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RELATIONSHIPS BETWEEN SEVERAL PROMINENT HEAT STRESS INDICES

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Report presenting correlations developed by NIOSH to provide a tool for comparing results of studies relating human responses to various environmental heat levels which have been used to describe the environmental heat level to which the subjects were exposed. The five indices of environmental heat stress that are correlated with each other are Corrected Effective Temperature (CET), Effective Temperature Corrected for Radiation (ETCR), Wet Bulb Globe Temperature (WBGT); Wet Globe Temperature (WGT), and the Belding-Hatch Stress Index (HSI).

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CONTENTS

ABSTRACT

The five indices of environmental heat stress that were correlated with each other are Corrected Effective Temperature (CET); Effective Temperature Corrected for Radiation (ETCR); Wet Bulb Globe Temperature (WBGT); Wet Globe Temperature (WGT); and the Belding-Hatch Heat Stress Index (HSI).

Investigators have conducted numerous studies relating human responses to various environmental heat levels in which they have used several different indices to describe the environmental heat level to which their subjects were exposed. This report presents correlations developed by NIOSH to provide a tool for comparing the results of these investigators. It is hoped that the data will contribute to a more precise definition of occupationally acceptable heat stress levels.

INTRODUCTION

Background

For many years, scientists have been searching for an environmental heat stress index which is physiologically valid over a wide range of hot environments. An excellent review of this search for a universal heat stress index was prepared by the late Dr. Harwood S. Belding[1]. Dr. Belding lists fourteen systems for rating heat stress and heat strain. Many of these systems had obvious limitations which prevented them from ever gaining widespread usage. Others became popular for a time and then lost their popularity because shortcomings were discovered or because an apparently better index was developed. Several of these indices are in use today, but none has achieved a position of universal acceptability because each index appears to have shortcomings in certain environments.

In order to understand what is meant by a heat stress index, it is important to understand the terms "heat stress" and "heat strain". Heat stress is the total heat load on the individual from both environmental and metabolic sources[2]. Heat strain is defined by Henschel as the sum of the biochemical, physiological, and psychological adjustments made by the individual in response to the stress[2]. These definitions are consistent with the engineering concepts of stress and strain. In other words, stress is "the force producing or tending to produce deformation in a body measured by the force applied per unit area"[3]. Strain is "the deformation resulting from a stress measured by the ratio of the change to the total value of the dimension in which the change occurred"[3]. The most common dimensions used to measure heat strain are body temperature, pulse rate, and sweat rate. Other physiological dimensions which can also be used as physiological indices of heat strain are: blood volume, total body water, kidney and liver functions, electrolyte concentration in the body fluids, hormone production, blood pressure, work capacity, and behavior[2].

As the preceding definitions indicate, heat stress is the total of the metabolic and environmental heat load. Therefore, in order to assess the heat stress on an individual, it is necessary to determine the heat load due to both metabolism and the environment. This report deals with methods of assessing heat load from the environment. Methods for determining metabolic heat load are described elsewhere.

The ultimate test of validity of an environmental heat stress index is its ability to provide us with a number which can be used to accurately predict how people will respond to the environmental conditions being measured. Numerous investigators have conducted studies relating human responses to a variety of environmental heat levels. Unfortunately, these investigators have used several different indices to describe the environmental heat level to which their subjects were exposed. For example, Lind[4] used the corrected effective temperature (CET). Jensen[5] used the wet bulb globe temperature (WBGT). Robinson[6] used effective temperature (ET), and Belding and Kamon[7] used the Belding-Hatch Heat Stress Index (HSI). The reason for reporting the correlations described in this report is to provide a tool for relating the results of these and other investigators.

Heat Stress Indices

The Effective Temperature (ET)[8,9] is an index of the warmth felt by the human body on exposure to various combinations of air temperatures, humidities and air velocities using as a reference the temperature of an environment with still, fully saturated air. The scale of ET was developed for fully clothed men as well as for men stripped to the waist. It reflects an environment which feels as warm as the still saturated reference environment[10]. For example, an environment which has an effective temperature of 70°F feels as warm as still saturated air at 70°F.

Two things should be noted about the ET. It is based on data from test conditions which did not include a radiant heat source. Therefore, it is not suitable in environments in which a radiant heat exists. Secondly, it relates all environments to an equivalent saturated environment. Recently, a different approach has been adopted by leading researchers in the field of air conditioning and heating engineering such as Gagge and Rohles. They have agreed that it is preferable to relate environments to an equivalent environment on the 50% relative humidity line. Based on this concept, they have developed new indices of thermal comfort such as "The Revised Model Comfort Envelope"[11] and the new "Effective Temperature"[12].

Bedford[13] revised the ET in order to make it applicable to environments which have radiant heat. He did this by the simple expedient of substituting the globe temperature for the dry bulb temperature on the ET nomograph. He called this index the Corrected Effective Temperature (CET). It requires one to know the wet bulb temperature, globe temperature, and air velocity of the environment.

Yaglou considered Bedford's correction for radiant heat to be inadequate. He introduced an additional correction to the ET index which substitutes a pseudo wet bulb for the psychrometric wet bulb in addition to substituting GT for DB. Yaglou[14] called this index the Equivalent Effective Temperature Corrected for Radiation which hereinafter is designated by ETCR. The pseudo wet bulb is determined by: (1) using a psychrometric chart to determine the absolute humidity of the air at the point where the dry bulb and wet bulb temperature lines intersect; (2) finding the intersection of this absolute humidity level and a dry bulb value equal to the globe temperature; and (3) reading the wet bulb temperature which corresponds to this intersection point. This wet bulb temperature is called the pseudo wet bulb.

Another modification to the effective temperature was introduced by Yaglou and Minard[15] for use in military training centers. They corrected the globe temperature to account for the absorptivity of the olive-drab colored military uniforms by the following computation: corrected globe temperature = 0.74 x 0.95 (black globe temperature - shade temperature) + shade temperature.

Once this corrected globe temperature is computed, the procedure for obtaining the value of the index is the same as described for the ETCR. In other words, the normal scale of the effective temperature nomograph is used to find the ET value corresponding to the intersection point of air velocity, corrected globe temperature, and pseudo-wet bulb temperature. Minard[16] referred to this index as the Effective Temperature Including Radiation (ETR).

The Wet Bulb Globe Temperature[15] was developed in order to have an easy to use index which considers radiant heat and air velocity. Originally, it was based on the psychrometric wet bulb temperature (WB) and the black globe temperature (GT) as follows: WBGT = 0.7 (WB) + 0.3 (GT). Subsequently, the WB was replaced by the natural wet bulb temperature (NWB) so that today the WBGT is a function of NWB, GT, and for outdoors, the dry bulb temperature. The weighting of these temperatures is expressed according to the following formulas:

Indoor applications:
$$WBGT = 0.3\ GT + 0.7\ NWB$$

Outdoor applications:
$$WBGT = 0.2\ GT + 0.7\ NWB + 0.1\ DB$$

The WBGT index has been used by the U.S. Marine Corp to reduce the number of heat casualties in training camp[17]. It has been used in several industry studies to evaluate the exposure level of workers. In one of these studies, Jensen and Dukes-Dobos[5] found that heat exposures based on the WBGT index can be used to predict the heat stress conditions which will result in workers showing signs of heat strain.

The Wet Globe Temperature (WGT) was developed by Botsford[18]. It consists of a dial thermometer with a heat sensor enclosed in a 2.5-inch diameter copper sphere covered with a wet black cloth. It was designed to take into account all the forms of heat exchange which affect man's response to hot environments, i.e., evaporation, conduction, convection, and radiation.

Belding and Hatch[19] developed an index of heat stress based on heat exchange equations. It's rationale is the concept that in order to maintain body temperature within the safe range, the body's heat loss must equal or exceed heat gain. Their Heat Stress Index (HSI) is the ratio of the body's heat load from metabolism, convection, and radiation (Ereq) to the evaporative cooling capacity of the environment (Emax). By multiplying this ratio by 100, we have the HSI. This can be expressed in equation form as follows:

$$HSI = \frac{M + C + R}{E_{max}} \times 100$$

where:
M = Heat load from metabolism
C = Heat gain or loss from convection
R = Heat gain or loss from radiation
E_{max} = Capacity of the environment to evaporate sweat and thus cool the body

In the HSI equation, it is important to keep the units consistent. If metric units are used, then M, C, R, and E_{max} should be in calories or kilocalories per unit of time. If the British system is used, the units should be in British Thermal Units per unit of time. If the new International System of Units (SI) is used, then these factors should be expressed in joules per unit of time or watts. As a further caveat, it should be pointed out that the coefficients for the various terms will be different for different systems of units.

Previous Reports

Walters[20] compared the WBGT with the CET in a variety of non-industrial environments. There were 34 data points used in computing the correlation between these indices. Out of these 34, there is one measurement which shows a substantial radiant heat source in the environment, i.e., dry bulb = 69.8°F and globe temperature = 91.3°F. The other data sets represent environments which had little or no radiant heat. The computed linear regression equation was: WBGT = 9.1 + 1.102 (CET) with a remarkably high correlation coefficient of 0.99. The range of the variables was:

DB:	69.3 - 109°F
WB:	56.9 - 100°F
GT:	68.8 - 102°F
Va:	10 - 410 ft/min.
WBGT:	62.5 - 102.7°F

Brief and Confer[21] reported correlations between several heat stress indices. The data were obtained in a climate controlled chamber. There were 34 sets of data representing 34 climates. The climates were selected to cover a broad range of conditions including high, intermediate, and low values of DB, WB, and GT. The ranges of these variables were as follows:

DB:	77 - 132°F
WB:	65 - 99°F
GT:	78 - 155°F

The correlation between WBGT and the other indices were reported with WBGT as the independent variable. A summary of the regression equations and the correlation coefficients is shown below:

Regression Equation	Corr. Coef.
WGT = -3.2 + 0.958 WBGT	0.967
HSI = -1827.1 + 22.584 WBGT	0.742
ET = 13.1 + 0.823 WBGT	0.913
ETCR* = 17.7 + 0.786 WBGT	0.966

The later regression line between ETCR and WBGT is shown in Figure 1.

Minard[22] reported a relationship between WBGT and the Effective Temperature Including Radiation (ETR). It is shown in Figure 1 along with the regression line reported by Brief and Confer. Minard did not report the best fit linear regression equation, but the correlation coefficient was shown to be 0.9767. He did plot the data on a graph with WBGT on the vertical axis and ETR on the horizontal. The line shown on Figure 1 is a line which appears to approximate the best fit relationship.

*It should be noted that there is a difference in terminology between the Brief/Confer paper and this report. Brief and Confer used Yaglou's method of correcting the ET and called the resulting index the CET. In this report, ETCR is used to symbolize Yaglou's correction and CET is used to symbolize Bedford's correction. Thus, in order to keep this report consistent the symbol ETCR is used in the fourth equation shown above even though Brief and Confer used CET on the left side of the equation.

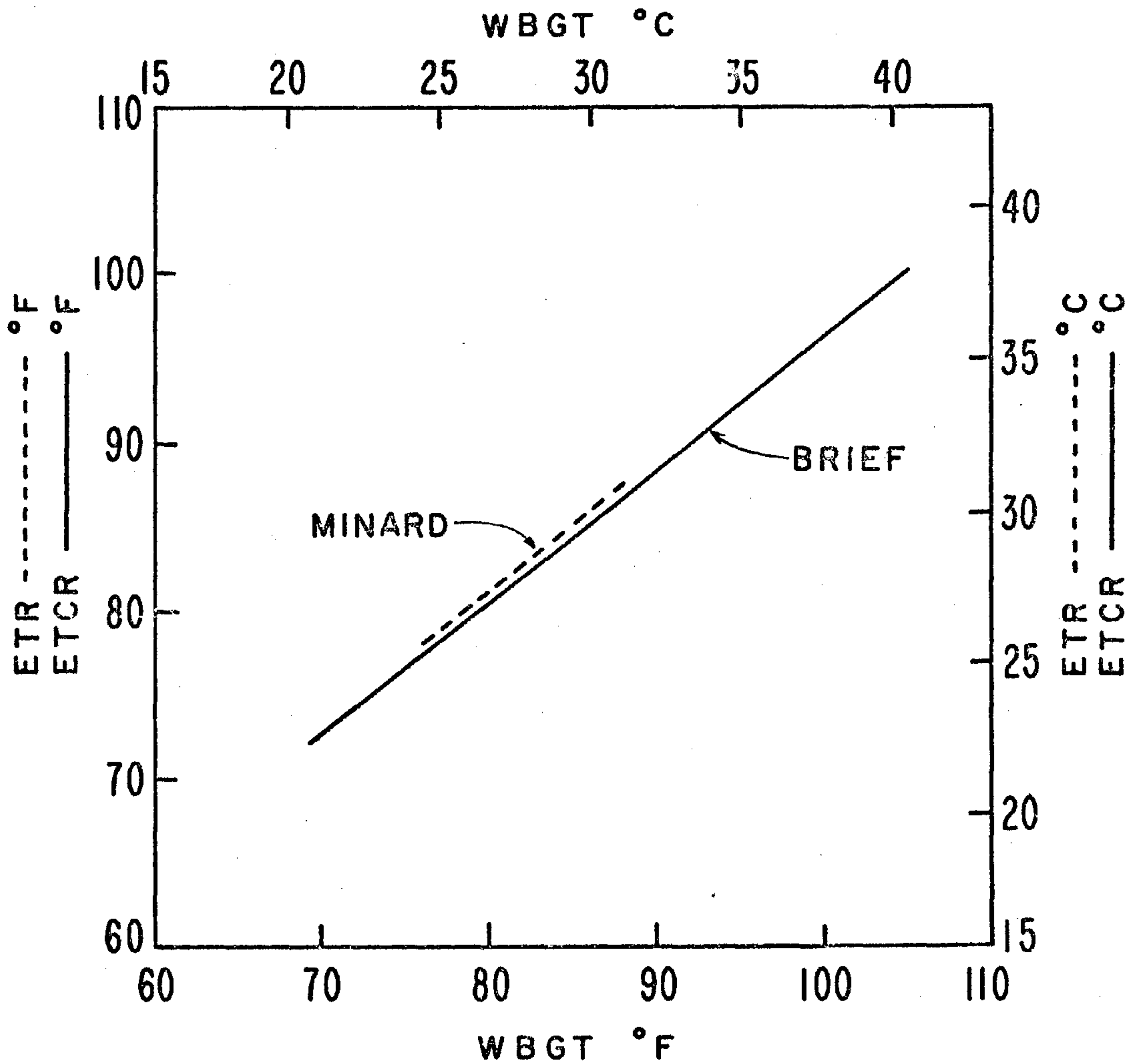

Figure 1. Comparison of linear correlations as found by Minard and Brief & Confer

The CET and the ETR are very similar indices. Minard[22] previously reported a linear relationship between the two indices having a correlation coefficient of 0.9983. The indices corresponded closely to the relationship CET = ETR (see Figure 2). Consequently, it is difficult to justify the continuing existence of two indices which are so similar. The choice of which index to retain is not difficult since the CET is easier to obtain. Therefore, throughout the remainder of this report, the ETR will be ignored in favor of the CET.

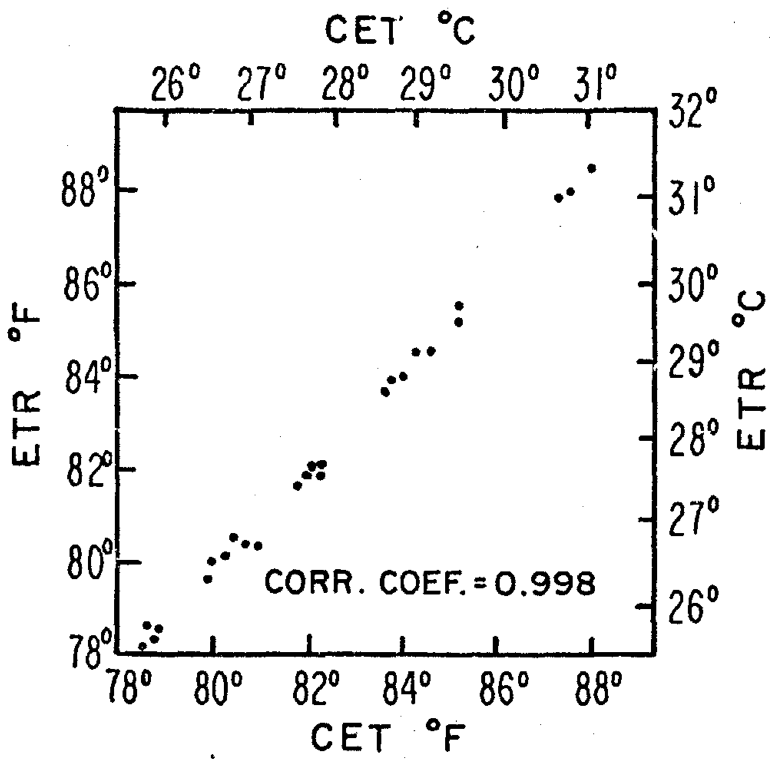

Figure 2. Relationship between Effective Temperature Including Radiation (ETR) and Corrected Effective Temperature (CET) reported by Minard.

Several investigators have reported correlations between the WBGT and WGT indices. Brief and Confer[21] found a correlation coefficient of 0.967 based on 34 points measured in a controlled climate chamber. Their regression equation was: WGT = -3.2 + 0.958 (WBGT). Sundin, et. al.,[23] found that a second order regression equation described the relationship between WBGT and WGT. The data used to compute this relationship was obtained in four industry studies which included a strip mine, an oil refinery, and aluminum reduction plant, and the Washington, D.C. steam tunnels. Their regression was: WBGT = 54.928 - 0.5599 (WGT) + 0.01175 (WGT^2). The correlation coefficient was 0.9755. Snook[24] reported a correlation coefficient of 0.948 for the WBGT-WGT relationship based on tests in a climate controlled chamber. The conditions included the twelve combinations of the following climatic factors:

Radiant Heat:	with		without
Air Movement:	high		low
Relative Humidity:	high	moderate	low

The regression lines determined by these investigators are shown in Figure 3 with WBGT as the dependent variable. The line from Brief was computed with WBGT as the independent variable; thus, the slope of the plotted line is not exact for WBGT as the dependent variable.

Botsford measured the WGT in 70 different thermal environments. The range of the various climatic parameters were as follows:

DB:	66 - 180°F
WB:	50 - 93°F
VPa:	5.4 - 19.8 mm Hg
Va:	30 - 2800 ft/min
GT:	70 - 180°F
WGT:	63 - 102°F

The relationship he found between ETCR and WGT is shown in Figure 4.

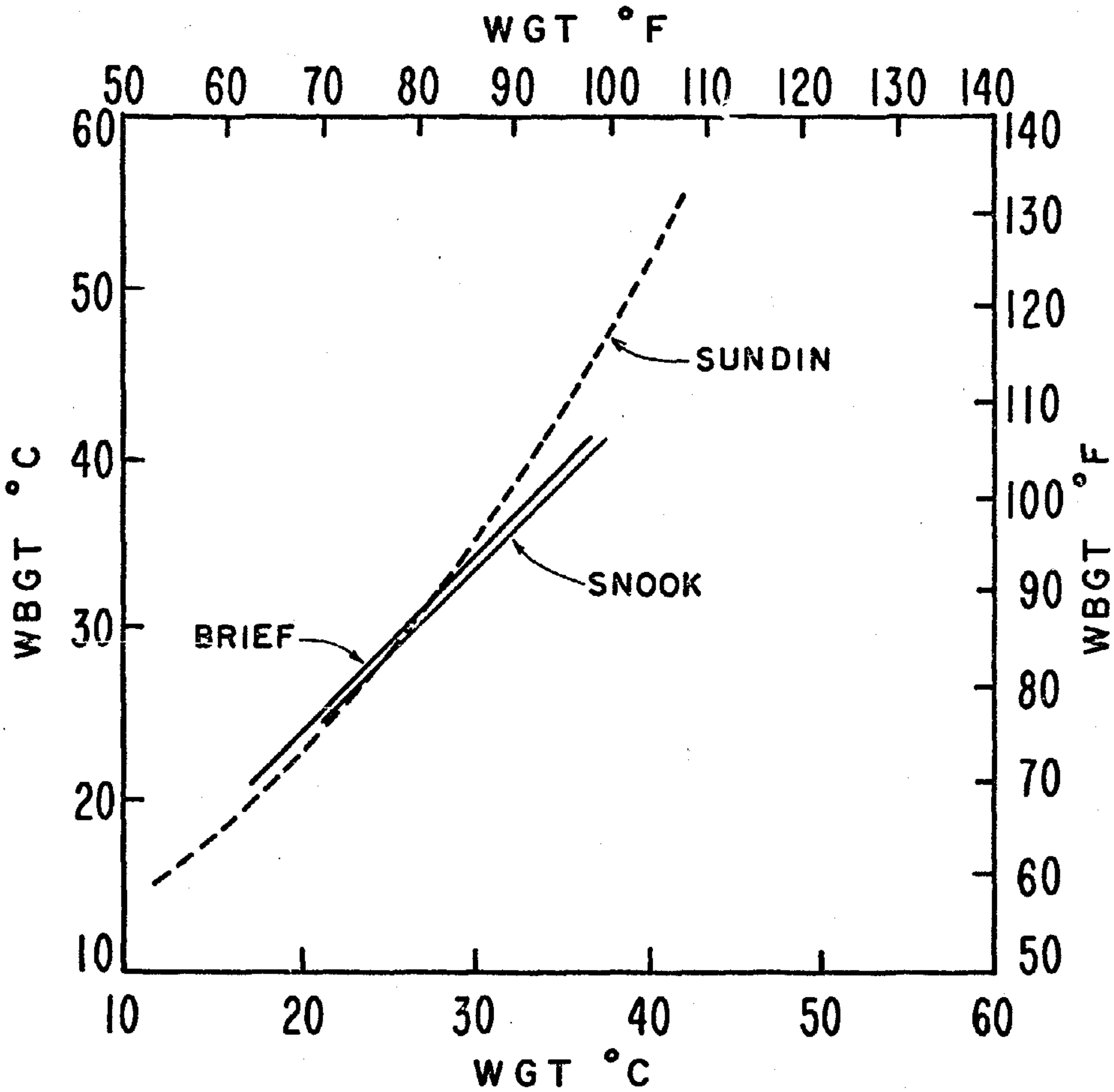

Figure 3. Regression lines found by different investigators between Wet Bulb Globe Temperature (WBGT) and Botsford's Wet Globe Temperature (WGT).

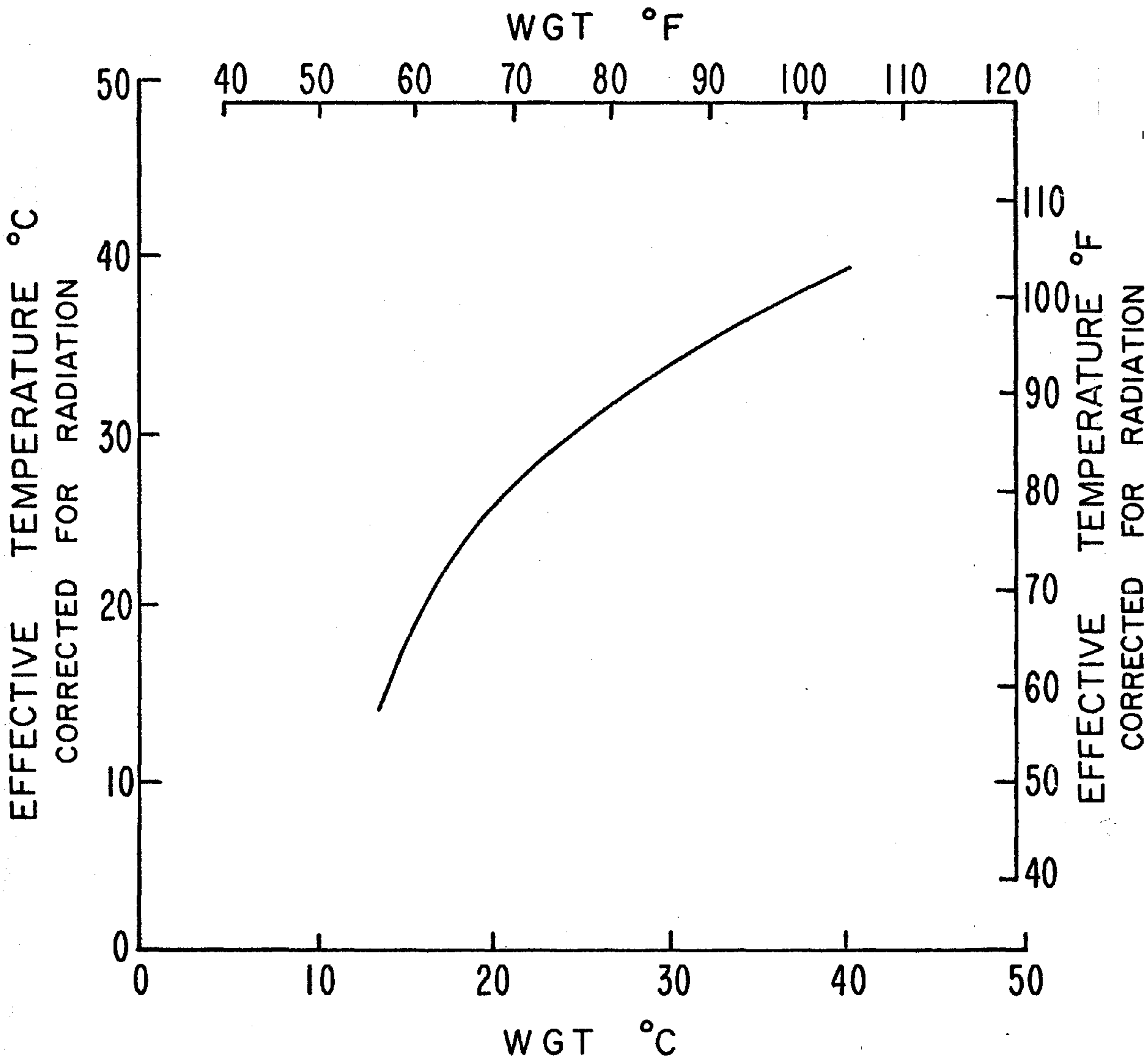

Figure 4. Relationship reported by Botsford between Effective Temperature Corrected for Radiation (ETCR) and Wet Globe Temperature (WGT).

METHODOLOGY

The Data

The data for our study was obtained[25] in fifteen industrial facilities selected because of their high heat stress potential. The specific industries represented a large cross-section of both environmental and architectural features in three different climatic zones of the continental United States. A complete list of the industries is included in a NIOSH technical report by Mutchler, et. al.[25] The three regions of the country were: the desert southwest; the temperate midwest; and the humid gulf coast.

At twelve of these survey sites, there were two week long surveys conducted. At the remaining three sites, the surveys were for only one week each.

At each of the fifteen survey sites, measurements were obtained for: (1) several worksites INSIDE the plant; and (2) local metereological data OUTSIDE the facility.

Each of these data sources composes a distinct data base. Each data base is composed of numerous sets of data which are measurements made simultaneously. Each set of data was recorded on an 80-column computer code sheet and keypunched onto an 80-column computer card.

The INSIDE data base was developed with automated instruments located at several worksites within the plant and connected to a central recorder. This data base also includes measurements made manually at the worksites. These manual measurements are far less numerous than the automated measurements. The OUTSIDE data base was obtained from instruments located on a metereological tower outside the plant and connected to the central recorder.

The INSIDE data consists of the temperatures measured at each of the work sites established within the plant. Dry-bulb, natural wet-bulb, and globe temperatures were automatically recorded once per hour for each site. The manually measured parameters included: ventilated dry-bulb, ventilated wet-bulb, and air velocity. In addition, some of these data sets include readings from a Botsford wetted globe thermometer (WGT).

The OUTSIDE data recorded at the plant includes the following climatic measurements: dry-bulb temperature, wind speed, wind direction, total sky cover, ventilated and natural wet-bulb temperatures, black globe temperature, and solar radiation.

Two additional data bases were generated by randomly selecting a sample from both the INSIDE and the OUTSIDE data bases. A summary of the four data bases follows:

#1. 2905 sets of measurements observed outside of the 15 plants.
#2. 200 sets randomly selected from the 2905 data sets in base #1.

Out of these 200 sets, 22 were not used because CET values could not be read from the nomograph due to extremely low GT and WB or when WB was several degrees higher than GT. Thus, this data base actually contained 178 usable sets of data.

#3: 1818 sets of measurements recorded at several different sites inside each plant (worksite).

#4: 200 sets randomly selected from the 1818 sets in data base #3. CET and ETCR values were read from the nomograph for each set. In addition, wet globe temperatures were available for 89 of these sets of data. WGT measurements had not been recorded for the other 115 points or for the data from outside of the plant (bases 1 and 2).

In order to determine whether or not there was a significant loss of accuracy resulting from compacting the large data bases into the more manageable sizes of 178 points and 200 points, several comparisons were made. Histograms were plotted showing the distribution of values for the total data base and for the randomly selected data base. Some of the histograms are included in the Appendix to illustrate the similarity between the total and the smaller data bases. Also, the means, standard deviations, and ranges of the various climatic variables are listed in tabular form in the Appendix for the total and the sample data bases. Generally, the means and standard deviations are quite close. The range of data in the total data base is typically greater than for the smaller data base due to data points in the extreme tails of the distributions.

Methods of Computing Indices

Wet Bulb Globe Temperature (WBGT)

Two methods of computing WBGT were used. For the outside of plant data, the equation used was:

$$WBGT = .7\ (NWB) + .2\ (GT) + .1\ (DB) \qquad (1)$$

where: NWB = Natural Wet Bulb Temperature ^{o}F
GT = Globe Temperature ^{o}F
DB = Dry Bulb Temperature ^{o}F

When computing heat exposure for the inside of plant data, the equation used was:

$$WBGT = .7\ (NWB) + .3\ (GT) \qquad (2)$$

Wetted Globe Temperature (WGT)

Wet Globe Temperatures were read from a Botsball Thermometer at indoor worksites only. Since this data was never automated, we are only able to obtain 89 readings out of the possible 200 for the randomly selected inside of plant data base. In addition, in order for a regression between WGT and CET (or any other index) to be compared fairly with another regression (such as WBGT vs. CET), the second regression was run using only those 89 sets of data for which WGT was defined. In other words, the 89 sets of data for which WGT was defined composes a fifth data base (which is a subset of the 200 randomly selected inside measurements). All meaningful comparisons between WGT and any other index or regression were made when the other index was computed from this fifth data base (89 sets for which WGT is defined).

Effective Temperature Corrected for Radiation (ETCR)

The ETCR values were obtained by the method described in the Ninth Edition of "Industrial Ventilation" by the Committee on Industrial Ventilation, American Conference of Governmental Industrial Hygienists, page 3-6.

Corrected Effective Temperature (CET)

The CET values were obtained by reading from the normal scale CET nomograph developed by Lee and Henschel[26] for use with SI units. The chart requires known values of WB, GT, and air velocity.

Heat Stress Index (HSI)

The equations used for calculating the HSI were those reported by Drs. Belding and Minard at the XVI International Congress on Occupational Health (September 1969, Tokyo, Japan). The equations are as follows:

$$R = 7.9\ (t_w - 35)\ \text{kcal/hr.}$$
$$C = 0.7\ V^{0.6}\ (DB - 35)\ \text{kcal/hr.}$$
$$E_{max} = 1.4\ V^{0.6}\ (VPa - 42)\ \text{kcal/hr.}$$

where: V is air velocity in meters/minute
VPa is water vapor pressure of air in mm Hg
t_w is radiant heat of the surroundings,
$t_w = GT + 0.24\ V^{0.5}\ (GT - DB)$
35 is assumed skin temperature in degrees centigrade
42 is vapor pressure of wet skin at 35C
GT is globe temperature in degrees centigrade
DB is dry bulb temperature in degrees centrigrade

The HSI was then computed as follows:

$$HSI = \frac{M + C + R}{E_{max}} \times 100$$

The above equations for M, R, C, and E_{max} use the old metric units. If SI units are used, the coefficients would be different, kcal would not be used, and Celsius degrees would replace centrigrade degrees.

RESULTS

Numerous correlations were calculated. Table 1 summarizes the relationships between the WBGT, CET, and HSI for outside conditions. Table 2 summarizes the relationships between these indices for the data obtained inside the plants. It should be noted that two regression equations are given for each two variable relationship because the best fit regression line depends on which variable is the dependent and which is the independent.

The poorest correlations were those in which an empirical index (WBGT, CET) was related to the rational index (HSI).

Table 1

Outside Data - Summary of Computed Regression Equations (^{o}F)

Regression Equation	N	Correlation Coefficient
WBGT = 21.2394 + 0.72538 x CET	178	0.90502
WBGT = 65.1876 + 0.32302 x HSI*	2860	0.76739
CET =-12.43178 + 1.1293 x WBGT	178	0.90502
CET = 61.8687 + 0.44645 x HSI*	173	0.91088
HSI*=-118.0838 + 1.82302 x WBGT	2860	0.76739
HSI*=-114.172 + 1.85842 x CET	173	0.91088

* HSI computed in metric units assuming metabolic heat load = 200 kcal/hr.

Table 2

Inside Data - Summary of Computed Regression Equations (^{o}F)

Regression Equation	N	Correlation Coefficient
WBGT = -22.7276 + 1.27744 x CET	200	0.96383
WBGT = 64.181 + 0.14256 x HSI*	1818	0.81939
CET = 22.0092 + 0.727216 x WBGT	200	0.96383
CET = 67.7716 + 0.10962 x HSI*	200	0.77796
HSI*= -273.353 + 4.70954 x WBGT	1818	0.81939
HSI*= -340.32 + 5.52114 x CET	200	0.77796

* HSI computed in metric units assuming metabolic heat load = 200 kcal/hr.

The wet globe temperature (WGT) was measured inside the plant at various times. Out of the 200 randomly selected points from inside the plant, there were 89 WGT measurements. Thus, correlations between WGT and the other indices are based on a sample size of 89 or less. Table 3 summarizes the results of correlations between WGT and WBGT, CET, and ETCR.

Regression Equation	N	Correlation Coefficient
WGT = 15.0771 + 0.7502 (WBGT)	89	0.88758
WGT =-4.1492 + 0.9814 (CET)	89	0.86641
WGT = 0.7244 + 0.9050 (ETCR)	88	0.84328
WBGT = 0.1937 + 1.0501 (WGT)	89	0.88758
CET = 22.4545 + 0.7649 (WGT)	89	0.86641
ETCR = 22.1049 + 0.7858 (WGT)	88	0.84328

Table 3. Summary of linear correlations between WGT and CET, WBGT, and ETCR as calculated from the inside data using the Fahrenheit temperature scale.

Figure 5 is a plot of the relationship between CET and WGT. Figure 6 is a plot of the relationship between CET and WBGT. The regression equations in ^{o}F are:

CET = 22.4545 + 0.7649 (WGT) N = 89
Correlation Coefficient = 0.86641

CET = 23.0004 + 0.7193 (WBGT) N = 89
Correlation Coefficient = 0.96395

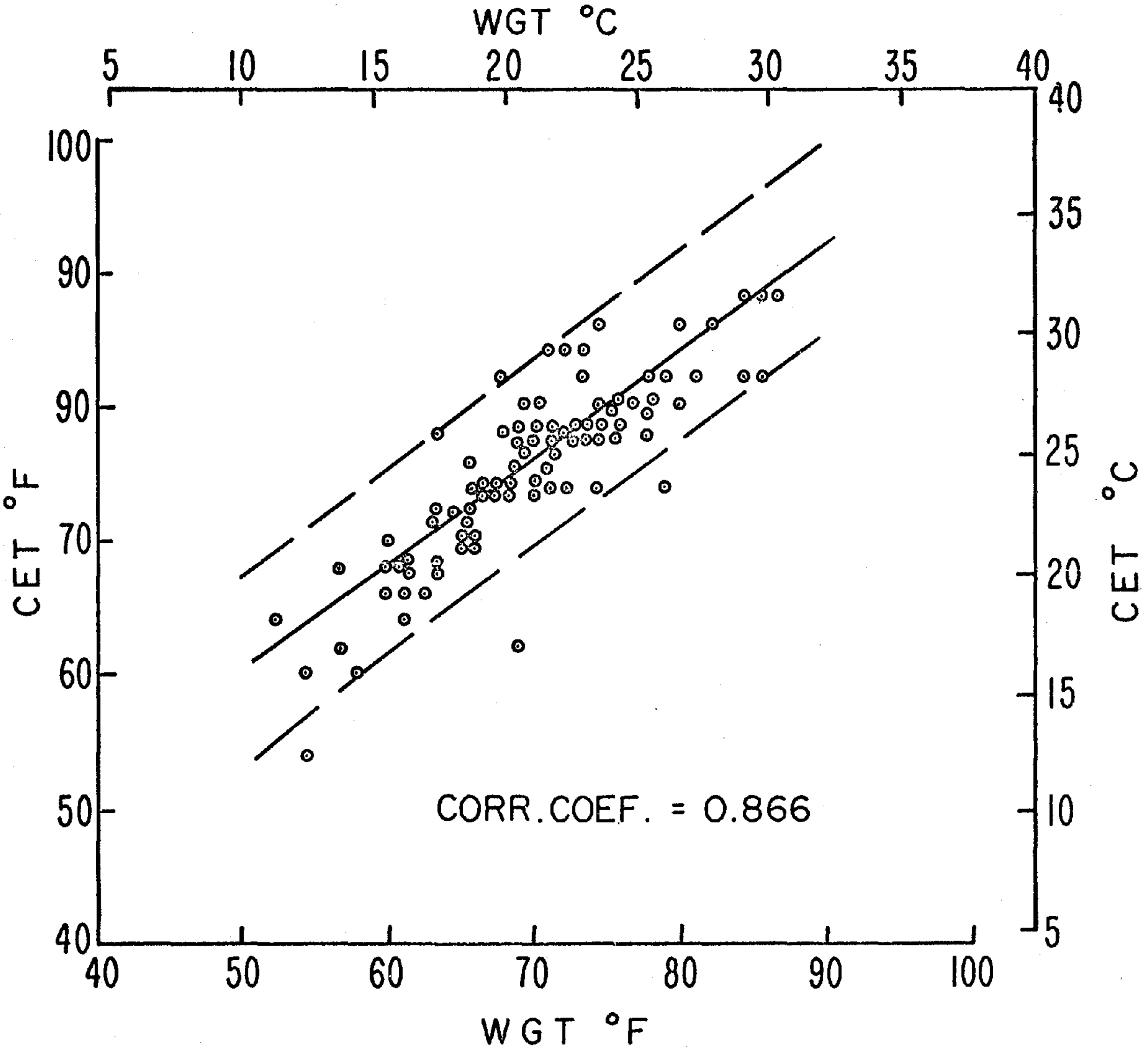

Figure 5. Relationship between Corrected Effective Temperature (CET) and Wet Globe Temperature (WGT). Plot shows linear regression line and 90% confidence band for the data.

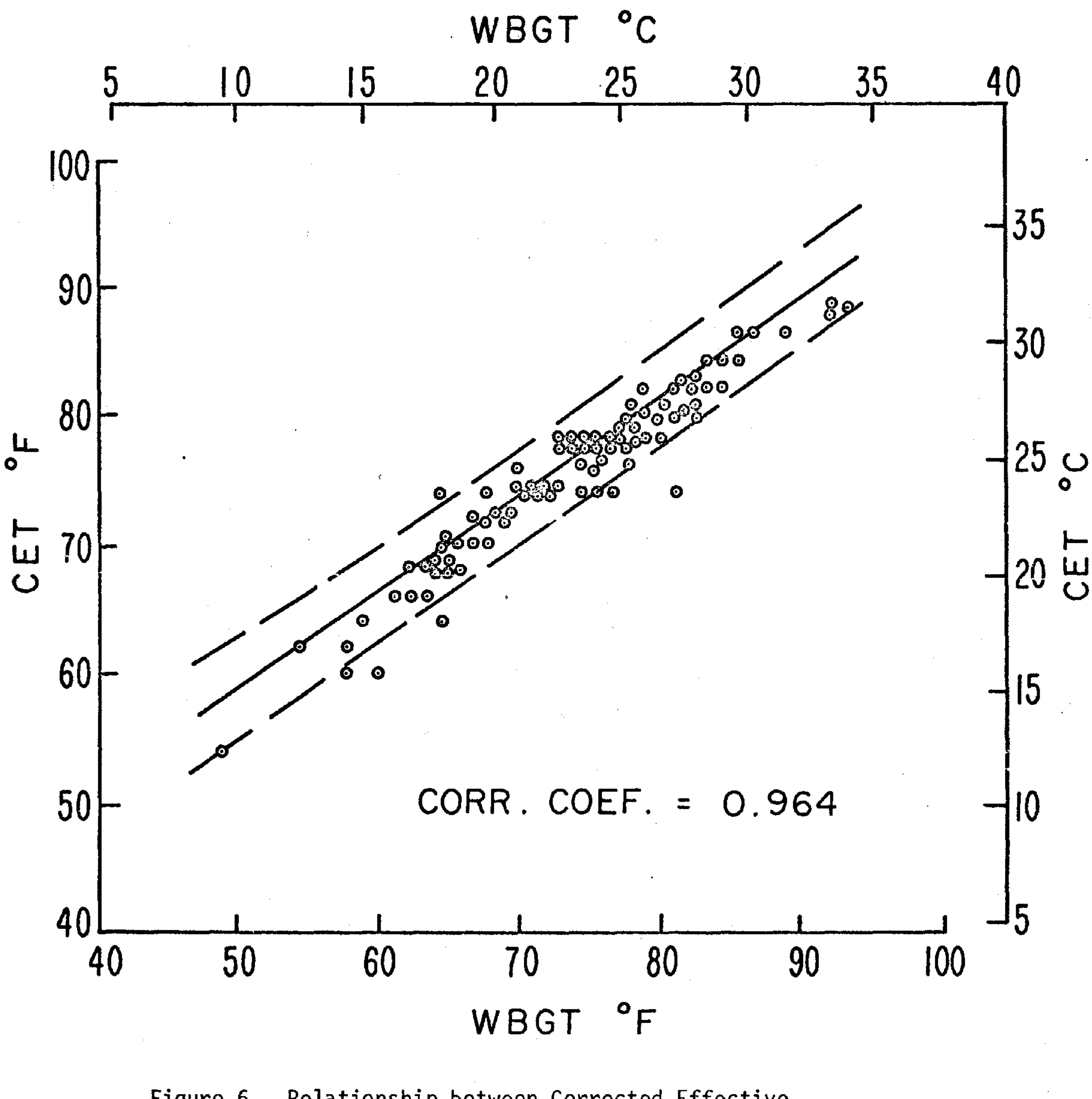

Figure 6. Relationship between Corrected Effective Temperature (CET) and Wet Bulb Globe Temperature (WBGT). Plot shows linear regression line and 90% confidence band for the data.

Figure 7 is a plot of the relationship between Effective Temperature Corrected for Radiation (ETCR) and Wet Bulb Globe Temperature (WBGT). The computed regression equation in ^{o}F is:

$$ETCR = 20.666 + 0.766\ (WBGT)$$
$$r = 0.9964$$
$$N = 88$$

Figure 8 is a plot of the relationship between ETCR and Wet Globe Temperature (WGT). The computed regression equation in ^{o}F is:

$$ETCR = 22.105 + 0.786$$
$$r = 0.8433$$
$$N = 88$$

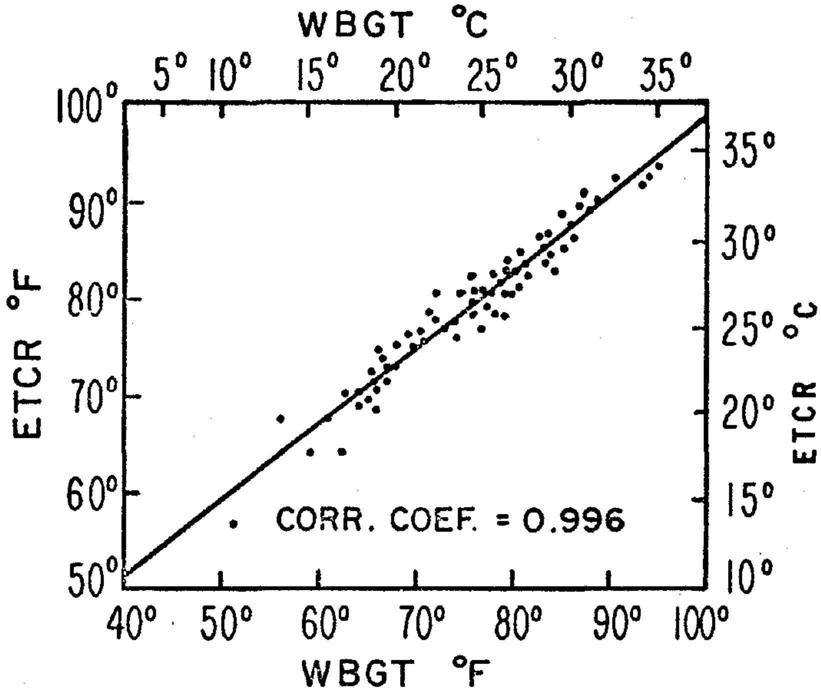

Figure 7. Relationship between ETCR and WBGT

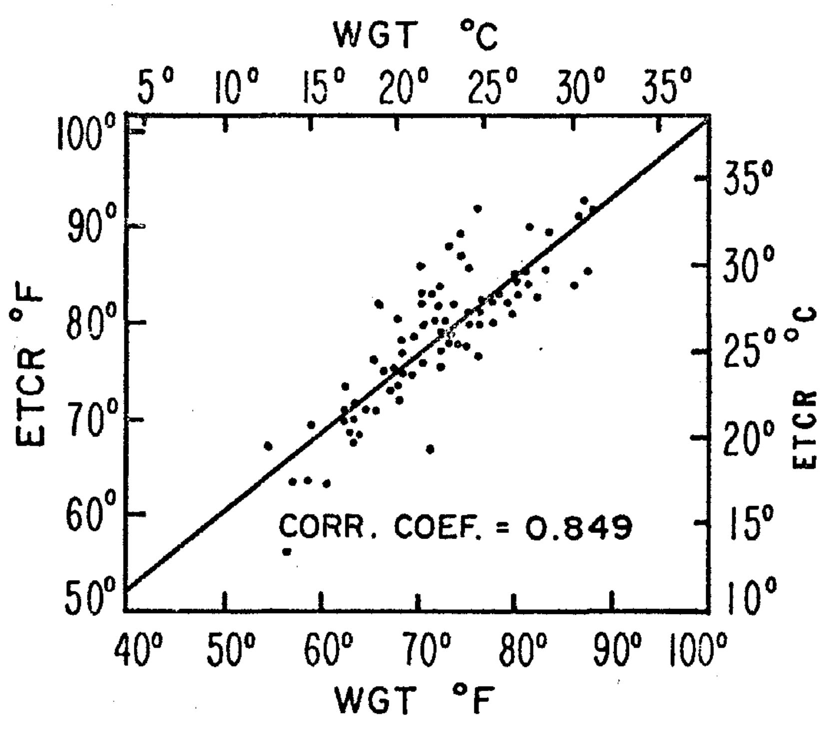

Figure 8. Relationship between ETCR and WGT

The regression lines relating WBGT and WGT were calculated to be:

$$WBGT = 0.1937 + 1.0501\ (WGT)$$
$$WGT = 15.0771 + 0.7502\ (WBGT)$$

$$N = 89$$
$$r = 0.88758$$

This relationship is shown graphically in Figure 9. Also included are the regression lines reported by other investigators for the WBGT-WGT relationship. The plotted regression lines have only been drawn through the range of WBGT's from which they were calculated. Thus, it can be seen that the regression line found by Jensen was from a lower range of conditions than the lines found by Brief and Snook.

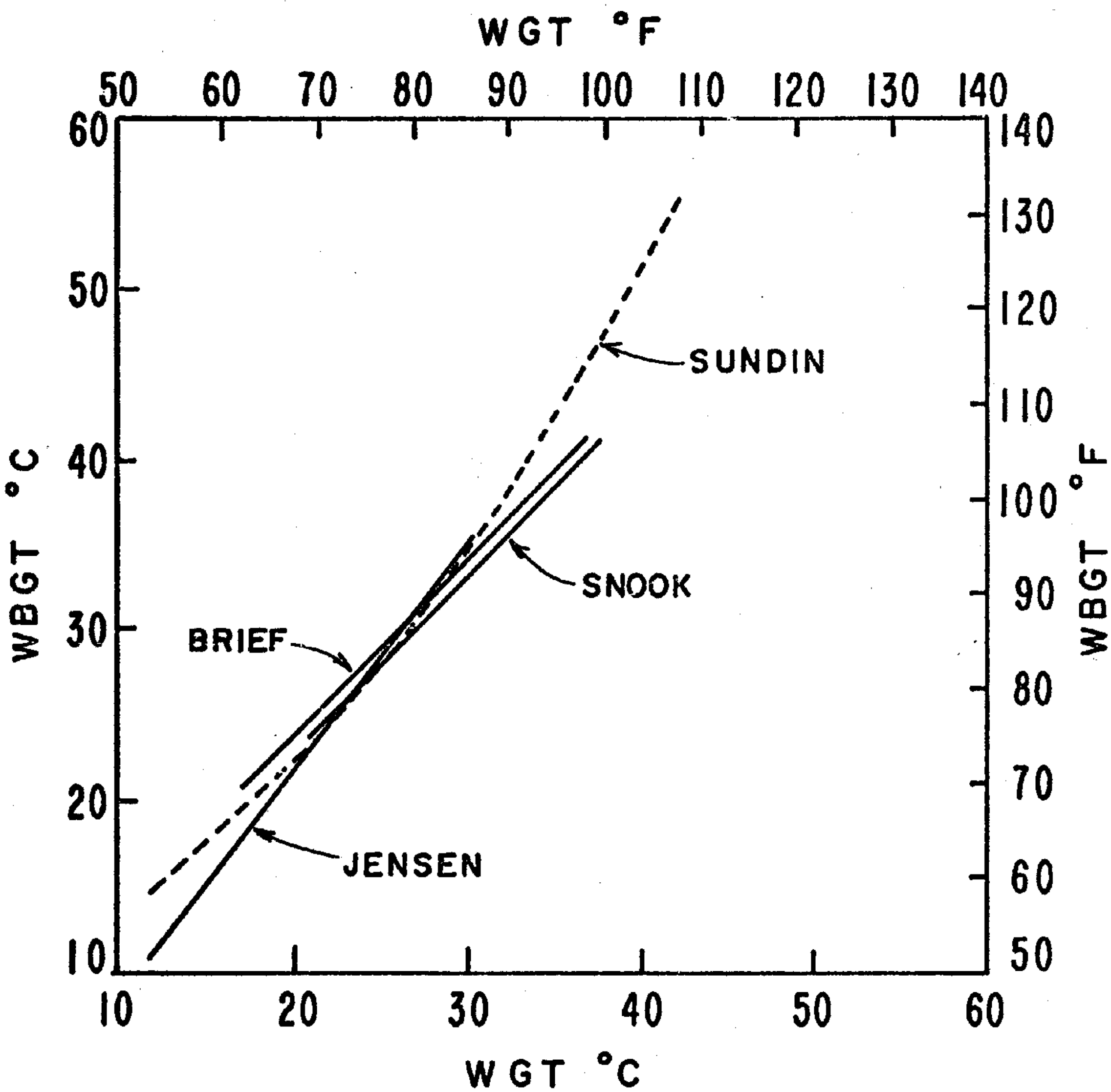

Figure 9. Comparison of regression lines found by different investigators between WBGT and WGT.

The correlation between the Effective Temperature Corrected for Radiation (ETCR) and the Corrected Effective Temperature (CET) is shown in Figure 10. The computed linear regression equation in ^{o}F is:

$$ETCR = -0.732 + 1.054\ (CET)$$

$$r = 0.9903$$
$$N = 200$$

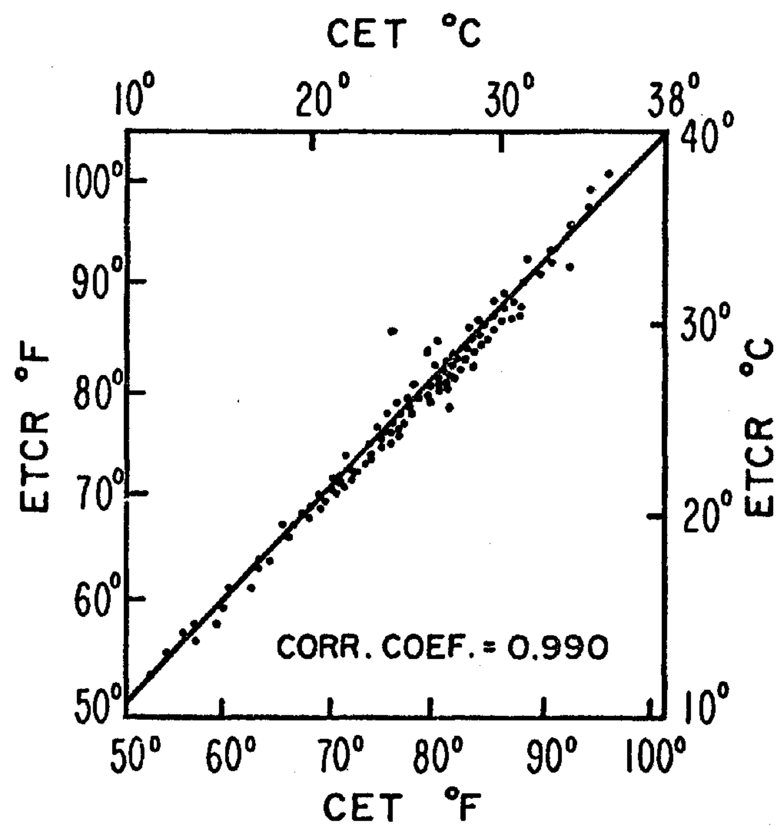

Figure 10. Correlation between ETCR and CET.

DISCUSSION

The correlations between WBGT and Effective Temperature Corrected for Radiation (ETCR) are interesting because they can be compared with similar correlations reported by previous investigators. A comparison of regression equations as determined by Brief and Confer, and this study as calculated for the inside data is as follows:

Jensen - Inside:
$$ETCR = 20.666 + 0.766\ (WBGT)$$
$$r = 0.9964$$
$$N = 88$$

Brief and Confer:
$$ETCR = 17.7 + 0.786\ (WBGT)$$
$$r = 0.966$$
$$N = 34$$

The regression equation of Brief and Confer is very similar to the equation determined in this study from the inside data. This can be clearly seen in Figure 11 where the two regression lines are presented graphically. Also included is a line fitting Minard's data. The regression lines are shown only over the range of data from which they were calculated. The similarity between the three regression lines is particularly significant when one considers that the data for each line comes from very different sources. Minard's data came mostly from outdoors in a hot humid climate. Brief's data came from a controlled climate chamber, and Jensen's data came from a variety of worksites in 15 hot industrial facilities.

The relationship between Botsford's WGT and the ETCR is shown in Figure 12. The curved line is the one reported by Botsford. The straight line is the one calculated from 89 inside the plant measurements (also shown in Figure 6). The difference may be due to the fact that Botsford's data were obtained in a controlled laboratory environment, whereas, Jensen's data were obtained in actual work sites. In the laboratory, the Botsball is easy to keep clean, while in many hot industrial areas, it is difficult to keep clean because particulate matter settles on the wet cloth covering. Also, in the laboratory, the conditions can be controlled, whereas, in many hot worksites, the climatic factors often change. When a climatic factor does change, the different instruments have different response curves, so we should expect greater variability in the correlations.

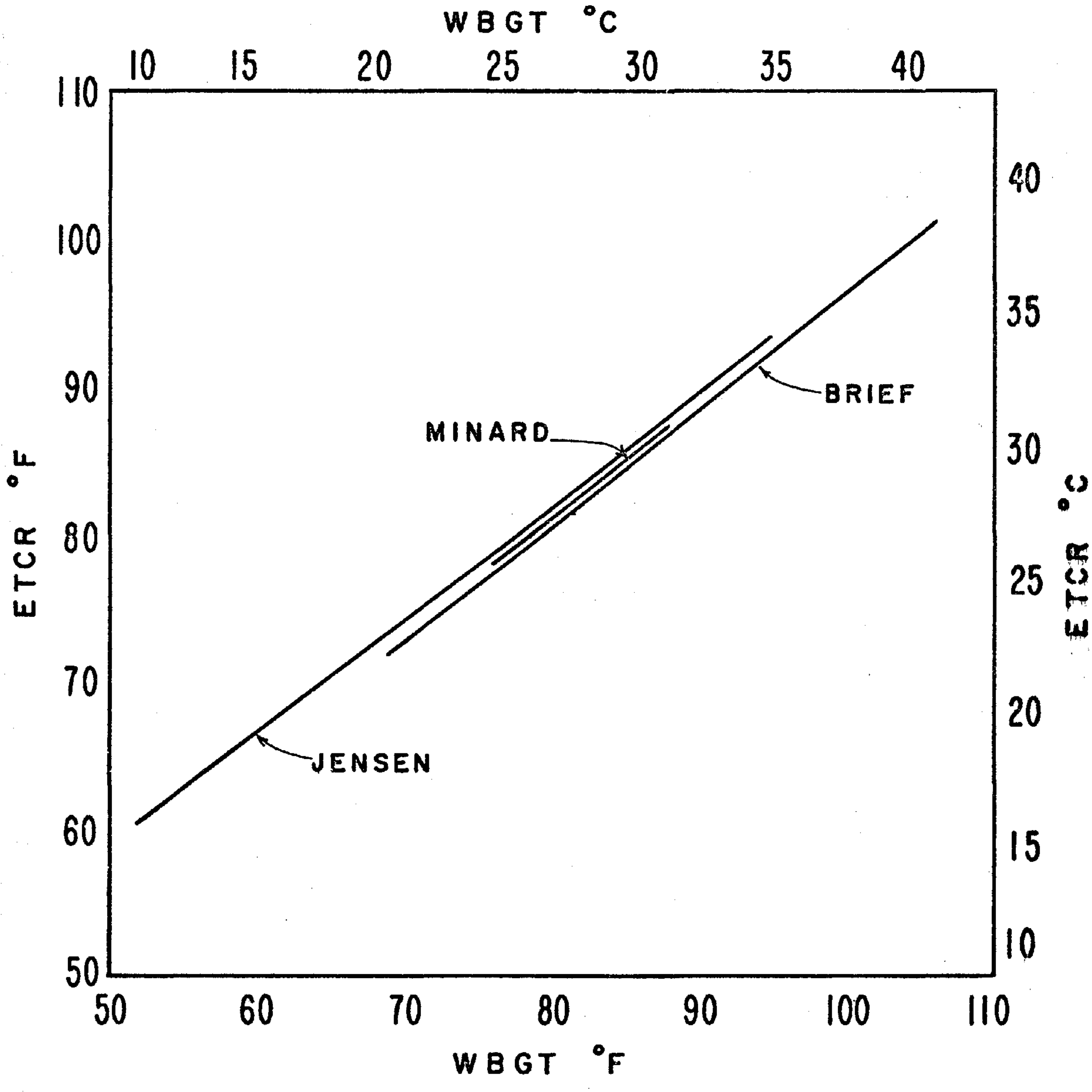

Figure 11. Relationship between ETCR and WBGT as previously reported by Minard and Brief and as found in this study by Jensen.

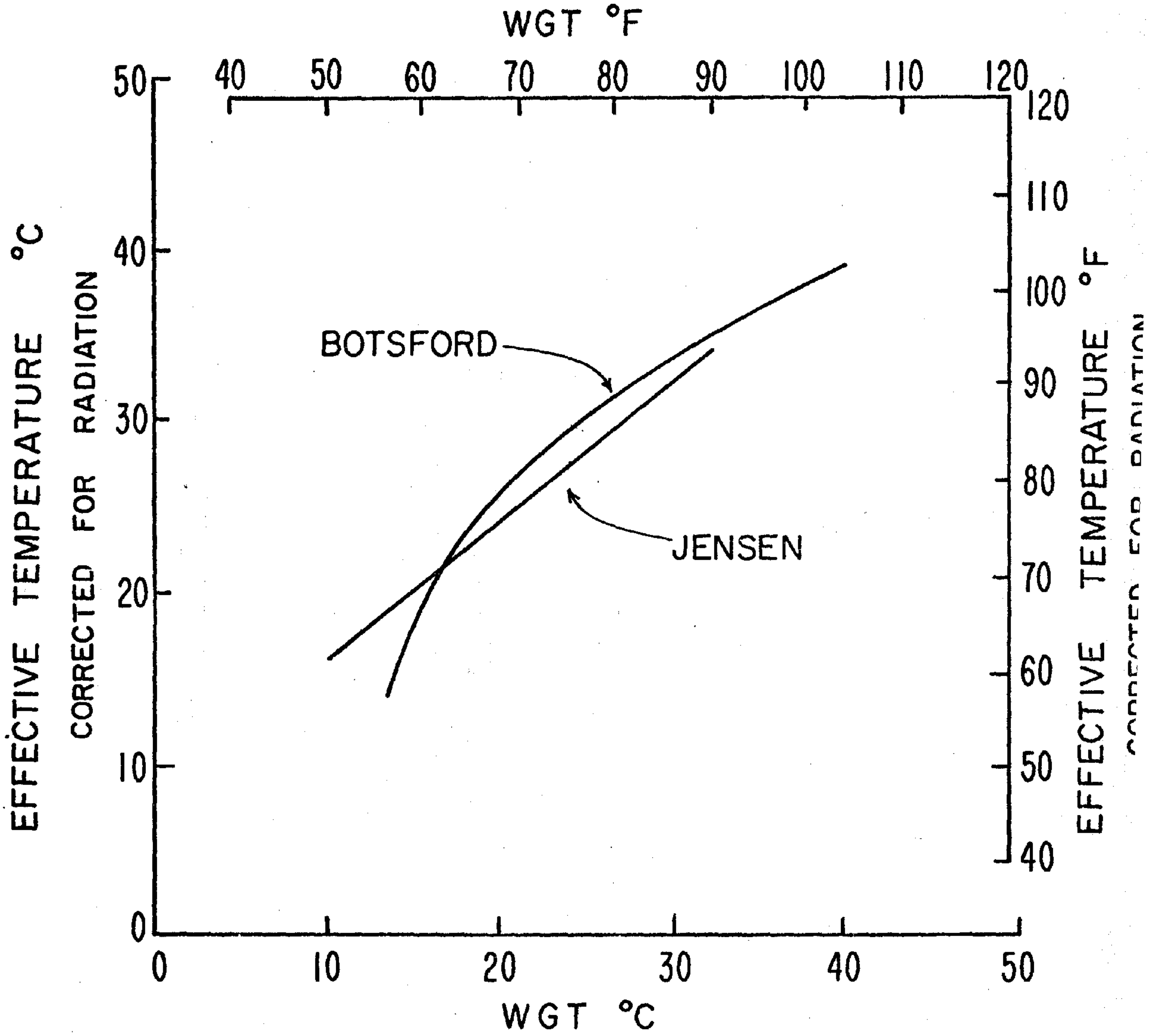

Figure 12. Relationship between Effective Temperature Corrected for Radiation (ETCR) and Wet Globe Temperature (WGT) as found by Botsford and as found in this study.

Another comparison of interest is the relationship between WBGT and CET. With this relationship, we are primarily interested in looking at CET as the dependent variable and WBGT as the independent variable. The regression equation reported by Walter's had the position of these indices opposite from what we want. Therefore, a regression line was computed from Walter's data with CET as the dependent variable. This line is shown on Figure 13. Also shown on Figure 13 are two regression lines computed from our data. The regression line computed from our inside data is very close to that computed from Walter's data. The regression line computed from our outside data differed from the other two in slope. The apparent explanation being that the range of the data extended much further into the cool to cold regions. The practical significance of the outside data regression lines may not be great, because these indices are normally used for hot environments. The correlations in cool environments do not have any apparent significance as far as establishing guidelines or standards for work in hot environments.

The more significant aspect of the correlations found in this study is the regression line for inside data. The WBGT-CET relationship formed one step in the development of the permissible exposure limits recommended by Dukes-Dobos and Henschel[25] and adopted as a Threshold Limit Value by the American Conference of Governmental Industrial Hygienists (ACGIH). The step involved translating Lind's study[4], which related human response to CET, into equivalent relationships using WBGT. Lind's results are shown in Figure 14. This figure shows the equilibrium rectal temperature of his subjects after exposure to the environment indicated on the abscissa in terms of CET. The three curves are for three different exercise levels (180, 300, and 420 kilocalories per hour).

The curves show that the subjects maintained a steady rectal temperature over a wide range of environments (prescriptive zone), but the hotter environments did cause their rectal temperatures to rise. Lind proposed that the upper limit of the prescriptive zone represents a valid physiological criterion for setting heat exposure limits in industry. Dukes-Dobos and Henschel as well as the ACGIH have accepted Lind's proposal in concept, although certain modifications have been introduced[25]. These modifications have to do with the point on the curve which is considered to be the upper limit of the prescriptive zone (ULPZ). In Figure 14, the ULPZ recommended by Dukes-Dobos and Henschel has been sketched in.

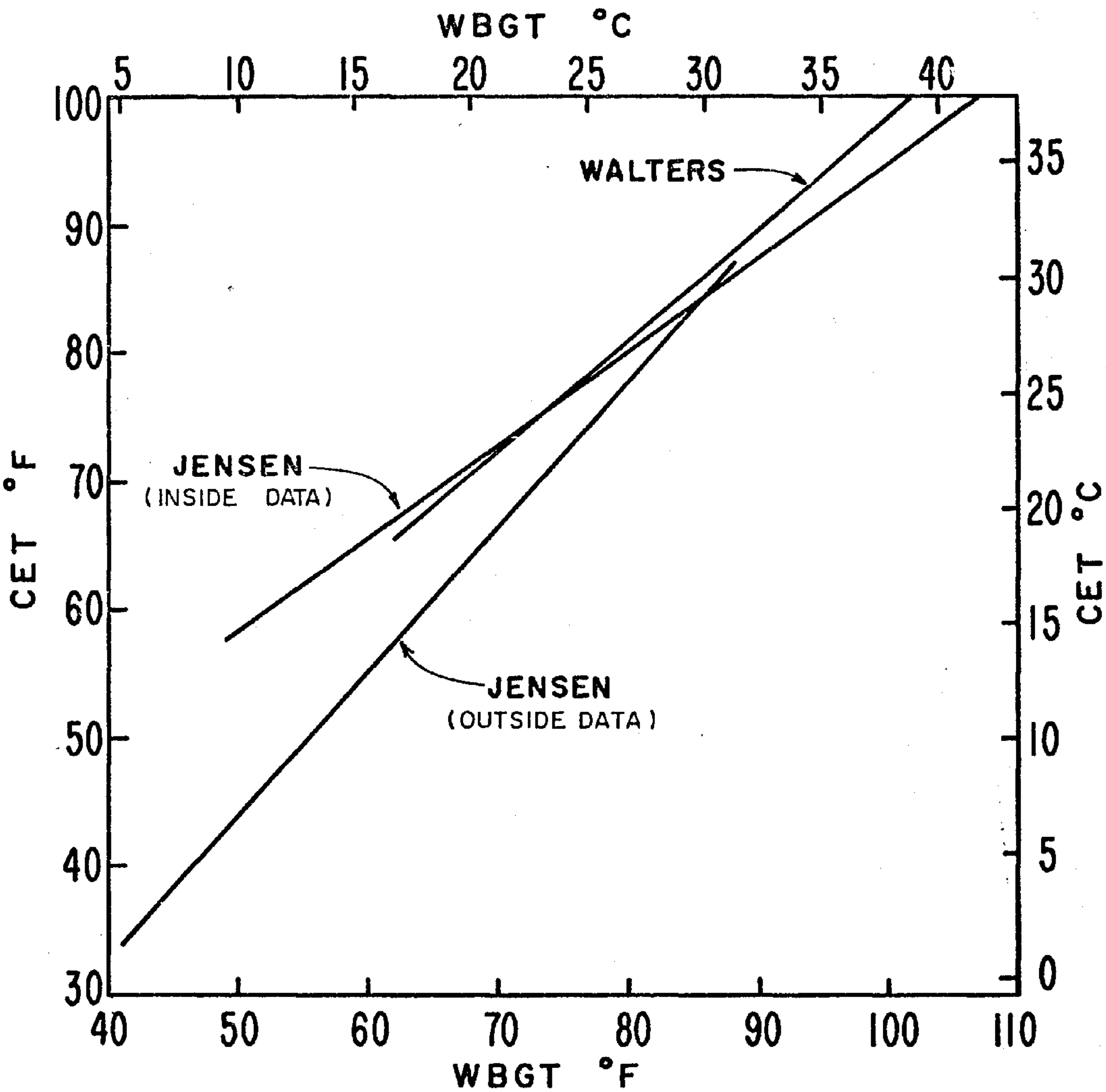

Figure 13. Regression lines relating CET and WBGT.

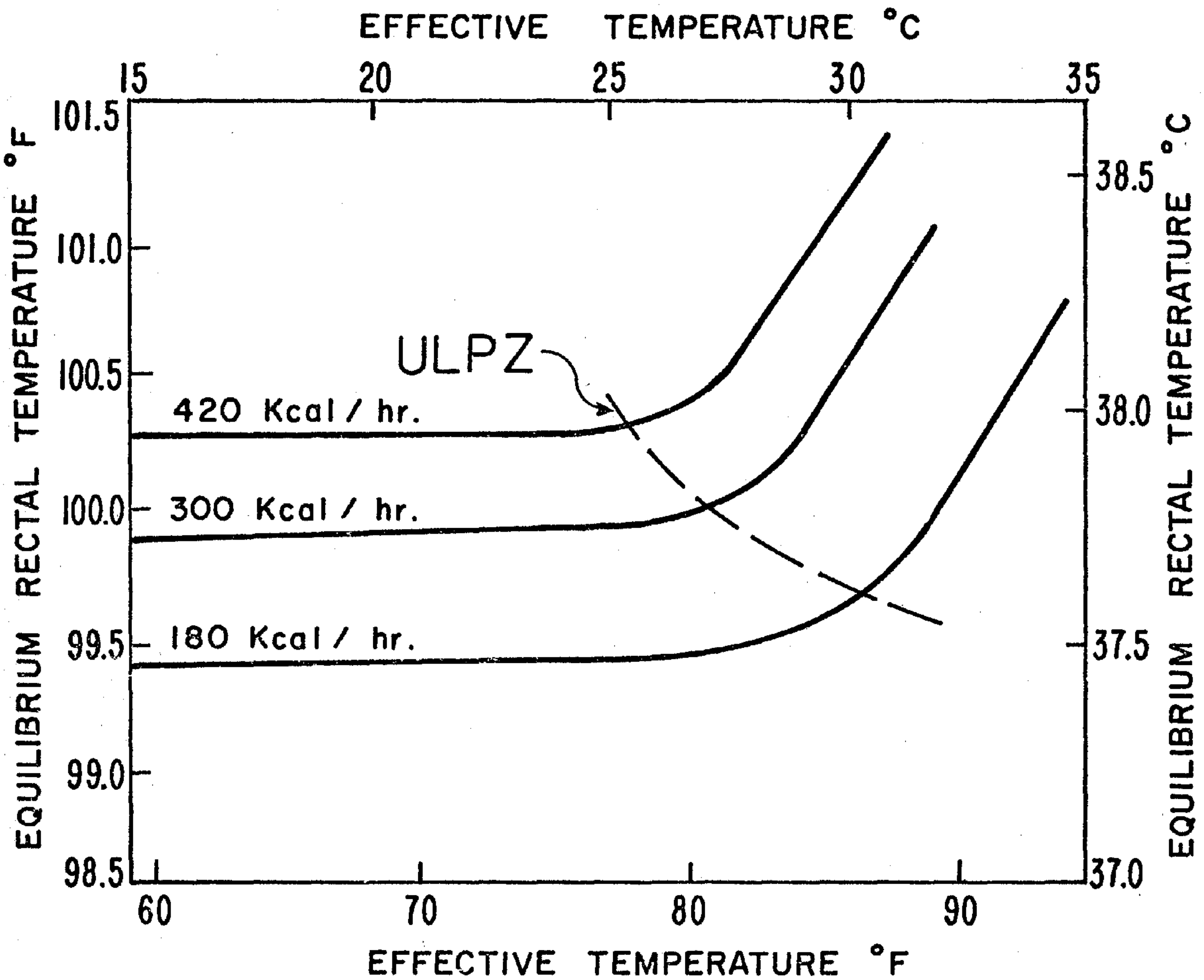

Figure 14. The equilibrium rectal temperature of one subject working at three metabolic rates (180, 300, and 420 Kcal/hr) in a wide range of climatic conditions (adapted from Lind).

CONCLUSIONS

The correlations between WBGT and CET are somewhat different than those previously reported. However, the nominal differences shown in Table 4 probably do not justify any change in the recommended limits. Perhaps, as more physiological data is obtained, there may come a time when a revision of the recommended limits would be appropriate. At that time, it would be best to use the regression lines reported here to convert from the CET index to the WBGT index.

In developing their recommendations for permissible exposure limits, Dukes-Dobos and Henschel used Walter's regression line to translate Lind's findings into WBGT. If Jensen's regression line is used instead of Walters, the recommended WBGT exposure limits would be somewhat different. The magnitude of this difference is small as the following table indicates.

	Metabolic Rate		
	Low	Medium	High
Walters' conversion	85.67	79.61	75.75
Jensen's conversion	87.13	80.11	75.63
Difference in °F WBGT	-1.46	-0.50	0.12

Table 4. The ULPZ in °F WBGT as computed from Walters' and Jensen's regression lines for WBGT = f (CET).

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APPENDIX

Several of the correlations reported in the text were based on sample of data sets rather than on the entire data base. In the correlations in which CET was involved, the sample was used in order to reduce the manual burden of reading the CET from a nomograph. In order to evaluate the representativeness of our sample, two comparisons were made. First, Tables A-1 and A-2 were prepared showing the mean, standard deviation, and range of the various climatic parameters in the total prepared for these same climatic parameters in order to see if the form of our sample distribution took the same shape as that of the total data base. Two representative pairs of histograms are included in this Appendix. The first pair of histograms (Tables A-3 and A-4) show the natural dry bulb temperatures measured inside the plants. The histogram on A-3 shows all the data whereas A-4 shows the sample data base. The second pair of histograms (Tables A-5 and A-6) show globe temperatures measured outside the plants. The histogram on A-5 shows all the data whereas A-6 shows only the sample data base.

Tables A-1 and A-2 indicate that the means and standard deviations for the various parameters are quite similar in the sample and the total data base. Of course, the range of the sample is narrower than that of the total population because the sample does not include many of the extreme values. A comparison of the pairs of histograms indicated that the sample data base provided us with a sample which is also representative in terms of form of distribution.

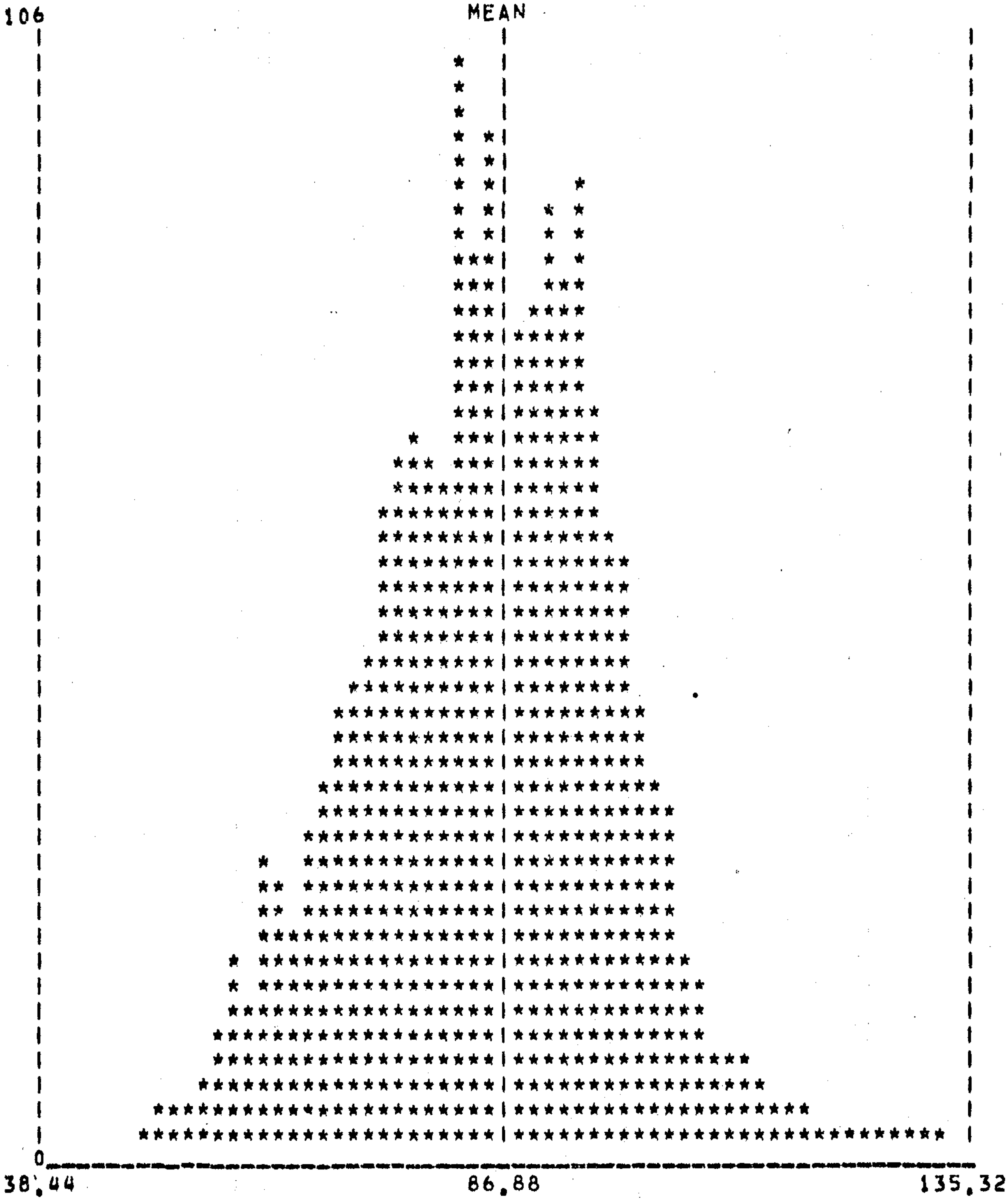
TABLE A 1

VARIABLE	1818 SETS OF MEASUREMENTS FROM WORKSITES WITHIN PLANT				200 RANDOMLY SELECTED SETS			
	MEAN	STD. DEV.	RANGE		MEAN	STD. DEV.	RANGE	
			LOW	HIGH			LOW	HIGH
NBF ($^{\circ}$F)	86.9	13.6	50.3	135.3	85.8	13.5	51.8	124.5
NWB ($^{\circ}$F)	69.8	9.2	44.8	97.0	68.8	9.4	45.5	97.0
GT ($^{\circ}$F)	92.9	17.0	53.2	158.9 207.68	92.2	16.0	54.4	158.9
VDB ($^{\circ}$F)	85.0	12.2	52.0	115.7	84.2	12.1	53.4	113.0
VWB ($^{\circ}$F)	68.0	8.7	46.0	90.5	67.1	8.8	46.0	82.4
WS (f/m)	91.2	86.2	20.0	1400.0	87.6	64.3	20.0	530.0
HUM (mmHg)	13.3	5.2	2.1	32.7	12.8	5.3	2.8	25.1
MRT ($^{\circ}$F)	100.6	23.2	34.0	250.0	100.5	21.3	55.0	188.0
CET ($^{\circ}$F)					77.2	8.0	52.7	95.5

TABLE A 2

VARIABLE	2905 SETS OF MEASUREMENTS FROM OUTSIDE OF PLANTS				178 RANDOMLY SELECTED SETS			
	MEAN	STD. DEV.	RANGE		MEAN	STD. DEV.	RANGE	
			LOW	HIGH			LOW	HIGH
DB(°F)	71.6	14.5	34.9	113.5	73.9	12.9	44.Ø	113.Ø
NWB(°F)	61.8	11.Ø	32.Ø	85.8	63.5	9.6	37.9	81.9
GT(°F)	76.1	19.7	32.Ø	136.Ø	78.5	18.4	4Ø.2	134.2
VWB(°F)	6Ø.8	11.Ø	32.Ø	8Ø.2	62.5	9.5	35.8	77.Ø
WS(f/m)	6Ø1.5	342.7	Ø.Ø	2376.Ø	577.6	315.6	Ø.Ø	14Ø8.Ø
HUM(mmHg)	11.6	5.7	Ø.7	24.9	12.Ø	5.5	1.4	23.5
MRT(°F)	89.4	44.2	2.Ø	258.Ø	92.4	41.6	32.Ø	192.Ø
CET(°F)					63.8	13.2	32.Ø	88.Ø

MEAN NDB: 86.8779
STANDARD DEVIATION: 13.5628
RANGE(DG F): 50.36 <= NDB <= 135.32
TOTAL OF 1818 OBSERVATIONS



MEAN NDB: 85.8238
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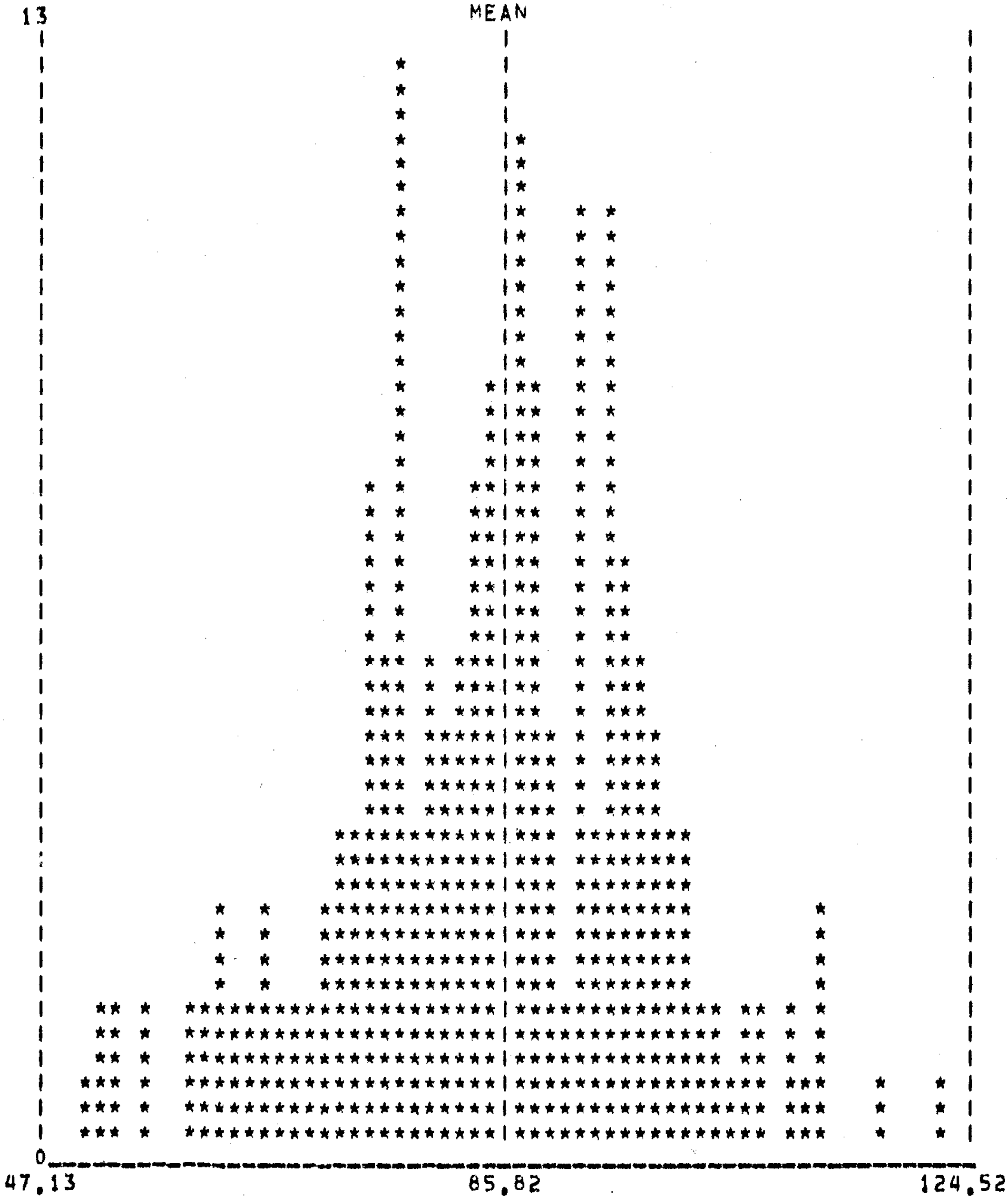
RANGE(DG F): 51.80 <= NDB <= 124.52
TOTAL OF 200 OBSERVATIONS



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RANGE(DG F): 32.00 <= GT <= 136.04
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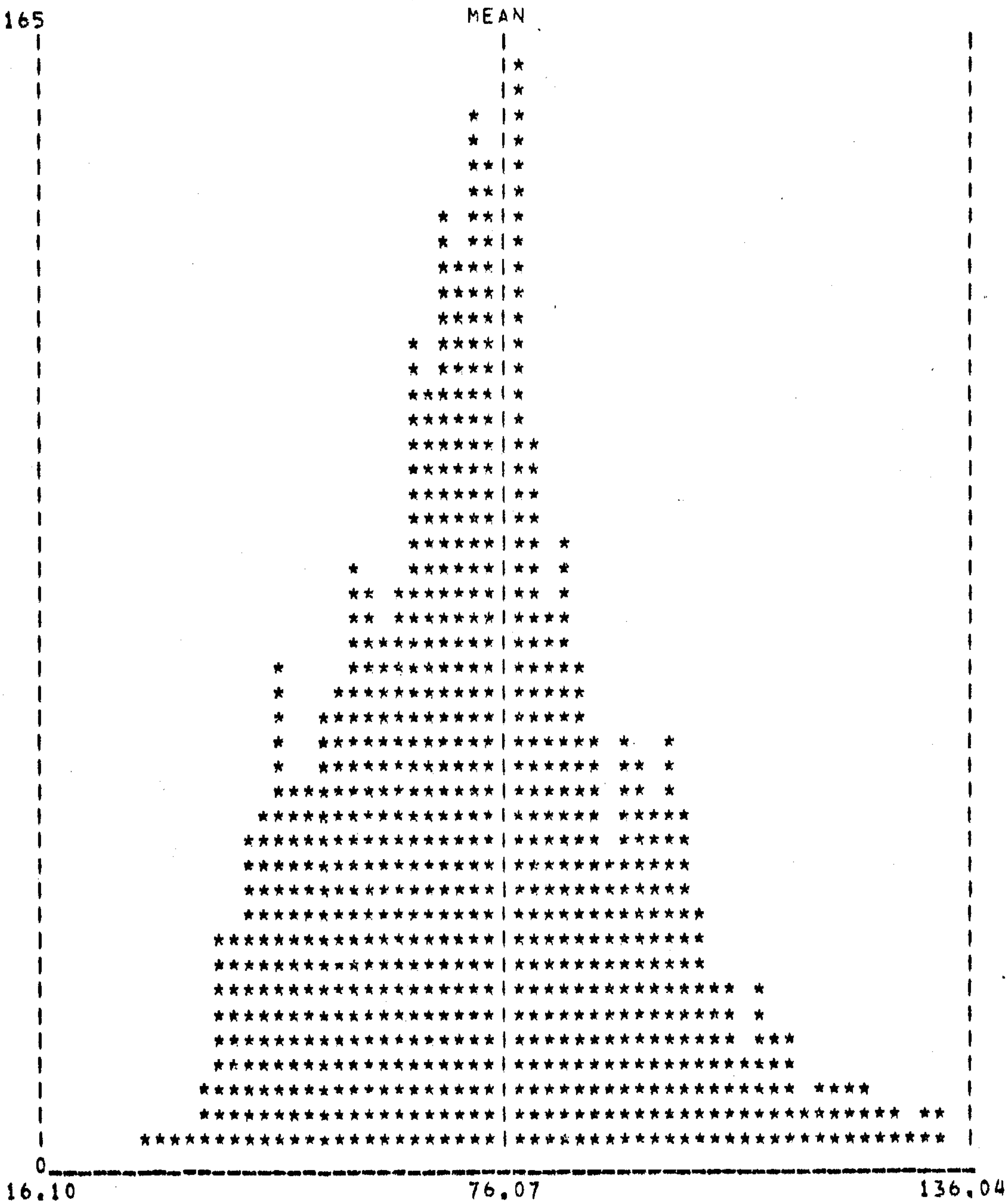

MEAN GT: 78.4610
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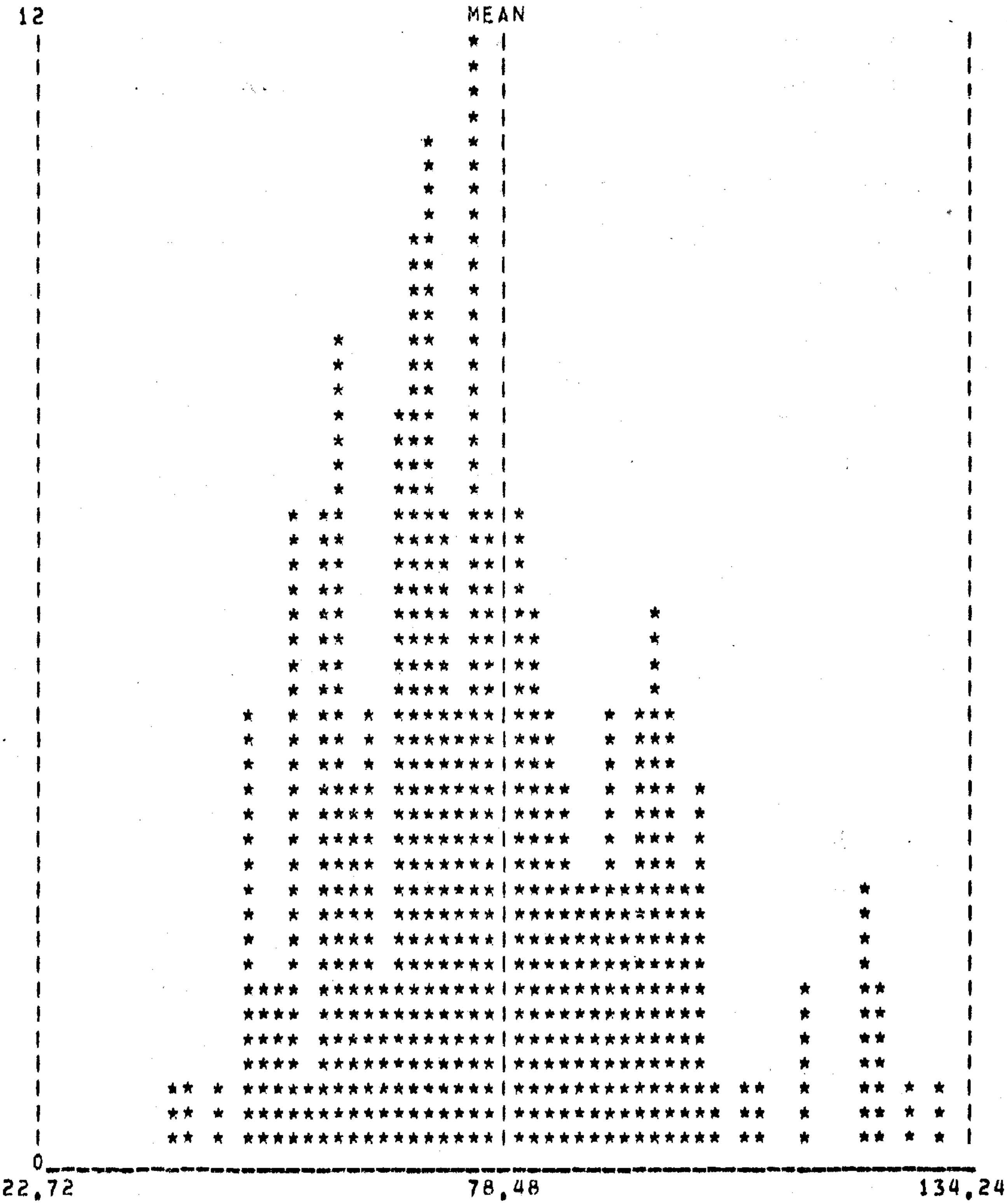
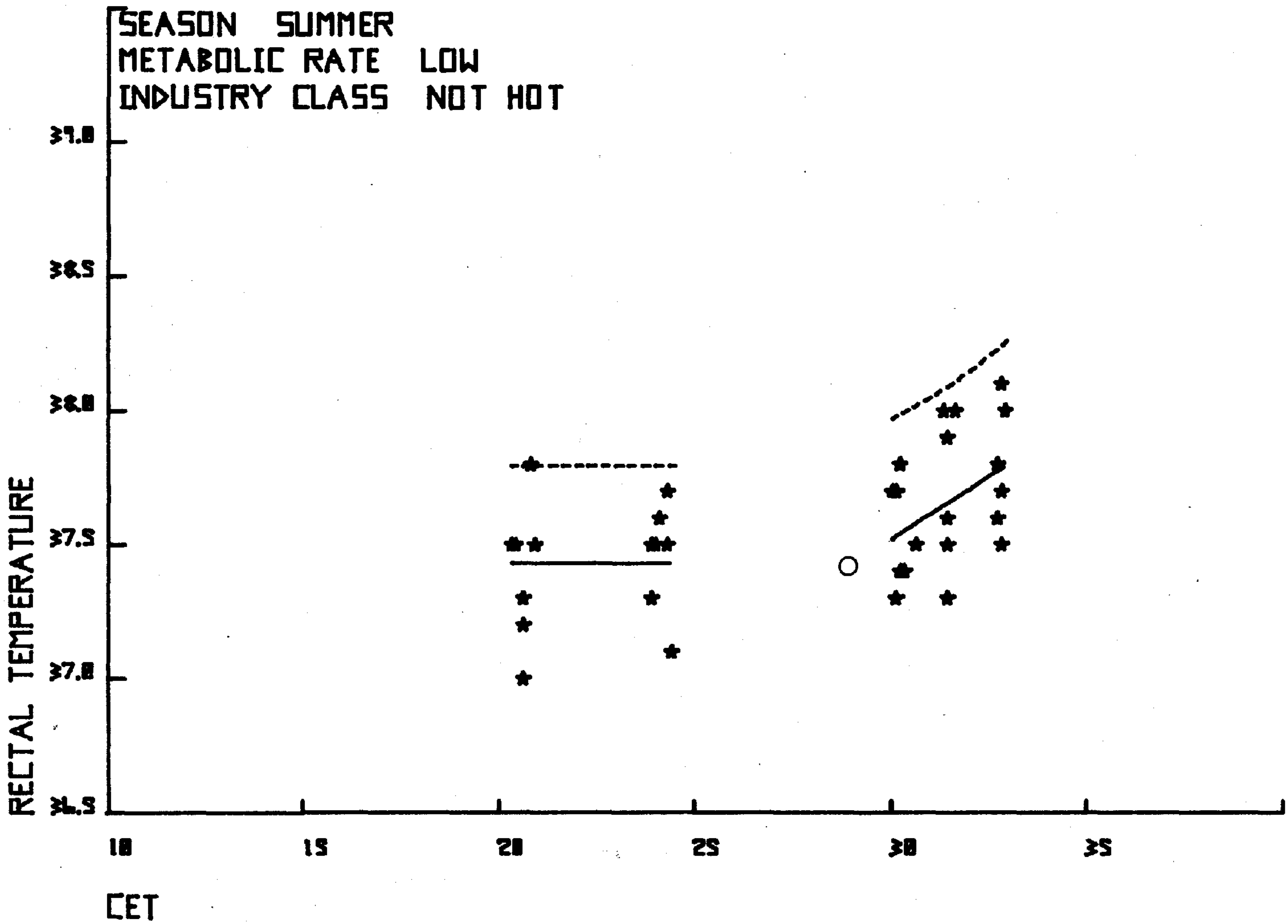
TOTAL OF 178 OBSERVATIONS



APPENDIX A

The following 96 graphs give the individual observations of rectal temperature and heart rate as a function of CET, WBGT, HSI and P4SR. The solid horizontal line is the mean of the observations below the expected ULPZ and the dotted horizontal line is the upper 90% confidence limit. The non-horizontal line is the regression line of the observations above the expected ULPZ. The non-horizontal dotted line is the upper 90% confidence limit for future expected values. The circle indicates the point where the two lines would intersect if they were extended.

