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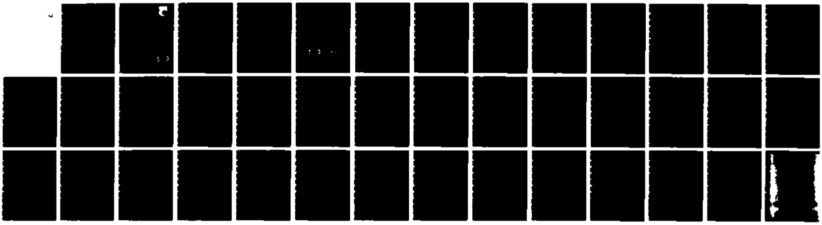

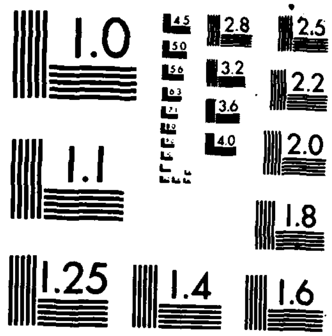


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# WEIGHT CHARACTERISTICS OF FUTURE SPACECRAFT THERMAL MANAGEMENT SYSTEMS

John W. Sheffield, Ph.D.

Mechanical and Aerospace Engineering
University of Missouri-Rolla

FEBRUARY 1984

FINAL REPORT FOR PERIOD JANUARY 1983 - OCTOBER 1983



AERO PROPULSION LABORATORY
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*FOR THE COMMANDER*

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This report presents the results of an investigation on the weight characteristics of future spacecraft thermal management systems. The sensitivity of the thermal management system weight to the performance requirements of both evolutionary and revolutionary spacecraft missions has been studied. A numerical analysis modelling the transient heat flow through the thermal management system was performed. The performance parameters included the peak thermal load and the peak-to-average thermal load ratio. In addition the sensitivity of the thermal management system weight to the choice of phase change material for heat storage was determined via a heat of fusion parametric analysis.

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# FOREWORD

The information presented in this report was generated during the performance of the task 11 of Contract No. F33615-81-C-2058. The technical work was carried out at the University of Missouri-Rolla, Department of Mechanical and Aerospace Engineering.

Dr John W. Sheffield was the principal investigator of the program. This is a final report which presents the results generated during the period of the program. The program was sponsored by the Aeronautical Systems Division of the Air Force with Ms V. J. Van Griethuysen of the Energy Conversion Branch at the Aero Propulsion Laboratory (AFWAL/POOC) serving as the technical monitor. The work was performed during the period of 1 January 1983 to 30 ~~September~~ OCT. 1983.

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# SYMBOLS

| | |
|---|---|
| A | Area of heat transfer |
| C | Specific heat of component |
| G | Specific weight of component |
| H | Latent heat of fusion of the phase change material |
| M | Mass of component |
| N | Number of cycles of the periodic heat rejection load |
| Q | Rate of heat flow from the thermal bus |
| Q' | Rate of heat flow through the heat pipes |
| Q'' | Rate of heat flow through the phase change material |
| Q''' | Rate of heat flow through the radiator |
| T | Temperature of component |
| t | Time variable |
| U | Coefficient of heat transfer |
| X | Melt fraction of the phase change material |

Subscripts

| | |
|---|---|
| 1 | heat pipes |
| 2 | phase change material |
| 3 | radiator |
| A | average |
| O | initial |
| P | peak |
| S | space |

## SECTION I

## INTRODUCTION

Future spacecraft missions under current consideration have introduced challenging technology needs for spacecraft thermal management systems. The thermal control, heat storage, heat transport, and heat rejection of the envisioned missions represent a set of major problems when the design constraints of spacecraft payload weight and volume are included. One of the challenging requirements of the thermal management system is the capability to handle large, peak-to-average ratio of the heat transfer rates [1]. Although current spacecrafts handle peak-to-average ratios of 10 to 1 by sensible heat storage, louvered radiators and variable conductance heat pipes, these techniques can not be employed for higher peak-to-average ratios without suffering significant weight penalties and imposing component temperature limitations.

The design of a thermal management system requires the measurement and determination of a large number of factors and their interdependence [2-3]. The integration of mission requirements and payload requirements might be considered as the first step in the overall design process. The second step before arriving at a preliminary design step is the system tradeoff [4] of the configuration, thermal structures and subsystems. The goal at this second step in the overall thermal design process is to meet all the payload and mission requirements.

This report primarily addresses spacecraft thermal management systems and components to provide a rational basis for the development of future technologies and to identify areas of basic research that are related to the needs of future systems. Results of the analysis are presented and recommendations are made regarding the necessary advancements needed to meet future requirements.

A numerical analysis modelling the transient heat flow through the thermal management system was performed. The time-averaged specific weights, i.e. the rate of heat transfer per mass of the subsystem, were obtained by numerical integration and the weights of the components were calculated. The sensitivity of the weights to the performance requirements was studied. The performance parameters included the peak thermal load and the peak-to-average thermal load ratio. In addition the sensitivity of the weights to the choice of phase change material for heat storage was determined via a heat of fusion parametric analysis. A final parameter which was analyzed was the length of time for the peak thermal load.

## SECTION II

## SELECTION OF THE BASELINE CONCEPT

### 1. INTRODUCTION

The task of this project was organized initially to develop a set of system level requirements for a large, pulsed-power loaded, thermal management system for future military spacecraft applications. Used as input to the development of preliminary design concepts, the system level requirements were defined parametrically. Six baseline design concepts are presented for comparison. The particular choice of design concepts was based solely on the need to have a range of thermal performance capabilities and not on potential comprehensive thermal management systems capable of handling all requirements. These design concepts are divided into two general classes: hybrid and passive systems. The hybrid systems involve some type of pumpe fluids, whereas the passive systems have no external pumping.

### 2. THERMAL MANAGEMENT SYSTEM CONCEPTS

Viable baseline concepts were generated by utilizing both variable conductance heat pipes and diode heat pipes, radiators, fixed body-mounted radiators, deployable radiators, and phase change material subsystems. Each concept has been synthesized by combining these components into a system to absorb the internally generated thermal energy and to transport the thermal energy to an external radiator and/or to an expendable material for rejection to space. Figures 1-6 illustrate the six concepts considered. The first concept shown in figure 1 is a simple system without phase change material for thermal buffering of the rejection heat load. This system is characterized by minimum thermal storage, variable conductance heat pipes for control of temperature, diode heat pipes for protection of the source and the radiator sized on the peak heat rejection load. Figure 2 shows a second passive control system with phase change material for thermal storage such that the radiator can be sized on an averaged heat rejection load. Figure 3 shows a system with the phase change material incorporated into the variable conductance heat pipe for thermal storage. The concept of micro-encapsulated phase change material allows for a maximized surface-to-volume ratio for the system. This characteristic of enhanced heat transfer along with the potential of the micro-encapsulated phase change material acting as a wicking material makes this third concept very promising. Figure 4 shows a system with the phase change material located at the radiator base. This system might combine the sensible heat storage of the radiator with the phase change material

