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Toward an Electrical Power Utility for Space Exploration

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TOWARD AN ELECTRICAL POWER UTILITY FOR SPACE EXPLORATION

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ABSTRACT

Plans for space exploration depend on today's technology programs addressing the novel requirements of space-based enterprise. The requirements for electrical power will be formidable: megawatts in magnitude, reliability for multi-year missions and the flexibility to adapt to needs unanticipated at design time. The reasons for considering the power management and distribution in the various systems from a total mission perspective--rather than simply extrapolating current spacecraft design practice--are discussed. A utility approach to electric power, being developed at the Lewis Research Center, is described. It integrates requirements from a broad selection of current development programs with studies in which both space and terrestrial technologies are conceptually applied to exploration mission scenarios.

Keywords: Space Exploration, Power, Electric Utility, Lunar Base, Mars Expedition

1. INTRODUCTION

It is the purpose of this paper to initiate a dialogue concerning the nature of the electrical power systems that will be needed to support space exploration of the sort envisioned by the "Bold New Initiatives:" extensive fleets of earth observing and planetary spacecraft, permanent lunar bases and manned missions to Mars. Studies of these missions performed by NASA and others now clearly show that power, with its extremely diverse range of applications, is the crucial resource. Most missions, especially the manned ones, will require orders-of-magnitude more power than current missions and unprecedented system reliabilities. Moreover, requirements will arise in the course of the missions that can not be fully anticipated during system design. This paper will review the essential characteristics of such power systems, and in particular, define the capabilities that must be provided by the power management and distribution subsystem in order to achieve these characteristics.

2. EXPLORATION REQUIREMENTS

Following the recommendations of the National Commission on Space (Ref. 1) and the Ride Report (Ref. 2), NASA has been conducting a variety of studies on planetary exploration missions and the technologies that will be required to support them. These are summarized in the Exploration Studies Technical Report (Ref. 3). The approach taken to identifying promising exploration options is shown in Figure 1. It proceeds through an iterative process of defining top-level strategies, performing a variety of case studies, and conducting broad trades on various technical options. It should be emphasized that this is an ongoing process that will be as strongly impacted by budgets and the political process as the technical results.

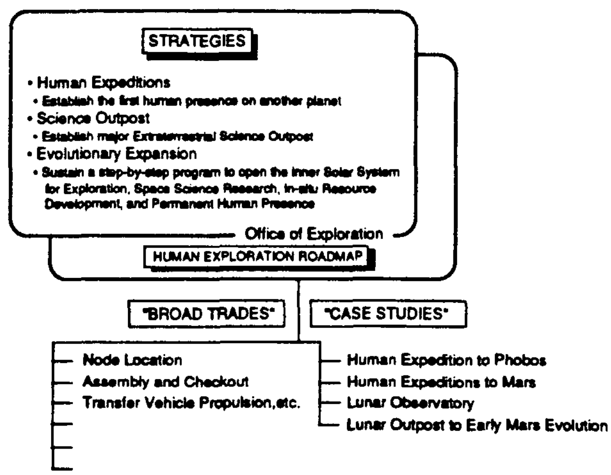

Figure 1 FY 1988 EXPLORATION STUDY APPROACH (Ref.3)

Probably the most difficult challenge facing the development of future electrical power systems will be to not only meet the requirements of the exploration missions, but to do it in such a way that the development efforts are not rendered irrelevant by the all-but-inevitable alterations in the direction of the programs. To do so, requires that we take into account the entire envelope of requirements defined by the studies, rather than focusing on those of one specific system or mission.

The studies make it clear that most of the missions must be accomplished through the integration of multiple diverse and complex activities rather than through the use of single integrated systems departing from and returning to the surface of the Earth.

This is illustrated in Figures 2 and 3 for two stages of a proposed human expedition to Phobos.

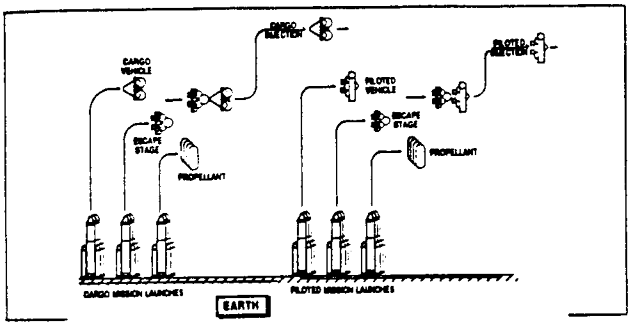

Figure 2 HUMAN EXPEDITION TO PHOBOS - EARTH ORBITAL OPERATIONS (Ref. 3)

