POWER SYSTEMS TAILORED FOR ASTRONAUTICAL APPLICATIONS

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Abstract

This report describes the performance criteria (efficiency, temperature and weight) of solar power systems and discusses effects of selective coatings on solar power systems. It discusses some of the requirements of flight vehicle power for flight vehicles, and enumerates specific power systems capable of meeting these overall requirements. It also shows how solar power systems fit into these requirements. The author has condensed solar power system optimization studies conducted by Mr. Leon Schipper of WADD and the AiResearch Division of the Garrett Corporation to graphically illustrate the need of high temperatures for minimum dynamic solar energy conversion system weight. Curves showing the applicability of spectrally selective coatings for enhancing high temperature operation are also presented.

Introduction

During the past few years this nation has been unavoidably placed in a race for space domination. One of the chief goals in this race is putting man into space. How can our current rocket technology and booster capability be utilized to successfully place a man in orbit? Can an earth environment be created in an orbiting vehicle to sustain human life in that vehicle? Is it possible to recover the orbiting vehicle for a safe return of the human payload to earth? These are the most formidable questions facing us as we pioneer the vistas of space and interplanetary travel with manned vehicles. Although we are rapidly uncovering answers to all of these questions through advanced technology, this paper will concern itself with questions related to flight vehicle power and the requirements for flight vehicle power. In addition, the devices used to meet these requirements, and the effect of temperature vs. efficiency on these devices will be discussed.

System Requirements

Flight vehicle power is defined as all power necessary to operate any vehicle in flight excluding the primary propulsion force, but includes the power required for electric propulsion and extraterrestrial sites. Flight vehicle power systems are composed of three basic sub-systems; the energy source, the energy converter and the transmission sub-system. The energy source can be considered as any form of energy that can be harnessed, and converted into useful flight vehicle power. The energy converter is a sub-system that harnesses or converts the energy source to a form of useful power required by a particular vehicle and the transmission sub-system conditions and transmits the power to the point in a vehicle where a specific function is to be performed. In considering these definitions, three basic energy sources for flight vehicle power systems are available, namely, chemical, nuclear and solar.

Having available these energy sources, the next logical consideration is that of the power domain in which these sources will be used within the next few years. Figure 1 shows the results of such a consideration. Represented in this figure are the predicted power requirements of several types of aerospace missions through 1973. It should be noted that five broad spectra of future vehicle power requirements are depicted in this figure.

Boost glide vehicles, pictured in the upper left-hand corner, are characterized by their requirements for reasonably large amounts of power during periods of boost, ascent and a descent. It is during these periods that aerodynamic vehicle control is used; as a consequence, requirements for hydraulic and/or pneumatic power predominate. At other times during a typical mission profile, power requirements will be largely electrical and will be of a lesser magnitude than the values shown on the curve. It is anticipated that durations of early versions of boost glide vehicles may be of the order of a few hours to a day or two. Chemically fueled power systems are expected to meet these short duration power requirements; however, there is an indication that durations as long as 30 days are possible. These longer durations will, perhaps, require power sources other than chemically fueled systems.

Power requirements for electric thrust devices conceivably covers three or four different types of mission requirements; large satellite orientation, limited orbital control, and major orbit transfer and interplanetary space travel. It is estimated that the power requirements for satellite orientation and orbital control will be from 2 to 30 KW whereas true electric propulsion dictates larger power extending upward from 50 KW to megawatts.

Short duration satellites, the gradually sloping curve in the lower right-hand portion of figure 1, cover a number of important requirements for relatively small amounts of power for intermediate durations extending possibly as long as a few days to two weeks. The following are typical of the mission requirements of short duration satellites:

a. limited life and early recovery
b. lunar probes, unmanned
c. emergency power
d. power during launch, maneuvering into orbit, orbit transfer and descent
e. intermittent power

As shown in figure 1, chemically fueled power systems (e.g. rocket propellants, fuel cells, batteries) can be used for these short duration satellites.

The last two curves in figure 1, Satellite Power for Reconnaissance and Communication and Weather Missions, are based on current systems developments up to 1965; beyond 1965 they represent trend estimates only. As shown, the power requirements for reconnaissance type satellites are expected to be of greater magnitude than those of communication and weather type satellites within the next few years.

Not shown in figure 1 are the power requirements for extra-terrestrial sites. Their particular power requirements are difficult to define at this time. Indications are that the upper power limit for such devices can be expected to be quite high, megawatts, to provide power for production of food, and power the mission equipment. For the most part, power systems for these sites will utilize the power system technology developed for flight vehicles with the additional consideration that, ultimately, the system might be partially assembled at the site and a degree of maintenance permitted for those which are manned.

Retrospectively, figure 1, taken as a whole, exhibits the fact that we can expect vehicular power requirements from a few kilowatts upward to megawatts within the next decade. Also, there will be a variety of aerospace vehicles within this time period having a variety of power systems (i.e. nuclear, solar or chemical) capable of meeting mission and power requirements of the particular vehicles and missions they are associated with.

A forecast of the kilowatts to load requirements for various types of general aerospace missions for the 1962 time period plotted against the duration that the load or power will be required is shown in figure 2. Boosters are expected to require power within a range of a few watts to 70-80 kilowatts with a duration between a few seconds to a few minutes. Other relatively short duration missions are fulfilled by boost glide and unmanned air vehicles. These vehicles will require 10 to 100 kilowatts with a mission duration measured in hours.

Represented in the right-hand corner of the figure are three other 1962 missions and vehicles--earth satellites, lunar vehicles and interplanetary vehicles. All of these missions are characterized by their long durations ranging from hours to years. Power requirements for the missions range from a few watts up to 30 kilowatts. Lunar vehicles for 1962 will not require more than 5 kilowatts as the maximum. It is most likely that these early vehicles will be unmanned lunar probes. If interplanetary vehicles are developed by 1962, they will probably utilize no more than 1 kilowatt of power for tracking, communication purposes and a degree of vehicle orientation. Like the lunar vehicles, they will probably be unmanned probes.

Conversion Devices

Figure 3 goes a step further in showing the requirements for flight vehicle power. With this figure an attempt is made to illustrate specific power systems for mission duration and power to load requirements. Without investigating the studies used in determining the curves shown, let us consider the figures of merit included in it.

The paramount figure of merit is system weight. Although not shown directly, it, nevertheless, appears indirectly as a deciding factor for the selection of a system for a given set of requirements. It is evidenced indirectly in the chemical consuming systems (on the left of the figure) being depicted as fulfilling the requirements for missions with durations up to one week. Since these devices consume their own fuel, which must be carried aboard as additional system weight, their duration is limited to the volume and weight of fuel that can be tolerated for a given vehicle based on the booster rocket capability when speaking in terms of satellite power sources. As our booster capability improves, however, it is possible for the chemical consuming devices to be optimum for longer durations, one week to a month.

Figure 3 also reflects an integration of a number of other factors such as availability or technical status, reliability, installation problems, cost and safety hazards. The integration of these factors is evident. For instance, even though greater booster capability tends to increase the duration capability of chemical consuming devices, the complexity or reliability factors for extra large fuel tankage systems tends to cancel the former. As another example, nuclear dynamic and solar dynamic systems are competitive weightwise up to about 50 KW, but the reliability and installation problems of packaging and unfolding solar concentrators for solar dynamic systems limits their usefulness to about 30 KW. In view of these factors, the boundaries laid out in figure 3 should not be regarded as being rigid but rather as being elastic and subject to considerable stretching if specific circumstances demand it. Further, the power levels (kilowatts to load) for the figure may be subject to considerable alteration as the sophistication of vehicle and power sub-system detail design accounts for factors and interreactions not possible to account for in the forecast.