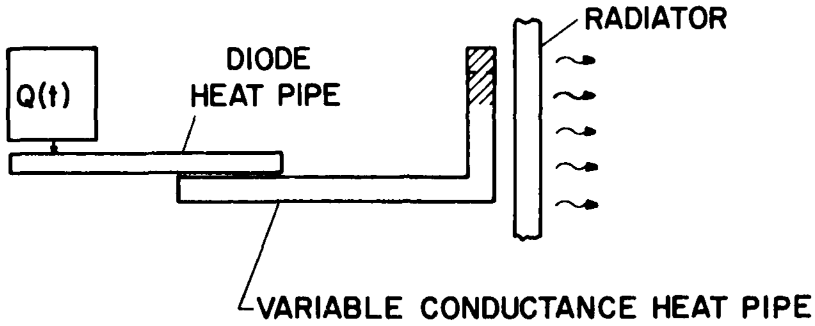



Figure 1 Passive Concept 1

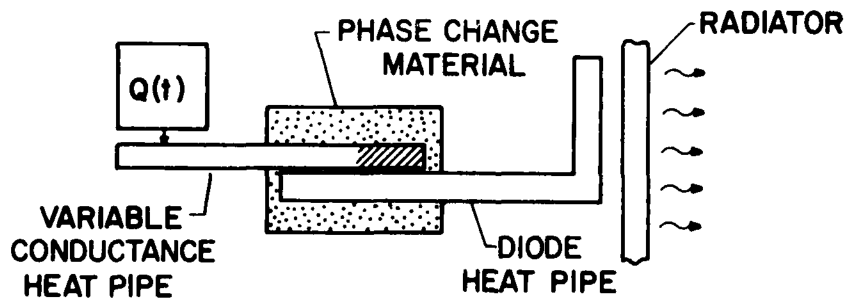



Figure 2 Passive Concept 2

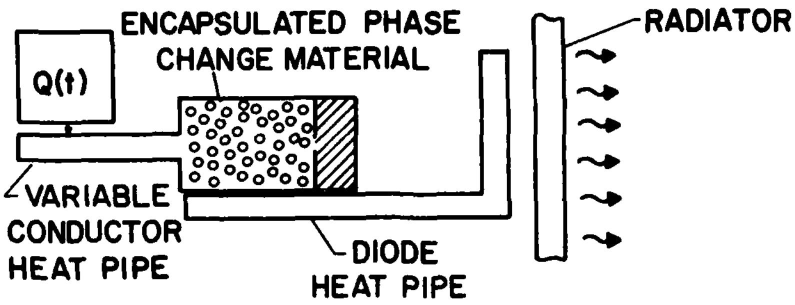



Figure 3 Passive Concept 3

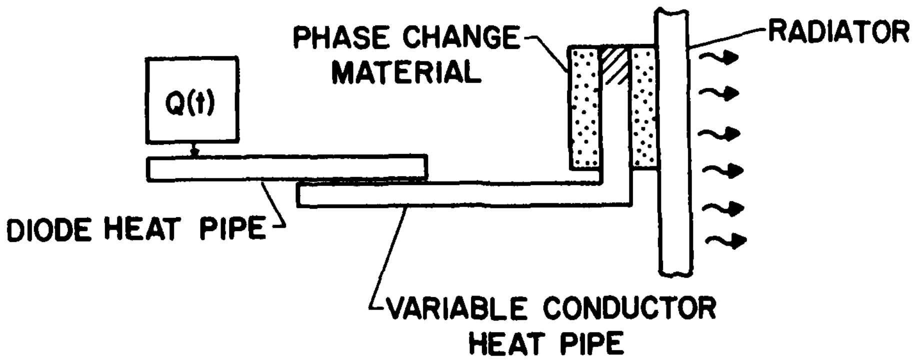



Figure 4 Passive Concept 4

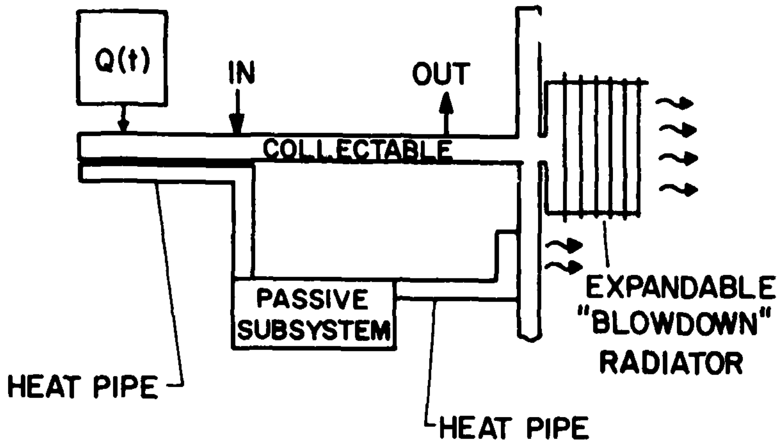



Figure 5 Active Concept 1

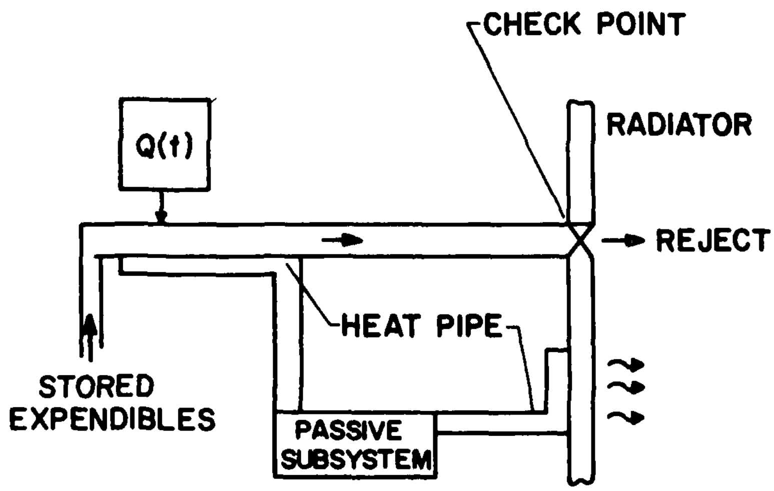



Figure 6 Active Concept 2

for optimized performance of the radiator. Figure 5 shows a schematic of a hybrid thermal control concept with a deployable radiator and "blowdown" bellows chamber for recycling collectables. This system is illustrated with a parallel passive option. Figure 6 shows a second hybrid system characterized by a rejection of expendables and a potentially minimized radiator size. Again, a parallel passive option is shown.

## 3. THERMAL MANAGEMENT SYSTEM REQUIREMENTS

In the overall scheme of a thermal management system for a future military spacecraft mission, several types of requirements are encountered. They include performance, physical characteristics, operational characteristics, environmental and trade penalties. Table 1 gives a sample of these requirements.

TABLE 1

Thermal Management System Requirements

| | |
|---|---|
| PERFORMANCE | Very large peak-to-average thermal loads [100/1 to 10,000/1] |
| | Isothermal character [temperature of bus = 50 C] |
| | Large heat fluxes [10 to 100 W/cm2] |
| | Large capacity heat pipes [10 to 1000 kW m] |
| | High performance [specific weight - 10 to 20 W/lb] |
| | Large overall thermal conductance [small temperature difference across the thermal management system] |
| PHYSICAL CHARACTERISTICS | |
| | Minimum weight and volume |
| | Maximized surface area-to-volume of the latent heat thermal storage system |
| | Modular design concept |
| OPERATIONAL CHARACTERISTICS | |
| | Maximized reliability [nominal orbit life - 10yr] |
| | Autonomous [maintenance free] |
| | Autonomous [self-controlling] |
| | Autonomous [99% design reliability for 10 yr] |
| | Minimized redundancy [minimized weight] |
| | Minimized moving parts [mechanical reliability and stability] |

ENVIRONMENTAL

- Pressurized/unpressurized compartment rated
- Minimum containment threat to payloads
- No toxic or flammable fluids in pressurized compartment
- Space radiation environment compatable

TRADE PENALTIES

- Weight, volume and area drivers in thermal management system
- Matching thermal interface of other thermal management subsystems

## 4. BASELINE CONCEPT

The baseline concept investigated in this project was one having three components: the heat transport heat pipes, the thermal storage system using a phase change material and the space radiators. This system was then used in a transient thermal analysis to determine the response for pulsed thermal loads. The transient thermal analysis used was the so-called lumped-system analysis and will be discussed in detail in the next section.

The baseline concept can be illustrated by a schematic diagram as seen in Figure 7. The thermal load originates at the thermal bus and is carried by the heat pipes to the thermal storage subsystem containing the phase change material. Next the heat load is rejected by the space radiators into the effective space sink.

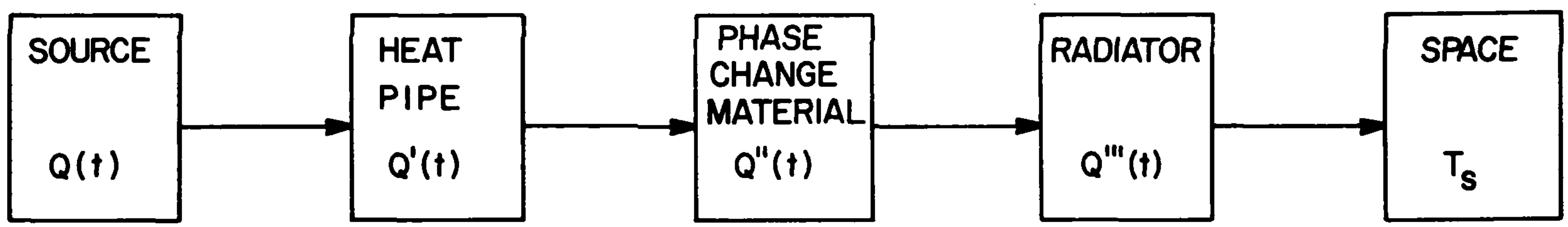



Figure 7 Schematic Diagram of Baseline Concept

## SECTION III

## ANALYTICAL MODELS

### 1. INTRODUCTION

This investigation used a simplistic approach to the modelling of the spacecraft thermal management system. The basic concept was to divide the system into the generic components for the thermal modelling. Three components were selected. They are the heat transport heat pipes, the thermal storage system using a phase change material and the space radiators. A transient thermal analysis was conducted to determine the response for pulsed thermal loads from the thermal bus. The transient thermal analysis was the so-called lumped-system analysis [5] where the spatial variation of temperature is neglected and the variation of the temperature of the component with respect to time is studied. In this method the geometry of the component is immaterial since the temperature is considered to be a function of time only; hence the analysis becomes very simple. A three-lump system was used to extend the study of the transients in a composite system consisting of the three different components.

### 2. TRANSIENT THERMAL ANALYSIS

The transient thermal analysis of the spacecraft thermal management system was the three-lump analysis. The mathematical formulation of the problem depends on the nummber of lumps considered for the system analysis and on the type of boundary conditions for the heat transfer. In this analysis convective boundaries conditions were used at all of the boundaries. It is assumed for the lumped-system analysis that the temperature distribution within the component at any instant is sufficiently uniform so that the temperature of the component can be considered to be a function of time only. When the temperature distribution within the component is assumed to be uniform, the variation of temperature takes place with time. The energy equation for a component may be stated as the following:

> The net rate of heat flow into a component through the boundaries is equal to the rate of increase of the internal energy of the component.

For the three-lump system, the energy balances for the three components respectively are as follows:

$$M_1 C_1 dT_1/dt = Q - Q' \qquad [1]$$

$$M_2 H_2 dX/dt = Q' - Q'' \quad [2]$$

$$M_3 C_3 dT_3/dt = Q'' - Q''' \quad [3]$$

Here M is the mass of the component, C is the specific heat of the component, T is the temperature of the component, X is the melt fraction of the phase change material, t is the time variable, H is the latent heat of fusion of the phase change material, and the Q's are the heat flow rates of the three components. These three heat flow rates are defined as follows:

$$Q'(t) = U_1 A_1 ( T_1(t) - T_2 ) \quad [4]$$

$$Q''(t) = U_2 A_2 ( T_2 - T_3(t) ) \quad [5]$$

$$Q'''(t) = U_3 A_3 ( T_3(t) - T_s ) \quad [6]$$

Here the "U" parameters are the overall heat transfer coefficients for the three components, and the "A" parameters are the associated areas of heat transfer of the three system components. Substituting Equations [4-6] into Equations [1-3] results in three linear, first order, ordinary differential equations for the transient variations of the temperature of the heat pipes, the melt fraction of the phase change material and the temperature of the radiators. The heat flow from the thermal bus is assumed to be a periodic function of time. For simplicity, a square wave function was selected as the periodic function. It can be shown that for the square wave of the heat flow that the ratio of the "peak-to-average" heat flows is equal to one plus the ratio of the "off-to-on" time periods. For example, the "peak-to-average" heat flow ratio for the special case of equal time "on" and "off" is equal to two.

The reference masses of the three components of the thermal management system for the spacecraft are defined by the following expressions:

$$M_1 = Q_A / G_1 \quad [7]$$

$$M_2 = Q_P N t_P / H \quad [8]$$

$$M_3 = Q_A / G_3 \quad [9]$$

Here the parameter "t" is the time of the peak heat load, the parameter "N" is the number of peak time intervals, and the parameters "G" are the specific weights of the components.