Below is a page guide to the figures in Appendix A.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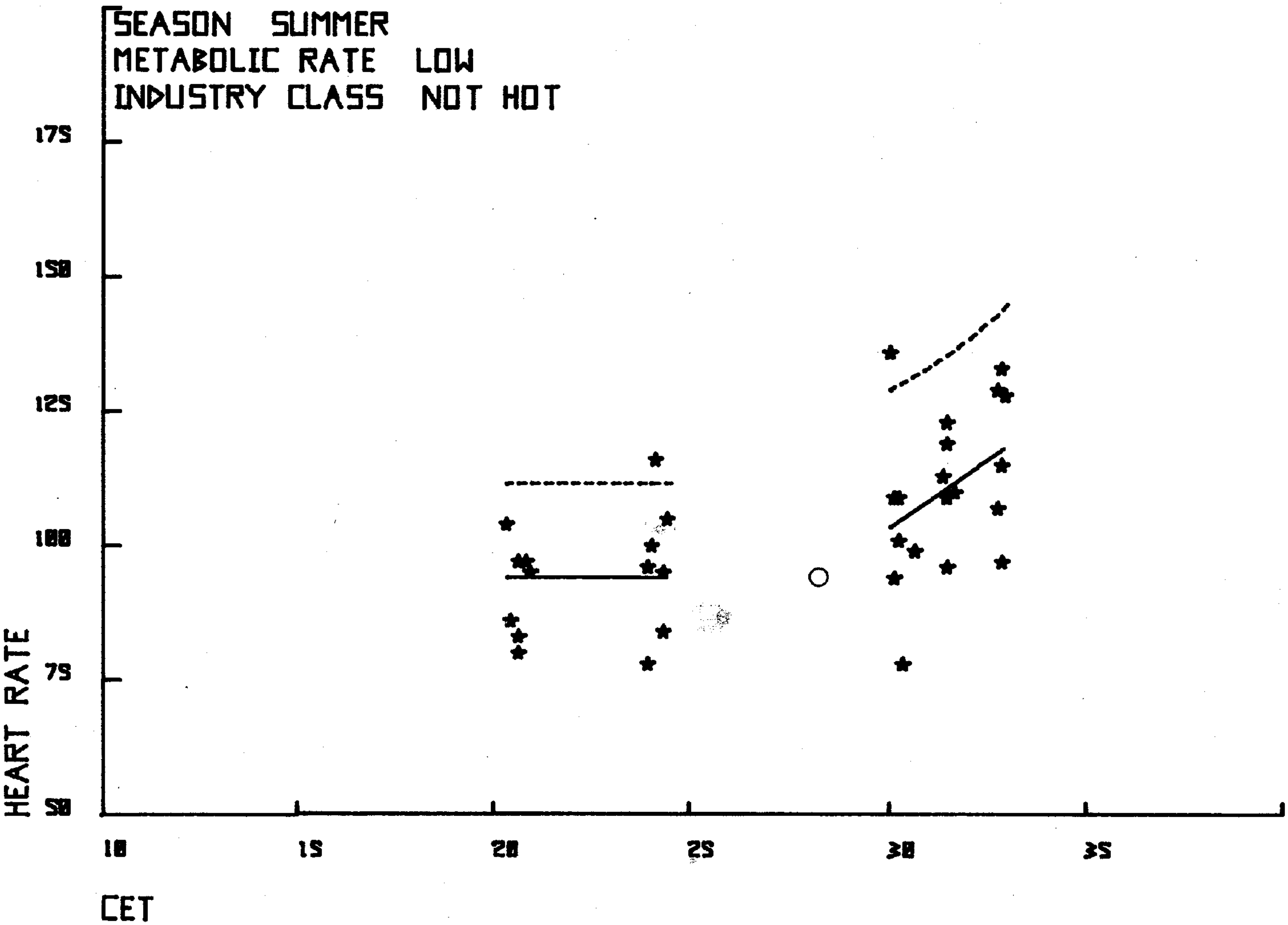
20
25
30
35
CET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75
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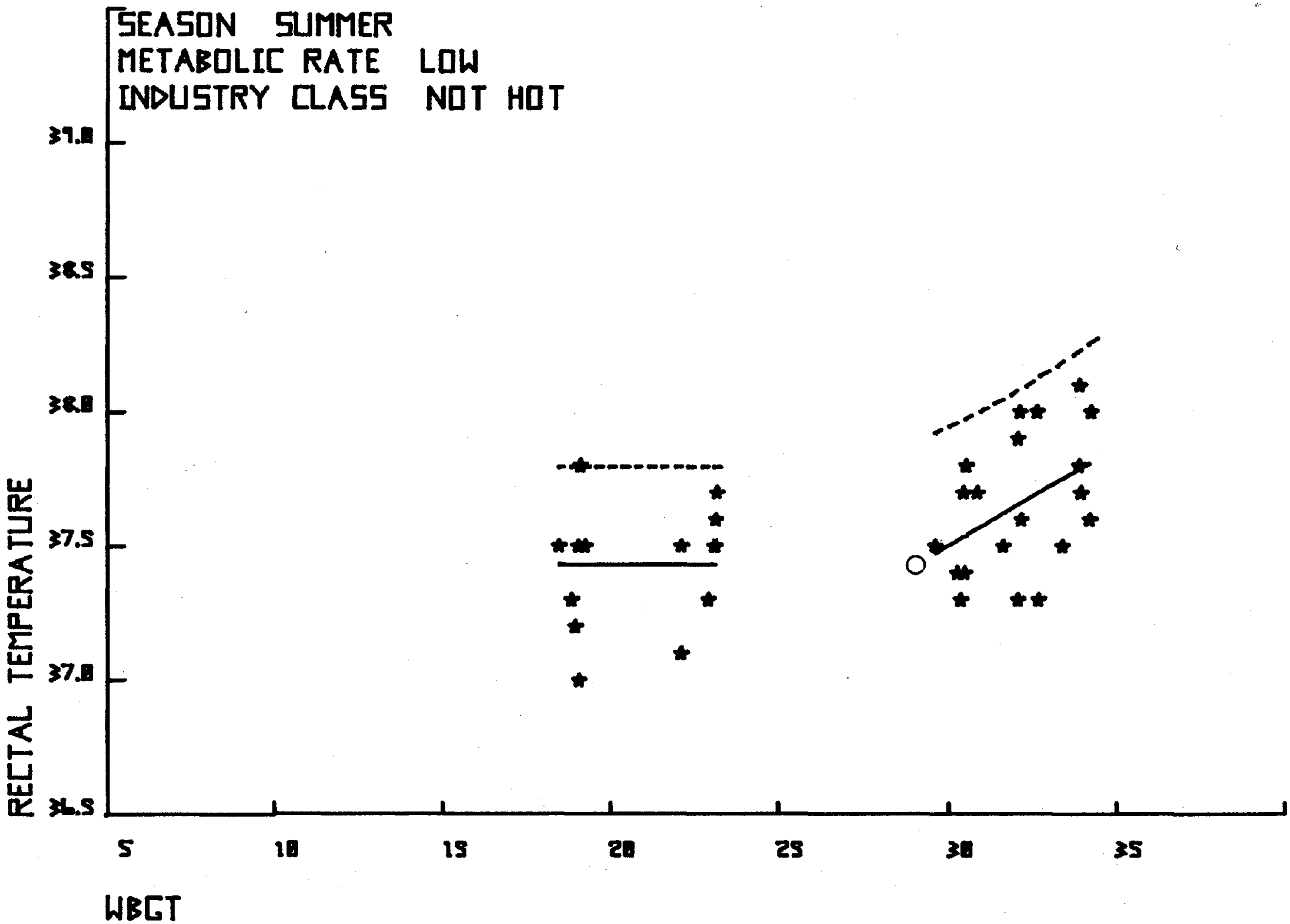
CET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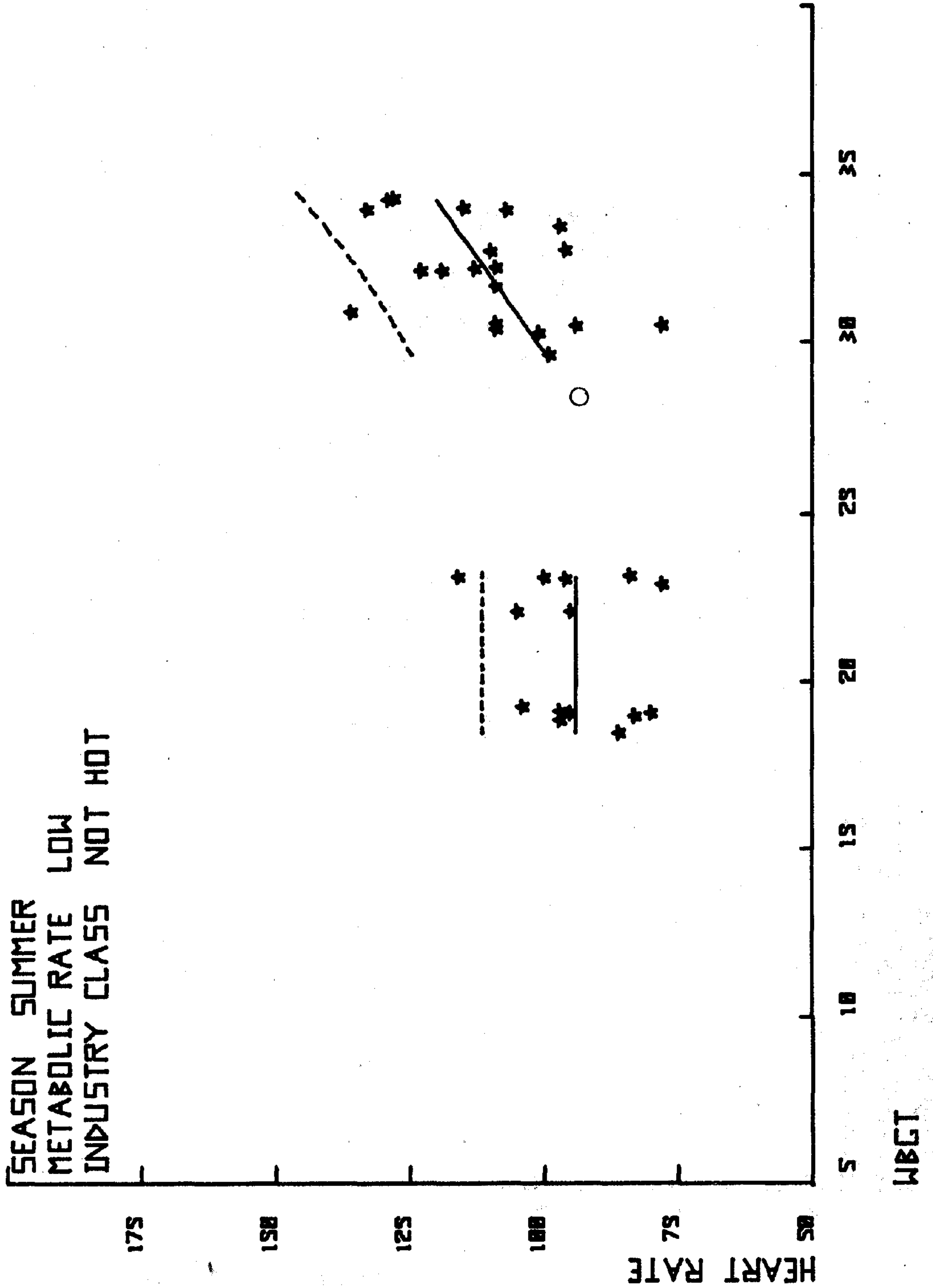
WBGT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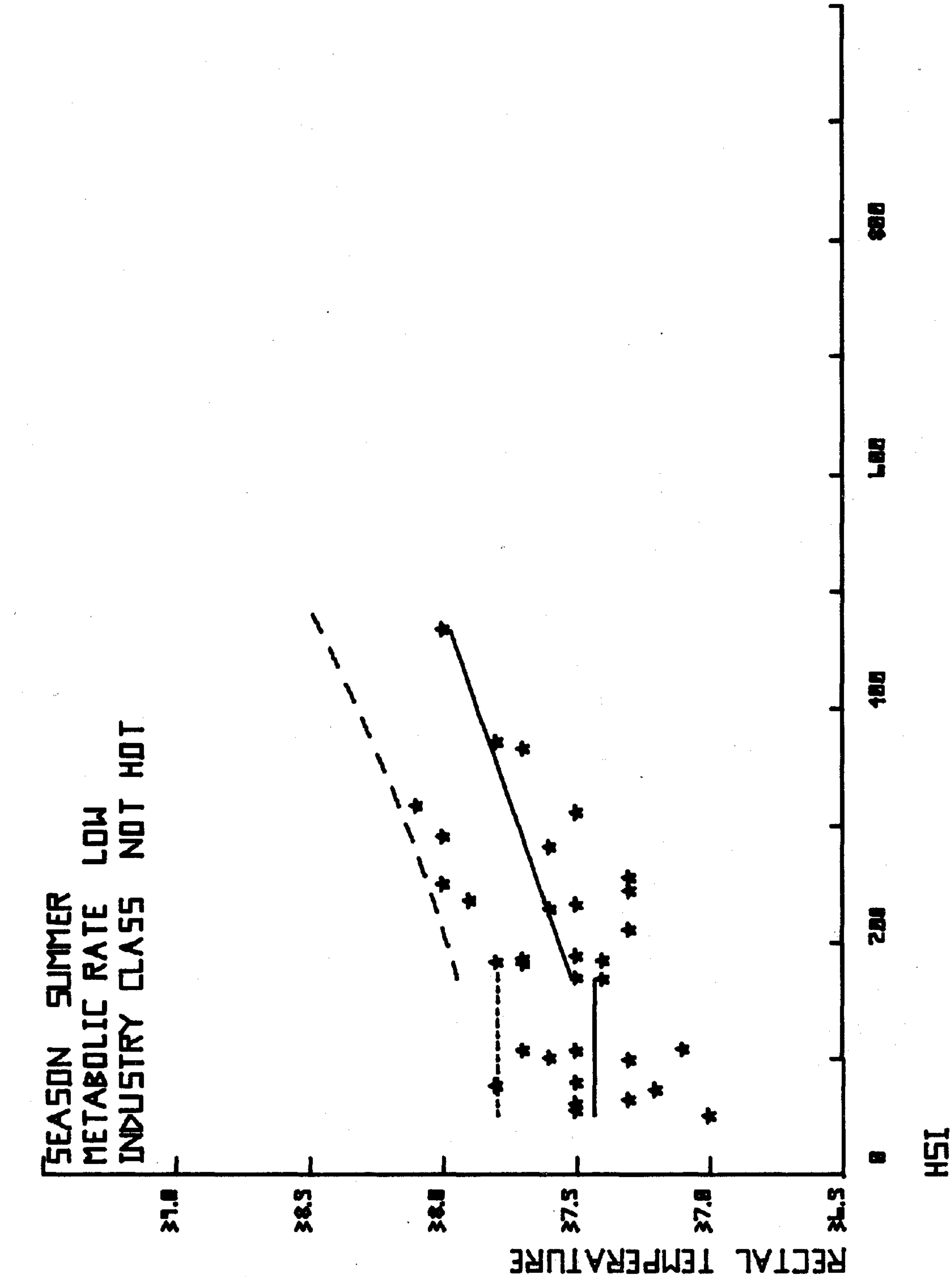
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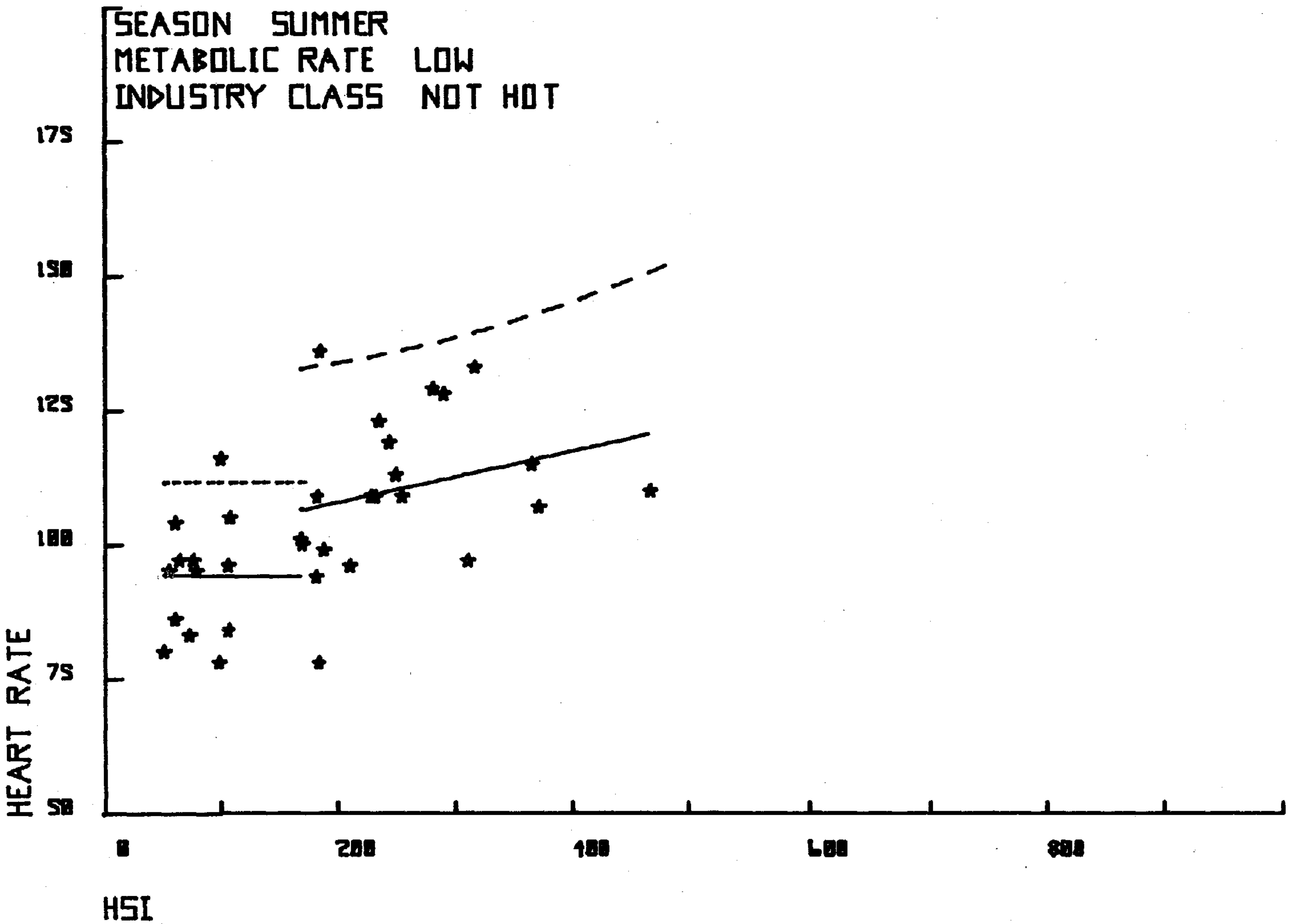
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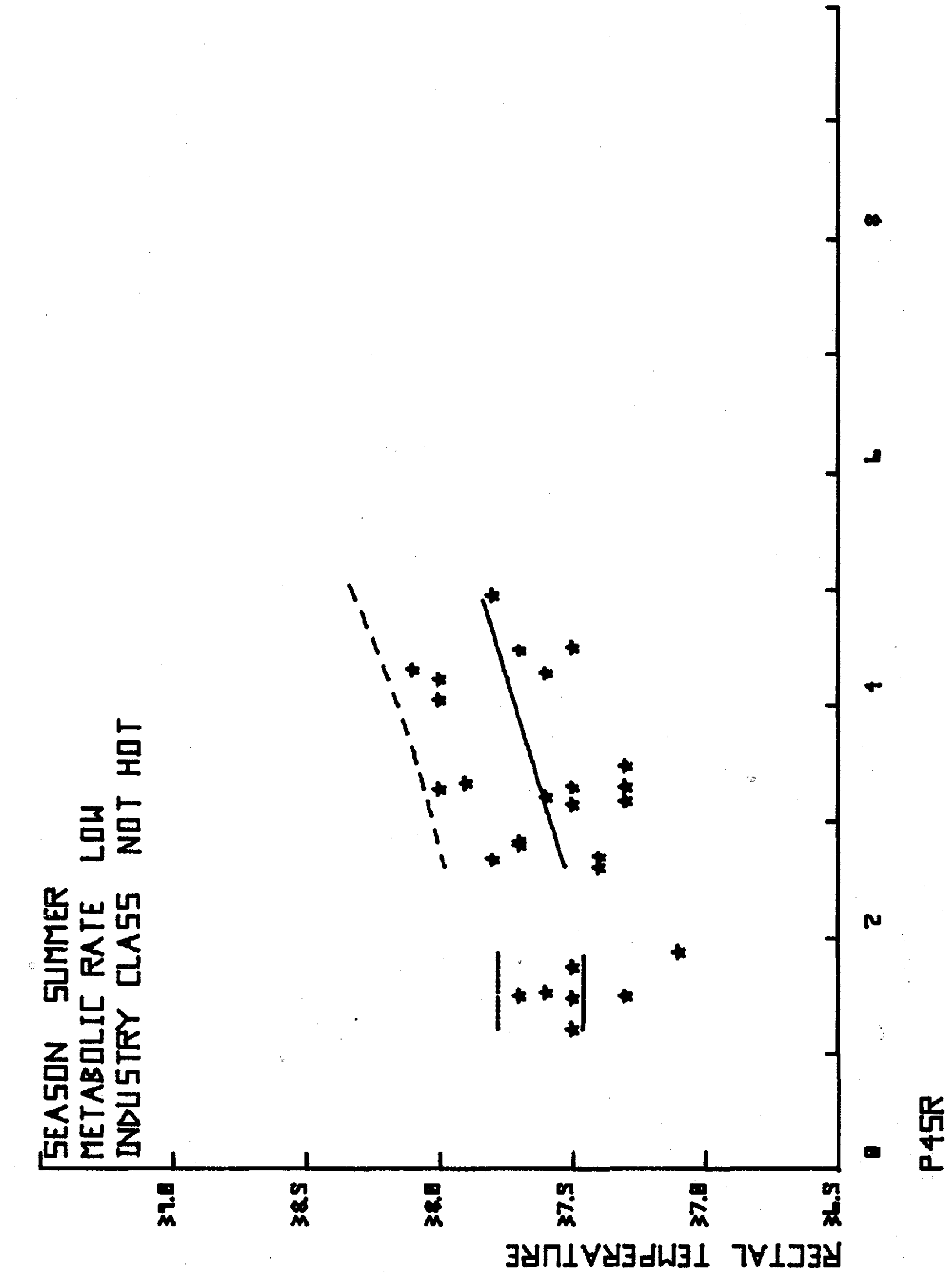
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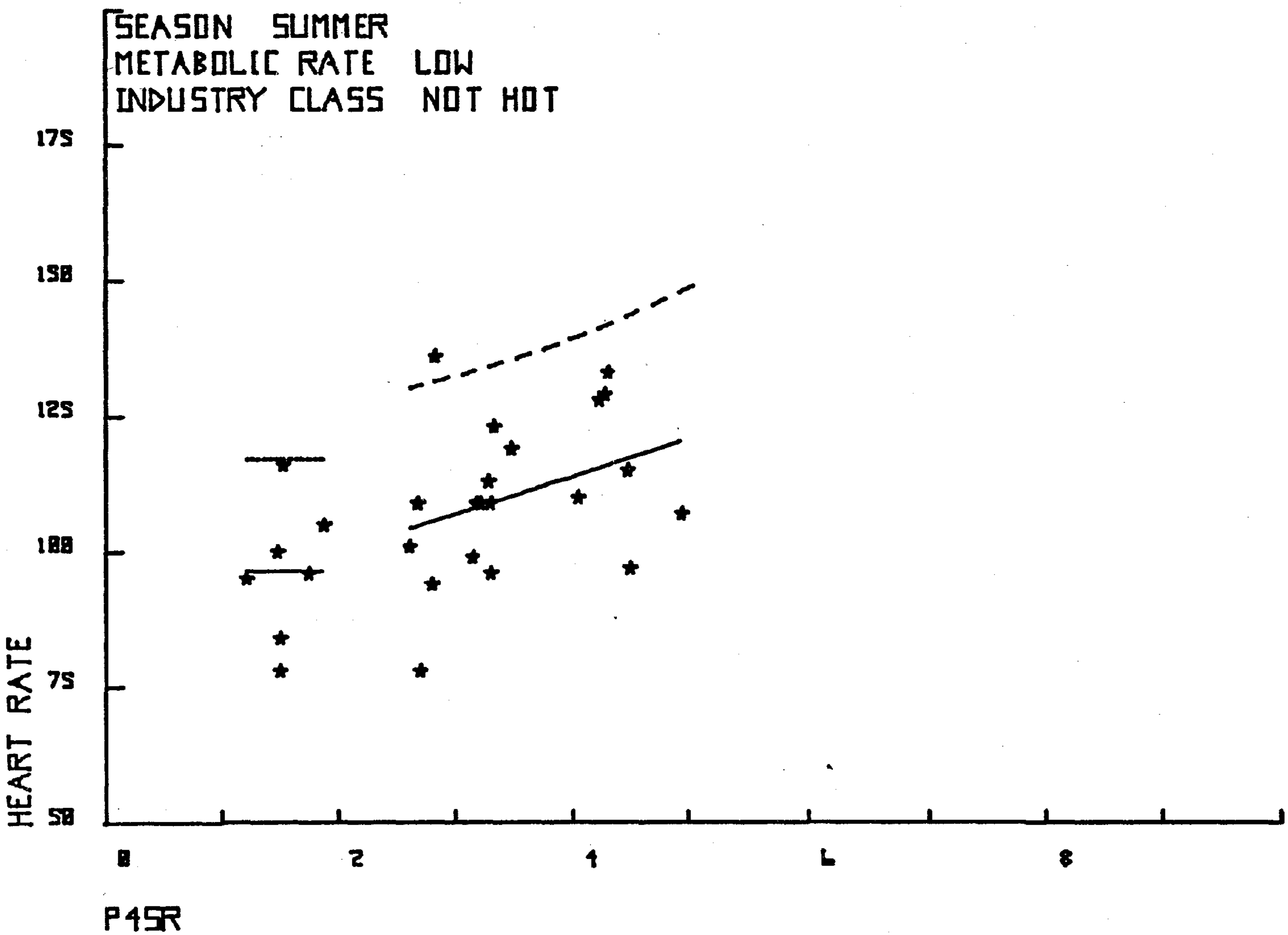
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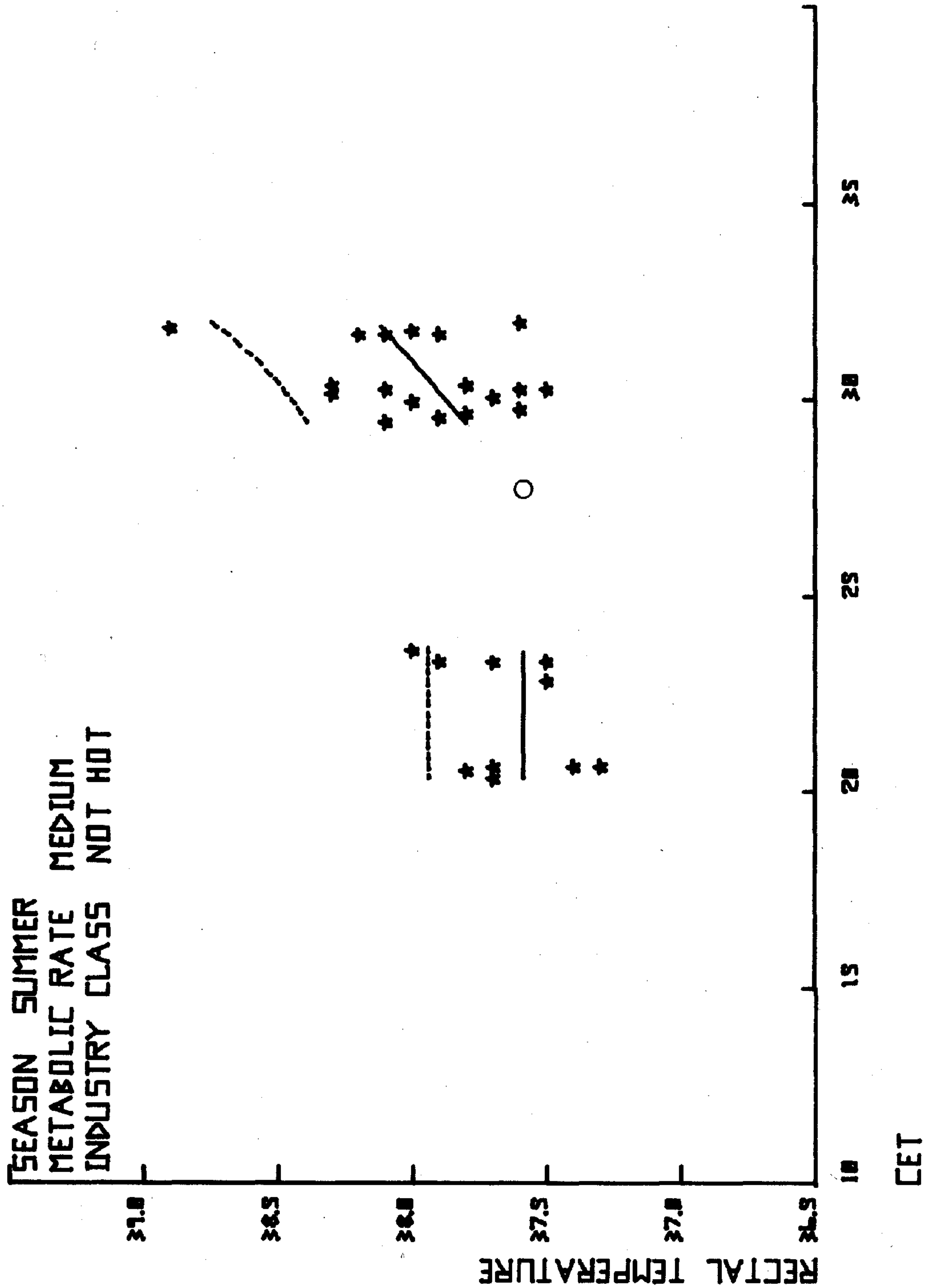

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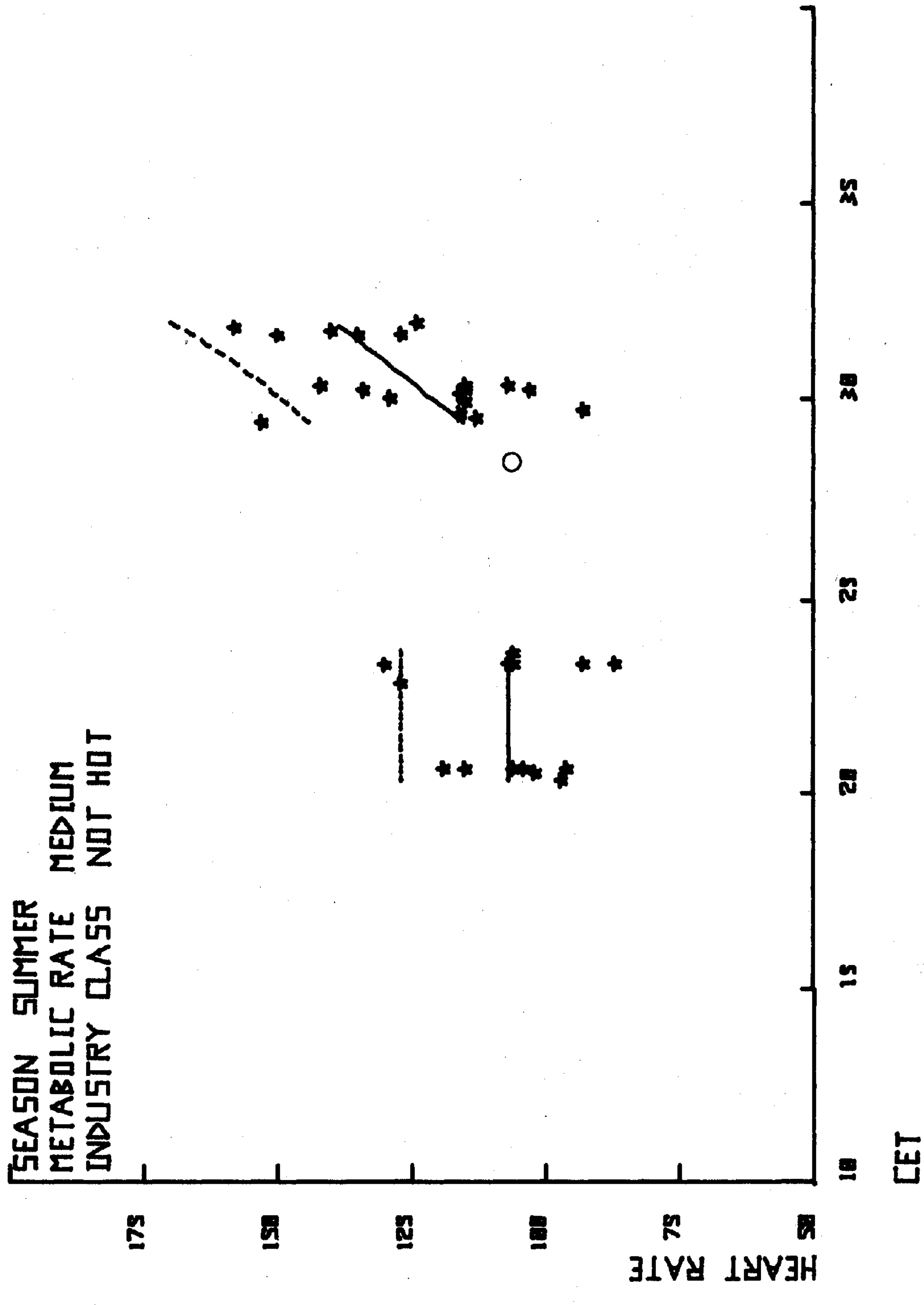
CET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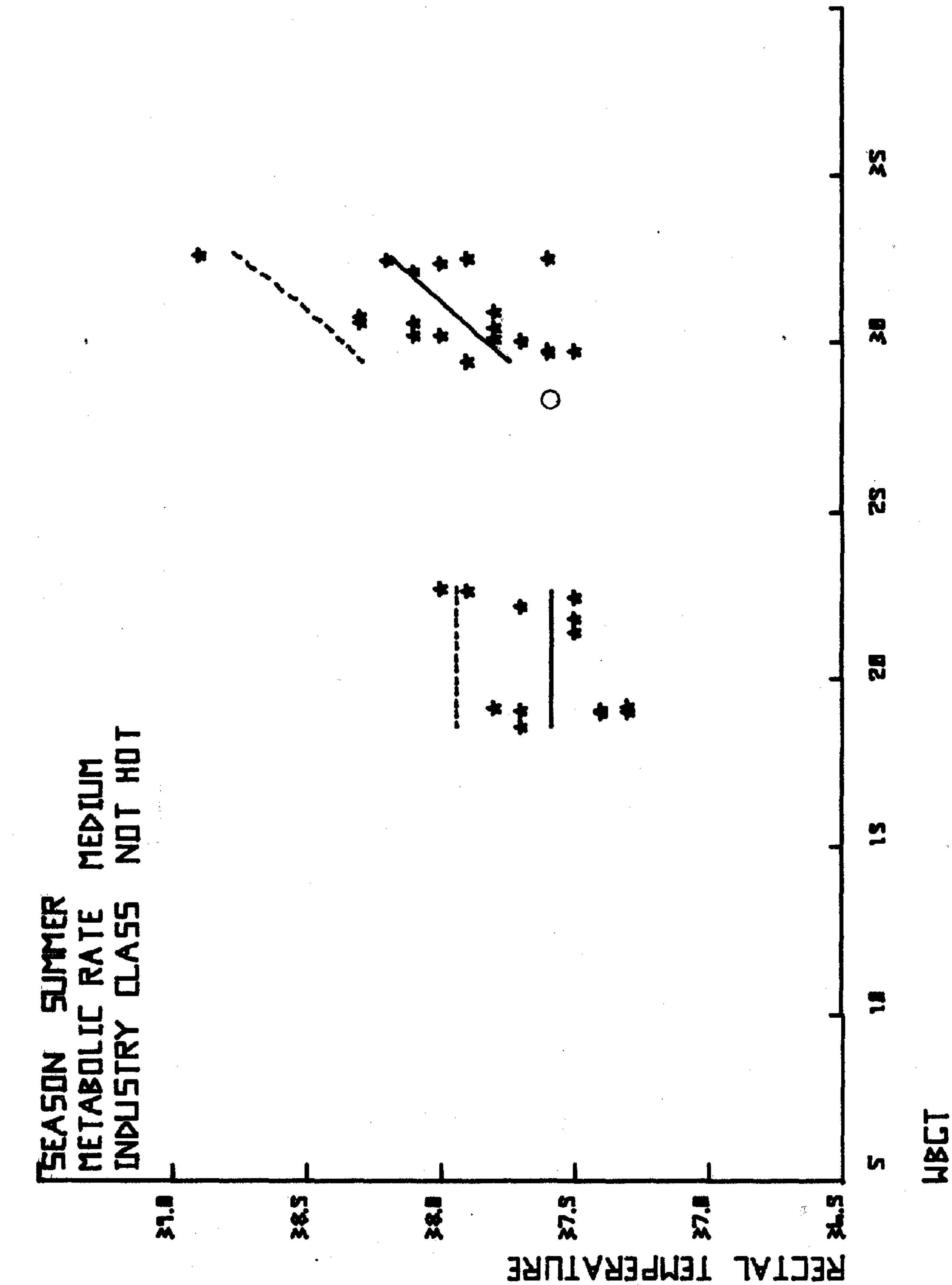
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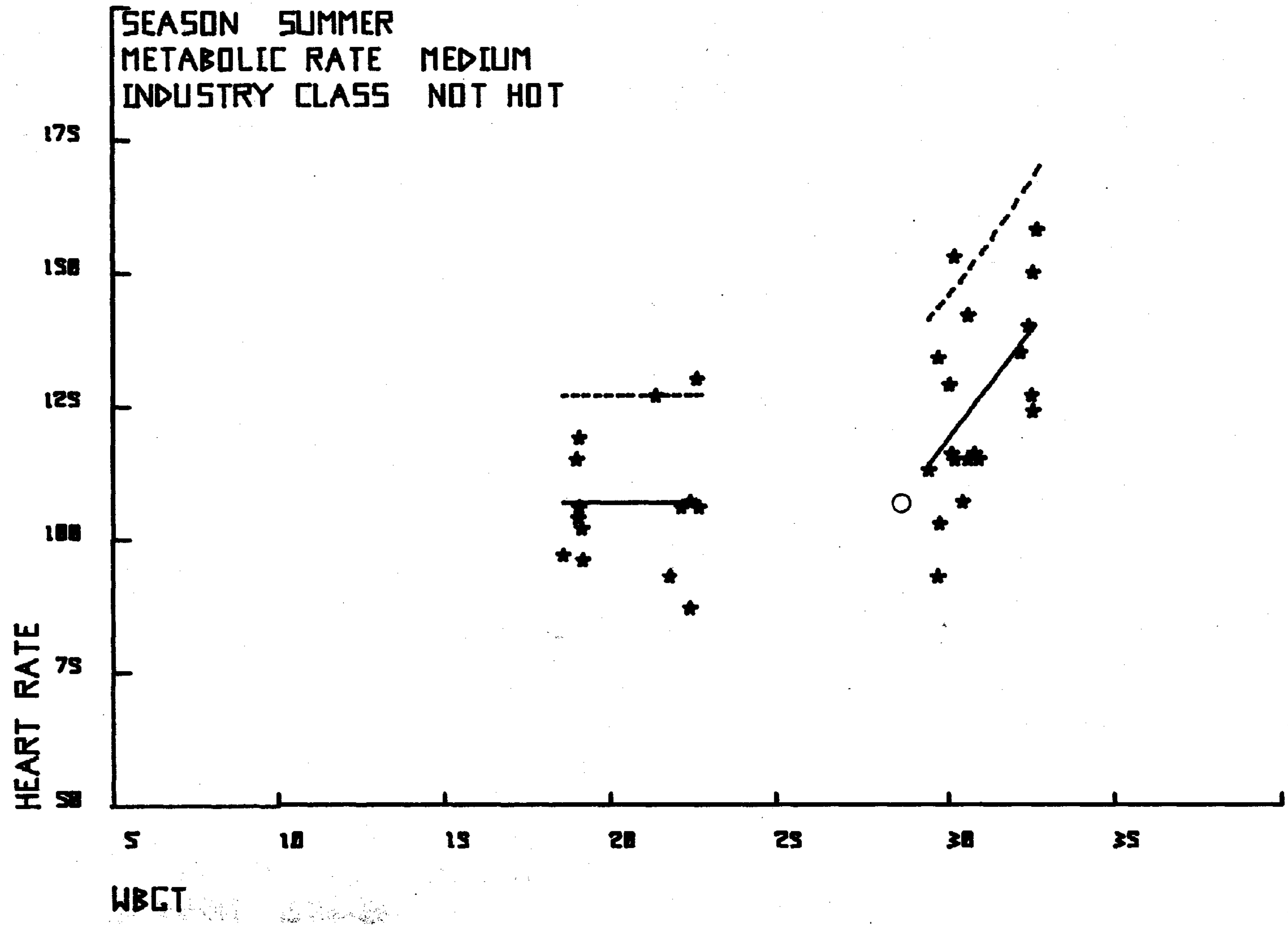
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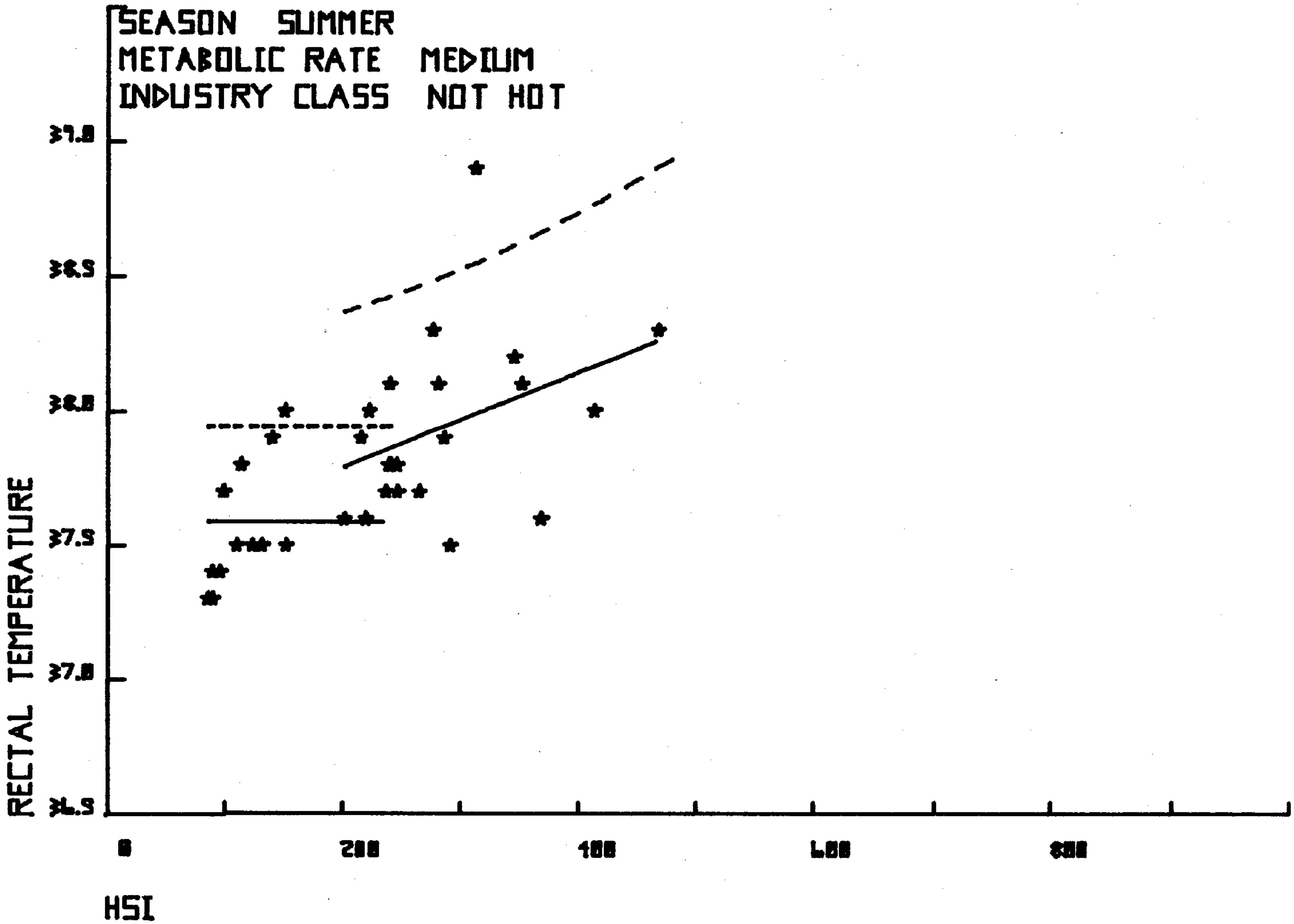
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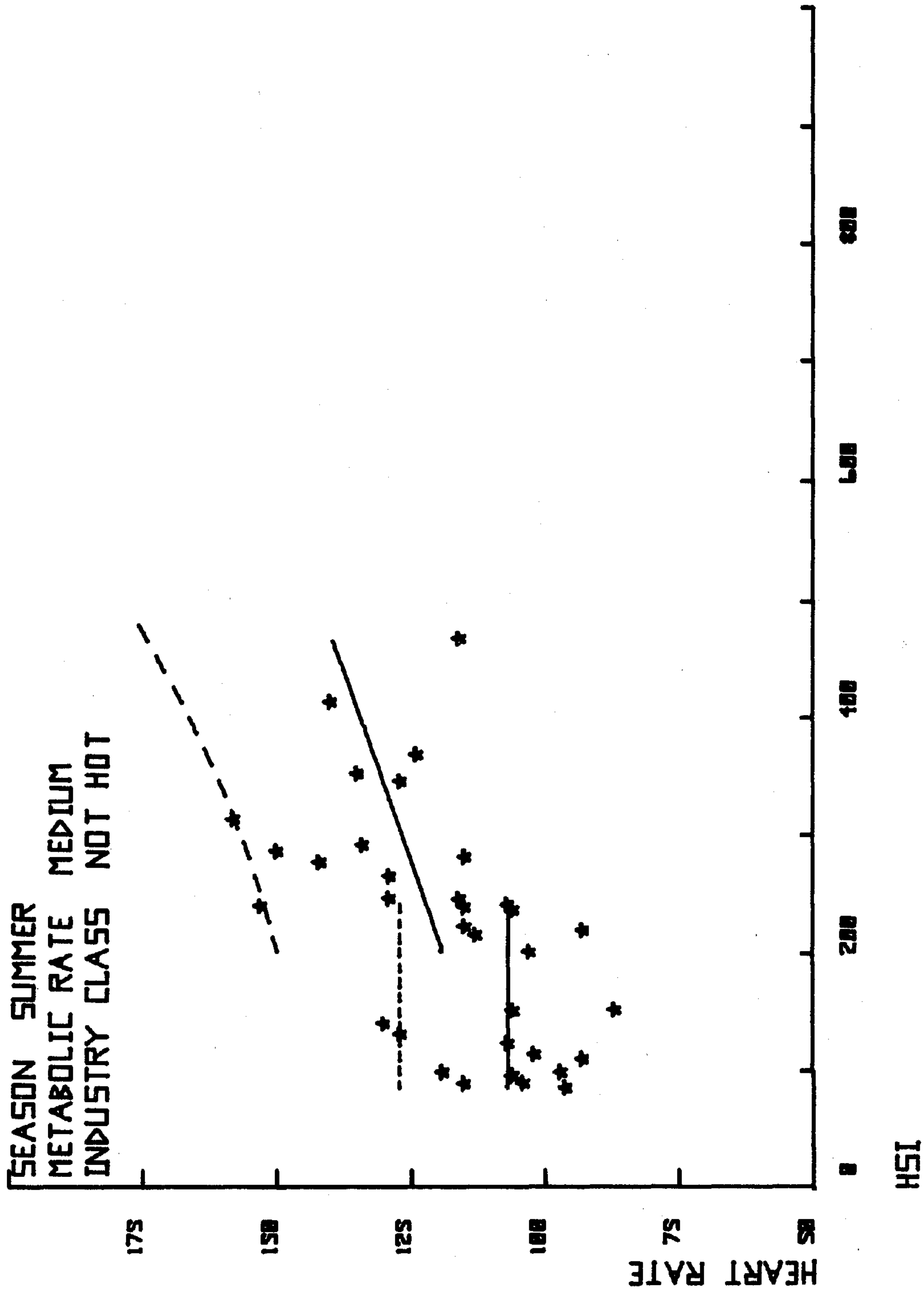
HSI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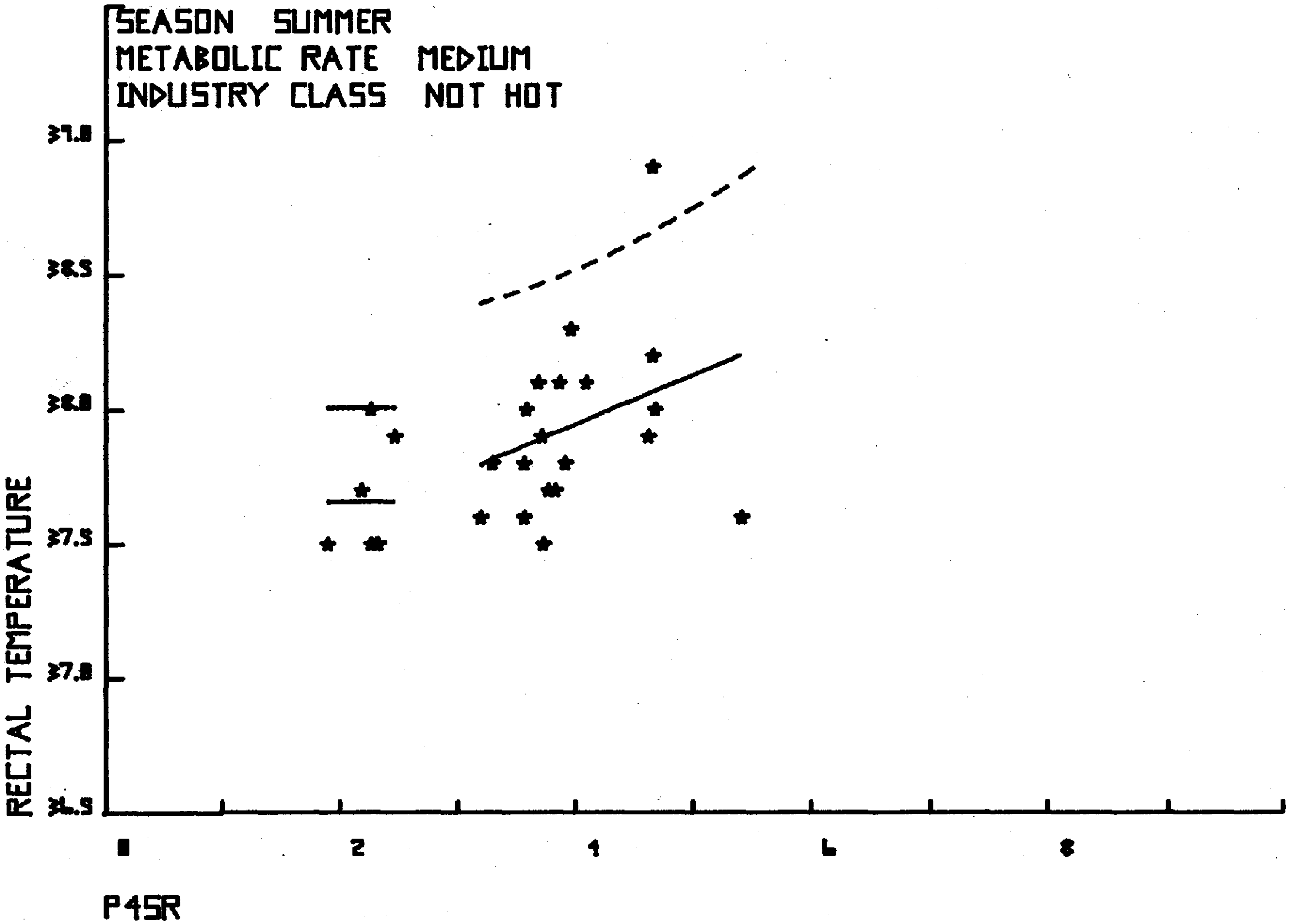
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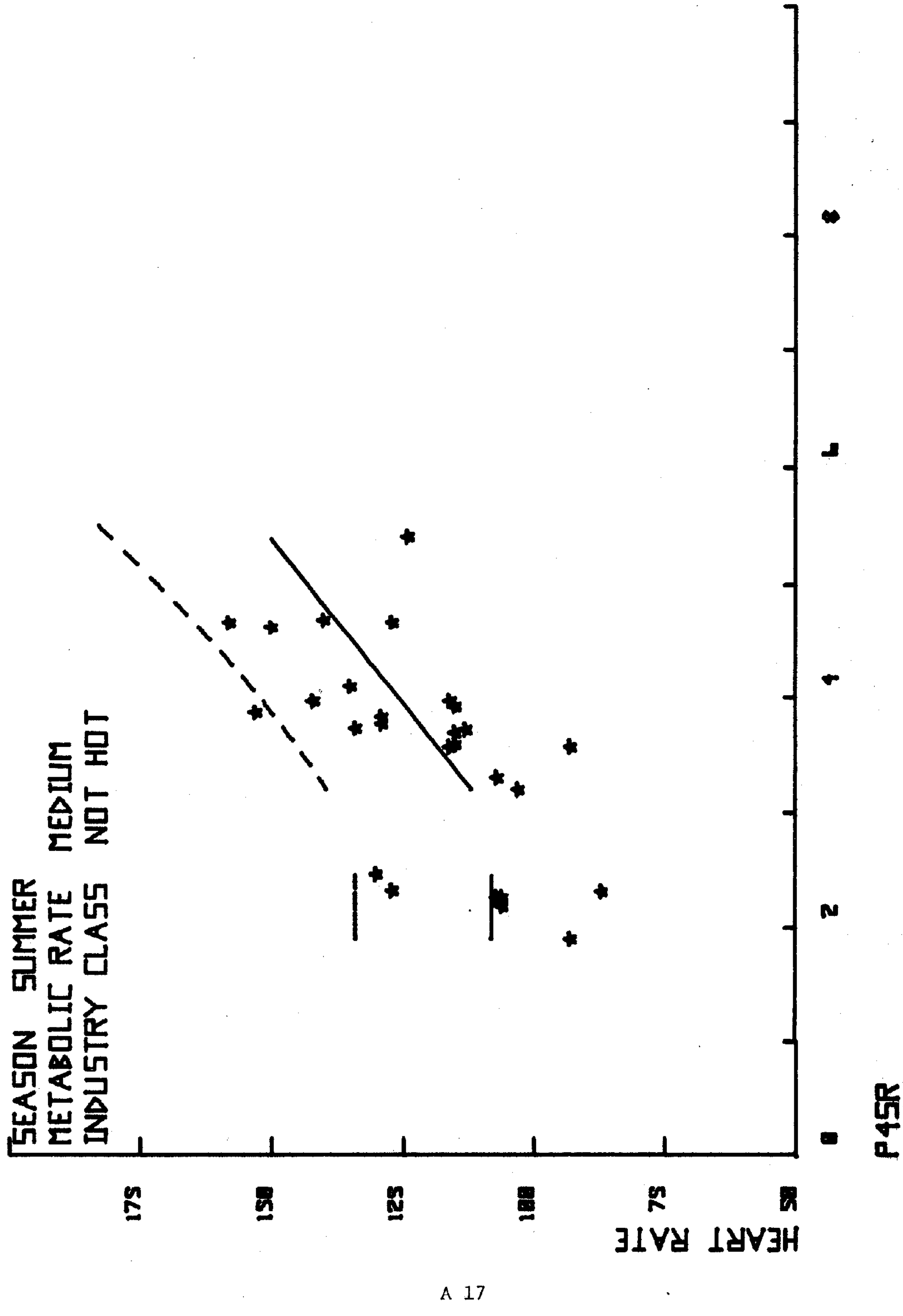
P4SR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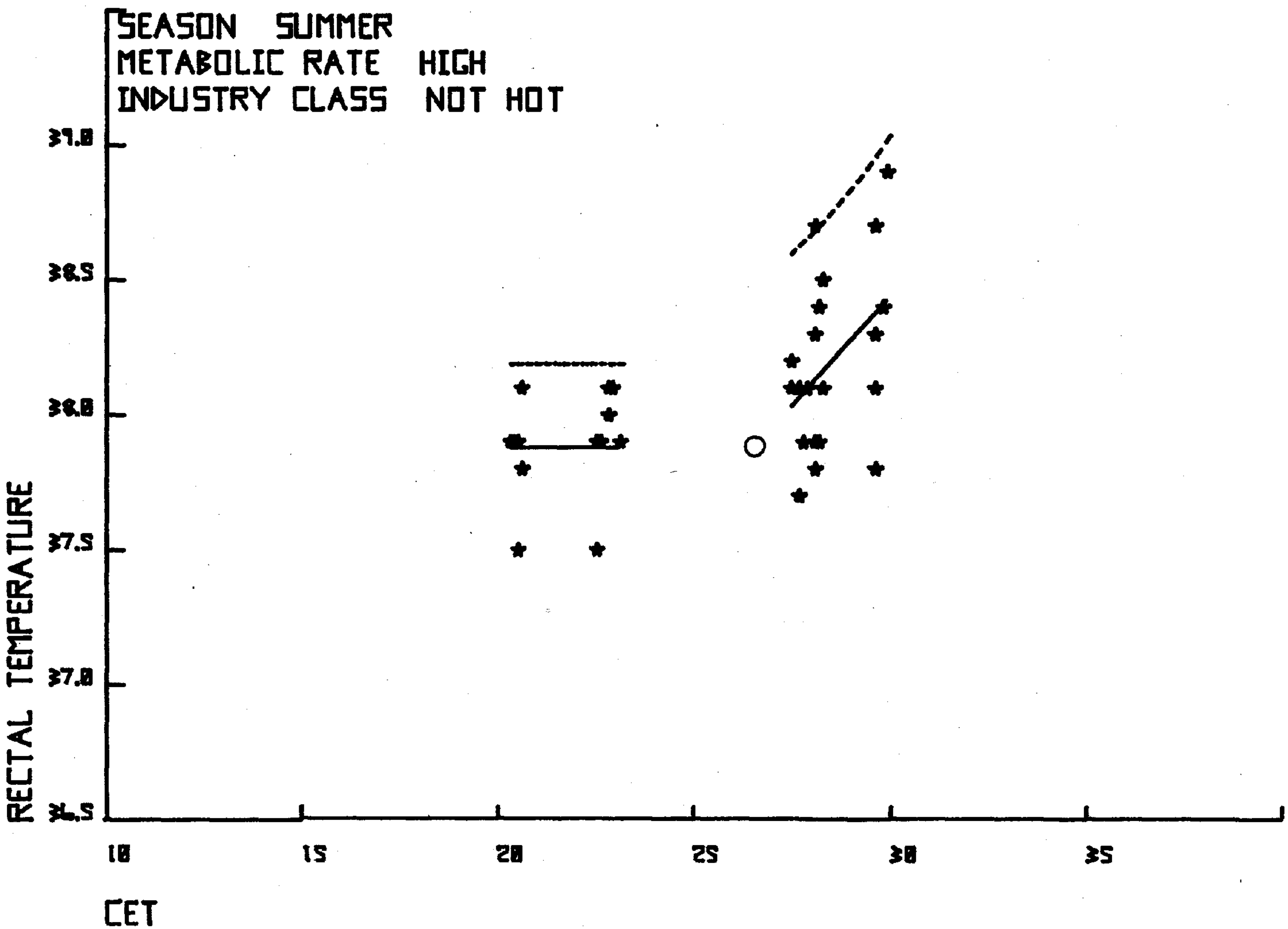
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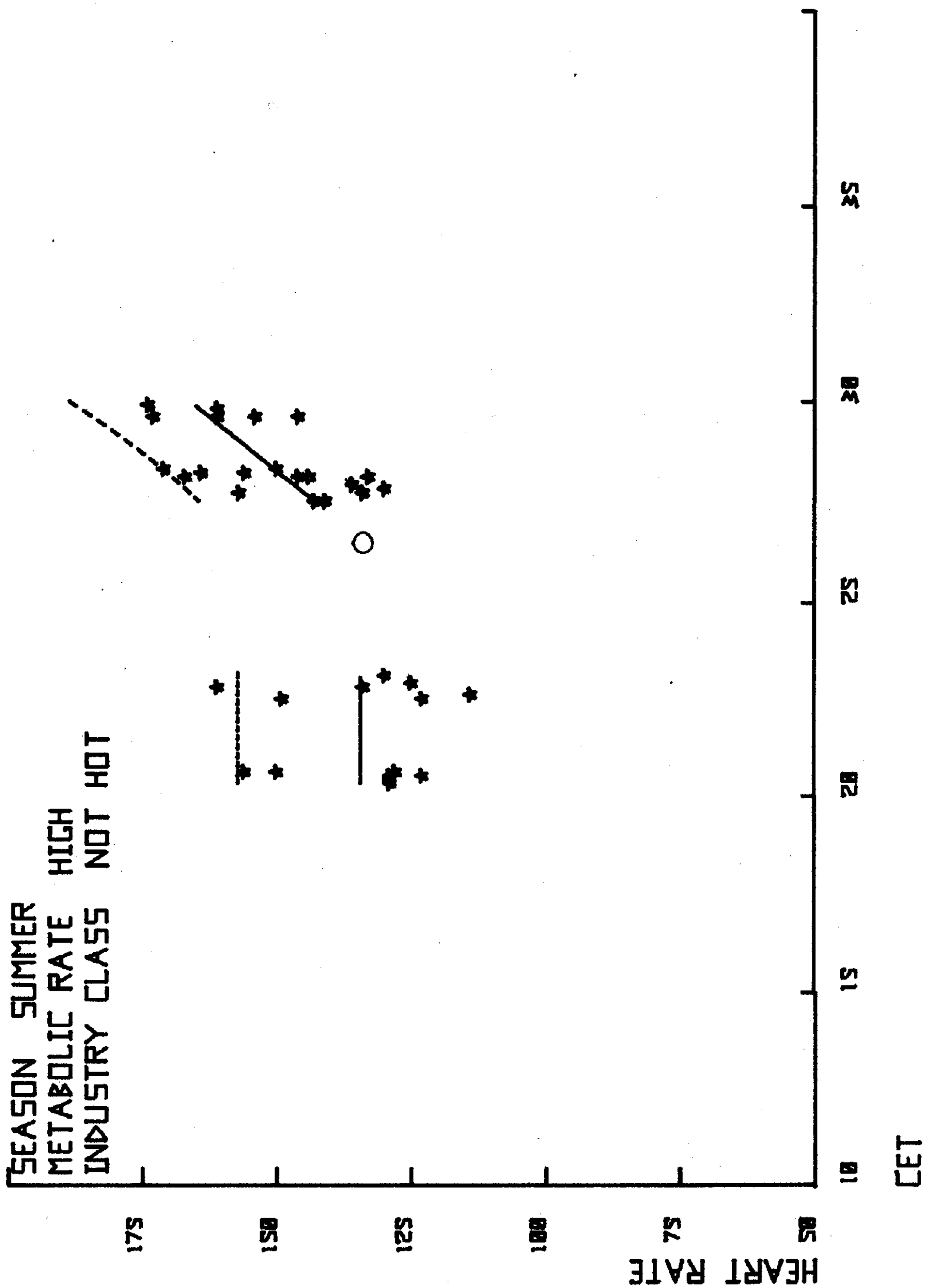
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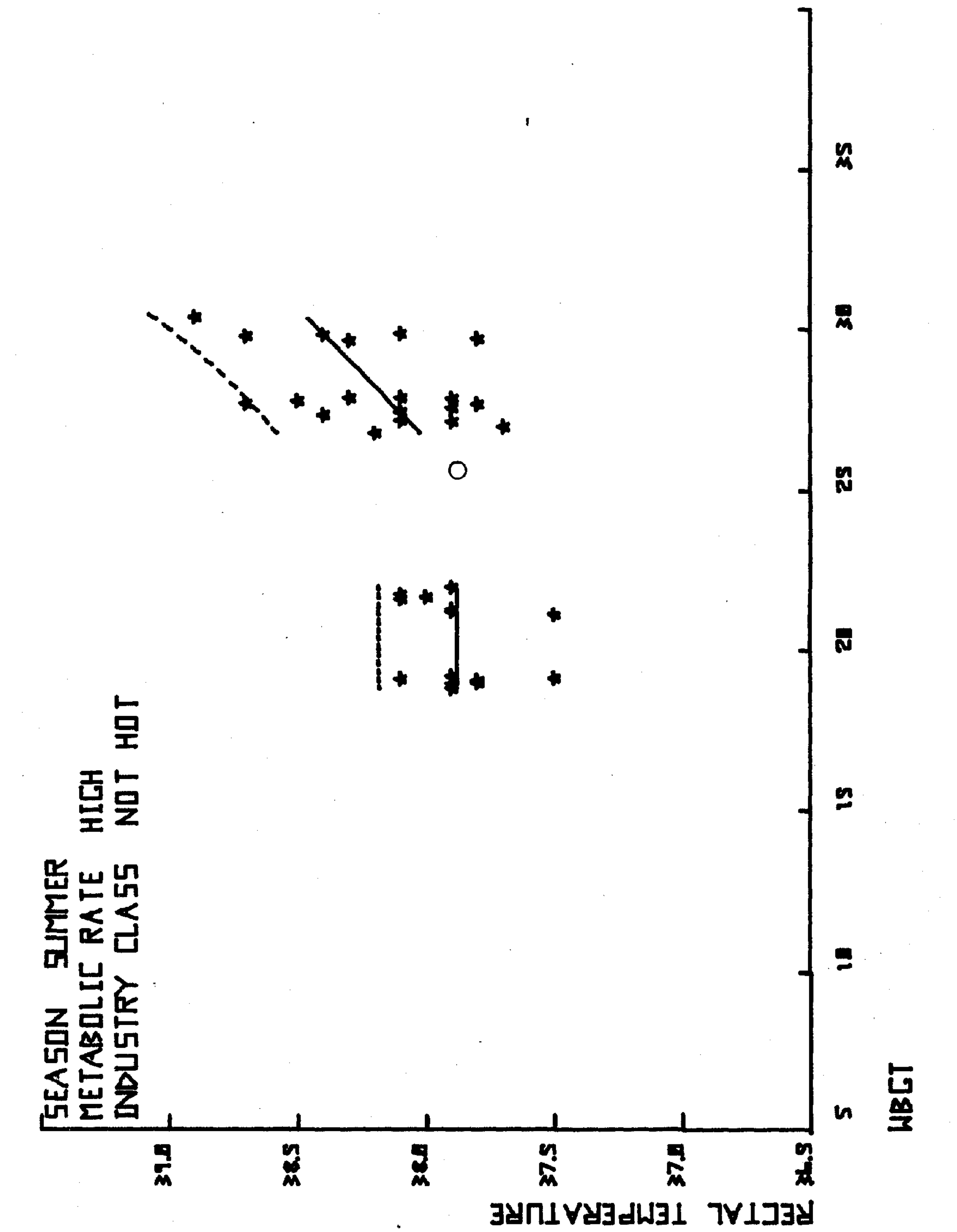
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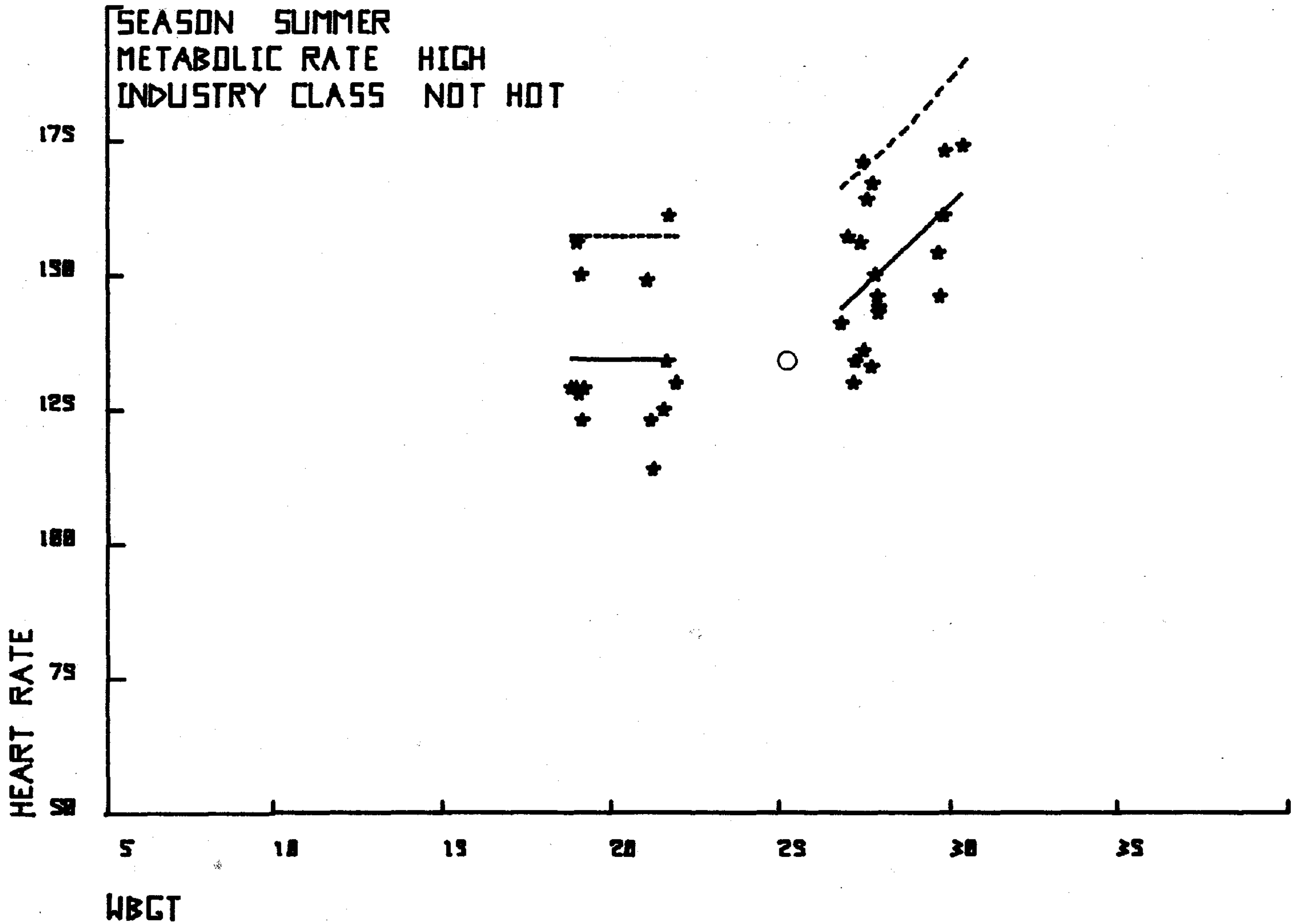
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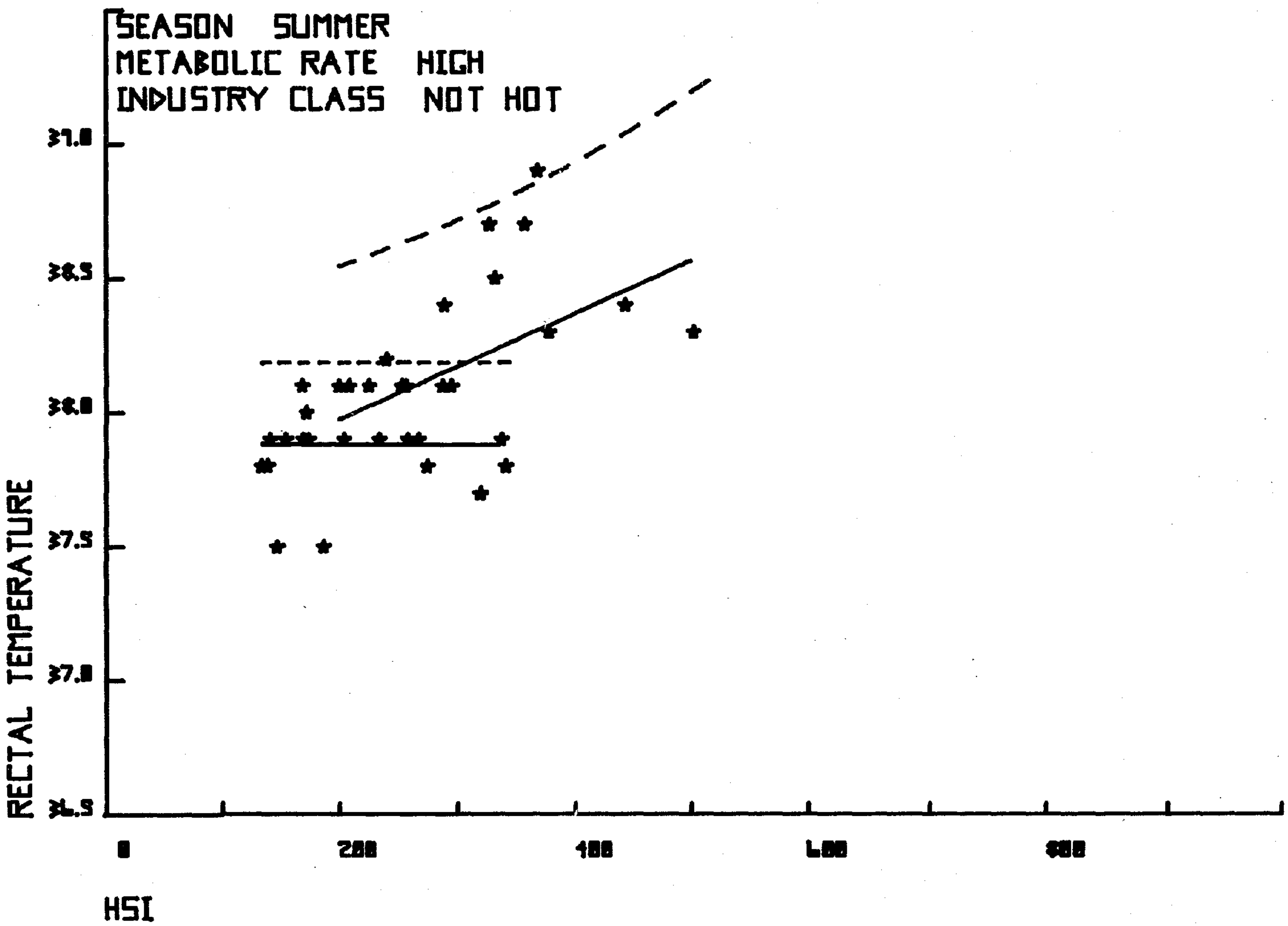
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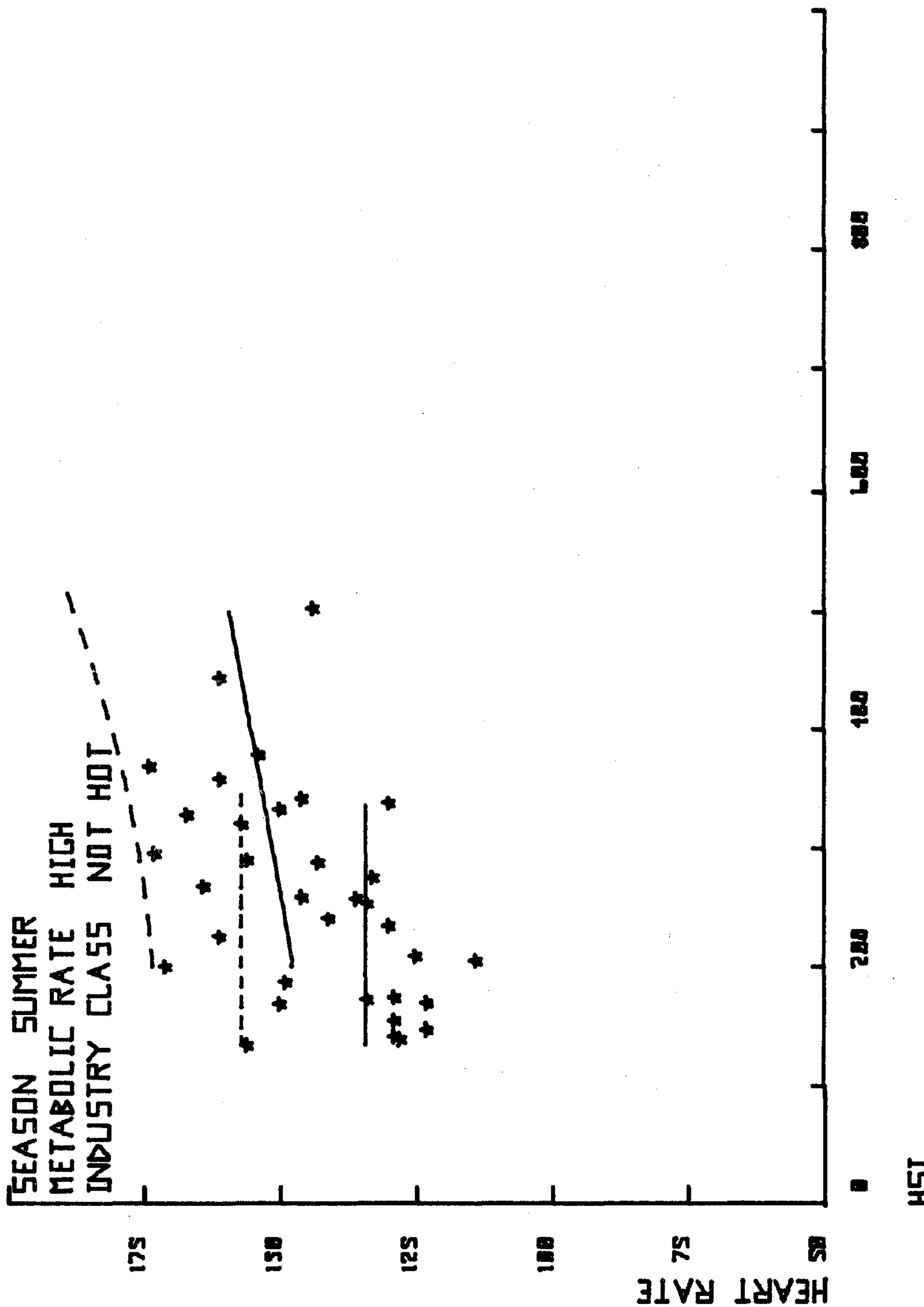
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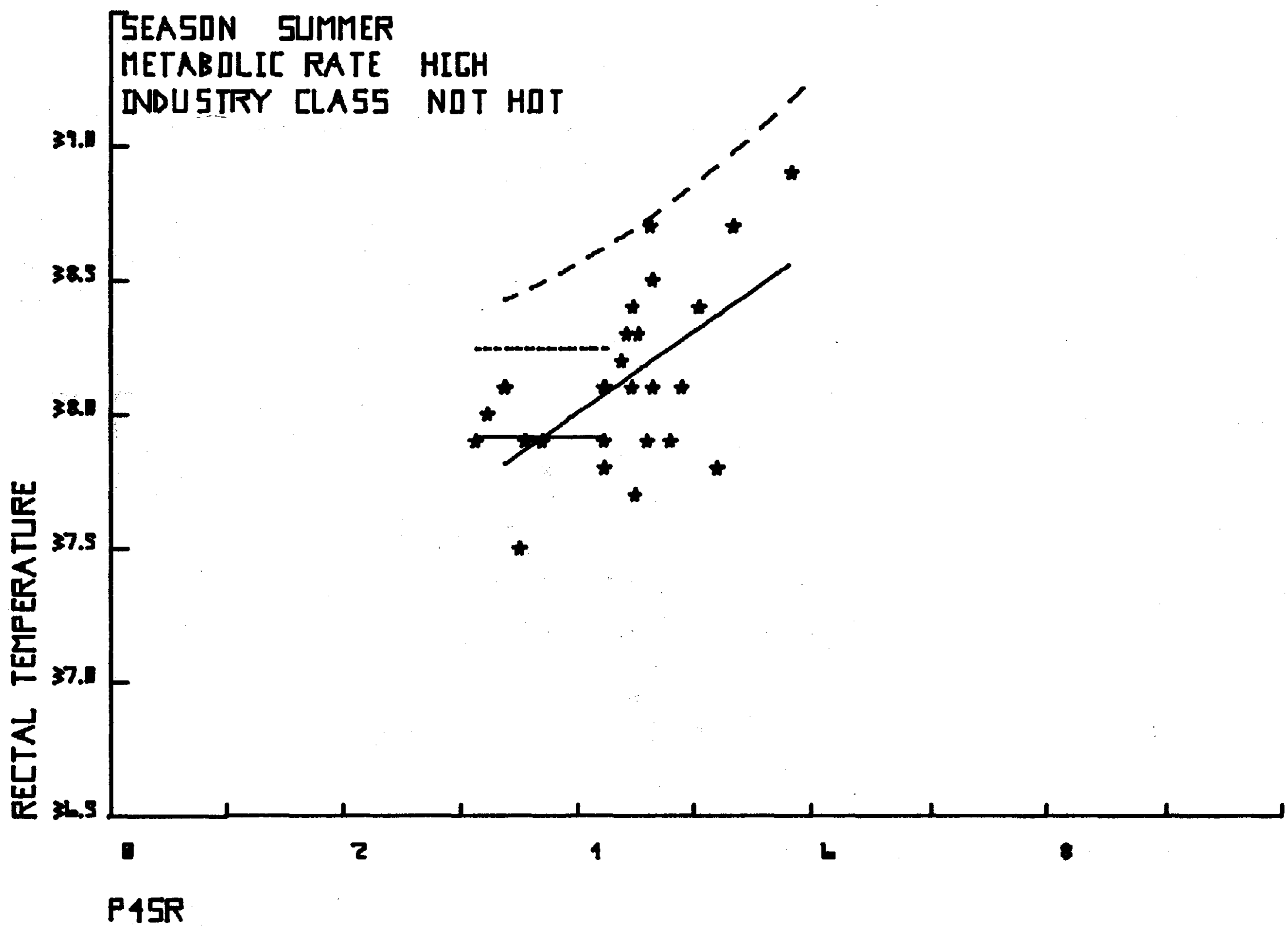
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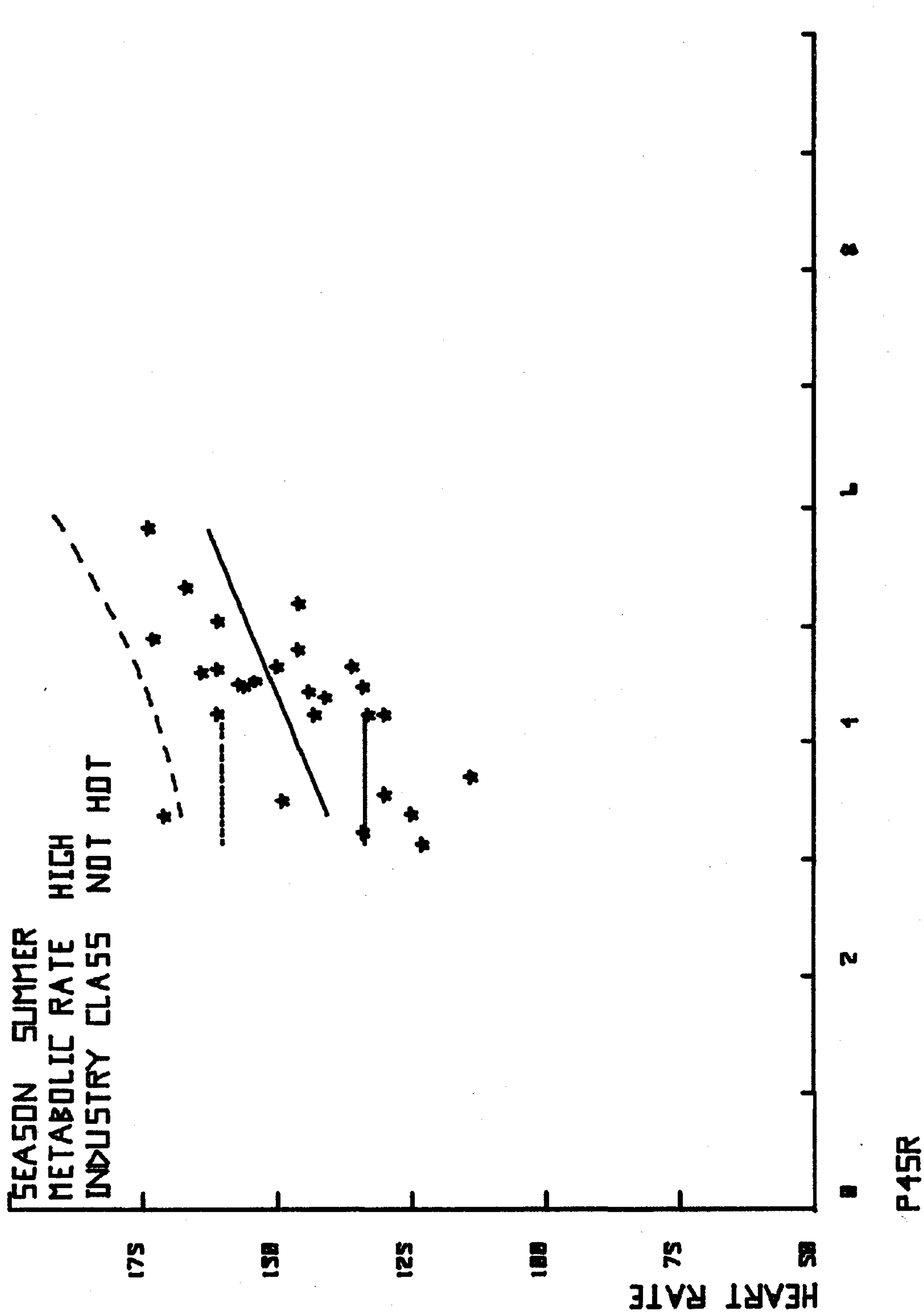
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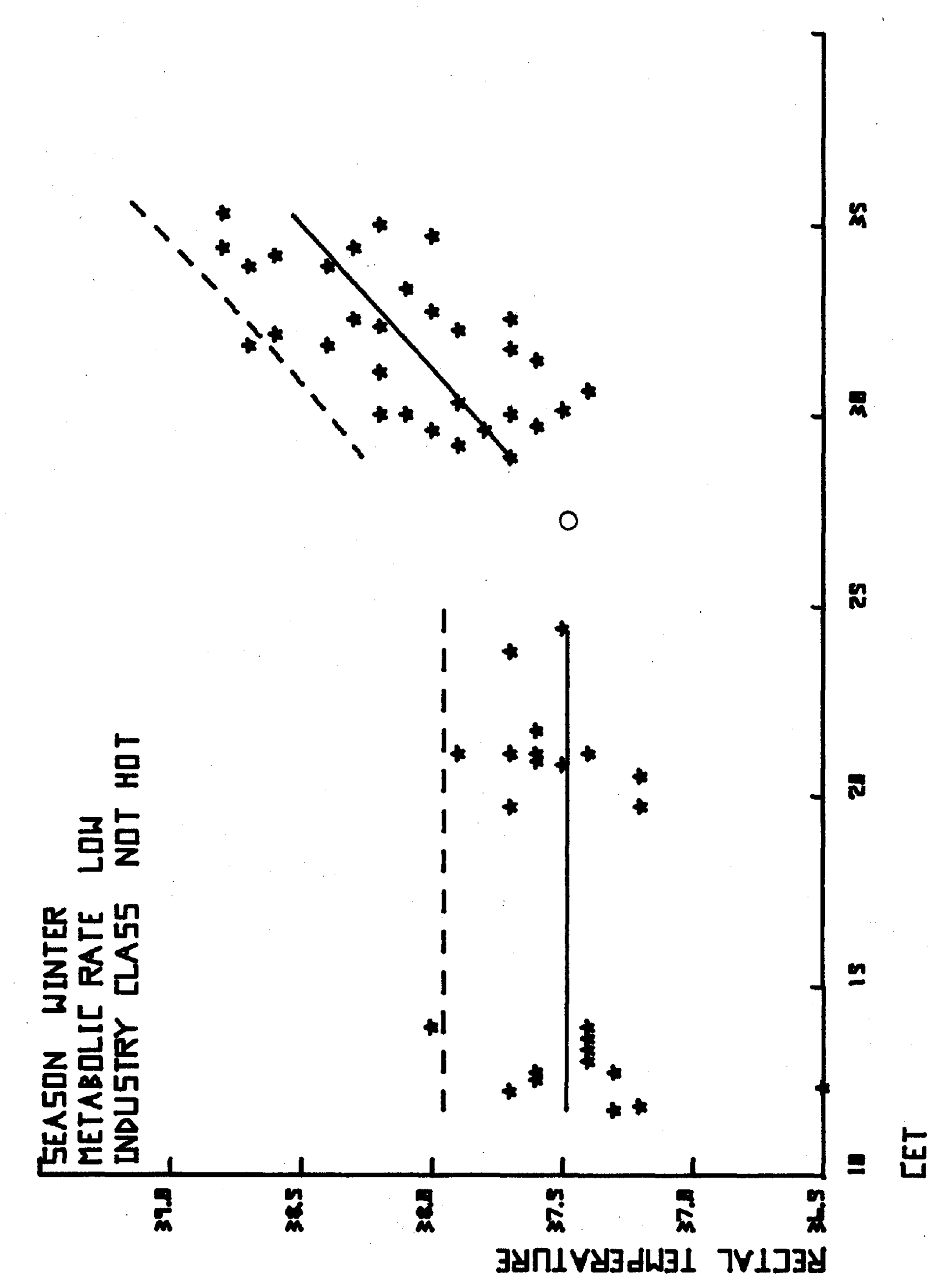
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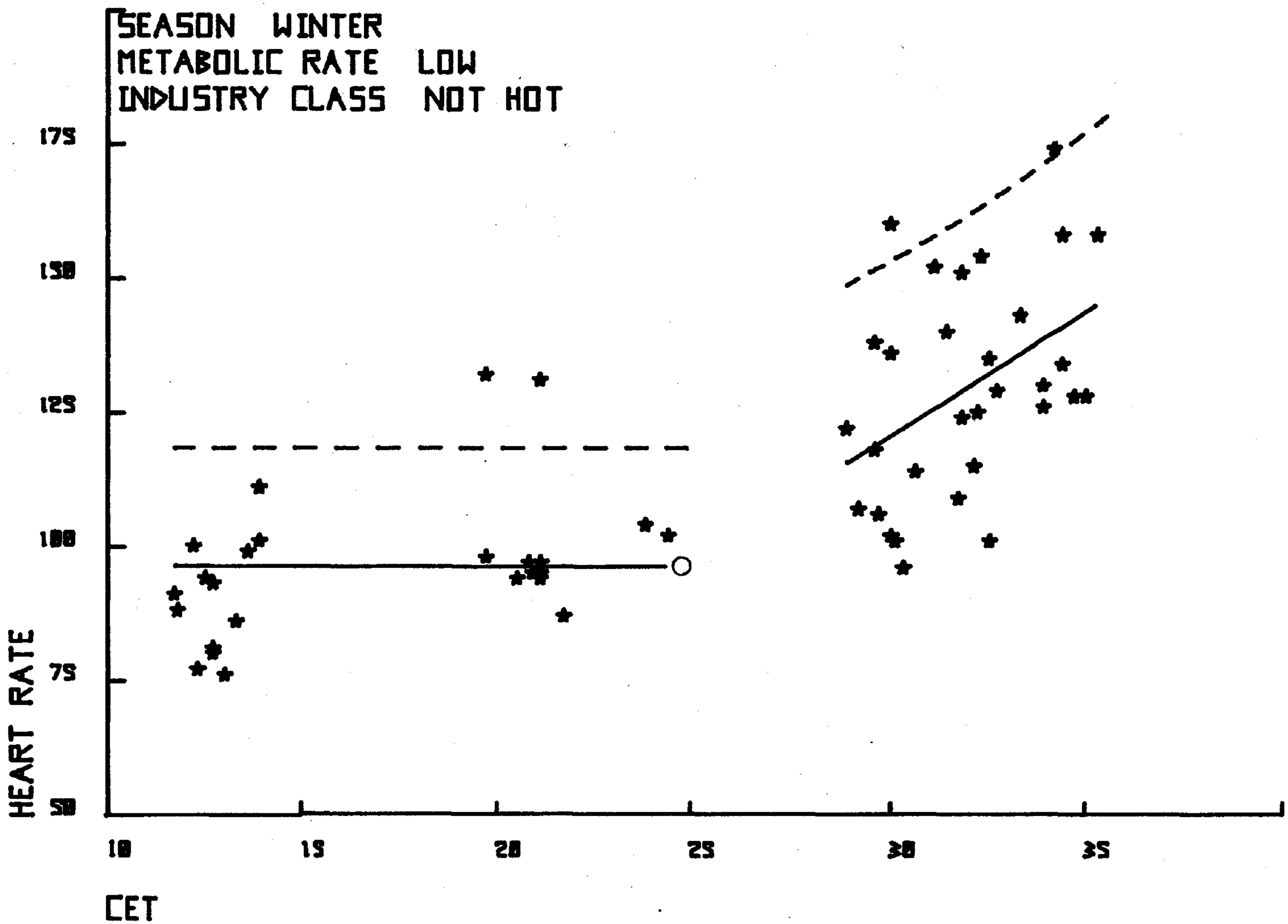
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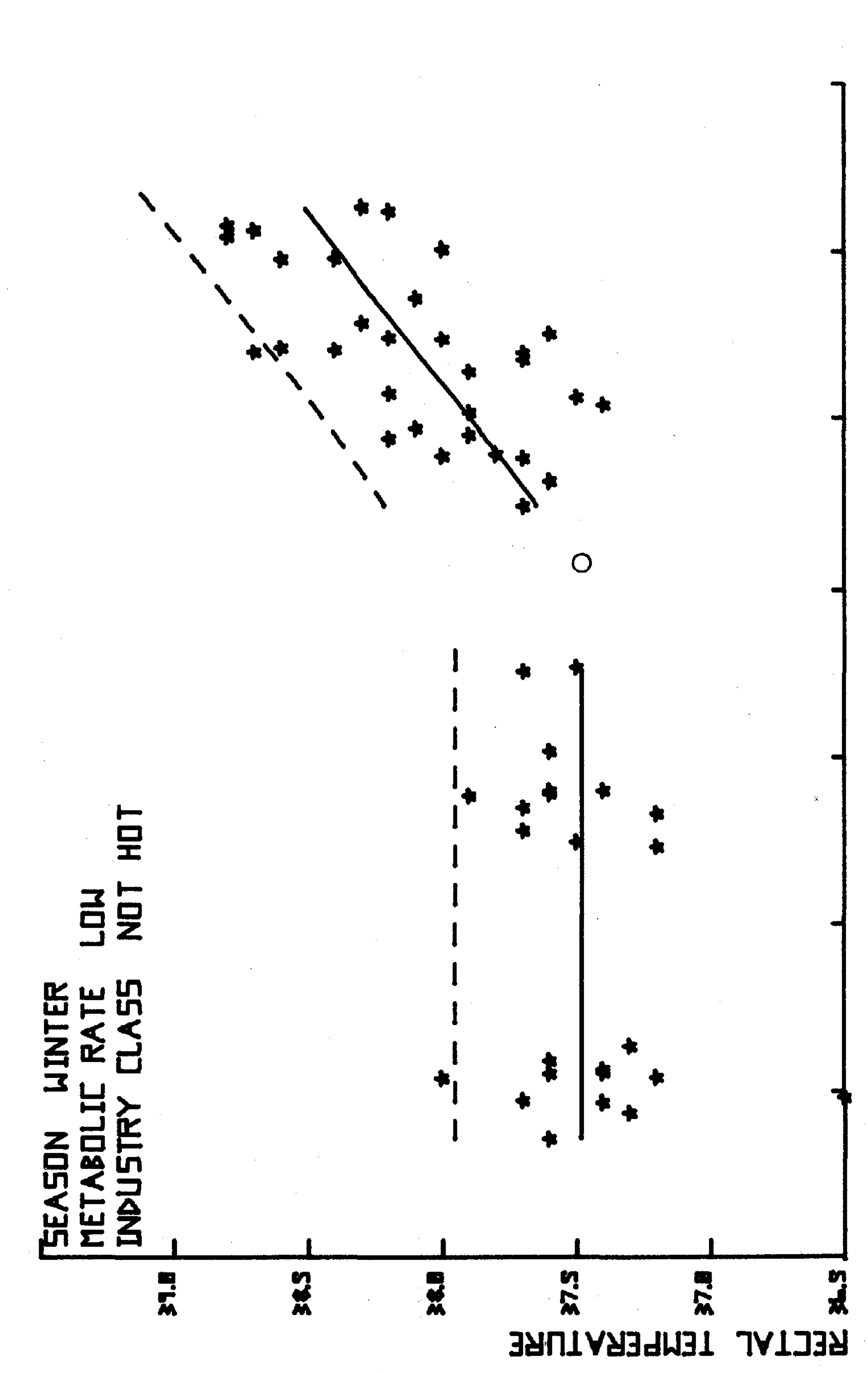
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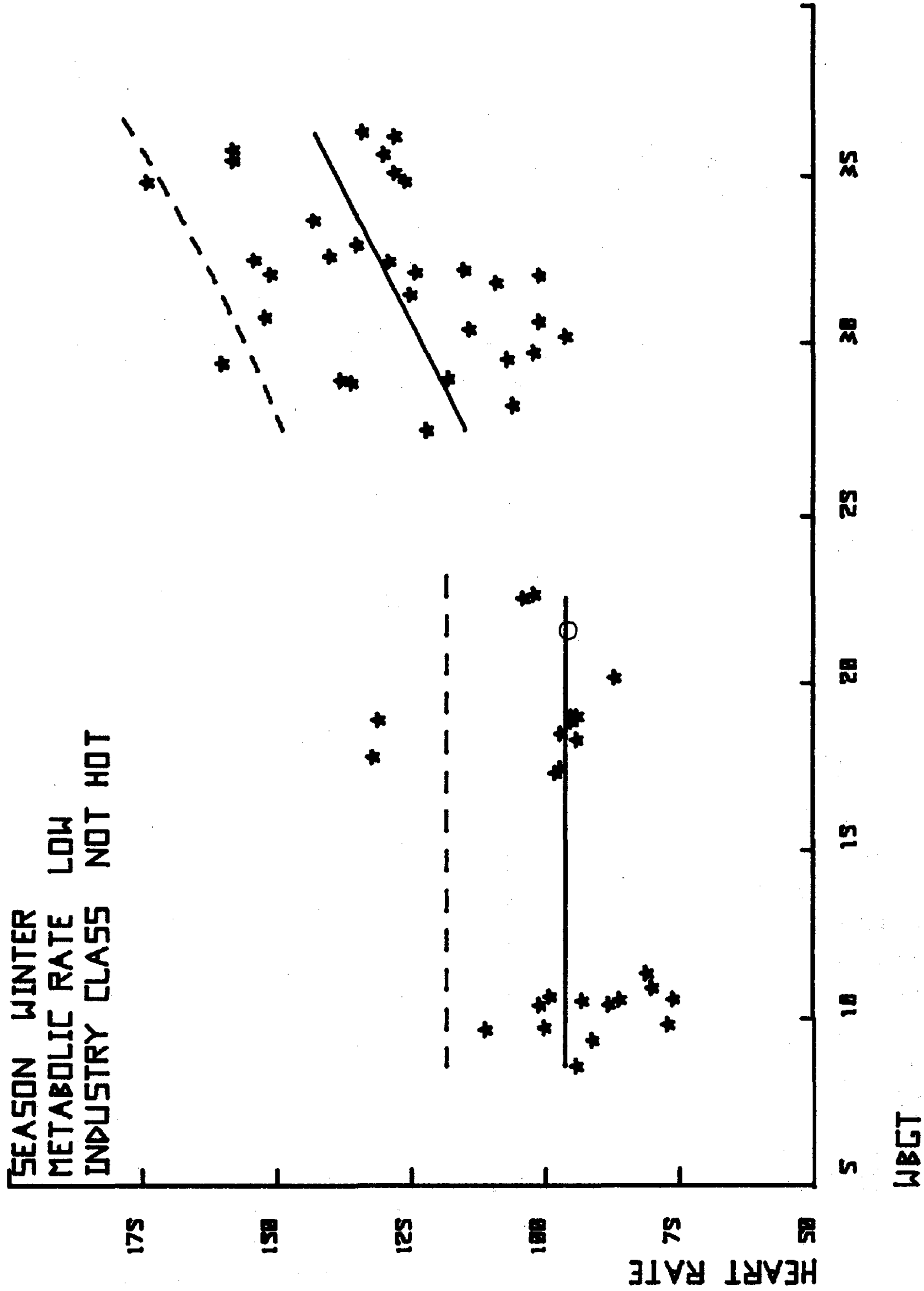
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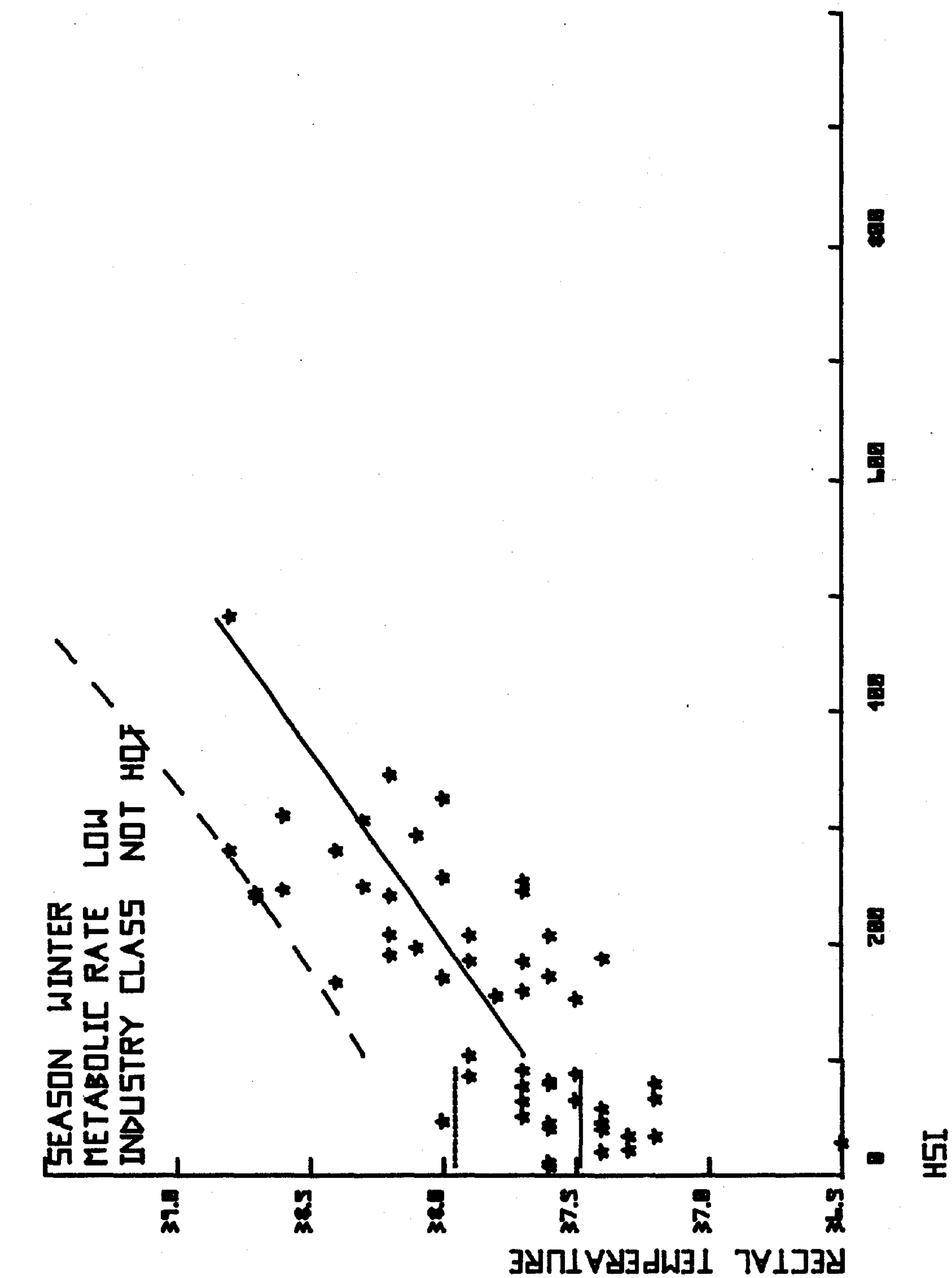
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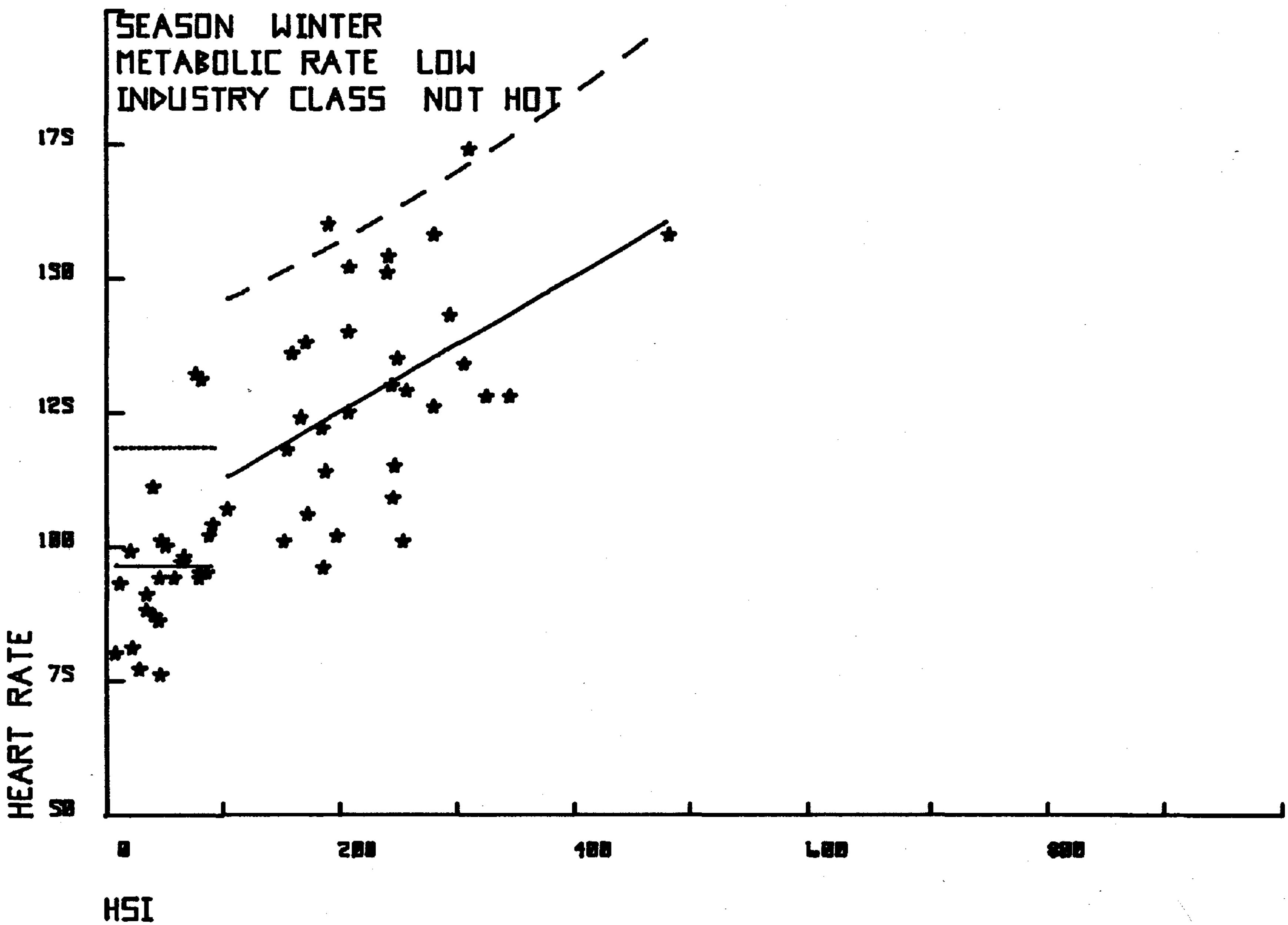
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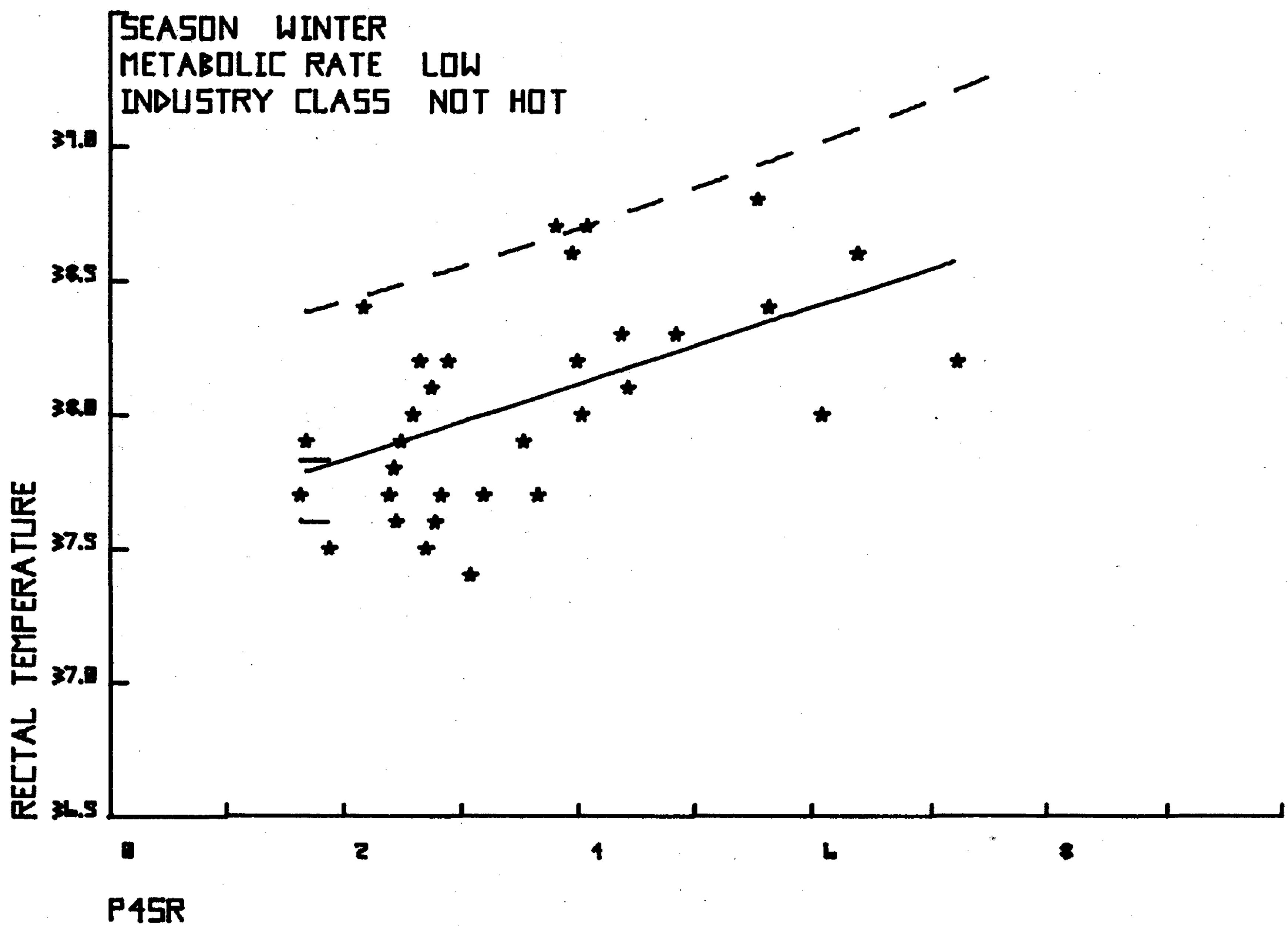
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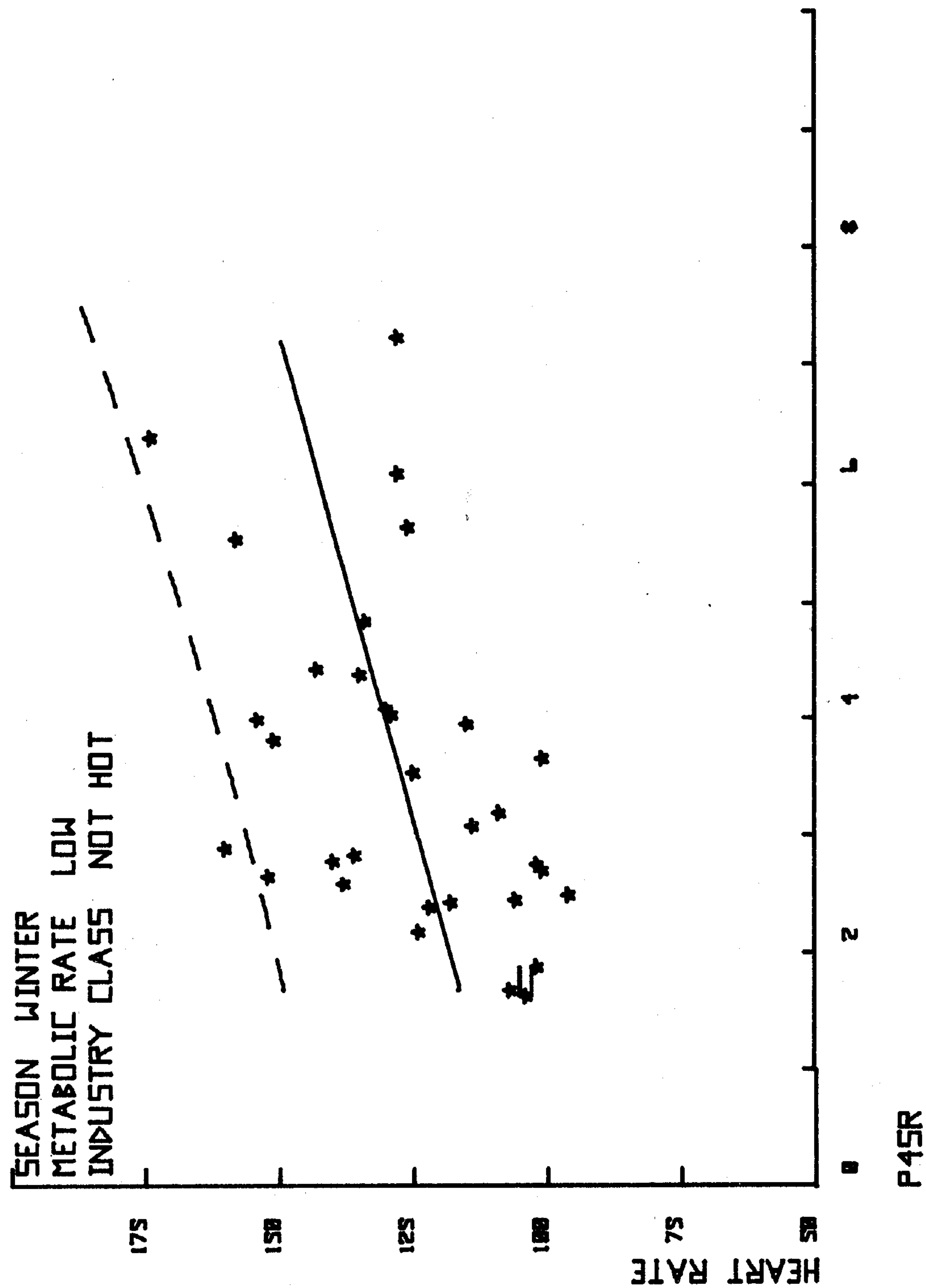
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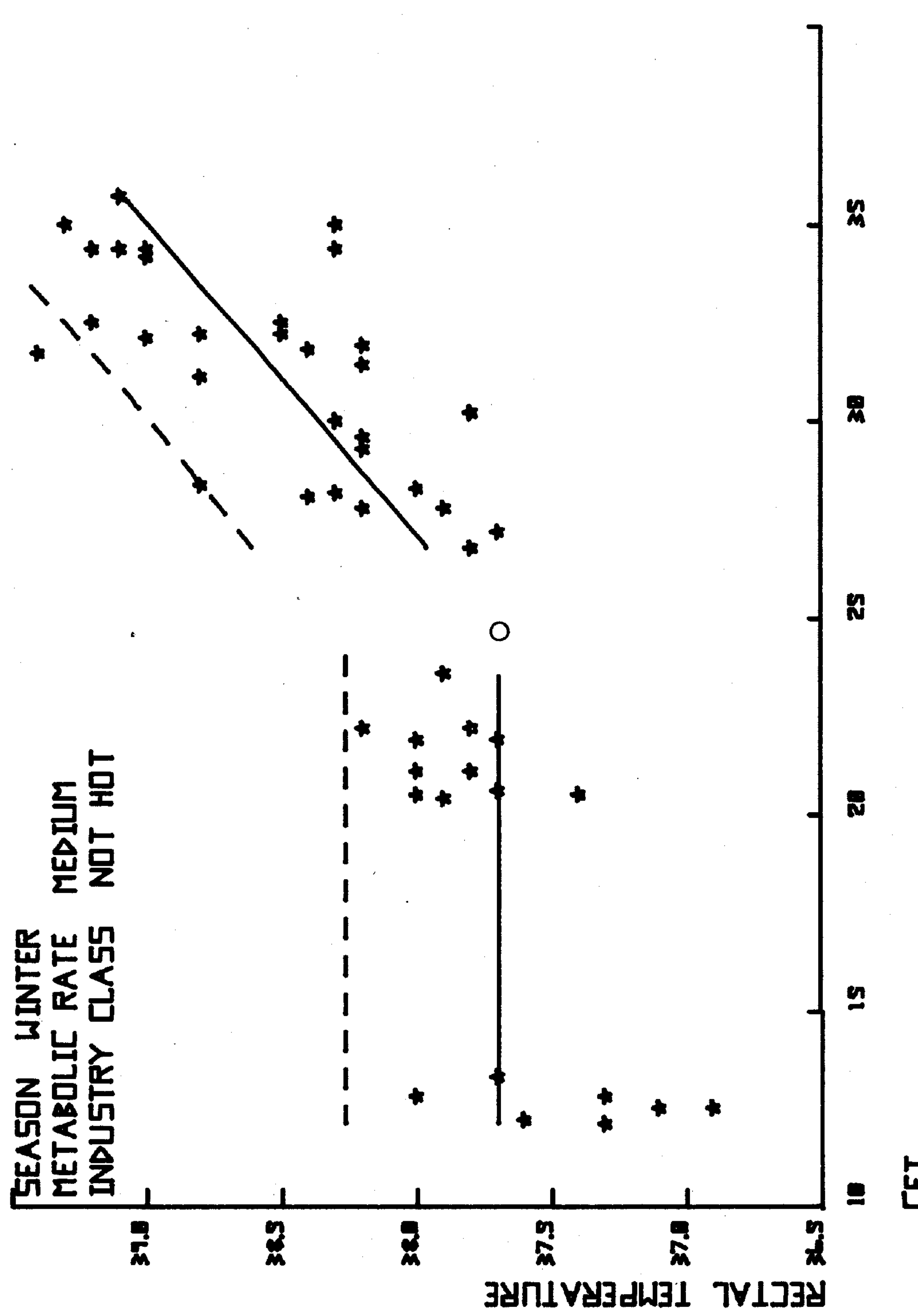
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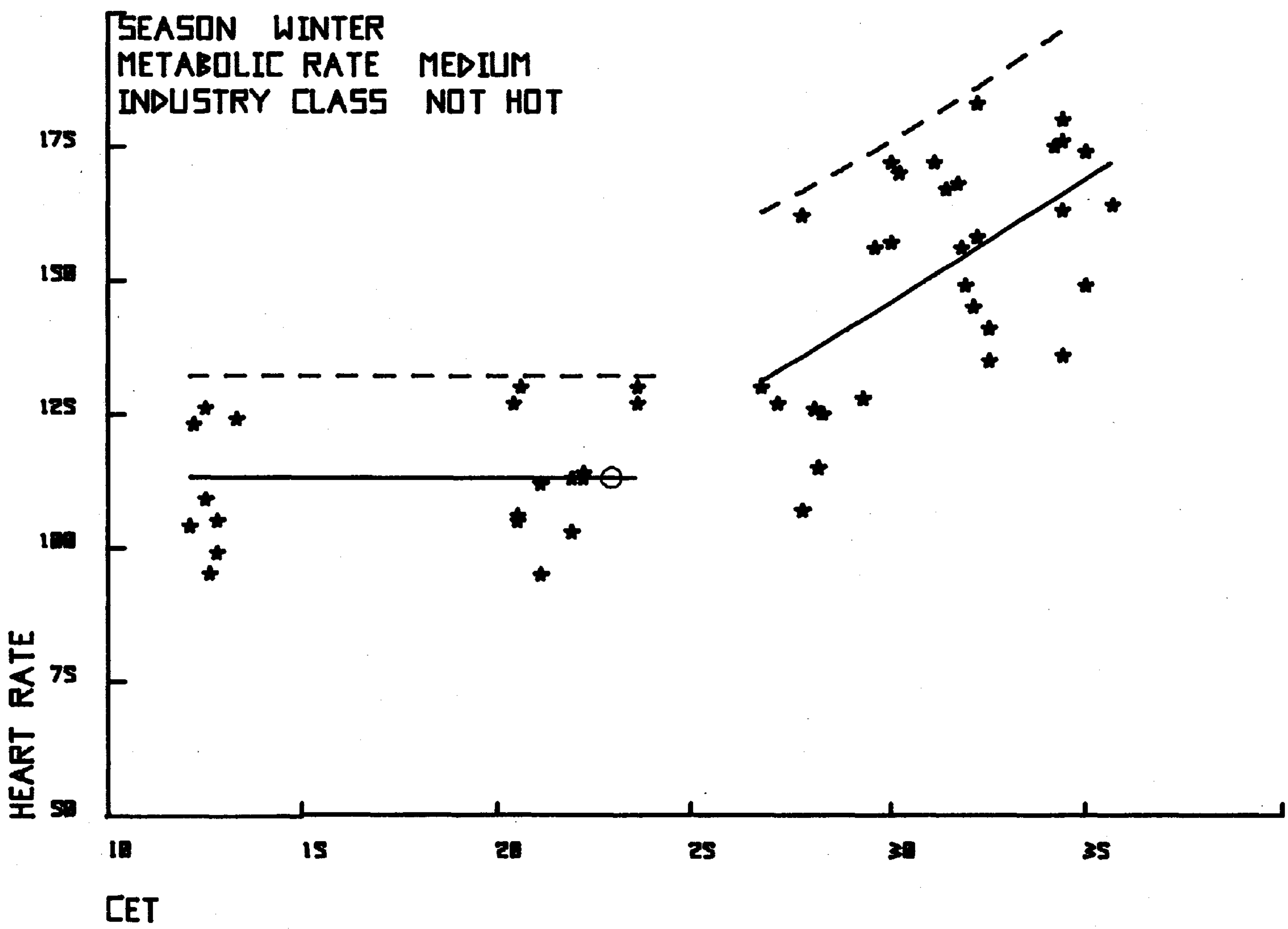
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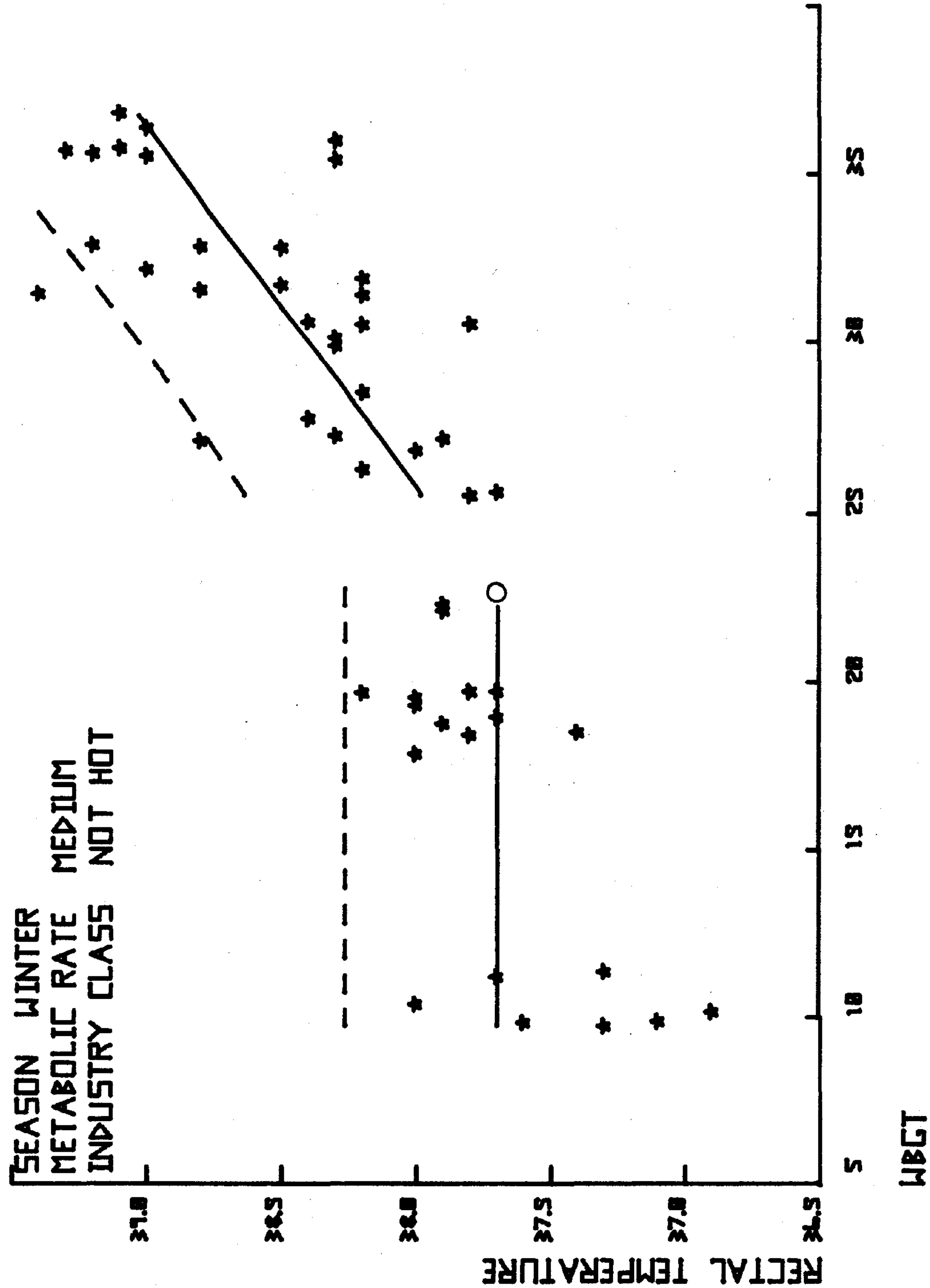
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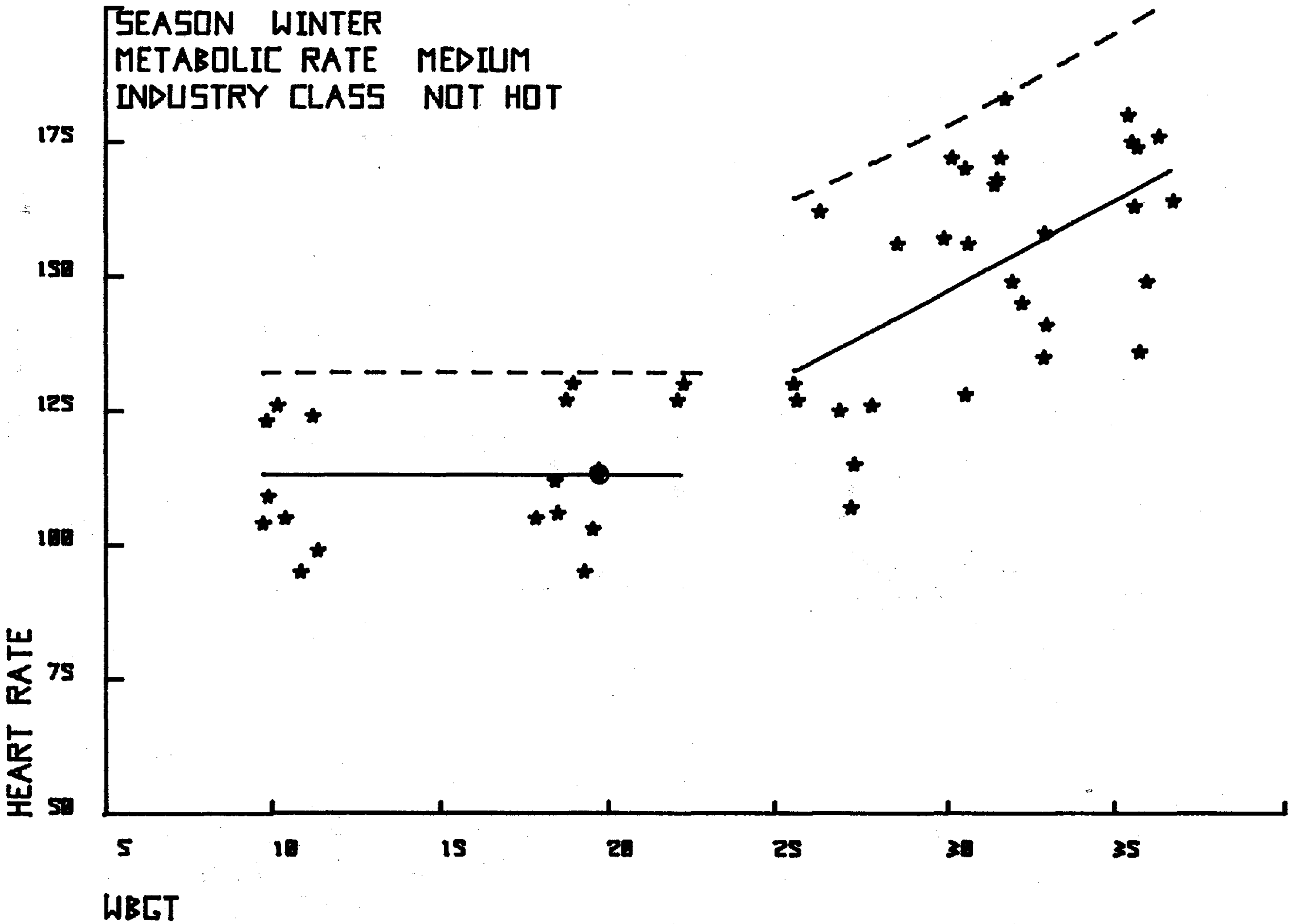
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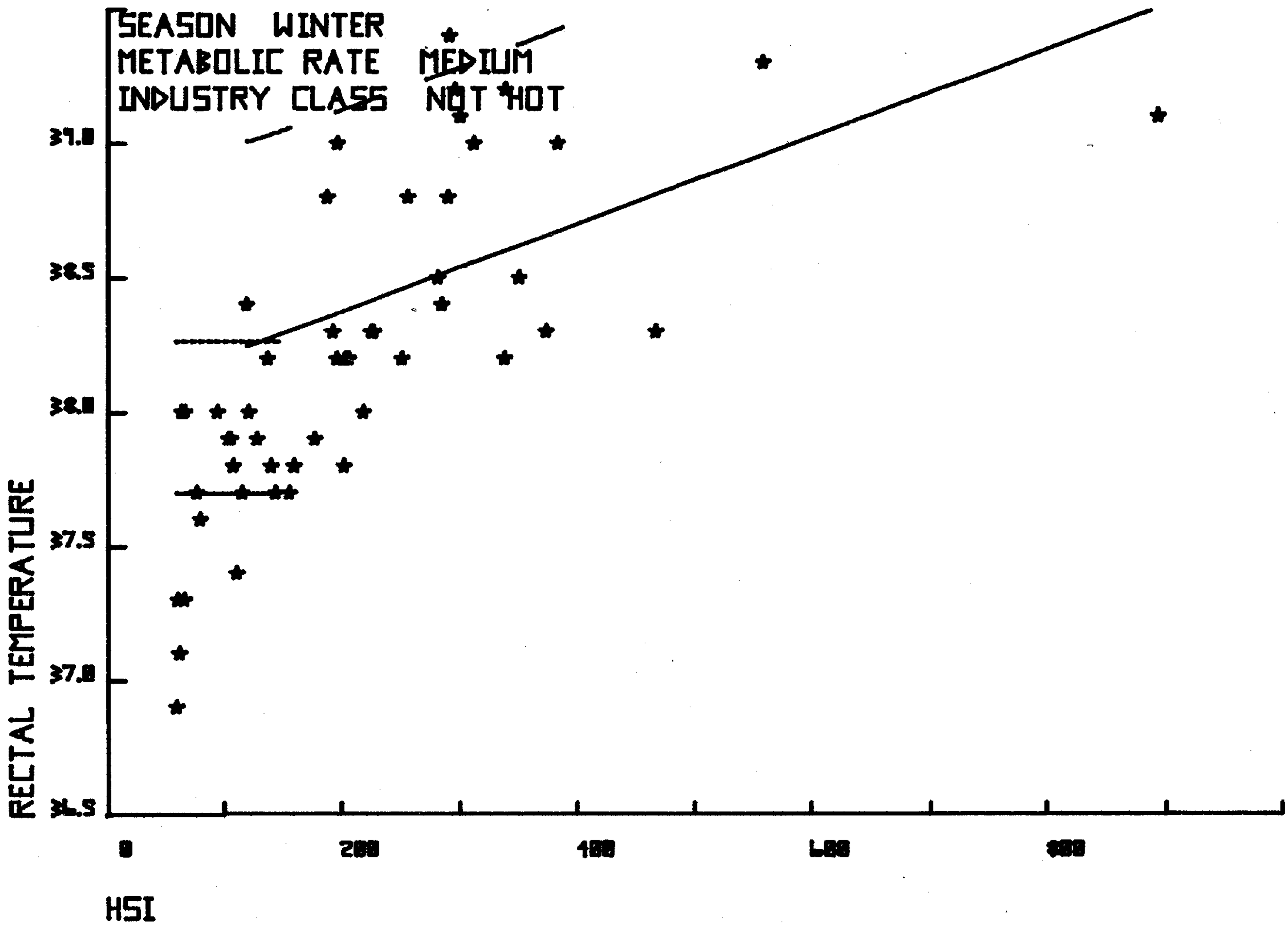
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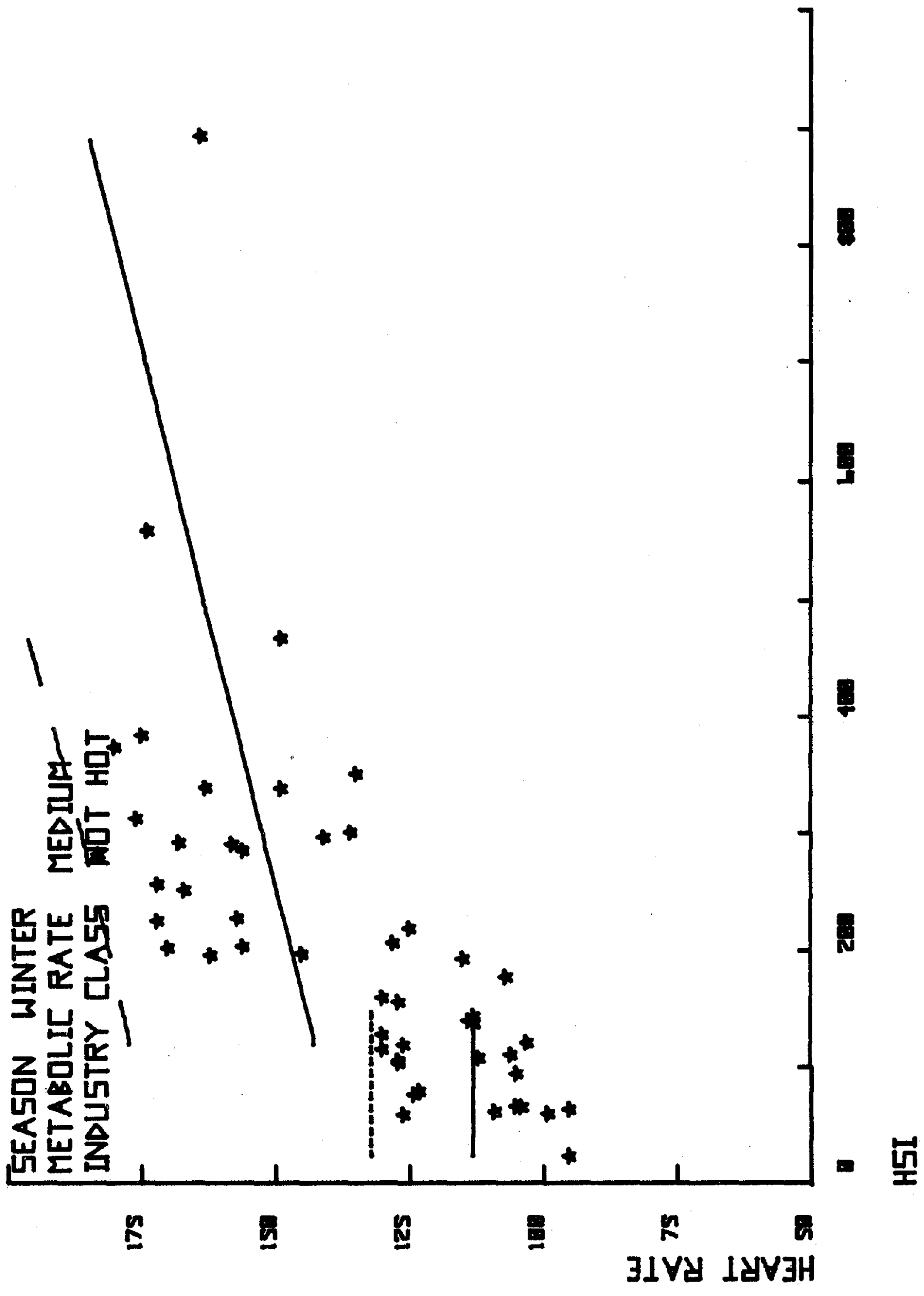
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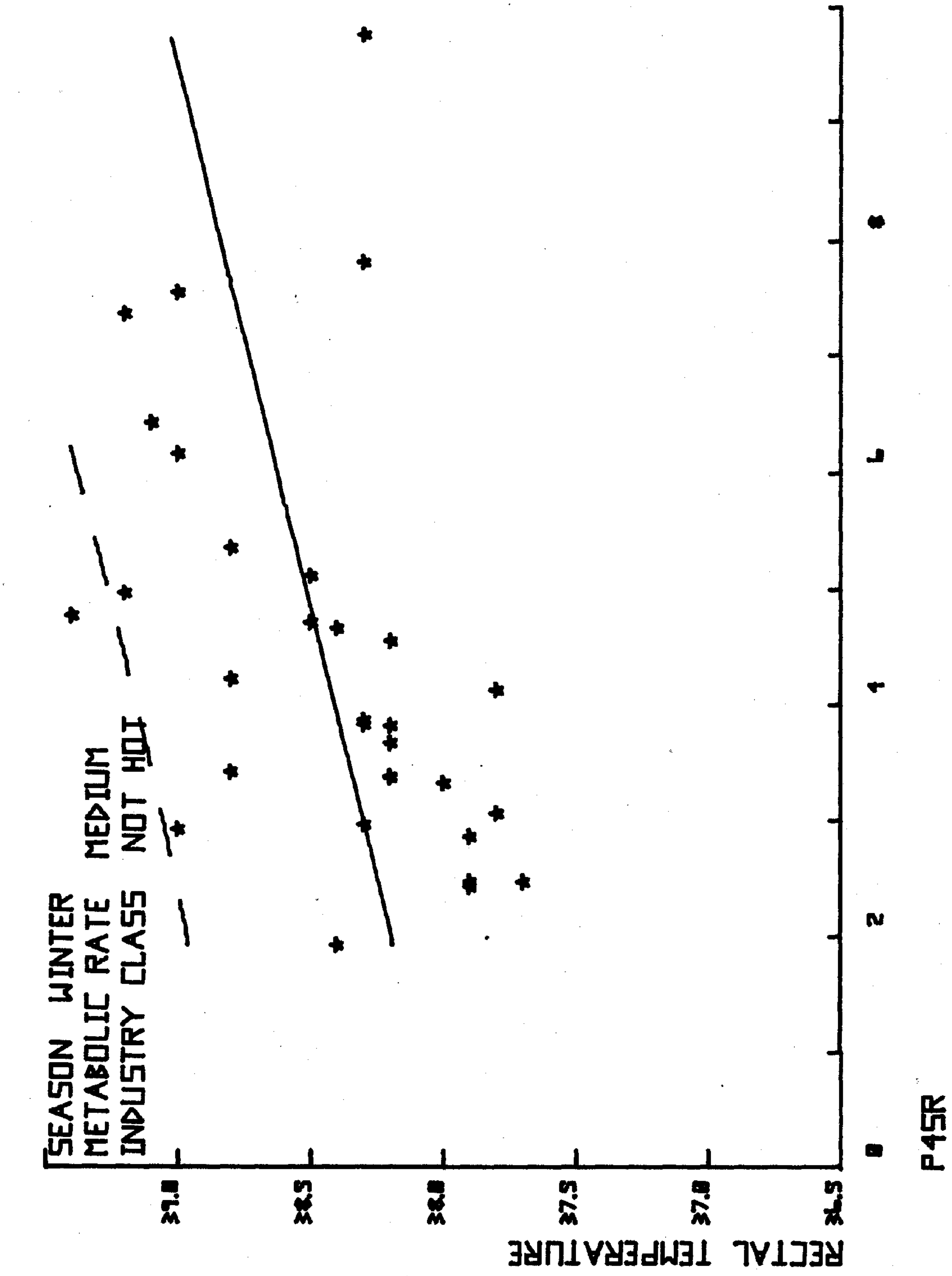
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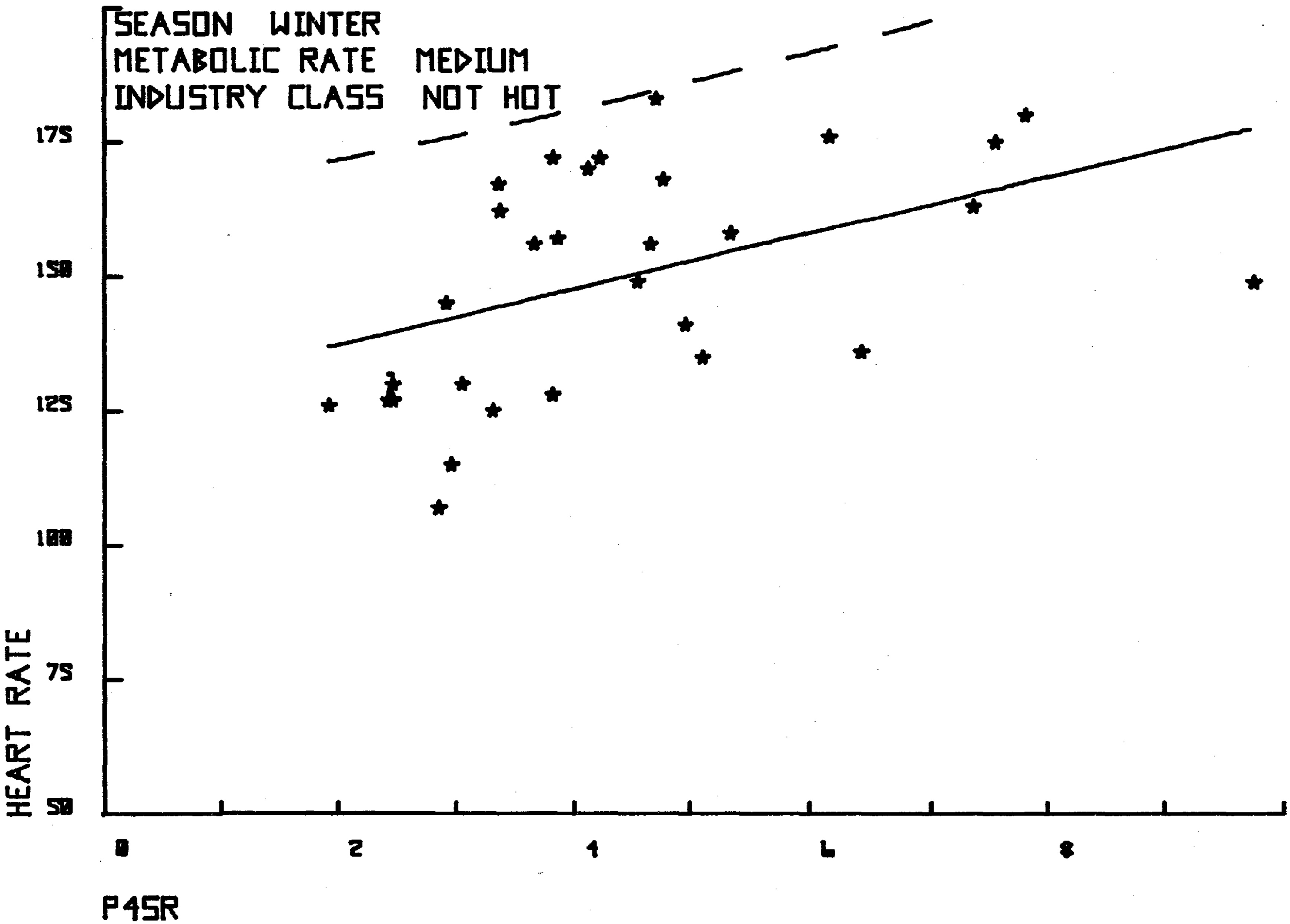

