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SOME OBSERVATIONS OF HEATED GALLIUM ARSENIDE HETEROFACE SOLAR CELLS

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ARSENIDE HETEROFACE SOLAR CELLS

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ABSTRACT

GaAℓAs/GaAs heteroface solar cells used in space offer advantages of higher operating temperatures and recovery from radiation damage using thermal annealing. Experiments were conducted to examine the effects on the room temperature photovoltaic properties of cells due to heating in a vacuum at temperatures encountered in radiation damage annealing. Some degradation of photovoltaic properties was observed for all the cells that were heated. The lifetime, due to heating, for a 20-percent degradation in output power was estimated for cells heated at 200° C and 400° C. The results for cells that were heated at 200° C for 1750 hours indicate a lifetime of at least 3 years. The results for cells that were heated at 400° C for 264 hours indicate that lifetimes in the range of 350 hours to 1400 hours may be expected. The results indicate that for cells that must be heated at 400° C the selection of fabrication techniques and materials is particularly important.

SUMMARY

Heteroface p-GaAℓAs/p-GaAs/n-GaAs solar cells were heated in a vacuum at 400° C for 266 hours and at 200° C for 1750 hours. Measurements were made, before and after heating, of photovoltaic properties for an illumination of one Sun equivalent. The photovoltaic properties measured were output power, short circuit current and open circuit voltage. Some supplementary measurements of leakage resistance, series resistance, and contact resistance were also made. The cells consisted of pieces of Langley fabricated cells with Cr/Au and Aℓ front contacts and pieces of a completed solar cell which was provided by Hughes Aircraft Company.

Based on the results of the measurements the following conclusions were reached.

<u>Concerning all of the cells</u>

Due to heating in a vacuum environment, at least two photovoltaic properties of each cell degraded.

<u>Concerning the cells heated to 400° C</u>

Assuming an extrapolation of the results to a 20-percent degradation of output power, the useful lifetime of the cells would be:

- About 2 to 24 hours for Langley cells with Cr/Au front contacts.
- About 350 hours for Langley cells with Aℓ front contacts.
- About 1400 hours for the Hughes cell.

<u>Concerning the cells heated to 200° C</u>

Excluding any long term adverse changes in leakage resistance or series resistance, the output power would probably not degrade more than 20 percent in 3 years due to heating at 200° C in a vacuum environment.

INTRODUCTION

GaAℓAs/GaAS heteroface solar cells used in space offer advantages of higher efficiency, particularly at high temperatures, and recovery from radiation damage using thermal annealing. Continuous operation between 200° C to 300° C may be required for solar concentration and near Sun missions. The ability to recover from radiation damage will be important in space, particularly for long-term missions. Electron radiation damage can be annealed in about 30 hours at 200° C.[1] Proton radiation damage can be annealed in periods of about 2 hours at 400° C.[2] In order to realize these advantages, it is necessary that the electrical properties of these solar cells do not degrade significantly due to heating in a vacuum environment.

The experiments presented here are part of an effort to examine the feasibility of developing a GaAs solar cell with a long useful lifetime at elevated temperatures. The objectives of these experiments were to examine the effects on the photovoltaic properties of cells heated at 200° C and 400° C in a vacuum. Photovoltaic properties studied were output power, short circuit current and open circuit voltage of the cells. These results were then used to estimate the probable useful lifetime associated with heating cells in a vacuum environment.

What constitutes a "long useful lifetime" depends on some specific application. For the purpose of discussion, the type of application, assumed, is a continuous electron damage annealing at 200° C with an occasional cycle to 400° C for about 2 hours to anneal out infrequent proton radiation damage. For operation at 200° C, a reasonable lifetime is stated in terms of the following question: Is it probable that 80 percent of the initial value of the photoelectric properties will remain after heating cells in a vacuum for 3 years at 200° C?

The two experiments consisted of heating cells in a vacuum and measuring their photovoltaic properties at room temperature in an atmospheric environment. One group of cells was heated to 400° C for a total of 266 hours and a second group of cells was heated to 200° C for a total of 1750 hours. The cells employed consisted of pieces of cells which were fabricated at Langley Research Center and pieces of a completed solar cell which was provided by Hughes Aircraft Company. Langley cells with Cr/Au and Aℓ front contacts were compared, since previous results, obtained for Langley cells heated to 400° C for 4 hours,[3] indicated that degradation of the open circuit voltage was significantly influenced by the choice of front contact metal.

SYMBOLS

I_{sc}	short circuit current, ma
J_{sc}	short circuit current density, ma/cm^2
P	output power density, mw/cm^2
R_{back}	resistance between back contacts, ohms
R_{front}	resistance between front contacts, ohms
$R_{leakage}$	leakage resistance, ohms
R_{series}	series resistance, ohms
Sun eqv.	an illumination which produces a short circuit current equivalent to an illumination of AMO.
AMO	illumination of the Sun at the Earth with no atmospheric absorption
V_{oc}	open circuit voltage, volts

APPARATUS AND PROCEDURE

Heteroface p-GaAℓAs/p-GaAs/n-GaAs cells were fabricated at Langley Research Center using the etch-back epitaxy process.[4] The GaAℓAs heteroface layers were 0.3 μm thick on single crystal GaAs substrates oriented 3° off the (100) orientation. The n-type substrates were Si-doped at 1-3 x 10^{17} carriers/cm^3, while the Zn-doped p-layers had a carrier concentration of approximately 8 x 10^{18} carriers/cm^3. The distance of the junction below the GaAℓAs/GaAs interface was 0.8 μm.

