FLIGHT VEHICLE POWER

Donald P. Mortel

Directorate of Aeromechanics, ASD

In my discussion I shall first define flight vehicle power, including a description of the methods to be employed for energy conversion. Subsequently, 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. Lastly, I will briefly present some of the power system materials problems that result from the space environment and the respective system operating features.

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

The power area is relatively broad, encompassing energy source technology; that is, 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.

I will, however, deal only 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 extract from the prime propulsion system, mechanically or otherwise, 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 will no longer be adequate; for in many cases, at least 10,000 hours of maintenance free, continuous, and 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 systematically explained in figure 1.

Figure 2 gives the schematic diagrams for some of the static conversion devices being considered:

a. Photovoltaic converter. A typical converter is a silicon solar cell. A material such as boron is diffused into one surface of the silicon 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 connected this movement of electrons does useful work.

b. The thermionic converter consists of two metal plates of different work functions. The cathode is a high work function material and the anode a low work function material. Heat energy is applied to the cathode, which causes electrons to boil off. These electrons collect 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. Typical heat source and heat sink temperatures are 3000°F at the source and 1200°F at the sink.

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 which is used as a power generator instead of a temperature measuring device. In this case, heat 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 junction, thus generating an electric current when the circuit is completed.

The devices just reviewed are categorized as static type generators. For this reason, they look very attractive from a reliability point of view.

The dynamic systems can utilize any of the three main energy sources discussed earlier, that is, nuclear, solar or chemical. The upper portion of figure 3 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 using the fuel to provide a certain amount of environmental control or cooling prior to its entrance as a fuel into 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 saving of weight.

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 3 a single loop system is represented by the solid lines. Heat is applied from a solar collector or reactor to a boiler where boiling of a working fluid occurs. Vapor thus generated passes through a turbine which drives the alternator. The vapor is then condensed to a fluid in a radiator, after which the fluid is pumped again 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. All three versions have their advantages and disadvantages. Generally, however, a single loop system is favored in a solar power unit and a multiple loop system is favored in a nuclear power unit.

There is one consideration, however, that is common in both the solar and nuclear systems, radiation at as high a temperature as is possible. The reason: 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 therefore the radiator becomes a major part of the system weight and volume. This is particularly applicable to the large nuclear system. 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. Hence, the radiator area could 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 and yet retain reasonable cycle thermal efficiencies. This is especially true for the high power output machines (above 100 kilowatts).

Now, let us 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 4 represents a synthesized forecast of the electrical load requirements for various types of general missions in the 1962 time period, plotted against the duration that the load or power will be required. 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 there is considerable overlap between areas.

a. Boosters are expected to require powers ranging from a few watts up to 70-80 kilowatts, but the duration for which 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 by the 1962 period will probably not need over 5 kilowatts of power as the maximum. The time duration will range from 1 day to 6 months.

e. Interplanetary vehicles, if they exist in the 1962 to 1966 period, will probably need no more than 1 kilowatt of power. However, the minimum duration for the power system will be 6 months on upward into years.

Figure 5 is the forecast for 1962 of the optimum application of energy conversion methods when considering minimum system weight. 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 of 1 day to a couple of weeks for power levels of about 7-8 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 6 is an overlay of figures 4 and 5 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 4 and the dashed lines represent the conversion methods of figure 5. It is evident that 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.

Looking into the 1966 and later periods, figure 7 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 are expected to reach approximately 10 megawatts, and durations of two years or more.

Figure 8 is the forecast of the optimum conversion methods expected in the 1966 period 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.

Looking at figure 9, which is an overlay of figures 7 and 8, and examining 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 satellites, 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, solar thermionic systems, or solar dynamic systems, depending on the power level. For those requirements over 30 to 40 kilowatts, the nuclear dynamic system will be required. The nuclear thermionic system, which has a possibility of being competitive in the 100 kilowatt level by 1966 is not shown on the chart.

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.

As the last part of my discussion, I would like to touch briefly on materials problem areas on some of the power units that require significant applied research attention. Specifically, these include the nuclear and solar dynamic conversion systems, the thermionic converter, the fuel cell and finally rechargeable batteries.

Aside from the inherent reliability problems of devices with moving parts, the nuclear and solar dynamic systems are today characterized by undesirably large components. This is a result of low system efficiencies and low operating temperatures. For the solar powered system, the solar energy collector is the largest component and reduction in collector diameter is essential. Small collectors are desirable: (a) to minimize storage volume in the payload package during launch, (b) to make practical the fabrication of optically-accurate mirrored surfaces, (c) to reduce the aerodynamic drag on space vehicles in low altitude orbits and (d) to minimize the probability of micrometeoritic damage to the collector-mirror surface. An increase in the overall system efficiency is the obvious answer to collector size reduction; however, this is almost inevitably achieved at the expense of higher system operating temperatures.

