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ADVANCED SPACE POWER SYSTEMS

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ABSTRACT

A technology applications study of magnetohydrodynamic (MHD) electrical generators was conducted to determine their uses in space. Many important uses were found, including military applications, long range communications and active sensors. Most importantly, it was found that, to retain a livable environment on earth, large scale heat-producing processes must be moved into space. MHD power conversion will play a key role in this effort.

INTRODUCTION

Since the first satellite, space systems have suffered from electrical power limitations which have reduced their overall value and utility. Recent developments, particularly in the field of magnetohydrodynamic (MHD) power generation, now promise to remove these limitations and thus greatly increase the value of space. Coupled with dramatic advances in space transportation in the near future, these developments promise human benefits far in excess of anything yet foreseen from the space program.

In 1969, prompted by its recognition of this possibility, the Space and Missile Systems Organization, assisted by the Air Force Aero Propulsion Laboratory, began to assess the uses of high power in space.

This study, even though not yet complete, has been quite startling. Profound changes to all aspects of technological civilization, military and civil, will result from the space systems made possible by high power electrical generators. We have only begun to explore the implications of high power in space.

TECHNOLOGICAL BACKGROUND

Before considering the uses of high power in space, it is essential to briefly review the technology of high power generators.

Traditionally, the space system planner has been limited to the low kilowatt power range and below by the available auxiliary power systems: solar cells, batteries, fuel cells, and radio-isotope generators. While some of these devices can provide highly reliable power for several years none of them can produce high power levels except in prohibitively massive configurations.

Recent research has established the feasibility of devices which will eliminate this high power constraint on space systems. These devices include cyrogenic and superconducting energy storage systems, advanced turbo-alternators and MHD power generators. As depicted in Figure 1, power supplies in the multimegawatt range can be made available around the end of the current decade and no theoretical limit on power level can be foreseen at this time.

The characteristics of the high power systems considered in this paper differ widely, so that different applications will need different power systems. The two most important parameters in the selection of a power system are power level and power duration. The advantageous regimes for each of the high power systems are plotted against these parameters in Figure 2.

For very short durations, energy storage systems (capacitors and inductors) appear best. For longer durations (more than a second) and power levels below the megawatt range, turbo-alternators are preferred. The heat source is changed depending upon the required power duration. When very high power levels are needed, MHD generators should be selected. The specific type of MHD system depends upon the necessary duration. When microsecond or millisecond pulses of high power are needed explosive MHD is appropriate. As duration increases, other types of MHD systems become attractive: first, combustion MHD systems (either rocket or airbreathing) and then nuclear MHD systems.

It should be noted that the dividing lines between these different power system regimes are not rigid. In specific cases, selection of a power system must also include consideration of secondary characteristics such as reliabilities, costs, etc.

As shown, MHD systems become competitive only at very high power levels. This relation holds because the power output of a MHD generator is a function of the cube of a characteristic length (such as channel length), while the system weight is a function of the square of that length. This effect is shown more explicitly in Figure 3, which depicts the expected performance of various power generation systems. Both the specific power of a steady-state system (i.e., a nuclear system) and the fixed weight of a short duration system improve with power level. For example, a 100 megawatt nuclear generator might weigh only 10 times as much as a 1 megawatt generator. For short duration power, specific weights range about 0.1 - 1.0 pound/kilowatt, so the fixed weight for a one minute, 100 megawatt MHD system could be around 25,000 pounds. Exact numbers cannot be assigned, of course, until the specific system application is analyzed in detail.

NEW CAPABILITIES

It is clear from the foregoing that high power systems will continue to be massive devices. The newly developed technology does, however, succeed in reducing their size enough so they can be used in space, where there is a need for them.

We believe that we have identified many needs for high power in space. With the intentions of stimulating new thought and discussion and of alerting potential users to the new possibilities we will now discuss a sample of these applications.