## 3. THERMAL MANAGEMENT SUBSYSTEMS' MODELS

The specific weights of the heat pipes and the radiators are evaluated at a peak-to-average heat flow of one, i.e. constant heat flow for the reference values. The effective, time-averaged, specific weights of the heat pipes and radiators can be calculated once the actual heat flows are obtained from the solutions of Equations [1-3]. The time-averaged specific weight of a heat pipe can be defined as the time-averaged heat flow divided by the mass of the heat pipe, and hence can be defined by the following expression:

$$G_{A1} = Q'_A / M_1 = ( Q'_A / Q_A ) G_1 \quad [10]$$

Similarly, the time-averaged specific weight of a radiator can be defined as the time-averaged heat flow divided by the mass of the radiator, hence can be defined by the following expression:

$$G_{A3} = Q'''_A / M_3 = ( Q'''_A / Q_A ) G_3 \quad [11]$$

The time-averaging is simply the time integral of the function divided by the time interval. The total mass of the thermal management system is the sum of the three components: the heat pipes, the phase change material and the radiators.

## SECTION IV

## WEIGHT SENSITIVITY STUDIES

### 1. INTRODUCTION

The sensitivity of the thermal management system weight of both evolutionary and revolutionary military spacecraft missions has been studied in this preliminary investigation. A numerical analysis modelling the transient heat flow through the thermal management system was performed. The performance parameters included the peak thermal load and the peak-to-average thermal load ratio. In addition, the sensitivity of the system weight to the choice of phase change material used for thermal buffering was determined via a parametric analysis.

### 2. PARAMETRIC STUDIES

One of the main objectives of this preliminary investigation on the characteristics of the mass of future spacecraft thermal management systems is to provide the rational basis for the development of future technologies. In light of this objective, the results of a parametric study are presented in this section. The sensitivity of the masses will be illustrated graphically. In particular the sensitivity of the mass of the baseline concept for the thermal management system is examined as a function of four parameters. These parameters are the heat of fusion of the phase change material of the thermal storage subsystem, the total time of the peak heat load needed to be rejected, the peak-to-average heat load ratio and the peak heat load. Table 2 gives the values of the various operational and thermophysical properties relevant to the modelling for the baseline case.

TABLE 2

Baseline Values of Parameters

| | |
|---|---|
| PEAK HEAT LOAD [WATTS] | 10,000. |
| SPECIFIC WEIGHT OF RADIATOR [WATTS/KG] | 50. |
| SPECIFIC WEIGHT OF HEAT PIPE [WATTS/KG] | 50. |
| HEAT OF FUSION OF PHASE CHANGE MATERIAL [KJ/KG] | 250. |
| SPECIFIC HEAT OF RADIATOR [J/KG K] | 875. |
| SPECIFIC HEAT OF HEAT PIPE [J/KG K] | 875. |
| TEMPERATURE OF SPACE [K] | 200. |
| TEMPERATURE OF RADIATOR INITIALLY [K] | 290. |

| | |
|---|---|
| TEMPERATURE OF PHASE CHANGE MATERIAL [K] | 300. |
| TEMPERATURE OF HEAT PIPE INITIALLY [K] | 310. |
| TIME OF PEAK HEAT LOAD INTERVAL [MIN] | 1. |
| NUMBER OF HEAT LOAD CYCLES | 2 |
| COEFFICIENT OF HEAT TRANSFER @ RADIATOR [W/M2 K] | 10. |
| COEFFICIENT OF HEAT TRANSFER @ PCM [W/M2 K] | 5. |
| COEFFICIENT OF HEAT TRANSFER @ HEAT PIPE [W/M2 K] | 1000. |

The values given in Table 2 were used as baseline values of the parameters in the numerical analysis. Selected results of the parametric study will be presented in graphical form. Figure 8 shows the trend of spacecraft thermal management system mass and phase change material mass as a function of the latent heat of fusion of the phase change material used as a thermal buffer of the pulsed reject heat. As the heat of fusion increases the total mass decreases until there is negligible change. Current candidate materials, such as high density polyethylene and calcium chloride hexahydrate, have sufficient values of latent heat of fusion such that the selection of the phase change material might not be based on maximizing the value of latent heat, but rather on other considerations (i.e. life, weight, heat flux tolerance and cost). Figure 9 shows the trend of the total mass of the thermal management system as well as the phase change material mass as functions of the time duration of the peak heat load. Examination of Equation (8) confirms the linear nature of the thermal management system mass as a function of the peak heat load time. Figure 10 illustrates the important characteristic of the thermal management system mass for a spacecraft with respect to the peak-to-average ratio of heat loads. Since the peak load is held constant for a particular case the variation of the peak-to-average heat load is obtained by decreasing the average heat load by varying the "on" and "off" times. Hence, the masses of the total system and the radiator decrease with respect to increases in the peak-to-average ratio of the heat load. Figure 11 shows the trends of the mass of the system and the mass of the radiator as functions of the peak heat load. The peak-to-average ratio of the heat load is held constant for this figure, thus the variations of the masses are linear with respect to the peak heat load. As the peak load increases, the thermal management system weight increases to handle the extra load.

To examine the effect of the selected values used in the base case, numerous other cases were considered. One set of parameters of particular interest is the specific weights of the radiator and the heat pipes. For illustration, Figures 12-15 graphically give variations of the masses as

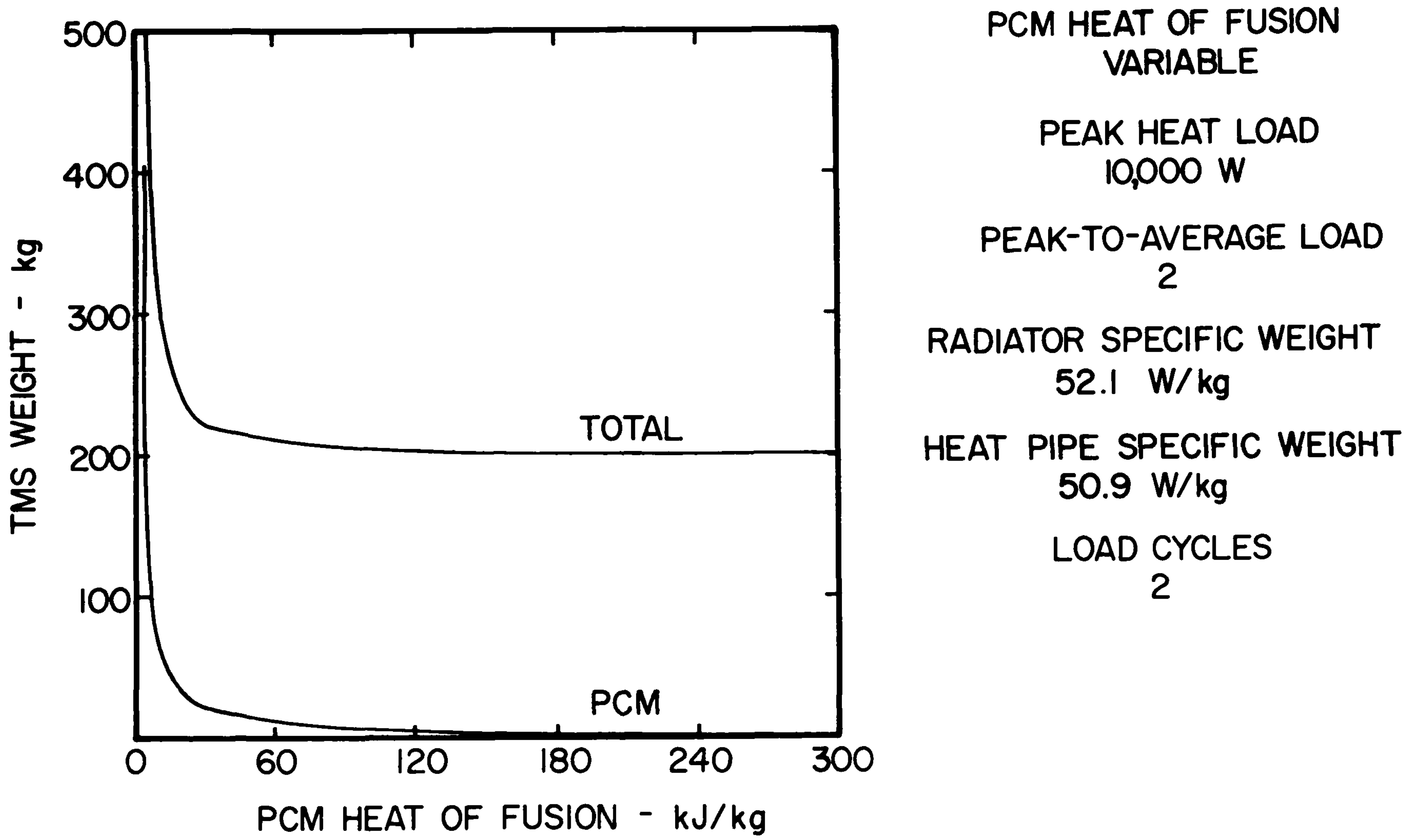



Figure 8 Spacecraft Thermal Management System Mass Versus Latent Heat of Fusion of the Phase Change Material

