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RESEARCH & DEVELOPMENT OF OPEN CYCLE FUEL CELLS

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National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Huntsville, Alabama 35812

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Second Quarterly Progress Report
Under Modification 4, Contract NAS 8-5392
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PREPARED FOR

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INTRODUCTION

This report is the Second Quarterly Progress Report issued under Modification Number 4 to Contract NAS 8-5392. Progress during the period of November 15, 1964 through February 15, 1965 is covered herein.

ABSTRACT

Design charts based on the study of the problem of storage in a low temperature environment are presented. The study on the range of applicability of a fuel cell power supply is expanded and basic subsystems examined. The subroutines on space radiators, and on fuel cell-rechargeable battery combinations being readied for insertion in the existing fuel cell power system parameter optimization computer program are described. The computer program for the mathematical representation of the static vapor pressure method of water removal is described.

SUMMARY

The effect of protracted storage in a low temperature environment on fuel cell systems was studied. Design charts are presented which show the optimum storage temperature and insulation thickness required to maintain a 2 KW system for various storage periods. In general, if the storage period exceeds six hundred hours, the optimum storage temperature is equal to the environment temperature, or to the lowest temperature which the fuel cell can withstand.

The results of a simplified analysis of a highly ideal rechargeable battery-fuel cell system are presented. The results show that there exist situations in which such a system will be optimum. The length of time over which load sharing of such a system was found to be optimum was less than 0.6 hours for the case considered.

The results of a literature survey on the fuel storage and supply package are reported. General equations of system weight are presented for the cases of supercritical and subcritical storage.

The study of the range of applicability of a fuel cell system in comparison with other auxiliary power supplies was continued. Radiators, a subsystem common to all power supplies, were examined. Figure 20 presents the relative capabilities of several systems.

The analysis required for the mathematical model of the static vapor pressure method of water removal is presented. The computer program is described and initial success is reported.

1.0 EFFECT OF ENVIRONMENTAL CONDITIONS ON FUEL CELL SYSTEM DESIGN

A brief summary of the analysis (1) * of the weight penalty, that the fuel cell system is subjected to, due to its storage in a low temperature environment is given below. This analysis was programmed for solution by a digital computer. Several problems were solved with this program to obtain the attached design charts.

1.1 A Brief Summary of the Analysis

A typical fuel cell assembly is shown in Figure 1. It was assumed that when the fuel cell canister was initially subjected to the low temperature environment it was at its normal operating temperature, T_o. Then, the fuel cells could be operated at some intermediate storage temperature T_i where the heat generated would equal the heat lost. To bring the fuel cells back to T_o, heat would have to be supplied. This heat could be obtained from (i) operating the fuel cells themselves, (ii) using stored energy from batteries, or (iii) some other chemical device. Additional weight W_a for these three alternatives is given by the following relationships.

(i) $$W_a = \frac{QM}{\Delta H} + \rho_i V_i + \rho_s V_s$$ where M is the molecular weight of water

(ii) $$W_a = \frac{4184}{B} + \rho_i V_i + \rho_s V_s$$

(iii) $$W_a = \frac{QM_r}{\Delta H} + \rho_i V_i + \rho_s V_s + W_r$$ where M_r is the molecular weight of reactants

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* References given in 7.0

where

$$Q = Wc\,(T_o - T_i)\,(t_s - t)\,(q_i + q_n + q_m + q_a)$$

q_i = Heat conducted through the canister insulation and finally radiated to the environment $= (K_i A_c / X_i)\,(1 - p)\,(T_i - T_{ie})$

$$= \sigma\, e_i A_c\,(1 - p)\,(T_{ie}^4 - T_e^4)$$

q_n = Heat lost through uninsulated portions of the canister walls

$$= \sigma\, e_W\, p\, A_c\,(T_i^4 - T_e^4)$$

q_m = Heat conducted through the mounts which attach the canister to the vehicle $= \dfrac{f_m K_m A_m}{X_m}\,(T_i - T_e)$

q_a = Heat lost through accessories such as pipes, etc.

$$= \sigma\, f_a\, e_a\, A_a\,(T_a^4 - T_e^4)$$

t = Time required for the fuel cell assembly to cool from its initial temperature at the beginning of storage period to the storage temperature. A separate analysis [1] was performed to determine this time.

t_s = Length of storage period.

1.2 Discussion

Several runs were made with the computer program to determine the best way of supplying heat to bring a fuel cell system back to its normal operating temperature after low temperature storage. These runs indicated that for a 2 KW system, operation of fuel cells themselves rather than using stored energy from batteries would result in a lighter overall system.

Several computer runs were also made for the case of a 2 KW fuel cell system operating at reduced level with both produced power and internal heat generation being used to balance the heat losses from the system, and then operating fuel cells at a higher power level to bring the system up to its normal operating temperature. It was assumed that the minimum allowable storage temperature for the fuel cells would be 233° K. In order to obtain a wide range of design information, two types of insulating materials were considered; super insulation with thermal conductivity = 1.11×10^{-4} KCal/hour meter ° C, and Glass Heat Felt made by Thompson Fiber Glass Company of Gardena, California, with thermal conductivity = 2.22×10^{-3} KCal/hour meter ° C. To give optimistic, realistic and pessimistic estimates of weight penalty, it was assumed that 1%, 5% and 20%, respectively, of the canister could not be completely insulated because of mechanical considerations. The bracketed numbers in the nomenclature (Section 1.3) are the values of the variables used to obtain Figures 2 through 12.

For super insulations, Figures 2, 3, and 4 give the optimum weight penalty in kilograms of insulation, metallic cover, and fuel required to store the fuel cells for various durations in a lunar environment at a temperature of 116° K. Figures 5, 6, and 7 give the optimum storage temperature for various lengths of storage periods. Figures 8, 9 and 10 present similar information for Glass Heat Felt type insulation. Note that Figures 5, 6 and 7 are approximate, which should be sufficient because for optimum insulation thickness, optimum storage temperature was 233° K (the minimum allowable), for all the cases.

Figures 8 and 12 present two important design graphs. They give the optimum insulation thickness for any length of storage period. Note that the optimum storage temperature becomes the minimum allowable storage temperature in the cases considered.

The optimum storage temperature for a 2 KW system for either super insulation or Glass Heat Felt was found to be 233° K, and the minimum insulation thickness was only slightly dependent on the percentage of the canister that could not be completely insulated because of mechanical considerations.

1.3 Nomenclature

A_a = Surface area of accessories, m^2 = (0.0241)

A_c = Canister surface area, m^2 = (0.835)

A_m = Cross sectional area of canister mounts, m^2 = (0.00101)

B = Battery constant, Joules/Kg = (3.96×10^6)

c = Heat capacity of fuel cell assembly, Cal/Kg ° K = (200)

e_i = Insulation cover emissivity = (0.09)

e_w = Canister wall emissivity = (0.09)

f_a = Correction factor for losses from accessories = (1)

f_m = Correction factor for losses through mounts = (1)

H = enthalpy of reaction, Cal/Kg mole

k_i	=	Conductivity of insulation Cal/sec m° K = (3.085×10^{-5}; 6.17×10^{-4})
k_m	=	Conductivity of canister mounts, Cal/sec m ° K = (0.0411)
M	=	Molecular weight, Kg/Kg mole
p_i	=	Insulation density, Kg/m^3 = (64.2)
p_s	=	Insulation cover density, Kg/m^3 (1605)
p	=	Fraction of canister surface without insulation = (0.01, 0.05, 0.20)
q	=	Heat loss rate, Cal/sec
Q	=	Thermal energy required to attain operation temperature, Cal
σ	=	Stephan-Boltzman constant, Cal/sec m^2 ° K^4 = (1.375×10^{-8})
t	=	Cool down time, sec
t_s	=	Storage time, sec
T_a	=	Average accessory temperature, ° K
T_e	=	Environment Temperature, °K = (116° K)
T_i	=	Storage Temperature, ° K
T_o	=	Operating Temperature, °K = (361° K)
T_{ie}	=	Temperature of insulation cover, °K
V_i	=	Insulation volume, m^3
V_s	=	Volume of material comprising insulation cover, m^3
W	=	Weight of fuel cell assembly, Kg = (56.5)
x_i	=	Insulation thickness, m
x_m	=	Length of canister mounts, m (0.0254)

2.0 COMPUTER PROGRAM FOR FUEL CELL PARAMETER OPTIMIZATION

The existing computer program (IBM 704) for fuel cell system parameter optimization is being modified and extended to include the use of secondary batteries for power peaking on irregular load profile missions. Subroutines are being added which compute the properties of reactant storage vessels and radiators as functions of the system operating parameters so that they can influence the optimization of the overall system. The effects of adding a water recovery subsystem will also be considered by the expanded program.

2.1 Fuel Cell-Rechargeable Battery Combination

The initial attack on this problem was made for load profiles having only two power levels. The method has been extended to a multi-step power profile with a maximum of fifty steps. The analysis is conducted by means of an iterative mathematical procedure to size a battery-fuel cell combination for minimum total weight. At each step in the iterative process, a slightly larger fraction of the power output during high load is allocated to the battery. A check is then made to determine if the battery can be recharged during the low level portions of the output power profile. The process continues until the sum of weights of the two devices reaches a minimum.

Since the computer programming of the rechargeable battery-fuel cell optimizing technique was becoming quite involved, an analysis was performed to determine the range of applicability of rechargeable batteries under an ideal set of conditions. These conditions were:

(a) A sufficient charging time would always be available during low level portions of the load profile;

(b) The power supplied by the fuel cells during any interval of time plus the power required to recharge the batteries would always be less than or equal to the maximum power supplied by the fuel cells.

(c) Battery weight was 0.018 kg per watt-hour capacity.

(d) Required charging current would never be greater than the maximum specified charging current.

(e) Charging and discharging efficiencies were equal to one.

(f) Weight of the voltage regulator was zero.

(g) No matter how far the battery was discharged, the system would always stay within the voltage regulation limits.

(h) It was always possible to recharge the batteries from the fuel cells.

2.1.1 Determination of the Range of Applicability of Rechargeable Batteries

A schematic drawing of the power-time plot (power profile) is shown in Figure 13. The nomenclature used is explained in Section 2.1.2. The following relationship was derived from the power profile shown in Figure 13.

$$E_d = E_c = (P_m - P_{fcm}) \; t_d$$

The supplementary storage battery used in conjunction with a fuel cell module would be useful in supplying peak power for only a relatively short period of time. As the duration of the peak power portion of the profile increased, the advantage of the battery over the fuel cell would diminish. In the limiting case, where nearly the entire profile is at the high power level, it is obvious that a fuel cell alone could best do the job. The purpose of this study was to determine the range of allowable duration of the peak power condition where a battery-fuel cell combination would be lighter than an all fuel cell system.

The first step in the procedure was to determine W_{mo}, the weight of an all fuel cell system. This was done with the system optimization program. The next step was to determine the weight, $W_{fc\,1}$, of the fuel cell system required to supply an amount of power equal to P_{fcm}. Then the weight of a battery required to make up the difference in power between P_m and P_{fcm} during peak power conditions was calculated from

$$W_B = \frac{(P_m - P_{fcm})\, t_d}{\alpha \rho_d}$$

The weight of the combination system required to handle the power profile was then:

$$W_{m\,1} = W_{fc\,1} + W_B$$

The relationship above is thus a function of peak power duration, t_d. When t_d was zero, $W_{m\,1}$ was of course found to equal W_{mo} since the battery weight, W_B, was zero and $W_{fc\,1}$ was equal to W_{mo}. As larger values of t_d were used in the equations, W_B was found to increase and $W_{fc\,1}$ to decrease in such a fashion that $W_{m\,1}$, the system weight, was less than the weight of an all fuel cell system, W_{mo}. The system weight was found to go through a minimum as a function of t_d. For a large enough t_d the combination system weight again equaled the weight of an all fuel cell system. Thus, a secondary battery-fuel cell combination would provide a lower weight system only when t_d was smaller than that critical limiting value. It was also discovered that the limiting value of t_d was dependent on the allowable depth of discharge for the battery. Typical results are shown on the next page.

Battery Discharge Depth	Maximum Discharge Time, Hours
100 %	0.595
75 %	0.445
50 %	0.298
25 %	0.149
10 %	0.060
5 %	0.030

For above conditions and for 100 % depth of discharge, Figures 14, 15 and 16 give the percentage weight saving that can be obtained by using rechargeable batteries for different discharge times and for different energy levels. It is apparent from these figures that for an ideal set of conditions, it would be advantageous to use rechargeable batteries when the discharge time is less than 0.6 hours for cases where 100 % depth of discharge is allowable.

Since power profiles with peak power demands for a short time (e.g. t_d = 1 minute) frequently occur, a detailed flow diagram has been constructed for a method to size a battery-fuel cell combination for minimum total weight. The flow diagram is now being used in writing a digital computer program. Upon completion of the program, a large number of problems covering a broad range of conditions will be solved and used to produce design curves.

2.1.2 Nomenclature

E_d = Energy discharged, watt hours

E_c = Energy required to recharge the battery, watt hours

P_m = Maximum power in the power profile, watts

P_{fcm} = Maximum power supplied by the fuel cells, watts

t_d = Discharge time, i.e., time during which the battery discharges, hours

W_{mo} = Minimum weight of the power system when fuel cells are the only source of power, i.e., when $P_{fcm} = P_m$, kg

W_{fc1} = Minimum weight of the fuel cell portion of the power system with fuel cells supplying a maximum power $= P_{fcm}$, kg

α = Depth of discharge

ρ_d = Energy density of the battery, $\frac{\text{watt-hours}}{\text{kg}}$

W_B = Weight of the battery, kg

W_{m1} = Weight of the power system when both fuel cells and battery are used as the sources of power, kg.

2.2 Space Radiators

A detailed flow diagram was constructed for a method of optimizing space radiators with respect to weight. A digital computer program has been written using the flow diagram and is being debugged. Upon completion of the program, a large number of problems covering a broad range of conditions will be solved and used to produce design curves.

2.3 Fuel Storage and Supply Package

The literature survey on Cryogenic Fuel Storage and Supply Package was continued during this quarter. A report by C. W. Spieth, et al, [2] was used as a basis for the simplified equations given below.

Information on the optimum weight of hydrogen and oxygen tanks for weights of hydrogen and oxygen below 40 and 20 pounds, respectively, was not given by Spieth. Hence, the following equations only apply for a weight of hydrogen greater than 40 pounds and a weight of oxygen greater than 20 pounds.