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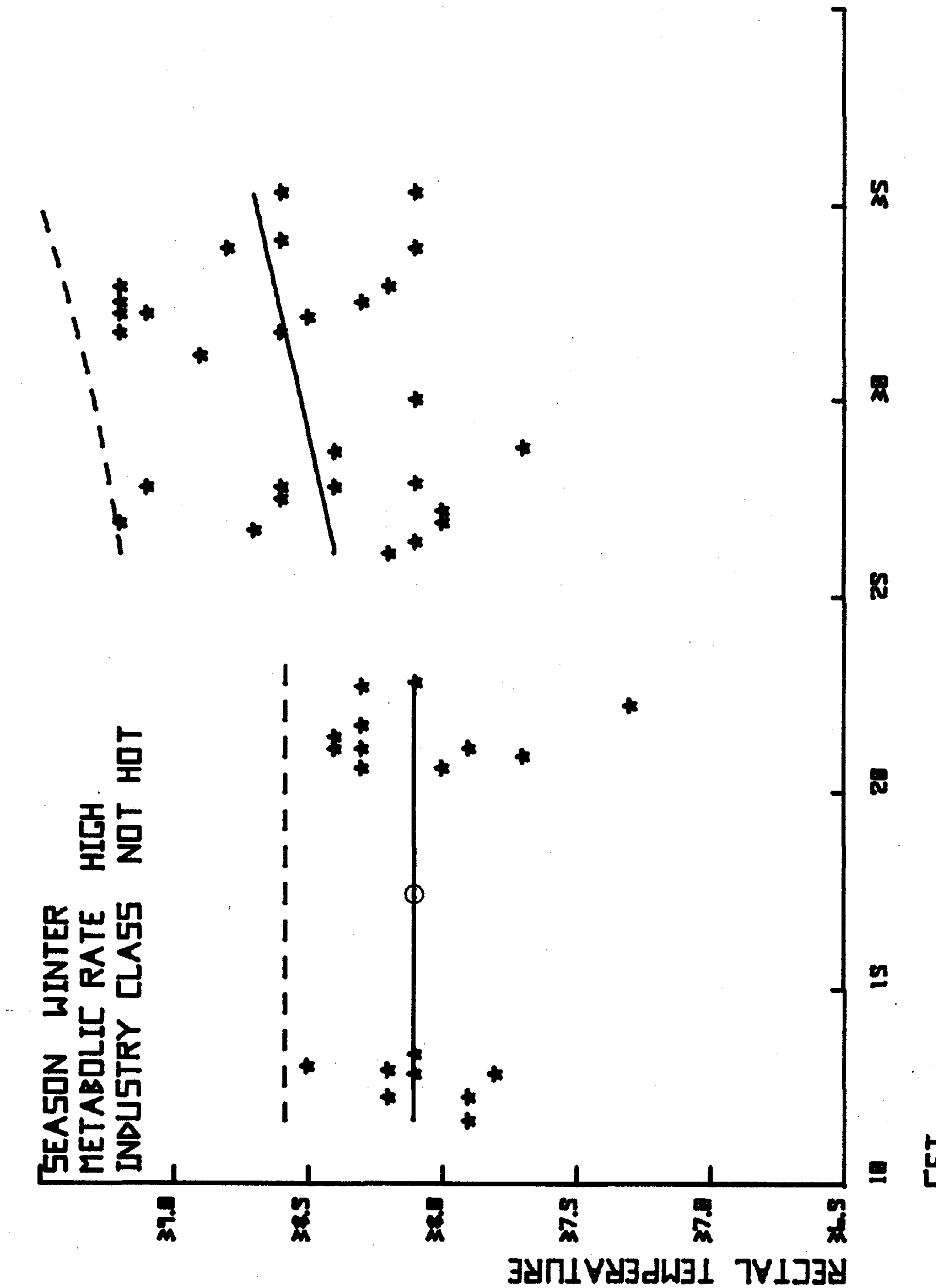

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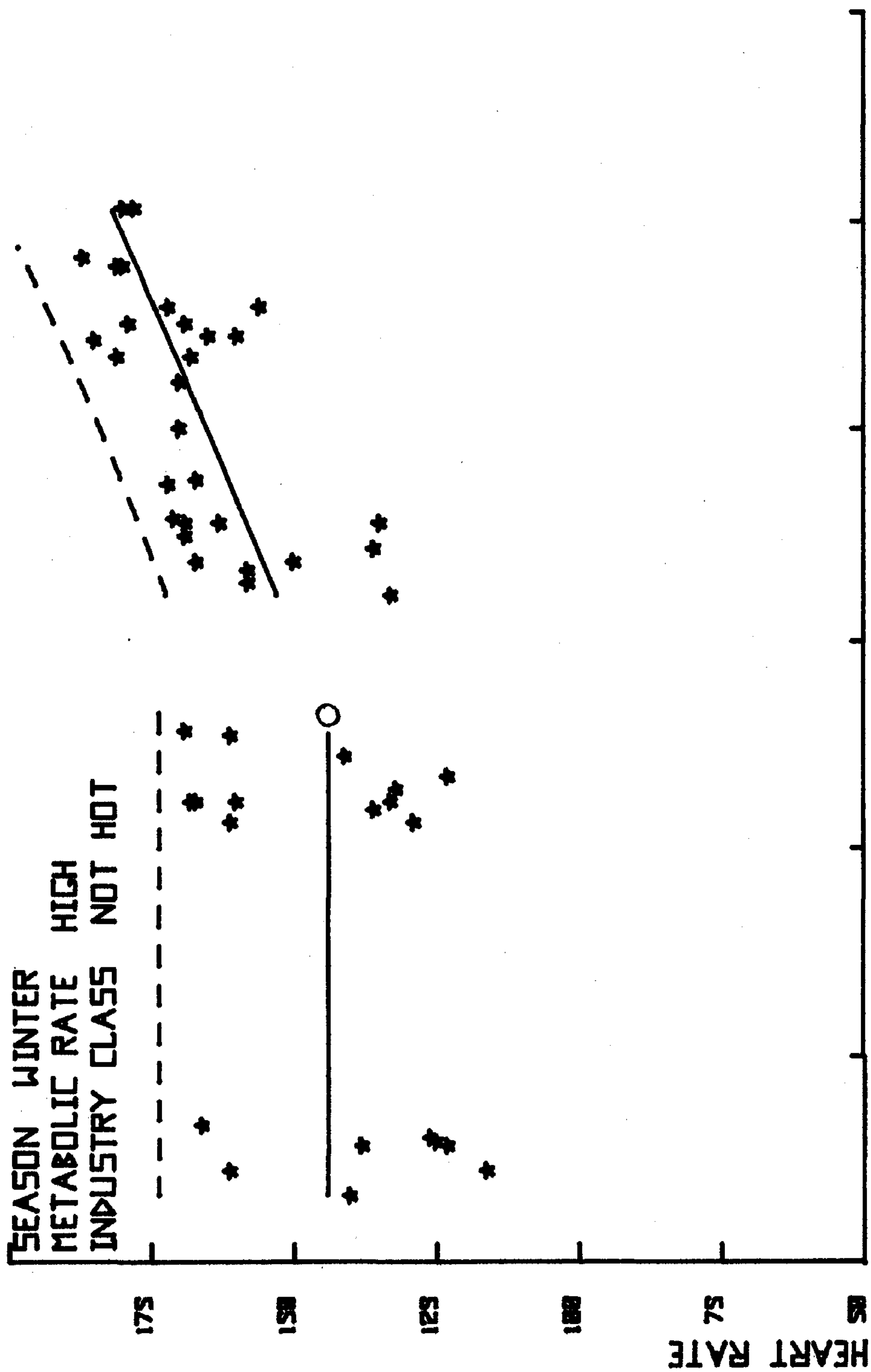
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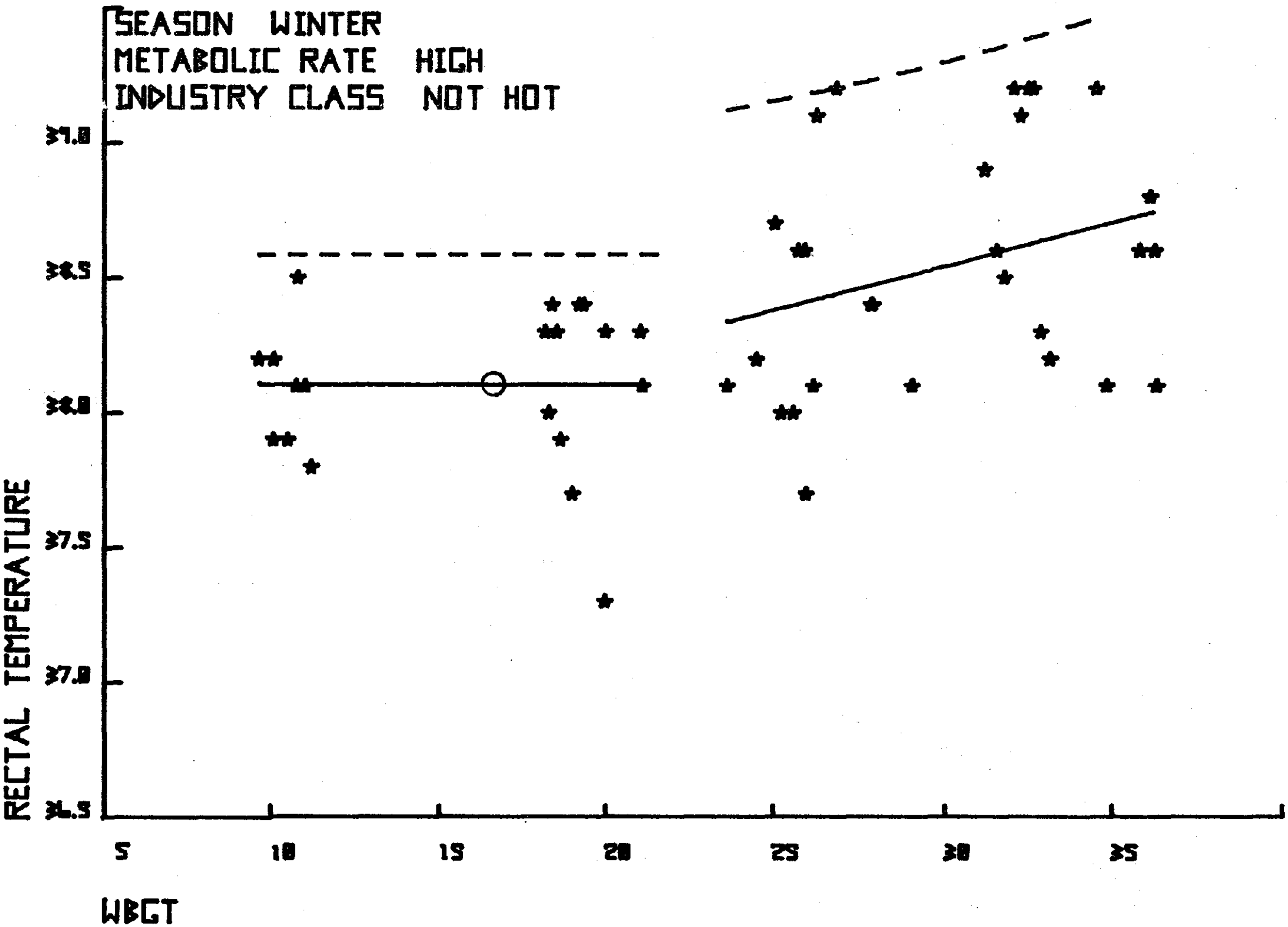
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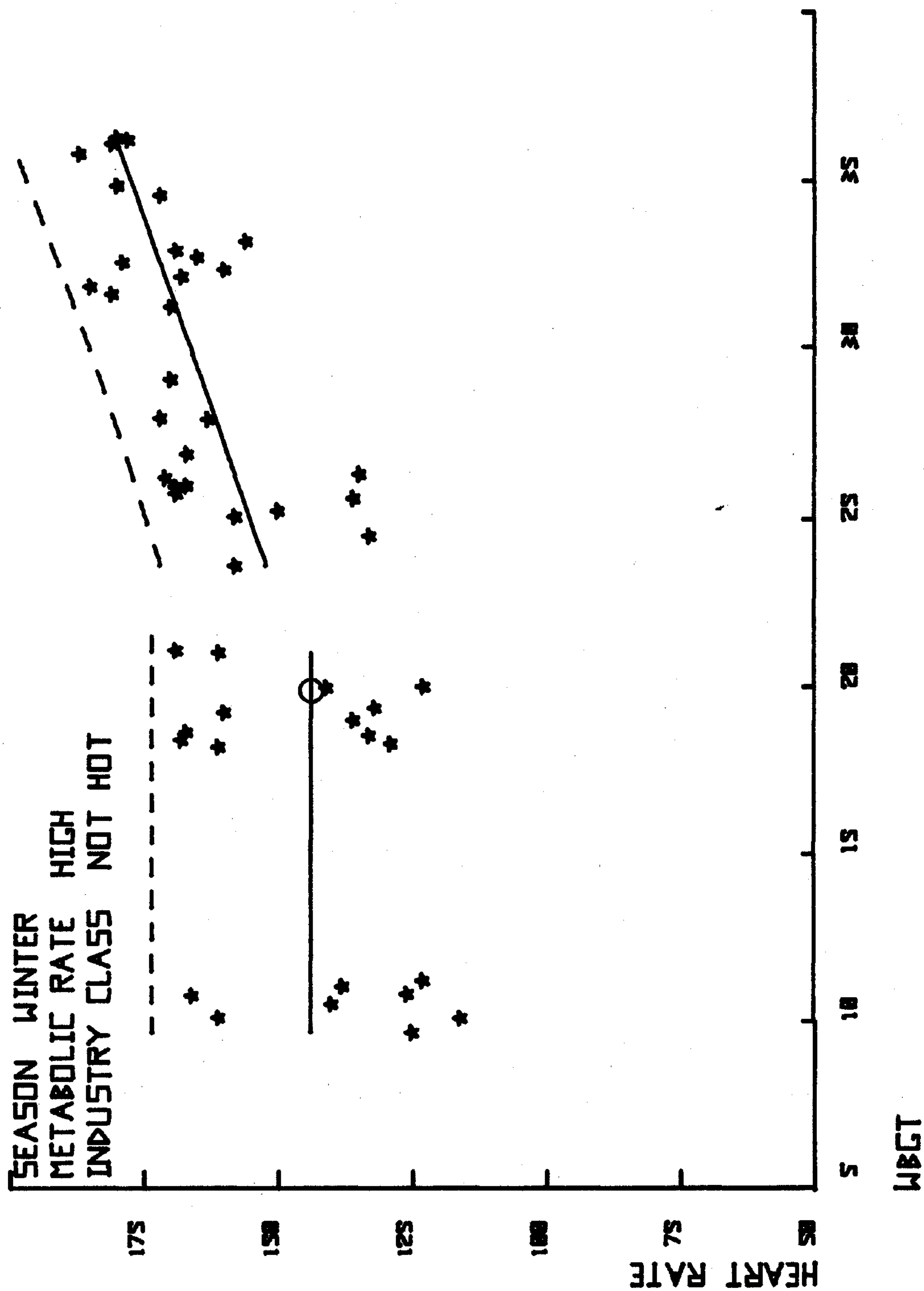
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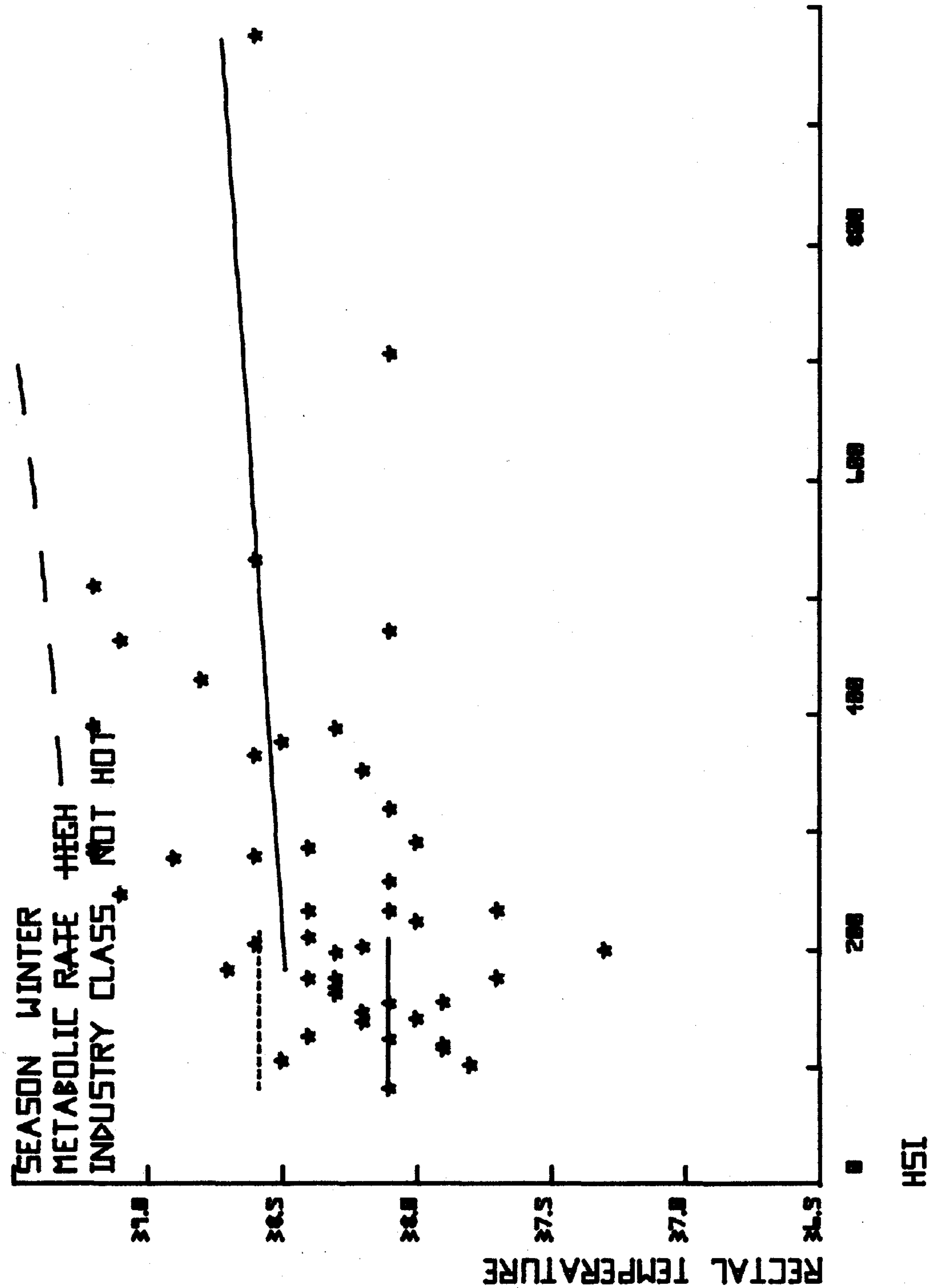
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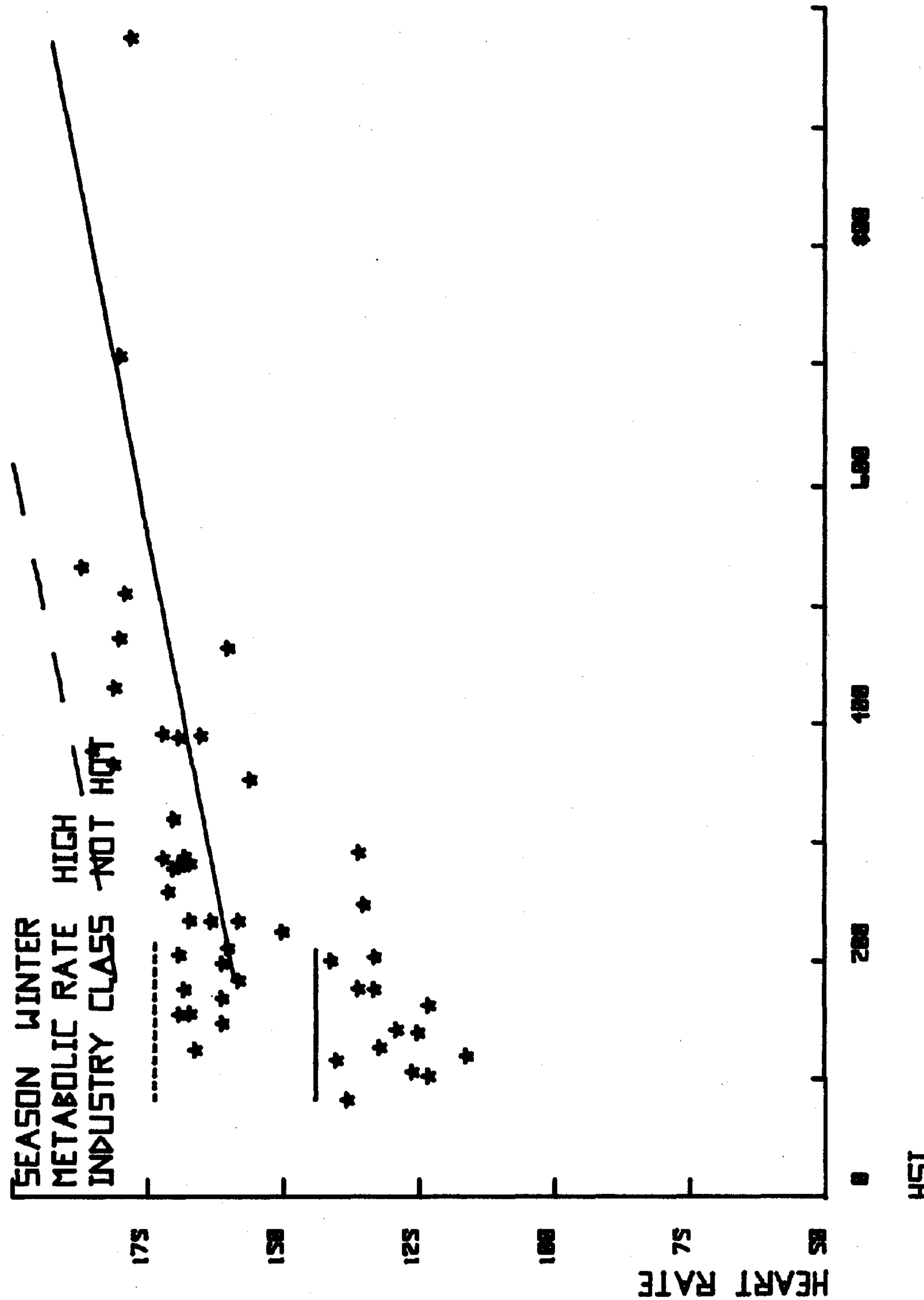

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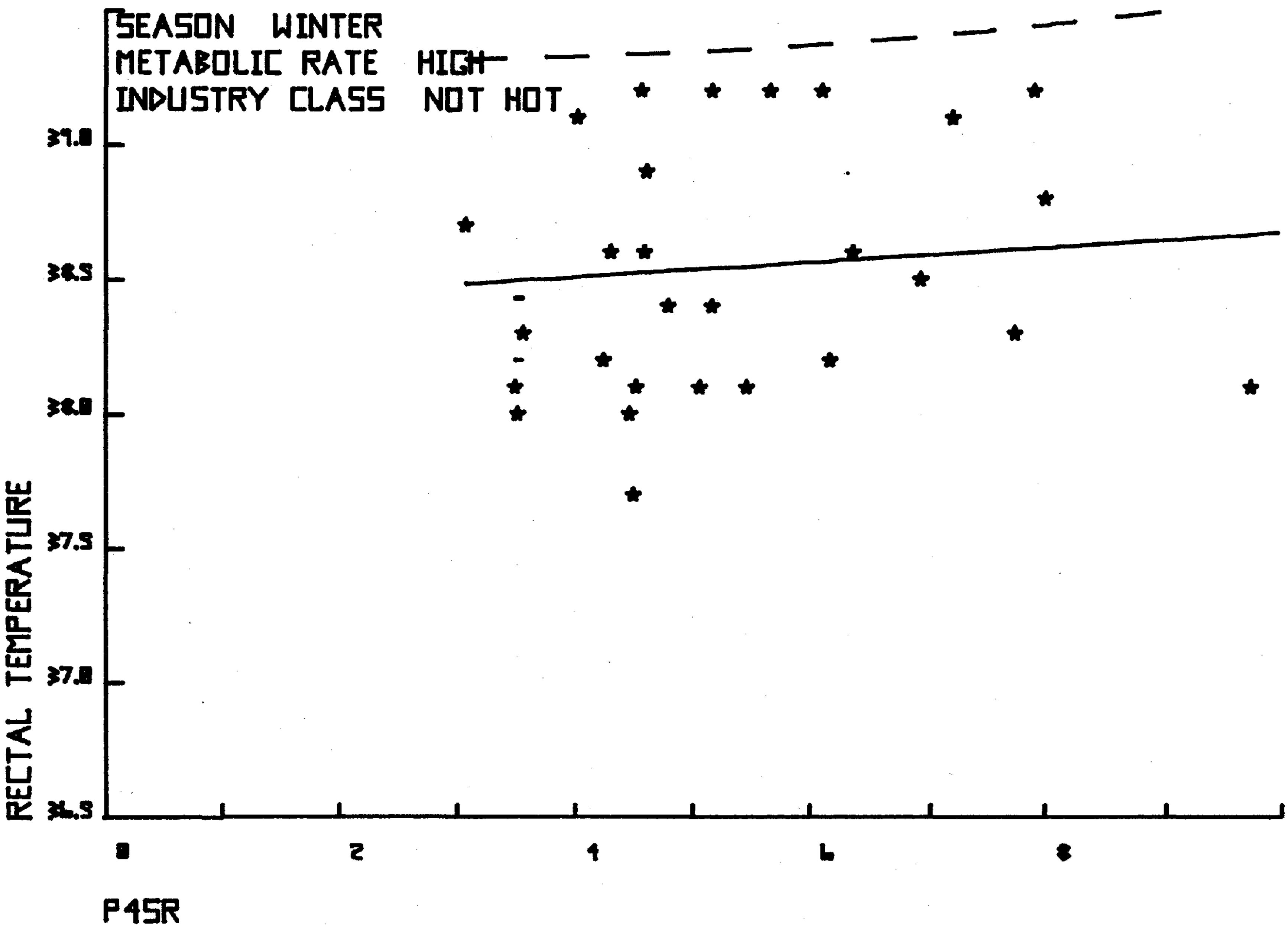
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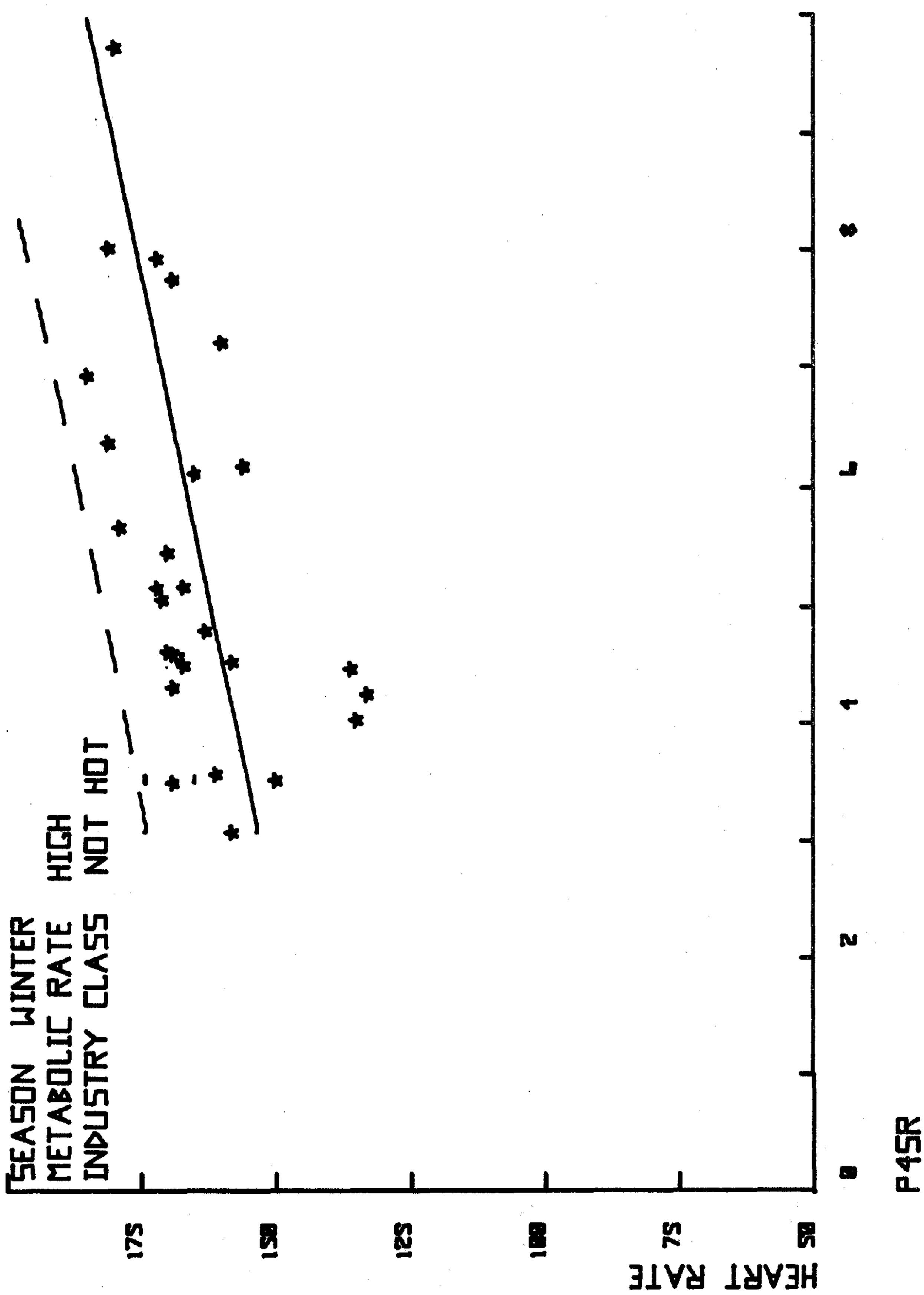
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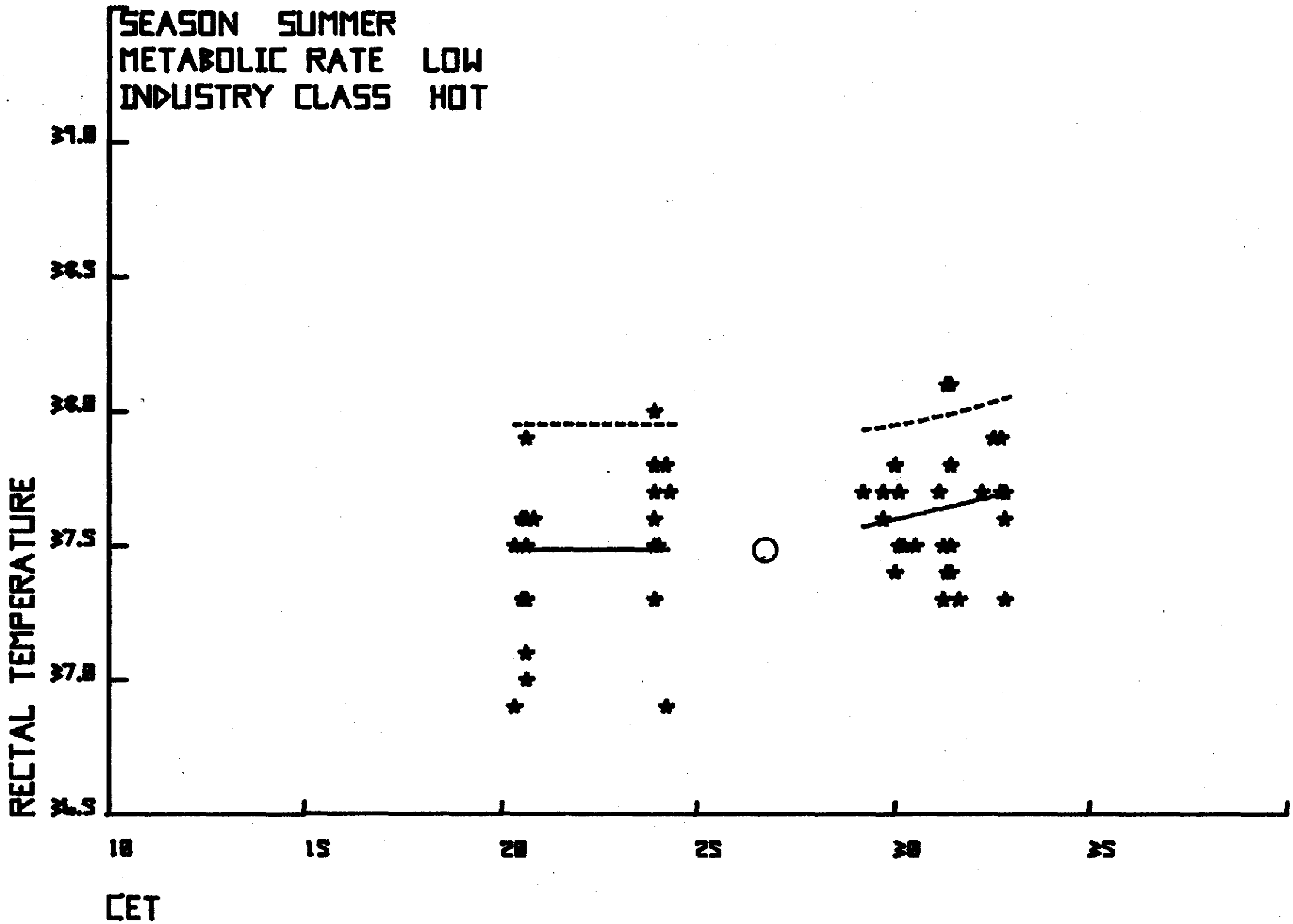
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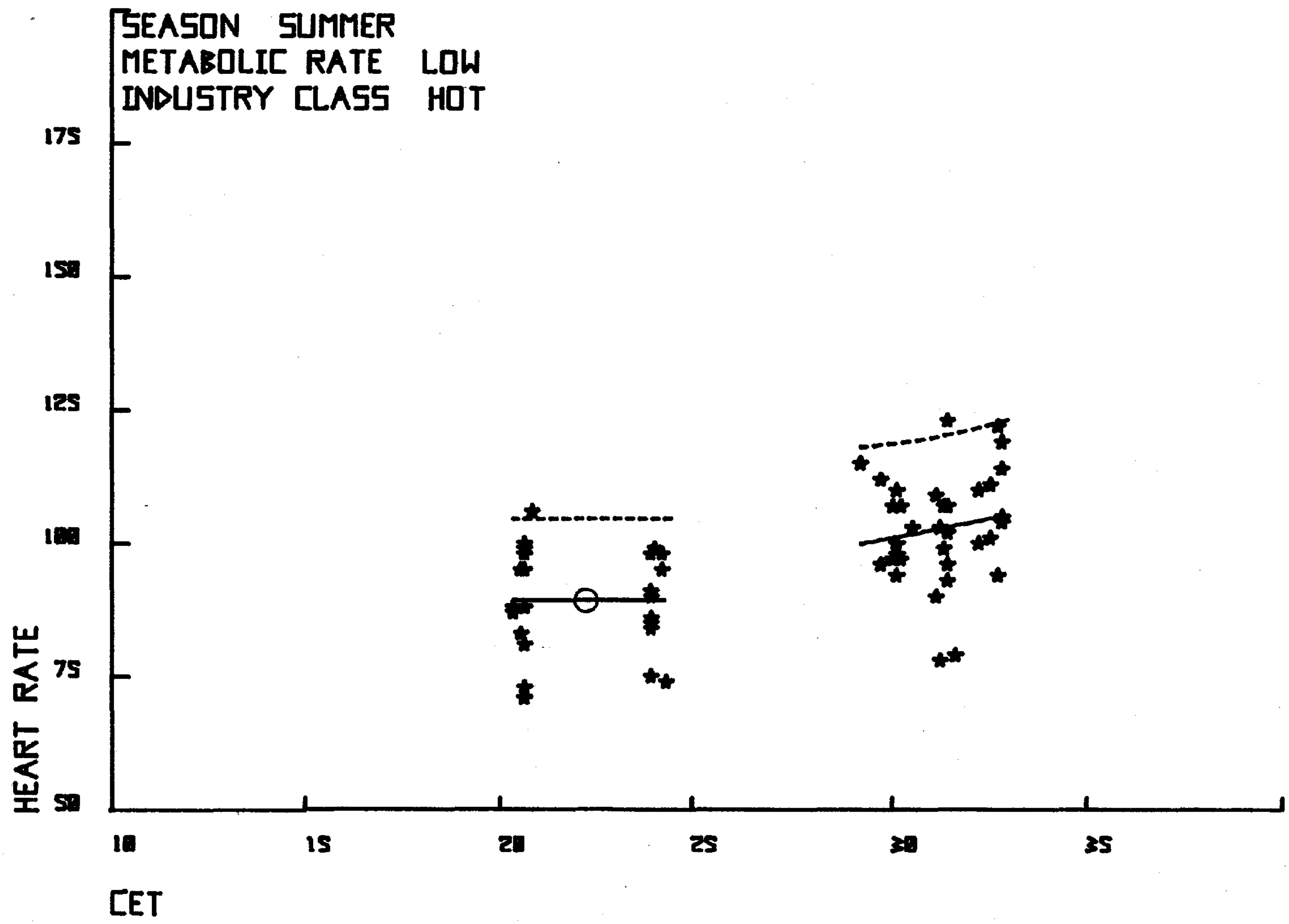
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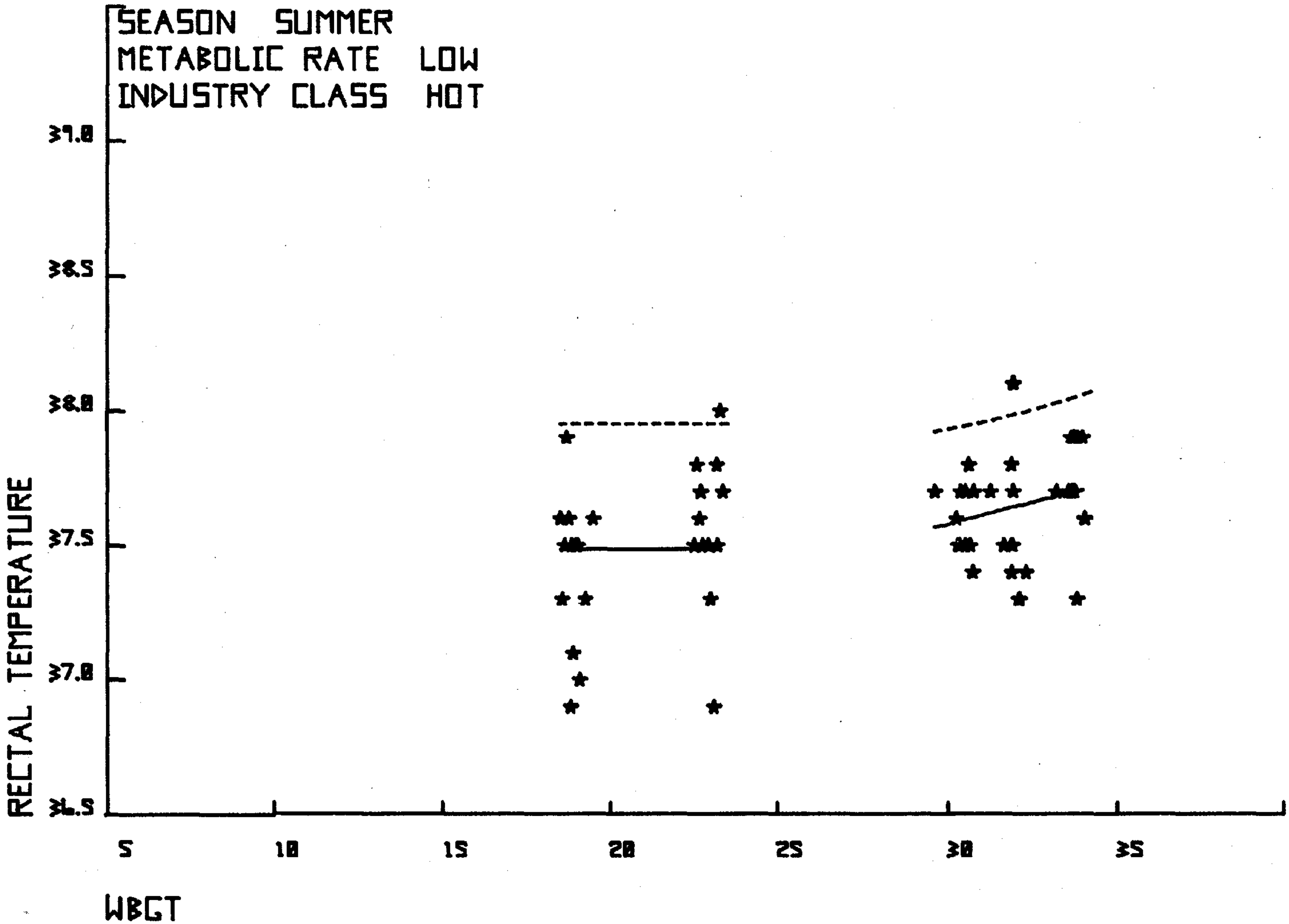
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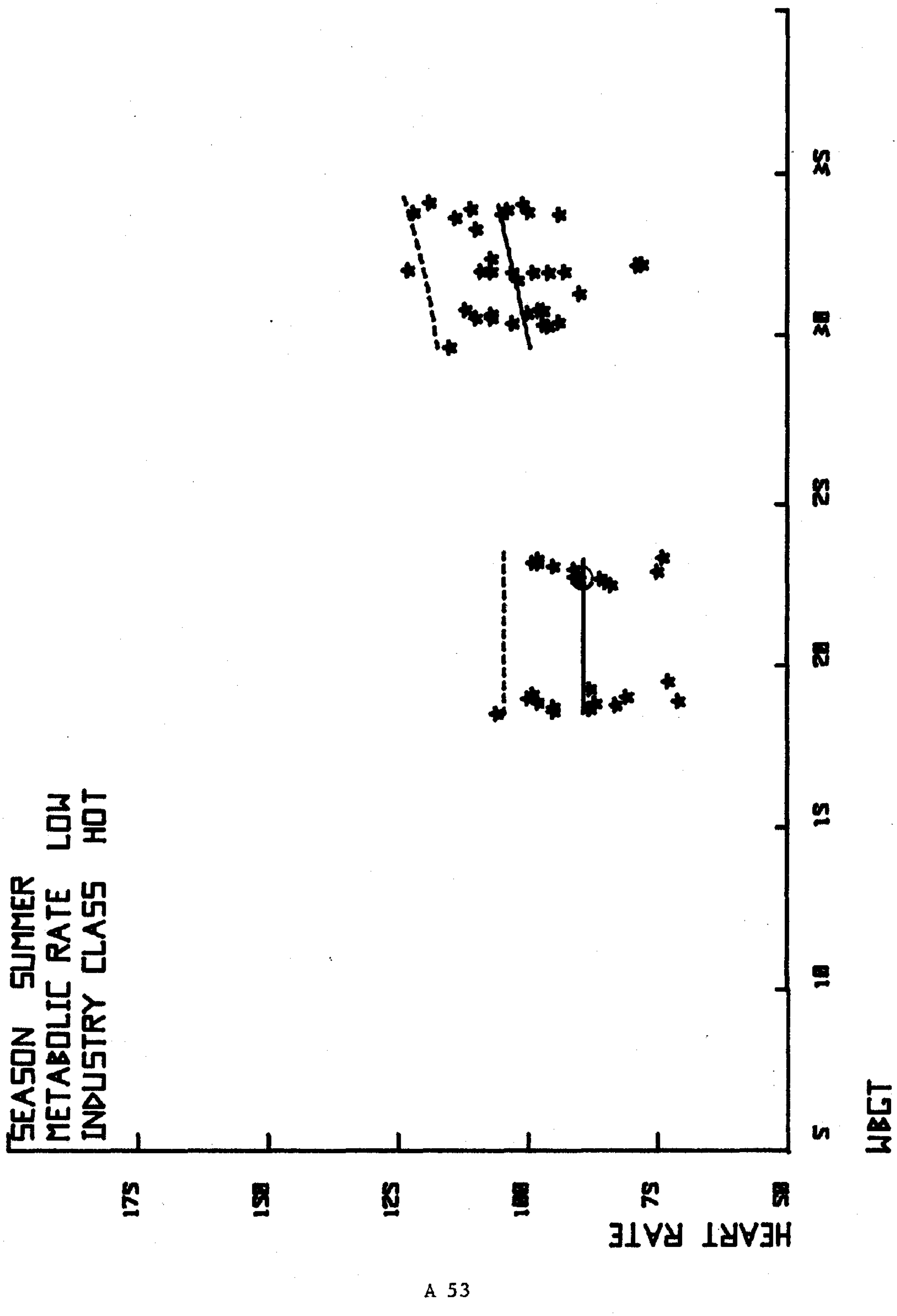
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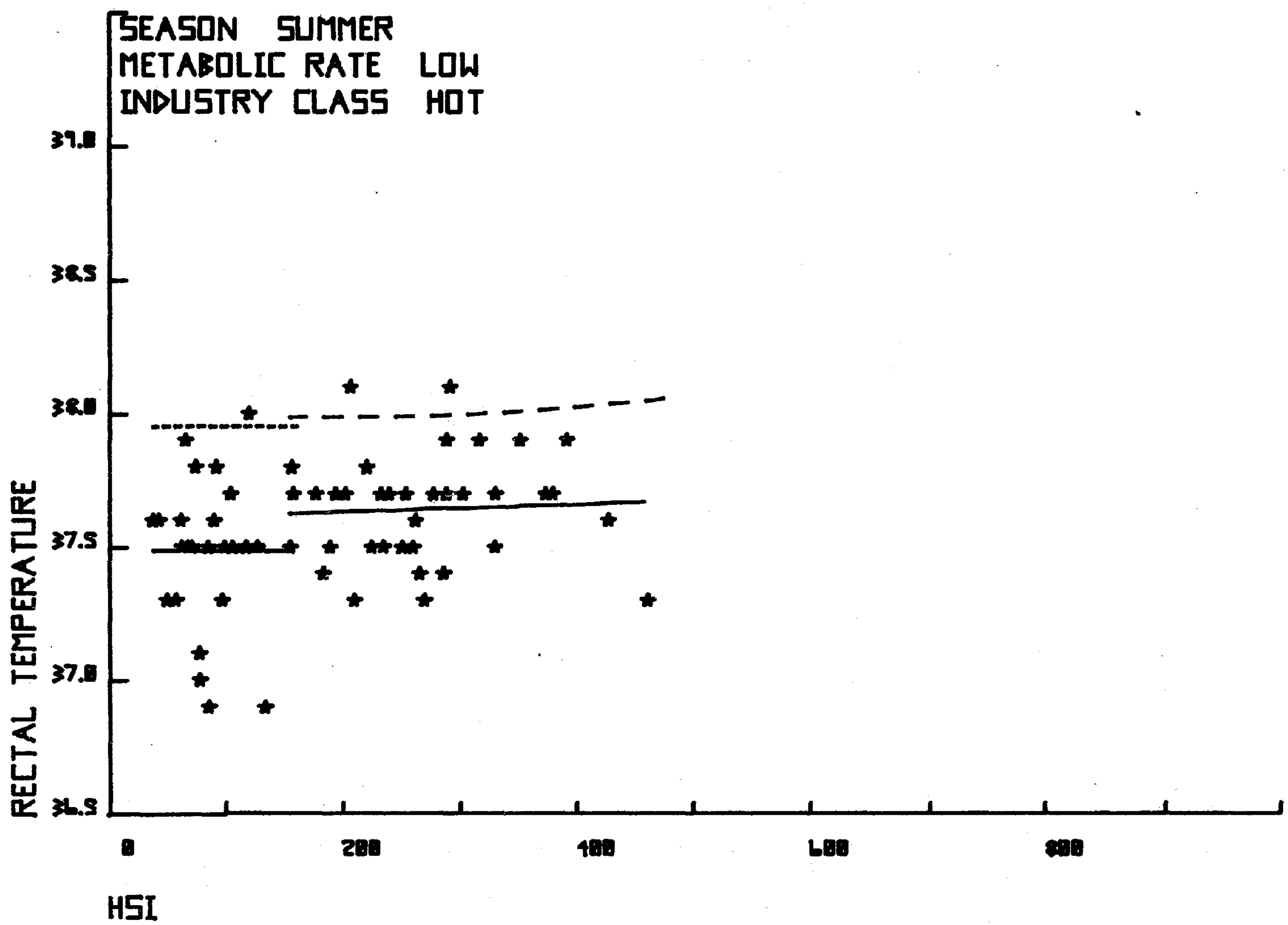
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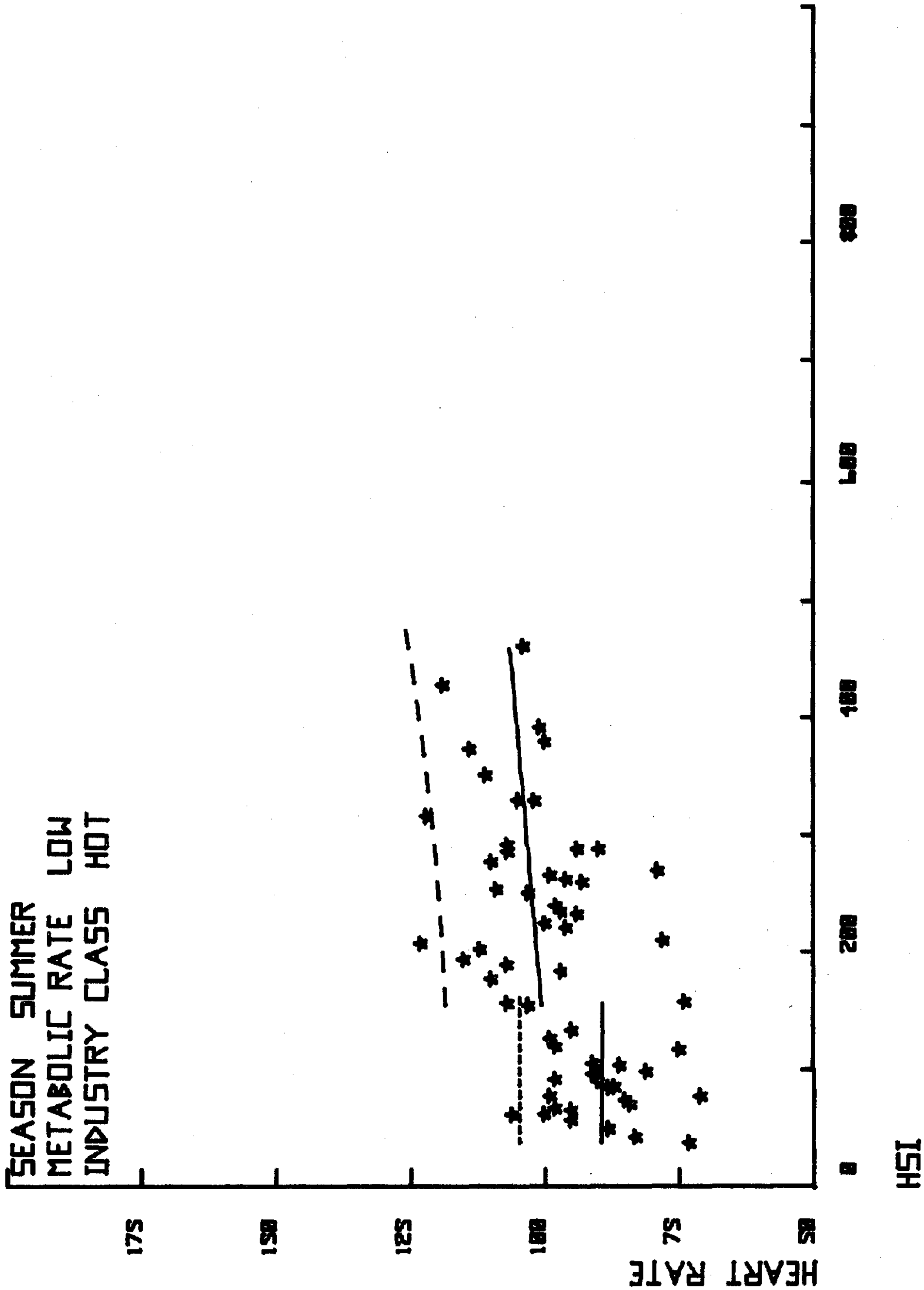
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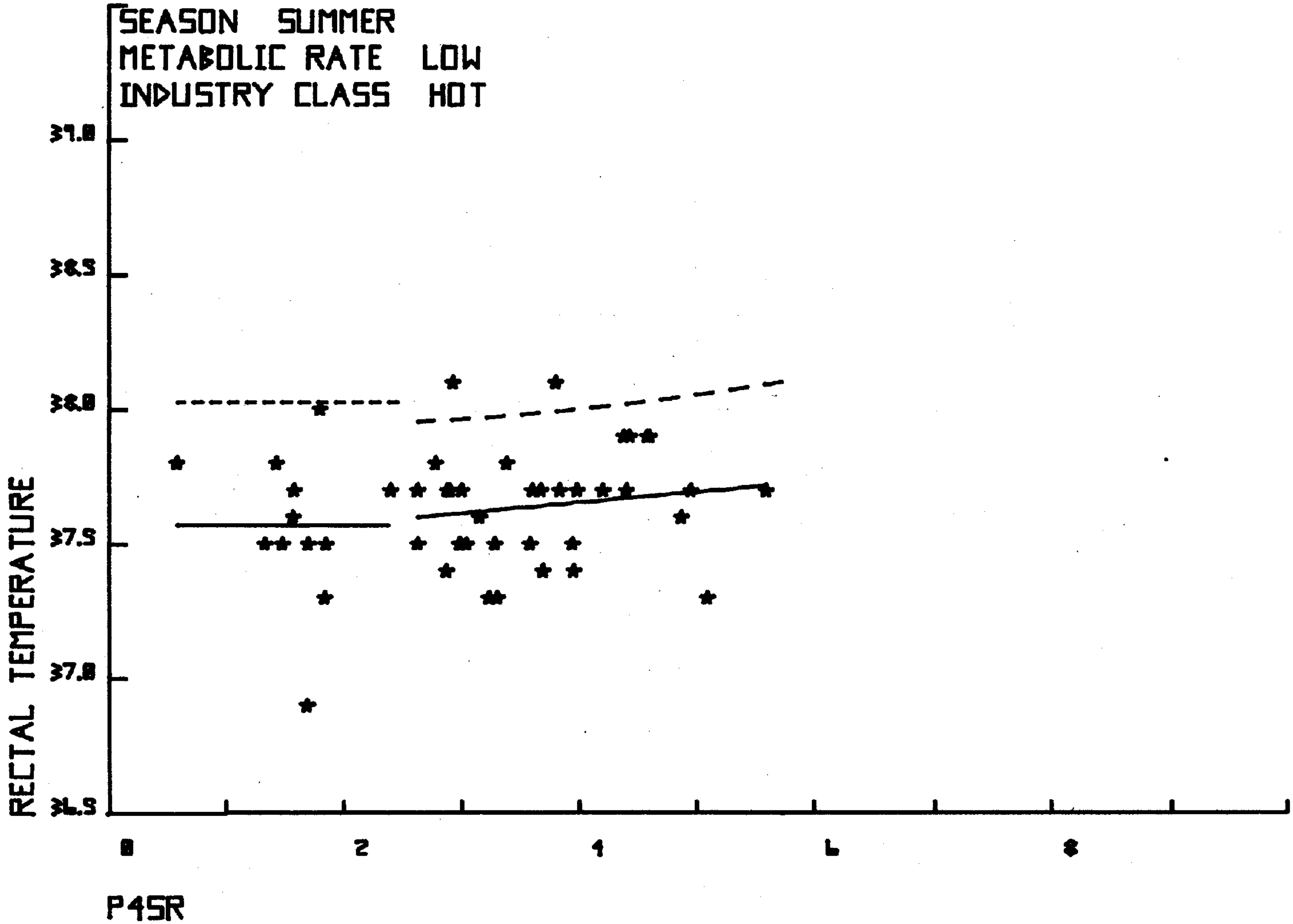
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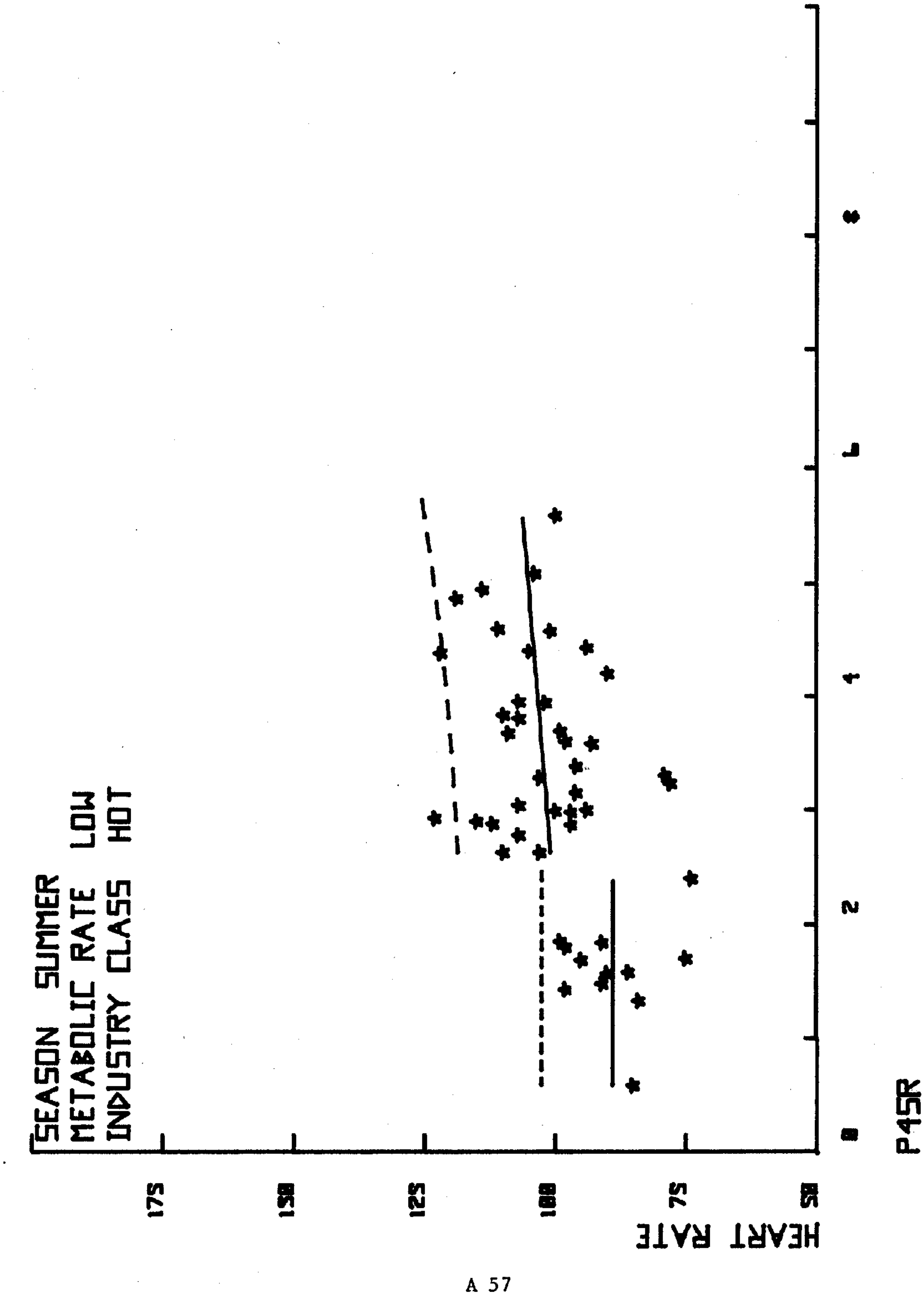

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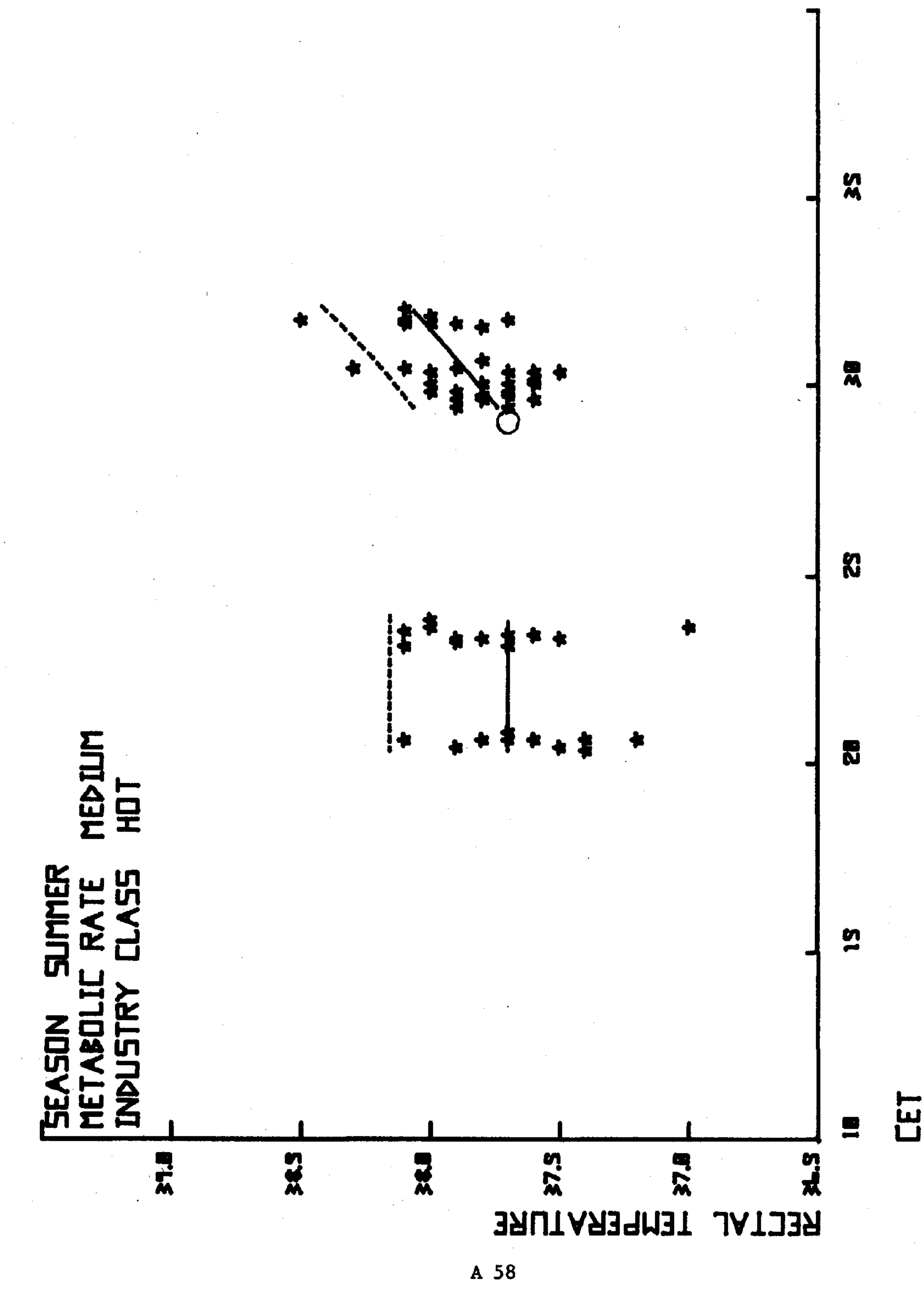