A. Military Applications

The military appears to be one of the chief beneficiaries of high power space systems. Unfortunately security considerations preclude discussion of some of the most interesting systems. As an example, high power jammers and other electronic countermeasure systems are obvious applications of high power technology.

As manned systems come into greater use, the need for accurate and rapid rendezvous capabilities will increase. This will be particularly true when satellite maintenance systems are developed, since systems of this nature will have to be able to rendezvous with failed satellites on very short notice.

This capability for fast rendezvous could require high powered radars, because malfunctioning satellites can well become totally inert. If, for instance, a satellite repair system needs highly accurate position data on small satellites at ranges around 10,000 km, it would require radar peak powers approaching 1 gigawatt. Depending upon pulse length and pulse repetition rate, average power levels of several hundred kilowatts to 1 megawatt will thus be required. Large turbo-alternators or MHD systems are logical power subsystem candidates for this application.

Another potential application, this one of interest to the tactical commander, is shown in Figure 4 The Surface Illuminator would essentially be a high powered, narrow beam searchlight mounted in a low or medium altitude satellite. By operating the illuminator at a non-visible wavelength and equipping friendly forces with appropriate sensors, an enemy would be denied the knowledge that he was being illuminated.

It seems most likely, however, that progress in low light level image intensifiers will render systems of this nature unnecessary. They will continue to be examined in case they should present an option that we may need to adopt in the future.

B. Communications

As increasingly sophisticated systems, particularly manned spacecraft, venture farther from earth, communications requirements will become increasingly severe. These spacecraft will not only be far more distant from earth than their predecessors, but they will generate more data. Thus, we will either have to accept extended transmission times, await the return of the spacecraft, or develop new communications systems characterized by high power and narrow beams. There are compelling reasons to prefer the last alternative.

Consider, for example, an unmanned probe of Saturn. The rings around this planet represent one of the most fascinating mysteries in the solar system; data collected in their immediate vicinity will be extremely valuable. It is also quite probable that the rings present a very severe danger of collision to spacecraft. Thus, it would be most unwise to depend upon an extended period of data transmission following planetary encounter. During close approach to the rings, data transmission should be real-time. Assuming a laser communication system with a beam divergence of 1 microradian and a detector sensitivity of 10^{-11} w/cm^2, this would require a power supply approaching 5 megawatts. Depending upon the encounter geometry, the resulting time in the vicinity of the rings, and other data requirements, either a chemical or a nuclear heat source would be necessary.

A manned Mars expedition, which might occur as early as 1986, is another excellent example. It seems certain that this mission will have to be capable of transmitting live TV several times throughout the flight (such as Mars capture, first landing, etc.) for three basic reasons:

1. Experience with Apollo has shown the value of maximum public participation in important phases of major exploratory flights. We will need to involve the American citizen even more in future flights so that he will come to appreciate the value and benefit of spaceflight.

2. There is always the possibility of catastrophic mission failure at a later stage of the flight. Therefore, as much data as possible should be transmitted as it is gathered.

3. Should a catastrophe (which prevented crew return) come from an unexpected source, we will need to know as much as possible about this event to guard against a recurrence in later missions. This requires a capability for real-time data transmission throughout the flight.

Basically, there are two means of providing the necessary capability; radio frequency or laser communications. A final choice cannot be made until the mission is planned in detail, but we can say that some of these communications systems will require high levels of prime power.

For instance, assume a manned Mars expedition and a high data rate SHF communication system with an earth-based receiver sensitivity, for this data rate, of 10^{-13} w/m^2. With a 1/4 degree beam divergence, this will require a beam power of nearly 1 megawatt to insure communications at all possible Mars-Earth ranges. Detailed tradeoff studies will be required before final selection of the communications and power subsystems can be made.

In some cases, the inner planets, at least, can be explored without the use of ultrahigh power levels for communications, but the explorations will certainly be enhanced if high power is available. Further, the attractiveness of high power communications is increased if active sensors of the type that we will now describe are used on the same mission.

