TRENDS IN FLIGHT VEHICLE POWER

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ABSTRACT

This paper on the trends of flight vehicle power describes briefly several techniques being considered for converting energy to useful power for anticipated future space missions. It also presents a synthesis of forecasts of future power requirements for general types of anticipated vehicles, and relates the area of application for which the various types of conversion methods are predicted to be optimum in meeting the forecasted requirements.

To present to you the picture of the future trends in the field of flight vehicle power, I will first define flight vehicle power, then some of the methods to be employed for energy conversion will be be described briefly, after which the forecasted power requirements of the future will be discussed, including a forecast of the conversion methods that are considered most likely to be optimum for application to the various type future missions.

Flight vehicle power is defined as all that power necessary to operate any vehicle in flight, excluding the primary propulsion, but including the power required for electric propulsion and for extra-terrestrial sites.

The power area is relatively broad, encompassing energy source technology, techniques to convert energy to useful electrical, hydraulic, and pneumatic power, the transmission of this power to the load, as well as the conditioning of the power to make it compatible with the utilization equipment.

This paper, however, will primarily deal with the energy conversion techniques and the application of these techniques to the power requirements for typical future space oriented missions.

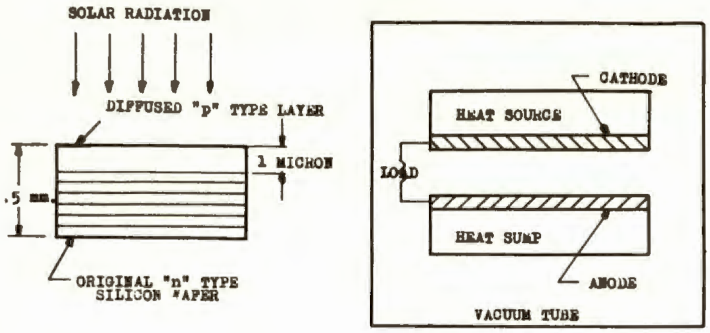
The advent of the space age has placed increasing emphasis on the exploration of new methods of converting energy to useful power. The power system must be self-sufficient, since we no longer can bleed the prime propulsion system, mechanically or otherwise, for the needed power. In fact, if electric propulsion is to be employed in space vehicles, the propulsion system will be highly dependent on the power system. In addition, the requirements for power are expected to increase drastically in terms of power level, low specific weight, operating time, and reliability. Durations of 1000 hours are no longer adequate, but at least 10, 000 hours of maintenance-free, continuous, reliable operation will be required.

The power level is expected to rise into the megawatt range.

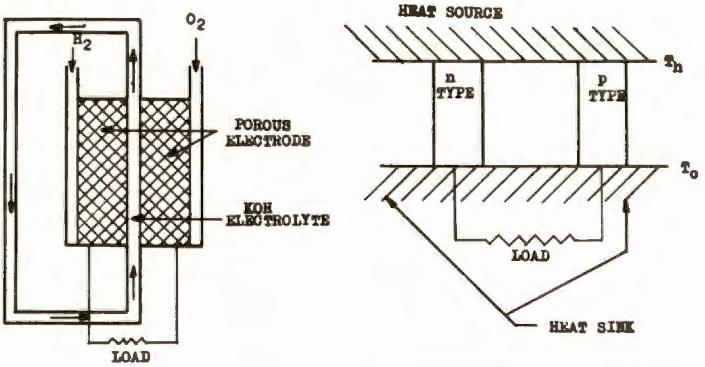
Before going into the predicted future power requirements, a review of the energy sources available and the methods that can be employed in converting this energy to useful power is in order, is given in Table 1.

A brief explanation of the operation of some of the static conversion devices which may be less familiar follows (Fig. 1 gives a schematic diagram of these devices):

(a) Photovoltaic converter. A typical converter is a silicon cell. Some material such as boron is diffused into one surface of the crystal to form a very thin "p" layer with the original crystal in the opposite surface forming the "n" layer. Photon energy from the sun causes electron movement within the material from the "n" layer to the "p" layer of the material. With a suitable external circuit this movement of electrons does useful work.

