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ANALYTICAL MODELING
OF
SPACECRAFT POWER SYSTEMS

FINAL REPORT

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Prepared for

National Aeronautics and Space Administration

Goddard Space Flight Center
Greenbelt Road
Greenbelt, Maryland 20771

Contract NAS5-26651

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16. Abstract

This report covers work performed on the Analytical Modeling of Spacecraft Power Systems Study.

Task 1 - Power System Modeling Techniques

1. Literature search - over 200 documents were reviewed for applicability to modeling techniques. Each model's capability/limitations/constraints were determined.
2. Industry survey - telephone contacts were made to industry to determine state-of-the-art modeling techniques.
3. Ideal system modeling techniques were defined.

Task 2 - Component Modeling Techniques

1. Existing models of solar arrays, batteries, shunt regulators, DC-DC converters and distribution networks were analyzed and the adequacy of each model was determined.

Task 3 - Comprehensive Power System Analytical Modeling Approach

1. Testing required to obtain accurate component models was determined
2. Procedures were outlined for developing a comprehensive power systems model.

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FOREWORD

Study Tasks 1, 2, and 3 were performed by the following personnel

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Task 3 - Comprehensive Power System Analytical Modeling Approach

All of the above contributed to Task 3.

CONTENTS

EXECUTIVE SUMMARY

Power subsystem analytical models have been used by government and industry for spacecraft design to perform configuration trade-offs, determine performance, specify thermal and electrical interfaces, verify stability and determine electromagnetic compatibility margins. Frequently, models provide analytical data in support of in-orbit anomaly resolution or predict future capability considering degraded operation.

Models will play an important role in design and verification of future large space platform and space station power subsystems. It is here that the need is most critical because design verification through integrated systems tests will be prohibitively expensive or impossible.

Consider a large space station with an orbital lifetime of 10 to 30 years. Experiment and power source modules having power characteristics unknown at the time of space station power system design will be launched into orbit by the STS and attached to the orbiting station. It is planned that new modules be attached to the station many years after station launch. Discovering power system incompatibility at the time of attachment will be expensive since an STS flight must be repeated if in-orbit repair is not possible. Instability of the power bus due to incompatibility may result in a dangerous condition for the entire station.

Therefore, a comprehensive power system model which is more accurate and flexible than today's models is required to verify through analysis, rather than integrated system tests, large power system performance and stability. This is a significant departure from today's integrated system verification through testing prior to launch. This report addresses improvements needed in current models and provides a roadmap to development of a comprehensive power system model.

SCOPE

This study examines spacecraft power subsystem models as documented in the literature and as determined from a survey of government agencies and industry. The state-of-the-art is compared to desired comprehensive power subsystem model attributes. Weaknesses or inadequacies in current models are identified as areas for improvement. An approach to comprehensive power subsystem model development is presented together with recommendations for test data base development required to verify and validate the model.

OBJECTIVES

The study objectives were to determine the capabilities of power system modeling techniques presently used by government and industry; to characterize available AC modeling capabilities for power system components typically utilized in 2-15 kW power systems; to delineate component modeling technique improvements, permitting accurate simulation of AC and DC characteristics of power system components; to develop an approach for orderly accomplishment of necessary analyses and device testing which support development of a comprehensive power system analytical tool.

SUMMARY OF RESULTS

We recommend a set of four fundamental model types, each of which performs a different, essential task. Together this program set comprises a comprehensive power subsystem model.

1. A power subsystem sizing and synthesis program, capable of estimating cost, mass, volume, area, and other attributes of a single-point design. This would be used only during the conceptual design phase of a spacecraft program.

2. A DC model of the power subsystem and its interfacing subsystems. This is used during phases* B, C, D, and E of the spacecraft program for studies of power consumption, responses of the subsystem to environmental changes, and prediction of steady-state voltage and current throughout the subsystem.

3. A small-signal AC model of the power subsystem and its components. This is used in phases C, D, and E for the purposes of estimating subsystem and intercomponent stability, bus impedance, and for determination of responses to small-signal transients.

4. A large-signal transient model used during phases C, D, and E of the program for the purpose of determining the response of the subsystem to large transients such as state changes and faults.

In the preceding paragraphs, model requirements have been defined. In the following are defined certain essential attributes or characteristics which all of the models must have in common to create a comprehensive modeling and analysis capability.

*The mission phases are defined in Section 3.0

a) Commonality and compatibility: Each of the types of models must maintain a commonality of reference with all of the others; i.e., they must all predict the same attributes and performance for the same subsystem.

b) Modularity: Each of the components of the power subsystem should be modeled as an independent module having the following attributes:

- Capable of being operated independently as a component model.
- Capable of being integrated into a power subsystem model.
- Capable of replacing or being replaced by an alternative model having different input requirements.
- Data base - each module must be provided with an independent data base specifically suited to its own needs.

c) Efficient use of both core memory and computation time.

d) Verifiability: Models should be verifiable as independent modules and as a complete integrated power subsystem. Verification data base must be provided independent of the model input data base.

e) Operational simplicity: The models must be designed for use by a working power subsystem engineer whose understanding of the program and computational facility are limited. Clearly stated, complete user documentation is essential to the successful use of such a complex set of models.

Consideration will also be given to the development of a program control format based upon MENU selection of program functions. This is desirable on systems containing CRT displays, and the potential advantages of such a system in terms of user simplicity and compatibility are great enough to deserve consideration.

Models may be divided into two categories: existing models which require only adaptation to the program structure, and new or improved models which require development. New model development proceeds through trade studies to select the approach to be used, development of the mathematical or logical algorithm, and coding. Trade studies and algorithm development can be done prior to or concurrently with the program structure development. Coding must await the development of program and data base structure before it can be accomplished efficiently.

For those models whose concepts are well understood, a data acquisition program can be initiated independently of the development of the final model code. However, where the model algorithms have yet to be developed, the form of the data required, and in some cases, the kind of data required to provide an input to the model are unknown or ill-defined. For these cases, it will be necessary to defer the development of a data acquisition program until the algorithm to be used has been defined.

Figure 3-3 (page 3-13) shows a suggested schedule for model and data base development. This schedule is flexible, and is capable of responding to variations in funding availability, NASA priority of interest and other factors.

1.0 INTRODUCTION

The growth in the size and complexity of spacecraft power systems, coupled with higher equipment switching frequencies and an increase in payload sensitivity to bus noise, has focused attention on a current major deficiency - the ability to design and test large power systems. Existing analytical models of spacecraft power systems have not kept abreast with these evolving requirements and, as systems grow in size, there are practical limits in the ability to ground test fully integrated power systems. Recent anomalous behavior experienced on both NASA and Air Force satellites underscores the need for better modeling techniques for both the design of stable power systems and the efficient management of power during the mission. The development of accurate analytical modeling techniques was cited as a highest priority item by the Power Subsystems Panel at the OSTA/OAST Flight Technology Improvement Workshop in 1979.

Uncertainties in the analytical modeling of power systems are derived from two basic sources: first, the component characteristics, especially the AC characteristics, are unknown or at best poorly defined. Consequently, DC models are used for most analyses, coupled with approximations for solar array simulations. Secondly, all-up systems testing with illuminated solar arrays has become impractical for multikilowatt systems due to the large area of illumination required and the risk of damage to the fragile lightweight structure deployed in a gravitational field. These problems will be significantly aggravated for the even larger systems projected for the future.

In those cases in which the inadequacy of DC power system modeling has been recognized, dynamic analyses have been performed. However, these analyses have proven to be both time consuming and expensive. In addition, the analyses have been handicapped by unknown or uncertain component characteristics. Only through a more thorough knowledge of both the AC and DC characteristics of the devices which make up the power system components can the AC/DC characteristics of the components be accurately simulated. With the accurate modeling of the components, future power system design and evaluation can be accomplished by the synthesis of the analytical system model. The development of the analytical model for power systems will also provide for accurate simulation of the solar array and battery, permitting realistic ground testing of the system and reliable system development. This development would facilitate the analysis of several approaches which could satisfy a set of given requirements, and allow optimization of the overall power system.

The study was divided into three basic tasks which are documented in this final report:

a) Task 1 - Power System Modeling Techniques

Conduct a state-of-the-art survey combined with a comprehensive review of power system computer modeling techniques/approaches used by industry for performing an accurate simulation of system performance of both earth-orbiting and interplanetary probe spacecraft. Identify the significant capabilities and drawbacks of each analytical technique, along with the areas in modeling which require significant improvements. Determine the simulation adequacy of dynamic load changes on the power bus performance.

b) Task 2 - Power System Component Modeling

Determine the adequacy of each AC and DC characteristic modeling technique for the components typically used in power systems operating in the 2 to 15 kW range. The improvements required in each of the modeling techniques will be specified, along with the degree of uncertainty associated with the present modeling approach.

c) Task 3 - Comprehensive Power System Analytical Modeling Approach

Outline the necessary procedures to permit the development of a comprehensive power system analytical model. This will occur after the review of the available analytical modeling techniques and will also include the areas in modeling which will require upgrading. Also to be identified are any power system component or device testing required to assemble the AC and DC characterization data base from which the component and power system models can be derived. The recommended or suggested order in which testing and analysis should be performed will be provided.

1.1 Study Objectives and Tasks

The primary objective of this initial phase of the power subsystem modeling development is to define the requirements of a comprehensive model (or set of models) for solar array - battery electric power subsystem. To accomplish this the study was divided into the following tasks:

Task 1. Determine the capabilities (and deficiencies) of the power subsystems modeling techniques presently in use.

Task 2. Determine the improvement required of each model.

Task 3. Define the requirements of a complete power subsystem model, and the procedures for development of a model and data base.

1.2 Study Results

1.2.1 Tasks 1 & 2 - Power Subsystem Models Presently in Use and Required Improvements

1.2.1.1 Steady State DC Performance Models

It is in this class of complete power subsystem models that the most extensive body of work was encountered. Most models are similar in nature, consisting of the major power subsystem components modeled empirically and tied together by a spacecraft-unique model of power subsystem logic. They have no AC or electrical transient capability, although some are capable of simulating thermal transients.

1.2.1.2 Small Signal (Linearized) AC Models

Such models are used primarily for stability analysis. Individual component Thevenin-equivalent linearized models are available for most components, but vary considerably in validity and applicability. Combinations of two or more such models have been made for specific stability analyses. All-up power subsystem models of this type have not been found.

1.2.1.3 Transient (Non-Linear) Models

Transient models of adequate accuracy are available for only a few power subsystem components. An all-up transient model of a direct energy transfer power subsystem has been simulated on a digital computer (Reference 67).

1.2.1.4 Power Subsystem Component Models

Batteries. Several models of battery performance have been encountered in the literature.

1. Look-up table model (A-28)*

2. Equivalent circuit model (A-27)

3. Empirical waveshape model

4. COMSAT/Billerbeck model (A-22)

The look-up table model is a DC steady-state model (thermal transients can be followed), and has been widely used by many companies. The model needs improvement in efficiency modeling and heat generation rate com[illegible]ation

The models are not universally applicable. Different data bas[illegible] must be used for different orbits, and to simulate battery we[illegible]t. [illegible]ete models are available only for NiCd batteries. N[illegible] model of NiH_2 or AgH_2 was found.

The equivalent-circuit model is also a steady-state model. It has the advantage of greatly reduced data storage requirements. As far as can be determined, this model has not been pursued since being reported in 1970.

The empirical waveshape model also has not been pursued after initial development. The pressure predictions of the model are not accurate and require improvement. It appears to be valid only for low earth orbit (LEO) applications.

The COMSAT/Billerbeck model (Reference 22) considers only discharge and therefore would have to be expanded if it is to be included in an overall power system model.

Power Distribution

Two modeling approaches were encountered:

1. Optimization based on mass

2. Optimization based on cost

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*A-XX refers to Appendix A document reference.

In the first case, the existing models do not account for fuse, switch and connector losses, which in some cases could override conductor losses. In the second case, the optimum conductor cross sectional area is determined as a function of the cost of the conductor, energy storage, solar array, thermal control and power conversion. Both models can be adapted for use by an overall systems model. Neither is suitable for use as a performance model, either AC or DC.

Solar Array

Because of the increasing size and reduced specific mass of future solar arrays, all-up testing may not be feasible, and accurate modeling becomes increasingly important.

Existing steady-state DC models of solar array electrical performance are generally very good, although shadow effect treatment and multiple sun illumination levels both require improvement.

Small-signal AC models are available, giving good first-order results. They are relatively easy to use. The needed data can be measured or computed without great difficulty. Considerable improvement in model results should be achievable by the addition of parasitic wiring capacitance, capacitance, cell-to-substrate capacitance, and photo-inductance effects to the model.

Three general approaches were found:

1. Model each cell individually.
2. Model the array as a multiple of a single cell.
3. Combinations of 1 and 2.

The first approach found provides a highly accurate performance analysis of an existing solar array, but requires voluminous data input and excessive measurement and computation cost.

The second presumes a single, uniform cell characteristic. Because of the large number of cells and their well controlled characteristics, this approach models the characteristics of the array (without failures) nearly as well as the first. However, its handling of an array containing failed or shadowed cells is inferior to that of the first.

No large-signal transient models were found.

DC-DC Convertor

Three approaches to converter modeling were identified:

1. Discrete average

2. Discrete time domain

3. General circuit analysis

The discrete average model is simple, easy to use, and accurate up to half of the switching frequency for AC analysis. The discrete time domain model is a detailed internal working model, useful for final design check. The general circuit analysis approach is versatile and easily expandable, however the cost increases with increasing complexity.

Shunt Regulators

Steady-state DC models have been made for two types of shunts, the partial-linear, and the full sequential segmented linear shunt, used in DSCS II, and HEAO, respectively.

An analytical model for AC small signal analysis does exist for the shunt regulator. This "shunt loop gain model" has the advantages of simplicity in final form, usefulness in predicting shunt subsystem stability, and ease of application to computer programs which accept s-domain transfer functions or differential equation inputs. It has, however, substantial limitations, some of which are as follows:

- Significant analytical effort is required to establish the model.
- It is difficult to alter the model.
- It does not provide large signal transient prediction capability.
- No power dissipation or element failure analysis is provided.
- It is applicable only in the linear operational mode.
- No control output prediction is provided.

To provide adequate modeling capability for the shunt (or partial shunt) regulator in a satellite power generation subsystem using a Solar Array Switching Unit (SASU), a network approach to modeling may be more appropriate. The equivalent network approach has the advantages of requiring minimal initial effort, is easily altered, provides easy prediction of individual component behavior, and allows large signal, small signal and DC performance analysis, as well as power dissipation predictions. The network approach has disadvantages, in that a sophisticated computer program with large network capacity is required, and that parameters for individual element models must be obtained.

Building blocks exist for both approaches to shunt regulator modeling (i.e., element models, element s-domain descriptions, and analysis programs. The synthesis of these blocks into an effective shunt regulator model to provide adequate computer analysis capability has not been accomplished at this time.

Power Control Models

The individual component models described above can be integrated into a complete power subsystem through the use of a power-control model. The spacecraft-specific power control model embodies all of the power subsystem control logic, including:

- Battery charge/discharge controls
- Switching controls
- Eclipse - daylight controls
- Sensor elements necessary to control subsystem logic.

Most of the power control models encountered have had only DC capability.

1.2.2 Task 3 - Model Development Procedures

For the development of an accurate power subsystem model, the following are required:

- A model of each power subsystem component, complete with model algorithm, and an adequate data base.
- A flexible, dynamic program structure capable of accommodating a wide variety of component models, some of which are presently ill-defined.

The comprehensive model is envisioned as a set of compatible specific purpose programs, each of which calls upon a library of power subsystem component models and data to model a wide range of power subsystem configurations. This approach minimizes both complexity and cost, while covering the entire range of model requirements, from the simplest sizing model through DC and AC performance, to the most complex transient model.

Driver program structure will require a flexible means of data storage and communication, so as to permit use of a wide variety of component models. Initial effort will focus on program structure development. This will permit the program to be used as soon as the first component models are available. This ensures program availability in the third year of the five-year effort.

Test Components

Component testing is required to generate an adequate data base. Battery testing is required to improve the efficiency/state of charge model and the heat generation/pressure model; and to expand its usefulness to a wider range of orbits, voltages, temperatures, etc.

In the area of power electronics, testing is required to characterize devices based on emerging technology, such as high voltage hybrid switches to be used for solar array reconfiguration and power bus control, MOSFETS to be used for digital control of solar arrays, and integrated circuits to be used to control switches.

Solar array testing is required to develop an accurate transient model. The dynamic impedance is a function of voltage and current. A better understanding of plasma effects is needed before a model can be developed.

Analysis or testing is required to improve the discrete average model of the duty cycle modulator. The inaccuracy is particularly pronounced for high performance converters employing multiloop control. The model is also unable to handle abnormal converter operations such as peak current protection mode of operation, saturation of magnetic components, and saturation of op-amp in the feedback control loops.

The discrete time domain model is relatively ineffective for large scale system simulation. The general circuit analysis technique is fairly well developed in SPICE2 and SCEPTRE which are available computer programs.

2.0 POWER SYSTEM MODELING TECHNIQUES (TASK 1)

Figure 2-1 shows the work flow for Task 1. A literature search was performed in order to review existing power system computer modeling techniques used by industry to simulate spacecraft power system performance. Over 200 papers/documents were identified and categorized into one of five areas:

1. Power Supply Electronics
2. Batteries
3. Solar Arrays
4. Solar Array Switching
5. Power Systems

Each document/paper was reviewed, and those having power system modeling applications listed in Appendix A. For each reference, the significant capabilities and drawbacks of the analytical technique were identified together with areas which require significant improvement. This information is summarized on technology evaluation summary charts. Each chart includes source identification, purpose and model description, capabilities, limitations and constraints, and areas of improvement. Technology evaluation charts are in Appendix A.

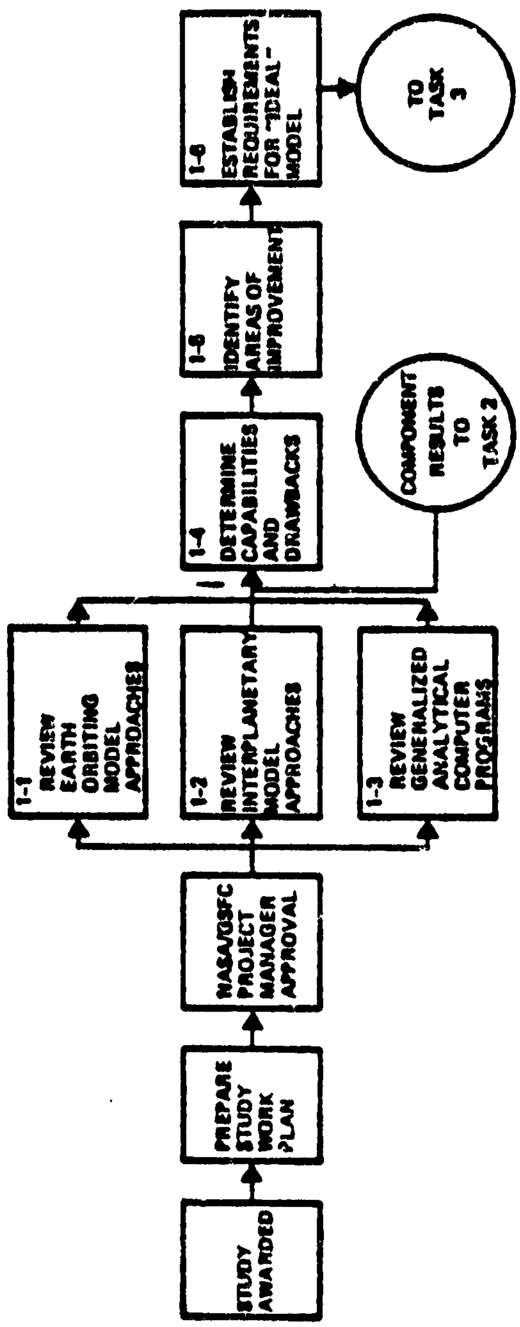
In addition to the literature search, an industry survey was conducted to determine on-going effort in power system modeling techniques. Results of this survey are in Appendix C. The following sections present a summary of the findings.

2.1 Components Modeling (Figure 2-2)

2.1.1 Battery Models

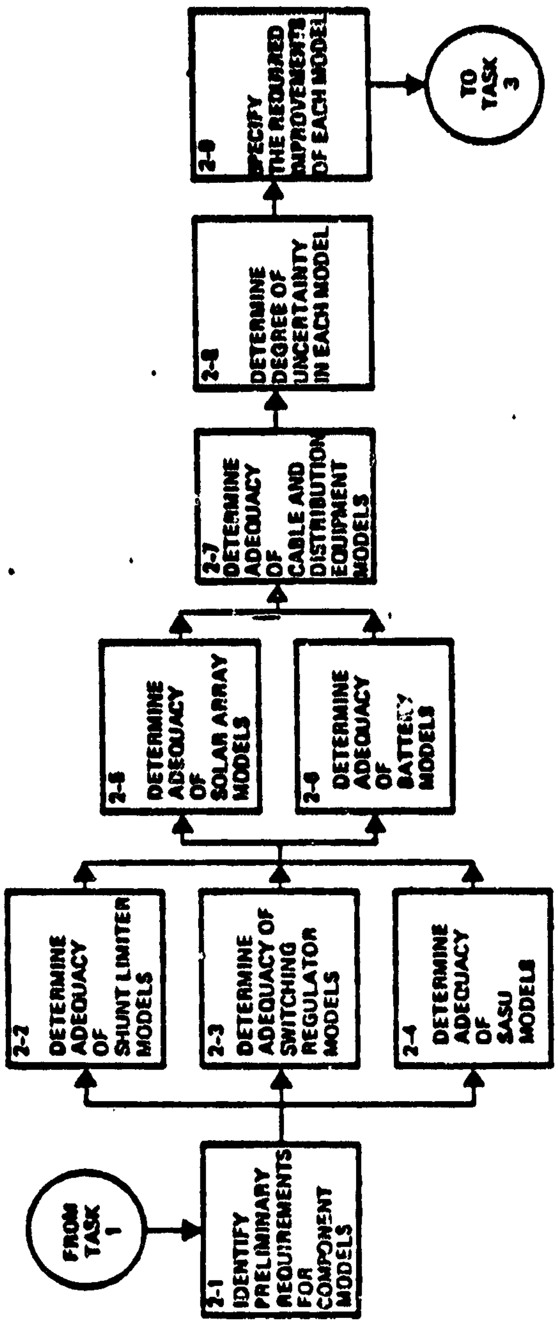
Several battery performance models have been encountered in the literature:

1. A look-up table model proposed by Bauer (A-28) in which the characteristics of the battery are stored in a large data bank. Linear interpolation and double-interpolation routines are used to find battery voltages, efficiencies, etc. The battery model is integrated into a complete power subsystem model by use of computerized pseudographical methods.



Task 1 Work Flow

FIGURE 2-1



Task 2 Work Flow Plan

FIGURE 2-2

2. An equivalent circuit model proposed by Zimmerman and Peterson (A-27) in which the battery is represented by an equivalent circuit of capacitors, diodes, resistors, and switches.

3. An unpublished model proposed by Bauer in which the current-voltage characteristics of the batteries are represented by a set of empirical equations designed to reproduce the shape of the battery charge and discharge curves.

4. A model of battery discharge voltage as a function of cycle life and temperature is reported by Billerbeck (A-22).

Table 2-1 details present model capabilities with respect to several attributes, and Table 2-2 describes existing models uncertainty/inadequacy.

Look-up Table Model

This model consists of several independent models, each of which is designed to represent a different characteristic of the battery cell. These are:

1. Data bank consisting of battery voltage as a function of relative current [current/cell capacity (A-Hr)], temperature, relative state of charge (percent remaining charge), and state of charge at the end of the preceding discharge (relative). By entering this data bank with temperature, state of charge, and depth of discharge arguments, and performing multiple interpolations, a single current-voltage curve for the cell at the desired set of conditions is obtained.

2. An efficiency model consisting of the incremental cell efficiency as a function of relative charge current and temperature. This table is valid only for the case in which the battery is charged from zero state of charge, and must be used with an accompanying algorithm to determine efficiencies during recharge from higher states of charge.

3. A battery heat generation model. This has taken several forms as the programs evolved, and is now an approximation of the thermodynamic heat generation properties of the battery cell, including energy storage as oxygen pressure. This permits modeling of the delay in heat evolution experienced in actual battery cells on repetitive cycling.

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BATTERY MODEL ATTRIBUTES	VOLTAGE & CURRENT	EFFICIENCY	STATE OF CHARGE	HEAT GENERATION, TEMPERATURE	INTERNAL PRESSURE	CELL AGING	CELL FAILURE MODEL	ORBIT CHANGE CAPABILITY	SMALL SIGNAL AC ANALYSIS	TRANSIENT ANALYSIS
	1	2	3	4	5	6	7	8	9	10

- MODELS FOR 1,2,3
  - ACCEPTABLE ACCURACY FOR GEO ORBIT
- MODELS FOR 4,5,8
  - HEAT GENERATION AND TEMPERATURE MODELS EXIST
    - -- TESTING/ANALYSIS/VERIFICATION REQUIRED FOR MULTIORBIT CAPABILITY
    - -- TESTING/ANALYSIS/VERIFICATION REQUIRED TO OBTAIN ACCEPTABLE PRESSURE MODEL
- MODELS FOR 6,7,10
  - CELL AGING MODELS AVAILABLE, **TESTING REQUIRED TO IMPROVE ACCURACY**
    - -- FUNCTION CYCLES, TEMPERATURE
  - NO KNOWN FAILURE OR TRANSIENT MODELS
    - -- TESTING/ANALYSIS/VERIFICATION REQUIRED
- MODELS FOR 9
  - MODELS AVAILABLE, THEVENIN EQUIVALENT

NOTE: ABOVE COMMENTS APPLY TO NiCd BATTERIES. ALL AREAS REQUIRE TESTING TO ACQUIRE AN ADEQUATE DATA BASE FOR OTHER TYPE BATTERIES

TABLE 2-1. COMPONENT MODEL CAPABILITY SUMMARY
BATTERIES

TABLE 2-2

BATTERY MODEL UNCERTAINTY/INADEQUACY

- HEAT GENERATION - CELL HEAT GENERATION MODELS WEAK - OFTEN GIVE POOR RESULTS WHEN ORBIT PARAMETERS CHANGED
- MULTIPLE ORBITS - MODELS FREQUENTLY DO NOT GIVE STABLE RESULTS AND DRIFT. RESULTS NOT IN AGREEMENT WITH FLIGHT DATA
- CELL TYPE - NO COMPLETE N_IH_2 OR A_gH_2 DATA BASE EXISTS
- RECONDITIONED CELL DATA BASE
- BATTERY CELL FAILURE MODEL/LOAD SHARING SIMULATION
- PULSE DISCHARGE/CHARGE DATA BASE

The look-up model has been used after varying degrees of modifications by several institutions, with a varying degree of success. JPL has modified it for use with interplanetary spacecraft. An independently generated tabular model was made for the SKYLAB power subsystem substituting an average recharge ratio efficiency model for the incremental model of cell efficiencies. NASA/GSFC uses a similar look-up model for general power subsystem evaluations.