For the large nuclear powered dynamic system, the radiator system is of major concern. It is predominantly the largest, and heaviest, single component. This characteristic, coupled with the fact that it is a fluid-carrying component, makes the entire system extremely vulnerable to failure by micrometeoriteic damage. Therefore every attempt should be made to radiate waste energy at as high a temperature as possible so that the radiator size may be drastically reduced. Again, the high radiator temperature reflects correspondingly higher temperatures upstream, in the system, in order to maintain reasonable system efficiencies. The trend toward higher system operating temperatures, eventually forces the designer to substitute water and mercury, the more conventional Rankine cycle working fluids, with fluids such as the alkali metals. (That is, rubidium, potassium, sodium etc.) However, the combination of these high-chemically reactive fluids, and high operating temperatures introduces severe problems of thermal stress, corrosion, mass transport phenomena of containment, and structural materials. Refractory materials appear to have promise but are relatively new and unproven.

Turning to some of the problems with the static methods of energy conversion, the first significant area is that of the thermionic converter. It operates at extremely high temperatures. Further, an easily ionized but highly chemically reactive gas, cesium, is used to neutralize space charge. Problems created by this chemical reactivity are: an undesirable rate of cathode material evaporation, high temperature hermetic seals, and with structural, joining, and containment materials. Corrosion problems are also caused by the cesium vapor.

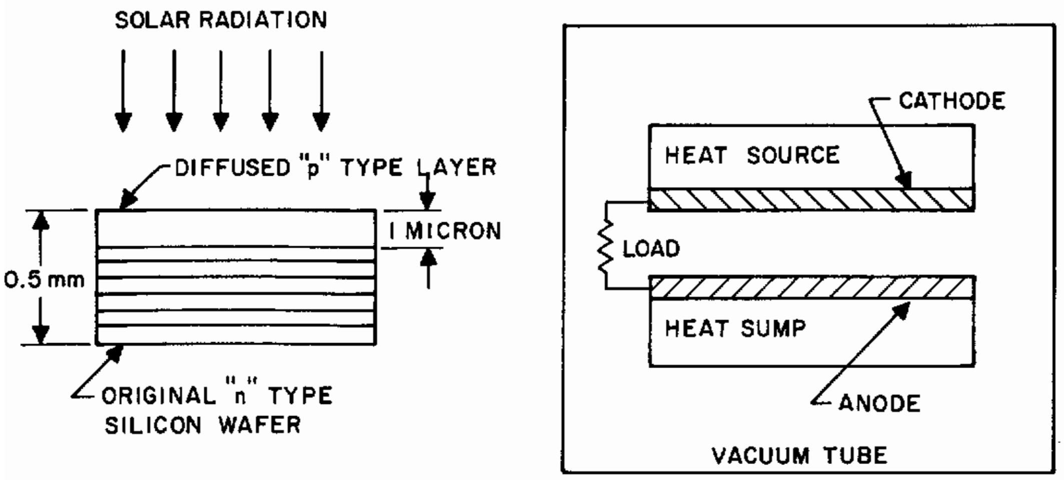
With respect to fuel cells, the most significant problem is that of obtaining suitable electrode materials to prevent "flooding." More specifically such "flooding" prevents the cell electrolyte from entering the porous electrodes, thus stopping the necessary chemical reaction from occurring.

The last power unit that I would like to cover is the rechargeable storage battery, those batteries used as energy storage devices for static solar power systems to provide continued electrical power to the satellite during "orbit-shadow." Nickel-cadmium batteries are the most widely used for this purpose at the present time; however, the problems of separator deterioration, temperature sensitivity and most important, low theoretical efficiency, are sufficient inducement to lean toward other types. For example, a watt-hrs/lb increase of four to one is theoretically possible with the silver-zinc battery as compared with the nickel-cadmium. The problem, however, with the silver-zinc battery is that silver migrates from the positive to negative electrodes. Theoretically, twelve to one increase in watt-hrs/lb is possible with fused salts, such as the Alkali-Aklaline Oxides. However, severe corrosion of containment materials is still a problem.

In conclusion, the energy conversion methods that are expected to be employed to fulfill projected mission requirements, whether static or dynamic, are relatively new and unproven. Serious problems face the system designers in attaining high power density and compact devices that are compatible with the space environment. These problems are only challenges. As in the past, research will bring to light not only many new materials but many new material systems as well. Problems are not just problems; they are challenges to be overcome.