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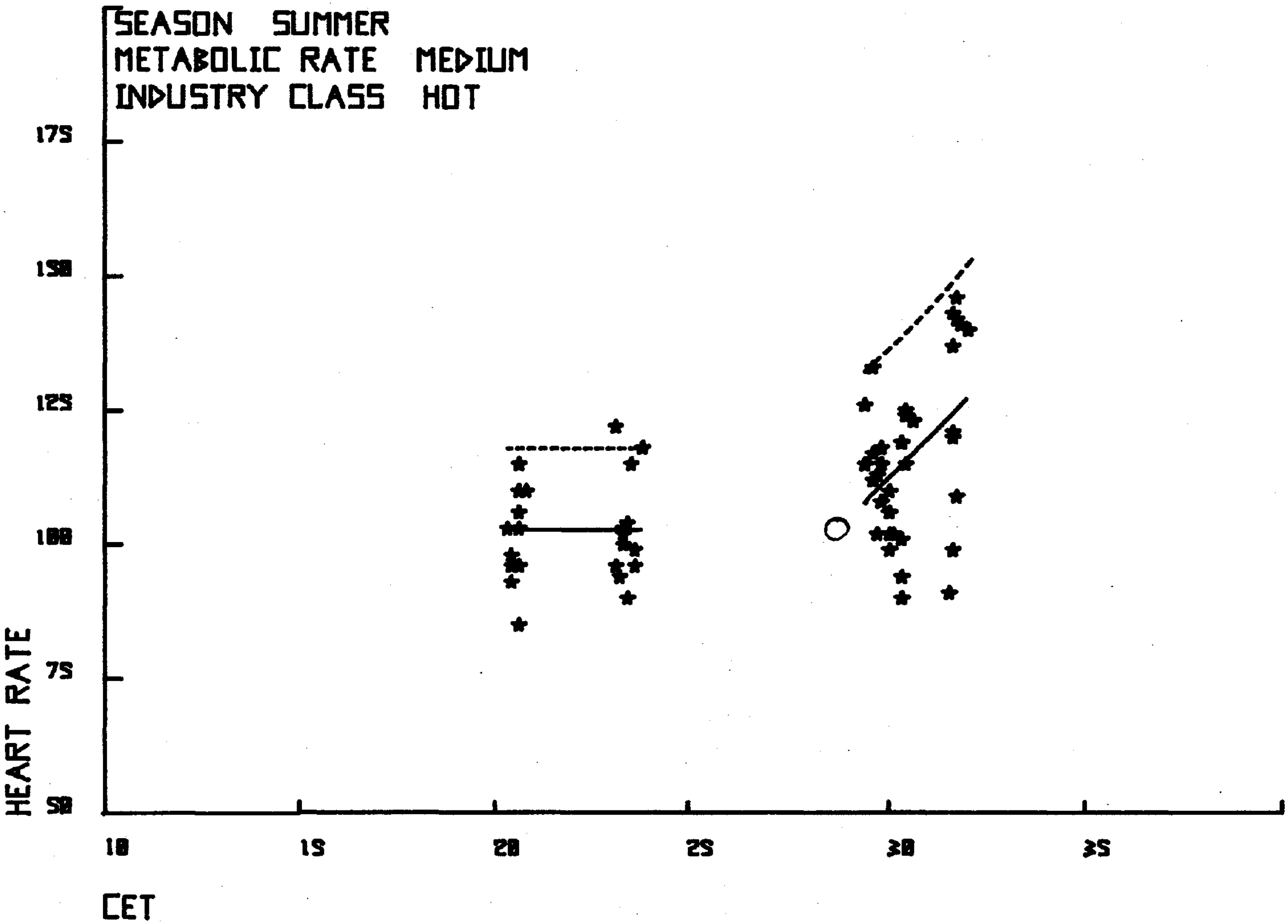
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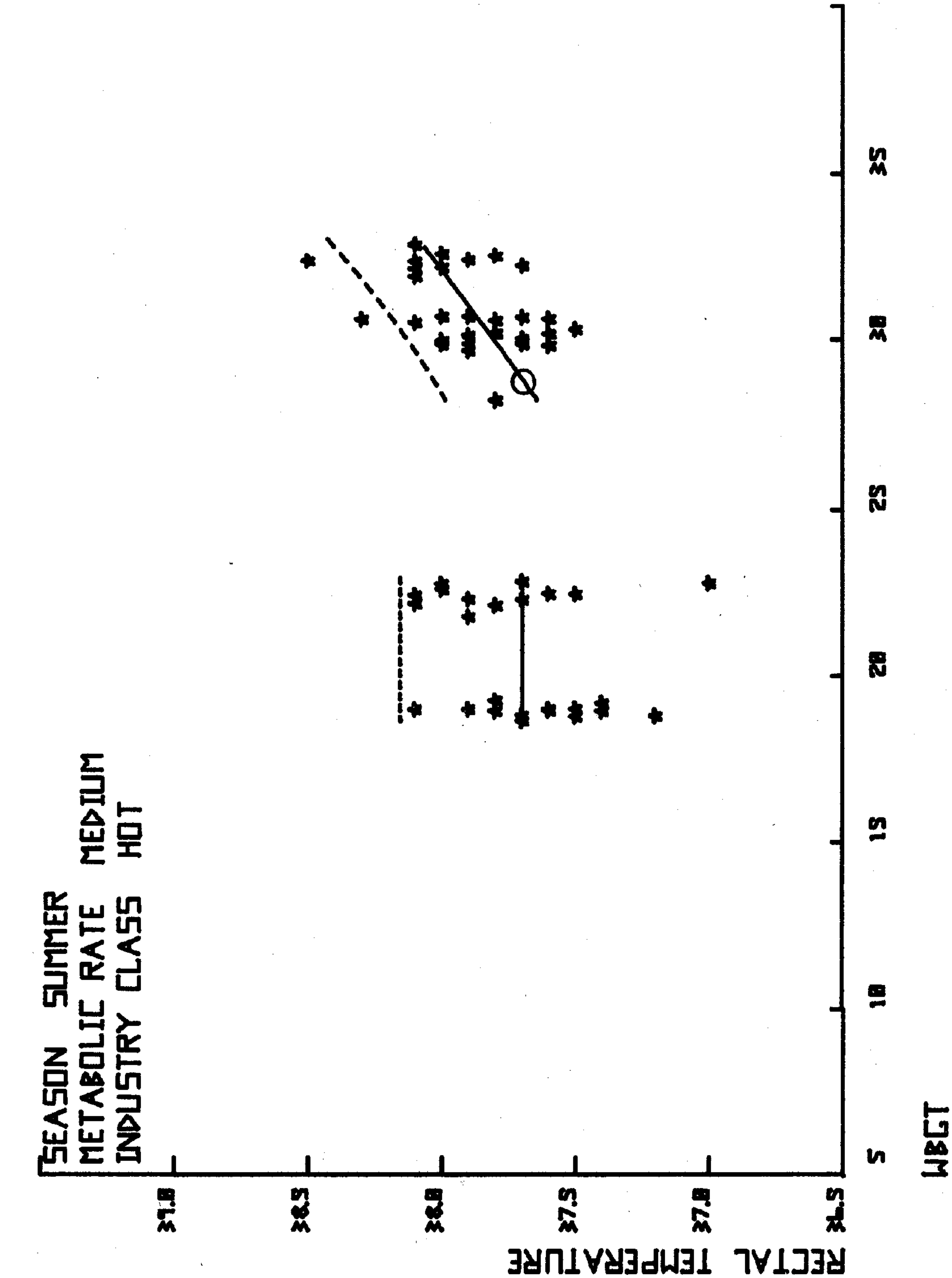
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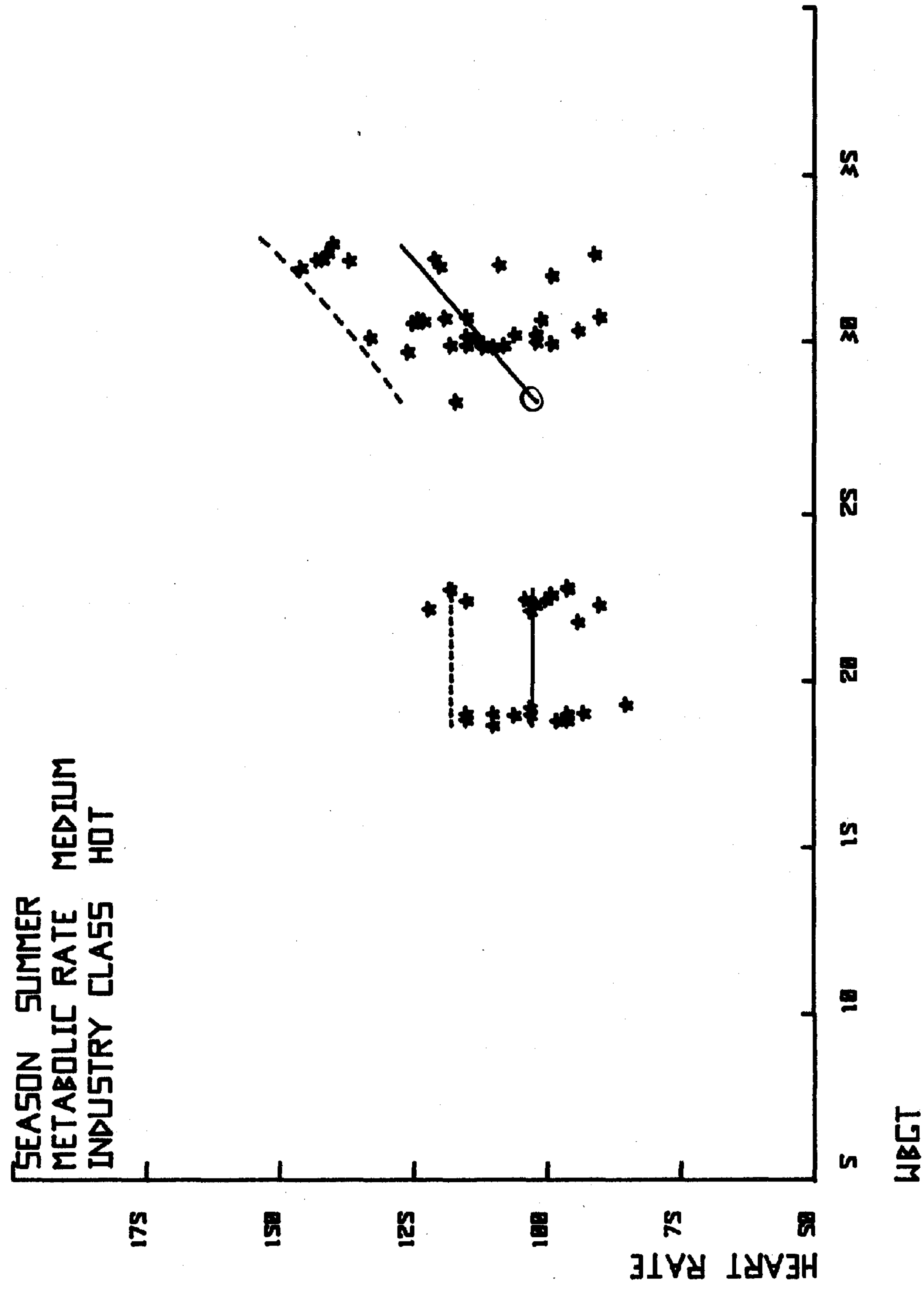
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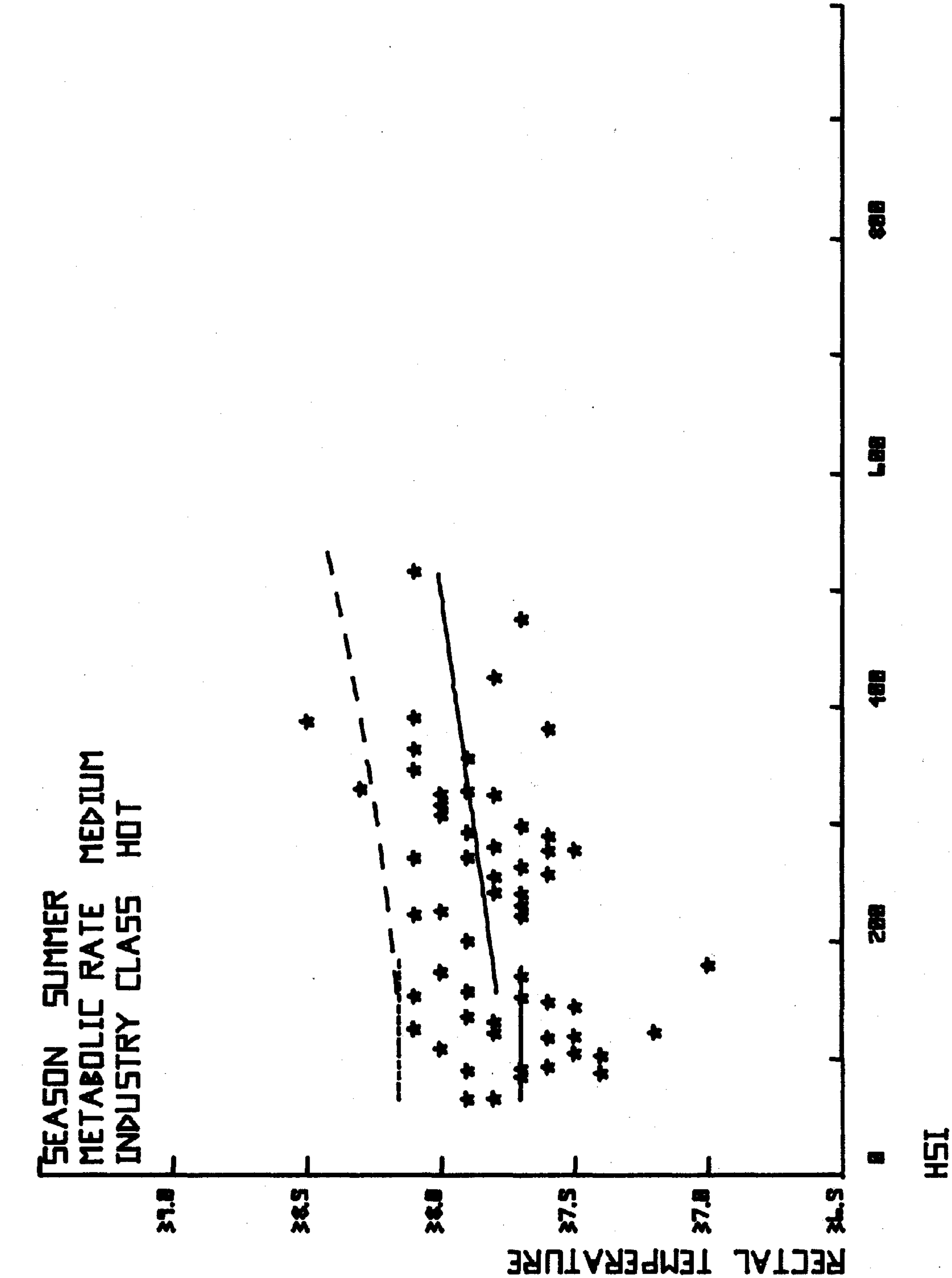
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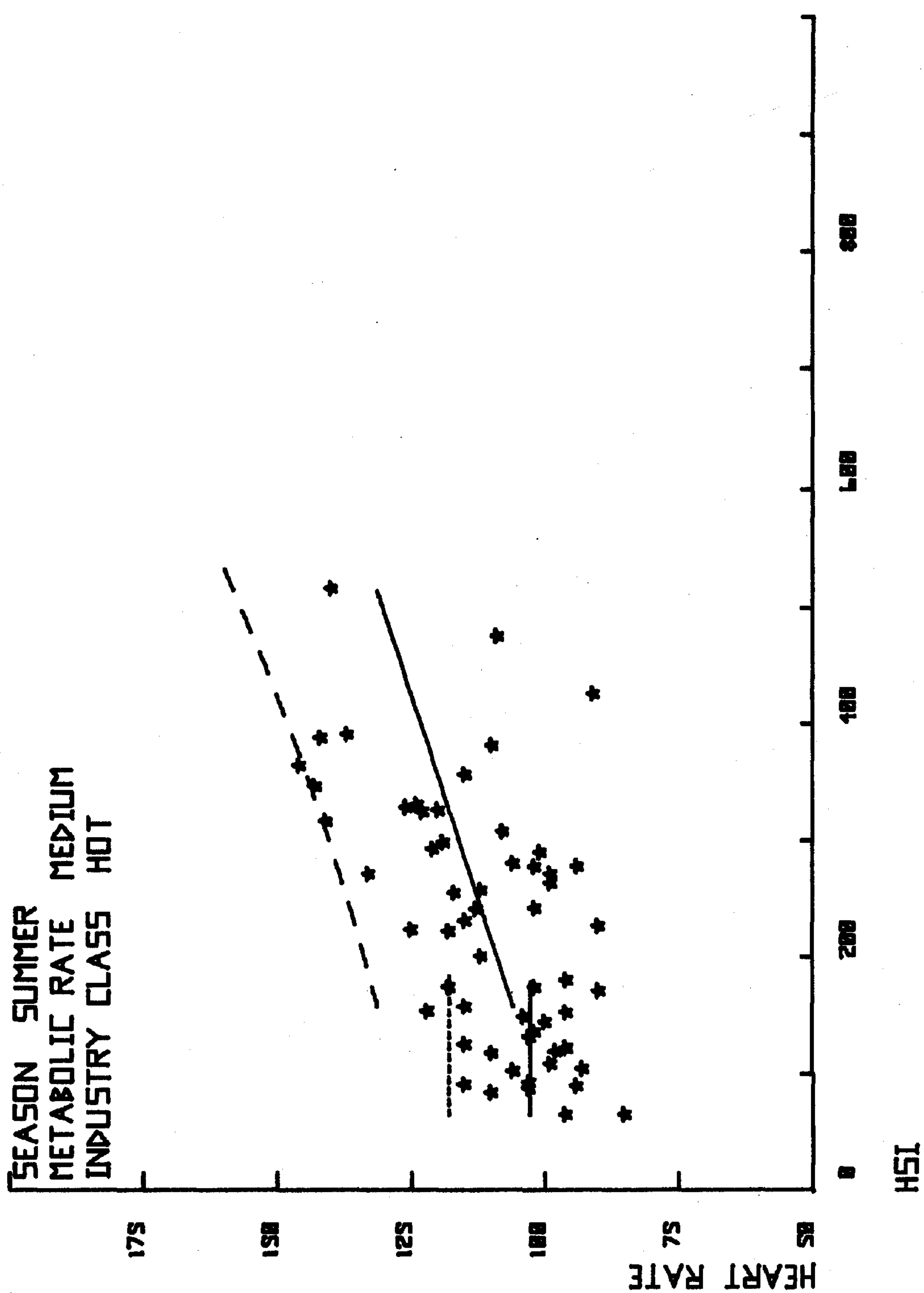
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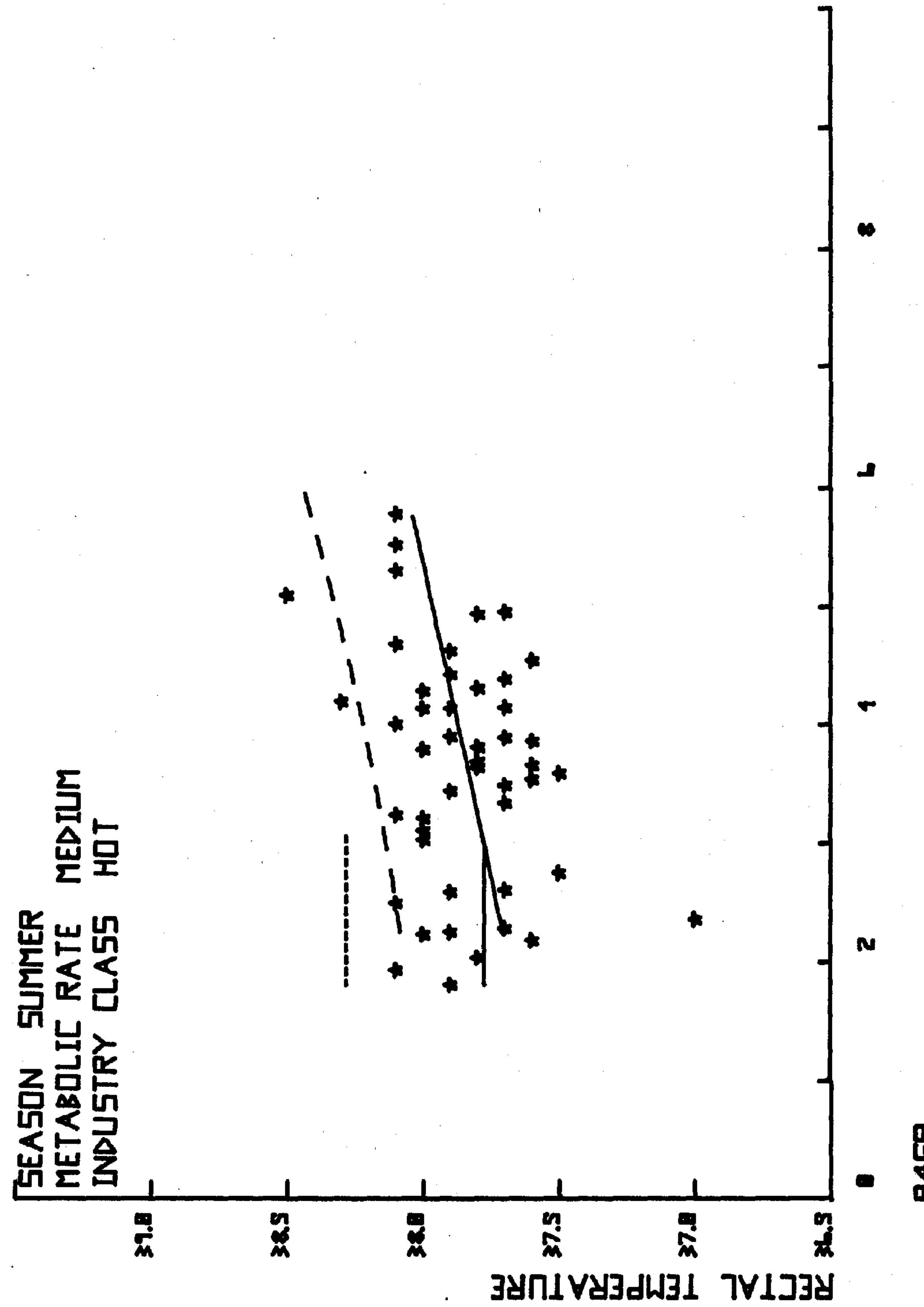
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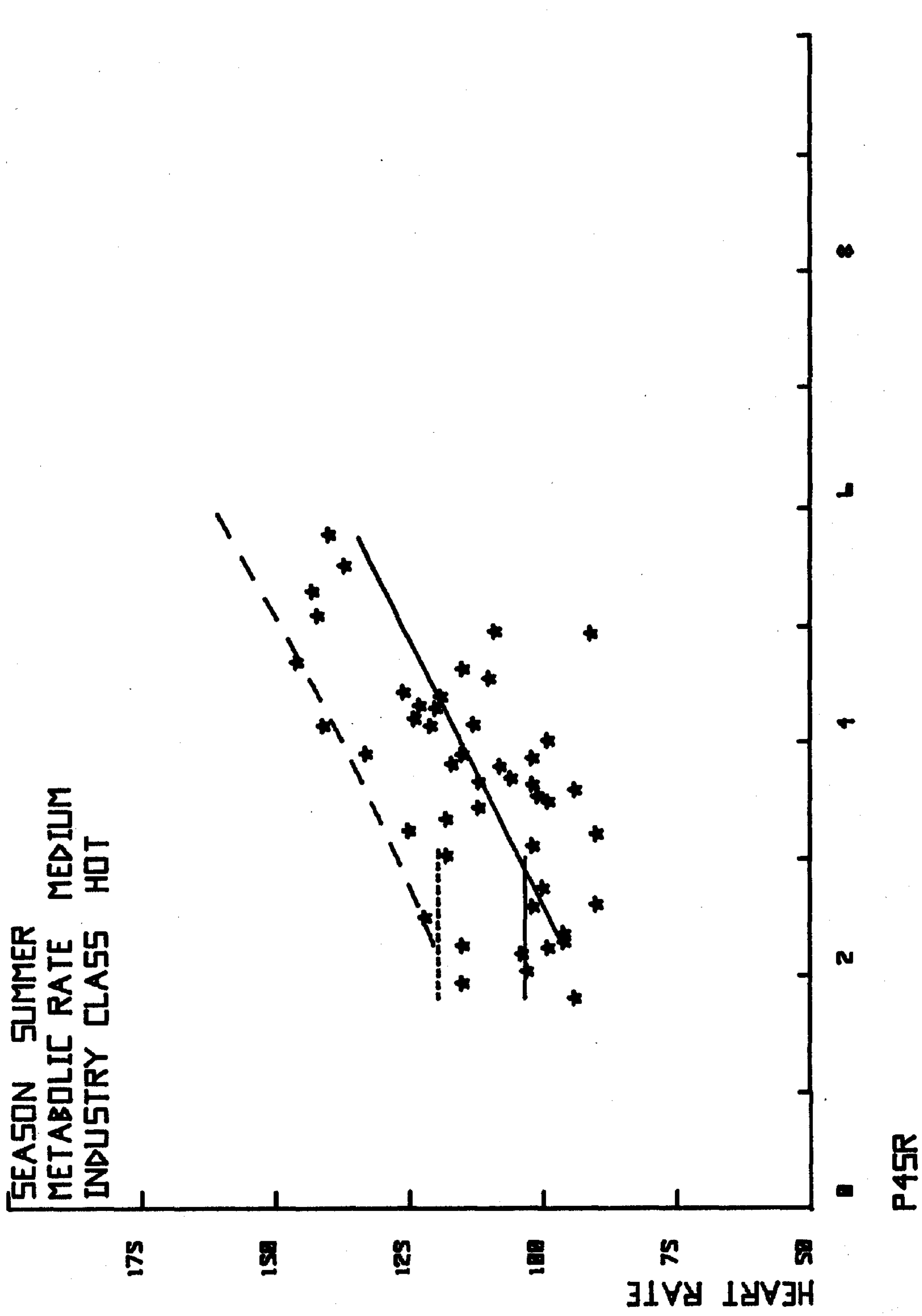
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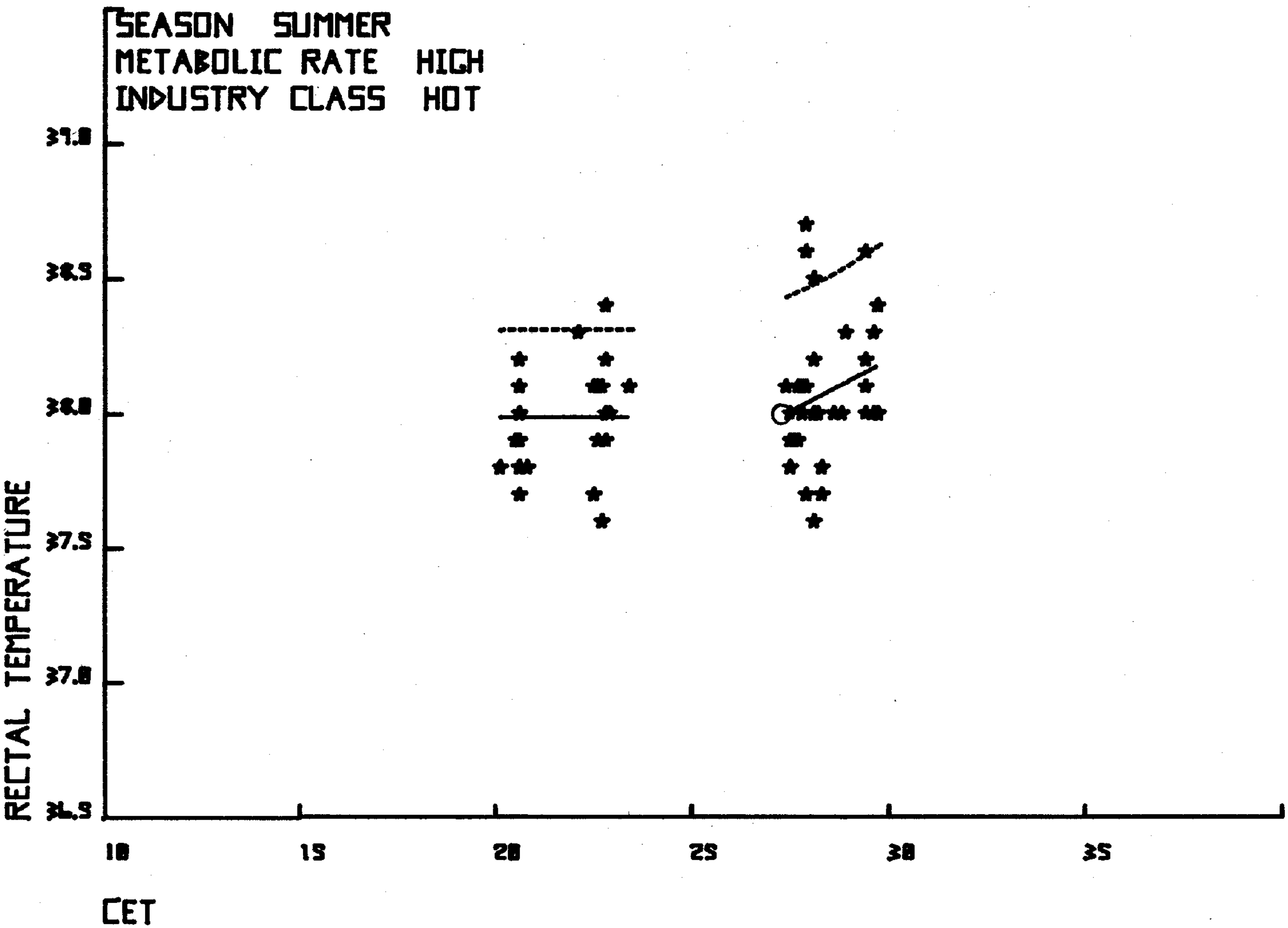
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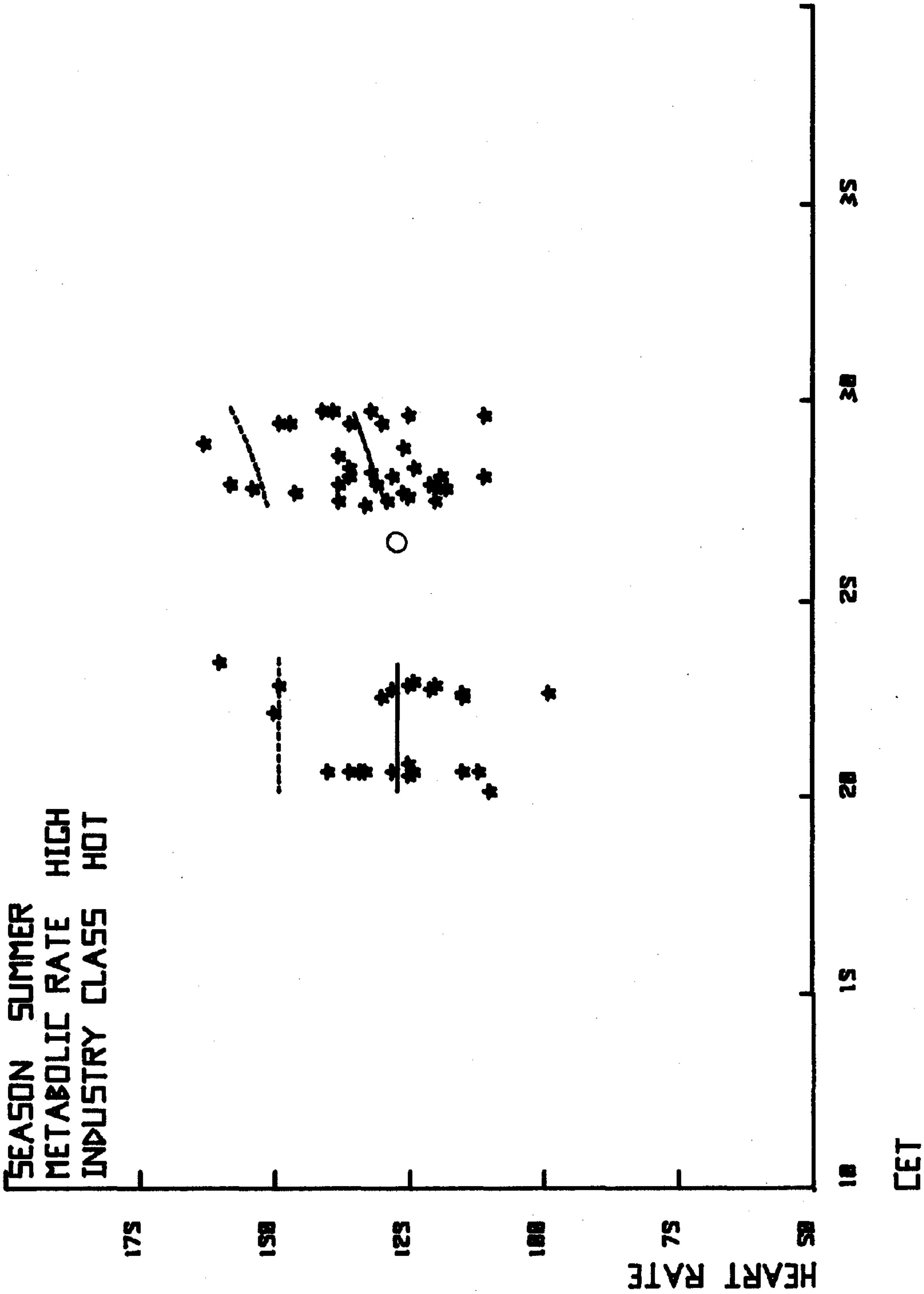
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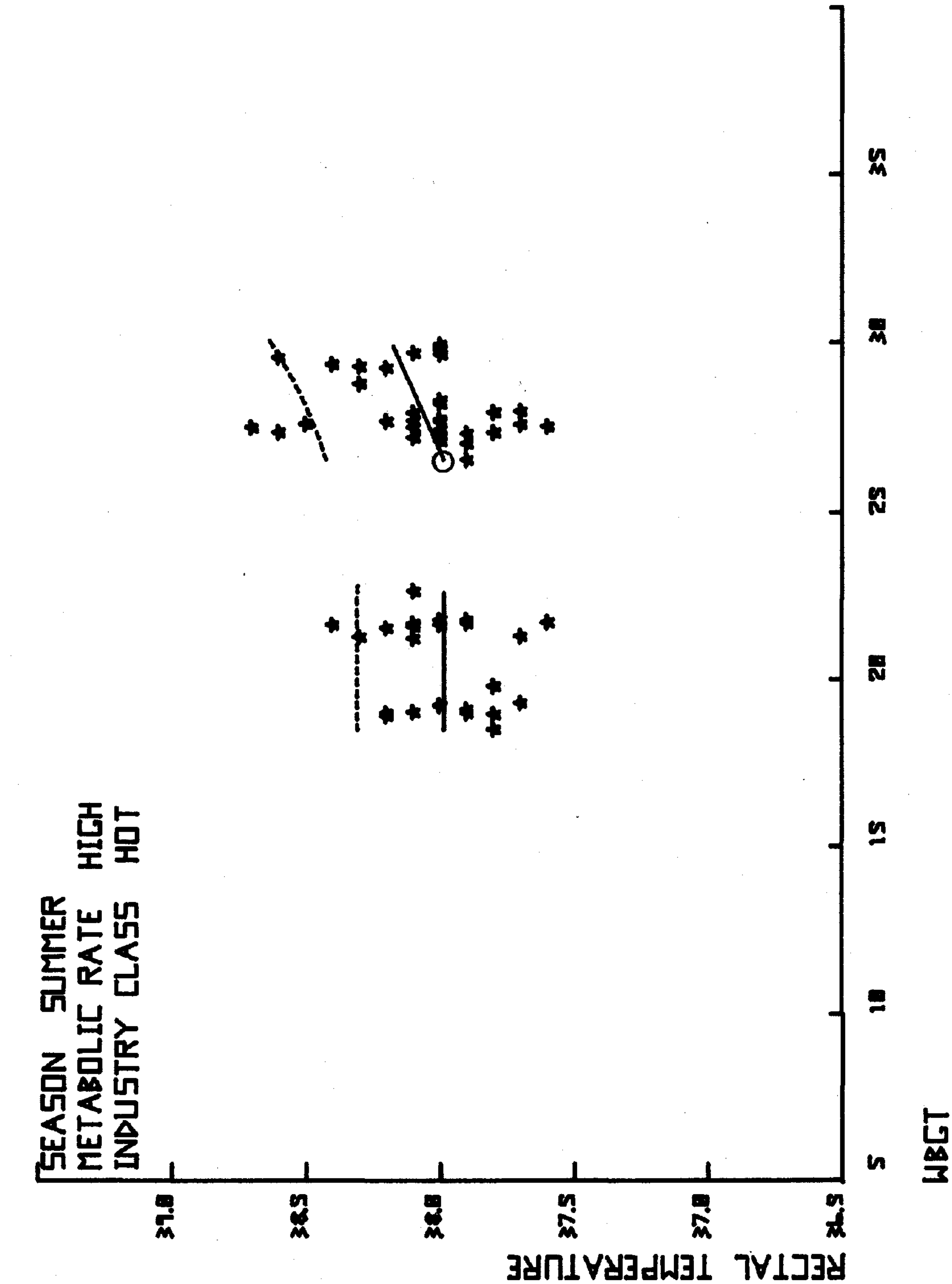
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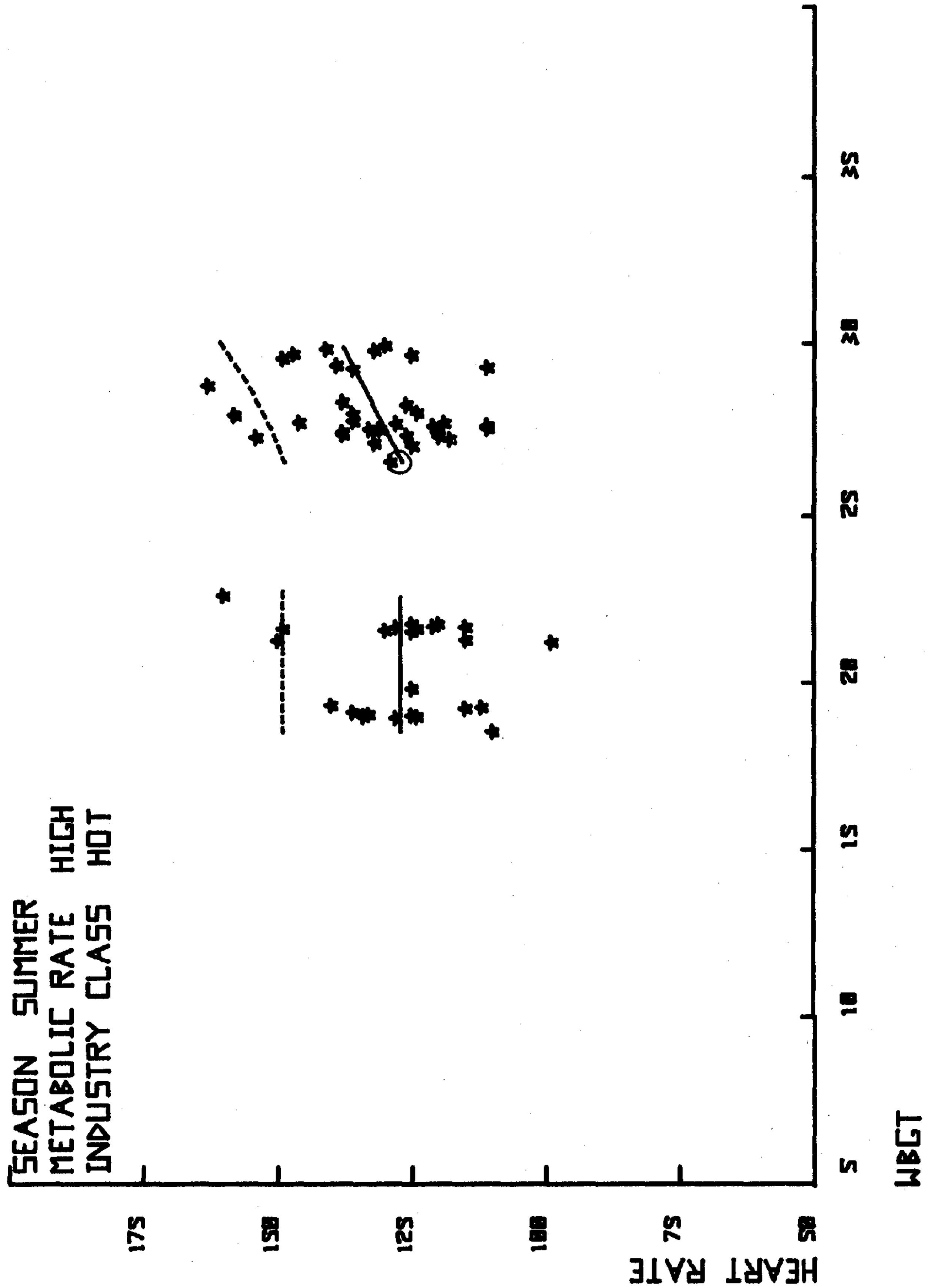
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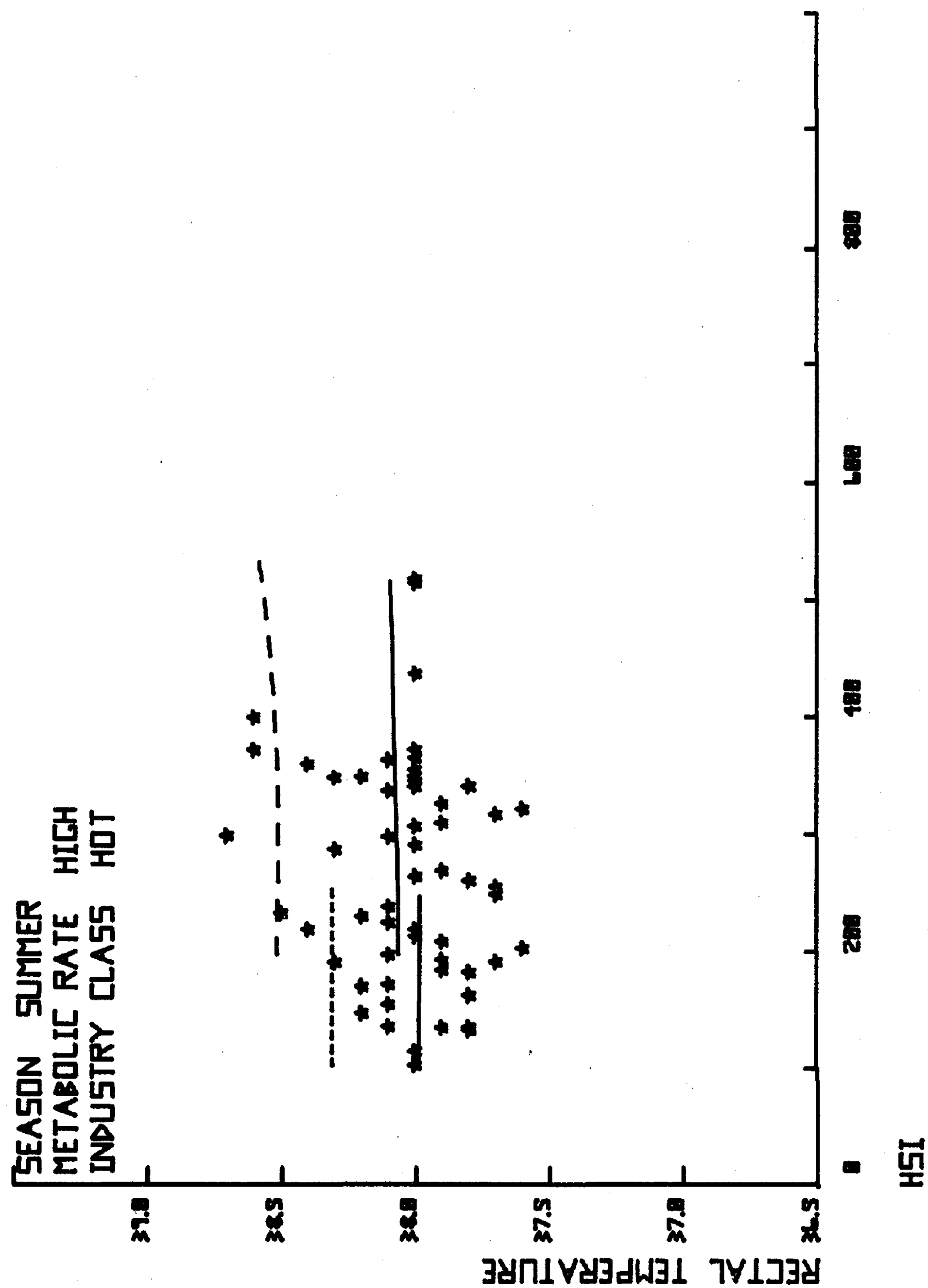
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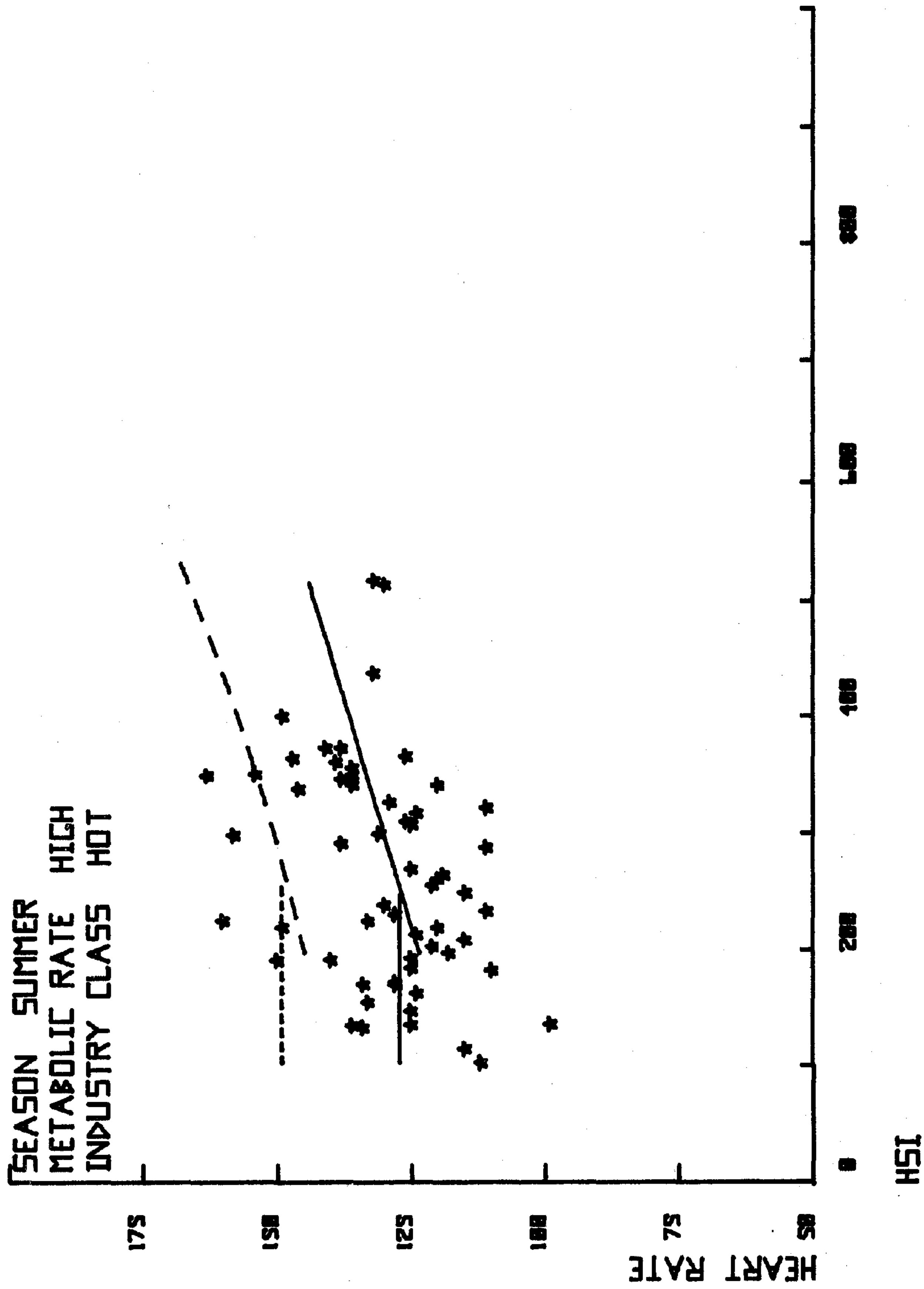
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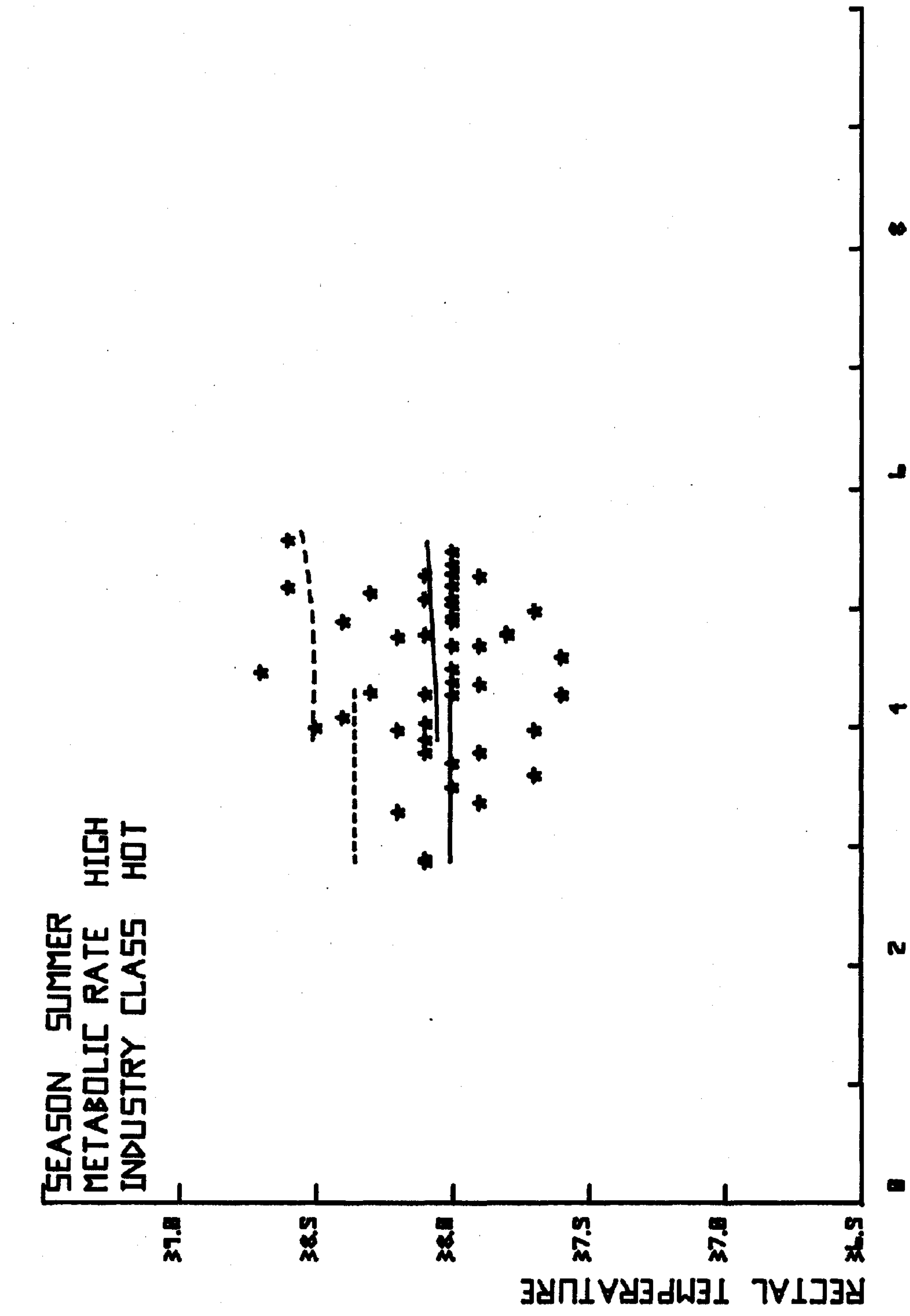
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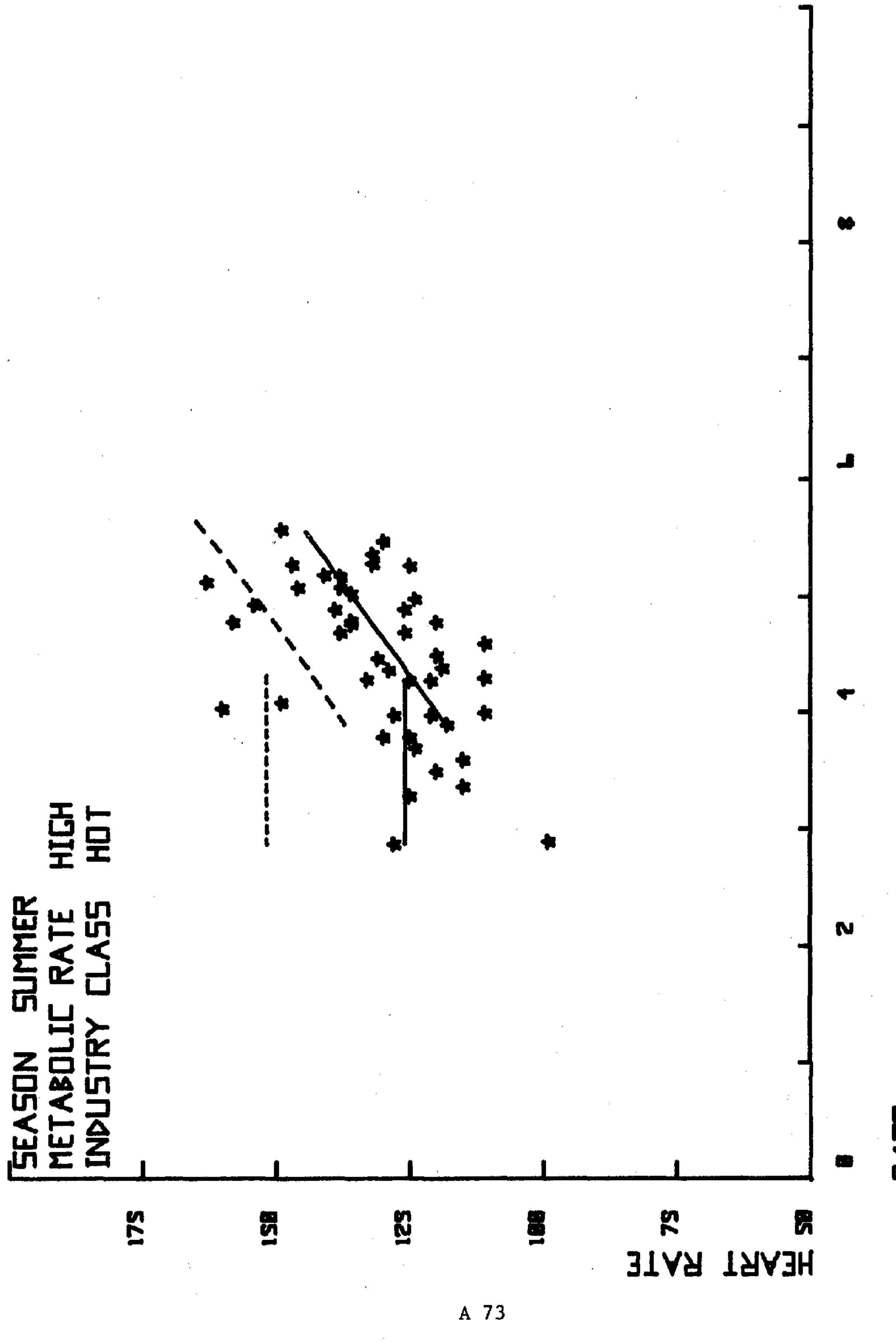
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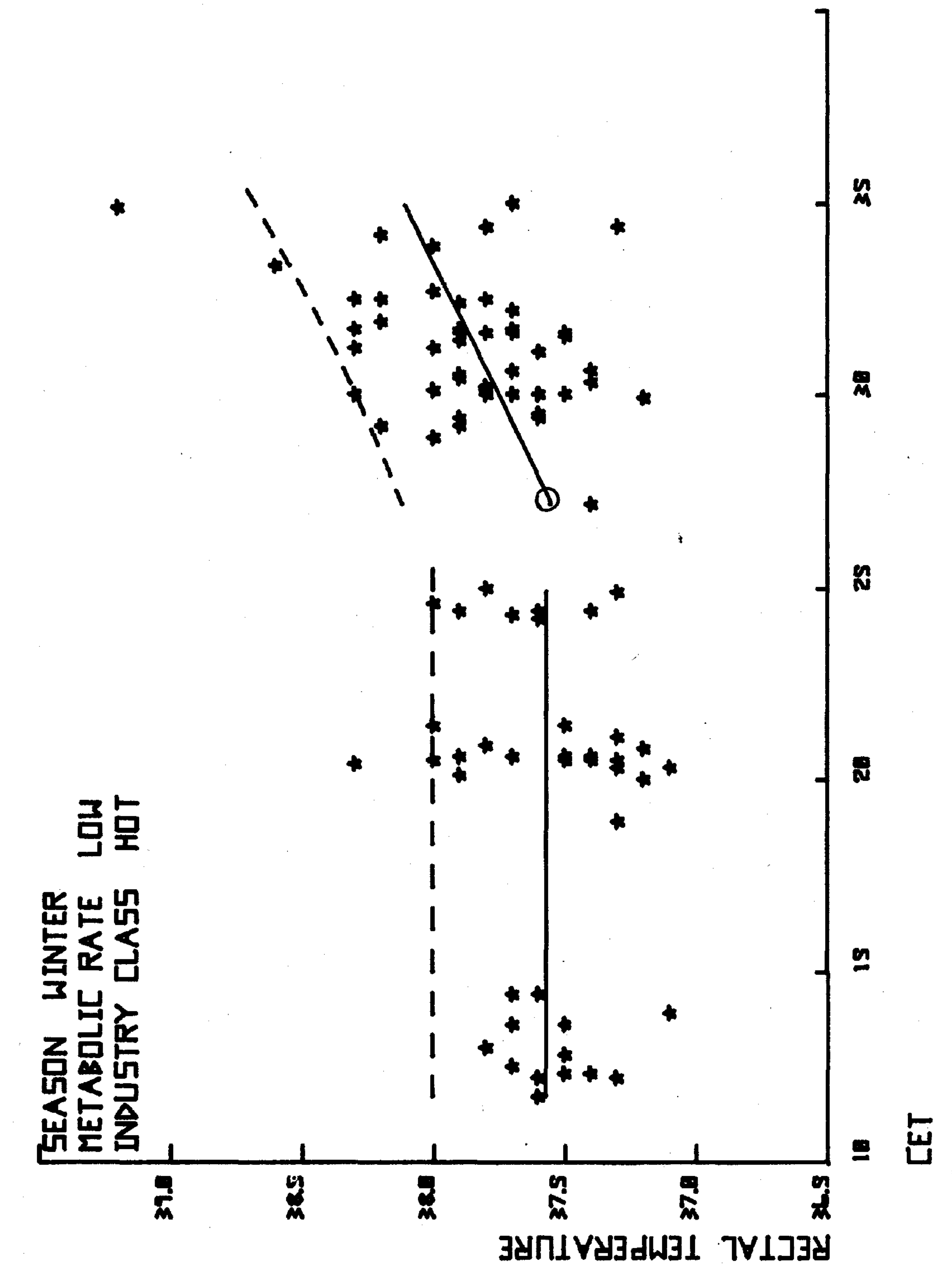
P45R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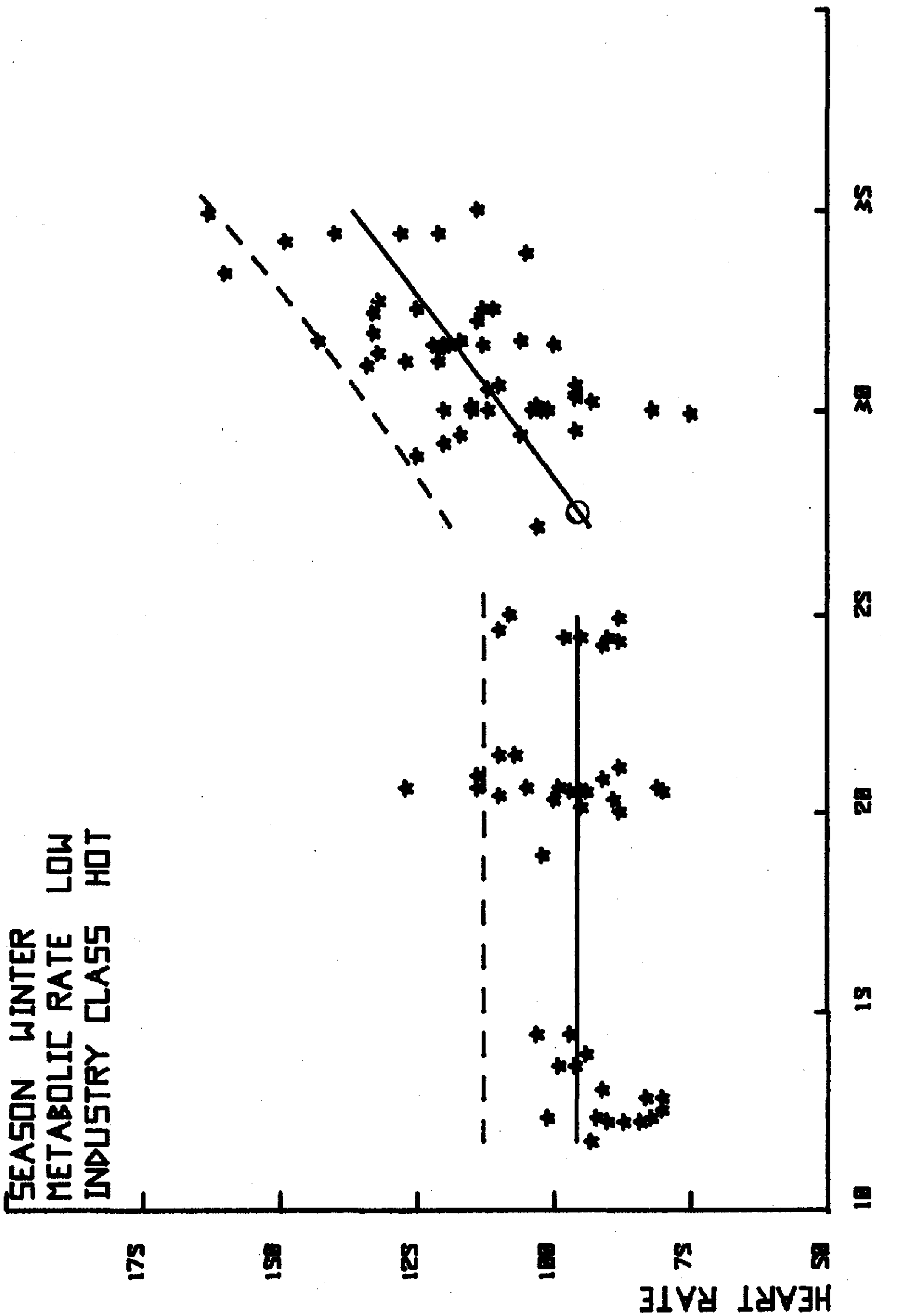
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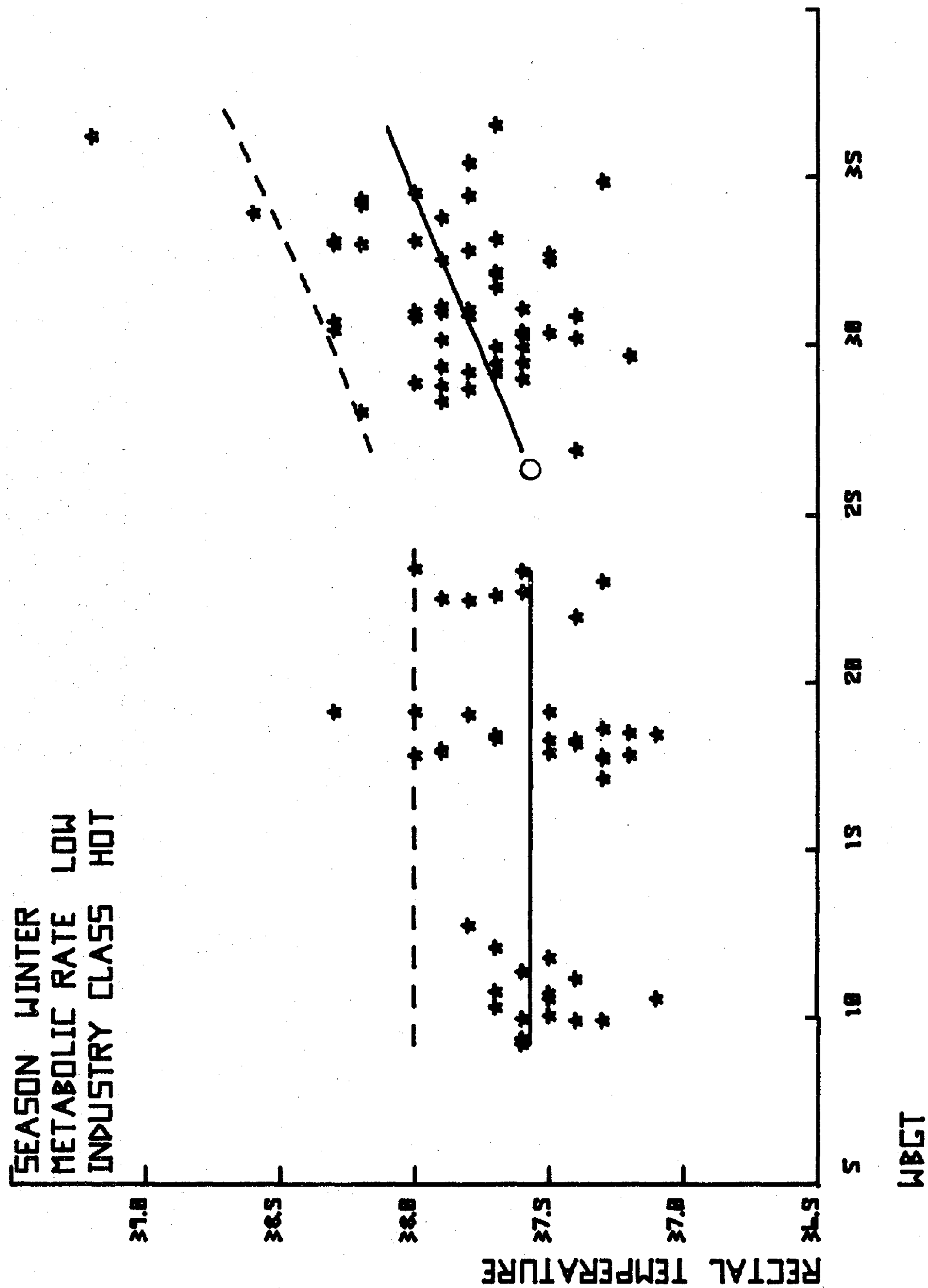
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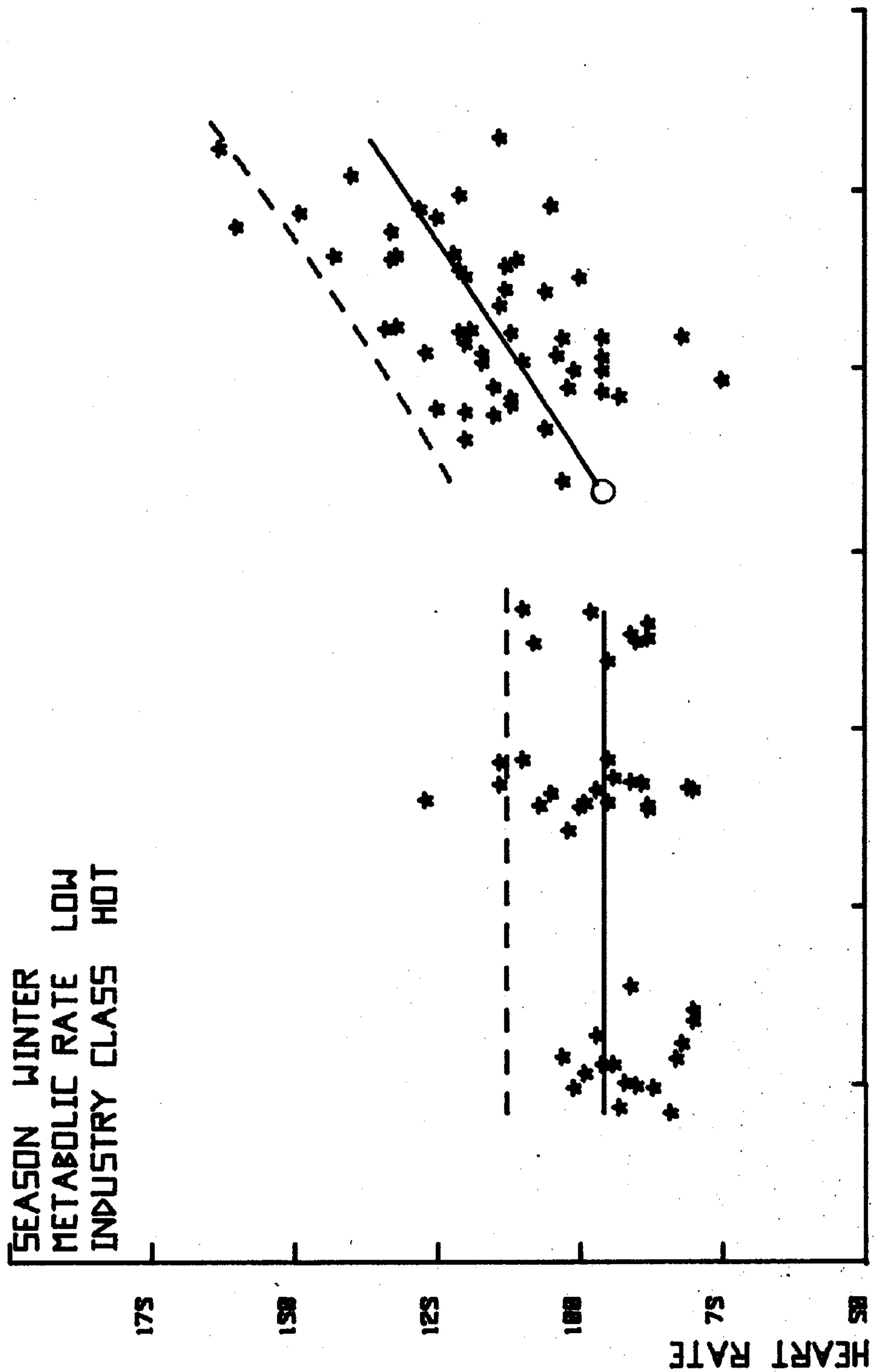
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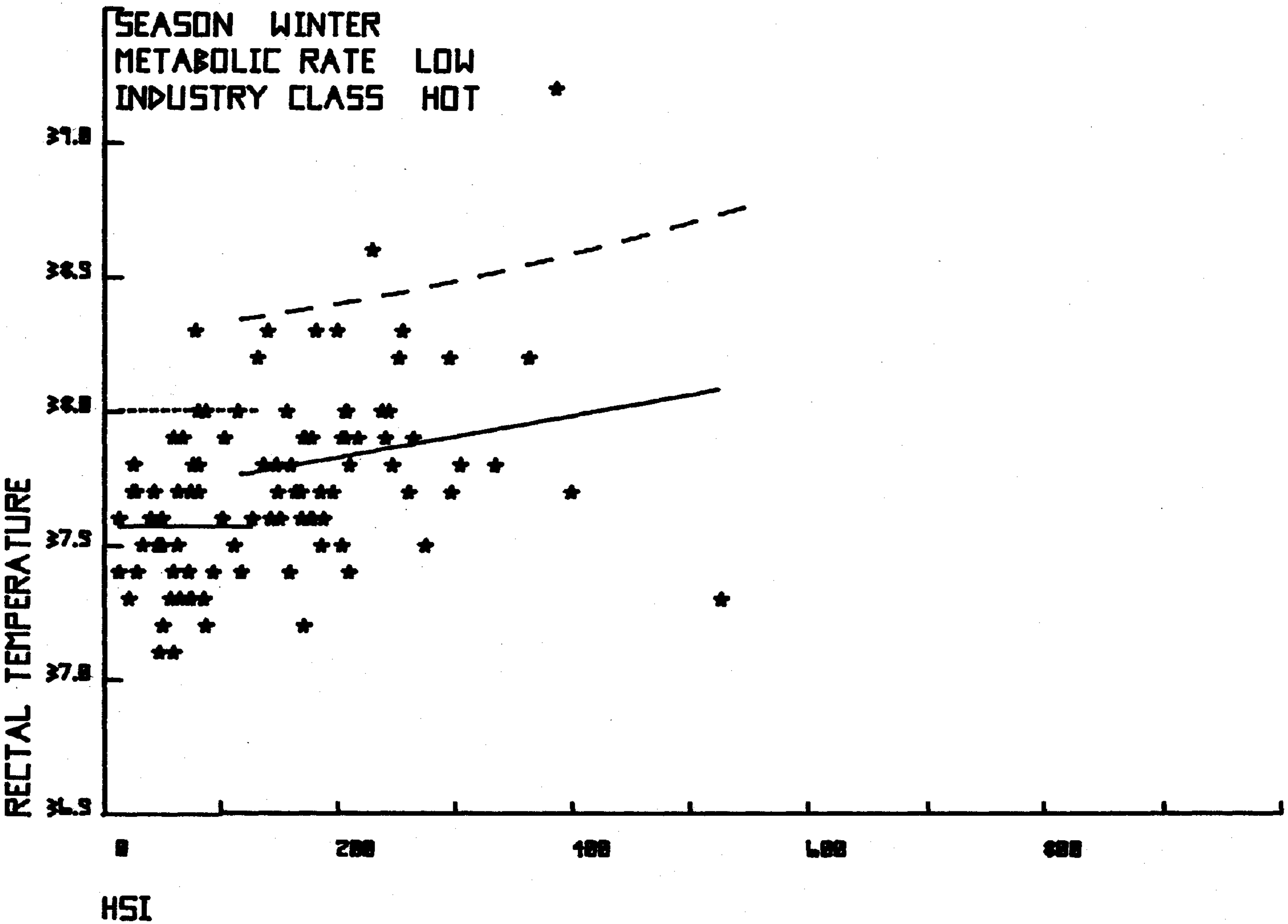
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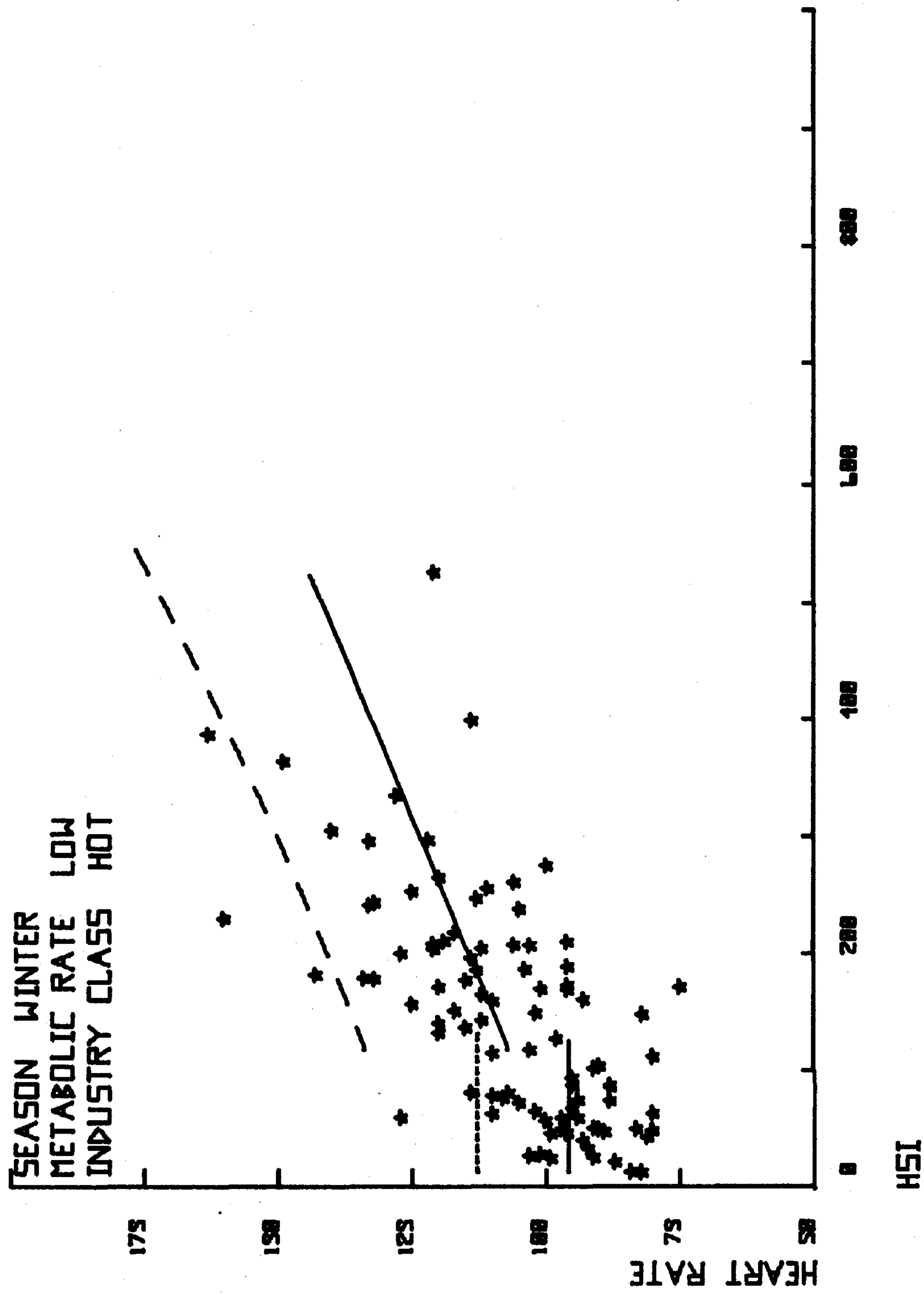
HSI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HEART RATE
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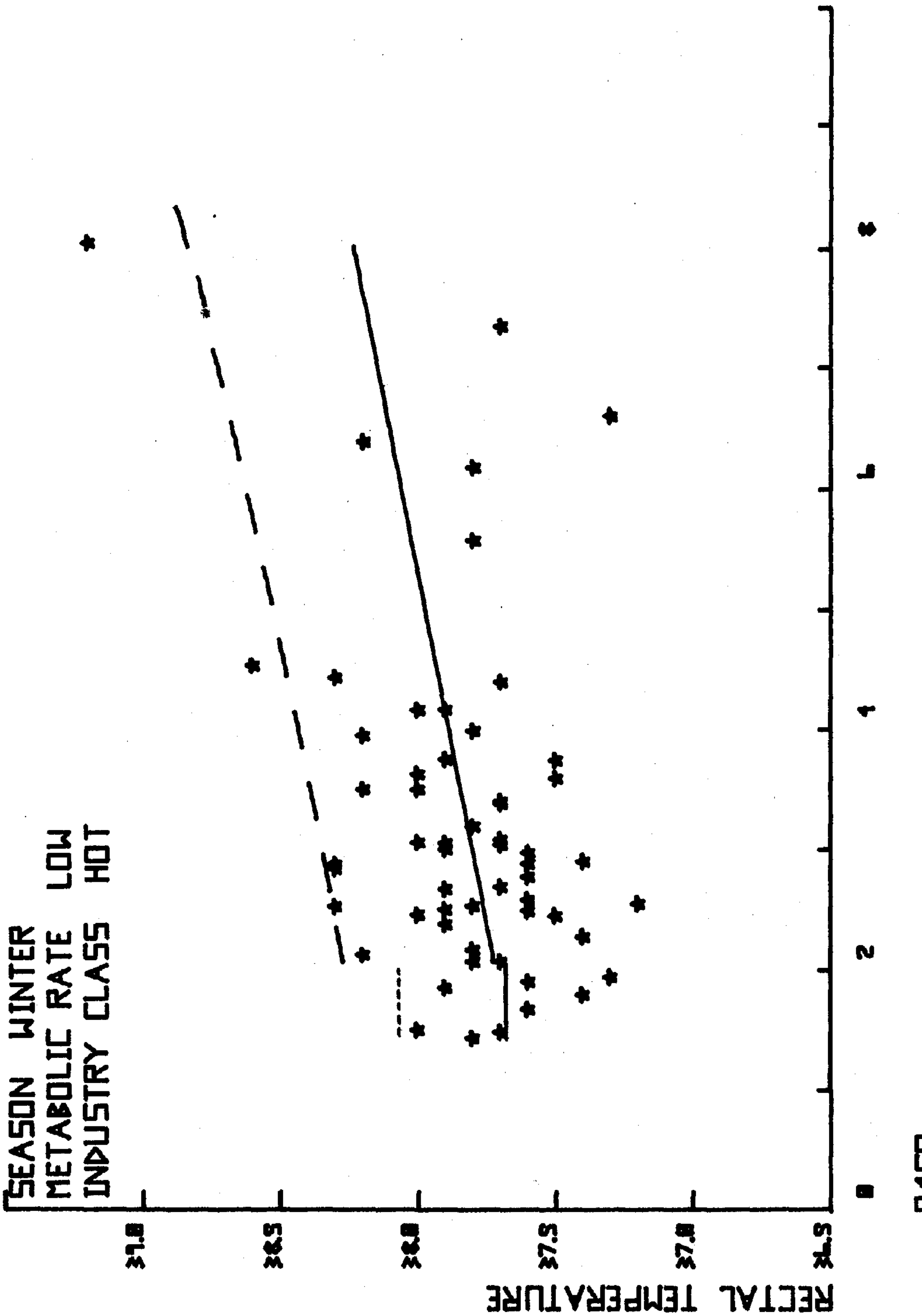

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METABOLIC RATE LOW
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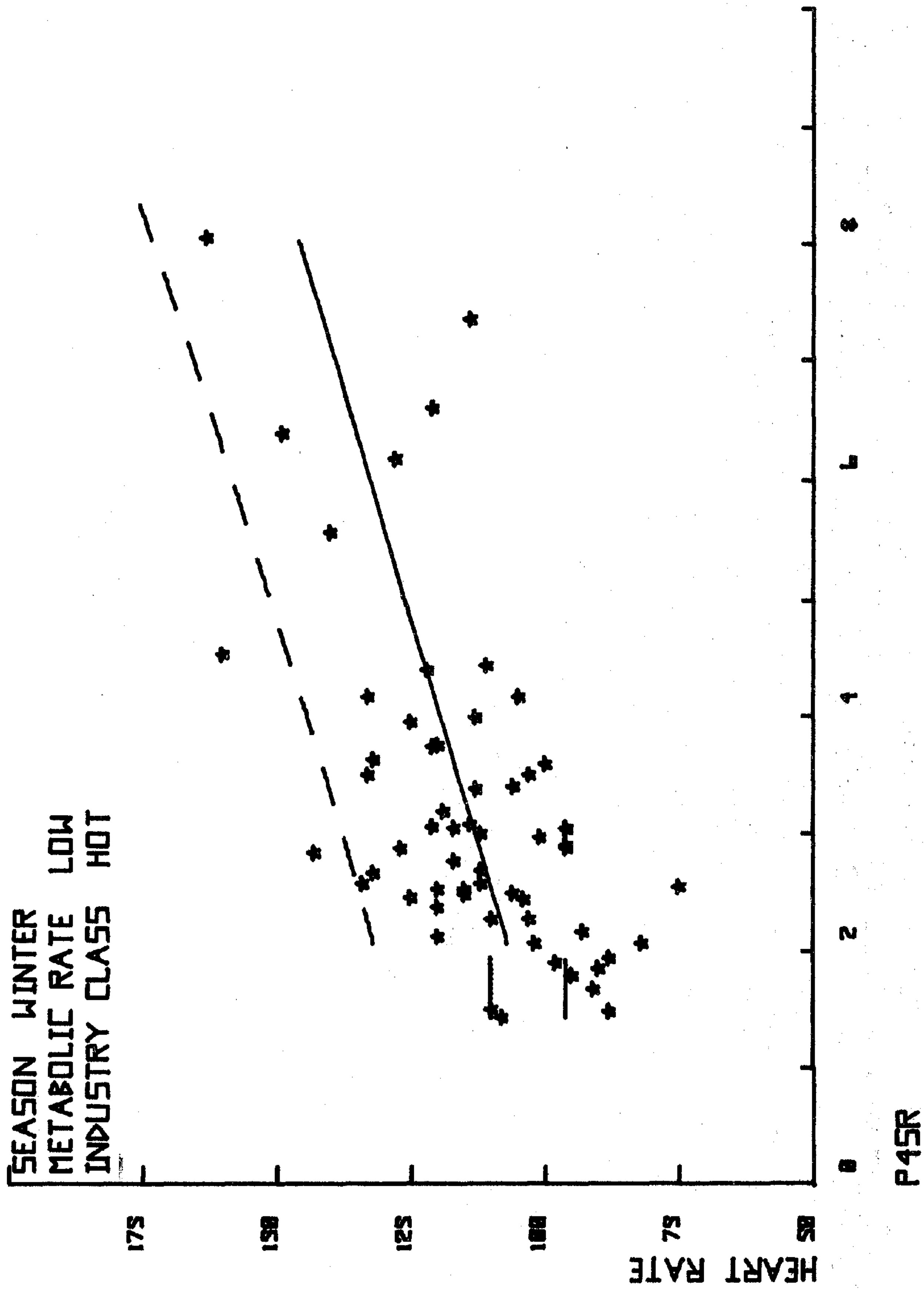
RECTAL TEMPERATURE
P45R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INDUSTRY CLASS HOT
HEART RATE
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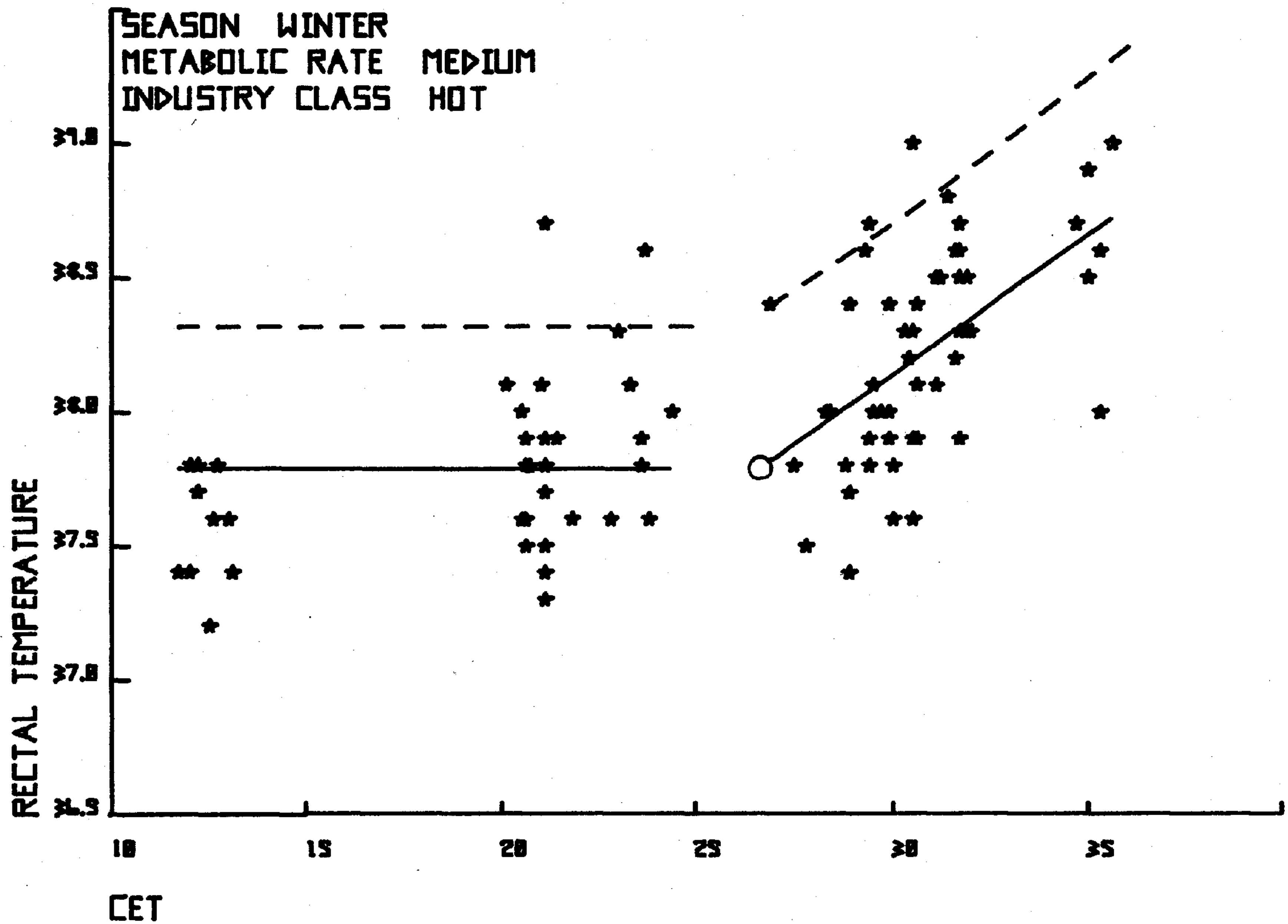
P45R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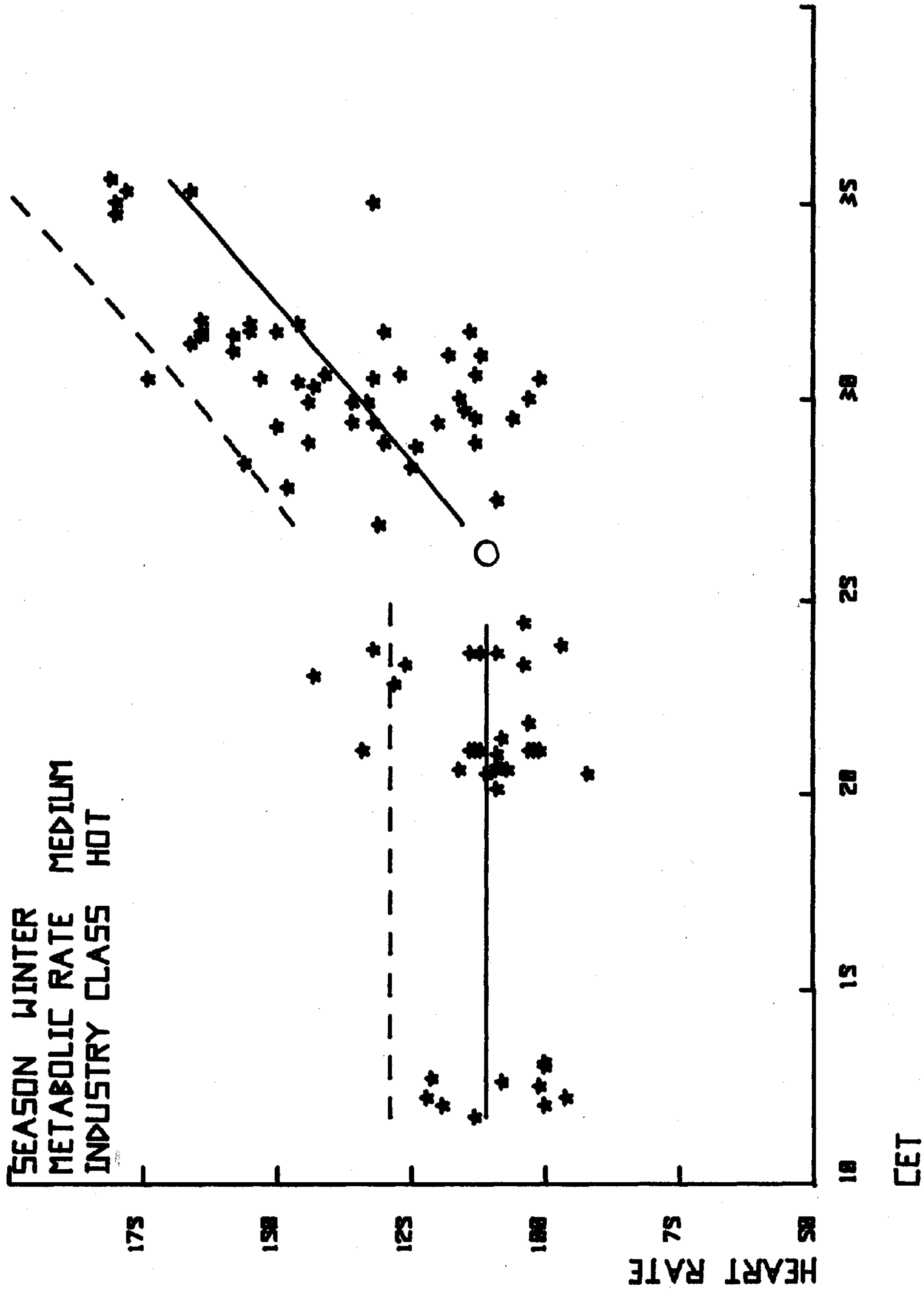
CET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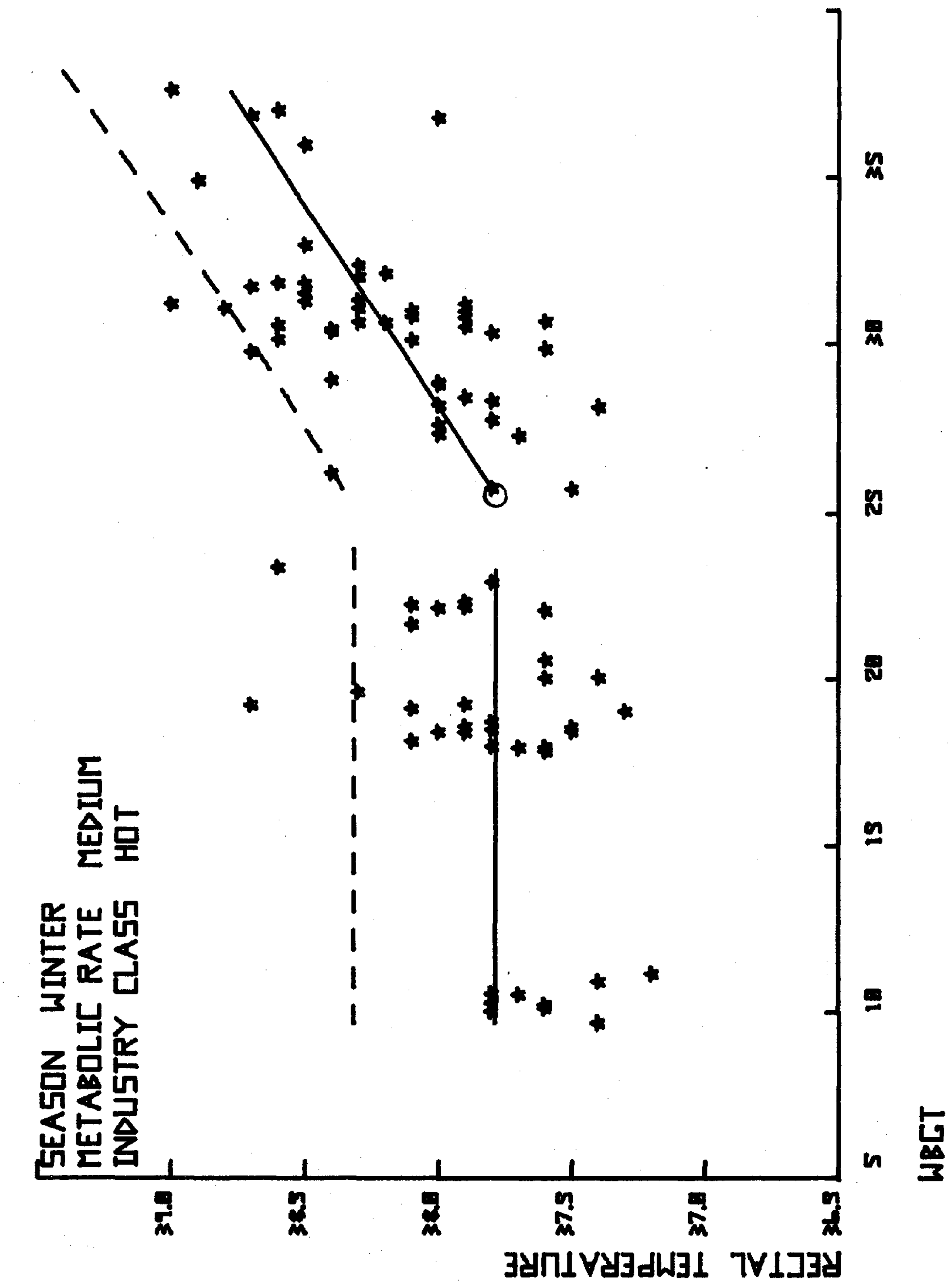

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INDUSTRY CLASS HOT
RECTAL TEMPERATURE
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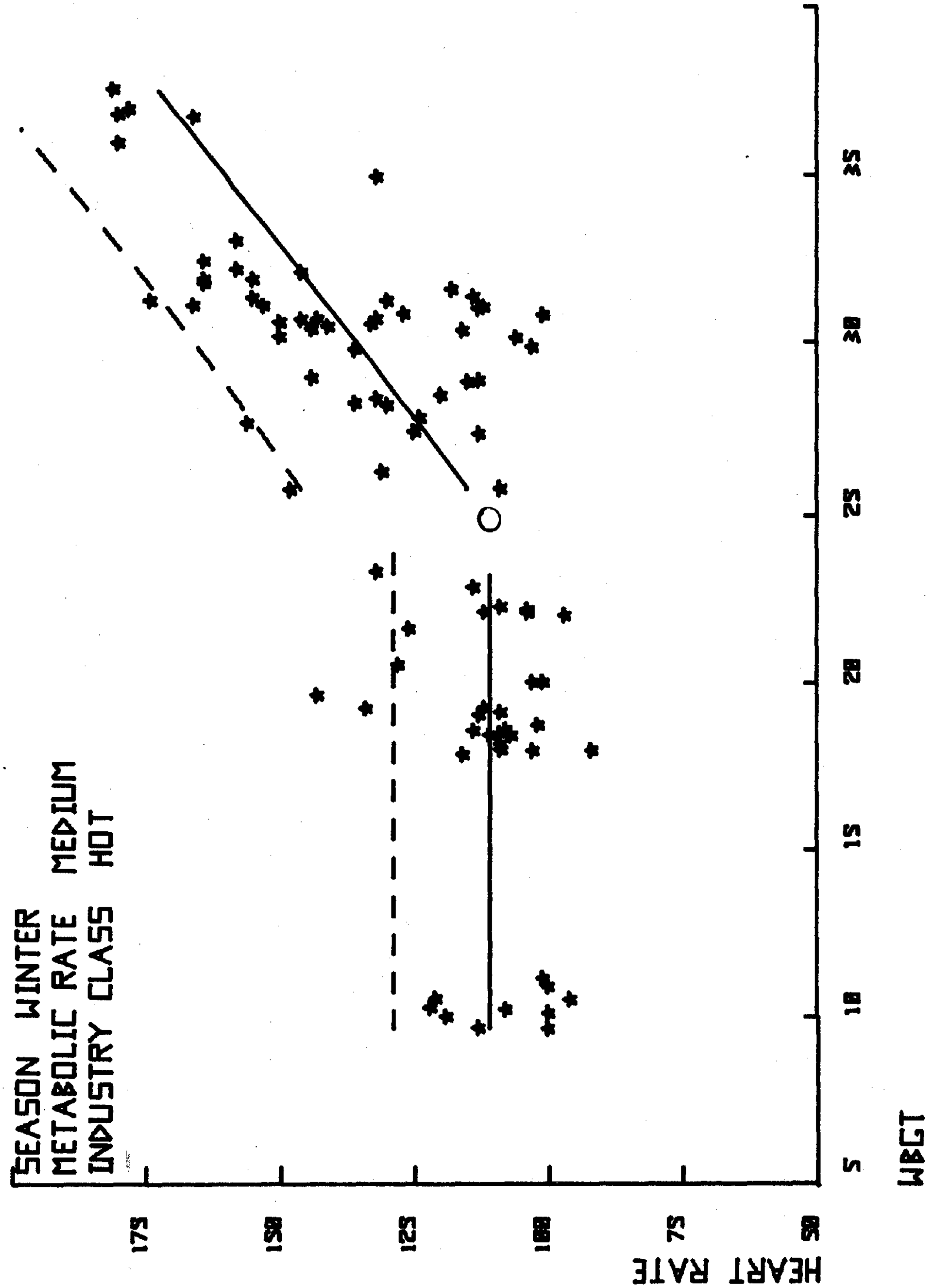
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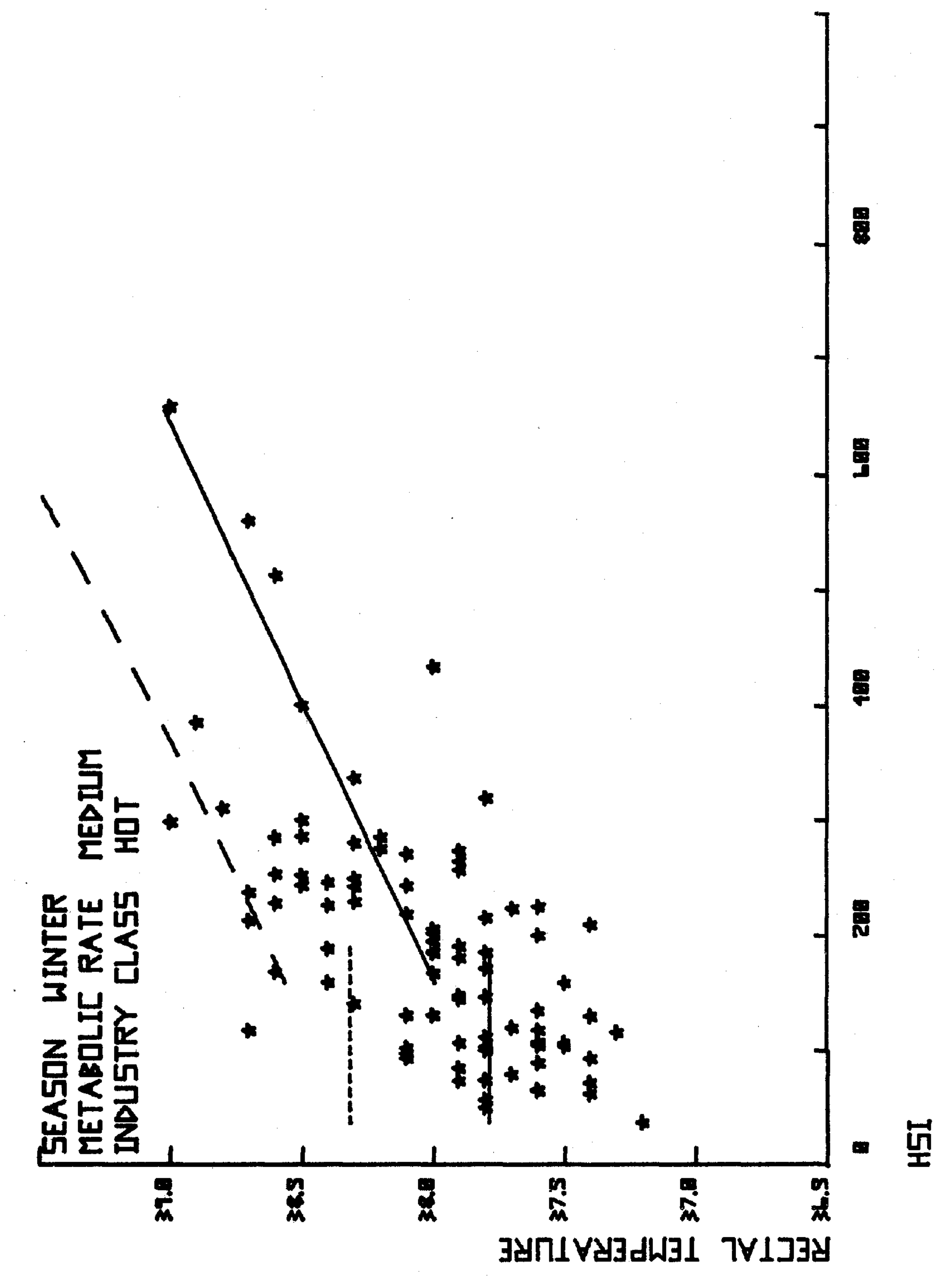