Model Capabilities: When combined with a battery charge model, a thermal model, and a power source model, the battery model is capable of making minute-by-minute predictions of battery voltage, current, temperature, state of charge and, potentially, internal cell oxygen partial pressure. In effect, it "flies" the battery through its mission, predicting all of the important characteristics of the battery in relationship with its environment. With additional programming, it is capable of simulating the performance of a battery or batteries containing one or more failed (or partially failed) cells.

Model Limitations: The look-up table model has a number of limitations: 1) It is incapable of modeling electrical transients. It is useful only at steady state. (Thermal transients, except in masses of very small time constant, can be followed accurately, provided that the interval between computations is short); 2) It does not account for actual capacity degradation due to loss of active materials, or conversion of active materials to the inactive state with cell usage. Instead, these losses are modeled as a voltage degradation, and require replacement of the current-voltage data set with a "degraded" set. The input data for the characteristics of the battery have to be modified for each set of battery conditions. Since these data consist of voluminous five-dimensional tables, it becomes expensive to generate a lifetime or cycle variant data base.

Accuracy considerations: Experience at TRW has led to the following estimates of accuracy.

Battery voltage	1.5%
Battery current	1.5%
State of charge	5.0 - 10.0%
Heat generation rate	Variable, depending upon stage of battery charge or discharge

Potential for improvement: Areas in which improvements could enhance the usefulness or range of applicability of the programs are:

- Development of an algorithm for manipulation of the voltage and efficiency data bases to reflect the variation in cell characteristics with life or cycle history. This would increase the range of applicability of the program.
- Development of an improved efficiency model. This would enhance accuracy of heat generation results, and state of charge results.
- Development of an improved heat generation model.

Equivalent Circuit Model of Zimmerman and Peterson (A-27)

This model consists of a battery steady-state equivalent circuit comprised of two or more large capacitors, a bidirectional diode pair, and a network of resistors. The bidirectional diode pair simulates battery cell voltage hysteresis and battery heat generation.

Model Capabilities: The model simulates the general shape of the battery charge and discharge curves, and the offset between them. With the addition of considerable complexity, it appears that the same model might be designed to simulate both steady-state and small signal AC behavior and heat generation hysteresis caused by nickel-cadmium cell oxygen storage. The amount of data storage required is small.

The original paper appeared in 1970, and no further development has been reported leading to the conclusion that in spite of its promise, the work was not pursued further, or was unsuccessful. No comparison is shown between flight or test data and the computer predictions.

Model limitations: One of the difficulties presented by this model is the requirement for input data in a form which is not directly measurable. The data conversion complexities are large, and data acquisition unwieldy. As model improvements are made for small AC signal performance, for oxygen storage modeling, etc., these complexities are likely to increase geometrically.

Empirical Waveshape Model (A-28)

The "Empirical Waveshape Model" assumes the battery charge/discharge characteristic wave to consist of three regions, a sloped plateau line in the mid-region, and two exponential functions added to the plateau to simulate the beginning and end of charge or discharge. The combination of these three functions model the zero-current cell voltage as a function of its state of charge. This "zero-current" voltage is then compensated for charge or discharge currents by adding or subtracting a voltage increment whose value is a function of the relative current.

The overall model contains a battery pressure and heat generation algorithm based upon thermodynamic relationships, and a tabular efficiency model similar to that described in the look-up table model.

Model capabilities: The model will predict battery voltage, current, heat generation rate, state of charge, and internal pressure of the battery cells. It is capable of expansion to include the modeling of partially failed cells.

Model limitations: The model requires an indirect and in some cases a trial-and-error derivation, of input parameters from available cycling data. In testing, the model maintained good agreement with actual cycling data over the range of 0 to 25°C in a single low earth orbit cycle comparison with test data. It has never been compared with test or flight data at other temperatures, or at varying depths of discharge. In multiple cycling runs it may require as many as 30 orbits for the model to converge from the assumed set of conditions to the final conditions in which equilibrium is achieved. Similarly, a large number of orbits may be required before it settles down as a result of a large change in system loads. This is not unlike the behavior of actual spacecraft.

Accuracy considerations: In the single test in which comparisons were made with low earth orbit test cycles, voltage, current, state-of-charge agreed with test data within 1-5%. Pressure predictions in a few test cycles showed a pattern of pressure variation in phase with that in the test cells but different in magnitude by as much as 50 to 100%.

Potential for improvement: The model fails to take into account the variation in current density with state of charge at constant current. The assumptions regarding the rates of reaction associated with the pressure and recombination reactions are oversimplified for best accuracy; further improvement is possible.

COMSAT/Billerbeck Model (A-22)

In this case the battery is modeled as a voltage generator whose output is a function of depth of discharge, in series with a fixed resistor, and compensated by temperature and aging factors. The model considers only battery discharge, and must be calibrated to the power subsystem prior to use.

Model capabilities: Given an assumed load current, an assumed spacecraft design, and field operation data from the spacecraft, the model will predict battery voltage at end of discharge (minimum battery voltage as a function of the number of cycles in orbit, and battery case temperature). An additional algorithm is used to include the effects of battery reconditioning.

Model limitations: Because the model does not consider battery charge, it will not predict performance under varying charge control conditions nor will it follow thermal transients. No heat generation data or pressure predictions are made. The model will not follow AC variations.

Model accuracy: The reported model accuracy appears to vary between 3% early in life to 10-15% later in life, when calibrated against early life data, and not including reconditioning. After several years of operational data have been acquired the model can be matched very closely to these data, and extended predictions made from this point.

2.1.2 Solar Array Models

The models encountered in the literature are discussed below. Table 2-3 summarizes model capabilities with respect to many attributes, and Table 2-4 describes the existing model uncertainty/inadequacies.

The classic first order model for solar cell behavior has received much attention and many papers have been published in this area. Shown in Figure 2-1 is the DC solar cell model. The current source I_{sc} is an illumination dependent constant current source. Diode D is an ideal diode whose characteristics are derived from the I-V characteristics of the solar cell being modeled. Resistance R_s and R_{sh} are lumped models for various effects occurring within the solar cell. R_s accounts primarily for the ohmic resistance of the semiconductor material of the cell as well as the ohmic contact resistance of the cell connections. R_{sh} accounts primarily for the surface leakage currents around the semiconductor junction.

SOLAR ARRAY MODEL ATTRIBUTES	DC PERFORMANCE	SMALL SIGNAL AC	LARGE SIGNAL AC	ORBIT MECHANICS	THERMAL EFFECTS	RADIATION EFFECTS	INTERCONNECT AND CABLING EFFECTS	PLASMA INTERACTIONS	AGING/DEGRADATION	SHADOW EFFECTS	SIZING
	1	2	3	4	5	6	7	8	9	10	11

MODELS FOR 1,7 (RESISTANCE)	• ACCEPTABLE ACCURACY FOR EARTH ORBIT, AND SOME INTERPLANETARY. AT LOW INTENSITY, LOW TEMP, CELL TO CELL VARIATIONS ARE NOT PREDICTABLE. (<.1sc, <-100°C).
MODELS FOR 2,3	• SMALL SIGNAL AC MODELS AVAILABLE, NO LARGE SIGNAL OR TRANSIENT MODELS AVAILABLE.
MODELS FOR 4	• ACCURATE MODELS AVAILABLE - MAY REQUIRE INTEGRATION WITH PERFORMANCE MODEL.
MODELS FOR 5	• ACCEPTABLE OVERALL MODELS.
MODELS FOR 6,9	• ACCEPTABLE MODELS FOR SILICON PLANAR ARRAYS, HOWEVER THERMAL CYCLING EFFECTS FOR MISSIONS LONGER THAN 5 YEARS IS BASED ON EXTRAPOLATIONS FROM SHORTER TERM DATA.
MODELS FOR 8	• NO ACCEPTABLE MODELS AVAILABLE.
MODELS FOR 10	• SHADOW ANALYSIS CAN BE TIME CONSUMING FOR SOME MISSIONS. AN AUTOMATED SYSTEM IS REQUIRED TO REDUCE COST AND ANALYSIS.
MODELS FOR 11	• ACCEPTABLE MODELS EXIST.
CONCENTRATOR ARRAYS	• MODELS ARE BEING DEVELOPED, TESTING REQUIRED FOR VALIDATION. • NEED OPTICAL MODEL • MIRROR AGING MODEL REQUIRED

TABLE 2-3 COMPONENT MODEL CAPABILITY SUMMARY
SOLAR ARRAYS

Solar Array Model
Uncertainty/Inadequacy

- FEW DOCUMENTS DEAL WITH INTEGRATION OF SOLAR ARRAY MODEL WITH ENTIRE POWER SYSTEMS MODEL
- LARGE SIGNAL MODEL REQUIRED
  - -- ACCOUNT FOR CAPACITIVE AND INDUCTIVE EFFECTS
  - -- ACCOUNT FOR RESISTIVE EFFECTS, CABLING
  - -- TRANSIENT ANALYSIS
- PLASMA INTERACTION
- CONCENTRATOR ARRAY OPTICAL MODEL NOT AVAILABLE

Table 2-4

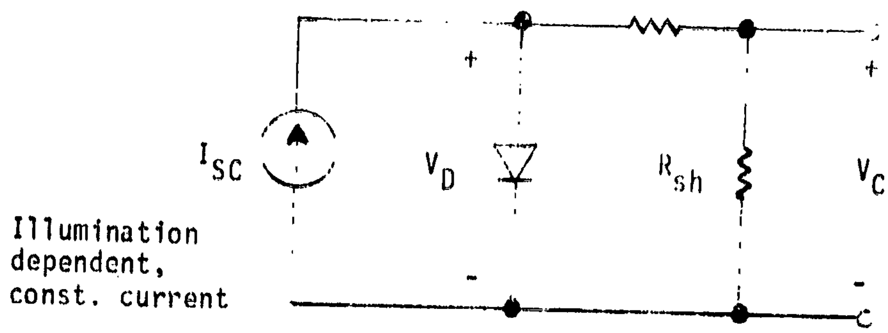


Figure 2-1. Classic DC Solar Cell Model

The advantages of the model pictured in Figure 2-1 are that it is a standard model used by many researchers to provide very good first order predictions of the DC behavior of the solar cell. The simplicity of the model makes it easy to use. It is necessary to obtain only a few circuit parameters in order to use the model. Since it is in the form of a circuit model comprised of standard circuit components, it can be easily used in conjunction with available circuit analysis computer programs.

Other DC circuit models for the solar cells have been developed. The models are generally refinements of the model seen in Figure 2-1, and are used to model what might be termed the second order effects in a solar cell. Generally, additional circuit elements are added in order to produce the desired second order effects. Shown in Figure 2-2 is a multiple element solar cell model. This type of multiple element model is used for such things as precisely modeling the effects of distributed series resistance or complex voltage dependencies. Multiple element models are also used to model high illumination (concentrator) devices as well as being used for modeling the effects of temperature changes in the various parts of the solar cell.

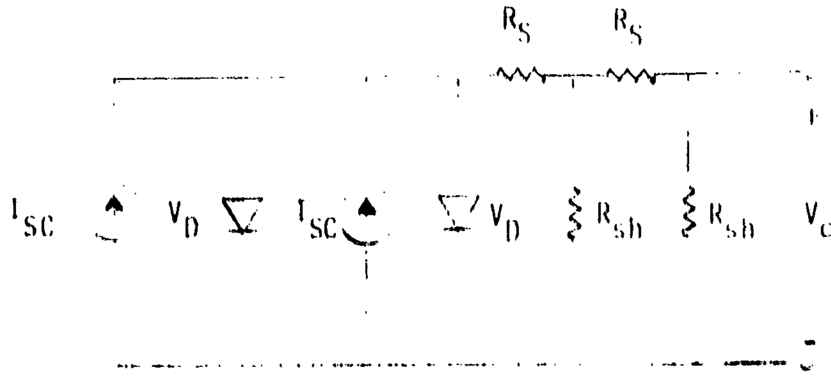
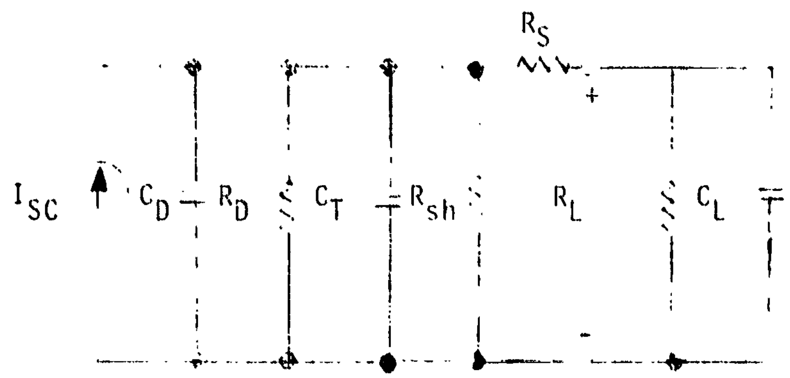


Figure 2-2. Multiple-element DC Solar Cell Model.

The standard large signal AC solar cell model is shown in Figure 2-3. Like the DC model, this model is simple and easy to use, producing good first order results. Various techniques are given in the literature for measuring the data and performing the calculations for obtaining the values of the model parameters. For the first order AC model, the parameters are dependent upon output voltage and current, cell temperature, cell illumination, and of course, physical cell dimension. It is therefore necessary to take these dependencies into account when model parameters are calculated.



I_{SC} = Constant current source

C_D = Diffusion Capacitance

R_D = Junction Resistance

C_T = Transition Capacitance

R_{sh} = Shunt Resistance

R_S = Series Resistance

R_L = Load Resistance

C_L = Load Capacitance

Figure 2-3. Small-signal AC Solar Cell Model

When dealing with a solar array model, as opposed to the solar cell model, several additional effects must be accounted for. These effects are best included in the model as additional circuit elements. The interconnection wiring of the solar array is modeled by additional resistors, inductors, and capacitors in both the DC and AC models. (Capacitance and inductance have no effect in the DC model.) The values for these additional model parameters are dependent on array size.

Substrate parasitic capacitance can become significant and therefore must be accounted for in the solar array AC model. Inductance effects produced by the incident illumination (photoinductance) have recently been shown to be on the order of 100 μH/cm² which can be significant in a solar array. The value of photoinductance observed is a function of both illumination intensity and illumination wavelength. More work needs to be done to produce an appropriate circuit element for inclusion of this effect.

In order to predict the dynamic effects of changes in the solar array such as cell failure, shading, eclipsing, or load changes, it is necessary to use a large-signal model. A satisfactory large-signal model for the solar cell has not been found. Previous dynamic models used the parameters C_t, C_d, R_d, R_s, and R_{sh} from the AC model to form a transient model. However, because of the significant variations in these parameters over wide ranges of voltages, currents, illumination and temperatures, this extension of the AC model is not suitable as a large-signal model. A means must be found to incorporate the appropriate circuit effects over the full large-signal range. The typical lumped parameter modeling technique may prove to be difficult to use for this task.

2.1.2.1 Array Modeling Approaches

The literature survey determined that there is a large amount of material dealing with the various aspects of solar cells, however, few documents deal with the integration of the solar cell model with the power subsystem.

Several approaches are proposed for modeling a solar array. First, it is possible to model an array by an interconnection of individual solar cells (individual cell model approach) as shown in Figure 2-4. This technique is straightforward and does not require a lot of modeling experience in order to use it. The parameters for the individual cell model are readily obtained using established measurement/calculation procedures. Shadowing effects as well as cell faults can easily be inserted into the array using this modeling approach. Since the individual parameters for each of the cells is entered into the model, the effects of parameter variation over an array of cells can readily be included. Additionally, changes in array structure as well as array expansions can be made by simply specifying a different interconnection scheme. Thus, the individual cell model approach seems to be quite general and conceptually easy to use.

The individual cell model does have certain disadvantages especially when larger arrays are treated. Most circuit analysis programs are not capable of analyzing arrays larger than a hundred cells. Those that will handle the larger arrays use an extremely large amount of computation time in performing the analysis. In addition, the previously mentioned advantage of being able to enter and vary each cell parameter on an individual basis can be a disadvantage in terms of user time for large arrays.

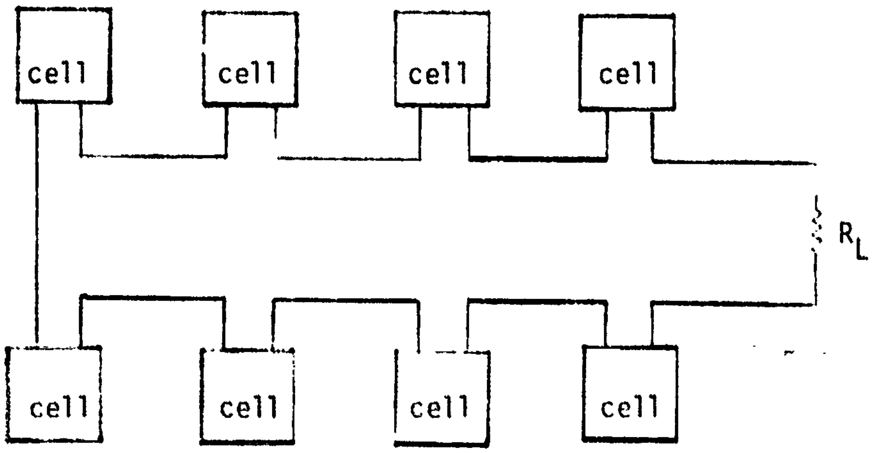


Figure 2-4. Individual cell approach to modeling a solar array.

Another approach is to use a single cell model to simulate the entire array (macro model approach). See Figure 2-5. The major advantage to this approach is its ability to minimize computer time and space needed to analyze array behavior. Parameters can be obtained in several ways from incorporating the measurement/calculation of the individual cells according to the interconnections to making terminal measurements at the array's connection points. Neither of these methods takes much more effort than would be needed for the individual cell model. Once these parameters are determined, only a single set of data is needed for input to the analysis program.

The disadvantages to the macro model approach include the fact that a new set of macro model parameters needs to be developed for each different array configuration. This tends to make the model less flexible than is desirable. Furthermore, shading and individual cell faults cannot be easily included in the macro model without, again, a redevelopment of model parameters. Individual cell parameter variation studies are also difficult to perform using the macro model approach.

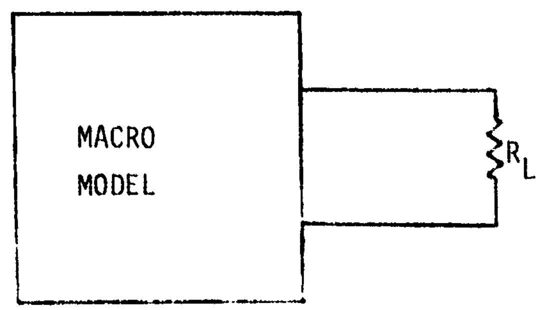


Figure 2-5. Macro model approach to modeling a solar array.

An approach which uses a combination of the macro model and the individual cell model as shown in Figure 2-6 could be very advantageous. This approach retains the flexibility of the individual cell model approach while still reducing the necessary computer time and space requirements.

Cell faults and groups of cell faults can be simulated with the combination model. Shadowing effects can be accounted for in much the same way as would be done in the individual model. Parameter variation studies can also be performed by varying individual cell parameters of the combination model and leaving the macro model subsection parameters fixed.

The disadvantage of using the combination model is the need to determine at least two sets of model parameters--one set for the group of individual cells and one set for the group of macro models. Another disadvantage is the need to develop a new set of macro parameters when it is desirable to include more or less of the individual cells of the array.

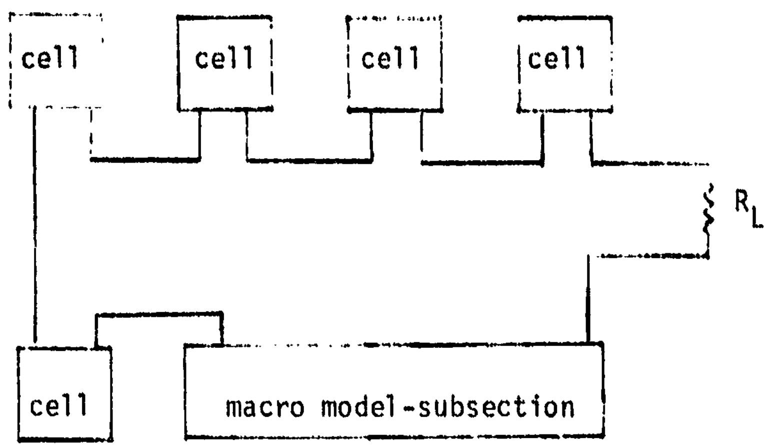


Figure 2-6. Combination macro model and individual cell model.

The choice of the modeling approach used depends upon the application at hand. For example, the macro model approach would be used for performing an overall system analysis. In this type of analysis it is presumed that the model of the solar array need not be as flexible or general as other types of analyses. For an analysis which is to investigate system component details, e.g., battery conditioner, etc., the solar array macro model will suffice. The individual cell combination model would be used when investigating solar array details. For this type of analysis it is likely that macro models would be used for the other system components.

2.1.2.2 Solar Array Model Requirements

Important Parameters

The objective of this section is to determine a preliminary set of performance standards and expectations which the solar array model must satisfy. Important solar array model output parameters include the array voltage and current and array power delivered. Temperature variation information is a necessary model output parameter. Temperature information needs to be coupled to the rest of the system to determine system heat flow. A more comprehensive modeling package would allow the user to perform further analyses on solar array size, magnetic effects, radiation effects, plasma effects, as well as aging and other degradation effects.

Required Input

The required inputs for the solar array model include a set of parameters for each of the elements of the array model being used. When using either the combination model or the individual cell model, it is necessary to input the interconnection scheme for the array. Another important input parameter is that of the array illumination characteristics. Included in the illumination characteristics are such items as intensity, frequency, and shadowing information. The ambient temperature must be included as a model input parameter in order to provide an initial point for a thermal effects analysis. For analysis which will perform a study of the behavior of the array when subjected to fault conditions, a set of cell faults must be specified. These faults should be of both the fixed and time-varying types.

The way in which the input parameters are entered depends upon the nature of the parameters as well as the way in which the parameter is measured/calculated. Parameters which are single valued can be input as constants. Other parameters which may be functions of network variables can be input in two different ways. Functional descriptions can be used to specify parameters whose values fit into particular functional forms.

A second way in which this type of parameter can be input is via a list of data points. These data points are likely to have been obtained from array measurements. Values used between data points can either be constant at the last specified data point value or can be a value obtained by interpolation.

Individual Element Requirements

In order to correctly model the solar array, the modeling requirements of the individual elements must be examined. It is essential to use the correct I-V characteristics for all elements of the model. Importantly, elements which are dependent upon other circuit parameters must exhibit the proper dependency characteristics. These characteristics must be determined in the measurement/calculation phase of the model development. For large arrays, it is very important to include the substrate capacitance effects. Careful examination of the resistance, inductance, and capacitance of the interconnections structure is required. In addition, it is necessary that each of the individual parts of the solar array model be capable of producing information usable in a thermal effects analysis.

2.1.2.3 Model Development Methodology

A solar array model development should start by first devising an appropriate circuit model and element configuration. During this phase of the development, it is necessary to determine a set of required parameters for a DC, AC, and transient analysis of an array. The parameter set for the individual cell model would be developed first, followed by the macro model and combination model parameter sets. Included in this phase of the development is the incorporation of the element parameter interdependencies.

The next phase of the development involves the verification of the model using experimental data. Model responses for typical and worst-case situations need to be calculated and compared to measured data. Limitations on the bounds of worst-case situations are determined by the experimental capabilities of the model developers. Broadening of the worst-case bounds as much as possible allows for more confidence in model predictions. produced for situations outside the measurement bound.

Once phases one and two have been successfully completed the model can be used to predict solar array behavior. It is at this point that the model is incorporated into the overall power system model.

2.1.2.4 Mathematical Skills Required

The developer of the solar array model must have a basic electrical engineering knowledge of spacecraft power generation subsystems and in particular, a significant knowledge of solar cells. Furthermore, the developer must have an understanding of circuit element representation and of the interdependencies of physical effects, e.g., the dependency of C_d on junction voltage. This requires a familiarity with semiconductor electronics.

In order to aptly implement the solar array model and integrate it within the comprehensive power system analysis package, it is necessary for the developer to have some basic programmer skills, and some understanding of numerical analysis methods. A background knowledge of available circuit analysis programs such as SPICE or SCEPTRE would also be very useful.

2.1.2.5 Modeling Objectives and Adequacy

The prime objectives of the solar array model is to accurately predict the behavior of an array of photovoltaic cells, and be usable in a comprehensive power system model.