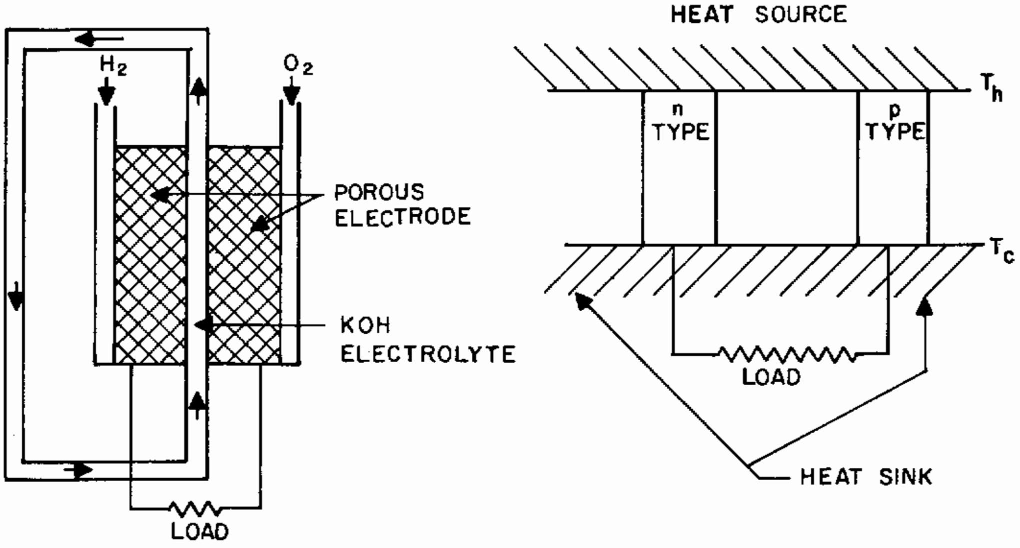
ENERGY SOURCE	CONVERSION DEVICE	VARIATIONS
CHEMICAL	DYNAMIC POWER UNITS	(A) OPEN CYCLE (B) POSITIVE DISPLACEMENT DEVICES (C) COMBINATION OPEN AND CLOSED CYCLE
	FUEL CELLS	(A) PRIMARY (B) REGENERATIVE
	BATTERIES	(A) PRIMARY (B) RECHARGEABLE
SOLAR	PHOTOVOLTAIC	(A) SOLAR CELLS (B) PHOTOEMISSION
	THERMIONICS	
	REGENERATIVE FUEL CELL	
	DYNAMIC MACHINERY	(A) STIRLING CYCLE (B) CLOSED RANKINE CYCLE
NUCLEAR	THERMIONIC	
	THERMOELECTRIC	
	REGENERATIVE FUEL CELL	
	DYNAMIC MACHINERY	(A) CLOSED RANKINE CYCLE

Figure 1.