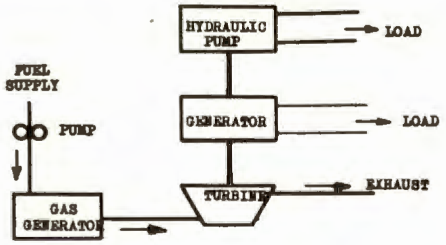


(a) SILICON SOLAR CELL (b) THERMIONIC CONVERTER

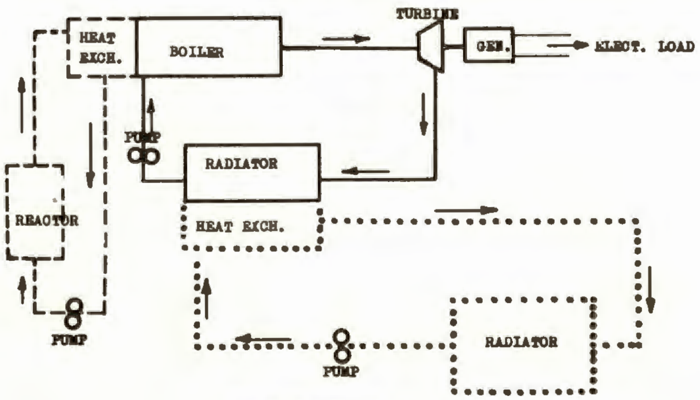


(c) FUEL CELL (d) THERMOELECTRIC CONVERTER

FIGURE 1. STATIC CONVERSION DEVICES



CHEMICAL POWER UNIT



SOLAR OR NUCLEAR
DYNAMIC POWER UNIT

FIGURE 2. DYNAMIC CONVERSION DEVICES

(b) The thermionic converter consists of two metal plates of different work functions, the cathode being a high work function material and the anode being a low work function material. Thermal or heat energy is applied to the cathode, causing electrons to be boiled off. These electrons will then be collected on the anode, which has a lower work function, producing an electrical potential between the plates; thus, with a suitable load circuit, the converter produces a flow of electrical current.

(c) The fuel cell converts chemical energy directly to electricity. In the example shown, hydrogen and oxygen are fed separately into the two electrodes. The two porous electrodes are separated by a KOH electrolyte. Under the influence of a catalyst in the hydrogen electrode, the hydrogen releases an electron. This electron flows through the load circuit to produce useful electric power and thus passes into the oxygen electrode reacting with the oxygen under a catalytic action to form water.

(d) The thermoelectric generator is an adaption of the thermocouple as a power generator in lieu of a temperature measuring device. In this case heat or thermal energy is applied to the "n" and "p" type materials, resulting in a flow of electrons between the "n" leg and the "p" leg, creating a potential between the hot and cold junctions, thus generating an electric current when the circuit is completed.

TABLE 1. ENERGY SOURCES AND CONVERSION DEVICES

Energy Source	Conversion Device	Variations
Chemical	Dynamic Power Units	(A) Open Cycle (B) Positive Displacement Devices (C) Combination Open and Closed Cycle
	Fuel Cells	(A) Primary (B) Regenerative
	Batteries	(A) Primary (B) Rechargeable
Solar	Photovoltaic	(A) Solar Cells (B) Photoemmission
	Thermionics	
	Regenerative Fuel Cell	
	Dynamic Machinery	(A) Stirling Cycle (B) Closed Rankine Cycle
Nuclear	Thermionic	
	Thermoelectric	
	Regenerative Fuel Cell	
	Dynamic Machinery	(A) Closed Rankine Cycle

The devices just discussed are categorized as static type generators, since no moving parts are required. For this reason, they look very attractive from a reliability point of view.

Probably of more interest in this meeting, however, are the dynamic type converters, which do use moving parts, will have bearings, and will require lubrication.

The dynamic systems can utilize any of the three main energy sources discussed earlier. The upper portion of Figure 2 gives a block diagram of a chemical dynamic power system. The fuel is burned in a combustion chamber to generate hot gases which drive a turbine. The turbine, in turn, drives a generator or hydraulic pump to extract the power. In this case, the hot gases are exhausted overboard. If a reciprocator is used in place of a turbine, either internal or external combustion can be utilized. If cryogenic fuels are used, there is the possibility of utilizing the fuel to provide a certain amount of environmental control or cooling prior to using it as a fuel in the power unit. Thus the penalty for the fuel volume and weight, which exists with chemical power units, can be partially charged to other subsystems and will result in a marked overall weight savings to a vehicle.