Both the front and back contacts were applied by R.F. sputtering. The contacts were about 0.4 μm thick. For three cells an argon R.F. etching step immediately preceded deposition of some of the contacts. The etching step removed about 0.03 μm in the region to be contacted. The back contacts were all Sn/Ag. The front contacts were either Cr/Au or Aℓ. Any alloying or processing of the contacts was done by heating in a vacuum. Since a common processing procedure was not employed, differences in processing will be discussed with the results. Pieces cleaved from these larger cells were used in the experiments. No antireflection coating was applied to these cells.

Six cells were obtained by cleaving a completed solar cell which was provided by Hughes Aircraft Company. Four of these cells were used to provide a reference for the illumination during measurements and two cells were heated in the experiments. The fabrication and characteristics of cells of this type are given in references 5 and 6. A few differences from the Langley cells used here are: a Be p-dopant, a Sn n-dopant, an epitaxially grown n layer, a (Au-Ge-Ni)Ag back contact, a (Au-Zn)Ag front contact, and an antireflection coating of TaO_x.

The cells were heated essentially in the dark in an open circuit condition. Heating was done in a vacuum at pressures between 10^{-7} to 10^{-6} torr. The cells rested in aluminum foil trays which were surrounded by an aluminum hearth. The temperature of the hearth was monitored by means of a thermocouple. Temperatures within the hearth were uniform to about 3° C.

Photovoltaic properties of the cells were measured at room temperature in an atmospheric environment after each heating cycle. The photovoltaic properties were open circuit voltage, short circuit current, and output power. Some supplementary measurements of leakage resistance, series resistance, and contact resistance were also made. Values of the properties were derived from dc voltage measurements. The essential apparatus consisted of digital voltmeters with input impedances greater than 10^9 ohms, calibrated resistors, a 1.5 volt battery, a thermocouple, a reference solar cell, and a tungsten lamp (type ELH) powered by a regulated dc supply. The lamp provided an illumination of about one Sun equivalent (equivalent short circuit current) when it was operated at about one half its rated input power. Neutral density filters were used to obtain repeatable reductions in illumination. A shutter was used to minimize the exposure of the cells. Electrical connections to the back contacts of the cells were made by resting the cells on a gold foil which was soldered to a brass plate. Connections to the front contacts were made by means of weighted gold wire probes. The temperature of the plate was monitored by means of a thermocouple.

Concerning the measured properties the following approximations or definitions were used. One Sun equivalent refers to the illumination, produced by the lamp, at the cell position. An illumination of one Sun equivalent produces the same short circuit current, for a reference cell, as would have been observed for an illumination of AMO. The accuracy of the implied comparison of short circuit currents is probably no better than about 5 percent. The short circuit current was assumed to be the current at a 1 ohm load for an illumination of 1 Sun equivalent and the current at 100 ohm load for an illumination of 0.0025 Sun equivalent. The output power was measured for a load equal to the open circuit voltage divided by the short circuit current. The leakage resistance was the apparent resistance (voltage/current) for an applied reverse bias of 1 volt with the cell in the dark. The illuminated area of the cells was used in deriving current and power densities. These areas were estimated from enlarged photographs of the cells. The illuminated areas encountered in these experiments ranged from 0.088 to 0.325 cm^2.

The results will be presented as two experiments. The first experiment considers cells that were heated at 400° C and the second experiment considers cells that were heated at 200° C. The procedure used to compensate for changes in room temperature and drifts in illumination was different for the two experiments.

Experiment I (cells heated at 400° C)

For the first experiment, measurements on the reference cell were interspersed with measurements on the heated cells. The measured values of the photovoltaic properties were corrected to a common temperature and illumination. Corrections, for differences in room temperature, were based on the observed temperature of the plate on which the cell rested and also the temperature coefficients given in reference 7. Corrections, for drifts in illumination, were based on interpolation of the observed short circuit current of the reference cell. The short circuit current of the reference cell was assumed to be stable during the experiment. Magnitudes of the applied corrections were approximately as follows. For the open circuit voltage the maximum correction was about 0.9 percent with an average correction of about 0.3 percent. For short circuit current and output power, the maximum correction was about 1.8 percent with an average correction of about 0.6 percent. The average corrections probably are comparable with the uncertainties inherent in the measurements.

The estimated uncertainties in the corrected values are about 0.1 percent for open circuit voltage, about 0.6 percent for short circuit current, and about 1 percent for output power. The estimated uncertainty in open circuit voltage is only due to uncertainties in illumination and cell temperature. Since measurements on the reference cell and the other cells were not simultaneous, the uncertainty in short circuit current could be at least as large as the average correction of 0.6 percent. The estimated uncertainty in output power is only due to uncertainty in illumination and uncertainty in load resistance setting of about 0.5 percent. The effects of non-uniformities in the light field have not been considered in these estimates of uncertainty.

Experiment II (cells heated at 200° C)

In the second experiment, the primary interest was to detect small changes in the photovoltaic properties. The apparatus was modified to allow for simultaneous measurements on two adjacent cells in the light field. Also, the uncertainty in load resistor setting was reduced to about 0.1 percent.

The following procedure was used in the measurements. In order to compensate for the effects of changes in room temperature and illumination, a photovoltaic property was measured simultaneously with a measurement of the same property of the reference cell. A single measured result for a given property was taken to be the ratio of the measured value to the corresponding value obtained for the reference cell. This procedure, including positioning of the cells in the light field, was repeated at least four times for each cell after each heating cycle.

In order to detect a change in a photovoltaic property, it is necessary to have some estimate of the degree to which a measurement can be repeated and some estimate of the stability of the apparatus and reference cell during the course of the experiment. Based on all of the measurements, the degree to which a single measurement could be repeated was approximately as follows: The average standard deviation was

- about 0.04 percent for the ratio of open circuit voltage
- about 0.22 percent for the ratio of short circuit current
- about 0.33 percent for the ratio of output power

The assumptions made concerning the long term stability of the apparatus and reference cell will be presented later with the results.

