. Signal-to-noise ratio — signal flux
9. Signal flux — directivity
10. Signal flux — aperture
11. Aperture — directivity
12. Efficiency — power
13. Signal flux — effective radiated power

Table B5.—Parameters For Which Empirical Relations Are Used

Parameters
1. Capacity — fidelity
2. Security — coverage
3. Total noise flux — wavelength
4. Total noise flux — angle
5. Total noise flux — location
6. Path loss — location
7. Capacity — output signal-to-noise ratio
8. Total noise flux — directivity
9. Efficiency — wavelength
10. Efficiency — bandwidth

Table B6.—Nonlinear Parameter Relations

Parameters
1. Delay — storage delay
2. Delay — coding delay
3. Delay — acquisition delay
4. Directivity — wavelength
5. Capacity — signal flux
6. Capacity — noise flux
7. Signal flux — wavelength
8. Signal-to-noise ratio — wavelength
9. Path loss — wavelength
10. Path loss — range
11. Path loss — angle
12. Reliability — duty cycle
13. Bandwidth — signal-to-noise ratio
14. Bandwidth — fidelity
15. Distortion — signal-to-noise ratio
16. Error rate — signal-to-noise ratio
17. Range rate — acquisition delay
18. Angle rate — acquisition delay
19. Angle rate — acquisition delay

Table B7.—Communications and Data-Handling Checklist

1. Configuration
    - a. Transmission distance
    - b. Type of communications: voice, data, video
    - c. Orbit and velocity
    - d. Stabilization characteristics
    - e. Structural configurations, protuberances, jet exhaust locations
    - f. Modulation method
    - g. Spectrum requirements
    - h. Maneuvers
    - i. Reentry attenuation
    - j. Earth's atmospheric conditions
    - k. Solar atmospheric conditions
    - l. Interplanetary environmental conditions
    - m. Intergalactic environmental conditions
    - n. Tracking method
    - o. Number and type of separate one-way links
    - p. Quantity of data or information required
    - q. Uses of data or information
    - r. Physical location of equipment
    - s. Form of data or information

2. Time considerations
    - a. Real time/nonreal time
    - b. Time-use profile of equipment
    - c. Access time to equipment
    - d. Useful life of data, for storage and retrieval, future analysis
    - e. Conversion time
    - f. Time sharing

3. Typical equipment found in subsystem
    - a. Memories (discs, drums, cores, delay lines)
    - b. Data processors
    - c. Display equipment
    - d. Input/output equipment
    - e. Converters, A/D, D/A
    - f. Operational amplifiers
    - g. Multiplexer
    - h. Encoders
    - i. Format generators
    - j. Antennas: whip, horn, parabolic, phased array, dipole
    - k. Transmitters
    - l. Receivers
    - m. Wave guides
    - n. Couplers, decouplers
    - o. Diplexers
    - p. Phase shifters
    - q. Transponder
    - r. Balun
    - s. Traveling wave tubes
    - t. Amplifiers
    - u. Oscillators
    - v. Modulators, demodulators
    - w. Discriminators
    - x. Filters
    - y. Signal conditioners

APPENDIX C

Thermal Control

The thermal-control subsystem maintains the temperature of the components of the system (i.e., usually the internal volume of a vehicle or structure) within an acceptable working range. Because thermal-control capability for ground equipment is already highly developed, this discussion primarily concerns spacecraft. A thermal-control checklist (table C1) appears at the end of this appendix.

REQUIREMENTS FOR SPACECRAFT THERMAL CONTROL

Most components on a spacecraft are electronic and are nominally capable of operating over temperature ranges from 150° to 200° F. However, the reliability levels required for spacecraft place restrictive limits on the allowable internal temperatures because of two major factors: (1) The use of special components whose performance is very temperature sensitive and (2) the severe effect of temperature on the reliability of electronic parts. An example of a component whose performance is very temperature sensitive is the sealed nickel-cadmium battery; this battery suffers a significant loss of capacity at temperatures below 20° to 25° F and above 80° to 90° F. The performance parameters of liquid and solid propellants are also highly temperature sensitive. With respect to the second factor, it is generally accepted from experience that the reliability of electronic parts is related to temperature by means of the Arrhenius Law (that is, an increase in temperature increases the failure rate exponentially). Instrument calibrations and the necessity of keeping the circuits in tune over ranges of temperatures also require close control of spacecraft temperatures. Gyros, stable oscillators, photomultipliers, and Vidicon tubes are components that require close temperature control.

Sometimes the thermal requirements may be met by the local control of temperature. More commonly, however, the affected components are spread so widely in the spacecraft that local control of temperature is not a feasible solution.

TYPES OF THERMAL CONTROL

PASSIVE

Passive thermal control is obtained by regulating the heat-transfer process between the spacecraft and its environment and within the spacecraft itself. Thus, the radiation heat-transfer process between the solar radiation flux, the planetary thermal surface flux, the albedo thermal flux, and the spacecraft outer surface is regulated by controlling the spacecraft thermal properties. The significant properties involved are the effective emissivity, absorptivity, and reflectivity of the surfaces over the spectra of the fluxes. Internal radiation heat-transfer processes may be controlled by controlling the internal geometry of the spacecraft and/or the internal surface properties of the spacecraft. Internal conduction heat transfer may be controlled by exercising control over the thermal conductivity of the structural members and the contact resistance at the joints.

ACTIVE

Mechanical control surfaces are widely used for the present generation of spacecraft. They may be categorized into two groups; the first group involves pseudo-passive surfaces (no vehicle power is required to activate the control), and the other group requires vehicle power for actuation.

Mechanical thermal-control surfaces usually consist of a combination of two coatings on the two surfaces that move relative to each other. Generally, one surface has a high absorptivity-to-emissivity ratio, and the other, a low ratio. As the vehicle and the corresponding surface cool, more surfaces with high absorptivity-to-emissivity ratio are exposed, and so an absorption of solar energy greater than its emission results; consequently, the spacecraft warms. The reverse process takes place as the spacecraft reaches a warmer temperature range. These control surfaces may be classified according to geometry and movement; for example, (1) rotary surfaces (e.g., the Maltese cross), which facilitate their application to single or double curved surfaces and (2) linear surfaces (e.g., grates and linear blinds or shutters), which are particularly adaptable to surfaces having relatively large flat areas.

The pseudo-passive drive devices are usually controlled by a bimetallic strip or spring, whereas the actively driven surfaces are generally controlled by a servomechanism that utilizes a temperature sensor. The spacecraft power supply produces the drive forces for the latter.

Active radiators may be used to increase or improve the available heat dissipation area. Fin-tube fluid radiators and endless-belt radiators are typical active thermal-control systems. The analytical techniques required to design these radiators are similar to those used to design the ground radiator systems. It may become possible for larger spacecraft to utilize internal heat-transfer systems that involve the flow of a mass such as circulating coolant. Again, the analytical techniques required for the design of such systems are similar to those for the ground systems, and thus no detailed coverage is included here.

BASIC HEAT-TRANSFER ANALYTICAL TECHNIQUES REQUIRED FOR SPACECRAFT THERMAL DESIGN

Spacecraft thermal design involves the establishment of the surface and internal temperature profile of the spacecraft, with consideration given to active thermal-control units, if they are involved. The basic analytical techniques that apply to passive thermal-control analysis also apply to mechanical active thermal-control analysis; thus it is unnecessary to distinguish in this discussion between the kinds of thermal control.

THERMAL CONDUCTION HEAT TRANSFER

The basis for conduction heat-transfer analysis is the Fourier-Poisson heat conduction equation. With time dependency (transient conditions), the resulting differential equations are generally too complex for direct use in analysis. Exact solutions for solids of various shapes are published, but computations are tedious. For example, the solution for a finite hollow cylinder contains an infinite series whose terms involve roots of a transcendental equation in Bessel functions. However, the Fourier-Poisson equation can be written as an algebraic equation by making use of the LaPlace transform. Approximate methods offer the only practical means for solving transient-heat-conduction problems. Such practical methods are based on graphic, numeric, and analogic means. The most practical analog is the analogy which can be made between heat-flow fields and electric current.