(a) SILICON SOLAR CELL

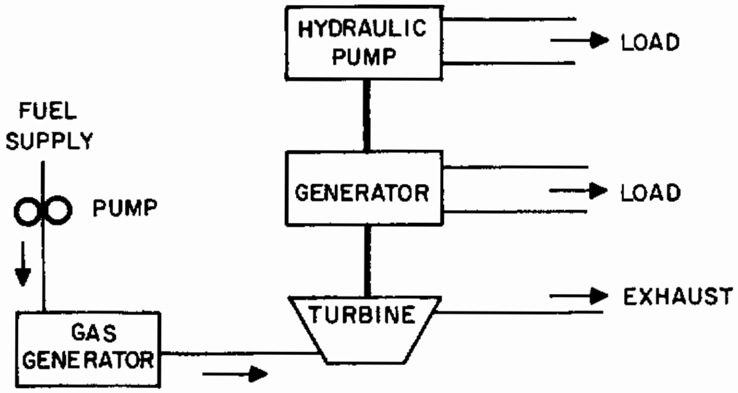
(b) THERMIONIC CONVERTER



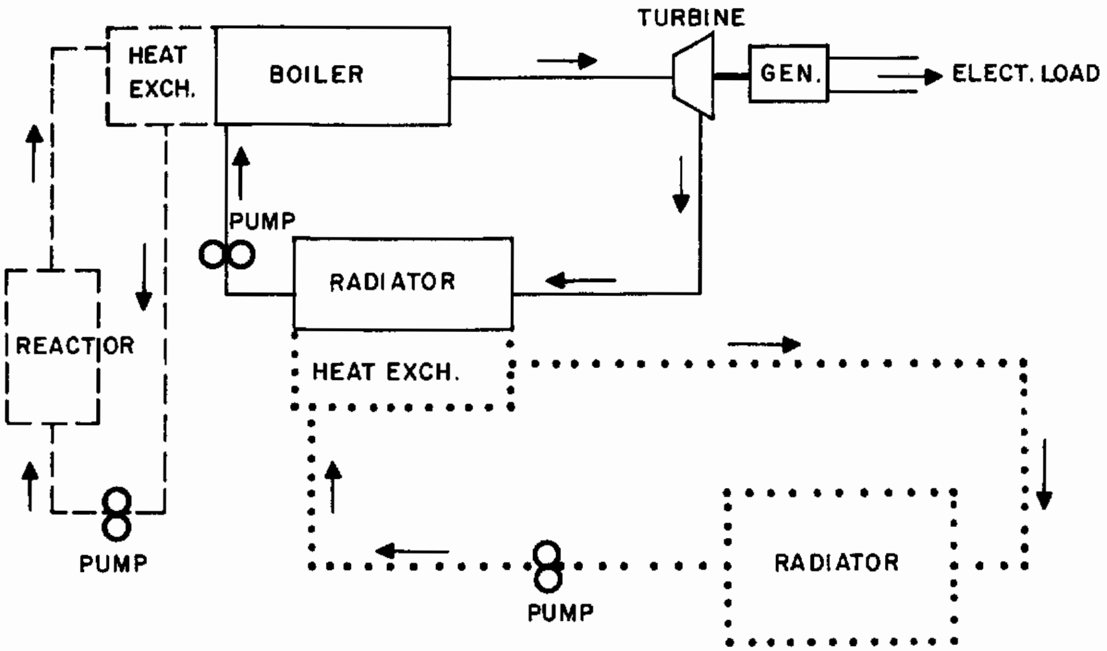
(c) FUEL CELL

(d) THERMOELECTRIC CONVERTER

Figure 2.



CHEMICAL POWER UNIT



SOLAR OR NUCLEAR DYNAMIC POWER UNIT

Figure 3.