Since the purpose of this experiment was to detect possible changes in the photovoltaic properties due to heating, an attempt was made to minimize the exposure of the cells to an illumination of 1 Sun eqv. A cell was exposed for about 4 seconds during a measurement. When not in use the cells were stored in the dark. At the end of the experiment, the accumulated exposure at 1 Sun eqv. was about 0.15 hours for the cells and about 1.2 hours for the reference cell.

RESULTS AND DISCUSSION

Experiment I (cells heated at 400° C)

Results for cells heated to 400° C for a total of 266 hours are presented in figures 1 through 10. These cells consisted of three Langley cells with Cr/Au front contacts, four Langley cells with $A\ell$ front contacts, and one Hughes cell. The Hughes cell was introduced into the set after the first heating cycle of 2 hours. This piece of a fully-processed cell had previously been heated for 4 hours at 400° C.

For the Langley cells, the initial values shown in figures 1 through 10 are values observed after deposition of the contacts and cleaving of the cells with no further processing or alloying of the contacts. With the cells in this condition it was possible to measure the open circuit voltage and leakage resistance but without contact alloying significant or meaningful values of short circuit current and output power could not be obtained. The first heating cycle of 2 hours was the contact alloying step employed for these cells.

Figures 1, 2, and 3 show the output power density, the short circuit current density and the open circuit voltage observed after each heating cycle.

During the 264-hour period consisting of cycle 2 and cycle 3, the output power of the Hughes cell was degraded about 3.7 percent. About a 3.4-percent decrease in short circuit current was the dominant change associated with the decrease in output power of the Hughes cell. A decrease in open circuit voltage of about 0.3 percent was observed for the same period. Extrapolation of the results to a 20-percent decrease in output power would yield a useful lifetime of about 1400 hours for the Hughes cell at 400° C.

Concerning the Langley cells, values of output power density greater than 10 mw/cm^2 will be assumed to be useful values. Useful values were observed for two cells with Cr/Au front contacts and for two cells with $A\ell$ front contacts. However, the trends for the two contacts differ. The largest values of output power density were observed for two cells with Cr/Au front contacts after 2 hours but after the third cycle the lowest values were observed for these two cells. One of these cells maintained a useful value for at least 26 hours. After the third cycle values of output power density for two cells with $A\ell$ contacts were within a factor of about 0.85 of the largest values observed for the cells with Cr/Au contacts. These results suggest that by employing $A\ell$ front contacts it should be possible to construct cells for which the output power would not degrade more than about 15 percent due to heating to 400° C for 264 hours.

For a 20 percent decrease in output power, estimated useful lifetimes for the Langley cells would be about 350 hours for cells with $A\ell$ front contacts and between 2 to 26 hours for cells with Cr/Au front contacts. However, one cell with a Cr/Au front contact survived for 26 hours but failed sometime during the next 240 hours of cycle 3.

The results for short circuit current density, figure 2, indicate some degrading for all of the cells. Except for one cell, with a Cr/Au contact, a large change in output power would not be anticipated due to the trends observed in short circuit current. Except for one cell, the decreases in short circuit current in a period of 264 hours can be included in a range of about 4 to 10 percent.

The results for open circuit voltage, figure 3, indicate some degrading for all of the cells.

For the cells with Aℓ contacts and a heating period of 264 hours, decreases in open circuit voltage in the range of 3 to 7 percent were observed. The final values for the four cells were distributed in a narrow range about an average value of 0.9 volts. For a Langley fabricated cell with an Aℓ front contact, a degrading of output power of about 11 percent might be expected due to a degradation of 7 percent in open circuit voltage and 4 percent in short circuit current as a result of heating at 400° C for 264 hours.

For the cells with Cr/Au front contacts, a reasonable value of open circuit voltage was observed for one cell after 26 hours. After 266 hours the open circuit voltage of all these cells degraded to values which were widely dispersed and significantly lower than for cells with Aℓ contacts. For cells with Cr/Au front contacts degrading of the open circuit voltage appears to be the dominant change associated with the degrading of the output power shown in figure 1. The large dispersion of values of open circuit voltage suggests that the degrading mechanism may be spacially localized and influence the open circuit voltage in a random manner with heating time.

Figure 4 shows the values of leakage resistance observed after successive cycles to 400° C. A decrease in leakage resistance with heating was observed for all the cells but the trends did not indicate a uniform rate or monotone behavior. The trends for some of the cells suggest an approach to a stable value. After 266 hours a large dispersion of values existed with the smallest values observed for cells with Cr/Au front contacts and the largest values observed for cells with Aℓ front contacts and also the Hughes cell.

Figure 5 shows a comparison, for the Langley cells, of the open circuit voltage values presented in figure 3 and the corresponding values of leakage resistance presented in figure 4. Also shown by the solid line in the figure is the trend obtained by measuring the output voltage of a Hughes cell which was shunted by external resistors. These results indicate a significant difference in the relationship of the leakage resistance and the open circuit voltage between the cells with Aℓ contacts and the cells with Cr/Au contacts. Cells with Aℓ contacts appear to follow the trend for an ohmic shunt. For the cells with Cr/Au contacts, the decreases in open circuit voltage are larger than could be obtained by ohmic shunting alone. The difference in trends between cells with Cr/Au and Aℓ contacts appears to depend on the level of illumination. Figure 6 shows a comparison for the same cells with the open circuit voltage observed at a lower level of illumination. A difference in trends between cells with Cr/Au or Aℓ contacts is not distinguishable at this level of illumination.

Shown in figure 7 are the leakage resistances observed for cells heated to 400° C for 266 hours and another set of cells which were heated to 250° C for 265 hours and then heated to 325° C for 265 hours. Decreases in leakage resistance are only apparent for cells heated at 325° C and 400° C. The larger decreases are associated with the cells with Cr/Au front contacts. The apparent trend with temperature suggests that a decrease in leakage resistance due to heating may not be a serious problem for cells heated to less than 250° C.

