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THE LIQUID DROPLET RADIATOR IN SPACE:

A PARAMETRIC APPROACH

THESIS

Gerald L. Buckner
Major, USAF

AFIT/GNE/ENP/87M-1

DEPARTMENT OF THE AIR FORCE

AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
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Master of Science in Nuclear Engineering

Gerald L. Buckner

Major, USAF

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Preface

The Liquid Droplet Radiator (LDR) consists of a column or sheet of liquid droplets moving through space from a droplet generator to a collector. The droplets carry the waste heat generated by a space power system and radiate this waste heat directly to space during their flight. The liquid droplets are collected at a lower temperature, reheated, and pumped to the generator and reused to continue to remove waste heat from the thermodynamic power cycle. This study was a parametric analysis of a cylindrical LDR to estimate its performance and operating characteristics using a varying pump specific mass.

I offer a well deserved expression of gratitude to my advisor, Lt Col Ronald Tuttle of the Air Force Institute of Technology at Wright-Patterson AFB, Ohio, for his instrumental guidance and patience during this project. Also, I would like to thank Dr. Alden Presler, Dr. Robert Siegel, Ms. Carolyn Coles, and Mr. Alan White of the NASA Lewis Research Center, Cleveland, Ohio, for their assistance and for providing current research information on the LDR. Ultimately, I must give my most heartfelt appreciation to my wife, Linda, for her understanding and her ability to manage our family and three children with little help from me for the past year and a half.

Gerald L. Buckner

Table of Contents

	Page
Preface	ii
List of Figures	iv
List of Tables	vi
List of Symbols	vii
Abstract	viii
I. Introduction	1
Background	1
Objective	3
Scope	4
Approach	4
Overview	4
II. Theory	5
III. Parameter Investigation	12
IV. Results	41
10 Kilowatt Heat Loss	41
100 Kilowatt Heat Loss	42
1000 Kilowatt Heat Loss	43
10000 Kilowatt Heat Loss	43
V. Conclusions and Recommendations	53
Bibliography	55
Appendix A: Computer Program Glossary and Listing	56
Appendix B: Pump Specific Mass	60
Vita	61

List of Figures

Figure		Page
1.	Schematic of a Liquid Droplet Radiator	3
2.	System Mass per Heat Loss vs Droplet Temperature: (10 Kw, Time = 0)	16
3.	System Mass per Heat Loss vs Droplet Temperature: (10 Kw, Time = 10 years)	17
4.	System Mass per Heat Loss vs Droplet Temperature: (10 Kw, Time = 20 years)	18
5.	System Mass per Heat Loss vs Droplet Temperature: (10 Kw, Time = 30 years)	19
6.	System Mass per Heat Loss vs Droplet Temperature: (100 Kw, Time = 0)	20
7.	System Mass per Heat Loss vs Droplet Temperature: (100 Kw, Time = 10 years)	21
8.	System Mass per Heat Loss vs Droplet Temperature: (100 Kw, Time = 20 years)	22
9.	System Mass per Heat Loss vs Droplet Temperature: (100 Kw, Time = 30 years)	23
10.	System Mass per Heat Loss vs Droplet Temperature: (1000 Kw, Time = 0)	24
11.	System Mass per Heat Loss vs Droplet Temperature: (1000 Kw, Time = 10 years)	25
12.	System Mass per Heat Loss vs Droplet Temperature: (1000 Kw, Time = 20 years)	26
13.	System Mass per Heat Loss vs Droplet Temperature: (1000 Kw, Time = 30 years)	27
14.	System Mass per Heat Loss vs Droplet Temperature: (10000 Kw, Time = 0)	28
15.	System Mass per Heat Loss vs Droplet Temperature: (10000 Kw, Time = 10 years)	29
16.	System Mass per Heat Loss vs Droplet Temperature: (10000 Kw, Time = 20 years)	30

17. System Mass per Heat Loss vs Droplet Temperature: (10000 Kw, Time = 30 years) 31

18. Droplet Temperature vs Pump Specific Mass: 10 Kw 32

19. Droplet Temperature vs Pump Specific Mass: 100 Kw 33

20. Droplet Temperature vs Pump Specific Mass: 1000 Kw 34

21. Droplet Temperature vs Pump Specific Mass: 10000 Kw 35

22. Specific Mass vs Pump Specific Mass: 10 Kw 36

23. Specific Mass vs Pump Specific Mass: 100 Kw 37

24. Specific Mass vs Pump Specific Mass: 1000 Kw 38

25. Specific Mass vs Pump Specific Mass: 10000 Kw 39

26. Specific Mass vs Heat Rejected for Various Times... 40
(for mp = 10.0 kg/(Kg/sec) only)

List of Tables

Table		Page
I.	Parameters Used for Calculations	12
II.	Results for 10 Kw Using Optimistic Values (Beta = 0.10, mc = 40.0)	45
III.	Results for 10 Kw Using Realistic Values (Beta = 0.20, mc = 100.0)	46
IV.	Results for 100 Kw Using Optimistic Values (Beta = 0.10, mc = 40.0)	47
V.	Results for 100 Kw Using Realistic Values (Beta = 0.20, mc = 100.0)	48
VI.	Results for 1000 Kw Using Optimistic Values (Beta = 0.10, mc = 40.0)	49
VII.	Results for 1000 Kw Using Realistic Values (Beta = 0.20, mc = 100.0)	50
VIII.	Results for 10000 Kw Using Optimistic Values (Beta = 0.10, mc = 40.0)	51
IX.	Results for 10000 Kw Using Realistic Values (Beta = 0.20, mc = 100.0)	52
X.	Pump Specific Mass Sample Values	60

List of Symbols

a	Radius of liquid droplets in the stream
β	Ratio of liquid mass in reheating station to droplet mass in the stream
c	Specific heat of the droplets
D	Diameter of the droplet stream
ϵ	Average emissivity of the droplets
η	Black-body view factor for a droplet at stream center
F	Gray-body view factor for a droplet at stream center
γ	Ratio of droplet kinetic energy to the heat rejected
L	Length of droplet stream
mc	Specific mass of droplet generator and collector
mp	Specific mass of pump
M_T	Total mass of system
n	Number of droplets per unit volume
P	Vapor pressure of droplets
$\dot{Q}$	Total droplet stream heat loss rate
$\dot{q}$	Single droplet heat loss rate
R	Gas constant
ρ	Droplet liquid density
σ	Stefan-Boltzmann constant
T	Droplet temperature
Tv	Temperature used in fitting vapor pressure curve
T_1	Droplet initial temperature at generator
T_2	Droplet temperature at collector
τ	Mission lifetime for radiator operation
V	Droplet stream velocity

(adapted from Reference 1)

Abstract

This study was a parametric investigation of the performance and operating characteristics of a cylindrical Liquid Droplet Radiator (LDR) for use in space. The LDR system mass per heat radiated was minimized as a function of the average droplet temperature at the collector. This study was similar to the work of Karl Knapp (1980), however a new pump specific mass term was used in the total system mass calculation. Knapp used a pump specific mass defined as kg-$sec^{2/3}/m^2$. This study used a pump specific mass term defined as pump mass per liquid mass flow rate to develop a physically meaningful pump specific mass term for use by design engineers. The new pump specific mass was varied from 10.0 kg/(kg/sec) to 40.0 kg/(kg/sec), based on available industry standard pumps. The average droplet temperature at the collector was calculated to minimize the LDR system mass for heat loss rates of 10 KILOWATT ~~Kw~~, 100 KILOWATT ~~Kw~~, 1000 KILOWATT ~~Kw~~, and 10,000 KILOWATT ~~Kw~~ for mission lifetimes of zero, ten, twenty, and thirty years. The initial droplet temperature at the generator was fixed at 300 degrees Kelvin. A silicon oil, Trimethylpentaphenyltrisiloxane (DOW 705), was modeled due to its low vapor pressure (approx. 3 x 10^{-8} Pa) at 300 degrees Kelvin. The variable pump specific mass term offers the design engineer a range of possible pump masses depending on system pressure and flow rate requirements.

THE LIQUID DROPLET RADIATOR IN SPACE: A PARAMETRIC APPROACH

I. INTRODUCTION

A successful space mission must have a source of electrical power whether the mission is manned, unmanned, scientific, or nationally strategic. The generation of this electric power will require the rejection of waste heat. For example, the Strategic Defense Initiative will have space based systems generating large amounts of electrical energy with much waste heat energy to be radiated to space. Other space applications requiring from 100 kilowatts to over 100 megawatts include: Space Based Radars, Nuclear/Electric Orbital Transfer Vehicles, Space Based (to page 3) Weapon Systems, and the Space Station (2:9.1). To operate these space power systems, a lightweight highly survivable radiator is considered the "enabling technology" (2:9.1). A Liquid Droplet Radiator (LDR) can be seven times lighter than conventional heat pipe radiators of similar size (4:14). Thus the LDR technology development can enable the Air Force and NASA to conduct their space missions with less mass in orbit and with resulting cost savings.

Background

A space power system must operate with the rejection of waste heat from the thermodynamic cycle used to generate the electrical energy for use in space. To reject this waste heat in space, radiators must be designed to operate efficiently in the harsh space environment. Traditional radiator designs for operation in space are the pure thermal radiator and the bimodal radiator. The thermal radiator (metallic fins for example) has been designed in various sizes to maximize area, minimize weight and size, and maximize protection from meteoroid damage. In the bimodal radiator, a small thermal radiator is used to reject heat for low power operations while for high power operations, a dump fluid, such as hydrogen, is used to remove excess heat by dumping it directly into space. These traditional radiators are not acceptable to meet the heat rejection requirements of multimegawatt space power systems of the future since radiator mass requirements will dominate these large power systems making them prohibitively massive and very expensive. Less massive radiator designs are needed to remove the increased waste heat from multimegawatt power systems for efficient space power generation. The liquid droplet radiator is one possible proposed design (3:1). The radiator coolant liquid is formed into aerosol droplets and passed as a column or thin sheet of droplets from a droplet generator through the vacuum of space to a collector (Figure 1). The waste heat is rejected to space by radiation from each droplet while in flight. The advantages of such a design include large droplet surface areas per mass, lightweight fluid mass, and lower sensitivity to meteoroid damage (4:1).

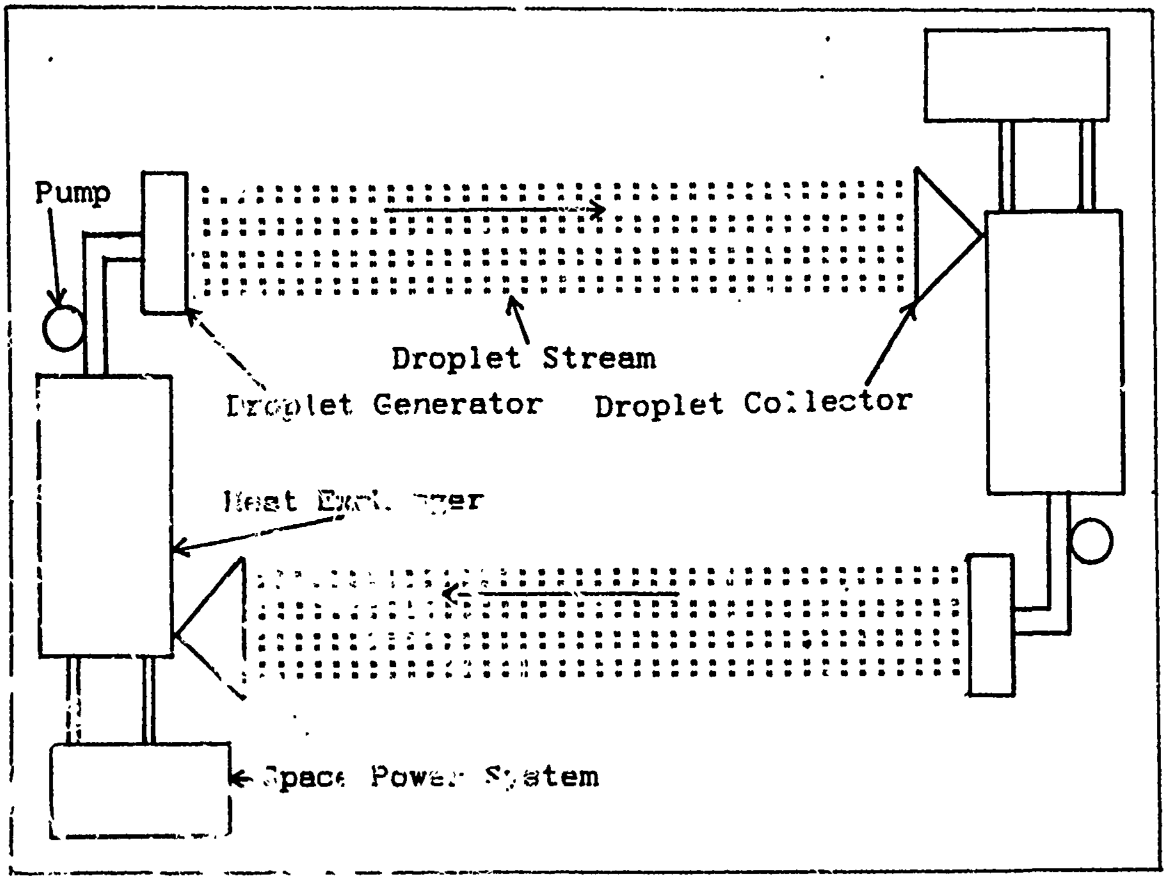

Figure 1. Schematic of Two Liquid Droplet Radiators (adapted from References 1 and 9)

Objective

The objective of this study was to investigate the performance and operating characteristics of a cylindrical LDR for use in space by minimizing the mass per heat radiated as a function of the average droplet temperature at the collector using a new pump specific mass term defined as pump mass per liquid mass flow rate. The new pump specific mass was varied from 10.0 kg/(kg/sec) to 40.0 kg/(kg/sec), based on available industry standard pumps, to offer the design engineer a range of possible pump masses depending on system pressure and flow rate requirements.

Scope

A silicon oil, Trimethylpentaphenyltrisiloxane (DOW 705), was used in this study in a low temperature heat rejection application with a 300 degrees Kelvin droplet temperature at the generator. The LDR stream length, stream diameter, droplet radius, and total system mass per radiated power were found for the minimum mass LDR system as a function of the average droplet temperature at the collector for heat rejection rates of 10 Kw, 100 Kw, 1000 Kw, and 10000 Kw with mission operation times of zero, ten, twenty, and thirty years.

Approach

The total LDR system specific mass was calculated as a function of the average temperature at the collector for a given set of fixed parameters and for varying pump specific mass values. The temperature corresponding to the minimum mass system was then used to calculate droplet stream length, diameter, and droplet radius for each case.

Overview

The theory of operation of the LDR droplet column is presented in Chapter II. The parameter investigation is presented in Chapter III for the new pump specific mass term. The results are presented in Chapter IV and conclusions and recommendations are presented in Chapter V.

II. THEORY

The LDR in this study was modeled as a cylindrical stream of droplets (Figure 1). The procedural approach for this study was adapted from Reference 1. The radiating stream is assumed to be shadowed so solar absorption need not be considered (1:3). A single droplet radiates heat as it travels through space and at any time this heat loss is given by:

$$\dot{q} = (4\pi a^2)\sigma F T^4 \tag{1}$$

where

$\dot{q}$ = droplet heat loss rate to space (joules/second)
a = droplet radius (meters)
σ = Stefan-Boltzmann Constant (5.67×10^{-8} watts/m^2-K^4)
F = average gray body view factor for droplet at stream center (less than one)
T = absolute droplet temperature at any time (Kelvin)

This equation models the droplet as a gray body with constant average emissivity. The instantaneous radiation rate is equal to the rate of energy loss resulting in this equation:

$$4\pi a^2 \sigma F T^4 = -c\rho \frac{4\pi a^3}{3} \frac{dT}{dt} \tag{2}$$

where

C = specific heat capacity (1670 joules/kg - K)
ρ = density of droplet (1000 kg/m^3)
t = droplet transit time (seconds)

The integration of Eq (2) and solving for time results in this equation for the droplet transit time:

$$\int 4\pi a^2 \sigma F \; dt = \int -c\rho \frac{4\pi a^3}{3} \frac{dT}{T^4}$$

$$t = \frac{c\rho a}{9\sigma F} \quad \frac{1}{T^3} - \frac{1}{T_1^3} \tag{3}$$

where

T_1 = initial droplet temperature (Kelvin)

The transit time from generator to collector is equal to L/V where L is the length of the droplet stream in meters and V is the droplet velocity in meters/second. The temperature, T, is equal to T_2 at the collector and Eq (3) can be solved for the droplet radius (a) by substituting $t=L/V$ and $T=T_2$ resulting in this equation:

$$a = \frac{9\sigma FL}{c\rho V} \frac{T_1^3}{(T_2/T_1)^{-3} - 1} \tag{4}$$

The average rate of heat loss from each droplet is given by:

$$\bar{\dot{q}} = \frac{\int_0^{L/V} \dot{q}dt}{\frac{L}{V}} = 4\pi a^2 \sigma F T_1^4 \frac{3(1-T_2/T_1)}{(T_2/T_1)^{-3} - 1} \tag{5}$$

For the stream volume with the number of droplets per cubic meter equal to n and the stream diameter given by D in meters, the total rate of heat loss for the stream is given by the following equation:

$$\dot{Q} = n\pi^2 a^2 D^2 L\sigma F T_1^4 \frac{3(1-T_2/T_1)}{(T_2/T_1)^{-3} - 1} \tag{6}$$

The gray body view factor from Reference 1 is given as:

$$F = \frac{1}{\frac{1}{\eta} + \frac{1}{\epsilon} - 1} \tag{7}$$

where

ε = the emissivity of the droplet surface
η = the conservative black body view factor for the droplet at stream center

The value for eta is used as a conservative average value for all the droplets and is given as (1:4):

$$\eta = 1 - \frac{\pi^2 n D a^2}{8} \tag{8}$$

Solving Eq (8) for n and substituting with Eq (7) into Eq (6), the expression for the total heat loss from the droplet stream is found to be:

$$\dot{Q} = BDL\sigma T_1^4 \frac{3(1-T_2/T_1)}{(T_2/T_1)^{-3} - 1} \tag{9}$$

where

$$B = \frac{8(1 - \eta)}{\frac{1}{\eta} + \frac{1}{\varepsilon} - 1}$$

The value for B is substituted into Eq (9) and the resulting equation is differentiated with respect to eta and the result set equal to zero in order to reasonably optimize the heat flow per unit area resulting in this equation for eta:

$$\eta^2\left(\frac{1}{\varepsilon} - 1\right) + 2\eta - 1 = 0 \qquad (10)$$

The total mass of the system results from the mass of the liquid to carry the waste heat, the mass of the generator and collector, the pump mass, and the extra liquid mass needed to replace evaporation losses. The total mass of the system is given by (adapted from Reference 1):

$$M_T = \frac{\dot{Q}(1+\beta)L}{CV(T_1-T_2)} + \frac{\pi(mc)\dot{Q}^2}{36}\left[\frac{(T_2/T_1)^{-3} - 1}{BL\sigma T_1^3(T_1-T_2)}\right]^2 + \frac{\dot{Q}(mp)}{C(T_1-T_2)} + \frac{\eta\dot{Q}}{F\sigma T_1^3}\,\frac{P(T_1)(T_1/Tv)\tau}{(T_1-T_2)(2\pi RT_1)^{1/2}} \qquad (11)$$

where

β = parameter variable, ratio of liquid mass in reheating station to mass in stream
mc = parameter variable, specific mass of droplet generator and collector per unit area (kg/m^2)
mp = parameter variable, pump specific mass (kg/(kg/sec))
$P(T_1)$ = vapor pressure of droplets at T_1 = 300 Kelvin (pascals)
Tv = value used to fit vapor pressure curve (15000 Kelvin)
R = gas constant (15.22 joules/kg-Kelvin)
τ = mission time (years)

The first term gives the mass of liquid needed to carry the amount of waste heat in the stream and the fraction of the total liquid mass in the reheating station. The second term is the mass of the droplet generator and collector. The third term is for the pump mass and includes the new pump specific mass (mp) in terms of pump mass per mass flow rate. The fourth term is the total mass lost due to evaporation or the amount of additional liquid mass needed to replace that lost to evaporation (1:8).