Can the conversion methods forecasted for 1962 meet the mission requirements of this time period? This question is answered in figure 4 which is an overlay of the two previous figures-- conversion methods and missions in terms of duration and power to load. It can be seen from this figure that all 1962 mission requirements can be met or fulfilled with the optimum conversion devices of this period.

It can also be seen that there is more than one optimum conversion device suitable for meeting a given set of mission requirements. As an example, earth satellite power requirements can be accomplished with five different conversion methods: fuel cells, photovoltaic, thermoelectric, thermionic converters and solar dynamic conversion systems. Before establishing the operational temperature criteria for a typical flight vehicle power system, let us briefly consider, in a simplified manner, the principle of operation of the systems shown in figure 3.

Operation Principles for Conversion Devices

The first group of devices to be considered are those called static conversion devices; a name implying that the device does not require moving parts to function. Static conversion devices are depicted in the lower right-hand corner of figure 3 as the intermediate to long duration range but have relatively low power to load capability. (An exception being possibly thermionics). Specifically, they include photovoltaic, thermionic, thermoelectric and fuel cell energy converters. Schematic diagrams of these systems are shown in figure 5.

A photovoltaic cell is a device which, when subjected to incident light energy of the proper wave length, generates a voltage difference and current proportional to the illumination level. This property of the cell is due to chemically bonded "p" and "n" type layers from which the cell is fabricated and their associated electrostatic fields.

The thermionic converter consists of two metal plates. Space between these plates is evacuated and heat from a nuclear or solar energy source is applied to one of them, the cathode, causing electrons to be boiled-off. The electrons then move across the evacuated space and are collected on the opposite plate or anode. This thermal emission process produces an electrical potential between the two plates and with a suitable load circuit, the converter will produce electric power.

Another method of converting heat or thermal energy into useful electricity is by the use of thermoelectric devices. Electrical current is produced in this device by the thermocouple effect wherein two dissimilar metals are bonded together and one junction is heated. An electric potential is created which, with a suitable load circuit, produces a flow of electricity.

The fuel cell is a continuous feed electrochemical device for converting chemical energy directly into electrical energy. It consists of an anode at which oxidation takes place, an electrolyte, and a cathode at which an oxidizing agent is collected and the external circuit. By continuously feeding the fuels through the electrodes, an electric potential is produced which can supply power to a load with the suitable circuitry. Shown in figure 5 is a high pressure type fuel cell. There are also low pressure and ion membrane types that operate on the same basic principle as described.

Other chemical consuming devices pictured in figure 3 are dynamic conversion systems, that is, systems in which a chemical-fuel and oxidizer or monopropellant, are combined or decomposed in a decomposition chamber, and their products of reaction are used to drive a prime mover. The prime mover used most frequently is a high speed turbine, coupled with an alternator to produce electric power.

Closed cycle dynamic conversion systems can employ nuclear or solar heat sources. These systems differ from the chemical consuming systems in that they are closed loop systems--the working fluid is continuously circulated in the system rather than discharged. Such a system is shown in figure 6. The working fluid, such as a liquid metal, is vaporized by either concentrated solar or nuclear thermal energy. It then passes through the other components in the system completing the closed-loop Rankine cycle.

Temperature Criteria for Solar Dynamic Conversion System

Having established the power range requirements for flight vehicle power and having defined some of the conceptual devices for supplying this power, let us now consider the temperature criteria of a typical system--a dynamic conversion solar power system. As stated before, system weight is of paramount importance, consequently; the variation of system weight with cycle temperature and cycle efficiency is of primary interest. The following analysis shows this variation.

For the system in question, its total weight can be represented as the sum of individual component weights or $W_T = W_{HR} + W_C + W_R$ (1) where W_C is the weight of the collector; W_{HR} is the weight of the heat receiver; and W_R is the weight of the condenser-radiator. The weight of other components (e.g. turbine, alternator, pump, controls, etc.) are not included as their relative contribution to system total weight is small and will remain constant for varying cycle conditions. Through division of equation (1) by power to load (KW_o), the total system weight in pounds per KW_o can be found. Thus, $W_T/KW_o = W_C/KW_o + \frac{W_{HR}}{KW_o} + \frac{W_R}{KW_o}$ (2) or in terms of other parameters:

$$W_T/KW_o = \frac{1}{\eta_c}\left\{\frac{K_c(1+f)}{\eta_h \eta_s \eta_r \eta_a S} + t_d/\lambda\left[1+\left(\frac{1-\eta_h}{\eta_h}\right)\left(\frac{1+f}{f}\right)\right] + \Phi_B + (1-\eta_c)\Phi_R\right\} \quad (3)$$

The parameters in this equation are defined as follows:

1. η_c is the cycle efficiency and is expressed by the relationship

$$\eta_c = \gamma\,\eta_{CARNOT} = \gamma\left(\frac{T_{MAX} - T_{MIN}}{T_{MAX}}\right) \quad (4)$$

Letting $T_{MAX}/T_{MIN} = \beta$ equation (4) becomes $\eta_c = \gamma(1 - 1/\beta)$ (5) The term γ in this equation is the deviation of the cycle being considered from the ideal Carnot cycle. Although $\gamma = f(\beta)$, it has been assumed to equal 0.35 for the studies presented herein.

2. K_c is collector specific weight in pounds per square foot of collector projected area. This parameter is assumed to be constant and equal to 0.2 lbs/ft^2.

3. f is the ratio of dark time or shadow period to sunlight time for a given orbit and time of year. A value of 0.5 has been chosen.

4. S is the incident solar flux at the collector surface. It is equal to 0.13 KW/ft^2 in earth space.

5. t_d is the length of the shadow period in hours for a given orbit. A value of 0.5 hr. has been chosen.

6. Φ_B is the specific weight in pounds per KW_o of the heat receiver tubing, insulation etc. A value of 0.5 lbs/KW_o has been chosen.

The other parameters in equation (3) are temperature dependant and are further defined by the following equations:

$$\eta_h \eta_s \eta_a \eta_r = \eta_{\text{COLLECTION}} = \alpha_B \left[\eta_r \eta_s - (1+f)\sigma \left(A_B/A_c \right) T_B^4 / S\gamma \right] \quad (6)$$

$$\eta_h = 1 - f\left(\frac{1}{1 - A_B/A_c\, \sigma T_B^4 / \gamma \eta_r \eta_s S} - 1 \right) \quad (7) \qquad \Phi_R = \phi_R / \sigma \epsilon_R \left(T_{MAX}/\beta \right)^4 \quad (8)$$

The parameters in equations (6) through (8) are defined as follows:

1. α_B is the solar absorptivity of the boiler surface. For a cavity heat receiver this parameter approaches unity.

2. γ is the ratio of solar absorptivity to total emissivity of the boiler surface. This parameter is also unity for a cavity heat receiver.

3. η_r is the inherent specular reflectivity of the collector surface. It is assumed to be equal to 0.9 for the following analysis.

4. η_s is the shadow factor resulting from the heat receiver shadow on the collector and is assumed to be 0.998.

5. σ is the Stefan-Boltzman constant.

6. T_{MAX} is the maximum cycle temperature.

7. A_B/A_c is the ratio of the area of the cavity receiver opening to the projected collector area. This ratio is assumed to be 1/1000.