Figures 8 and 9 show the open circuit voltages, corresponding to figure 7, for two levels of illumination. For the cells heated to 325° C, a decrease in open circuit voltage is only apparent in figure 9 for the lower level of illumination for which the open circuit voltage is more sensitive to the presence of shunt resistance.

As shown in figure 10, except for one cell with a Cr/Au front contact which degraded by 38 percent, the decreases in short circuit current in a period of 264 hours can be included in a range of about 4 to 10 percent, for the cells heated at 400° C. Also shown in the figure are results obtained for two different sets of cells which were heated for comparable periods but at lower temperatures. A decrease in short circuit current was observed for all of the Langley cells that were heated in a vacuum. The loss decreased significantly with a decrease in temperature. For a temperature of 200° C the loss was probably less than one percent and approaches the uncertainty in making the measurements.

For the results shown in figure 10 at 400° C, two of the $A\ell$ front contact cells have values comparable with the value observed for the Hughes cell. These results are somewhat surprising since the Langley cells have a more volatile and mobile p-dopant and no antireflection covering. This suggests that the degrading of the short circuit current, observed here, may be independent of the type of p-dopant and the use of an antireflection coating. Another possibility is that the antireflection coating may be degrading.

<u>Other observations</u>

During the third heating cycle at 400° C, the color of the Cr/Au front contacts changed from gold to silver for two of the cells. These two cells exhibited the largest output power density after the first 2 hours of heating. A color transition from gold to silver for gold films on GaAs substrates which were heated has been reported in reference 8. It was suggested that the silver color might be due to the color of Au-Ga compounds and it was shown that the transition temperature depended on the film thickness and the ambient pressure. For a film thickness of 0.275 μm and a pressure of 10^{-6} torr the color transition occurred at a temperature of 400° C in about 5 minutes.

A change in color was not observed for the Aℓ front contacts or the Hughes front contact which all remained silver colored.

Experiment II (cells heated at 200° C)

The remainder of this paper will be directed toward presenting the results observed for seven cells that were heated in a vacuum at 200° C in three cycles for a total of 1750 hours (about 6.6 percent of 3 years).

The primary objective in these measurements was to detect small changes in the photovoltaic properties. The photovoltaic results are presented as ratios to an initial value, that is as fractions of an initial value. Flags on the symbol of an individual cell reflect only the propagated uncertainty estimated from repeated measurements of a property. The uncertainty is not indicated when it lies within the dimensions of a symbol. As an aid in presenting the photovoltaic results, a dashed line indicates the value of an exponential function which eventually degrades to zero but has a value of 0.8 after 3 years.

Some initial conditions for the 11 cells used in the experiment are shown in table I. Seven cells were heated, one unheated cell was used as a reference cell, and measurements were made on three unheated cells as a check on the stability of the apparatus and reference cell.

Figure 11 shows the results for the three unheated Hughes cells. These results determine the limit of accuracy of the experiment if it is assumed that the photovoltaic properties of the three cells are stable at room temperature. The limit for measurements of open circuit voltage was about 0.1 percent, short circuit current about 0.2 percent, and output power about 0.5 percent. Since the results for the unheated cells meet the criterion that they are not decaying at a rapid enough rate so as to fall below 0.8 in 3 years, as shown by the dotted line, it will be assumed that during the experiment the apparatus and reference cell were stable enough to determine if changes due to heating would meet the same criterion.

Results, for the heated cells, of the measured open circuit voltage, short circuit current, and output power are shown in the upper part of figures 12, 13, and 14. After 1750 hours at 200° C, a degrading of at least two of the three photovoltaic properties was observed for all seven cells. The largest change observed for each property was about 1.6 percent in open circuit voltage, about 2.6 percent in short circuit current, and about 6.5 percent in output power. The second largest change in output power, of about 4 percent, may be more meaningful, since other measurements indicated that the back contact of the cell showing the largest change in output power was deteriorating significantly.

After the first and second cycles only two cells come close to meeting the exponential criterion for all three photovoltaic properties. These two cells, represented by the square and rotated square symbols, had been heated to 400° C for 266 hours prior to this experiment. After the third cycle (1750 hours) five cells come close to meeting the criterion for the three properties and six cells nearly meet the criterion for open circuit voltage and short circuit current. These results suggest that, during the course of the experiment, the change in fractional value per unit time decreased with time as compared to the exponential function for which the change in fractional value per unit time is constant. For example, if the first 750 hours was assumed to be a processing step and only the change occurring in the last 1000 hours were considered (as assumed in the lower part of figures 12, 13, and 14), then six cells meet the criterion for output power and all seven cells meet the criterion for open circuit voltage and short circuit current.

Figure 15 shows the average fractional value for the five cells which meet the criterion for output power after 1750 hours. Figure 16 shows the average fractional value for the six cells which meet the criterion for output power when only the last 1000 hours is considered. During the 1750 hour period, the changes in output power appear to be most closely associated with changes in short circuit current in the early portion of the period and most closely associated with changes in open circuit voltage in the later portion of the period. This transition may be easier to see in figure 16 where the results have been normalized after cycle 0, cycle 1, and cycle 2, that is, after the cells had been heated for 0, 249, and 750 hours.

If it is assumed that the rate of decrease of the output power becomes stable at a rate consistent with the changes observed for the last cycle, then it appears probable that the output power would not degrade more than 20 percent due to heating the cells at 200° C for 3 years in a vacuum environment. It is also necessary to assume that no significantly adverse changes in leakage resistance or series resistance of the cells will occur in 3 years since other measurements, on the five cells represented in figure 15, indicate that the observed changes in the photovoltaic properties are not significantly associated with observed changes in leakage resistance or series resistance of these five cells.