The general Fourier-Poisson equation for transient heat conduction is

$$\frac{\partial T}{\partial t} = \alpha \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right)$$

where

α	k/wc determined by material properties
k	thermal conductivity
w	specific weight
c	specific heat
T	temperature
t	time
x, y, z	coordinates

Graphic solution methods are based on the finite difference technique; that is, the derivative is replaced with a finite difference. Since partial derivatives of temperature with respect to both time and spatial quantities exist in the Fourier-Poisson equation, it is necessary to use that finite difference of temperature with respect to both time and distance. The graphic procedures are simple in one-dimensional problems but are rather complex in cylindrical coordinates, especially when the problem of the cylindrical interface of different materials is encountered. Reference C1 presents an adequate discussion of the graphic procedure. The graphic method has the advantage of simplicity; irregularities in temperature distribution or variations in thermal properties are easily accounted for by simple scale adjustments, and minor errors tend to be spread and average out as the solution proceeds. Accuracy depends on the fineness of time and space intervals, choice of scale, and precision of the graphic construction. However, there is one serious limitation; time and space intervals must be so related that $\alpha\Delta T/\Delta x^2 = 1/2$ in the Cartesian coordinate system and similarly in the cylindrical system. A free choice of time and space intervals is not possible in the graphic method, as one is fixed by the other. Furthermore, graphic construction necessary for obtaining the precision desired may be time consuming. Numerical procedures, although generally more costly than graphic methods, in this case are more desirable since they are amenable to the precision of computer solution.

Numerical procedures use digital computers to carry out the repetitive finite-difference solutions for the Fourier-Poisson equation. Explicit solutions in which "each future temperature is considered an explicit function of the present temperature of the region in question and of the other regions in thermal contact" are restrictive in that neither is a free choice of time and space interval possible nor is the simple guide $\alpha\Delta T/\Delta x^2 = 1/2$ adequate. Instead, stability criteria must be established if disconcerting oscillations in the solution are to be avoided. On the other hand, implicit solutions in which "future temperatures are functions simultaneously of each other and the present temperature taken singly" have been shown to be stable for any mesh size in time and space. Reference C2 is an example of the implicit numerical method, which has at least one drawback; it involves the definition of many numerical relations, and the resulting solution is unwieldy. References C3 and C4 are good general references for numerical procedures.

Numerical Techniques

A variety of numerical techniques is available. Reference C5 shows a computerized numerical solution technique. This computer program is a one-dimensional transient conduction program that allows for variation of the material properties and heat source with temperature and time within a maximum of 10 regions and over a maximum of 50 mesh intervals. Since this program does not include expressions for computing radiation heat transfer, it is necessary to express radiation heat loss as an "equivalent conductive heat loss." An equivalent conductivity can be computed by equating a conduction equation to the general radiation equation and solving for the conductivity. This solution results in a cubic equation in temperature which can be handled by the computer program.

Analog Techniques

At least two conditions must be satisfied to establish a valid field analog: (1) The differential equations describing the two fields in question must be similar and (2) the physical boundary conditions must be related. The first practical method for representing transient heat conduction by an electric analog was indicated in 1936 by the Dutch engineer Beuken. He recognized that a scale factor could be introduced to allow use of practical values of electric resistors and capacitors without altering the results provided that the time intervals were altered in the same proportion. This provides for automatically proceeding (in time) solutions by use of electric resistors and capacitors to simulate their counterparts (thermal resistance and mass) in the thermal field.

A new electric analog for transient heat conduction was first mentioned by Liebmann of England in 1951. He described this analog as an electric resistance network representing the difference equations defining the problem to be solved. In a Liebmann resistance network, voltages approximate temperatures, network resistors approximate spatial features, and series resistors approximate the thermal constants of the heat conduction paths. The voltages corresponding to initial temperatures are impressed at the boundaries and throughout the analog at the free ends of the series resistors. The new potentials, corresponding to new temperatures after Δt, will appear at the nodes of the network resistors. By applying these new potentials to the boundaries of the series resistors the process may be continued for $n\Delta t$ intervals of time. A practical resistance network analog for the solution of one-dimensional, transient heat-transfer conduction problems might be as follows: (1) Set all network resistors to simulate the steady-state thermal resistances of the problem; (2) set all series resistors to simulate the transient phase of the problem; and (3) set the electric potentials to simulate the initial temperatures at the various spatial positions in the thermal problem.

The Liebmann analog method closely parallels the Binder-Schmidt graphic procedure in that finite intervals of both time and space are used. This attribute of increasing time in discrete intervals allows great flexibility in complex problems of transient heat transfer. The Liebmann analogy is based on implicit (backward difference) relations, so that freely chosen time and space intervals may be independent of any stability criteria that restrict both the graphic and the explicit (forward difference) numerical methods. (Complete descriptions of these methods are given in refs. C6 to C10.)

Graphic Techniques

The procedure employing graphic techniques is also based on the finite difference solution to the differential equation. Let any plane figure be divided into an arbitrary number of finite equal intervals of thickness Δx. Let time be stepped by arbitrary but finite intervals Δt. Consider the actual temperature distribution to be represented by a series of straight lines connecting the temperatures at the boundary planes of the space intervals.

Reference C1 gives a complete description of this method. The forward difference approximation, otherwise referred to as the explicit method, is utilized. If the term $2\alpha\Delta t$ divided by Δx^2 equals 1, then the new temperature position x, at time $t + \Delta t$, equals the temperature at $x - \Delta x$ at time t plus the temperature at $x + \Delta x$ at time t divided by 2; hence a rather simple iterative procedure is involved. When there are area variations, as in a cylindrical section, certain scale modifications must be defined before the Binder-Schmidt straight-line graphic procedure can be applied. When there are variations in thermal conductivity, as with heat flow through a metal pipe wall surrounded by a layer of insulating material, certain refinements must be made before the straight-line graphic method of finite differences can be used. However, these procedures have been derived and are workable.

Analytical Techniques

The general heat-transfer problem applicable to a spacecraft is one in which conduction and radiation are the two mechanisms of heat transfer structured within a problem wherein there are time-dependent heat sources and time-dependent boundary conditions. This type of problem is very difficult to solve, and, in general, its solution requires the use of an approximation such as the solution of a series of steady-state problems. An analytical technique has been developed for solving the time-dependent problem by considering only conduction heat transfer (ref. C11). Briefly, reference C4 consists of a procedure for extending the separation-of-variables technique to heat conduction problems with time-dependent heat sources and boundary conditions. A modification of the "separation" method, similar to the one made when seeking vibration solutions and applicable to linear partial-differential equations, transforms problems of this general class into a set of transient and steady-state subproblems for which solution methods are well established. Results take the form of quasi-static expressions superimposed upon a product series involving characteristic functions of the corresponding uniformly excited cases. The method is thus suitable for extending existing solutions to time-dependent heat source and end conditions, as well as offering an alternative approach which is sometimes more convenient than the better known integral methods.

THERMAL RADIATION

The term "radiation" here describes energy transmitted by means of electromagnetic waves in the thermal spectrum. When radiation impinges on a surface of a body, it is partially absorbed, partially reflected, and, if the body is transparent, partially transmitted. The relation between the absorbed, reflected, and transmitted energy is, according to the law of conservation of energy,

$$a + r + t = 1$$

where

a absorptivity (that is, the fraction of the incident radiation absorbed)
r reflectivity
t transmissivity

The relative magnitudes of a, r, and t depend not only on the surface characteristics, body geometry, and the material, but also on the wavelength. The reflection of radiation from a surface may be either diffuse or regular. In regular reflection the angle of incidence of a radiation ray is equal to the angle of reflection. However, regular reflection occurs only on highly polished surfaces, and most materials used in engineering practice are rough. The reflection of an incident bundle of rays from a rough surface is very nearly isotropic, that is, distributed indiscriminately in all directions. The analysis of radiation problems is considerably simplified when limited to diffuse radiation, and in the following discussion it will be assumed that reflection and emission are diffuse.