The results of the survey indicated that spherical tanks would be lighter than the cylindrical tanks and gave the following relationships.

A. Supercritical Storage

Hydrogen was assumed to be stored at 250 psia and oxygen was assumed to be stored at 850 psia.

Shape: Spherical
Inner tank material for hydrogen tank: Ti 6Al - 4V
Inner tank material for oxygen tank: 6061-T6Al
Outer tank material for both oxygen and hydrogen: 0.020" thick magnesium
Density of insulating material: 16 pounds per cubic foot

$$W = 3.16\, W_H^{0.914} + 9.73\, W_H - 20$$

where,

W_H = Weight of hydrogen, pounds

W = Total weight of fuel storage and supply package.

B. Subcritical Storage

Hydrogen was assumed to be stored at 20 psia and oxygen was assumed to be stored at 100 psia.

Shape: Spherical

Inner tank material for both hydrogen and oxygen tanks: Ti 6Al - 4V

Outer tank material for both hydrogen and oxygen tanks: magnesium

Density of insulating material: 7 pounds per cubic foot

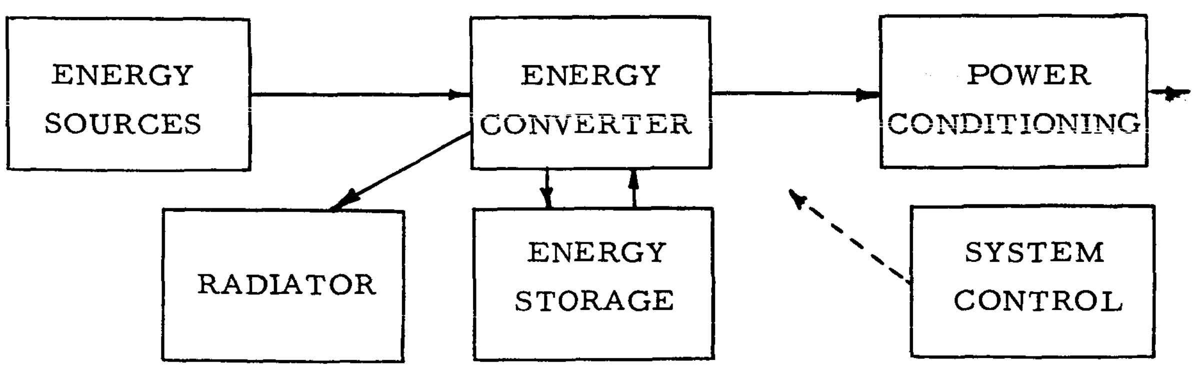
$$W = 2.575\, W_H^{0.914} + 8.15\, W_H + 21$$

3.0 RANGE OF FUEL CELL APPLICATION

During the quarter the literature survey of the auxiliary power supplies for space was continued. New systems were studied and subsystems common to most power supplies studied in detail.

3.1 Generalized Auxiliary Power Supply

In block diagram form, the major components or subsystems of an auxiliary power supply are in general arranged in a form as shown below.



These subsystems are considered in the following sections.

3.2 Energy Sources

The sources of energy generally considered for application in the space environment are: solar energy, nuclear energy, and chemical energy.

Solar energy has the advantage of not requiring the presence of an expendable fuel. At the distance of the earth from the sun (1 astronomical unit) the useful thermal power crossing a square foot plane, whose perpendicular is in the direction of the sun, is 130 watts. This power varies with the inverse of the square of the distance to the sun. Thus

$$J = \frac{0.130}{r^2} \qquad \frac{KW}{Ft^2}$$

where r is the distance from the sun in astronomical units.

The solar power can either be intercepted by the power conversion device, or by a concentrator usually in the form of a mirror. The efficiency of a mirror is presented in Figure 17.

A solar power system has the disadvantage of not operating whenever the system is in a shadow. This requires the presence of an energy storage subsystem. The system also requires a high degree of orientation control.

The nuclear energy source has the advantage of continuous operation regardless of environment. Although the fuel must be carried, the energy available per pound of nuclear fuel is very high.

Nuclear energy sources usually require shielding which may constitute a major portion of the weight of the power supply. For missions which include the presence of a man, the shielding requirements are likely to be prohibitive. For missions which include instruments to measure the radiation level of the space environment, a nuclear energy source may not be acceptable.

Chemical energy systems are not affected by position in space and do not require shielding. However, they do require the use of an expendable fuel. For this reason chemical energy systems are usually only considered for missions of up to 1000 hours duration.

3.3 Radiator

In the space environment the most desirable mechanism for the removal of waste heat from a vehicle is often radiation. Most power supply systems have an efficiency and power level which requires the use of a waste heat radiator. A rough approximation of the size of the radiator can be determined from

$$A_{RAD} = \frac{P_{RAD}}{\sigma \epsilon T^4}$$

If the value of the laminar weight (weight per unit area) of the radiator is known, the weight per unit of power input is given by

$$\frac{W}{P_{input}} = \left(\frac{W}{A}\right) \frac{(1 - \eta)}{\sigma \epsilon T^4}$$

This equation has been evaluated for various values of η and T in Figures 18 and 19. Specific values of ϵ and $\frac{W}{A}$ were used, but any other values can be substituted easily. The values of η and T cover the entire range of efficiencies and radiator temperatures associated with the conversion devices.

These figures emphasize the desirability of using highly efficient devices operating at high heat rejection temperatures. This is especially true in systems which produce large amounts of electrical power.

3.4 Energy Conversion Systems

Energy conversion systems which use solar energy are: Photovoltaic devices, thermionic diodes, and the various turbo and reciprocating devices. The systems which use nuclear energy include: Thermoelectric couples, thermionic diodes, and turbo and reciprocating machinery. The devices using chemical energy include:

Fuel cells, batteries, and turbo and reciprocating machinery. Some of these devices are discussed in more detail in the following sections.

3.4.1 Thermionic Diodes

The thermionic diode is a device for the direct conversion of heat to electrical energy. The diode consists of two electrodes separated by a small gap. One of the electrodes is heated to a temperature high enough so that the electrons within it have energies greater than the work function of the metal. These electrons can leave the electrode and may arrive at the other electrode which is made up of a material of lower work function. Electrical balance is maintained by allowing electrons to return to the original electrode through an external load.

The efficiency of the device is limited to between 20 and 30%. However, the high operating and consequent high heat rejection temperature permits the use of very light radiators. The completely static nature of the device is attractive from a reliability point of view, however, the high temperatures result in many materials problems.

At the present stage of development, the efficiencies are from 10% to 15% and the life characteristics are poor. This system does have much promise and is being rapidly developed.

3.4.2 Rankine Cycle Turbo-Machinery

Rankine Cycle power plants are covered in great detail in "Design of Space Power Plants" by Donald B. Mackay (Prentice-Hall). It is pointed out that the best fluid would be sodium, however, this fluid requires temperatures presently beyond the capability of available materials. Mercury is used in most systems being planned at the present time.

The efficiency of a Rankine Cycle converter is usually around 20%. Heat rejection temperatures are near 1060° R.

3.4.3 Brayton Cycle Systems

The Brayton Cycle system is similar to a Rankine Cycle, however, the working fluids are inert gases such as helium. This eliminates many of the materials problems associated with the Rankine Cycle devices, and higher reliability is usually attained. The system efficiency is similar to that of a Rankine Cycle system, but the radiator temperature is usually lower. This causes the radiator weight and thus the system weight to be higher than that of a Rankine Cycle system.

3.5 Specific Systems

Figure 20 presents the system specific weight (pounds/Kw output) of several systems which either exist or could exist. The fuel cell lines are based on Allis-Chalmers Breadboard #2 developed under NASA Contract Number NAS 8-2696, and on computer runs made by R. Desai in 1963 - 1964 to determine the optimum fuel cell for a particular mission.

The SNAP data points are from published data. The systems shown have a radioisotope heat source. Systems numbered 5, 6 and 7 use thermoelectric conversion. System 8 uses thermionic conversion and was not optimized to give minimum weight.

The hydrogen-oxygen reciprocating engine was reported in a paper presented at the AIAA Third Biannual Aerospace Power System Conference.

An interesting concept for a system is reported by H. Schuerch and W. Robbins in "Rotary, Deployable Space Power Supply" (Report ARC-R-153, N64-33801). They describe the system in the following way. "deployable solar concentrator and reflection system, - rotary mercury steam engine (Huettner Turbine), - the electrical power generator (alternator) and its associated radiation cooler, - the heat rejector, built as a rigid, elongated conical radiator . . . augmented by a deployable solid state convective heat transport device in the form of a running belt system . . . and - the passive, heliotropic orientation system in the form of the peripheral torquing and modulating vanes located at the reflector rims."

Especially interesting are their concepts of the deployable concentrator, and of the heat rejector. The mirror would be made of a coated plastic and would be held in place by rotating the entire system. This would eliminate many of the supporting structures needed for a non-rotating system. The rotation may also aid in the heat transfer within the boiler. In zero-g, there is no natural convection, so that rotation creates a g field. The belt type radiator, although having an inherent low reliability, is interesting in concept. This method may require less parasitic power than a fluid transfer agent. The following is a tabulation of system properties as given by Schuerch and Robbins

Power Output (KW)	15	150
Diameter - deployed (ft)	50	190
- folded	8.3	11
Mirror Area (ft^3)	1500	17,158
Mirror Efficiency	80%	66%
Absorber Efficiency	66%	70%
<u>Mercury Rankine Converter System</u>		
Temperature inlet °F	1097	1097
Radiator Temperature °F	620	620
Efficiency	17.3%	17.3%

Weight (pounds)

Mirror	65	558
Boiler	18	87
Condenser	94	326
Belt System	---	264
Working Fluid	12	68
Turbine and alternator	30	150
Housing, ducts . . .	26	135
Total	245	1588

Giving the systems an arbitrary life of 1.1 years, they appear as systems 9 and 10 on Figure 20.

The possibility of meteorite damage to the components of the system has not been examined. It is possible that the mirror would remain effective after numerous punctures. However, the ability of the spinning mirror to remain in one piece may become less as the number of punctures increases.

In the power system of Schuerch and Robbins there is no provision for energy storage. If the system ever entered a shadow it would not continue to supply electrical power. If the length of time in shadow for the entire mission is not excessive, a fuel cell system could be considered.

In "Energy Conversion for Space Power" edited by N. W. Snyder, data on two systems is presented by M. D. Parker and C. L. Smith (p-557). Both systems produce 5 KW of output power in a 300 mile earth orbit. The solar energy source is used for both systems and an energy storage system is provided. Their characteristics are presented in the following table:

	Sterling Cycle	Rankine Cycle
Engine Efficiency %	37.5	13
NAK Inlet Temperature ° F	1250	1250
Radiator Temperature ° F	150	500
Radiator Area ft^2	160	96
Solar Collector Area ft^2	283	816
Solar Collector Diameter-ft	19	32.3
Weight Breakdown - pounds		
Solar Collector	112	310
Absorber	20	53
Reservoir	45	124
Power Conversion System	237	126
Radiator	36	25
Structure	75	115
Liquid Inventory	42	55
Total	567	808
Specific Power pounds/KW	113	161

These two systems appear on Figure 20 as Systems 11 and 12.

3.6 Future Work

More specific systems will be examined and the missions for which they are expected to find use outlined. The possibility of the use of a fuel cell system for such missions will be examined.

4.0 MATHEMATICAL MODEL OF STATIC MOISTURE REMOVAL PROCESS

The mathematical model, a mathematical representation of the static vapor pressure method of water removal is being developed to study the operating characteristics of Allis-Chalmers fuel cells under various loads, temperatures, pressures and initial states. It is known that concentration gradients develop in the electrolyte and gas cavities across the length of the cell (gas inlet to purge exhaust) and perpendicular to the plane of the asbestos matrix. The function of the mathematical model is to correlate these gradients with the various operating parameters and determine how long it takes these gradients to develop. It is hoped that the dynamic internal state of the fuel cell may eventually be correlated with fuel cell performance.

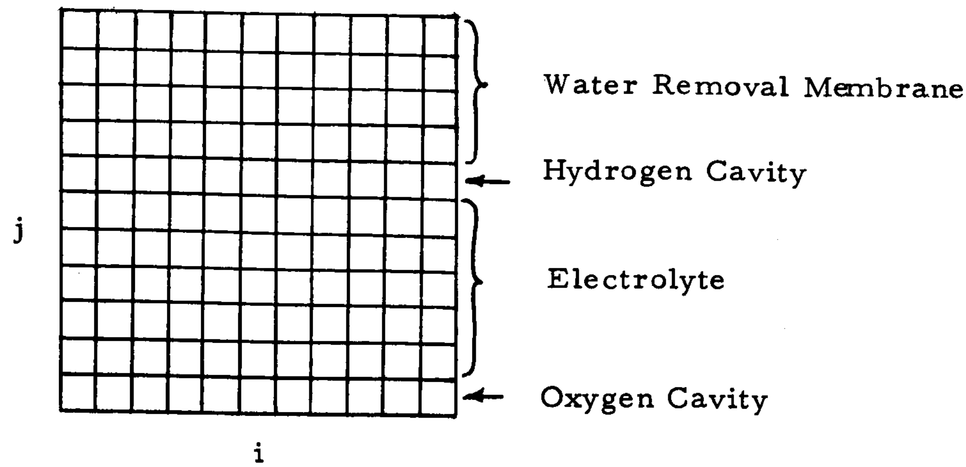
4.1 Development of the Model

As shown in the illustration, the cross section of the cell was divided into 121 two-dimensional elements to examine the concentrations of chemical species.

Several processes occur inside the fuel cell that account for the development of concentration gradients; diffusion of water into the electrolyte and gas cavities, water consumption at the oxygen electrode, water production at the hydrogen electrode, water transport through the elements due to gas flow, and diffusion between the gas cavity and electrolyte. One or more of these processes occur in all the elements of the model.

Diffusion takes place in the electrolyte and water removal membranes in the liquid phase, and in the hydrogen and oxygen cavities in the vapor phase. The net flow of water between two parallel planes is given by the following equation. Nomenclature appears in Section 4.3.

$$\frac{dW}{dt} = \frac{DAV}{dL} \left(C_{i-1,\,j} - 2\,C_{i,\,j} + C_{i+1,\,j} \right)$$



The equation applies to diffusion in the i direction. A similar expression was written for diffusion in the j direction.

