SPACECRAFT SYSTEM OVERVIEW OF SPACE POWER AT GEOSTATIONARY EARTH ORBIT

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Increased power at Geostationary Earth Orbit (GEO) at an affordable cost will have a large impact on spacecraft at that orbit. This paper discusses the OAST Spacecraft Systems Office's goals, power requirements at GEO, GEO environment and design considerations, power system elements and opportunities for technological improvements, and a communication example showing the value of additional power.

Introduction

The Spacecraft Systems Office's goal, Figure 1, is to define and implement new technology tasks that will provide cost effective operational spacecraft for the 1990's that meet new challenging mission performance requirements at an affordable reduced cost. In Figure 2 the office addresses three classes of spacecraft: large space systems at Low Earth Orbit (LEO); advanced spacecraft at Geostationary Earth Orbit (GEO); and advanced planetary spacecraft. This paper discusses those program goals and performance requirements devoted specifically to this meeting's subject, space power systems at GEO.

Power System Requirement at GEO

The Office of Aeronautics and Space Technology (OAST) maintains a NASA mission model which documents NASA's 5-year planning plus hopeful missions for the future. Figure 3 shows a summary of the GEO mission model presented at a meeting of this group in December 1978. Figure 4 shows similar information taken from the model in April 1980. A comparison of these two figures shows that the model is becoming more conservative. Storm sat, disaster warning, and global navigation have been dropped from the model. The requirements of the satellite power system have been reduced significantly. The global communication system has been replaced by the 20/30 program. A conclusion that can be made from comparing these two figures is that there is a continuing requirement for power up to 10 kw and the additional power up to 75 kw will be useful in the future. Consistent with OAST's goals, power technology advancements should be accomplished at an affordable cost.

GEO Environment and Design Considerations

GEO is a hostile environment that has an impact on a power system design. Spacecraft charging at GEO must be evaluated and understood. Figure 5, trade-off studies must be conducted to evaluate the impact of different levels of spacecraft grounding and shielding. The high radiation GEO environment rapidly degrades materials, parts and components. This is particularly important because we are facing requirements for increasingly longer life. Current life requirements are for two to three years with goals of from five to seven years and future requirements identified for up to twenty years. The degradation and life requirements are further aggravated by the fact that system performance requirements are defined in terms of "end of life" performance. Current brute force solutions to long life all result in increased weight. The technology challenge is to achieve 20 year performance life time with reduced weight and at reduced cost.

The present transportation system to GEO involving the Shuttle IUS combination makes an on-orbit maintenance philosophy prohibitively expensive if not impossible. Systems designed for GEO must meet spec performance with little or no scheduled maintenance. This means reliability is a continuing requirement. The present techniques are all using "pedigreed" parts which involve extensive testing to meet tight reliability requirements and are expensive. It is clear that the technologist must find new solutions to providing this reliability at significantly reduced costs.

The technologist must also maintain a constant awareness of the manner in which his designs drive implementation costs. The affordability issue of future space missions has put a major new emphasis on awareness of controlling cost drivers with new technology. Continuing work with current materials and the development and application of new materials with an awareness of cost, will result in the development of cost-effective designs. The significant challenge is to develop and verify these new materials and designs for the GEO environment.

The application of automation techniques is expected to reduce costs and improve performance of new designs in several ways including, but not limited to: self test, management of redundant paths, fault tolerant design permitting significant degradation within spec, and the elimination of costly, continuing ground operations.

The onboard spacecraft power defines the data management system capacity in bits/sec. It also defines the size and cost of ground receivers. The spacecraft power system provides interface to all spacecraft services. More power on orbit at decreased cost will result in a major redistribution of priority spacecraft services. More power on orbit also will impact the design and use of ground receivers.

Power system weight is a technology challenge at GEO. The power system for communication satellites historically has ranged from 16-20% of total spacecraft weight.

Figure 6 lists some of the spacecraft system characteristics that will be influenced by a forecast expansion of available power. Current spacecraft are designed by the integrated analysis and systematic distribution of spacecraft resources. Power is one of the budgeted resources. If you can increase the available power at no increase in weight and a decrease in cost, the total spacecraft performance can be improved. Added calibration and temperature control can improve the performance and life of the attitude control system. Increased power can simplify the complex electronic circuitry that is necessary for signal computation and conditioning. Additional power will improve design margins of electronics, and will redistribute spacecraft weight and performance. Spacecraft system design studies are necessary to determine the optimum utilization of more onboard power.