The solar array model must be capable of performing in three different analysis modes: DC analysis, AC analysis, and transient analysis. The individual objectives in each of the three different analysis modes are listed below:

DC - voltage vs. illumination
- current vs. illumination
- output power vs. illumination
- temperature effects predictions
- load variation prediction
- sensitivity effects due to resistance changes
- fault condition predictions

AC - output parameters vs. frequency
- output impedance determination
- sensitivity effects due to R's, L's, and C's
- shadowing
- fault transients
- system transients

Model Adequacy

A set of criteria are defined below which can be used to determine the degree of adequacy of the solar array model:

- Accounts for all physical effects including the proper I-V characteristics, impedance, shadowing effects, fault effects, in all applicable modes.
- Obtains the necessary degree of precision.
- Performs the analysis necessary without using inordinate amounts of computer time or space.
- Usable in conjunction with other power system component models.
- Does not require a high degree of mathematical skill of complex measurements/calculation so that it is easily usable.

2.1.2.6 Necessary Development Efforts

Two areas of development effort are necessary in order to produce a solar array model which can be used in the comprehensive power system model. First, the presently available model needs to be improved to satisfy the previously stated objectives.

The development efforts which still need to be performed for the presently available model (individual cell model) are:

- Account for all series resistance effects within the array.
- Account for all inductive and capacitance effects within the array.
- A means of methodically specifying various interconnect schemes.
- A means of easily accounting for the effects of shadowing and cell faults.

The second effort necessary is to develop an appropriate macro model which satisfies the objectives. Third, a method must be developed for determining the parameters for the many possible types of macro model subsections which will be used in the combination model. Besides development of the macro model subsection itself, the other important components of the model which must be developed are:

- The interface between the macro model which will convey other important array information, e.g., thermal effects information.
- An accurate set of parameters for macro models for various sized array subsections.
- A method to input shadowing and fault data.
- A means of analyzing the sensitivity of the array performance to parameter variations.

In addition to the development efforts listed above, pertaining primarily to the solar array, it is necessary to develop a structure for the overall system model into which the array model will fit. This structure may be loosely defined initially, but will likely become more constrained as the development of the comprehensive model system progresses.

2.1.2.7 Uncertainties

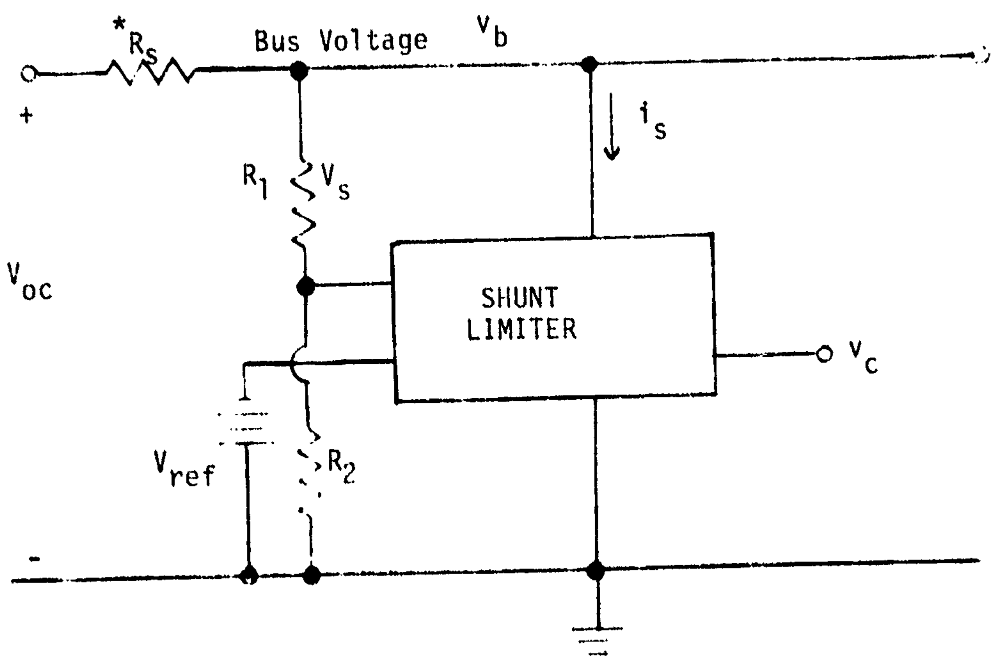
The major uncertainty for the solar array modeling effort lies in the transient analysis model. Little is reported in the literature on a working large-signal model for solar arrays. The amount of time and effort necessary to extend the DC and AC models to a workable large-signal model could be substantial.

The other area of uncertainty in the solar model development is that of the macro model. The points which seem most uncertain about this development effort are: choice of the appropriate parameters, method for calculating/measuring macro model parameters, and how can flexibility be built into the macro model or combination model scheme.

2.1.3 Shunt Regulator

There were few publications on shunt regulator models. The literature usually addresses techniques and design of shunt regulators, and not computer modeling schemes. Table 2-5 summarizes the present capabilities of shunt regulator models with respect to various attributes. Table 2-6 summarizes the uncertainties/inadequacies of existing models.

Schematic and Definition



TWO CATEGORIES

- Linear
- PWM

INPUTS

Typically V_{ref} & V_b & V_{oc}

OUTPUTS

Typically v_c & i_s & v_b

*The term shunt regulator inherently includes a series dropping resistor, R_S. Since this resistance is the solar array series resistance in this case, circuitry excluding this element is termed a shunt limiter since it only limits bus voltage upper value.

SHUNT REGULATOR MODEL ATTRIBUTES	DC PERFORMANCE	SMALL SIGNAL AC	LARGE SIGNAL AC	SIZING	THERMALLY INTEGRATED	FAILURE MODES/ STABILITY
	1	2	3	4	5	6

MODELS FOR 1,2	WELL UNDERSTOOD AND ACCURATE FOR SINGLE ARRAY LUMPED SHUNT NO MODELS FOR SASU AND PARTIAL SHUNT
MODELS FOR 3,5,6	LIMITED CAPABILITY FOR SINGLE ARRAY LUMPED SHUNT NO CAPABILITY FOR SOLAR ARRAY SWITCHING UNIT (SASU).
MODELS FOR 4	NO MODELS AVAILABLE
ALL MODELS	INHERENTLY LINKED TO SOLAR ARRAY. DECOUPLING IS EASY FOR SINGLE ARRAY SHUNT, BUT MUCH MORE COMPLEX FOR SASU OR PARTIAL SHUNT CONFIGURATION.

Table 2-5. COMPONENT MODEL CAPABILITY SUMMARY
SHUNT REGULATORS

SHUNT REGULATOR MODELS
UNCERTAINTY/INADEQUACY

- VERY LIMITED PUBLICATIONS ON SHUNT REGULATOR MODELS
  - DESIGN ORIENTED
  - INCLUDED IN SOME OF THE OVERALL MODELS, PSIM, ETC.
- GENERALIZED CIRCUIT MODEL CAN BE UTILIZED
  - SPICE HAS BEEN USED BY TRW FOR ANALYSIS OF SHUNT REGULATOR/LOAD FILTER INTERACTION AND STABILITY MARGIN ANALYSIS.
  - VERIFICATION BY BREADBOARD AND ENGINEERING MODEL TESTS (UNPUBLISHED)
  - SIGNIFICANT ANALYTICAL EFFORT REQUIRED TO ESTABLISH THE MODEL
  - NO POWER DISSIPATION OR ELEMENT FAILURE ANALYSIS
- NO DOCUMENTED TRANSIENT MODELS WERE FOUND

TABLE 2-6

Definition of Shunt Operational Modes

Mode 1: Sensed voltage below setpoint voltage to activate shunt. Shunt active element off.

Mode 2: Sensed voltage above setpoint voltage. Shunt elements activated. Linear type shunt has some active elements in linear region. PWM shunt at less than maximum duty cycle.

Mode 3: Sensed voltage above setpoint voltage. All linear shunt active elements saturated. PWM shunt at maximum duty cycle.

Performance

The standard criteria for evaluating the performance of the shunt regulator are as follows:

- DC Voltage Regulation*
- Transient Response*
- Stability
- Starting
- Saturation
- Active Element Dissipation
- Output Impedance (dV_b/di_s)
- Regulation Sensitivity $(V_b \max - V_b \min)$
- Input Regulation* $(dV_b/(dV_{oc} \times V_b)) \times 100\%$
- Load Regulation* $((V_b \text{ min load} - V_b \text{ full load})/V_b \text{ min load}) \times 100\%$
- Temperature Coefficient*, $TC(\%/C°) = \pm (V_b \max - V_b \min) \times 100\% / (V_b \text{ ref} \times (T_{max} - T_{min}))$
- Ripple Rejection*

V_b = Bus voltage

i_s = Shunt current

V_{oc} = Solar array open circuit voltage

*Performance evaluation must consider solar array open circuit voltage and series resistance (V_{oc} & R_{sa}).

2.1.3.1 Modeling Approaches

Two modeling approaches have been analyzed. They are the network approach and the functional block approach. The characteristics of each are shown below.

Network Approach	Functional Block Approach
1. System expressed in terms of individual elements. Each element usually defined in terms of a thru variable & an across variable.	1. System expressed in terms of block diagram, differential equations, or transfer functions.
2. Basic elements are storage elements, dissipative elements, sources. Allows use of standardized models.	2. Basic elements are mathematical & logical operations. System models frequently custom developed.
3. Good component level visualization.	3. Good system level visualization.
4. Requires high level program, large computer capacity, & numerical analysis skills in operator. Program usually performs as network analyst internally.	4. Requires network analyst to develop models as functional blocks.
5. Easy initialization operations.	5. Substantial initialization effort.
6. Easy to alter parameters of network for sensitivity analysis & worst case analysis & design change.	6. Difficult to alter parameters as required by sensitivity analysis or design change.
7. Network may be very large at system level.	7. Hard to handle discontinuous systems.
8. Some programs may require further data reduction to obtain frequency domain data.	8. Must provide all initial conditions for state variables.
9. May be able to handle multiple topology & discontinuous systems.	9. No need for equivalent circuit.
	10. Most useful in frequency domain & small signal transient analysis.

MATHEMATICAL AND ENGINEERING SKILLS REQUIRED TO DEVELOP SHUNT REGULATOR MODEL

The development of a shunt regulator model requires basic electrical engineering knowledge of spacecraft power generation and distribution subsystems. In addition, the following skills are required:

- Basic electrical engineering knowledge of spacecraft power generation subsystem.
- Network analysis skills.
- Semiconductor modeling and analysis skills.
- Numerical analysis and computer programming skills.
- Non-linear analysis skills.

Important Parameters to be Analyzed

1. DC Modeling

   - Worst-case: drift, eclipse, radiation degradation, mission life fatigue, temperature variation, etc.
   - Voltage regulation under all variations of bus loads and solar array configurations.
   - Survivability: ability to continue regulation in the event of component failure.
   - Semiconductor component stress.
   - Shunt contribution to spacecraft thermal loads.
   - Power regulation of peak power tracker (PPT).

2. Small Signal AC Model

   - Stability under worst-case as listed in DC modeling. Quantify stability in terms of gain and phase margins in the frequency domain against worst-case variants.
   - Output impedance versus frequency.
   - Interaction with system components: bus filter, switching regulator input filter, solar array switching, switched shunts.
   - Shunt element overlap: increasing sensed voltage causing additional shunt element to become active and decreasing sensed voltage causing saturated shunt element to come out of saturation.

- Small amplitude step or ramp transient response.
- Individual control loop characteristics.
- Operation at threshold of solar array section switching.
- Stability of variable reference voltage control loop for peak power tracker operation.
- Phase relation between sensed voltage (regulated voltage) and shunt element voltage for partial shunt.

3. Large Signal Model

The large signal model must accurately predict performance during step load changes, solar array section switching, surge suppression (such as solar array radiation barrage), and setpoint voltage crossing.

The effects of the following parameters must be considered in a transient response model.

- Regulation sensitivity.
- Sequential shunt switching.
- EMI response
- Non-linear characteristics.
- Settling time.
- Sensed (regulated) voltage overshoot.
- Sequential element burn-out.
- For PWM shunt: steady-state ripple injected onto the bus.

4. System Interaction

The shunt model must account for the following interactions with the power system.

- Interaction between shunt (bus) filter capacitance and resistance and the shunt.
- Interaction between switching regulator input filter and the shunt.
- Effect of step load and source changes (within and beyond the limits of shunt sensitivity).
- Effect of periodic load and source variations both sinusoidal and non-sinusoidal (within and beyond the limits of shunt sensitivity.
- Interaction of shunt with negative resistive characteristic of the power conditioning switching regulator.
- Effect of shunt on solar array operating in current/voltage model.

MODELING REQUIREMENTS FOR INDIVIDUAL PIECE PARTS USED IN SHUNT REGULATOR MODEL

In some cases a transfer function approach is not adequate to predict overall performance, and it is necessary to model some of the parts or functions internal to the shunt. Modeling requirements are given as a function of the shunt mode.

1. Mode 1 Operation

Network Approach. Shunt filter element values, bus loads, solar array segment models.

Functional Block Approach. Shunt filter transfer function, solar array source mathematical description, and load input impedance description.

2. Mode 2 Operation

Network Approach. Solar array source: Topic discussed under solar array modeling and analysis.

Reference voltage: Independent or dependent voltage source equivalent to actual zener or peak power transfer characteristic.

Error amplifiers: Feedback circuit passive elements values and amp model element parameters including input capacitance and resistance, DC gain output voltage dependent resistance divider expressions.

Majority voting: Generalized model to be developed.

Shunt element sequencer: Generalized model to be developed.

Sequential shunts: passive component values, parameter evaluation procedure for voltage dependent capacitors and current sources of active shunt elements.

Bus filter: passive element values capacitance, capacitor equivalent series resistance, swamping resistance.

Load model: As determined by applicable modeling and analysis section dealing with particular load.

Functional Block Approach.

Transfer functions: Determine range of linearity about appropriate operating points for AC small signal models for each functional block as previously listed. Determine minimal mathematical expression to predict gain and phase characteristics of each functional block.

Differential equations: Determine linear and non-linear differential equation for each functional block.

3. Mode 3 Operation

Network Approach. Shunt filter element values, bus loads, solar array segment models, and shunt element dissipation resistor values.

Functional Block Approach. Transfer function of shunt filter in parallel with shunt element dissipative resistors, solar array source description, and load input description.

MODELING OBJECTIVES

1. Test performance of shunt at system and subsystem level against design requirements.

2. Provide sufficient flexibility to accept various shunt configurations.

3. Serve as design aid to analyze existing designs and help effect improved design.

4. Simulate power generation subsystem components mission performance in advance of hardware construction.

5. Utilize existing models and analysis programs to the maximum extent possible.

MODELING ADEQUACY

1. Network Approach

- Modeling techniques for components exist.
- Computer programs exist.
- Can provide analysis objectives of AC and DC modeling.
- Easily adapted to new technology.
- Exact models not yet developed.
- Cataloged procedures for modeling not yet developed.

2. Functional Block Approach

- Limited existing modeling techniques.
- Models not easily adapted to new technology.
- Cannot provide verification of design criteria such as power dissipation, component degradation, etc.

- Computer analysis programs exist.
- Development efforts to satisfy modeling objectives are quite imposing and must be done individually for each of the typical shunt regulator configurations.

2.1.4 DC-DC Converters

Most of the (DC-DC Converters) models described in this section were developed to analyze or simulate a voltage regulator from the point of view of converter performance, and converter operation (mode). Stability analysis was the prime motivation for most of the work reported in the literature. As models were developed, by-products became available, such as audio susceptibility, output impedance, etc. However, the kind of model that is needed for power system modeling is completely different than the ones developed to date.

Table 2-7 summarizes the capabilities of present DC-DC converter modeling with respect to various attributes. Table 2-8 summarizes the existing models uncertainty/inadequacy.

The linear regulator has the advantage of ease of design and analysis, and no EMI problems. The disadvantage is that it is dissipative and heavy. The switching converter has less mass and less thermal dissipation than the linear regulator. It is more difficult to design and produces EMI.

2.1.4.1 Switching Regulator Performance Categories

1. DC Model Performance Categories:
   - input voltage range
   - output voltage range
   - output power range
   - DC regulation
   - mode of operation - continuous current, discontinuous current
   - semiconductor component stress
   - worst-case analysis
   - EMI performance
   - output ripple voltage

2. Small Signal AC Model Performance Categories:
   - stability (margins of stability)
   - audiosusceptibility
   - output impedance
   - step load transient response (small load transient)
   - input filter interaction

single and multi-loop control

duty cycle pulse modulation schemes

characteristics and compensation of control loops

3. Large Signal Model Performance Categories

step change of input voltage

step change of output current

global stability (large signal stability)

starting transient

nonlinearities such as saturation of magnetic components, saturation of Op Amp

protection circuits

4. System Interaction

interaction between switching regulator and input filter

interaction between switching regulator and unknown source impedance

interaction between switching regulator and payload (reactive load)

2.1.4.2 Switching Regulator Modeling Techniques

Average model (Caltech)

Power Stage: Taking advantage of the much lower output filter resonant frequency in relation to the converter switching frequency, the nonlinear switching power stage is approximated by a continuous small signal linear model.

Approaches:

- topology deduction to form a linear circuit model
- equation derivation to form a linear state-space model

Both applicable to either continuous current operation or discontinuous current operation

Analog to Discrete-time Conversion: Obtain output-voltage-to-duty cycle transfer function through describing function technique.

Input Filter: Identify interaction between the input filter and other two functional blocks.

Component Model Capability Summary
DC-DC Converter

DC-DC CONVERTER MODEL ATTRIBUTES	DC PERFORMANCE	SMALL SIGNAL AC	LARGE SIGNAL AC	TRANSFORMER MODEL	INPUT FILTER MODEL	THERMALLY INTEGRATED	EMI EFFECTS
	1	2	3	4	5	6	7

MODELS FOR 1,2	WELL UNDERSTOOD, ACCURATE
MODELS FOR 3,5	LIMITED CAPABILITY - PRECISE INPUT DATA IS REQUIRED FOR LARGE SIGNAL AC ANALYSIS
MODELS FOR 4,7	LIMITED CAPABILITY
MODELS FOR 6	WORST-CASE MODELS EXIST - PRECISE INPUT DATA REQUIRED

Table 2-7

DC-DC CONVERTER
UNCERTAINTY/INADEQUACY

- DC - SMALL SIGNAL AC MODEL
  - DISCRETE AVERAGE MODEL
    - DATA BASE DOES NOT CONTAIN ALL COMMONLY USED CONFIGURATIONS
    - CURRENTLY USED VALIDATION TECHNIQUE LACKS ACCURACY
  - DISCRETE TIME DOMAIN MODEL
    - COMPLEX, HIGH COST
    - COMPONENT LIBRARY NEEDS EXPANSION
- LARGE SIGNAL MODEL
  - AVERAGE MODEL
    - LACKS ACCURACY ON SHORT TIME CONSTANT TRANSIENT
    - LACKS NONLINEAR PROPERTIES OF OP-AMP PROTECTION CIRCUIT AND TRANSFORMER SATURATION
- DISCRETE TIME DOMAIN MODEL
  - DIFFICULT TO GENERALIZE FOR UNIVERSAL APPLICATION
- GENERAL CIRCUIT ANALYSIS PROGRAMS
  - DETAILED ANALYSIS RESULTS IN CUMBERSOME INPUT AND HIGH RUN COSTS

TABLE 2-8

Merits

The average model is simple and easy to use, and it is readily applicable to complex circuits and systems. The model addresses both DC performance and small signal AC low frequency performance. It accepts either the transfer function form or the equivalent circuit form for the linear model.

Limitations

The average model only preserves the input-output properties of the converter. The original properties of a state variable (inductor current) is lost in the process of averaging. Consequently, the average model cannot be directly used for multiloop control systems which sense the output voltage and inductor current (or voltage).

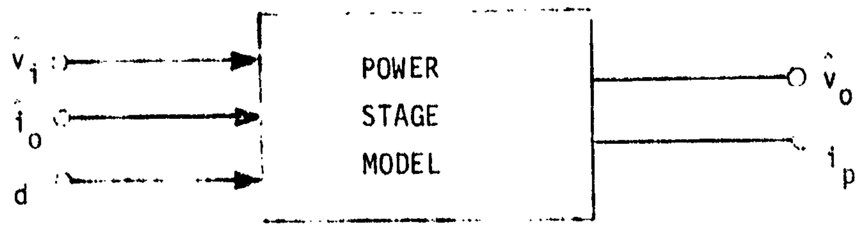
The large signal model is not readily available for transient and start-up analysis. There is diminishing accuracy beyond 10-20% of switching frequency. Not suitable for high-gain wide bandwidth regulators, such as high performance regulators employing multi-loop control schemes.

The canonical circuit model cannot be used directly to implement the multi-loop control.

Extended Average Model

The extended average model was developed for application to multiloop control systems. The three-input, two-output average model is shown below.

SMALL SIGNAL POWER STAGE MODEL



Inputs: line disturbance $\hat{v}_i$
load disturbance $\hat{i}_o$
duty cycle disturbance $\hat{d}$

Outputs: output voltage disturbance $\hat{v}_o$
switch current disturbance $\hat{i}_p$

The extended model has the following added advantages over the original average model:

1. Equivalent circuit model representing the original properties of the converter's input, output, state variables.
2. State variable model for state space analysis.
3. Transfer function model for classical frequency domain feedback control analysis and design.

Discrete Impulse Response Model

This method is based on calculation of the state vector perturbations at the switching instances; these are discrete in nature. The approach is to represent the power stage with a linearized discrete impulse response model, and then applying the z-transformation. The discrete time domain model is then transferred into the frequency domain.

Merits

Accurate power stage model up to one-half the switching frequency for AC analysis. (The theoretical limit of any linearized model.)

Limitations

The model requires complex analytical derivations, requiring a high degree of mathematical background. It is difficult to incorporate an input filter, and the model only provides duty cycle to output voltage transfer function. The model cannot be readily used to study disturbance from the line voltage and the load.

For a complex switching converter system, no closed form analytical model can be derived. Numerical techniques have to be comployed.

Discrete Average Model

The discrete average model is derived by combining the techniques of the average model and the discrete impulse response model. The approach is to use the average techniques to derive a model for state variables. (State variables are well behaved and continuous.) Then, use discrete time representation to derive an output voltage expression. (Since the output voltage is discontinuous due to the filter ESR.)

Merits

Improved accuracy of the average model in high modulation frequency up to one half of the switching frequency. The technique retains the simplicity of the average model. The model is easy to use, and is presented in the form of circuit model, transfer function model, and state space model. It is suitable for single-loop and multi-loop control modeling and analysis.

Limitations

Difficult to use for transient and start-up analysis.

Discrete-Time Domain Analysis

Using state space representation, a nonlinear discrete-time system is derived that models the converter exactly. This system is linearized about its steady-state solution.

Modeling Approach

Exact formulation of state equations. Use Newton iteration to solve for the exact equivalent state.

The system is linearized about the equilibrium to obtain linear time-invariant model.

Use z-transformation and obtain frequency domain transfer function representation.

Merits

No assumption is made. Most accurate small signal linear model for stability analysis.

Can predict high frequency (subharmonics of the switching frequency) instability.

The formulated recurrent state equation leads to a cost-effective performance analysis.

Limitations

Basically, it is a numerical analysis. No closed-form solution is derived to provide physical insight. It is a small signal model, and requires background in state space modeling and numerical analysis.

Discrete Time Domain Simulation

The discrete time domain analysis techniques are extended to large signal simulation.

Modeling Approach

Exact formulation of state equation.

Based on recurrent discrete time domain analytical expression.

Propagate recurrent equation through numerical computation.

Merits

Large signal analysis and simulation.

Exact duplication of the circuit behavior.

Capable of start-up simulation.

Simulation of large signal transients.

Capable of incorporating all system nonlinearities.

A combined analytical and numerical scheme that provides a cost-effective simulation faster than other general purpose simulation programs such as SCEPTRE, SPICE ICAP, etc.

Limitations

Relatively ineffective for large system simulation, since the user has to provide state space representation of the system.

Large Signal Average Model

In this model the average techniques previously described are extended to perform large signal analysis.

Power stage model: Using the average technique to represent the switching power stage by an averaged continuous-time domain equivalent circuit.

Error processor model: Since the error processor is a linear, no approximation is made. The saturation effect of the op-amp however can be incorporated in the model.

Duty cycle pulse modulator model: The exact duty cycle implementation can be simulated incorporating the basic ramp and threshold implementation.

Merits

The simplified power stage model provides an effective large signal simulation.

The model is easily adaptable to existing circuit analysis programs such as ICAP, SPICE 2, SCEPTRE, etc.

Limitations

In general, it is difficult to include some protection features such as transistor peak current protection, because the inductor current (and transistor current) is approximated by its average value.

It is difficult (if not impossible) to be extended to simulation of converter employing a multi-loop control technique where the instantaneous inductor current (transistor current) or inductor voltage is sensed to provide the necessary ramp for duty cycle implementation.

It is difficult to include different duty-cycle control schemes such as constant T_{on} control, constant T_{off} control, constant frequency control, and variable T_{on}, variable T_{off} control, etc.

<u>A Combined Discrete and Average Technique for Large Signal Model</u>

Approach

A compromise between complexity and accuracy. The converter is first represented by discrete time equation. The system is then approximated by a continuous time representation that remains in the nonlinear properties of the original system.

Merits

Nonlinear time varying circuit for large signal simulation.

Linear time invariant circuit model for small signal analysis.

Capable of implementing different duty cycle control.

Capable of implementing single-loop control and multi-loop control.

The model remains in the nonlinear properties of the original system and therefore is able to implement the protection features and various saturation effects of the system.

Limitations

The method is not well documented, therefore the utilities and limitations of the method are not clearly understood at the present time.