Kirchhoff's law states that no surface can absorb or emit more radiation than can a black one. The black body is therefore an ideal radiator that absorbs all of the incoming radiation. A corollary of Kirchhoff's law is that the absorptivity and the emissivity of any body are equal, or $a = e$. For a black body both a and e are equal to 1. The surface element of a black body radiates diffusely in all directions. Total rate of emission per unit area and unit time is called the emissive power E. It varies with the fourth power of the absolute temperature according to the relation

$$E = \sigma T^4$$

where σ is the Stefan-Boltzmann constant whose value is 0.1714×10^{-8}, E is in Btu/hr-square foot, and T is in degrees Rankine. Reference C12 is an excellent reference for radiation heat transfer as applied to the thermal control of spacecraft.

The three basic methods for thermal-radiation analysis are closely related and differ only in their point of view. The most widely used method is that of Hottel presented in reference C13. In reference C14 this method has been extended to include gaseous radiation with space variations in the temperatures of the bodies participating in the exchange process. Hottel's method, when applied to a system of n gray bodies, yields a series of equations for n^2 transfer quantities, which can be solved to obtain equivalent shape factors and to calculate the rate of heat transfer between any two radiation surfaces. The second method makes use of the analogy between radiation heat transfer and electric circuits. It is a network method originally proposed by Poljak in 1935 and subsequently refined by Oppenheim (ref. C15). It is most convenient for black-body problems but may also be used if an analog computer is available to obtain numerical solutions for radiation between gray surfaces. The network method can also be applied to radiation in enclosures with surfaces having wavelength-dependent radiation properties (ref. C16). In reference C17 a method similar to Hottel's approach is described. However, with the use of certain reciprocity relations the amount of labor required in obtaining a numerical solution is reduced. These methods can only be applied to systems in which the radiation is diffuse or isotropic.

Network Method

The basis of the radiation network method is the analogy of the black-body emissive power as electric potential and the surface shape factor as the branch conductance between two nodes at potentials E_i and E_j exchanging a current q_{ij}. Because of the reciprocity relation, the conductance is independent of the direction of flow. In the case of a reradiating surface (i.e., a surface which diffusely reflects and emits radiation at the same rate at which it receives radiation), the equivalent network conductance may be used in place of the usual conductance. The network method can also be applied to gray surfaces (see refs. C15 and C18). A good discussion of the network method and typical network diagrams are presented in reference C12.

Determinant Method

The determinant method involves setting up the equations for the net rate of radiation heat transfer for each surface as a function of the heat transfer with the other surfaces. In these equations, the specific areas of each of the surfaces, their emissive powers, and a set of absorption factor coefficients (defined as the fraction of the radiation emitted by one surface which is absorbed by the other) are involved. This fraction includes the radiation along all paths (i.e., reflections as well as re-reflections). Therefore, for each surface there is an equation. The usual determinant method is used for solving the set of simultaneous equations. The availability of a computer makes the determinant method a practical one for some structures, but for really complex structures the network method may be most practical.

Orbital Considerations

For elliptic orbital paths, the altitude of the satellite in any orbit position can be calculated if the eccentricity and the perigee altitude of the orbit and the radius of the parent body (generally a planet) are known. The computation of radiation to the satellite in orbit is simplified if a coordinate system based on orbital parameters is established. Reference C19 presents such a coordinate system treatment. Most industry thermal-analysis computer programs use the orbital parameter coordinate system. The principal objective of the analysis of the orbital path of the spacecraft is the location of the sun vector with respect to both the satellite and the planet. This is necessary for the computation of reflected and direct solar radiation. It is then necessary to fix the orientation of specific spacecraft surfaces with respect to the solar vector and the planetary vector.

Thermal Similitude Techniques

Another approach to thermal analysis is an experimental one. A full-scale model of the spacecraft (or a scaled-down version) is placed within a cold-wall vacuum chamber and is radiated with simulated sunlight, simulated reflected sunlight from the Earth, and simulated earth thermal radiation. With increasing booster capabilities, spacecraft may become so large that full-scale models are no longer practical because of the size constraints on the space-simulation chambers and the associated high-vacuum pumps, refrigerated walls, beams of simulated sunlight, and associated equipment. Reference C20 presents an adequate discussion of similitude in thermal models of spacecraft. The development in this reference results in four scaling factors. Certain difficulties arise when the linear scale factor is altered: (1) Either the conductivity of the materials involved must be altered by the same factor or (2) if the thermal conductivities are kept the same in the model as in the full-scale version, the intensity of radiation must be multiplied by the scale factor to the 4/3 power, and the temperatures of the spacecraft must be multiplied by the scale factor to the 1/3 power. The practical difficulties of such an approach are apparent, but it is likely that experimental analysis on scaled-down models will be important in the future. Reference C21 presents a thermal similitude analysis which results in the development of six independent prototype-to-model scaling factors. One of these factors involves the thermal contact conductance. It is stated in reference C21 that the main advantage of thermal modeling may come from its use in analyzing some particular thermal aspect of a design rather than the complete design. Modeling is also useful in the experimental determination of radiation exchange coefficients (that is, view factors). Modeling can be used to reduce or enlarge surfaces to convenient sizes for experimentation.

APPLIED METHODS FOR SPACECRAFT THERMAL DESIGN

All analytical techniques discussed in the preceding subsection on orbital considerations are used for thermal analysis of spacecraft. Over the past few years, complete digital computer programs have been developed by industry to utilize the network methods for solving problems containing conduction and radiation heat transfer. Numerical techniques are utilized for solving the finite difference equations involved in the network method, and the orbital position analysis is generally handled by a subroutine. The necessary view factors are a required input to the programs, and hand calculations based on geometric considerations are usually made. However, the mechanical integrator can be used as an aid in calculating these geometrical view factors. References C22 to C29 show the computerized analysis techniques presently used by industry.

REFERENCES

C1. Benedict, Robert P.: Transient Heat Flow, Electro-Tech., vol. 73, no. 12, Dec. 1961, pp. 94-111.

C2. Leppert, G.: A Stable Numerical Solution for Transient Heat Flow. Paper No. 53-F-4, ASME, Oct. 1963.

C3. Emmons, H. W.: The Numerical Solution of Heat Conduction Problems. Trans. ASME, vol. 65, Aug. 1943, p. 607.

C4. Dusinberre, G. M.: Numerical Methods for Transient Heat Flow. Trans. ASME, vol. 67, Nov. 1945, p. 703.

C5. Wagner, R. J.: Heat 1 - A One-Dimensional Time Dependent or Steady-State Heat Conduction Code for the IBM-650. IDO-16877, Phillips Petroleum Co., Apr. 1963.

C6. Schneider, P. J.: Conduction Heat Transfer. Addison-Wesley, Inc. (Reading, Mass.), 1955, p. 254.

C7. Beuken, C. L.: Heat Losses in the Periodic Operation of Electrical Ovens. Thesis, Triltsch and Huther (Berlin), 1936.

C8. Liebmann, G.: A Discussion on Conduction in Solids and Fluids, Proc. General Discussion on Heat Transfer of IME and ASME. Sept. 1951, p. 300.

C9. Liebmann, G.: A New Electrical Analog Method for the Solution of Transient Heat-Conduction Problems. Trans. ASME, vol. 78, Apr. 1956, p. 655.

C10. Liebmann, G.: Solution of Transient Heat-Transfer Problems by the Resistance Network Analog Method. Trans. ASME, vol. 78, Aug. 1956, p. 267.

C11. Ojalvo, I. U.: Conduction with Time-Dependent Heat Sources and Boundary Conditions. Int. J. Heat Mass Transfer, vol. 5, 1962, pp. 1105-1109.

C12. Kreith, Frank: Radiation Heat Transfer and Thermal Control of Spacecraft, Publ. No. 112, Oklahoma Eng. Station, Oklahoma State Univ., Apr. 1960.

C13. Hottel, H. C.: Radiant Heat Transmission. Ch. 4 in Heat Transmission by W. B. McAdams, third ed., McGraw-Hill Book Co., Inc., 1954.

C14. Hottel, H. C.; and Cohen, E. S.: Radiant Heat Exchange in a Gas-Filled Furnace. J. AICHE, vol. 4, 1957, pp. 3-14.