C. Active Sensors

To date almost all scientific data from space has been gathered by passive sensors; i.e., sensors that respond to some radiation or particle emitted by an external natural source. No attempt has been made to actively probe objects in space and then observe the reflected radiations. Doing so could generate much new and interesting data.

In most cases, high power will be required for active sensors. Since reflection of a signal is generally required, (unless, for example, transmission through an intervening medium is being studied), the signal strength at the receiver obeys an r^{-4} law rather than an r^{-2} law.

As an example, a detailed radar map of Mars might be one of the more useful products of a manned expedition. Coupled with samples from a few sites, it would reveal much about the geology of Mars. This map could be made by a spacecraft in a polar orbit a few thousand kilometers above the surface of the planet. If we assume a receiver sensitivity of 10^{-16} w/m^2 and 1/4 degree divergence, of the transmitted beam, the radar will be able to detect 1 m^2 objects when it has a peak power of 1 megawatt. The system could have an average power of 1 kilowatt, pulse length of 1 microsecond, and a pulse repetition rate of 1000 pulses per second. In this case, superconducting energy storage systems could convert an average input power of a few kilowatts (depending upon efficiencies) into megawatt pulses.

For improved coverage and resolution, it might be desirable to sweep the radar beam from side to side as it moves along the surface. If the beam is swept 5 degrees to either side of the centerline, the pulse repetition rate would be increased by 40 times. If the transmitter efficiency is assumed to be 30%, an average input power of 130 kilowatts is required. This suggests a nuclear turbo-alternator system, unless other subsystem requirements substantially raise the power needs.

A planet which could yield most interesting data to radar probes is Venus. Power requirements would be much more severe in this case since the beam would have to pass twice through a very dense, severely attentuating atmosphere. It does not appear that we can define a system for the detailed radar mapping of Venus until more data concerning its atmosphere is in hand. In particular, the unusual index of refraction needs to be studied.

A logical approach would be to fly a radar probe on an unmanned flyby past Venus. The system would not be designed for more than a few minutes operation, but would be very powerful. Using the same pulse repetition rate and pulse length as the Martian example above, a one gigawatt peak power would require an average power of one megawatt. For five (5) minutes operating time, an open cycle, combustion driven MHD system would weigh around 3000 pounds.

With the data developed on this flight, it should be possible to design a long-term radar system, probably powered by a nuclear MHD generator, which could make a detailed map of the surface of the planet. This could then be flown on a planetary orbiter, either manned or unmanned.

The asteroid belt is another interesting subject for investigation by active sensors. Information on this region is most important for two basic reasons:

1. No theory of the origin and evolution of the solar system can be satisfactory unless it explains the origin of the asteroid belt. Since the belt is an unique phenomenon, study of it could well give clues of particular importance to an understanding of the complete system.

2. Knowledge of the size and distribution of asteroids in the belt will be most important in the structural design and orbit determination of spacecraft enroute to the outer planets. This is particularly true in the case of manned visits to the outer planets.

The exact power requirement for such a radar mission cannot be defined without a detailed statistical analysis to determine just what sort of data is really required. It is nonetheless safe to assume that very high power levels will be required. Consider an example. If it is desired to detect 1 m^2 targets out to a range of 100,000 km, a radar peak power of several gigawatts is required. Under the same conditions as discussed before, this leads to an average power requirement of several megawatts. Further, a continuous source would be required, since the belt is between two and three astronomical units wide. Considering efficiencies, a logical candidate for this case appears to be a nuclear MHD system with a continuous power output around 10 megawatts.

This brief list does not by any means exhaust the possibilities for active sensors. Interesting missions could be based upon two cooperative spacecraft, one of which illuminates a target (such as a comet) at a frequency of interest while the second observes the transmitted electromagnetic radiation. Modification of waves reflected from layers deep within the atmospheres of the Jovian planets could yield much information concerning their structure. In short, the field of active sensors for planetary exploration is a brand-new area made possible by the advent of high power space auxiliary power systems. Being a new area, it is wide open for new discoveries.