To find the stream length L to minimize the total mass for a given set of the other parameters, Eq (11) is differentiated with respect to L and set equal to zero resulting in this equation:

$$L = \left[\frac{\pi CVT_1\dot{Q}\left[(T_2/T_1)^{-3} - 1\right]^2 (mc)}{18B^2(1+\beta)(\sigma T_1^4)^2(1-T_2/T_1)}\right]^{1/3} \qquad (12)$$

This equation for L is substituted into Eq (11) and when the total heat rejection rate is divided through the equation, the following equation for the specific mass of the system in terms of Kg/Kw is found (adapted from Reference 1):

$$\frac{M_T}{\dot{Q}} = \frac{3\dot{Q}^{1/3}}{2(1-T_2/T_1)^{4/3}}\left[\frac{(1+\beta)\left[(T_2/T_1)^{-3} - 1\right]}{BCVT_1\sigma T_1^4}\right]^{2/3} \times \left(\frac{(mc)\pi}{18}\right)^{1/3}$$

$$+ \frac{(mp)}{C(T_1-T_2)} + \frac{\eta P(T_1)(T_1/Tv)\tau}{F\sigma T_1^4(1-T_2/T_1)(2\pi RT_1)^{1/2}} \qquad (13)$$

Possible inaccuracies in the direction of flight of the liquid droplets may cause the stream to widen at the collector and droplet mass will be lost. To minimize this stream widening, the length to diameter ratio (L/D) is held fixed at a recommended value of 250 (1:10). Equation (11) is rewritten by using Eq (9) resulting in Eq (14) below where the only dimensions appearing are in the ratio L/D (adapted from Reference 1):

$$\frac{M_T}{\dot{Q}} = \frac{(1+\beta)(L/D)^{1/2}\left[(T_2/T_1)^{-3} - 1\right]^{1/2} \dot{Q}^{1/2}}{CVT_1(3B\sigma T_1^4)^{1/2}(1-T_2/T_1)^{3/2}} + \frac{(mp)}{C(T_1-T_2)}$$

$$+ \frac{\pi(mc)\left[(T_2/T_1)^{-3} - 1\right]}{12B\sigma T_1^4(L/D)(1-T_2/T_1)} + \frac{\eta P(T_1)(T_1/Tv)\tau}{F\sigma T_1^4(2\pi RT_1)^{1/2}(1-T_2/T_1)} \qquad (14)$$

The stream diameter is found from Eq (9) for a fixed L/D ratio as:

$$D = \frac{\dot{Q}^{1/2}\left[(T_2/T_1)^{-3} - 1\right]^{1/2}}{\left[3B(L/D)\sigma T_1^4\right]^{1/2}(1-T_2/T_1)^{1/2}} \qquad (15)$$

The length L of the droplet stream is found for the same fixed L/D ratio by multiplying the value of D from Eq (15) times L/D. The droplet radius a is found from Eq (4) after L is calculated.

The stream velocity is found from an equation for the ratio of droplet kinetic energy to the total heat rejection rate (1:6) as:

$$\gamma = \frac{V^2}{2C(T_1-T_2)} \tag{16}$$

or solving for the stream velocity

$$V = (2C\gamma(T_1-T_2))^{1/2} \tag{17}$$

The value of gamma is required to be much less than one to reduce this ratio and thus keep the pump power within a small fraction of the total heat rejection rate (1:6).

The equations in this chapter represent LDR operation under steady-state conditions. A detailed design of a LDR would involve many other factors such as the wear of moving parts, problems of corrosion and erosion, deployment and start up techniques, the effects of variable heat loads, temporary shutdowns, and possible on-orbit servicing (1:10).

III. PARAMETER INVESTIGATION

Parameter values were selected for use in Eq (13) and the total system specific mass was calculated as a function of the average droplet temperature, T_2, at the collector for various pump specific mass values. The ratio, L/D, was calculated using the droplet temperatures corresponding to the minimum mass system. If the L/D value was greater than 250, a new minimum specific mass was calculated using Eq (14) with L/D fixed. The parameter values used for the calculations are shown in Table I and were adapted from Reference 1 except for pump specific mass (mp). Refer to Appendix B for calculation of some typical mp values.

TABLE I

Parameters Used for Calculations

Parameter	Value	Dimensions
γ	0.005	none
ε	0.7	none
β	0.10 * 0.20 **	none none
mc	40.0 * 100.0 **	kg/m^2 kg/m^2
mp	10.0 15.0 20.0 25.0 30.0 35.0 40.0	kg/(kg/sec) " " " " " "

* optimistic value ** realistic value (1:13)

The total system specific mass was found using Eq (13) or Eq (14) for fixed $L/D = 250$ ratio for a range of pump specific mass values as shown in Table I for the two values of β and mc using the computer program in Appendix A. The curves generated by these calculations are shown in Figures 2-17 for heat loss rates of 10 Kw, 100 Kw, 1000 Kw, and 10000 Kw and mission times of zero, ten, twenty, and thirty years. The parameter values used in Figures 2-17 were $\beta = 0.10$ and $mc = 40.0\ kg/m^2$ equivalent to 5 millimeters of steel and called optimistic values (1:A-1). A similar set of data (no figures) was calculated with $\beta = 0.20$ and $mc = 100.0\ kg/m^2$ equivalent to 12 millimeters of steel and called realistic values (1:A-3). In both cases $\gamma = 0.005$ and $\epsilon = 0.7$ for the calculations. No figures were generated for the second set of data to avoid redundancy. The temperature values tabulated in Chapter IV for T_2 were those values corresponding to the minimum points on each of the curves. These temperatures are the average droplet temperatures at the collector after the droplets radiated their waste heat to space as a function of the pump specific mass for the minimum mass system. The minimum point on each of the curves in Figures 2-17 shows a reduction in the droplet temperature at the collector with increasing pump specific mass and increasing total system specific mass.

A comparison of the average droplet temperature, T_2, at the collector for the minimum mass case as a function of pump specific mass is shown in Figures 18-21 for each β and mc parameter value for various mission times and heat loss rates. In Figures 18-21 the lower four curves were obtained using the optimistic values of β and mc from Table I. The upper four curves were obtained using the realistic values of β and mc . The symbols on the curves are the actual temperature data points found as a function of pump specific mass for the minimum mass system for the indicated times and heat loss rates.

In Figures 22-25 a comparison of the system specific mass (Kg/Kw) as a function of pump specific mass, mp, (kg/(kg/sec)) is shown for the indicated heat loss rates and mission times. In Figures 22-25 the lower four curves were obtained using the optimistic values of β and mc from Table I, while the upper four curves were found using the realistic values of β and mc. The symbols on the curves are the actual specific mass data points found as a function of pump specific mass for the minimum mass system.

The system specific mass as a function of the heat loss rate is shown in Figure 26 for the indicated mission times. Again, the lower four curves were obtained using the optimistic values of β and mc from Table I, while the upper four curves were found using the realistic values of β and mc . This figure is for a pump specific mass value of 10.0 kg/(kg/sec).

The following key is for the symbols on the curves in Figures 2-17 representing the different pump specific mass values used to generate the curves.

Symbol	mp Value
□	10.0
△	15.0
◇	20.0
✡	25.0
✳	30.0
+	35.0
×	40.0

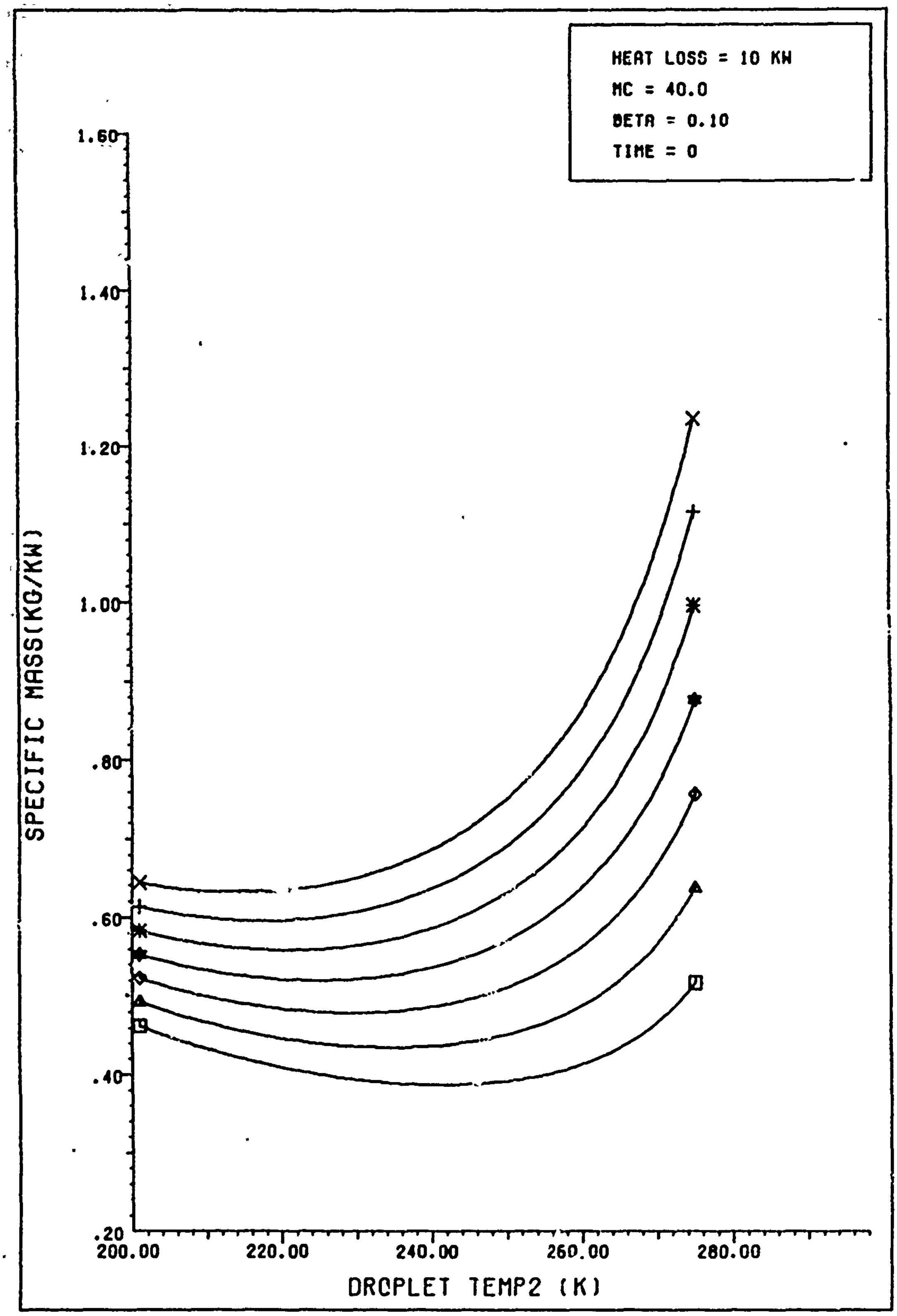

Figure 2. System Mass per Heat Loss vs Droplet Temperature: (10 Kw, Time = 0)

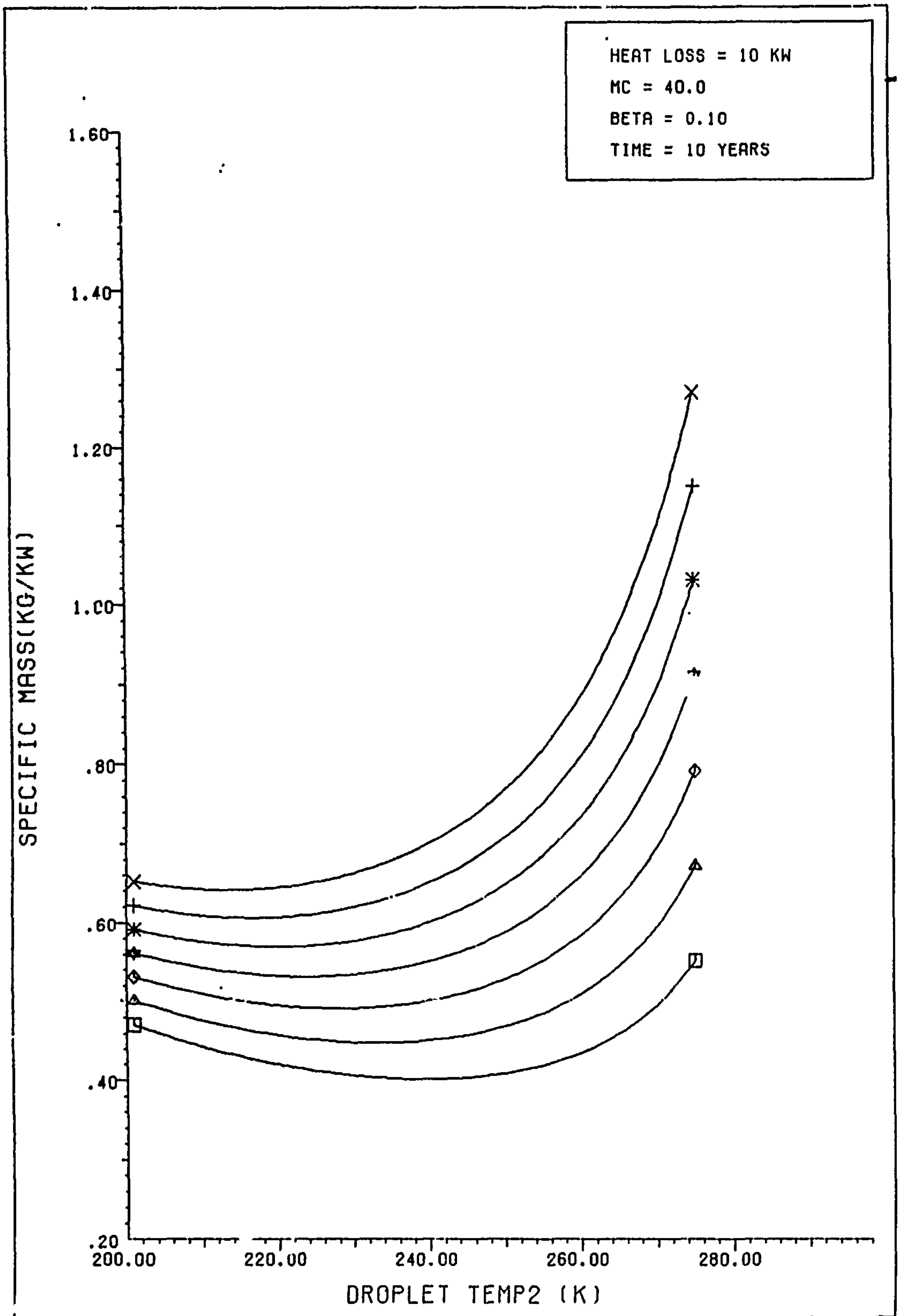

Figure 3. System Mass per Heat Loss vs Droplet Temperature: (10 Kw, Time = 10 years)

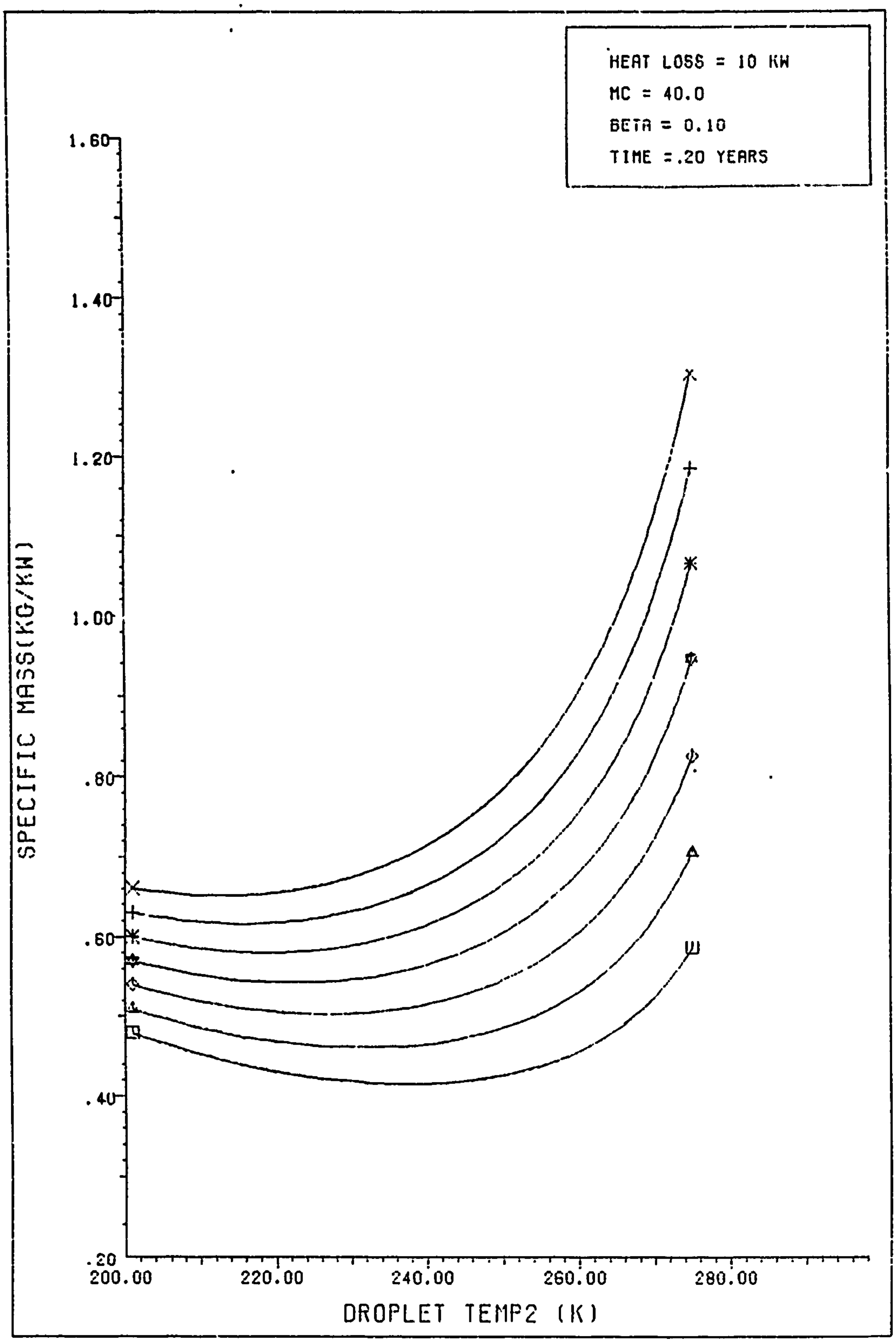

Figure 4. System Mass per Heat Loss vs Droplet Temperature: (10 Kw, Time = 20 years)