The water produced at the anode is proportional to the electrical current in the section. This term, given by:

$$\frac{dW}{dt} = \frac{I\,i}{F} \quad ,$$

applies only to the elements in the electrolyte that are adjacent to the hydrogen cavity.

The water consumed at the cathode is equal to half the amount of water produced at the anode. The following equation applies to the elements in the electrolyte which are adjacent to the oxygen cavity.

$$\frac{dW}{dt} = \frac{I\,i}{2F}$$

The next equation represents the net addition of water into the elements in the gas cavities due to the flowing gas stream (convection).

$$\frac{dW}{dt} = \frac{It}{10\,n\,F} \quad \frac{(12 - i)\, R_o\, T_{i-1,\,j}\, C_{i-1,\,j}}{P_j - C_{i-1,\,j}\, R_o\, T_{i-1,\,j}} - \frac{(11 - i)\, C_{i,j}\, R_o\, T_{i,\,j}}{P_j - C_{i,\,j}\, R_o\, T_{i,\,j}}$$

The integer n is equal to 2 for the hydrogen cavity and 4 for the oxygen cavity.

Water diffusion from the electrolyte into the gas cavities, and vice-versa, was calculated by considering the liquid at the gas-liquid interface to be in equilibrium with the water vapor above the interface. Empirical relationships were then derived from tabulated data giving interface concentration versus vapor pressure. Since these relationships were temperature dependent, another empirical relationship between the constants obtained for the concentration equilibrium and temperature was derived. An exponential approximation, given below, provided sufficient accuracy.

$$C_{interface} = a\, C^{n}_{gas}$$

4.2 Computer Program For the Model

A computer program has been developed which computes the water concentration in each model element as a function of time. Basically, the program operates by storing the initial concentrations and other input data, computing the change in concentration in every element for a certain time interval and adding these increments to the initial concentrations. The new concentrations are then printed out and recorded in the storage locations of the old concentrations. This process proceeds until the model system comes to or approaches an equilibrium state.

The present version of the program will compute the concentrations for any current distribution, any gas or water removal cavity pressure, and any temperature distribution in the oxygen, hydrogen, and water removal cavities.

All relationships and properties that are temperature, pressure, and/or current dependent are taken into account in this program.

The results obtained from the program thus far are encouraging. The concentration gradients developed as anticipated. However, a great deal of computer time was required to achieve equilibrium because the time increment per iteration has to be very small. If the time increment was too large (greater than 0.05 second), the system solutions of the equations did not converge or reach an equilibrium state. Increasing the time increment as the system approached equilibrium or incorporating some other feature should speed up the program considerably.

It is anticipated that design information will arise from this study.

4.3 Nomenclature

$\frac{dW}{dt}$	Net water transported (moles/second)
D	Diffusion coefficient of water in KOH (cm^2/second)
A	Cross sectional area (cm^2)
U	Ratio of effective area for diffusion to the total area
dL	Distance between elements perpendicular to the flow of water (cm)
C	Water concentration (moles/cc)

I_i	Current per section (amperes)
I_t	Total current (amperes)
F	Faraday's constant (96, 500 coulombs per gram equivalent)
R_o	Universal gas constant (dyne cm/g mole °K)
a	Empirical constant (unitless)
n	Empirical constant (unitless)

5.0 CONCLUSIONS

The analysis of the storage of a 2 KW system in an environment of 117° K has been completed and design charts presented. For storage periods of duration greater than 600 hours it was found that the optimum storage temperature approached the environment temperature, or the lowest temperature which the fuel cell can withstand. The optimum insulation thickness was found to be zero for storage periods less than 400 hours. It increases rapidly after that length of time to a value of 0.0035 meters at 800 hours of storage (using super insulation). The added weight for this case would be 4.1 Kg.

A highly ideal rechargeable battery-fuel cell combination was found to be optimum for peak-power load sharing of durations up to 0.6 hours.

The literature survey of fuel storage and supply packages resulted in equations representing the weight of a system for the cases of supercritical and subcritical storage. For missions of normal energy requirements (400 KW-hour) subcritical storage has a weight advantage.

6.0 FUTURE WORK

1. Expansion of the computer program for fuel cell system parameter optimization will be continued. Debugging of the computer programs for the space radiator study and of the computer program for parallel battery-fuel cell combinations should be completed. The programs will then be used to create design tables for use in the fuel cell system parameter optimization program.

2. The study of the range of application of fuel cells versus other types of auxiliary power supplies should be completed.

3. The mathematical model of the static moisture removal system will be studied and an attempt will be made to reduce the computer time-real time ratio to a reasonable level.

4. Effort will be expended in the area of fuel cell module reliability and in formulating a mathematical model of cell degradation.

7.0 REFERENCES

1. Research and Development of Open Cycle Fuel Cells, NAS 8-5392-QPR-001, First Quarterly Progress Report, Research Division, Allis-Chalmers Manufacturing Company, November 15, 1964.

2. Cryogenic Tanks for Integrated Auxiliary Power and Environmental Control Systems Phase I, by C. W. Spieth, et al. Beachcraft Engineering, Report Number 9756A of March 1961.

3. Energy Conversion for Space - Editor, N. W. Snyder "Sterling Engine Development for Space Power" M. O. Parker and C. L. Smith.

4. Design of Space Powerplants - D. B. Mackay (Prentice-Hall, 1963).

5. Nuclear Energy in Space - E. S. Pedersen (Prentice-Hall, 1964).

6. Rotary, Deployable Space Solar Power Supply - by H. Schuerch and W. Robbins, N64-33801.

7. Power Systems - Advances and Levels, by E. Ray and D. Rose, in Astronautics and Aeronautics, January 1965, pages 36 - 43.