Circuit Analysis and Simulation Programs

The direct simulation method is capable of giving detailed information about the system because of the detailed modeling associated with each electronic part.

Approach

Use existing circuit analysis programs such as SPICE 2, SCEPTRE, ICAP, etc., to simulate switching power converters.

The component models such as semiconductor devices and magnetics are presented either in the form of equivalent circuits or state equations.

Merits

Easy to implement provided that the component models are available. Easy to determine the component stress and circuit particulars. In general, it is more versatile and flexible to accommodate changes in circuit parameter values control modes, and output options for a large class of converter circuits.

SCEPTRE program is capable of interfacing with any FORTRAN subprogram provided by users.

Limitations

Lack of semiconductor and magnetic component library for switching applications.

Lack of effective numerical integration routine to handle stiff differential equations with wide separation of time constant. This is often the case when non-ideal switching component models are utilized. It results in either excessive computer execution time or numerical instability.

Switching Converter Modeling Requirements

Power Stage Model - Topologies:

1. Buck converter
2. Boost converter
3. Buck/boost converter
4. Forward converter
5. Ćuk converter
6. Half-bridge converter
7. Parallel converter
8. Full-bridge converter

Mode of Operation:

1. Continuous current
2. Discontinuous current

Analog Error Processor Model:

1. Single loop control
2. Multi-loop control

Pulse Modulator Model

1. Constant frequency
2. Constant $V_I T_{ON}$
3. Constant T_{ON}
4. Constant T_{OFF}
5. Variable T_{ON}, T_{OFF} and frequency

Power Converter Modeling Considerations

The selected modeling technique(s) should be general enough to incorporate a variety of power converter configurations, and duty cycle control modes. It should be capable of arbitrary control implementation using single loop or multiloop control. In developing the best approach, the following areas should be considered:

1. Accuracy of the model
2. Complexity
3. Expendability
4. Modularity
5. Verifiability

6. Cost-effectiveness
7. Easy to use
8. Generality/limitation to particular power stage configuration
9. Generality/limitation to particular duty cycle control scheme
10. Generality/limitation to converter operating mode

Power Converter Modeling Objectives

1. Accuracy of terminal characteristics
2. Accuracy of AC model for stability and dynamic performance
3. Simplified internal working model
4. Capable of DC, AC, and transient analysis
5. Time domain model for large signal simulation
6. Frequency domain model for small signal analysis
7. Capable of predicting system interactions such as input filter interactions
8. Equivalent circuit model and transfer function model
9. Model adaptability to canned circuit analysis programs such as SPICE 2, SCEPTRE, ICAP, etc.

The most applicable modeling and analysis technique depends on the following considerations:

1. The analysis objectives: worst-case analysis; DC analysis; AC analysis; transient analysis
2. Accuracy required
3. Type of control circuit used
4. Nature of disturbance
5. User's background
6. Capability of the host computer

Proposed Switching Converter Modeling Schemes

1. DC and smallsignal AC model.

   Power stage: discrete-average model

   Duty cycle modulator: describing function

   Error processor: transfer function model

2. Large signal model.

   Power stage:
   a) discrete-average model for cost-effective analysis and simulation
   b) discrete time domain simulation
   c) direct circuit simulation programs.

Duty cycle modulator:	direct simulation using equivalent circuit model or nonlinear differential equivalent
Analog error processor:	direct simulation using equivalent circuit model or differential equations

The particular chosen modeling techniques should be simple and effective for large system simulation. On the other hand, it should be accurate enough for detail study and trouble-shooting. These apparently conflicting objectives require multiple converter models to be established and a particular one is selected for a specific application.

Development Efforts

The development efforts needed to establish proper modeling tools for the proposed modeling schemes are summarized as follows:

1. DC and small signal model

   Power stage model:

   - The discrete-average technique is currently developed under the support of NASA Lewis Research Center, Grant No. NSG-3724.
   - Discrete-average model for three basic converters; buck, boost, and buck/boost, have been demonstrated.
   - The discrete-average model should be represented in the following forms for generality:
     - state space model
     - transfer function model
     - equivalent circuit model
   - The modeling scheme should be extended to other converter types to establish a component (converter) library

   Duty cycle modulator model.

   - The accuracy of the duty cycle modulator model is limited to only low modulation frequencies using the describing function technique.
   - The inaccuracy of the pulse modulator model is particularly pronounced for high performance converters employing multi-loop control.
   - An improved modeling scheme is desirable.

2. Large signal model

   Power stage model:

   - Discrete-average model - advantages:

     A simplified internal working model; the model is simple, easy to use, and cost-effective.

- Discrete-average model - disadvantages:

  The model is unable to handle abnormal converter operations such as peak current protection mode of operation; saturation of magnetic components; saturation of op-amp in the feedback control loops.

- Discrete time domain analysis & simulation - advantages:

  Exact duplication of circuit behavior capable of incorporating all system nonlinearities.

  Accurate and cost-effective.

- Discrete time domain analysis & simulation - disadvantages:

  Relatively ineffective for large scale system simulation.

- Direct circuit analysis & simulation - advantages:

  Easy to implement, flexible and versatile. SPICE 2 and SCEPTRE are available CAD programs for converter simulations.

- Direct circuit analysis & simulation - disadvantages:

  Time consuming for implementation and numerical integrations.

2.1.5 Cabling and Distribution

Table 2-9 summarizes the capabilities of the distribution/cabling modeling techniques with respect to various attributes. Table 2-10 summarizes the existing model uncertainties/inadequacies. Cabling and distribution optimization models fall into two classes:

1. Mass optimization
2. Cost optimization

In the first case the optimum distribution weight is determined as a function of conductor mass and conductivity, the specific mass of the source and storage elements. The existing models reviewed fail to account for fuse, switch and connector losses, which in some cases could override conductor losses.

In the second case the optimum conductor cross sectional area is determined as a function of conductor, energy storage, solar array, thermal control, and power conversion costs. In general, the optimum cost cabling is heavier than the minimum mass model. The cost model has no provision for insuring a cable at least as large as the minimum mass model.

Component Model Capability Summary
Distribution/Cabling

DISTRIBUTION MODEL ATTRIBUTES	LINE RESISTANCE	CONNECTOR, FUSE RESISTANCE	SWITCH RESISTANCE	LINE INDUCTANCE	LOOP INDUCTANCE	INTERLINE CAPACITANCE	LINE-TO-GROUND CAPACITANCE	THERMALLY INTEGRATED	SIZING
	1	2	3	4	5	6	7	8	9

• MODELS FOR 1, 8	• WELL UNDERSTOOD, ACCURATE
• MODELS FOR 2,3,8	• GENERALLY ENTERED AS A WORST CASE RESISTANCE. TESTING MAY BE REQUIRED TO DETERMINE OPERATING CHARACTERISTICS OVER A WIDE RANGE OF ELECTRICAL AND THERMAL CONDITIONS
• MODELS FOR 4,5	• LINE INDUCTANCE HAS BEEN MODELED, NO LOOP INDUCTANCE MODELS WERE FOUND. - PRECISE INPUT DATA IS REQUIRED FOR TRANSIENT ANALYSIS
• MODELS FOR 6,7	• THESE HAVE BEEN MODELED ON A SMALL SCALE - PRECISE INPUT DATA IS REQUIRED FOR TRANSIENT ANALYSIS
• MODEL FOR 9	• NO COMPLETE MODEL EXISTS. SOME MODELS SIZE BASED ON MINIMUM MASS, OTHERS SIZED ON MINIMUM COST

Table 2-9

DISTRIBUTION MODEL
UNCERTAINTY/INADEQUACY

- DIFFICULTIES OF ESTIMATING DISTRIBUTED INDUCTANCES, CAPACITANCES DUE TO MUTUAL COUPLING/CABLE ROUTING EFFECTS
- VARIABILITY OF CONNECTOR, SWITCH CONTACT RESISTANCES WITH AGE
- SENSITIVITY OF HYBRIDS AND I/C'S TO TRANSIENTS
  - -- MAKES TRANSIENT PREDICTION AND ANALYSIS DESIRABLE
  - -- MAKES DIRECT TESTING UNDESIRABLE DUE TO DANGER OF PART OVERSTRESS

TABLE 2-10

2.1.6 Modeling of Complete Power Subsystems

Several general classes of power subsystem modeling programs appear in the literature. These are:

1. Generalized circuit and systems analysis models.
2. Dedicated pseudographical models of specific subsystems.
3. Hybrid computation models.

Table 2-11 summarizes the capabilities of specific models studied, and Table 2-12 summarizes the adequacy/limitations of power subsystem models.

2.1.6.1 Generalized Computational Models

The generalized computational models, as a class, are represented by programs such as SPICE, SCEPTRE, ECAP, ICAP, TESS, and a number of others. Variations and extensions to these programs are also reported.

All have similarities in that they offer a set of typical component models which are assembled into a network of interconnecting nodes. Each individual component model must be reducible to one or more first-order differential equations which are solved by matrix arithmetic to find a solution at each point in time.

Many of these programs have the ability to accept parametric data in the form of equations or functions, piecewise linear parametric data, or as user-supplied FORTRAN routines. The supplied equations and routines must meet the criterion of being reducible to differential equation form.

When used with accurate models of individual components, these programs are generally capable of performing non-linear DC and transient analyses, and AC analyses if the AC signal is small enough to permit the assumption of linearity within the range of interest. This class of generalized programs shares certain limitations:

1. With increasing numbers of components, the memory requirements increases dramatically. By use of dynamic memory management it is possible to permit an unlimited problem size, but only at the cost of an increase in computation time.

2. Aside from the memory management problem, an increase in problem size results in a geometric increase in computation time. This makes the analysis of large, complex systems expensive.

ORIGINAL PAGE IS
OF POOR QUALITY

POWER SUBSYSTEMS REFERENCE	COMPLETE SYSTEM	DC ANALYSIS	SMALL SIGNAL AC ANALYSIS	LARGE SIGNAL AC ANALYSIS	POWER SUBSYSTEM/ LOAD INTERACTION	INTEGRATED THERMAL MODEL	ORBIT MECHANICS/ TRAJECTORIES	MULTI-ORBIT CAPABILITY	BATTERY CHARGE-DISCHARGE	SOLAR ARRAY DEGRADATION	GENERAL PURPOSE	LOAD PROFILE EFFECTS	RESTART CAPABILITY	POWER SUBSYSTEM SIZING
SPICE 2	X	•	•								•			
2 Performance Prediction Program Weiner & Weinstein	•	•			•	•		•	•	X		•		x
3 SKYLAB Model Imamura, Conn, Peszko, Scott	•	•			•		•	•	•	X		•		
4 General Model Coggi & Barker	X	•			•	•	•	•				•		
6 Power Systems Stability Lukens			•								•			
7 Solar Panel Volt. Regulation Gates & Muldoon		•										•		
9 Satellite Pwr. Syst. Bauer PSIM	•	•			•	•		•	•	X		•	•	X
14 Maximizing S/C Energy Ostwald	•	•						•	•	X		•		
17 Explorer Energy Balance Program Broderick	•	•					X	•	•	X		•		
22 Pwr. Systems, GEO Billerbeck		•							Battery Degradation	•				X
26 Energy Balance Program NASA/GSFC	•	•					X	•						X

Note: References are keyed to Appendix A

SELECTED POWER SUBSYSTEM MODELS CAPABILITY SUMMARY

o-Has capability
x-Limited capability
Blank-No capability

TABLE 2-11

ADEQUACY/LIMITATIONS OF POWER SUBSYSTEM MODELS

- LIMITED ABILITY TO DO SMALL SIGNAL AC ANALYSIS
- NO ABILITY TO DO LARGE SIGNAL AC ANALYSIS
- LIMITED ABILITY OF MODEL TO FUNCTION IN TRANSITION ORBITS OR ELLIPTICAL ORBITS
- ONLY ONE MODEL WAS FOUND TO HAVE RESTART CAPABILITY
- SOLAR ARRAY MODELS LACK PLASMA INTERACTION DATA
- SOME MODELS CAN BE USED FOR SIZING, HOWEVER IT IS GENERALLY COST EFFECTIVE TO USE A SIMPLER MODEL
- MODEL VALIDATION DATA IS LACKING. THIS IS REQUIRED IF THE MODEL IS TO BE USED AS A SYSTEM VERIFICATION TOOL

TABLE 2-12

By permitting the entry of data in the form of functions and subroutines, the more modern versions permit the summarization of the performance of large numbers of components by a single (or a small set of) transfer functions, thus reducing the problem size for large system to more manageable proportions. However, the program then becomes more difficult to run, for a suitable transfer function for each "box" or circuit must be found, which adequately describes its operation under all conditions within the range of interest. For some components this can become a formidable task.

2.1.6.2 Dedicated Pseudographical Models

Dedicated models of individual power systems have been used successfully in many cases. In these the logic and properties are programmed into the computer model and may be in a variety of forms, including logical equations, subroutines, and piecewise linear approximations. One is not limited to any specific form, nor is the ability to form a first-order derivative essential, although differentiability may be a convenience in the use of some numerical solution routines. Because of the lack of adequate mathematical descriptions of some power subsystem components such as batteries, the solution method used will usually take a pseudographical form, i.e., the computer will find the solution by finding the intersection of two tabular functions.

This type of model is capable only of DC analyses, although if heat generation is considered, and if the thermal time constants are much longer than the electrical time constants (which they invariably are), the system will follow thermal transients in an electrical system very well.

Program accuracy is limited by the accuracy of the model logic, the input data, and the accuracy of the interpolation or spline routines used for finding the solution.

Execution speed and cost of such programs tends to be much less than that for the generalized circuit and system routines for large systems, and the accuracy greater, primarily because the design flexibility of the individual component models is greater.

2.1.6.3 Hybrid Models

In hybrid modeling the mathematical transfer functions used to simulate the performance of circuits or boxes are replaced by analog computer models having the same function. The analog-modeled transfer function outputs are used in the same way as the mathematical transfer functions in a generalized type of program. The result in theory is to speed up the computation (as compared with all-up part models). The method has an additional degree of flexibility. By placing the parameters of each analog model under the control of the digital program, it is possible to vary the transfer functions of several such models simultaneously so as to converge toward a desired solution. At this stage, it is not clear how far this method has been developed.

2.1.7 Industry Survey

In order to determine the actual usage of models, an industry survey was conducted. Because of the nature of the subject and the limited time, not all companies were contacted, and some of the data is necessarily brief. However, the message is clear that no overall comprehensive model is in existence, and no effort is underway to develop such a model.

Aerospace Corporation

- General purpose solar array model
  - Input: Array geometry, sun angles, radiation dose rate, solar cell parameters, temperature characteristics, mission length.
  - Output: I-V table, and solar array I-V curve plotted.
  - Limitations: DC model. Array temperature and distance from sun must be determined by user as an input.
- Power system simulation program
  - Variation of TRW's PSIM program. No transient analysis capability.

BOEING Aerospace

- Simplified sizing program
  - Battery and solar array characteristics have to be changed to reflect degradation and aging.
- Performance verification program
  - Input: Orbit parameters, load profile, attitude pointing profile, solar array pointing profile, max battery DoD, line losses.
  - Output: Thermal data, including transients, DC analysis, voltage, current, state-of-charge, system sizing requirements.
    - no electrical transient capability
    - developed for direct energy transfer and centralized regulator systems

Ford Aerospace

- Improved SPICE (1 SPICE), ECAP
  - Developing detail models for standard converter design.

Lockheed Missiles and Space

- Sizing model
  - Proposals, initial concepts
- Performance Verification
  - On-going spacecraft
  - Mission specific
  - No transient capability
  - Verified by test

General Electric

- Energy balance program - low earth orbit
  - Steady-state DC
  - No transient analysis

Martin Marietta (Denver)

- Photovoltaic system test prototype model
  - General purpose terrestrial or space, with or without battery
  - No transient analysis
  - Verified by tests
- Developing new version of SPICE
- SKYLAB computer program

RCA

- Energy balance computer program
  - Multiple orbit capability
  - Computer system
  - Linearized electronic component models
  - No transient capability
  - No interactive thermal model

TRW

- SOLAR
  - Predicts solar array output I-V curves
  - Accounts for degradation factors
  - Accurate, easy to use
  - Interactive, rapid turn around
  - Validated by flight data
  - Requires multiple runs for complex array geometry
  - Requires service program to input tape for power subsystem program

TRW (Cont'd)

- SOLGRAD
  - Same as SOLAR except
    - -- two-dimensional thermal gradient model
    - -- provides tape for power subsystem program
    - -- more complex data input required
- HOTSPT
  - Predicts heat generated in solar cells as a function of shadowing or breakage, and the resultant solar array I-V curves
    - -- not integrated into power subsystem model
    - -- assumes all cells have same reverse characteristics
- BATMODL
  - Predicts current, voltage, heat generation, internal pressure, soc of battery cells in low earth orbit
  - Not fully tested or validated
- DISTRIB
  - Determines minimum mass cable for a given set of loads and power source mass per watt.
- PSIM
  - Energy balance/power system performance computer program
  - Uses solar array tape from SOLGRAD
  - Models complete power system with load and thermal interfaces
  - Restart capability
  - Voltage, current, heat generation, battery SOC
  - Secondary distribution networks not modeled
  - No AC or transient capability
  - Used for the following spacecraft: HEAO, FSC, DSCS II, DSP

2.1.8 Ideal Power Systems Model Requirements

The first requirement of an ideal model is that it must be user-oriented. The model must be capable of performing configuration trade studies to determine the optimum power system for a particular spacecraft. It must be capable of analyzing the available options and quantifying the results. Optimization may be on either cost or mass, or on some other parameter, such as minimum solar array size, or minimum radiator size. This flexibility has to be comprehensive enough to minimize changes downstream in a project where it can become very costly. An output of the trade studies is the initial power system sizing.

- solar array power and area
- energy storage mass and dissipation
- distribution system mass
- regulator mass and dissipation

The model must also be capable of identifying design and performance inadequacies as the subsystem requirements evolve. Early prediction of potential problems will minimize design changes.

To insure development of stable and reliable power systems the model must predict system stability margins and be accurate enough to allow sensitivity analyses to be performed.

The above requirements can only be met by a very sophisticated computer program with very accurate models of all of the power system components and loads. This accuracy is not required for initial trade studies and initial power system sizing. A much simpler program could do the job, and it appears that it would be used for specific applications. An example would be to have separate programs to compute:

1. Initial trades and sizing.
2. Nominal performance predictions.
3. Off nominal or design limit verification. Failure analysis, and performance in a degraded mode.
4. Transient analyses - system stability

These could all be contained on a tape and the desired function and models called by command.

3.0 COMPREHENSIVE POWER SUBSYSTEM MODELING APPROACH

Requirements

The uses, and therefore the requirements, of a power subsystem model vary with the phase of the spacecraft development program in which they are applied. Figure 3-1 outlines the work flow plan followed for this task.

Program Phase A: Concept definition and selection

In this phase of the program neither the requirements of the power subsystem, nor its configuration, are well-defined. The effort of the contractor is to define the requirements and characteristics of a power subsystem and to select a configuration which will meet those requirements. The customer has the task of evaluating the selected configuration to determine whether or not it is best suited to the requirements. In this phase, only a sizing or synthesis model can be used effectively. Performance models cannot be used effectively until the design has been advanced to the point at which a reasonably accurate model can be constructed.

Phase A Model Requirements

The Phase A model must perform at least the following tasks:

- Provide an estimate of the relative cost, weight, volume, solar array area, and other optimization criteria for a large set of possible power subsystem configurations.
- Provide for each power subsystem candidate configurations, interface information necessary for the definition of the requirements placed upon other spacecraft subsystems by the power subsystem. (For example, heat dissipation, mass distribution, torque induced by rotating machinery, etc.)

Many such models already exist. Most are proprietary, and documentation tends to be relatively poor. This type of model is a relatively simple one to construct, and represents little technical challenge. Its usefulness lies primarily in its ability to

- Provide rapid response
- Minimize Phase A study costs
- Avoid overlooking some important factors
- Provide a vehicle for customer evaluation of proposed configurations.

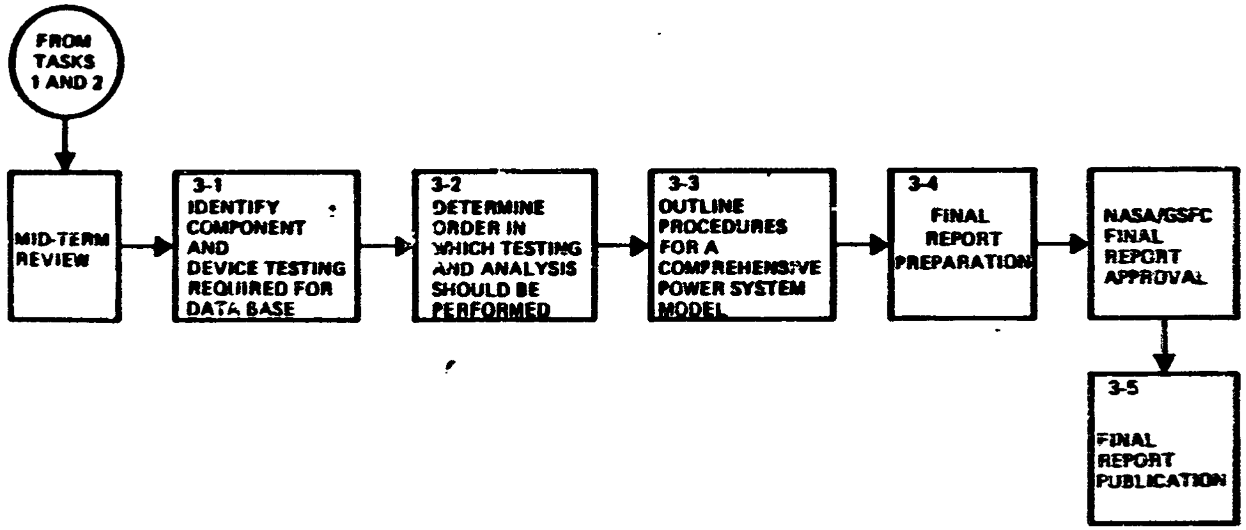


Figure 3-1. Task 3 Work Flow

Program Phase B - Preliminary Design

In Phase B, the design concept has been selected and the major contractor effort is directed toward the development of implementation concepts. General circuit design types are roughed out, but component values have not all been selected, and the definition of the power requirements, while improved, is still not firm. Little or nothing is usually known about the individual loads other than their approximate power consumption and the required input voltages. Circuit definition and power distribution network definition has not yet reached the point where either AC or transient modeling is possible in a meaningful way. Only if the power subsystem consists of existing hardware which has been extensively characterized can the AC and transient modeling be done at this stage. Even then, the spacecraft-unique distribution system will be unavailable for use in an all-up model. A DC model can be extremely useful in Phase B for the definition of many of the power subsystem characteristics.

Phase B Model Requirements

The Phase B DC model is used primarily to verify the power and energy balance characteristics of the power subsystem, and to provide assurance that there is sufficient power and stored energy to meet mission requirements, given the assumed characteristics of the power subsystem components. The requirements of such a model are:

- Predict voltage, current and heat output of each power subsystem component (including batteries).
- Predict the voltage, current input required for each component to deliver the required output.
- Predict voltage drops in the interconnecting harness and power distribution harness.
- Predict energy content of energy storage devices, such as batteries
- Simulate the electrical and thermal response to
  - load changes
  - loss and return of solar array illumination
  - commands

- environmental changes (such as solar input, albedo, s/c orientation)
- spacecraft configuration changes (before and after deployment)
- predictable failures.

Predictions are made as a function of time. The total time span of interest is one of multiple orbits.

Program Phase C - Detailed Design

During Phase C the designs are completed. All parts have been defined, and both electrical circuit designs and physical layouts have been completed. Engineering models have been constructed, and some measurements have been made for the purpose of characterizing their performance. These measurements provide a more accurate estimate of power subsystem component DC performance, permitting further DC performance predictions for the entire power subsystem at considerably improved accuracy.

Also during Phase C, sufficient detail is generated to permit the construction of AC and transient models of the components of the power subsystem. Early in this phase, such models are useful in performing trade studies on alternative detailed circuit designs. Toward the end of this phase, AC and transient models are used to analyze the interaction between components of the power subsystem.

Phase C Model Requirements

DC Models: Requirements are the same as for Phase B, except that the accuracy with which some of the power subsystem components have been characterized is improved as a result of measurements.

Small-Signal AC Models: The primary use of small-signal AC models is a determination of component and/or subsystem stability. Such a program should be capable of performing the following predictions:

- Determination of component stability. Such predictions are usually in the frequency domain in terms of gain and phase margins. As such, they are independent of time.
- Individual control loop characteristics, stability, gain, phase margins.

- Input-output impedance as a function of frequency.
- Small-signal transient response.
- Capability of including component interactions, particularly those of input and output filters.

Large-Signal Transient Models: Like the DC model, the large-signal transient model is non-linear, and operates in the time domain. However, for economic reasons, the transient model is limited in its time span to periods of very short duration; of the order of milliseconds. The use of such transient models is to predict the voltage and current transients which occur as a result of an outside stimulus or internal failure of a component. The resultant prediction is then examined to determine whether or not it will have a deleterious effect upon the operation of the component or other components of the system. The requirements of such large-signal transient models are as follows:

- Predict the voltage and current transients at the input and/or output of a power subsystem component (or set of components);

  as a result of an external stimulus,
  as a result of an internal failure.

Program Phase D - Hardware Construction and Spacecraft Integration

In this phase, flight hardware is constructed and the complete spacecraft is assembled. Measurements are made characterizing the performance of the individual components of the system. In smaller spacecraft, an integrated subsystem test is usually performed to determine the overall performance of the system. However, with increasing spacecraft size and increasing power levels, the difficulties inherent in such integrated subsystem tests multiply. No new kind of subsystem model is needed in Phase D. The same DC, small-signal AC, and transient models are used. However, more accurate results should be attainable because the measured characteristics of individual flight hardware components are used as inputs in place of the earlier estimates of component performance.