Figure 17 shows the leakage resistance observed after each cycle. The changes in leakage resistance indicated in figure 17 would not be observable as changes in open circuit voltage for an illumination of 1 Sun eqv. For the cell (represented by the quarter circle symbol) with the lowest value of leakage resistance, the changes in leakage resistance are observable as changes in open circuit voltage at a lower level of illumination, as shown in figure 18. Except for this cell, none of the other changes in open circuit voltage indicated in figure 18 can be related to changes in leakage resistance. At this lower level of illumination, the most stable open circuit voltages were observed for the two cells (represented by the square and rotated square symbols) that had previously been heated to 400° C for 266 hours.

Figure 19 shows the results for short circuit current observed at a lower level of illumination. After 1750 hours all seven cells meet the exponential criterion. The general trend of the results is essentially the same as was observed for an illumination of 1 Sun eqv.

Figure 20 shows the series resistance estimated after each cycle, using the method described in reference 9. With the possible exception of the cells represented by the right triangle and quarter circle symbols, the observed changes in short circuit current and output power cannot be accounted for by relation to changes in these estimates of series resistance. This statement is based on the stability of the estimated series resistances, not on the apparent values of series resistance obtained by this method. This method requires a reversal of the direction of current through the cell contacts and assumes that the connection to the cell surface is ohmic (not rectifying). To some degree, most metallic connections to a semiconductor are (rectifying) not ohmic. The degree to which the values of series resistance, shown in figure 20, represent the operating series resistance of the cells is not known at this time.

A change in short circuit current at an illumination of 1 Sun, which is due to a change in series resistance with heating, should be reflected as a comparable change in the ratio of the short circuit current at 1 Sun to the short circuit current at a significantly lower level of illumination. Figure 21 shows the ratio of the short circuit current at 1 Sun eqv. to the short circuit current at 0.0025 Sun eqv. after each cycle. Figure 22 compares the results averaged for all seven cells to the normalized average 1 Sun values. Figure 23 compares the results averaged for the five cells which met the exponential criterion for output power after 1750 hours to the average fractional short circuit currents for the same five cells. These comparisons indicate that the changes in series resistance are not sufficient to account for the observed changes in short circuit current at 1 Sun eqv.

The observed change in short circuit current is probably related to some mechanism other than a change in series resistance, say, for example, a change in the optical properties of the cell surface due to heating in a vacuum.

Three of the cells had a pair of back contacts and a pair of front contacts. Figure 24 shows the resistance between the two back contacts and the resistance between the two front contacts after each cycle.

Concerning the results for the back contacts and their possible association with the results for short circuit current and output power: No change in photovoltaic properties would be expected, for the cell represented by the triangle symbol. For the other two cells the increasing resistance indicates that at least one of the contacts in the pair is deteriorating. If only one contact in the pair deteriorated, then no change in photovoltaic properties would be expected. Considering the maximum possible change in series resistance due to deterioration of these back contacts, the estimated associated decrease in output power observed after the third cycle would be about 1 percent for the cell represented by the quarter circle symbol and about 4 percent for the cell represented by the right triangle symbol.

The cells represented by the right triangle and quarter circle symbols did not meet the criterion for output power after 1750 hours (figure 14), whereas, only the cell represented by the quarter circle did not meet the criterion for short circuit current (figure 13).

The results, shown in figure 24, for the resistance between the front pair of contacts indicate a possible decrease in resistance of the contacts to the surface, a possible decrease in resistance of the p-layers or both. The observed decreases in short circuit and output power are not expected to be associated with the changes observed in the resistance of the front pairs of contacts.

CONCLUDING REMARKS

Heteroface p-GaAℓAs/p-GaAs/n-GaAs solar cells were heated in a vacuum at 400° C for 266 hours and at 200° C for 1750 hours. Measurements were made, before and after heating, of photovoltaic properties for an illumination of one Sun equivalent. The photovoltaic properties measured were output power, short circuit current, and open circuit voltage. Some supplementary measurements of leakage resistance, series resistance, and contact resistance were also made. The cells consisted of pieces of Langley fabricated cells with Cr/Au and Aℓ front contacts and pieces of a completed solar cell which was provided by Hughes Aircraft Company.

Based on the results of the measurements the following conclusions were reached.

<u>Concerning all of the cells</u>

Due to heating in a vacuum environment, at least two photovoltaic properties of each cell degraded.

<u>Concerning the cells heated to 400° C</u>

Assuming an extrapolation of the results to a 20 percent degradation of output power, the useful lifetime of the cells would be:

- About 2 to 24 hours for Langley cells with Cr/Au front contacts.
- About 350 hours for Langley cells with Aℓ front contacts.
- About 1400 hours for the Hughes cell.

The dominant changes associated with degrading of the output power appear to be:

- A decrease in both open circuit voltage and leakage resistance for the Langley cells.
- A decrease in short circuit current for the Hughes cell.

Comparable degradation of short circuit current was observed for both the Hughes cell and Langley cells.

The relationship between the open circuit voltage and leakage resistance differs significantly for Langley cells with Cr/Au front contacts and Aℓ front contacts. For cells with Cr/Au front contacts, the observed changes in open circuit voltage are larger than can be attributed to ohmic shunting alone.

Concerning the effect of temperature in the range 200° C to 400° C

For comparable heating periods, the resultant changes in short circuit current, open circuit voltage, and leakage resistance are shown to be reduced by a decrease in temperature.

Concerning the cells heated to 200° C

Excluding any long term adverse changes in leakage resistance or series resistance, the output power would probably not degrade more than 20 percent in 3 years due to heating at 200° C in a vacuum environment.