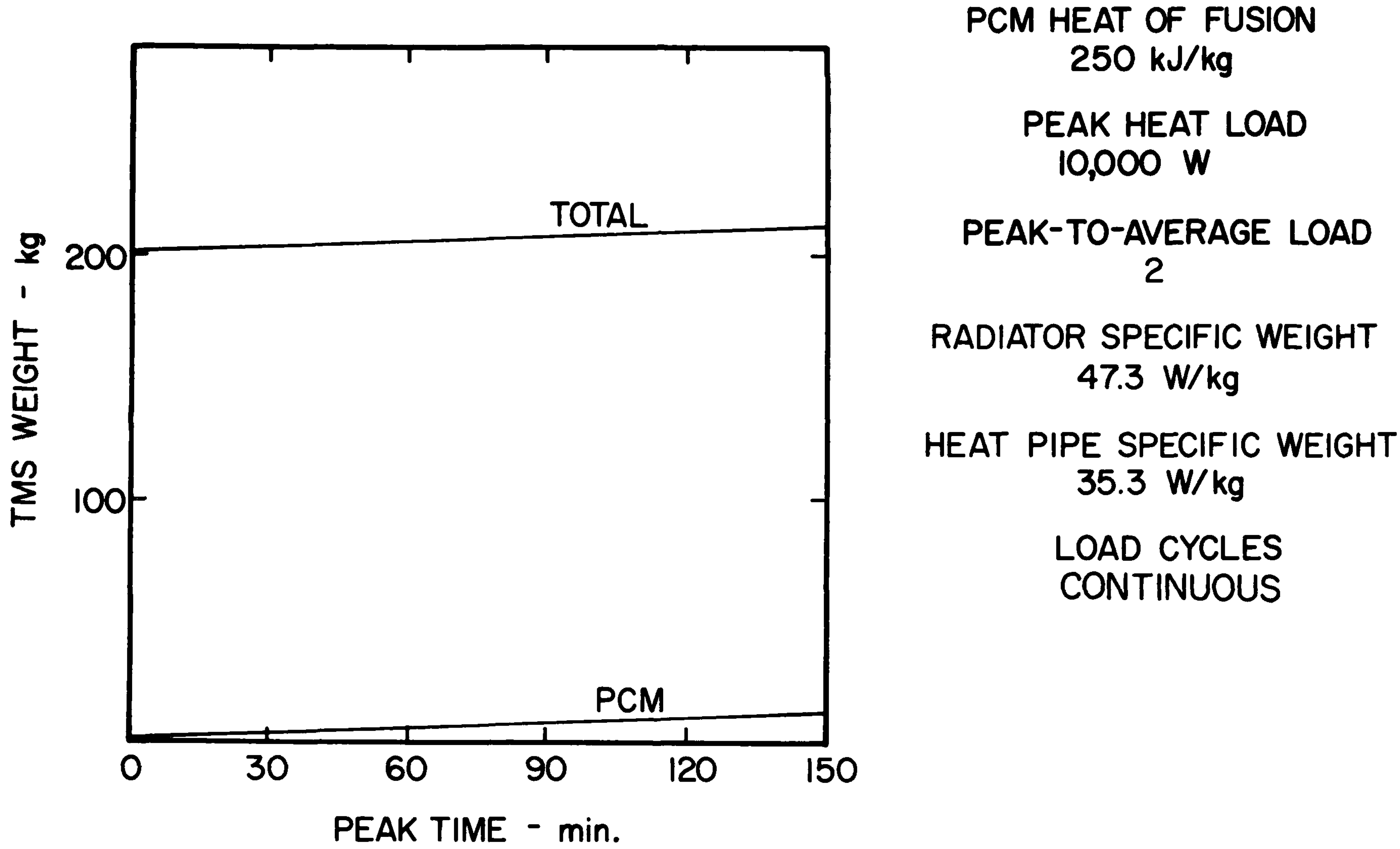



Figure 9 Spacecraft Thermal Management System Mass Versus Time of Peak Heat Load

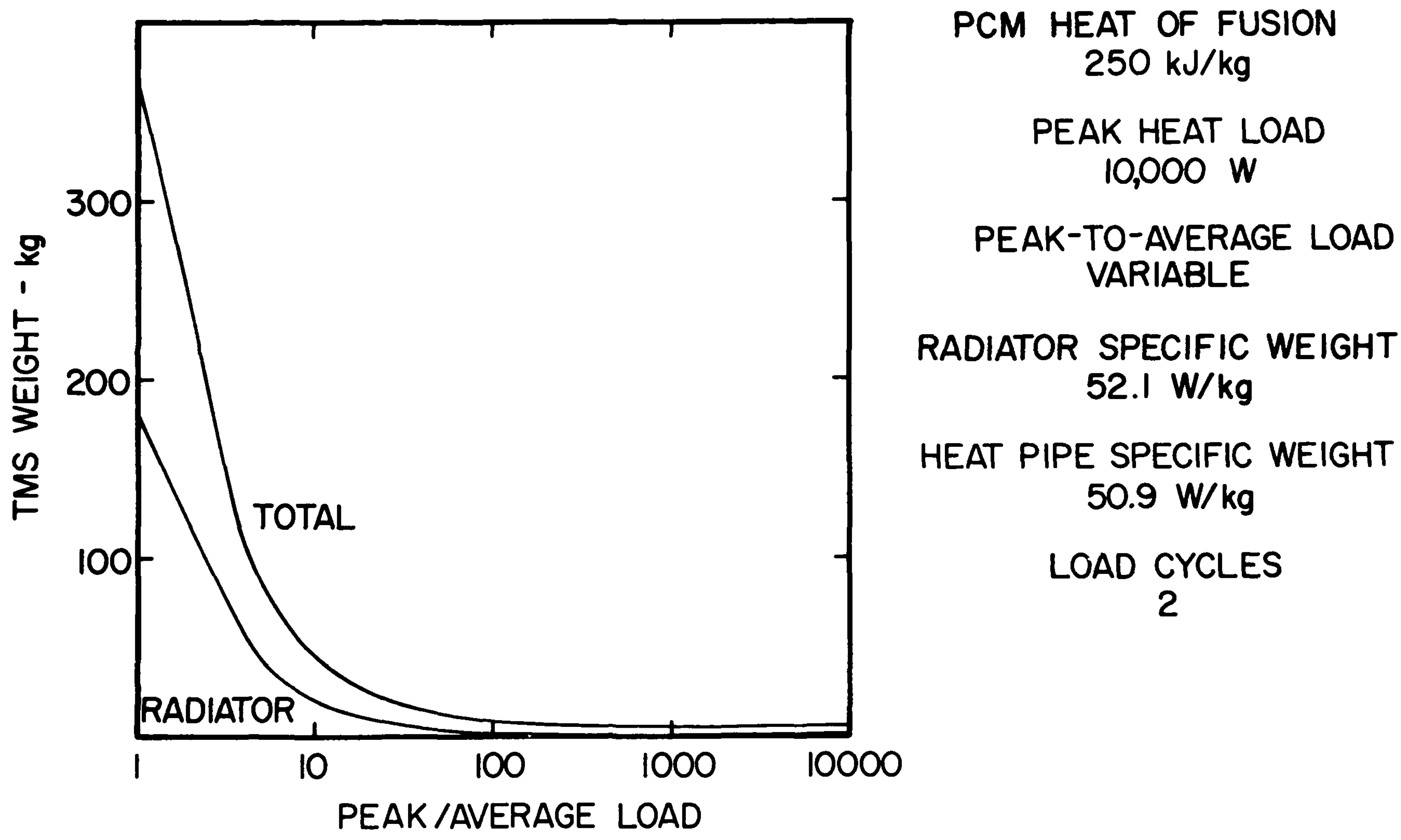



Figure 10 Spacecraft Thermal Management System Mass Versus Peak-to-Average Ratio of Heat Loads

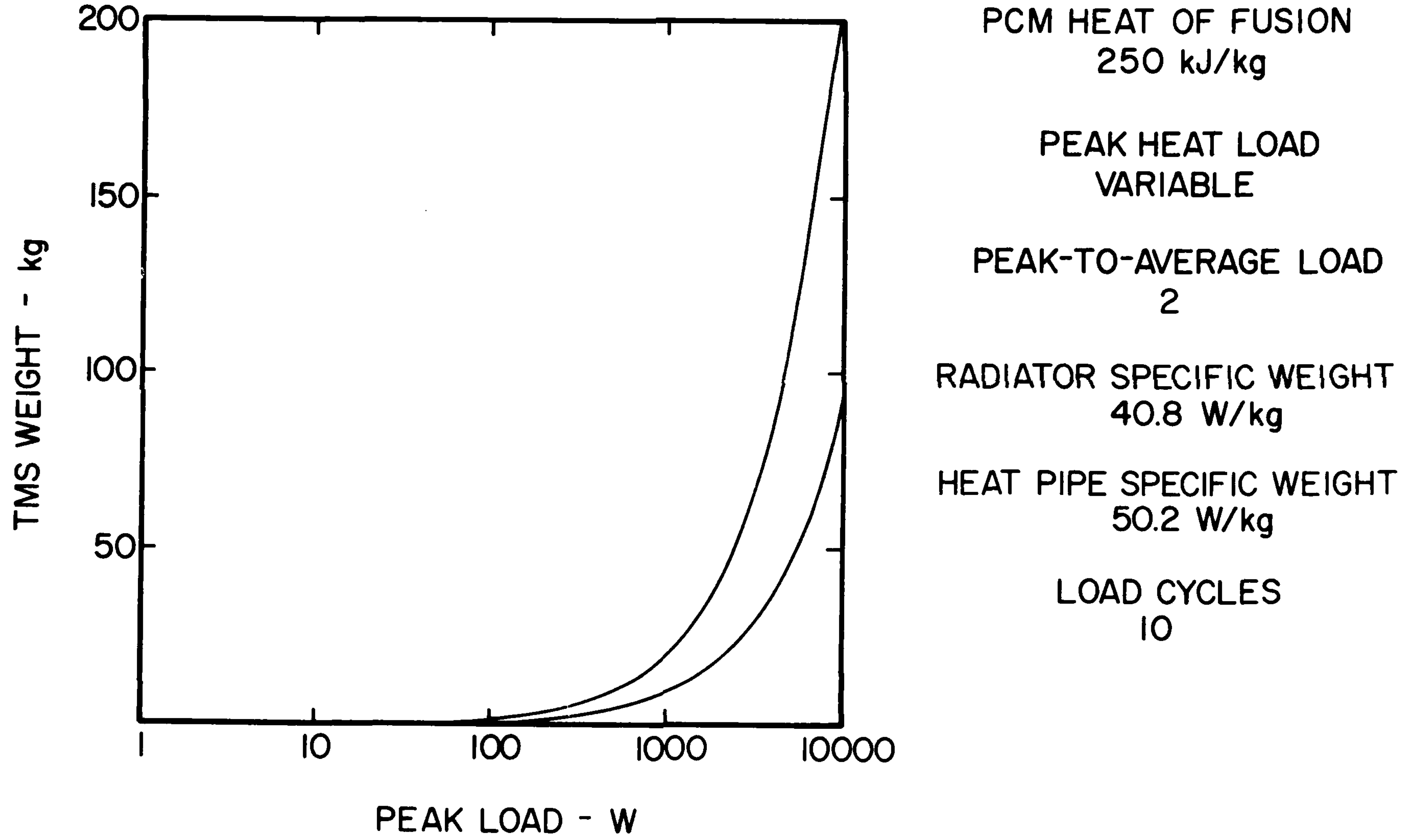



Figure 11 Spacecraft Thermal Management System Mass Versus Peak Heat Load

functions of the four parameters used in the base case. With the exception of the specific weights, the values of the parameters given in Table 2 remained the same for Figures 12-15. The radiator and heat pipe specific weights were calculated to be 11.1 and 11.8 watts/kg respectively for these figures. Again, the general dependence of the masses to the four selected parameters can be seen in these figures. This is further exemplified by a comparison with figures 8-11 as to how the radiator and the heat pipe specific weights affect the overall thermal management sytem.