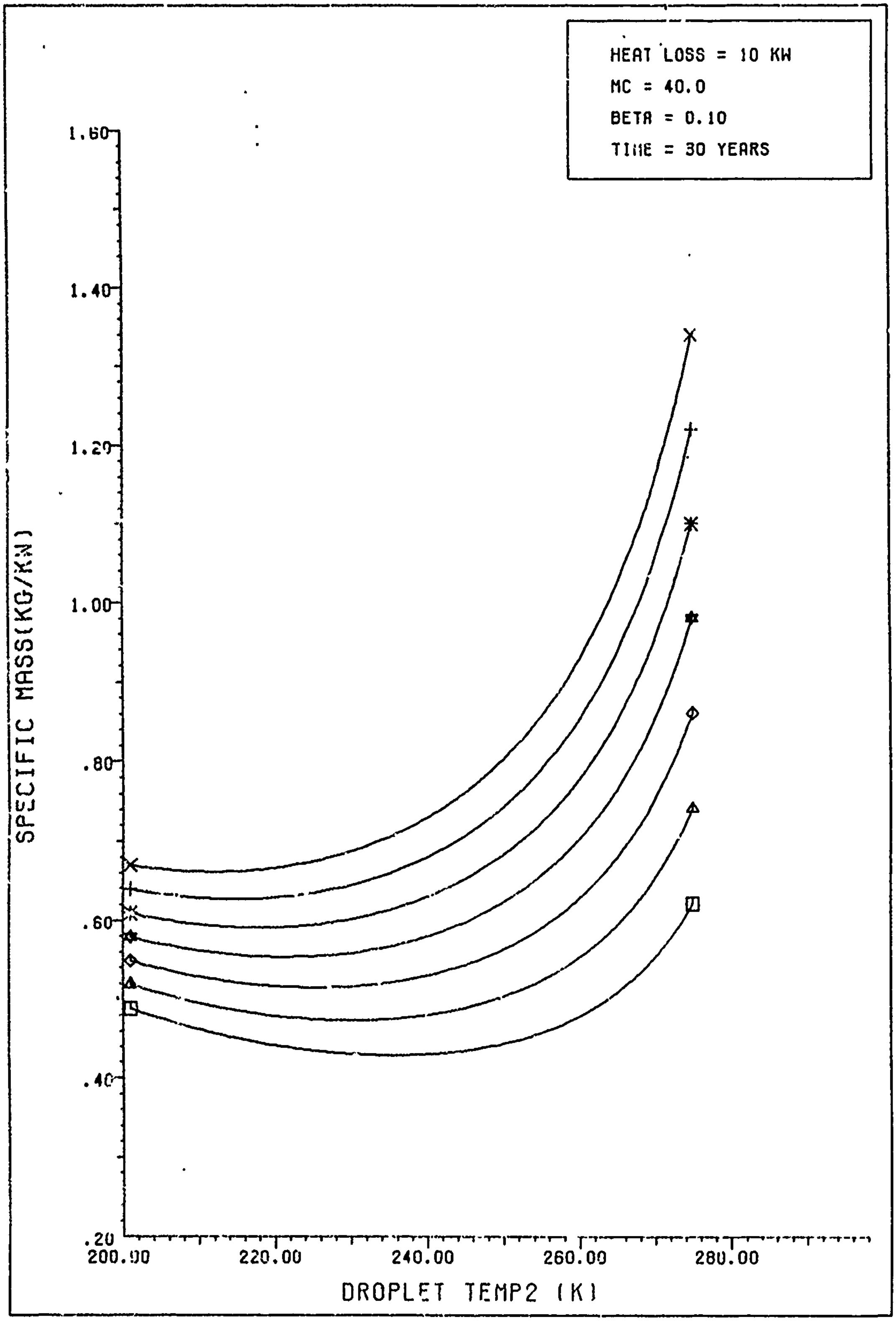

Figure 5. System Mass per Heat Loss vs Droplet Temperature: (10 Kw, Time = 30 years)

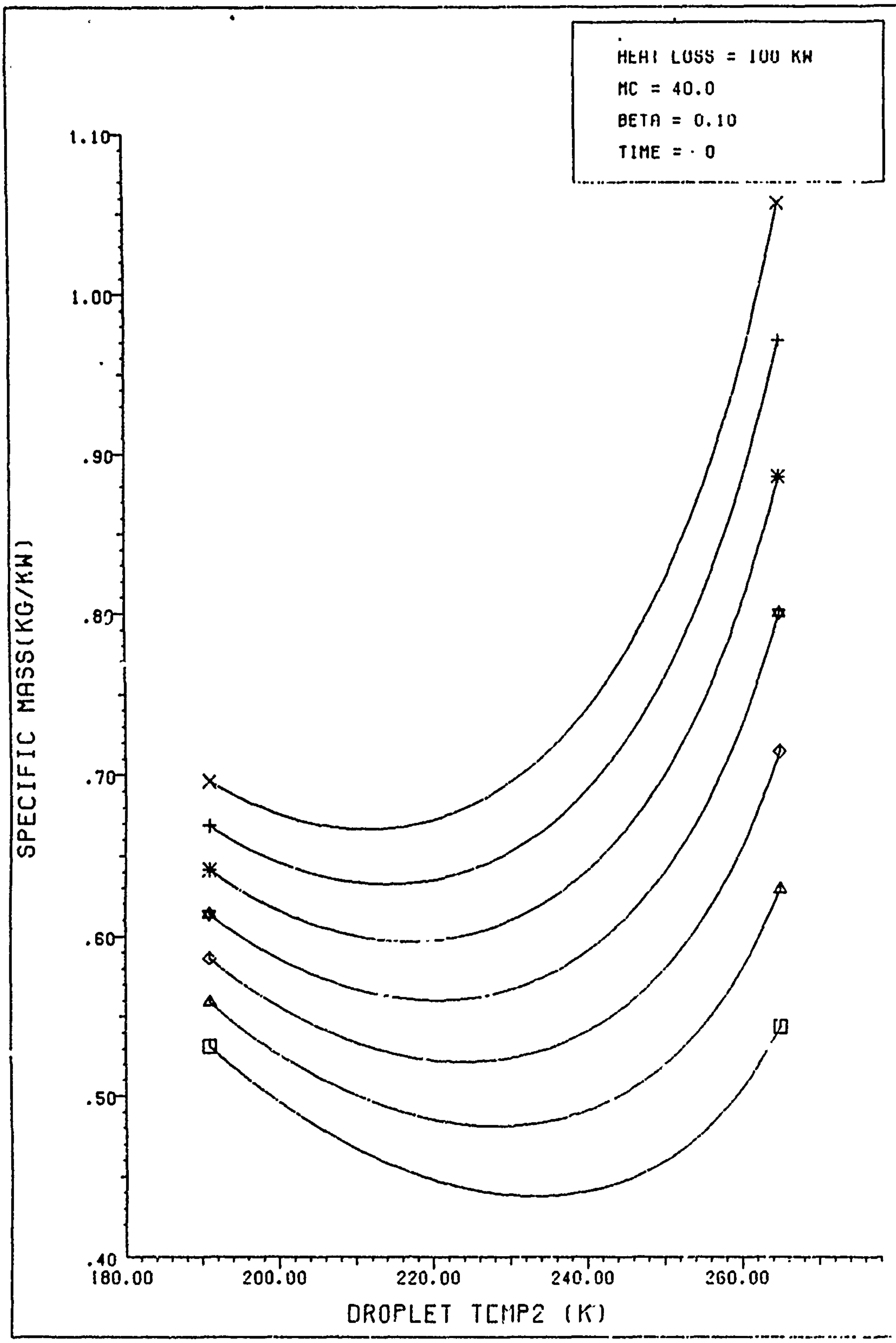

Figure 6. System Mass per Heat Loss vs Droplet Temperature: (100 Kw, Time = 0)

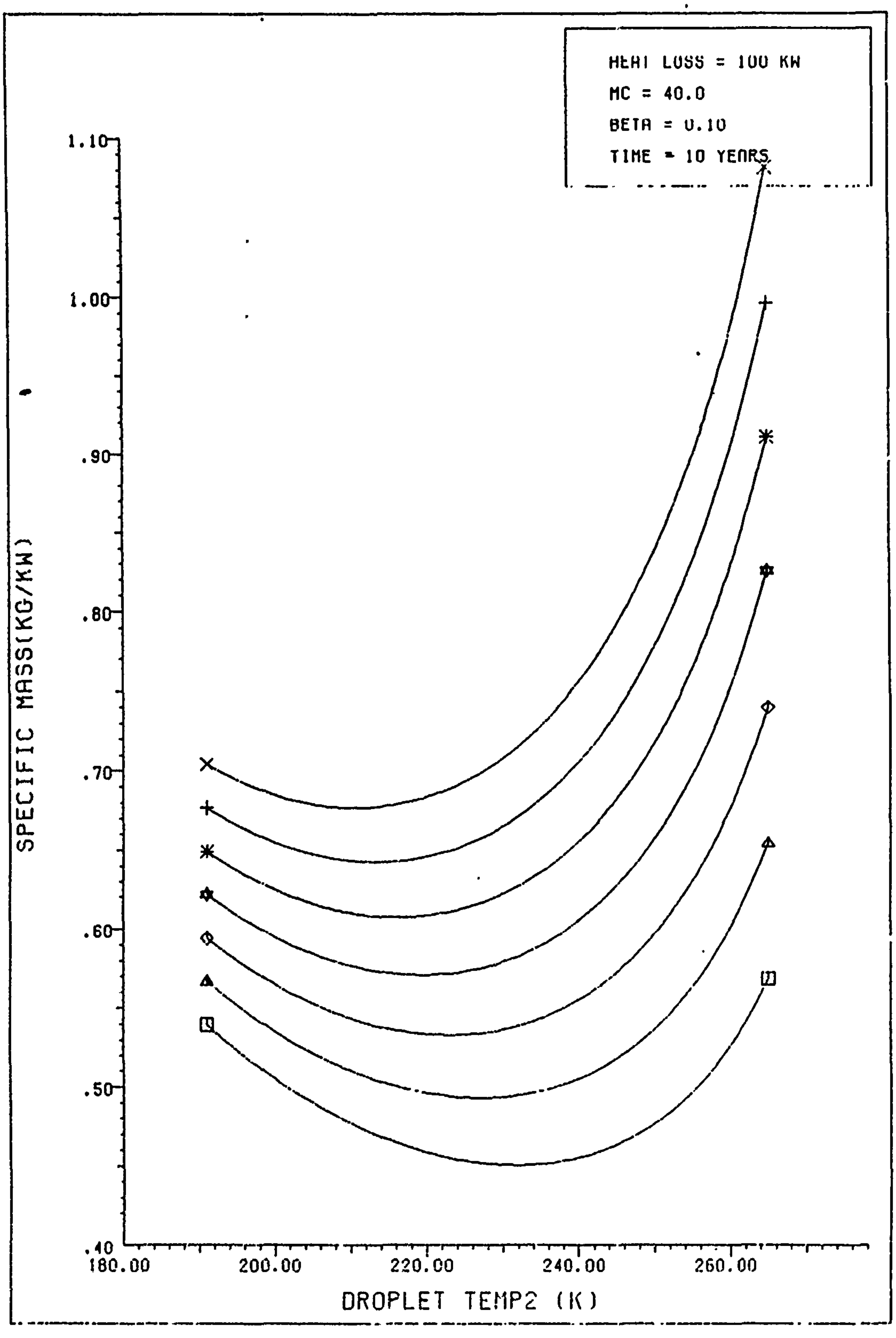

Figure 7. System Mass per Heat Loss vs Droplet Temperature: (100 Kw, Time = 10 years)

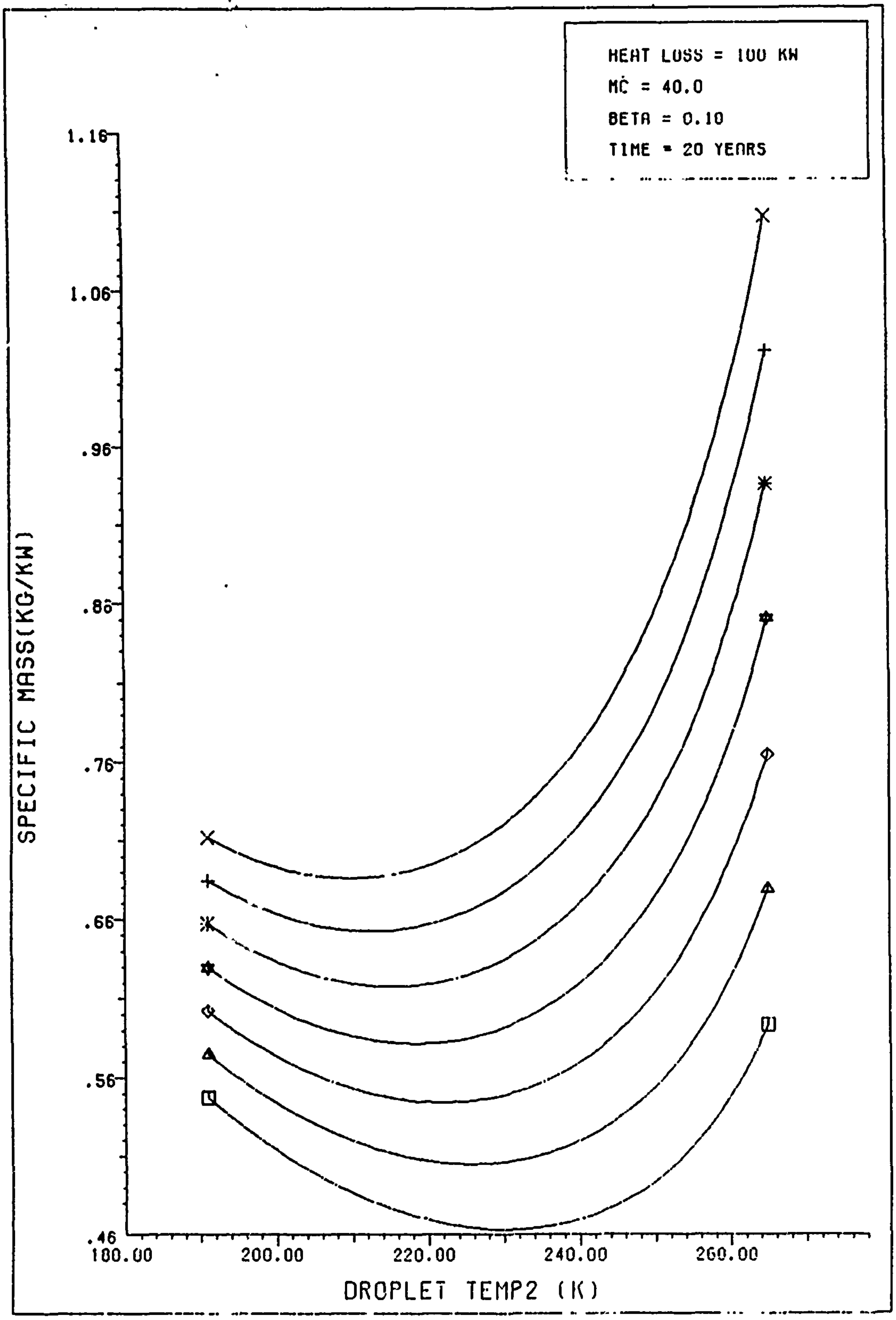

Figure 8. System Mass per Heat Loss vs Droplet Temperature: (100 Kw, Time = 20 years)

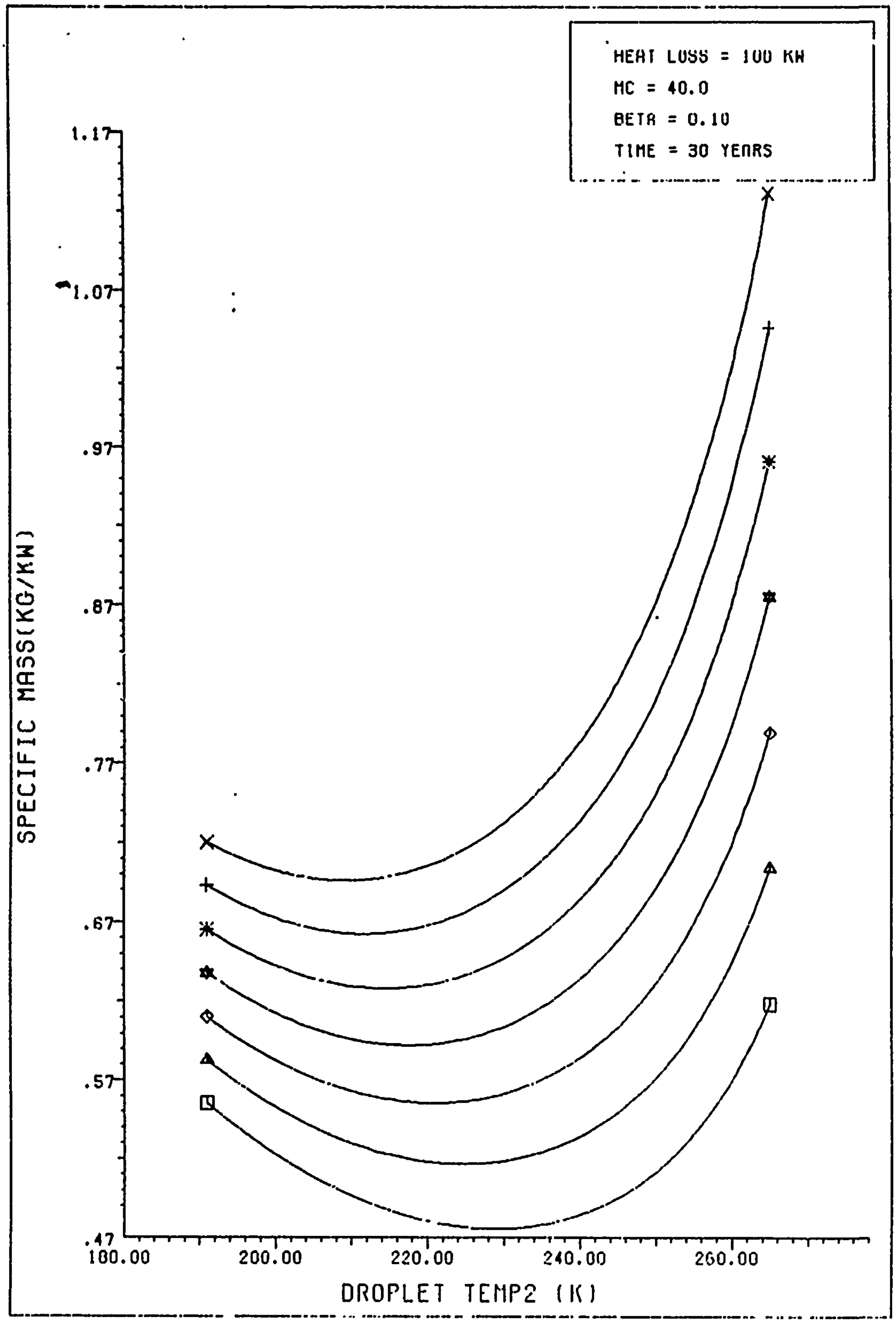

Figure 9. System Mass per Heat Loss vs Droplet Temperature: (100 Kw, Time = 30 years)