During the 1750 hour heating period, the dominant changes associated with degrading of the output power appeared to be changes in short circuit current in the early portion of the period and changes in open circuit voltage in the later portion of the period.

The observed changes in open circuit voltage and short circuit current are larger than can be attributed to the observed changes of leakage resistance and series resistance.

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TABLE I.- INITIAL VALUES FOR CELLS USED IN 200 °C HEATING EXPERIMENT

Illumination 1 Sun eqv.
Temperature 22 °C

Plotting symbol	V_{oc} (volts)	J_{sc} (ma/cm^2)	P (mw/cm^2)	Front contact	Prior heating temperature, time
○	.9972	32.4	24.9	Hughes	- -
□	.9588	33.3	23.5	Hughes	400 °C, 266 hrs
◇	.8989	22.2	13.3	Al	400 °C, 266 hrs
△	.9781	22.8	14.0	Al	450 °C, 0.2 hrs 400 °C, 1.7 hrs
◺	.9659	24.1	15.1	Al	400 °C, 24 hrs
◗	.9341	19.0	11.3	Al	400 °C, 24 hrs
⌓	.9626	23.4	14.8	Cr/Au	250 °C, 265 hrs 325 °C, 265 hrs
⬡	.9880	32.4	24.4	Hughes	- -
◊	1.0002	32.1	-	Hughes	- -
⌂	.9564	32.3	-	Hughes	- -
Reference	.9786	32.1	22.8	Hughes	- -

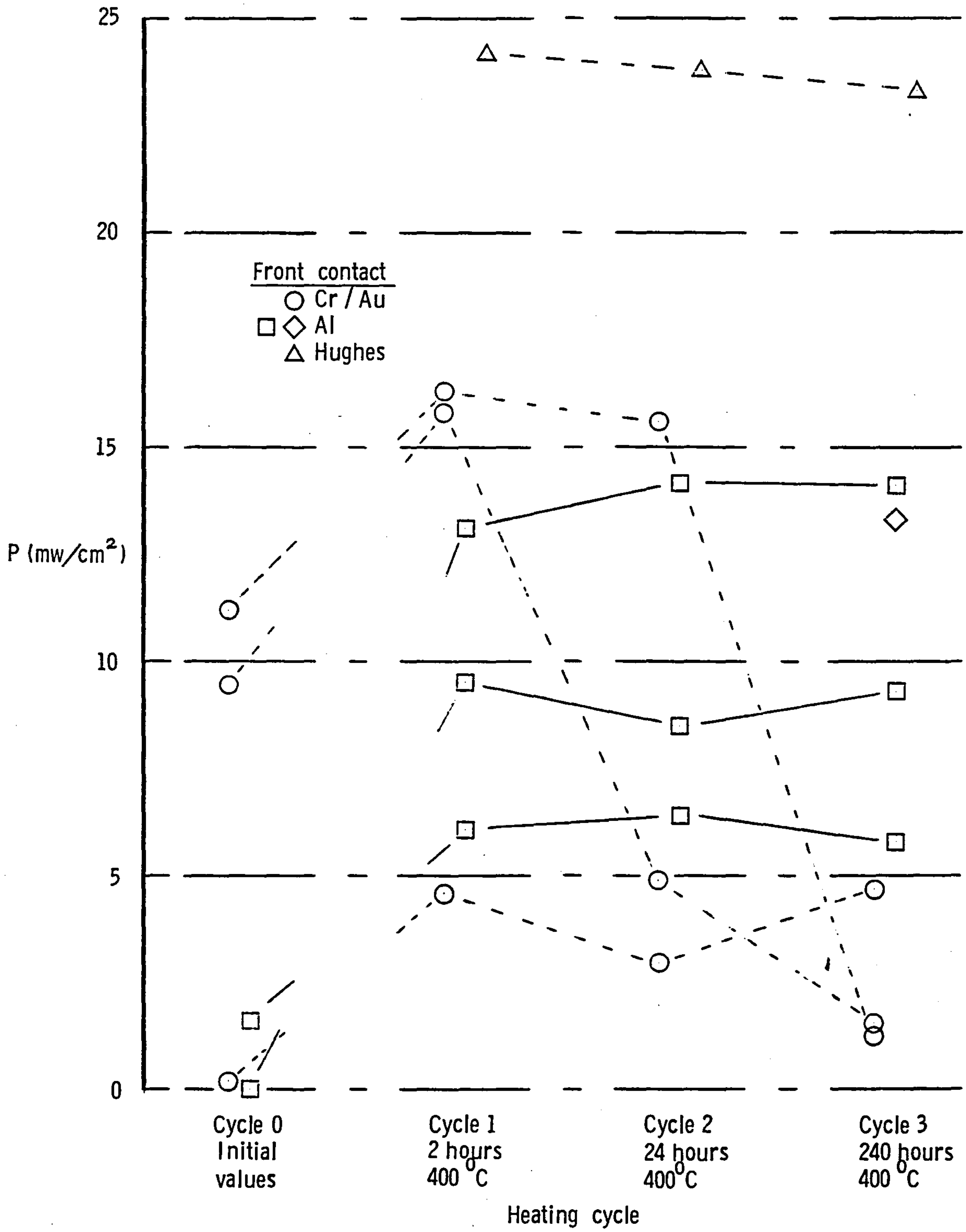

Figure 1.- Output power density at 1 Sun eqv. and 21°C after successive heating cycles.