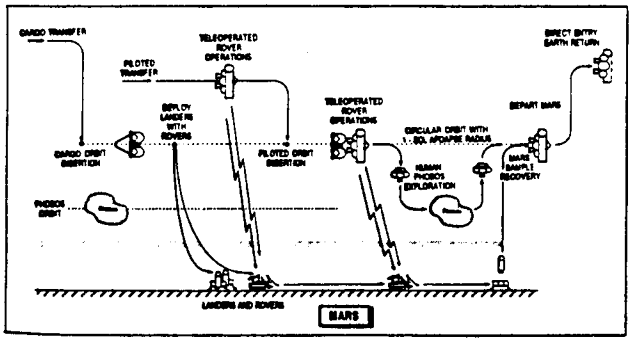

Figure 3 HUMAN EXPEDITION TO PHOBOS - MARS/PHOBOS ORBITAL OPERATIONS (Ref. 3)

A corollary is that both space-based operations and a space-based infrastructure will become integral elements of space exploration. Operations will include on-orbit assembly, on-orbit servicing, planetary landing and assent, and rendezvous. The infrastructure will be comprised of space stations, vehicle accommodation (assembly) facilities, transportation depots, orbit transfer stages, and a variety of smaller systems such as orbital maneuvering vehicles, manned maneuvering units and communications relays. Furthermore, lunar and planetary bases will require infrastructures of similar complexity.

The studies further show that a comprehensive approach to space electrical power management systems must be compatible with at least the following requirements:

1. Scaleable from kilowatts to multiple megawatts
2. System lifetimes and mean times between failure of up to 50 years
3. A wide variety of sources ranging from photovoltaics to nuclear reactors
4. A wide variety of storage systems including those on planetary rovers
5. Compatibility with a broad range of natural and system induced environments, including planetary surfaces, LEO, deep space, reactor fields, etc.
6. Capable of providing power for on-orbit servicing and of being serviced
7. Compatible with on-orbit assembly; e.g. subsystems must be able to exchange or share power
8. Capable of autonomous operation
9. Minimum mass
10. Maximum efficiency
11. Assured system and personnel safety
12. Minimum EMI and other emissions

3. UTILITY POWER

It would be easy to conclude that the preceding requirements are so broad as to preclude a comprehensive approach to space electrical systems, and indeed current practice is to design end-to-end power systems whose resemblance to other systems tends to be purely coincidental (e.g. because they share a common design team). Terrestrial power utilities, however, successfully meet a similar--and an even broader--range of requirements. It is our belief that the current exploration studies are showing that the reasons that led to the creation of terrestrial electric utilities are rapidly emerging in space exploration and will lead to their analogues in space. The primary characteristics of terrestrial electric utilities, e.g., flexibility, user transparency, ease of maintenance and high system reliability, provide a system robustness that will be vital importance to space exploration.

Flexibility - If exploration is indeed a process of discovery, it is also impossible to fully preplan the missions; changes in direction will be more the norm than the exception. This means that the electrical systems must be engineered with the flexibility needed to adapt to both planned and unplanned redirections, emergencies, etc. The electrical system for lunar outpost, for example, must have the ability to evolve into one for a base that is planned after the outpost is operational.

User transparency - Transparency refers to the ability of an electric utility to provide power on demand, to provide a simple interface (e.g. an outlet), and to isolate loads from transients and other disturbances caused by the other loads on the system. Transparency has not even been considered in most space systems both because of their paucity of power and the need to minimize their considerable costs; usually every watt was programed in advance, or elaborate procedures were established to avoid system upsets as loads are switched in and out. In the planning for Space Station Freedom, it was recognized that such procedures would become impossibly cumbersome and limit the complex and dynamic mix of activities which were envisioned. Consequently, 75 kilowatts of power were provided and a utility approach was taken to the power distribution system. Even so, attached loads have grown to several times the system capacity. In order to retain a large degree of user transparency NASA is developing autonomous systems for load scheduling and control of the power system. Since the exploration missions will be significantly more complex than Space Station Freedom, we believe that user transparency will be crucial to their success.

On-orbit assembly - The terrestrial assembly of missions at Kennedy and other space centers requires extensive staff and facilities. This is true even for payload integration into the STS which was designed to be a flexible, general purpose vehicle. It is unreasonable to expect that the on-orbit assembly of a manned Mars probe as was shown in Figure 2 or the growth of a lunar base can be achieved without addressing all the issues that made these complexes necessary. One is the provision of electric power for a wide variety of operations. It is obvious that this becomes all but impossible unless the different systems have compatible power systems; for example, the power at a vehicle assembly center must be compatible with that of the vehicle stages in order to provide auxiliary power during their check-out.