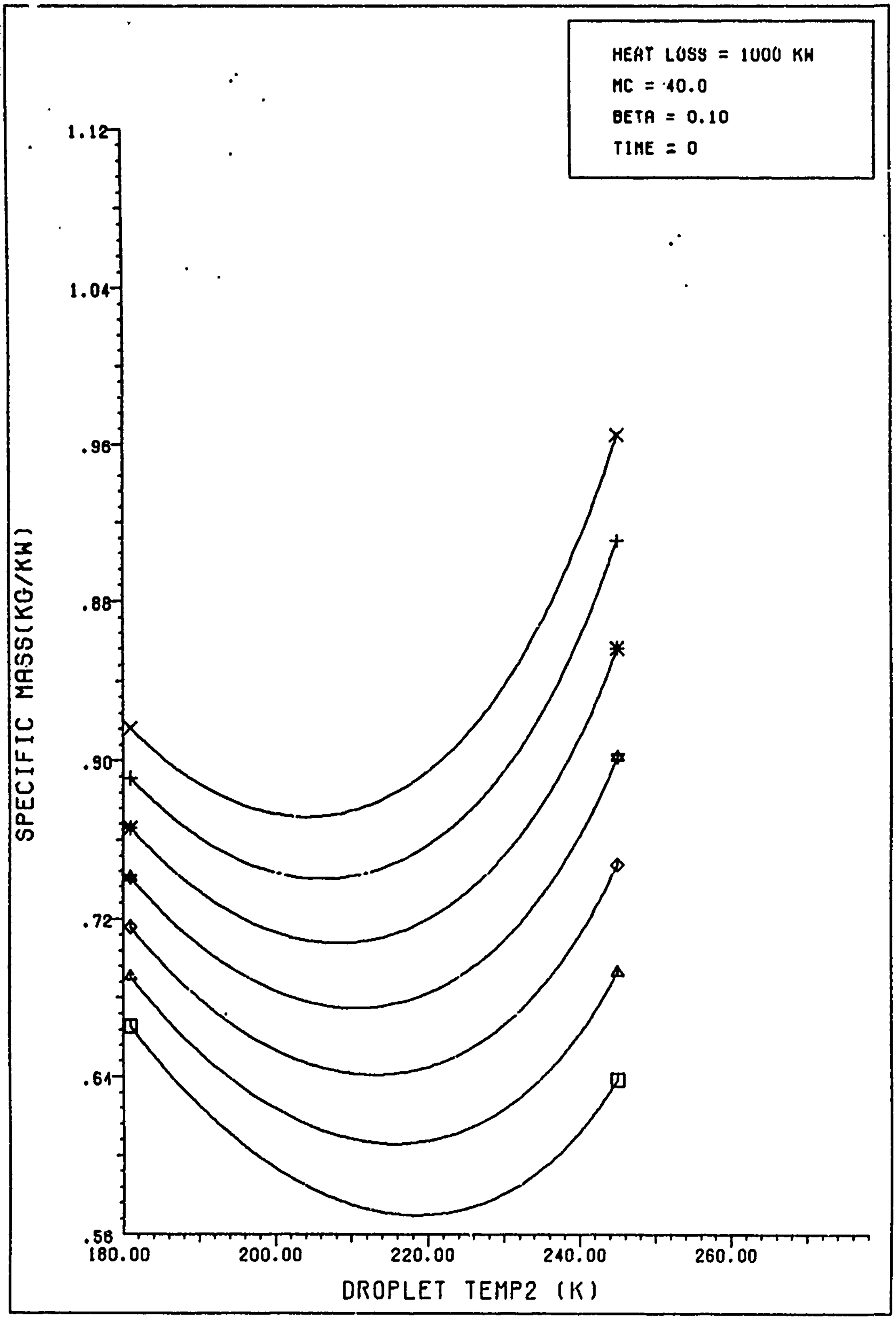

Figure 10. System Mass per Heat Loss vs Droplet Temperature: (1000 Kw, Time = 0)

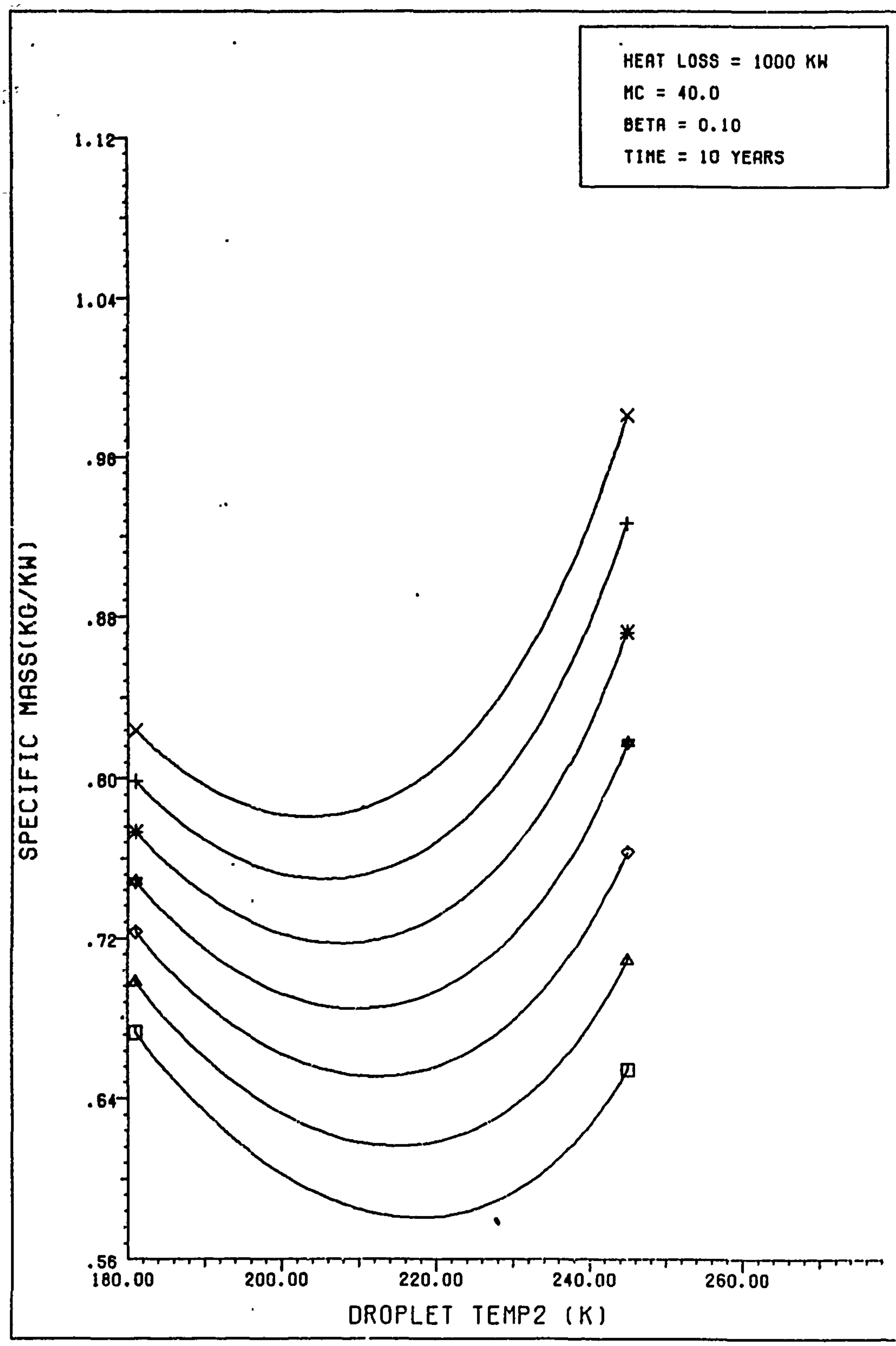

Figure 11. System Mass per Heat Loss vs Droplet Temperature: (1000 Kw, Time = 10 years)

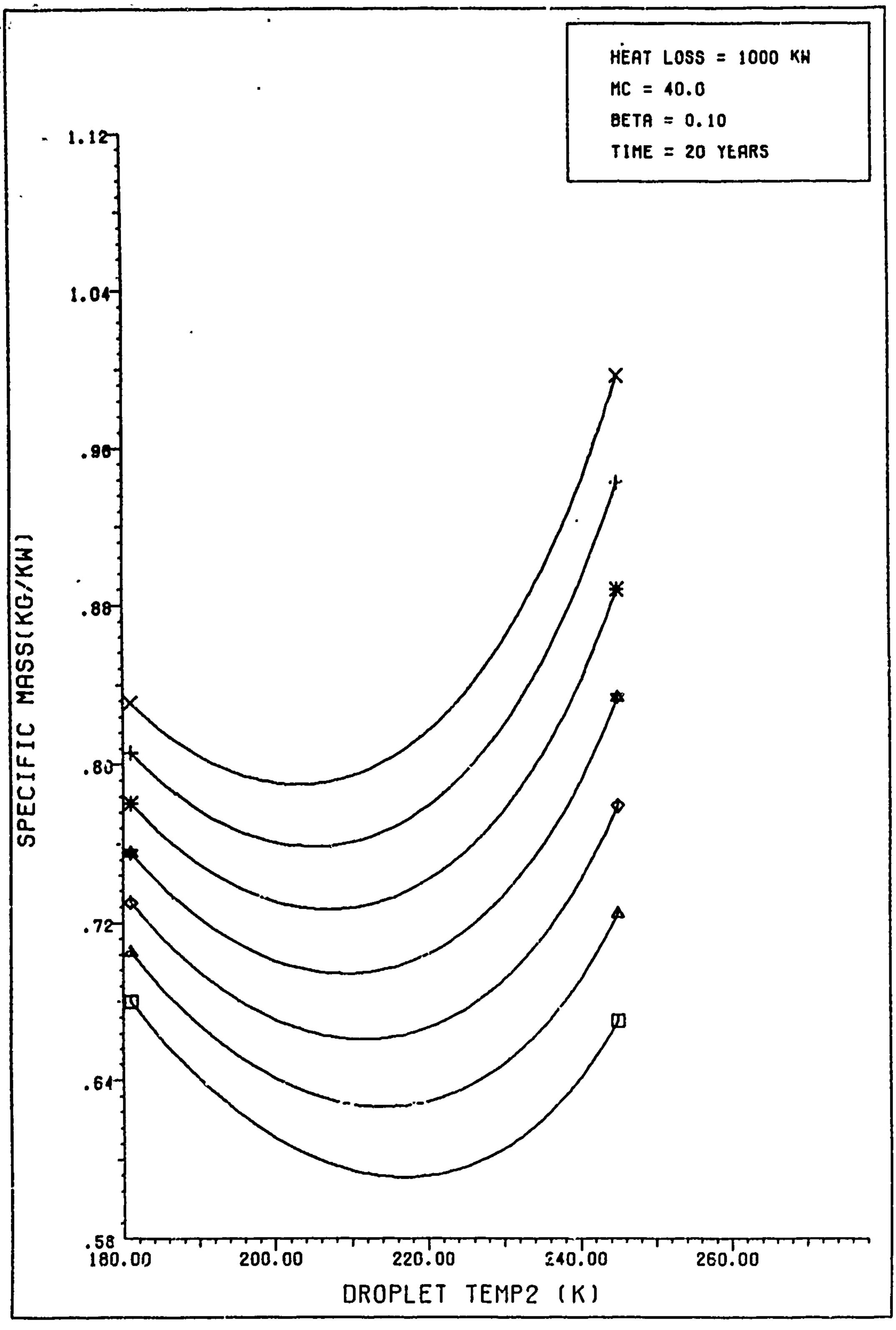

Figure 12. System Mass per Heat Loss vs Droplet Temperature: (1000 Kw, Time = 20 years)

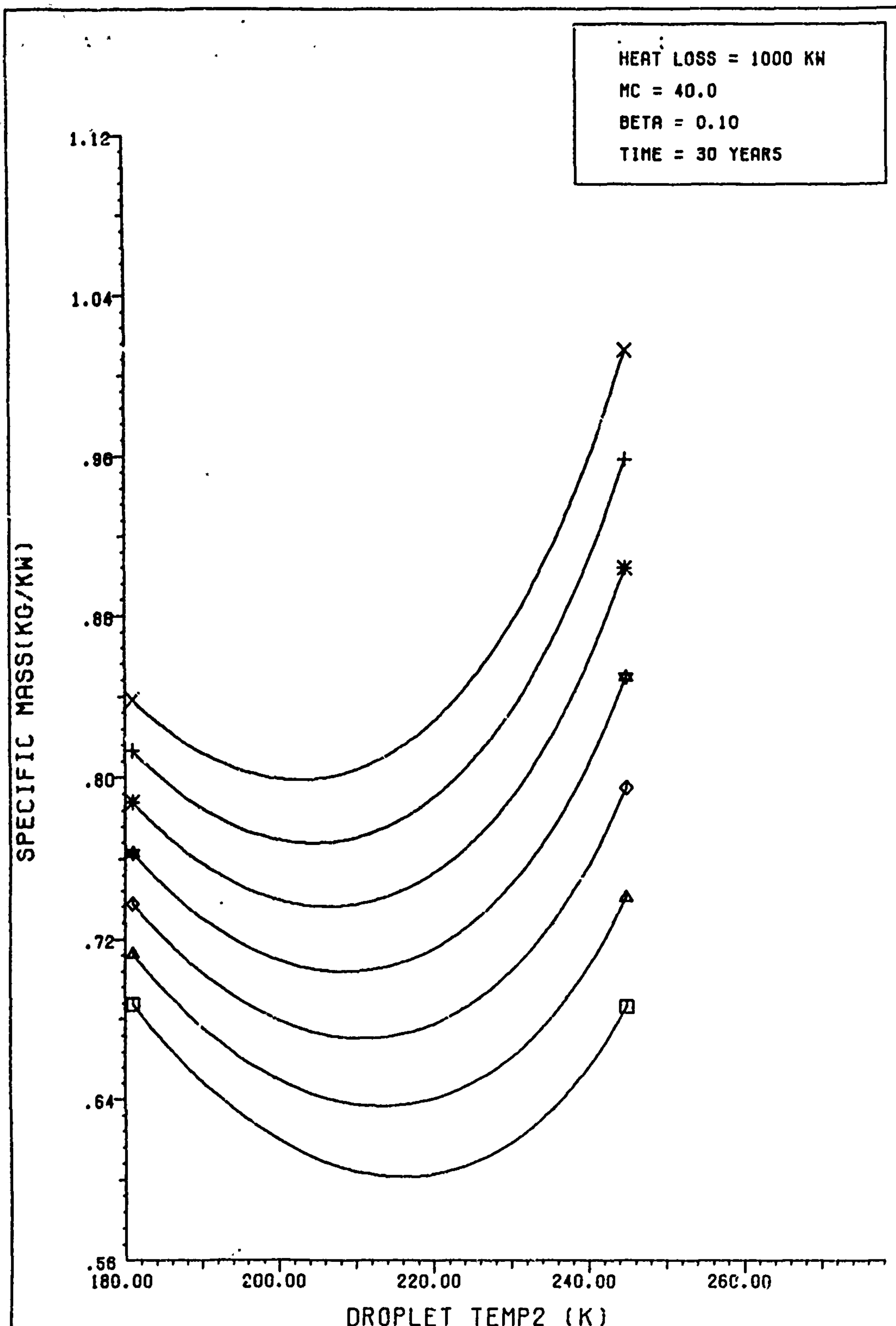

Figure 13. System Mass per Heat Loss vs Droplet Temperature: (1000 Kw, Time = 30 years)

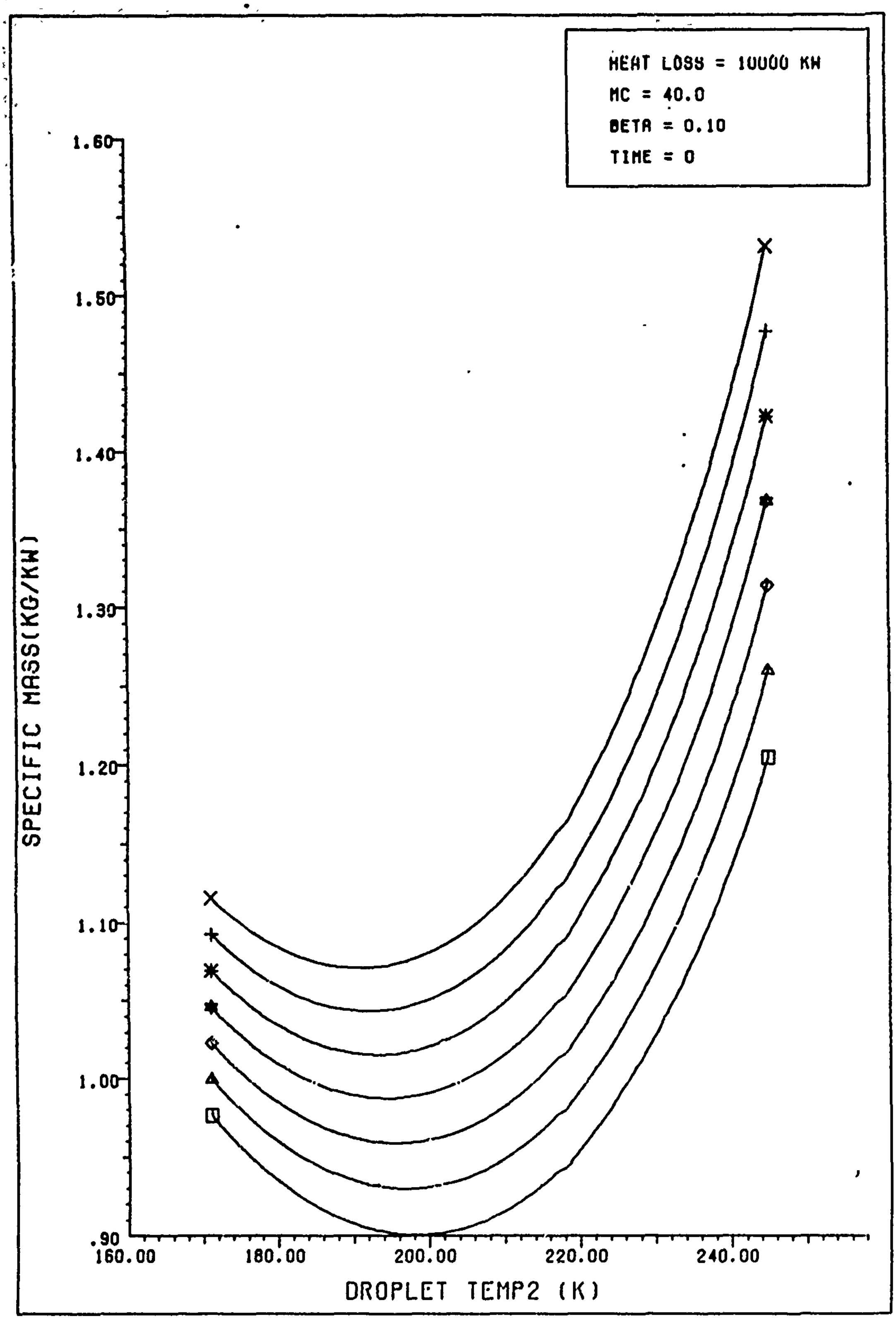

Figure 14. System Mass per Heat Loss vs Droplet Temperature: (10000 Kw, Time = 0)