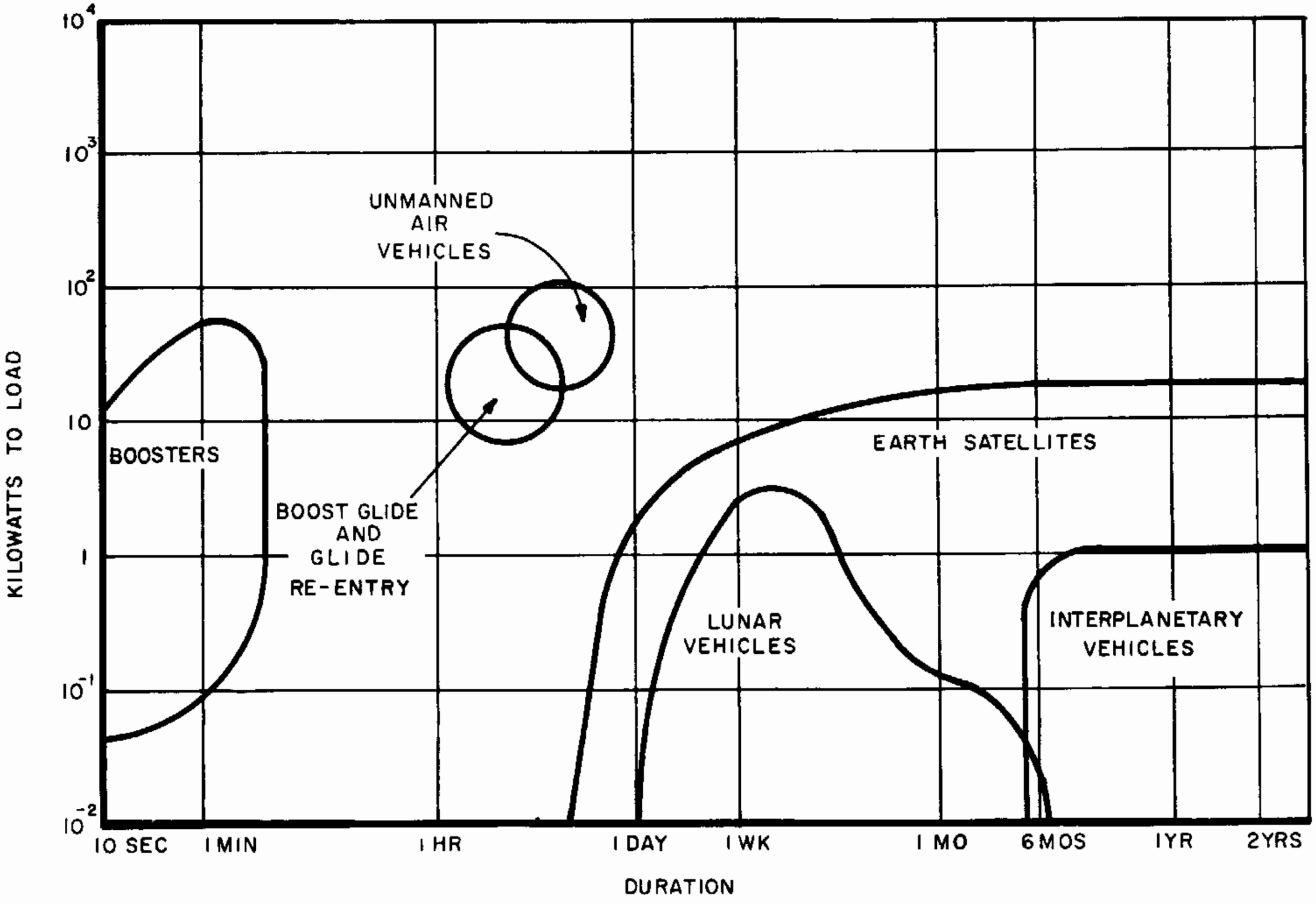


Figure 4. Synthesis of Forecasts of 1962 Requirements for Flight Vehicle Power

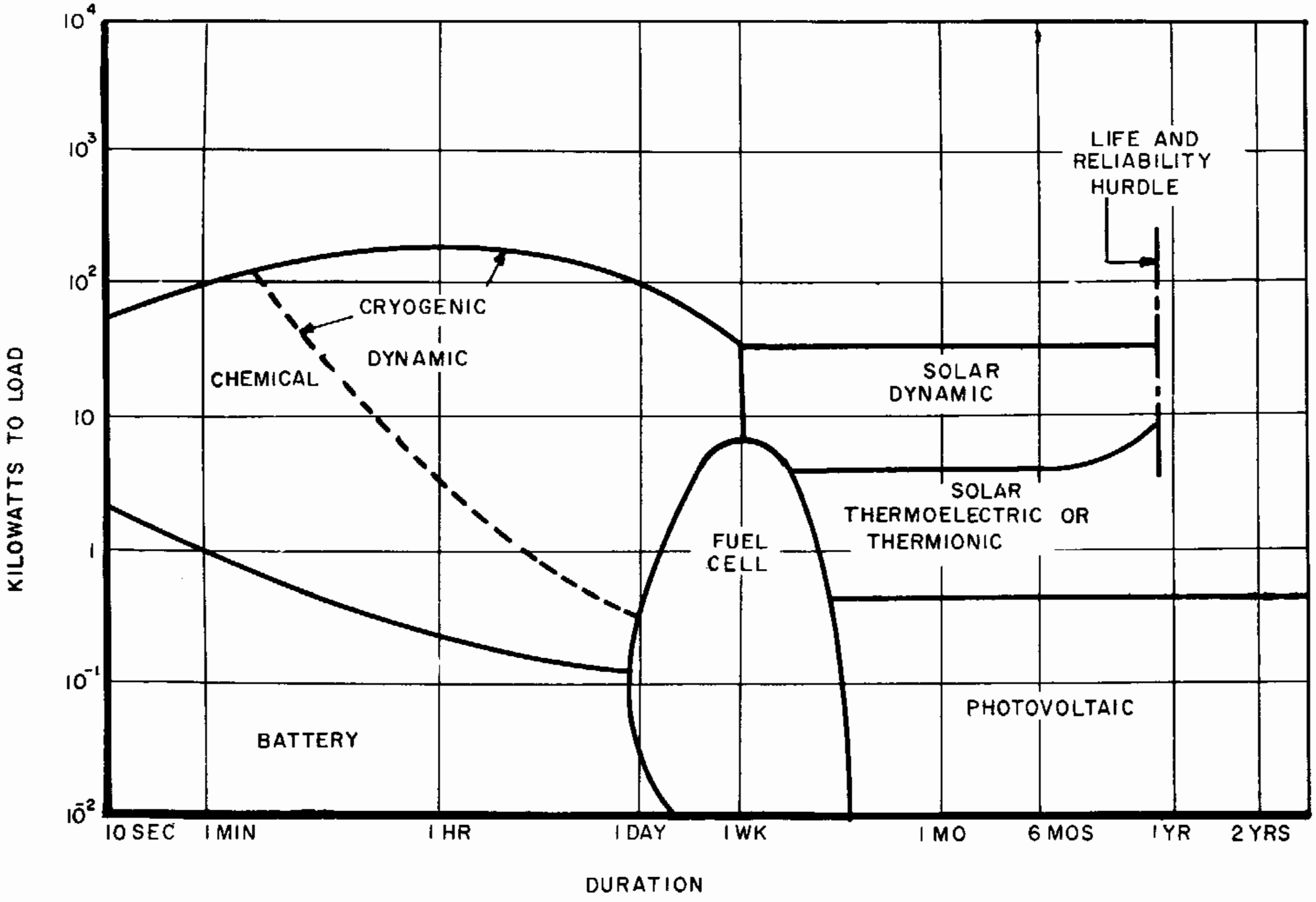


Figure 5. Synthesis of Forecasts of 1962 Areas of Optimum Application of Energy Conversion Methods