Some interesting economies can be effected if two or more high power applications are flown on the same mission. For instance, a 10 megawatt nuclear generator on a manned Mars mission could be used part of the time for radar mapping and the rest of the time for high data rate communications with Earth. The cost of the generator would then be amortized over both systems.

These applications become even more attractive if the spacecraft's propulsion reactor can also be used as a power reactor. Since a liquid metal MHD system only requires peak temperatures of the order of 2000° K, there does not seem to be any major technological advances necessary to incorporate such power systems into solid core nuclear rockets, although major redesigns will be necessary.

D. Planetary Environment

Everyone is well aware of the developing crisis of the environment. The public is increasingly up in arms, energetic political action is beginning, detailed analyses of ecological systems are underway, new laws against pollution are being enacted, etc., etc. In short, a full scale attack against particulate and local pollution of the environment is being mounted.

A very serious point has been missed. Given enough effort and enough energy, we can eliminate every form of environmental pollution except one. We can reuse all of our scrap and garbage, we can remove all smoke particles from exhaust, we can return all water to the rivers as clean as it was when we removed it. We can, in fact, convert all our processes into closed cycles except for one very important aspect: heat. Any real process must reject waste to its environment in some manner. This is a fundamental limitation imposed upon us by the Second Law of Thermodynamics and there is no foreseeable way, even in theory, to overcome it.

The unseen problem, then, is this; the planetary biosphere of the earth is a heat sink of definite capacity. Once that capacity has been exceeded, serious damage (i.e., wholesale extinction) must follow for all components of the biosphere, including man. This eventuality can only be avoided if evolutionary processes can adapt the biosphere to higher temperatures during the time in which heat addition is occurring. And the pacing of human activity is too rapid to permit such evolutionary adaptation.

For instance, over the past decade the total electrical energy generated throughout the world has increased by an average of 7.85% per annum. This represents a doubling of energy output every ten years. Projected into the future, as in Figure 7, we see that 50 years hence our energy output will be 40 times that of today, and just one century hence, it will be 1300 times that of today. In one century, we will be generating enough heat to raise the temperature of all the oceans by 0.001 degree per year.

Nor is there much chance of reversing this trend. Energy availability per capita is a fairly good measure of standard of living, and the United States presently enjoys a 6 to 1 advantage over the rest of the world in this regard. Even if the U.S. value could be frozen, the pressures for higher standards of living throughout the globe would create just as meteoritic a rise in power demand. And since the U.S. standard of living is by no means uniform, pressures for increased energy availability in this country are likely to be irresistible also.

Nor does electrical generation represent the total energy pollution of the environment. Other large scale processes, such as ore smelting and transportation, contribute significantly to the problem, although we have not as yet been able to attach any numbers to them.

Clearly, we must begin to take action to reduce or eliminate the energy pollution of the biosphere. There are only two alternatives; we can reduce our energy requirements, and thus return to a pre-technological civilization, or we can move our large scale heat-producing processes into space, where the universe is available as a heat sink. There does not appear to be any way to implement the first alternative, even if we should wish to: therefore, we must implement the second.

There will be two keys to our success in this undertaking: transportation and power. We will first need to determine which processes can be moved into space and which must remain on the Earth. Those which we can move into space must then be made as independent of Earth as possible in order to reduce the transportation requirements, since any transportation system will itself reject heat to its environment.

Space power requirements will be far in excess of any predictions made so far. We expect that they will be of the same order of magnitude as the foreseen power requirements for the earth as a whole; that is, 10^{15} or 10^{16} kilowatt-hours per year. Assuming continuous usage, this translates into a need for total installed generating capacities of 10^{11} to 10^{12} kilowatts. We can seriously expect these space power requirements to arise within a century.