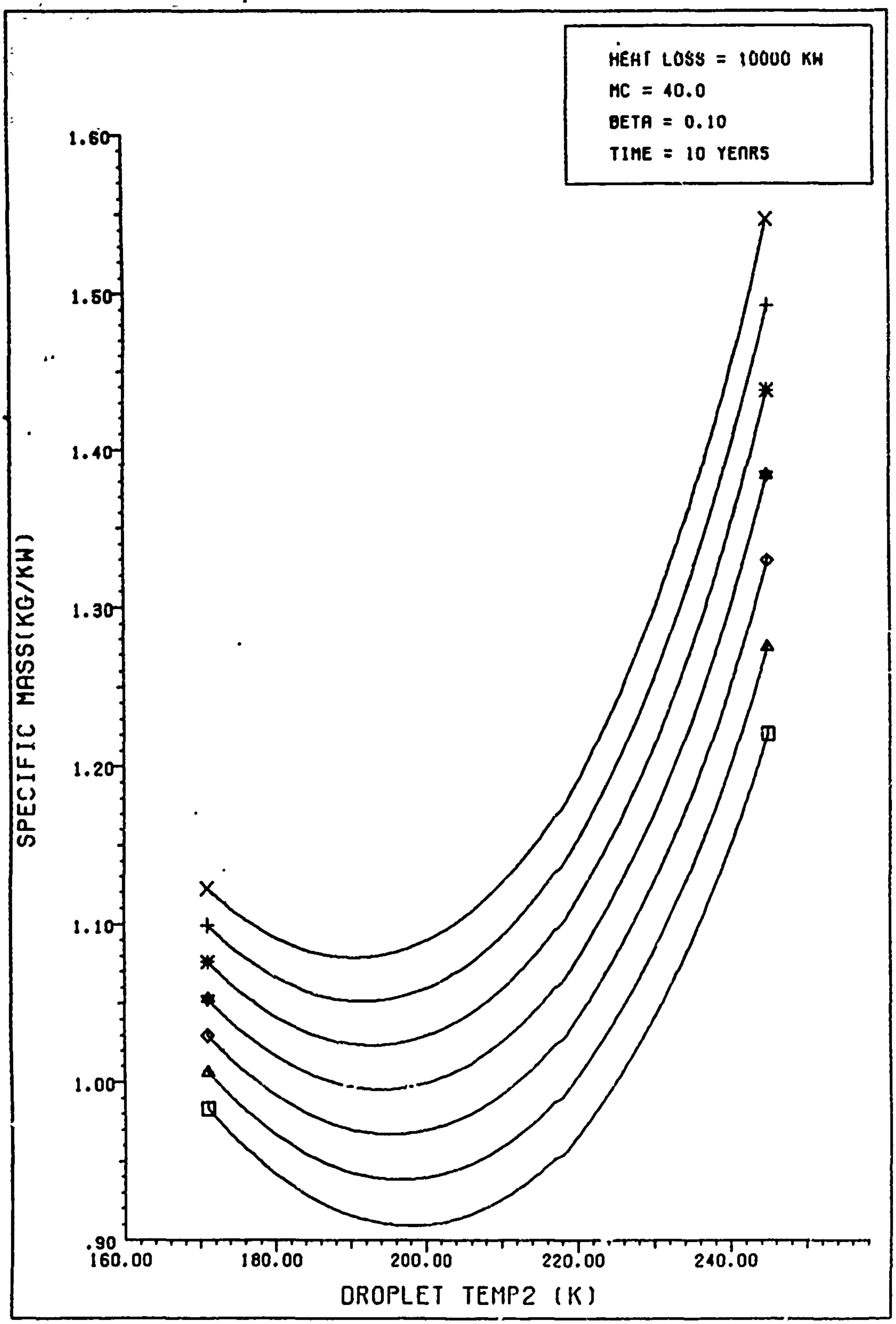

Figure 15. System Mass per Heat Loss vs Droplet Temperature: (10000 Kw, Time = 10 years)

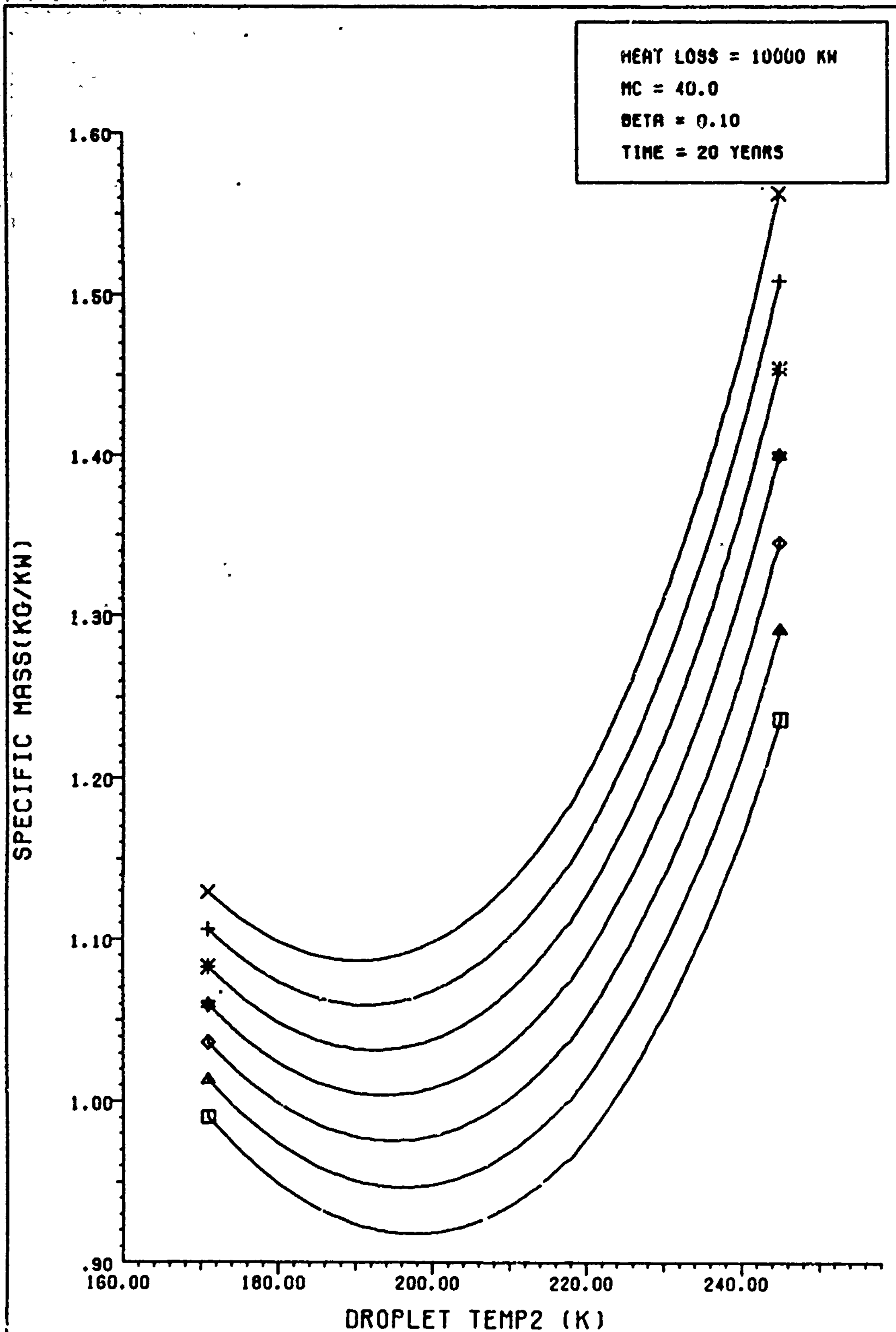

Figure 16. System Mass per Heat Loss vs Droplet Temperature: (10000 Kw, Time = 20 years)

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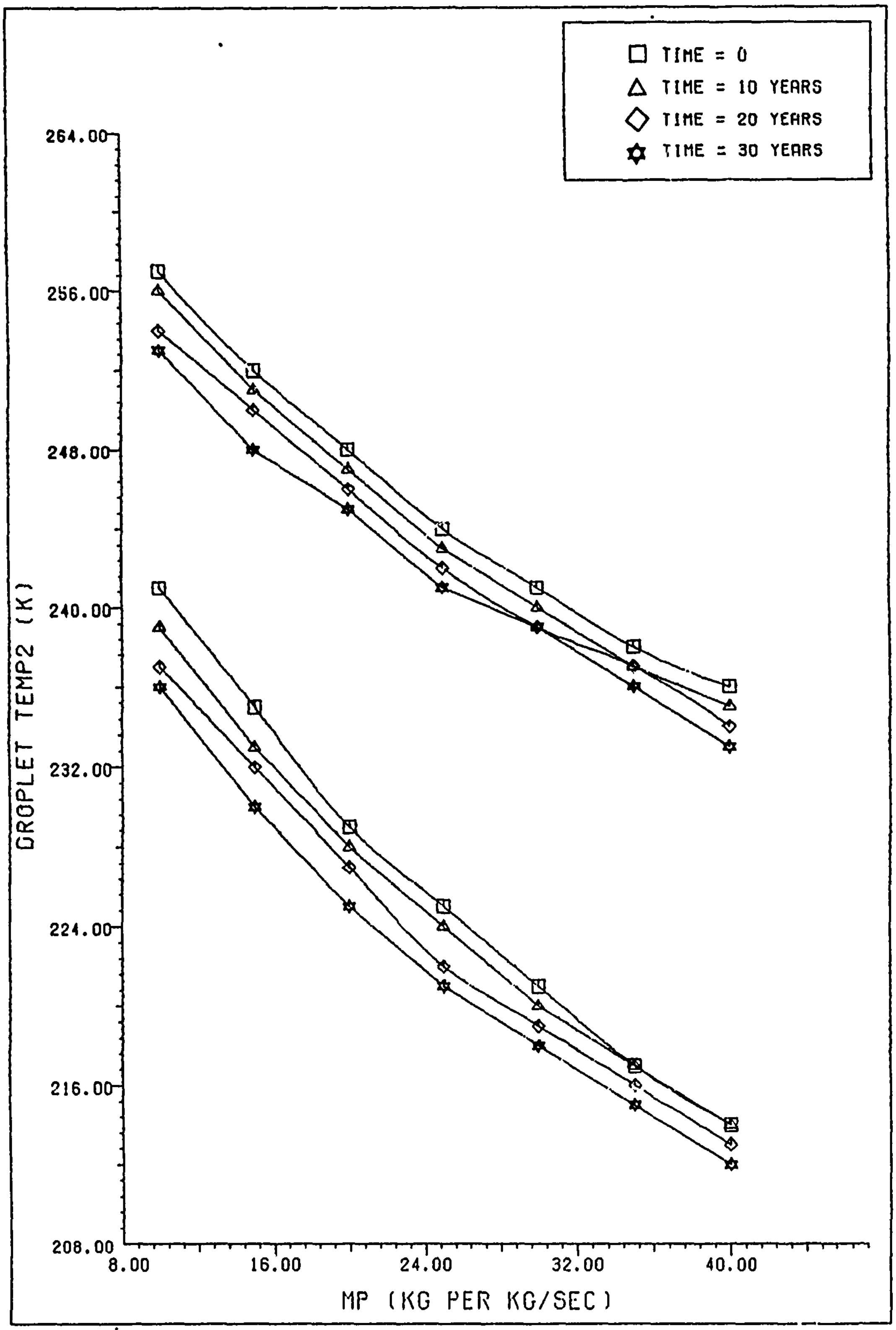

Figure 18. Droplet Temperature vs Pump Specific Mass: (10 Kw)

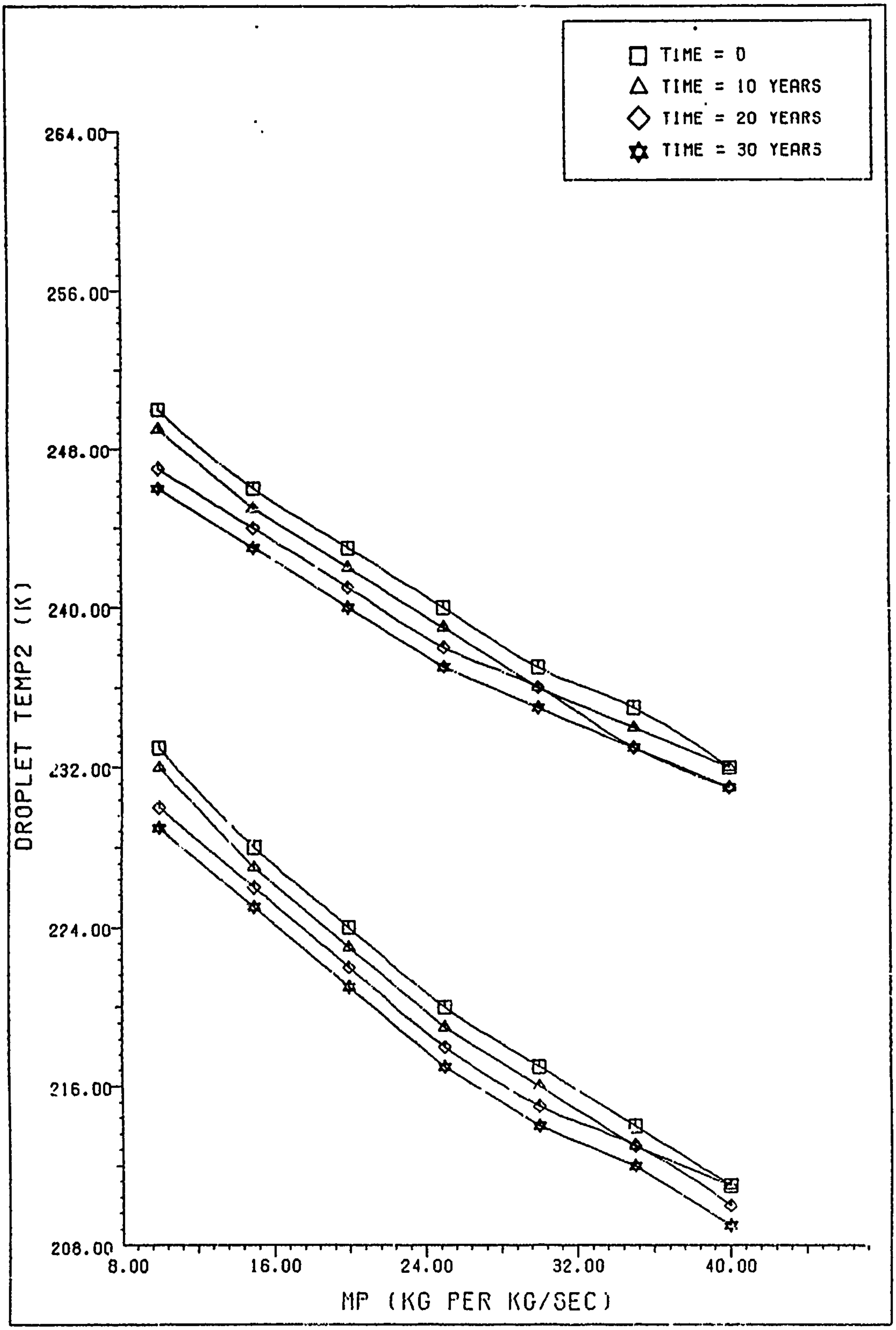

Figure 19. Droplet Temperature vs Pump Specific Mass: (100 Kw)

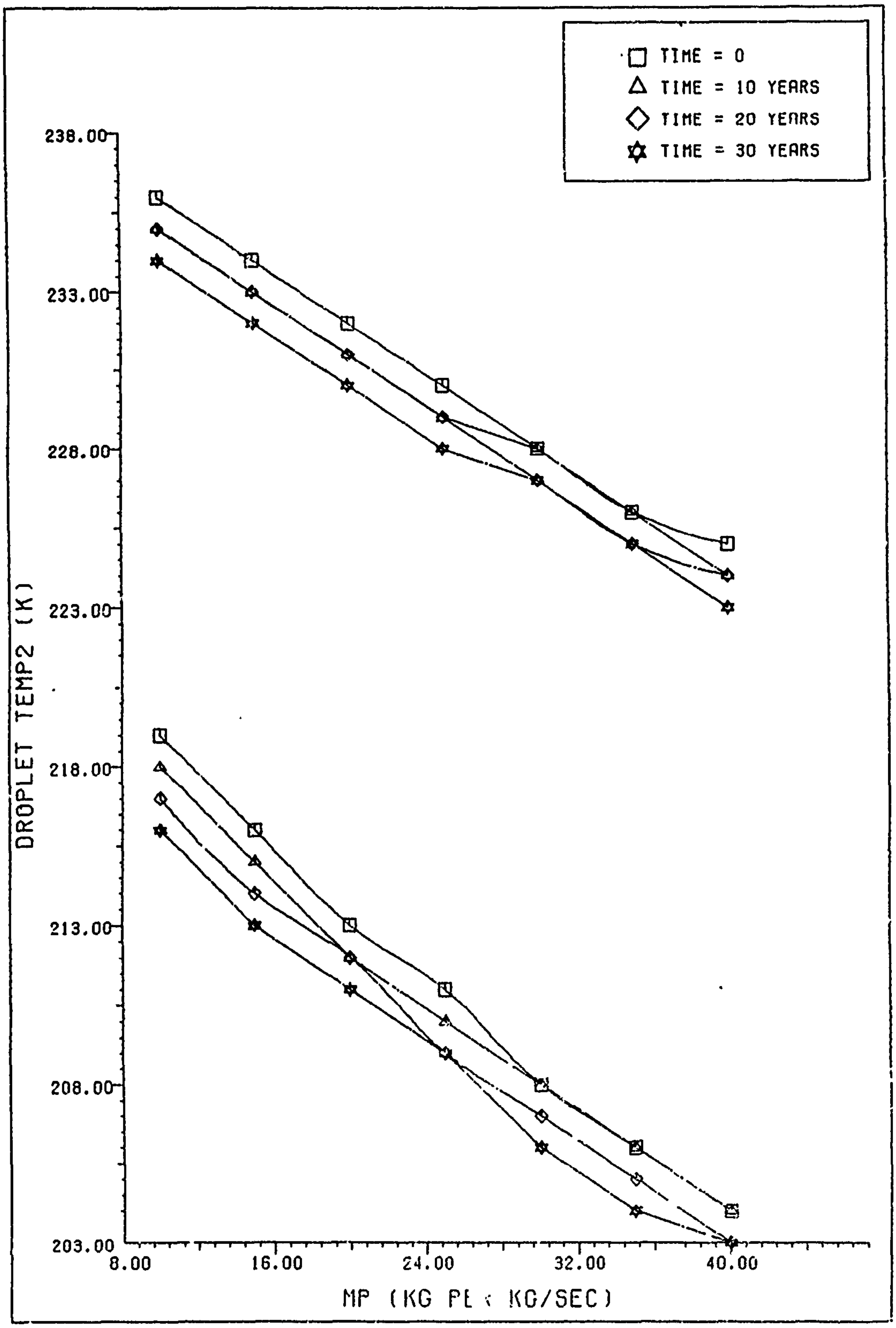

Figure 20. Droplet Temperature vs Pump Specific Mass: (1000 Kw)