8. ϕ_R is the specific weight of the radiator in lbs/ft^2 including header and meteorite protection weight. This is taken to be 5 lbs/ft^2.

9. ϵ_R is the total emissivity of the radiator surface. It is assumed to be 0.8.

(The parametric values as stated are either indicative of the current state of the art, or are believed to be achievable through applied research and advanced technology. The optical parameters in items 1, 2 and 9 are dependant upon the temperature of bodies which they are associated with, but, for the sake of simplicity and illustration, hypothetical values independent of temperature were chosen.)

By substituting, rearranging, and simplifying equations one through eight, the following relationships exist for the specific weights of the collector, heat receiver and radiator:

$$W_c/KW_o = K_c (1+f) / \eta_c \alpha_B S \left(\eta_r \eta_s - (1+f) \sigma T_B^4 / 1000 S \gamma \right) \quad (9)$$

$$W_{HR}/KW_o = 1/\eta_c \left[t_d/\lambda \left\{ 1 - \left(1/\eta_h - 1 \right)\left(1/f + 1 \right) \right\} + \Phi_B \right] \quad (10)$$

$$W_R/KW_o = \left(1/\eta_c - 1 \right) \phi_R / \sigma \epsilon_R \left(T_{MAX}/\beta \right)^4 \quad (11)$$

The parameter λ appearing in equation ten is the heat of fusion in KW-HR/LB of the energy storage medium. This parameter varies with Tmax as a different medium must be chosen at each Tmax, because of the different melting points of the media. A list of values for the temperatures chosen follows:

$T_{MAX} = 1500°R$ $\lambda = 0.351$ (LiH)
$T_{MAX} = 2000°R$ $\lambda = 0.132$ (NaF)
$T_{MAX} = 2500°R$ $\lambda = 0.146$ (Be)
$T_{MAX} = 3000°R$ $\lambda = 0.146$ (Be)

Using the previously chosen values for the constants in equations nine through eleven, figures five through eight were determined with weight per KW_e being the dependant variable and Tmax and η_c as the independent variables.

These curves clearly illustrate the effect operation temperature and cycle efficiency have on component and system total weight. Figure 7, a family of reflector specific weight curves, indicates that reflector specific weight is practically constant for cycle efficiencies greater than 40%. The small spread in the curves indicates that reflector weight is almost independent of maximum cycle temperature, particularly at higher cycle efficiencies. The heat receiver curves, Figure 8, are very similar to the reflector curves in that they have somewhat the same shape. It should be noted, that these curves are based on the assumption that Φ_B, (boiler tubing, insulation, etc. weight) will remain constant even though boiling or maximum cycle temperature increases. This assumption is highly unlikely, but, due to the complexity of expressing Φ_B as a function of η_c and Tmax, the assumption is used for this paper. Problematically, Φ_B will increase with increasing Tmax with an overall effect of making the curves in Figure 8 more temperature dependant. Also of interest is the approximate coincidence of the curves for Tmax equal to 2000°R and 2500°R in the same figure. This results from the unique number relationship between the storage capacity the energy storage mediums used and their respective temperatures. The family of curves presented in Figure 9 reflect an entirely different trend than the previous curves. First, they are parabolic rather than hyperbolic and, secondly, they are quite temperature dependant. Due to these properties, it can be said that there is an optimum or minimum radiator weight occurring at about 7% cycle efficiency. Since Figure 9 was computed for an assumed cycle deviation of 0.35, the radiator temperature, T_{MIN}, is constant for a given η_c and Tmax. The end result of Figures 7 through 9 is Figure 10, total system specific weight. It can be seen from the curves in this figure that there is an optimum cycle efficiency for any given maximum cycle temperature at which minimum specific weight occurs. Also shown, in most cases, is the reduction of system total weight when the maximum operating temperature is increased.

Other than the need for high cycle temperatures, the analysis presented illustrates the fact that improvement of the various components in the system is desirable but care should be exercised in realizing this improvement. For instance, it would appear that the system should operate at a 7% cycle efficiency when examining radiators alone, but systemwise, operation at this efficiency would not allow optimum total system weight.

It should be recognized that the specific weight curves presented herein are intended to show the trend to high cycle boiling temperature and optimum cycle efficiency only. Many of the parameters (e.g. γ, ϕ_R and Φ_B) assumed to be constant in the analysis are actually dependant upon η_c and/or Tmax and will consequently cause the resultant curves to change. Irregardless of their variation, the trend towards higher cycle operating temperatures and minimum specific weight at an optimum cycle efficiency will prevail.

Effects of Selective Coatings on System Weight

In conclusion, one last consideration is made--that of the effect of selective coatings on specific weight. For this consideration, a coating with $\alpha_B = 0.9$ and $\tau = 20$ is assumed to be available for applying to the boiler or heat receiver at each of the four operating temperatures. It is also assumed that a surface type heat receiver can be designed such that the previously assumed concentration ratio of 1000/1 can be realized. Using these basic assumptions in equations (9) and (10), the curves shown by broken lines in figures 7, 8 and 10 were plotted. From them it is evident that selective coatings reduce total system weight and the magnitude of optimum cycle efficiency.

Summary

To summarize, we have seen that there appears to be a very wide domain of power requirements for advanced type aerospace vehicles. Secondly, there are a number of devices being developed which will be capable of meeting these requirements. Thirdly, high cycle temperatures are desired to reduce the overall weight of the system. Lastly, selective coatings will aid substantially in realizing these higher cycle temperatures, and consequently, reduced system weight will be realized. In short, let us paraphrase an old advertisement, "When lighter solar powered systems are built, they will be selectively coated."