Another parameter of interest in the investigation is the number of heat load cycles. To illustrate the effect of this parameter, Figures 16-19 graphically give the variations of the masses as functions of the four parameters used in the base case. With the exception of the number of heat load cycles, the values of the parameter given in Table 2 remained the same for Figures 16-19. The number of heat load cycles was selected to be ten. Again, the general dependence of the masses to the four selected parameters can be seen in these figures.

The solutions of the transient energy balances given by Equations (1-3) give the variations of the temperature of the heat pipes, the melt fraction of the phase change material and the temperature of the radiator with respect to time. Figure 20 illustrates the transient nature of these temperatures. The heat pipe temperature can be seen to be an oscillating function of time while the radiator temperature undergoes a continuous decrease approaching the space temperature. Substitution of the results of the Equations (1-3) into Equations (4-6) yields the transient heat flow rates. Figure 21 shows the transient nature of these heat flow rates Again, the heat pipes undergo rapid pulses while both the phase change material and the radiators undergo continuous changes in their values of heat flow rates. The results shown in Figures 20-21 were obtained for the base case as defined by the values given in Table 2.

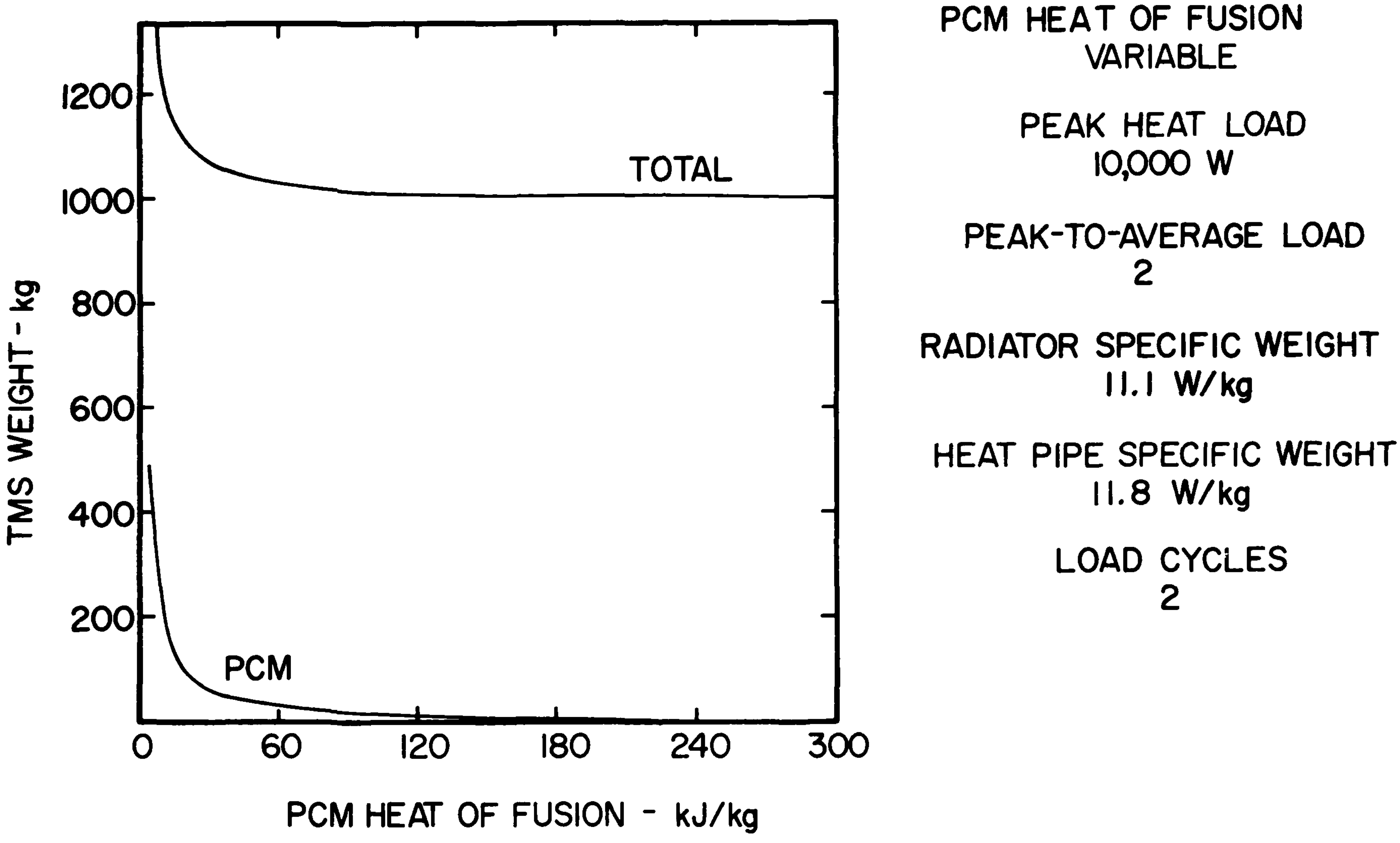



Figure 12 Spacecraft Thermal Management System Mass Versus Latent Heat of Fusion of the Phase Change Material

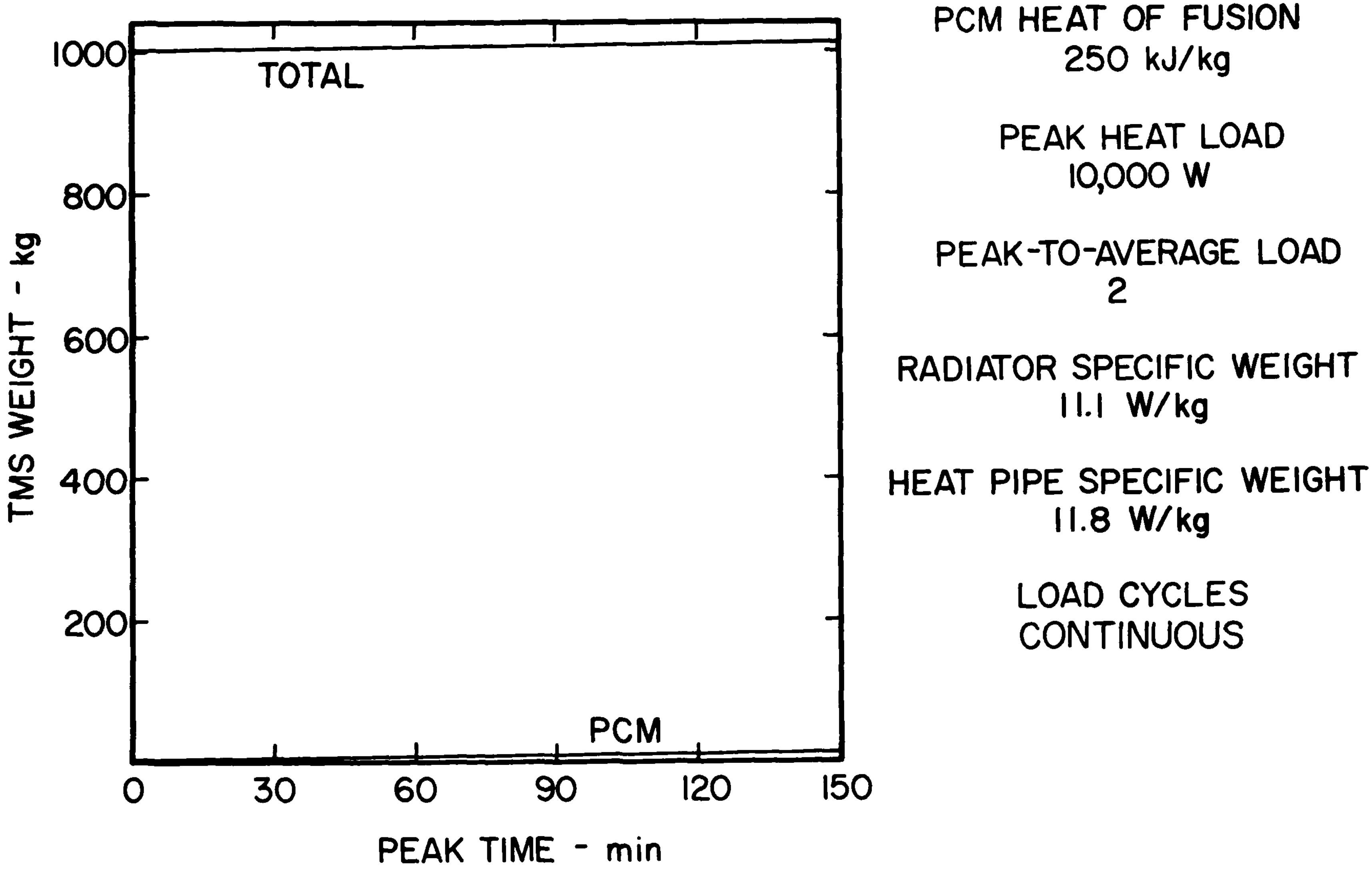
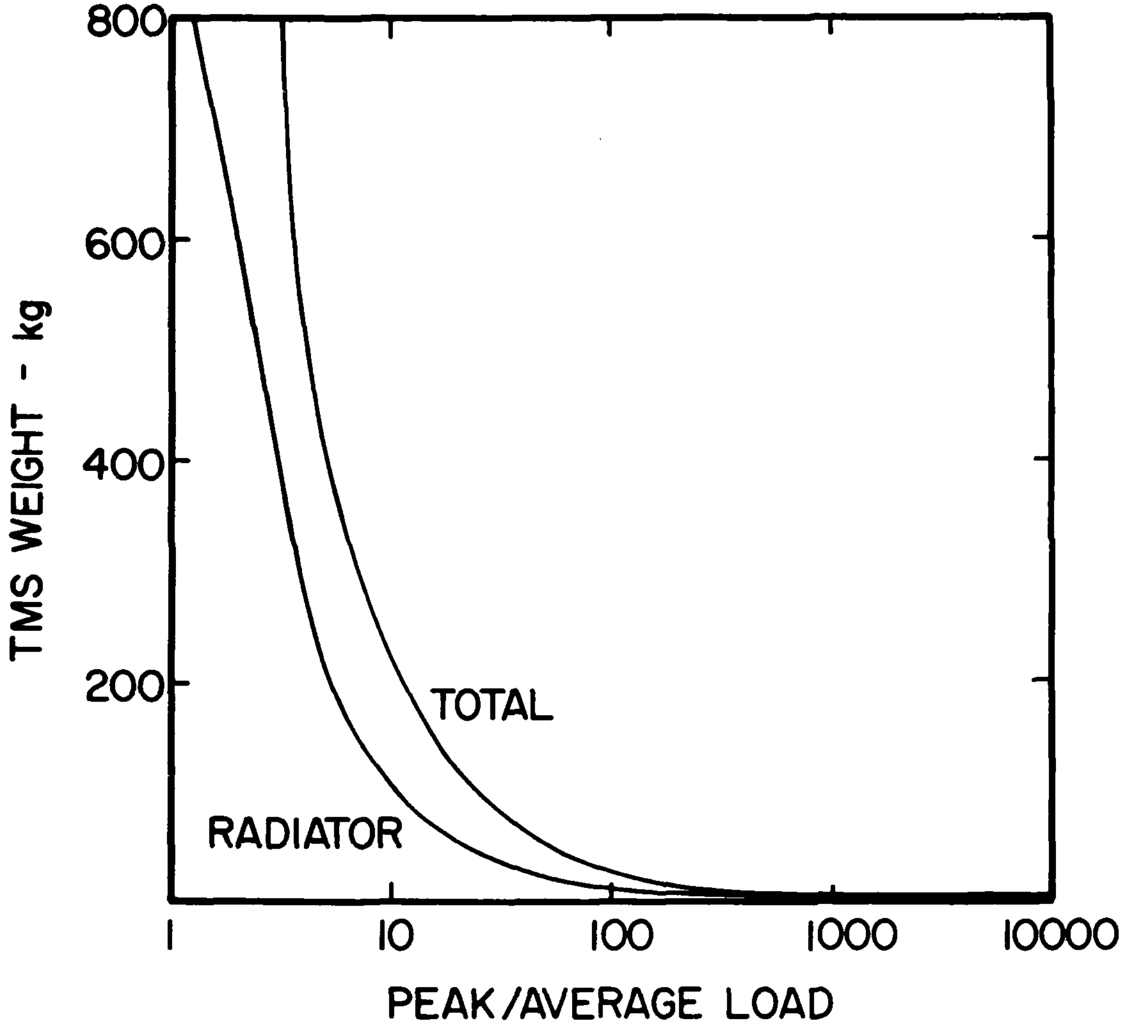



