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"AN ENTIRE ANALYSIS OF DRASTIC PARAMETERS INFLUENCING THE PERFORMANCE OF PHOTOVOLTAIC SOLAR ENERGY CONVERSION"

BY

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ABSTRACT

This paper investigates the drastic parameters affecting the performance of the photovoltaic solar energy conversion. Temperature and collection efficiency of the silicon solar cell opted for research are some of these parameters. The theory of the photovoltaic effect is utilized to anticipate the performance-especially the maximum efficiency. It exists from the interaction between the optical properties of the semiconductor under consideration which determine the utilized fraction of the solar spectrum, and its electrical characteristics. Graphical representation and discussion of the results are exhibited at the end of the research.

1. INTRODUCTION

The photovoltaic effect can be defined as the generation of a potential when radiation ionizes the region in or near the built - in potential barrier of a semiconductor. It is characterized by a self-generated e.m.f. and the ability to deliver power to a load.

A potential barrier can be formed in a semiconductor by several means. The two techniques of most interest by photovoltaic cells are:

1) The deposition of a suitable transparent metallic film by evaporation or sputtering onto a semiconductor as in the selenium cell, and
2) The p-n junction formed by introduction of a suitable type impurity into the opposite impurity type semiconductor.

The electrical characteristic of a photovoltaic cell can be understood by the accompanied figure which displays the exact equivalent circuit of certain cell in whic
of series and shunt capacit. and resistances
consideration[1]. It consists of a constant
a non-linear junction impedance, and a load

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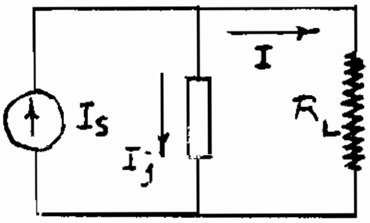
Light causes a current I, to flow in the load; the magnitude of which is the difference between the generated short-circuit current (I_s) and the current flowing in the non-linear junction (I_j). The latter which is known as the usual junction current is given by[1]:



Simple equivalent circuit of illuminated cell.

$$I_j = I_o\ (e^{\lambda V} - 1) \qquad \text{..........(1)}$$

This expression yields the i-v characteristic of the p-n junction photovoltaic cell.

where I_o is the reverse saturation current.
V is the voltage applied to junction
λ is given by:

$$\lambda = e/kT$$

(In practice, $\lambda = e/AkT$ where $A > 1$)
k being the Boltzmann constant is
$= 1.3805 \times 10^{-23}$ Joules. Degree^{-1})
and T the absolute temperature.

$$\text{Since } I_s = I_j + I \qquad \text{..........(2)}$$

$$I = I_s - I_j$$

$$= I_s - I_o\ (e^{\lambda V} - 1) \qquad \text{..........(3)}$$

The maximum voltage (V_{max}) occurs when I = 0

$$\therefore V_{max} = \frac{1}{\lambda} \ln \left(\frac{I_s}{I_o} + 1\right) \qquad \text{..........(4)}$$

The maximum power delivered (P_{max}) is represented by the largest rectangle that can be fitted into the fourth quadrant of the i-v characteristic of the cell. The squarer the current-voltage characteristic, the higher the efficiency[1]. In the previous work of anticipating the maximum efficiency, authors has neglected the effect of reflection losses in addition to take the collection efficiency to have a unity. The collection efficiency is the measure of the carriers passing through the circuit (I_s) to the total number of carriers generated in the solid perunit time. The purpose of our paper is to investigate the drastic parameters which affect the performance of one of avital important type of solar cells (i.e. Silicon) under the condition of numerous practical constraints. A complete analysis and discussion of the results obtained are exhibited and introduced.

2. MAXIMUM EFFICIENCY

It is defined as the ratio of the maximum electrical power output to the solar power arriving on unit area. It is given by[2]:

$$\eta_{max} = \eta_c (1-r)(1-e^{-\alpha l}) e n_{ph}(E_G) \frac{\lambda V_{mp}}{(1+\lambda V_{mp})} \cdot \frac{V_{mp}}{N_{ph} E_{AV}}$$

2.1. Collection efficiency(η_c)

It has the following definition:

$$\eta_c = \frac{\text{Carriers passing through the circuit}(I_S)}{\text{Total no of carriers generated in the solid per unit time.}}$$

This is ascribed by the fact that all the minority carriers which are generated in the solid by the radiation do not contributed to the power developed in the load[2]. This is because some of them recombine with majority carriers either inside the volume or at the surface.

i.e. $$\eta_c = \frac{I_s}{(1-r)(1-e^{-\alpha l}) e n_{ph}(E_G)}$$

where r is the index of refraction. There is another index (n) the relation between both is

$$r = (n-1)^2/(n+1)^2$$

These indices estimate the reflection losses n has not been measured for many of the materials of possible interest. It must be therefore estimated from the empirical relation due to Moss namely:

$$E_G\, n^4 = 173$$

α is the absorption constant for the radiation. To maintain high (η_c), α may locate in the range of:

$$10^4 < \alpha < 10^6 \quad cm^{-1}$$

for radiation near the absorption edge, l is the n-region extension.

For efficient absorption, it is necessary that

$$l \simeq \alpha^{-1} \quad i.e.$$

$$10^{-4} < l < 10^6 \quad cm$$

2.2. $n_{ph}(E_G)$

It is the following summation:

$$n_{ph}(E_G) = \sum_{\nu = \frac{E_G}{h}}^{\nu = \nu_{max}} n_{ph}(\nu)$$

where $n_{ph}(\nu)$ was chosen to be the no of photons of energy $h\nu$ in the intervals

$$\Delta\left(\frac{1}{\lambda}\right) = 10^{-5} \ cm^{-1}$$

and ν_{max} is the maximum frequency in the solar spectrum. This no of photons is derived and plotted versus E_G according to the atmospheric conditions2.

2.3. Solar power arriving on unit area (U)

It is the product of N_{ph} E_{AV} where:

N_{ph} is the total number of photons in the solar spectrum and

E_{AV} is the average energy of such photons. This solar power is a function of the absorption conditions and is demonstrated from a standard table.

2.4. V_{mp}

V_{mp} is the voltage at maximum power transfer which can be verified from the relation2:

$$e^{\lambda V_{mp}}(1 + \lambda V_{mp}) = \frac{I_s}{I_o} + 1 = e^{\lambda V_{max}}$$

where $\lambda = e/kT$

V_{max} is the open circuit voltage

To demonstrate V_{mp}, it is indispensible to determine I_o and I_s. The former can be calculated from

$$I_o = A \; e^{-E_G/kT}$$

The A was computed for silicon which results in:

$$I_o = 1.44 \times 10^8 \; e^{-E_G/kT}$$

I_s, on the hand, can be computed from the relation

$$I_s = {}_c(1-r)(1-e^{-\alpha l}) \; e n_{ph}(E_G)$$

2.5. Representation of the conditions of atmosphere.

Two parameters have often been used to represent of the complex and varying conditions of the atmosphere and its effect on the intensity and spectrum of the energy. These parameters are:

a) Optical air mass(m), which can be defined as 1/cos Z where Z is the angle between a line vertical to the observer and a line through the observer and the sun (i.e. when the sun is 60° from vertical, m = 2).

b) W, the perceptible water in a vertical column in the atmosphere measured in cm. W = 0 corresponds to a relative humidity of about 50 percent.

3. Investigation of the drastic parameters influencing performance of is solar cell.

3.1. Problem constraints.

The problem of investigating the essential parameters affecting the performance of solar cell of silicon type, is tackled under the constraints of:

a) Various absorption conditions
   (a.1) m = 0, W = 0 outside atmosphere.
   (a.2) m = 1, W = 0 See level, Sun at Zenith.
   (a.3) m = 2, W = 0 See level, Sun at 60° from Zenith.
   (a.4) m = 1, W = 0 Cloudy day.

b) Two conditions of collection
   (b.1) Collection efficiency (η_c) = 1
   (b.2) Collection efficiency (η_c) = 0.65

c) Different operating temperatures of the solar cell under consideration initiating from 273 °K till 548°K.