An Illustrative Example

A 1000 beam, high power, short terrestrial tail, proliferated receiver communication system has been chosen as an example (see Figure 7) to illustrate the tremendous impact larger quantities of affordable space power can base on future programs. This system would locate a spacecraft at a longitude East of the United States to optimize the incident of sunlight on the arrays during periods of peak traffic at night between the United States and Europe. It would base a multiplicity of small receivers located across the country.

The shorter ground links required with many receiver stations will tend to reduce the total system costs. Link characteristics are shown on Figure 7 and a bit flow rate about equal to the current national telecommunications experience was assumed with a market of 80 x 10^6 users. These assumptions calculate to an on orbit requirement of approximately 75 kw of power.

Under certain reasonable cost assumptions it has been determined a communication system that has many small diameter receivers with short ground links is a highly competative low cost system. Examination of a variety of advanced communication schemes involving proliferated interacting users shows that if we can achieve a goal of 100 kw systems at $\$100(10)^6$ for 10 year operational life, the expanded power system can provide sufficient system cost reduction compared to present projected system cost to support the economics of such a new communication system.

Thus affordable space power can open the door to an exciting new communication system that will stimulate the need of a large new expanded terrestrial system. The ground portion of this system will materialize as an expanding new industry.

Major Power Subsystem Elements

The series of charts contained in this section show the system design considerations and trade-offs used in conducting a spacecraft power system design and the design of the major components that make up the power system. These charts display the power system technology tasks that must be conducted in parallel with hardware technology development.

Figure 8 shows the integration of considerations necessary to conduct a power system design study. It starts with an analysis of system requirements and concludes with system technology documentation for advanced development and a definition of hardware technology requirements.

Figure 9 shows the solar array technology trade-offs. Note that aside from the power system and component technology there are major additional considerations that affect the technology outputs. These additional considerations include the broad areas of packaging, operations, and environment.

Figure 10 shows the design considerations and technology challenges to meet the life goal of 20 years for solar array actuators. Applicable technology may be from new advances in mechanisms, or it may be in the design of control circuitry.

Figure 11 shows the challenge of power distribution. The major technology challenge relates to voltage level, grounding, and techniques to transmit power across rotating joints.

Figure 12 shows the considerations of technology challenges to energy storage systems.

Conclusions

Current spacecraft are designed by an integrated analysis and systematic distribution of spacecraft resources. Power is one of the budgeted resources. If the available power can be increased at no increase in weight and a decrease in cost, total spacecraft performance improvement can be provided. Added calibration and temperature control could be provided that will improve the performance and life of the attitude control system. Increased power can simplify the complex electronic circuitry that is necessary for signal computation and conditioning. Additional power will improve design margins of electronics, and will redistribute spacecraft weight and performance.

The major technology challenges for space power systems for GEO are capacity 25-75 kw and life 20 years at minimum weight and affordable costs.

It is further forecasted that as a fallout of the above technology goals additional power will become available. This additional power will make a major impact on future communication spacecraft design and will stimulate a broad new companion ground based communication industry.

SPACECRAFT SYSTEMS

GOAL

- DEVELOP COST-EFFECTIVE OPERATIONAL SPACECRAFT AND SPACE OPERATIONS FOR THE 1990'S
  - INCREASE CAPABILITIES
  - DECREASE COSTS