Program Phase E - Flight Operations

In this phase the spacecraft is placed into operational orbit (or flight path) and is operated. The uses of power subsystem models in this phase of spacecraft operation are:

- Failure diagnostics and predictions of off-nominal operation
- In the case of in-flight maintainable spacecraft, predictions of changes is the performance of the power subsystem as a result of changes in the spacecraft power demand or power subsystem configuration.
- System health status/component performance.

Although no new types of programs are required to accomplish these aims, additional requirements may be placed upon each of the program types to include the following capabilities:

- Model a fairly extensive set of plausible failure modes.
- Follow changes in spacecraft load and power subsystem configuration.

Figure 3-2 shows a block diagram for a power system model.

3.1 Model Attribute Requirements

In the preceding paragraphs, we have defined the things the models must do. In the following are defined certain essential attributes or characteristics which all of the models must have in common to create a comprehensive modeling and analysis capability:

- Commonality and compatibility: Each of the types of models must maintain a commonality of reference with all of the others; i.e., they must all predict the same attributes and performance for the same subsystem.
- Modularity: Each of the components of the power subsystem should be modeled as an independent module having the following attributes:

  Capable of being operated independently as a component model

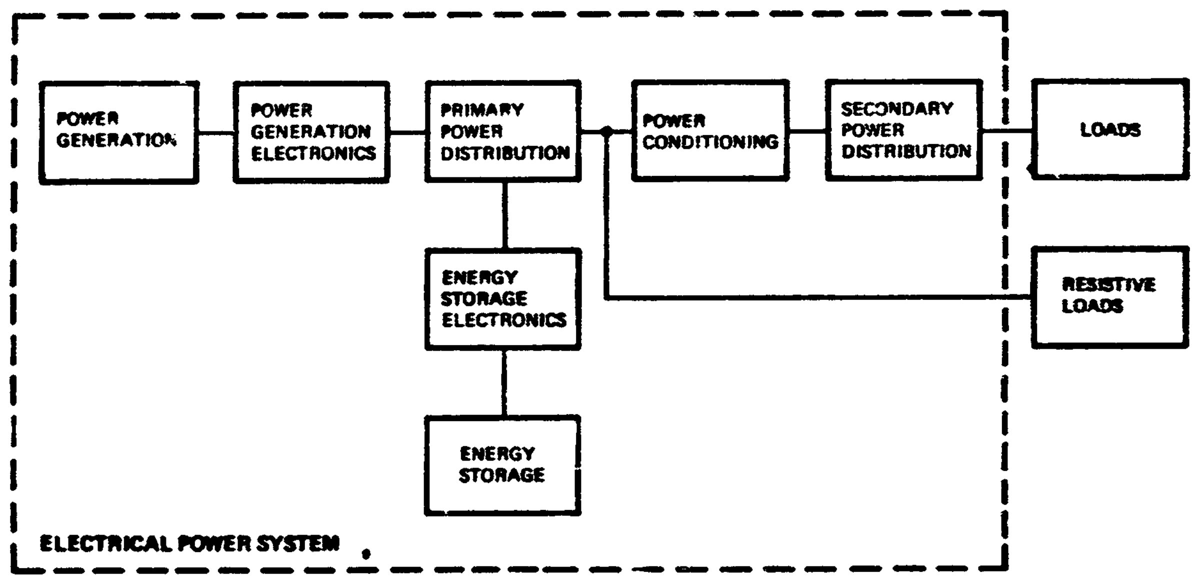
  Capable of being integrated into a power subsystem model

  Capable of replacing or being replaced by an alternative model having different input requirements

  Data base - each module must be provided with an independent data base specifically suited to its own needs.

COMPREHENSIVE POWER SYSTEMS MODEL

BLOCK DIAGRAM



- COMPONENT MODELS ARE REQUIRED FOR EACH BLOCK FOR EACH OF THE FOUR TYPES OF ANALYSES.

FIGURE 3-2

- Efficient use of both core memory and computation time.
- Verifiability - models should be verifiable as independent modules and as a complete integrated power subsystem. Verification data base must be provided independent of the model input data base.
- Operational Simplicity - The models must be designed for use by a working power subsystem engineer whose understanding of the program and computational facility are limited. Clearly stated, complete user documentation is essential to the successful use of such a complex set of models.

3.2 Single Comprehensive Program vs Independent Programs

The need for four types of programs has been identified, each of which has different uses, and uses different methods to accomplish its objectives. It is possible, however, to design a single program containing the four programs which will accomplish all of the required objectives without severe penalties in either computation time or memory requirements by the use of overlays and segmentation methods. By this means, only those parts of the program which are being used are resident in memory at execution time.

3.3 Proposed Modeling Concept

The comprehensive Power Subsystem Model is envisioned as a set of four programs, either entirely separate, or combined into a larger segmented program, the desired part of which is called into core memory at execution time. Each program is equipped with a set of component models. These are selected by the user and are interconnected by the program to form an integrated power subsystem model. Figure 3-3 shows an overview of program structure. The operation of the program is as follows:

- Based upon the case instructions and input data, the executive selects the desired program segments and the specific power subsystem component models required for the run, and copies them from the disc library.
- An object program is generated, containing only those program segments and component models necessary for the specific run, and loaded into memory for execution.

- The data manager, under executive direction, selects the required input data for each of the component models, reads the data from disc packs into a common storage area, and forms an index of data location. Depending upon the size of data banks, random-access disc operations may be substituted for in-core data storage.
- During program execution, component model output data are generated, stored in the computer memory, and indexed under the control of the data manager. They may subsequently be written to disc or tape.
- At appropriate points in program execution, the output data are retrieved from storage and printed or plotted.

A program structure of this kind represents a compromise between minimizing computer RAM memory size and program execution costs. As the data bank sizing and data manager execution costs become clearer, an optimum memory field will become definable.

3.3.1 Computer Language

Prior to coding, consideration will be given to the selection and use of computer language. However, unless significant advantages are found in one of the other scientific languages, FORTRAN 77 will be used. It is felt that this language is the richest in available internal functions, and the most commonly understood of all languages in use in the scientific and engineering community.

3.3.2 Display Formats

Consideration will also be given to the development of a program control format based upon MENU selection of program functions. This is desirable on systems containing CRT displays, and the potential advantages of such a system in terms of user simplicity and compatibility are great enough to deserve consideration.

3.3.3 Program Development

Figure 3-4 shows a suggested schedule for model and data base development. This schedule is flexible, and is capable of responding to variations in funding availability, NASA priority of interest and other factors. It should however follow the general flow of Figure 3-5, and is subject to certain constraints upon the order in which the various phases of the effort are carried out.

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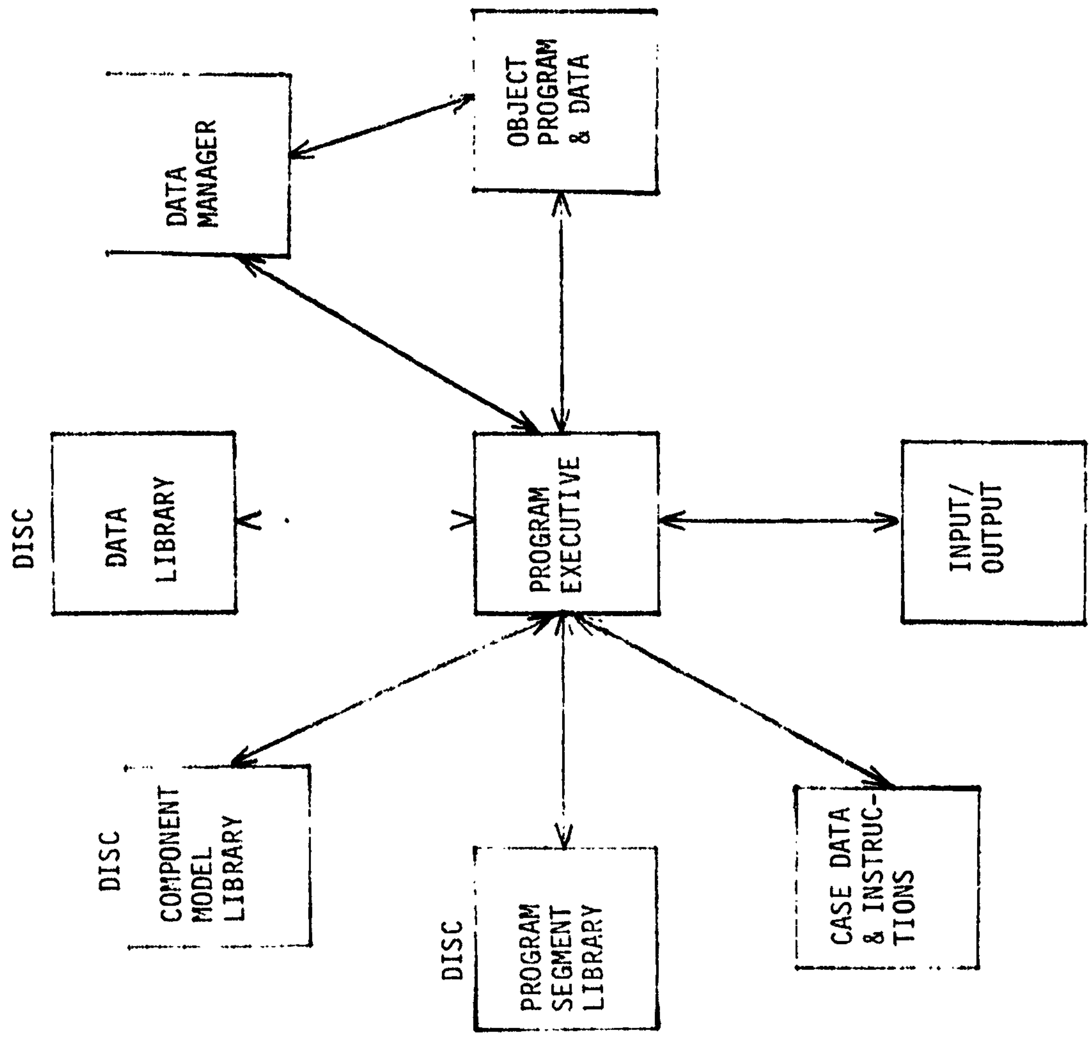

Figure 3-3 Program Structure, First Level

Driver Program Development

It will be necessary to complete a detailed definition of the driver program, data base structure, and data manager before beginning coding of the individual models of power subsystem components. Failure to do this could result in severe incompatibility between component models and the driver which operates them. Coding of the driver can be delayed, to some extent, but should have been completed and debugged prior to their first attempt at running an all-up power subsystem model test.

Model Development

Models may be divided into two categories: existing models which require only adaptation to the program structure, and new or improved models which require development. New model development follows the flow of Figures 3-6 through 3-10, proceeding through trade studies to select the approach to be used, development of the mathematical or logical algorithm, and coding. Trade studies and algorithm development can be done prior to or concurrently with the program structure development. Coding must await the development of program and data bus structure before it can be accomplished efficiently. Component models are independent and modular, so that updating a component model does not require changing the code of the executive program.

Data Base Development

For those models whose concepts are well understood, a data acquisition program can be initiated independently of the development of the final model code. However, where the model algorithms have yet to be developed, the form of the data required, and in some cases the kind of data required, to provide an input to the model are unknown or ill-defined. For these cases, it will be necessary to defer the development of a data acquisition program until the algorithm to be used has been defined. Data base acquisition requirements are shown in Tables 3-1 through 3-5.

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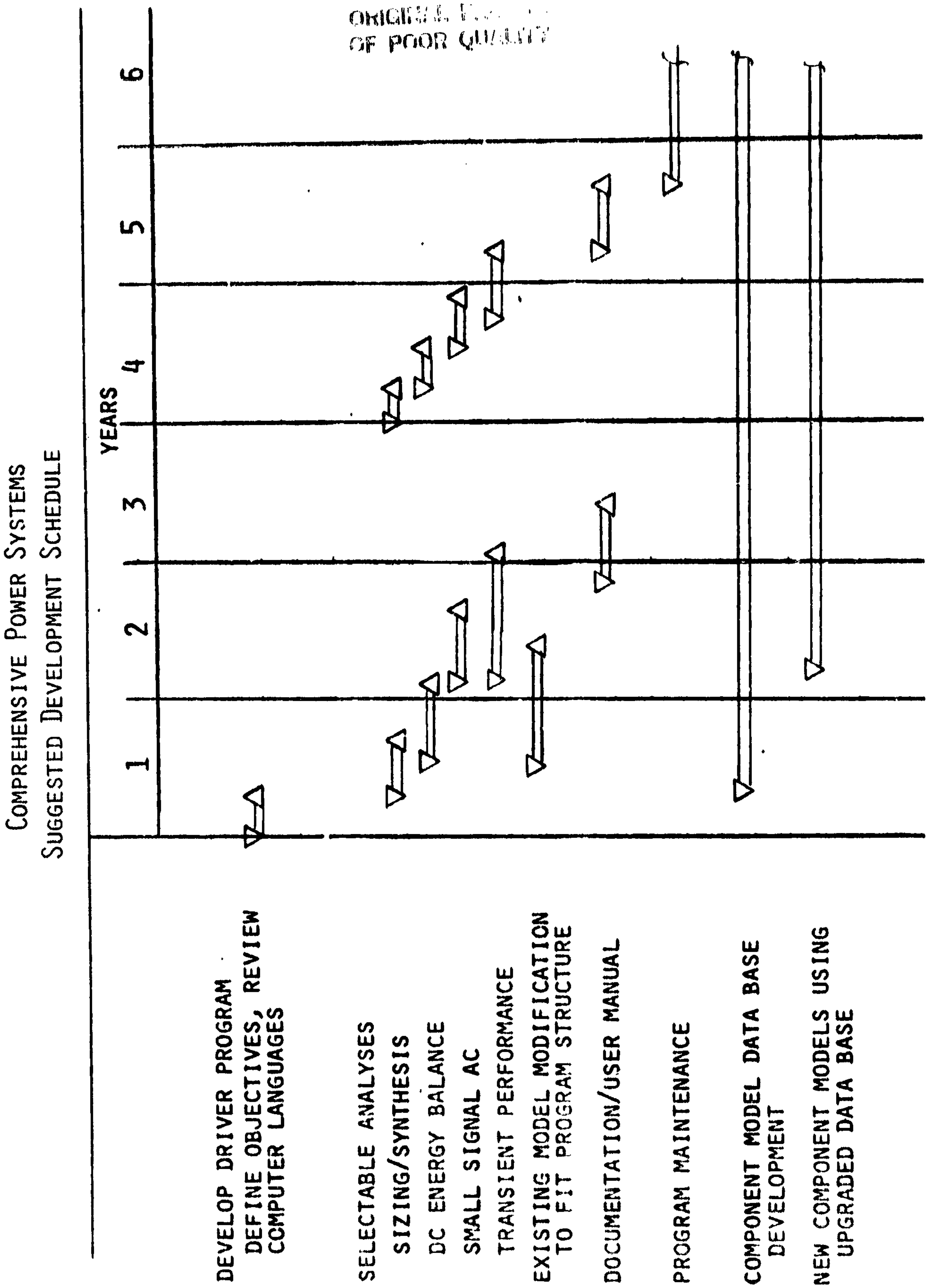