3.2. Tackling the problem.

The maximum efficiency, the maximum voltage (O.C.Voltage), the voltage corresponding to maximum power transfer, the short-circuit current, the reverse saturation current and the load impedance at maximum power transfer, all these parameters are computed and deduced under the influence of prementioned constraints. The calculations are executed for all cases and we satisfy here with the demonstration of a single case out of these numerous cases. All the results are plotted to reveal the behaviour of each parameter, Table 1 displays the results attained for the constraints of $m = 1$, $W = 0$ outside atmosphere and $\eta_c = 1$, $I_s = 4.4856 \times 10^{-2}$.

Table (1)

(Performance of S_i Solarcell for $m=1$, $W=0$, $\eta_c=1$)

t°C	0	25	75	125	175	225	275
T°K	273	298	348	398	448	498	548
λ	42.507	38.941	33.346	29.157	25.902	23.302	21.176
I_o	$10^{-13} \times 3.0369$	$10^{-11} \times 1.6483$	$10^{-9} \times 8.6849$	$10^{-7} \times 9.473$	$10^{-5} \times 3.623$	$10^{-4} \times 6.670$	$10^{-3} \times 7.2144$
V_{max}	0.6050	0.5581	0.4635	0.3692	0.2749	0.1812	0.0933
V_{mp}	0.5307	0.4813	0.3848	0.2919	0.2040	0.1232	0.0563
$\eta\%_{max}$	21.5044	19.3355	15.1042	11.0557	7.2589	3.8649	1.2953

There are some features to be unequivocal:

1) The parameter λ is independent of the absorption conditions and the collection efficiency. However, it is a function only of temperature.

2) The reverse saturation current (I_o), similarly depends only on the energy gap potential (E_G) and the temperature, that is, their values are used for any atmospheric & collection conditions.

3) However, the short-circuit current (I_s) has a unified value for certain restrictions of m & w and η_c.
(For m = 1, w = 0 & $\eta_c = 1$, $I_s = 4.4856 \times 10^{-2}$).

Fig. "1" reveals the relation between the maximum efficiency and temperature when there is no reflection or transmission losses ($\eta_c = 1$) for different atmospheric conditions. One can conclude that increasing the temperature causes a considerable drop in the max. efficiency. This phenomenon is correct for all atmospheric conditions. Moreover, we remark a coincidence of these characteristics for various constraints of m & w. However, this is not satisfied for the case of $\eta_c = 0.65$ as displayed in Fig."2".

There is a divergence in the maximum efficincy for all temperatures taken except for t = 275°C (548°K) which has nearly the same maximum efficiency. The maximum divergence is attained for t = 0 (273 °K).

Fig. "2" demonstrates an important phenomenon of having the highest possible maximum efficiency for any temperature at m=1, w = 0 (Sea level & sun at Zenith).
On the other hand the characteristics of m = 0, w = 0 and m = 2, w = 0 are considered the same which means that under these restrictions of atmospheric conditions, we have the same maximum effeciency for certain temperature.

One can conclude also that the max. efficiency for the case of m = 1, w = 0 (Sealevel & Sun at Zenith) has twice that corresponding to the cases of m = 0, w = 0 & m = 2, w = 0. Investigating the case of m = 0, w = 0 (outside atmosphere) through Fig."3", we verify that the condition of $\eta_c = 1$ leads to approximately twice the max. efficiency of the case of $\eta_c = 0.65$ for any temperature in the range opted (273 - 548 °K). However, the rate of decay of the latter is not pronounced like the characteristic of $\eta_c = 1$. The largest percentage of the max. efficiency at the constraint of $\eta_c = 1$ has about 21.5.

Fig."4" explains the variation of max. efficiency versus temperature for the case of m = 1, w = 0, Sea level, sun at Zenith. A slight difference between the characteristics of $\eta_c = 1$ & $\eta_c = 0.65$ is attained in the max. efficiency for any temperature. However, the case of $\eta_c = 1$, has naturally, the upper curve. Also the rate of reduction in the max. efficiency is considerable on increasing the temperature.

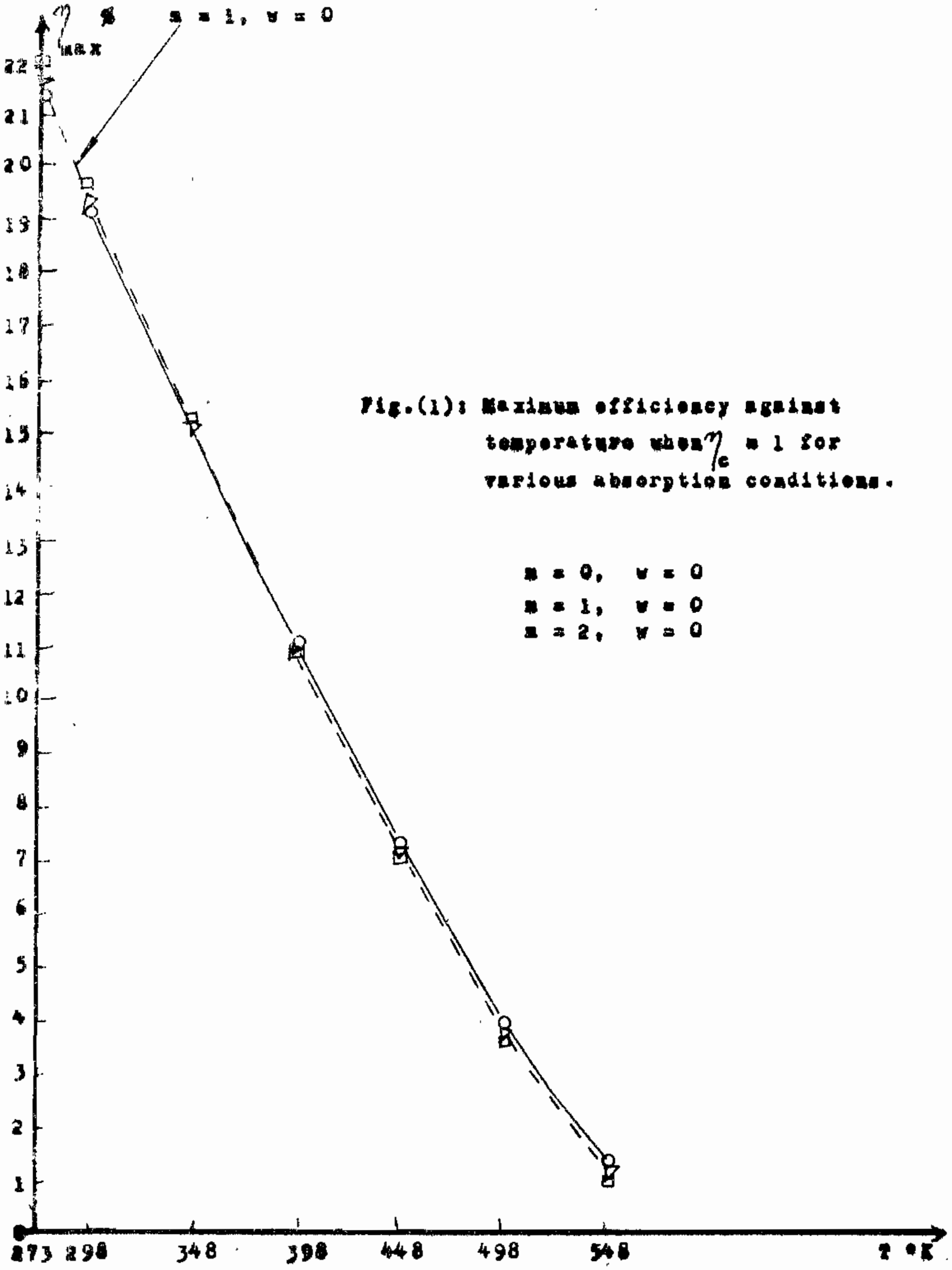


Fig.(1): Maximum efficiency against temperature when η_c = 1 for various absorption conditions.