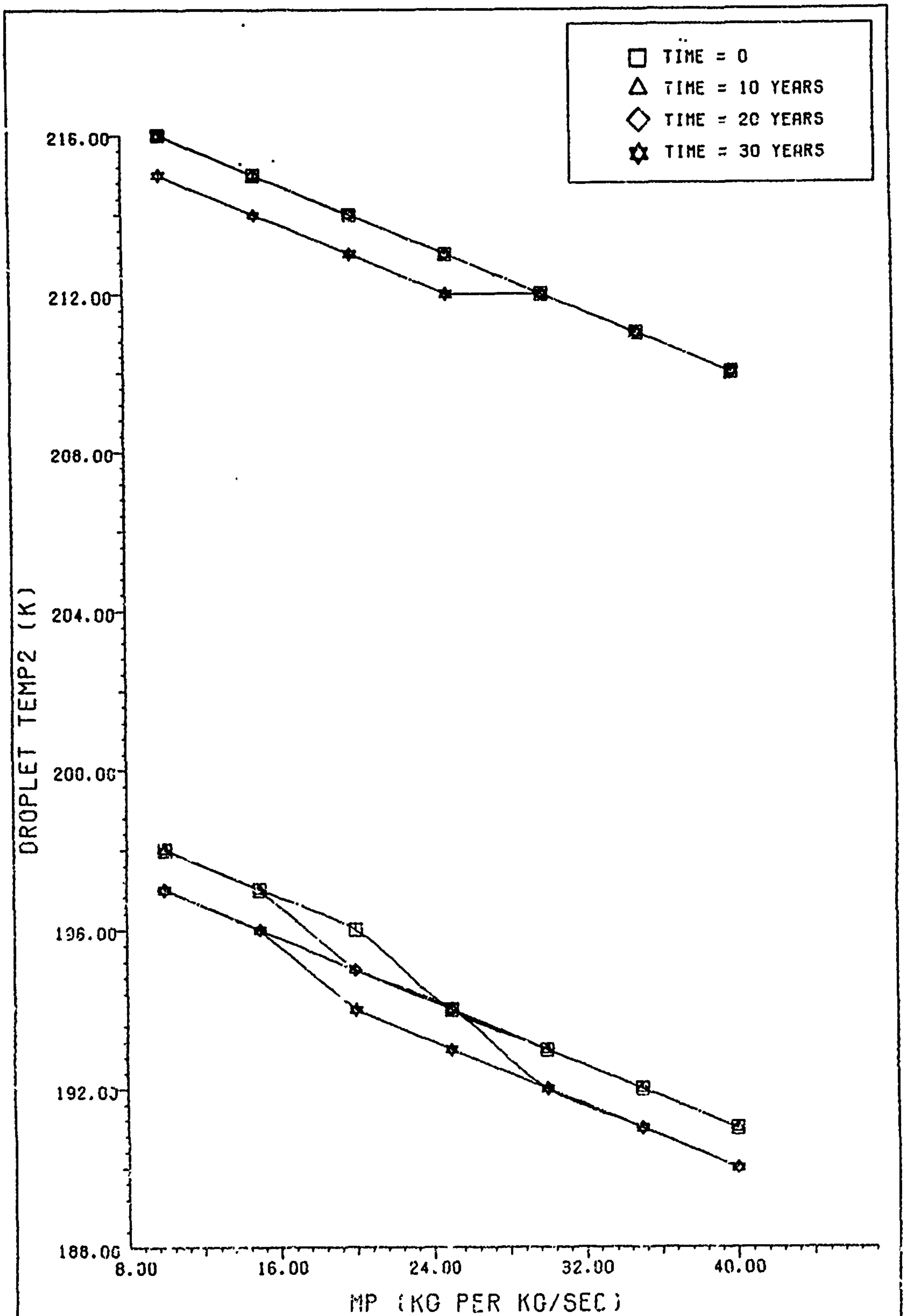

Figure 21. Droplet Temperature vs Pump Specific Mass: (10000 Kw)

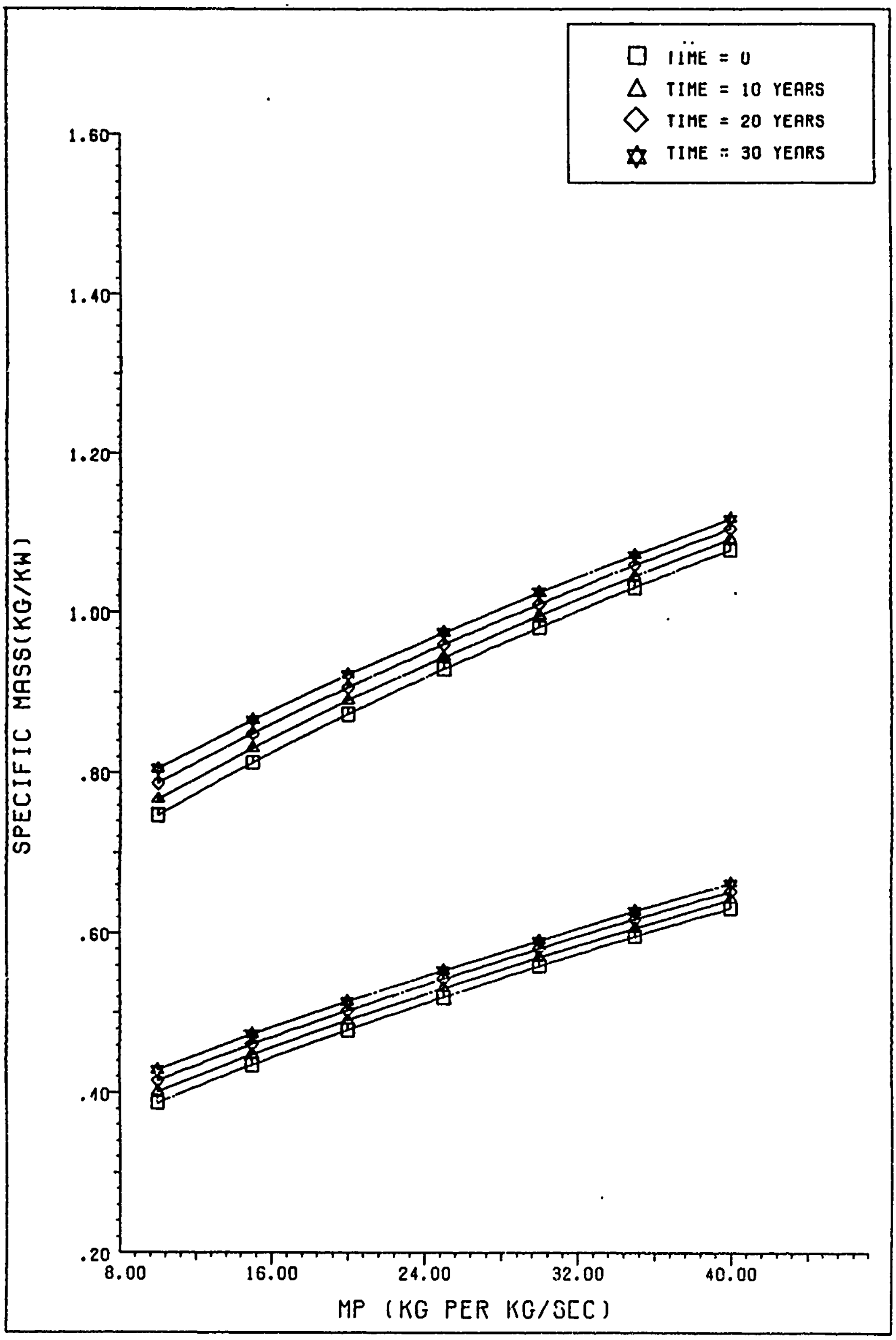

Figure 22. Specific Mass vs Pump Specific Mass: (10 Kw)

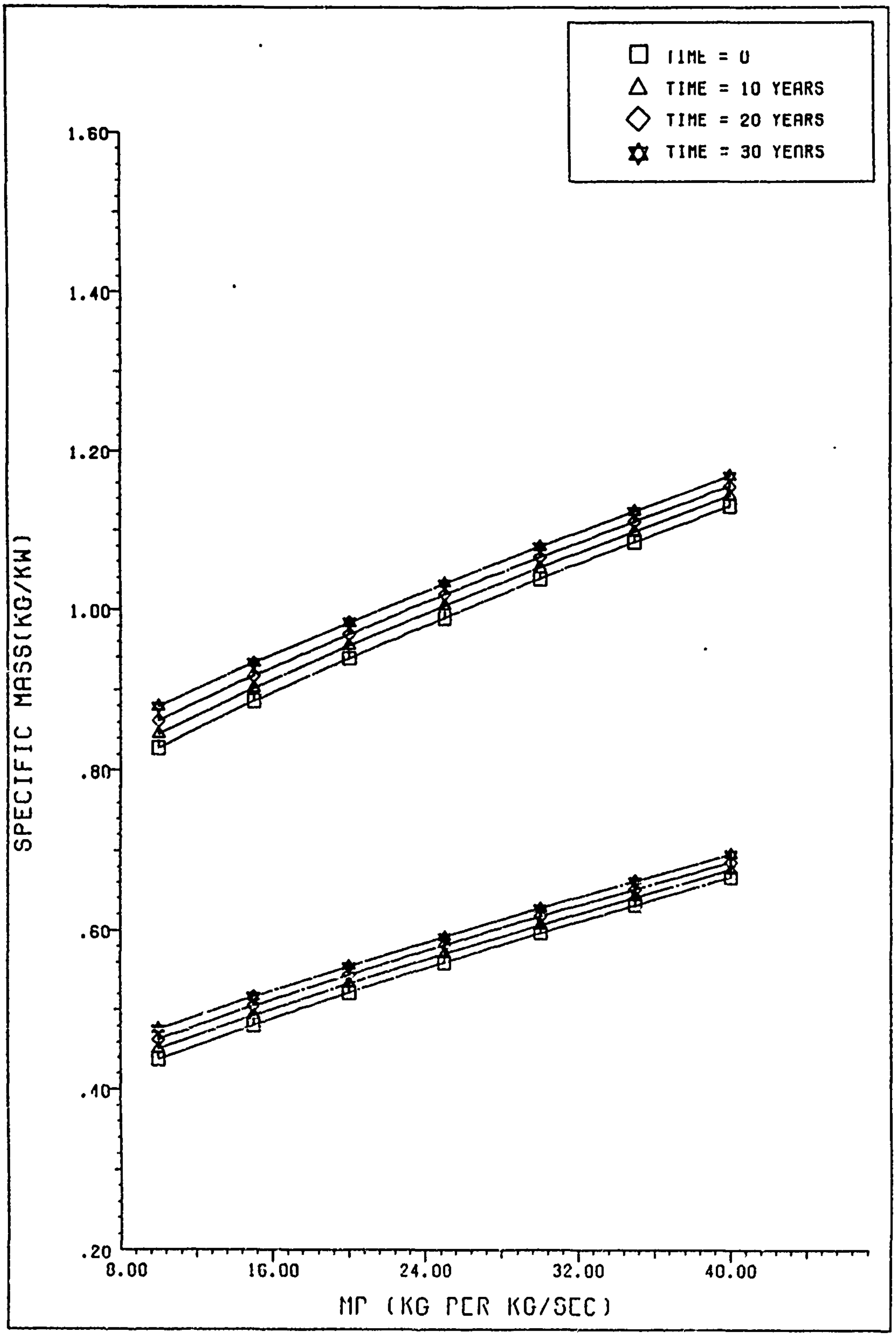

Figure 23. Specific Mass vs Pump Specific Mass: (100 Kw)

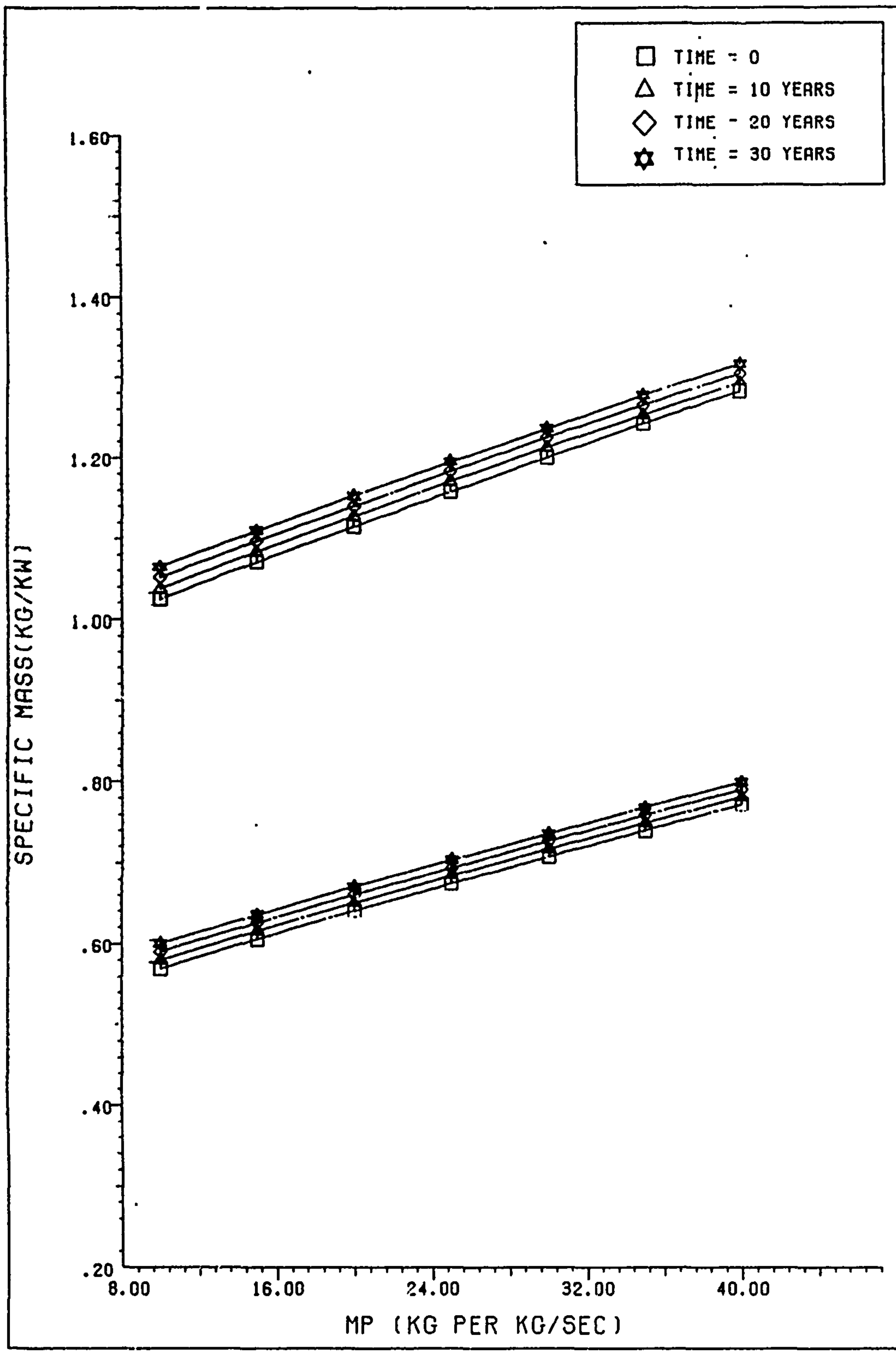

Figure 24. Specific Mass vs Pump Specific Mass: (1000 Kw)

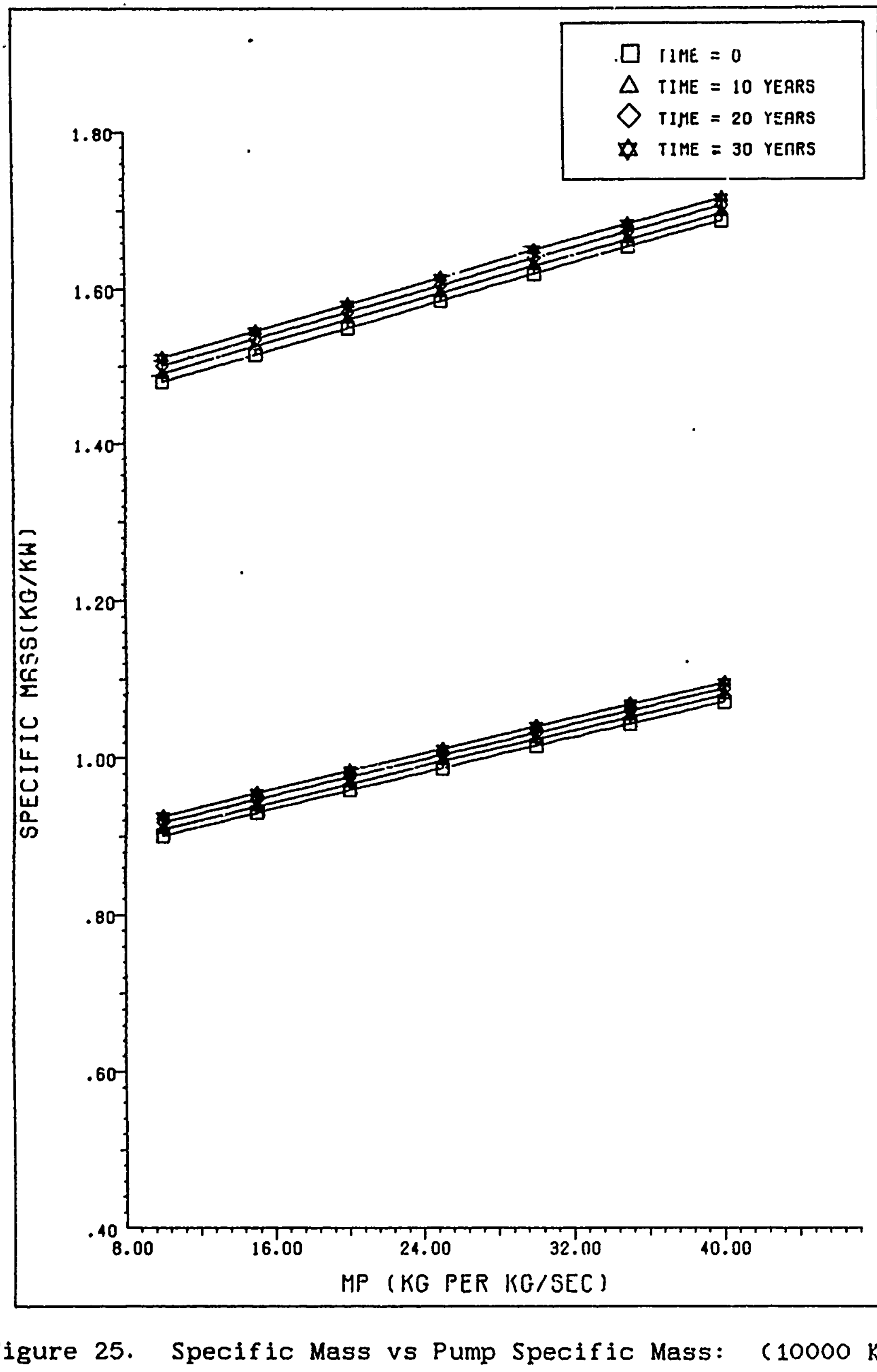

Figure 25. Specific Mass vs Pump Specific Mass: (10000 Kw)