C15. Oppenheim, A. K.: Radiation Analysis by Network Method. Trans. ASME, vol. 78, 1956, pp. 725-735.

C16. Bevans, J. T.; and Dunkle, R. V.: Radiant Interchange Within an Enclosure. J. Heat Transfer, vol. 82, Feb. 1960, pp. 457-473.

C17. Gebhart, B.: Unified Treatment for Thermal Radiation Processes — Gray, Diffuse Radiators and Absorbers. Paper 57-A-34, ASME, 1957.

C18. Kreith, F.: Principles of Heat Transfer. Int. Textbook Co. (Scranton, Pa.), 1959.

C19. Katz, A. J.: Determination of Thermal Radiation Incident Upon the Surfaces of an Earth Satellite in an Elliptical Orbit. Paper presented at IAS Natl. Summer Meeting (Los Angeles, Calif., June 28-July 1, 1960), Grumman Aircraft Eng. Corp., 1960.

C20. Papell, S. Stephen; and Trout, Arthur M.: Experimental Investigation of Air Film Cooling Applied to an Adiabatic Wall by Means of an Axially Discharging Slot. NASA TN D-9, 1959.

C21. Jones, B. P.: Thermal Similitude Studies. J. Spacecraft and Rockets, vol. 1, July-Aug. 1964, pp. 364-369.

C22. Anon.: Environmental Control Study of Space Vehicles. Part II — Thermal Environment of Space. Gen. Dynamics/Convair, Nov. 1, 1960. (Available from CFSTI as AD 276853.)

C23. Anon.: Environmental Control Study of Space Vehicles. Part II — Thermal Environment of Space. Added suppl., Gen. Dynamics/Convair, Nov. 1, 1960. (Available from CFSTI as AD 276854.)

C24. Anon.: Environmental Control Study of Space Vehicles. Part II — Thermal Environment of Space. Suppl. B: Tabular Presentation of Planetary Thermal and Planetary Albedo Radiation Incident to Space Vehicles. Gen. Dynamics/Convair. (Available from CFSTI as AD 276855.)

C25. Anon.: A Digital Computer Program for the Calculation of Transient Temperatures in a Space Vehicle. Gen. Dynamics/Convair, Apr. 1963.

C26. Anon.: Program for Determining Temperatures of Orbiting Space Vehicles. North Am. Aviation, Apr. 1961. (Available from CFSTI as AD 285271.)

C27. Anon.: Program for Determining the Thermal Environment and Temperature History of Orbiting Space Vehicles. North Am. Aviation, Mar. 7, 1962. (Available from CFSTI as AD 285270.)

C28. Anon.: Radiation Heat Transfer Analysis for Space Vehicles. North Am. Aviation, Sept. 1962. (Available from CFSTI as AD 288610.)

C29. Goetzel, Claus G.; Rittenhouse, John B.; and Singletary, John B.; eds.: Space Materials Handbook. Tech. Doc. Rep. No. ML-TDR-64-40, AF Materials Lab., Res. and Tech. Div., AF Systems Command, Wright-Patterson Air Force Base, Jan. 1965.

Table C1.—Thermal Control Checklist

1. Configuration
    - a. Passive (thermal blankets, paints, finishes)
    - b. Active (louvers, shutters)
    - c. Combination of both passive and active
    - d. Growth potential
    - e. Localized thermal control for experiments and subsystems

2. Time considerations
    - a. On- and off-cycle times for heat-producing electrical systems
    - b. Radiation, from the Sun, Earth, space, etc. (i.e., time exposed to such radiation)

3. Output parameters

    Temperature level of components during mission (operating and nonoperating)

4. Input parameters

    Specification requirements for various components (operating and nonoperating)

5. Subsystem internal parameters and considerations
    - a. Heat transfer characteristics (emissivity, thermal capacity, etc.)
    - b. Geometry and location of components

6. Typical equipment assemblies
    - a. Radiating surfaces
    - b. Louver

7. Parameters external to subsystem (input parameters)
    - a. Distance from Sun, Earth (solar radiation intensity)
    - b. Position in the solar system
    - c. Atmospheric drag (if any)
    - d. Prelaunch time on pad

APPENDIX D

Structure

The structure subsystem provides positional and structural integrity and protection to the components of the system. Although certain structural techniques lack exactness of analytical rigor, the use of safety factors in design and analysis and the performance of development tests provide the necessary conservatism for obtaining reasonable assurance in structural hardware at the sacrifice of weight and cost savings. As the mechanisms of failure and load distributions on complex assemblies become better understood, more exact techniques for analysis, testing, and weight and cost savings will be developed. The following discussion is divided into structural design problem areas. Each problem area is briefly described and the methods of solution are discussed. A structure checklist is included as table D1 and additional information is given in references D1 to D45.

MECHANICAL PROPERTIES - THERMAL AND CORROSIVE ENVIRONMENTS

Allowable properties for materials subjected to thermal and corrosive environments are determed from extensive specimen test programs. Values presented in most publications represent test results at the low end of scattered data; thus a highly probability (90 to 99 percent) of obtaining at least the specified values is guaranteed. Because of the scatter in the data and the low values quoted, the assurance of load-carrying capabilities is high, but accuracy is poor. This problem will be alleviated when probabilistic design replaces "safety factor" design. (See refs. D1 to D3.)

MECHANICAL PROPERTIES - NUCLEAR ENVIRONMENT

The discussion on thermal and corrosive environments also applies to mechanical properties of a structure in nuclear environments, except that problems associated with specimen test results are compounded. The major problem is that of obtaining at reasonable cost multiple specimen data which are representative of the true environment. Because data presented in most references are based on a limited number of samples and cover a limited range, values of material properties must often be obtained by extrapolation in untested regions or linear interpolation over fairly large intervals when the relationship of environment magnitude to material properties is not linear. (See refs. D2 and D4.)

STRUCTURAL RELIABILITY

Structural reliability techniques could provide more accurate design and analysis than do safety factor techniques because they account for probabilistic variation in applied loads and allowable properties. Most present techniques consider the Gaussian distribution representative for all random variables. However, before industry takes advantage of structural reliability techniques, much effort must be expended on test programs to determine (1) accurate distributions (since Gaussian may not apply), (2) a standard analysis procedure for components and assemblies, and (3) establishment of an allowable risk (probability of failure) criterion. (See refs. D5 to D9.)

MATERIAL PROPERTIES - SPACE VACUUM

See preceding subsection on mechanical properties in a nuclear environment. An additional factor of concern is the limited ability of test equipment to duplicate the natural environment. (See ref. D2.)

SHOCK AND IMPULSE LOADING

In recent years, major efforts have been made toward understanding and analyzing shock and impulse loading. However, there exists neither a completely accepted technique for determining the ultimate load capability of a complex structure that experiences an impulse load nor a standard technique for relating shock load-carrying capabilities to static load-carrying capability over the impulse loading time range. The standard design method is the design and testing of full-scale development hardware; this method keeps the cost at an acceptable level and affords some assurance, but it lacks exactness. (See refs. D4 and D10.)

THERMAL STRESSES

The straightforward technique for analyzing structure for thermal stresses is found in many standard textbooks. It is also rather easily used for composite structures, where the differences in thermal expansion coefficients, moduli of elasticity, and material thickness are the principal variables. The main difficulty associated with thermal stress analysis is the analytical determination of the temperature distribution, which is tedious when done manually. However, with computerized techniques good estimates can be obtained rapidly. (See refs. D2 and D11 to D14.)

RADIATION SHIELDING

The work associated with radiation shielding may be divided into three major areas of concern: (1) The distributions of dosages to be expected (depending on calendar year and month, location in space, orientation of axes, etc.); (2) the representative allowable dosage levels for spacecraft components (depending on time of exposure, flux, etc.); and (3) the least weight, least cost, or most effective method for shielding. Measurement of dosages and their distributions with time is progressing but is limited by the number of satellites and space probes (from which such data must be derived). Allowable dosages for components are being determined by tests and experience with satellites traversing the Van Allen belts. The major design problem is that of providing enough shielding at the right time and place and at a cost and weight that are appropriate to the mission objectives. The present trend is to predict when radiation levels will increase and to take adequate measures (i.e., reorient spacecraft) to allow use of minimum-weight shielding. (See refs. D2 and D4.)