In the case of solar or nuclear systems, the Rankine closed cycle is the most popular. There can be several variations of the Rankine cycle, namely, single-loop, two-loop, and three-loop systems. On the lower half of Figure 2 a single-loop system is represented by the solid lines. Heat is applied from a solar collector or reactor to a boiler. The steam or gas generated passes through a turbine which drives the alternator. The steam is then condensed in a radiator, after which the fluid is pumped back through the boiler. The dashed lines indicate the addition of a second loop where a fluid is used to cool the reactor. This fluid, after being heated by the reactor, is passed through the heat exchanger-boiler, where the second fluid is vaporized for use in the turbine loop. This vapor, after doing work in the turbine, is condensed in a radiator, thus making a two-loop system. A third loop can be added as depicted by the dotted lines. In this case, a heat exchanger is used in lieu of a radiator in the turbine loop to condense the vapors by use of a third fluid. The waste heat picked up by the third fluid is then carried to a radiator for dissipation to space. There are advantages and disadvantages of all three versions. Generally, however, a single-loop system is favored in a solar power unit and a two-loop is favored for a nuclear power unit.

There is one consideration, however, that is common in both the solar and nuclear systems. This is the desire to radiate at as high a temperature as is possible. The reason for this is that the amount of heat which can be radiated to space per unit area is proportional to the fourth power of the temperature of the radiating surface. Since the overall cycle efficiency of these systems is rather low, a large amount of waste heat must be dissipated, and thus the radiator becomes a major portion of the system weight and volume. To give an example of the effect that the radiator temperature has on radiator surface area, compare a 300 kilowatt Rankine machine radiating at 700°F with one radiating at a temperature of 1200°F. At 700°F the radiator surface area would be approximately 1890 square feet as compared to 485 square feet when radiating at 1200°F. In other words, the radiator area can be reduced by nearly a factor of 4 by going to the higher temperature. It is for this reason that a great deal of emphasis has been placed on investigating such fluids as rubidium, potassium, sodium and lithium as the working fluids, to permit operation at very high cycle temperatures. This is especially true for the high power output machines (above 100 kilowatts).

Now, to examine the trends of requirements for power for various types of typical missions, and the types of power conversion systems which are expected to be most optimum to fulfill these forecasted requirements in the 1962 and 1966 time period. Figure 3 represents a synthesized forecast of the kilowatt to load requirements for various types of general missions in the 1962 time period, plotted against the duration that the load of power will be required:

(a) Boosters are expected to require power ranging from a few watts up to 70-80 kilowatts, but the duration that the power is needed is low, ranging from a few seconds up to a few minutes.

(b) Boost glide and unmanned air vehicles will require 10 to 100 kilowatts, with duration measured in hours.

(c) Earth satellites require power ranging from a few watts up to approximately 30 kilowatts, with durations ranging from hours to years.

(d) Lunar vehicles for the 1962 time period will probably not need power levels of over 5 kilowatts as the maximum. The duration that the power will be required will range from 1 day to 6 months.

(e) Interplanetary vehicles, if they exist in 1962, will probably utilize no more than 1 kilowatt of power. However, the minimum duration for the power system for such a vehicle will be 6 months on upward into years.