Figure 3-4

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PROGRAM DEVELOPMENT FLOW

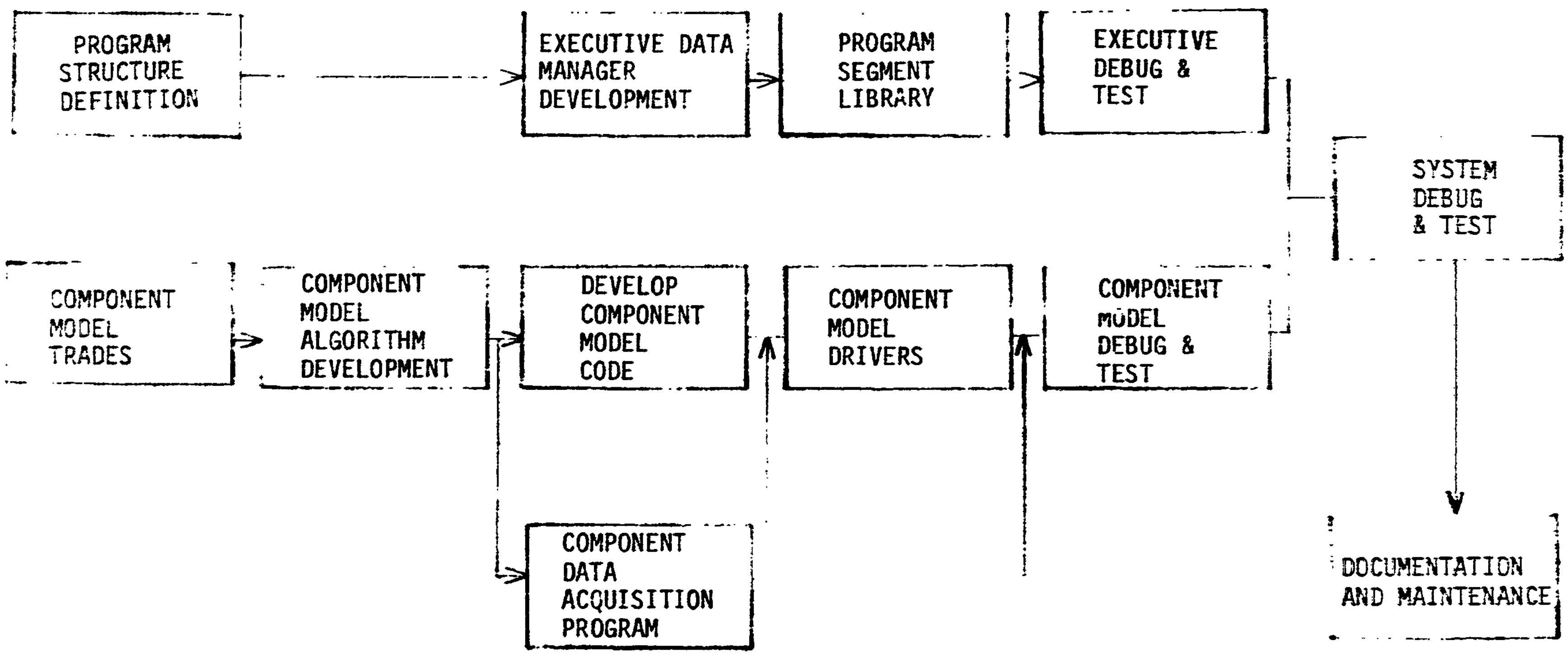

FIGURE 3-5

A SUGGESTED BATTERY MODEL DEVELOPMENT APPROACH

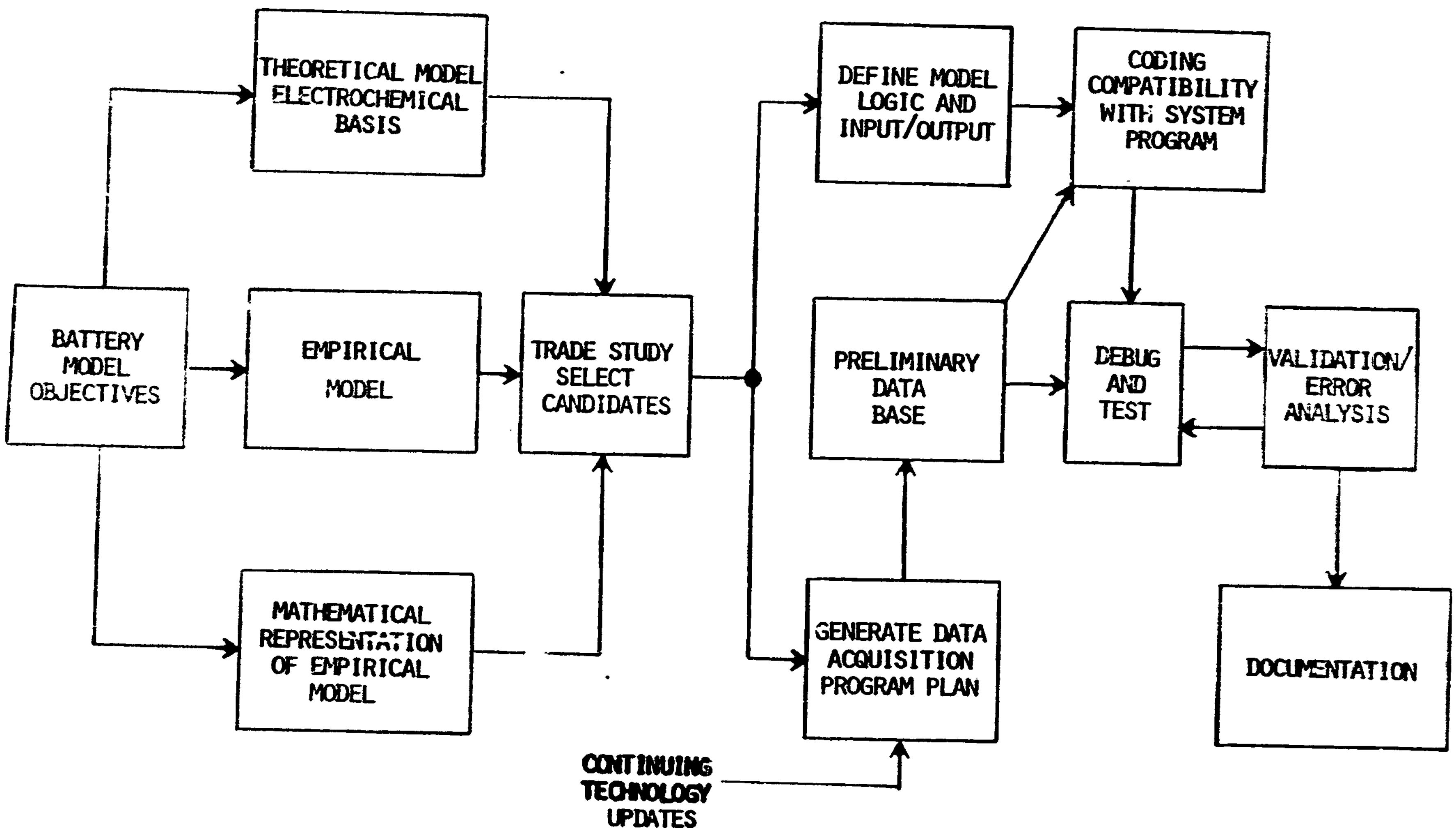

FIGURE 3-6

A SUGGESTED DISTRIBUTION MODEL DEVELOPMENT APPROACH

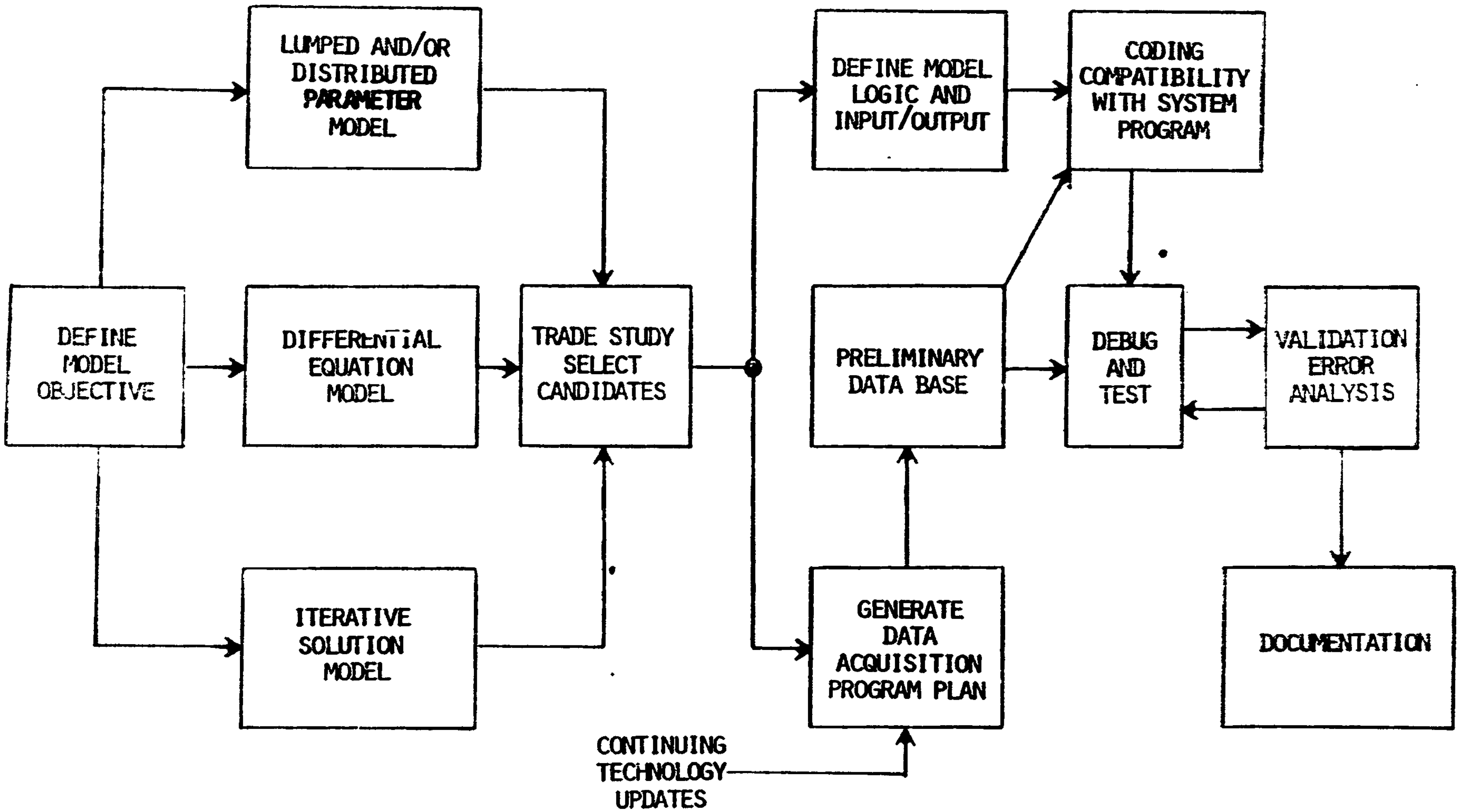

FIGURE 3-7

A SUGGESTED SOLAR ARRAY MODEL DEVELOPMENT APPROACH

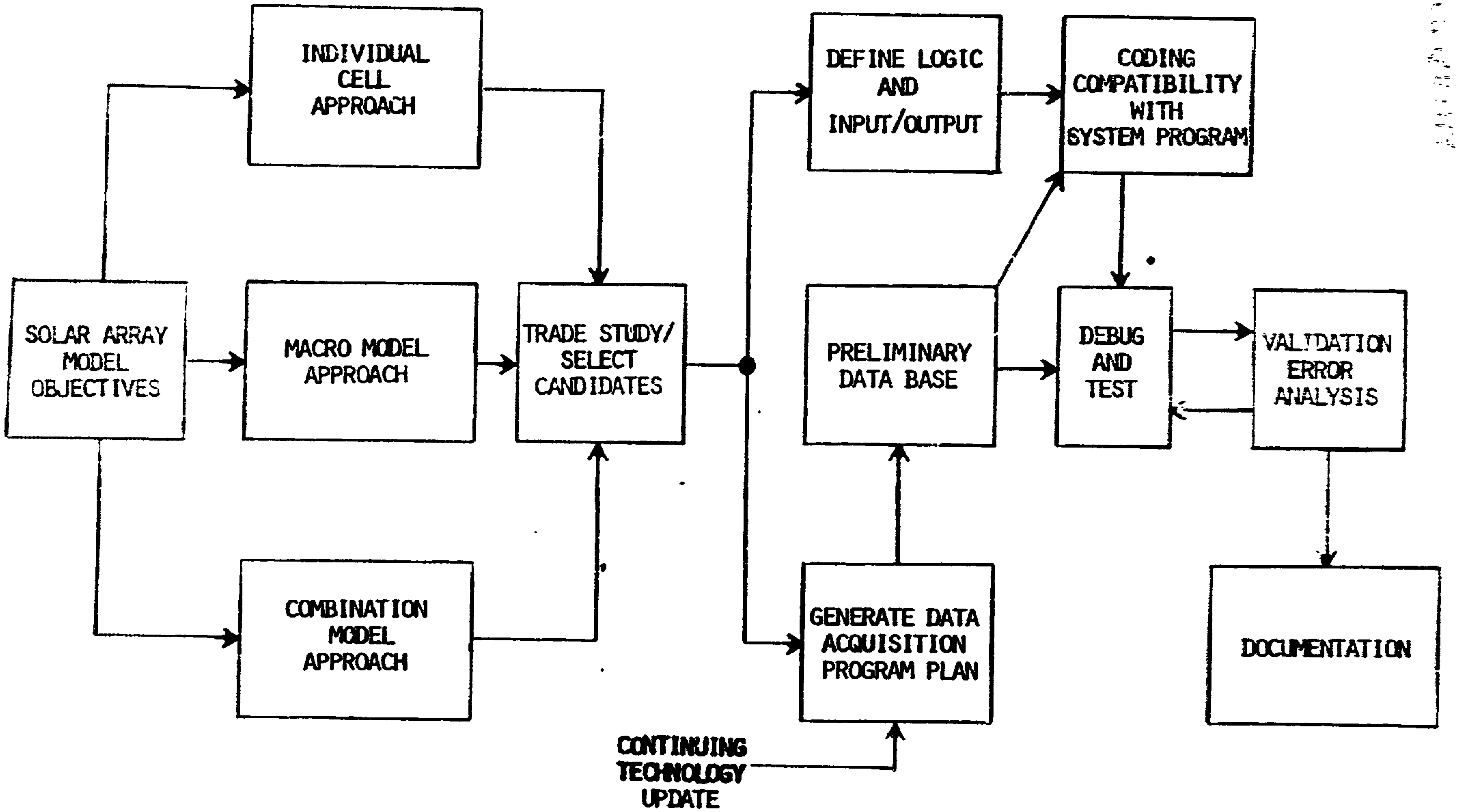

FIGURE 3-8

A SUGGESTED SHUNT REGULATOR MODEL
DEVELOPMENT APPROACH

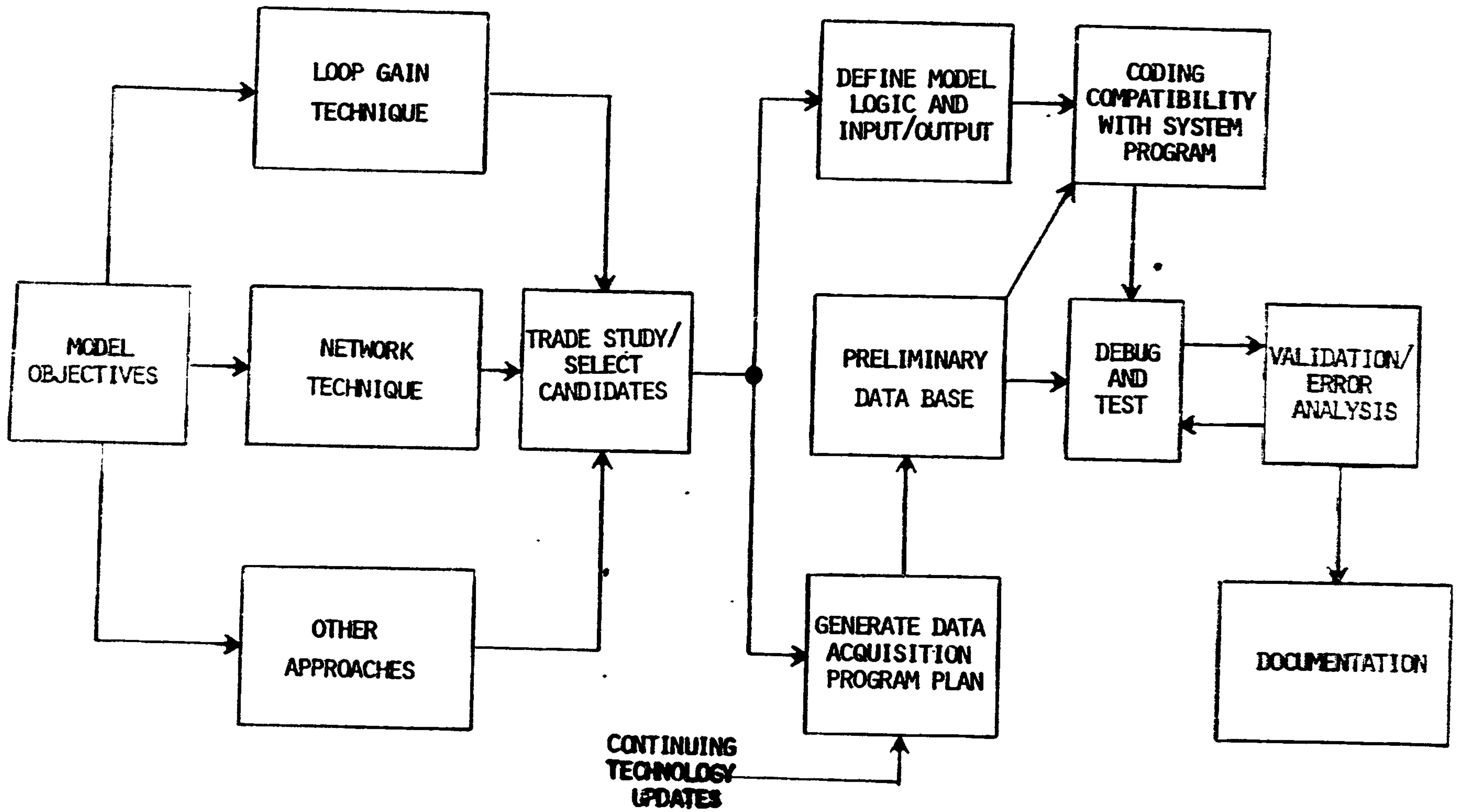

FIGURE 3-9

A SUGGESTED DC-DC CONVERTER MODEL DEVELOPMENT APPROACH

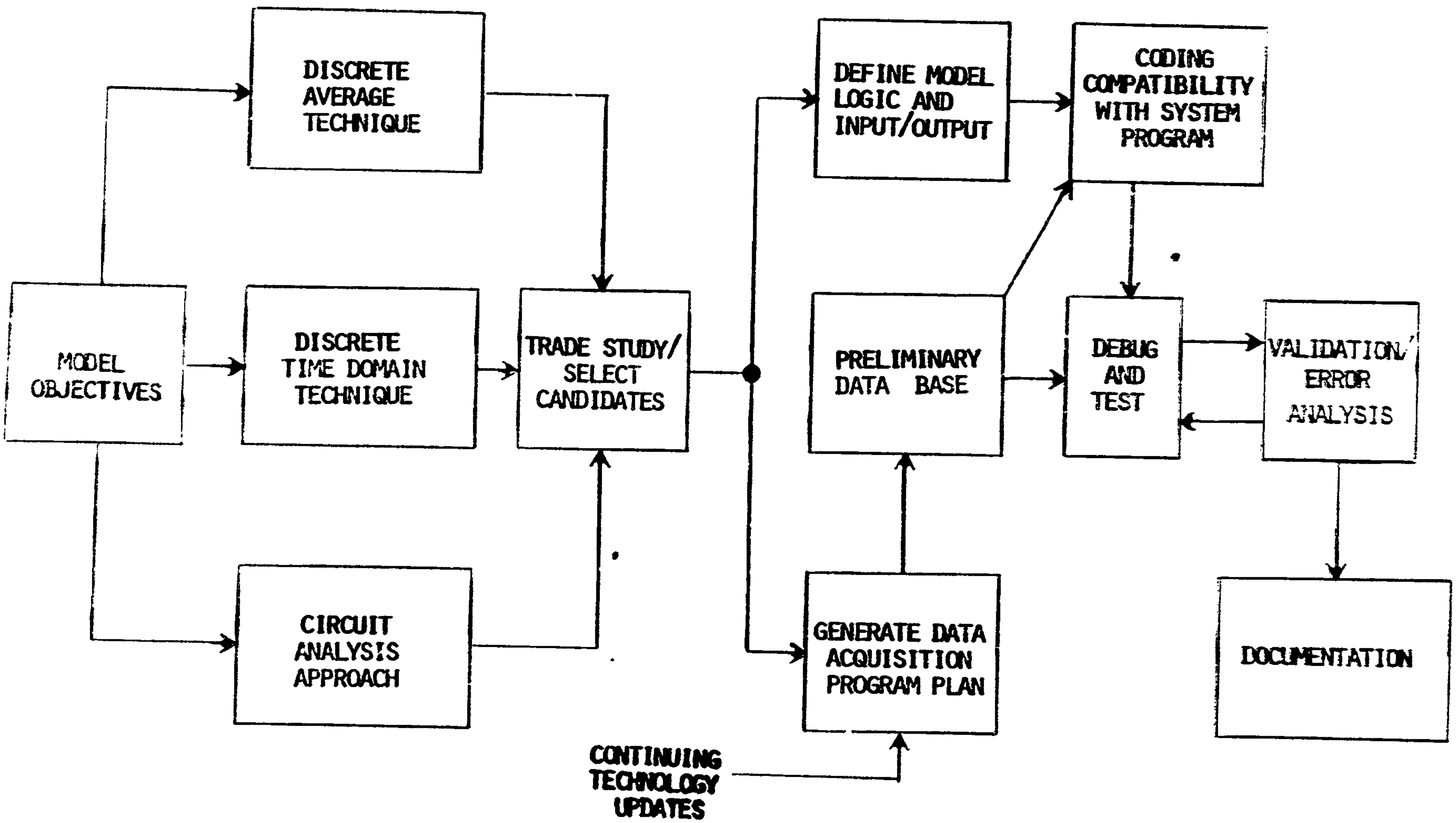

FIGURE 3-10

DATA BASE ACQUISITION - BATTERIES

- SUGGESTED ORDER OF TESTING
  - EFFICIENCY/SOC
  - HEAT GENERATION/PRESSURE
  - CYCLING PULSED LOAD/CHARGING
    - AC MODELING
  - AGE-LIFE
  - HIGH VERSUS LOW VOLTAGE
  - CELL SIZE
  - HIGH/LOW TEMPERATURE
  - VENDOR-VENDOR VARIATIONS
- SUGGESTED TESTING OF BATTERY TYPES
  - N_IC_d
  - N_IH_2
  - A_gH_2
  - OTHER

TABLE 3-1

Data Base Acquisition - Power Distribution

- SUGGESTED ORDER OF TESTING
  - NEW DEVICES
    - -- SOLID STATE SWITCHES
    - -- SEMICONDUCTORS
    - -- HYBRIDS
    - -- INTEGRATED CIRCUITS
    - -- ON-GOING TECHNOLOGY

TABLE 3-2

DATA BASE ACQUISITION - SOLAR ARRAYS

- SUGGESTED ORDER OF TESTING
  - RADIATION DAMAGE, PROTON DOMINATED ORBITS
  - COVER GLASS AGING, ADHESIVE AGING
  - TRANSIENT RESPONSE
  - THERMAL CYCLING BEYOND 5 YEARS (> 30,000 CYCLES)
  - SPACE PLASMA INTERACTION

- CONCENTRATOR ARRAYS
  - SPECTRAL REFLECTANCE OF SPECIFIC COATINGS
  - MIS-ALIGNMENT AFFECTS
  - ...EX THERMAL EFFECTS ON CONES, CELLS AND STRUCTURE
  - ...AL-OPTICAL PROPERTIES OF SURFACES

TABLE 3-3

C-2

DATA BASE ACQUISITION - SHUNT REGULATORS

- SUGGESTED TESTING
  - NEW DEVICES - ELEMENT PARAMETER LIBRARY
    - -- SOLID STATE SWITCHES
    - -- MOSFETS
    - -- HYBRIDS
    - -- CONTROL CIRCUITS
    - -- ON-GOING TECHNOLOGY
  - DEVELOP ELEMENT PARAMETER LIBRARY
  - FOR DIGITAL SHUNTS, DEVELOP METHODS IN TIME DOMAIN USING SAMPLE DATA TECHNIQUES

TABLE 3-4

DATA BASE ACQUISITION
DC-DC CONVERTERS

- SUGGESTED ORDER OF TESTING
  - LARGE SIGNAL AC, TRANSIENT RESPONSE
  - TRANSFORMER
    - COUPLING
    - LEAKAGE
    - SATURATION
  - DEVELOP ELEMENT PARAMETER LIBRARY
  - ON-GOING TECHNOLOGY

TABLE 3-5

4.0 CONCLUSIONS

The literature search/industry survey confirmed that no comprehensive power subsystem model exists.

It is anticipated that a set of four fundamental types of models are required, each of which performs a different, essential task. Together, this program set permits comprehensive modeling of a power subsystem.

1. A power subsystem sizing and synthesis program, capable of estimating cost, mass, volume, area, and other attributes of a single-point design. This would be used only during the conceptual design phase of a spacecraft program.

2. A DC model of the power subsystem and its interfacing subsystems. This is used during phases B, C, D, and E of the spacecraft program for studies of power consumption, energy balance, heat generation and absorption, responses of the subsystem to environmental changes, and prediction of steady-state voltages and current throughout the subsystem.

3. A small-signal AC model of the power subsystem and its components. This is used in phases C, D, and E for the purposes of estimating subsystem and intercomponent stability, bus impedance, and for determination of responses to small-signal transients.

4. A large-signal transient model used during phases C, D, and E of the program for the purpose of determining the response of the subsystem to large transients such as state changes and faults.

APPENDIX A

LITERATURE SEARCH REFERENCES

The following abbreviations are used in the references:

IECEC, Intersociety Energy Conversion Engineering Conference
IEEE, Institute of Electrical and Electronic Engineers
PCSC, Power Conditioning Specialist Conference

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APPENDIX B

TECHNOLOGY EVALUATION SUMMARY CHARTS

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TECHNOLOGY EVALUATION SUMMARY

REF. NO.	SOURCE IDENTIFICATION	PURPOSE/MODEL DESCRIPTION	CAPABILITIES, LIMITATIONS/CONSTRAINTS	AREAS OF IMPROVEMENT
1	SPICE 2: "A Computer Program to simulate Semiconductor Circuits" L. W. Nagel Memorandum No. ERL-M520 Electronics Research Lab College of Engineering University, 9 May 75	SPICE is a computer program that: • simulates the electrical performance of an electronic circuit • circumvents many of the practical problems that are encountered in circuit characterization. <u>Model Description</u>: The circuit is represented in mathematical terms, and numerical analysis procedures that correspond to typical laboratory measurements are performed. The circuit designer chooses the analyses that are performed and, by analogy, the measurements that are made upon the circuit. The output of the simulation program therefore simulates the results of laboratory measurements.	<u>Capabilities</u>: SPICE is a digital computer program that: • Simulates the electrical performance of electronic circuits. • Determine the operating point of the circuit, the time domain response of the circuit, or the small-signal frequency-domain response of the circuit. • Contains models for the common circuit components and is capable of simulating most electronic circuits. • Can be adapted for use on CDC 6450, IBM, Honeywell, UNIVAC, RCA and PDP computer systems. • Performs DC analysis, transient analysis and AC analysis. • Has been used for modeling regulator and local filter interaction and stability at TRW on several programs. • Verified by test at the power subsystem level and at the system level.	SPICE should be capable of interfacing with other types of computer programs (e.g. it should be able to take inputs from Fortran program and output data to a Fortran program).

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TECHNOLOGY EVALUATION SUMMARY

REF. NO.	SOURCE IDENTIFICATION	PURPOSE/MODEL DESCRIPTION	CAPABILITIES, LIMITATIONS/CONSTRAINTS	AREAS OF IMPROVEMENT
2	Power Subsystem Performance Prediction (PSPP) Computer Program H. Weiner, S. Weinstein (Modification of TRW PSIM Program)	This Computer Program is designed to: • Simulate the characteristics and interactions of a solar array, battery, battery charge controls, zener diodes power conditioning equipment and the battery-spacecraft and zener diode-spacecraft thermal interface. • Examine the operation of the orbiter power subsystem during critical phase of the Viking Mission. • Examine the capability of the power subsystem to meet mission requirements and margins for solar array, battery and power conditioning equipment subassemblies. • Estimate battery temperatures and thermal performance margins. • Establish voltage and temperature cutoff levels for battery charge control. • Determine solar array zener diode loads. • Estimate boost-mode circuit requirements. • Determine optimum method of power subsystem control.	Capabilities: This program is capable of using a graphical analysis method, implemented for the computer, to obtain the subsystem operating point through the load analysis. Limitations: • The power conditioning and distribution group, as presently used in this program, contains only the boost regulator characteristics. Hence, the user requirements for the power subsystem are presented in terms of the unregulated DC loads. (Boost Regulator Output). • Unique to Viking Orbitor • No transient capability.	• Future program versions should include the characteristics of the complete set of subassemblies in this group. • Generalize model for use in other spacecraft. • Expand battery model to include trajectories other than synchronous orbit.

TECHNOLOGY EVALUATION SUMMARY

REF. NO.	SOURCE IDENTIFICATION	PURPOSE/MODEL DESCRIPTION	CAPABILITIES, LIMITATIONS/CONSTRAINTS	AREAS OF IMPROVEMENT
2	Power Subsystem Performance Prediction Computer Program	● Observe the effects of various failure modes in power subsystem elements. ● Examine worst-case and nominal performance of a power subsystem. ● Establish a battery energy balance for each orbit.	(Continued)	

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TECHNOLOGY EVALUATION SUMMARY

REF. NO.	SOURCE IDENTIFICATION	PURPOSE/MODEL DESCRIPTION	CAPABILITIES, LIMITATIONS/CONSTRAINTS	AREAS OF IMPROVEMENT
3	Computer Simulation Concept for a Large Solar Array/Battery Power System M. S. Imamura, A. C. Corr, A. J. Peszko, P. C. Scott	The basic purpose of the simulation model is to: • Provide the capability to generate and evaluate the power system performance characteristic under various operating conditions during the preflight phase. • Assist in the resolution of mission timeline changes as well as problems and anomalies during the on-going mission. • Calculate parameters for a specific time increment. • Provide increased accuracy. The concept represents an achievable compromise among these factors in providing an integrated simulation model for a large solar array/battery power system. • Written to support the Skylab Program.	<u>Capabilities</u>: Generation of system and component performance data for an arbitrary set of input conditions (attitude, temperature, electrical load, failures, etc) Determination of the effects of subsystem component and redundant bus failures on the EPS output. Determination of the sensitivity of EPS performance to changes in mission parameters such as power level, orientation maneuvers, Beta angle, and configuration. A subsystem or combination of subsystems may be bypassed in the main program. Alternately, each subsystem program is capable of running separately. <u>Limitations/Constraints</u>: The program is capable of providing continuous performance data throughout the mission. The spacecraft can be operated in two major attitude modes: the Solar Inertial (SI), and the earth pointing or Z-axis Local Vertical (Z-LV). Calculation interval must be small enough to minimize errors, especially during the Z-LV mode. Validatedagainst flight data.	• Generalize the program to handle other power systems. • Reduce minimum time increment from 30 seconds to a few seconds. • Analysis of EPS performance and energy balance.

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REF. NO.	SOURCE IDENTIFICATION	PURPOSE/MODEL DESCRIPTION	CAPABILITIES, LIMITATIONS/CONSTRAINTS	AREAS OF IMPROVEMENT
4	"G-189 P Generalized Power System Simulation Program" J. V. Coggi, F. S. Barker IECEC 1972 Paper #729098	The model consists of the following: A general simulation routine. Two user-generated subroutines which implement power subsystem logic. Input data banks. Fuel cell modelling subroutines. Component modeling routines for pump, radiator, heat exchanger, tanks, and electrical loads. No description given of solution algorithms or model routines, other than a general description of basic function.	Capabilities: Predict consumables use, coolant flow, fuel cell voltage, heat flow and temperature. Follows temperature transients. Limitations: Will not follow electrical transients. Model routines required for each non-standard electronic component or part.	Difficult to assess due to generality of description.

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REF. NO.	SOURCE IDENTIFICATION	PURPOSE/MODEL DESCRIPTION	CAPABILITIES, LIMITATIONS/CONSTRAINTS	AREAS OF IMPROVEMENT
6	An Analytical Method for Determining Direct Current Power System Stability F. E. Lukens	The purpose of this model is: ● To predict system stability before system tests are started, thus possibly preventing costly design modifications. ● To perform the computational part of the analysis with a linear AC circuit analysis computer program such as ECAP. Being able to use such programs rather than transient simulation programs will save time and money.	<u>Capabilities</u>: This model is capable of stability analysis of DC and small signal AC system (linear transformation), not the large transient signal condition. <u>Restrictions</u>: The accuracy of the method is limited only by the accuracy of the switching regulator and line filter models. -- Examples -- <u>Line Filter Restrictions</u>: The filter must exhibit a driving point function of a positive real network at the a - a' port with all other input ports shorted. <u>Switching Regulator Restrictions</u>: A totally linear model for the switching regulator must exist and a linear model must be used for the switching regulators. The switching regulator chopping frequency must be higher than the lowest line filter break frequency and the switching regulator open loop gain cross over frequency by an acceptable margin. A ten to one margin should definitely be acceptable. The load impedance tied to the regulator output contains no right half plane numerator or denominator zeros. This program is limited to the interaction between a switching regulator and a line filter. It is not an overall power subsystem model.	Eigenvalue/Eigenvector method may be derived for each system components. The system stability can be assessed by an interconnection matrix which connects all system components together.

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REF. NO.	SOURCE IDENTIFICATION	PURPOSE/MODEL DESCRIPTION	CAPABILITIES, LIMITATIONS/CONSTRAINTS	AREAS OF IMPROVEMENT
7	Computer Simulation of Solar Panel Voltage Regulation M. T. Gates, W. J. Muldoon	The purpose of this simulation is to identify possible excess power dissipation or excess satellite bus voltage. Early identification of these problems allows easier design changes, and rapid analysis allows more possible design changes to be checked. The simulator's analysis is done in a simple two-step procedure: the individual regulator analysis and the combined system performance. Finding the power dissipated in each unit is one of the basic purposes of the simulation. Model Description: This paper models the interaction between a solar array and a partial shunt voltage regulator. It predicts: • Bus voltage • Tap voltage • Shunt current and power dissipation. • Operates beyond normal regulation range (regulator saturated)	Constraints: This computer simulation models a satellite voltage regulator system used on cylindrical satellites. The voltage regulation method requires an electrical connection (tap) in each array of solar cells. The connection leads through a regulator to the system ground. Restrictions: • One restriction to the analysis is that all of the arrays for a regulator should have the same parameters. • Simulates only DC solar array. • This is not a complete power system program. Capabilities: 1) Calculates shunt thermal dissipation and bus voltage as functions of load and shunt currents. 2) May be used for preliminary sizing and interfacing definitions.	The simulation may be improved by relaxing the restrictions.

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REF. NO.	SOURCE IDENTIFICATION	PURPOSE/MODEL DESCRIPTION	CAPABILITIES, LIMITATIONS/CONSTRAINTS	AREAS OF IMPROVEMENT
11	ACSL User Guide/Reference Manual	Control language for Advanced Continuous Simulation Language. This is a program for general system simulation. Components are represented by time-dependent, non-linear differential equatuions, or by Fortran subroutines which generate such equations. Similar to SPICE, TESS, and many others.	Capable of both steady-state and transient analysis. Limitations: Accuracy with which the differential equations represent the components. Large computation costs for large systems.	Not feasible to assess without detailed examination.
12	Multi-Optimal Differential Equation Language (MODEL) NASA Contract NAS 5-25635, Task 5 B. G. Zimmerman, Old Dominion Systems, Inc.	Similar to 32 - Control language for system simulation program. Program translates differential equation model into FORTRAN 4. Accepts additional models as FORTRAN routines.	Cannot be evaluated from data presented. Example is not electrical model.	Cannot be evaluated from data presented.