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RECTAL TEMPERATURE
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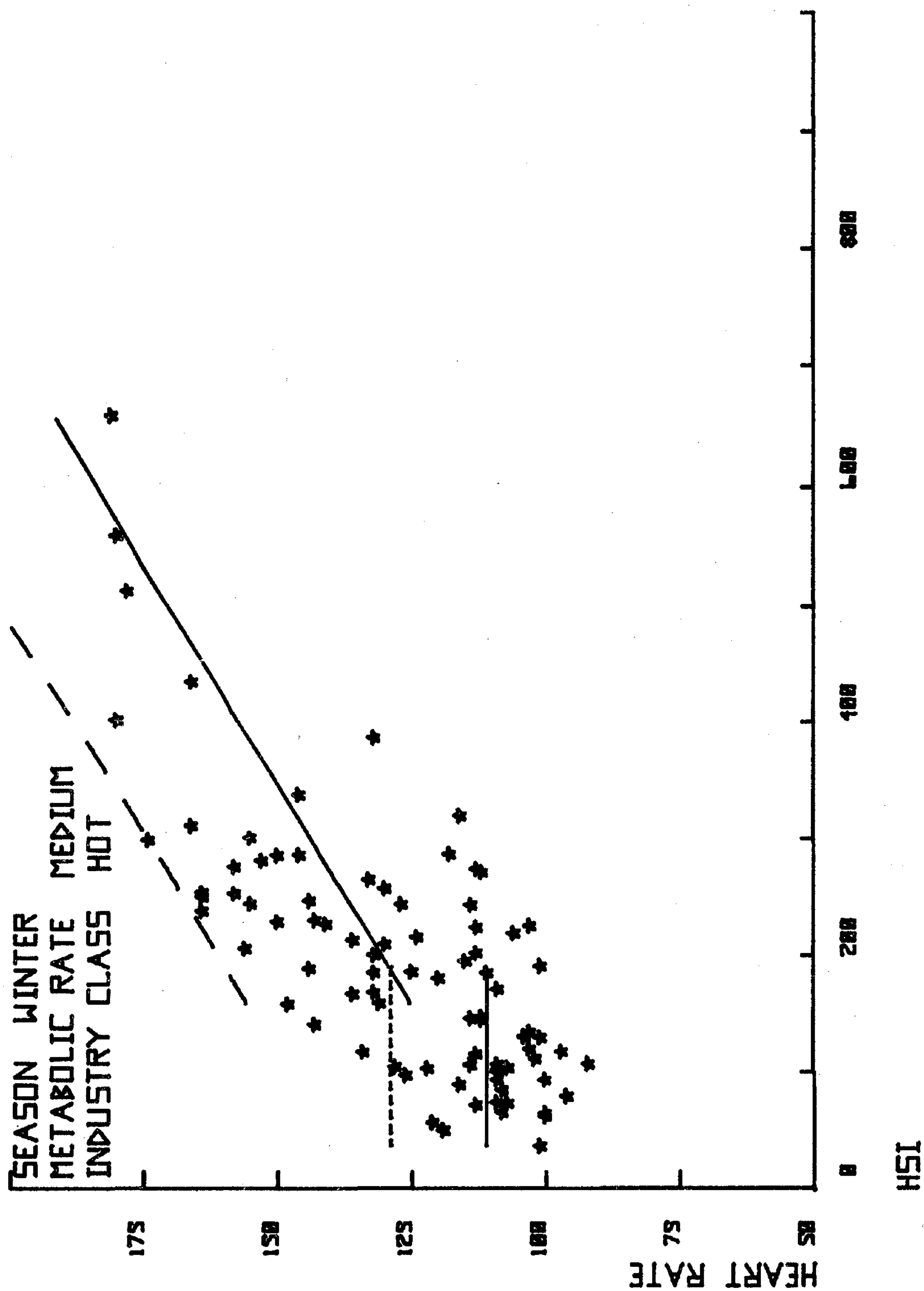
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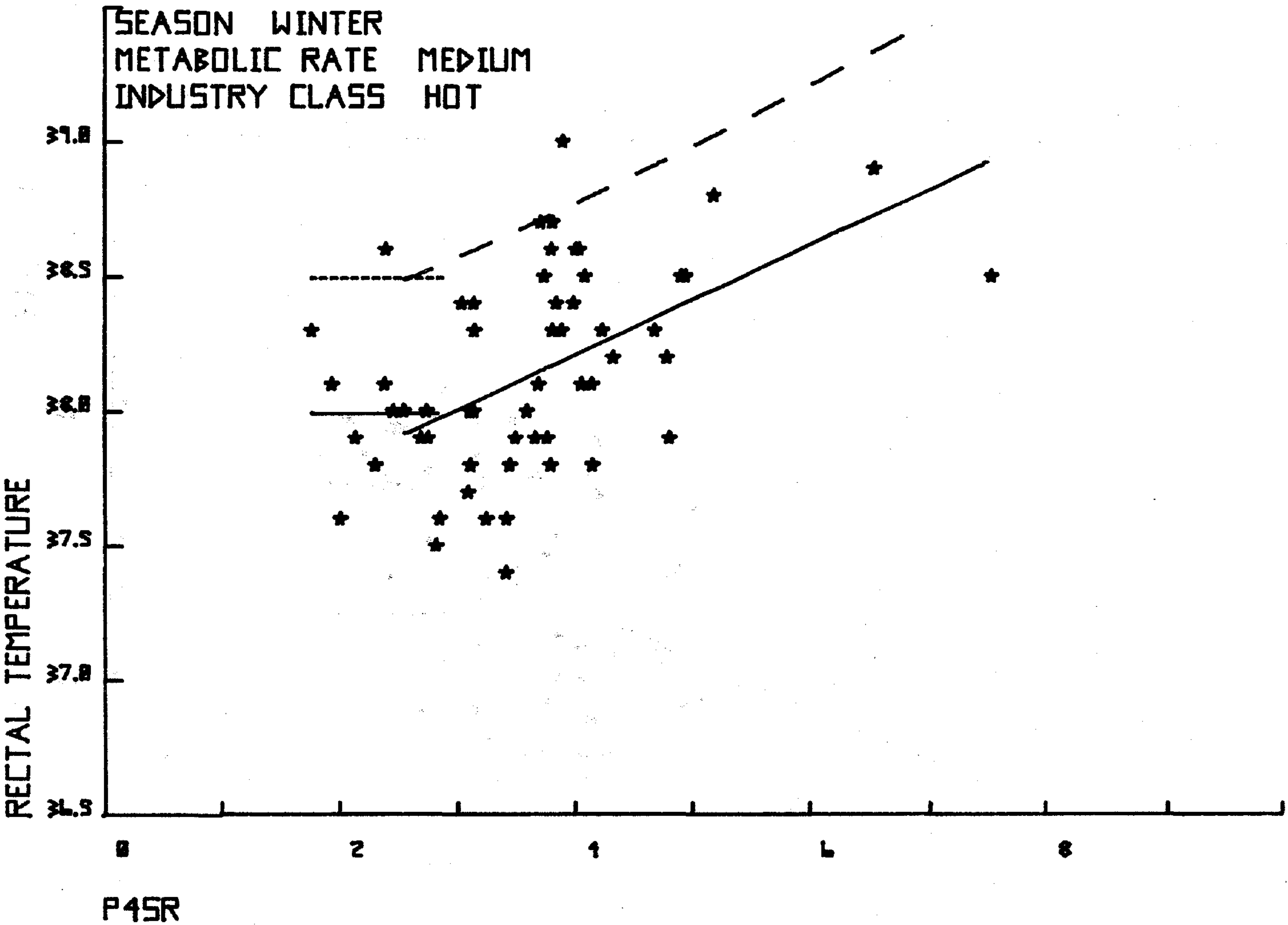

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INDUSTRY CLASS HOT
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RECTAL TEMPERATURE
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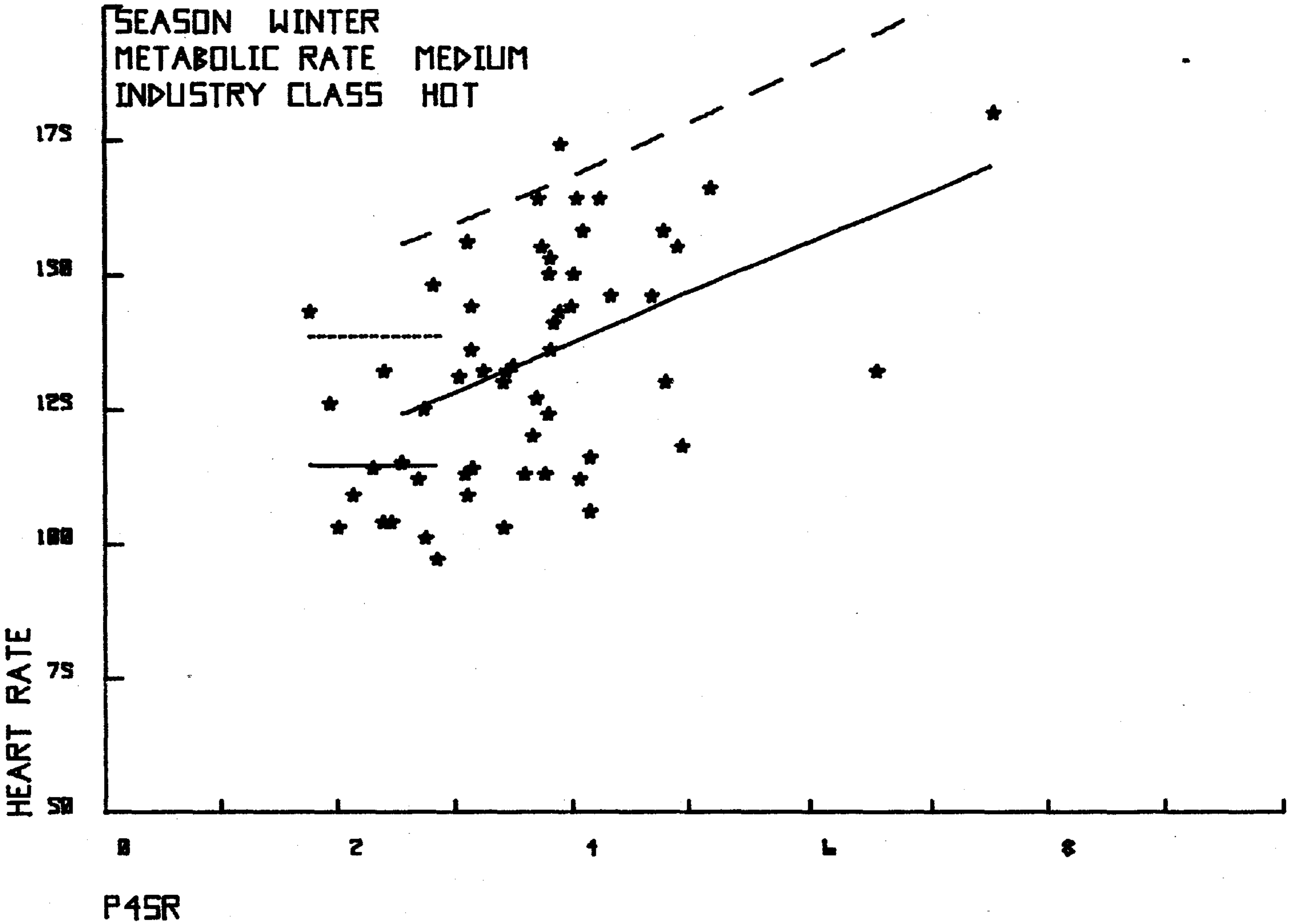
P4SR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INDUSTRY CLASS HOT
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HEART RATE
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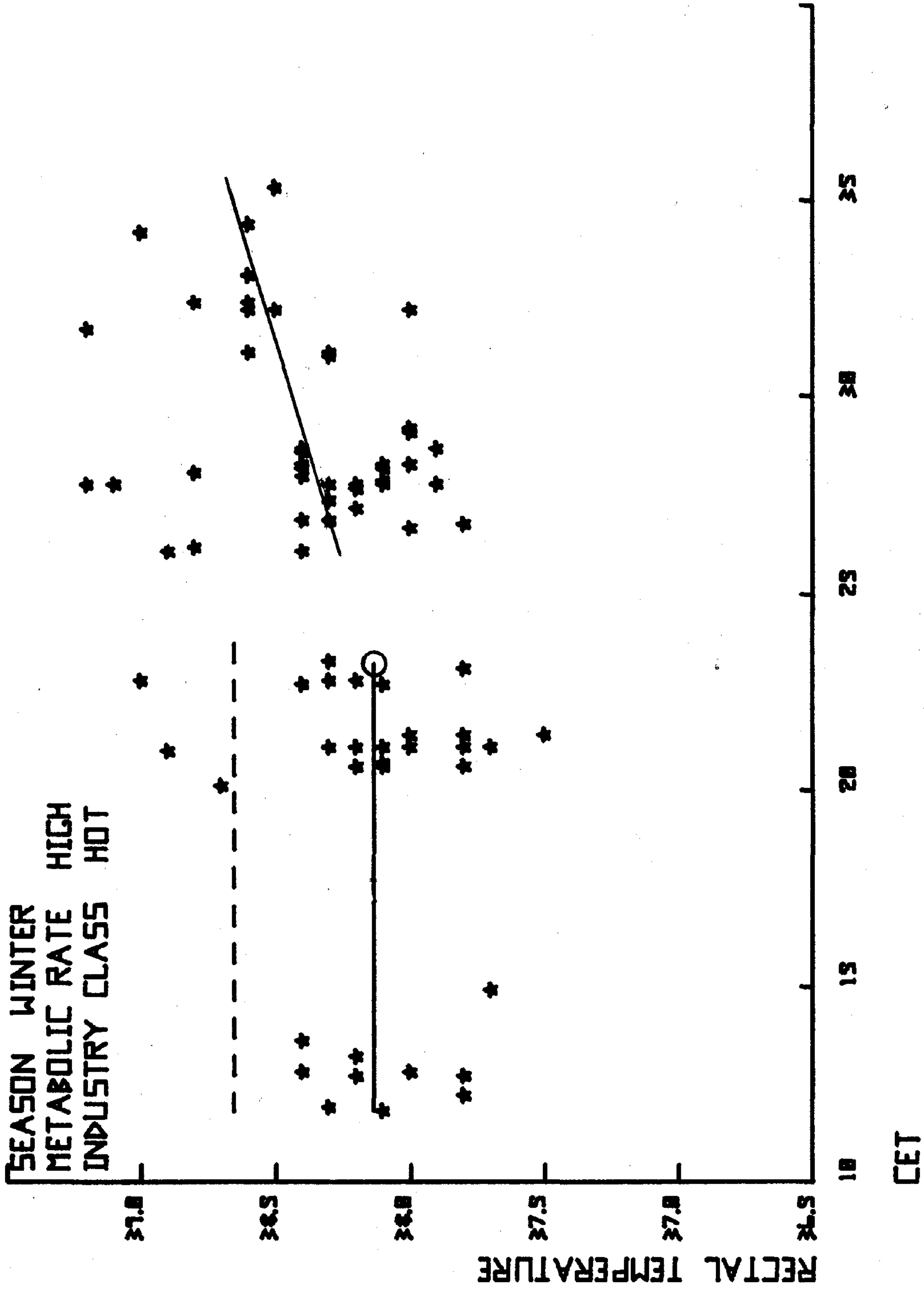
P4SR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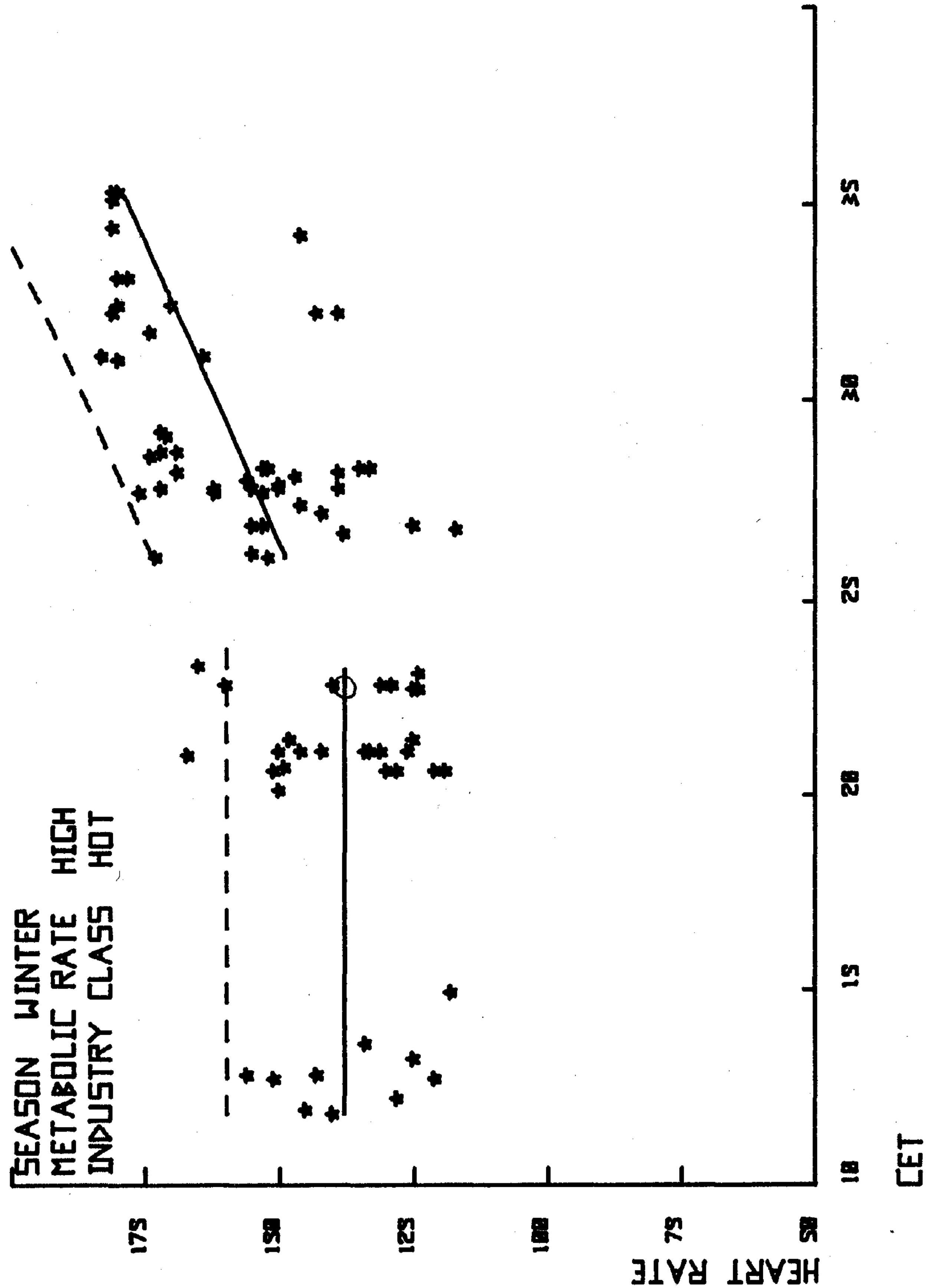
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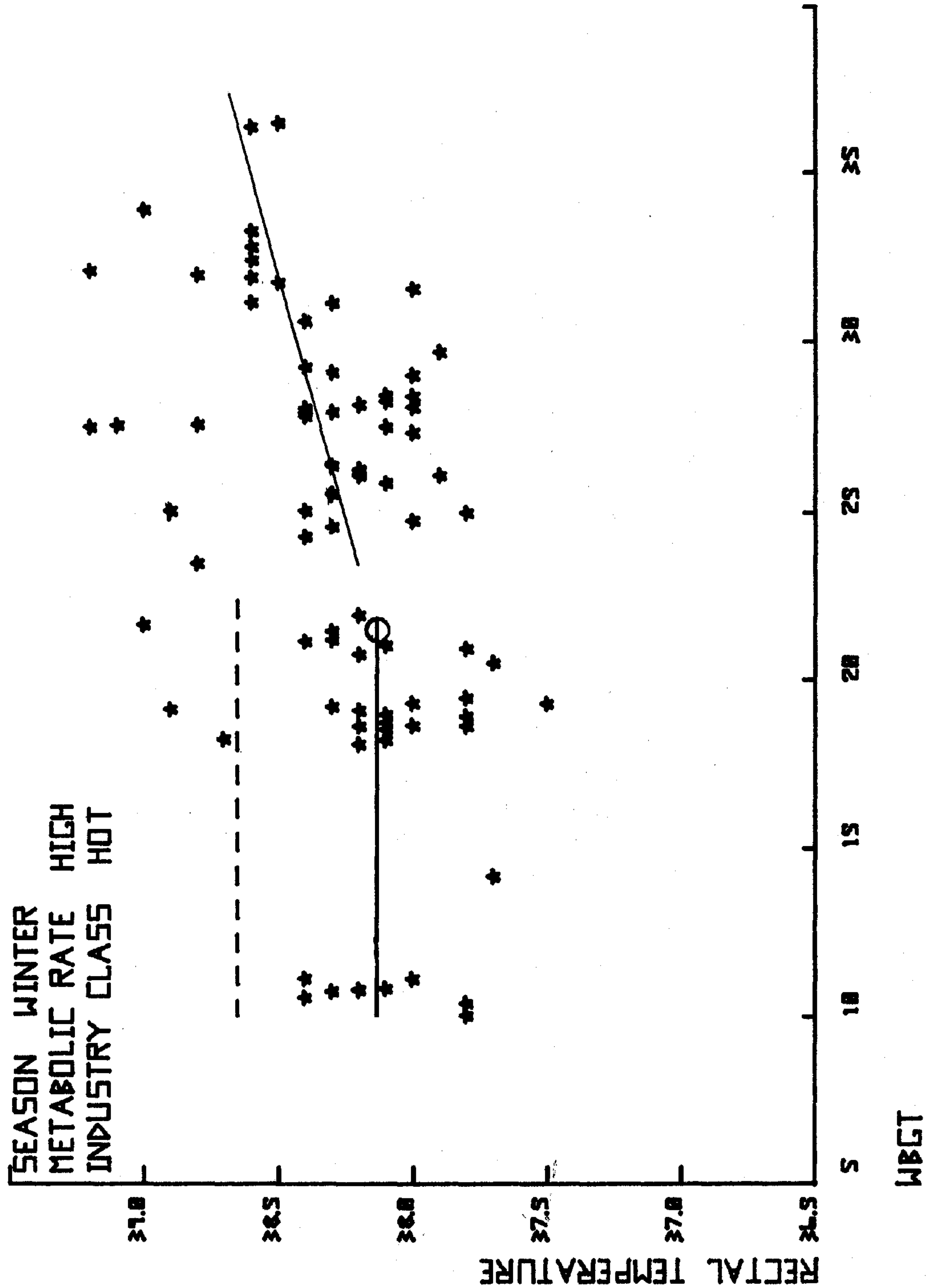
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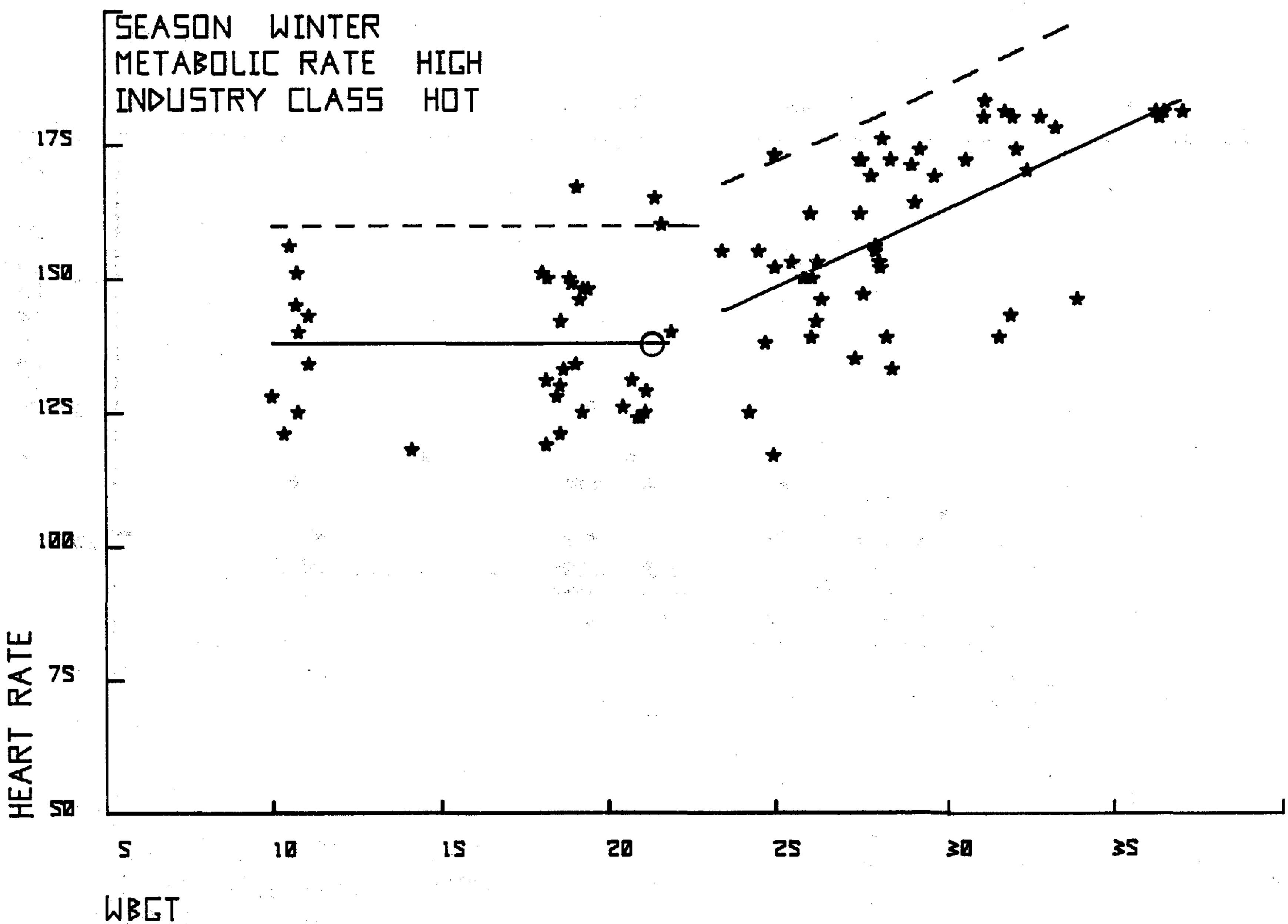
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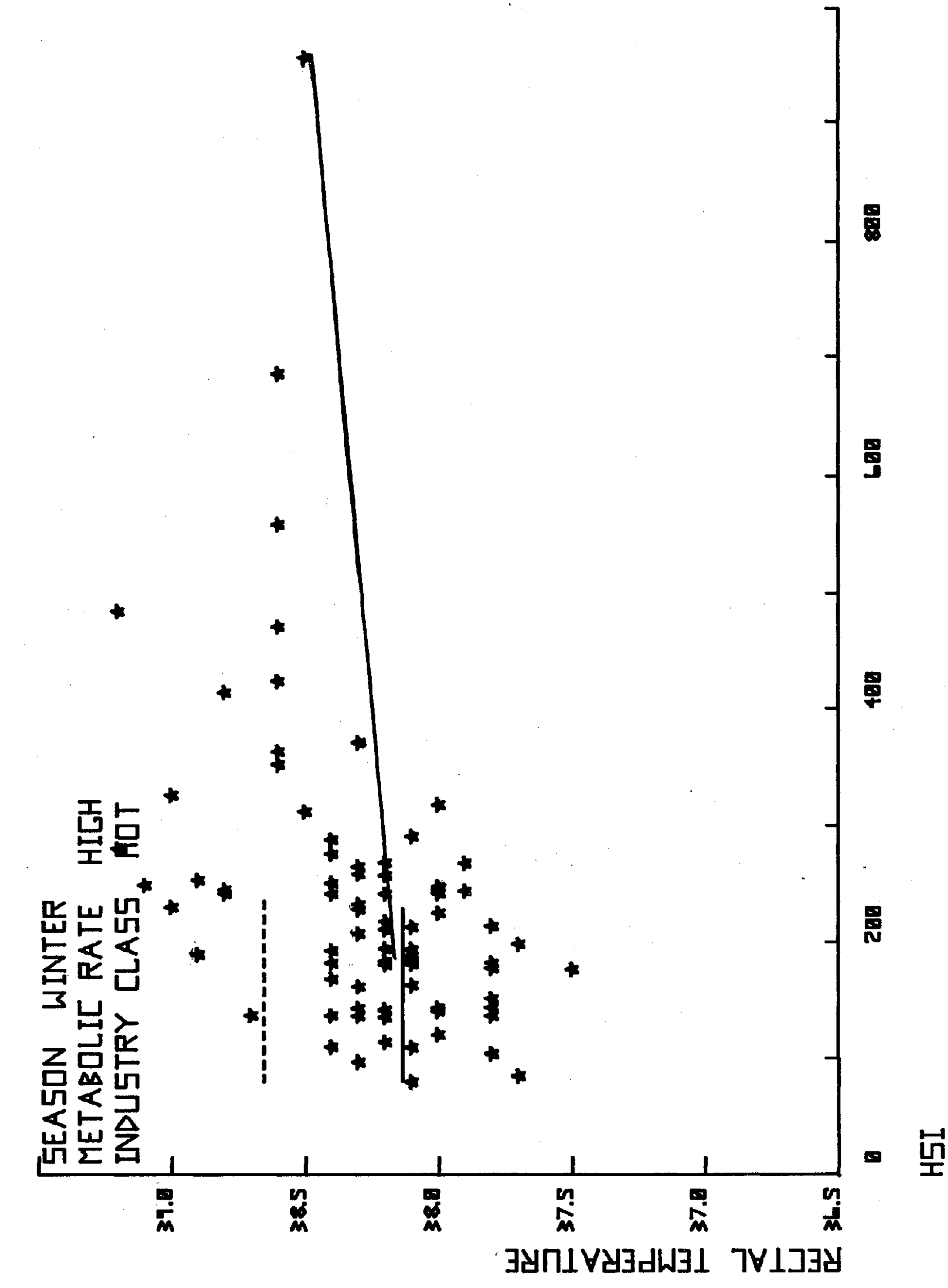
35
WBGT

A 93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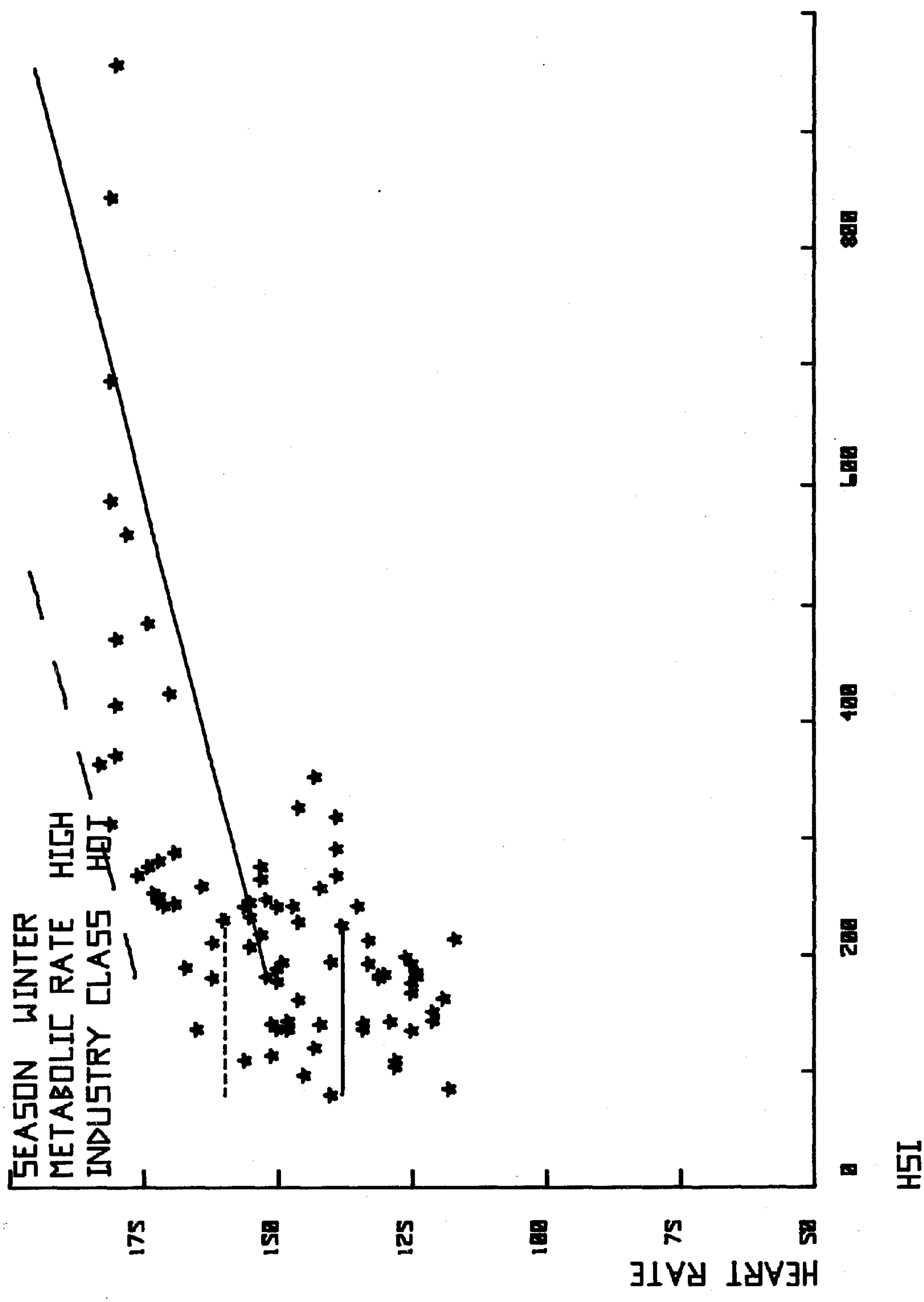
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HEART RATE
HSI
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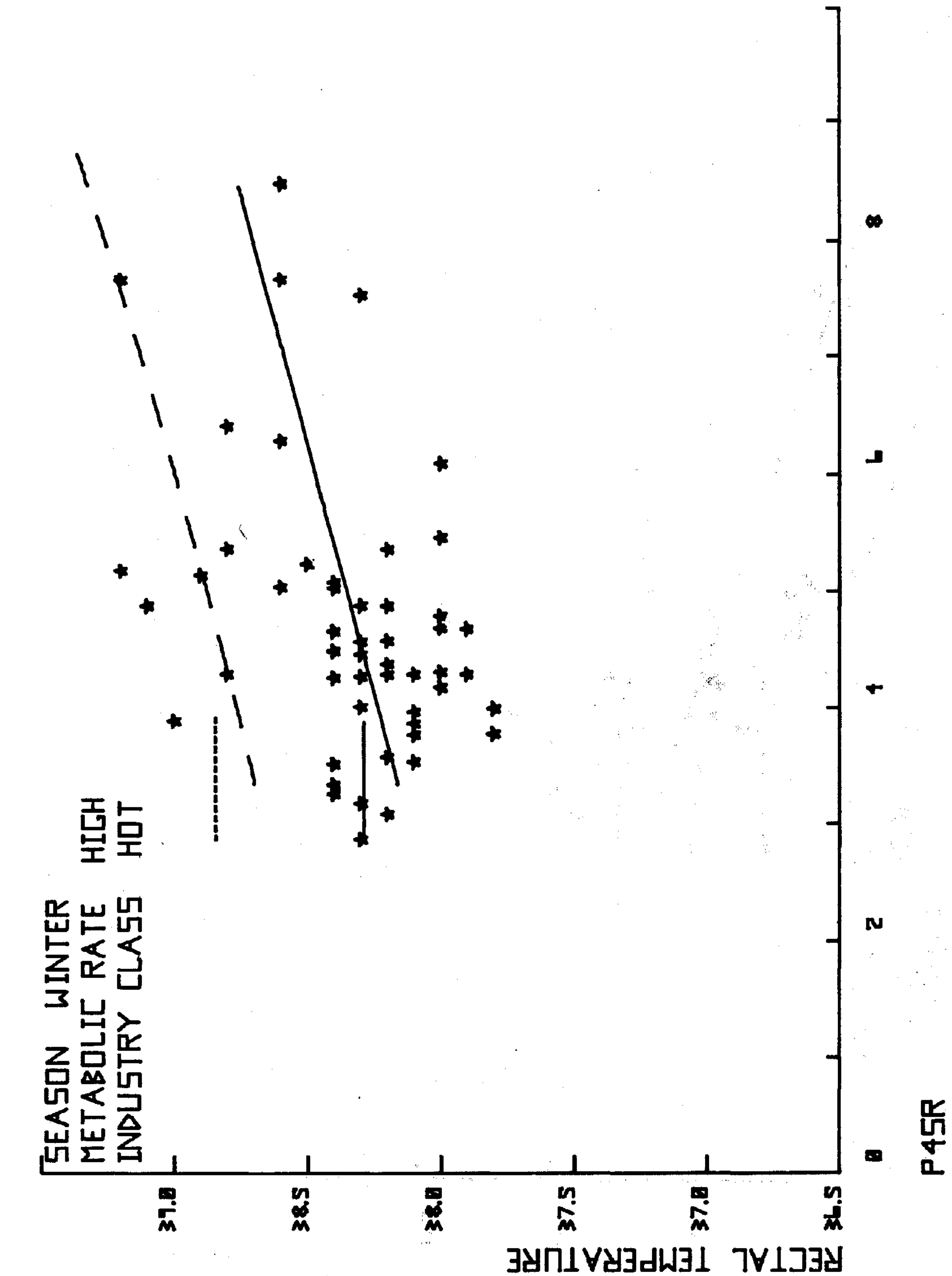
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INDUSTRY CLASS HOT
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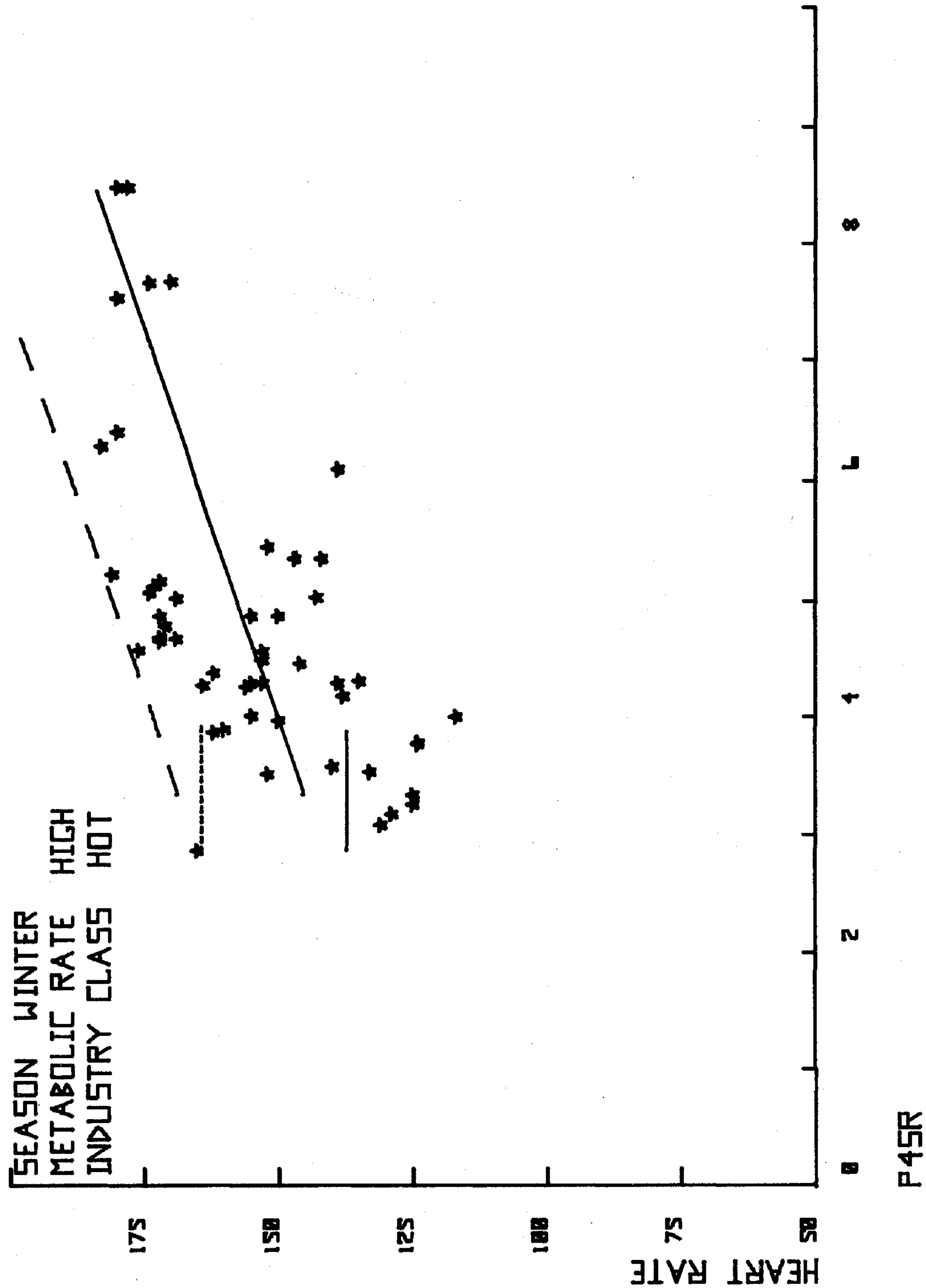
6
8
P45R

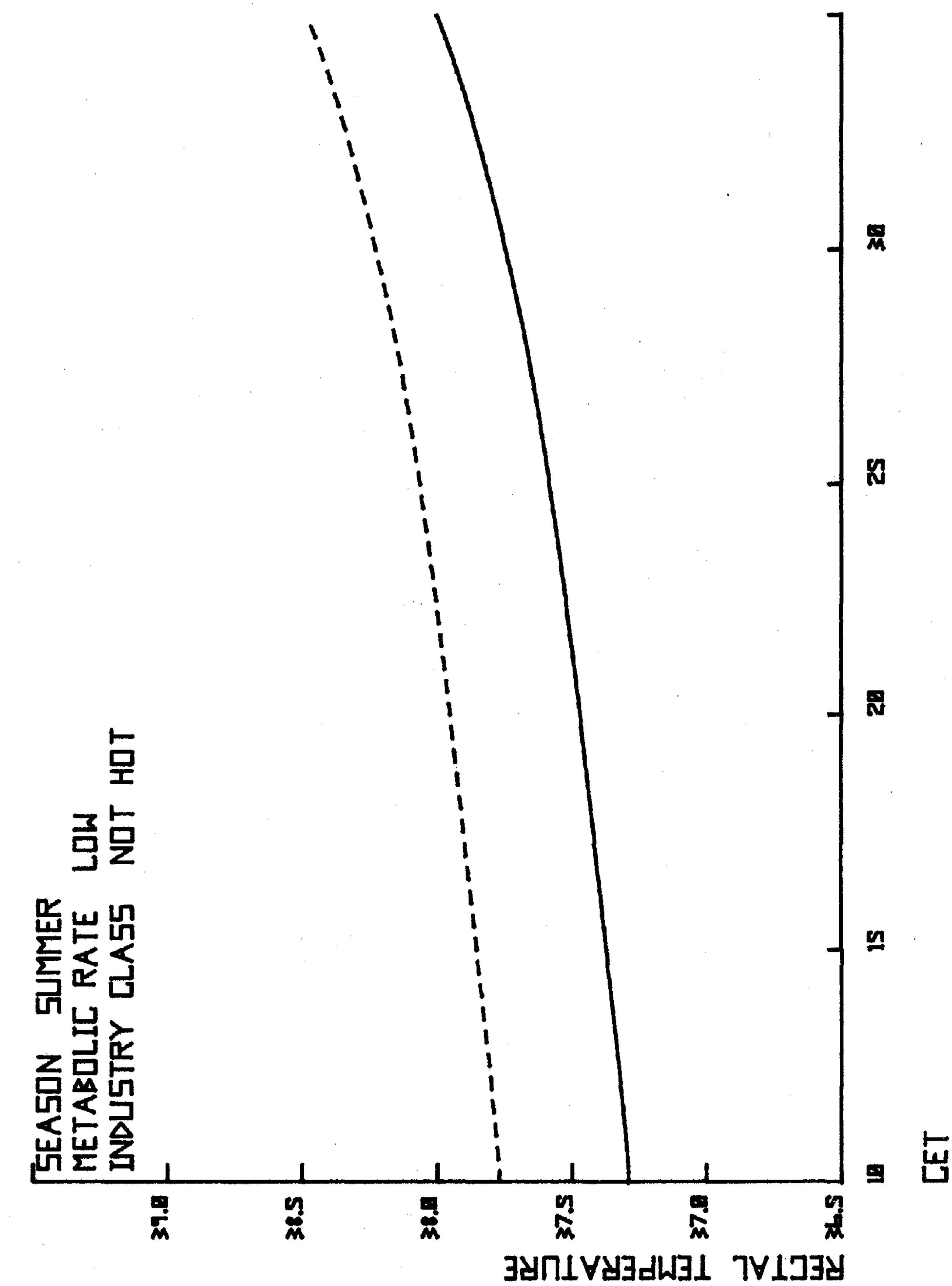

SEASON WINTER
METABOLIC RATE HIGH
INDUSTRY CLASS HOT
HEART RATE
175
150
125
100
75
50
0
2
4
6
8
P45R

APPENDIX B

The following 96 graphs give the predicted rectal temperature and heart rates after one hour of work over the ranges of CET, WBGT, HSI, and P4SR observed in this study. These predictions are based on the multiple regression equations described in the test. The solid line gives the predicted value and the dotted line is the 90% confidence limit for an individual.

Below is a page guide to the figures in Appendix B.

		Metabolic Rate		
		Low	Medium	High
NOT-HOT GROUP				
Summer				
	CET	2,3	10,11	18,19
	WBGT	4,5	12,13	20,21
	HSI	6,7	14,15	22,23
	P4SR	8,9	16,17	24,25
Winter				
	CET	26,27	34,35	42,43
	WBGT	28,29	36,37	44,45
	HSI	30,31	38,39	46,47
	P4SR	32,33	40,41	48,49
HOT GROUP				
Summer				
	CET	50,51	58,59	66,67
	WBGT	52,53	60,61	68,69
	HSI	54,55	62,63	70,71
	P4SR	56,57	64,65	72,73
Winter				
	CET	74,75	82,83	90,91
	WBGT	76,77	84,85	92,93
	HSI	78,79	86,87	94,95
	P4SR	80,81	88,89	96,97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INDUSTRY CLASS NOT HOT
RECTAL TEMPERATURE
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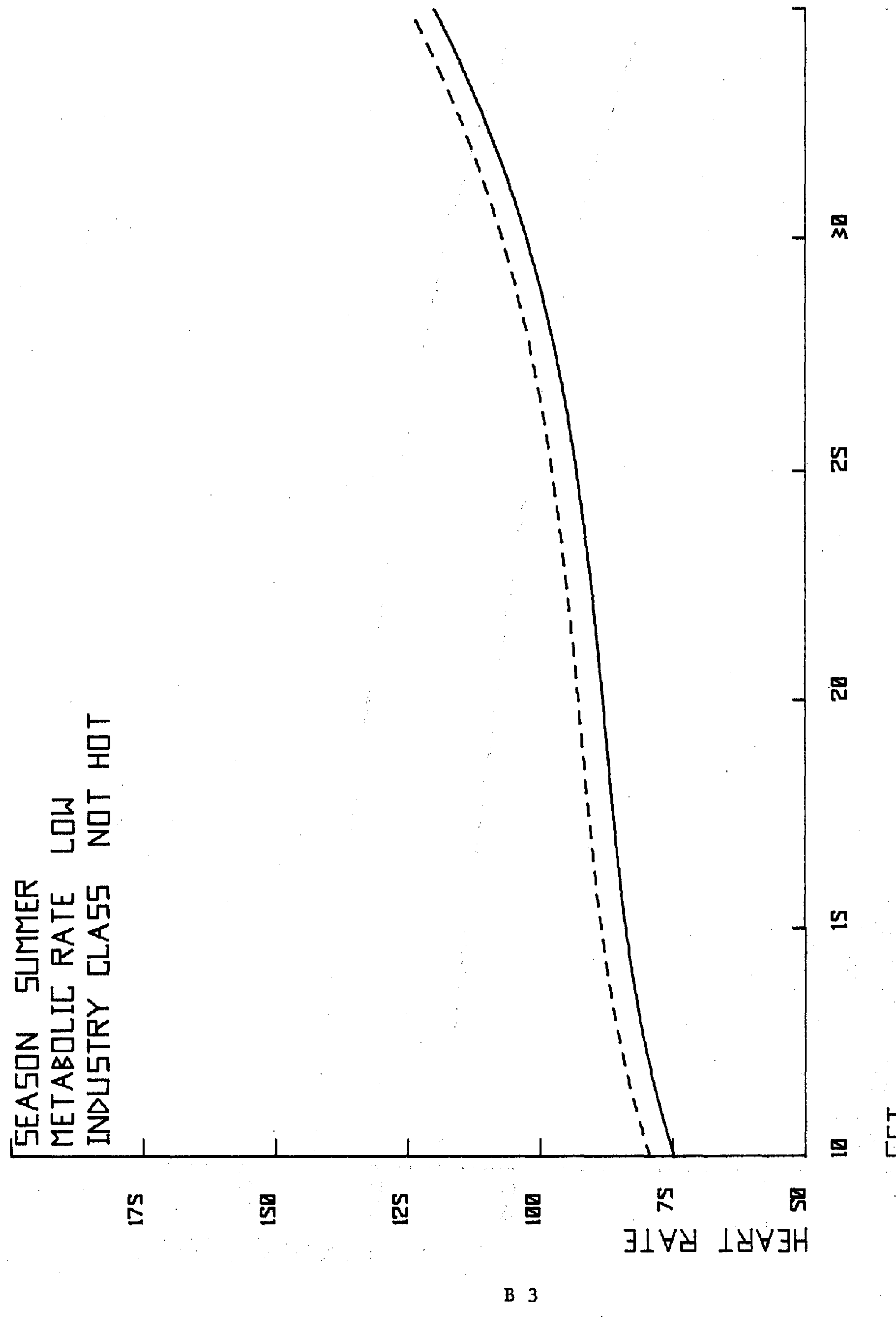
25
30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METABOLIC RATE LOW
INDUSTRY CLASS NOT HOT
HEART RATE
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150
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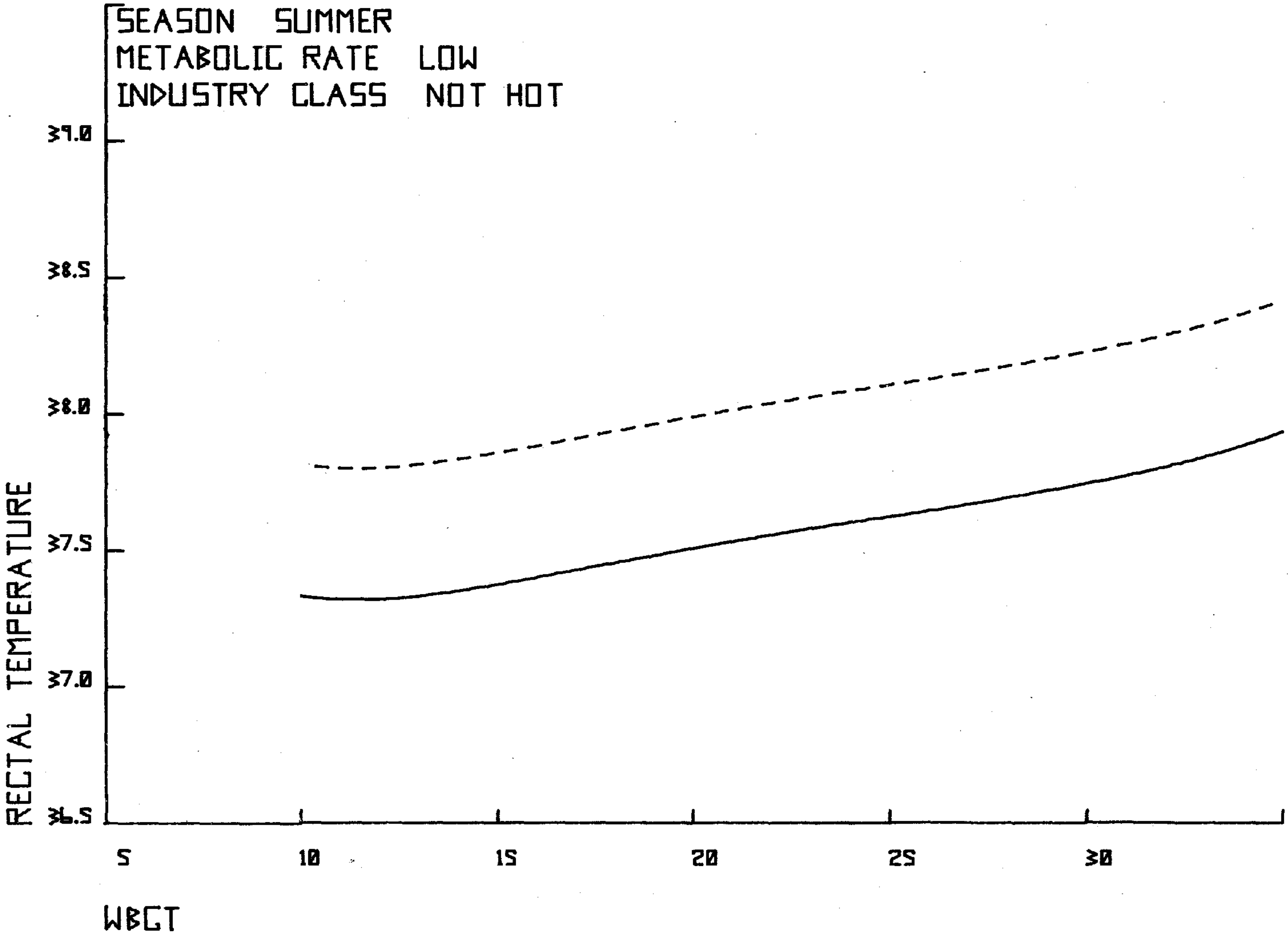
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METABOLIC RATE LOW
INDUSTRY CLASS NOT HOT
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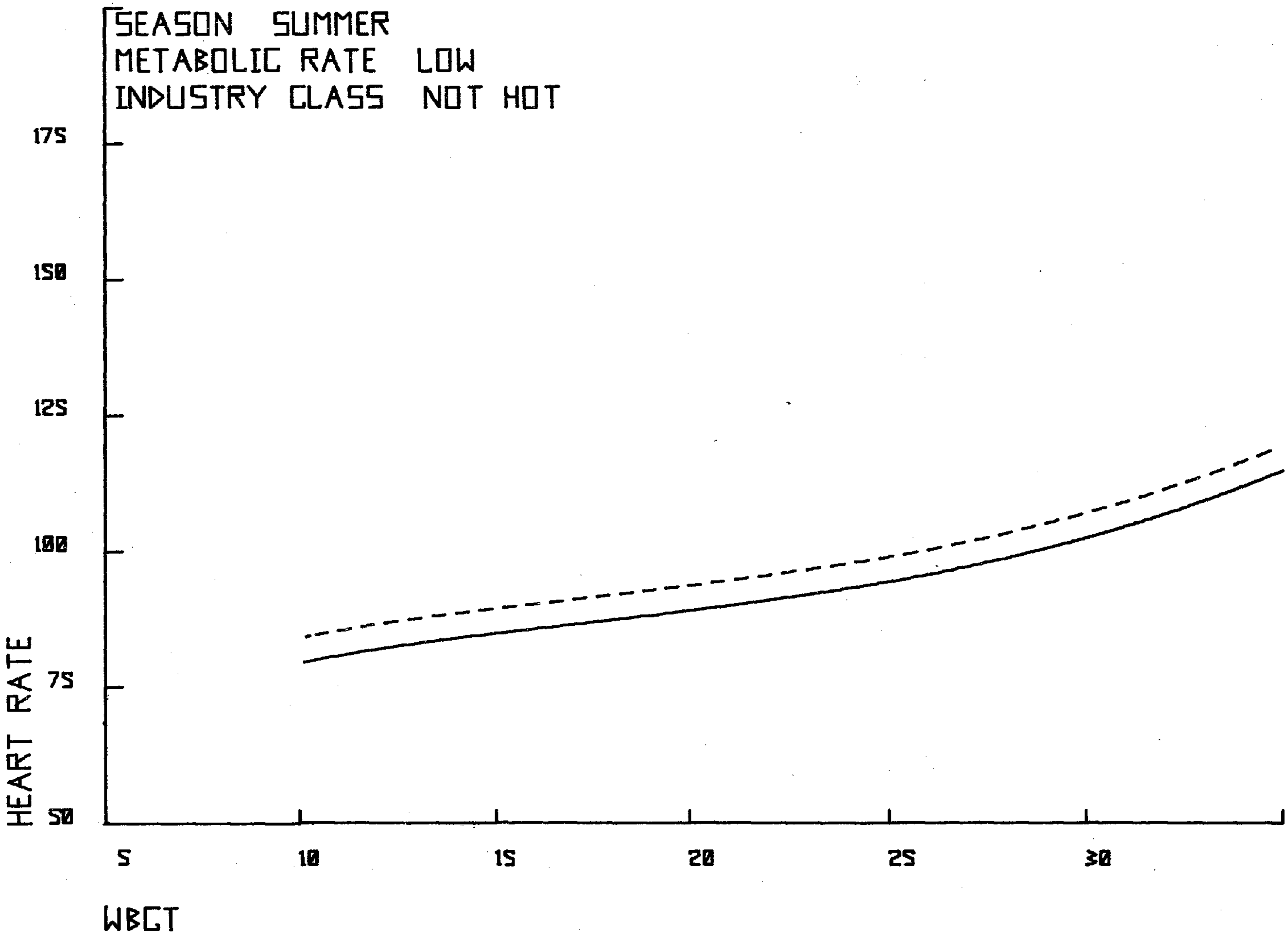
WBGT