LIST OF ILLUSTRATIONS

FUEL CELL ASSEMBLY

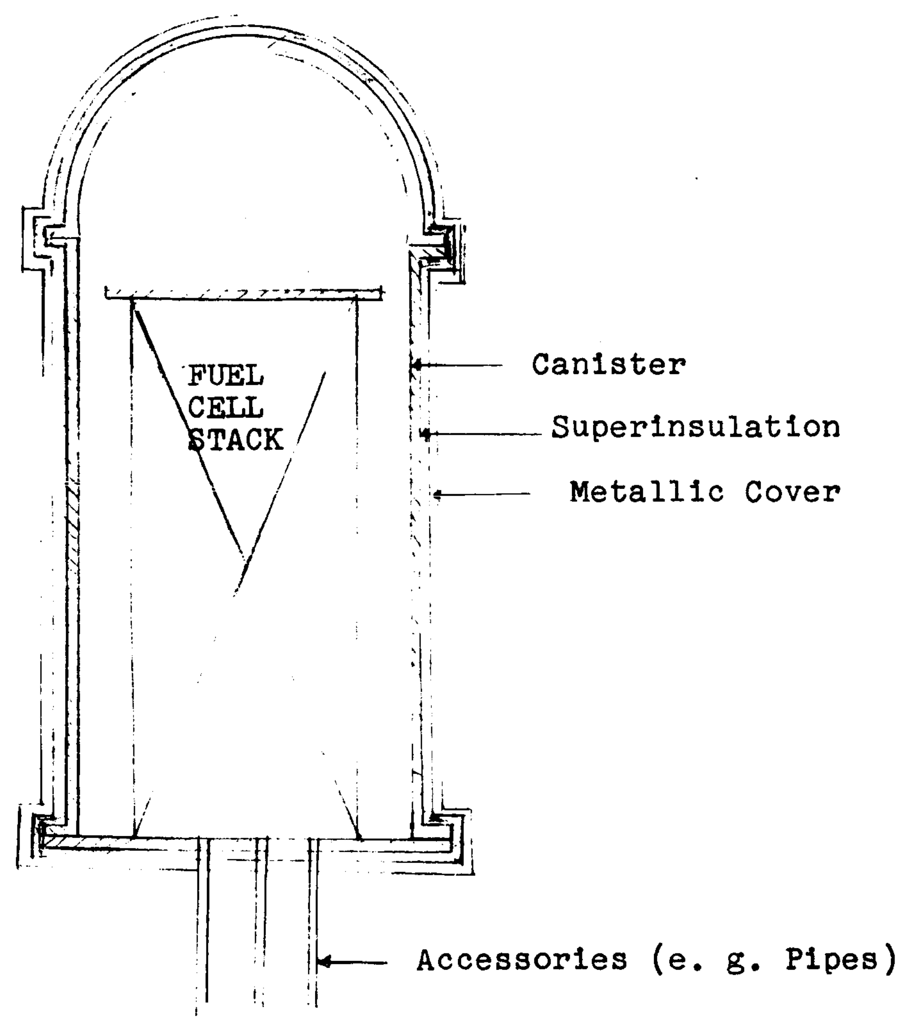


Figure 1

OPTIMUM ADDITIONAL WEIGHT REQUIRED TO MAINTAIN A 2KW SYSTEM FOR VARIOUS STORAGE PERIODS

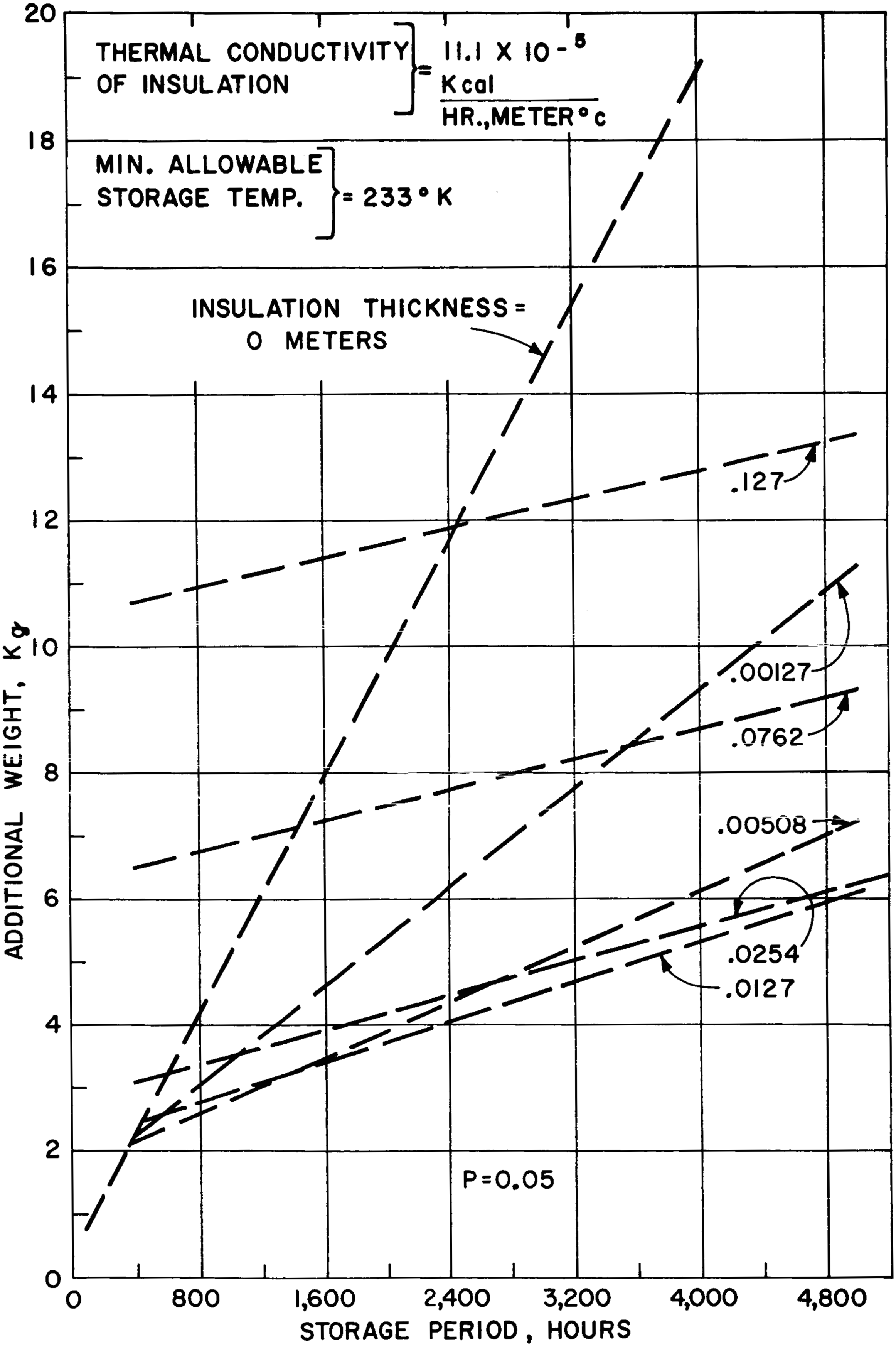


FIGURE 2

OPTIMUM ADDITIONAL WEIGHT REQUIRED TO MAINTAIN A 2KW SYSTEM FOR VARIOUS STORAGE PERIODS

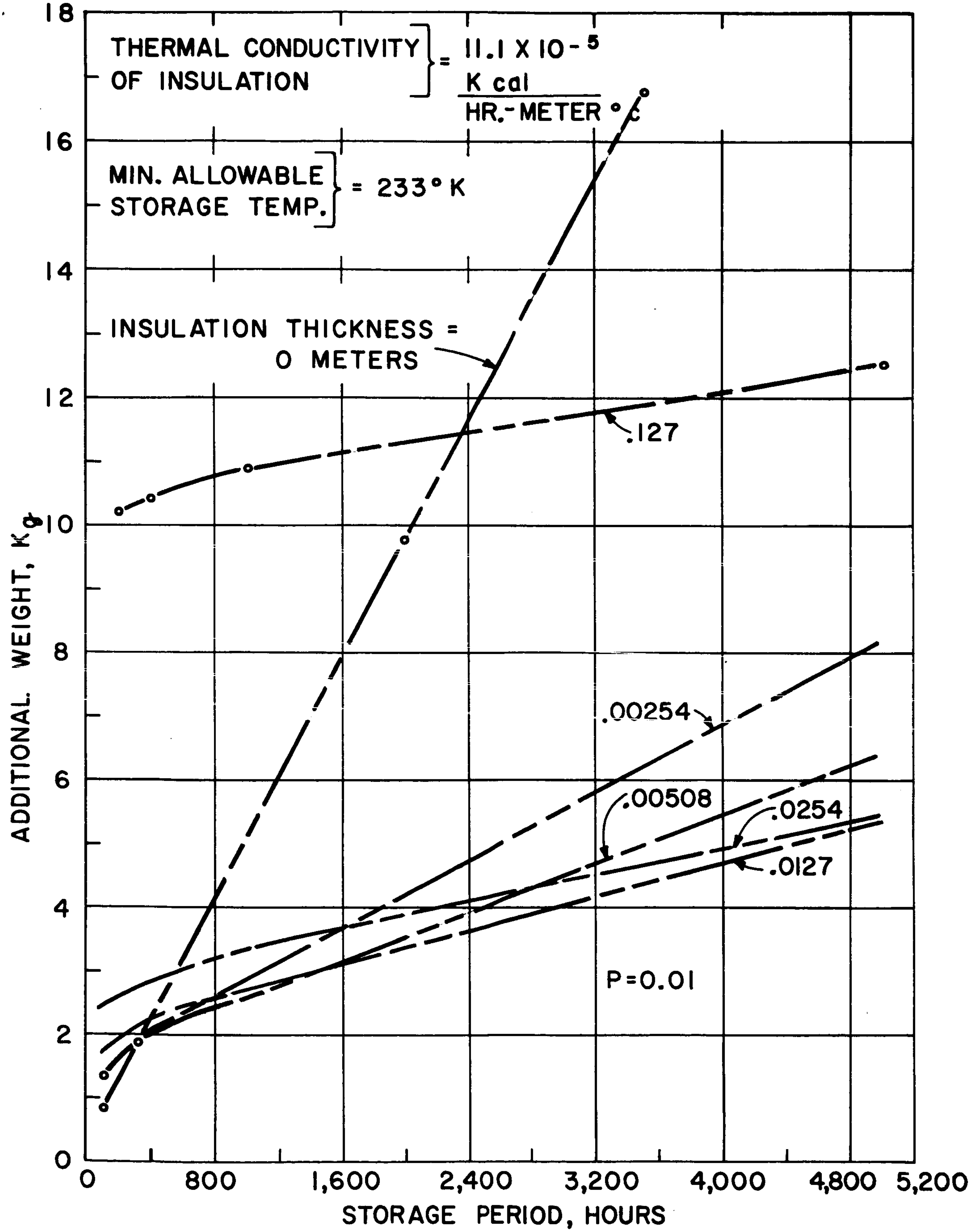


FIGURE 3

OPTIMUM ADDITIONAL WEIGHT REQUIRED TO MAINTAIN A 2KW SYSTEM FOR VARIOUS STORAGE PERIODS

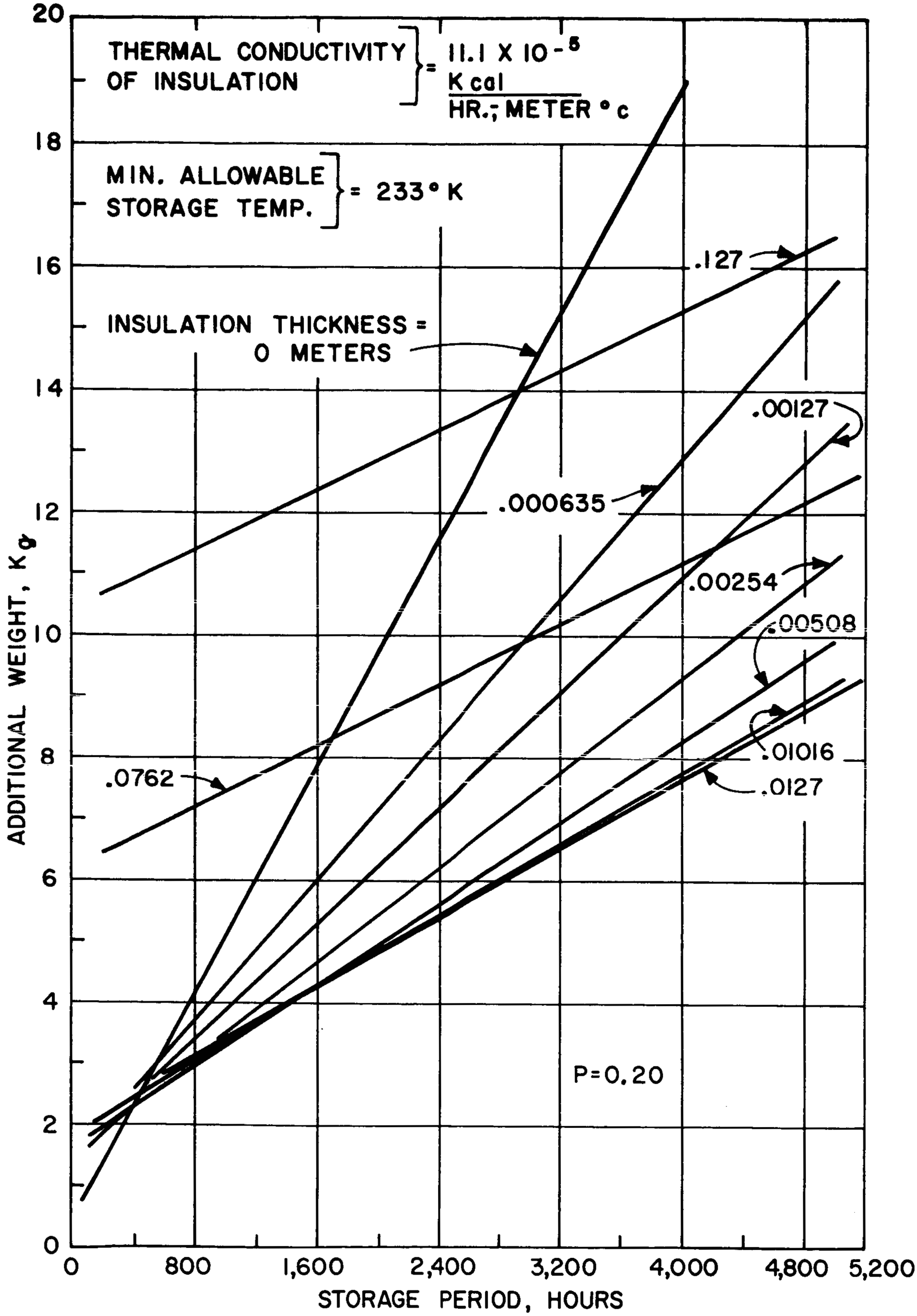


FIGURE 4

OPTIMUM STORAGE TEMP. FOR VARIOUS STORAGE PERIODS

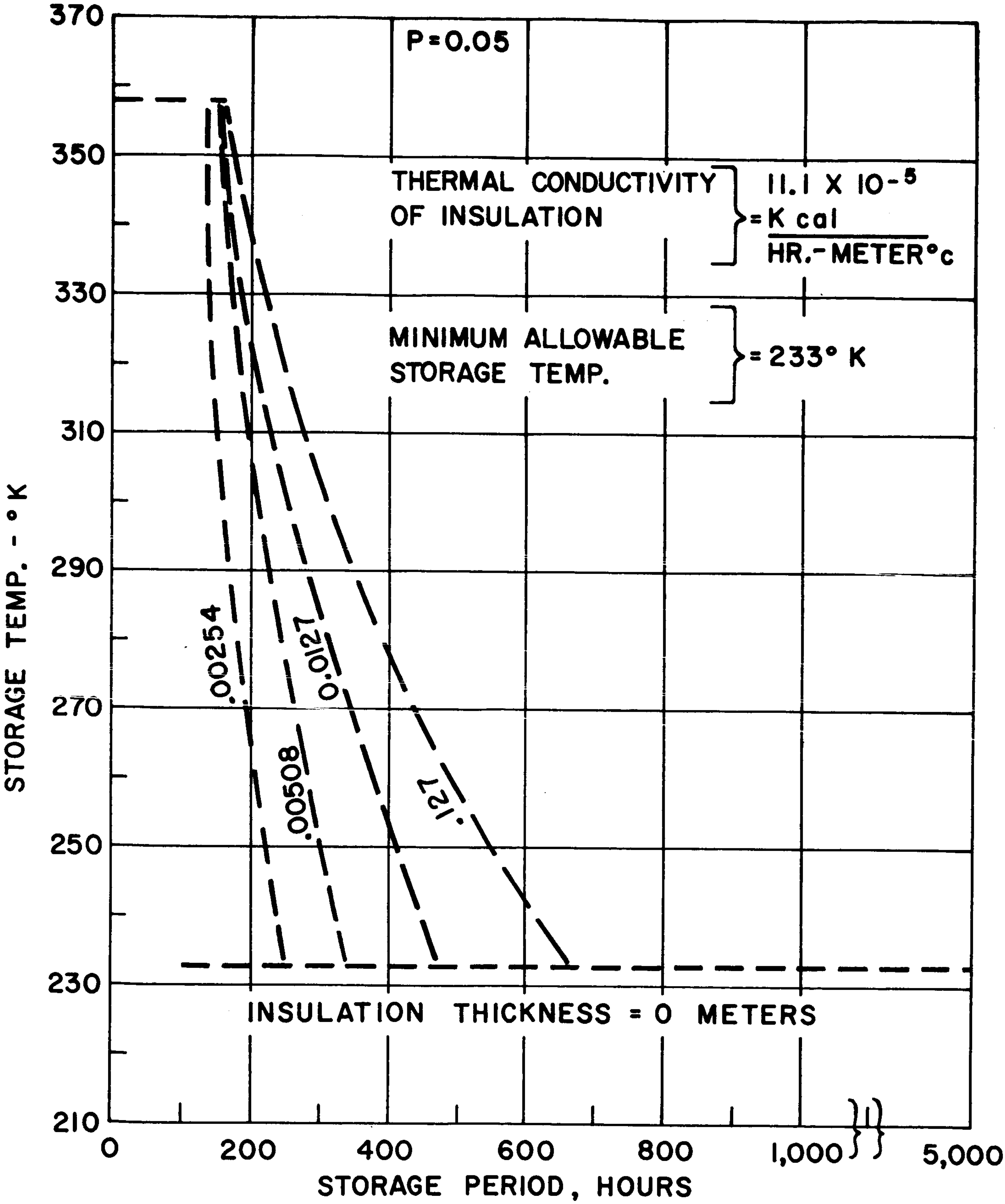


FIGURE 5

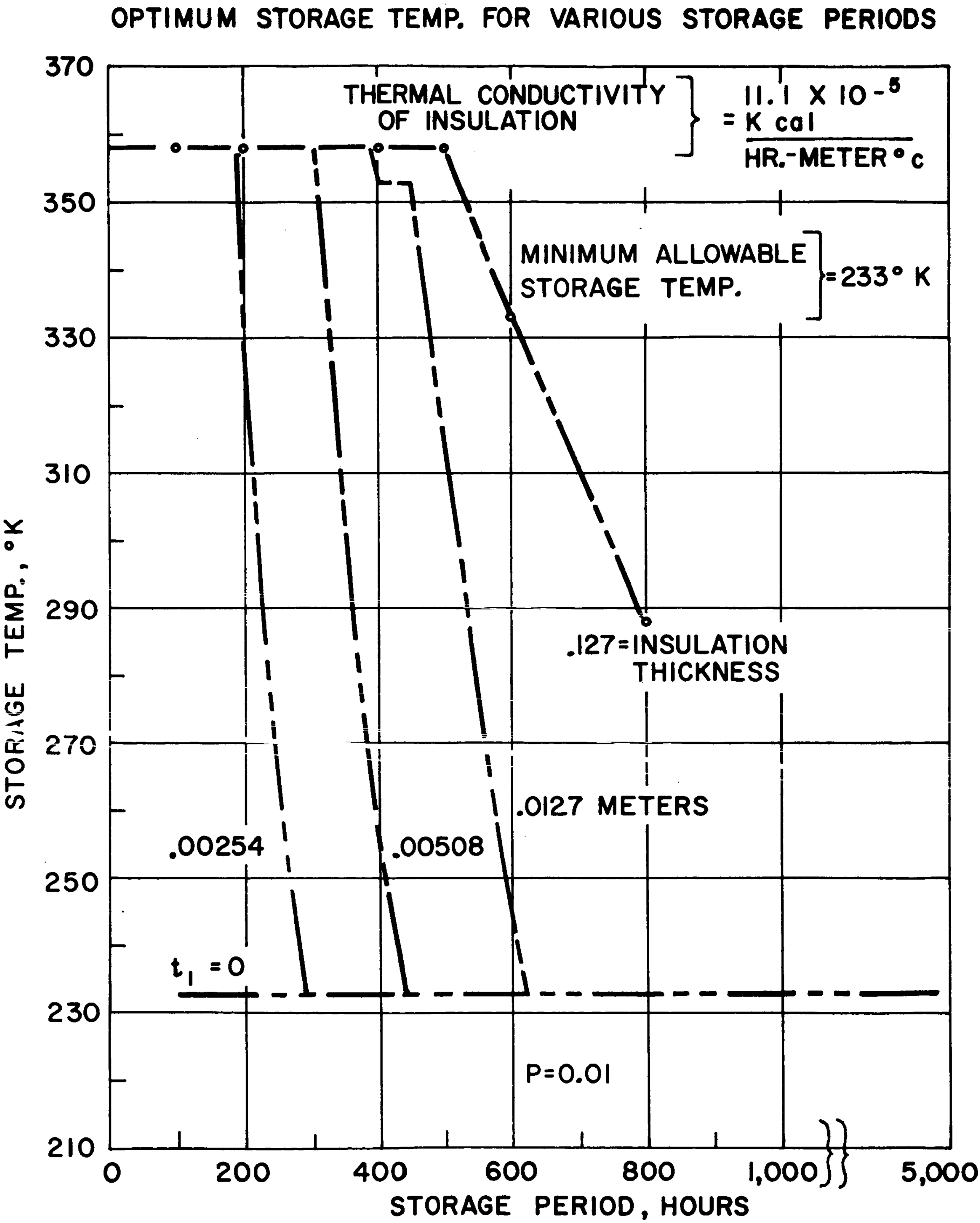

OPTIMUM STORAGE TEMP. FOR VARIOUS STORAGE PERIODS
THERMAL CONDUCTIVITY OF INSULATION = 11.1 X 10^-5 K cal / HR.-METER °c
MINIMUM ALLOWABLE STORAGE TEMP. = 233° K
.127 = INSULATION THICKNESS
.0127 METERS
.00254
.00508
t1 = 0
P=0.01
STORAGE TEMP., °K
STORAGE PERIOD, HOURS
370
350
330
310
290
270
250
230
210
0
200
400
600
800
1,000
5,000