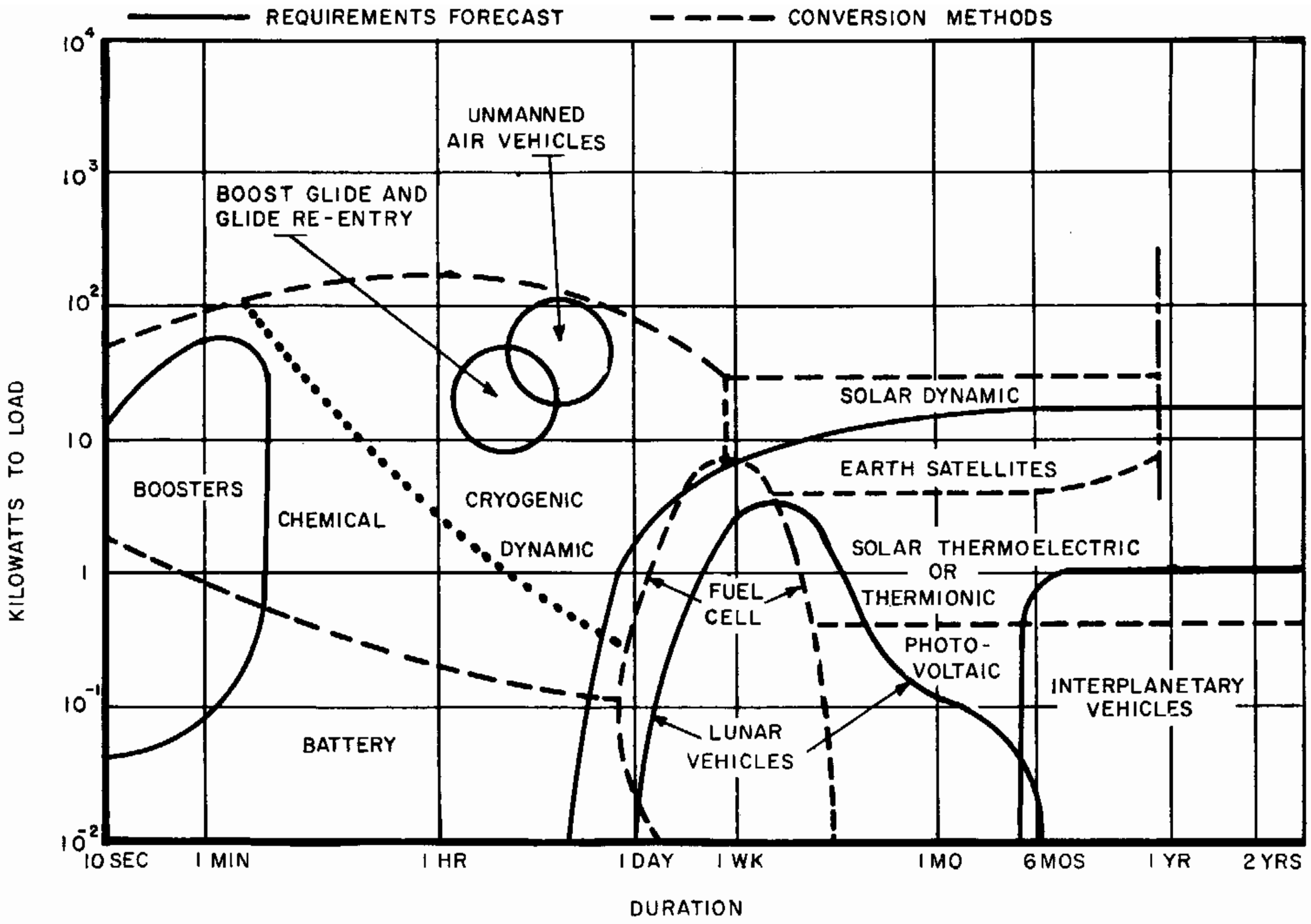


Figure 6. Overlay of 1962 Forecast Requirements and Energy Conversion Methods

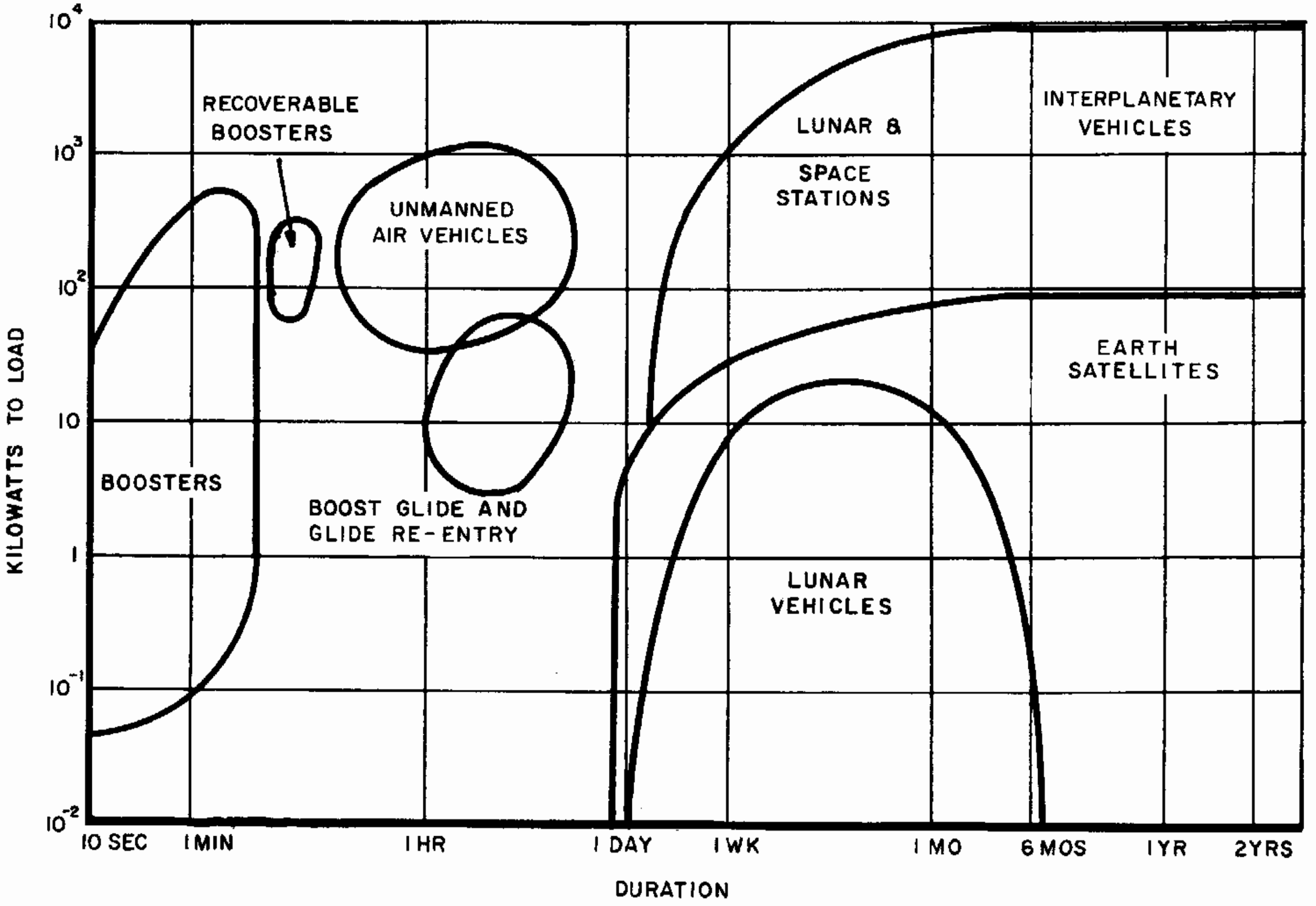