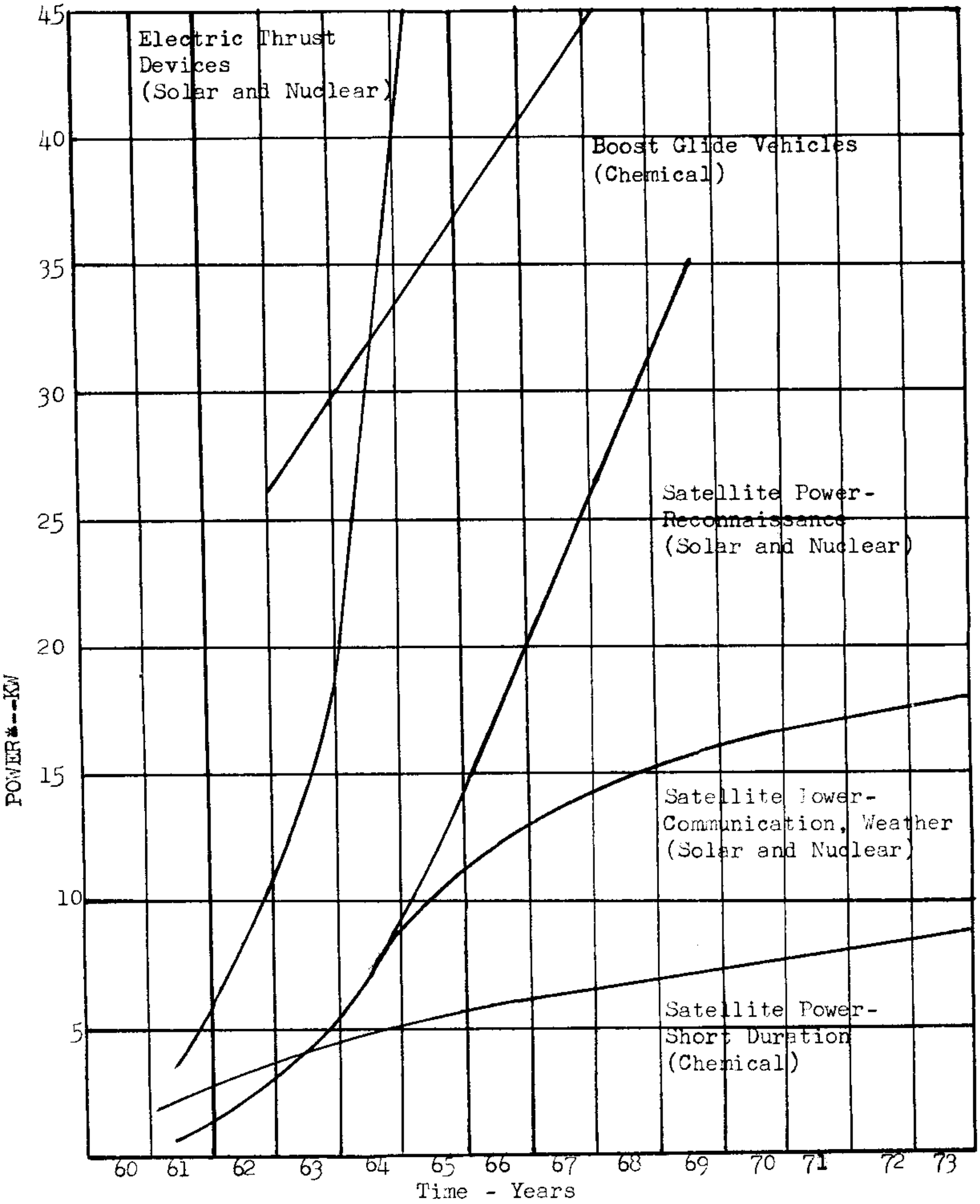


Figure 1 Forecasted Power Requirements

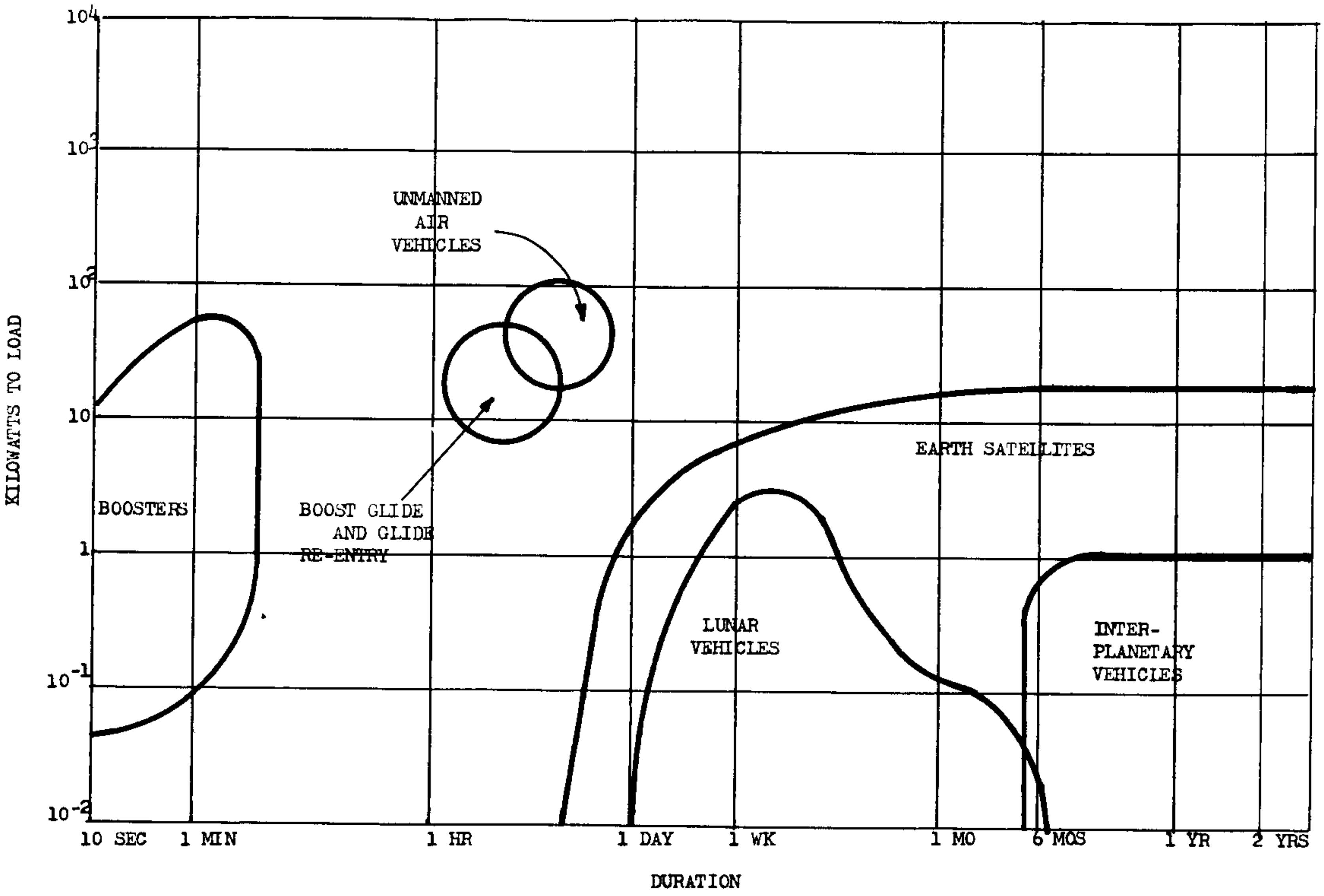


Figure 2 Synthesis of Forecasts of 1962 Requirements for Flight Vehicle Power