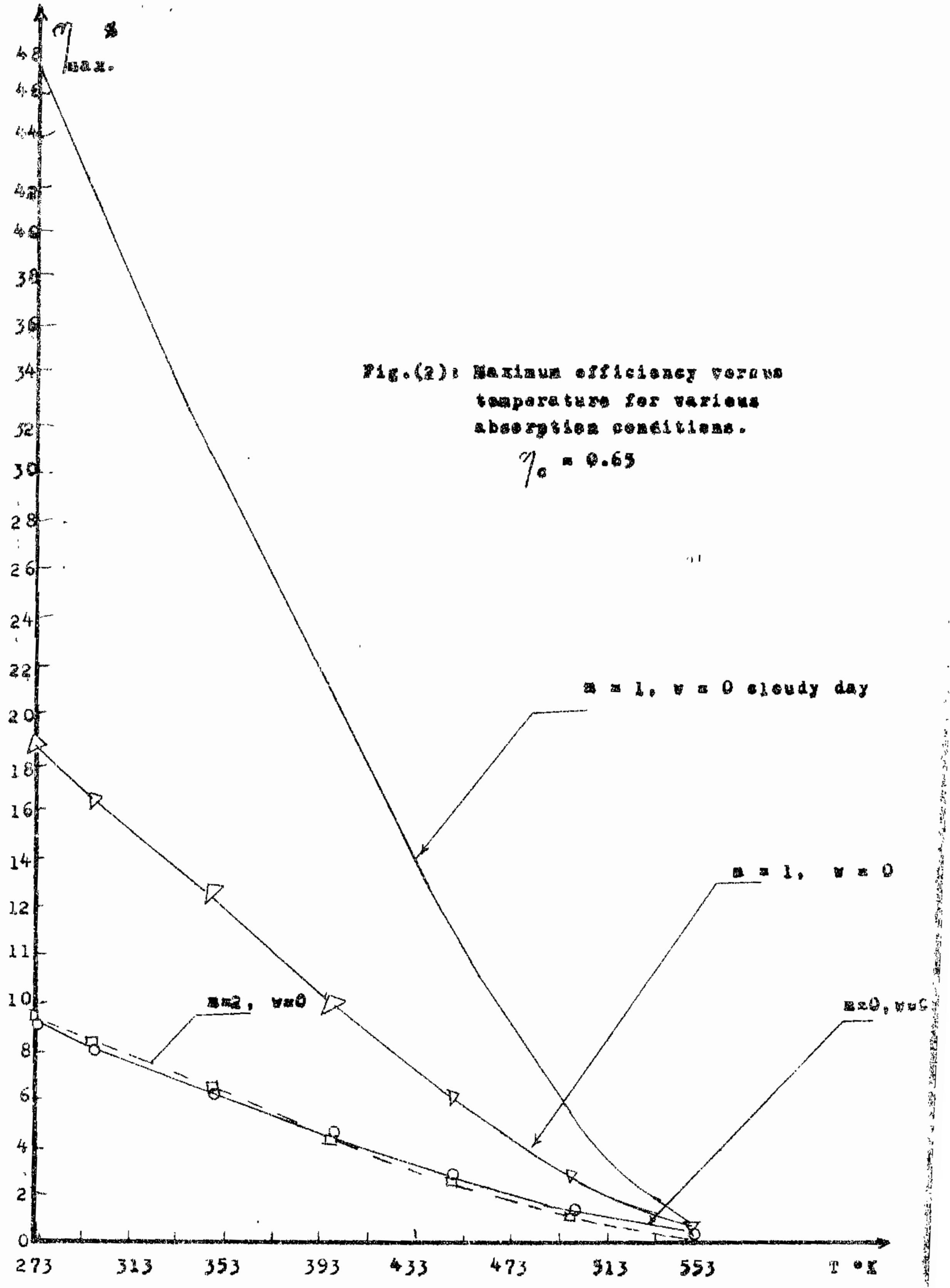


Fig.(2): Maximum efficiency versus temperature for various absorption conditions.

$\eta_c = 0.65$

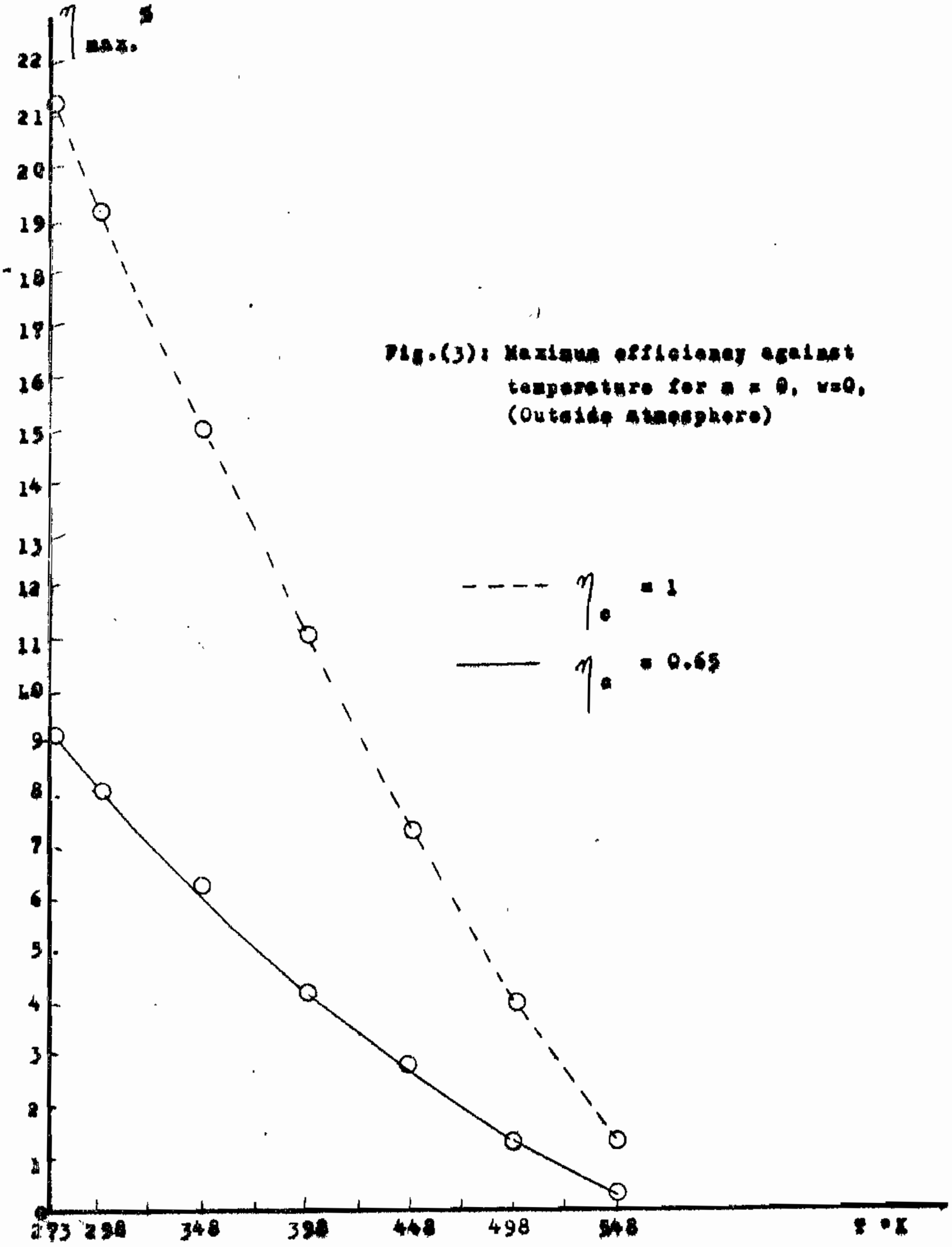


Fig.(3): Maximum efficiency against temperature for m = 0, w=0, (Outside atmosphere)