FIGURE 1

SPACECRAFT SYSTEM
10 YEAR PLANNING GOALS

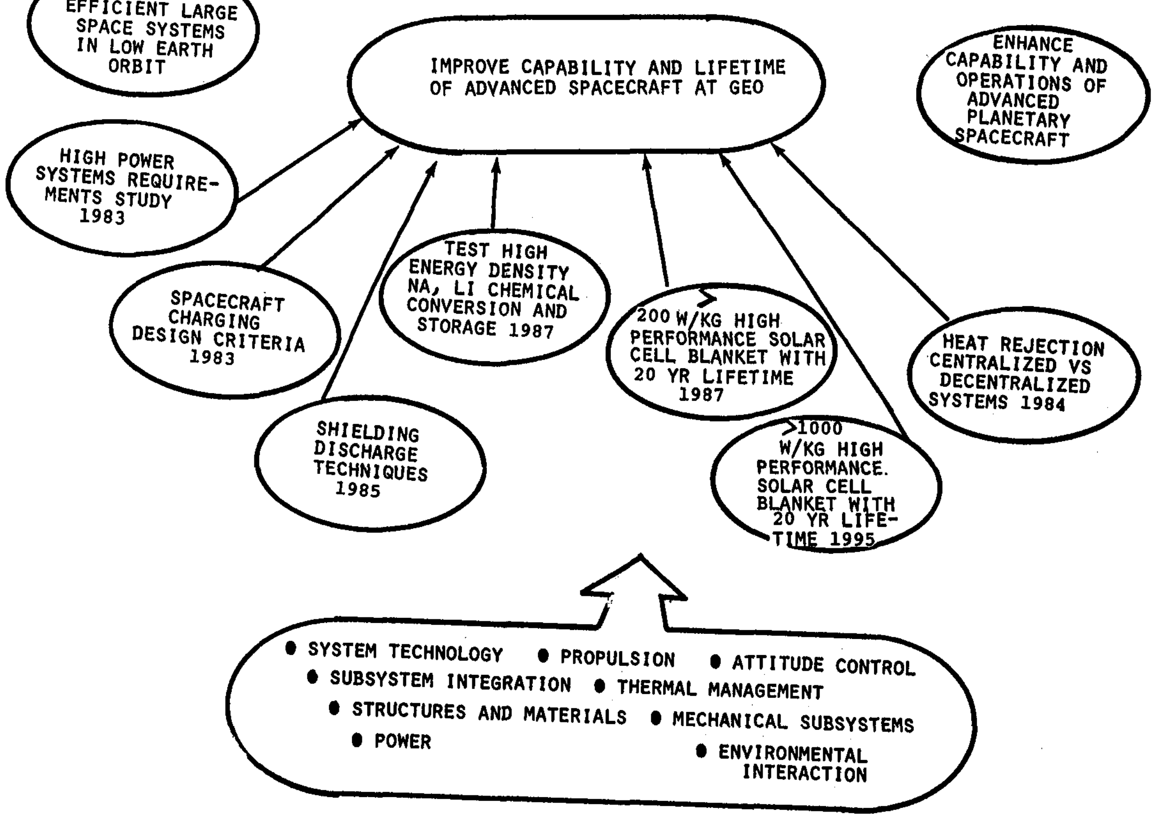

FIGURE 2

OAST SPACE SYSTEMS TECHNOLOGY MODEL
CHARACTERISTICS OF GEO SATELLITES AND PLATFORMS

MISSION NAME*	LAUNCH DATE	OBJECTIVE	SIZE (m)	MASS (kg)	LIFE (yr)	POWER** (kW)
STORMSAT (MESOSAT) (P)	1985	TO PREDICT ADVENT OF STORMS USING SPECTRAL SIGNATURES OF ATMOSPHERE			10	1 (H)
PUBLIC SERVICE COMMUNICATIONS SATELLITE (L)	1986	TO PROVIDE DIRECT DELIVERY OF HEALTH SERVICES, IMPROVED EDUCATIONAL, PUBLIC SERIVCES	60		10	5 (H)
GEOSTATIONARY PLATFORM (L)	1987	TO PROVIDE COMMUNICATION, OBSERVATION, NAVIGATION, SURVEIL-LANCE SERVICE	50	8,200	15	25 (M)
GLOBAL COMMUNI-CATIONS SYSTEM (L)	1987	TO PROVIDE INTERNATIONAL, PERSONAL COMMUNICATION; ELECTRONIC MAIL, TV BROADCASTS	50	30,000		150 (L)
DISASTER WARNING SYSTEM (L)	1988	TO DETECT ONSET OF FOREST FIRES, FLOODS, STORMS, INSECTS, ETC.	60	10,000		75 (L)
GLOBAL NAVIGA-TION SYSTEM (L)	1995	TO PROVIDE ACCURATE GEOLOCATION FOR INDIVIDUALS, VEHICLES	4 km	1,200		2 (H)
SATELLITE POWER SYSTEM (L)	2000+	TO CONVERT SOLAR ENERGY TO RF AND BEAM IT TO EARTH	20 km	10^8	30	5 GW (H)
SPACE BASED RADIO TELESCOPES (L)	1995	TO ENABLE INTERGALACTIC RESEARCH TO DETERMINE ORIGIN, DEFINITION OF UNIVERSE, SEARCH FOR EXTRA-TERRESTRIAL INTELLIGENCE	0.3 to 3 km	10^5	15	80 (L)