Figure 13 Spacecraft Thermal Management System Mass Versus Time of Peak Heat Load




PCM HEAT OF FUSION
250 kJ/kg

PEAK HEAT LOAD
10,000 W

PEAK-TO-AVERAGE LOAD
VARIABLE

RADIATOR SPECIFIC WEIGHT
11.1 W/kg

HEAT PIPE SPECIFIC WEIGHT
11.8 W/kg

LOAD CYCLES
2

Figure 14 Spacecraft Thermal Management System Mass Versus Peak-to-Average Ratio of Heat Loads

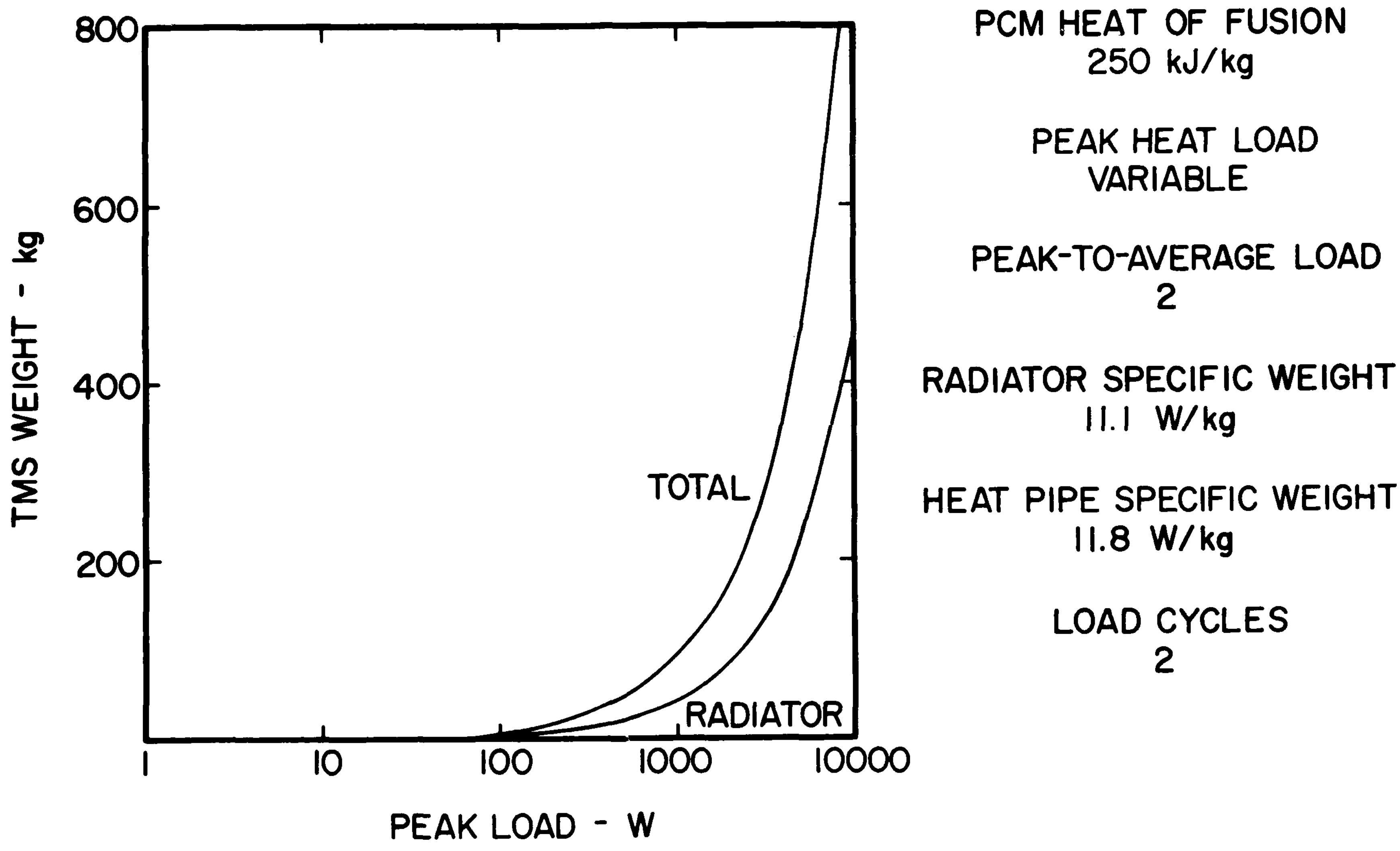



Figure 15 Spacecraft Thermal Management System Mass Versus Peak Heat Load

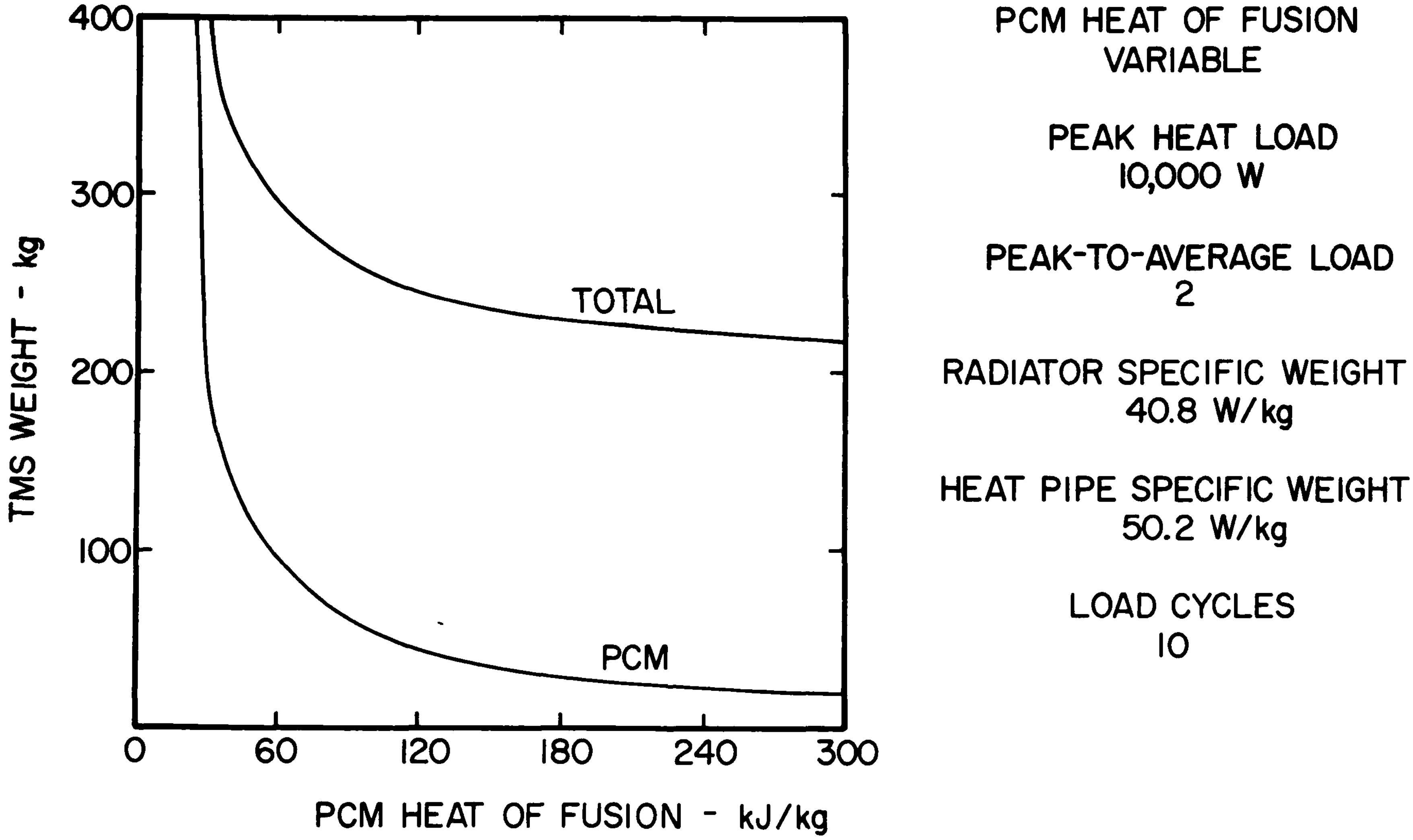



Figure 16 Spacecraft Thermal Management System Mass Versus Latent Heat of Fusion of the Phase Change Material