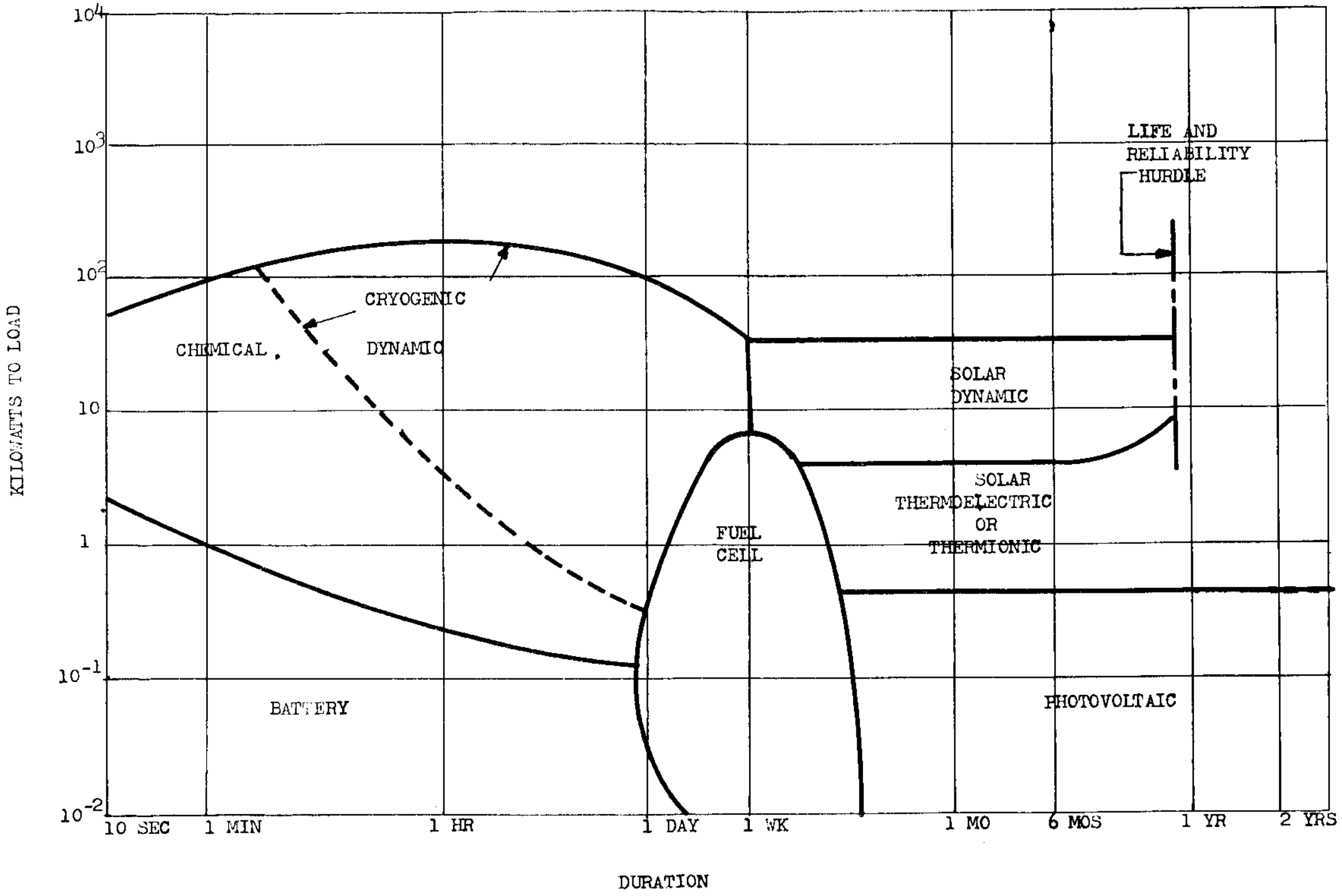


Figure 3 Synthesis of Forecasts of 1962 Areas of Optimum Application of Energy Conversion Methods

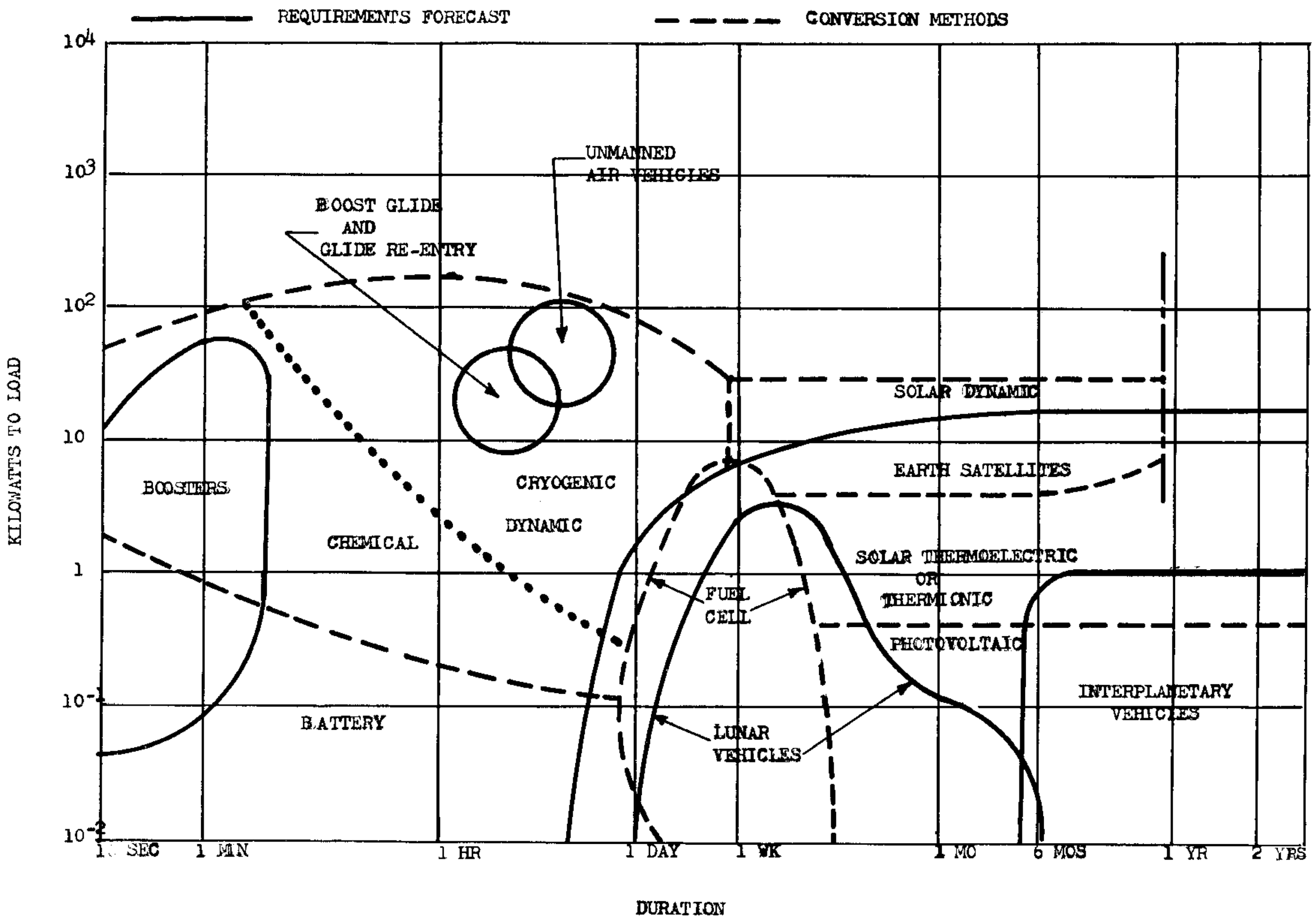
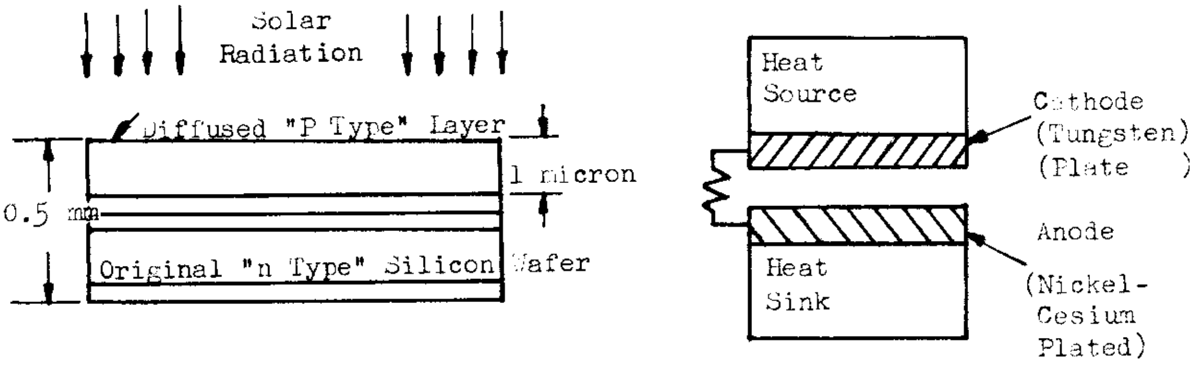