SEASON SUMMER
METABOLIC RATE LOW
INDUSTRY CLASS NOT HOT
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HEART RATE
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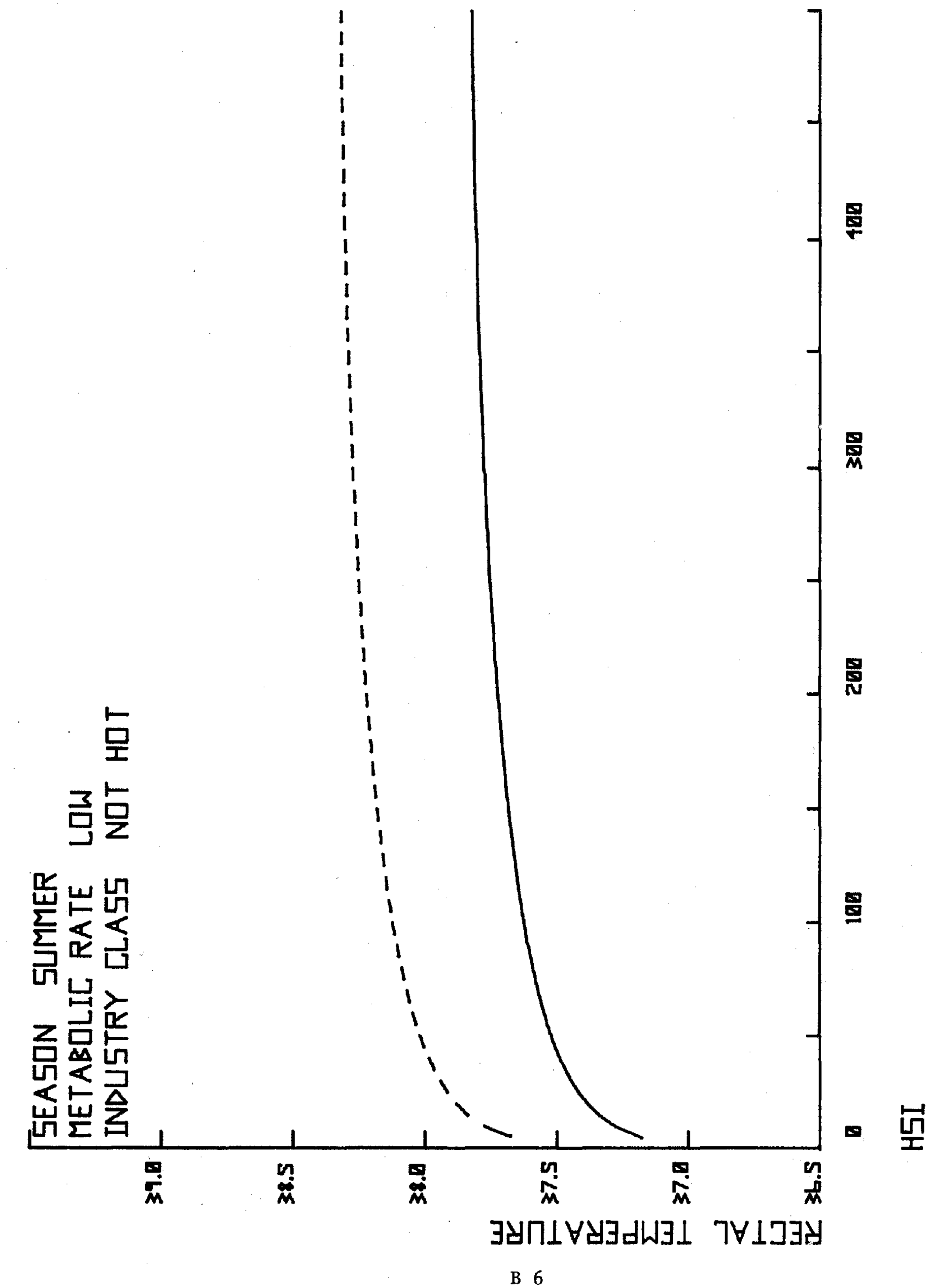
WBGT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INDUSTRY CLASS NOT HOT
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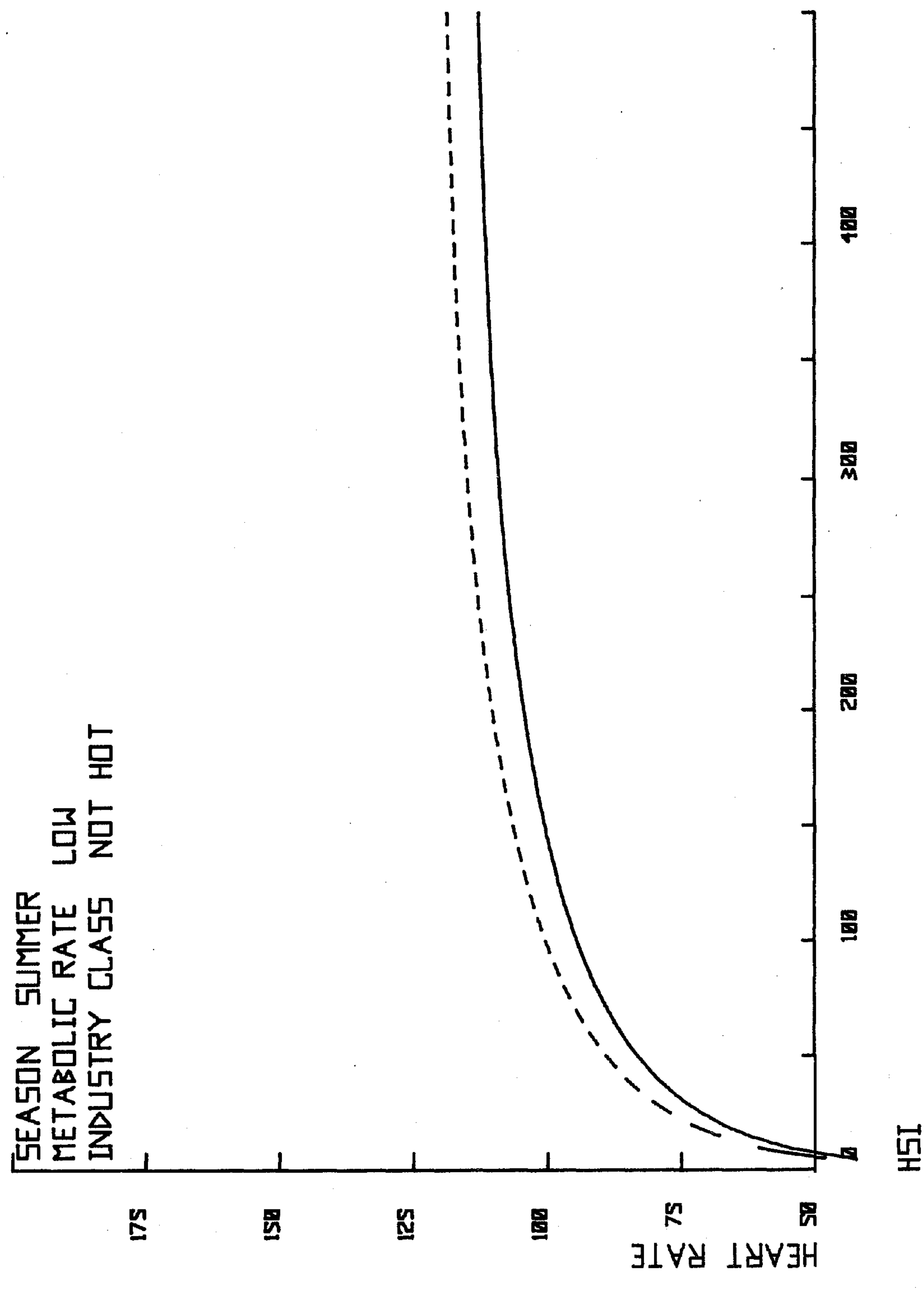
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HEART RATE
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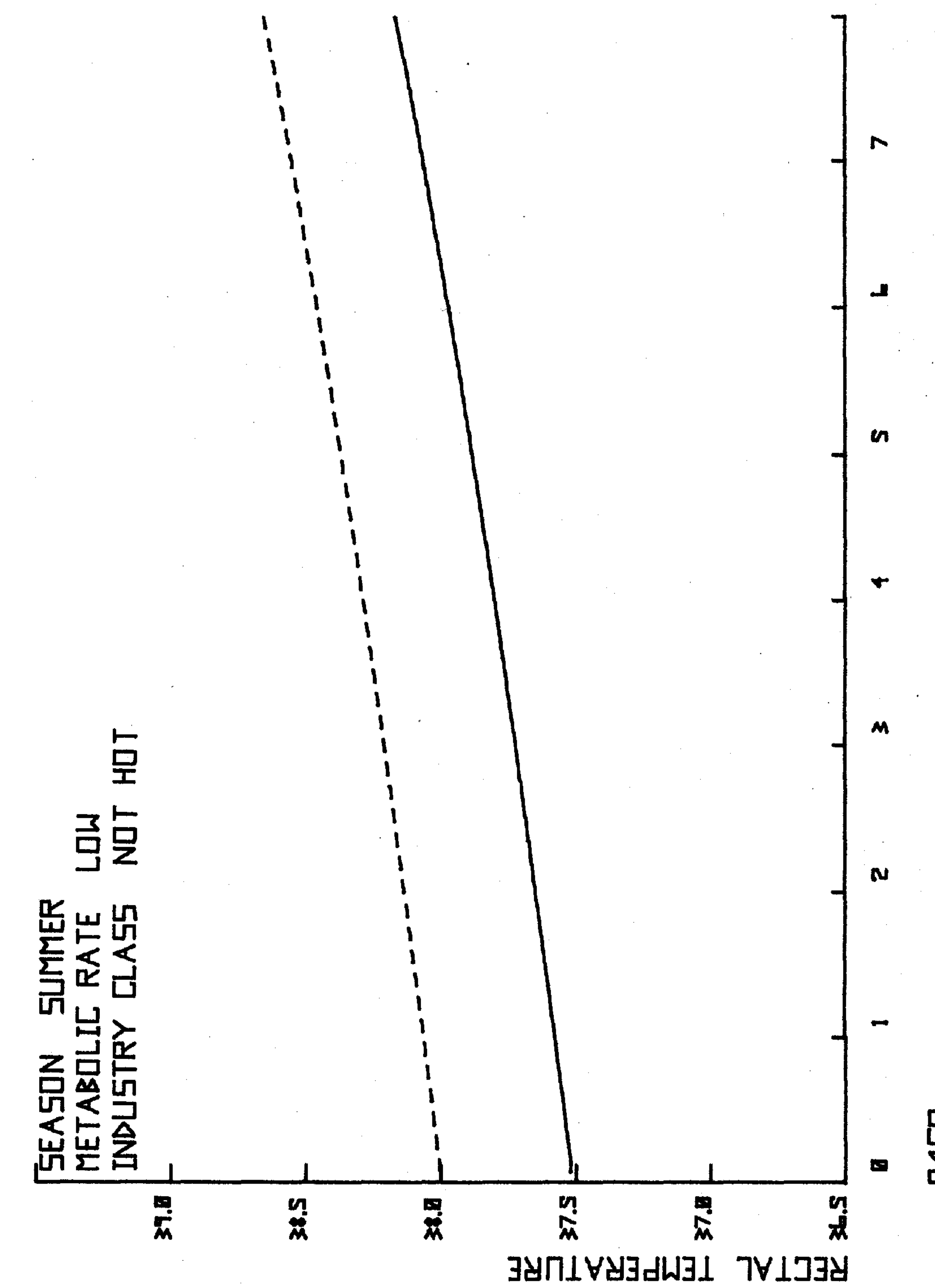
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INDUSTRY CLASS NOT HOT
RECTAL TEMPERATURE
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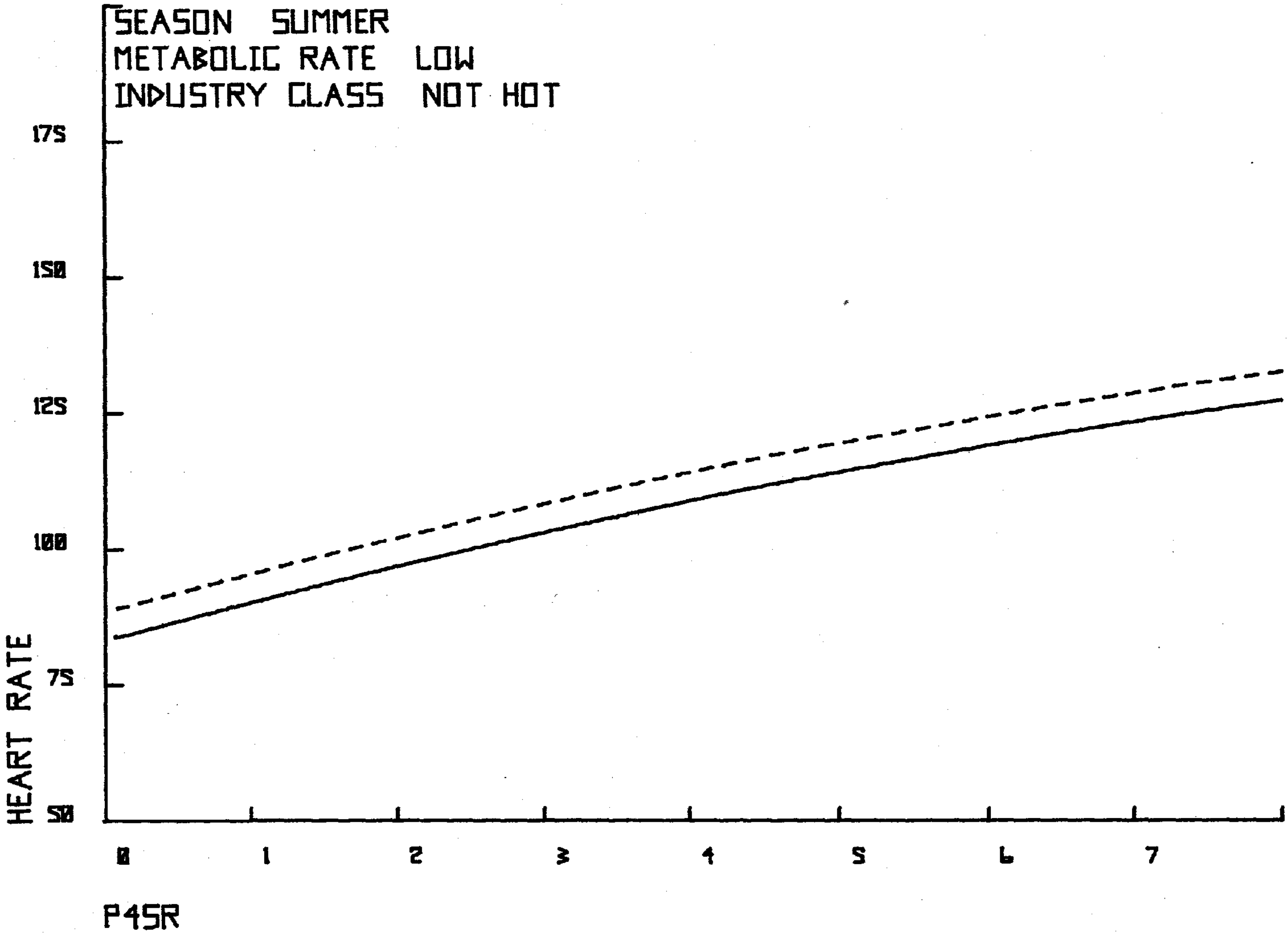
P45R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HEART RATE
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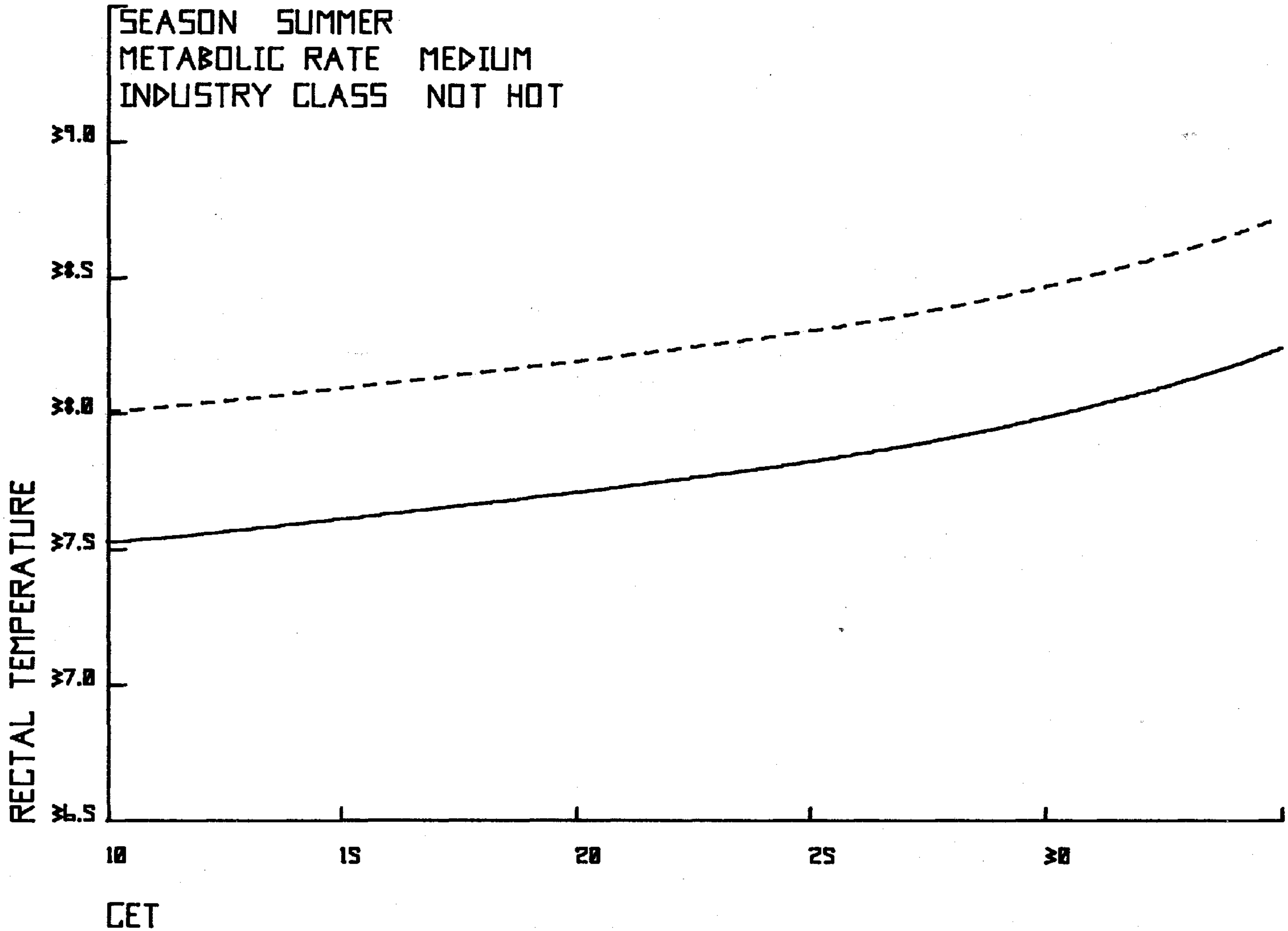
P4SR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INDUSTRY CLASS NOT HOT
RECTAL TEMPERATURE
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25
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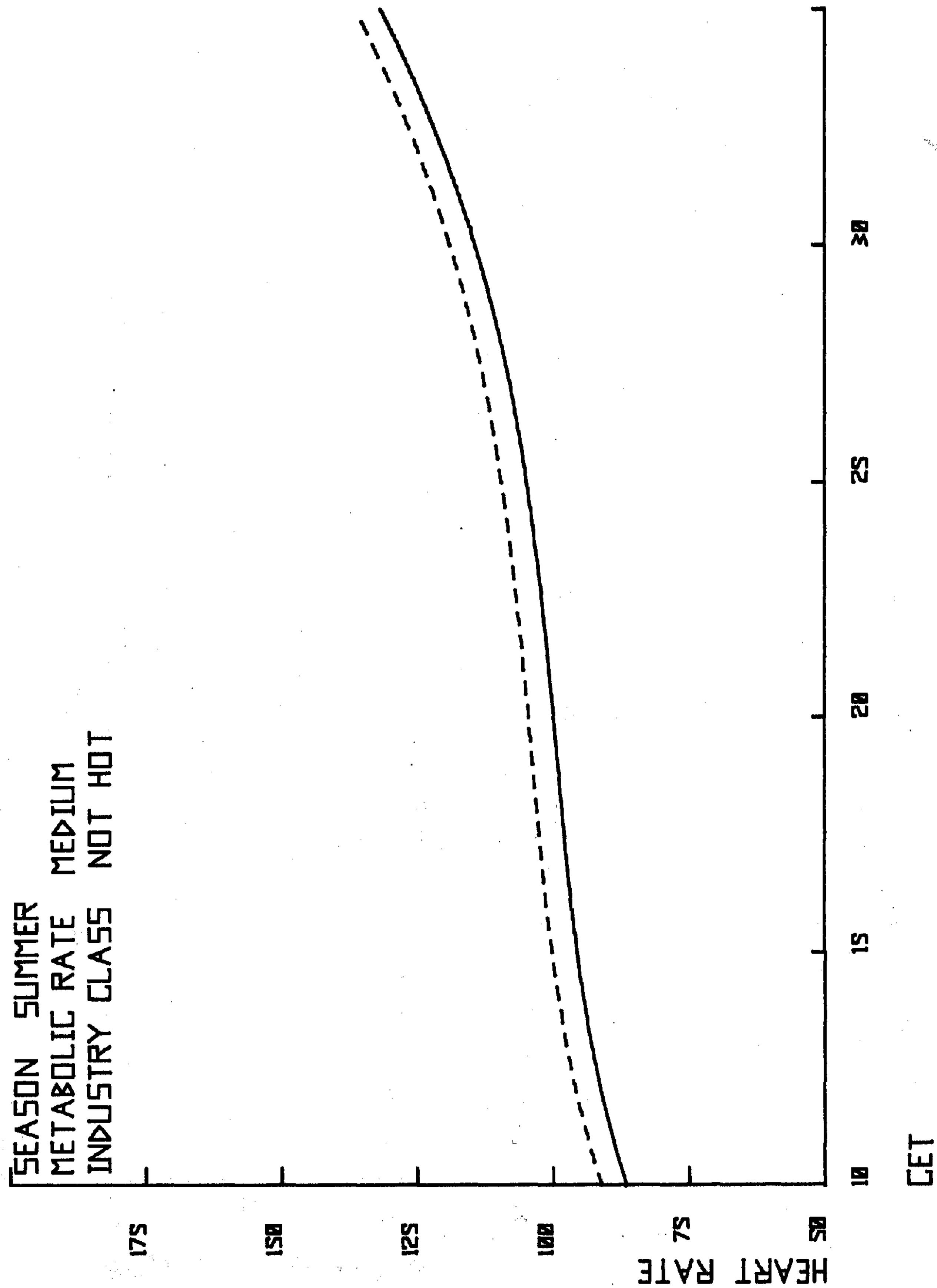
CET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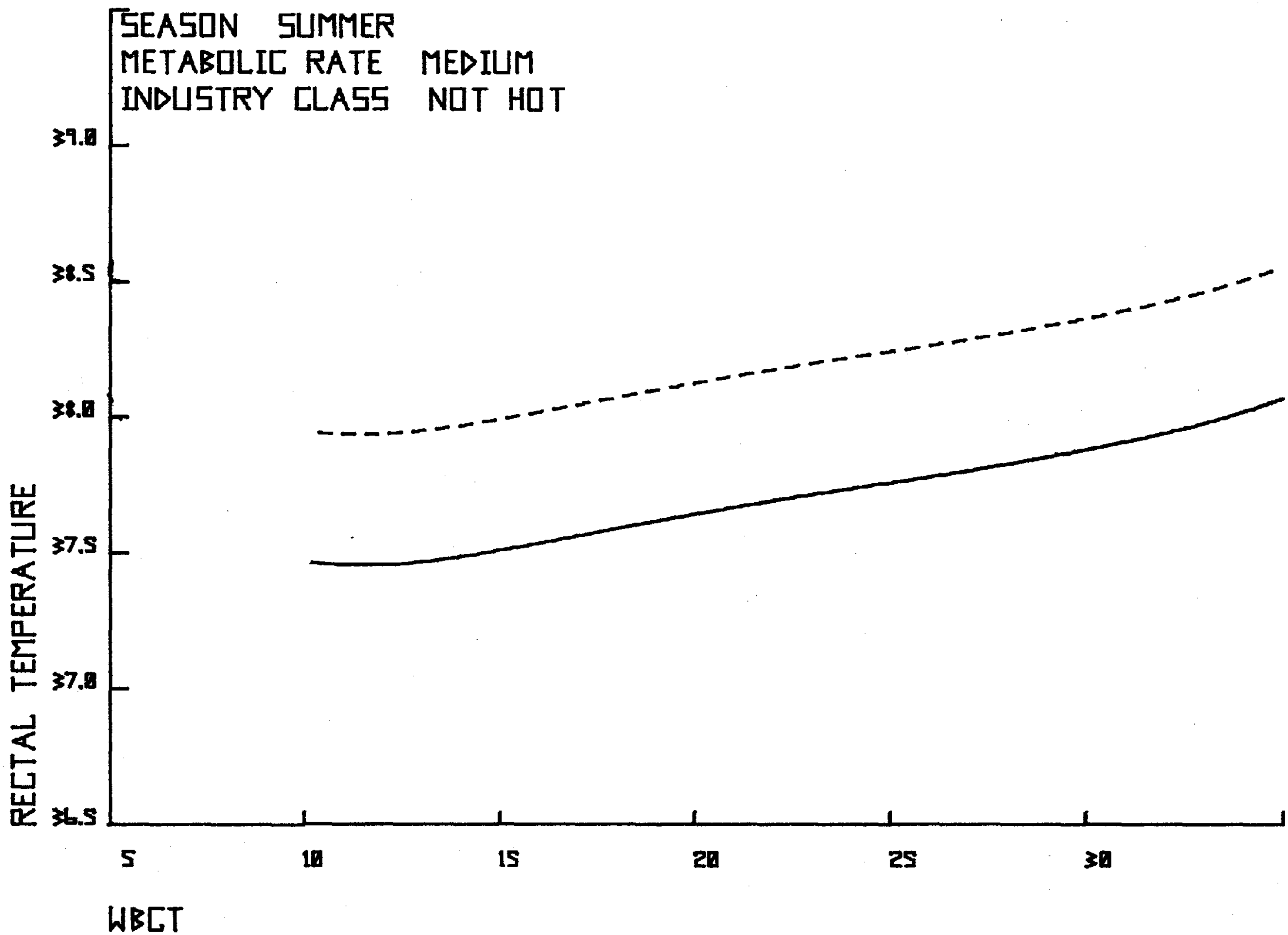
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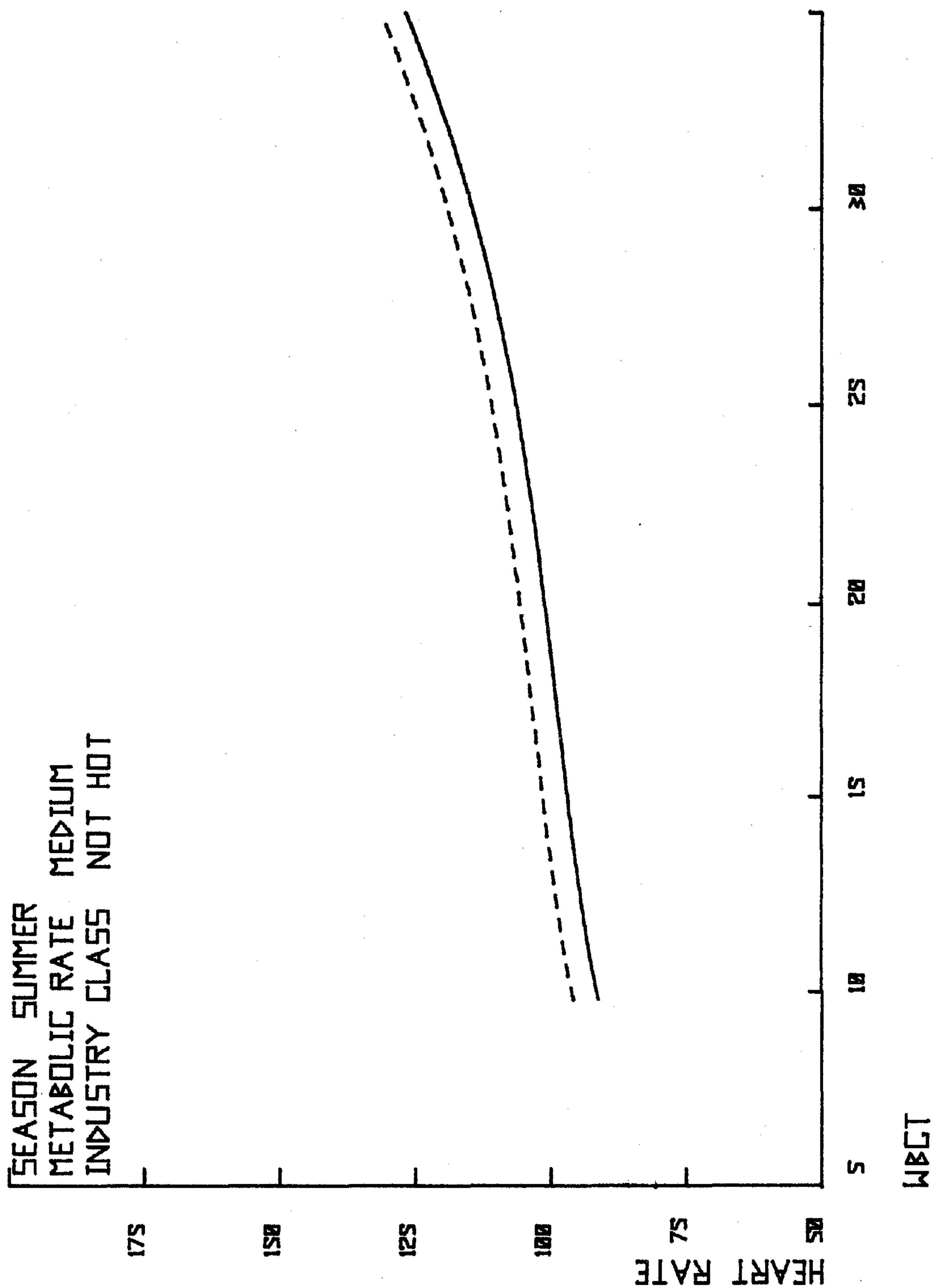
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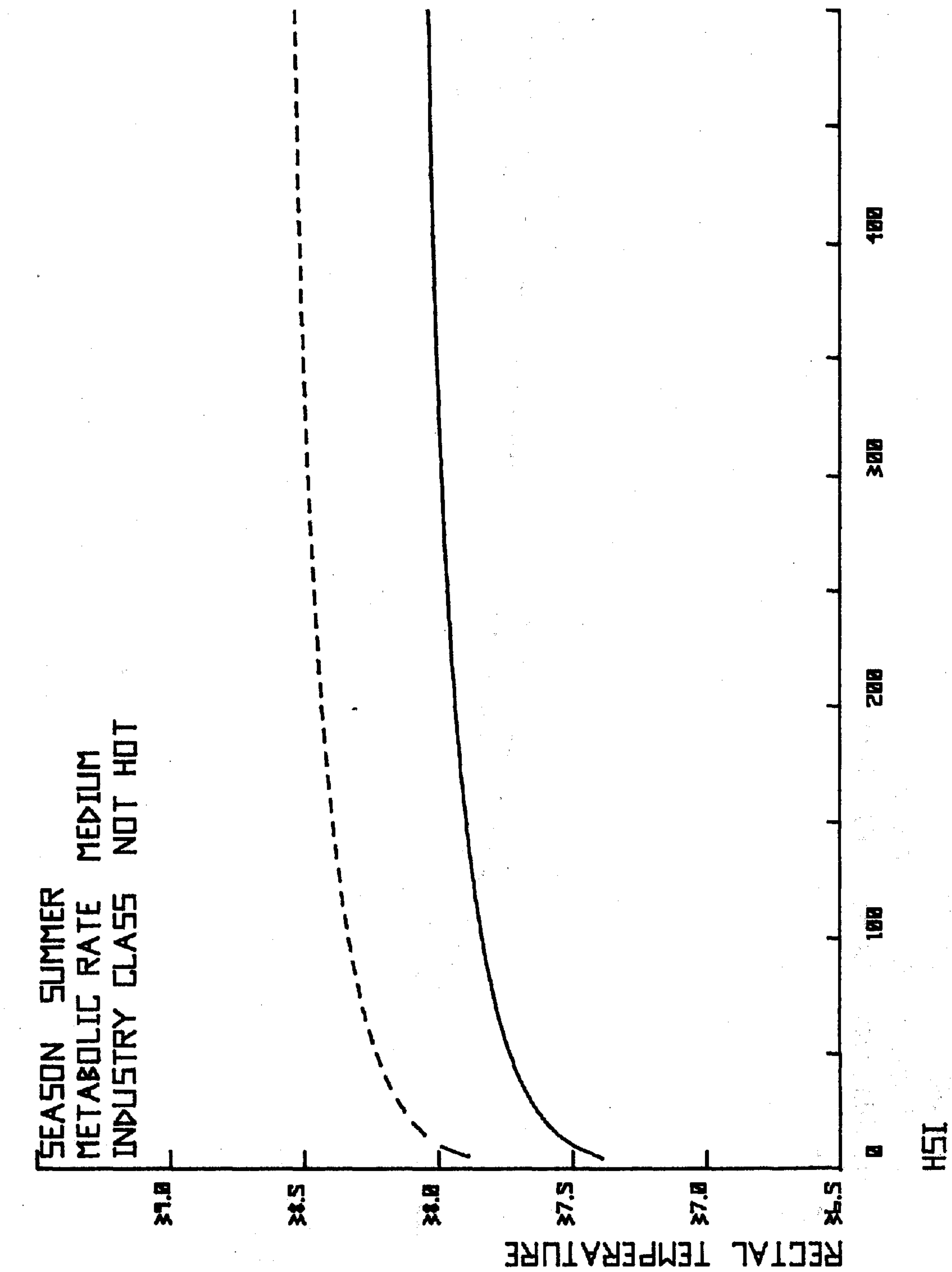
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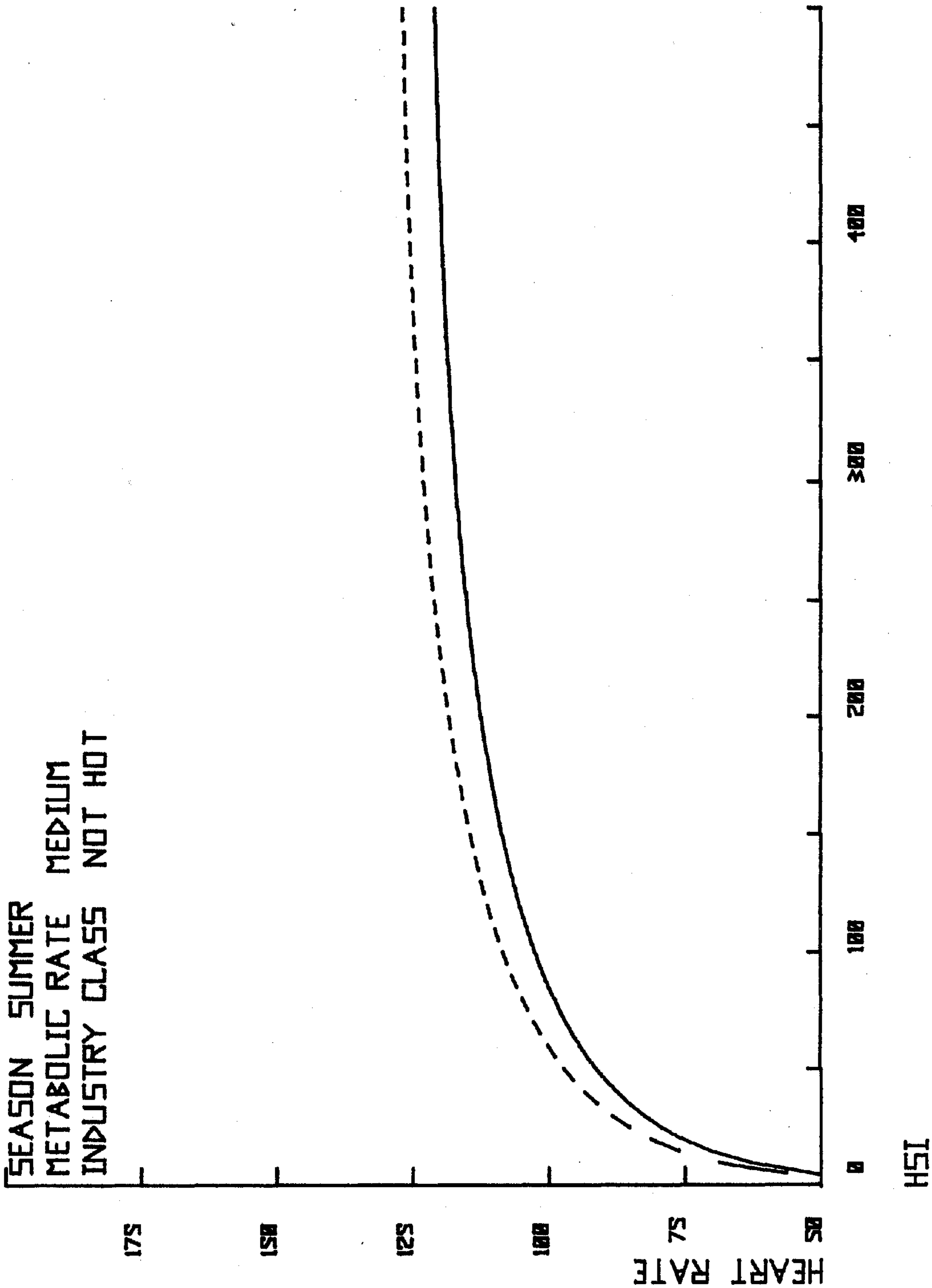
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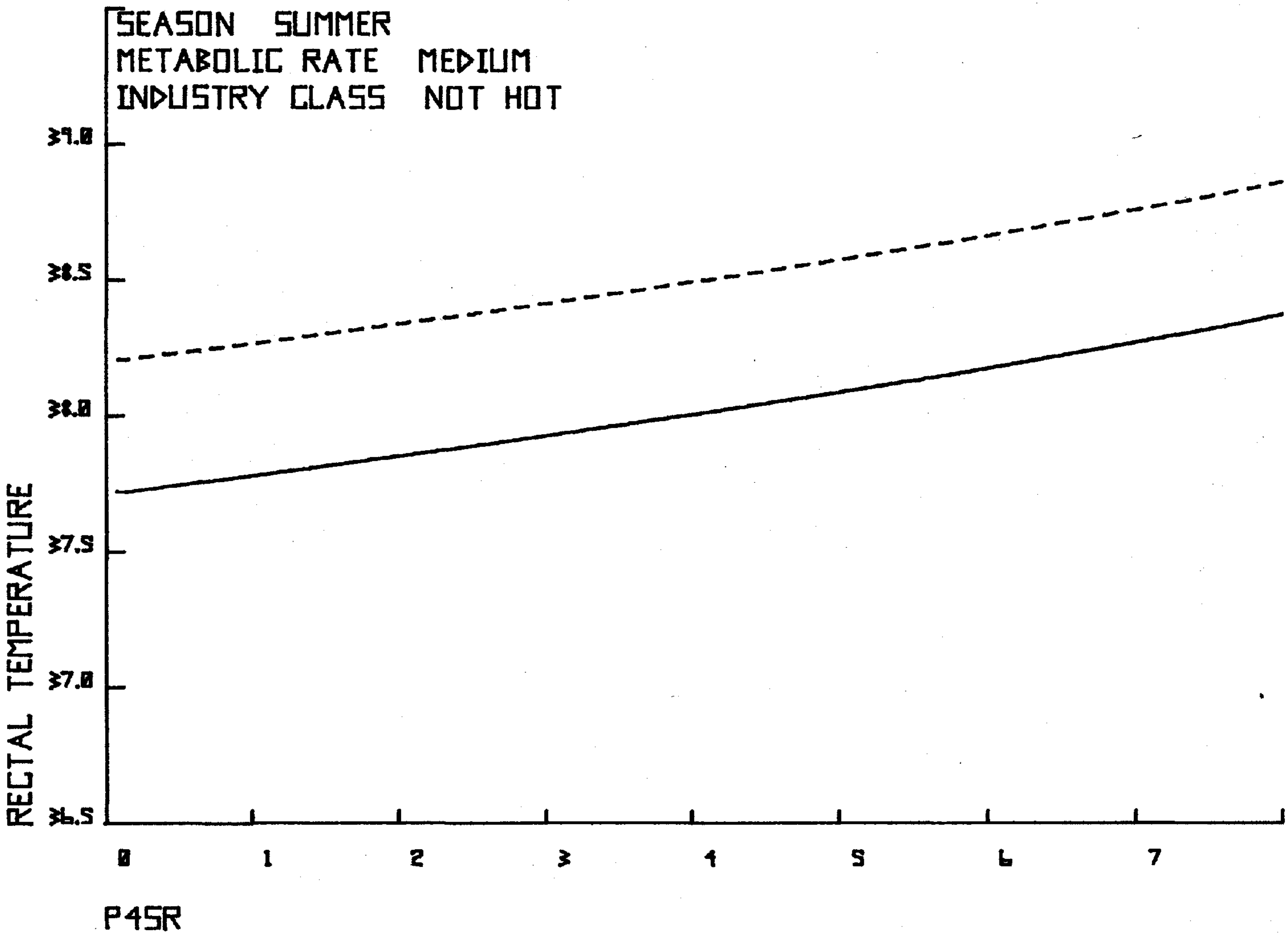
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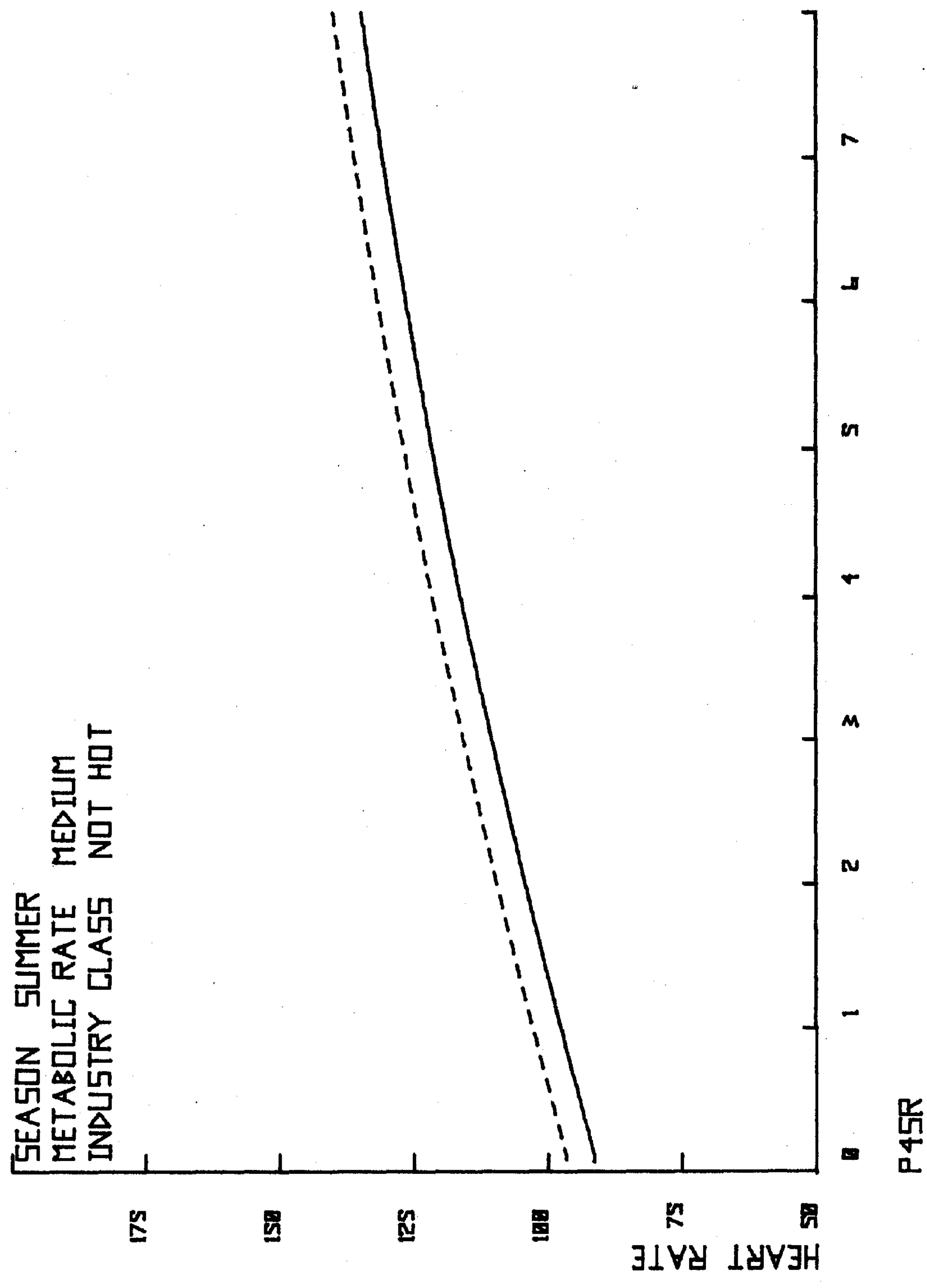
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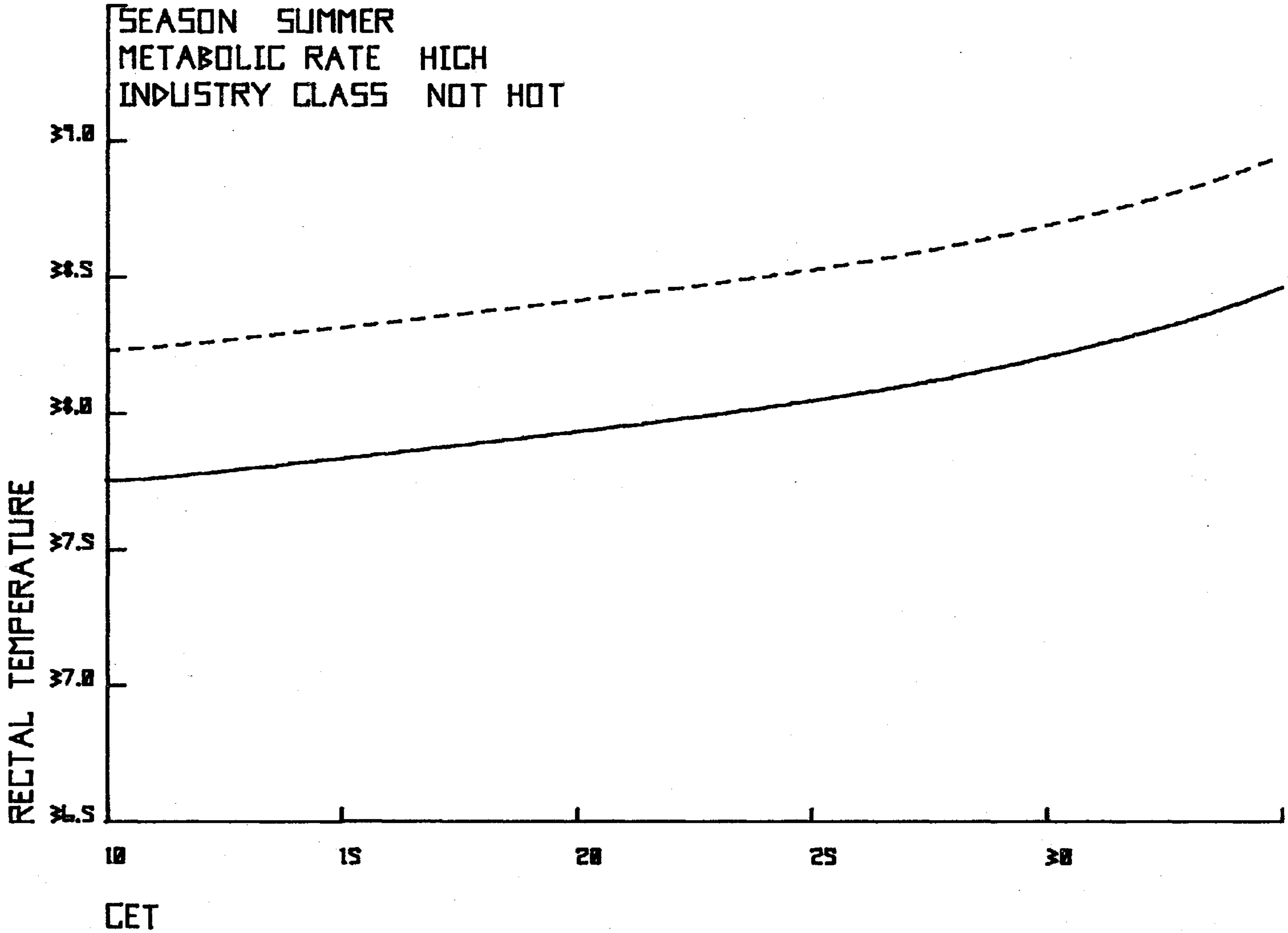
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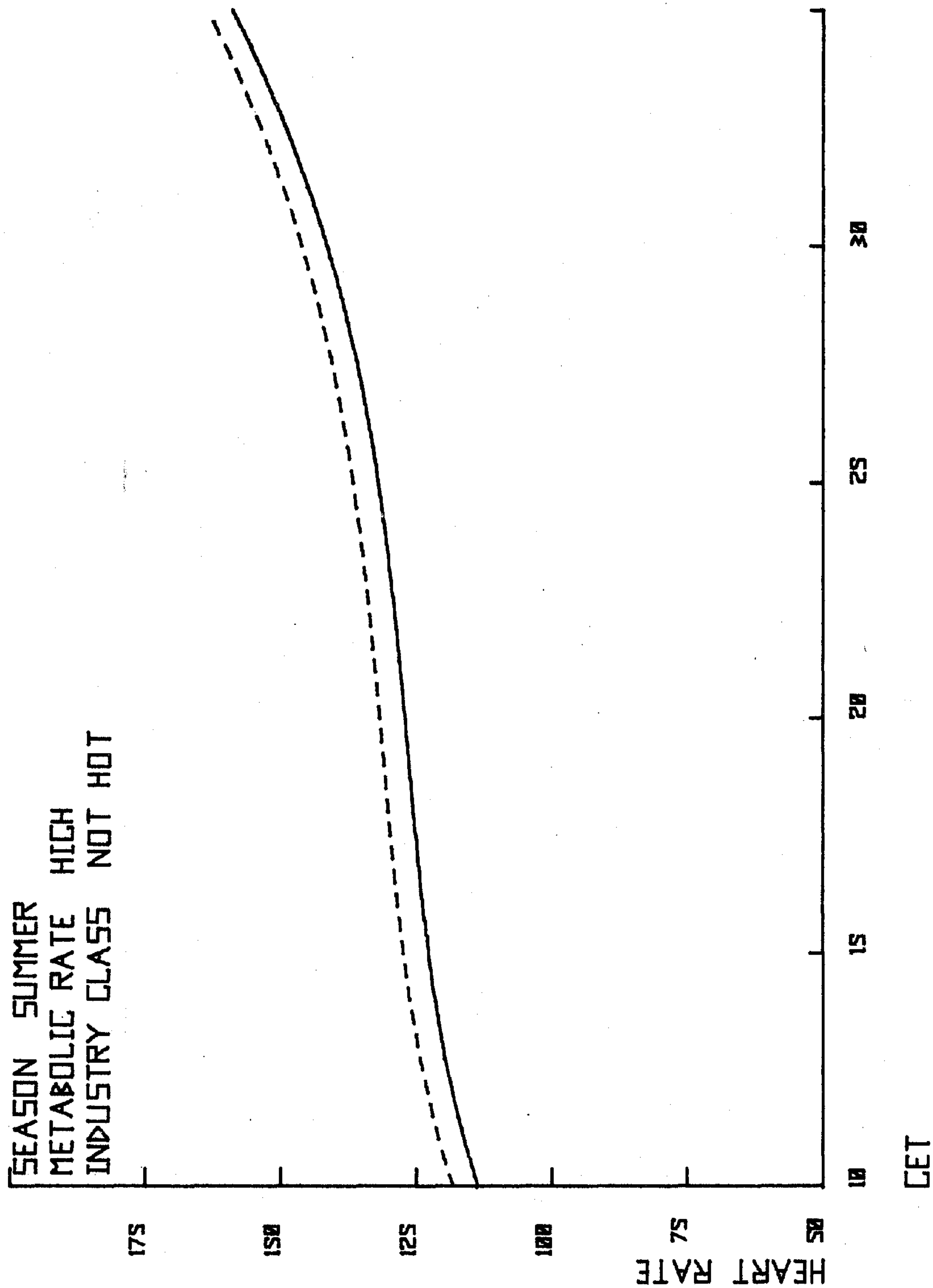
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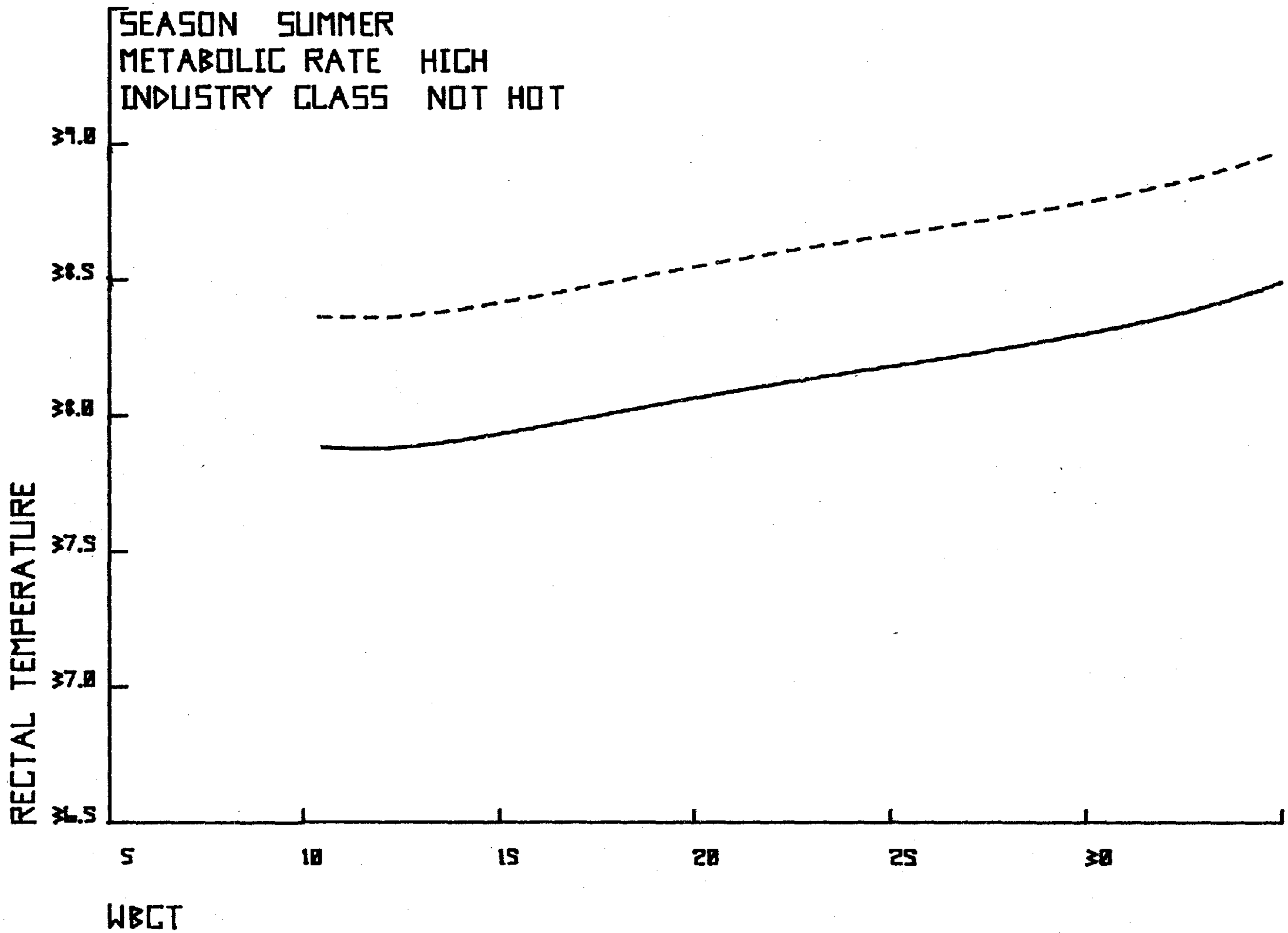
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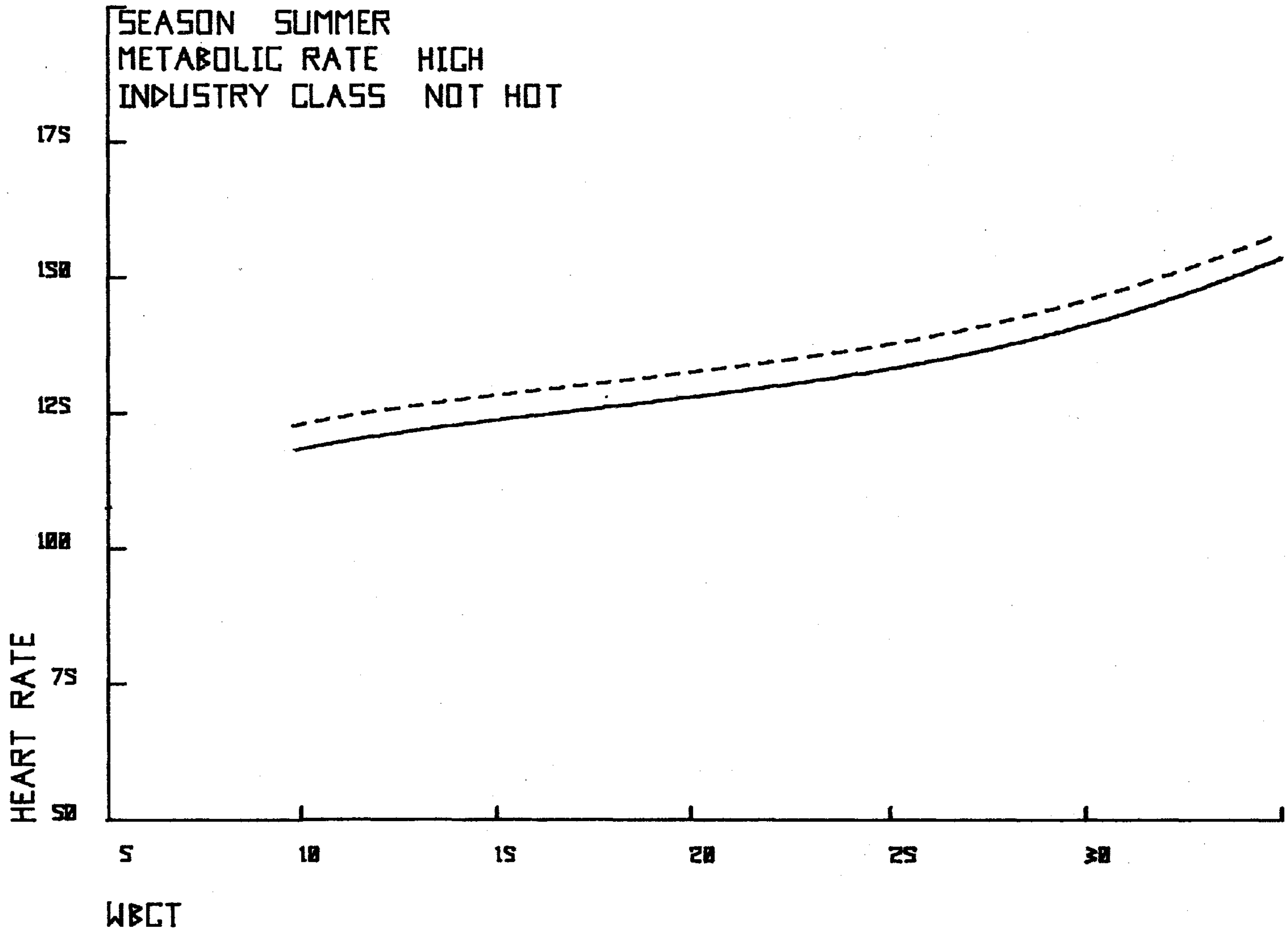
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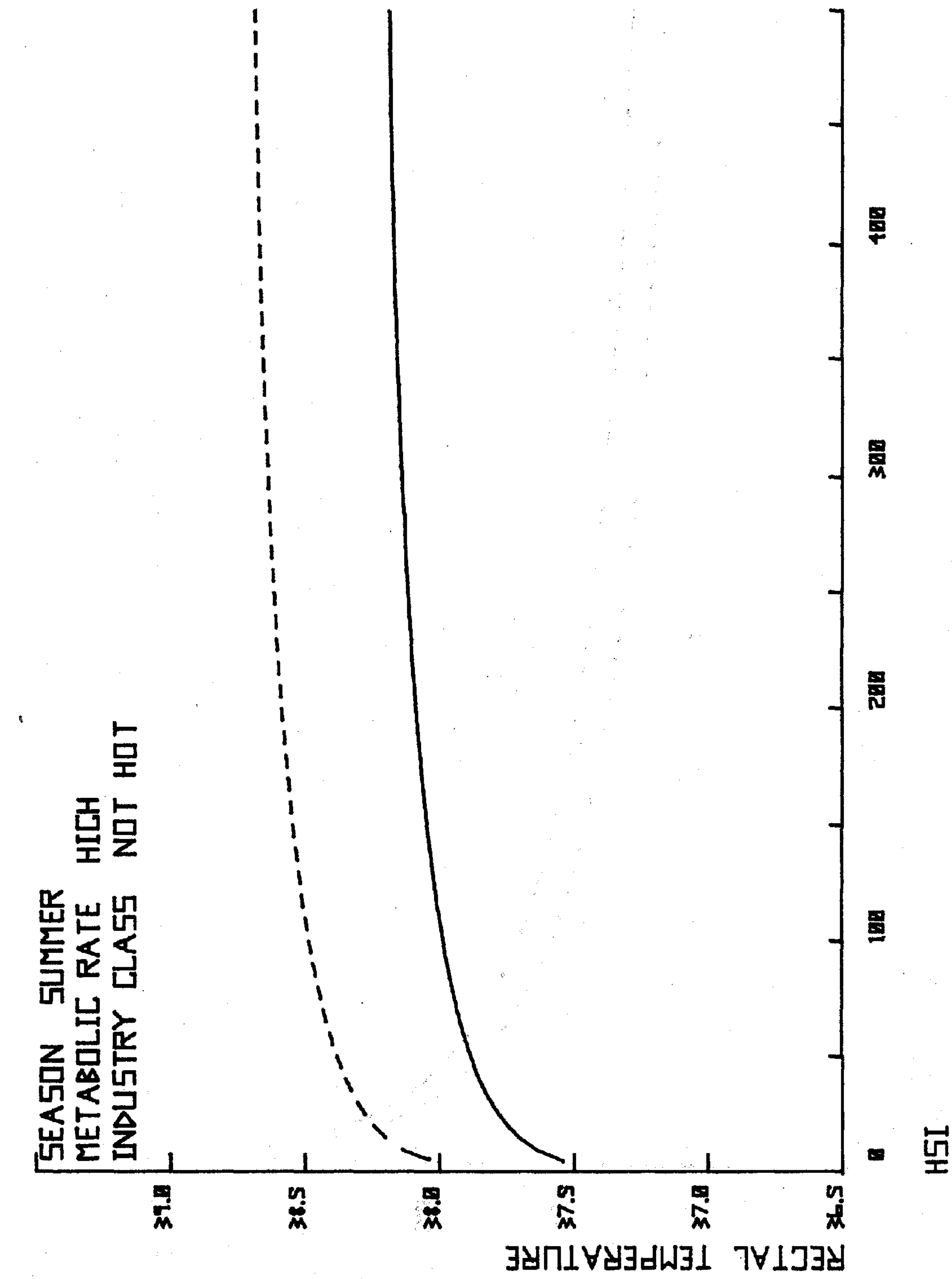
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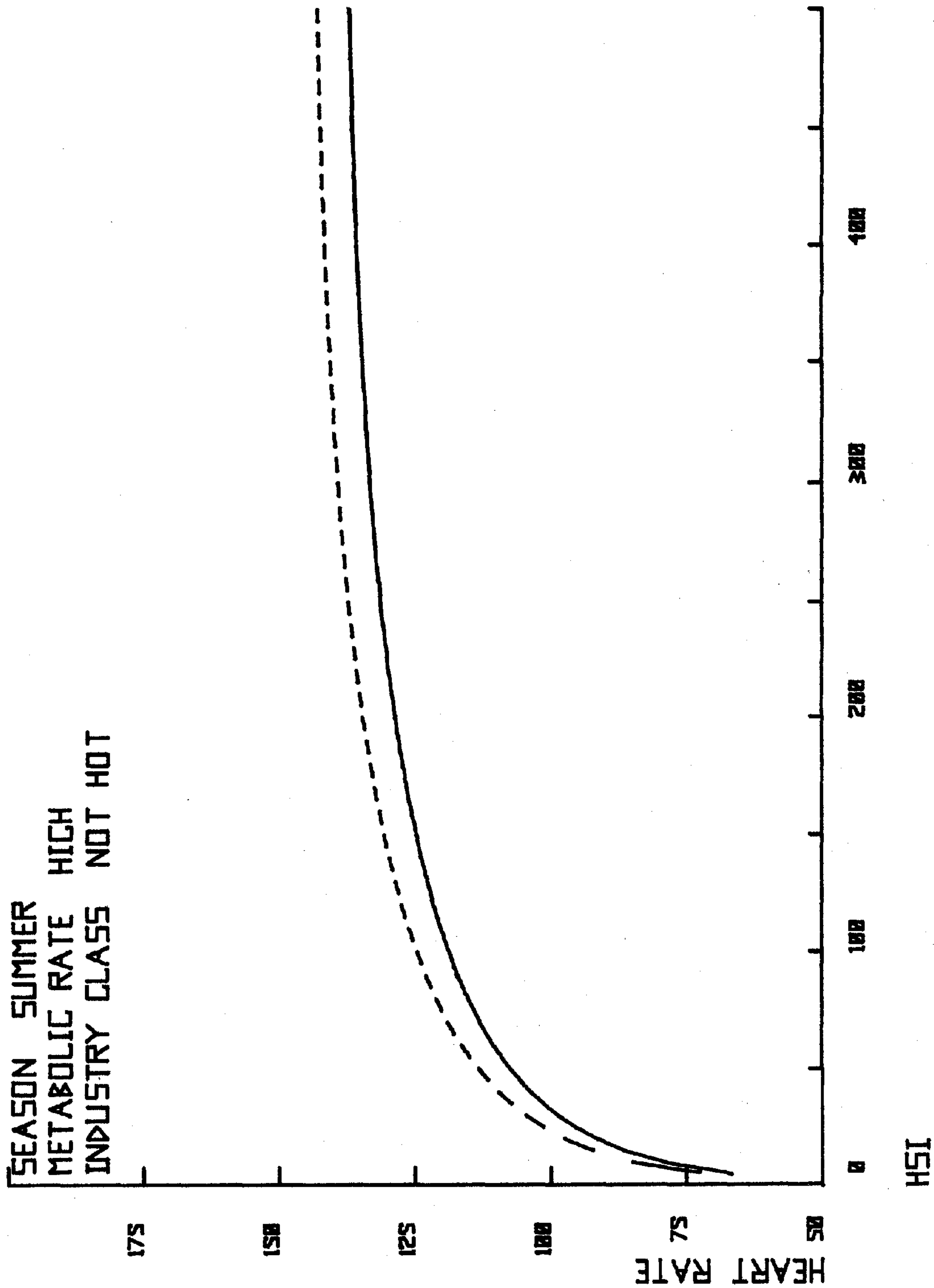
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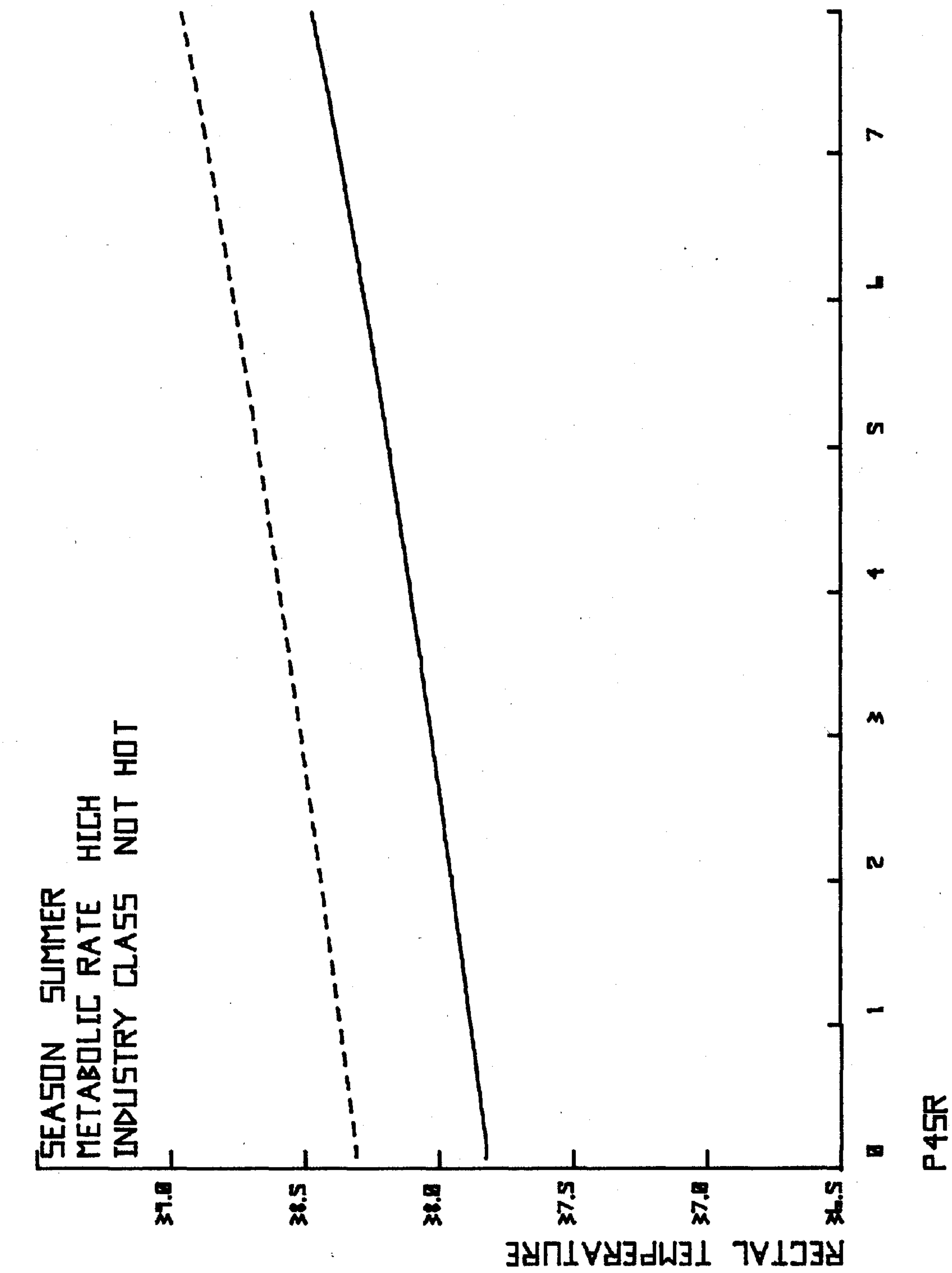
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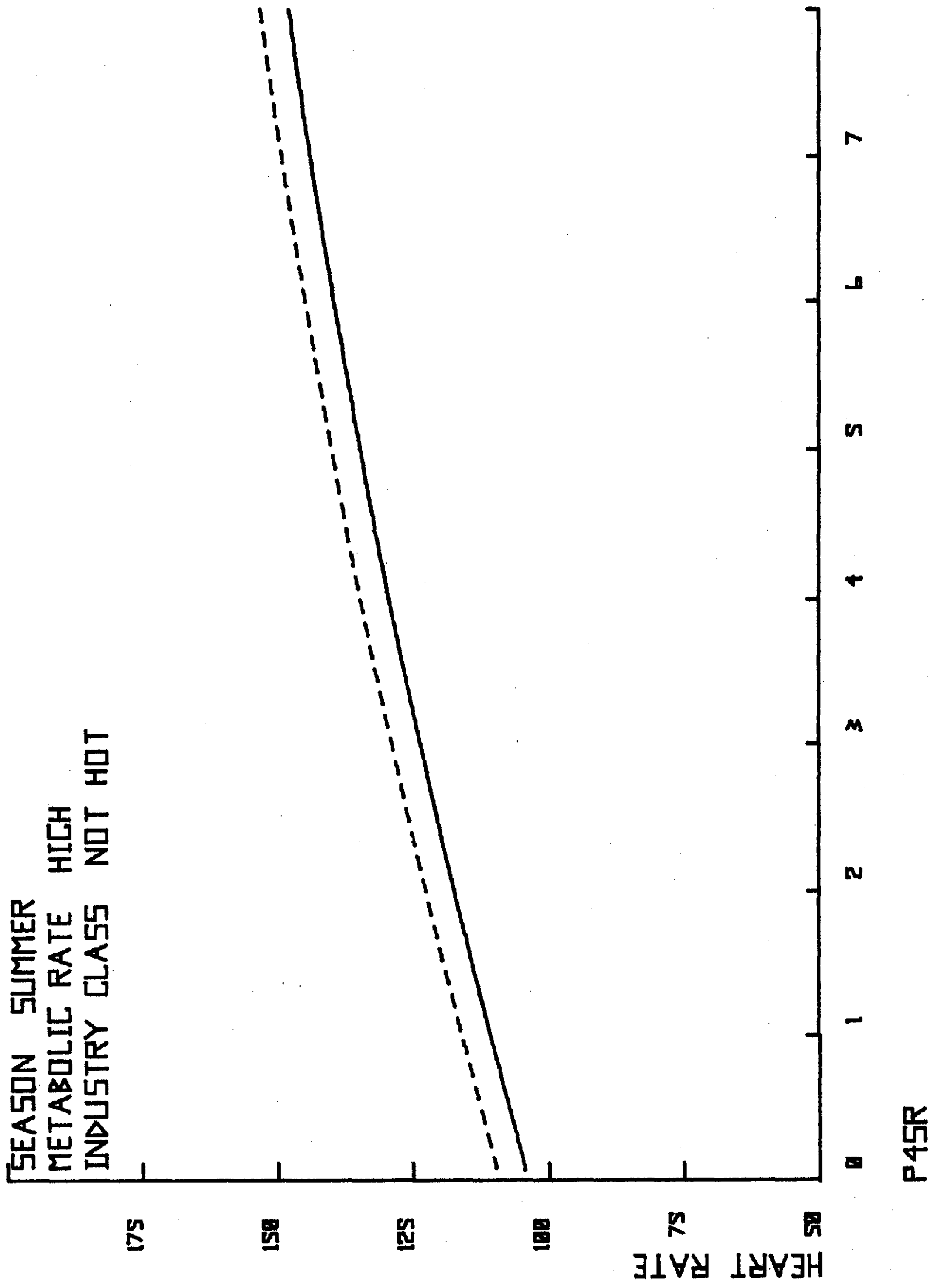
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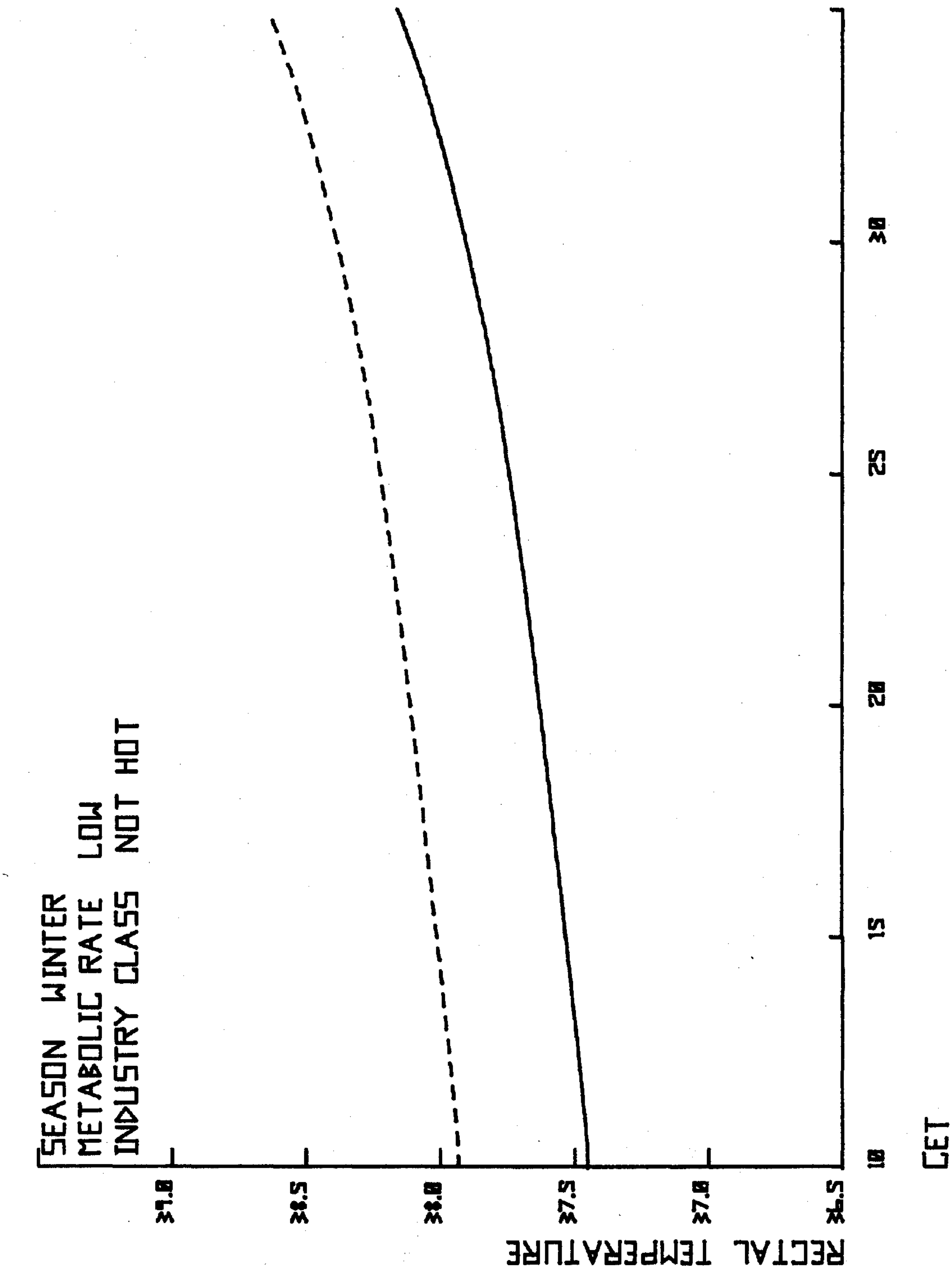
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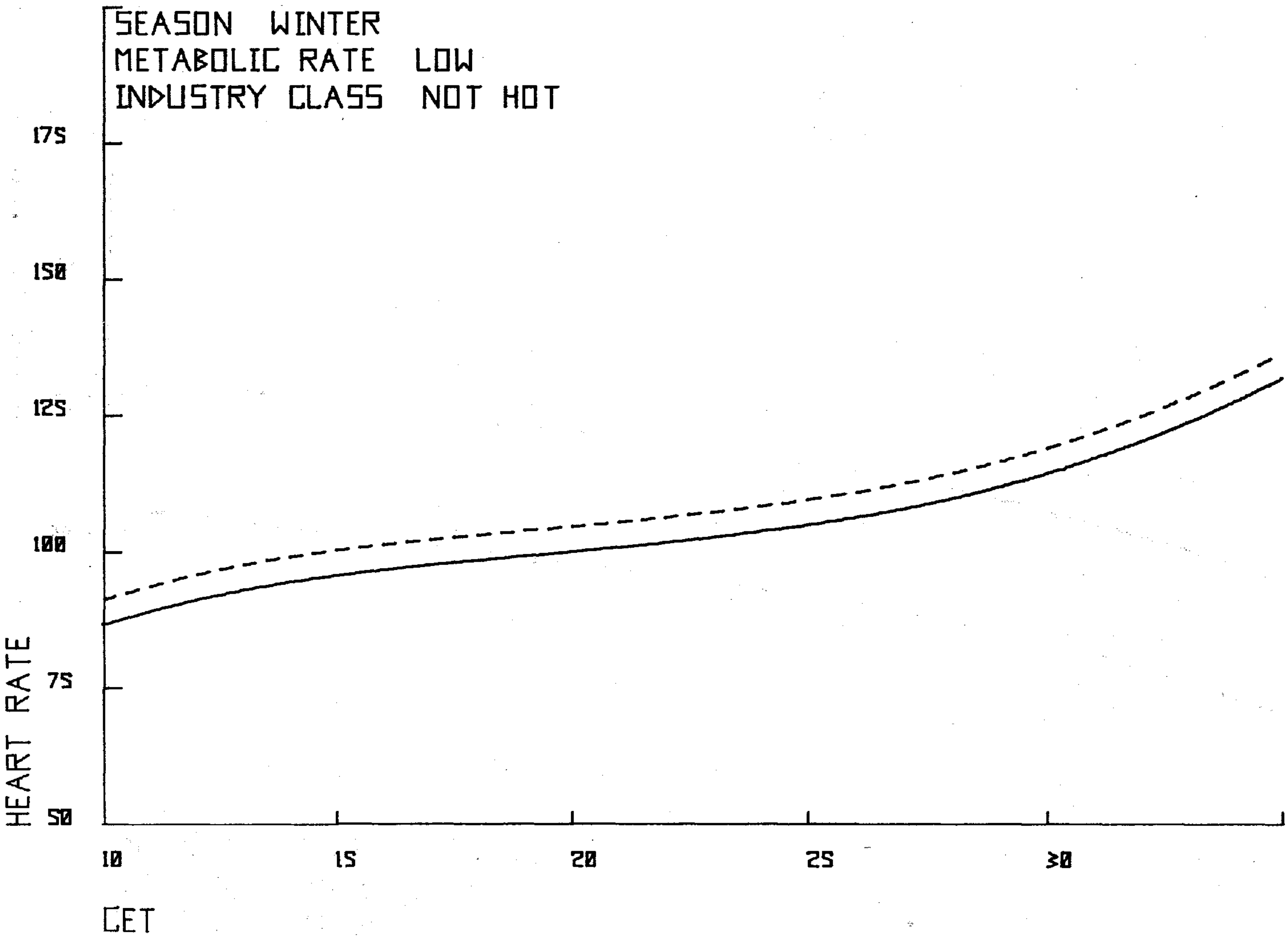
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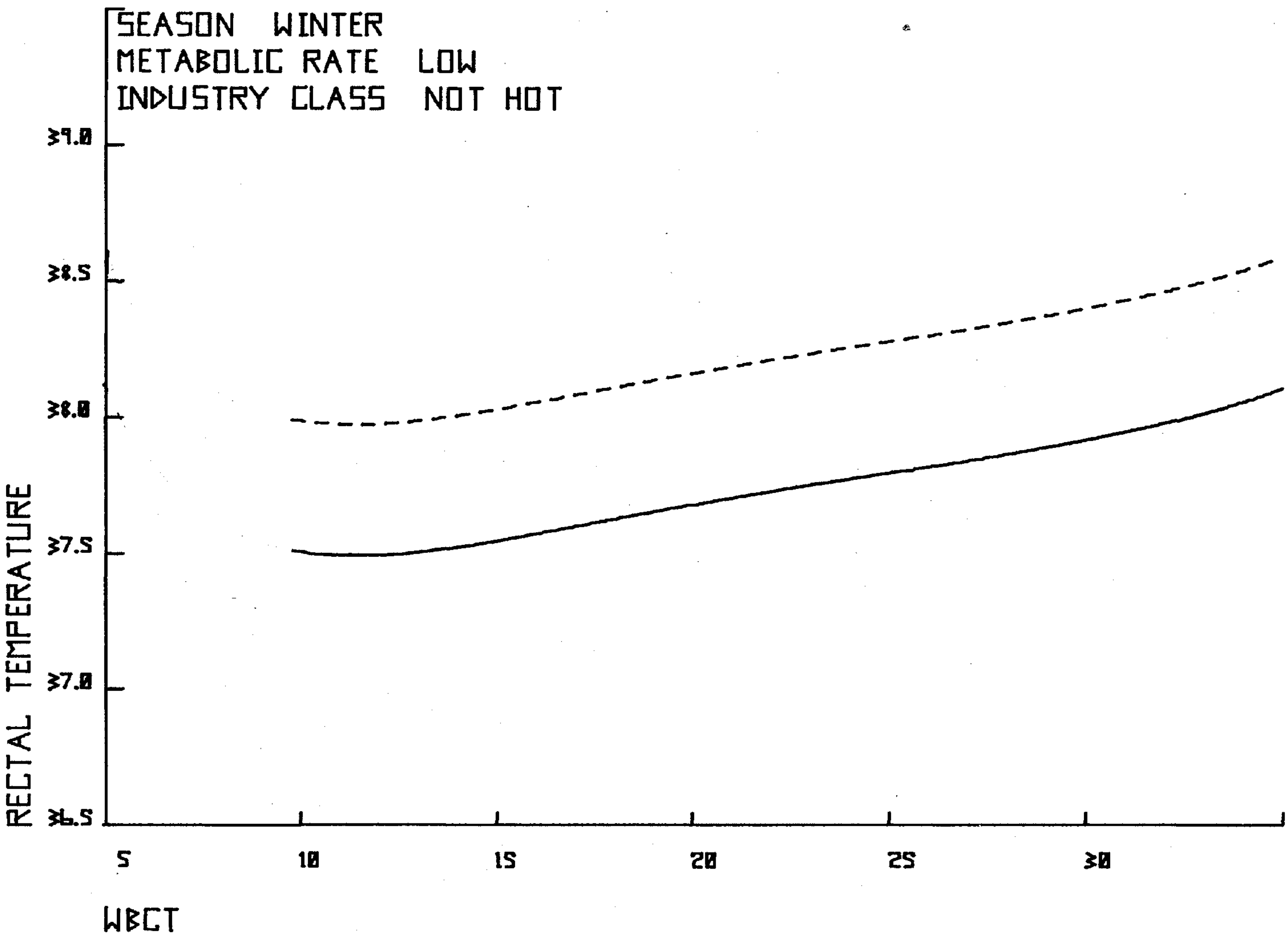
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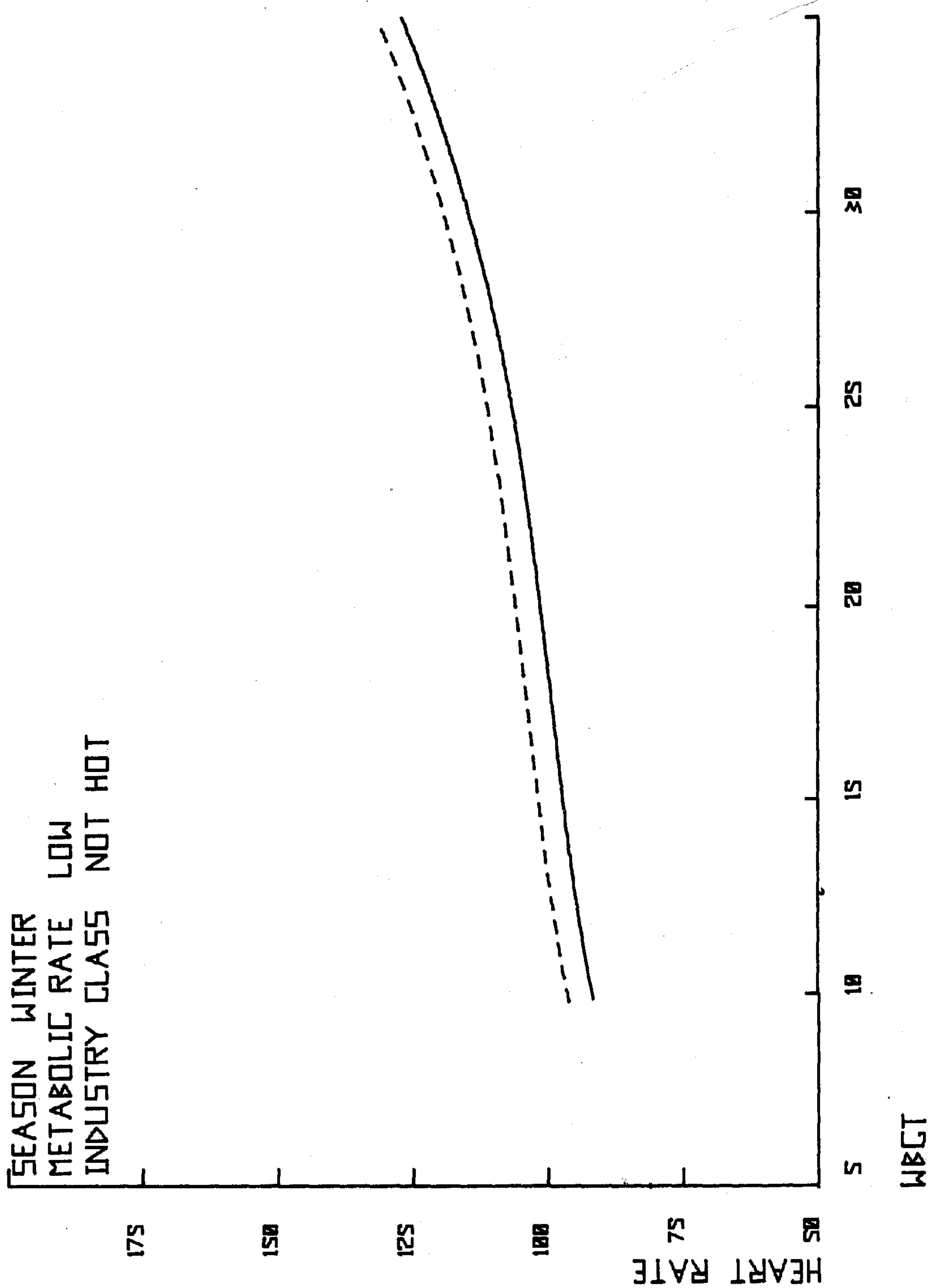
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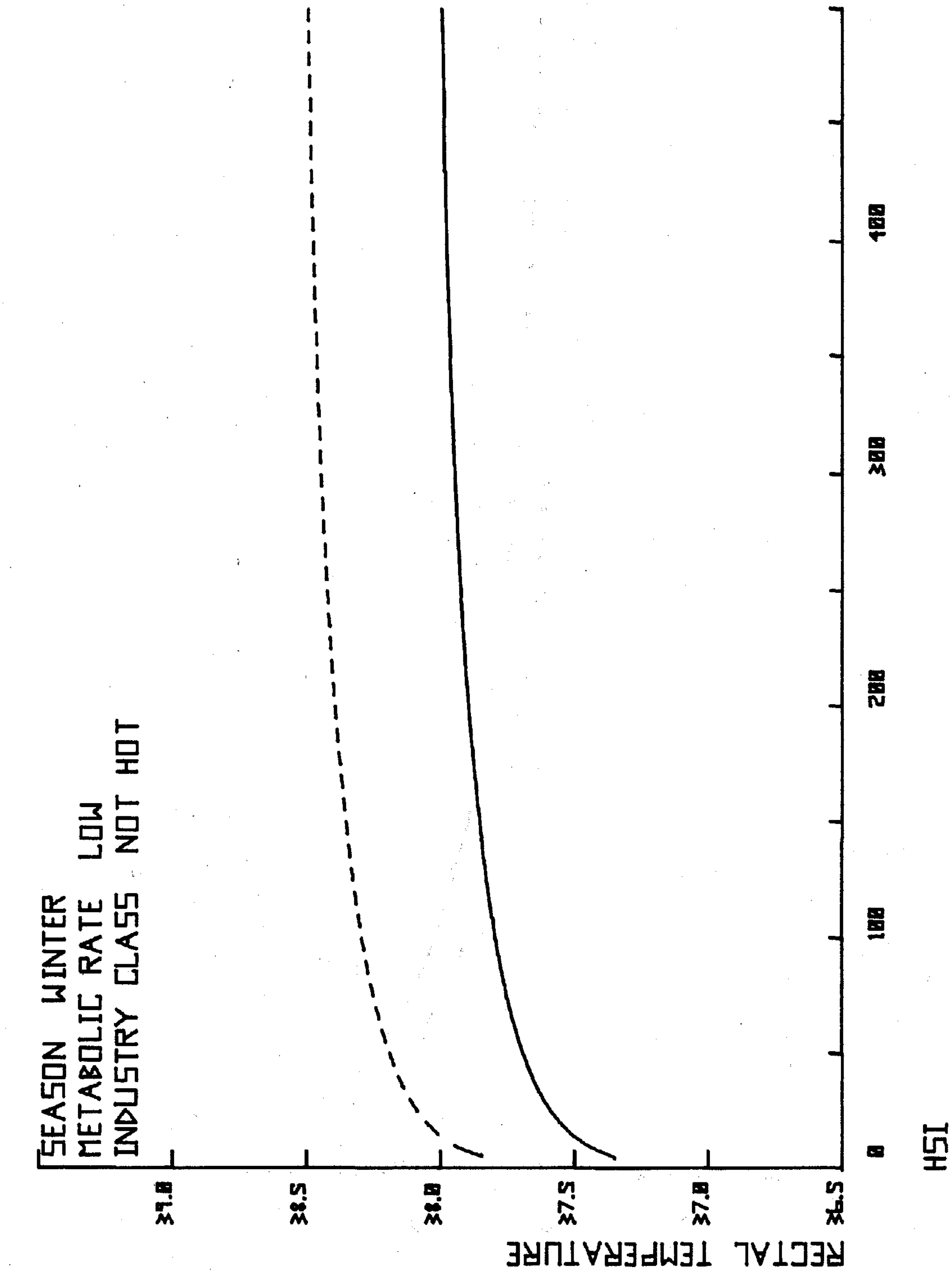
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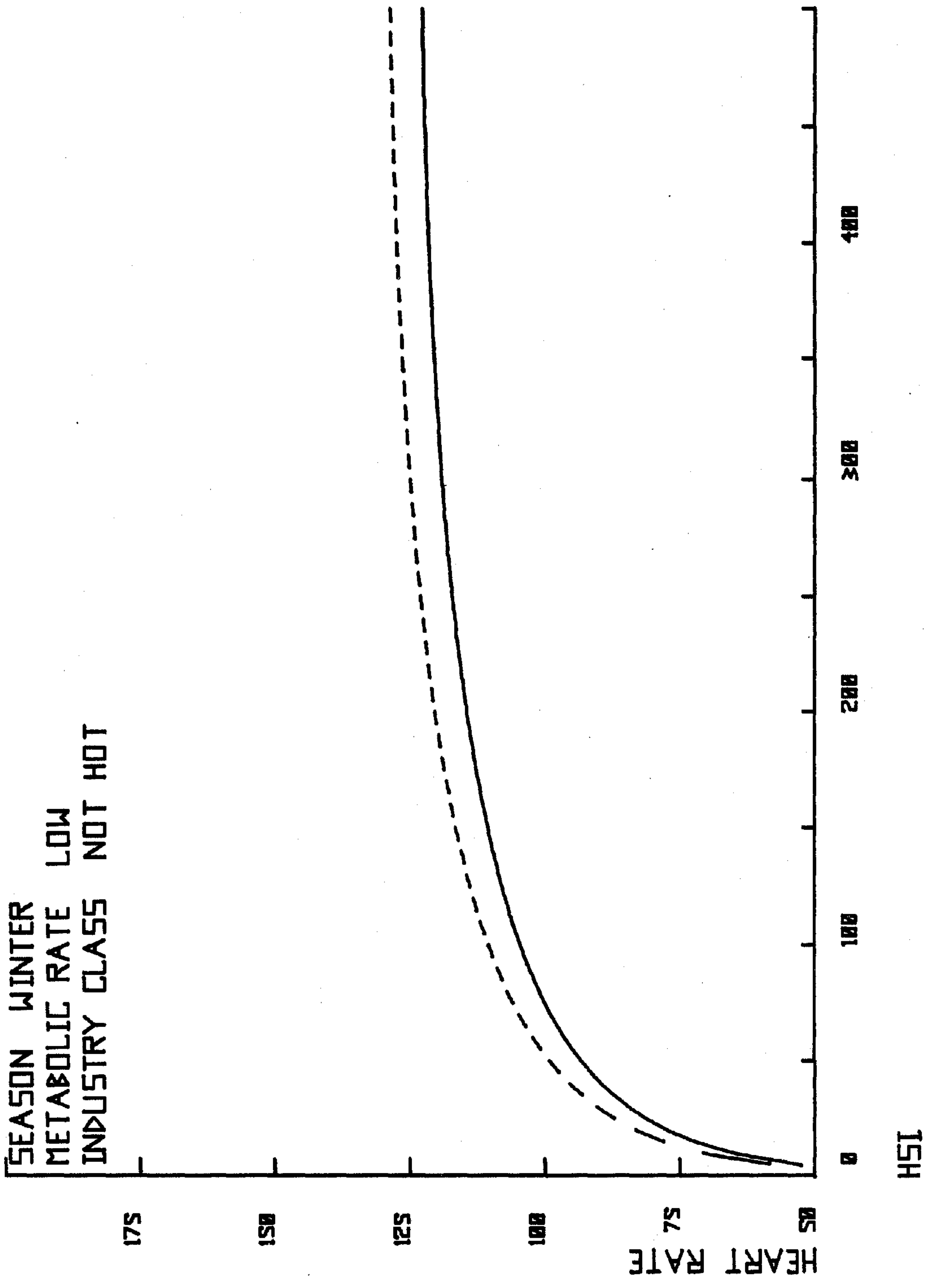
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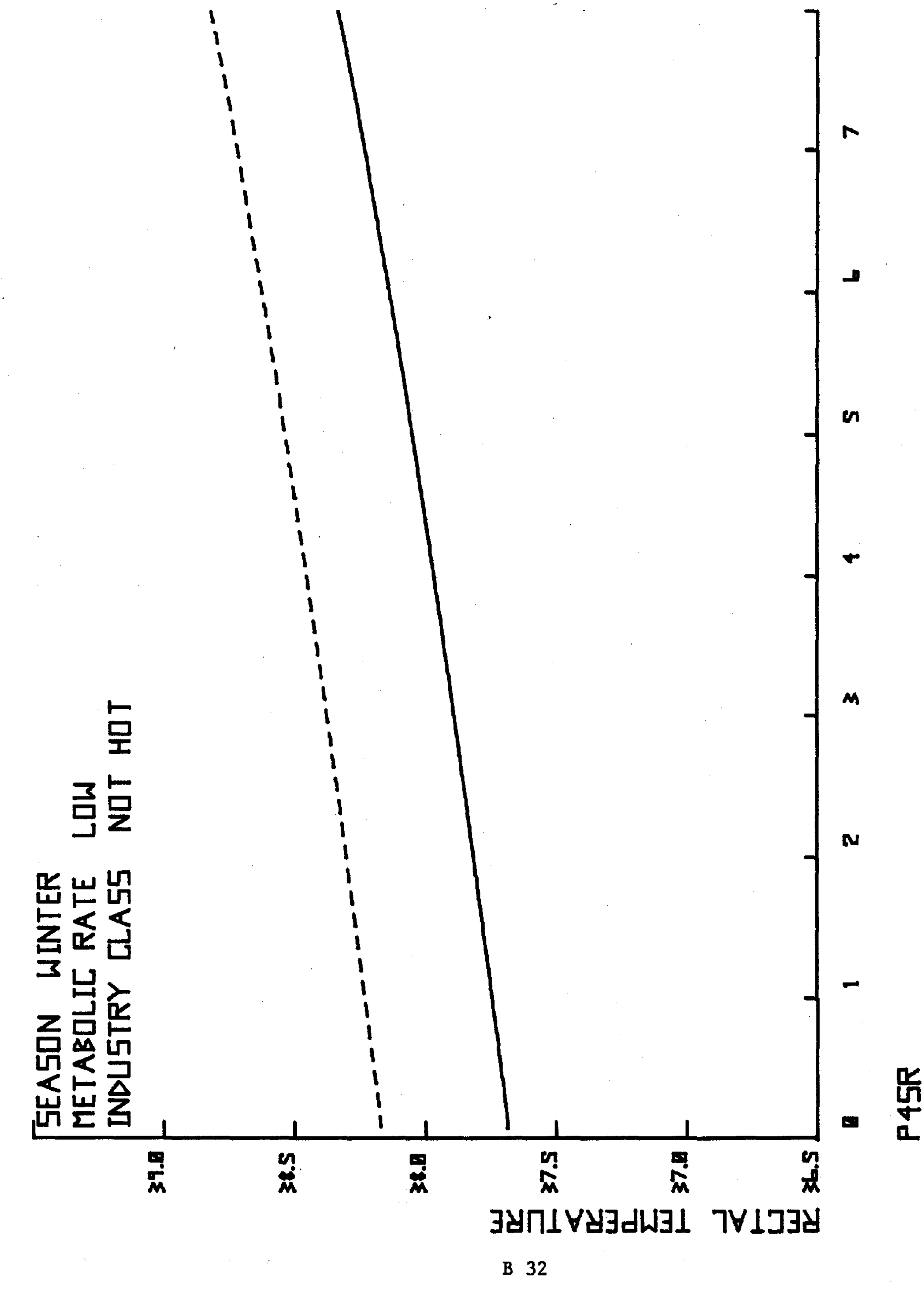
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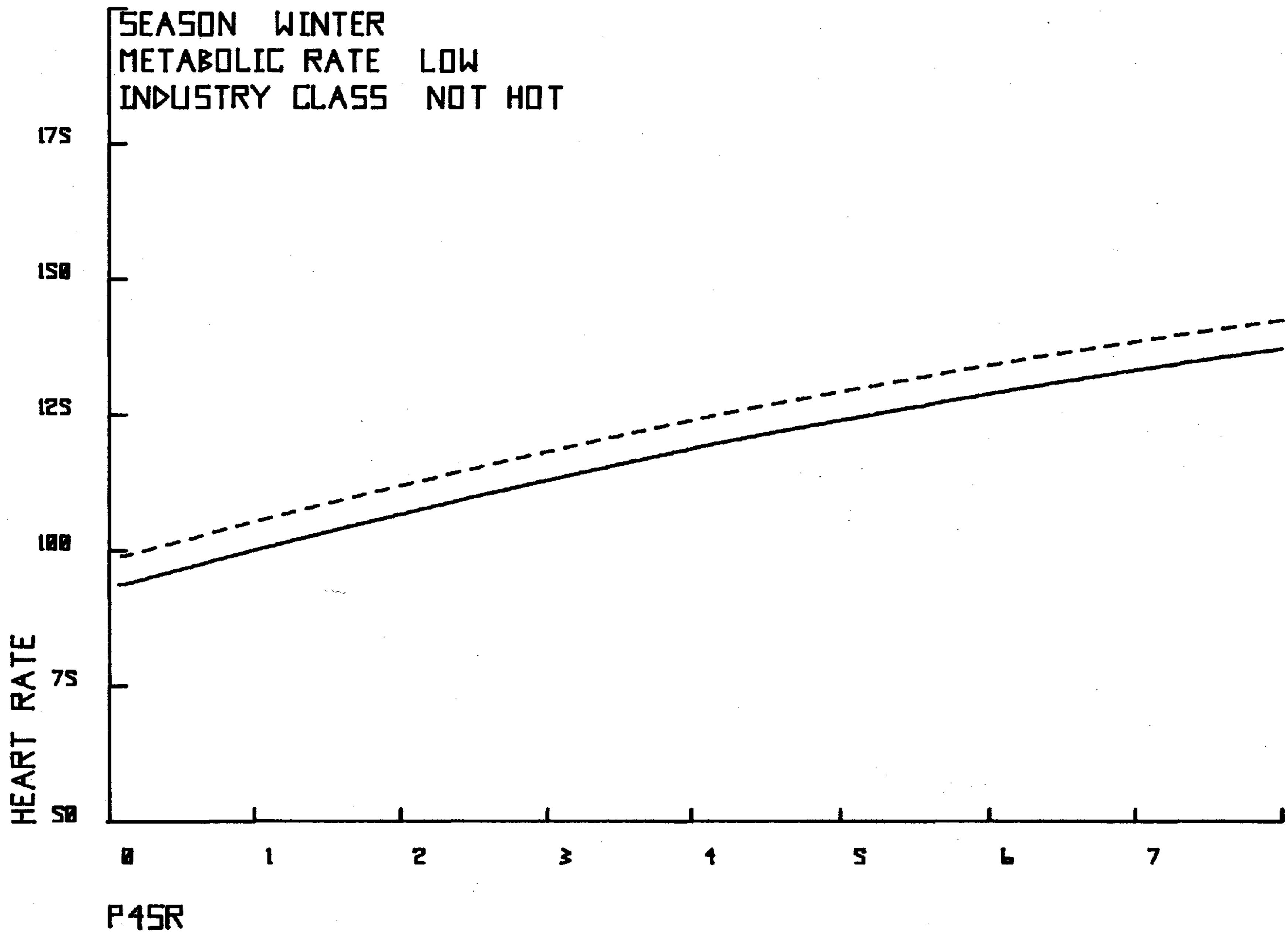
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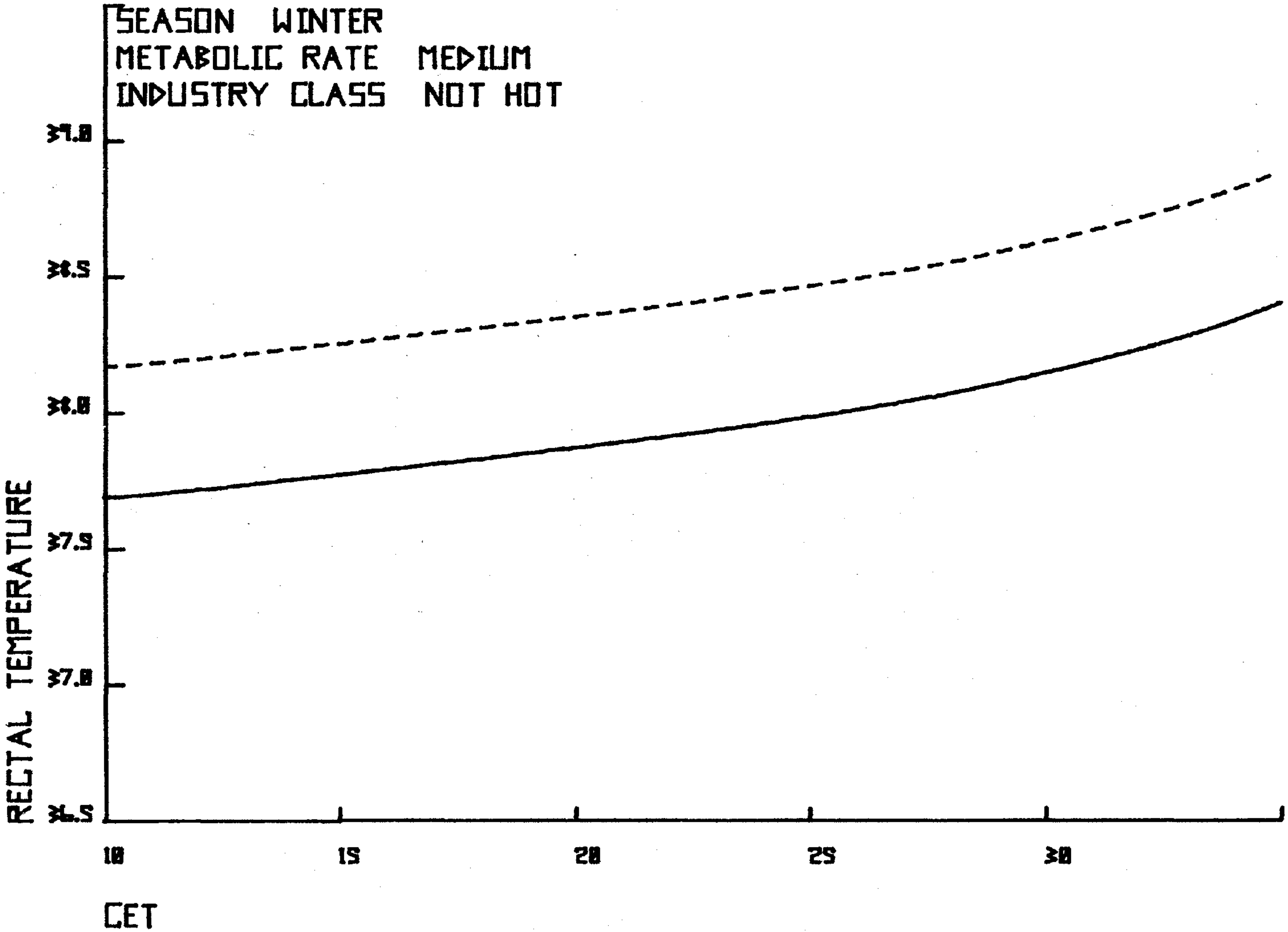
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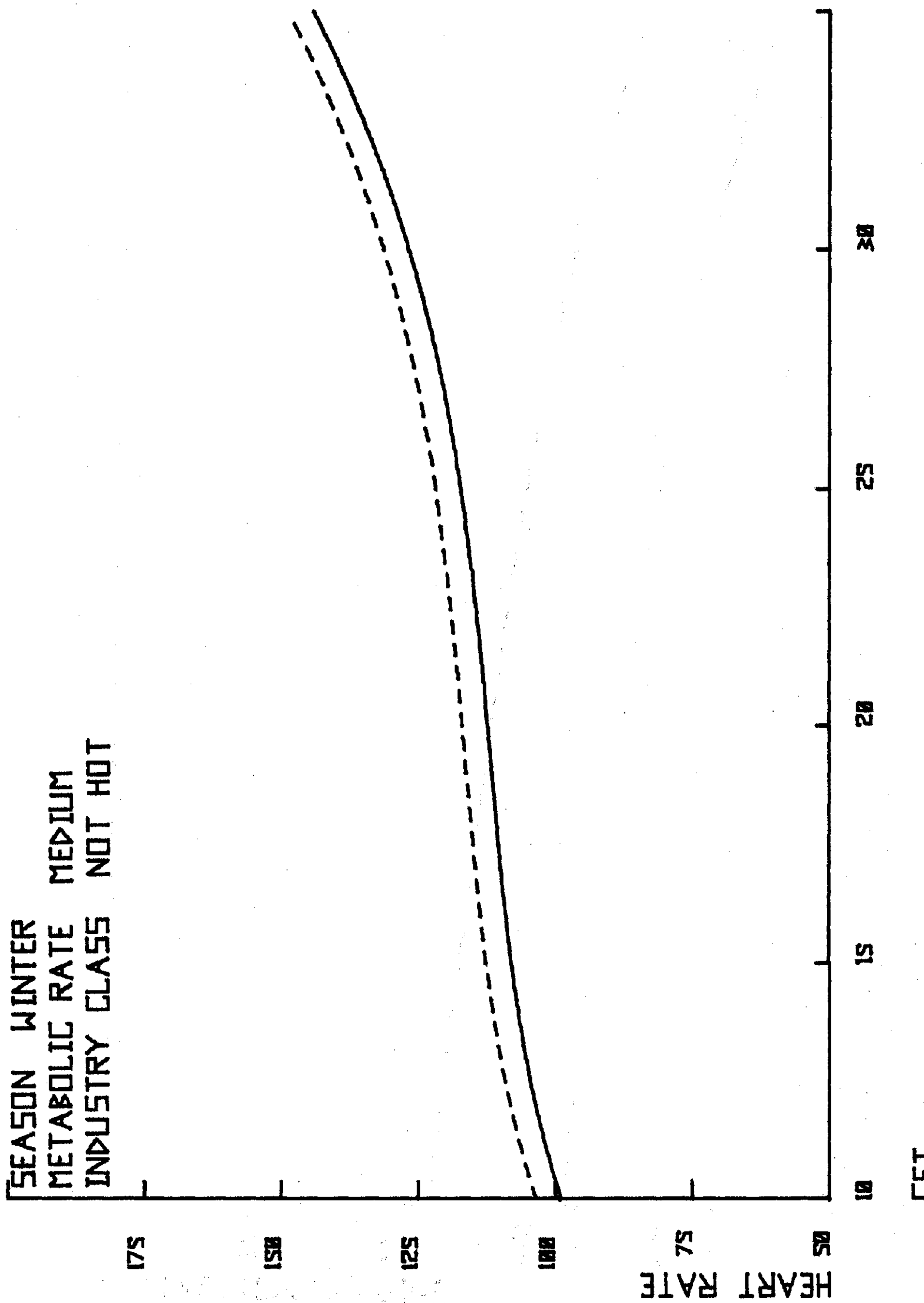
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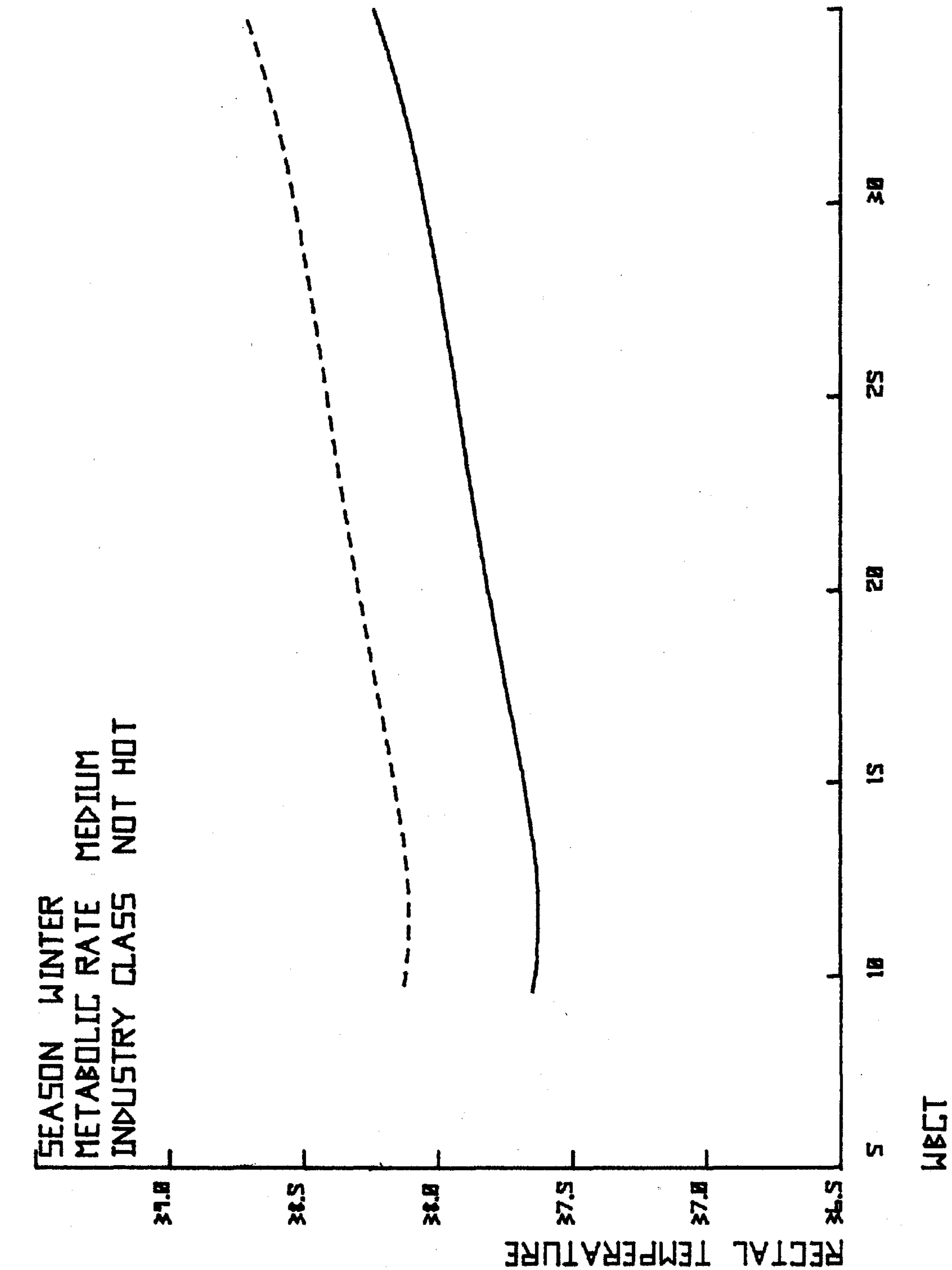
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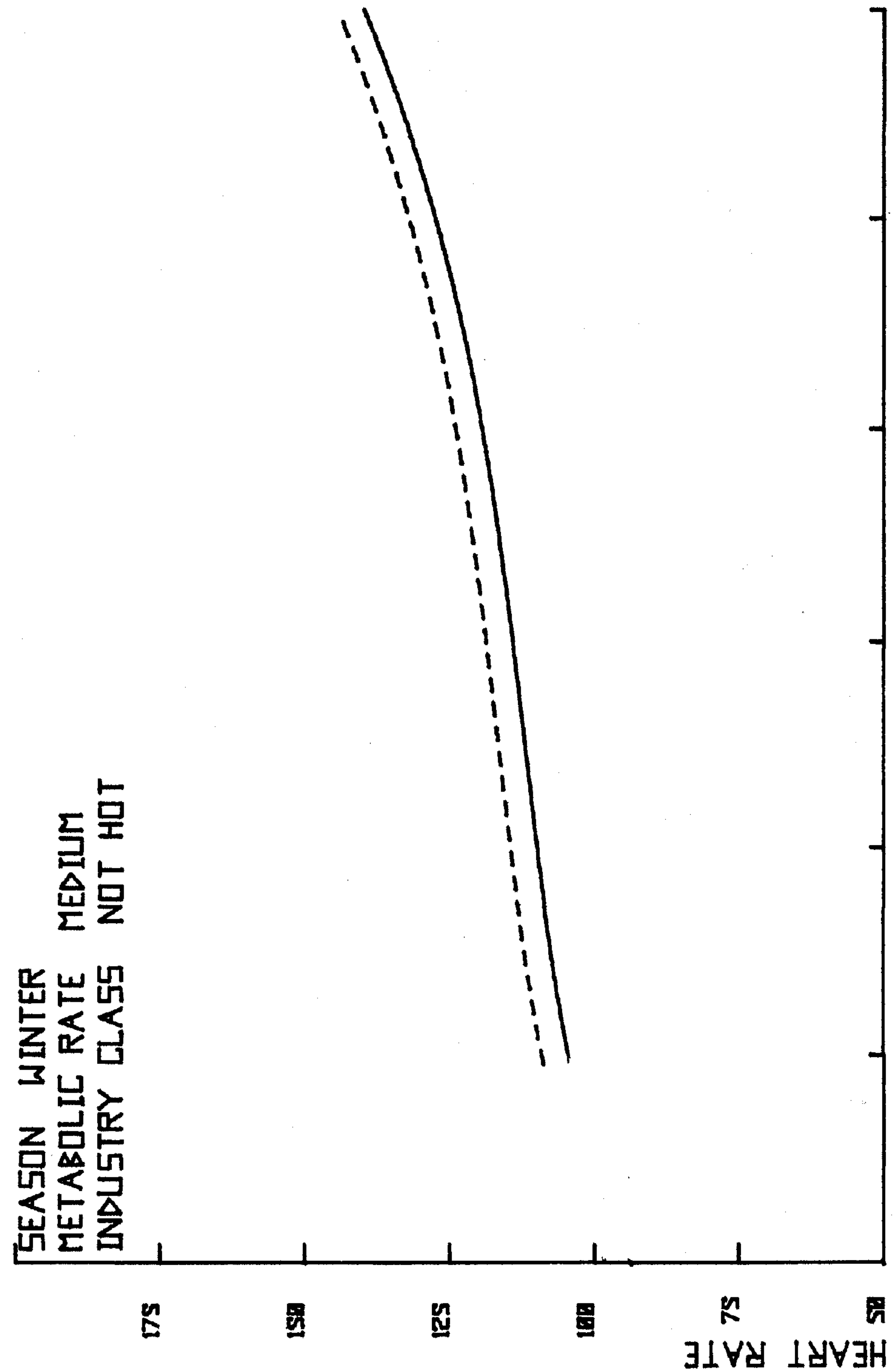

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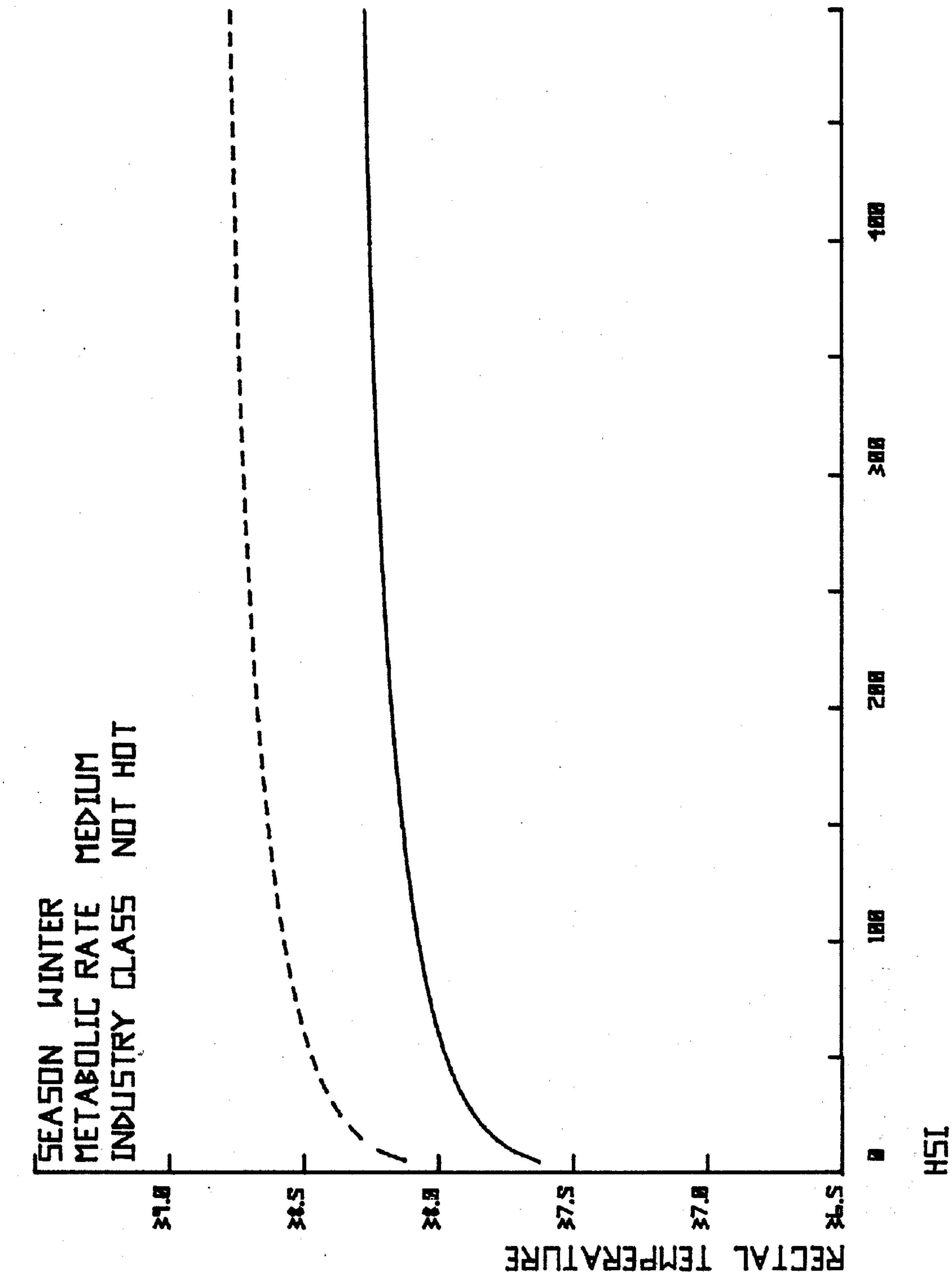
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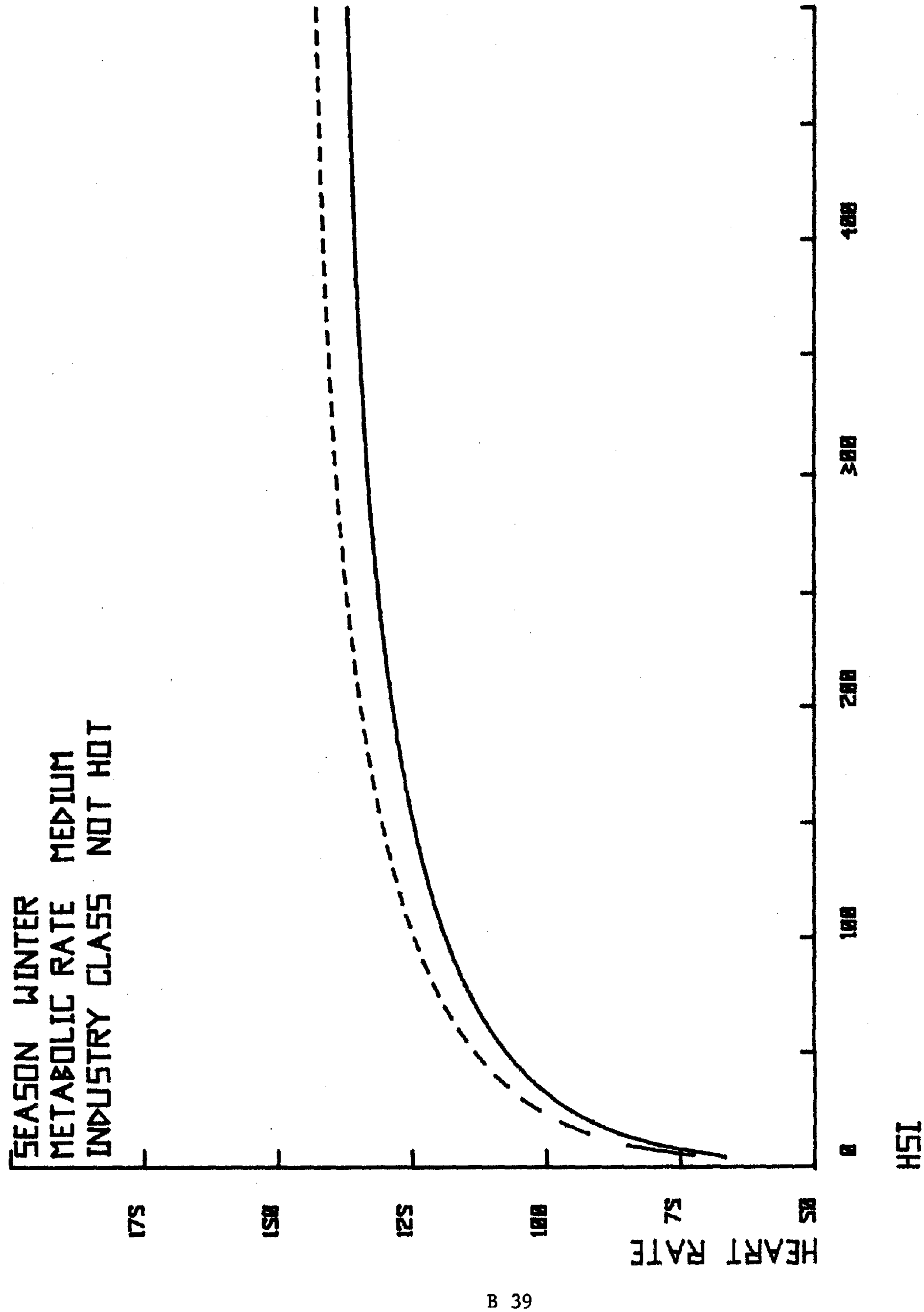
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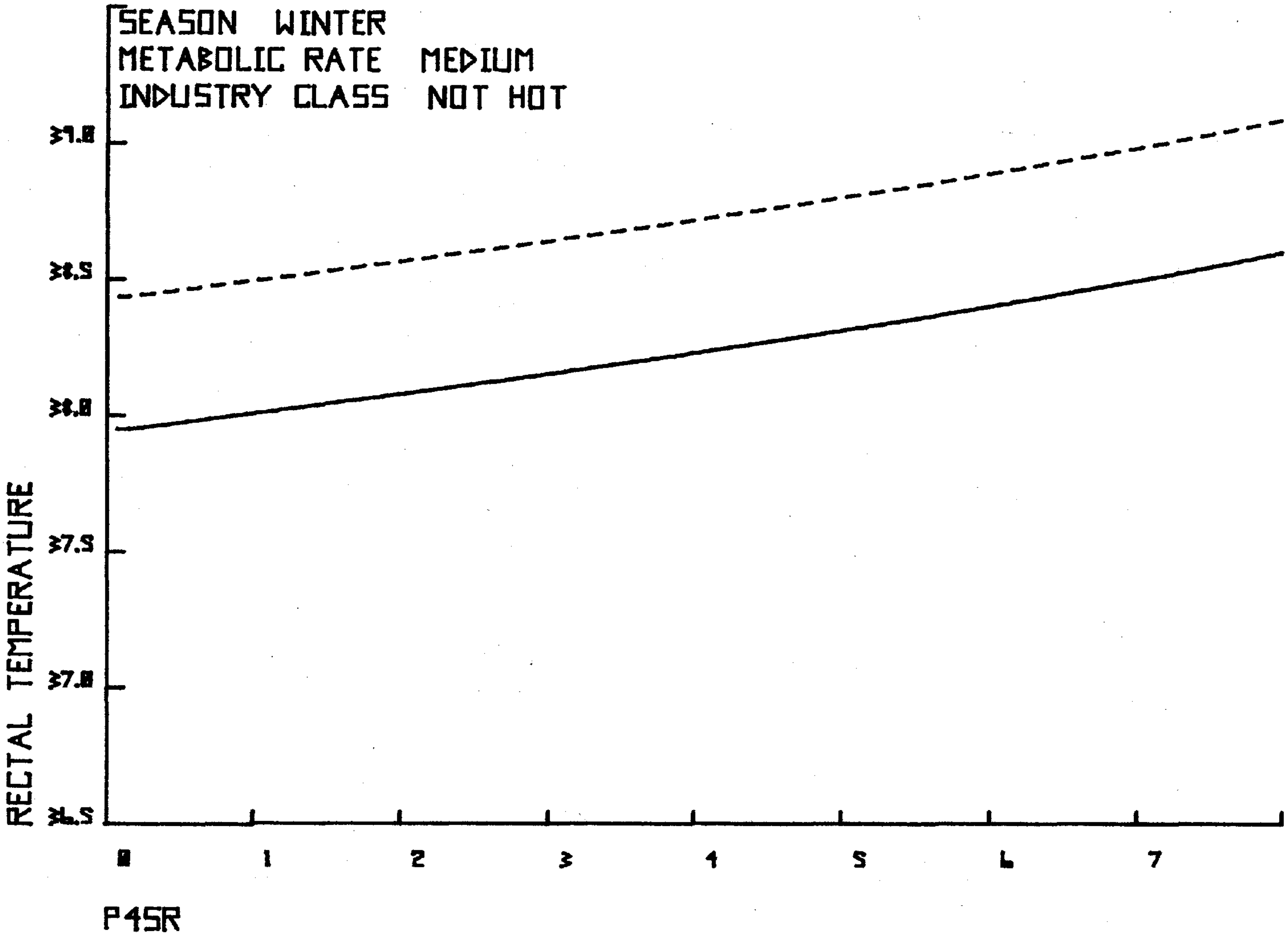
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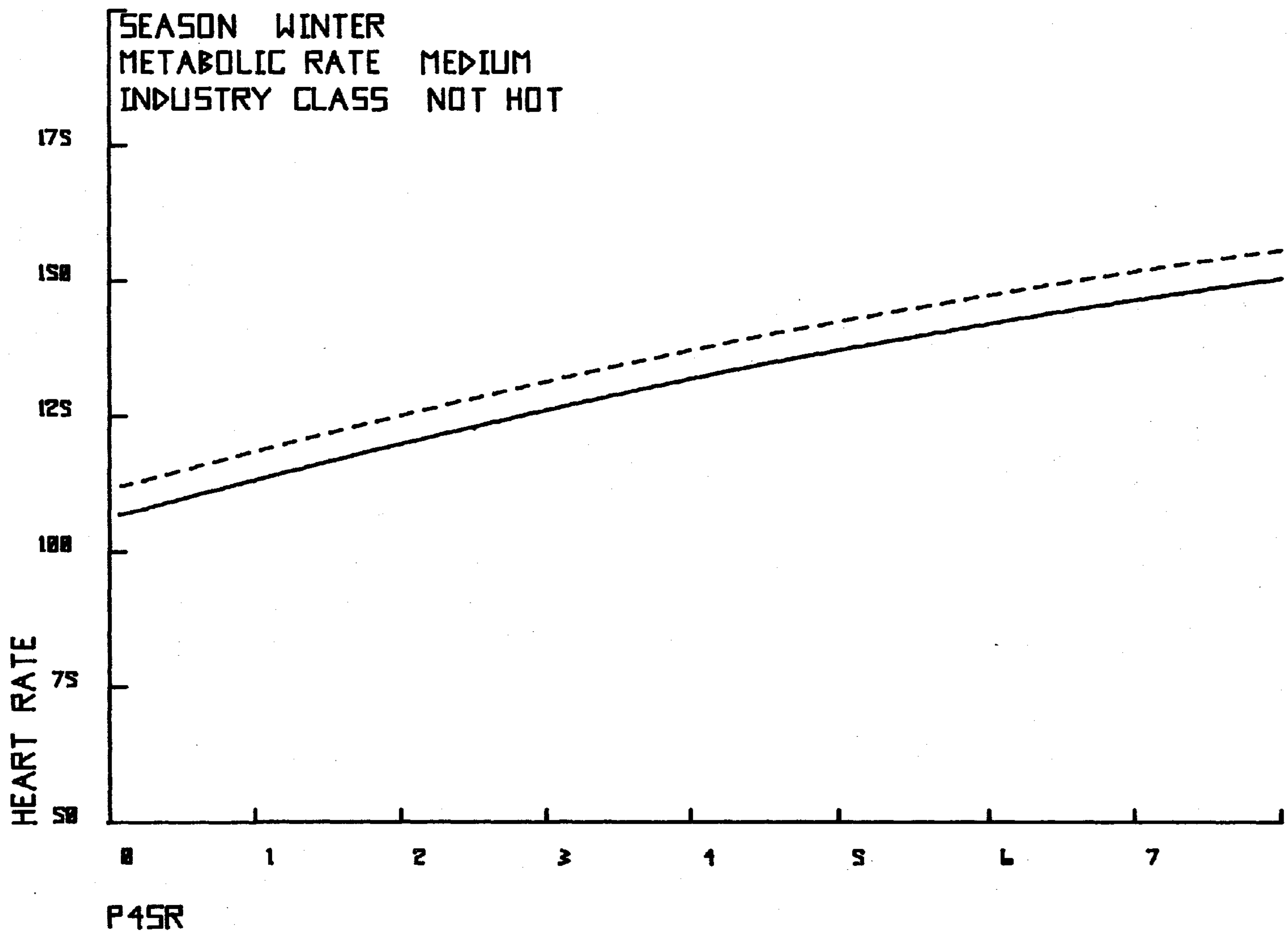
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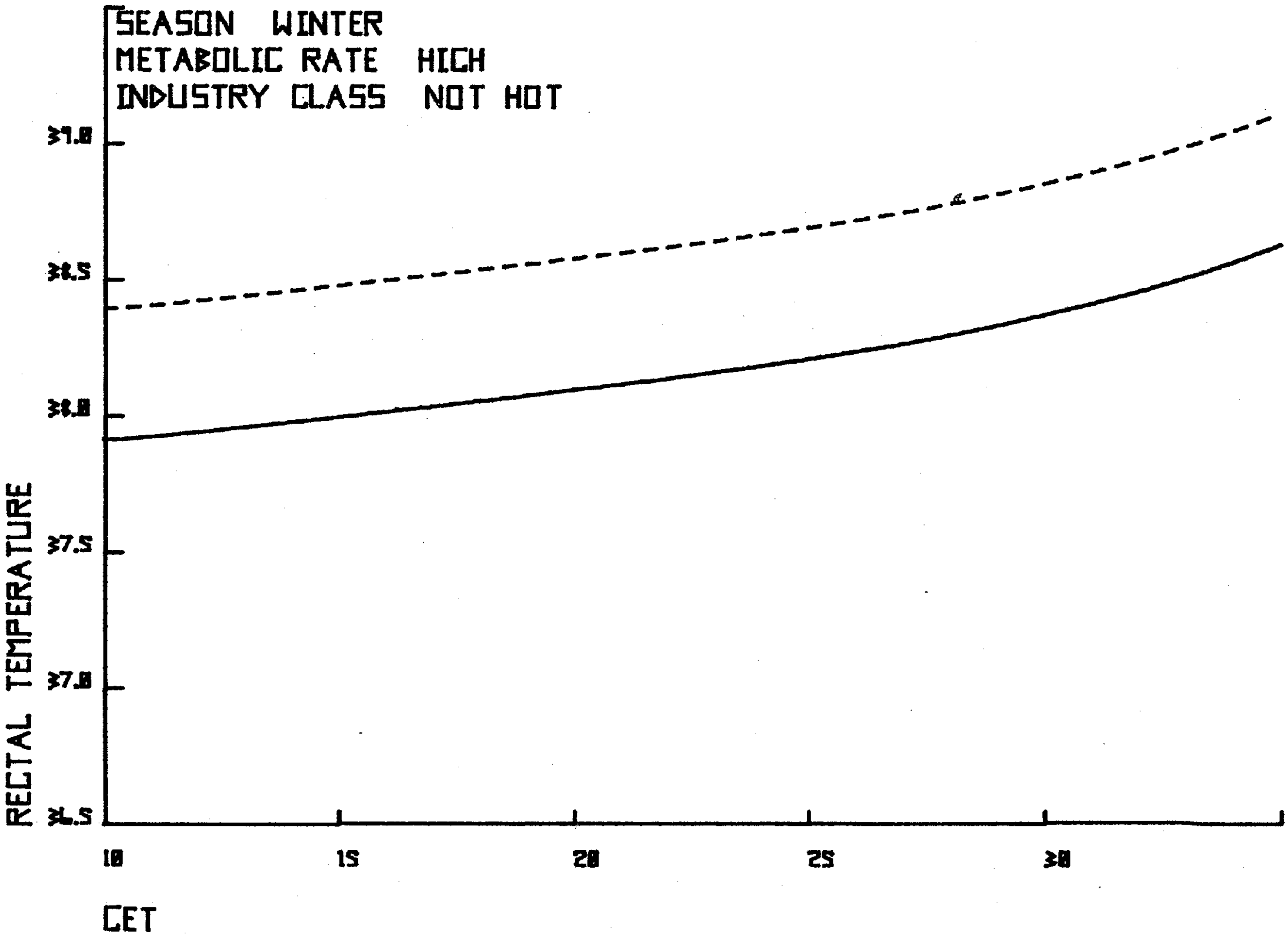
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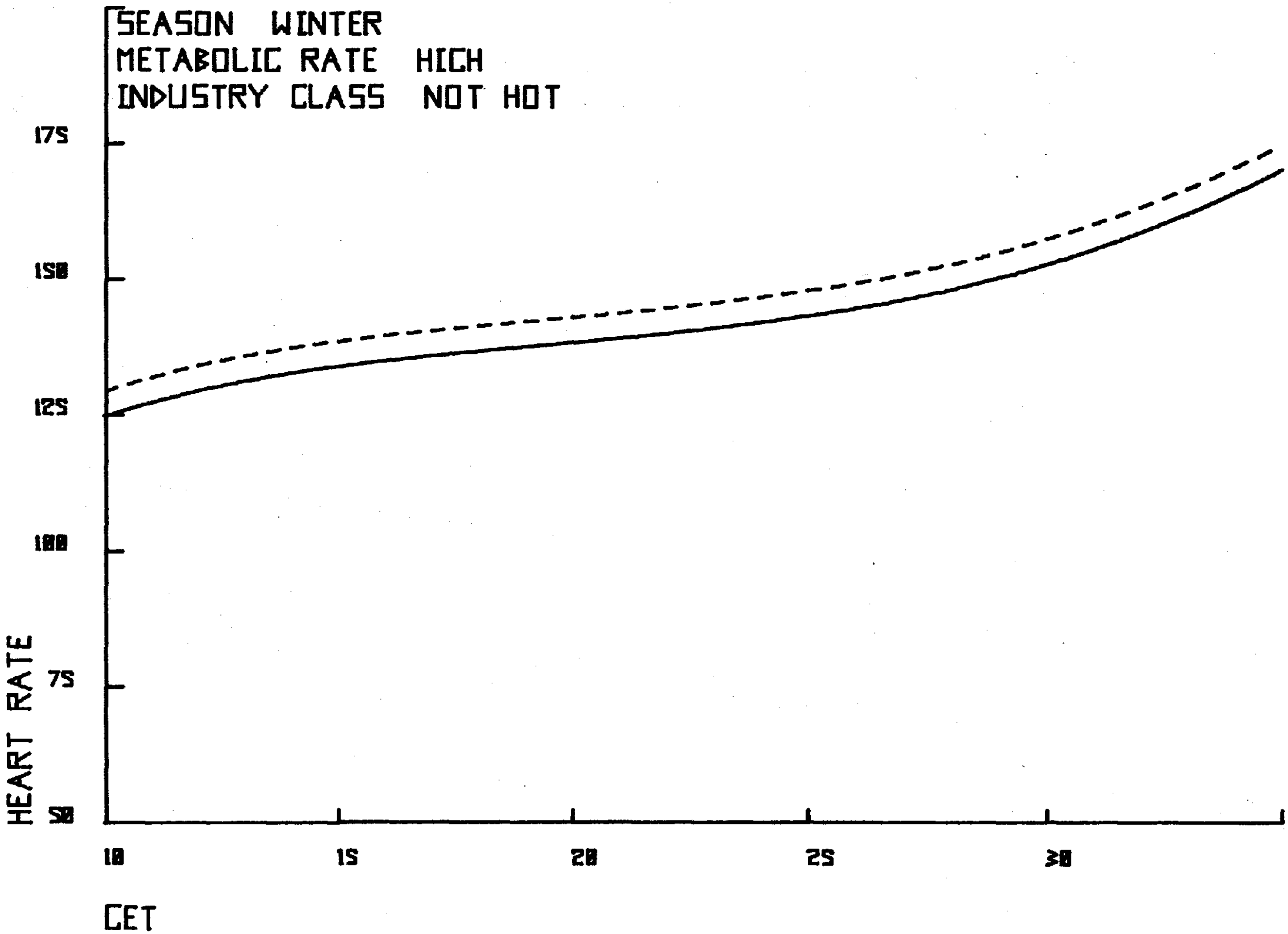
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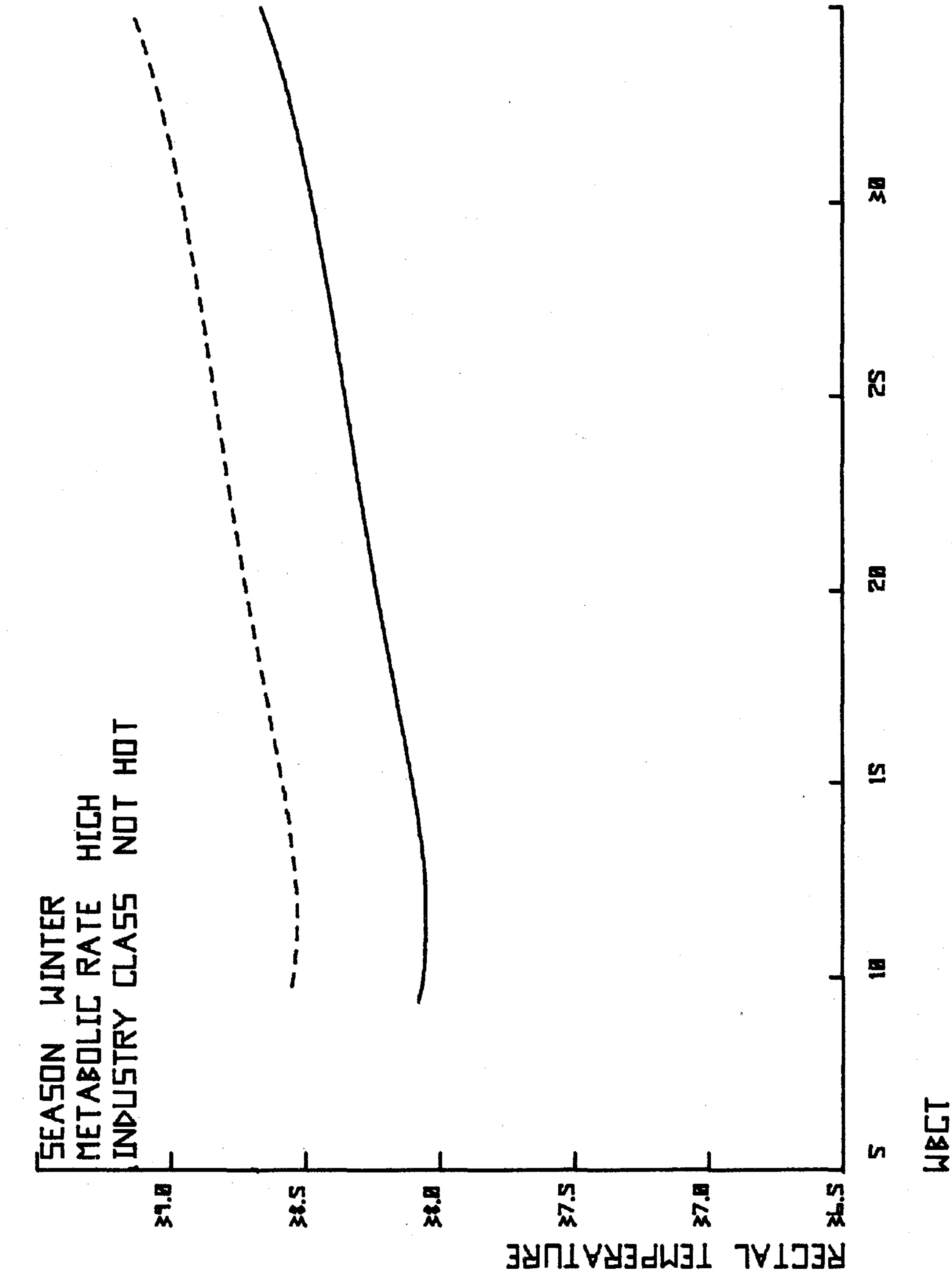
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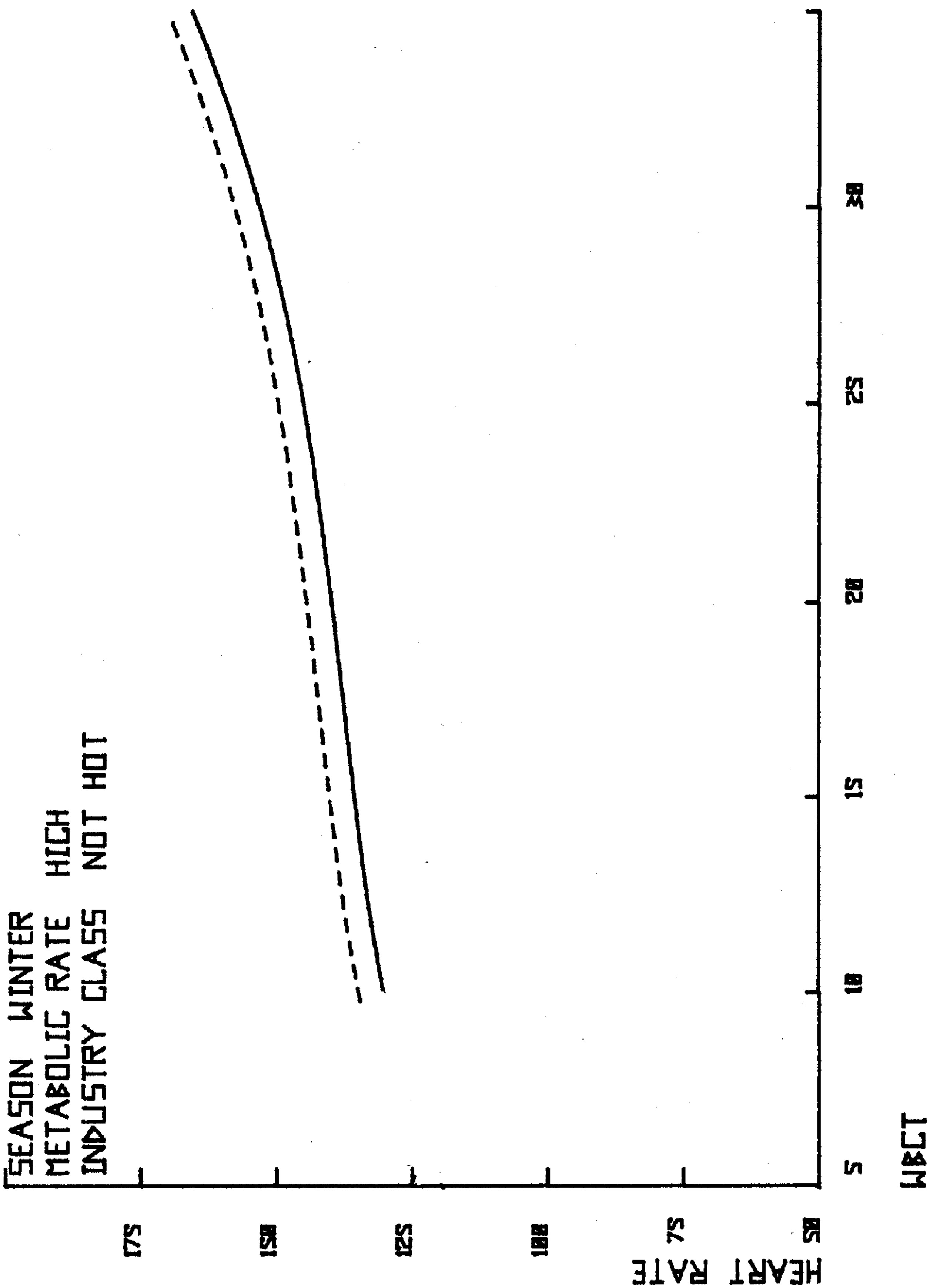
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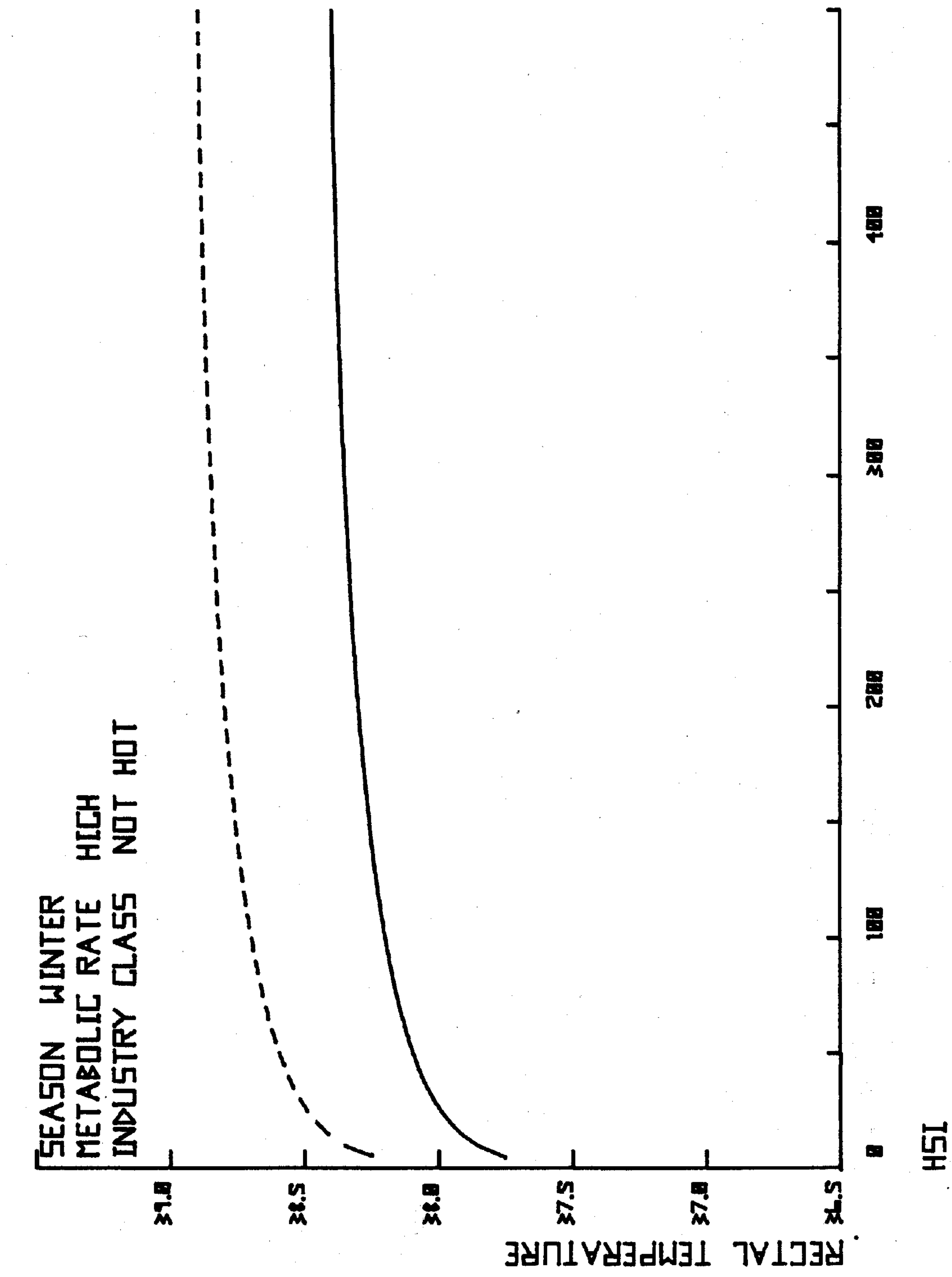
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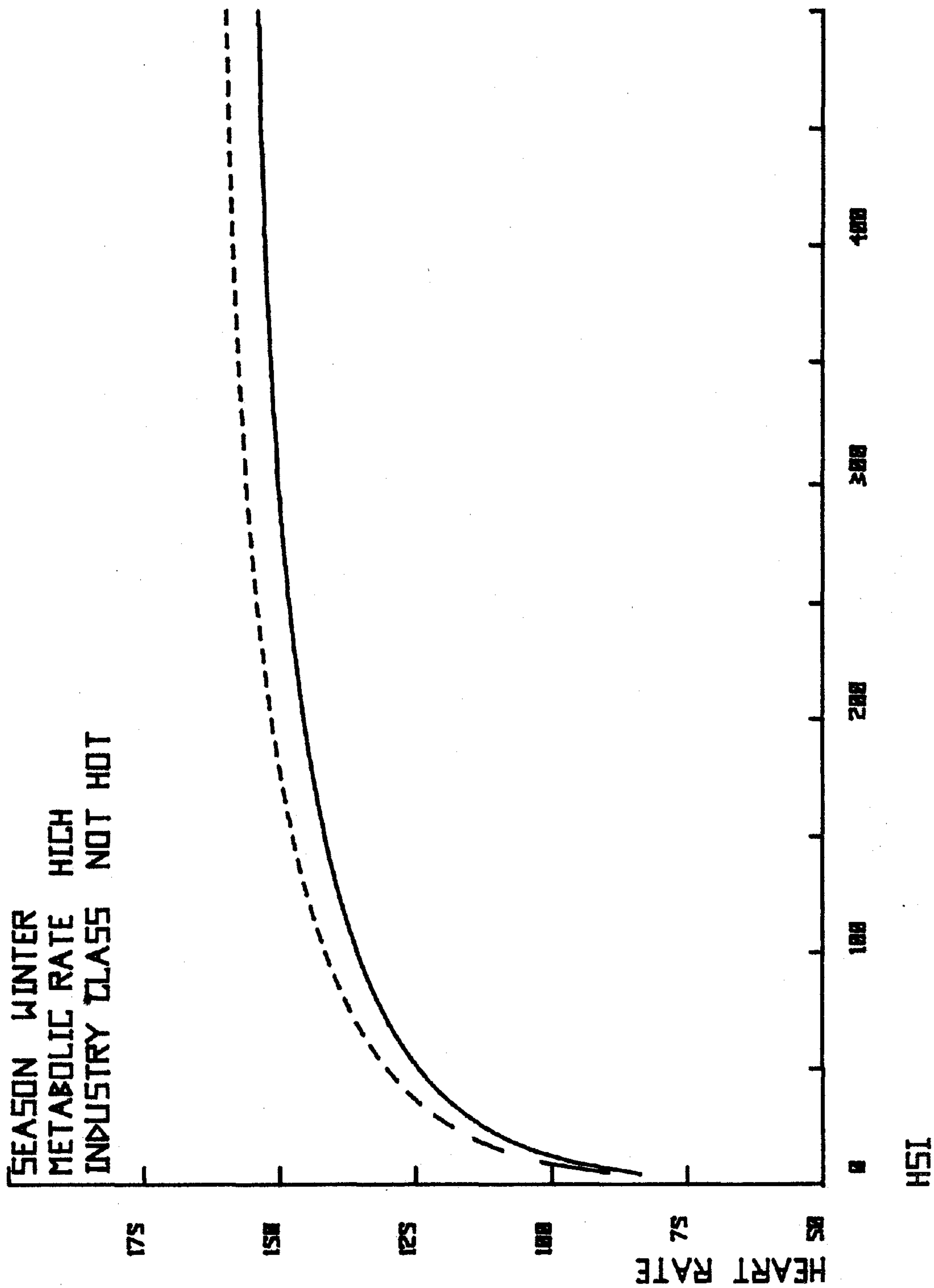