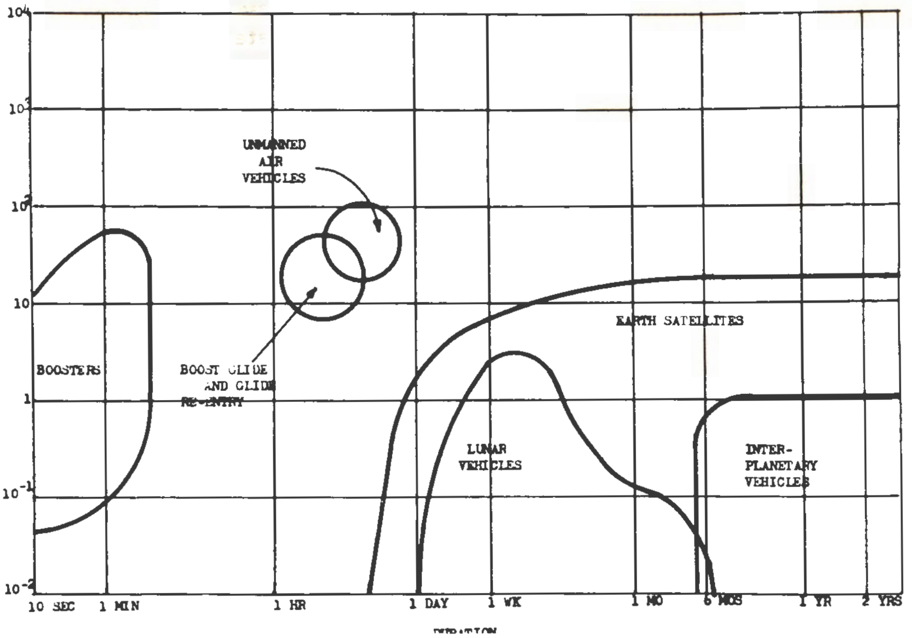


FIGURE 3. SYNTHESIS OF FORECASTS OF 1962 REQUIREMENTS FOR FLIGHT VEHICLE POWER

One should keep in mind when reviewing all of the remaining figures that the lines do not represent firm boundaries but should be looked at as bands since considerable overlap between areas will probably exist.

Figure 4 is the forecast for 1962 of the optimum application of energy conversion methods. From this we can see that the battery can fulfill the needs for power of 1 kilowatt for 1-minute duration to 100 watts for 1-day duration. The chemical dynamic systems will provide the power for systems requiring up to 100 kilowatts for periods of 1 day to 1 week. You should note that the cryogenic type system is expected to fulfill the 1-week requirement. The fuel cell will also compete for durations

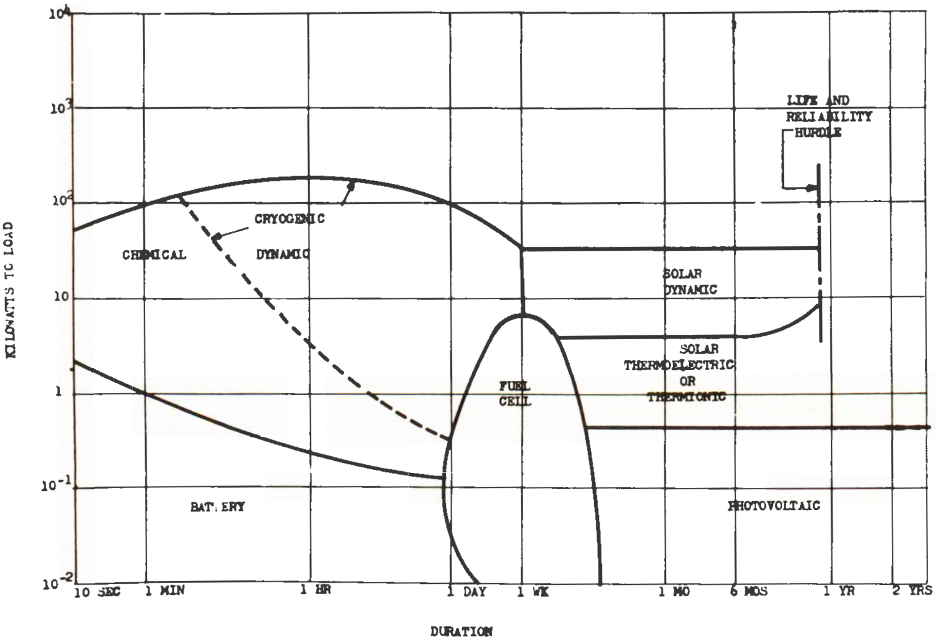


FIGURE 4. SYNTHESIS OF FORECASTS OF 1962 AREAS OF OPTIMUM APPLICATION OF ENERGY CONVERSION METHODS

of 1 day to a couple of weeks for power levels of about 7 to 8 kilowatts. For the long duration missions extending into years, the photovoltaic systems have been and will continue to be favored for power levels up to from 500 to 600 watts, with solar thermionic systems expected to be the most optimum for power levels of from 500 watts up to 5 to 6 kilowatts. Above this level, up to about 30 kilowatts, the solar dynamic systems will be most competitive. It should be noted that the dynamic systems are considered to have a major life and reliability hurdle at about the 1-year level.