TECHNOLOGY EVALUATION SUMMARY

REF. NO.	SOURCE IDENTIFICATION	PURPOSE/MODEL DESCRIPTION	CAPABILITIES, LIMITATIONS/CONSTRAINTS	AREAS OF IMPROVEMENT
8	Performance Analysis of Satellite Electric Power Systems by Computer Simulation Mel Schwartzburg	The purposes of this computer program are: • To perform an electrical analysis and a thermal transient analysis of a satellite electric power subsystem consisting of a solar array, battery and power controls. • To represent an achievable compromise between the desirable complete electrical analysis given by the nodal analysis type of program and the excessive cost and complexity of such efforts. • The desirability of using computer simulation is not limited to the performance analysis of existing electric power subsystems, but also finds application in determining the load capability of a proposed subsystem. This is particularly true of subsystems with wide variations in solar array current and voltage, and a complex battery-satellite thermal interface. Accordingly, a graphical technique was developed for using the Power Subsystem Orbital Performance Analysis Computer Program to determine the maximum system load capability.	<u>Capabilities</u>: 1) Predicts electrical and thermal interaction between EPS and the rest of the spacecraft. Because the typical spacecraft battery dissipates heat in an unpredictable manner and the battery temperature has a significant impact upon the performance of the electric power subsystem as a whole, the electrical analysis must be combined with a transient thermal analysis of that portion of the spacecraft whose thermal characteristics interact with the electric power subsystem. 2) Capable of simulating synchronous and multiple orbits. 3) Capable of power subsystem DC simulation. 4) Models load on/off as functions of time/temperature. 5) Models S/A, battery, power subsystem logic and charge controls of multi-batteries system. 6) Allows simulation of subsystem failure mode, such as complete failure of one batteries/charge control failure with results of battery heating. 7) Battery model includes thermal subroutine which calculates battery dissipation as function of operating point and subsequent battery temperature response.	The battery heat evolution routine, for example, while consistent with basic theory, requires considerably more work before it can be considered to be broadly applicable. In addition to improvement of existing routines for better accuracy or wider applicability, the capability of the program requires extension into areas far neglected. Examples of things which require only the desire and the funding for their accomplishment are the following: 1. Extension of the heat dissipation calculations to other power-handling equipment, such as the power control unit and equipment converters. 2. Addition of load summation and load variation capability to the program, so that a variable-load mission can be flown readily.
9	Computer Simulation of Satellite Electric Power System Paul Bauer			
10	Analysis of Solar Array/Battery Lock-up by Computer Simulation of Electric Power System Performance Mel Schwartzburg Used at TRW for the analysis of the following spacecraft: HEAO FSC DSCS II DSP			

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REF NO.	SOURCE IDENTIFICATION	PURPOSE/ MODEL DESCRIPTION	CAPABILITIES, LIMITATIONS/CONSTRAINTS	AREAS OF IMPROVEMENT
8, 9, 13	Schwartzburg/Bauer Computer	Programs (Continued) ● Particularly applicable to spacecraft where EPS and battery is thermally coupled to the rest of spacecraft and EPS heat dissipation.	8) Performs valid flight. 9) Includes solar array/regulator interfacing model. 10) Models bus voltage variation, power subsystem components and temperature. -- Variations -- 11) Ascertain analytically with a higher degree of resolution and accuracy. 12) It is a training program. 13) Predicts the following parameters throughout the entire spacecraft power system: ● voltages ● currents ● heat generation ● temperatures 14) and the following battery parameters ● temperature ● internal pressure ● charging/discharging current ● terminal voltage ● state-of-charge ● recharge ratio	3. Addition of a multiple orbit capability with a variable eclipse duration so that a satellite can be flown. If necessary, through a variable eclipse season. 4. Integration of this program into a large program which performs a detailed thermal analysis of the satellite as a whole. At present, this is considered feasible mainly because of the high cost of accurate thermal transient analyses for multiple node systems. 5. Adaptation of the program to real-time simulation of satellite performance in orbit, using telemetered data. 6. Implementation of a search procedure for iterative use of the analytic program to determine system load capability.

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REF NO.	SOURCE IDENTIFICATION	PURPOSE/ MODEL DESCRIPTION	CAPABILITIES, LIMITATIONS/CONSTRAINTS	AREAS OF IMPROVEMENT
8. 9. 13	Schwartzburg/Bauer	Computer Programs (Continued)	Limitations: 1) Model is no good in the low earth orbit (LEO). 2) Battery model is limited to test data and the extrapolation of them. 3) Not capable of doing transient analysis. 4) Requires external data input. 5) DC analysis only - will follow thermal but not electrical transients. *6) Limited to circular orbits. Applicable to non-circular only with difficulty. Needs internal orbit mechanics model. *7) Models only primary power subsystem to main bus. The secondary power, distribution networks are not modeled. *Cumbersome to use in response to S/C attitude changes. Requires internal sun vector model. ** Battery model is primitive. Weakest part of program needs improved model. ** Solar array model has primitive shadow analysis.	Needs improved model where shadows are significant. *No significant technical challenge - just tasks. **Significant technical challenge.

TECHNOLOGY EVALUATION SUMMARY

REF NO.	SOURCE IDENTIFICATION	PURPOSE/ MODEL DESCRIPTION	CAPABILITIES, LIMITATIONS/CONSTRAINTS	AREAS OF IMPROVEMENT
10	Modeling & Analysis of Power Processing System" Y. Yu, F. C. Y. Lee, J. Kolecki Pp. 11-24 IEEE-PESC 1979	Purpose of the program is to provide an engineering tool to reduce the design, analysis, development time & thus the cost in achieving the required performance for power processing equipment and systems.	Capabilities: • Optimum designs • Cost-effective • Provides a fast & accurate design and mass optimization tradeoff tool. • To determine the analog signal processor design to meet a given set of performances. • This is not a power subsystem model.	Continued MAPPS effort will aim at the following goals: • Analyze performances for commonly-used power processing equipment and selected systems. • Detailed power circuit design optimization to meet given power-related performance requirements for most commonly used power circuit configurations. • Standardized control circuit design to meet control-related performance requirements. • Provides cost-effective tools for the identification of optimal system configurations and system failure-mode analysis.

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14	Maximizing the Usable Energy from a Spacecraft Power System L. T. Ostwald	The purposes of this model are: • To determine operating limits and optimize the design of an improved power system • To size and match the energy generation, control, and storage components for a power system with a capacity of about 300 watt hours per orbit • To evaluate the performance of the power system under a variety of launch and orbital conditions by stimulating the main elements of the generation, storage, and charge control system on a digital computer • To verify the match between solar array and batteries and to determine the effects of variations in the solar array temperature profile on the system operation. Model Description • Energy balance program • Models loads as resistive and constant power • Models battery current and voltage with charge and discharge curve fit to cubic equations. • Models array as single IV curve, shifted for temperature as function of time.	Limitations/Constraints: • No AC, thermal, electrical transient calculation capabilities. • No thermal interface • No heat generation/temperature prediction • Four restrictions on the selection of cell size are: 1) the availability of cell sizes, 2) the need for redundancy so that the failure open of a single cell does not cause catastrophic failure or seriously shorten the life of the observatory, 3) the desirability of using just one type and capacity of cell, and 4) size, weight, cost, and flight experience. • Battery model does not account for efficiency variation (uses constant recharge ratio), battery temperature changes battery performance with depth of discharge. Capabilities: The computer simulation was able to determine the battery charge and discharge for one-time only (launch) and orbit cycling conditions. • Predict bus voltage, stored energy, load current and power, array current and power.	• The program should be able to handle more than one type and capacity of solar cells. • Battery model should be improved to account for a variable recharge ratio.

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15	DTIC Report #AD-A011 348	Super Sceptre Manual Manual for preprocessor for SCEPTRE program, permitting its use on mechanical systems, transfer functions, and digital logic systems. User inputs transfer functions or logic functions in the form of user-supplied FORTRAN subroutines, tables of piecewise linear approximations, or first-order differential equations.	Capable of analysis of large systems which can be described in terms of transfer functions or other listed forms. Limitations are the degree of accuracy with which the transfer functions describe the actual functions.	
16	Computer-aided Analysis of Power Electronic Circuits Containing Tyristors Antognetti, P. Massobrio, G. LaRegina, M. Parodi, S. University of Genoa Instituto de Electrotechnica	Shows method of applying SPICE to circuit analysis.	Highly specialized application. Not applicable to general power subsystem modeling.	

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17	X-711-77-95 Applications Explorer Mission Energy Balance Computer Program P. J. Broderick NASA GSFC	A pseudographical program for determination of energy balance in a solar array battery spacecraft power subsystem. Contains: ● simple array model (will accept external input for more complex arrays. Load models for: ● PWM voltage regulator ● DC/DC converter ● Inverter ● Series dissipative voltage regulator ● Shunt	Capability of reported program limited to direct energy transfer systems. Has since been expanded to accommodate other systems. Computes battery state of charge, current, voltage at given temperature (or input temperature profile). Bus voltage, recharge ratio, and other subsystem parameters. System losses modeled as an additional load. Will accept load profiles as a function of time. Limitations: ● Fails to address battery efficiency question. ● Will accept temperature input profiles. ● Will not compute temperatures.	Limited data bank size limits battery data accuracy. Needs thermal interface. Battery efficiency model.

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18	System Modeling and Structure Optimization Using Hybrid Computer Techniques C. H. Beck R. L. Drake K. Ming Department of Electrical Engineering Tulane University	Combines analog and digital computer operations. Analog computer models individual components, but changes parameters of model under digital control. This avoids the fixed model found in most digital models.	Capabilities: Improves speed of execution of dynamic models significantly. Lower capital and computation costs. Limitations: Requires real-time hardware - oriented programming.	
19	SCEPTRE, A Second Generation Transient Analysis Program S. R. Sedore, IBM Federal Systems Division	General description of SCEPTRE program. Of general applicability.		

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21	NASAP: Network Analysis for Systems Applications Program: Present Capabilities of a Maintained Program R. M. Carpenter NASA Electronics Research Center, Cambridge, MA	This paper discusses the present capabilities of NASAP, including flow graph construction and evaluation, input-output formulation and available subroutine.	This computer program can be applied in the following aspects: • Frequency dependent or time dependent, linear and non-linear, active and passive elements. • Sensitivity analysis • Transient and frequency response	This program may be improved by combining its capabilities with the existing SPICE power system on computer

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22	Long Term Prediction of Power System Performance for Geosynchronous Spacecraft W. J. Billerbeck	Limited applicability model of spacecraft power system performance. Requires flight data calibration before prediction.	Directed primarily at aging of power subsystems. No interactive heat generation, temperature calculations. Addresses only battery discharge.	
	Power Management and Control for Space Systems Finke, et al NASA Conf. Pub. #2058	Gives mathematical basis for transmission line optimizations.	Simple optimization of power transmission. Does not address switching, fuse, connector or contact impedances. Useful only for first-cut analysis.	

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24	State-Variable Analysis of Non-linear Circuits with a Desk Computer Dr. E. Cohen NASA Technical Memo 83876 GSFC July 1981	The purpose of this paper is to analyze the transient performance of the most non-linear circuits or systems. The starting point of a computer program is a set of first-order differential equations and algebraic equations describing the system.	The computer program is interactive and offers many options to the user. Among which is plotting of the results. It was used very successfully for the transient analysis of short-circuit failure of the switching transistor of a power module.	This method may not be useful for large transient disturbances. Other methods, i.e., Lyapunov's 2nd method, describing function approaches, simulation method etc., needs to be explored.
20	Automatic Transient/AC Sensitivity Analysis with Applications J. V. Leeds, Jr. Ass't. Professor Electrical Engineering Rice University Houston, Texas	The purpose of this paper is to provide sensitivity calculations for single parameter and multiple parameter sensitivities for ciruits and systems.	One distinct advantage of the method is that currently available digital network analysis programs such as ECAP and NET-1 can be used without modification for sensitivity calculations.	

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28	Energy Balance Computer Program for Advanced Nimbus Power Systems P. J. Hyland, P. Rasmussen RCA-AED, December 1968	The computer program was originally developed by RCA for the simulation of the TIROS power system and was subsequently used for Lunar Orbiter, and Nimbus.	1) Multiple orbit capability 2) Contains solar array model, battery model, charge/discharge control model, output regulator model. 3) Accepts mix of constant current and constant power loads, as well as resistive loads. 4) Does not have interactive thermal model, and therefore does not provide accurate simulations for most GEO applications. 5) No transient capability. 6) No array shadowing model. 7) Linearized electronic component models are used.	With minor modifications the capability could include: 1. Unregulated bus systems 2. Array limited systems 3. Series regulated systems 4. Direct energy transfer systems Major modifications: 1. Interactive thermal model 2. Transient capability 3. Array shadowing 4. Dynamic electronic component models.

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37	H. G. Zimmerman & P. G. Peterson. "An Electrochemical Equivalent Circuit for Storage Battery/Power System Calculations by Digital Computer. IECEC Transactions, 1970	Battery model - simulates the charge/discharge characteristics of a battery as a function of temperature, current, etc. Models battery capacity as a very large capacitor. Modifies the capacity model for charge/discharge hysteresis effects and activation polarization effects by use of a bi-directional diode model in series with another capacitance	Approximates the wave shape of a battery on charge or discharge. No comparisons with flight or test data are shown to enable evaluation of the models accuracy. No information on the performance on partial discharge applications. Models the heat generation in batteries. Fails to take into account the pressure storage phenomenon. This would lead to severe thermal transient inaccuracies. Stated to permit dynamic modeling. However effects of inductance are not treated, and very large capacitance used to simulate electrochemical capacity would tend to cause large errors in small signal ac modeling. Actual limitations of the model not shown. Some discussion of the means of deriving the model input parameters from test data, but no actual data given. Major advantage is relatively small data storage requirement.	Difficult to evaluate. Model in early stage of development, and apparently untested. Probably extensive effort required to generage an accurate model.

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23	Unpublished work "Battery Mathematical Computer Model" P. Bauer	Battery cell performance model including: Empirical cell voltage model Look-up table of efficiencies Heat generation model Primary advantage over table look-up models is small data storage requirements.	Predicts battery voltages, currents, heat rates, temperatures, states of charge in a cycling regime of varying or constant depth of discharge. In low-earth orbits, good voltage, current, state of charge agreement in the 5-25C temperature range, for a single constant DOD cycle. Moderate to poor agreement in synchronous orbit applications. Limitations: - No small signal AC capability - Inadequately tested. Range of applicability unknown. - Stability unknown. - Requires trial-and-error process for matching model performance to cell performance. Possible capability for prediction of cell internal pressure behavior.	Requires detailed test and evaluation before need for improvement can be assessed.

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REF. NO.	SOURCE IDENTIFICATION	PURPOSE/MODEL DESCRIPTION	CAPABILITIES, LIMITATIONS/CONSTRAINTS	AREAS OF IMPROVEMENT
29	Durando, A. R., and Leondes, C. T. "NiCd Cell Simulation: A New Model for Satellite Power Systems Application" Electrochemical Society 1976, February.	Thermodynamically based model of a NiCd cell, plus a thevenin equivalent circuit.	Predicts reversible potential, electrolyte concentration, heat generation efficiency. Does not predict cell terminal voltage. Fails to account for oxygen storage phenomena, and for variation of cell voltage with state of charge.	One of the deficiencies of existing models is the variability of the cell reversible potential, which is used in the determination of cell voltage and other factors This could be useful in conjunction with other models of cell dynamic performance to form a complete model.
30	Selman, J. R. "Performance and Current Distribution Modeling of Batteries and Fuel Cells" Aichem, E. 0065-8812-4208-0204	Not a model: Presents a method of predicting cell voltage, efficiency and heat generation based upon a model of cell electrode overpotentials, and the effect upon overpotentials of current distribution in the electrodes and electrolyte. Contains simplifications making it useful in performance prediction of porous electrodes.	Method does not appear to take into account overpotential variation as a function of stage of charge, or side reactions, such as overcharge, although it appears to be generally applicable, and might by additional complexity be applied to simultaneous charge and overcharge reactions.	N/A

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31	20 KW Battery Study 30 July 1971, TRW Systems for NASA GSFC	Provides parametric data and preliminary Power Subsystem configuration optimization for subsystems in 25 to 35 KW range Develops relationship between independent variables such as bus voltage, battery voltage, number of power subsystem channels and weight, cost and reliability. Power loss is data generated.	Allows comparison of different general types of power subsystems configurations, and exposes deficiencies in power system technology or data availability used in power subsystem analysis. Optimization primarily limited to batteries On-orbit resupply is modeled and resupply strategies/intervals determined. Model primarily applicable to preliminary studies of large systems involving sizing, resupply, reliability and cost. No capability to model dynamic electrical system performance.	Component weight, cost size data base needs update. Model range should be expanded to include smaller systems down to 1 KW. Model should include electrical performanc . subroutines.
32	Alkire, R., and Beck, T. "Tutorial Lectures in Electrochemical Engineering and Technology"	A tutorial directed toward partial electrochemical modeling of battery and fuel cells directed primarily toward modeling of current distribution in the electrodes.	Not a model in itself, this paper suggests a potentially valuable approach to the problem of current distribution effects upon battery overpotential. Worth further effort to understand, and possibly apply it	
33	Montalenti, P., and Stangerup, P. "Thermal Simulation of NiCd Batteries for Spacecraft"	Combination of a 500-node thermal model of a battery and thermodynamic derivation of heat generation parameters.	Predicts battery temperatures and heat generation. Oversimplified model fails to account for exygen storage phenomenon, self-discharge.	See limitations.

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REF. NO.	SOURCE IDENTIFICATION	PURPOSE/MODEL DESCRIPTION	CAPABILITIES, LIMITATIONS/CONSTRAINTS	AREAS OF IMPROVEMENT
34	Final Report "Space Vehicle Electrical Power Processing, Distribution and Control Study"	Contains mathematical basis for distribution system optimization, but no actual model. Parametric results of several case analyses.	Capable of finding optimum distribution weight as a function of conductor mass and conductivity and specific weight of source and storage elements. Limitations: - Fails to address fuse, switch, connector losses, which may override conductor losses.	
35	Internal TRW IOC 70-3215.1-046, "Optimum Cable Power Loss (20KW Power System Study)" H. Weiner to P. Bauer, 2/25/70	Contains mathematical basis for distribution system optimizations, source code or subroutines (FORTRAN), parametric results.	Finds optimum distribution mass as function of conductor mass and conductivity and specific mass of source. Limitations: - Lumps source and storage elements into source. - Fails to address fuse, switch, connector losses.	
36	Internal TRW IOC 34579-018, "Transmission Cost Design Note - (250KW Study)". C. Sollo, 2/15/80	Contains mathematical basis for distribution system optimization based on all power subsystem components cost.	Finds optimum cross sectional area of distribution cabling based on the cost of the conductor, energy storage, solar array, thermal control, power conversion. Fuse, switch and connector losses are factored into power conversion.	

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37	SEMCAP EMC Computer Modeling Program J. A. Spagon, et al TRW	Model Purpose Identify spacecraft circuits susceptible to EMI. Develop system designs which are compatible. Determine EMC margins over wide frequency range. Generate EMC specifications and evaluate spec waiver requests. Model Description In developing the various generator, receptor, and transfer models, the attempt was made to provide the maximum amount of versatility possible with a limited number of models. To provide this flexibility, the models allow a large number of variable parameters to be specified. The functional modeling task is to specify appropriate models and the associated parameters needed to model all of the important generators and receptors of a system. In many cases, standard values of certain parameters can reduce the effort involved in functional modeling. For example, typical wiring parameters can be used in place of actual values with little loss in accuracy.	Models EMI sources (generators), receptor circuits, and wiring between source and receptor. Frequency range variable from very low audio to microwave region. Generator Models Periodic pulse Aperiodic pulse Ramp step Single frequency Receptor Models (Filters) Band pass Low Pass High Pass Wiring Models Wire to E and H-fields E- and H-field to wires Wire to wire coupling Single wires-twisted pair wiring Shielded/Unshielded wire Shields grounded single-point and multiple point. Common impedance coupling	Integration of SEMCAP analytical model with power subsystem AC models so that stability and EMC margins are determined simultaneously. Allows wiring/grounding approaches (which are frequently at the heart of system stability problems) to be evaluated analytically.

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37	SEMCAP Continued	The parameters required for the generator models are time domain descriptions of the signals involved. Spectral information can also be used, if available. Receptors require a voltage sensitivity and filter description parameters. Both generator and receptor circuits require a number of parameters describing the wiring configuration. These are wire length, height above ground, wire radius, and source and load resistance. Shield parameters required are the shield radius, the shield thickness, the shield conductivity, the shield hole fraction, the shield bare wire length, and the shield pigtail loop area.		

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33	Finke, R.C. et al " Power Management and Control for Space Systems " NASA Conference Publication 2058	Mathematical derivation of a method of power transmission line weight optimization. Optimizes the weight of a total system including power generation transmission, and heat rejection Finds the optimum transmission line for a system weight optimum	Not a model , but capable of being developed into one. Limitations: Ignores the mass and losses of peripheral equipment such as connectors, fuses and other protective equipment, controls and switchgear.	

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39	Efficiency Calculations for $Al_xGa_{1-x}As$-GaAs Heteroface Solar Cells A. M. Sekela, et al.			
40	A. A Regulated Solar Array Model - A Tool for Power Systems Analysis J. M. Voss, J. G. Gray	Design of a solar array simulator is discussed as it relates to using the simulator as a tool for evaluating photovoltaic systems.	Both dc and ac operations are considered. The classical solar array model is detailed in A. Many system parameters are required.	
41	B. The Design and Performance of an 11 KW Solar Array Simulator D. R. Smith, and G. A. O'Sullivan	Mathematical models for the simulator are discussed. Reference A simply provides the math tools for developing a simulator. For B, performance of the actual system is given in terms of voltage and current responses.		

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45	A. "A Modified Single Diode Model for High Illumination Solar Cells Simulation Work" R. T. Otterbein, et al.	Investigates applicability of single solar cell model to design involving optical concentration. Performs parameter fits to classic solar cell model. Primarily a dc circuit model described in A.	Reference A uses readily available parameters to perform the modeling. Experimental results do not agree well with modeling results at high concentration for A.	Improve the model in A to accurately model high level concentration.
47	B. "Analysis of High-Efficiency Silicon Solar Cells" H. T. Weaver, et al	A complete mathematical model approach used in B. Experimental results are compared to modeling results.	No circuit modeling provided in B.	Extend the detailed results of B to provide a circuit model.
44	"Two Modified Single Diode Models for Simulating Solar Cells with Distributed Series Resistance" R. T. Otterbein, D. L. Evans	Need for careful evaluation of series resistance is discussed. Experimental methods for determining the solar cell R_s are described.	Models given are capable of precisely accounting for the series resistance effects in a solar cell.	Perform testing to obtain required data base.
45	"An Evaluation of the Methods of Determining Solar Cell Series Resistance" M. S. Imamura, J. I. Portscheller	Multiple element models are given to be used to simulate the effects of R_s.	Model parameters are not readily available. Requires testing.	

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43	Solcel II: An Improved Photovoltaic System Analysis Computer Program E. R. Hoover	Models entire photovoltaic power system including: -Array orientation effects -Collector types and temperature effect -Lead-acid battery storage -Three types of power conditioner including (1) single DC/AC inverter with load dependent efficiency curve; (2) two DC/AC inverters in parallel with a common load dependent efficiency; (3) a black box device with constant efficiency. -Four methods of photovoltaic conversion: (1) max. power tracking; (2) floating battery (3) voltage regulator; (4) temperature degraded efficiencies. -Power distribution with variable load profile -Economic modeling included -Sensitivity analysis can be performed	Built-in restrictions on cell type. Primarily useful for ground-based systems. Multiple batteries/chargers-Multi-channel system Shunt model Charge control model Heat dissipation Thermal interface	Could adapt portions of the program to be used in spacecraft modeling. Expand to NiCd-NiH2 batteries. Needs thermal interface.

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[illegible]	"A Better Approach to the Evaluation of the Series Resistance of Solar Cells" By K. Rajkanan, and J. Schewchun	A means of plotting universal solar cell I-V characteristics is given. Temperature effects are taken into account.		
48	"Experimental Determination of Series Resistance of p-n Junction Diodes in Solar Cells" P. J. Chen, et. al.	Three experimental techniques for R_s determination using ac impedance measurements are given.	Method is simple and produces rapid results. Accuracy limited only by measurement bridges being used. Methods do not work for all solar cell types; dependent upon the ac impedance being within certain ratios of one another.	Perform testing to obtain the necessary data base.
49	"AC Impedance of Silicon Solar Cells" D. W. Zerbel, and D. K. Decker	Models ac behavior of solar cells.	Can provide steady-state and transient analysis parameters for solar cell models.	Acquire data on new cells
50	Capacitance of Solar Cells and Panels Under Various Load Conditions A. Schloss	Explains how to obtain the ac impedance values. Frequency sweep measurements used.	Need to extrapolate results in order to apply them to an overall array.	
51	"Measurement of Free Carrier Lifetime in an Illuminated Solar Cell from Capacitance Measurements" S. Y. Harmon, and C. E. Backus	Discusses how to obtain certain detailed model parameters from physical measurements.	Uses parameters determined from the measurements to predict second order effects.	Determine to what extent the second order properties will affect the overall power system.