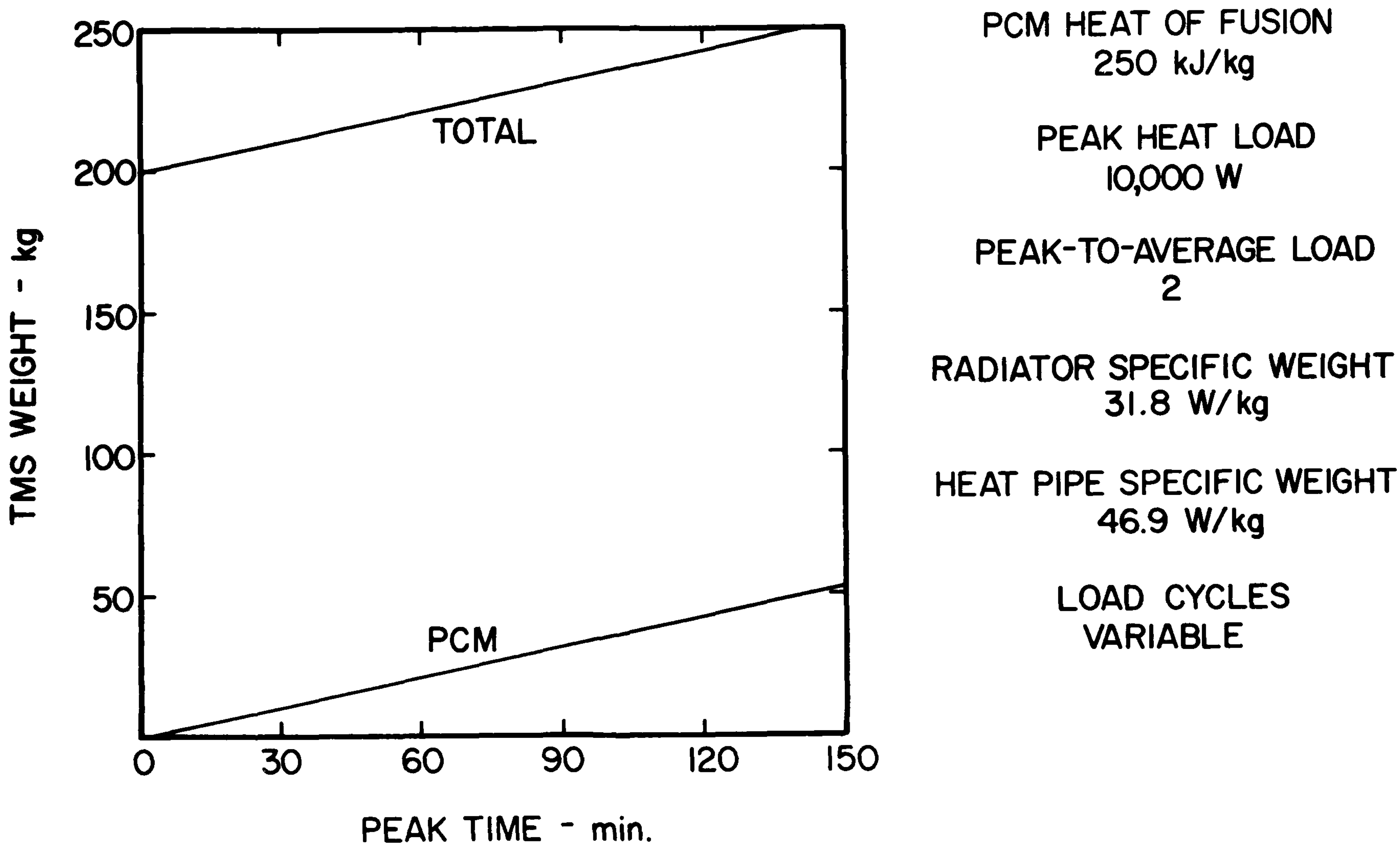



Figure 17 Spacecraft Thermal Management System Mass Versus Time of Peak Heat Load

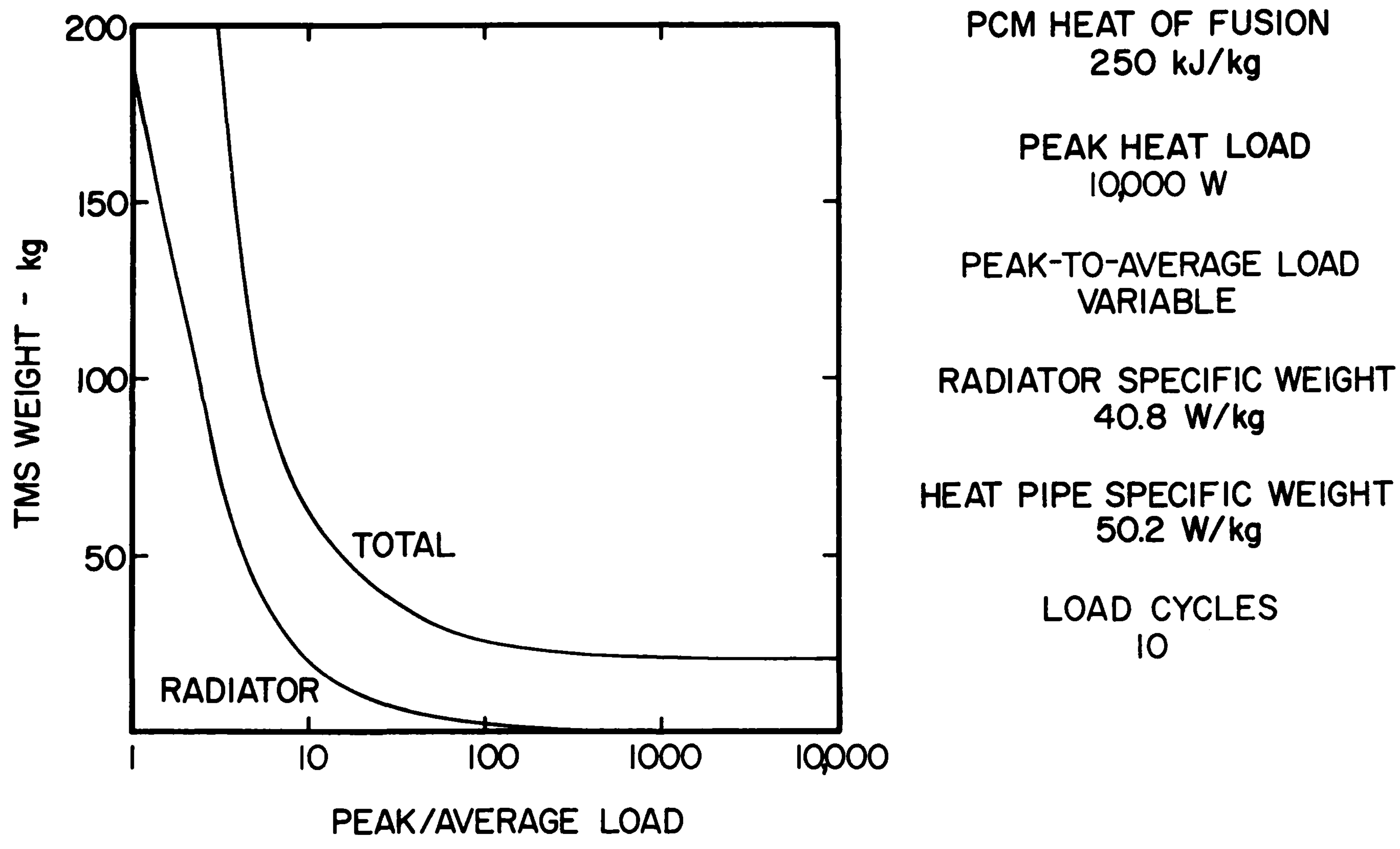



Figure 18 Spacecraft Thermal Management System Mass Versus Peak-to-Average Ratio of Heat Loads