Apparently, the only way to generate power of this magnitude is controlled fusion. Although we do not as yet have a clear picture of the manner in which we will finally control the fusion process, there is at least a good chance that the power conversion process will be quite similar to current concepts of MHD power generation concepts. Therefore, we must advance our understanding of MHD power conversion concepts.

CONCLUSION

Examination of the potential of high power generators in space has identified many system applications which are both desirable and feasible. Since this is only a first look, we are confident that many more applications will be uncovered as the technical community becomes aware that high power is in fact available for use in space.

More importantly, we have discovered that high power in space is not only useful, but mandatory. If we do not develop these high power systems, we will be unable to use the universe as our primary heat sink. Instead, we will continue to use the biosphere as a heat sink. Thus, unless we move energetically into space we will in time destroy the biosphere and, with it, ourselves.

SPACE POWER SUPPLY DEVELOPMENT POSSIBILITIES

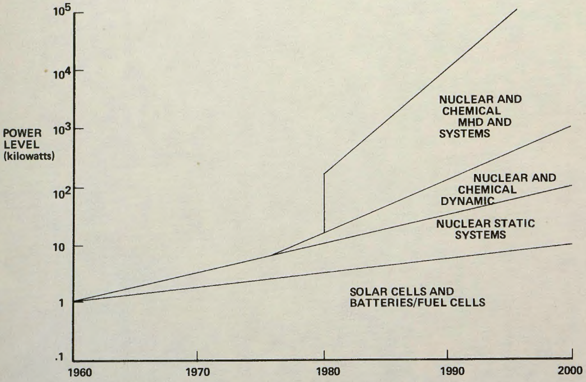
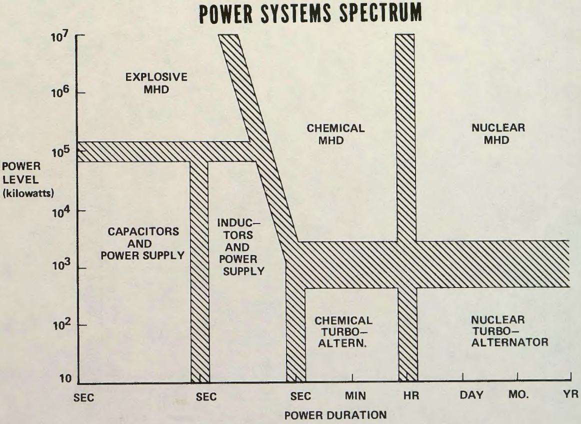