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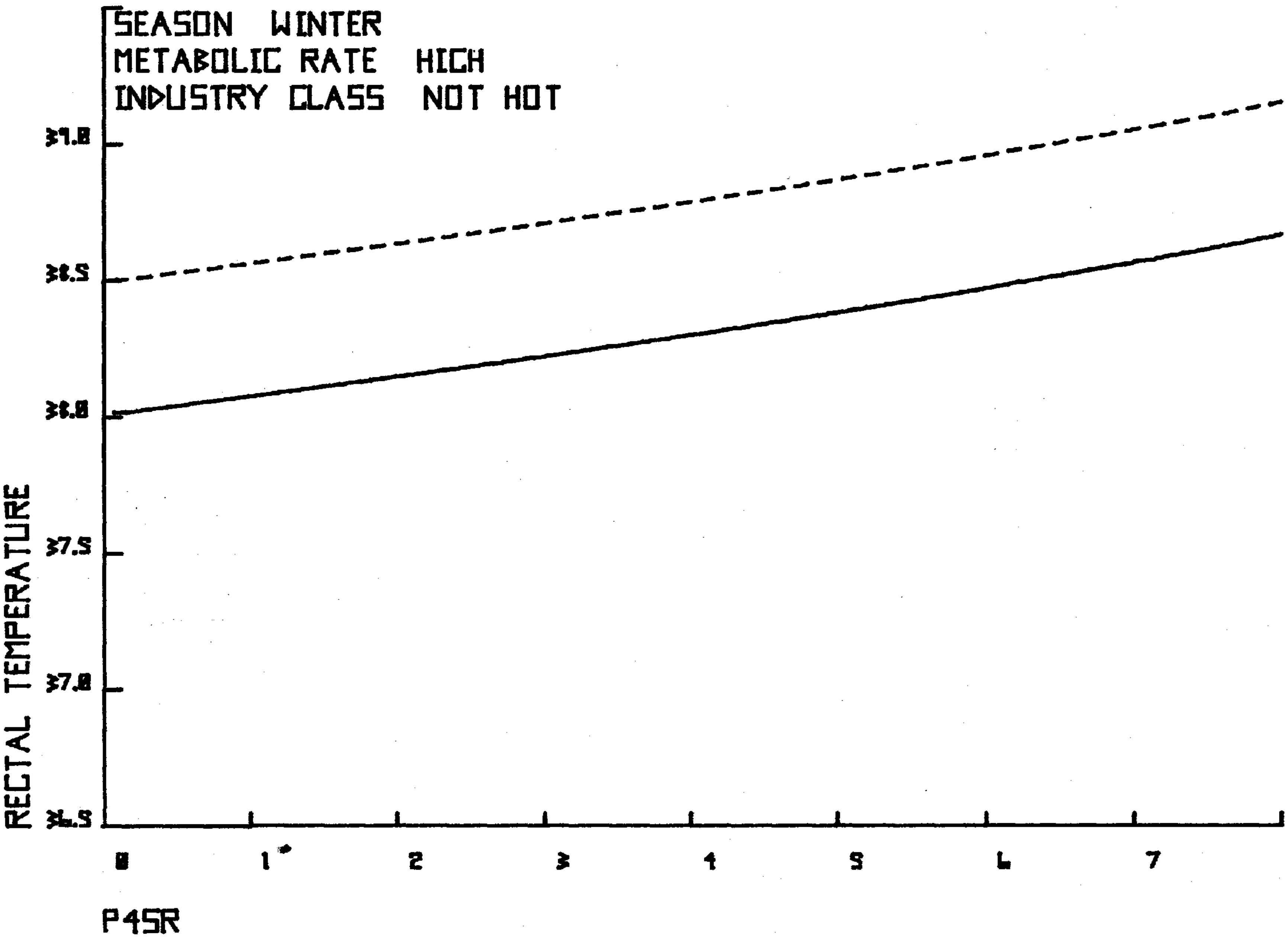
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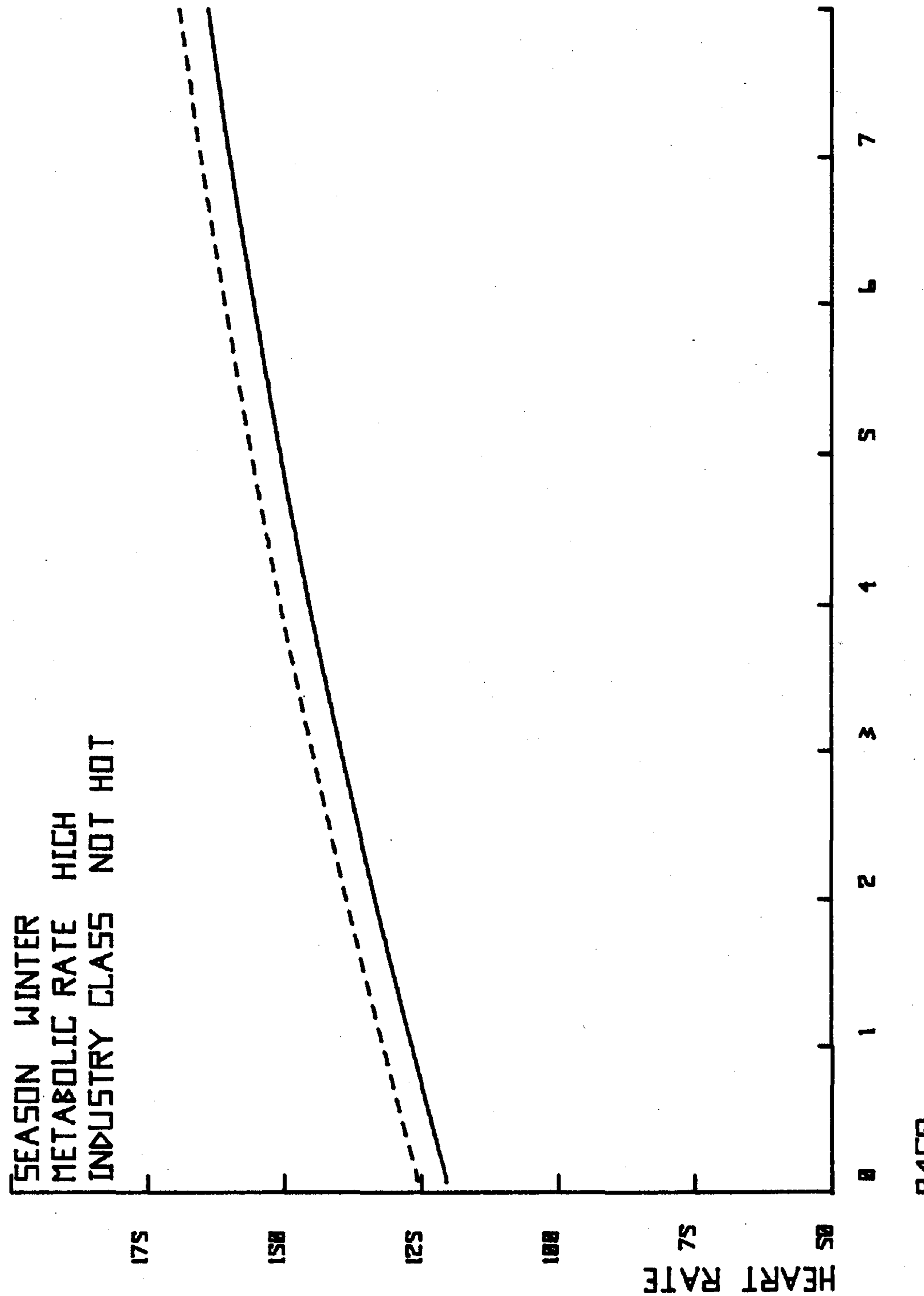
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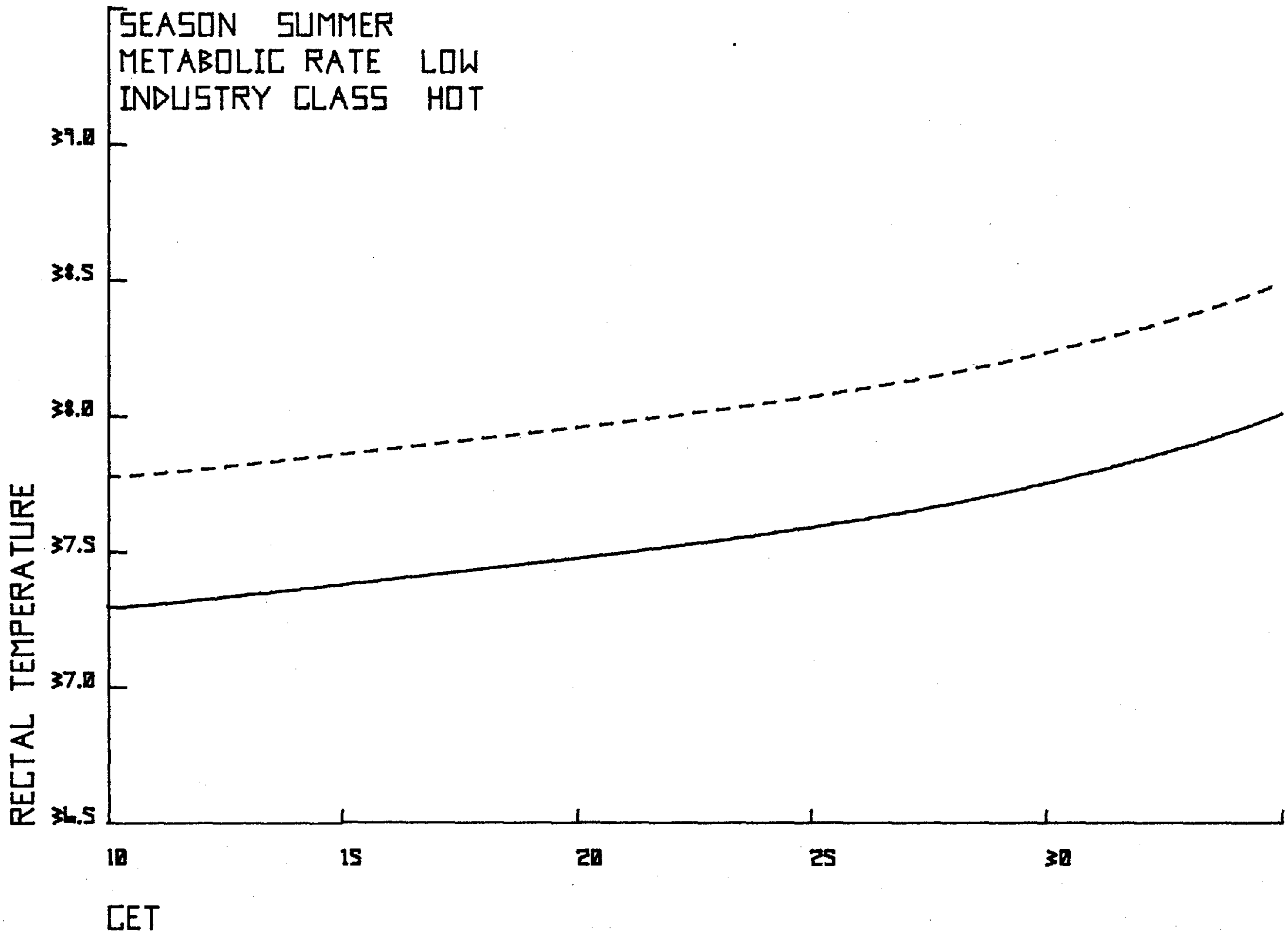
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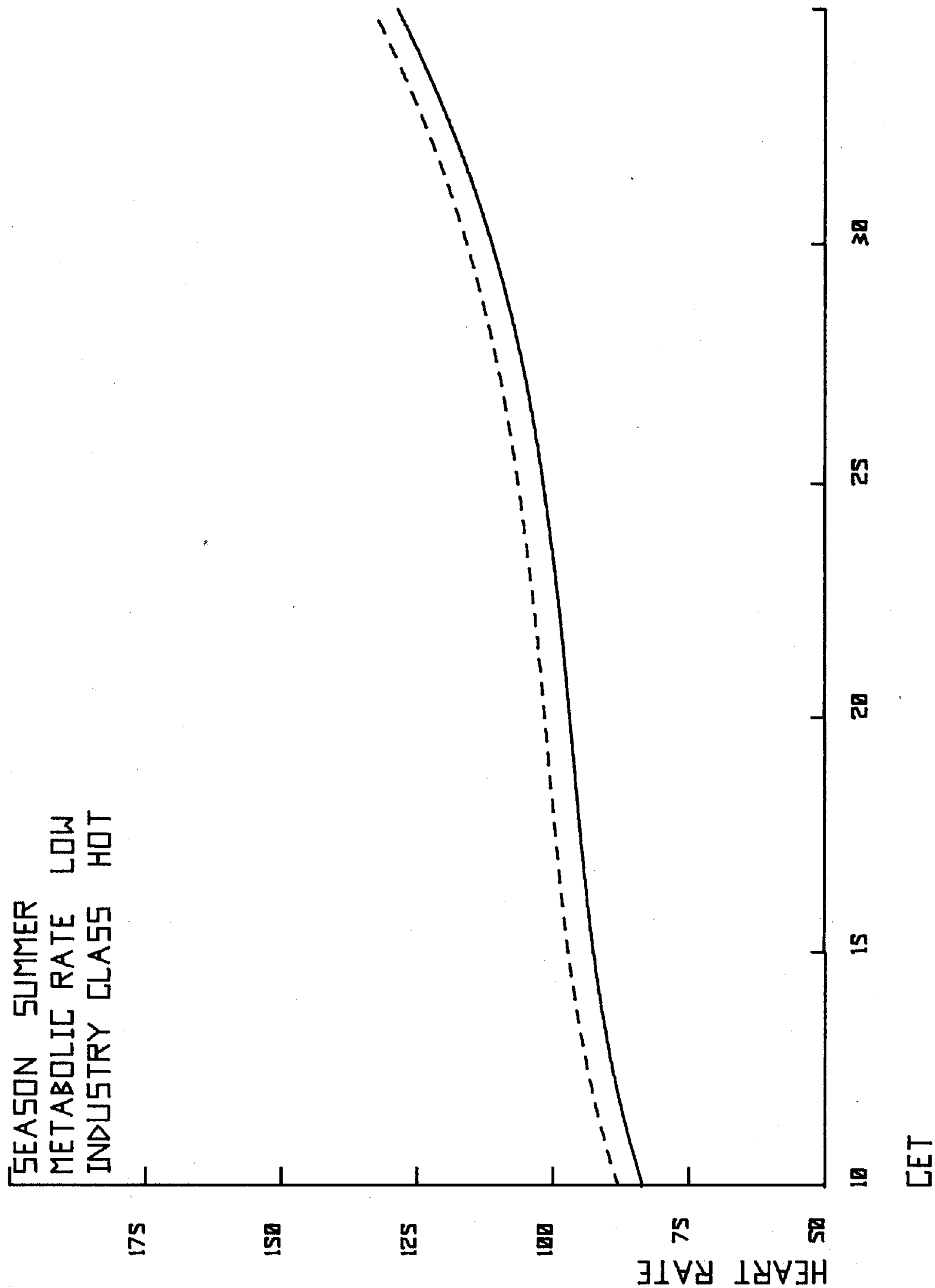
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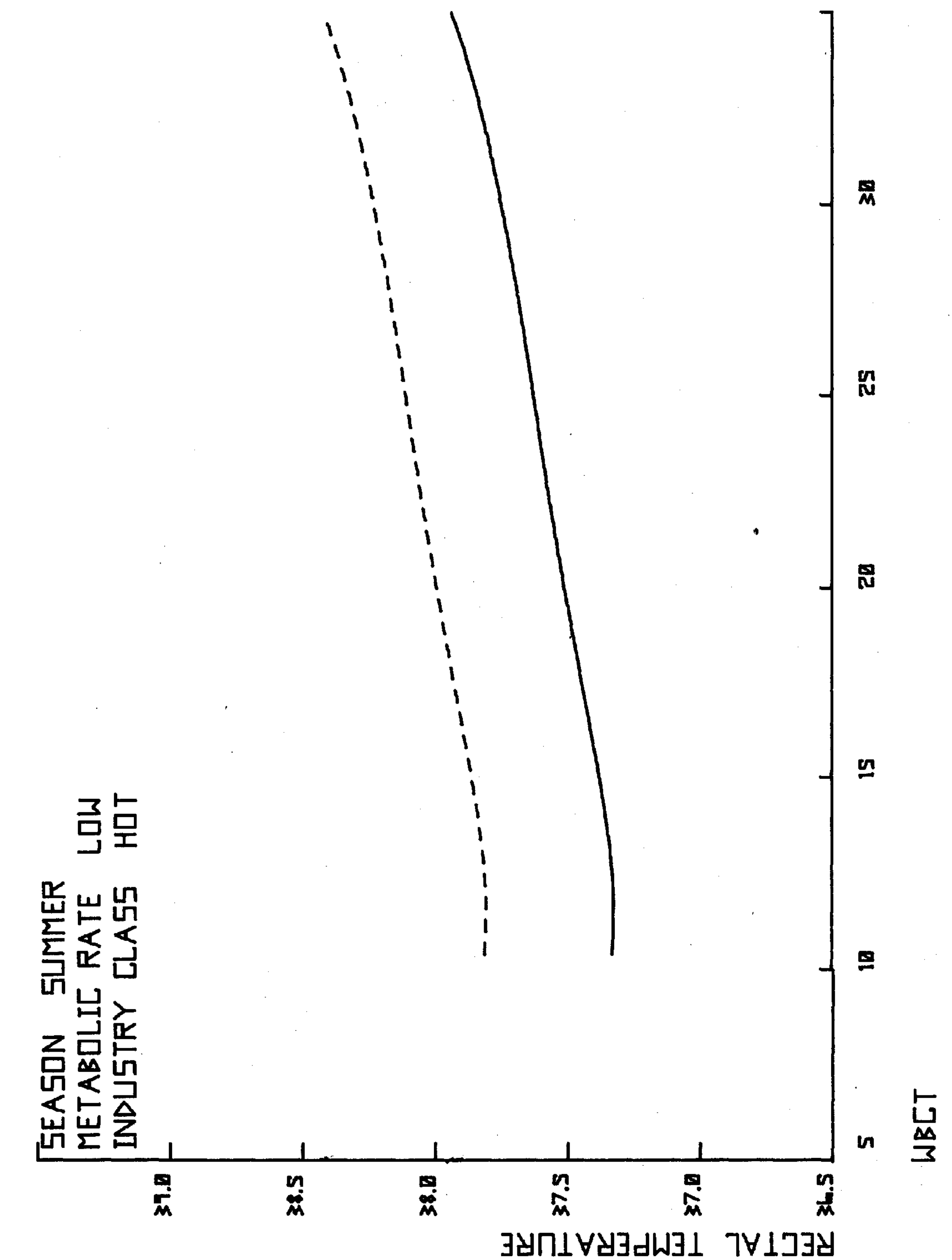
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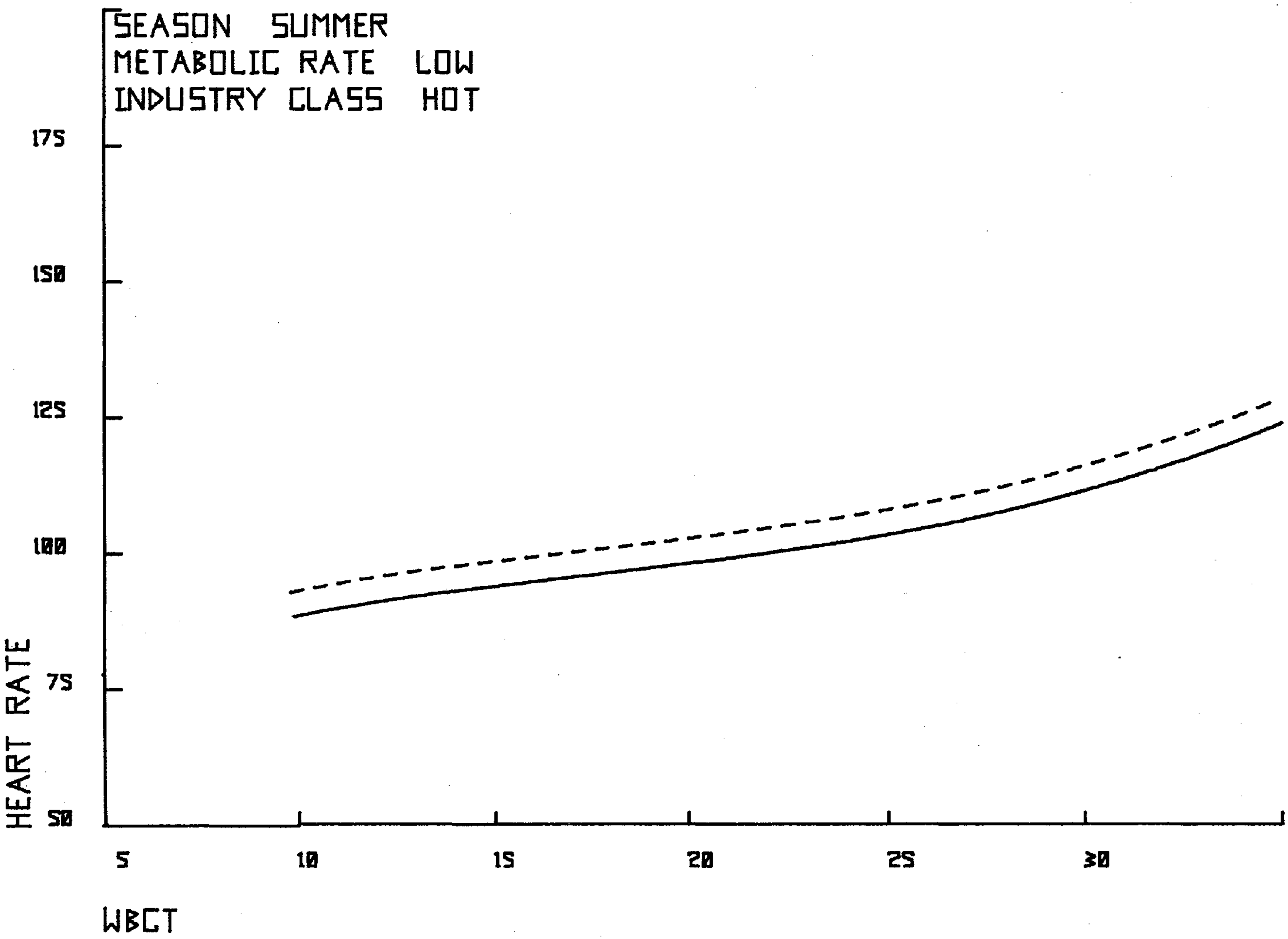
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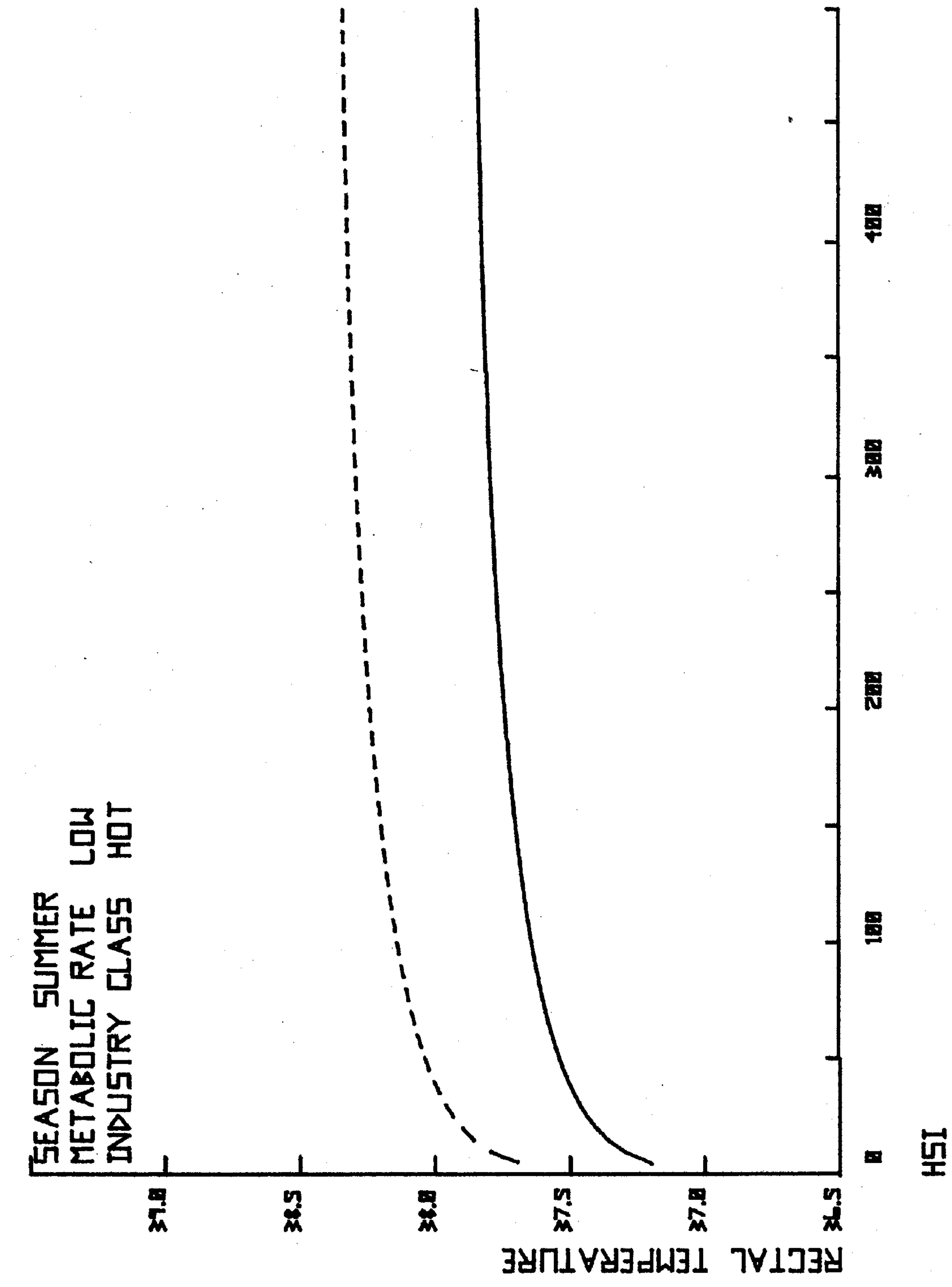
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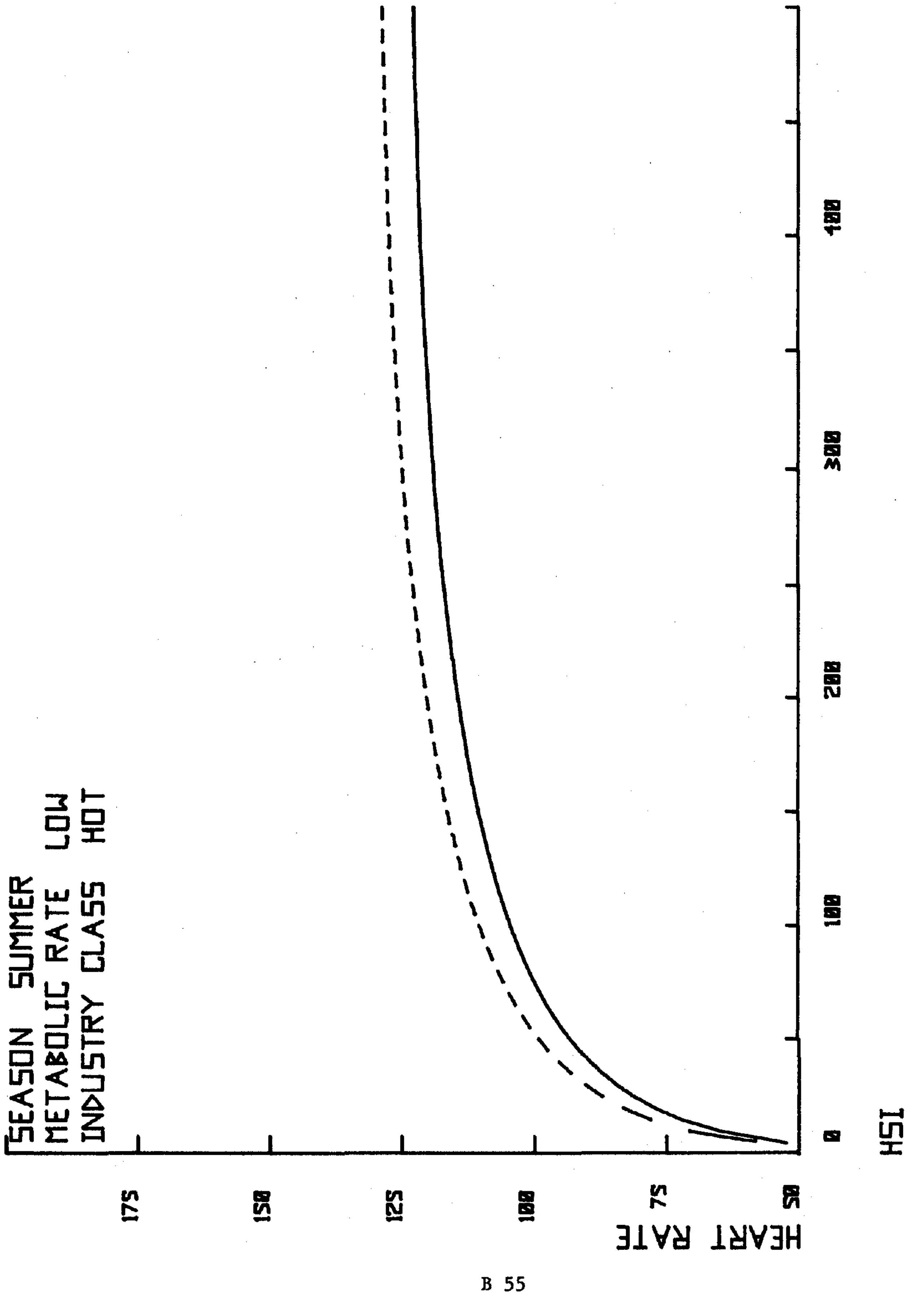
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HEART RATE
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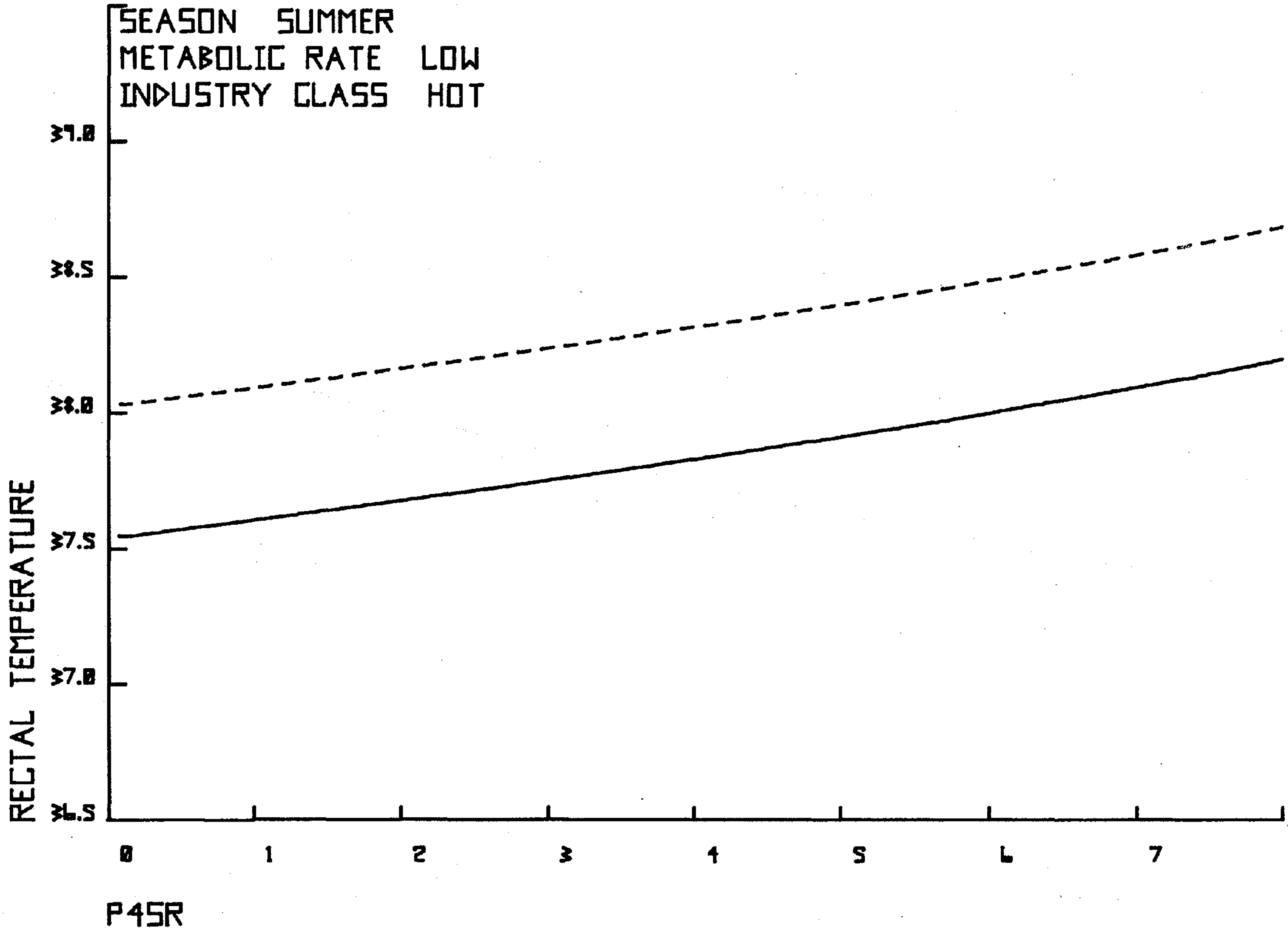
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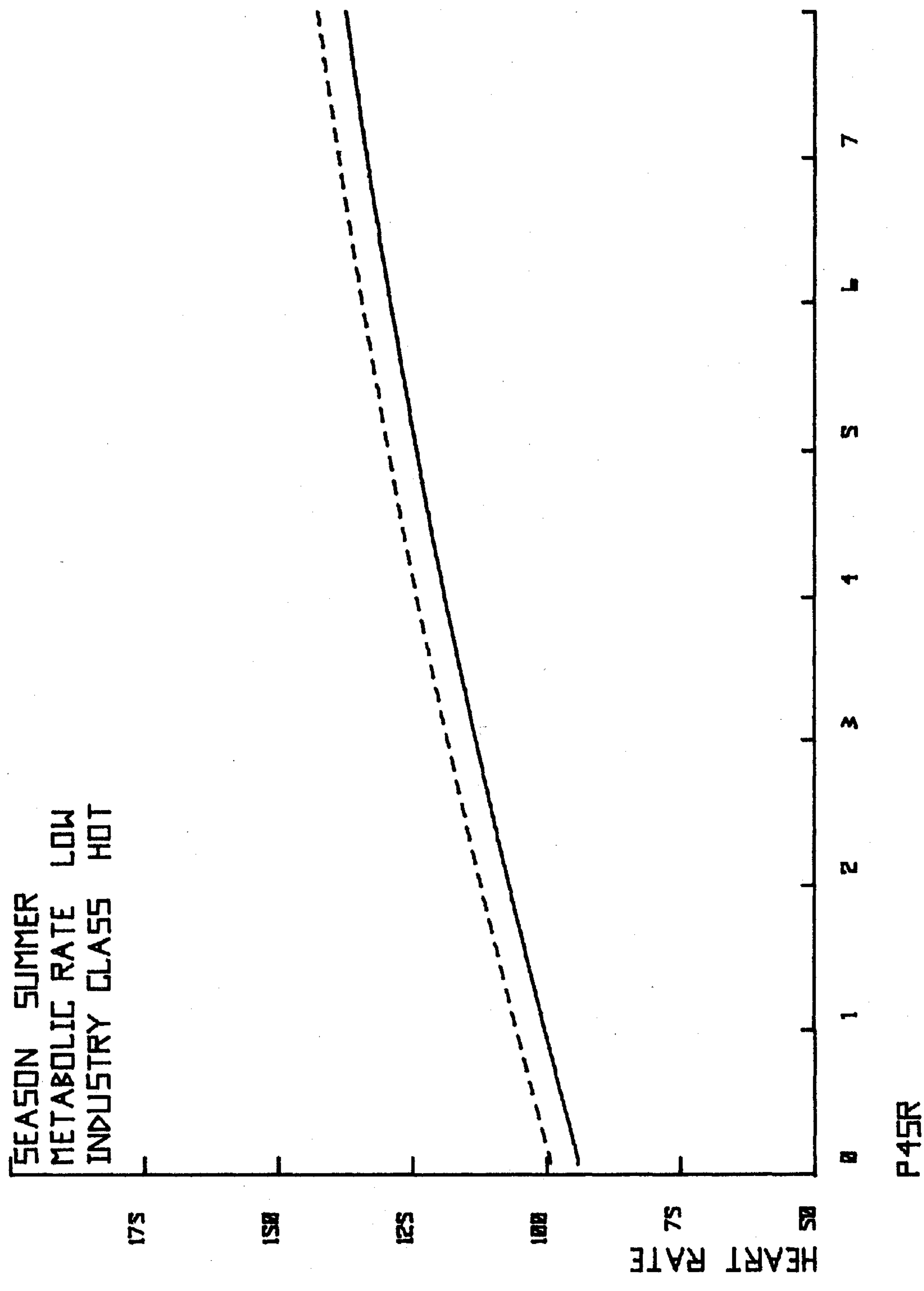
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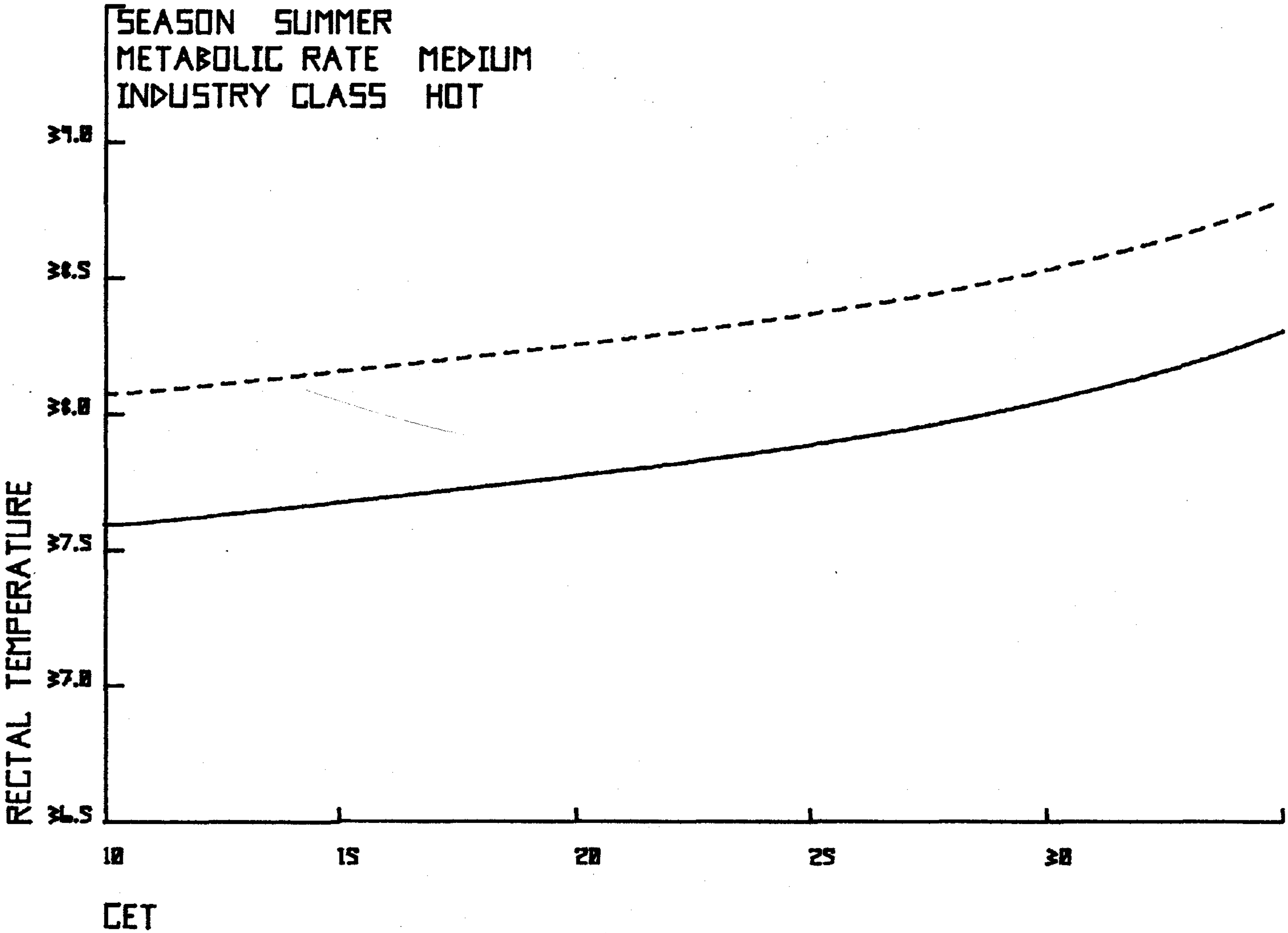
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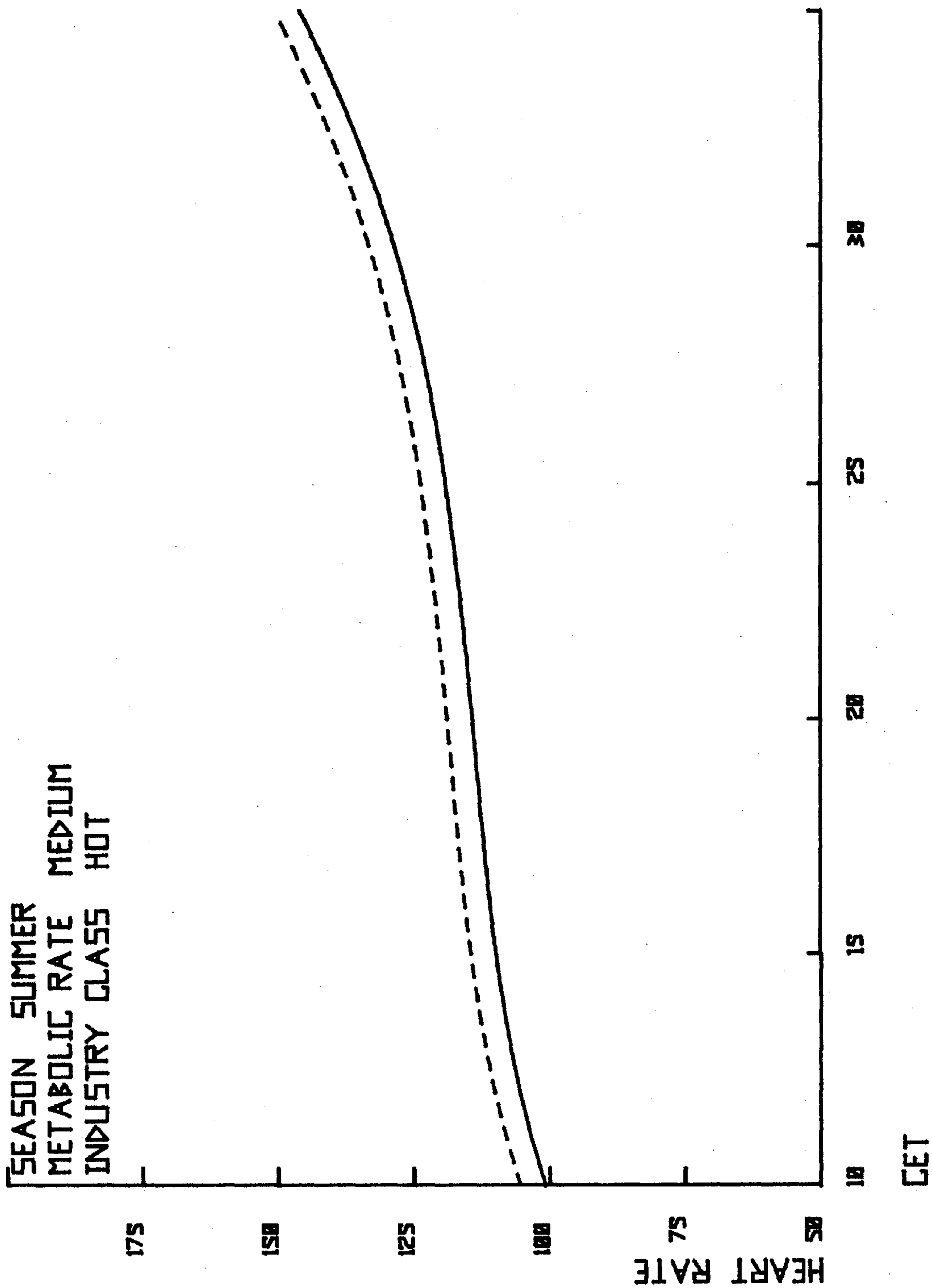
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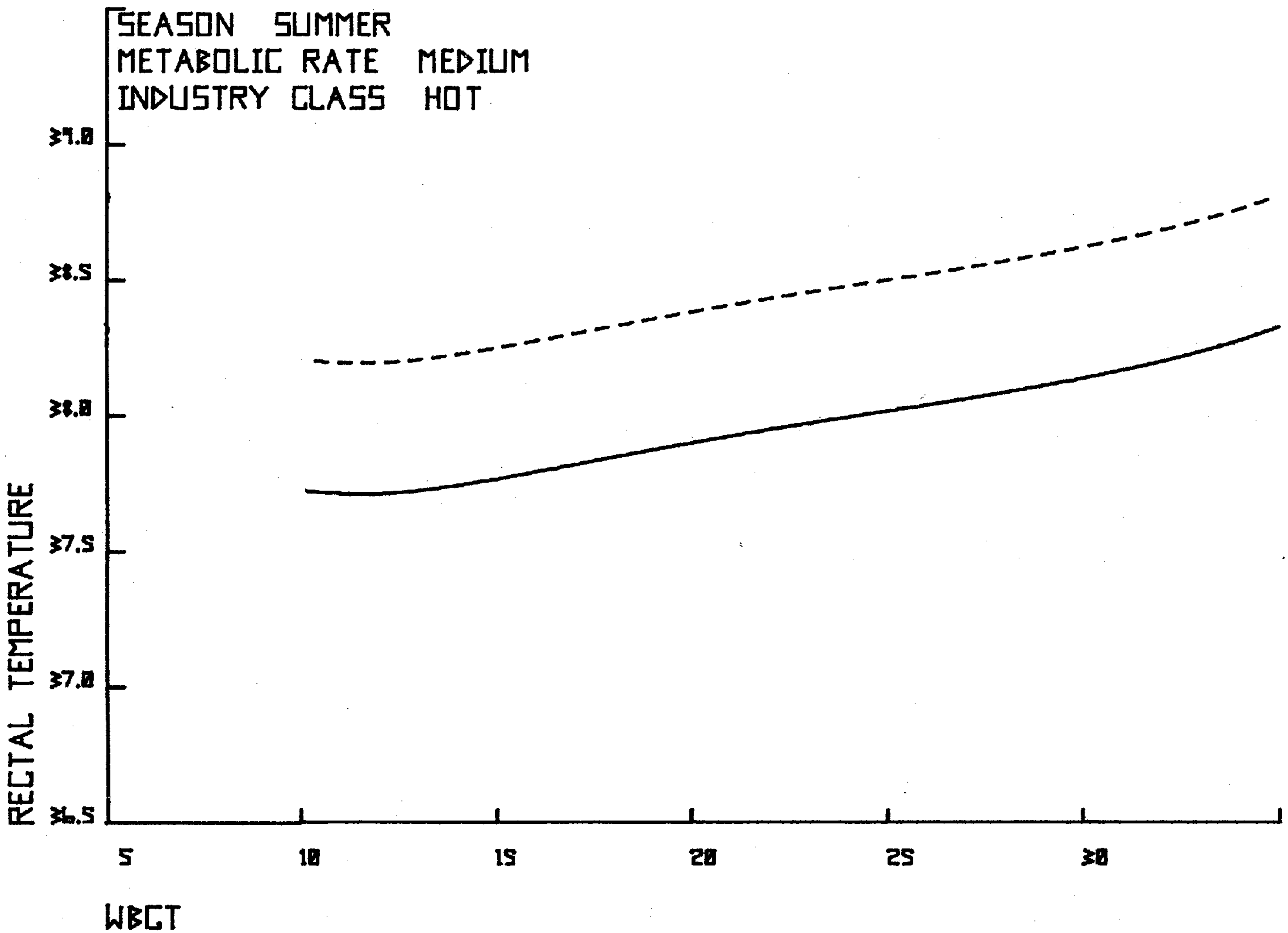

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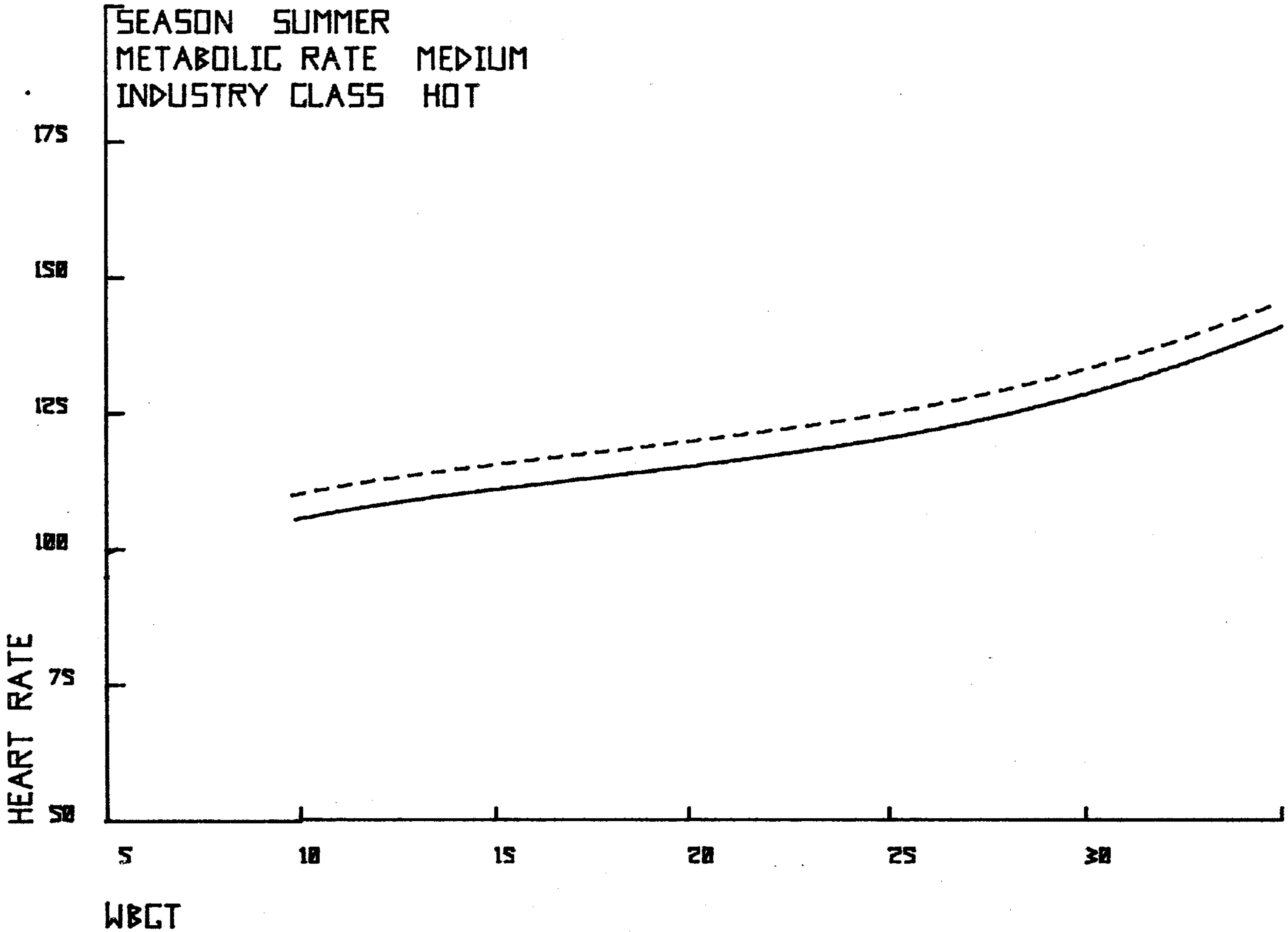

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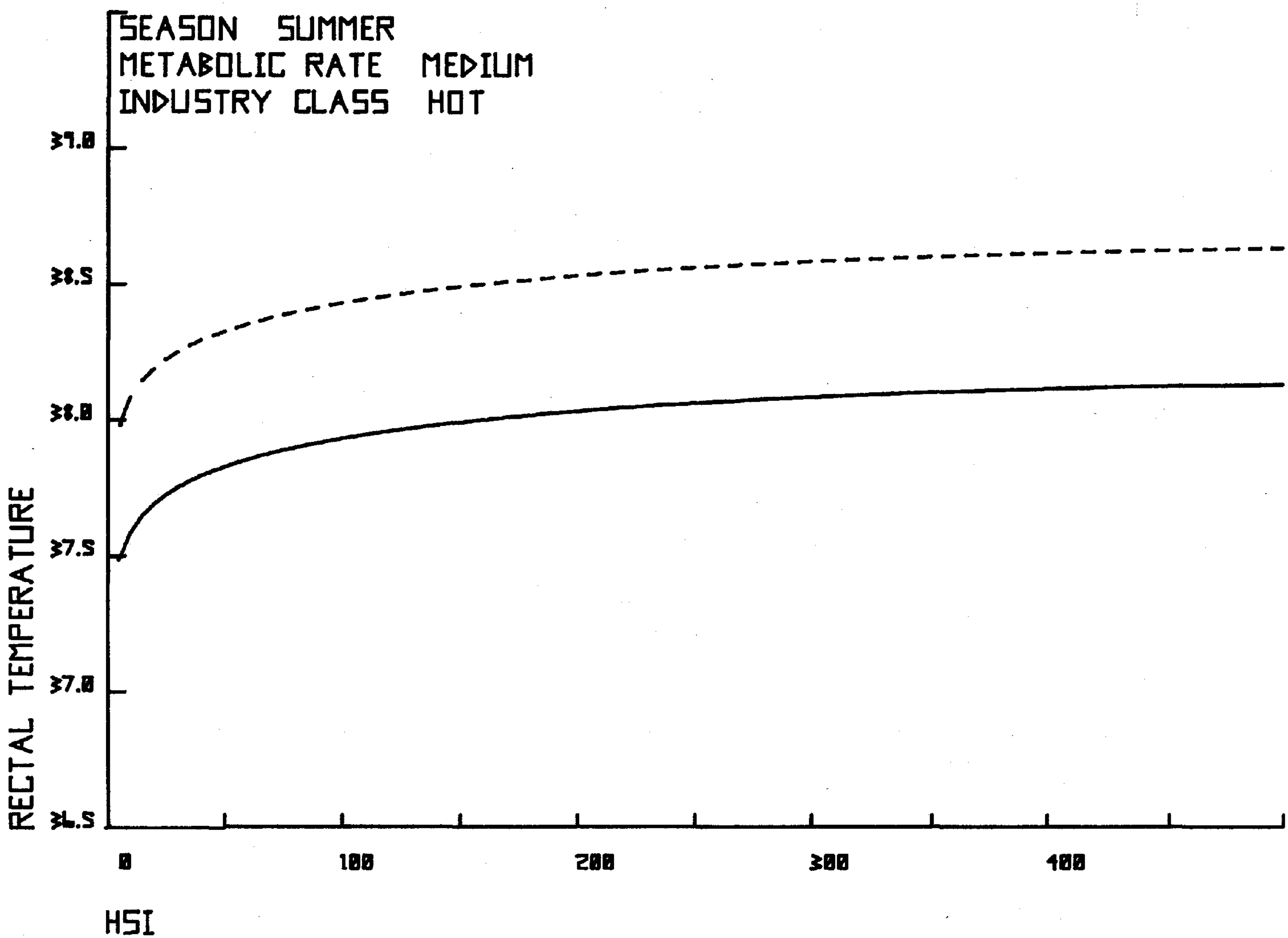
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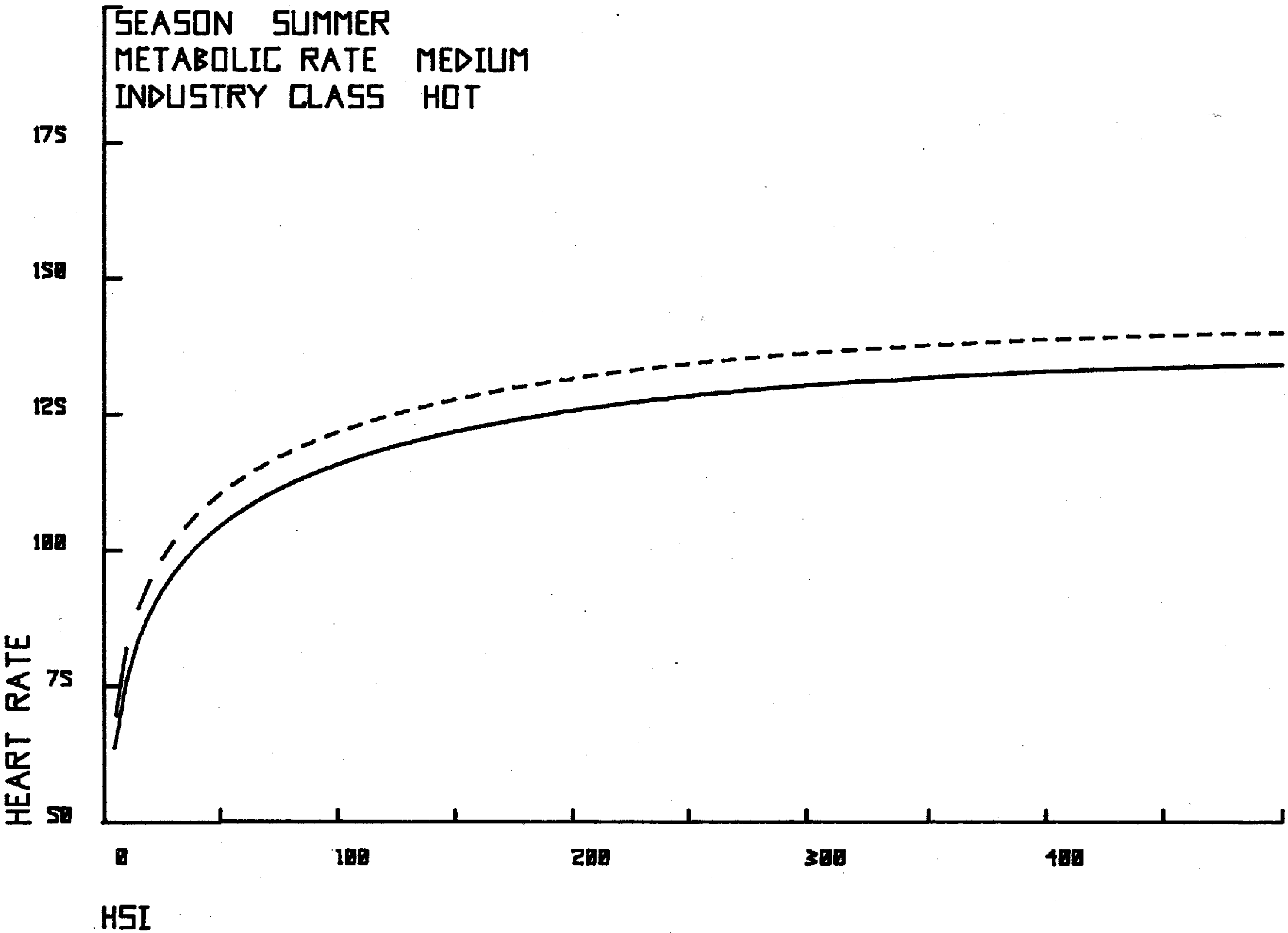
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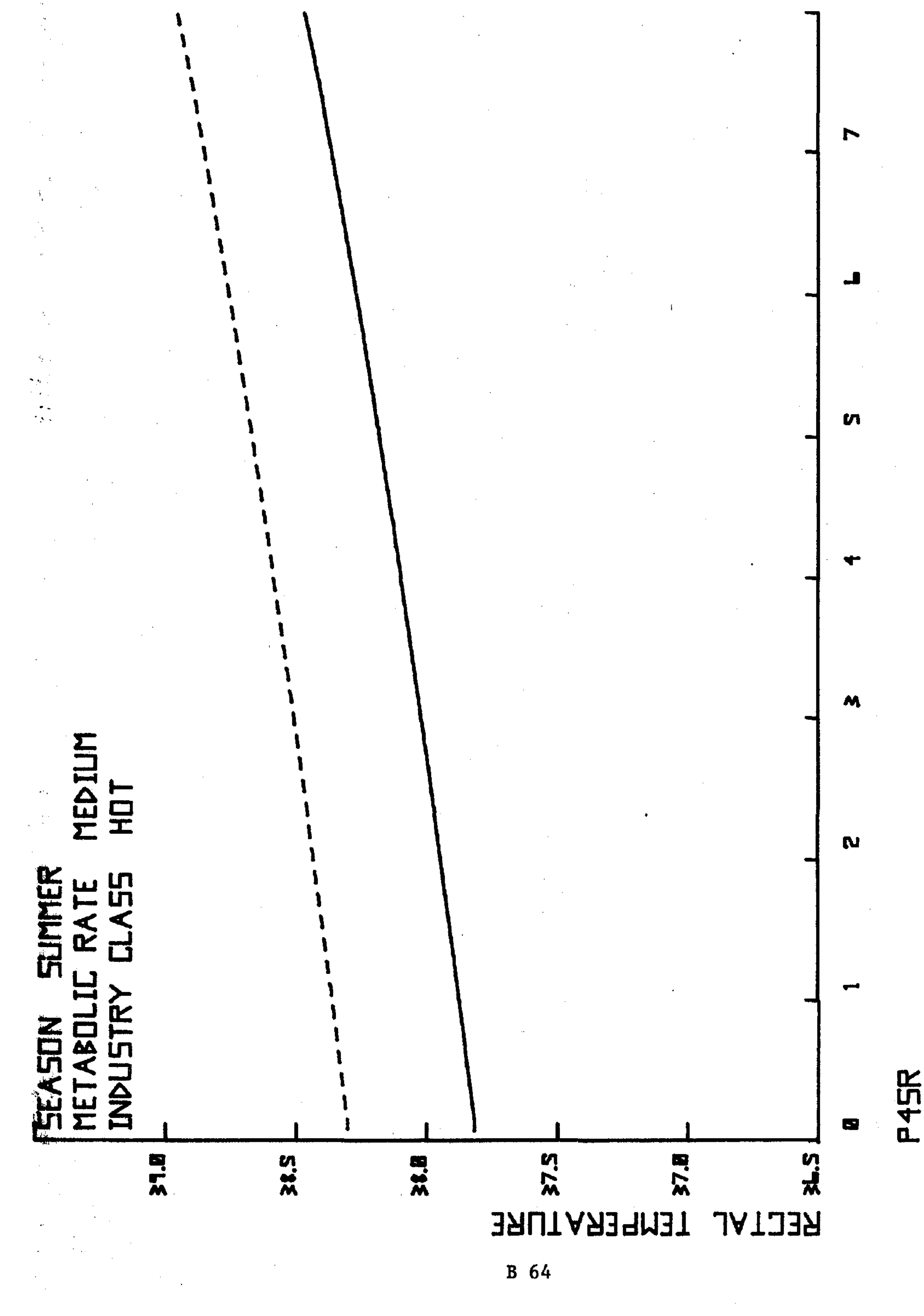
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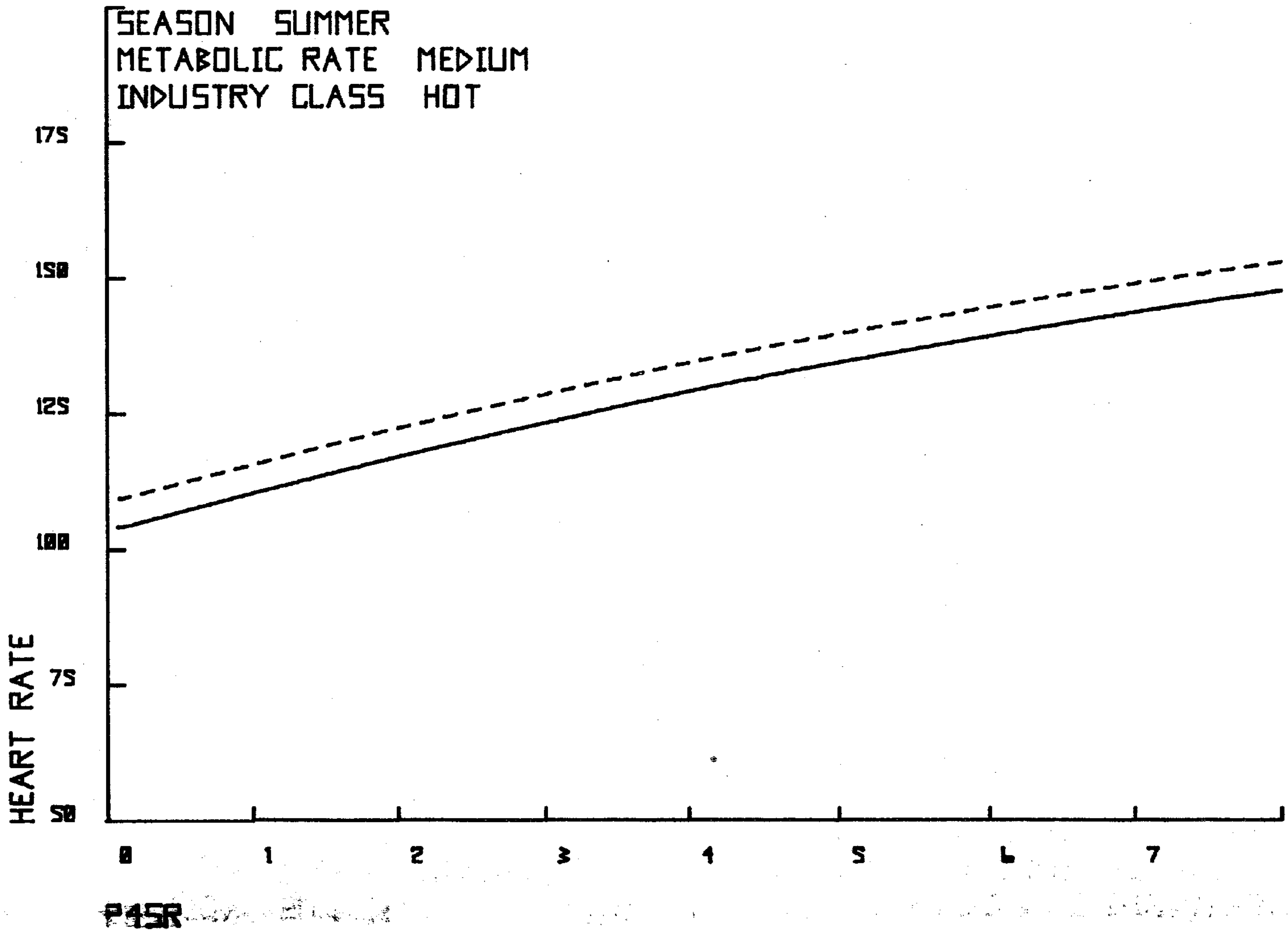
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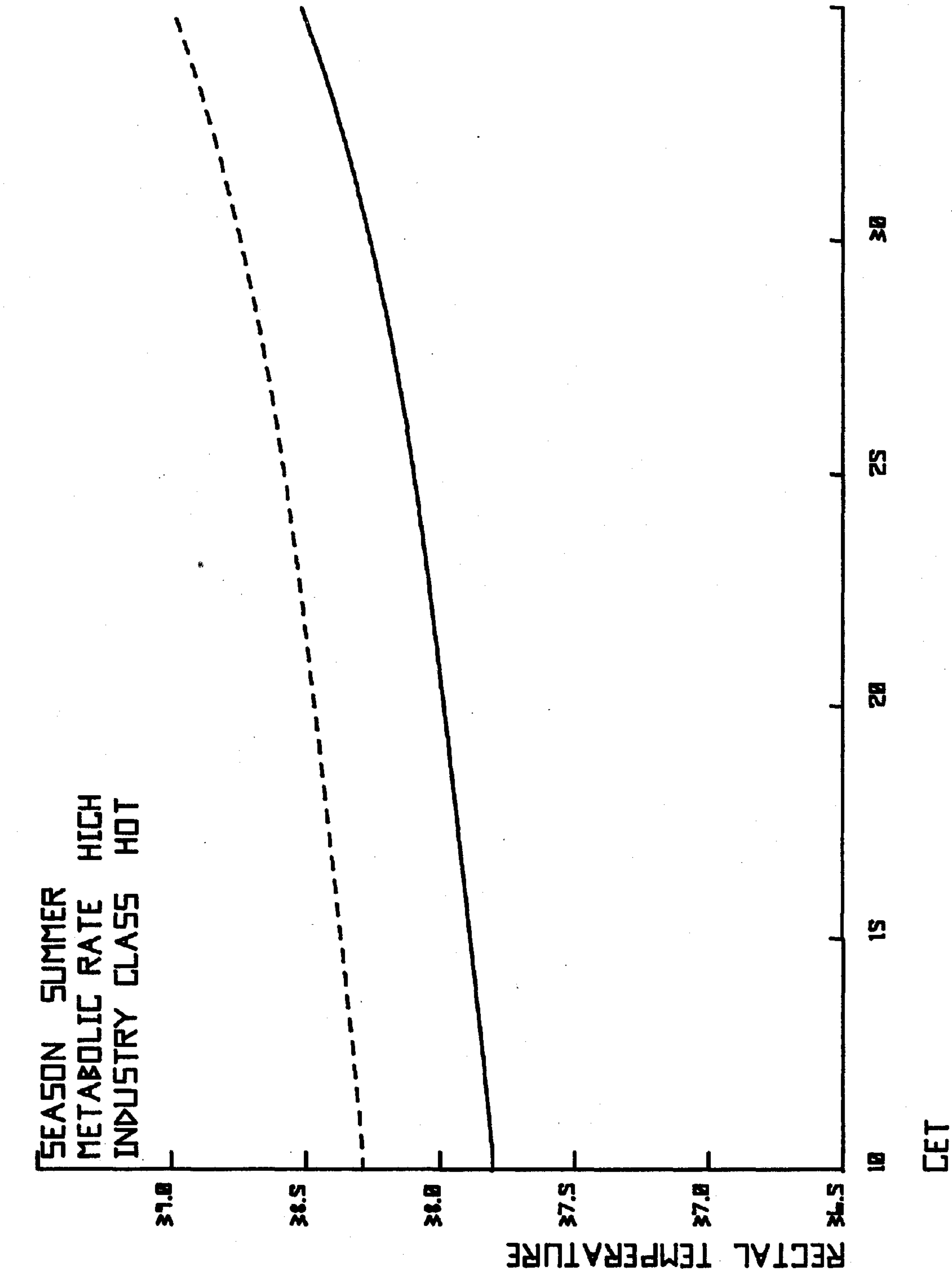
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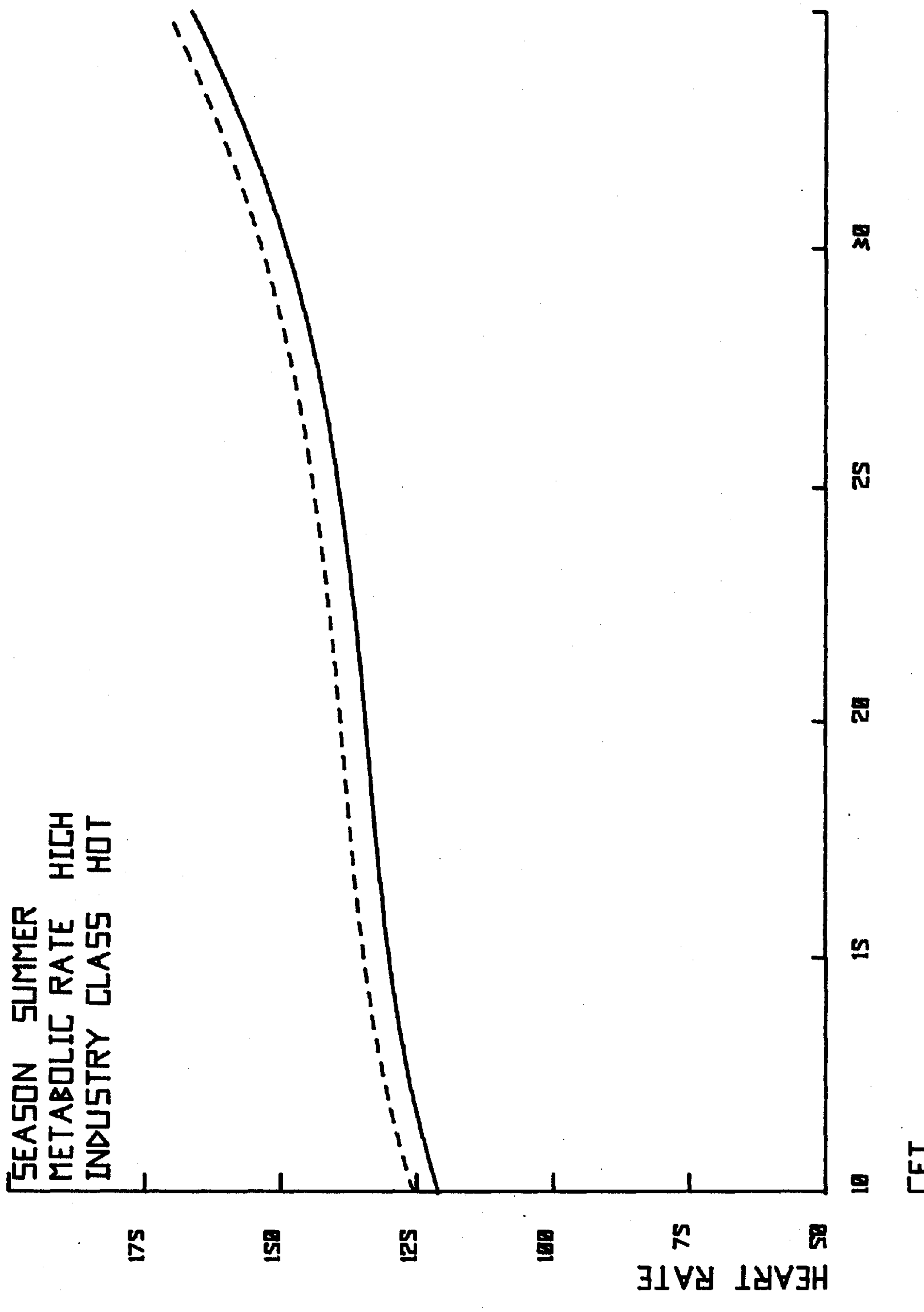
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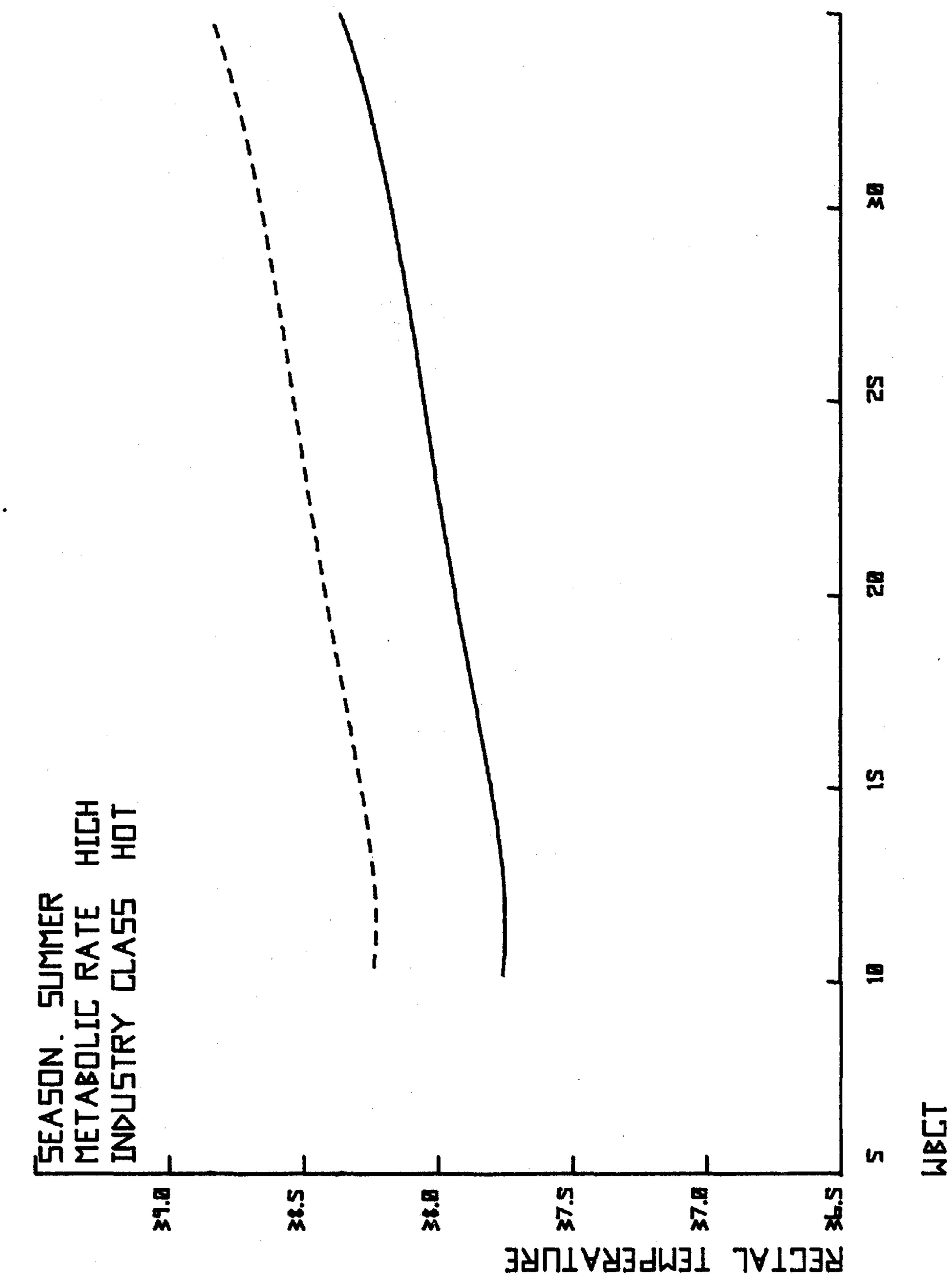
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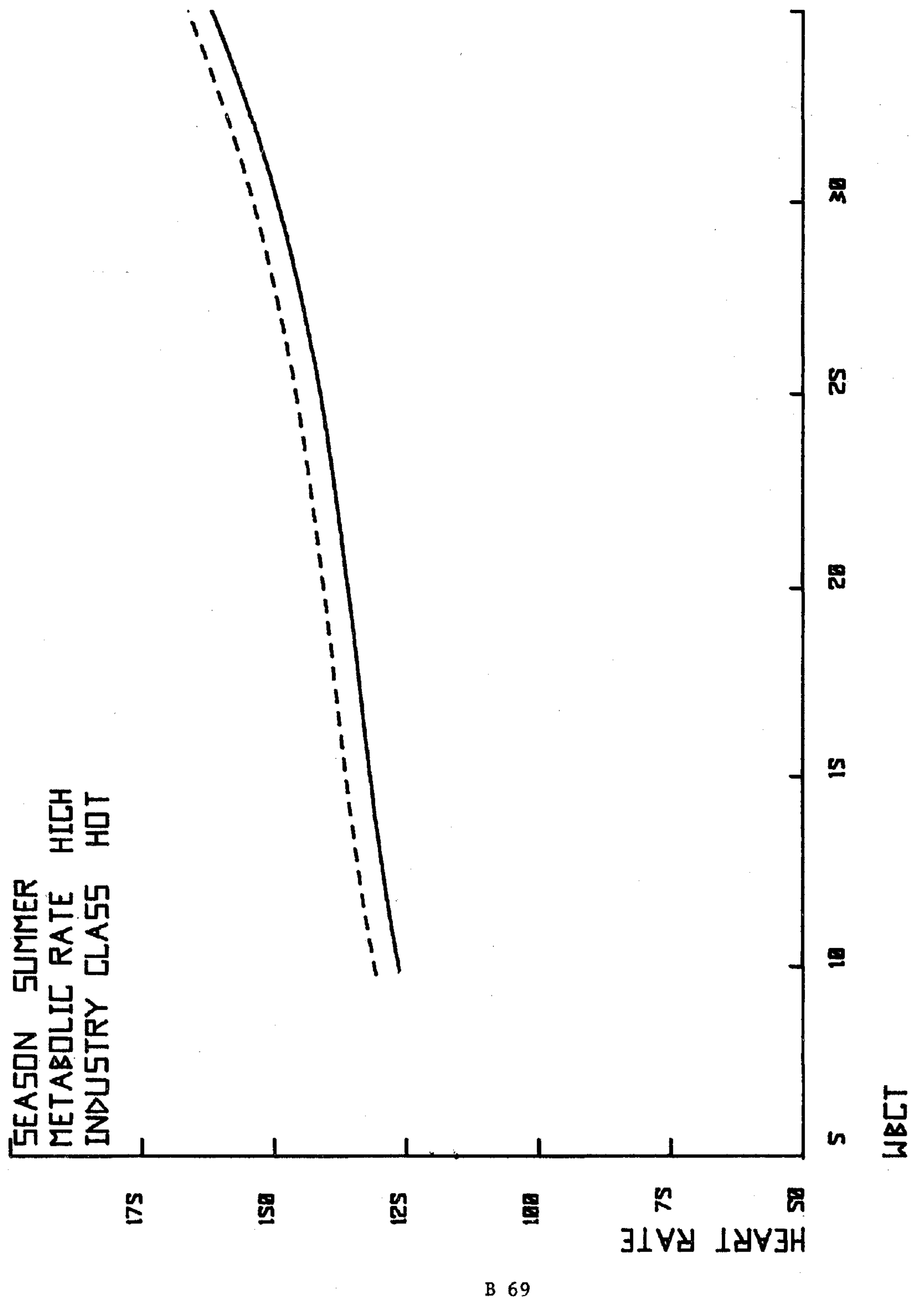
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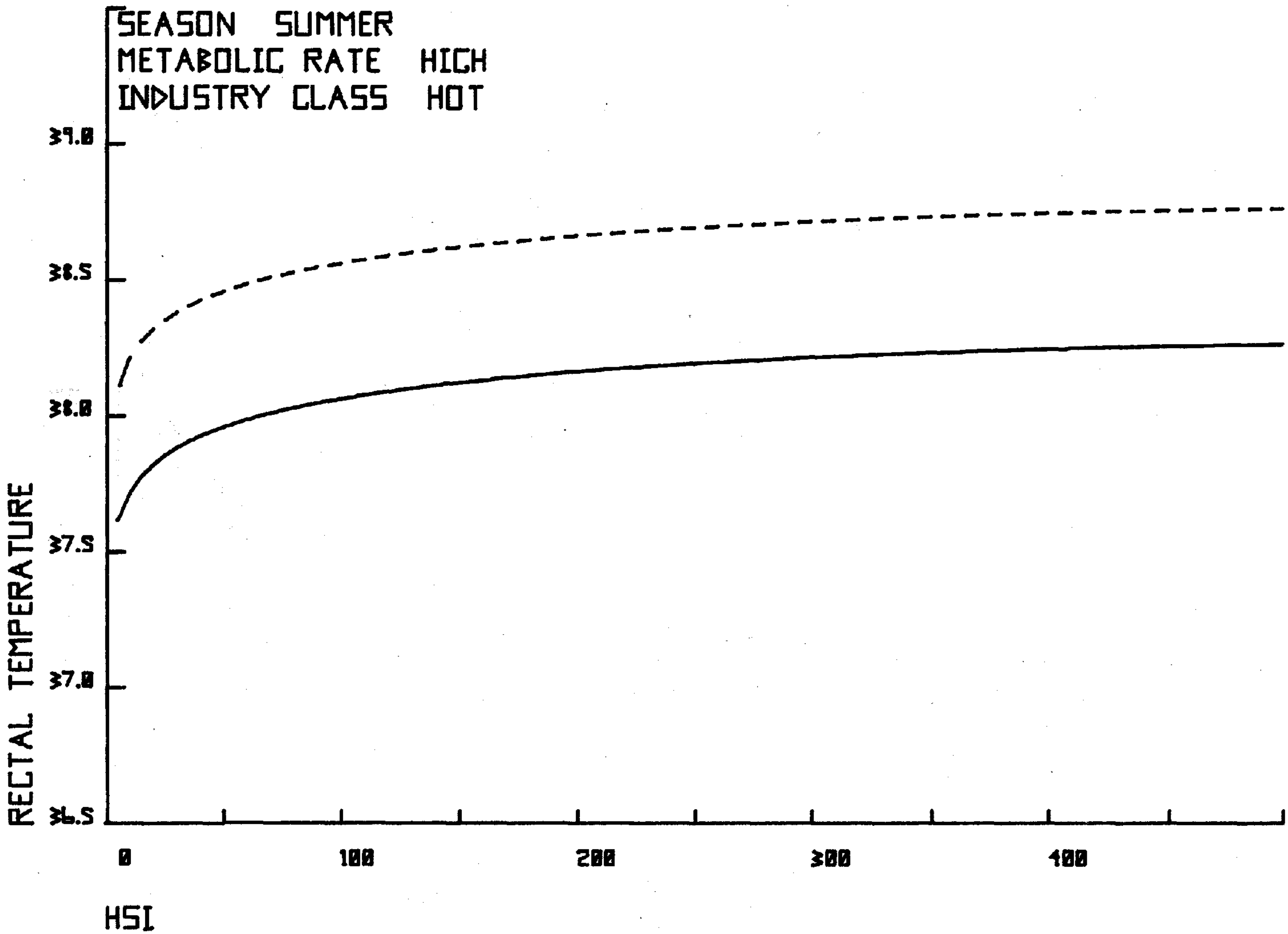
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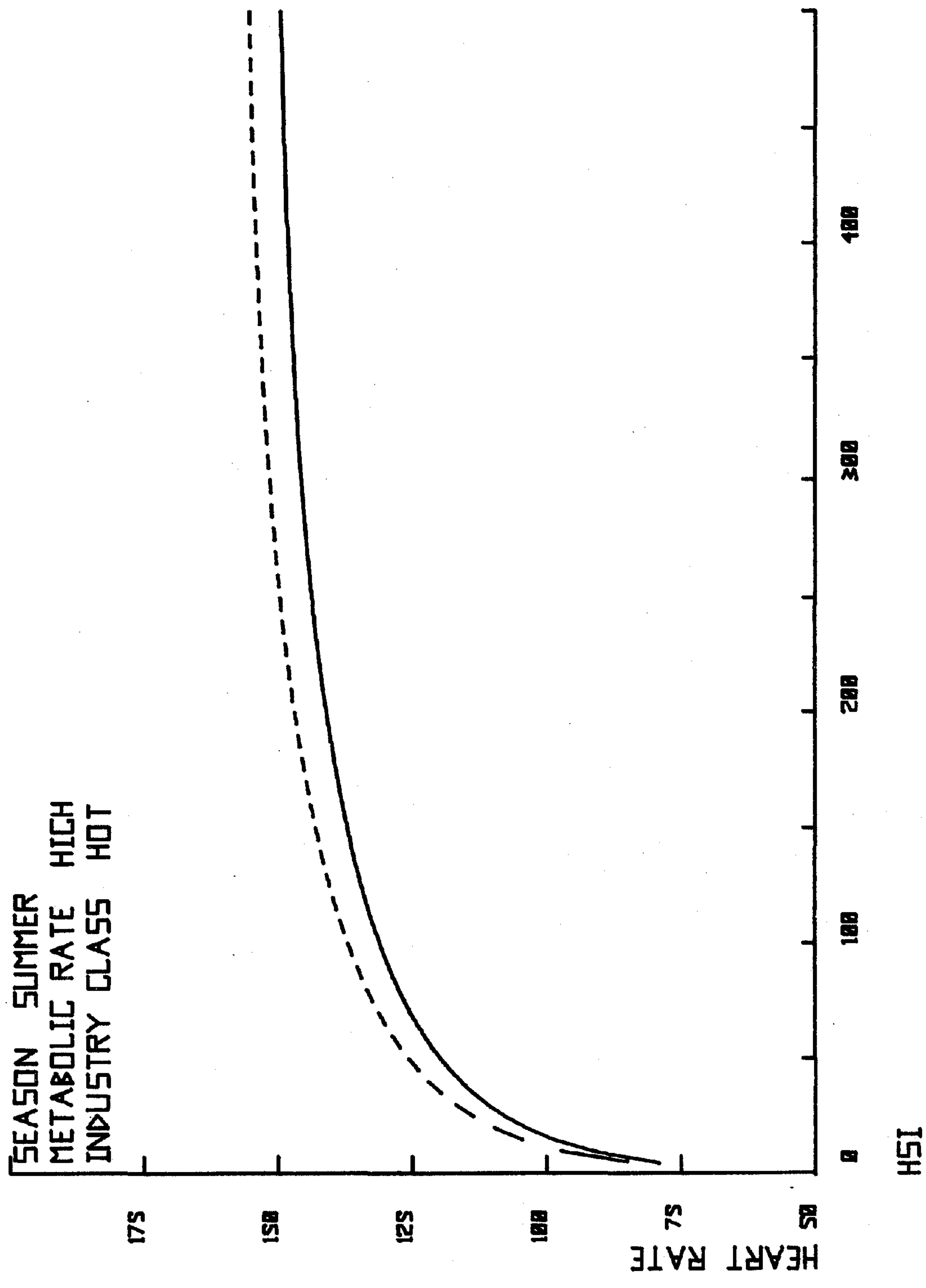
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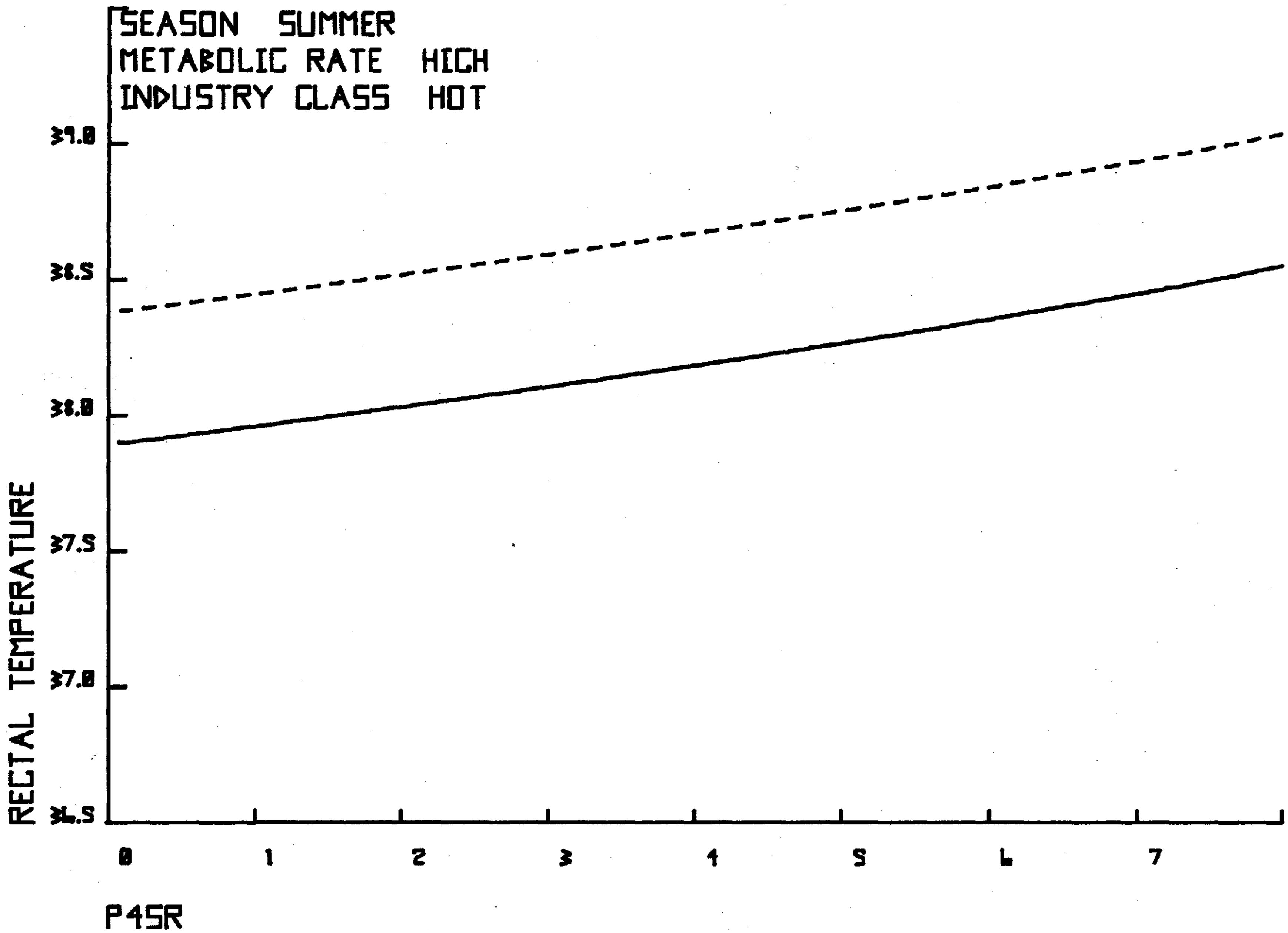
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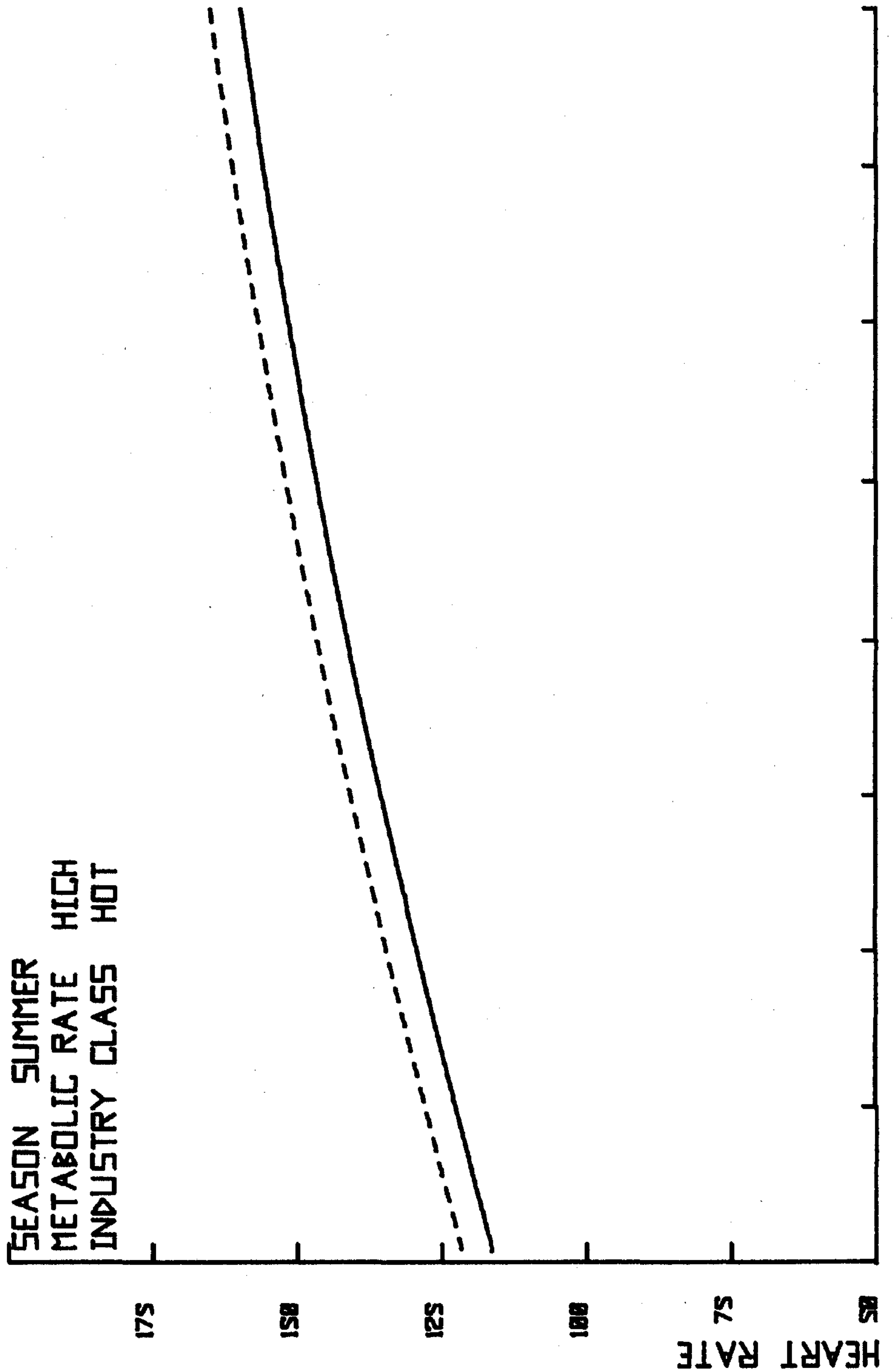
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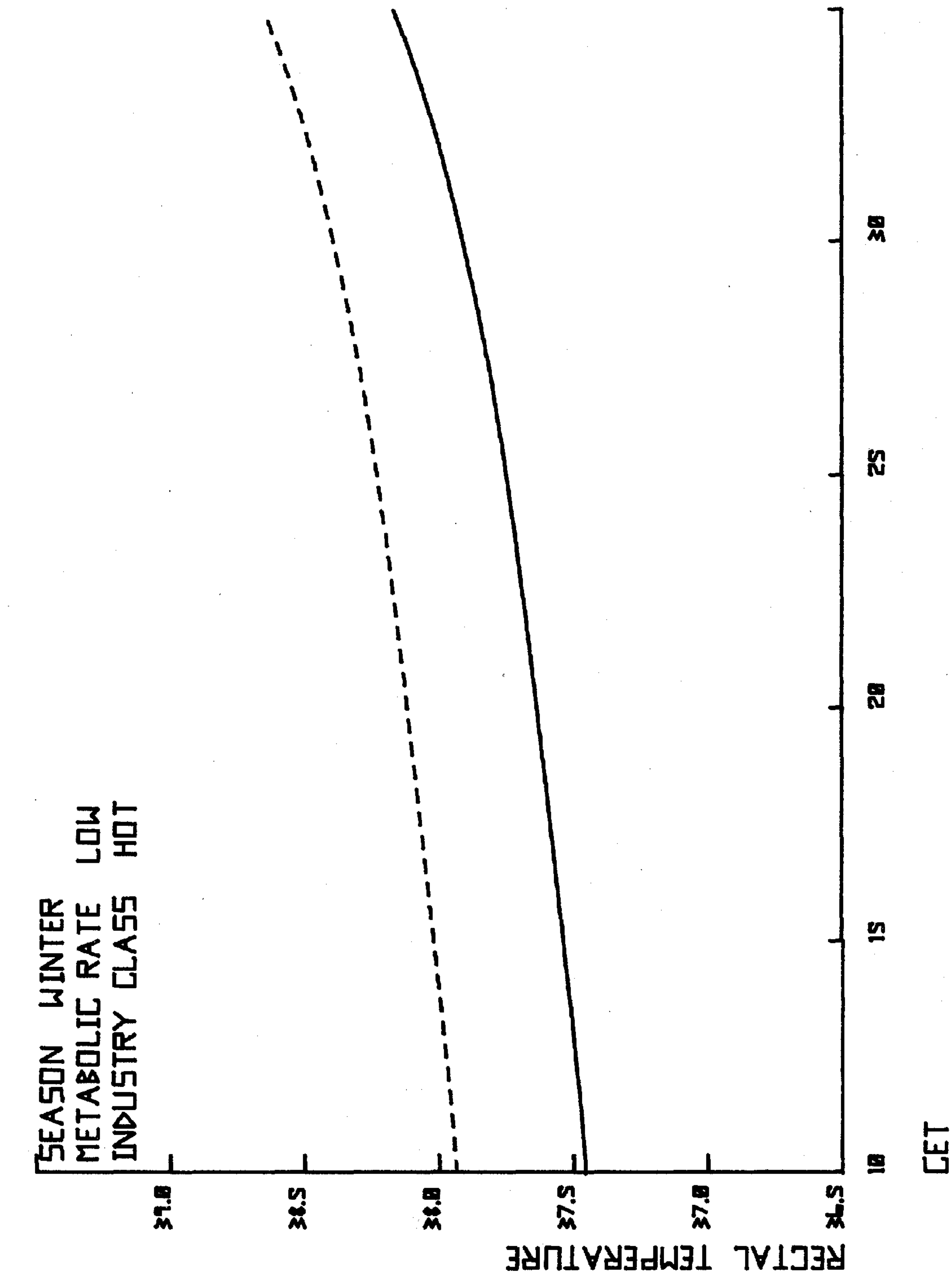
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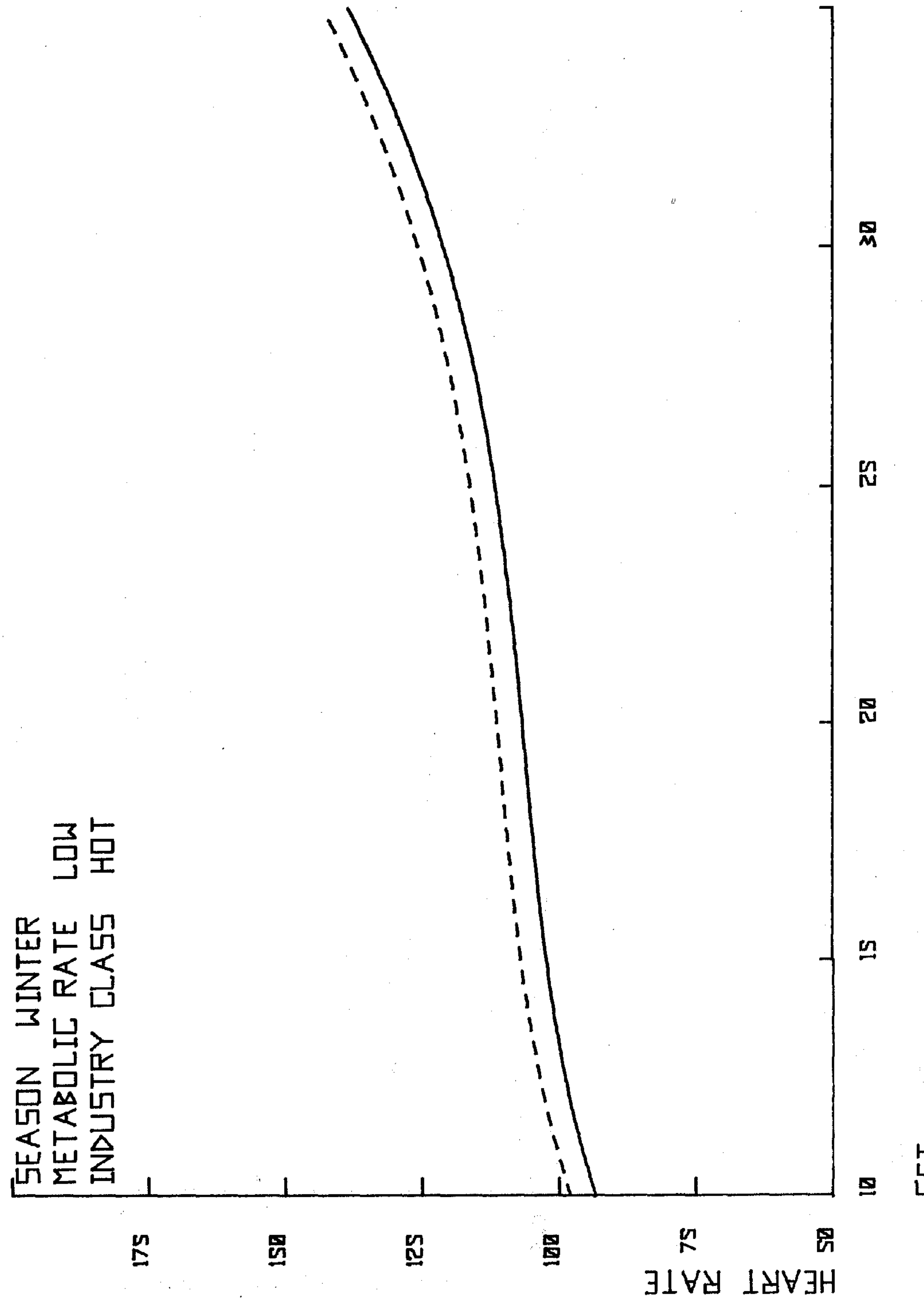
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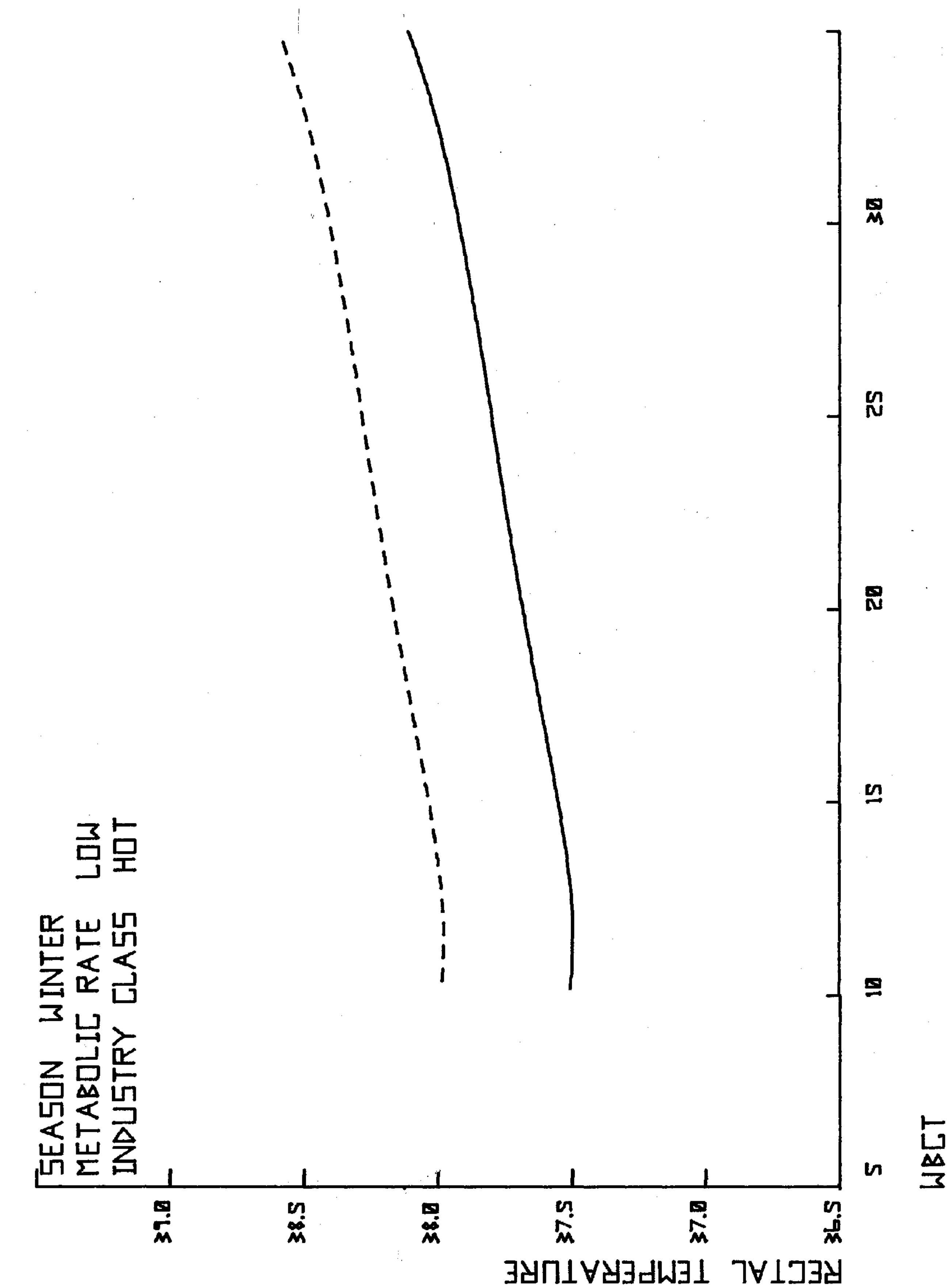