On-orbit Servicing - In its report to Congress, NASA identified a number of design criteria that must be followed in order to make on-orbit servicing practical. In addition to the limitations imposed on designs by replacement logistics, both EVA and robotic operations requirements dictate the use of orbital replacement units. Their design, in turn, mandates the careful definition of all interface standards including the electrical power busses.

Reliability and lifetime - Sufficient experience has now been gained with space systems to make it clear that the system reliabilities required for the exploration missions cannot be achieved with any degree of certainty by merely improving component reliability; even if the components could be developed, validation procedures would be prohibitive. Therefore it must be achieved through intelligent redundancy management. The electric utilities have achieved extremely high reliabilities through the interconnection of numerous sources and loads on a redundant grid, and by using standardized interface elements that can be rapidly replaced or repaired. Essentially infinite system life is achieved by providing standards and methods so that individual elements can be replaced or upgraded without interruption of service.

While the use of a transmission grid is not feasible in most exploration missions, with the notable exception of lunar and planetary bases, the principles are. Two factors are important. First, the degree of redundancy that must be designed into a system to assure mission success depends not only on the probability of failure, but also on the mean time to repair; i.e. a failure reduces the degree of system redundancy by one until it is repaired. Second, the transportation times associated with providing repairs or replacements from Earth will be enormous. In combination, these factors require systems to be significantly over designed unless spares and/or sources of backup power are locally available. For the complex missions envisioned, these options become practical only if the various systems are engineered for a high degree of spares commonality and with compatible electrical interfaces, respectively.

4. ELECTRICAL SYSTEMS DEFINITION

While the exploration missions will not be carried out for a number of years, it is important to develop a utility approach to their electrical systems now. It will both draw attention to significant technology issues, and hopefully reduce conflicts resulting from the need to resolve alternatives after opinions have become entrenched.

The utility approach to space exploration power does not imply a monolithic approach to the engineering individual electrical systems, but it does require an understanding and awareness of the total mission requirements so that the individual systems are not sub-optimized at the expense of total mission goals and/or costs. In view of the diverse and immature state of the exploration missions, the evaluation of various approaches to electrical systems for them is a formidable task. Since the impact of any design decision depends on the details of the particular exploration mission that is ultimately chosen, it is necessary to develop an approach to making decisions that will yield valid results under all eventualities.

We are approaching the problem of defining electrical systems for the exploration mission power systems through the iterative process shown in Figure 4. For a given mission, it consists of four interrelated activities: 1) the identification of the space domains and the drivers that they impose on the systems designs, 2) design studies of individual systems and the subsystems/components that comprise them, 3) mission analyses to identify requirements imposed by the systems interactions with each other, and 4) broad, mission wide, trade studies to evaluate the net results of the various design decisions.

As appropriate, various system parameters, such as voltage or frequency, or interface elements, such as connectors, will be considered for standardization, and candidate standards will be proposed and evaluated. Clearly some degree of standardization is needed, but many options and combinations of them are possible. Because experience has taught us that the setting of such standards can be a contentious activity, we believe it is important to first establish a consensus on the need and requirements for them before embarking on an effort to define standards.

In the first element of defining a utility-type electrical systems for an exploration mission, the space domains involved are analyzed to identify the system design drivers. These provide the general requirements to the mission analyses and the design studies. For example, transportation costs determine the mass sensitivity of the designs, while the degree of availability of resources or a local infrastructure determines the reliability/lifetime requirements. Environmental conditions, insolation and the length-of-night drive a variety of requirements. Most of these factors are already being determined in the ongoing mission definitions studies, but additional factors may be identified as the studies progress.

Mission analysis, the second element, derives additional electrical system requirements from the mission scenario and requirements, including specifications of the power level,the type of conversion and storage systems, and the type and number of attached loads. It also provides any requirements for growth, autonomous operation, transfer of power between systems during on-orbit assembly, or criteria for minimization of spares and other logistics. Again, much of this information is already being generated in the on-going mission studies, but additional work must be performed to extract the electrical system requirements.

Using the requirements derived in the first two elements, the design studies establish the basic characteristics and figures of merit for the electrical systems for all the various vehicles, platforms, habitats needed for the mission under consideration. These studies are supported by conceptual design studies which provide the specifica-the subsystems and components that comprise them.

Finally, the above results are combined into broad trade studies that quantify the results of design approaches or parametric variations mission under consideration. As additional missions are defined and analyzed, we anticipate that the comparisons of the various results will both illuminate the true requirements for a space power utility and provide an early identification of the technology developments that will be needed to carry out space exploration.