*MISSION STATUS: L, LONG RANGE; P, POSSIBLE

**CONFIDENCE LEVEL OF ESTIMATE: H, HIGH; M, MODERATE; L, LOW

FIGURE 3

OAST SPACE SYSTEMS TECHNOLOGY MODEL
CHARACTERISTICS OF GEO SATELLITES AND PLATFORMS

MISSION NAME*	LAUNCH DATE	SIZE (M)	MASS (KG)	LIFE (YR)	POWER** (KW)
C-7 NARROW BAND PROGRAM (O)	1988	-			2
C-4 GEOSTATIONARY PLATFORM DEMONSTRATION (P)	1990	80X30	5000-8000	8-10	25-40
C-3 30/20 GHZ ANTENNA WIDE BAND PROGRAM (P)	1986		1250		1-4
GPS (A/F)			-	5	
U-11 SPACE POWER TECH-NOLOGY DEMO. (O)	TBD	5-10X10M ARRAYS			50
A-15 VERY LONG BASELINE RADIO INTERFEROM-ETER (C)	1990	30-60M, 1-22 GHZ, OUT TO 5000 KM		MINIMUM 3 YEARS	TBD (2 KW)

A - APPROVED, P - PLANNED, C - CANDIDATE, O - OPPORTUNITY

FIGURE 4

WHAT DOES SYNCHRONOUS ORBIT MEAN TO SPACE POWER SYSTEM?

- o HOSTILE ENVIRONMENT
  - SPACECRAFT CHARGING, GROUNDING, SHIELDING
  - RADIATION COMPONENT DEGRADATION
- o REMOTE LOCATION
  - WEIGHT
    - o SOLAR ARRAY EFFICIENCY
    - o SYSTEM OPERATING VOLTAGE
    - o BATTERY CAPACITY AND DESIGN
    - o DESIGN ON END OF LIFE PERFORMANCE
  - 10 TO 20 YEAR LIFE
    - o COST OF REPAIR
    - o REDUNDANCY
    - o RELIABILITY
- o COST
  - DEVELOPMENT
    - o FUNDAMENTAL WORK ON MATERIALS, TECHNIQUES
  - DESIGN AND TEST
    - o INTEGRATION OF AUTOMATION FOR SELF MANAGEMENT WILL PROVIDE INTEGRATED SENSORS AND SWITCHING TO FACILITATE TEST
  - LAUNCH
    - o REDUCED WEIGHT
    - o REDUCED INTEGRATION TEST
  - MAINTENANCE AND REPAIR
    - o FAULT TOLERANT DESIGN TO MINIMIZE DEGRADATION
  - OPERATIONS
    - o AUTOMATION TECHNIQUES TO REDUCE CONTINUED DIRECT LABOR BY GROUND OPERATIONS
- o COMMUNICATION
  - 1000 BEAM
  - HIGH POWER
  - SHORT TERRESTRIAL TAILS
  - PROLIFERATED RECEIVERS
  - LOCATION (EAST OF U.S. TO OPTIMIZE SUN a RIGHT FOR PEAK TRAFFIC U.S. TO EUROPE

FIGURE 5

WHAT DOES SYNCHRONOUS ORBIT MEAN TO SPACE POWER SYSTEM? (CONTINUED)

- POWER SYSTEM CHARACTERISTICS
  - AVERAGE LOAD
    - 1 KW OPERATIONAL
    - 25 - 40 KW FORECAST NEED
    - 75 KW CREATE NEW MARKETS AND IMPACT SPACECRAFT DESIGN
  - OPERATING LIFE
    - 1 - 3 YEARS CURRENT CAPABILITY
    - 1 - 5 YEARS CURRENT GOALS
    - 1 - 10 YEARS CURRENT INCENTIVES
    - 20 YEARS FORECAST
  - POWER SYSTEM 10 - 20% SPACECRAFT WEIGHT
    - ARRAYS 35%
    - BATTERIES 35%
    - CONDITIONING AND REGULATION 8%
    - DISTRIBUTION 22%
  - POWER ON ORBIT DEFINES
    - SYSTEM CAPACITY IN BITS/SEC FREQUENCY
    - GROUND ANTENNA SIZE AND COST
  - POWER USERS ON BOARD SPACECRAFT
    - PAYLOAD
    - DATA MANAGEMENT
    - ATTITUDE CONTROL
    - INSTRUMENTATION
    - THERMAL MANAGEMENT
    - COMMUNICATION
  - MORE POWER ON ORBIT AFFECTS
    - ALL OTHER SPACECRAFT SUBSYSTEMS
    - COST AND THEREFORE SIZE OF MARKET OF GROUND USERS