GENERAL ELASTIC ANALYSES

General elastic analyses covering a broad class of problems are well defined and relatively simple to use. All elastic analyses use the following assumptions: (1) Stress is proportional to strain (Hooke's Law), (2) the material is homogeneous, and (3) the deflections are small in comparison with the original dimensions. Many of the references contain sufficient theory for performing the analyses. The major improvement is the use of computers for complex structural configurations. (See refs. D2, D10 to D12, D13, and D15 to D22.)

COMPUTERIZED ELASTIC ANALYSES

The application of computers to complex elastic analyses has permitted investigations that were once considered too time consuming and costly. The computerized techniques make an important assumption in addition to those stated in the preceding subsection on general elastic analyses; this basic principle is that, when idealized, any structure, however complex, may be broken into sufficient numbers of substructures (bars, panels, and joints) which are amenable to computer analysis. The three principal problems are (1) representative idealization, (2) an adequate "bookkeeping" system, and (3) the time, cost, and capacity of existing computers. However, computerized elastic analyses (which are being expanded to inelastic analyses) are a major advance in structural engineering. (See refs. D3 and D23 to D26.)

TIME-DEPENDENT ANALYSES

Viscoelastic and creep analyses are being applied on a regular basis in industry today, for example, in the analysis of solid propellant grains. Because of the detail involved, these analyses also lend themselves to computerization and thus share many of the problems of computerized elastic analyses. Two additional problems under investigation are (1) determination of representative physical properties and (2) determination of realistic failure criteria. With adequate safety factors these analyses provide assurances unobtainable in the past, and, as the state-of-the-art develops, these safety factors can be adjusted proportionately. (See refs. D4 and D21.)

INTERNAL PRESSURE

The present techniques for discontinuity analysis of thin-walled ($R/t > 10$) pressure vessels have proven to be accurate to within 5 to 10 percent. The latest advancement in this technique is computerization. Areas presenting the most problems are thick-walled vessels and bosses in thin-walled vessels, where stress distribution is to be determined. The use of photoelectric analyses provides an effective technique for investigation of thick-walled structures under pressure. (See refs. D10, D11, D20, and D27.)

AEROELASTIC EFFECTS

Design and analysis of rigid-body flight loads may involve errors of 50 to 100 percent if aeroelastic effects are not considered. By using the structural rigidity (EI) as a basic measure of resistance to aeroelastic effects, computerized analytical techniques can evaluate adequately the structural response and hence the change to rigid-body flight loads. (See refs. D11 and D28.)

EXTERNAL THERMAL ENVIRONMENT

Before thermal stresses in internal structure are determined, it is necessary to determine the external thermal environment due to high temperature trajectories and externally induced thermal effects (e. g., solar flares). Techniques presented in the references yield good first-order approximations of the thermal environment. The more tedious task of determining the circumferential temperature distribution requires greater time and lacks exactness. (See refs. D2, D4, and D29.)

GUST AND WIND SHEARS

Traditionally, gust and wind shears have been determined by means of testing. References D29 and D30 provide the values of the applied loads and the methodology for structural analysis appropriate to these loads.

EXTERNAL PRESSURE

The determination of the value of the maximum external pressure created by flow over a surface of revolution is well covered in the literature. The major problem in accurate determination of the pressing stresses is due to the unsymmetrical circumferential distributions which are difficult to qualify exactly. This problem and the related one of structural buckling due to unsymmetrical pressure loading are currently under investigation. (See refs. D2, D4, D31, and D32.)

RIGID-BODY FLIGHT LOADS

The techniques used to determine rigid-body flight loads are found in intermediate textbooks on stress analysis or mechanics. The loads generated are only as accurate as estimates of thrust levels, drag coefficients, speed, and especially weight distribution and total weight. Where these are accurately known, computations are usually accurate to within 5 to 10 percent. (See refs. D2, D11, and D17.)

NOISE

References D29, D30, D33 and D34 give a comprehensive methodology for approximating noise levels. The generation of noise is subject to many variables (configuration, rigidity, air pressure, density, etc.), and therefore highly accurate determinations are difficult. Another problem is the determination of the distribution both externally and internally, longitudinally and circumferentially. At present, all approximate analyses must be verified by test and measurement.

VIBRATIONS

The three major problems are (1) accurate prediction, (2) adequate theoretical analysis, and (3) ability to perform representative tests. The most common methodology specifies a sinusoidal environment in place of and hopefully encompassing the random environment. Vibration tests are performed to determine the resonance points, and then guidelines are used to insure that these resonance points are damped out in the operating region; this method is costly and time consuming, but necessary. (See refs. D2, D29, and D30.)

METEORITE BOMBARDMENT AND PROTECTION

Currently, the two major efforts are determinations of (1) meteorite sizes and impact velocities and (2) the maximum amount of additional structural weight required for protection. The large amount of statistical data from the space program is being related to periods of activity, location in space, composition, etc. The analytical technique for determining the penetration effect on structure is presented in references D2, D29, and D30.

FATIGUE

On long missions, the problem of fatigue will be of major concern. To date there is no unified theory for accurately predicting fatigue. Research seeks to understand the failure mechanism and the causes. The effort on dislocation theory seems promising; however, this work must be developed before it applies to the R & D analysis of complex structures. Common approaches are contained in references D4, D11, and D35.

REFERENCES

D1. Anon.: Strength of Metal Aircraft Elements. MIL-Hdbk-5, Armed Forces Supply Support Center (Washington, D.C.), May 1, 1963.

D2. Purser; Faget; and Smith: Manned Spacecraft: Engineering Design and Operation. Fairchild Publ. (New York, N.Y.), 1964.

D3. Anon.: Computer Prediction of Environmental Effects on USAF Material. FDL-TDR-64-107, Flight Dynamics Lab., Res. and Tech. Div., U.S. Air Force Systems Command, Wright-Patterson Air Force Base, Oct. 1964.

D4. Glasstone, S.: The Effects of Nuclear Weapons. U.S. Atomic Energy Comm., Apr. 1962.

D5. Kurschner, H. E.; and Brunn, E. R.: A Parametric Study Concerning the Structural Factor of Safety for Aerospace Vehicles. Rept. No. RTD-TDR-63-4084, United Aircraft Corporate Systems Center (Farmington, Connecticut), United Aircraft Corp., 1964.

D6. Freudenthal, A. M.: Aspects of Reliability Under Conditions of Elevated Temperature Creep and Fatigue. Contract AF 33/616/-6288, Ohio State Univ. and Wright-Patterson Air Force Base, Mar. 1963.

D7. Bouton, I.: The Implementation of Reliability Concepts in Structural Design Criteria. Paper No. 64-571, presented at Fourth Cong. of Int. Council Aeron. Sci. (Paris, France), Aug. 1964.

D8. Klein, L. V.: The Use of Stochastic Theory in Optimum Structural Design. M.S. Thesis, Univ. of Calif. at Los Angeles, June, 1965.

D9. Broding, W.; Diederich, F.; and Parker, P.: Structural Optimization and Design Based on a Reliability Design Criterion. J. Spacecraft, vol. I, no. 1, Jan. 1964.

D10. Roark, R.: Formulas for Stress and Strain. Third ed., McGraw-Hill Book Co., Inc., 1954.

D11. Abraham, L. H.: Structural Design of Missiles and Spacecraft. McGraw-Hill Book Co., Inc., 1962.

D12. Timoshenko, S.: Elements of Strength of Materials. D. Van Nostrand Co., Inc., 1949.

D13. Shandley, F.: Strength of Materials. McGraw-Hill Book Co., Inc., 1957.

D14. Islinger, J.; and McDowell, E.: Determining Structural Deflections in the Presence of Radiant Heating. First AIAA Annual Meeting (Washington, D.C.), July, 1964.