FIGURE 6

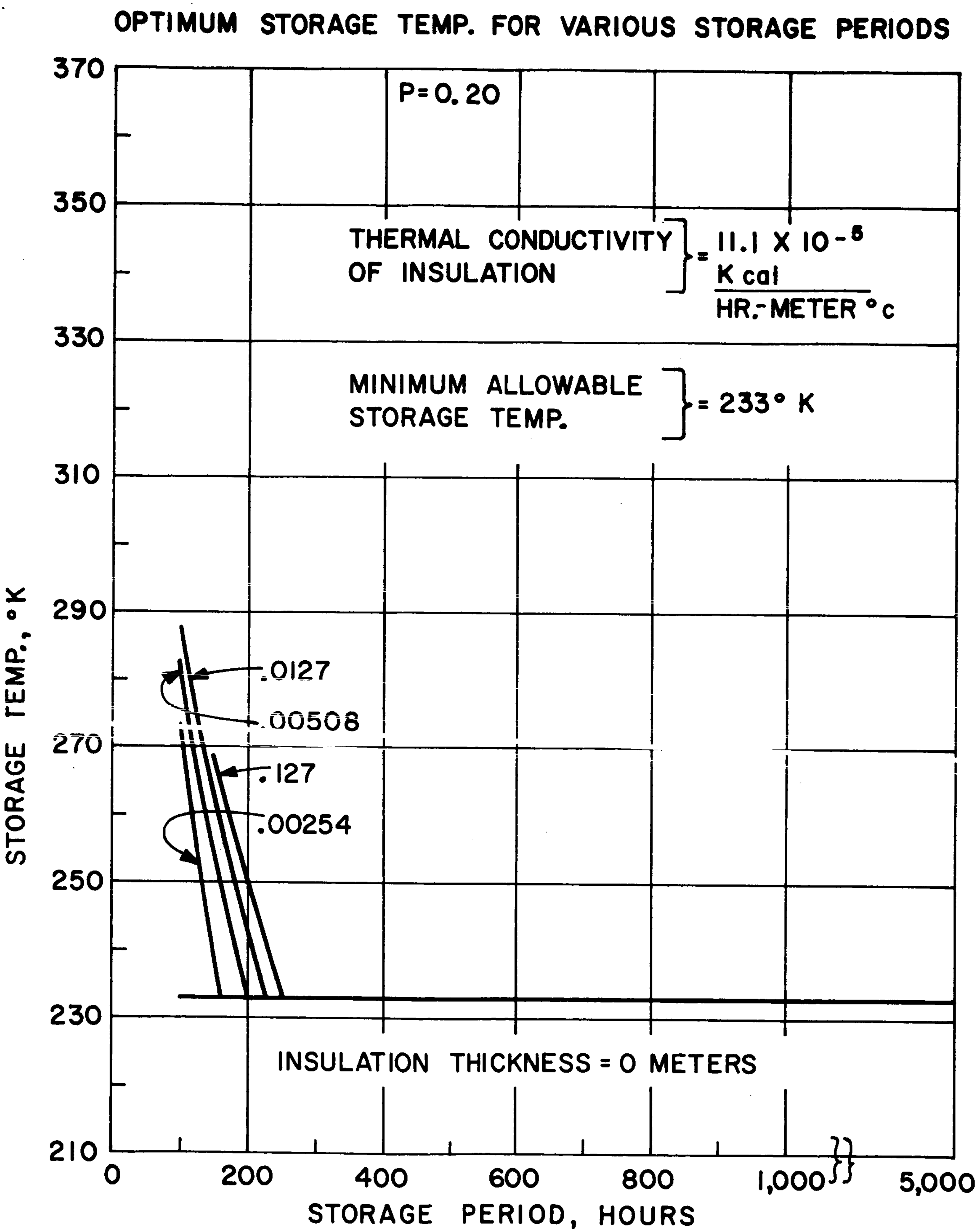
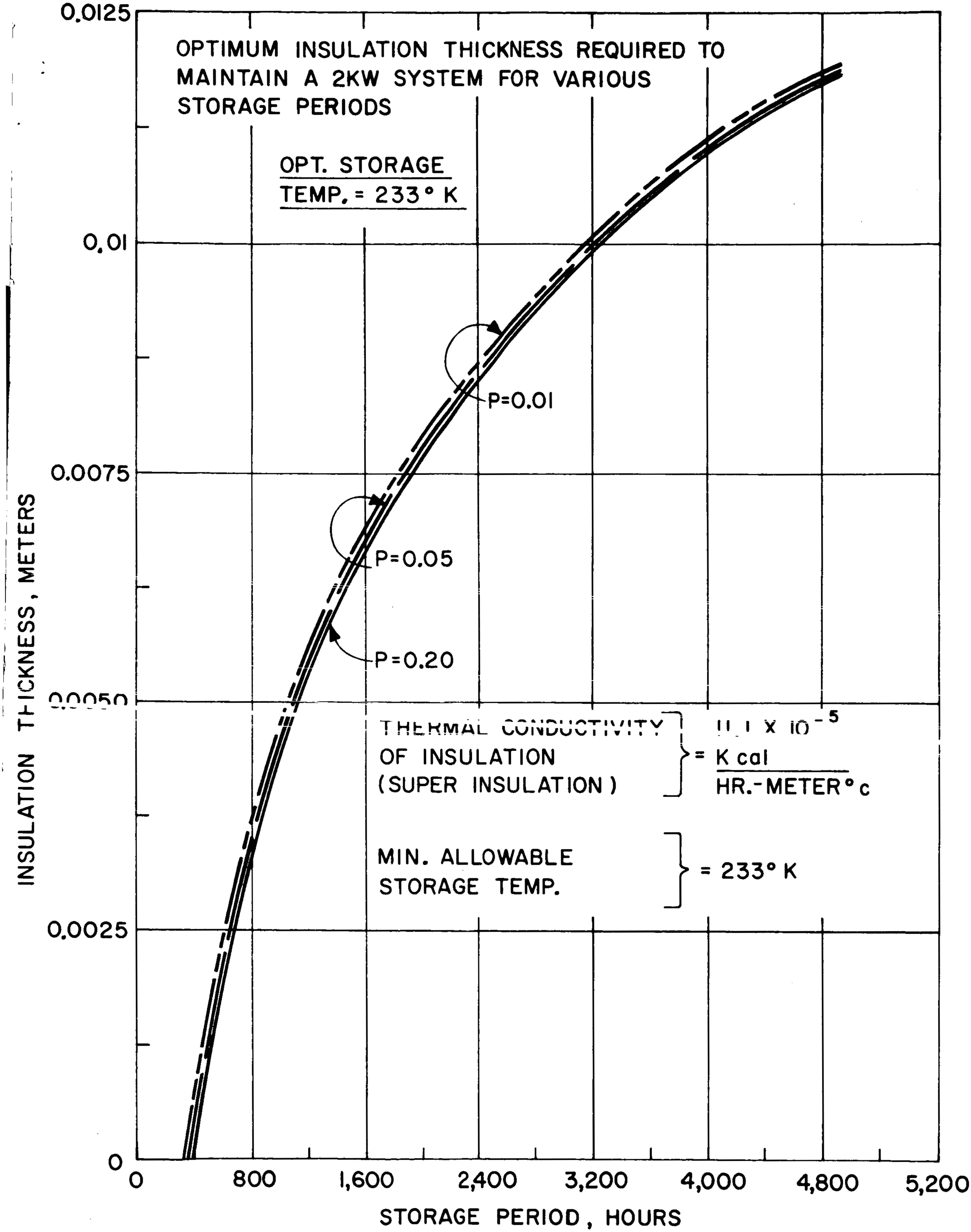

OPTIMUM STORAGE TEMP. FOR VARIOUS STORAGE PERIODS
P=0.20
THERMAL CONDUCTIVITY OF INSULATION = 11.1 X 10^-5 K cal / HR.-METER °c
MINIMUM ALLOWABLE STORAGE TEMP. = 233° K
.0127
.00508
.127
.00254
INSULATION THICKNESS = 0 METERS
STORAGE TEMP., °K
370
350
330
310
290
270
250
230
210
0
200
400
600
800
1,000
5,000
STORAGE PERIOD, HOURS

FIGURE 7



OPTIMUM INSULATION THICKNESS REQUIRED TO MAINTAIN A 2KW SYSTEM FOR VARIOUS STORAGE PERIODS
OPT. STORAGE TEMP. = 233° K
P=0.01
P=0.05
P=0.20
THERMAL CONDUCTIVITY OF INSULATION (SUPER INSULATION)
= K cal / HR.-METER° c
MIN. ALLOWABLE STORAGE TEMP. = 233° K
INSULATION THICKNESS, METERS
0.0125
0.01
0.0075
0.0050
0.0025
0
0
800
1,600
2,400
3,200
4,000
4,800
5,200
STORAGE PERIOD, HOURS

FIGURE 8

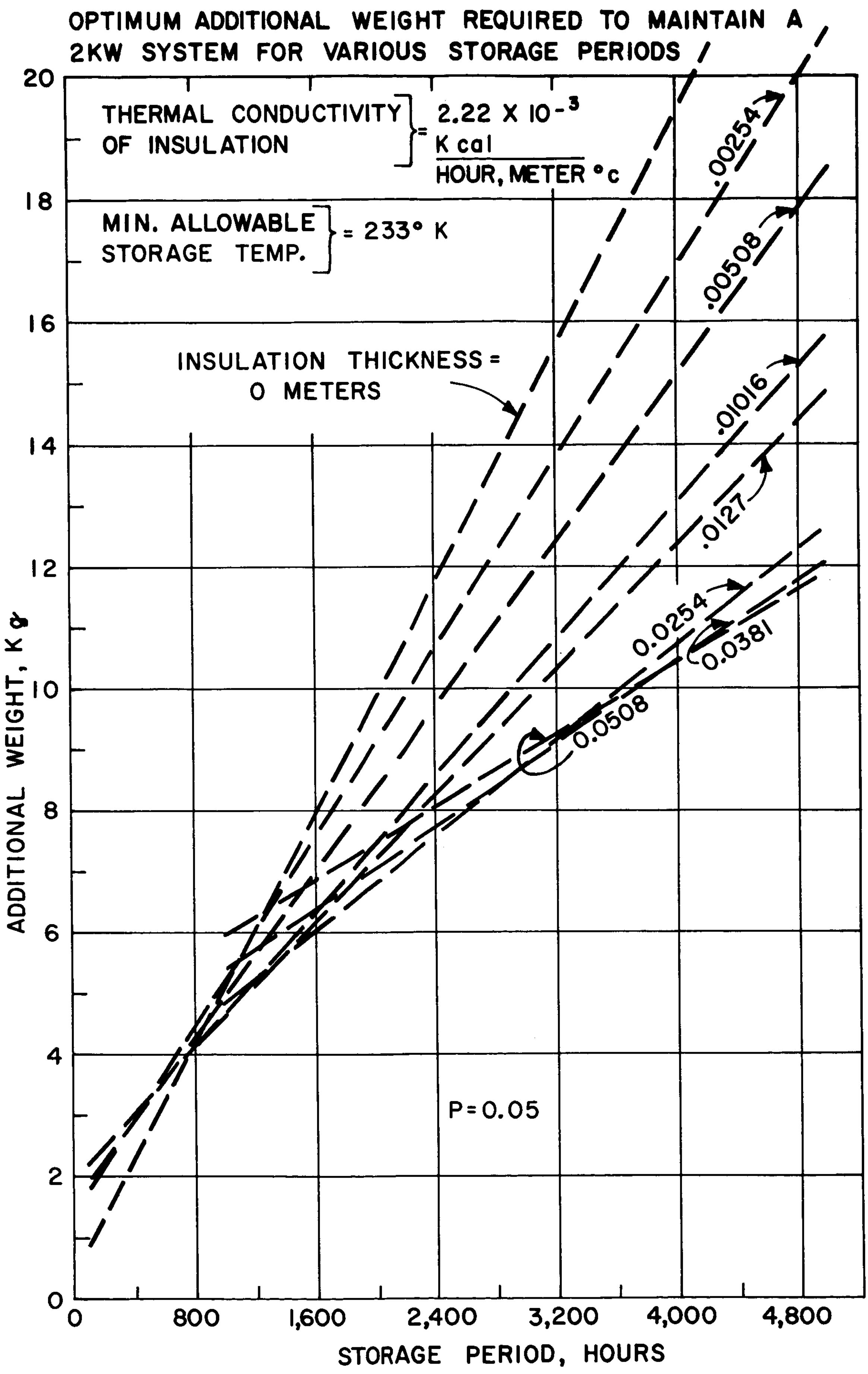

OPTIMUM ADDITIONAL WEIGHT REQUIRED TO MAINTAIN A 2KW SYSTEM FOR VARIOUS STORAGE PERIODS
THERMAL CONDUCTIVITY OF INSULATION = 2.22 X 10^-3 K cal / HOUR, METER °c
MIN. ALLOWABLE STORAGE TEMP. = 233° K
INSULATION THICKNESS = 0 METERS
.00254
.00508
.01016
.0127
0.0254
0.0381
0.0508
P=0.05
ADDITIONAL WEIGHT, Kg
STORAGE PERIOD, HOURS
0
2
4
6
8
10
12
14
16
18
20
800
1,600
2,400
3,200
4,000
4,800