FIGURE 5 (CONT.)

IMPACT OF SURPLUS POWER ON SPACECRAFT DESIGN

- IMPROVE PERFORMANCE
  - ADD CALIBRATION
  - ADD TEMPERATURE COMPENSATION
- SIMPLIFY CIRCUITRY
  - IMPROVE REGULATION
- IMPROVE RELIABILITY
  - INCREASE MARGIN
- SIMPLIFY INTERFACES
- REDISTRIBUTE BETWEEN SUBSYSTEMS
  - WEIGHT
  - PERFORMANCE
- PROVIDE MORE SPACECRAFT SYSTEMS OPTIONS

FIGURE 6

FIRST ORDER ASSUMPTION OF EXPANDED COMMUNICATION MARKET

- o ASSUME SHORT TERRESTRIAL TAILS
- o ASSUME THE FOLLOWING LINK PARAMETERS
  - FREQUENCY 20 GHz
  - TERRESTRIAL DISK 0.6 M
  - TERRESTRIAL RECEIVER 300K
  - BANDWIDTH 100 MHz/BEAM
  - LOSS IN ATMOSPHERE 10^2
  - USER DATA RATE 10^5
- o ASSUME THE FOLLOWING MARKET
  - USERS 8×10^7
  - FRACTIONAL RECEIVER/TRANS/DAY 1.2×10^{-2}

  THEN TOTAL BIT FLOW IS
  - $8\ (10)^7 \times 1.2(10)^{-2} + (10)^5 = 10^{11}$
- o ASSUME A SATELLITE WITH
  - $(10)^3$ BEAMS
  - $(10)^3$ CHANNEL/BEAM
  - $(10)^5$ BIT/CHANNEL
  - 20 CHANNEL SIGNAL TO NOISE
- o SYSTEM COST SENSITIVITY TO QUANTITY OF RADIATED POWER

RF POWER	GROUND ANTENNA DIAMETER	POWER PLUS RF	ANTENNA (GROUND)	TOTAL
4.3 KW	(0.6M)	0.1	8	9.1
32 KW	(0.22M)	0.77	0.59	1.36

- o POWER GOALS
  - 100 KW SYSTEMS @ \$100M
  - 10 YEAR OPERATION
  - PRODUCE ADDITIONAL UNIT EACH 2 1/2 YEARS

  OR

  - \$10/KW HR.

FIGURE 7

THIS GIVES A

- 163.2 DBW/MI^2/Hz X 10^8

GIVES

- $163.2(10)^8$ $9(10)^{12}$ TOTAL RF POWER
  (43 KW TOTAL RF POWER ALL US)

TOTAL POWER ON BOARD

- 43(6) + 50 = 300KW

IF YOU PAINT ONLY 10% OF US

TOTAL SATELLITE POWER 0.1 (43)(6) + 50 = 75KW

FIGURE 7 (CONT'D)