Figure 5 is an overlay of Figures 3 and 4 to permit the formation of a mental picture of which power systems will fit the various types of projected missions. The solid lines represent the mission power requirements of Figure 3, and the dashed lines represent the conversion methods of Figure 4. As can be seen, the battery and chemical dynamic systems of the hydrazene type can fulfill the requirements for boosters. The cryogenic chemical dynamic systems will dominate for the unmanned air vehicles and boost glide and glide re-entry type vehicles. Fuel cells, thermionics, and photovoltaics will be the competing power systems for lunar vehicles, depending on the specific power level and the length of mission required. The earth satellites, again depending on the specific power requirement and duration, will be able to use fuel cells, photovoltaics, solar thermionics, or solar dynamic type systems. The power requirements for the early projected interplanetary vehicles will probably rely on photovoltaics or solar thermionics to fulfill the long duration projections shown.

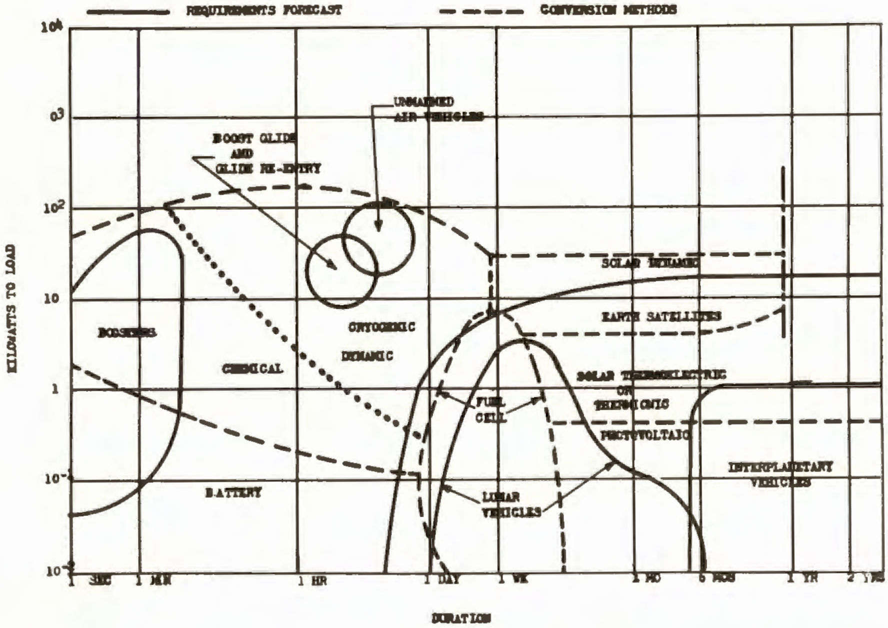


FIGURE 5. OVERLAY OF 1962 FORECAST REQUIREMENTS AND ENERGY CONVERSION METHODS

Projecting now into 1966, Figure 6 is a forecast of the power levels required for missions expected in that era. Generally the power levels are expected to increase markedly for each type mission, with new requirements added for the recoverable boosters and lunar and space station type missions. It is well to note that the power requirements for lunar and space stations and for interplanetary vehicles is expected to reach approximately 10 megawatts, and durations of two years or more will be desired.

Figure 7 is the forecast of the optimum conversion methods expected in 1966 for various power levels and duration requirements. This chart shows that the power level capability of cryogenic dynamic systems and fuel cells is expected to increase by an order of magnitude from the 1962 capability, and the large nuclear dynamic system now appears.