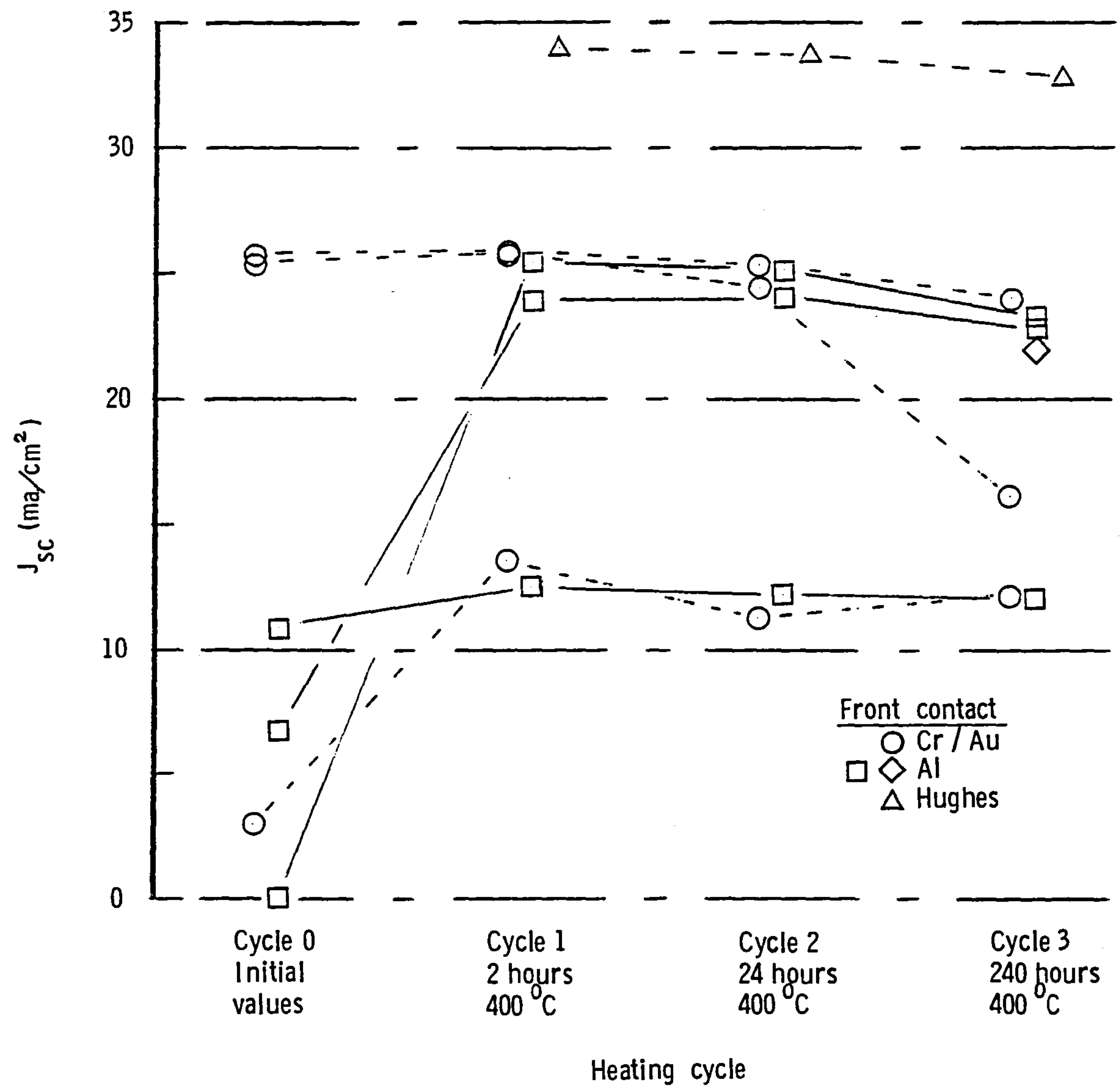

Figure 2.- Short circuit current density at 1 Sun eqv. and 21°C after successive heating cycles.