Figure 7. Synthesis of Forecasts of 1966 Requirements for Flight Vehicle Power

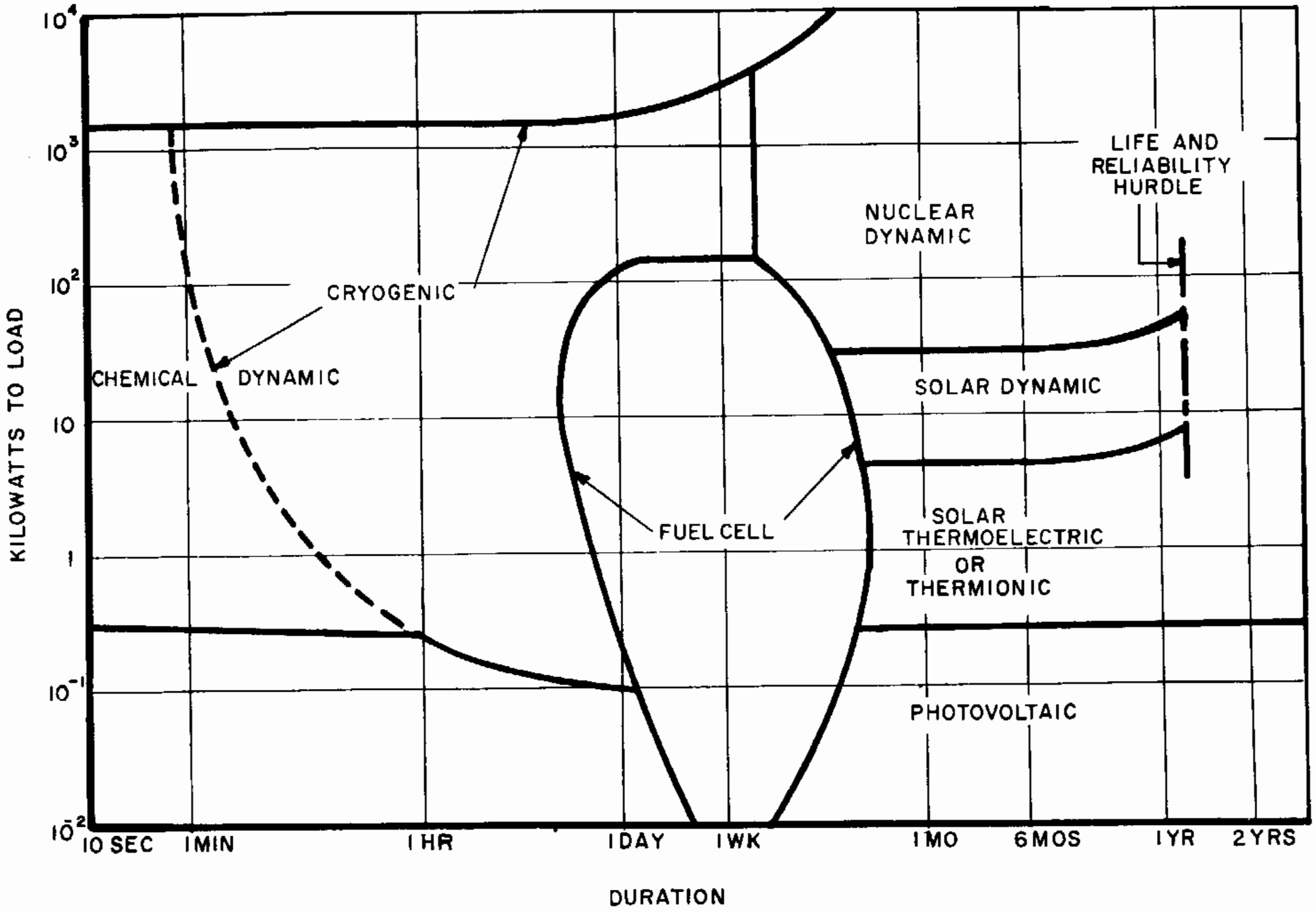


Figure 8. Synthesis of Forecasts of 1966 Areas of