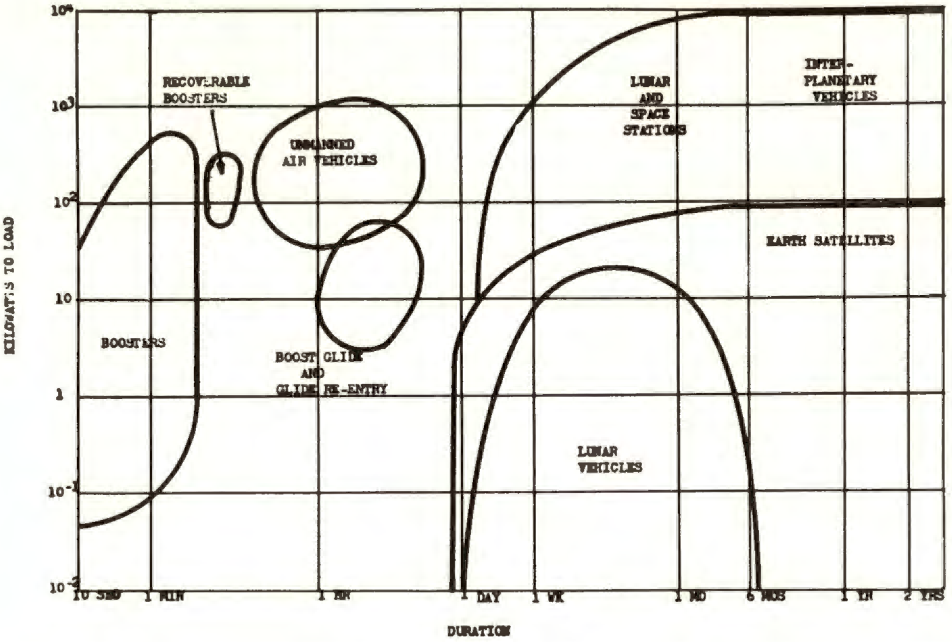


FIGURE 6. SYNTHESIS OF FORECASTS OF 1966 REQUIREMENTS FOR FLIGHT VEHICLE POWER

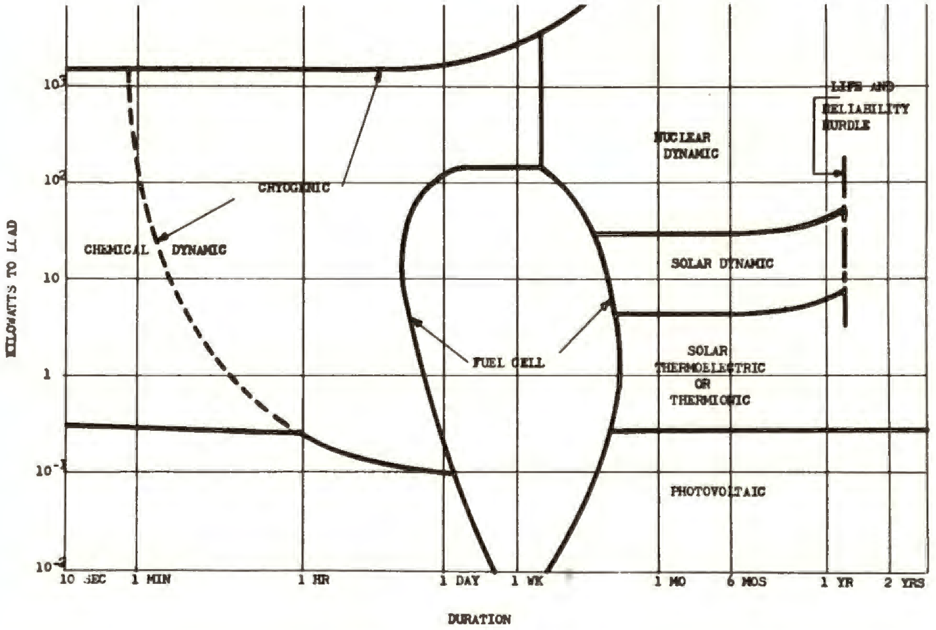


FIGURE 7. SYNTHESIS OF FORECASTS OF 1966 AREAS OF OPTIMUM APPLICATION OF ENERGY CONVERSION METHODS

Looking at Figure 8, an overlay of Figures 6 and 7, to examine the mission power requirements for 1966 against conversion method capability, one can see that the battery, hydrazene and cryogenic chemical power units are expected to fulfill the booster power requirements. The cryogenic dynamic power systems will also be optimum for recoverable boosters, unmanned air vehicles and the boost glide type vehicle, with the fuel cell as a possible contender in the boost glide type vehicle. The requirement for power for lunar vehicles and earth satelites, depending on specific vehicle power level requirements and duration requirements, will be met by fuel cells, photovoltaics, solar thermionics or solar dynamics. The fuel cell is expected to cover the requirements for missions of from 1 day to 6 months for power levels up to 20-30 kilowatts, with the missions of more than six months requiring photovoltaic systems, solor thermionic systems, or solar dynamic systems, depending on the power level. For those requirements over 30-40 kilowatts, the nuclear dynamic system will be required. Not shown on the chart, however, is the nuclear thermionic system, which has a possibility of being competitive in the 100-kilowatt level by 1966.