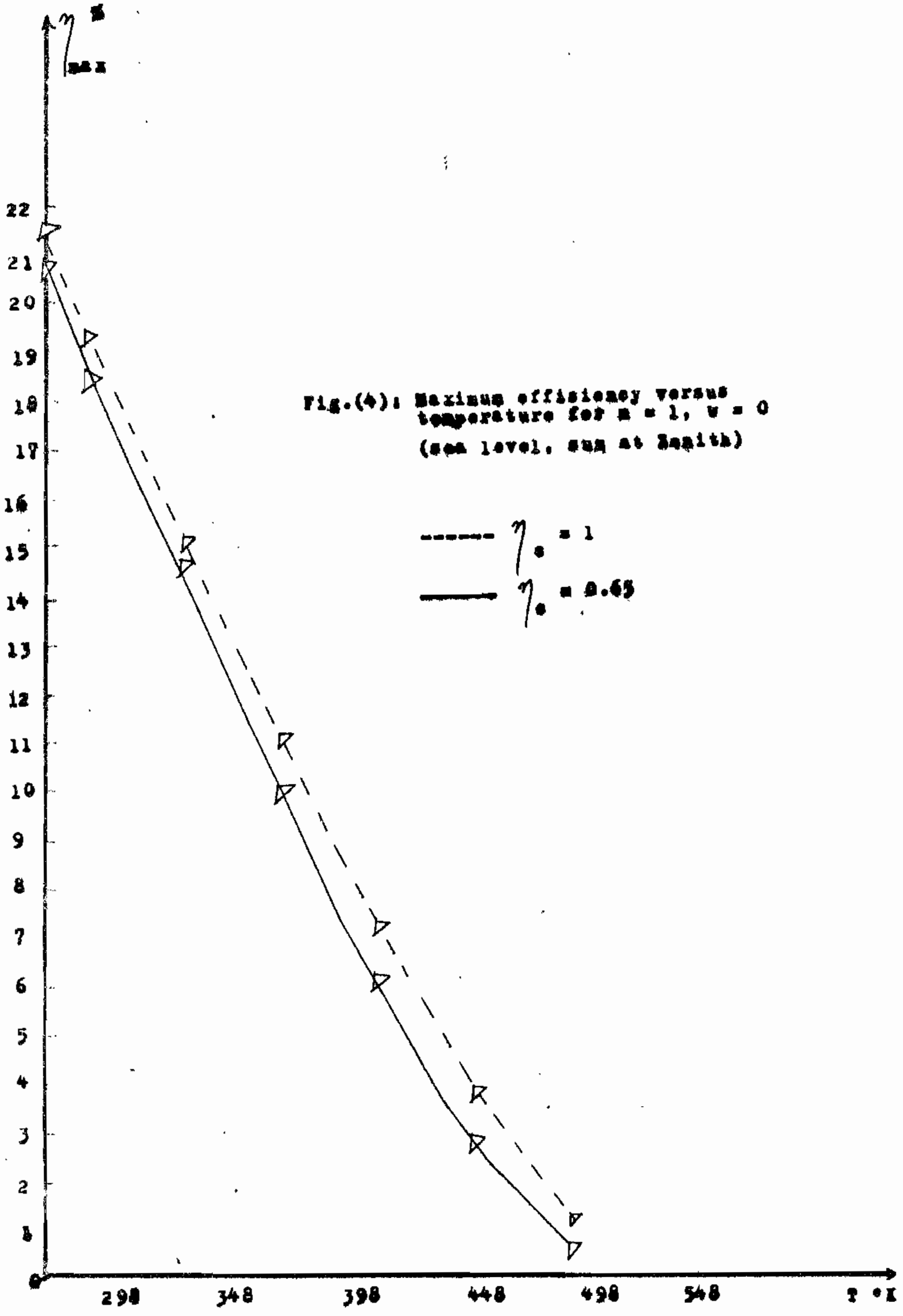


Fig.(4): Maximum efficiency versus temperature for m = 1, w = 0 (sea level, sun at Zenith)

The analysis of the characteristics plotted through Fig."5" for the constraint m = 2, w = 0, Sea level, sun at 60° from Zenith verifies a pronounced divergence between the curves of $\eta_c = 1$ & $\eta_c = 0.65$. However this divergence decays in the direction of higher temperatures and arrives to its minimum at the temperature of 275 °C.

The behaviour of the max. voltage against temperature is represented graphically in Fig. "6" under the conditions of $\eta_c = 0.65$ and m = 0, w = 0, m = 1, w = 0 & m = 2, w = 0. One can note that the open circuit voltage at any temperature has nearly the same value although we have various atmospheric conditions. Also, the max. voltage has a negative slope i.e. its characteristic decays with increasing the temperature.

Fig."7" shows the change of the voltage corresponding to the max. power transfer with the temperature under the preceding constraints of Fig."6". We conclude the same notes prementioned with respect to the max. voltage (V_{max}). Looking for Fig."8", the comparison of (V_{max}) versus temperature on having $\eta_c = 1$ & $\eta_c = 0.65$reveals a moderate divergence between these characteristics in addition to the decay phenomenon with increasing the temperature.

Fig."9" explains the manner of variation of (V_{mp})against the temperature for m = 0, w = 0, outside atmosphere, when $\eta_c = 1$ and 0.65. The difference between the two characteristics does not exceed 0.02 volt at any temperature.

Fig."10" demonstrates the effect of temperature on the logarithm of the reverse saturation current (I_o). This characteristic shows a continuous rise of ln I_o towards the positive direction of the logarithm.

Fig."11" reveals the behaviour of the shortcircuit current for various restrictions of atmospheric and collection restrictions of atmospheric and collection which leads to the following conclusions:

1) η_c = 1 curve is the upper characteristic comparable with that of η_c = 0.65.

) m = 0, w = 0 constraints have the highest short-circuit current for certain collection efficiency. However, the conditions of m = 1, w = 0, cloudy day, have the lowest one.

) For both cases of $\eta_c = 1$ & $\eta_c = 0.65$, the constraint of m = 1, w = 0, sea level, sun at zenith has a greater short-circiut current than that of m = 2, w = 0, sea level, sun at 60° from zenith.

egarding Fig."12", the load impedance at maximum power transer (R_{mp})/temperature characteristics are represented graphiclly under the effect of the prementioned restrictions. The ollowing important features are noted:

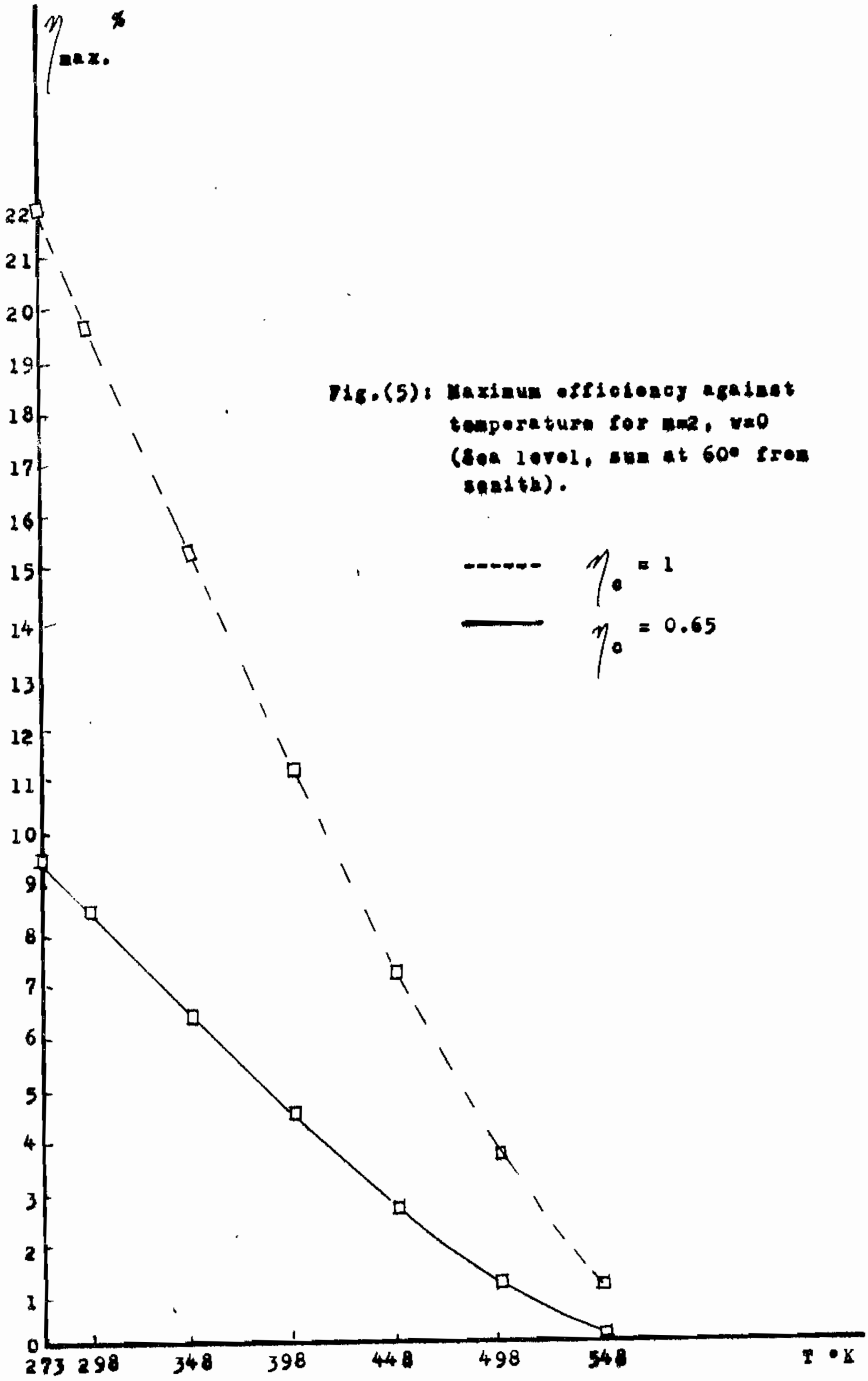


Fig.(5): Maximum efficiency against temperature for m=2, v=0 (Sea level, sun at 60° from zenith).

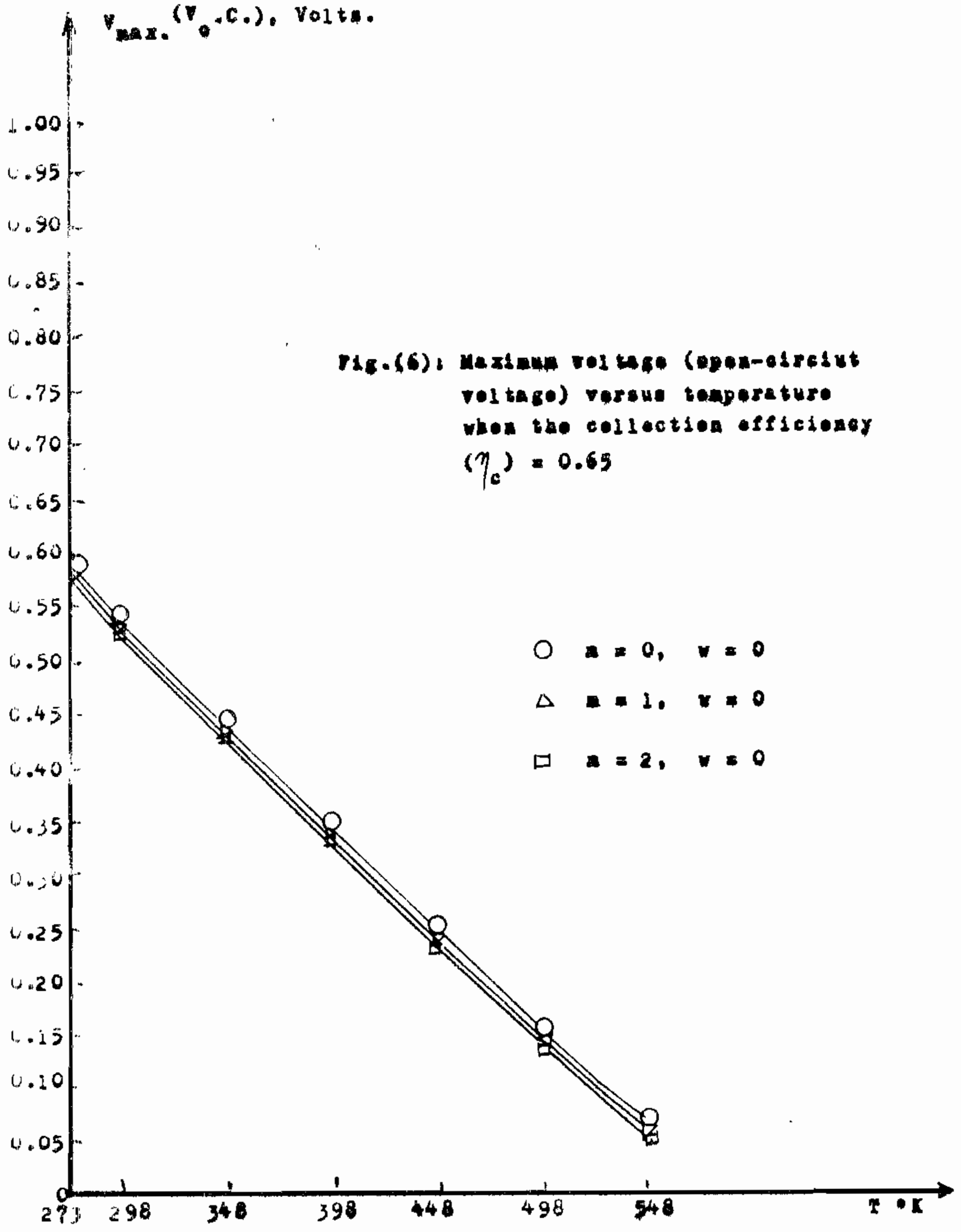


Fig.(6): Maximum voltage (open-circuit voltage) versus temperature when the collection efficiency (η_c) = 0.65