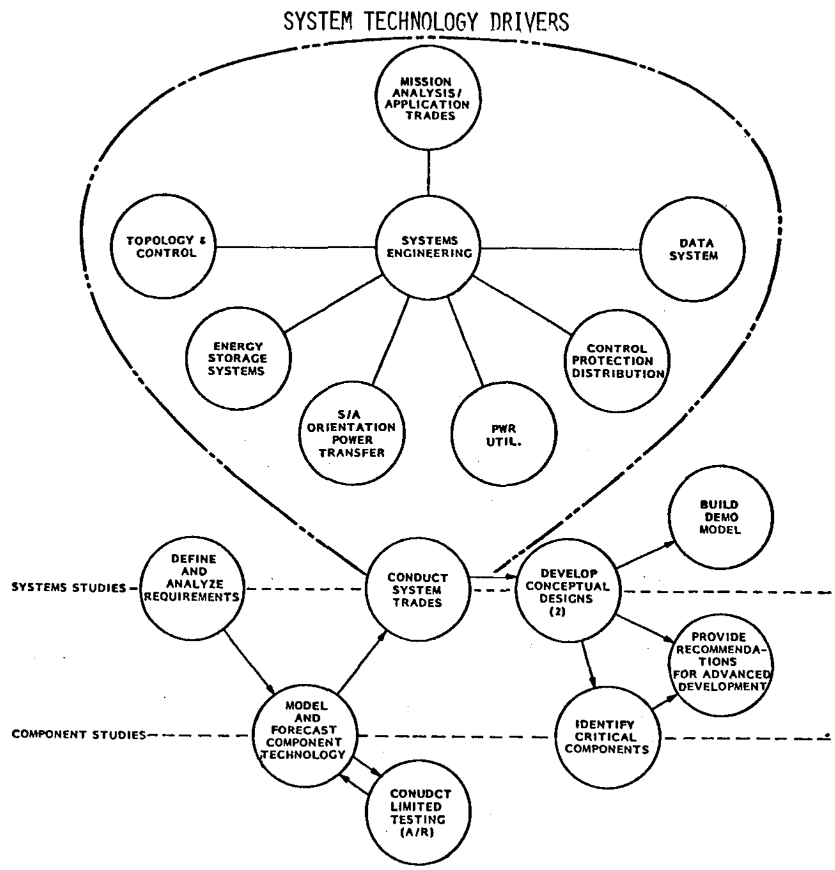

FIGURE 8

SOLAR ARRAY TECHNOLOGY TRADEOFFS

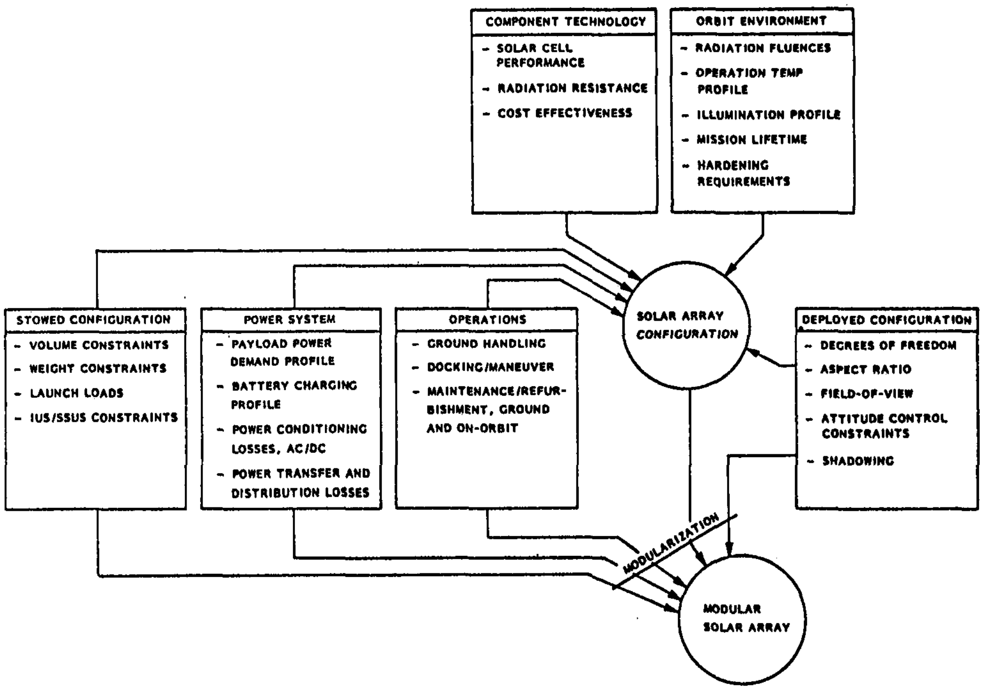

FIGURE 9