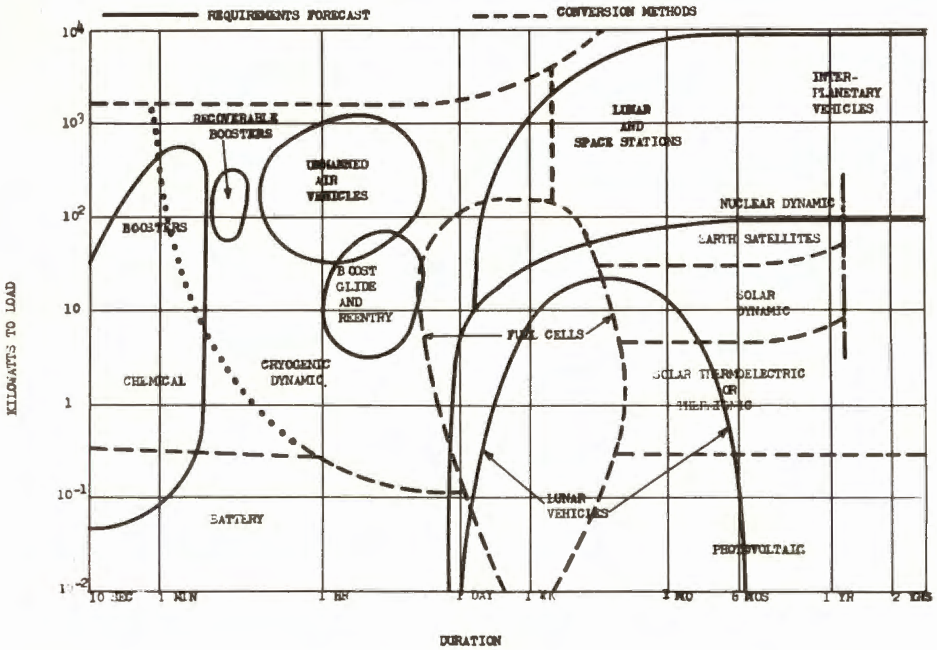


FIGURE 8. OVERLAY OF 1966 FORECAST REQUIREMENTS AND ENERGY CONVERSION METHODS

For lunar stations, space stations, and interplanetary vehicles, there is little doubt that the nuclear dynamic system will be the major contender in the 1966 time period. For periods later than this, the static type nuclear thermionic converter may play some role for this type of vehicle.

Finally, it should be stated that the success of flight vehicle power is one of the major factors toward the successful exploitation of space. The energy conversion methods that are expected to be employed to fulfill the projected requirements discussed, whether static or dynamic, are relatively new and unproven, and therefore considerable research and development will have to be done to completely optimize and sucessfully develop and apply any of the conversion methods discussed. The dynamic type systems, be they chemical, solar, or nuclear, are expected to play a major role in fulfilling the power requirements of the future. We do, however, have the major hurdle of reliability and durability to conquer.

While the bearing and lubrication problem is not the only one to be solved, it is a major obstacle to overcome before the dynamic systems can be considered completely trustworthy. The role of the lubrication industry in solving this problem is an important one toward the success of flight vehicle power and the ultimate full exploitation of space.