FIGURE 9

OPTIMUM ADDITIONAL WEIGHT REQUIRED TO MAINTAIN 2KW SYSTEM FOR VARIOUS STORAGE PERIODS

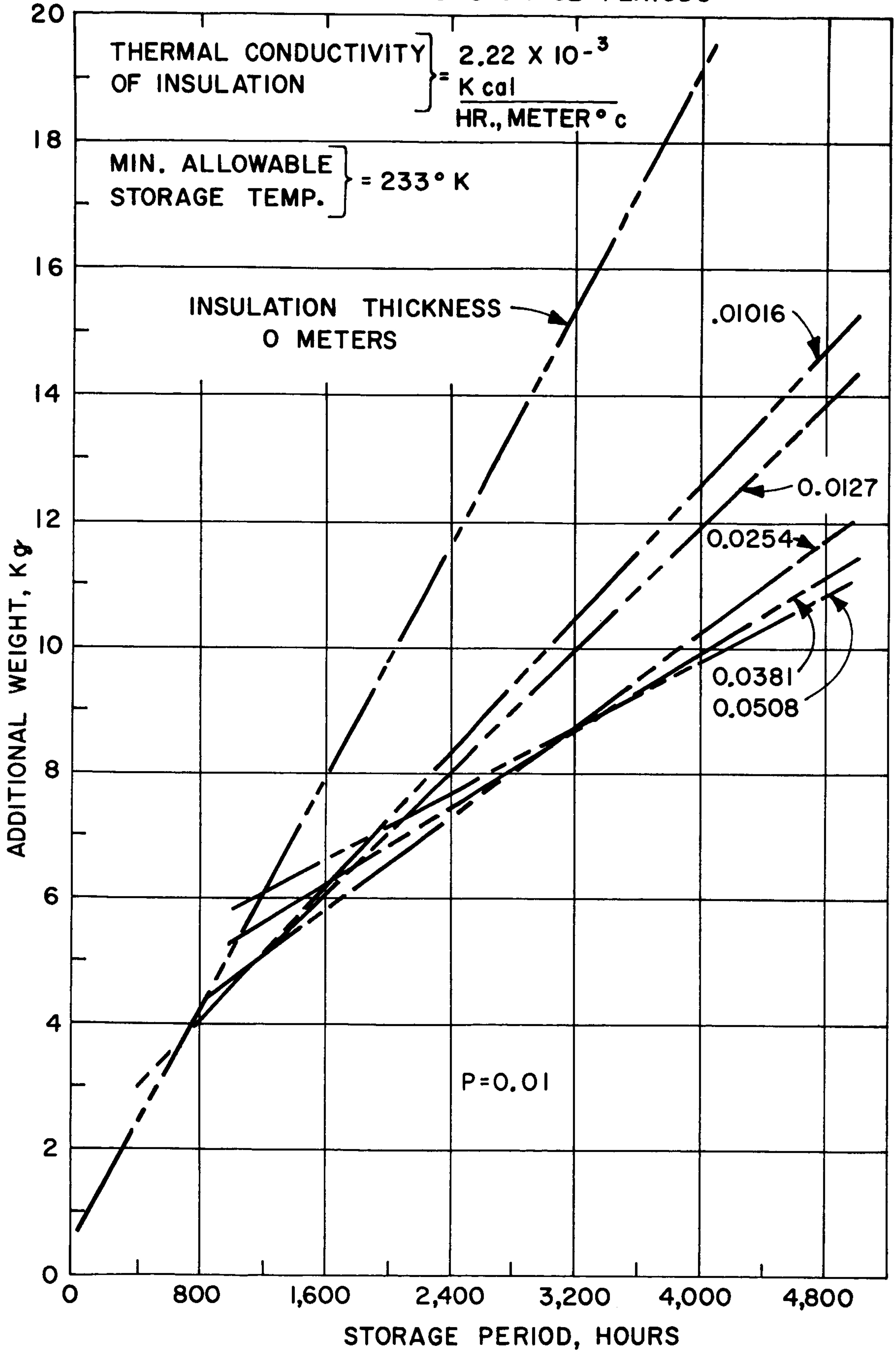


FIGURE 10

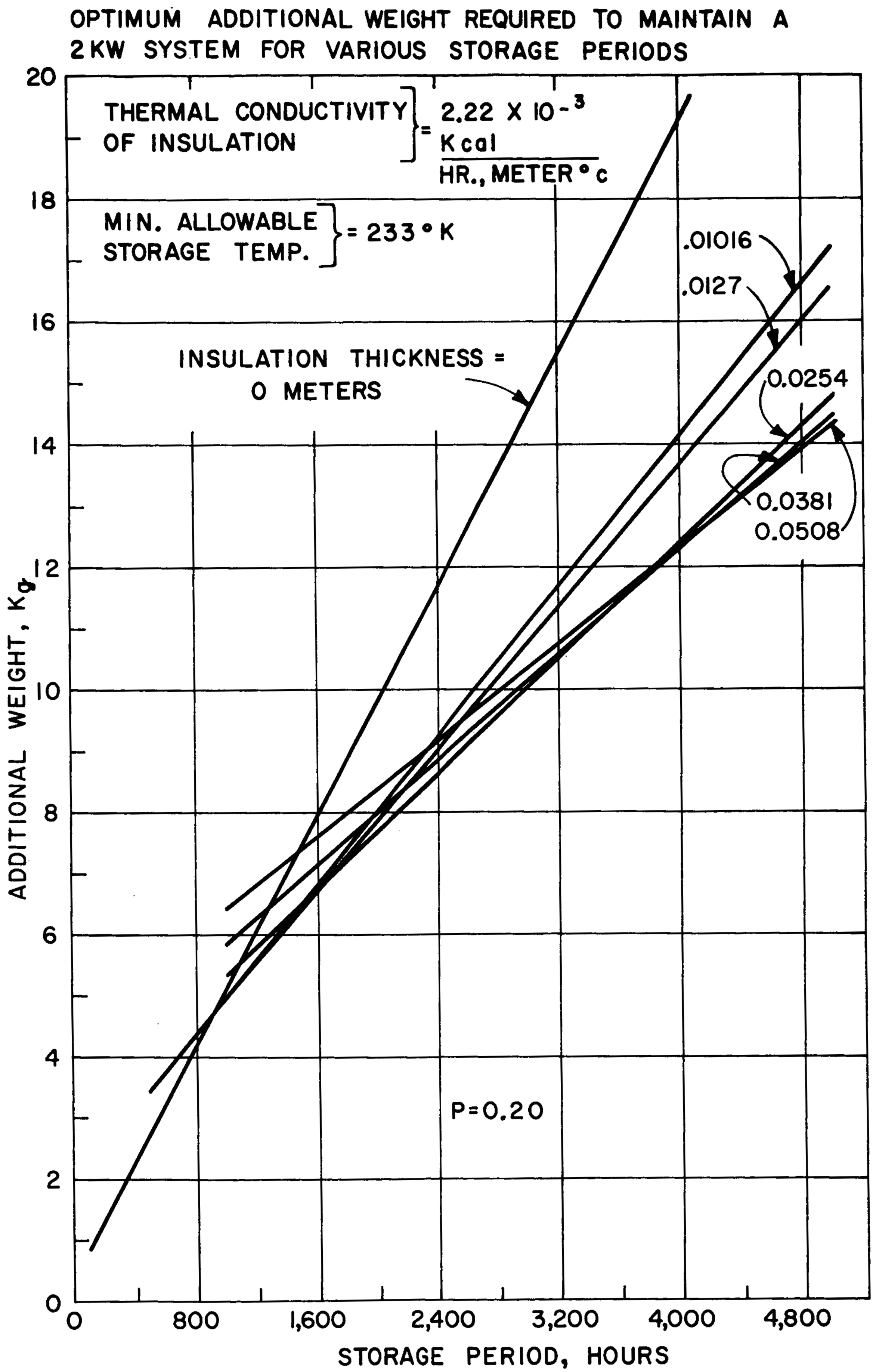

OPTIMUM ADDITIONAL WEIGHT REQUIRED TO MAINTAIN A 2 KW SYSTEM FOR VARIOUS STORAGE PERIODS
THERMAL CONDUCTIVITY OF INSULATION = 2.22 X 10^-3 Kcal / HR., METER °c
MIN. ALLOWABLE STORAGE TEMP. = 233 °K
INSULATION THICKNESS = 0 METERS
.01016
.0127
0.0254
0.0381
0.0508
P=0.20
ADDITIONAL WEIGHT, Kg
STORAGE PERIOD, HOURS
0
2
4
6
8
10
12
14
16
18
20
0
800
1,600
2,400
3,200
4,000
4,800

FIGURE 11

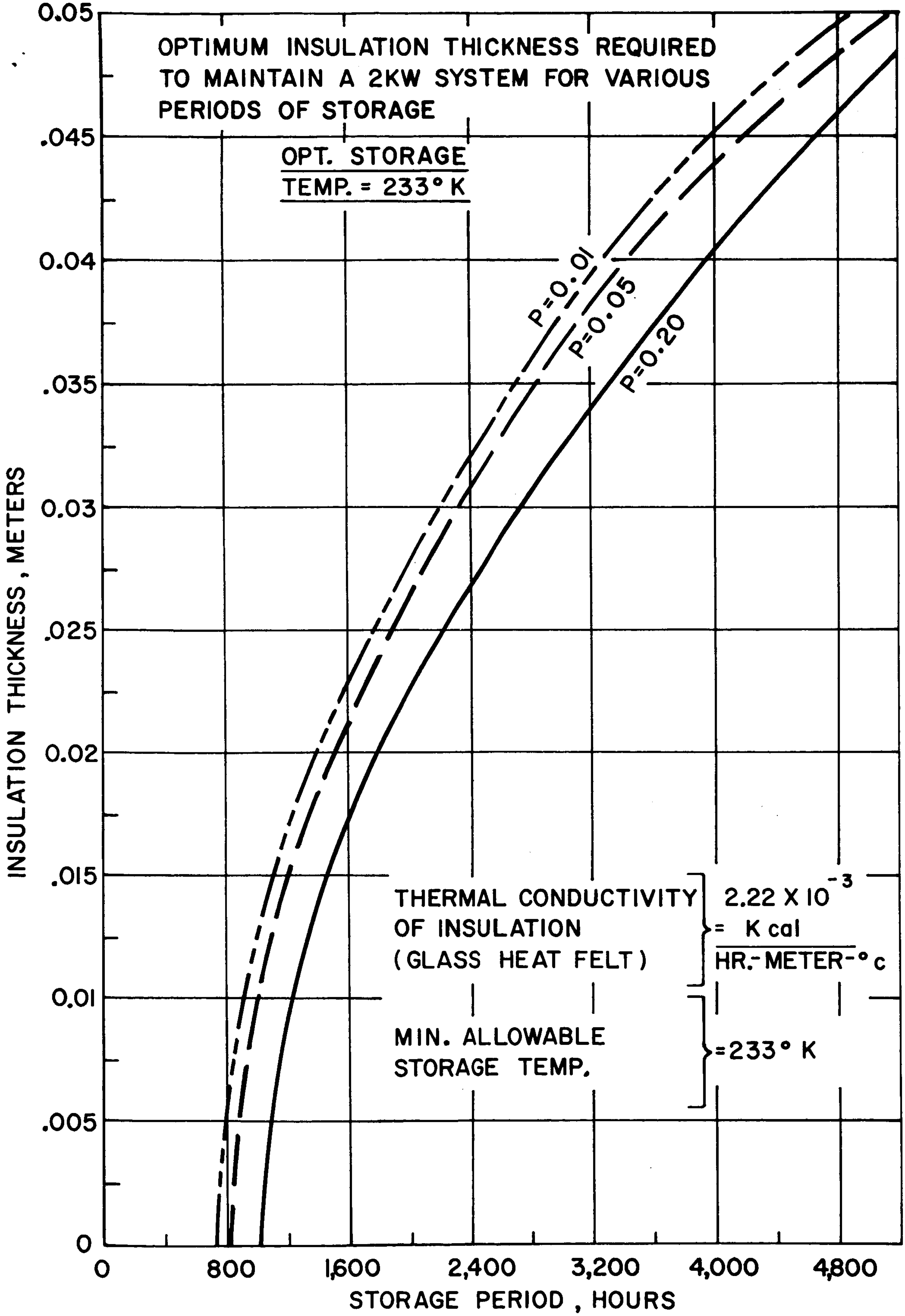
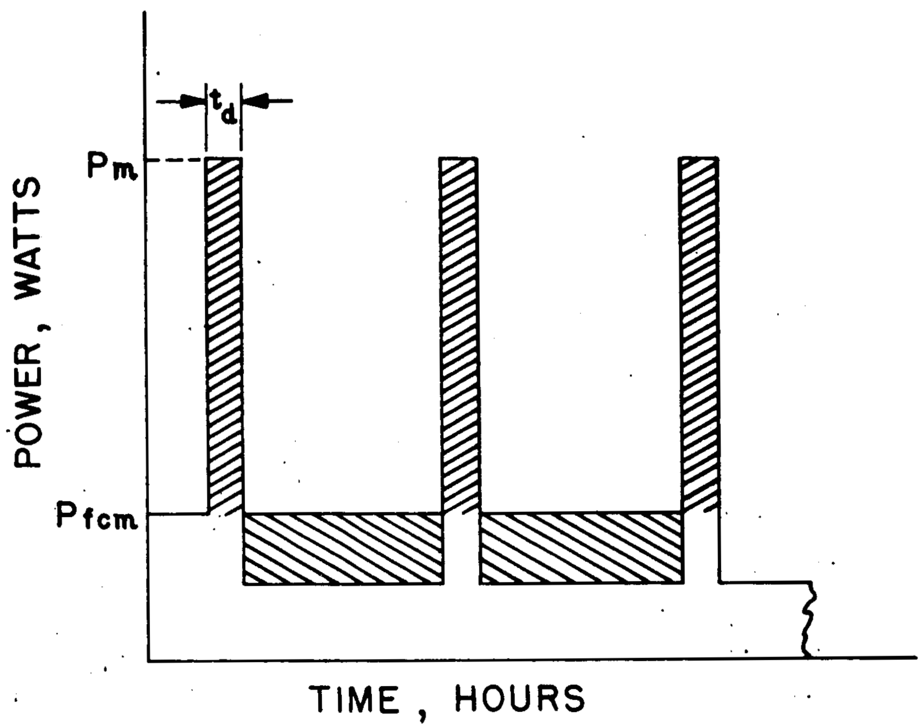

OPTIMUM INSULATION THICKNESS REQUIRED TO MAINTAIN A 2KW SYSTEM FOR VARIOUS PERIODS OF STORAGE
OPT. STORAGE TEMP. = 233° K
P=0.01
P=0.05
P=0.20
THERMAL CONDUCTIVITY OF INSULATION (GLASS HEAT FELT) = 2.22 X 10^-3 K cal / HR.-METER-°C
MIN. ALLOWABLE STORAGE TEMP. = 233° K
INSULATION THICKNESS, METERS
0.05
.045
0.04
.035
0.03
.025
0.02
.015
0.01
.005
0
STORAGE PERIOD, HOURS
0
800
1,600
2,400
3,200
4,000
4,800