Figure 4 Over Lay of 1962 Forecast Requiremtns and Energy Conversion Methods



Photovoltaic

Thermionic Converter

THERMOELECTRIC

FUEL CELL

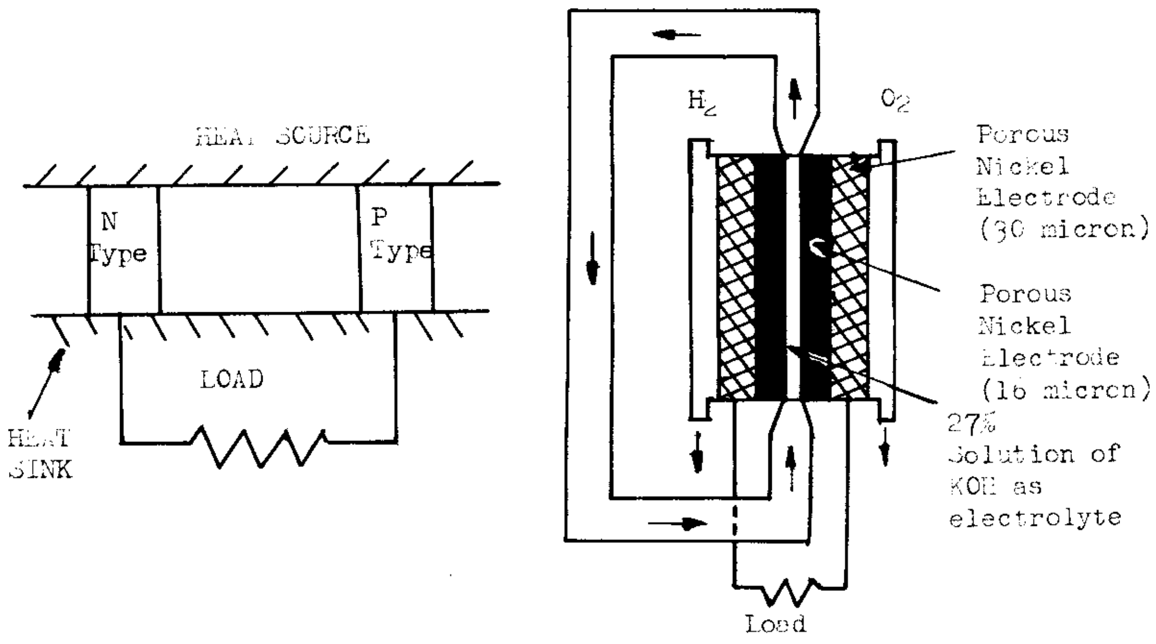


Figure 5 Static Conversion Devices