SOLAR ARRAY ACTUATOR

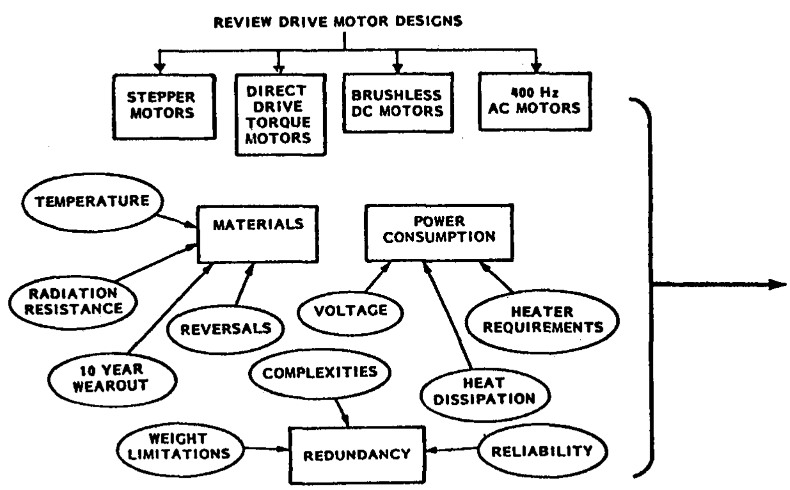

FIGURE 10

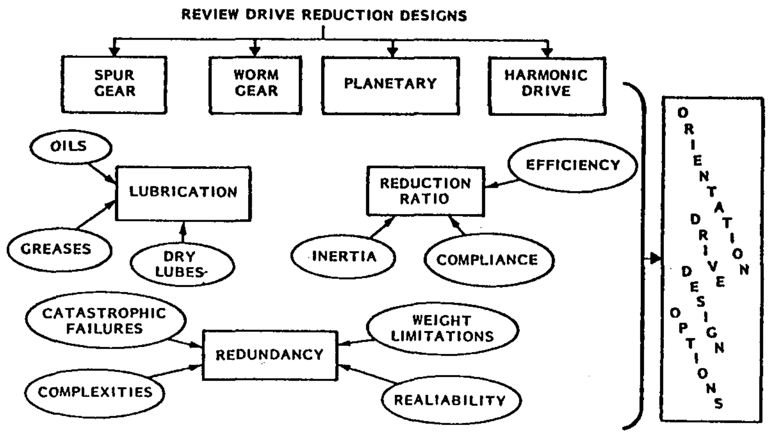

FIGURE 10 (CONT'D)