D15. Kinney, J.: Indeterminate Structural Analysis. Addison-Wesley Publ. Co., Inc. (Reading, Mass.), 1957.

D16. Peterson, R.: Stress Concentration Design Factors. John Wiley & Sons, Inc., 1953.

D17. Peery, D.: Aircraft Structures. McGraw-Hill Book Co., Inc., 1950.

D18. Abraham, L.: Space Technology. Volume I — Spacecraft Systems. NASA SP-65, 1965.

D19. Anon.: Composite Constructure for Flight Vehicles — Design Procedures. MIL Hdbk. 23, Armed Forces Supply Support Center (Washington, D.C.), 1961.

D20. Bruhn, E.: Analysis and Design of Aircraft Structures. Vol. I — Analysis and Design of Stress and Strain. Tri-State Offset Co. (Cincinnati, Ohio), 1958.

D21. Stowell, Elbridge Z.: A Unified Theory of Plastic Buckling of Columns and Plates. NACA Rept. 898, 1948.

D22. MacNaughton, J.: Unfurlable Metal Structures for Space Craft. Paper presented to Astron. Symp., Canadian Aeron. and Space Inst., Mar. 1963.

D23. Denke, P.: A Computerized Static and Dynamic Aircraft Structural Analysis System. Paper presented at SAE Int. Automotive Cong. and Exposition (Detroit, Mich.), Jan. 1965.

D24. Taig, I.: Computer Applications in the Development of Efficient Aircraft Structure. J. Royal Aeron. Soc., vol. 67, Nov. 1963.

D25. Best, G. C.: Completely Automated Weight-Minimization Method for High Speed Digital Computers. J. Aircraft, vol. I, no. 3, May-June 1964.

D26. Ryder, F.: Direct-Analog Computers for Structures. Doc. 461, Republic Aviation Corp. (Farmingdale, L.I., N.Y.), 1961.

D27. Baker, B.; and Cline, G.: Influence Coefficients for Spherical Shells. LMSD-480817, Lockheed Missiles and Space Div. (Sunnyvale, Calif.), Lockheed Aircraft Corp., 1960.

D28. Crandell, S.: Random Vibration in Mechanical System. Academic Press (New York, N.Y.), 1963.

D29. Anon.: Stochastic Disturbance Data for Flight Control System Analysis. ASD-TDR-62-347.

D30. Anon.: Structural Vibrations in Space Vehicles. WADD Tech. Rep. 61-62, Dec. 1962.

D31. Ames Research Staff: Equations, Tables, and Charts for Compressible Flow. NACA Rept. 1135, 1953.

D32. Syvertson, Clarence A.; and Dennis, Davis: A Second-Order Shock-Expansion Method Applicable to Bodies of Revolution Near Zero Lift. NACA Rept. 1328, 1957.

D33. Oslake, J. J.; Haight, N. L.; and Oberste, L. J.: Acoustical Hazards of Rocket Boosters. Vol. I: Physical Acoustics. Tech. Rept. U-108:96, Aeronutronic, Inc., Nov. 30, 1960, (Available from CFSTI as AD 253234.)

D34. Lassiter, Leslie W.; and Hess, Robert W.: Calculated and Measured Stresses in Simple Panels Subject to Intense Random Acoustic Loading Including the Near Noise Field of a Turbojet Engine. NACA Rept. 1367, 1958.

D35. Frank, J. J.: Predicting Fatigue Life of Structures for Random and Sinusoidal Vibrations. Machine Design, vol. 36, June 18, 1964, pp. 203-206.

D36. Grubin, C.: Docking Dynamics for Rigid-Body Spacecraft. AIAA J., vol. 2, no. 1, Jan. 1964.

D37. Newman, M.; and Fonay, M.: Thermal Stresses in Unsymmetrically Heated Circular Rings. Machine Design, Data Sheet, vol. 36, Jan. 1964.

D38. O'Connell, R. F.: A Digital Method for Redundant Structural Analysis. J. Aerospace Sci., vol. 29, no. 12, Dec. 1962, pp. 1414-1420.

D39. Archer, J. S.: Consistent Matrix Formulation for Structural Analysis Using Influence-Coefficient Techniques. Paper No. 64-488, First AIAA Annual Meeting (Washington, D.C.), July 1964.

D40. Gayley, C.; Kellogg, W.; and Vestire, E.: Space Vehicle Environment. P-1335, The RAND Corp., July 7, 1958.

D41. Johnson, F. S.: Satellite Environment Handbook. Second Ed., Doc. 895006, Lockheed Missiles and Space Corp. (Sunnyvale, Calif.), 1961.

D42. Schmit, L. A.; and Fox, R. L.: An Integrated Approach to Structural Synthesis and Analysis. Fifth AIAA Annual Structures and Materials Conference (Palm Springs, Calif.), Apr. 1964, pp. 294-315.

D43. Harris, J. D.; and Lipson, C.: Cumulative Fatigue Damage Due to Spectral Loading. Proc. Third Annual Aerospace Reliability and Maintainability Conf. (Washington, D.C.), June-July, 1964, pp. 589-592.

D44. Haugen, E.: Statistical Methods for Structural Reliability Analysis. Proc. Tenth Natl. Symp. on Reliability and Quality Control (Washington, D.C.), Jan. 1964, pp. 91-121.

D45. Lowe, R. T.: Mechanical Shock, Shock Spectra, Shock Testing and Acceleration. Proc. Annual Tech. Meeting, Inst. of Environmental Sci. (Philadelphia, Pa.), Apr. 1964, pp. 73-87.

Table D1.—Structure Checklist

1. Configuration
   a. Envelope (dynamic and static)
   b. Weight
   c. Inertia and ratio of inertias about different axes
   d. Center of gravity
   e. Relative location of subsystems
   f. Mounting of components
   g. Adapters and separation devices
   h. Appendage experiment provisions
   i. Growth potential

2. Time considerations
   a. Lifetime requirements
   b. Storage before launch
   c. Mission time and environments

3. Output parameters
   a. Minimum deflection of structural elements
   b. Withstand flight loads
   c. Withstand mission environments
   d. Separation equipment
   e. Spin-up angular velocity

4. Input parameters
   a. Flight loads
   b. Separation signals
   c. Environments
      Vibration—sinusoidal, random
      Temperature range
      Radiation

5. Subsystem internal parameters and considerations
   a. Temperature generated by electric equipment
   b. Vibration transmitted through the structure
   c. Shock loading transmitted through the structure
   d. Materials

6. Typical assemblies
   a. Spacecraft body
   b. Spacecraft appendages (solar panels, experiment booms, gravity-gradient booms)

7. System integration
   a. Compatibility for use with booster
   b. Ease of maintenance

APPENDIX E

Guidance and Control

The guidance and control subsystem (which includes attitude control, stabilization, guidance, and flight control for the purposes of this discussion) performs all the pointing and path control functions required by the system. It should be noted that pointing requirements for some portions of a spacecraft, for instance, may be independent of those for the basic vehicle. This situation can occur with elements such as solar panels, antennas, and experiment containers.

SUBSYSTEM PARAMETERS

The basic parameters which describe the required performance of the guidance and control subsystem from the system standpoint are (1) accuracy (the limits within which a pointing direction must be held) and (2) relative stability (the maximum allowable angular rate between the limits).

The subsystem accuracy parameter carries substantially the same connotation as does the system accuracy parameter. The relative stability parameter introduces the specific consideration of the subsystem response to nonnominal inputs and perturbations. That is, in order to maintain the desired accuracy, the response of the subsystem not only must provide the desired accuracy but also must exhibit stable response to spurious inputs. The subsystem "speed of response" parameter is influenced by the allowable drift rate.

A guidance and control subsystem checklist is given in table E1.

SYSTEM RELATIONSHIPS

The system parameters that impose requirements on accuracy and relative stability are primarily (1) payload sensitivities and (2) trajectory. The sensitivities and resolution requirements of the payload sensors impose limits on the errors allowable in their pointing directions and on the maximum relative motion between the sensor and its target. The relative motion aspect brings the trajectory parameter into consideration because the natural relative motion due to the trajectory may influence the relative stability problem. (Table E2 presents some typical current relationships between system requirements and requirements of attitude accuracy and drift rate.)