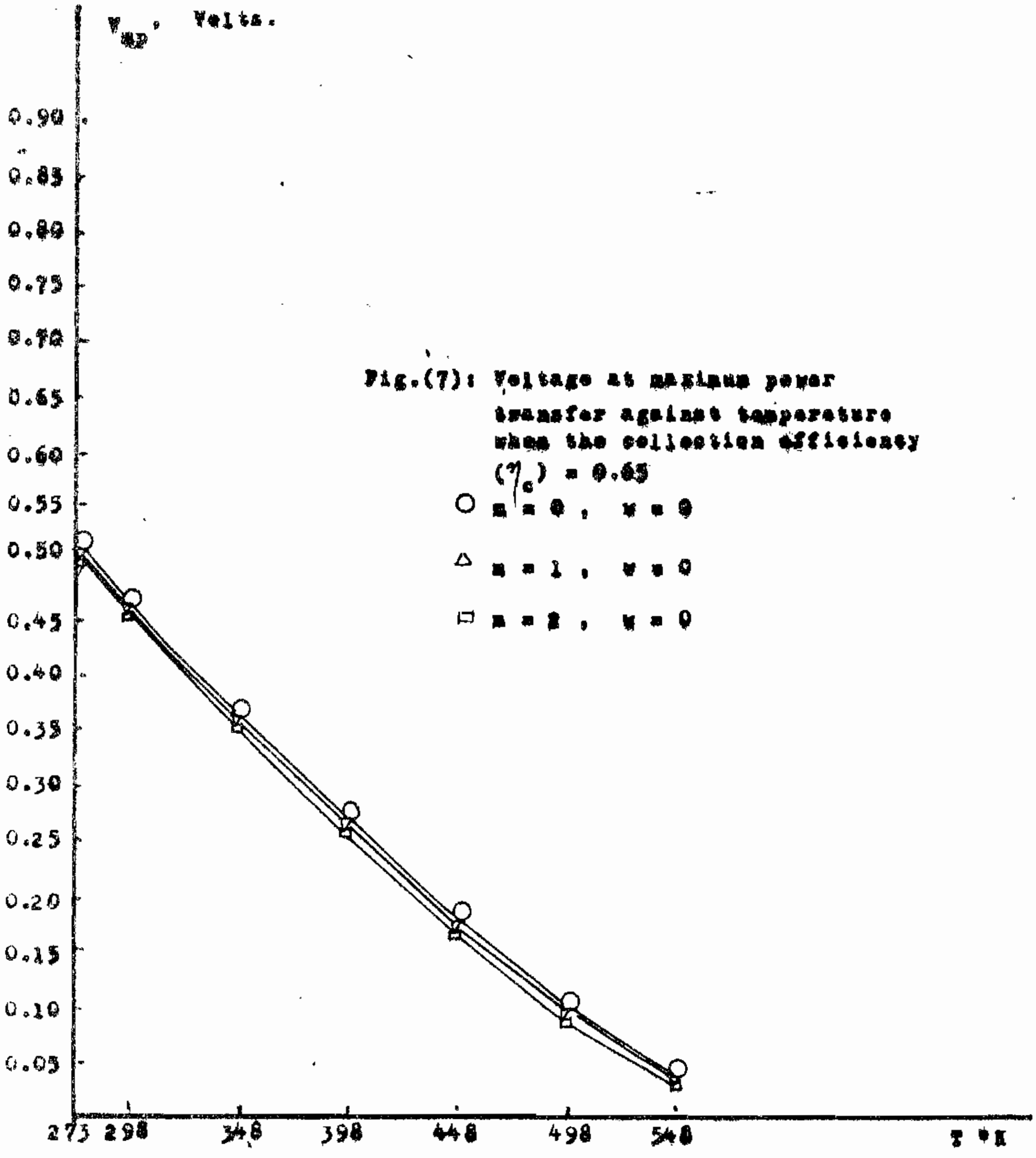


Fig.(7): Voltage at maximum power transfer against temperature when the collection efficiency (η_c) = 0.65

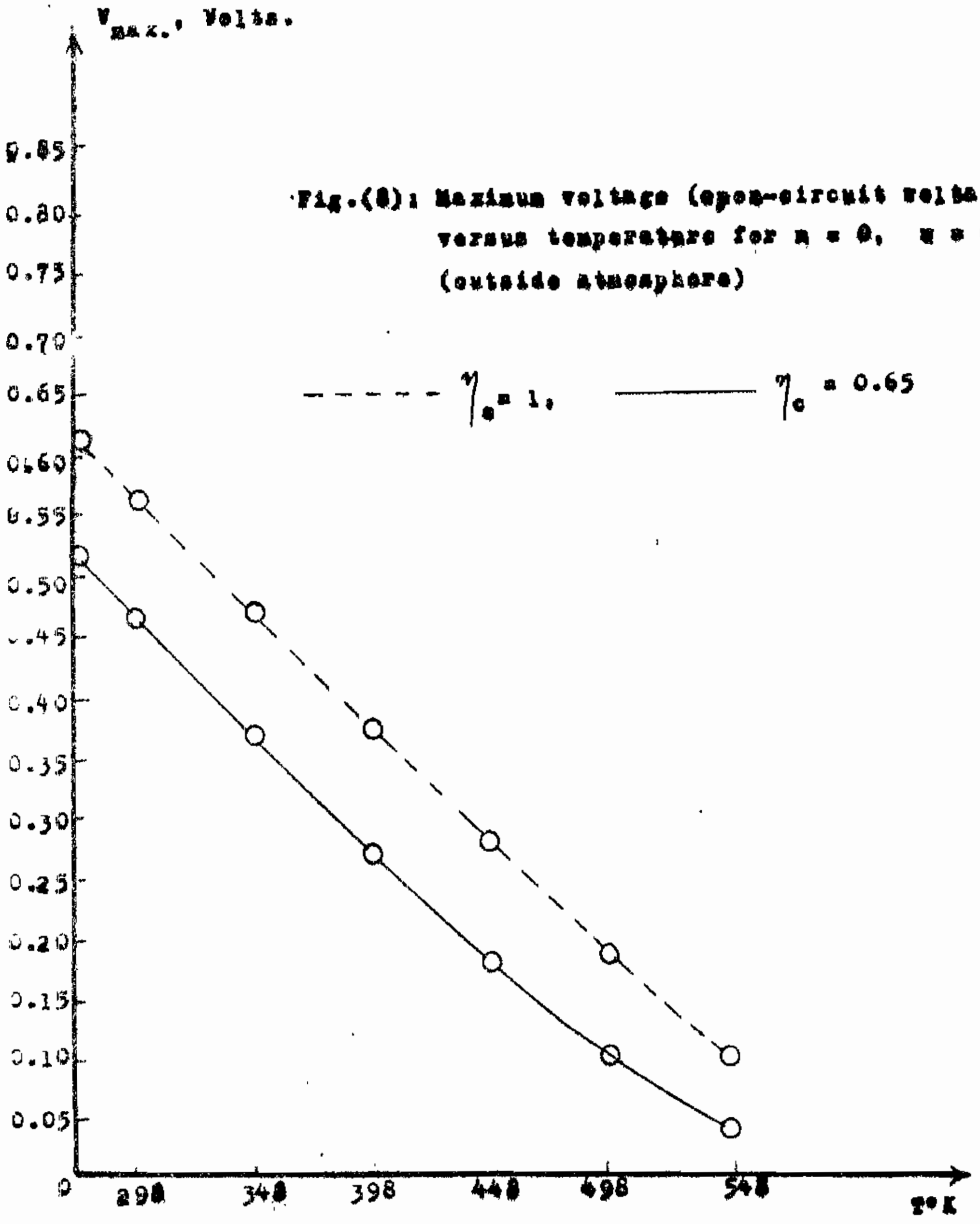


Fig.(8): Maximum voltage (open-circuit voltage) versus temperature for n = 0, u = 0 (outside atmosphere)