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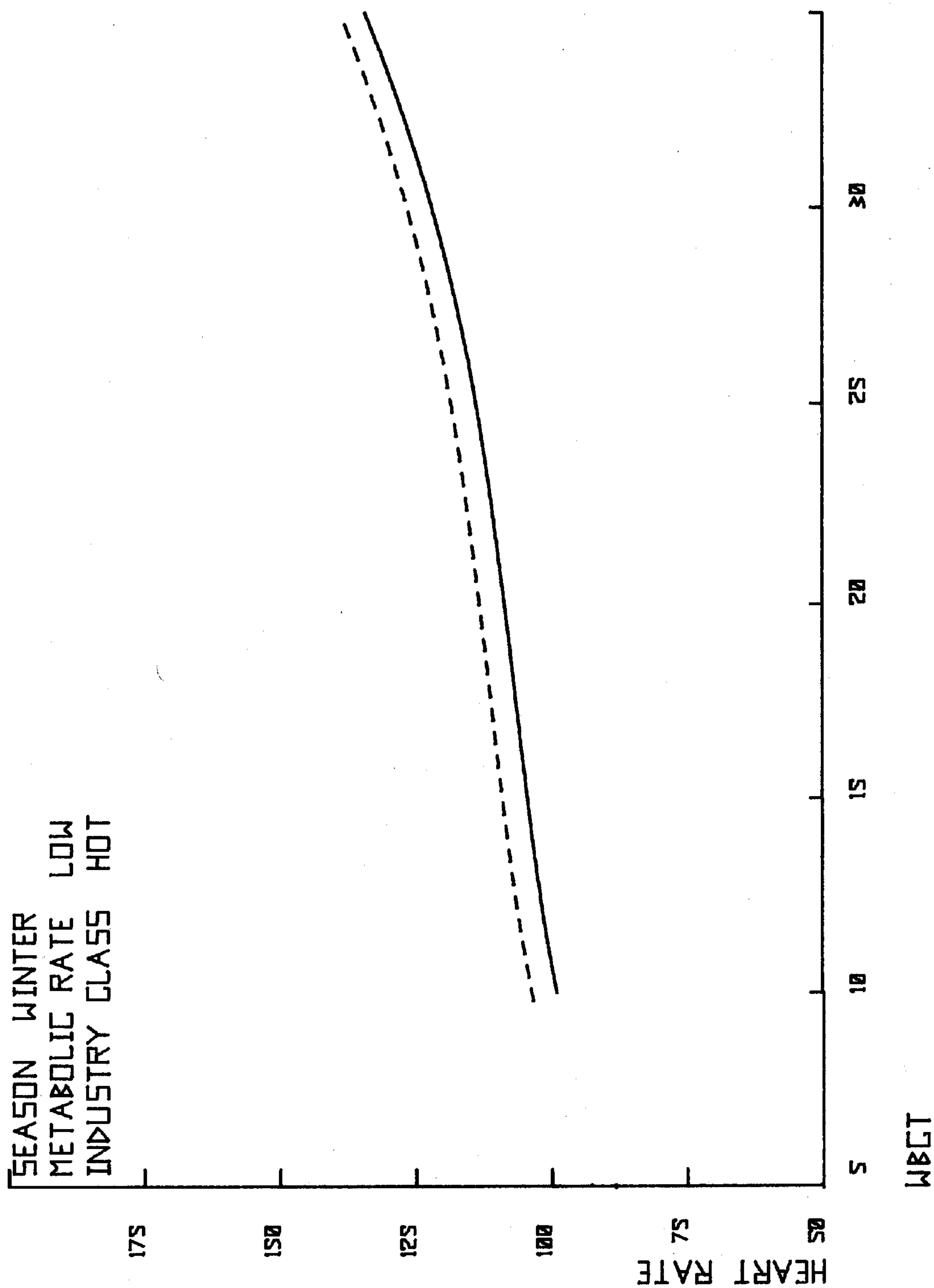
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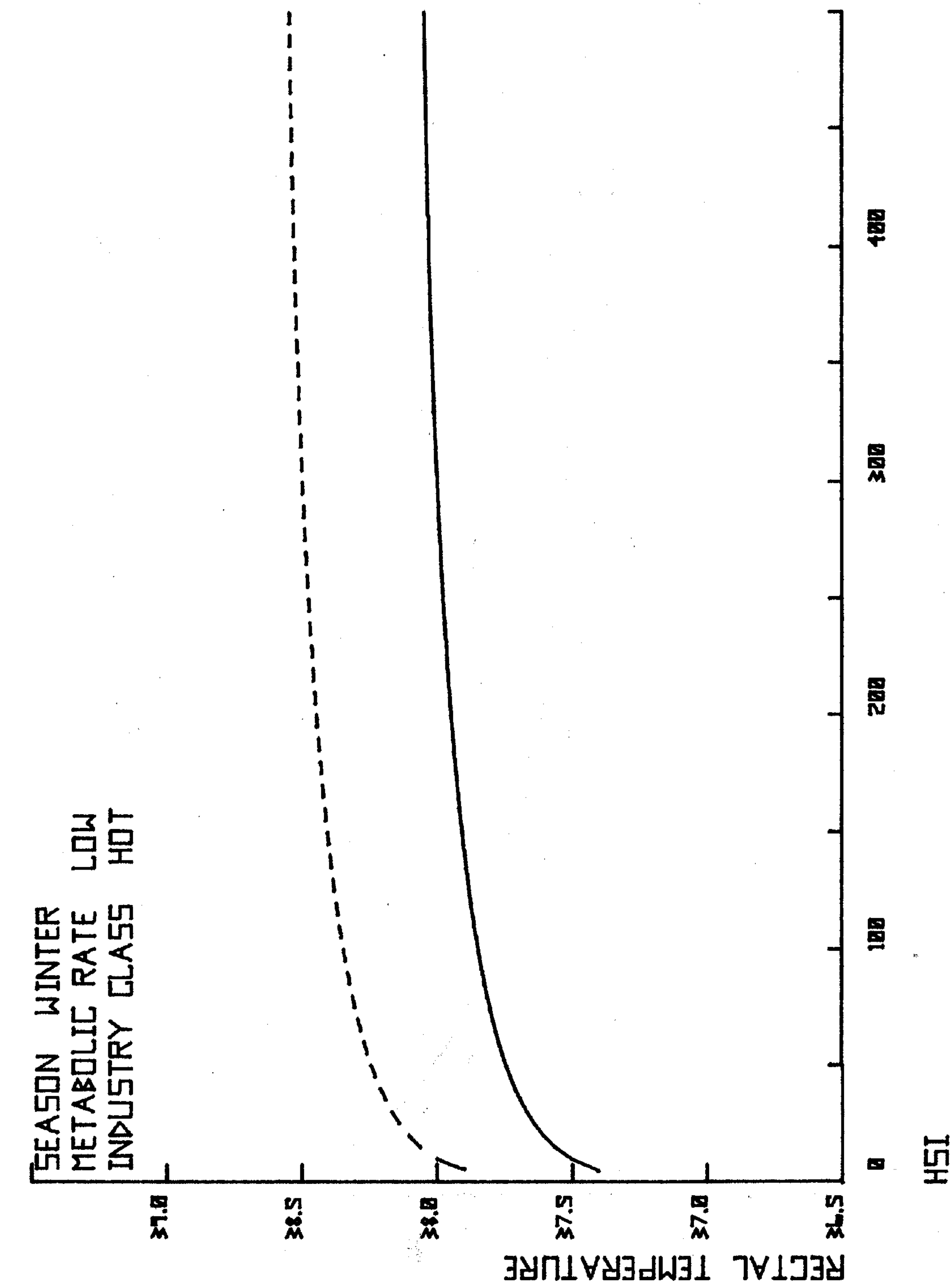
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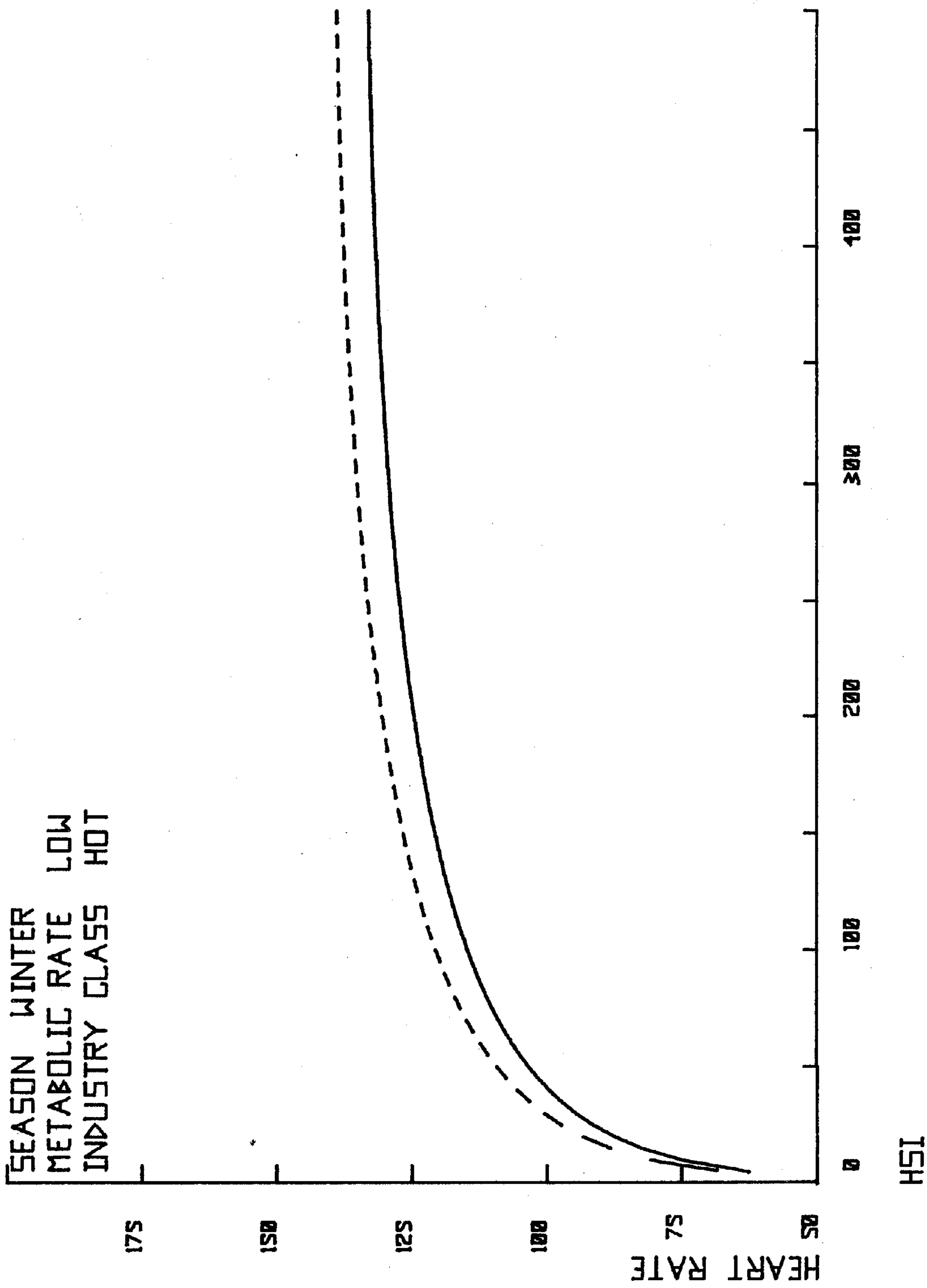
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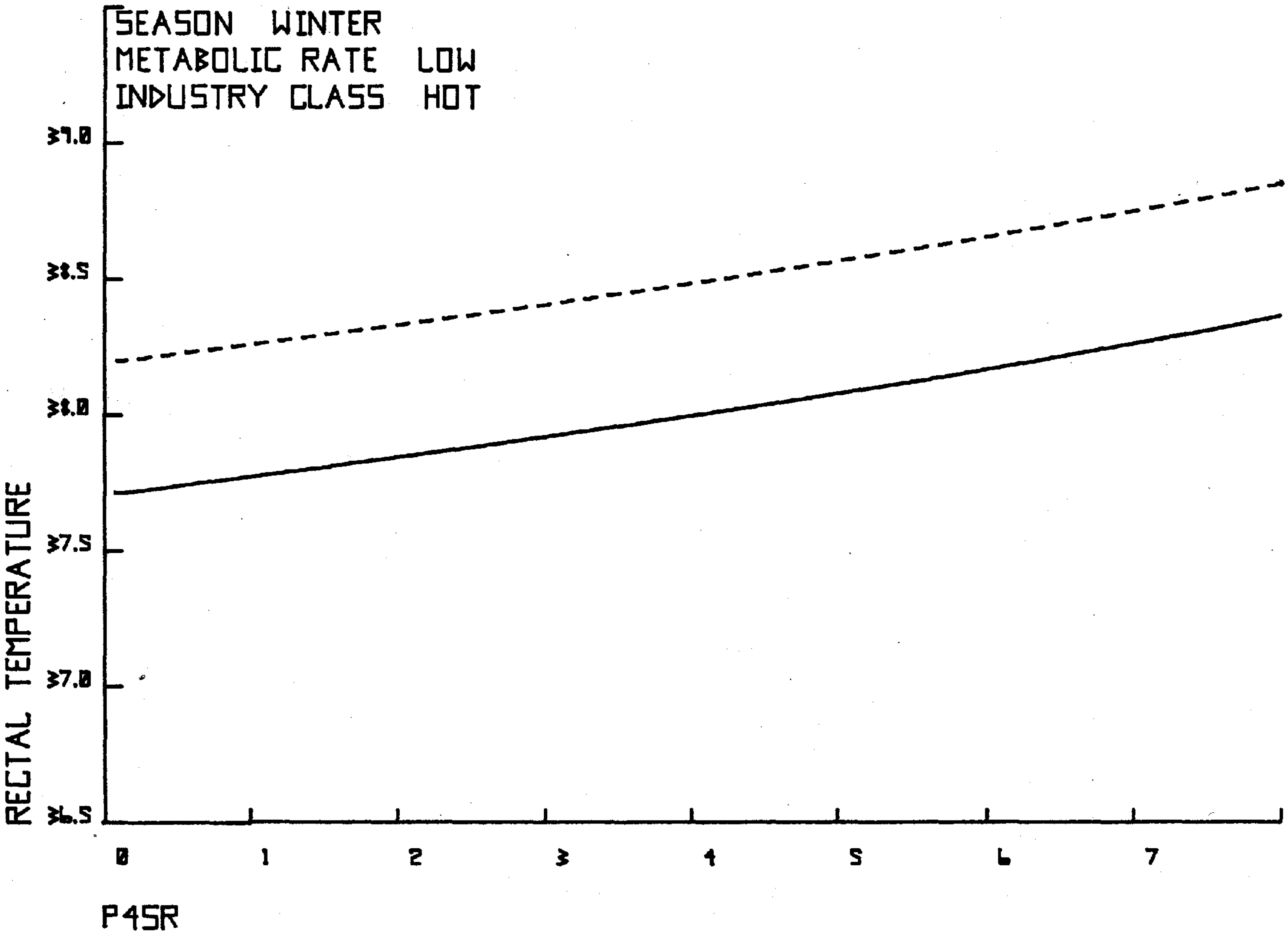
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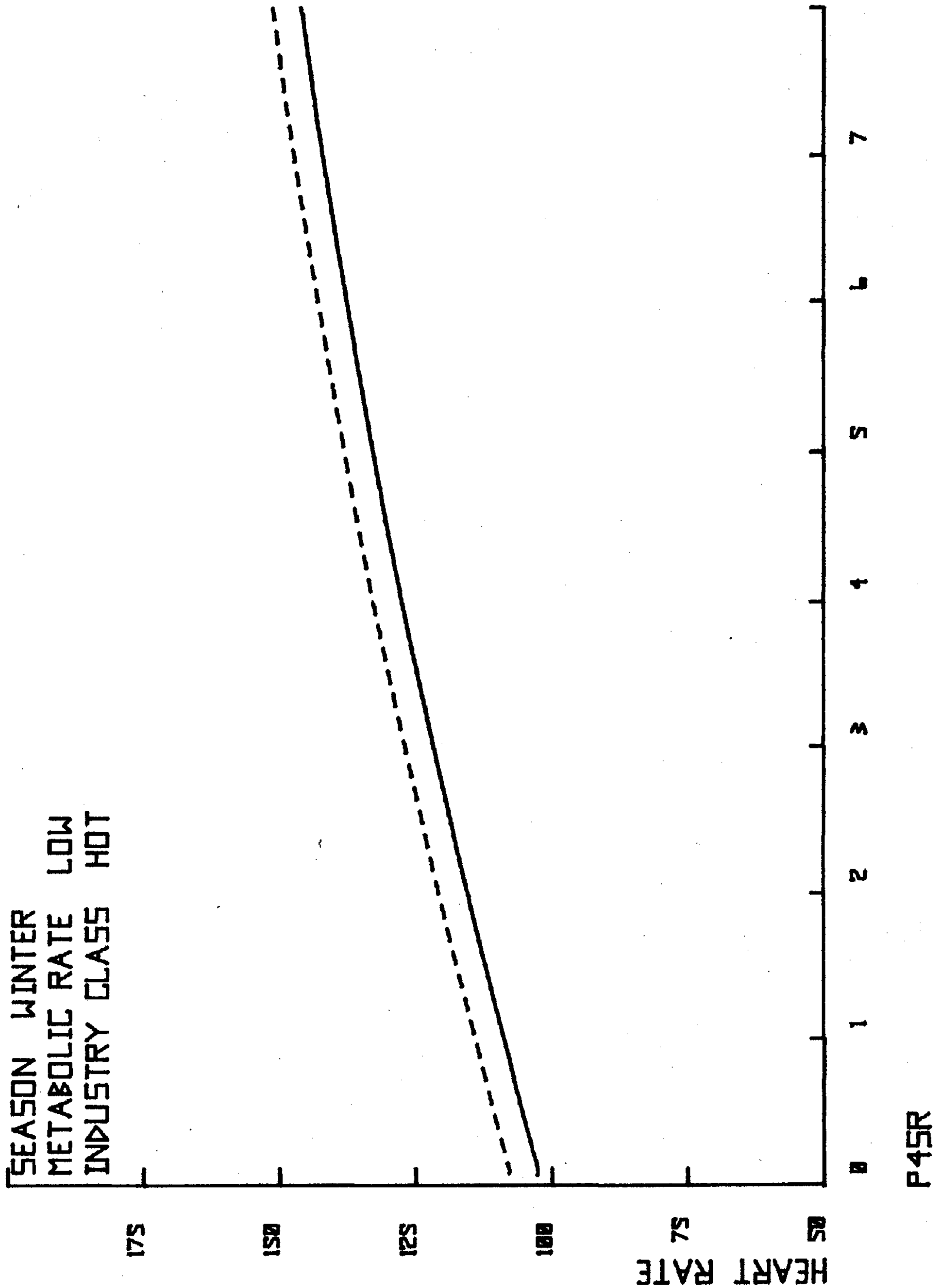
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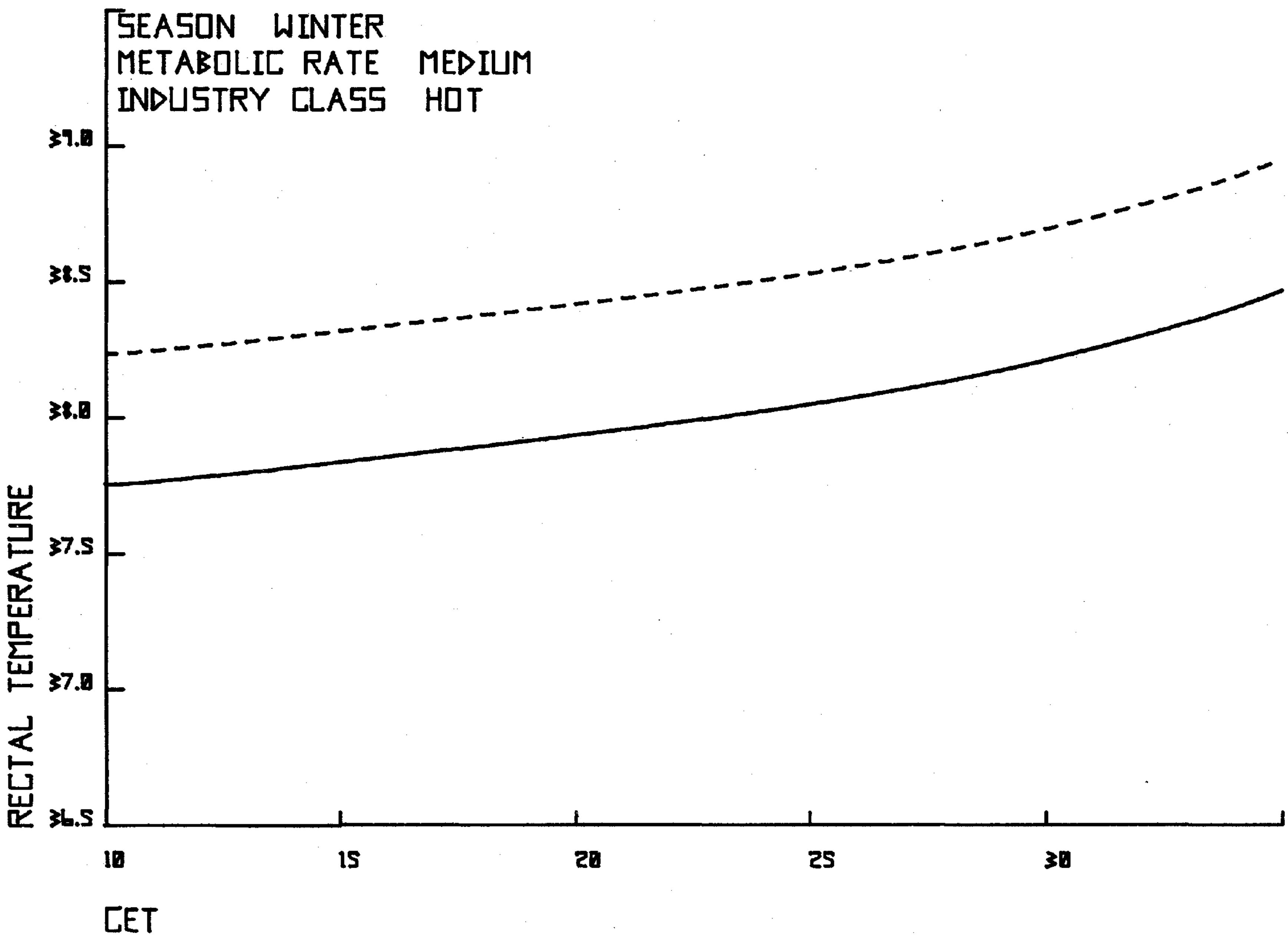

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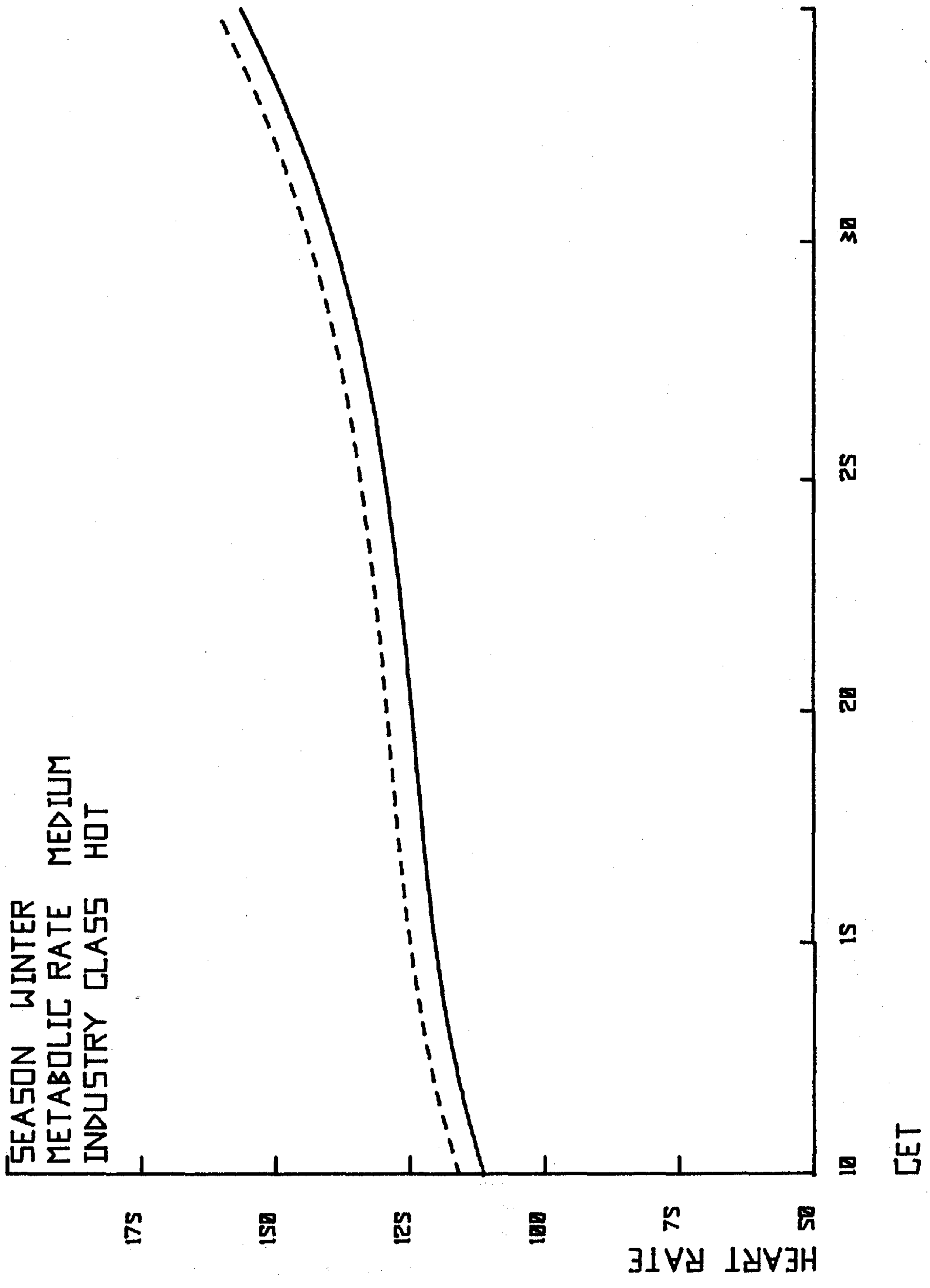
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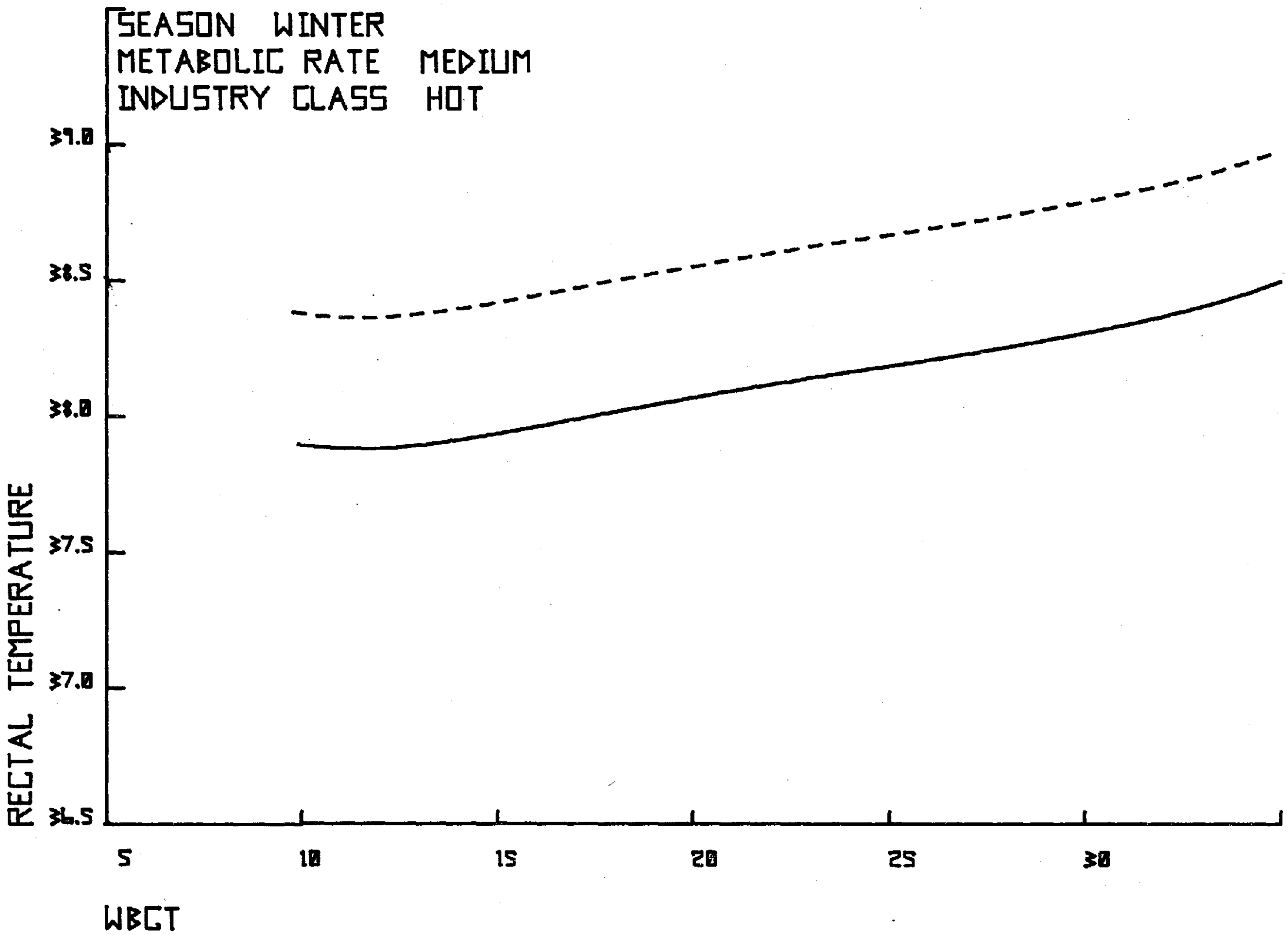
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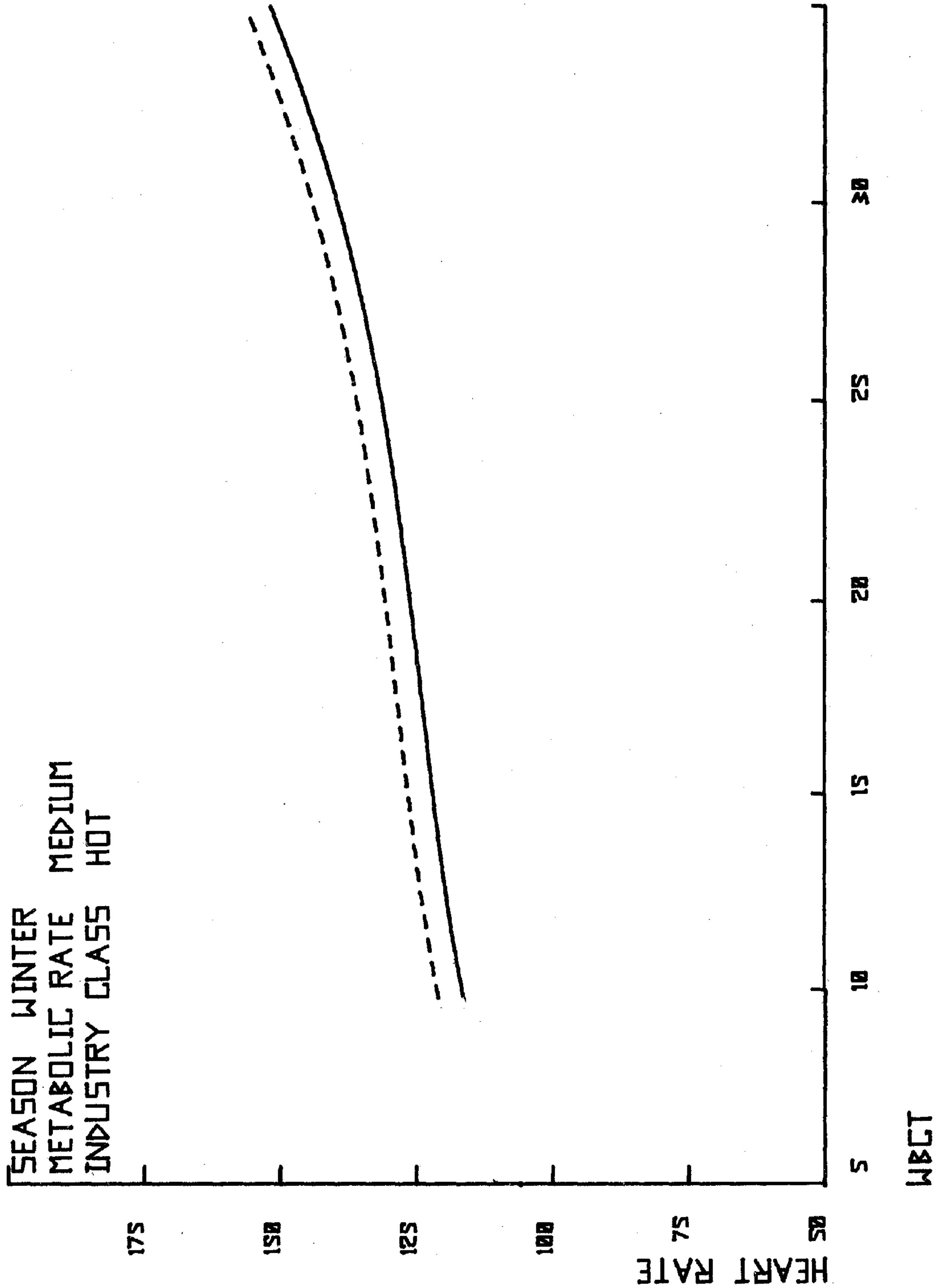
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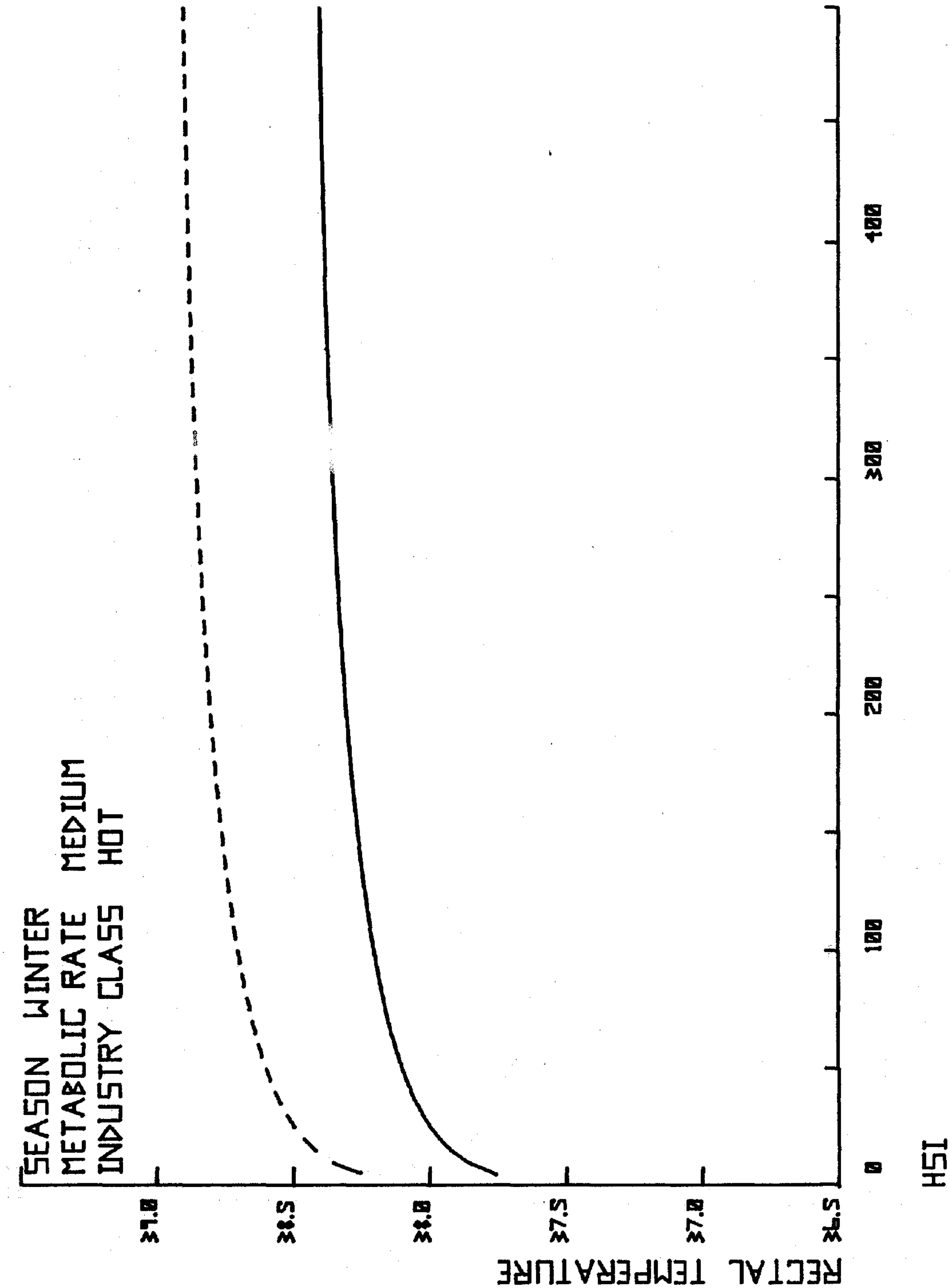
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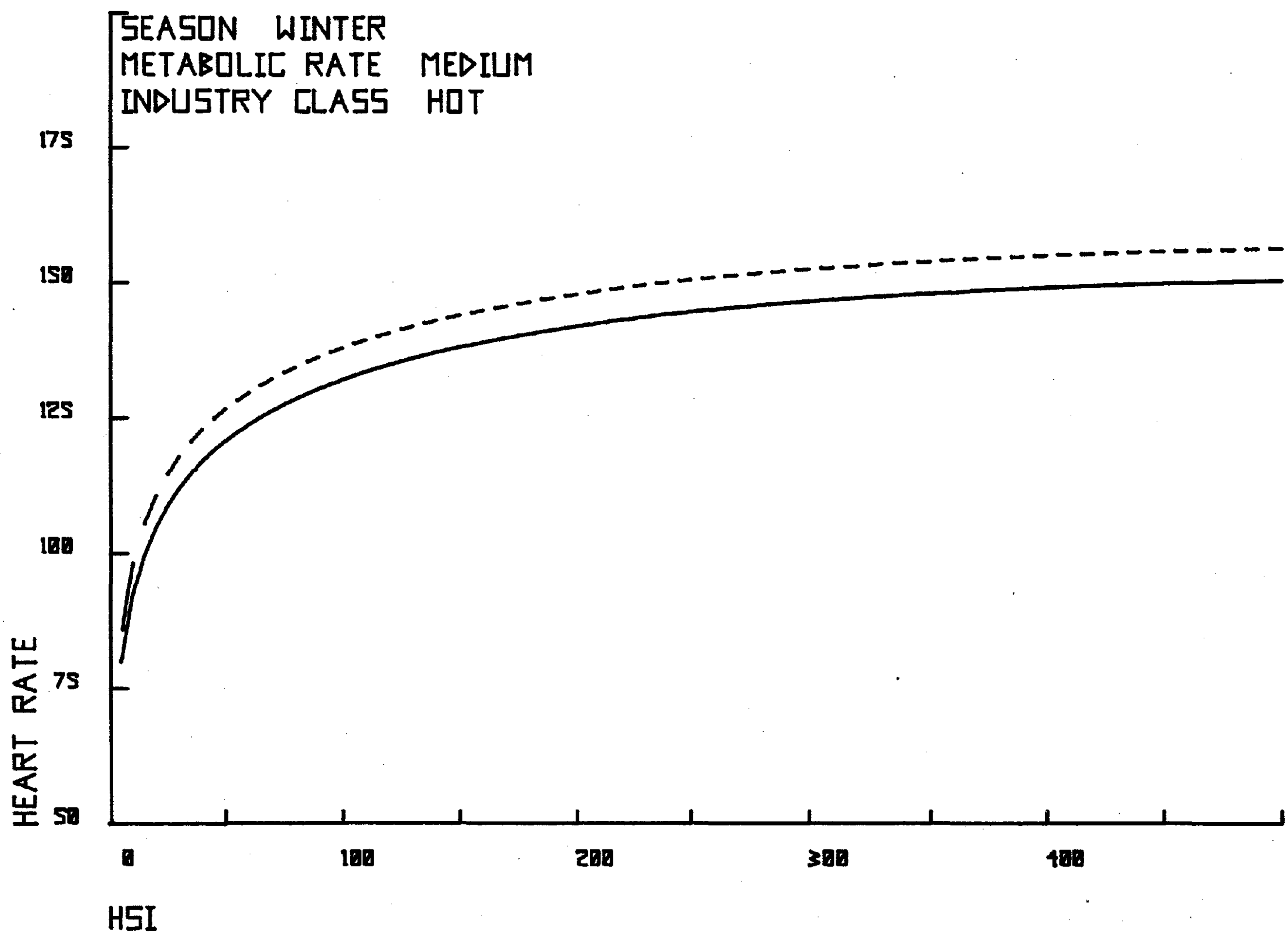

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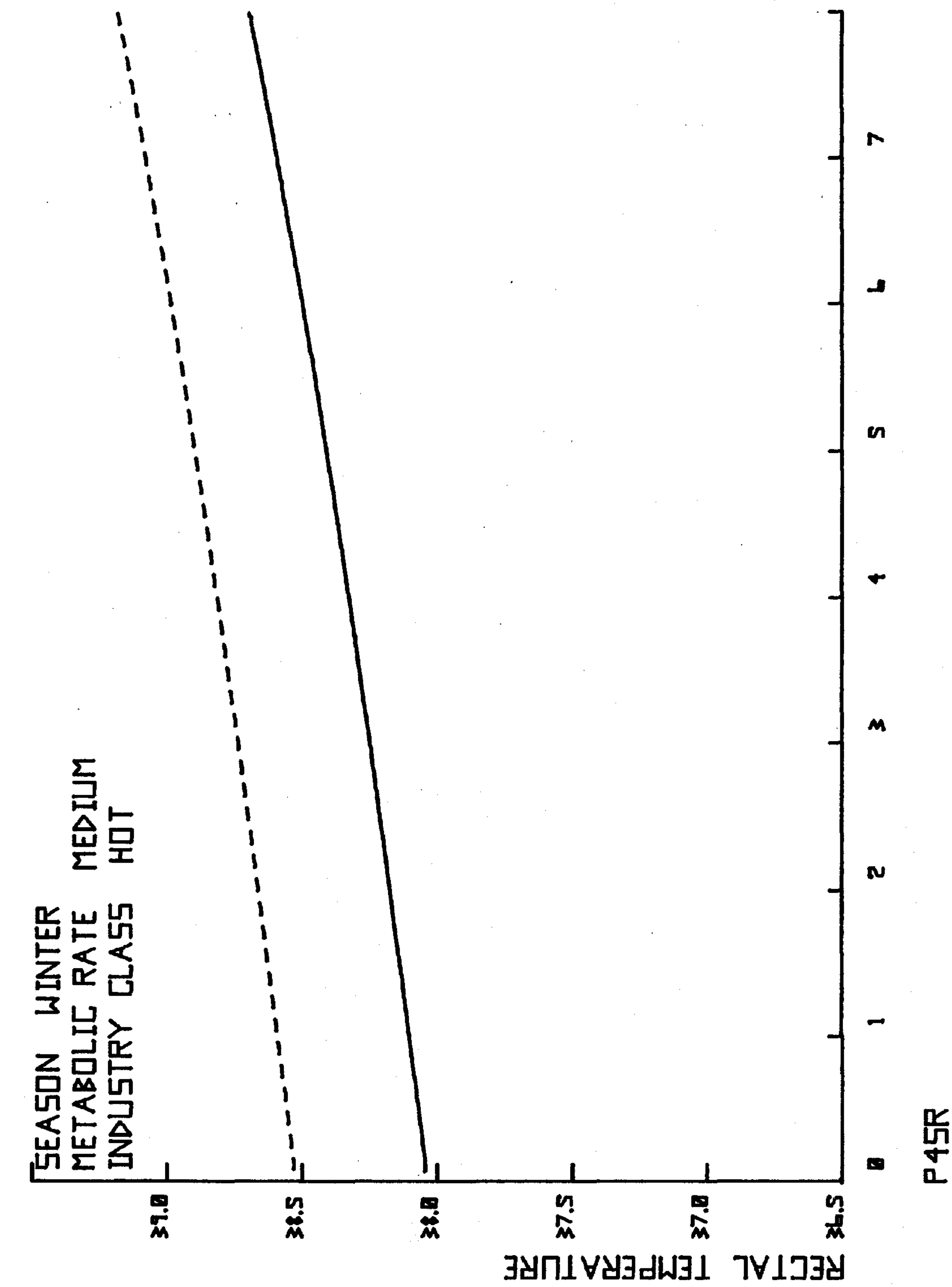
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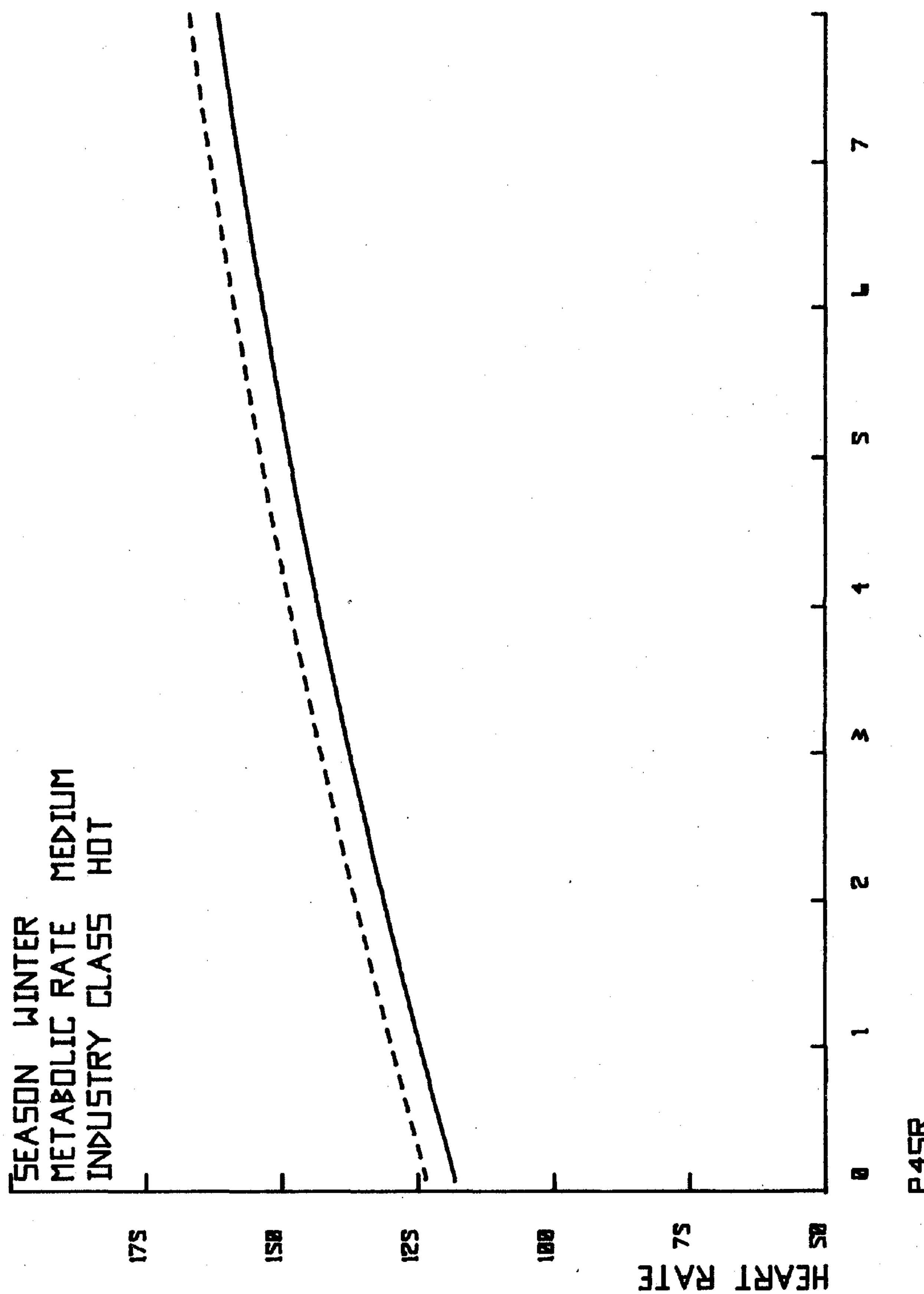
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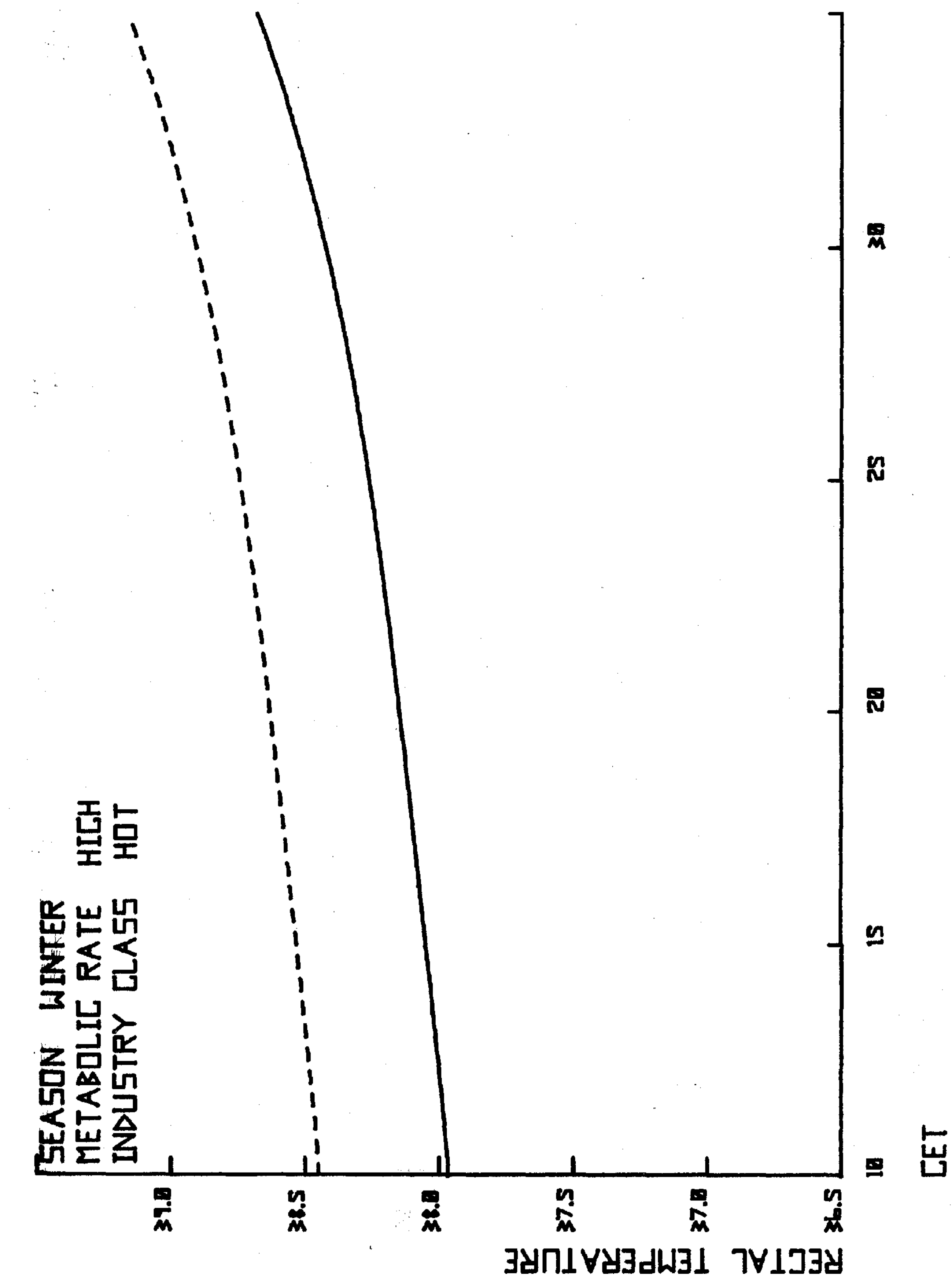
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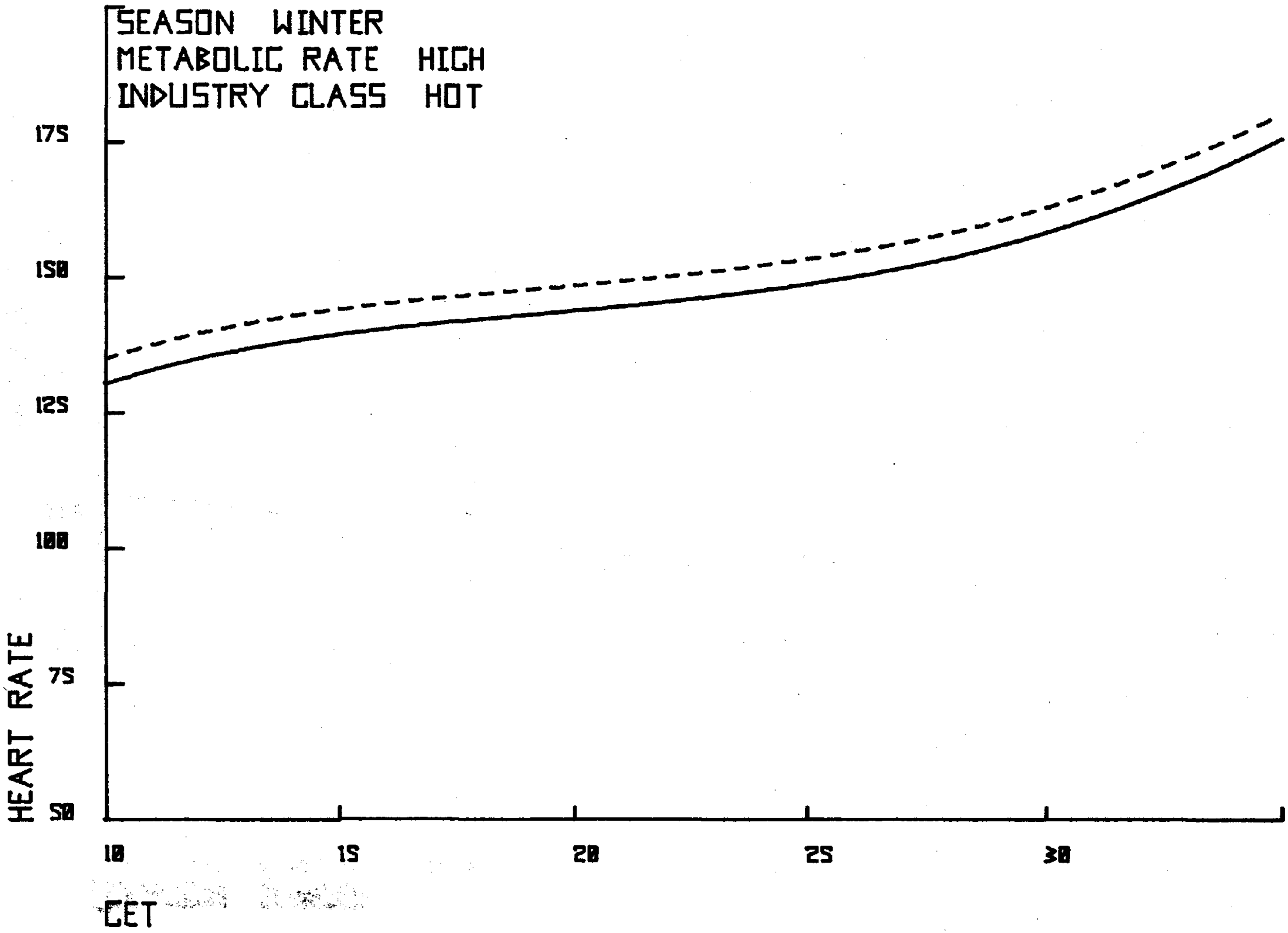

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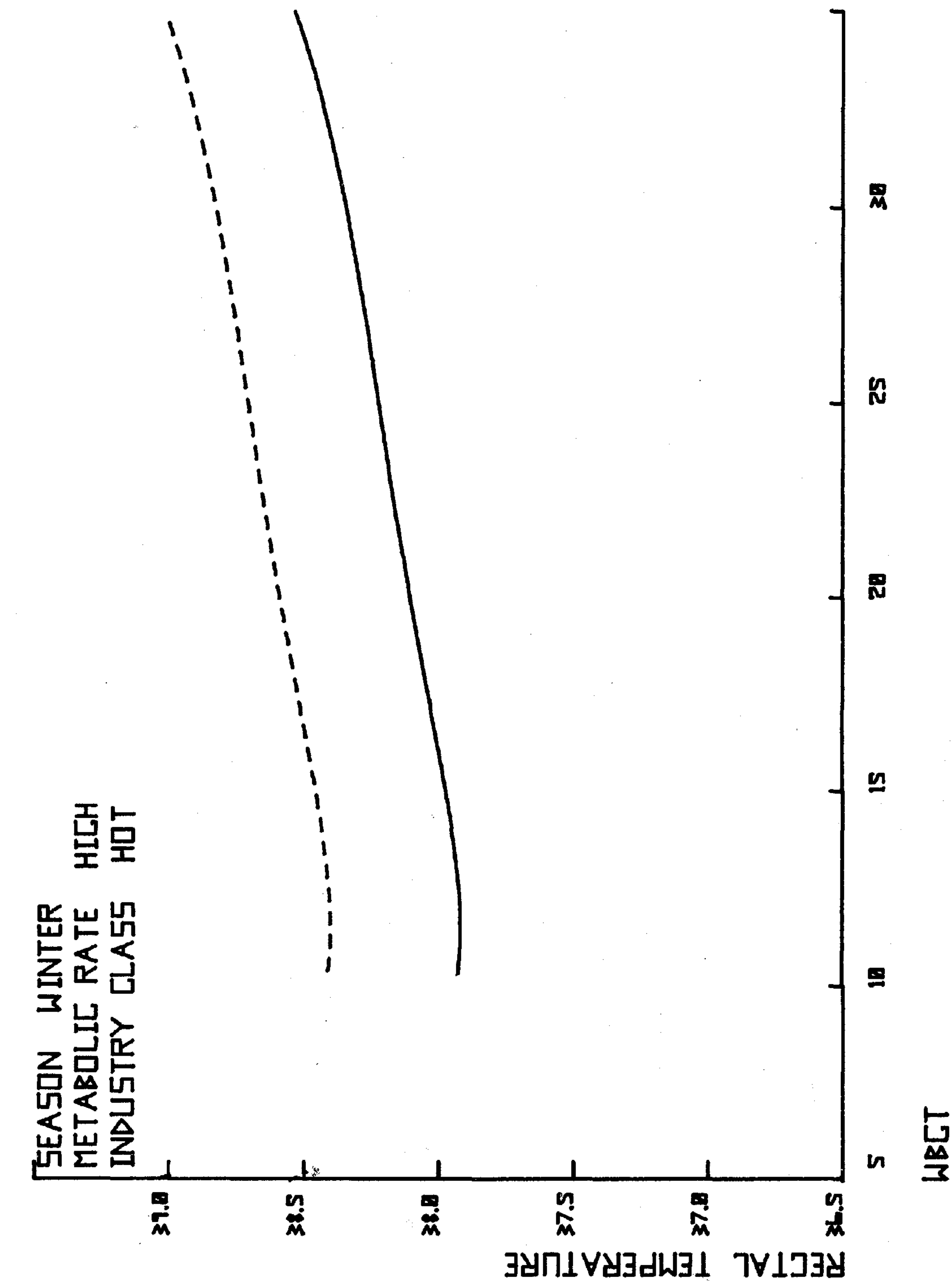
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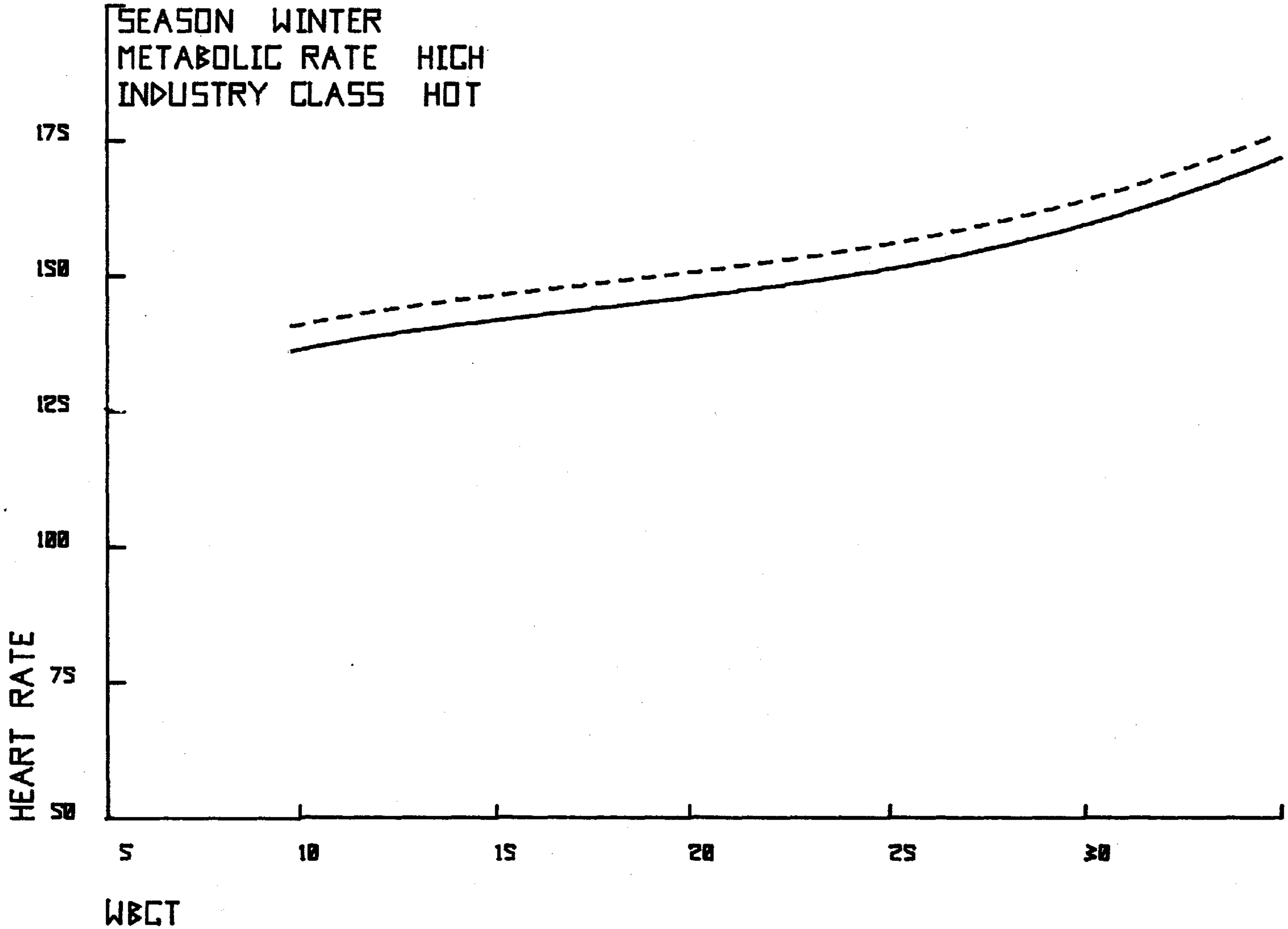
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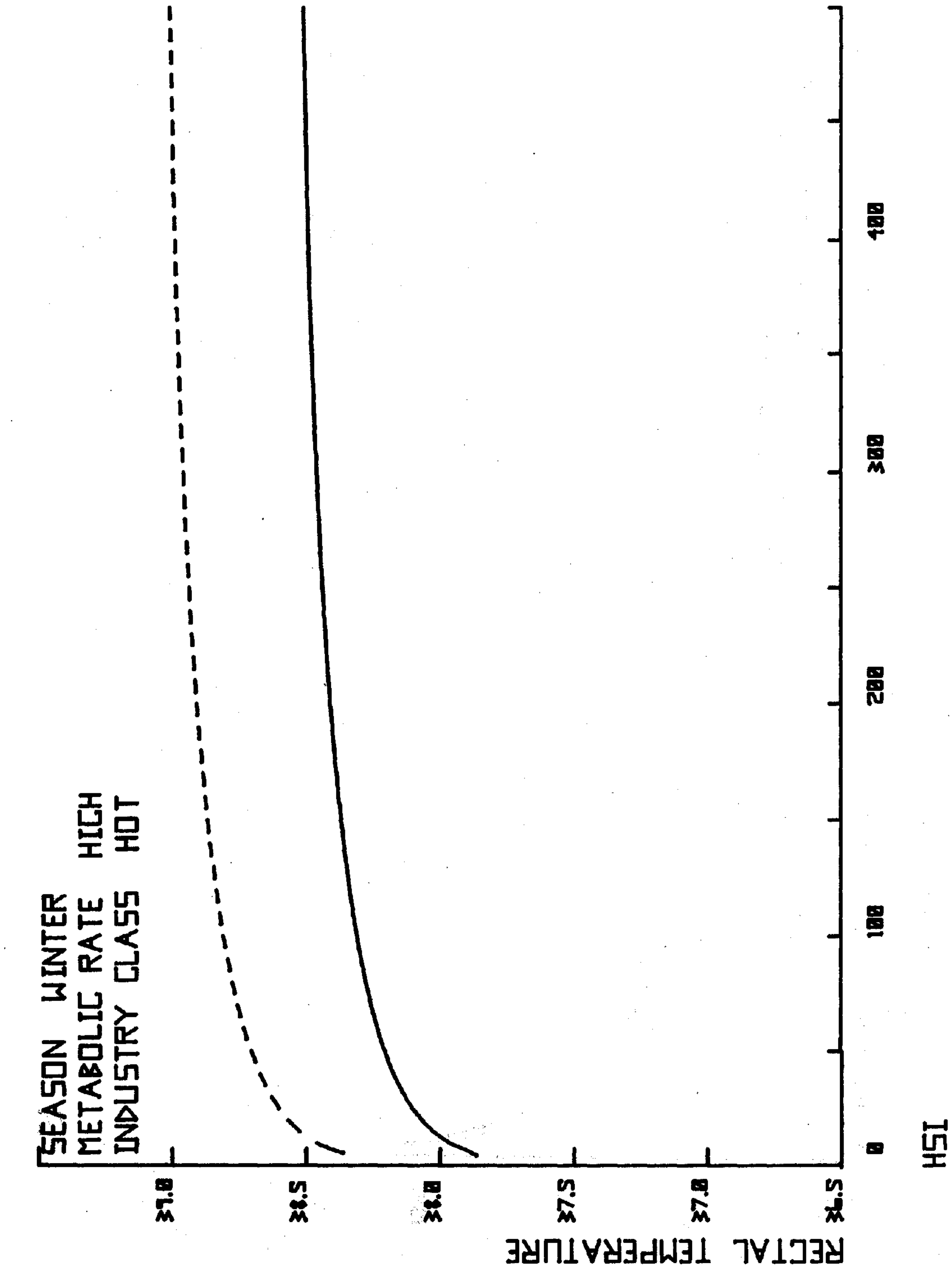
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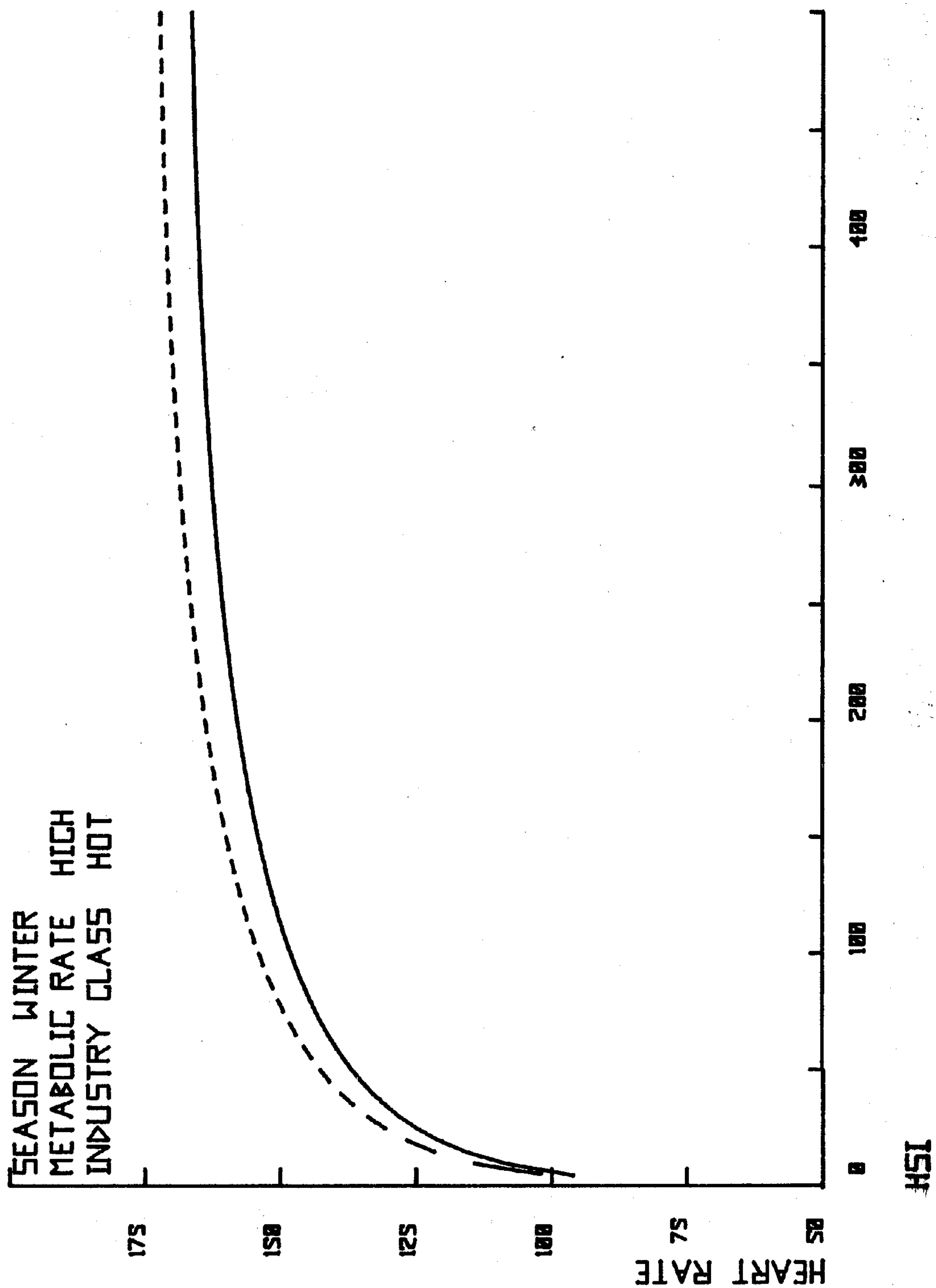
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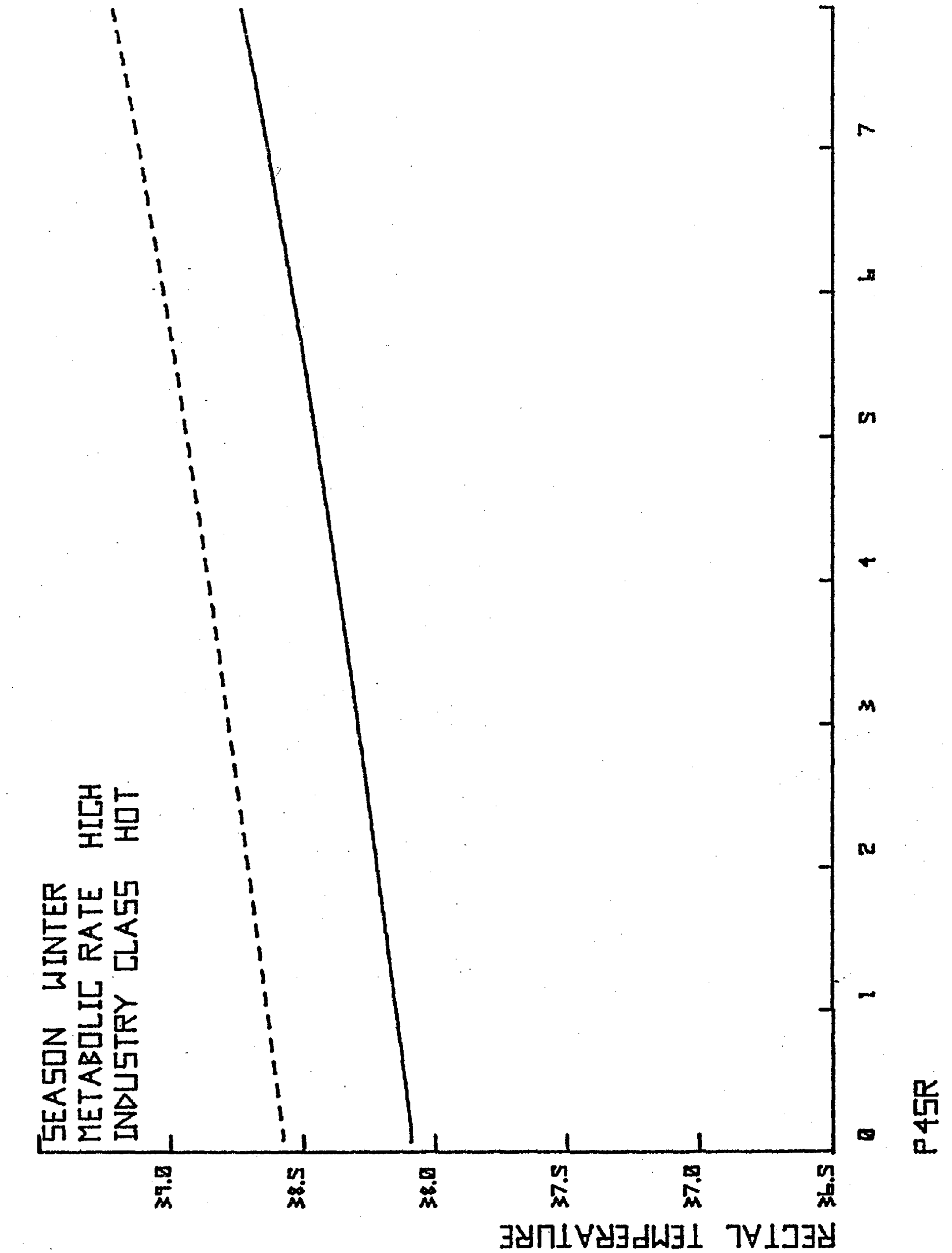

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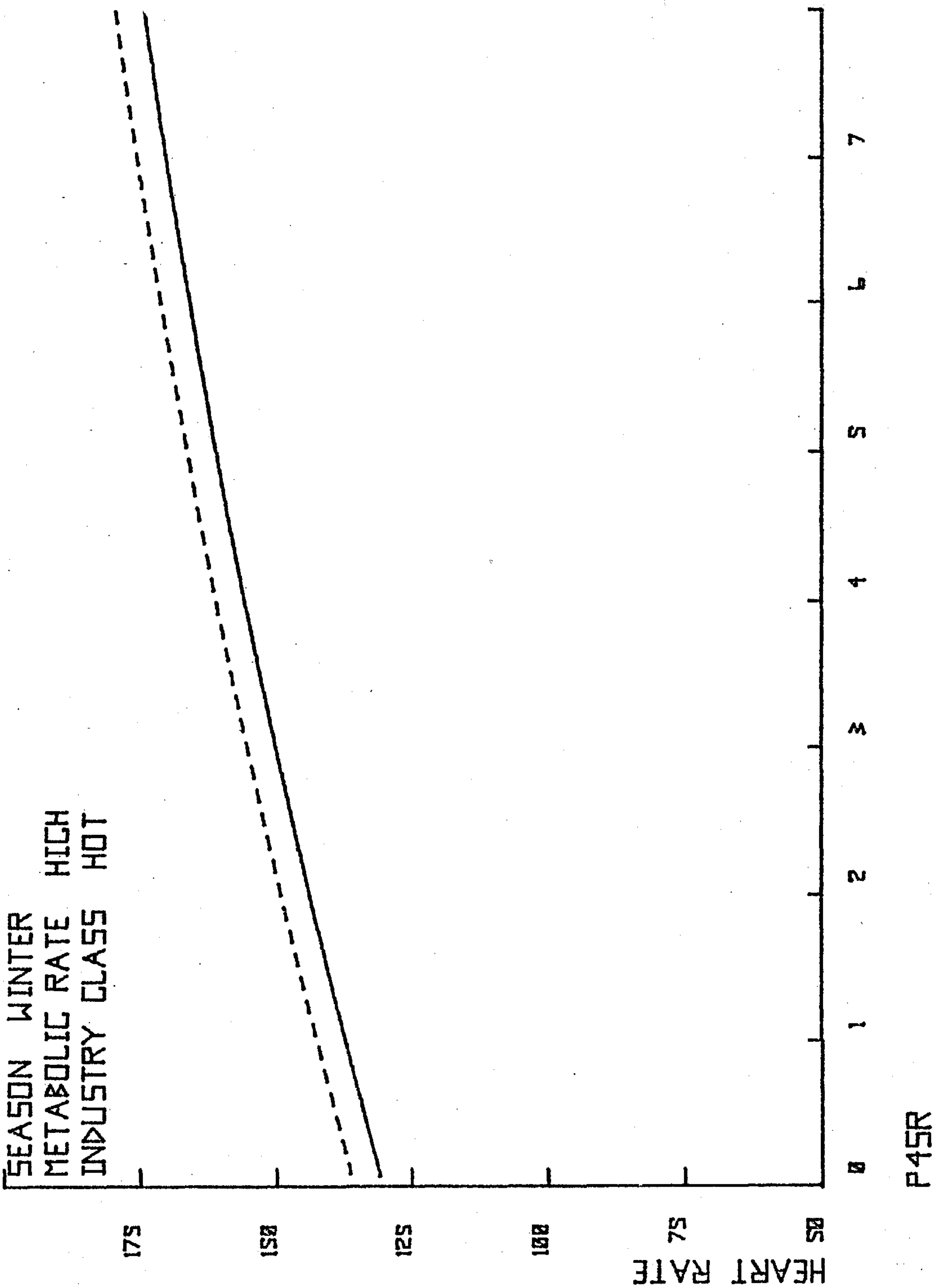
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