ANALYSIS TECHNIQUES

Numerous analytical techniques are available that permit the attitude control and stabilization system (ACS) engineer to preview in some limited fashion the effectiveness of a postulated ACS configuration. The central problem is to specify clearly the requirements that characterize the desirable ACS for the application of interest. From the standpoint of dynamic qualities, the control requirements may be categorized into three basic specifications: (1) Relative stability expressed by the percent of the first overshoot and the number of overshoots, the peak value of the closed-loop, output-input amplitude ratio, the gain and phase margins of the open-loop frequency characteristics, etc.; (2) speed of response expressed in terms of time constants (rise or settling time) or in terms of bandwidth (cutoff frequency or frequency of peak overshoot); and (3) accuracy expressed in terms of the allowable error referenced to the controlled variable (maximum, average, or root-mean-square error).

Other factors that influence the dynamics of the ACS can also be investigated to a limited extent via analytical techniques. These factors include the normal variations of the power supply voltage and frequency and the profile of temperature, humidity, and other environmental conditions.

Unfortunately, there is no concise way to represent and demonstrate analytically the overall effectiveness of the optimum, near-optimum, or even the desirable ACS configuration. Often the selected ACS design is not based on performance, but on reliability, weight, or cost considerations.

References E1 to E7 are more recent general publications containing compilations of analysis and design techniques for space-vehicle, attitude-control systems. Specific analytical techniques are presented in the following subsections; separate groupings are made for linear and nonlinear control systems, because the analysis varies for these two systems. Additional references for further details are also given.

LINEAR SYSTEMS

Five basic techniques are most frequently applied in control-system analysis to investigate stability characteristics. The underlying assumptions for these techniques are: (1) Most control systems may be described approximately by a linear differential equation with constant coefficients and (2) a system so described is stable if the characteristic equation of the system contains no positive real roots or complex roots with positive real parts.

Routh and Hurwitz Criterion

The Routh and Hurwitz method is a test to determine the number of roots with positive real parts in the characteristic equation of the control system. The transfer function in the control system is expressed in the form of a fraction with polynomials of s in the numerator and denominator. The stability of the system is dependent on the location of the zeros of the denominator polynomial, which is of the general form

$$D(s) = a_n s^n + a_{n-1} s^{n-1} + a_{n-2} s^{n-2} + \ldots + a_0$$

The zeros of the polynomial are found as solutions of the equation $D(s) = 0$.

The major disadvantage of this technique is that it does not determine the degree of instability or indicate what parameters might be changed to improve the system stability characteristics. (For a step-by-step application, see ref. E3, pp. 309-314.)

Nyquist Stability Criterion

The Nyquist technique is applied by constructing a polar-plane plot of the open-loop transfer function that takes the form

$$G(s)H(s) = \frac{\left(a_0 + \ldots + a_m s^m\right)\left(c_0 + \ldots + c_j s^j\right)}{\left(b_0 + \ldots + b_n s^n\right)\left(d_0 + \ldots + d_k s^k\right)}$$

The Nyquist stability criterion may be used for analysis of multiloop systems; by starting with the innermost loop and proceeding outward one can determine the types of compensation required to improve the stability characteristics of a system.

Bode Diagram

The Bode diagram presents the same information as that in the Nyquist diagram in a different form. The Bode diagram of a given frequency function consists of two curves: the magnitude curve, which is a plot of the magnitude of the function in decilogs against the logarithm of the frequency; and the phase curve, which is a plot of the phase angle of the function in degrees against the logarithm of the frequency. The relative ease of construction and the capability of accepting a wide range of values with the logarithmic scale are advantages of the Bode diagram. (See ref. E1, pp. 2-21 through 2-29 and 2-35 through 2-56.)

Nichols Chart

The Nichols chart is a graphical aid used in the analysis of open-loop frequency response and closed-loop frequency response. (See ref. E3, pp. 350-351.)

Root-Locus Method

The root-locus method is particularly applicable to the analysis of transient response corresponding to a given frequency response. This technique involves the construction of a graphic polar plot of the location of the closed-loop poles as a function of a gain factor. The degree of system stability is determined by the change in the position of the closed-loop poles as the gain factor is varied. The major disadvantage of this method is that it is time consuming.

NONLINEAR SYSTEMS

If the nonlinearities of a system are not large, linearized approximation techniques are often applied. However, in nonlinear systems certain phenomena occur that have no analogous correspondence in linear systems. Brief discussions of four commonly used techniques follow. More complete compilations of techniques are to be found in reference E4 (pp. 3.43 through 3.74) and reference E5.

Describing Functions

Describing functions are analytical tools based on sinusoidal responses of nonlinearities. A describing function is the ratio of the amplitude of the fundamental component of a nonlinearity to the amplitude of the sinusoidal input to the nonlinearity. There are several disadvantages to these functions: (1) Time-varying elements are not considered part of the nonlinearity, (2) generally, only one nonlinearity can be properly accounted for; (3) transient response of the system is not included in the analysis; and (4) if the input to the nonlinearity is a sinsoidal signal, only the fundamental component of the output may influence the input signal through the control loop. (See refs. E8 to E11.)

Phase-Space Technique

The phase-space technique is only concerned with second-order systems. The optimum response is defined as the response that is completed in the minimum time with no overshoot. The phase-space technique is a graphical solution of the following equation:

$$\frac{d^2x(t)}{dt^2} + a\left(x, \frac{dx}{dt}\right)\frac{dx(t)}{dt} + b\left(x, \frac{dx}{dt}\right) = 0$$

A plot of dx/dt as a function of x is constructed for various values of initial conditions.

Limitations to this technique are as follows: (1) It applies to second-order systems only, (2) only the time response to the initial conditions of the systems can be explored, and (3) the nonlinearities can only be signal dependent. (See refs. E12 to E14.)

Lyapunov Techniques

The objective of the Lyapunov techniques is to determine whether a given system is stable, and Lyapunov's method of examining the stability of a set of nonlinear differential equations is used. The major advantage is that the nonlinear differential equations that describe the system need not be solved. (See refs. E15 and E16.)

Numerical Solution Methods

Numerical methods are used when the transient response of the system is needed. Analog and digital computers play a major role in the analysis of nonlinear systems because they not only yield answers to the frequency-response problems but also indicate the allowable limits of nonlinearities and limits due to functional and environmental variations of the elements comprising the control system.

REFERENCES

E1. Truxal, John G., ed.: Control Engineers' Handbook. McGraw-Hill Book Co., Inc., 1958.

E2. Smith, Otto J. M.: Feedback Control Systems. McGraw-Hill Book Co., Inc., 1958.

E3. Newton, George C., Jr.; Gould, Leonard A.; and Kaiser, James F.: Analytical Design of Linear Feedback Controls. John Wiley & Sons, Inc., 1957.

E4. Roberson, Robert E., ed.: Methods for the Control of Satellites and Space Vehicles. Volume II: Control System Mechanization and Analysis. WADD Tech. Rept. 60-643, Wright-Patterson Air Force Base, July 31, 1960.

E5. Ergin, E. I.; Norum, V. D.; and Windeknecht, T. G.: Techniques for Analysis of Nonlinear Attitude Control Systems for Space Vehicles. Volume IV: References and Bibliography. ASD-TDR-62-208, Wright-Patterson Air Force Base, June 1962.

E6. West, J. C.: Analytical Techniques for Nonlinear Control Systems. D. Van Nostrand Co., Inc., 1961.

E7. Anon.: Proceedings of the Optimum System Synthesis Conference. ASD-TDR-63-119, Wright-Patterson Air Force Base, Feb. 1963.

E8. Kochenburger, R. J.: A Frequency Response Method for Analyzing and Synthesizing Contractor Servomechanisms. Trans. AIEE, vol. 69, pt. I, 1950, pp. 270-284.

E9. Kochenburger, R. J.: Limiting in Feedback Control Systems. Trans. AIEE, vol. 72, pt. II, 1953, pp. 180-194.