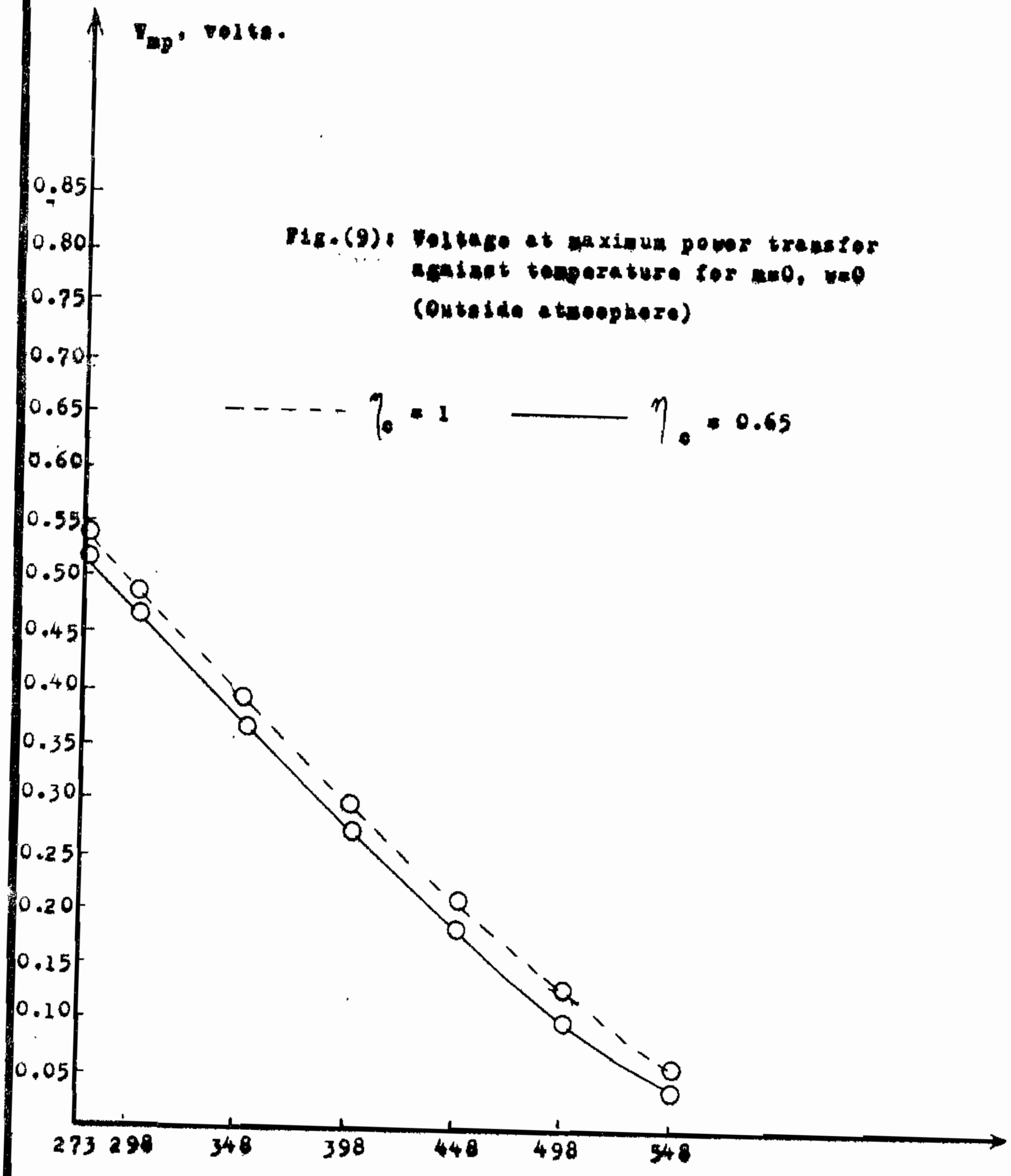


Fig.(9): Voltage at maximum power transfer against temperature for m=0, w=0 (Outside atmosphere)

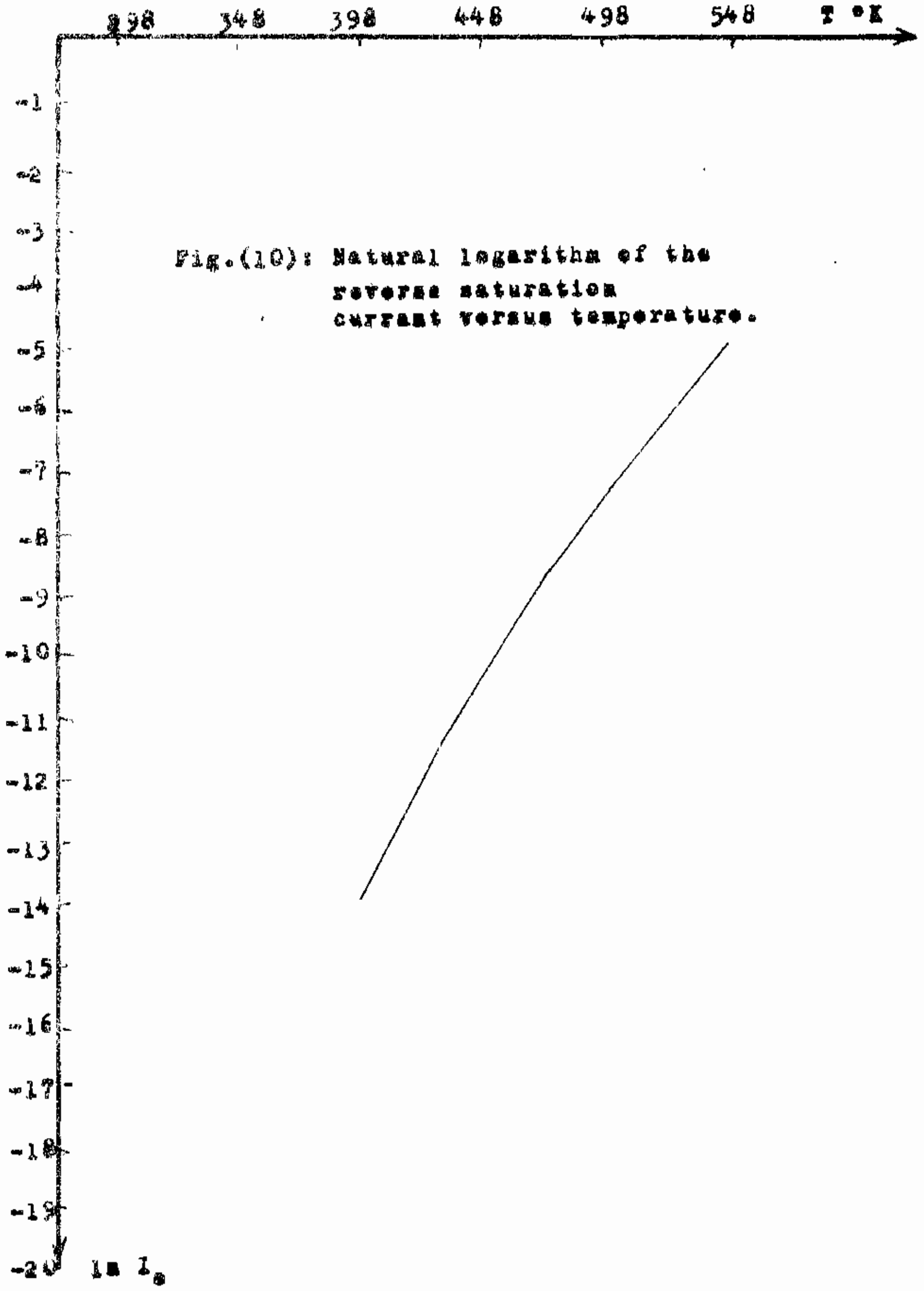


Fig.(10): Natural logarithm of the reverse saturation current versus temperature.