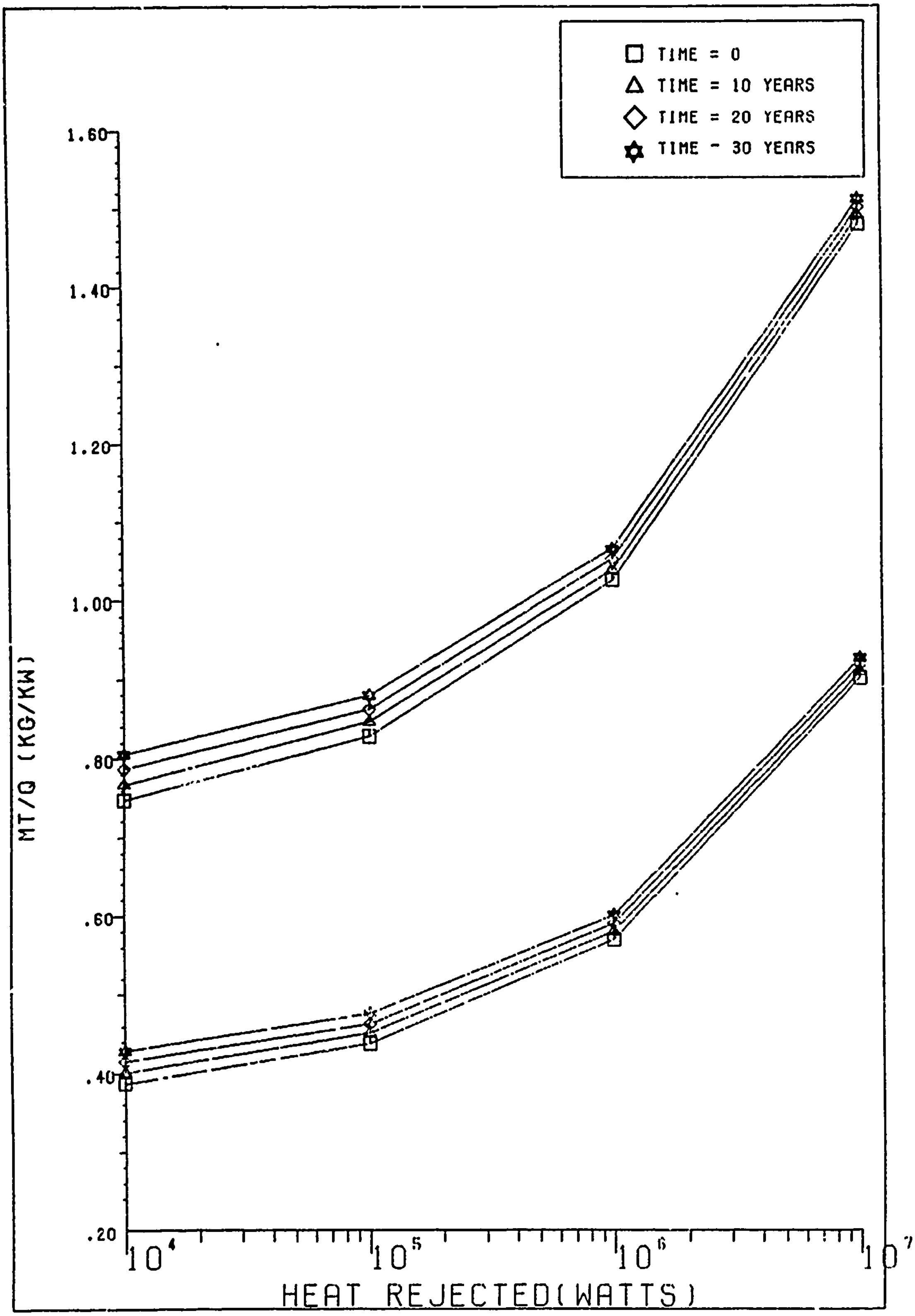

Figure 26. Specific Mass vs Heat Rejected for Various Times (for mp = 10.0 kg/(kg/sec) only)

IV. RESULTS

The numerical results are shown in Tables II-IX with Knapp's values also listed (1). The average droplet temperature at the collector, total LDR specific mass, LDR length, diameter, and droplet radius were calculated for each value of the new pump specific mass (mp) for the minimum mass system for four different heat loss rates and four different mission times.

10 Kilowatt Heat Loss

In the optimistic case, Table II, Knapp's values were within four percent of the LDR temperature, length, and diameter values for the 10.0 and 20.0 pump specific mass (mp) values. However, Knapp's results for total system specific mass best fit the mid range of mp values (20.0 to 25.0). For the droplet radius, Knapp's values were approximately one half the radius values for the low mp values.

The opposite occurred using the realistic parameter values, Table III, where Knapp's results for temperature, length, and diameter values agreed within two percent for the mp value of 40.0, while the total system specific mass was within thirteen percent agreement. Knapp's droplet radius values were again approximately one half the radius values for an mp value of 40.0. There was an apparent typing error in Knapp's report for the droplet radius for the ten year mission time.

The results in Figure 18 show a lower droplet temperature at the collector with increasing pump specific mass, while Figure 22 results indicate a corresponding increase in the total system specific mass with increasing pump specific mass.

100 Kilowatt Heat Loss

In the optimistic case, Table IV, Knapp's values for total specific mass, temperature, length, and diameter best agreed within three percent for the lower mp value of 10.0, except for the droplet radius. Knapp's droplet radius was approximately one half the droplet radius for the mp value of 10.0.

A similar result was observed for the realistic values, Table V, where Knapp's results for total specific mass, temperature, length, and diameter were in very good agreement within five percent for the mp values of 15.0 and 20.0. For this range of mp values, Knapp's droplet radius was low again by approximately one half the calculated radius values. There were apparently typing errors in the Knapp paper for the stream diameter at twenty and thirty year mission times.

The results in Figure 19 show a lower droplet temperature at the collector with increasing pump specific mass, while Figure 23 results indicate a corresponding increase in the total system specific mass with increasing pump specific mass.

1000 Kilowatt Heat Loss

In the optimistic case, Table VI, Knapp's values for temperature, total specific mass, length, and stream diameter were found to agree within eight percent with all values for a mp value of 10.0, except for the droplet radius. The Knapp radius values were again approximately one half the calculated radius values for the mp value of 10.0.

For the realistic case, Table VII, Knapp's values of temperature, total specific mass, length, and stream diameter were found to agree within two percent with all values for a mp value of 10.0, except for the droplet radius. The radius was again approximately one half the calculated radius values for the mp value of 10.0

The results in Figure 20 show a lower droplet temperature at the collector with increasing pump specific mass, while Figure 24 results indicate a corresponding increase in the total system specific mass with increasing pump specific mass.

10000 Kilowatt Heat Loss

For the optimistic case, Table VIII, Knapp's values for temperature, total specific mass, length, and stream diameter were found to agree within seven percent with all values for a mp value of 10.0, except for the droplet radius. The Knapp study droplet values were approximately three fifths of the calculated radius values for the mp value of 10.0.

For the realistic case, Table IX, Knapp's values of temperature, total specific mass, length, and stream diameter were found to agree within three percent with all values for a mp value of 10.0, except for the droplet radius. For the mp value of 10.0, Knapp's radius values were approximately one half the calculated radius values.

The results in Figure 21 show a lower droplet temperature at the collector with increasing pump specific mass, while Figure 25 results indicate a corresponding increase in the total system specific mass with increasing pump specific mass.

TABLE II

Results for 10 Kw Using Optimistic Values
(Beta = 0.10, mc = 40.0)

Mission Time		Pump Specific Mass (kg/(kg/sec)) 10.0	15.0	20.0	25.0	30.0	35.0	40.0	Knapp
0	T_2=	241	235	229	225	221	217	214	243
	$M_T/\dot{Q}$=	0.387	0.435	0.479	0.520	0.559	0.596	0.631	0.501
	L=	71.8	73.8	75.9	77.4	78.9	80.6	81.8	70.8
	D=	0.287	0.295	0.304	0.310	0.316	0.322	0.327	0.283
	a=	7.8	6.5	5.6	5.0	4.6	4.1	3.9	3.6
10 years		239	233	228	224	220	217	214	237
		0.401	0.448	0.491	0.531	0.570	0.606	0.642	0.511
		72.5	74.5	76.3	77.8	79.3	80.6	81.8	72.7
		0.290	0.298	0.305	0.311	0.317	0.322	0.327	0.291
		7.3	6.2	5.4	4.9	4.4	4.1	3.9	3.2
20 years		237	232	227	222	219	216	213	231
		0.415	0.461	0.503	0.543	0.581	0.617	0.652	0.523
		73.2	74.9	76.7	78.6	79.7	80.9	82.2	74.8
		0.293	0.299	0.307	0.314	0.319	0.324	0.329	0.299
		6.9	6.0	5.3	4.7	4.3	4.0	3.8	2.8
30 years		236	230	225	221	218	215	212	228
		0.429	0.474	0.515	0.554	0.591	0.627	0.662	0.536
		73.5	75.6	77.4	78.9	80.1	81.4	82.7	75.9
		0.294	0.302	0.310	0.316	0.321	0.326	0.331	0.303
		6.7	5.7	5.0	4.6	4.2	4.0	3.7	2.7

Units: T_2 (K), $M_T/\dot{Q}$ (kg/Kw), L (m), D (m), a (microns)

TABLE III

Results for 10 Kw Using Realistic Values
(Beta = 0.20, mc = 100.0)

Mission Time		Pump Specific Mass (kg/(kg/sec))							Knapp
		10.0	15.0	20.0	25.0	30.0	35.0	40.0	
0	T_2=	257	252	248	244	241	238	236	237
	$M_T/\dot{Q}$=	0.747	0.813	0.873	0.929	0.981	1.031	1.078	1.21
	L=	67.1	68.5	69.7	70.9	71.8	72.8	73.5	72.7
	D=	0.268	0.274	0.279	0.284	0.287	0.291	0.294	0.291
	a=	13.3	11.1	9.7	8.5	7.7	7.1	6.7	3.2
10 years		256	251	247	243	240	237	235	234
		0.767	0.831	0.890	0.944	0.996	1.044	1.092	1.23
		67.4	68.8	70.0	71.2	72.2	73.2	73.8	73.8
		0.270	0.275	0.280	0.285	0.289	0.293	0.295	0.295
		12.8	10.7	9.3	8.2	7.5	6.9	6.5	*8.0
20 years		254	250	246	242	239	237	234	234
		0.787	0.849	0.906	0.960	1.010	1.059	1.105	1.24
		67.9	69.1	70.3	71.5	72.5	73.2	74.2	73.8
		0.272	0.276	0.281	0.286	0.290	0.293	0.297	0.295
		11.9	10.3	9.0	8.0	7.3	6.9	6.3	3.0
30 years		253	248	245	241	239	236	233	234
		0.805	0.866	0.922	0.975	1.025	1.072	1.118	1.25
		68.2	69.7	70.6	71.8	72.5	73.5	74.5	73.8
		0.273	0.279	0.282	0.287	0.290	0.294	0.298	0.295
		11.5	9.7	8.8	7.7	7.3	6.7	6.2	3.0

Units: T_2 (K), $M_T/\dot{Q}$ (kg/Kw), L (m), D (m), a (microrons)
* possible typo in Knapp study

TABLE IV

Results for 100 Kw Using Optimistic Values
(Beta = 0.10, mc = 40.0)

Mission Time		Pump Specific Mass (kg/(kg/sec))							Knapp
		10.0	15.0	20.0	25.0	30.0	35.0	40.0	
0	T_2=	233	228	224	220	217	214	211	237
	$M_T/\dot{Q}$=	0.438	0.481	0.522	0.560	0.597	0.632	0.667	0.437
	L=	236	241	246	251	255	259	263	230
	D=	0.943	0.965	0.984	1.004	1.020	1.030	1.050	0.920
	a=	19.5	17.1	15.5	14.1	13.1	12.2	11.4	10.0
10 years		232	227	223	219	216	213	211	234
		0.451	0.493	0.533	0.571	0.607	0.642	0.676	0.450
		237	242	247	252	256	260	263	233
		0.947	0.970	0.989	1.009	1.024	1.040	1.051	0.933
		19.0	16.7	15.1	13.7	12.8	11.9	11.4	9.5
20 years		230	226	222	218	215	213	210	234
		0.463	0.505	0.544	0.582	0.618	0.652	0.686	0.463
		239	244	248	253	257	260	264	233
		0.956	0.974	0.994	1.014	1.030	1.040	1.057	0.933
		18.0	16.3	14.7	13.4	12.5	12.0	11.2	9.5
30 years		229	225	221	217	214	212	209	231
		0.476	0.517	0.555	0.592	0.628	0.662	0.696	0.476
		240	245	250	255	259	261	266	237
		0.960	0.979	0.999	1.019	1.035	1.046	1.062	0.95
		17.6	15.9	14.4	13.1	12.2	11.7	10.9	8.5

Units: T_2 (K), $M_T/\dot{Q}$ (kg/Kw), L (m), D (m), a (microns)

TABLE V

Results for 100 Kw Using Realistic Values
(Beta = 0.20, mc = 100.0)

Mission Time		Pump Specific Mass (kg/(kg/sec))							Knapp
		10.0	15.0	20.0	25.0	30.0	35.0	40.0	
0	T_2=	250	246	243	240	237	235	232	246
	$M_T/\dot{Q}$=	0.828	0.886	0.939	0.990	1.039	1.086	1.131	0.979
	L=	218	222	225	228	231	233	237	221
	D=	0.87	0.89	0.90	0.91	0.93	0.93	0.95	0.88
	a=	32.7	28.6	26.0	23.8	21.8	20.6	19.0	12.0
10 years		249	245	242	239	236	234	232	243
		0.846	0.902	0.955	1.005	1.053	1.099	1.144	0.995
		219	223	226	229	232	235	237	224
		0.88	0.89	0.90	0.92	0.93	0.94	0.95	0.90
		31.6	27.7	25.2	23.1	21.2	20.1	19.0	11.4
20 years		247	244	241	238	236	233	231	243
		0.862	0.917	0.969	1.019	1.066	1.112	1.156	1.010
		221	224	227	230	232	236	238	224
		0.89	0.90	0.91	0.92	0.93	0.94	0.95	*0.090
		29.5	26.8	24.5	22.4	21.2	19.5	18.5	11.4
30 years		246	243	240	237	235	233	231	243
		0.879	0.933	0.984	1.033	1.080	1.125	1.169	1.0[illegible]5
		222	225	228	231	233	236	238	224
		0.89	0.90	0.91	0.93	0.93	0.94	0.95	*0.090
		28.6	26.0	23.8	21.8	20.6	19.5	18.5	11.4

Units: T_2 (K), $M_T/\dot{Q}$ (kg/Kw), L (m), D (m), a (microns)
* possible typo in Knapp study

TABLE VI

Results for 1000 Kw Using Optimistic Values
(Beta = 0.10, mc = 40.0)

Mission Time		Pump Specific Mass (kg/(Kg/sec))							Knapp
		10.0	15.0	20.0	25.0	30.0	35.0	40.0	
0	T_2=	219	216	213	211	208	206	204	222
	$M_T/\dot{Q}$=	0.570	0.606	0.641	0.675	0.708	0.740	0.772	0.528
	L=	797	810	822	831	844	854	863	781
	D=	3.19	3.24	3.29	3.32	3.38	3.41	3.45	3.12
	a=	43.4	40.5	37.8	36.2	33.9	32.4	31.1	24.0
10 years		218	215	212	210	208	206	204	222
		0.580	0.616	0.651	0.685	0.717	0.749	0.781	0.539
		801	814	827	835	844	854	863	781
		3.21	3.26	3.31	3.34	3.38	3.41	3.45	3.12
		42.4	39.6	37.0	35.4	33.9	32.4	31.1	24.0
20 years		217	214	212	209	207	205	203	222
		0.591	0.626	0.661	0.694	0.727	0.759	0.790	0.550
		805	818	827	840	849	858	868	781
		3.22	3.27	3.31	3.36	3.40	3.43	3.47	3.12
		41.4	38.7	37.0	34.6	33.1	31.7	30.4	24.0
30 years		216	213	211	209	206	204	203	219
		0.601	0.637	0.671	0.704	0.736	0.768	0.799	0.561
		810	822	831	840	854	863	868	793
		3.24	3.29	3.32	3.36	3.41	3.45	3.47	3.17
		40.5	37.8	36.2	34.6	32.4	31.1	30.4	22.7

Units: T_2 (K), $M_T/\dot{Q}$ (Kg/Kw), L (m), " (m), a (microns)

TABLE VII

Results for 1000 Kw Using Realistic Values
(Beta = 0.20, mc = 100.0)

Mission Time		Pump Specific Mass (kg/(kg/sec))							Knapp
		10.0	15.0	20.0	25.0	30.0	35.0	40.0	
0	T_2=	236	234	232	230	228	226	225	237
	$M_T/\dot{Q}$=	1.025	1.071	1.115	1.158	1.200	1.242	1.282	1.032
	L=	735	742	749	756	763	770	774	727
	D=	2.94	2.97	2.99	3.02	3.05	3.08	3.09	2.91
	a=	67.1	63.4	60.1	57.0	54.1	51.5	50.2	32.0
10 years		235	233	231	229	228	226	224	237
		1.038	1.084	1.128	1.171	1.213	1.253	1.293	1.046
		738	745	752	759	763	770	778	727
		2.95	2.98	3.01	3.04	3.05	3.08	3.11	2.91
		65.2	61.7	58.5	55.5	54.1	51.5	49.0	32.0
20 years		235	233	231	229	227	225	224	237
		1.052	1.097	1.140	1.183	1.225	1.265	1.305	1.068
		738	745	752	759	767	774	779	727
		2.95	2.98	3.00	3.04	3.07	3.10	3.11	2.91
		65.2	61.7	58.5	55.5	52.8	50.2	48.9	32.0
30 years		234	232	230	228	227	225	223	234
		1.065	1.110	1.153	1.195	1.237	1.277	1.316	1.074
		742	749	756	763	767	774	782	738
		2.97	2.99	3.02	3.05	3.07	3.10	3.13	2.95
		63.4	60.1	57.0	54.1	52.7	50.2	47.8	30.0

Units: T_2 (K), $M_T/\dot{Q}$ (kg/Kw), L (m), D (m), a (microns)

TABLE VIII

Results for 10000 Kw Using Optimistic Values
(Beta = 0.10, mc = 40.0)