E10. Halstenberg, R. V.: Combined Hysteresis and Nonlinear Gains in Complex Control Systems. Symp. on Nonlinear Control, Aug. 1957.

E11. Grief, H. D.: Describing Function Method of Servomechanism Analysis Applied to Most Commonly Encountered Nonlinearities. Trans. AIEE, vol. 72, pt. II, 1953, pp. 243-248.

E12. Hung, J. C.; and Chang, S. S. L.: Switching Discontinuities in Phase Space. IRE Natl. Conv. Record, pt. 4, 1957.

E13. Kuba, R. E.; and Kazda, L. F.: A Phase Space Method for the Synthesis of Nonlinear Servomechanisms. Trans. AIEE, vol. 75, pt. II, Nov. 1956, pp. 282-289.

E14. Tsien, H. S.: Engineering Cybernetics. McGraw-Hill Book Co., Inc., 1954, ch. 10.

E15. Kalman, R. E.; and Bertram, J. E.: Control System Analysis and Design Via the Second Method of Lyapunov. Trans. ASME, vol. 82, J. Basic Eng., June 1960, pp. 371-393.

E16. Antosiewicz, H. A.: A Survey of Lyapunov's Second Method. Contributions to the Theory of Nonlinear Oscillations. Ann. Math. Studies (Princeton, N.J.), vol. 4, no. 41, 1958.

Table E1.—Guidance and Control Subsystem Checklist

1. Configuration
    a. Stabilization, active: spin
    b. Stabilization, passive: gravity gradient, magnetic
    c. Attitude control sensors; Earth, Moon, Sun, star sensors (intensity or horizon)
    d. Attitude control error signal amplifiers
    e. Attitude control actuators: thrust devices, reaction wheels, magnetic devices
    f. Weight, size, center of gravity
    g. Manual axis control (joystick)

2. Time considerations
    a. Acquisition time for attitude control sensors; reacquisition time in the event of loss of signal
    b. Reliability — mission time

3. Input parameters (functional requirements)
    a. Requirement
        (1) Spacecraft attitude control per axis
        (2) Solar array attitude control per axis
        (3) Payload attitude control per axis
        (4) Stabilization per axis
        (5) Trajectory correction — midcourse maneuver
        (6) Special attitude control requirements at encounter
        (7) Initial angular velocity about each axis during acquisition mode
        (8) Angular velocity about each axis during tracking mode
        (9) Accuracy of alinement of each axis during tracking mode
        (10) Tracking override capability (command system signal to stop tracking and start acquisition mode) per axis
        (11) Solar pressure
        (12) Vibration environment: sinusoidal, random
        (13) Temperature range
    b. Trajectory-determined parameters
        (1) External perturbations (Earth, Moon, Sun, etc.)
        (2) Sensor scanning range (angular)

4. Subsystem internal parameters and considerations
    a. Method of and specifications for attitude sensing
        (1) Earth horizon scanning
        (2) Sun sensing
        (3) Star tracking
        (4) Inertial sensing
    b. Method of and specifications for rate feedback
        (1) Rate gyros
        (2) Derived rate
    c. Method of and specifications for actuation
        (1) Cold gas expulsion

Table E1.—Guidance and Control Subsystem Checklist—Continued

    - (2) Reaction wheel
    - (3) Magnetic torquer
  - d. Method of and specifications for stabilization
    - (1) Solar vane
    - (2) Spin stabilization
    - (3) Gravity gradient
  - e. Control methods during midcourse maneuver (autopilot, etc.)
  - f. Discrimination requirements for sensors; light gates, stellar intensity gates, IR wavelength discrimination for Earth horizon sensors
  - g. Combination or separation of electronics for each channel (axis for which orientation required)
  - h. Error signal amplification requirement
  - i. Reaction wheel parameters
  - j. Thrust device parameters
  - k. Redundancy requirements in view of reliability requirements and system configuration
  - l. Spin stabilization; angular speed plus tolerance
    - (1) Spin speed resolution
    - (2) Spin-axis orientation accuracy
    - (3) Despin capability
  - m. Gravity gradient
    - (1) Orbital inclination
    - (2) Minimum number of inversions
    - (3) Eccentricity change capability
    - (4) Damping capability to reduce initial tumbling rates, damping capability to damp-out transient disturbances
    - (5) Limit of steady-state librations from all natural disturbance torques

- 5. Typical equipment assemblies
  - a. Sun acquisition and tracking
    - (1) Optical system
    - (2) Sun sensors in pitch, yaw (acquisition and tracking)
    - (3) Sun gate
    - (4) Sun gate sensors
    - (5) Command system relays
    - (6) Pitch and yaw gyros
    - (7) Gyro transformer rectifier
    - (8) Pitch and yaw preamplifiers
    - (9) Pitch and yaw switches (actuator controllers)
    - (10) Switching amplifier compensator (derived rate) pitch and yaw
    - (11) Derived rate reset (pitch and yaw)
    - (12) Diode switch (pitch and yaw)
    - (13) Gas valves, nozzles (pitch and yaw)
  - b. Star acquisition and tracking
    - (1) Acquisition gate
    - (2) Optical system

Table E1.—Guidance and Control Subsystem Checklist—Concluded

- (3) Star sensor
- (4) Mode command relays
- (5) Roll preamplifier
- (6) Roll switch
- (7) Roll switching amplifier compensator (derived rate)
- (8) Roll diode switch
- (9) Gyro power supply (intermittent load inverter, 400 ~ 3Ø-gyro transformer rectifier)
- (10) Roll gyro
- (11) Roll gas valves and nozzles

c. Infrared horizon sensors (Earth, Moon, other planets)
- (1) Sensor
  - (a) Temperature sensor: thermistor bolometer, thermopile
  - (b) Photoemissive detector: photomultiplier, Vidicon
  - (c) Photoconductive detector: lead sulfide crystal
- (2) Scanning device
  - (a) Rotating prism
  - (b) Rotating mirror
  - (c) Positor mirror
- (3) Field current generator (positor)
- (4) Dither oscillator (positor)
- (5) Schmitt trigger
- (6) Position amplifier
- (7) Logic circuitry
- (8) Voltage regulator

d. Midcourse maneuver
- (1) Turn command generator
- (2) Autopilots
- (3) Autopilot power supply
- (4) Propulsion system (midcourse engine)
- (5) Spacecraft timer
- (6) Thrust initiation (midcourse engine)
- (7) Thrust termination (midcourse engine)

Table E2.—Typical Attitude Accuracy and Drift Rate Requirements

System mission	Attitude references	Accuracy and drift rate requirements
Observation of celestial objects from Earth orbit	Line of sight to observed object, direction perpendicular to line of sight	Line of sight to observed object, ± 0.1 sec; rotation about line of sight, ± 1 min
Measurement of physical quantities out to 60,000 miles while in Earth orbit	Local vertical, direction perpendicular to orbit plane, line of sight to Sun	Local vertical, ± 2° Orbit plane, ± 5° Line of sight to Sun, ± 20°
Solar measurements from low Earth orbit	Line of sight to Sun	Oriented experiments line of sight to Sun, 1 min of arc
Meteorological study of Earth's atmosphere from Earth orbit	Local vertical, direction perpendicular to orbit plane	Point accuracy of TV and IR sensors, ±1° (drift must be less than 0.5°/sec)
24-hr satellite communications	Local vertical	Earth-pointing accuracy of directional antenna, ±1°
Low-to-medium-altitude communications satellites	Local vertical	Radiation axis of symmetry, ±5° of local vertical
Venus probe	Roll axis lies along Sun-probe line, pitch axis perpendicular to Earth-probe line	Pointing accuracy in reference directions (cruise mode): pitch and yaw, ±1°; roll, ±3.7° (at Earth-probe-Sun angle of 20° to 160°) Pointing accuracy of high gain antennas, ±70 mrad (at up to 60,000,000 km) Pointing accuracy of thrust vector (thrust mode), ±80 mrad
Lunar probe		Orientation of solar cells, 10° Orientation of high-gain antenna, 2°

☆ U.S. GOVERNMENT PRINTING OFFICE : 1968 O—285-150

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Notes, and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D.C. 20546