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63	Design of the HEAO Main Bus Shunt Regulator R. D. Middlebrook, S. G. Kimble Subroutine Shunt is a steady-state computer model of a HEAO type sequentially operated multi-stage linear shunt. By TRW	Designing of the HEAO main bus shunt regulator is discussed in terms of a design-analyze-measure iteration loop. Small signal and large signal design criteria are presented. A twelve parallel segment sequentially activated shunt approach is used. The shunt system is divided into functional blocks, the REA (redundant error amplifier) and the STA (shunt transconductance amplifier). Quantified circuit data is presented. Transfer function analysis is used in the design process. Design is an advanced version of a frequently applied technique of shunt regulation. The model has been verified by flight data.	Capabilities: The quantified information provided for the circuitry may be sufficient to provide the basis for development of a subsystem dynamic model for computer analysis. A steady-state model is developed. Limitations: Equivalent circuits and transient models are not developed.	Develop subsystem transient models

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67	A Digital Computer Simulation and Study of a Direct Energy Transfer Power Conditioning Program. W. W. Burns III H. A. Owens, Jr. T. G. Wilson G. Rodriquez J. Paulkovich	A digital computer simulation technique is discussed for study of transient behavior of aggregate power conditioning systems. Particulars are: Simulations are for the main bus regulator of the International Ultraviolet Explorer spacecraft. Functional block diagram approach is preferred over network topology approach. A small computer, PDP 11/45 is used. Analysis program is CSMP. Modes of system operation are written. Ten linearly independent non-linear equations form the network topology for each mode. Shunt element transient response examples are given.	<u>Capabilities</u>: Power system transient studies are possible. Subsystems may be modeled independently in terms of multiple input single output state equations using a block diagram approach. <u>Limitations</u>: While simulation results are presented for the shunt limiter element, only qualitative discussion is made with respect to the shunt model used. Functional block approach is not easily adjusted for network alterations.	Simulation results are governed by the mathematical models provided. Appropriately accurate models must be provided. Simulation runs are somewhat long. Utilization of a large and faster computer should be considered. Adaptation of the techniques to an advanced systems analysis program such as SCEPTRE or SPICE2 would also allow the analysis to accept network models.

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73	Microprocessor Controlled Digital Shunt Regulator F. R. K. Chetty, W. M. Polivka, R. D. Middlebrook	Shunt regulation of the main bus voltage is accomplished using an active shunt having the usual error amplifier and transconductance amplifier functional blocks. Voltage across the shunt dissipative element provides input information to a micro-processor which provides control signals to a solar array switching unit.	Capabilities: Allows modular approach to solar array construction. Microprocessor control may be more easily integrated into the system control scheme. Changes in control requirements or adaptive control is software implemented. Limitations: Transient analysis may be somewhat complex due to the switched nature of the control loops. Subsystem models suitable to computer analysis of the power system are not provided.	Develop models suitable for CAD system level analysis.

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82	Comparison of Candidate Solar Array Maximum Power Utilization Approaches E. N. Costogue S. Lindena	A parallel tracker maximum power point tracking concept is presented which proposes that a PWM switching regulator be used as a shunt regulator to obtain MPPT. The switching regulator input VI characteristic is a function of duty cycle and thereby may be made to appear to the solar array as a variable resistive load.	Capabilities: Resistive power curves have stable operating points at their intersection with solar array power curve. Limitations: No modeling or analysis of a switching regulator acting as an input voltage regulator is provided.	Modeling and analysis of a switching regulator acting to regulate its input voltage is required.
76	Integrated Electronics Solar Array Control Unit S. G. Kimble J. F. Wise	Shunt regulators are used to form a power control subsystem. An active shunt is designed with constant transconductance from DC to its control loop cross-over frequency. This shunt regulates the bus voltage of the on-line solar array modules. Switched shunts are used to shunt sections of solar array modules thus providing control of the number of solar array modules providing power to the bus. Active and discrete control electronics are used. Computer-aided analysis using ECAP was performed during the design phase.		

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103	Battery Cell Control and Protection Circuits H. L. Layte, D. W. Zeruel	Shunt limiter circuitry for battery control is described which: • was developed over a number of design programs • has multiple control inputs from battery cell parameters • provides control signals to other units • operates in floating, proportional, nad crowbar modes • provides cell excessive discharge protection • operates in large signal mode • uses non-linear control elements such as tunnel diodes • has high current shunt which operates in a forward and a reverse mode • has, in operation, provided high reliability of battery operation for several years per unit	Capabilities: Basic circuitry, operating modes, and static characteristic curves are given. Circuitry design is advanced and proven operationally. Limitations: No dynamic operation characteristics or equivalent circuit models are given.	Develop models suitable to do computer analysis of dynamic power system component interactions. Complete model must be multiple input/multiple output.

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	3557 Shunt Regulation/ Load Interaction Stability Model TRW - Unpublished	Worst-case analysis of linear shunt limiter: - stability analysis (SPICE 2 AC model of REA and Linear Shunt Segment) - DC regulation - Analysis (SPICE 2) DC model of REA and linear shunt segments - Bus regulation - Load filter	Capabilities: AC Model Combines solar array regulator and user load input filter models to determine system bode plots. Provides amplitude and phase as a function of frequency. Determines effect of load filter characteristics on system gain and phase margins. DC Model Operating point information, DC sensitivity of output with respect to element parameter variation. Limitations: ● No capability in SPICE 2 for component tolerance variation. ● Model converges only with linear transistor models. Non-linear transistor effects not compatible with present model.	Non-linear model needs to be developed for solution convergence.

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TECHNOLOGY EVALUATION SUMMARY

REF NO.	SOURCE IDENTIFICATION	PURPOSE/ MODEL DESCRIPTION	CAPABILITIES, LIMITATIONS/CONSTRAINTS	AREAS OF IMPROVEMENT
109	G.W.Wester and R.D.Middlebrook" Low Frequency Characterization of Switching DC-DC Converters" IEEE PESC 1972.	Power Stage: Taking advantage of the much lower output filter resonant frequency in relation to the converter switching frequency the nonlinear switching power stage is approximated by a continuous small signal linear model. Approaches: (1) Topology deduction to form a linear circuit model. (2) Equation derivation to form a linear state space model. Both applicable to continuous current operation or discontinuous current operation. Duty-cycle controller: Obtain output voltage to duty cycle transfer function through describing function technique.	Capabilities: (1) The average technique provides the dc model and the small signal model. (2) Linear model in either transfer function form or equivalent circuit form. (3) Gain more insight on converter parameter design. (4) Simple, easy to use. The analytical skill resides in many design engineers. (5) Readily applicable to high-order and complex circuit and systems. Limitations: (1) Large-signal model is not readily available to transient and start-up analysis. (2) Diminishing accuracy beyond 10-20 percent of the switching frequency Not suitable for high-gain wide-Bandwidth regulators' Such as high-performance regulators employing multi-loop control schemes) (3) The canonical circuit model can not be used directly to implement multi-loop control.	(1) Accuracy in high frequencies (2) Large signal Modle (3) Applicability to multi-loop control (4) Improve the accuracy of the duty-cycle PWM model
110	R.D.Middlebrook and S.Cuk "A Generalized Unified Approach to Modeling Switching Converter Power Stages" IEEE PESC 1976.			
111	S.Cuk and R.D.Middlebrook, "A General Unified Approach to Modeling Switching DC-DC Converters in Distinuous Conduction Mode", IEEE PESC 1977			
114	H.A.Owen, J.G.Ferrante and A.Capel,"Continuous Time Models for PWM Switch Converters in Heavy and Light Modes",EAS Technical Note in Press, July 1976,Noordwijk, The Netherlands.			
115	H.A. Owen and A. Capel," Simulation and Analysis Methods for Sampled Power Electronics Systems " IEEE PESC 1979.			
116	W.M.Polivka, P.R.K.Chetty R.D.Middlebrook,"State Space Average Modeling of Converter with Parasiticss and Storage Time Modulation", IEEE PESC 1980			

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TECHNOLOGY EVALUATION SUMMARY

REF NO.	SOURCE IDENTIFICATION	PURPOSE/ MODEL DESCRIPTION	CAPABILITIES, LIMITATIONS/CONSTRAINTS	AREAS OF IMPROVEMENT
117	F.C.Lee, F.Mahmoud and Y.Yu "Adaptive-Control Switching Buck Regulator- Implementation, Analysis and Design" IEEE AES Trans. Vol. AES-16 No. 1, January 1980	Extended Average model Power stage model: The three input two-output modle includes: (1) Disturbance form the input voltage. (2) Disturbance from the output current. (3) Disturbance fron the control loop (4) Directly applicable to any single-loop or multi-loop control	Capabilities: Same as the average modle except the model can be readily usedfor (1) multi-loop control analysis and design. (2) Analysis of disturbance from the converter output Limitations: Same as the average model	(1) Improvement of the accuracy of the power stage model at high frequencies (2) Improvement of the accuracy of the PWM model
118	M.Mahmoud, F.C.Lee and Y.Yu "Analysis and Design of An Adaptive Multi-loop control Two-Winding Buck-Boost Regulator", IECI Trans. Feb. 82			
119	F.C.Lee Y.YU and F. Mahmoud "A Unified Design Procedure for a Standardized Control Module for DC-DC Switching Regulators", IEEE PESC.80.	The equivalent power stage model representing the original properties of the converter's input, output and state variables.		
120	R.A.Carter and F.C.Lee "Investigation of Stability and Dynamic Performance of Switching Regulators Employing current-injected Control", IEEE PESC 1981.	power stage can be represented by a state variable model for computer analysis Power stage can be represented by transfer function model for classical frequency domain feedback control analysis and design		

TECHNOLOGY EVALUATION SUMMARY

REF NO.	SOURCE IDENTIFICATION	PURPOSE/ MODEL DESCRIPTION	CAPABILITIES, LIMITATIONS/CONSTRAINTS	AREAS OF IMPROVEMENT
121	R.P.Iwens, Y.Yu and J.E. Triner,"Time Domain Modeling and Stability Analysis of an Integral Pulse Frequency Modulated DC-DC Power converters", IEEE PESC 1975	(1) Exact formulation of the converter by state equations (2)Using Newton Iteration to solve for the exact equilibrium state numerically, (3)The system is linearized about the equilibrium state to obtain a linear time-invarient model (4)Using z-transformation to obtain frequency domain transfer function representation (5)Using state space and digital computer exclusively to analyze the switching power converter.	Capabilities: (1) It is most accurate small-signal linear discrete model for stability analysis, since no assumption is made in the model. (2)The model can predict high-frequency instibility(Subharmonics of the switching frequency oscillation) (3)The formulated recurrent state equation leads to cost effective performance analysis. (4)The model is applicable to both continuous inductor current and discontinuous inductor current operations. (5) The model is applicable to single-loop and multi-loop control. (6) The model is not restricted to any specific duty-cycle control implementation.	The limitations are inherent. No improvement can be made to further the techniques
122	F.C.Lee, R.P.Iwen, and Y.Yu "Generalized Computer-Aided Discrete Time Doamin Analysis and Modleing of DC-DC Converters", IEEE PESC 1977			
123	R.P.Iwen,F.C.Lee and J.E. Triner, "Modeling and Analysis of DC-DC Converters with Continuous and Discontinuous Inductor Current", Second IFAC Symposium on Control in Power Electronics and Electrical Devices, Dusseldroff, West Germany, October 1977.			
124	Y.YU. R.P.Iwen,F.C.Lee and L.Inouye,"Development of Standardized Control Module for DC-DC Converters," NASA Report, NAS3-18918, March 1980		Limitations: (1) Basically, it is a numerical analysis. No closed form solution is derived to provide physical insight. (2) It is a small signal model (3) The approach requires background in state space modeling and numerical analysis.	
125	Y.Yu,F.C.Lee,P.P.Warren and H.W.Wangenheim," Modleing and Analysis of Power Processing Systems," NASA Report, NAS3-19690, Nov. 1977			

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REF NO.	SOURCE IDENTIFICATION	PURPOSE/ MODEL DESCRIPTION	CAPABILITIES, LIMITATIONS/CONSTRAINTS	AREAS OF IMPROVEMENT
126	F.C.Lee and Y.Yu, "Computer Aided Analysis and Simulation of Switched DC-DC Converters," IEEE IAS Trans. Vol. IA-15, No 5, sept. 79	Exact formulation of state equation Based on recurrent discrete time domain analytical expression Propagate recurrent equation through numerical computation.	Capabilities: (1) Large signal analysis and simulation. (2) Exact duplication of circuit behavior (3) Capable of start-up simulation (4) Simulation of Large signal transients. (5) Capable of incorperating all the system nonlinearities. (6) A combined analytical and numerical scheme that provides a cost effective simulation faster than other general purpose simulation programs such as SCEPTRE, SPICE, ICAP, etc. Limitations: (1) Relatively ineffective for large scale system simulation, since the user has to provide state space representation of the system.	
127	Y.Yu, R.P.Iwen, F.C.Lee and L.Inouye, 'Development of Standardized Control Module for DC-DC Converters", NASA Report, NAS3-18918			
128	S.S. Kelkar, 'Input Filter Compensation for Switching Regulators", Ph.D. Dissertation, VPI&SU, to be published in 1982			
129	T.V. Papathomas and J.N. Giacopelli, 'Digital Implementation and Simulation of An Average Current Controlled Switching Regulator", IEEE PESC 1979.			

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REF NO.	SOURCE IDENTIFICATION	PURPOSE/ MODEL DESCRIPTION	CAPABILITIES, LIMITATIONS/CONSTRAINTS	AREAS OF IMPROVEMENT
130	R.Prajoux, J.C. Marpinard and J. Jalade," Establissement de Modeles Mathematiques pour Regulateurs de Ruissance a Modulation de Longeur d' Impulse (PWM)" ESA Scientific and Technical Review, Vol.2, No.1, 1976	Represent the power stage with a linearized discrete impulse reponse model Applying z-transformation, the discrete time model is then transferred into the frequency domain	Capabilities: Accurate power stage model up to 1/2 of the switching frequency which is the theoretical limit of any linearized model. Limitations: (1) Complex analytical derivations. Need high degree of mathematical background (2) Difficult to incorperate an input filter. (3)Only provide duty cycle to output transfer function. (4)The model can not be readily used to study disturbance from the line voltage and the load. (5)For complex switching converter no closed form analytical model can be derived. Numerical techniques have to be employed.	Equivalent circuit model State space model Disturbance from the input voltage and the load
131	F.C.Lee, Y.Yu and J.E.Triner "Modleing of Switching Regulator Power Stage with and Without Zore-Inductor Current Dwell Time", IEEE IECI Trans, Vol.IECI 26, No. 3, August 1979			
132	F.C.Lee" Discrete Time Domain Modeling and Linearization of a Switching Buck Converter", International Symposium on Circuits and Systems, Tokyo, Japan , July 1979			

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REF NO.	SOURCE IDENTIFICATION	PURPOSE/ MODEL DESCRIPTION	CAPABILITIES, LIMITATIONS/CONSTRAINTS	AREAS OF IMPROVEMENT
133	D.J.Short and F.C.Lee "An Improved Switching Regulator power stage Model Using Discrete and Average Techniques" to be published in IEEE PESC 1982.	Using the average techniques to derive an modle for the state variables of the power converter (inductor current and capacitor voltage wavefroms are continuous and well behaved and can be averaged)	Capabilities: Improve the accuracy of the power stage model in high frequencies, up to 1/2 of the switching frequency Retain the simplicity of the average model.	Need to develop a large signal model
134	D.J.Short, " An Improved Power Stage Modle using Discrete and Average Techniques Ph.D Dissertation, VPI&SU, to be published in 1982	Use discrete time representation to derive an output voltage expression. (Since the output voltage is discontinuous due to the filter ESR)	The model is easy to use. It is represented in the form of circuit model transfer function model and state space model Suitable for multi-loop control and single-loop control modeling and analysis.	

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REF NO.	SOURCE IDENTIFICATION	PURPOSE/ MODEL DESCRIPTION	CAPABILITIES, LIMITATIONS/CONSTRAINTS	AREAS OF IMPROVEMENT
135	V. Bello, "Easy to Use Models for the Dynamic Study of power Converters in A Wide Range of Operating Conditions," IEEE PESC 1980	Power stage model: Using the average technique to represent the switching Power Stage by a averaged continuous-time equivalent circuit.	Capabilities : The simplified power stage model, without switching action, provides an effective large signal simulation.	The applicability of the model to to switching power converter in general not to be limited to a specific converter configuration and control scheme.
136	K. Harada and T.Nabeshima "Large-Signal Transient Response of A Switching Regulator", IEEE PESC 1981	Error processor model: Since the error processor is linear no approximation is made. The saturation effect of the Op-Amp however, is incorperated in the model	The model is easily adapible to existing circuit analysis programs such as ICAP, SPICE, SCEPTRE, etc. Limitations:	
137	H.A.Owen and A.Capel," Simulation and Analysis Methods for Sampled Power Electronics Systems", IEEE PESC 1976	Duty-cycle pulse modulator model The exact duty cycle implementation can be simulated incorperating the basic ramp and threshold implementation.	In general, it is difficult to include some protection features such as transistor peak current protection, because the inductor current(and transistor current) is approximated by its averaged value.	
138	G.W.Wester and D.R.Middelbrook,"Low frequency Characterization of Switching DC-DC Converter", IEEE PESC 1972		It is difficult to be extended to simulation of converter employing a multi-loop control techniques where the instantanuous inductor current (or transistor current) or inductor voltage is used to provide the necessary ramp for duty cycle implementation. It is difficult to include different duty cycle control schemes such as; Constant T_{on} control, constant frequency control, constant T_{off} control, and variable T_{on} variable T_{off} control, etc.	

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TECHNOLOGY EVALUATION SUMMARY

REF NO.	SOURCE IDENTIFICATION	PURPOSE/ MODEL DESCRIPTION	CAPABILITIES, LIMITATIONS/CONSTRAINTS	AREAS OF IMPROVEMENT
139	R. Prajoux, J.Jalade, J.C. Marpinard and J.Mazankine "Easy-to-Use Models for the Dynamic Study of Power Converters in a Wide Range of Operating Conditions" IEEE PESC 1981	A compromise between complexity and accuracy The converter is first represented by discrete time equation. The system is then approximated by a continuous time representation that remains the nonlinear properties of the original system.	Capabilities: Nonlinear time varying circuit is derived for large signal simulation. Linear time-invariant circuit is derived for small signal analysis The model is capable of implementing different duty cycle control The model is capable of implementing differnet single-loop and multi-loop control The model remains the nonlinear properties of the original system and therefore is able to implement protection features and various saturation effects of the system Limitations: The method is not well documented. It is difficult to judge the limitations of the model.	

Appendix C

Industry Survey

TECHNOLOGY EVA -TION SUMMARY - TELECON

REF NO.	SOURCE IDENTIFICATION	PURPOSE/ MODEL DESCRIPTION	COMMENTS	DESIRED AREAS OF IMPROVEMENT
	Aerospace Corp. E. Berry - MTS (213) 648-6273	General purpose solar array model originally TRW's AM136 model, modified for military missions. Used for determining array performance.	Inputs: array geometry, sun angles, radiation dose rate, DES and installation factors, basic solar cell parameters, mission length, temperature coefficients, parametric solar cell characteristics as a function of time. Output: IV table, IV curve plotted Limitations: Array temp over array and distance from sun must be determined by user as input.	Incorporate limitations of solar array.
		Power system simulation program modified TRW's Model 35 program used for all missions.	Limitations: • thermal loop cannot be closed • no transient analysis capability • power conditioning - in & out voltages & efficiency only. Capability: • battery charging algorithms used are different for each mission.	Limitations of program are desired inputs for improvement
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TECHNOLOGY EVA ~TION SUMMARY - TELECON

REF NO.	SOURCE IDENTIFICATION	PURPOSE/ MODEL DESCRIPTION	COMMENTS	DESIRED AREAS OF IMPROVEMENT
	Boeing Aerospace J. Barton (206) 655-6473	Two basic programs (systems): 1. Simplified for approx sizing of conceptual studies, proposals, etc. 2. Detail performance of final design Component Programs: 3. Solar array pointing profile 4. Battery cycling (complete history) Objectives: for Nos. 1 & 2. Basic sizing of solar array & batteries to achieve energy balance. Calculate expected range & voltages throughout system. For No. 3: Verify solar array pointing profile for compatibility with attitude control s/s pointing profile. For No. 4: Calculate specific battery usage for worst-case orbit. The above system programs have been developed for direct energy transfer & centralized regulated configurations.	Power System Program Limitations: • Battery parameters have to be changed to reflect degradation and reconditioning. • Cannot do electrical transients analysis. Capability: • Can close thermal loop & handle thermal transients. • Can do body mounted or paddle mounted solar arrays. • Can do dc, average ac • Can handle interactions between components. Inputs: Orbital parameters, load profile, attitude pointing profile, solar array pointing profile, max battery depth of discharge, line losses, elect. equip. characteristics. Output: Tailored for anything desired, IV curves, solar array sizing, battery sizing vs profile. Data Base: IRAD testing & industry survey.	Eliminate human interface between computer to determine solar array and battery sizing. Otherwise, very happy with results.

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TECHNOLOGY EVA -TION SUMMARY - TELECON

REF NO.	SOURCE IDENTIFICATION	PURPOSE/ MODEL DESCRIPTION	COMMENTS	DESIRED AREAS OF IMPROVEMENT
	Ford Aerospace Palo Alto, CA Mr. V. Funderburk-Mgr. (415)494-7400 X4101	Improved Spice (I Spice), ECAP		Developing power system model & detail models for standard converter design during 1982. ● want time domain analysis, turn-on transients, etc. ● want to improve data base in electronics & solar cells.
	Lockheed Missiles & Space Co Sunnyvale, CA R. Corbett - Supervisor (408)742-3305	<u>Program</u>: For new business, proposal, etc. activity. Preliminary sizing of solar array, battery, power conditioning		
		<u>Program</u>: For on-going spacecraft. Simulates a time line basis. Programs are modified for missions.	<u>Limitations</u>: - Cannot handle transient phenomena - Does not have thermal model, can't close thermal loop <u>Capabilities</u>: - Energy balance - on limited scale - Data base - IRAD testing for battery cycle life, temp, D of D, etc.	Unknown

TECHNOLOGY EVA TION SUMMARY - TELECON

REF NO.	SOURCE IDENTIFICATION	PURPOSE/ MODEL DESCRIPTION	COMMENTS	DESIRED AREAS OF IMPROVEMENT
	General Electric Valley Forge Aaron Kerpitch - Staff (215) 962-3199	Energy Balance Program Used for low earth orbit	Can do steady-state dc; can't do transient analysis; can't close thermal loop. Inputs: Time profile, body or paddle mounted array, loads, degradations component characteristics.	Now in development is a new power system configuration model.

TECHNOLOGY EVA TION SUMMARY - TELECON

REF NO.	SOURCE IDENTIFICATION	PURPOSE/ MODEL DESCRIPTION	COMMENTS	DESIRED AREAS OF IMPROVEMENT
	Martin Marietta (Denver) Matt Imamura-Tech. Mgr. (303) 977-0701 Steve Grout-Prog. Instructor (303)927-3998	1. Photovoltaic system test prototype model. General purpose model for determining total output performance on earth or in space for solar array with or without battery. Assist design analysis and mission operations.	Used for direct energy transfer system & has capability for closely regulated systems. • can handle steady-state dc only • interactions between component included Limitations: • no signal ac • no transient analysis • doesn't close thermal loop Output: Earth/space Total power & energy for month & year Total power & energy available for month & year Input: Solar insolation, load profile and other parameters, i.e., solar battery temp, degradations, efficiency, etc., & battery characteristics. Component models approaches: Solar irradiance model, battery model, power system configuration model (Det. or diss pated), power distribution model. Data Base: Battery models used IRAD and industry data. Same for solar array/	None for No. 1 program satisfactory.
		2. Continued next page		

TECHNOLOGY EVA TION SUMMARY - TELECON

REF NO.	SOURCE IDENTIFICATION	PURPOSE/ MODEL DESCRIPTION	COMMENTS	DESIRED AREAS OF IMPROVEMENT
		2. Skylab computer program (SEPS) Skylab electrical power system. Detail design analysis of array battery, power processing and distribution, detail circuit analysis solution model.	Detail reported in 1972 San Diego IECEC. Highlights provided. Capabilities: Determine operating points throughout mission with fixed array, shadowing, etc. Detail design analysis Interactions between components Steady-state dc Real time performance Constraints were time and costs, therefore, simple model. Limitations: No signal ac No transient analysis Cannot close thermal loop Outputs: To be used for 6 major subroutines: Attitude control, solar array, battery, power conditioning, electrical loads, distribution. Inputs: Body coordinates, celestial coordinates, orbital parameters, etc. all component voltage & current profiles.	Incorporate limitations for "grandiose program" but are satisfied with dollar constraints.
		3. Developing new version of SPICE.	Have been using ECAP, SEPTRA and MTRAC. Although SPICE more efficient than these programs, they want to improve SPICE.	Simultaneously dc transients

TECHNOLOGY EVAL ION SUMMARY - TELECON

REF NO.	SOURCE IDENTIFICATION	PURPOSE/ MODEL DESCRIPTION	COMMENTS	AREAS OF IMPROVEMENT
	Pockwell Int. Seal Beach Sid Brethertone - MTS (213) 594-3127	Global Positional Satellite (GPS) Power System Simulation Model	Capability: Straight linear dc Limitations: - No transients analysis - Cannot close thermal loop - No orbital data - Data Bank Input: - Operating characteristics of array - Set a config. of pwr system e.g., panel deployed or not deployed - Vehicle spinning or 3 axis, eclipse time, length of orbit, load profile, battery temp, state of charge at BOL. Output: - Time history of battery state of charge - Shunting - Load demand as a function of time - Interaction between system elements Data Base: - Simplified IV curve - TRW's Bauer battery handbook on NiCd batteries - Program load profile generator Program Sufficient for needs.	IPAD money will be used for developing new complete power system simulation model for large s/c with power levels of 25 to 100KW. Will have stability analysis, thermal loop will be closed, integrated subsystem approach.