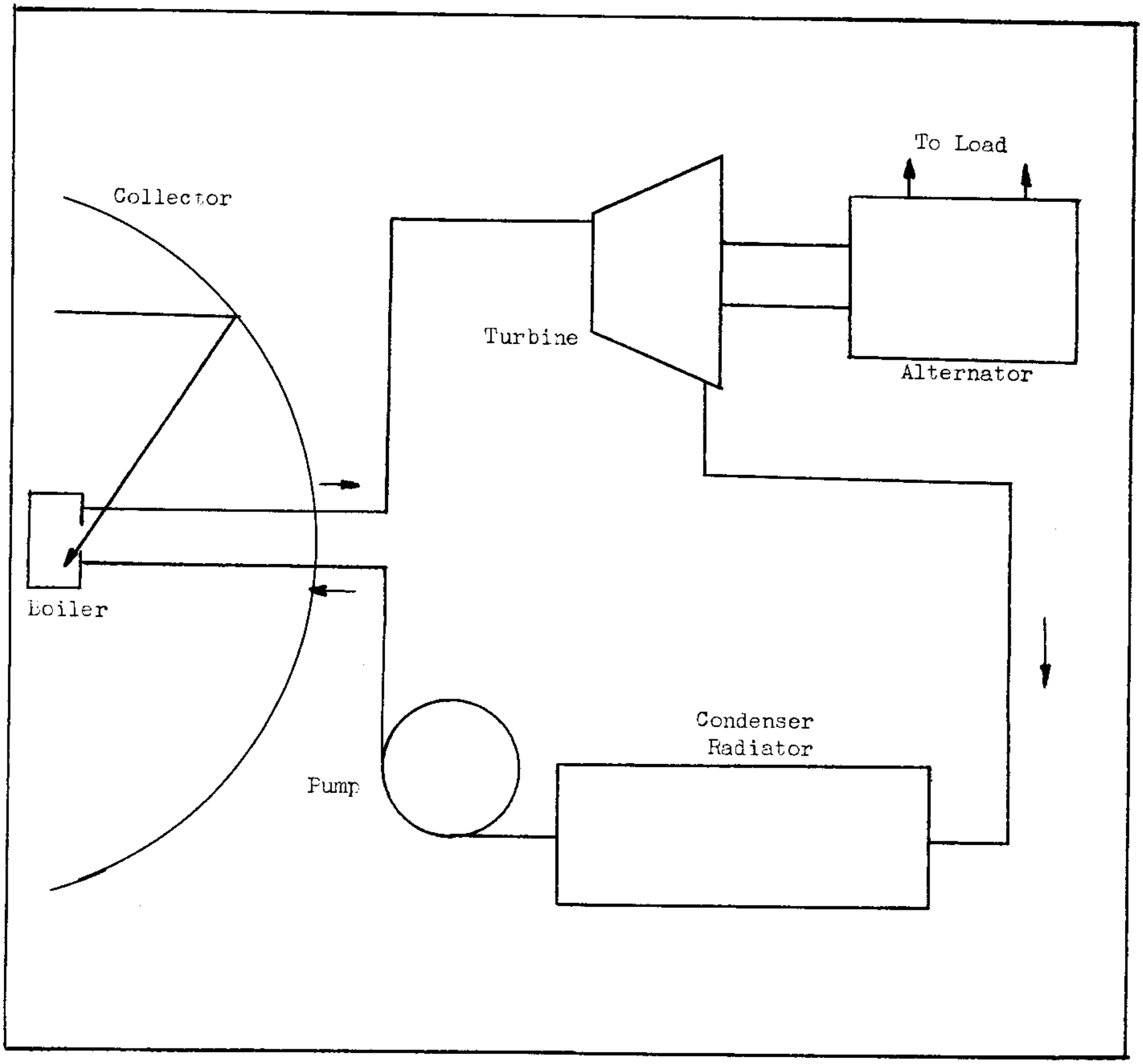


Figure 6 Dynamic Energy Conversion Thermodynamic System

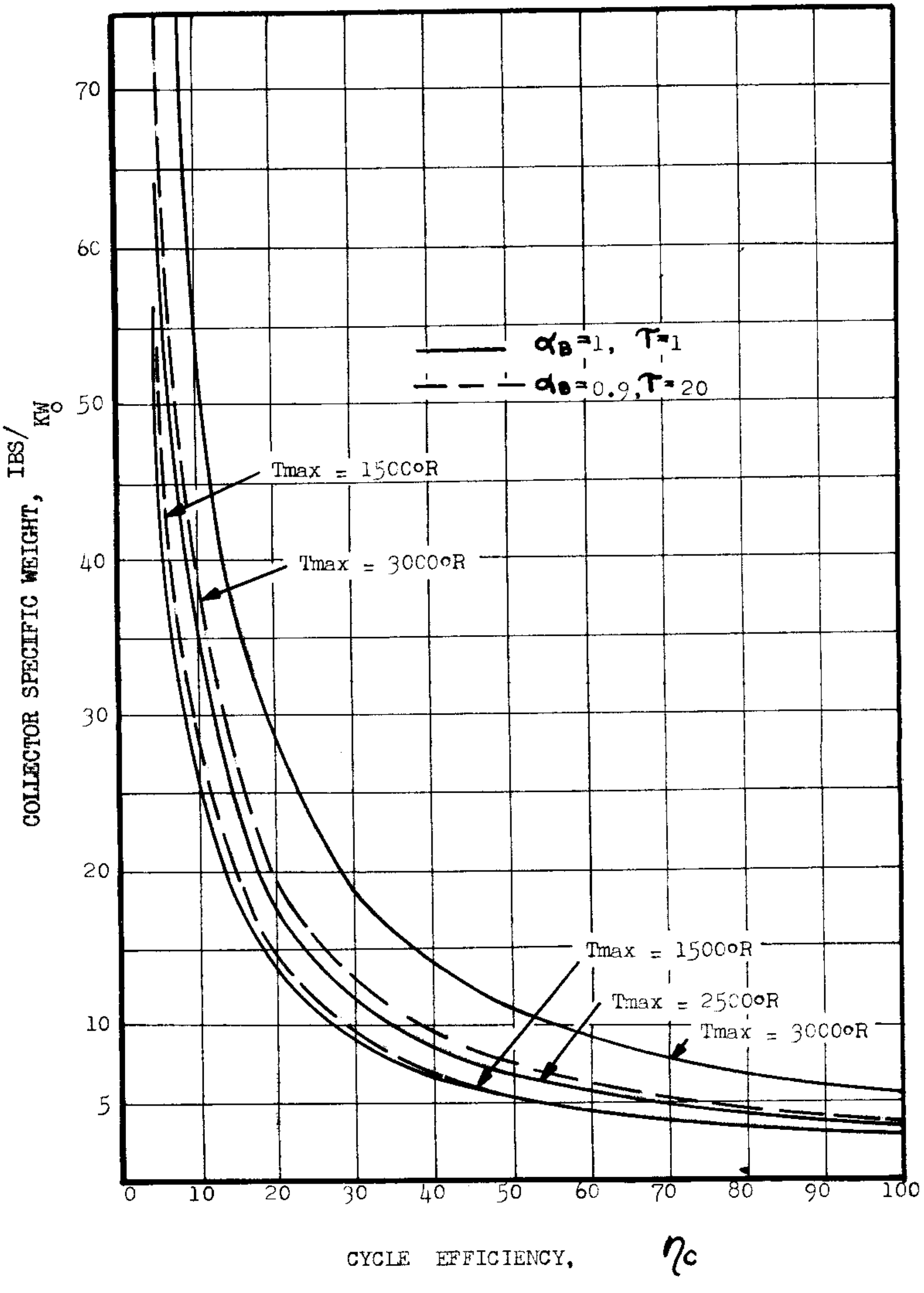


Figure 7 Collector Specific Weight

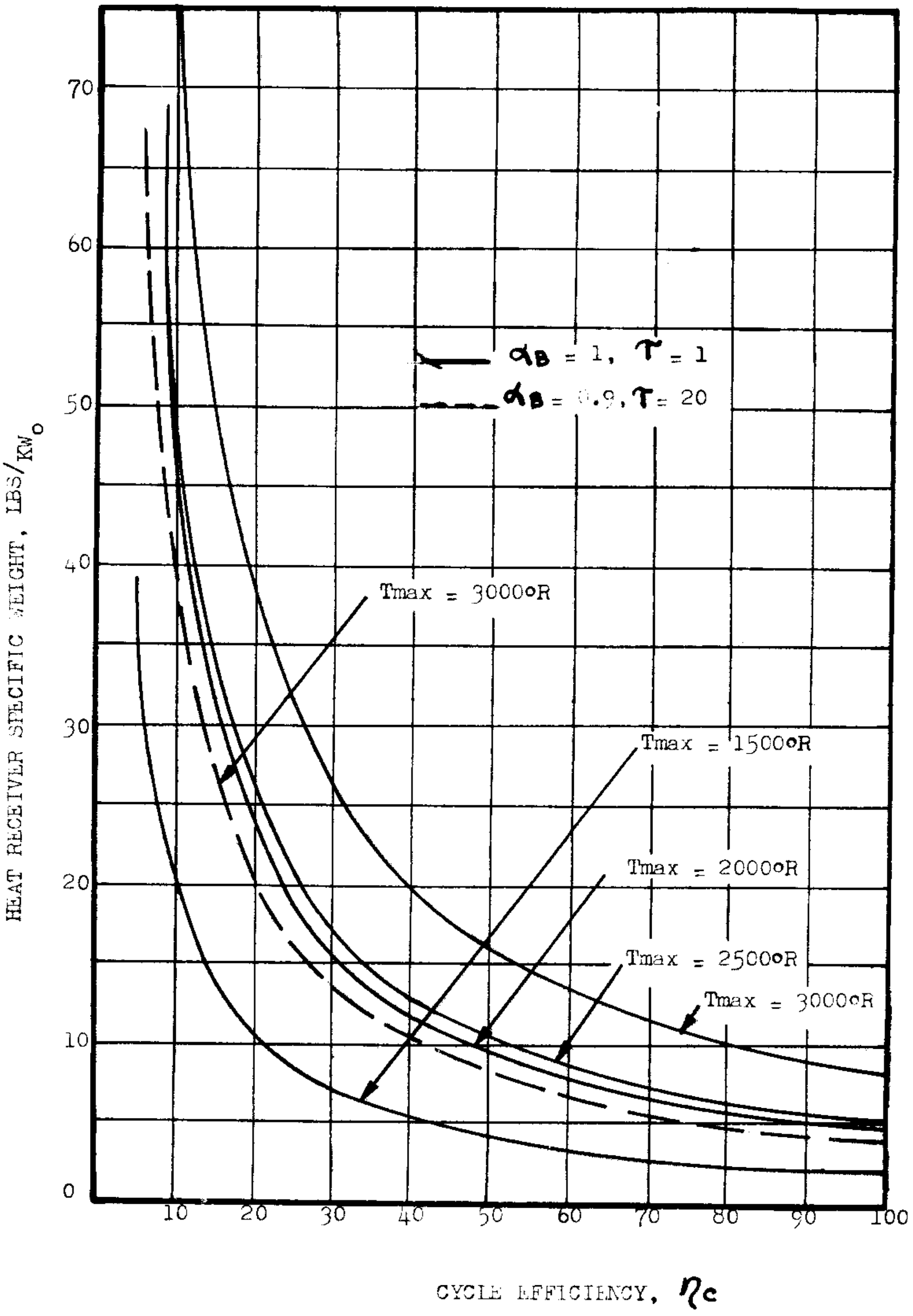