FIGURE 12



E_d = ENERGY DISCHARGED

E_c = ENERGY REQUIRED TO RECHARGE THE BATTERY

FIGURE 13

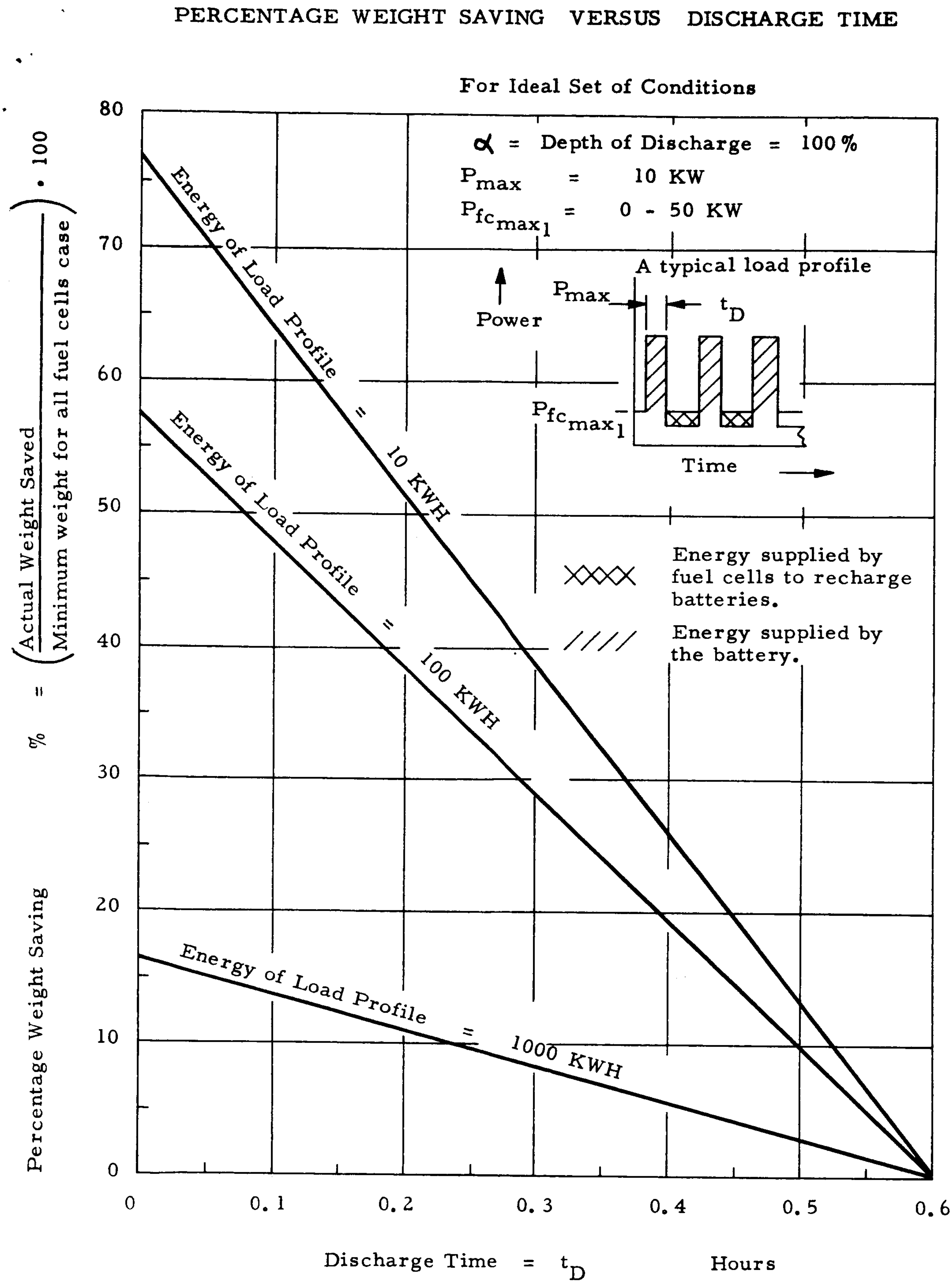

PERCENTAGE WEIGHT SAVING VERSUS DISCHARGE TIME
For Ideal Set of Conditions
α = Depth of Discharge = 100 %
P max = 10 KW
P fc max 1 = 0 - 50 KW
A typical load profile
Power
P max
t D
P fc max 1
Time
Energy supplied by fuel cells to recharge batteries.
Energy supplied by the battery.
Energy of Load Profile = 10 KWH
Energy of Load Profile = 100 KWH
Energy of Load Profile = 1000 KWH
Percentage Weight Saving
% = (Actual Weight Saved / Minimum weight for all fuel cells case) • 100
80
70
60
50
40
30
20
10
0
0
0.1
0.2
0.3
0.4
0.5
0.6
Discharge Time = t D Hours

Figure 14

PERCENTAGE WEIGHT SAVING VERSUS DISCHARGE TIME

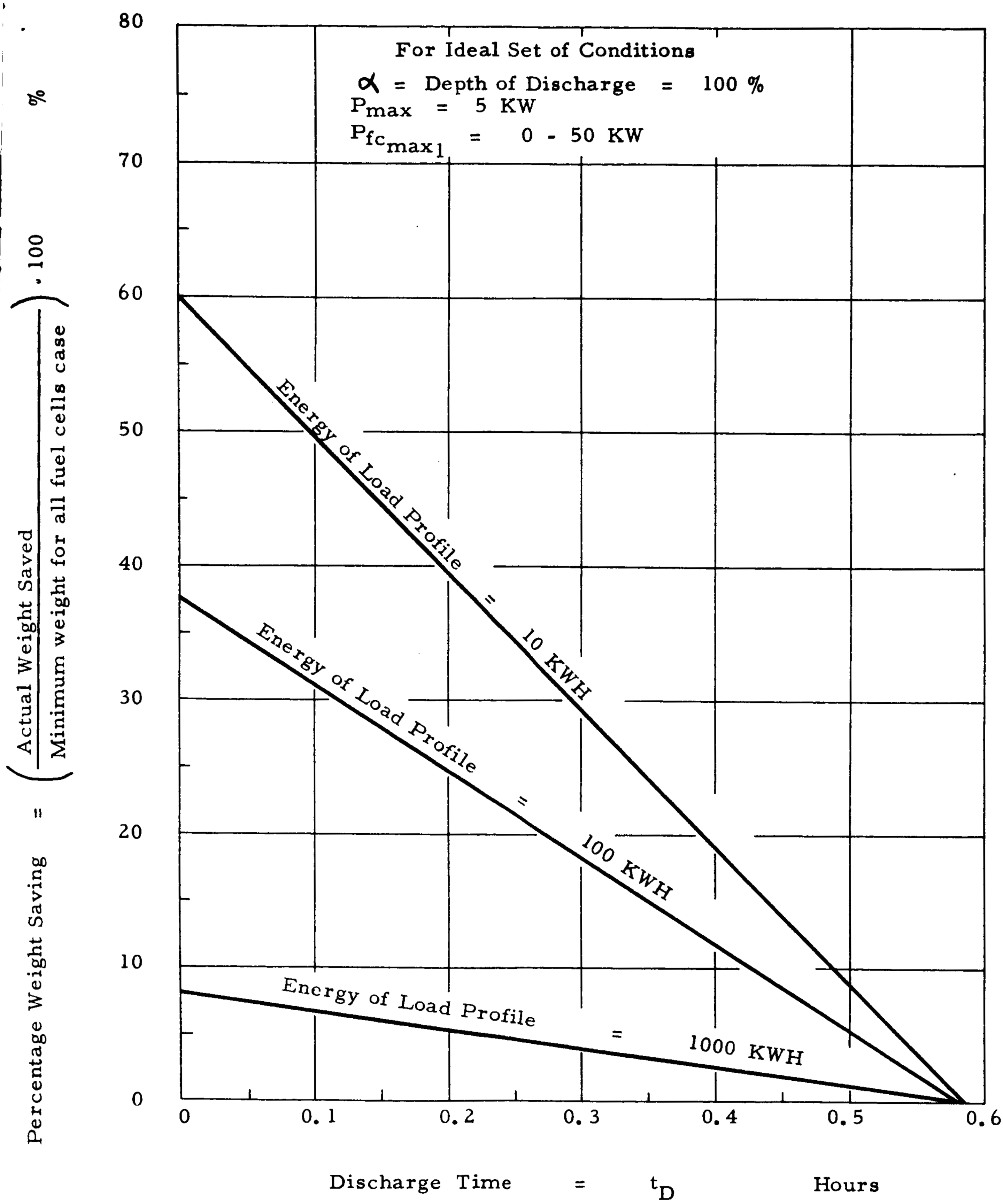


Figure 15

PERCENTAGE WEIGHT SAVING VERSUS DISCHARGE TIME

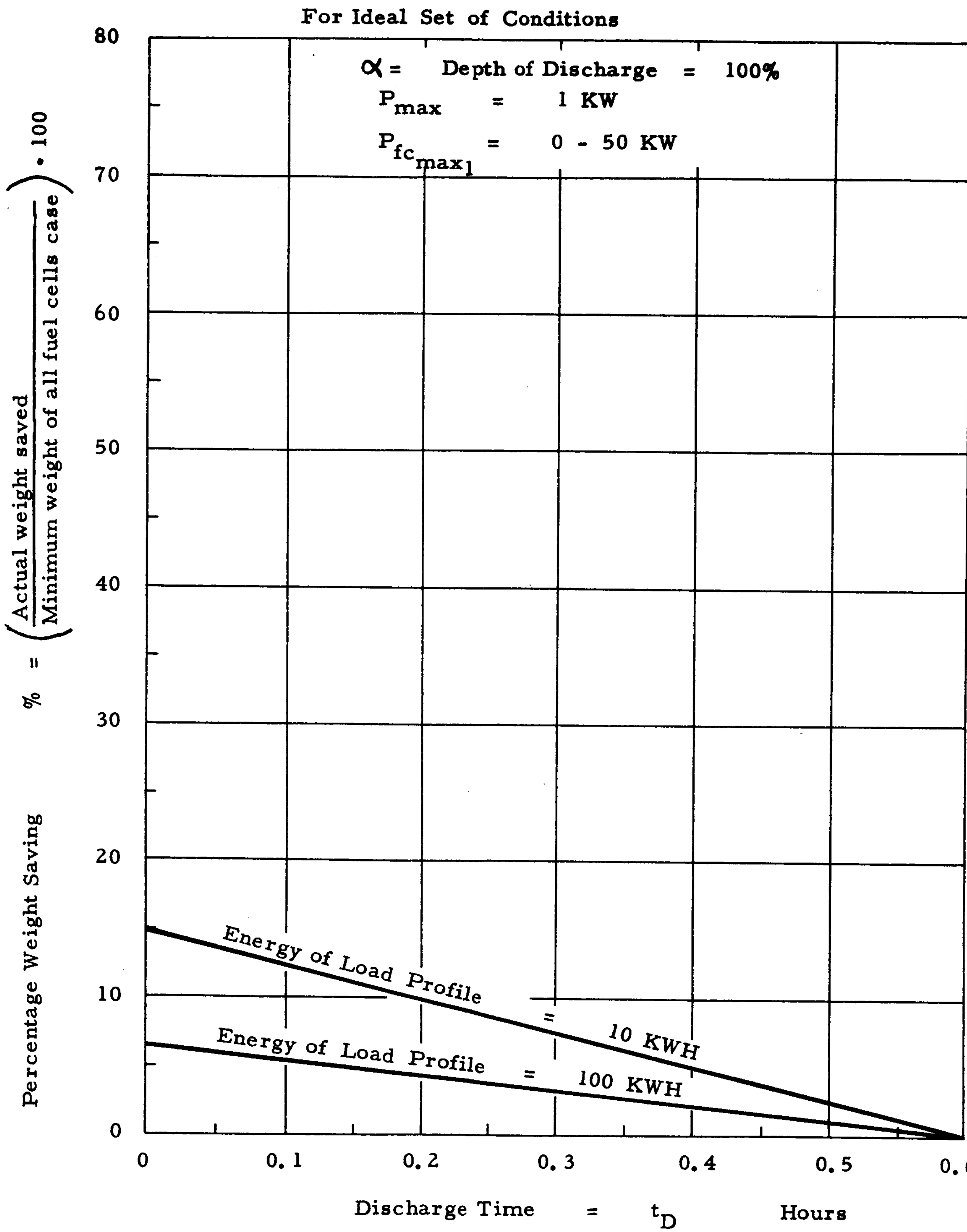


Figure 16

MIRROR EFFICENCY

ASSUMPTIONS

1. $\frac{\text{DIAMETER ABSORBER}}{\text{DIAMETER MIRROR}} = .02$
2. ABSORBER COATED WITH DEPOSITED COPPER OXIDE
3. DEPOSITED SILVER MIRROR