Mission Time		Pump Specific Mass (kg/(kg/sec))							Knapp
		10.0	15.0	20.0	25.0	30.0	35.0	40.0	
0	T_2=	198	197	196	194	193	192	191	201
	$M_T/\dot{Q}$=	0.901	0.930	0.959	0.987	1.016	1.043	1.071	0.845
	L=	2823	2839	2855	2889	2906	2923	2940	2759
	D=	11.3	11.4	11.4	11.5	11.6	11.7	11.8	11.0
	a=	86.8	85.0	83.3	80.0	78.4	76.9	75.4	53.0
10 years		198	197	195	194	193	192	191	201
		0.909	0.938	0.967	0.996	1.024	1.052	1.079	0.857
		2823	2839	2872	2889	2906	2923	2941	2759
		11.3	11.4	11.5	11.6	11.6	11.7	11.8	11.0
		86.8	85.0	81.6	80.0	78.4	76.9	75.4	53.0
20 years		197	196	195	194	192	191	190	201
		0.918	0.947	0.976	1.004	1.032	1.059	1.087	0.866
		2839	2855	2872	2889	2923	2941	2959	2759
		11.4	11.4	11.5	11.6	11.7	11.8	11.8	11.0
		85.0	83.3	81.6	80.0	76.9	75.4	73.9	53.0
30 years		197	196	194	193	192	191	190	198
		0.926	0.955	0.984	1.012	1.040	1.068	1.095	0.875
		2839	2855	2889	2906	2923	2941	2959	2807
		11.4	11.4	11.6	11.6	11.7	11.8	11.8	11.2
		85.0	83.3	80.0	78.4	76.9	75.4	73.9	51.0

Units: T_2 (K), $M_T/\dot{Q}$ (kg/Kw), L (m), D (m), a (microns)

TABLE IX

Results for 10000 Kw Using Realistic Values
(Beta = 0.20, mc = 100.0)

Mission Time		Pump Specific Mass (kg/(kg/sec)) 10.0	15.0	20.0	25.0	30.0	35.0	40.0	Knapp
0	T_2=	216	215	214	213	212	211	210	*232
	$M_T/\dot{Q}$=	1.48	1.52	1.55	1.59	1.62	1.65	1.69	1.44
	L=	2560	2573	2587	2600	2614	2628	2642	2507
	D=	10.2	10.3	10.3	10.4	10.5	10.5	10.6	10.0
	a=	128	125	122	119	117	114	112	72.0
10 years		216	215	214	213	212	211	210	216
		1.49	1.53	1.56	1.59	1.63	1.66	1.70	1.45
		2560	2573	2587	2600	2614	2628	2642	2546
		10.2	10.3	10.3	10.4	10.5	10.5	10.6	10.2
		128	125	122	119	117	114	112	68.0
20 years		216	215	214	213	212	211	210	216
		1.50	1.54	1.57	1.61	1.64	1.67	1.71	1.46
		2560	2573	2587	2600	2614	2628	2642	2546
		10.2	10.3	10.3	10.4	10.5	10.5	10.6	10.2
		128	125	122	119	117	114	112	68.0
30 years		215	214	213	212	212	211	210	216
		1.51	1.55	1.58	1.62	1.65	1.68	1.72	1.47
		2573	2587	2600	2614	2614	2628	2642	2546
		10.3	10.3	10.4	10.5	10.5	10.5	10.6	10.2
		125	122	119	117	117	114	112	68.0

Units: T_2 (K), $M_T/\dot{Q}$ (kg/Kw), L (m), D (m), a (microns)
* possible typo in Knapp study

V. CONCLUSIONS AND RECOMMENDATIONS

This study was a parametric analysis of the Liquid Droplet Radiator (LDR) using a new pump specific mass (mp) term defined as pump mass per liquid mass flow rate to calculate the minimum LDR system mass per heat radiated as a function of the average droplet temperature at the collector. The characteristics of total system specific mass, stream length, stream diameter and droplet radius were calculated as a function of the average droplet temperature at the collector for the minimum system mass for a range of mp values from 10.0 to 40.0 kg/(kg/sec) by increments of five. The results of this study indicate the new specific pump mass term provides a physically meaningful term for design engineers to use on future LDR systems by offering a range of pump masses depending on pressure loss and flow rate design requirements.

The assumed values of the parameters used in this study should be the subject of futher research to provide possible improvements to the values. These parameter values include the ratio of liquid mass in the reheating station to droplet mass in the stream, the average emissivity of the droplets, the ratio of droplet kinetic energy to heat rejected, the conservative black body view factor for a droplet at stream center, the change of vapor pressure of the droplets with changing temperature, and the specific mass term for the generator and collector. A previous study by Knapp (1) using the same values for these parameters with a different pump specific mass defined as kg-sec$^{2/3}$/m^2 provided results within a few percent agreement with the characteristic results of this study for total system specific mass, average droplet temperature at the collector, and LDR stream length and diameter calculated with a mp value of 10.0 kg/(kg/sec) primarily for the heat loss rates of 100, 1000, and 10000 Kilowatts in both the optimistic and realistic cases. Knapp's results for these characteristics at 10 Kilowatts best fit the values obtained with mp = 10.0 for the optimistic case and best fit the characteristic values obtained with mp = 40.0 for the realistic case. Also, Knapp's droplet radius was low in all cases by approximately one half the calculated values of this study.

Additionally, the total system specific masses calculated in this study were lower than the 10 kg/Kw value (1:14) for heat pipe or fluid loop radiators at the 300 K temperature level. This reduced mass per heat radiated makes the LDR superior to traditional heat pipe and fluid loop radiators for high power space applications.

Further analysis is needed to understand differences in the results at the 10 Kilowatt heat loss rate. Additional analysis at different heat loss rates may provide some insight. Also higher droplet generator temperatures using a liquid metal might be used to observe the effect on the calculated characteristics. Continued work in each of these areas will provide the necessary research to enable the LDR to become the radiator of choice for future space missions.

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Appendix A

Computer Program Glossary and Listing

```
50 '****************GLOSSARY********************************
60 '
70 ' A     - radius of spherical particles
80 ' AH    - variable in quadratic formula
90 ' B     - variable (function of ETA and EPS)
100 ' BE   - variable in quadratic formula
110 ' BETA - ratio, liquid mass in reheating station to mass in stream
120 ' C    - specific heat of droplets
130 ' CE   - variable in quadratic formula
140 ' D    - diameter of droplet stream
150 ' EPS  - emissivity of droplets
160 ' ETA  - black-body view factor for a droplet at stream center
170 ' F    - gray-body view factor for a droplet at stream center
180 ' GAMA - ratio of kinetic energy to the radiated energy
190 ' L    - length of droplet stream along z-axis
200 ' MPQR - mass per watt of radiated heat loss
210 ' PI   - 3.14159
220 ' PT   - vapor pressure of droplet at temperature T1D
230 ' QTSD - total rate of heat loss to space from droplet stream
240 ' R    - gas constant
250 ' RHO  - density of droplet
260 ' SIG  - Stefan-Boltzmann constant, 5.67E-08 watts/meter^2-kelvin^4
270 ' SMGC - specific mass of droplet generator and collector
280 ' SMP  - specific mass of pumps
290 ' TAU  - mission lifetime
300 ' T1D  - initial temperature of droplets
310 ' T2D  - final temperature of droplets at end of stream
320 ' TV   - temperature used in fitting vapor pressure curve
330 ' V    - velocity of the stream
340 ' W1-W5 - variables in MPQR equation
350 '
```

```
10 ' PROGRAM:  TSMYLDR   -USES A NEW TERM FOR THE PUMP MASS IN MPQR
15 ' EQUATION.  VARY LINE 580 FOR T2D TO GET MINIMUM  MPQR.
20 ' QTSD, TAU, AND SMP MUST ALSO BE DESIGNATED  AT INPUT.
30 ' THE VALUES FOR BETA AND SMGC MUST BE CHECKED (LINES 440 & 460)
35 ' FOR EITHER THE OPTIMISTIC VALUES OR THE REALISTIC VALUES.
40 '
360 '*****DEFINE VARIABLES FOR DOW 705 SILICON OIL FLUID
370 '
380 PI= 4*ATN(1)
390 T1D= 300                'KELVIN
400 T7= 15000               'KELVIN
410 C= 1670                 'JOULE/KILOGRAM-KELVIN
420 RHO= 1000               'KILOGRAM/CUBIC METER
430 GAMA= .005              'ASSUMPTION
440 BETA= .1                'ASSUME
450 EPS= .7                 'ESTIMATED
460 SMGC= 401               'ASSUME (KILOGRAMS/SQUARE METER)
470 R= 15.22                'JOULE/KELVIN
480 PT= 3.001E-08           'NEWTONS/SQUARE METER
490 SIG= 5.67E-08           'WATTS/METER^2-KELVIN^4
500 DIM MPQR(100)
510 '
520 '*******************************PERFORM CALCULATIONS
530 '
540 CLS
550 GOSUB 820               'CALCULATE ETA AND F
560 GOSUB 690               'ASK FOR INPUT
570 I= I+1  : J= J+1        'INITIALIZE COUNTERS
580 T2D= 230 + I            'VARY T2D TO FIND MINIMUM MPQR
590  PRINT:PRINT"T2D";T2D
600  B= (8*(1-ETA))/((1/ETA)+(1/EPS)-1)    :'PRINT"B"B
610  GOSUB 950              'CALCULATE MPQR
620  IF LD > 250 THEN LD=250 : GOSUB 1180      'CALC MPQR FOR L/D= 250
630  IF MPQR(J-1)= 0 THEN MPQR(J-1)= 9.999999E-21
640  IF ABS((MPQR(J)-MPQR(J-1))/MPQR(J-1)) > .0001  THEN GOTO 570  'TO CONVERGE
650  QTSD=(((8*(1-ETA)*D*L*SIG*T1D^4)/((1/ETA)+(1/EPS)-1))*((3*(1-(T2D/T1D)))/
        ((T2D/T1D)^-3-1))) :PRINT"L650 QTSD";QTSD
660 LPRINT"           CONVERGED TO THESE VALUES"
670 END
680 '
690 '***************************REQUEST INPUT PARAMETERS
700 '
710 INPUT"QTOT IN WATTS";QTSD:PRINT
720 INPUT"TIME IN YEARS";TAU:PRINT
730 INPUT"PUMP SPECIFIC MASS (KG PER KG/SEC)";SMP
740 LPRINT"             Q TOT=";QTSD;"WATTS":PRINT
750 PRINT"Q TOT=";QTSD;"WATTS":PRINT
760 LPRINT"           TIME=";TAU;"YEARS        SMP=";SMP;"KG PER KG/SEC"
770 PRINT"TIME=";TAU;"YEARS":PRINT
780 TAU= TAU*3.1536E+07       'CONVERT TIME IN YEARS TO SECONDS
790 LPRINT"            T2      MT/Q      L         D          A"
800 RETURN
810 '
```

```
820 '*************************************CALC ETA AND F
830 '
840 IF EPS= 0 THEN EPS= 1.00001E-30
850 IF EPS= 1 THEN ETA= .5 : GOTO 900
860 AH= ((1!/EPS)-1!)
870 BE= 2!
880 CE= -1!
890 ETA= (-BE + SQR(BE^2 - 4*AH*CE))/(2*AH)
900 F= 1/((1/EPS)+(1/ETA)-1)
910 PRINT USING"EPS=##.##    F=##.####    ETA=##.####";EPS;F;ETA
920 PRINT
930 RETURN
940 '
950 '*****************CALC MASS PER WATT HEAT LOSS- MPQR
960 '
970 V= SQR(GAMA*2*C*(T1D-T2D))    : PRINT"V"V;"GAMMA"GAMA
980 W1= (3*QTSD^(1/3))/(2*(1-(T2D/T1D))^(4/3)) :'PRINT"W1"W1
990 W2= (((1+BETA)*(((T2D/T1D)^-3)-1))/(B*C*V*T1D*SIG*T1D^4))^(2/3):'PRINT W2
1000 W3= ((SMGC*PI)/18)^(1/3) :'PRINT"W3"W3
1010 W4= SMP/(C*(T1D-T2D))     :'PRINT"W4"W4
1020 W5= (ETA*PT*(T1D/TV)*TAU)/(F*SIG*T1D^4*SQR(2*PI*R*T1D)*(1-(T2D/T1D)))
1030 'PRINT"W5"W5
1040 MPQR(K)= (W1*W2*W3)+W4+W5
1050 PRINT USING"MPQR=##.##### KILOGRAMS/KILOWATT    EQN 23";MPQR(K)*1000
1060 L= ((PI*C*V*T1D*QTSD*((T2D/T1D)^-3-1)^2*SMGC)/(18*B^2*(1+BETA)*
     (SIG*T1D^4)^2*(1-(T2D/T1D))))^(1/3)
1070 D= QTSD^(2/3)*(((2*(1+BETA))/(3*B*C*V*T1D*SMGC*SIG*T1D^4))^(1/3))*
     ((((T2D/T1D)^(1/3))/(1-(T2D/T1D))^(2/3)))
1080 A=(9*F/RHO)*(1/(C*V*T1D*B)^(2/3))*((PI*SMGC*SIG*T1D^4)/(18*(1+BE^A)))^(1/3)
     *QTSD^(1/3)/(((T2D/T1D)^-3-1)^(1/3)*((1-(T2D/T1D))^(1/3)))
1090 LD= L/D
1100 'PRINT "L=";L;"METERS"
1110 'PRINT"D=";D;"METERS"
1120 'PRINT"A=";A;"METERS"
1130 'LPRINT SPC(10) T2D; MPQR(K)*1000; L; D; A
1140 PRINT T2D; MPQR(K)*1000; L; D; A
1150 PRINT"EQN 13   L/D=";LD :PRINT
1160 RETURN
1170 '
```

```
1180 '***************CALC MASS PER WATT HEAT LOSS- MPQR (FOR L/D= 250)
1190 '
1200 V= SQR(GAMA*2*C*(T1D-T2D))    : PRINT"V"V;"GAMMA"GAMA
1210 W1= ((1+BETA)*SQR(LD)*((T2D/T1D)^-3-1)^(1/2)*QTSD^(1/2))/
        (C*V*T1D*SQR(3*B*SIG*T1D^4)*(1-(T2D/T1D))^(3/2))
1220 'PRINT"W1"! 1
1230 W2= (PI*SMGC*((T2D/T1D)^-3-1))/(12*B*SIG*T1D^4*(LD)*(1-(T2D/T1D)))
1240 'PRINT"W2"W2
1250 W3= SMP/(C*(T1D-T2D))       :'PRINT"W3"W3
1260 W4= (ETA*PT*(T1D/TY)*TAU)/(F*SIG*T1D^4*SQR(2*PI*R*T1D)*(1-(T2D/T1D)))
1270 'PRINT"W4"W4
1280 MPQR(J)= W1+W2+W3+W4
1290 PRINT USING"MPQR= ##.#### KILOGRAMS/KILOWATT    EQN 26";MPQR(J)*1000
1300 D= (QTSD^(1/2)*((T2D/T1D)^-3-1)^(1/2))/((3*B*LD*SIG*T1D^4)^(1/2)*
        (1-(T2D/T1D))^(1/2))
1310 L= D*LD
1320 A= (9*SIG*F*L/(C*RHO*V))*(T1D^3/((T2D/T1D)^-3-1))
1330 'PRINT"L=";L;"METERS"
1340 'PRINT"D=";D;"METERS"
1350 'PRINT"A=";A;"METERS"
1360 LPRINT SPC(10) T2D; MPQR(J)*1000; L; D; A
1370 PRINT T2D; MPQR(J)*1000; L; D; A
1380 PRINT"EQN 14   L/D";L/D
1390 RETURN
```

Appendix B

Pump Specific Mass

The work in Reference 1 used two values for pump specific mass with units of kg-sec$^{2/3}$/m^2. The optimistic value was given as 1000 kg-sec$^{2/3}$/m^2 and the realistic value was 2000 kg-sec$^{2/3}$/m^2. These values made little physical sense from a design point of view. This study used a new pump specific mass (mp) for a centrifugal pump in terms of the pump mass per mass flow rate. The new mp values were varied from 10.0 to 40.0 as shown in Table I. This range of values appeared reasonable from available stainless steel pump data (8:583). Additionally, Mattick and Taussig (4:14) describe a droplet radiator system where the value of mp was found to be 10.05 kg/(kg/sec). Therefore a range of mp values was used in this study to observe the effect on the operating characteristics of the LDR. A sample of mp values shown below was calculated from Reference 8.

TABLE X

Pump Specific Mass Sample Values

Pump Model	mp (kg/(kg/sec))
J7005-30	9.12
J7005-35	10.07
J7005-20	13.26
J7005-10	18.87

VITA

Major Gerald L. Buckner was born on 10 January 1953 in Shelby, North Carolina. He graduated from high school in Dallas, North Carolina, in 1971 and attended the United States Military Academy where he received a Bachelor of Science Degree in Basic Science and a commission in the US Army in June 1975. He served as a Vulcan Platoon Leader, Redeye Section Leader, Weapon System Maintenance Officer, and Vulcan Battery Executive Officer at Fort Bragg, North Carolina; Chaparral Platoon Leader, Assistant Air Defense Operations Officer, and Chaparral Battery Commander in Korea; and Training Effectiveness Analysis Branch Chief at Fort Bliss, Texas, during his six year tenure in the US Army. He received a Master of Arts Degree in Management from Webster University in June 1981 while at Fort Bliss. In July 1981 he transferred to the US Air Force as a Nuclear Research Officer and was assigned as a student in the Air Force Institute of Technology Education With Industry program at the Savannah River Laboratory, Aiken, South Carolina, until June 1982. He then served as a Nuclear Research Program Manager at the Air Force Technical Applications Center, Patrick AFB, Florida. While at Patrick AFB, he received a Master of Science Degree in Space Technology from the Florida Institute of Technology. He entered the graduate Nuclear Engineering Program in the School of Engineering, Air Force Institute of Technology, in August 1985.

Permanent address: Route 2, Box 218
Mooresboro, NC 28114

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This study was a parametric investigation of the performance and operating characteristics of a cylindrical Liquid Droplet Radiator (LDR) for use in space. The LDR system mass per heat radiated was minimized as a function of the average droplet temperature at the collector. This study was similar to the work of Karl Knapp (1980), however a new pump specific mass term was used in the total system mass calculation. Knapp used a pump specific mass defined as $kg\text{-}sec^{2/3}/m^2$. This study used another pump specific mass term defined as pump mass per liquid mass flow rate to develop a physically meaningful pump specific mass term for use by design engineers. The new pump specific mass was varied from 10.0 kg/(kg/sec) to 40.0 kg/(kg/sec), based on available industry standard pumps. The average droplet temperature at the collector was calculated to minimize the LDR system mass for heat loss rates of 10 Kw, 100 Kw, 1000 Kw, and 10,000 Kw for mission lifetimes of zero, ten, twenty, and thirty years. The initial droplet temperature at the generator was fixed at 300 degrees Kelvin. A silicon oil, Trimethylpentaphenyltrisiloxane (DOW 705), was modeled due to its low vapor pressure (approx. 3×10^{-8} Pa) at 300 degrees Kelvin. The variable pump specific mass term offers the design engineer a range of possible pump masses depending on the system pressure and flow rate requirements.