5. CURRENT ACTIVITIES

Information needed for the definition of a space power utility is now becoming available at a rapid and increasing rate: the NASA Office of Exploration is conducting a systematic investigation of the pros and cons of a wide variety of approaches to the basic strategies of space explorations; much environmental data has been gathered on the Moon and the planets; the electrical system for Space Station Freedom is being designed as a utility and is thus providing an invaluable base of engineering; and increasing attention is being paid to understanding operational problems such as on-orbit servicing. In the Power Technology Division at the Lewis Research Center, we are attempting to integrate this information in order to guide the definition of a utility approach to space power.

We are also conducting our nearer term technology programs in a way that will shed further light on exploration issues. At the system level, we have been studying the requirements and design issues for a serviceable on-orbit technology test bed. Aprincipal objective is to be able to compatibly support orbital replacement units containing proprietary equipment from unrelated companies; the definition of suitable interface standards, and power and other bus structures is essential to success. A second example is a technology program to provide electromechanical actuators and an integrated power system for the Advanced Launch System Program. It extend the electric utility concept to the replacement of high maintenance hydraulic and pneumatic systems, and it also provides the requirements definition needed to extend the utility concept to launch vehicles.

Lastly, in collaboration with the Space Station Freedom organization, we are developing autonomy technology by automating their test bed. We anticipate extending this activity to exploration missions when the current project is completed.

At the component level, we have a variety of efforts directed at expanding the environmental envelope, e.g., temperature, radiation fields and plasmas, in which electrical systems can operate. We are also attempting to extend the power capabilities to the megawatt level while reducing the specific mass of typical components by an order of magnitude.

6. CONCLUSIONS

We have become convinced that the ambitious exploration goals can be achieved at reasonable costs only if a utility approach to the development of power is adopted. An effort has been initiated to define such an approach, and information is being collected through a combination of liaison with related projects/research, and enhancing our own ongoing technology research. Because a utility would impact all those involved in exploration, we invite and encourage all others to join us in this quest.

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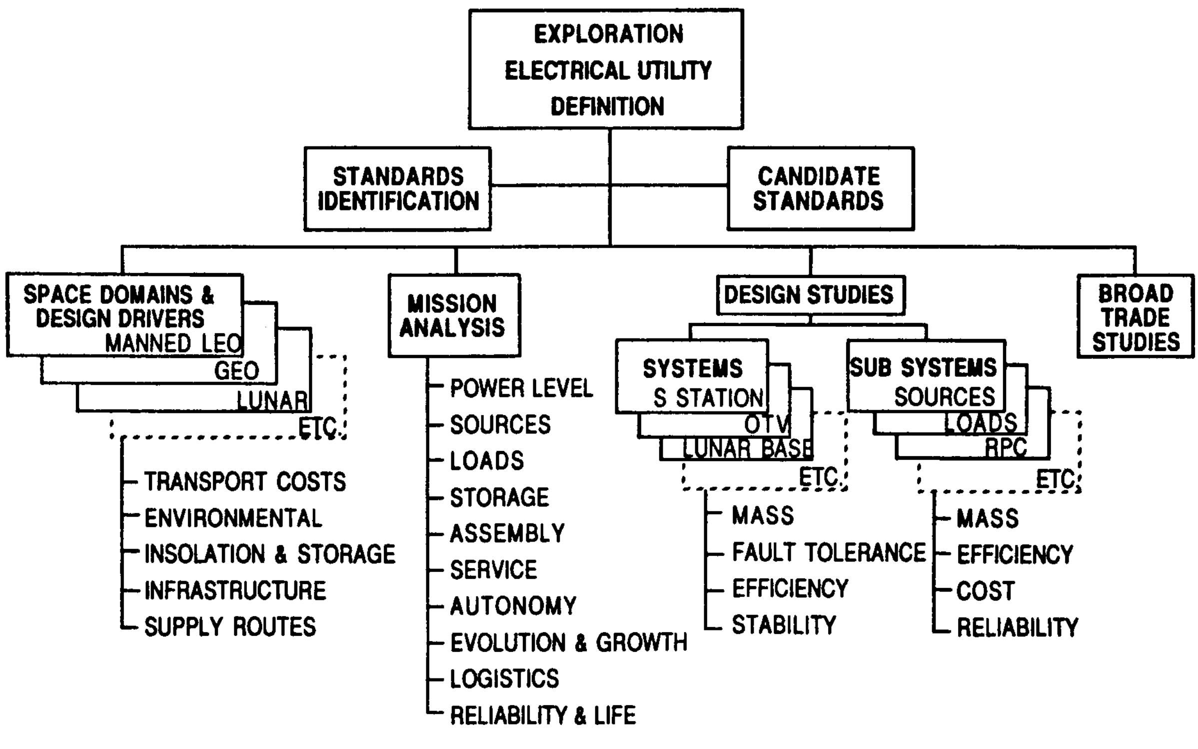

Figure 4 ELEMENTS OF UTILITY DEFINITION PROCESS

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