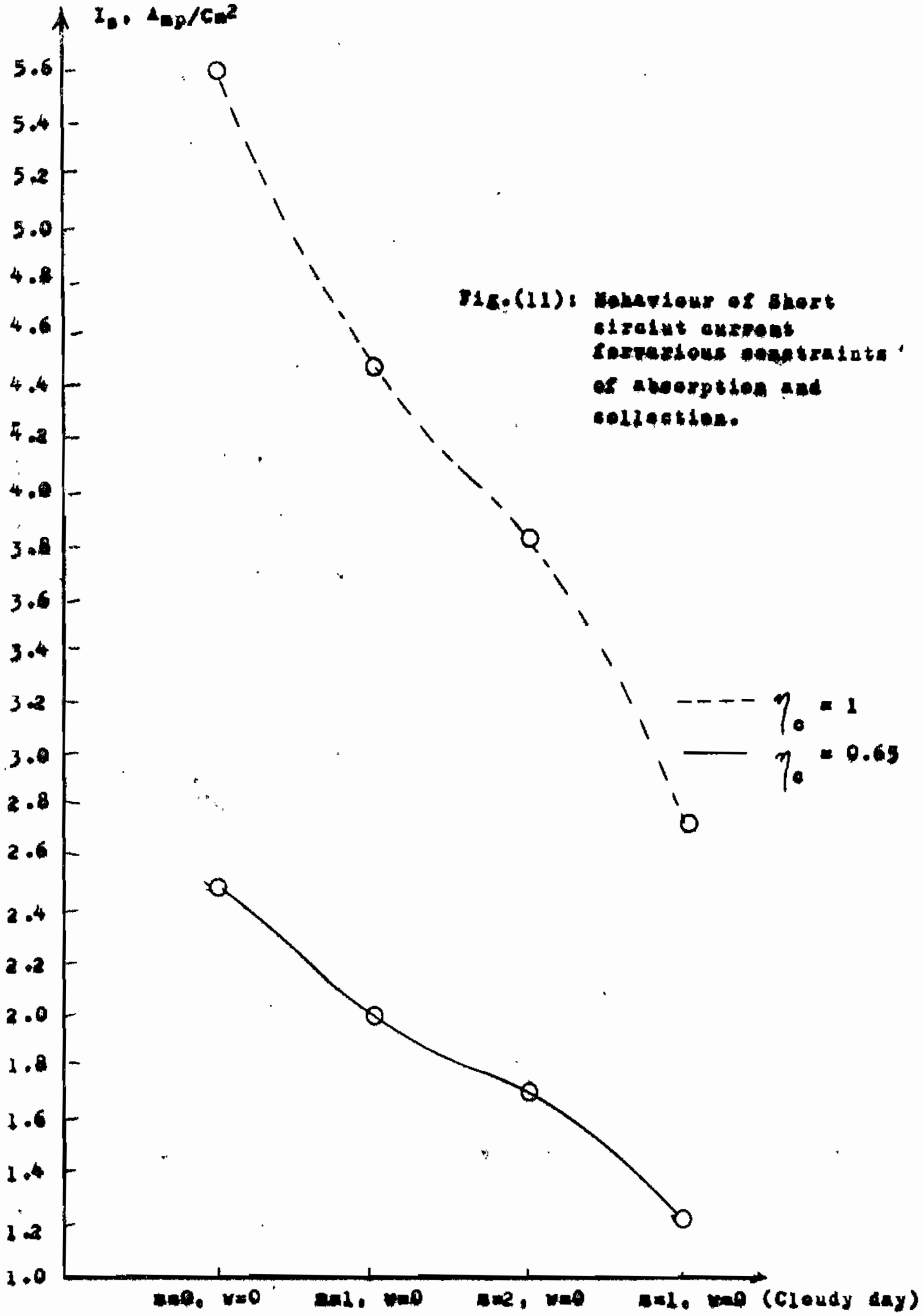


Fig.(11): Behaviour of Short circuit current forvarious constraints of absorption and collection.

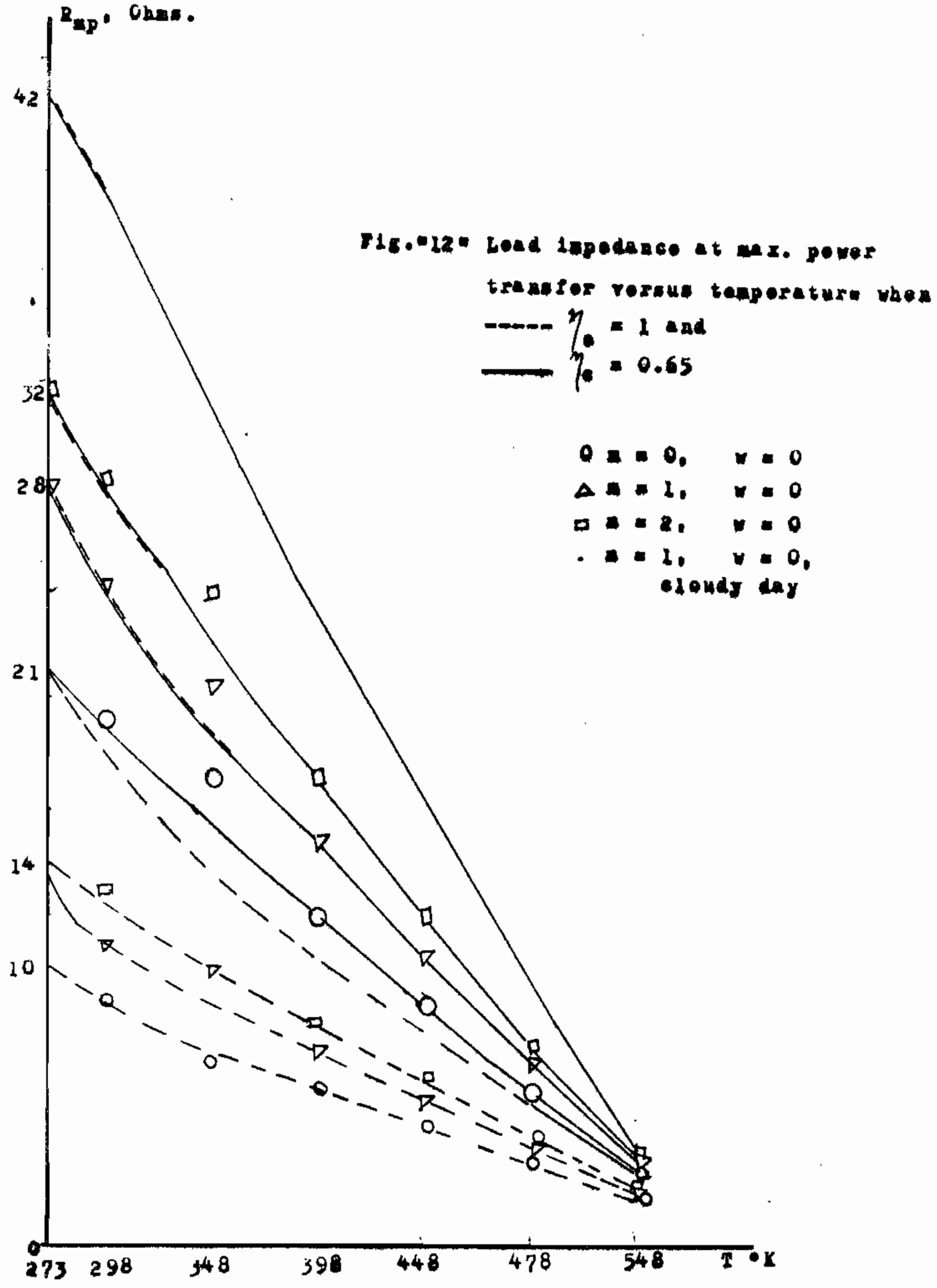


Fig."12" Load impedance at max. power transfer versus temperature when
----- η_e = 1 and
——— η_e = 0.65

1) R_{mp} drops gradually as the temperature increases and arrives the minimum on having T = 548°K, the upper limit of the temperature range. The max. rate of this drop belongs the constraints of m = 1, w = 0, cloudy day and η_c = 0.65 while the min. one is of the case of m = 0, w = 0 & η_c = 1. This can be ascribed by looking for the mathematical expression of R_{mp}. The effect of temperature on the numerator λI_o exceeds its effect on the denominator $(e - \lambda V_{mp})$. Consequently this influence is considerable on I_o where R_{mp} decreases as I_o increases with temperature.

2) All the characteristics of R_{mp}/T °K at η_c = 0.65 locate up to that belonging η_c = 1.

3) At any collection efficiency, the characteristic of m = 1, w = 0, cloudy day represents the highest R_{mp}/T °K one comparable with other constraints.

4) AT 548 °K, the maximum temperature of our option, R_{mp} has the same ohmic value approximately for certain η_c. Moreover, this value for both cases of collection efficiency is considered, as a rough approximation, the same. This leads to the fact that as the temperature of operating condition of S_i solar cell increases, a great convergence is attained between R_{mp} values for various conditions of m & w.

However, a great separation is obtained when the temperature arrives 273 °K.

4. CONCLUSIONS:

From the preceding analysis of the variables affecting the theoritical performance of silicon solar cell, we have the following conclusions:

1) Increasing the temperature leads to a considerable drop in the maximum efficiency.

2) Various atmospheric conditions does not influence the maximum efficiency/temperature characteristic when the collection efficiency (η_c) equals to one i.e. there is no reflection or recombination losses. This phenom enon is not fulfilled for the case of η_c = 0.65.

3) The maximum efficiency at the upper limit of temperature opted (548 °K) is independent of the atmospheric conditions (m & w).

4) The highest possible maximum efficiency occurs when m = 1 and w = 0 (Sea level and sun at Zenith) relative to other atmospheric conditions. This phenomenon is correct for any temperature.

5) The restriction of η_c = 1 results in max. efficiency having twice that corresponding to η_c = 0.65 for any temperature.

6) The open circuit voltage ($V_{max.}$) at any temperature has nearly the same value for different atmospheric conditions, that is, $V_{max.}$ has a weak response with respect to the atmospheric conditions. Moreover, $V_{max.}$ decays as the temperature increases.

7) For, V_{mp}, the voltage corresponding to the maximum power transfer, we have the same previous conclusion belonging to $V_{max.}$

8) The short-circuit current has higher values at $\eta_c = 1$ than that of $\eta_c = 0.65$. Also the restrictions of $m = 0$, $w = 0$ yield the highest short-circuit current at certain collection efficiency.

9) The load impedance at max. power transfer (R_{mp}) decays as the temperature increases.

0) As the temperature increases, a great convergence is attained between (R_{mp}) values for various atmospheric conditions (m & w).

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