Figure 1



POWER SYSTEMS SPECTRUM

Figure 2

POWER SYSTEM PERFORMANCE VS. POWER LEVEL

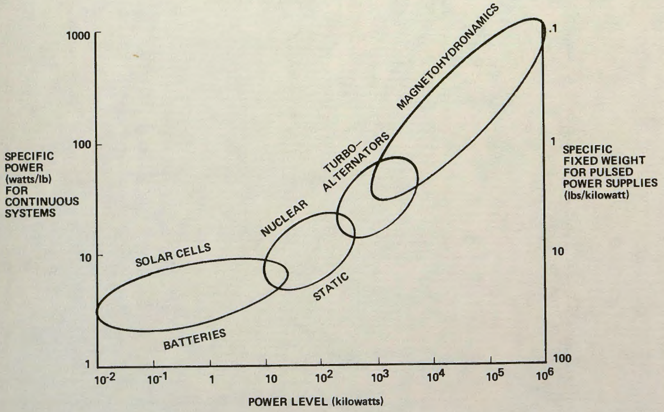


Figure 3

SURFACE ILLUMINATOR

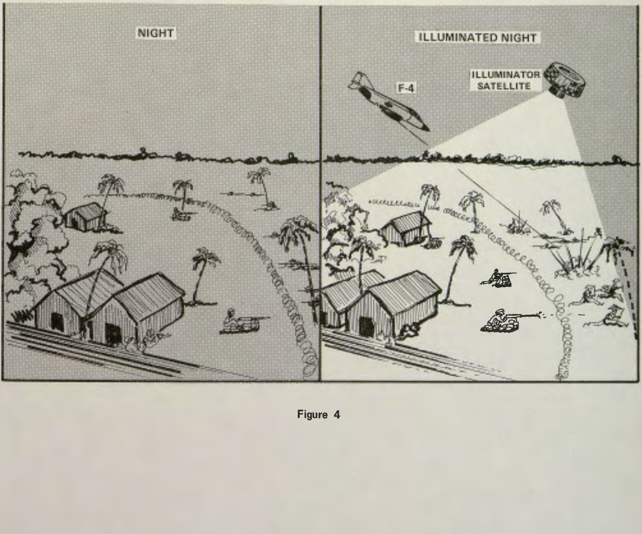
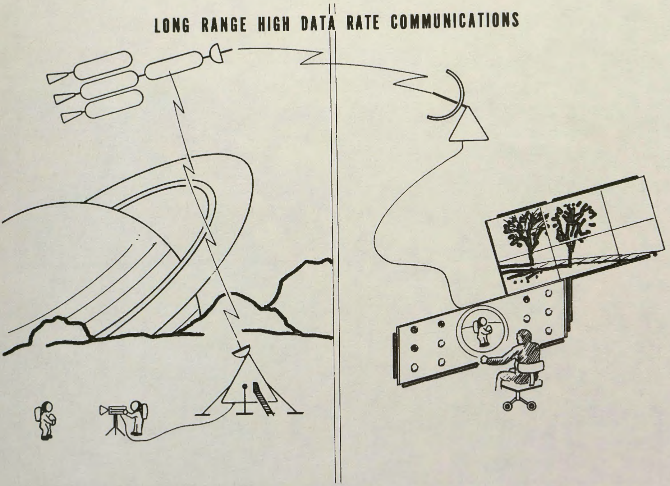


Figure 4



LONG RANGE HIGH DATA RATE COMMUNICATIONS

Figure 5

ACTIVE SENSORS FOR PLANETARY EXPLORATION

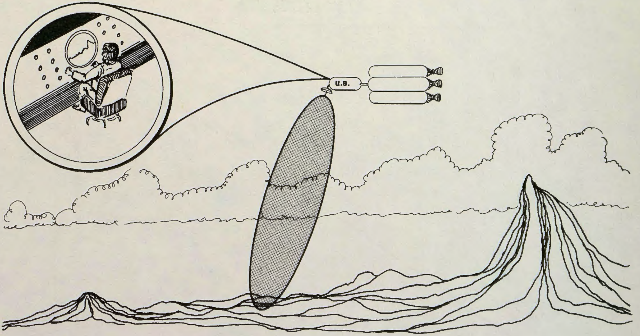


Figure 6

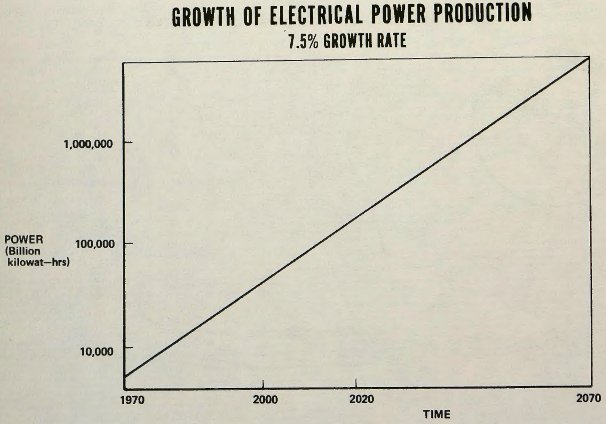

GROWTH OF ELECTRICAL POWER PRODUCTION
7.5% GROWTH RATE
POWER (Billion kilowat–hrs)
1,000,000
100,000
10,000
1970
2000
2020
2070
TIME

Figure 7