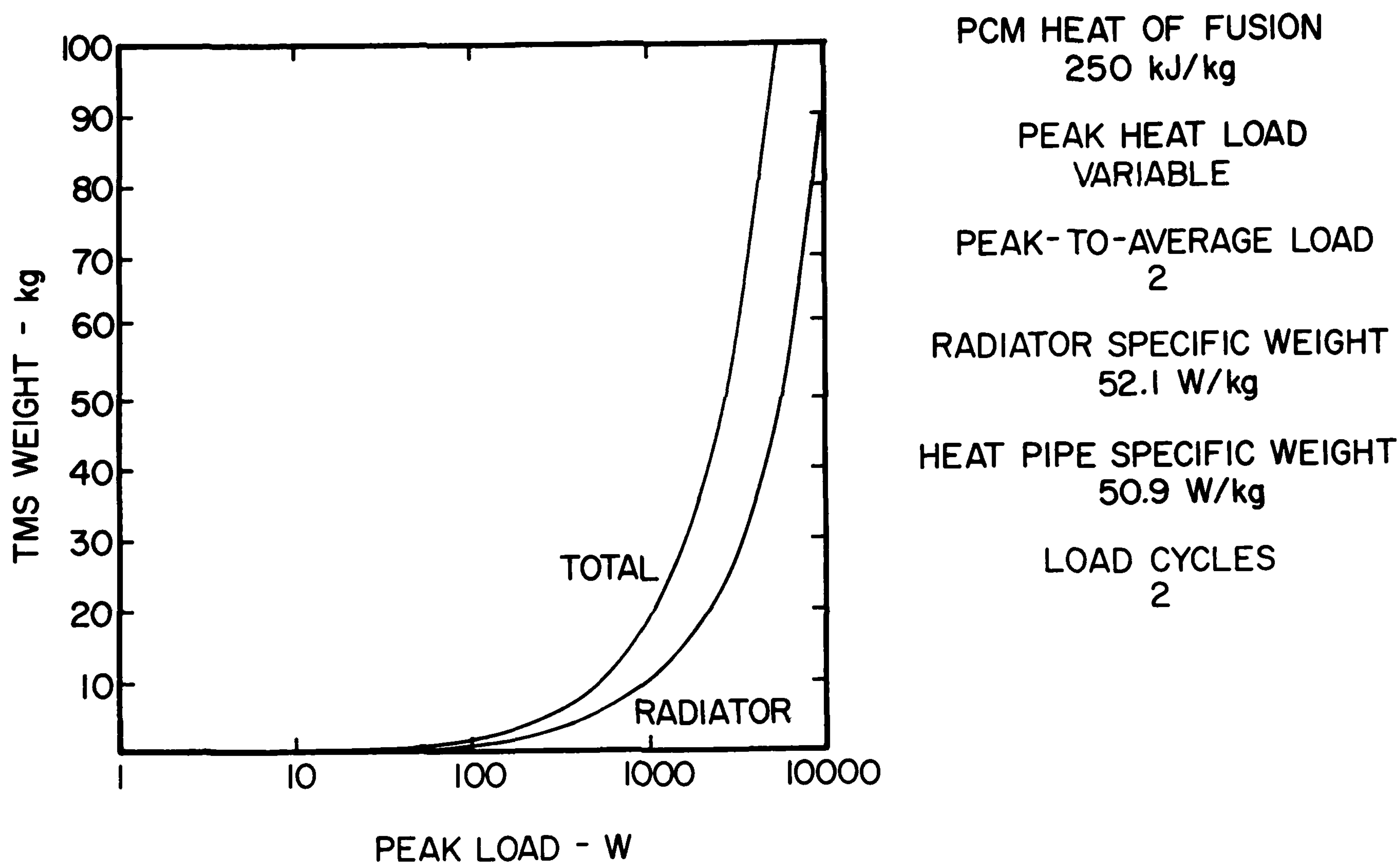



Figure 19 Spacecraft Thermal Management System Mass Versus Peak Heat Load

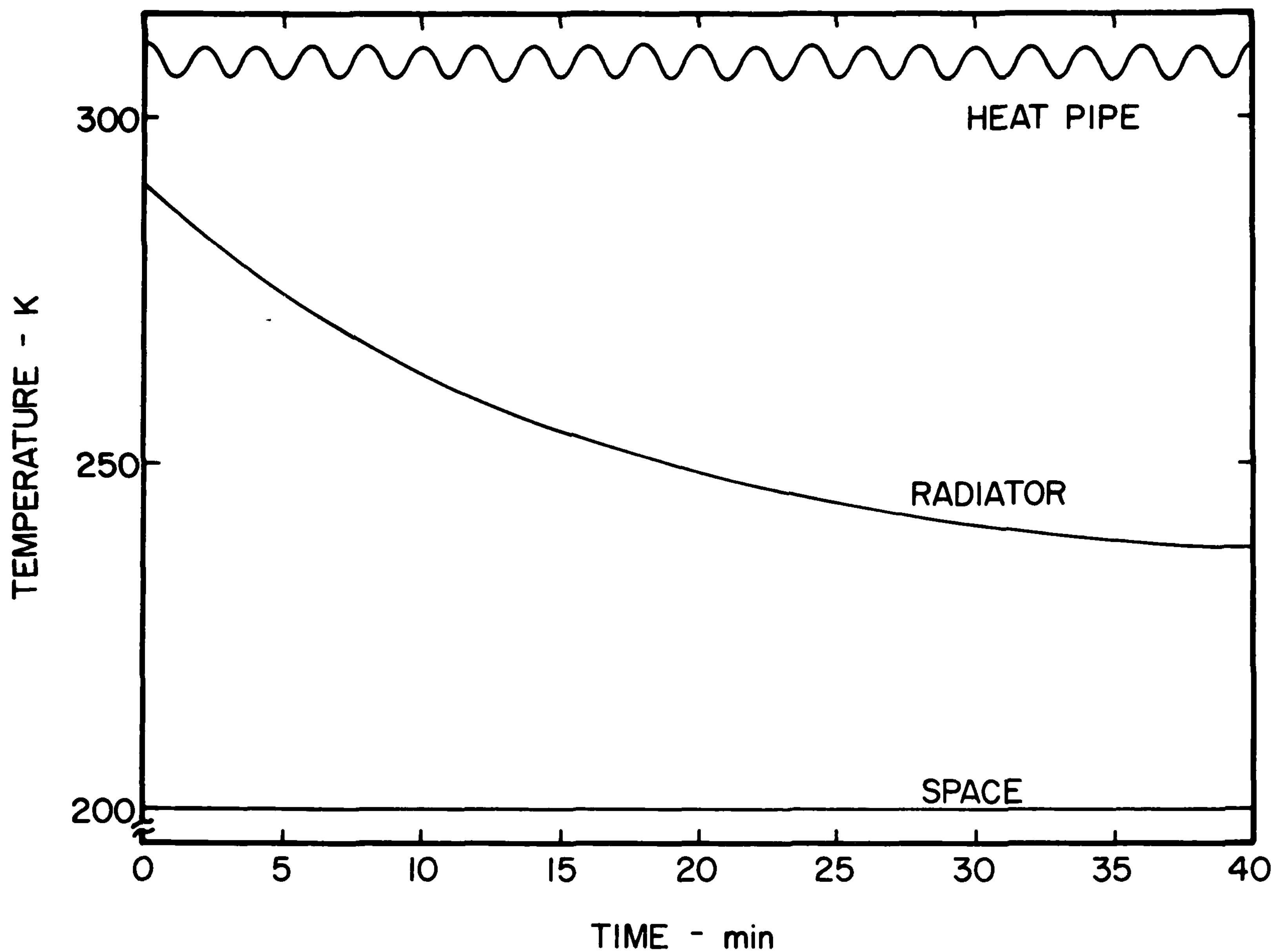



Figure 20 Temperature Versus Time

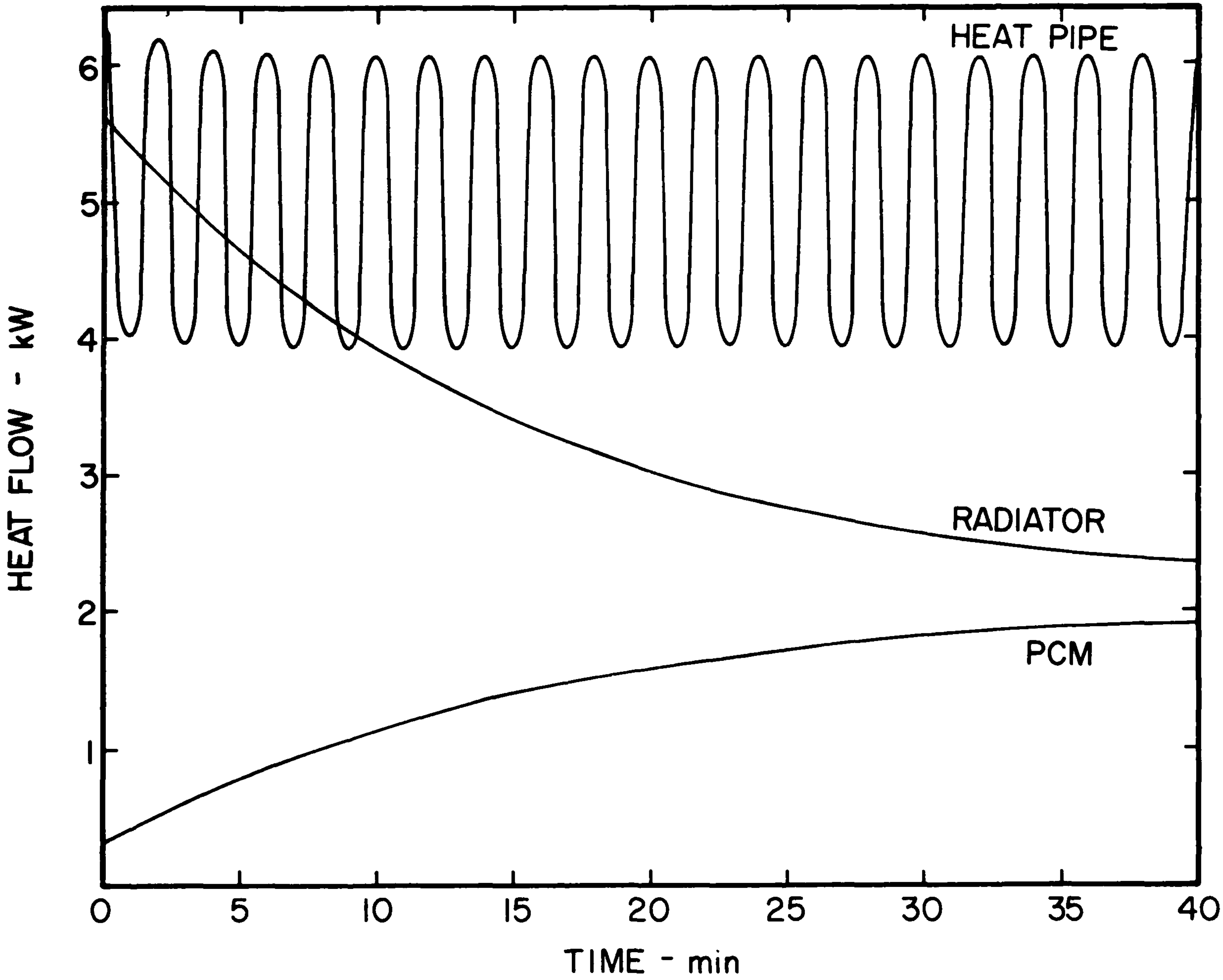



Figure 21  Heat Flow Versus Time

## SECTION V

## CONCLUSIONS

The results of this investigation of the weight characteristics of future spacecraft thermal management systems have been presented to identify the effect of the thermal response to four specific parameters: PCM heat of fusion, peak time, peak/average load, and peak load. The selective results presented illustrate many of the thermal problems which may be encountered in developing future systems of thermal control. It is difficult to compare the various operational parameters discussed without giving considerable attention to the total system in which a particular parameter is evaluated [6-8]. However, Table 2 gives a set of values for the important parameters that characterize the power conditioning thermal response of a pulsed heat rejection load. The solutions of the governing equations for the heat flow through the thermal management system were used in calculating time-averaged component specific weights which differ from the values given in Table 2. An attempt was made to examine only special cases where the values of the parameters were self-consistent.

The application of phase change materials for thermal buffering of temperature sensitive equipment from pulsed heat loads of future spacecraft thermal management systems appears to satisfy the objectives. The selection of the candidate materials might be based on high latent heat of fusion, however, the final selection probably will not be based solely on an optimized latent heat of fusion. The specific weights of the radiators and the heat pipes are operational dependent on numerous parameters. Actual values of the specific weights should be obtained after the thermal response of the systems have been determined. Novel heat pipe and radiator designs will be required to achieve the desired performance.

It is felt that the procedure presented in this report represents an important step towards addressing the issues of future military spacecraft thermal control and management systems. The capability of treating multiple component responses to the pulsed heat rejection loads along with the simplicity of the method of analysis are additional attributes of significance.

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