POWER TRANSFER TECHNOLOGY

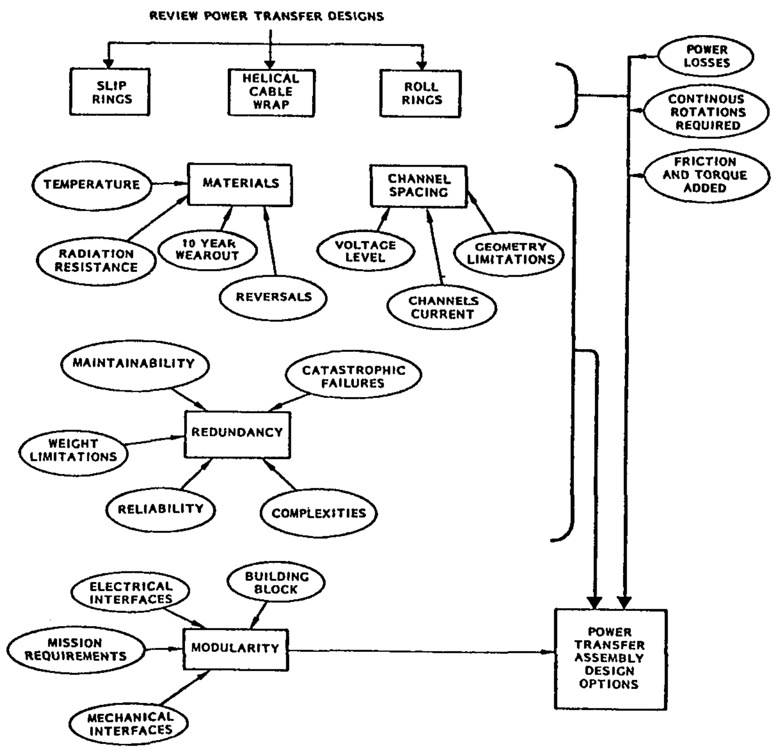

FIGURE 11

ENERGY STORAGE SYSTEM

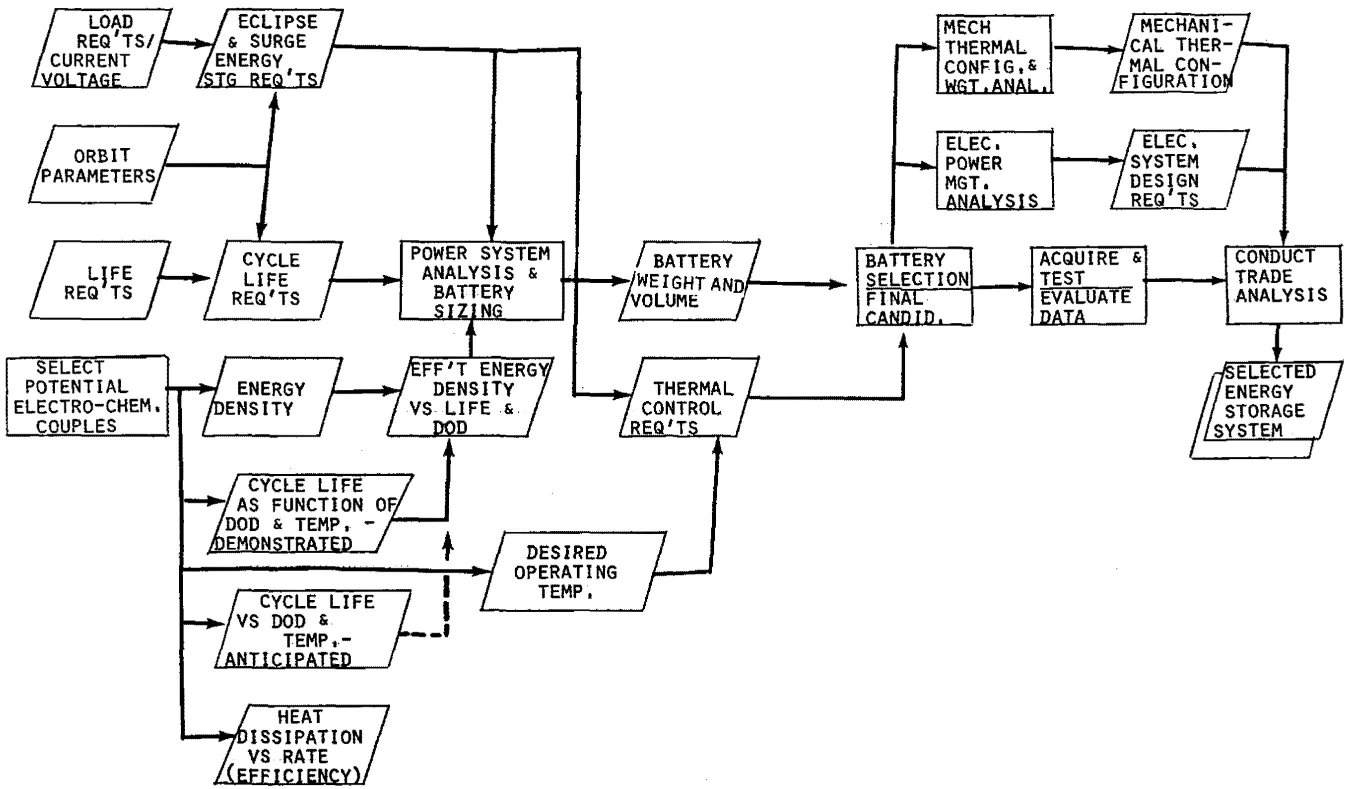

FIGURE 12

CONCLUSION

TECHNOLOGY MUST MOVE FORWARD TO PERMIT UP TO 20 YEAR LIFE IN THE GEOSYNCHRONOUS ORBIT ENVIRONMENT AT MINIMUM POWER LINK OF 25 - 40 KW FOR:

- o MINIMUM WEIGHT
- o AFFORDABLE COST

FIGURE 13

FORECAST

AS A FALL OUT OF THE TECHNOLOGY REQUIREMENTS JUST STATED, ADDITIONAL POWER WILL BE AVAILABLE THAT WILL:

- o MAKE A MAJOR IMPACT ON FUTURE SPACECRAFT DESIGN
- o STIMULATE BROAD NEW COMPANION GROUND BASED COMMUNICATION INDUSTRIES

FIGURE 14