Figure 8 Heat Receiver Specific Weight

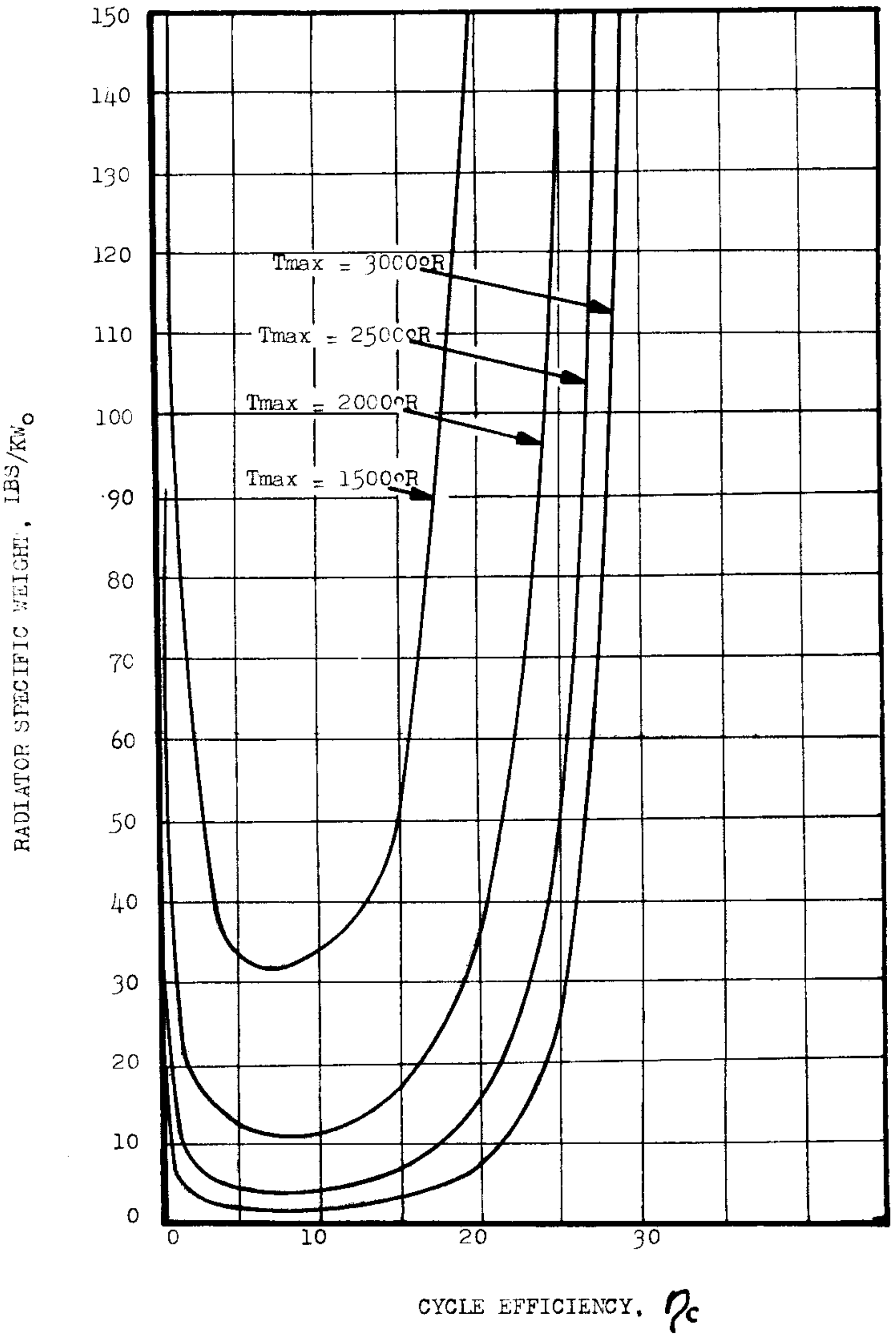


Figure 9 Radiator Specific Weight

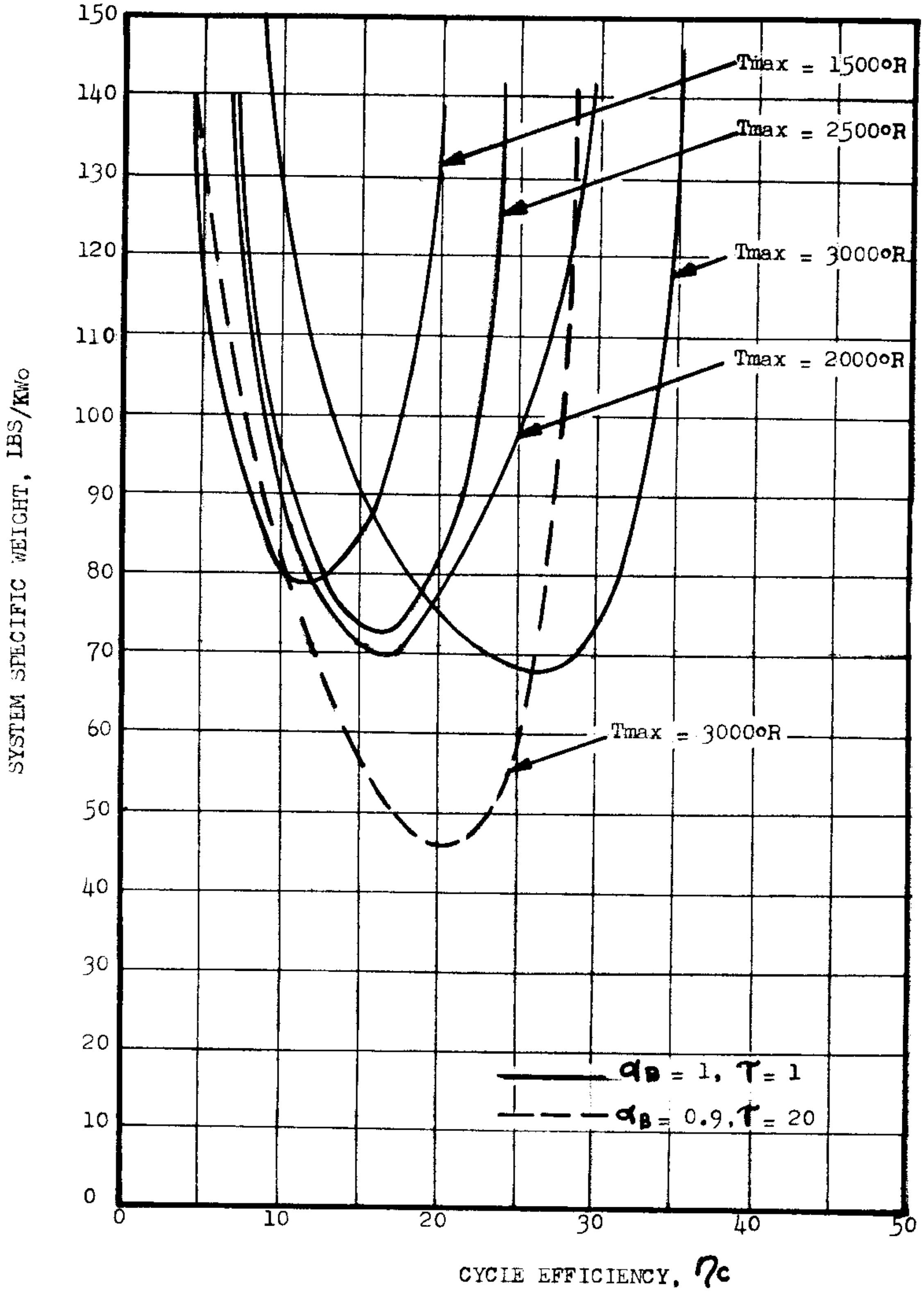


Figure 10 Overall System Specific Weight