Optimum Application of Energy Conversion Methods

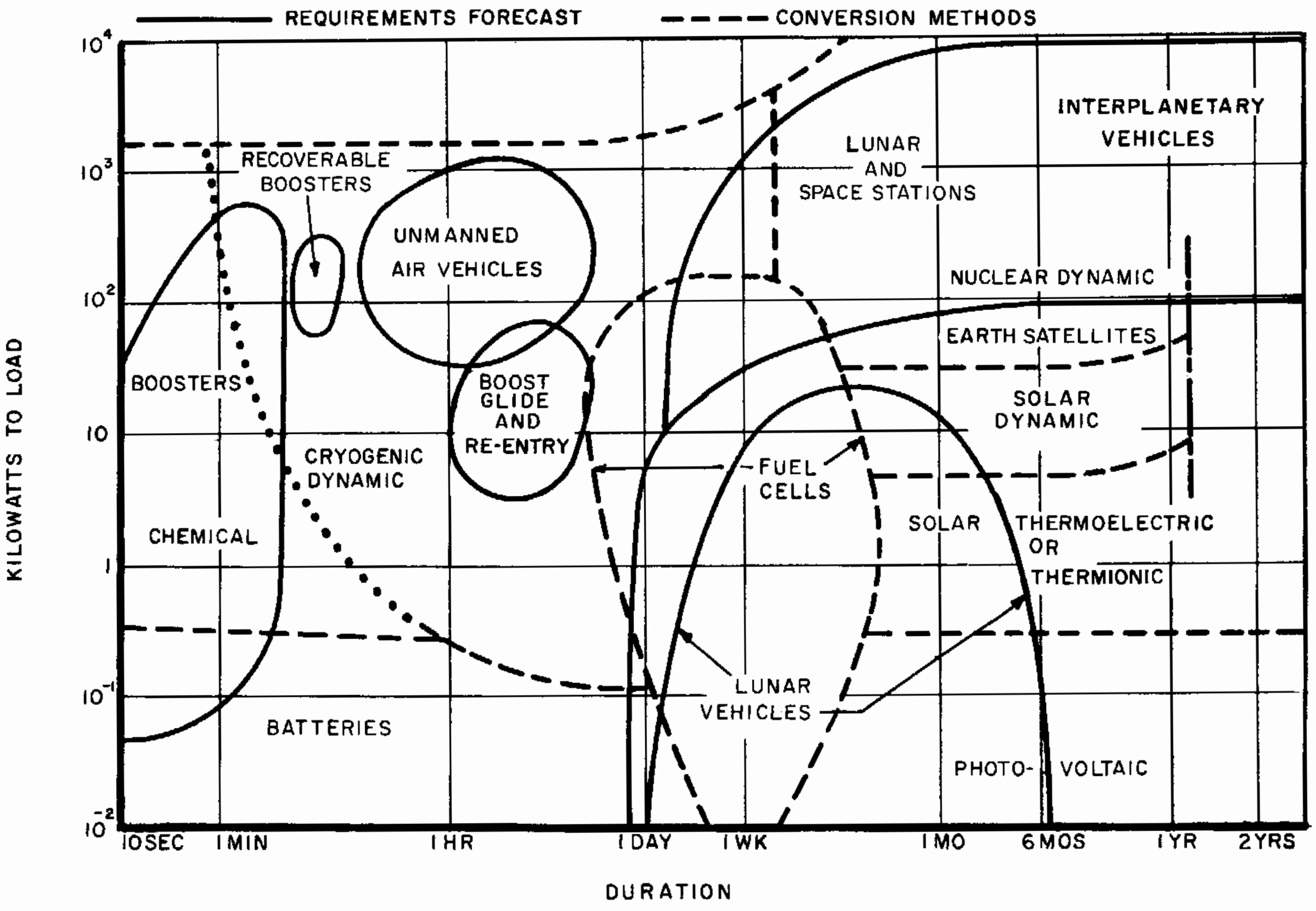


Figure 9. Overlay of 1962 Forecast Requirements and Energy Conversion Methods