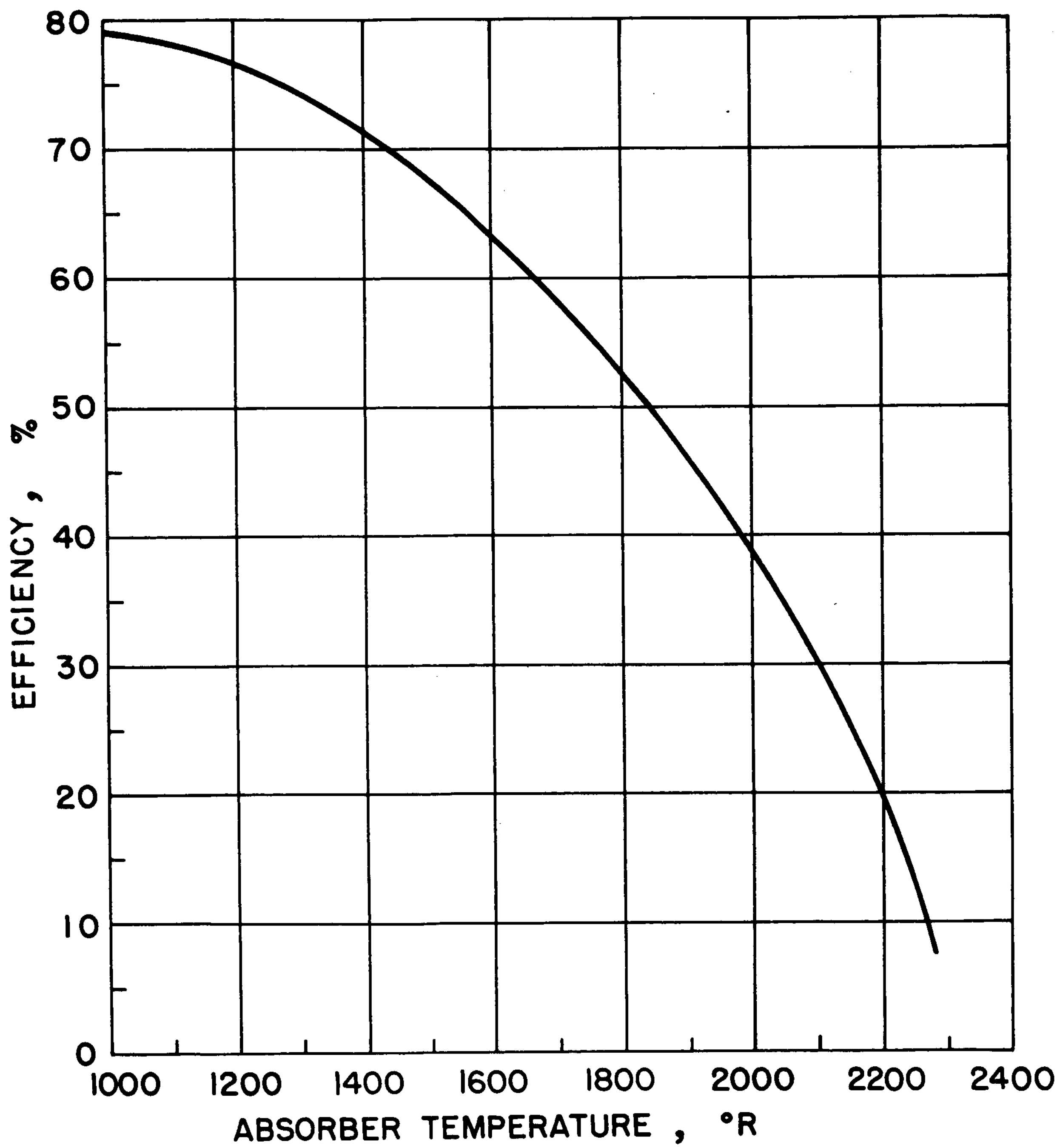


FIGURE 17

RADIATOR SPECIFIC WEIGHT LB / KW

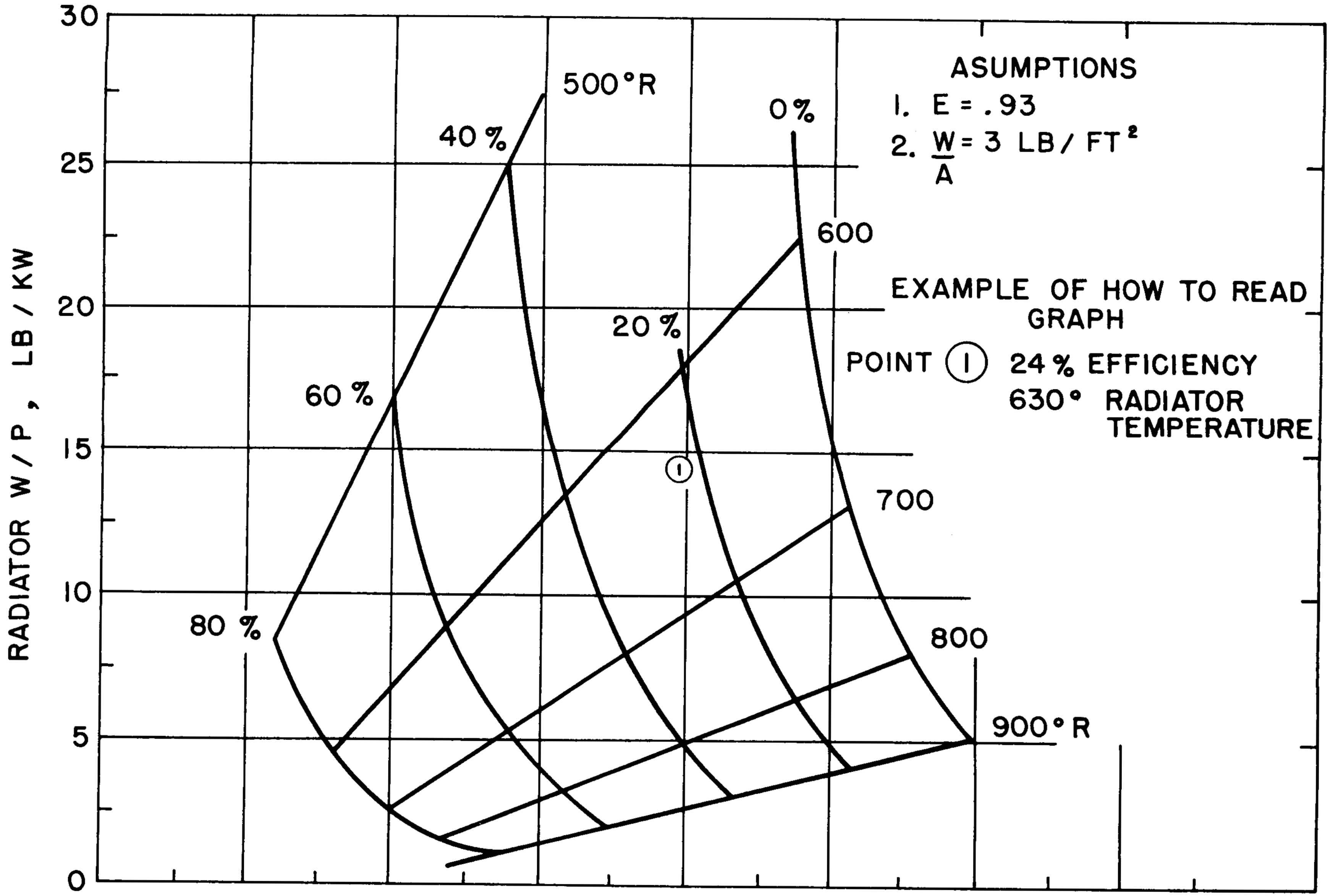


FIGURE 18

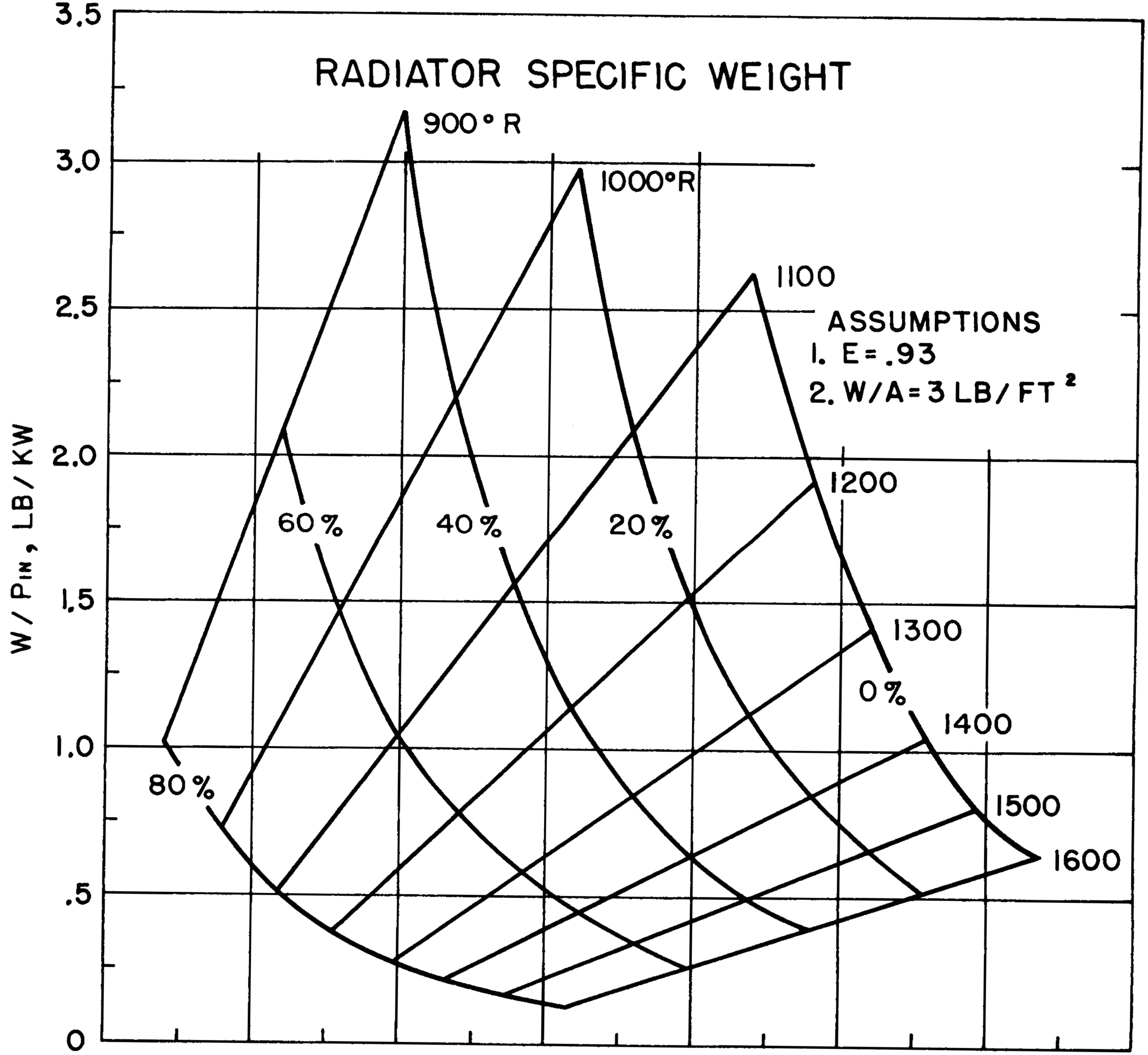

RADIATOR SPECIFIC WEIGHT
900° R
1000°R
1100
1200
1300
1400
1500
1600
ASSUMPTIONS
1. E= .93
2. W/A=3 LB/FT²
60%
40%
20%
0%
80%
W/PIN, LB/KW
3.5
3.0
2.5
2.0
1.5
1.0
.5
0

FIGURE 19

SYSTEM SPECIFIC WEIGHT VS MISSION TIME

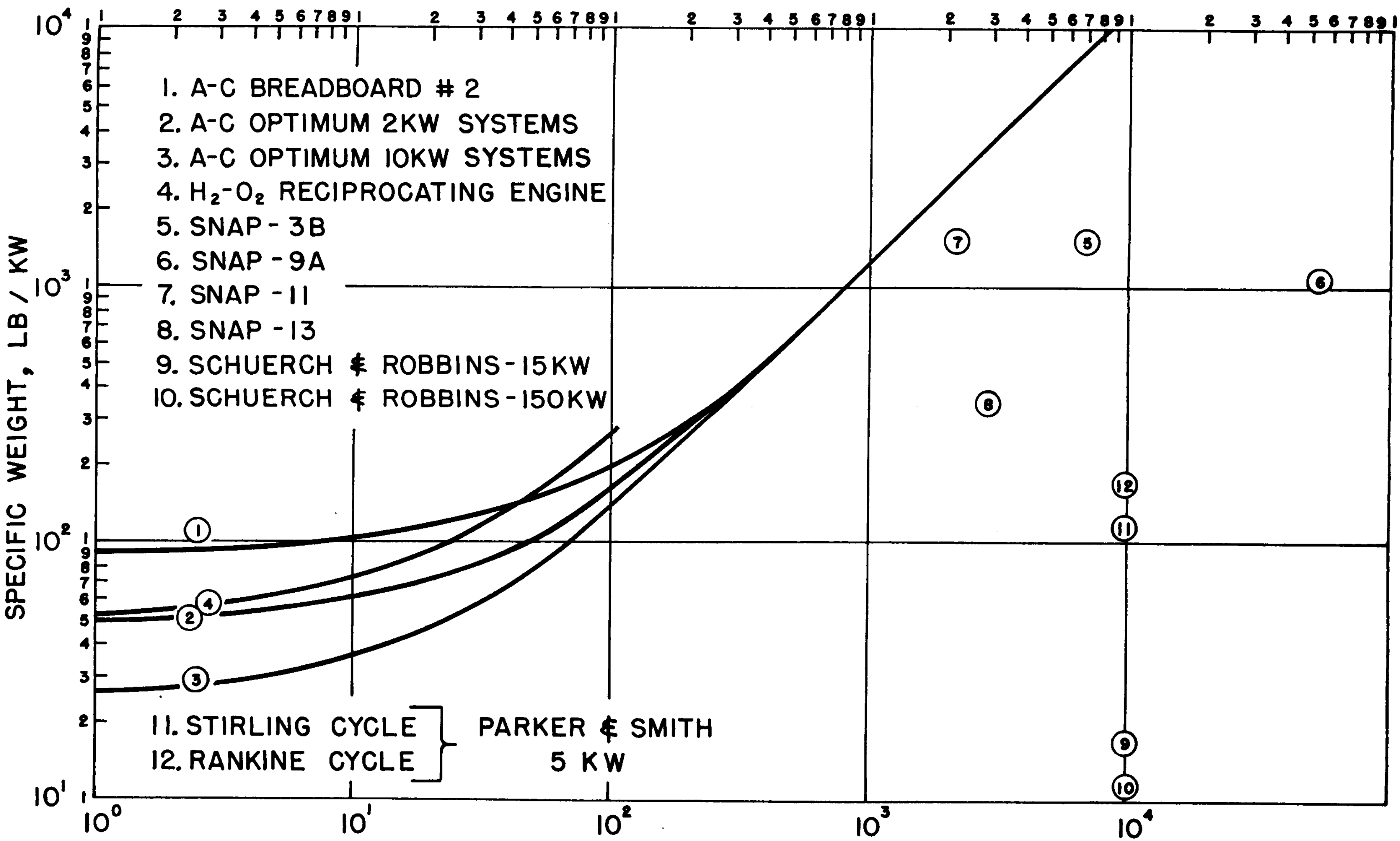


FIGURE 20