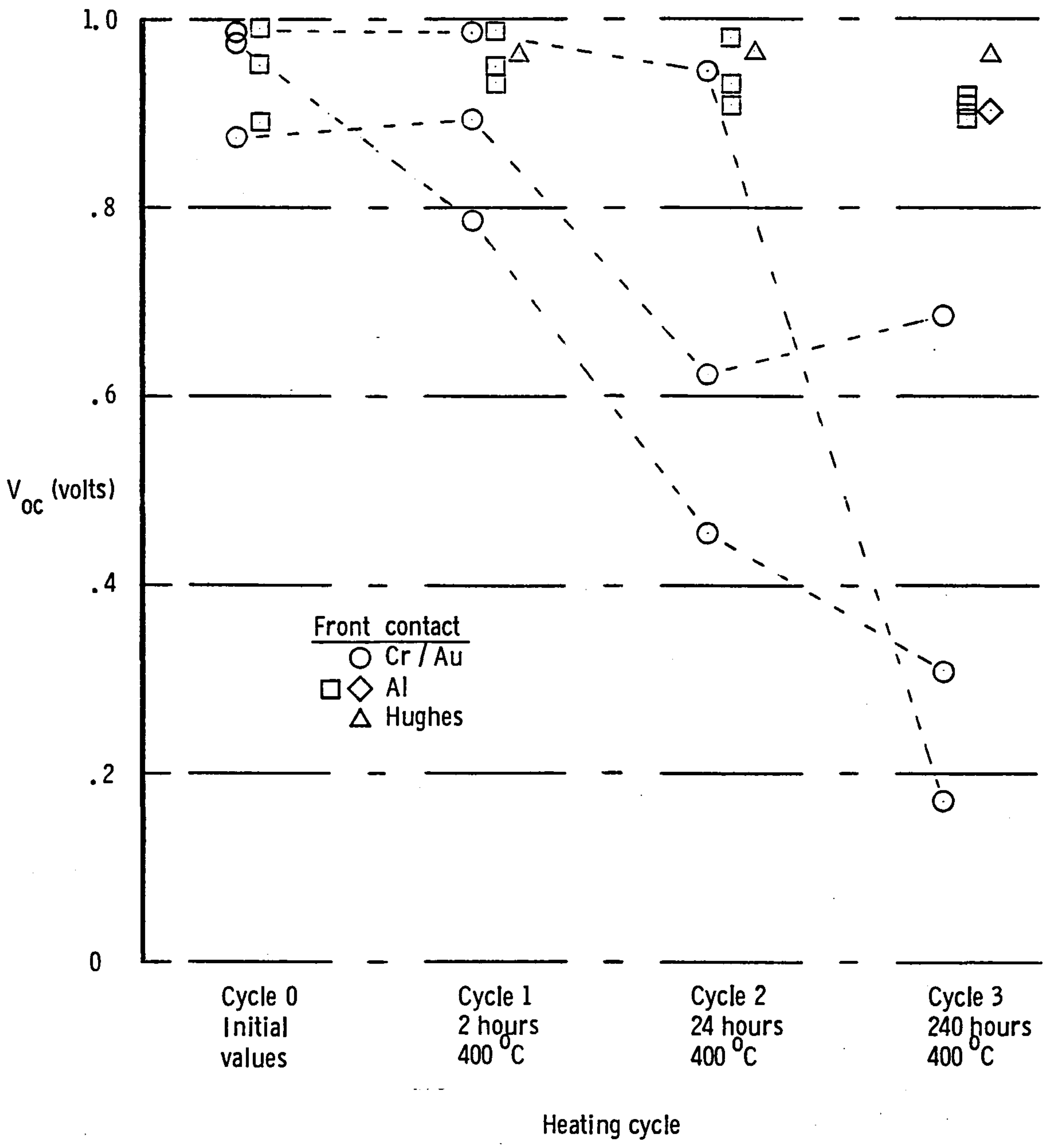

Figure 3.- Open circuit voltage at 1 Sun eqv. and 21°C after successive heating cycles.

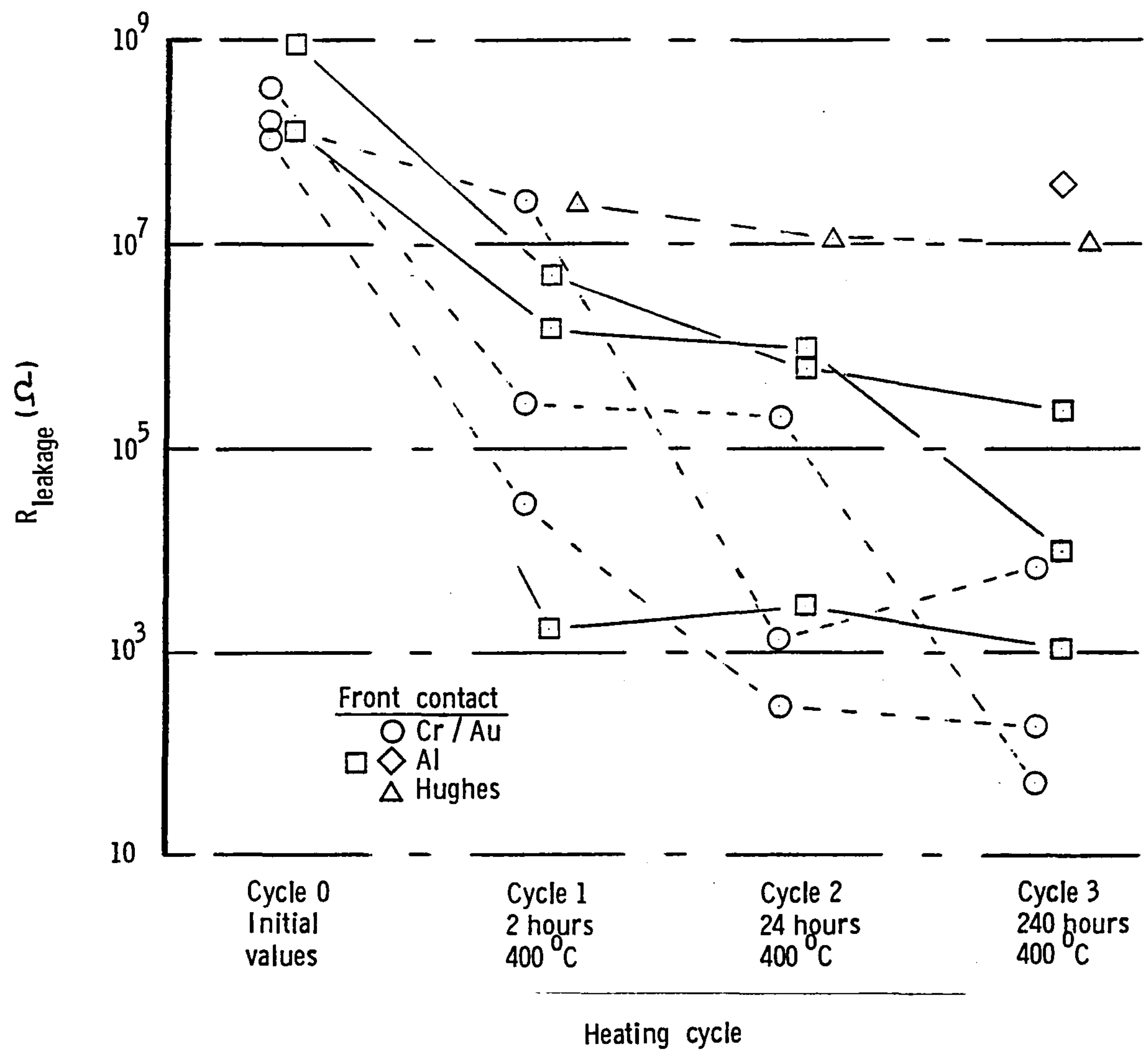

Figure 4.- Leakage resistance after successive heating cycles.

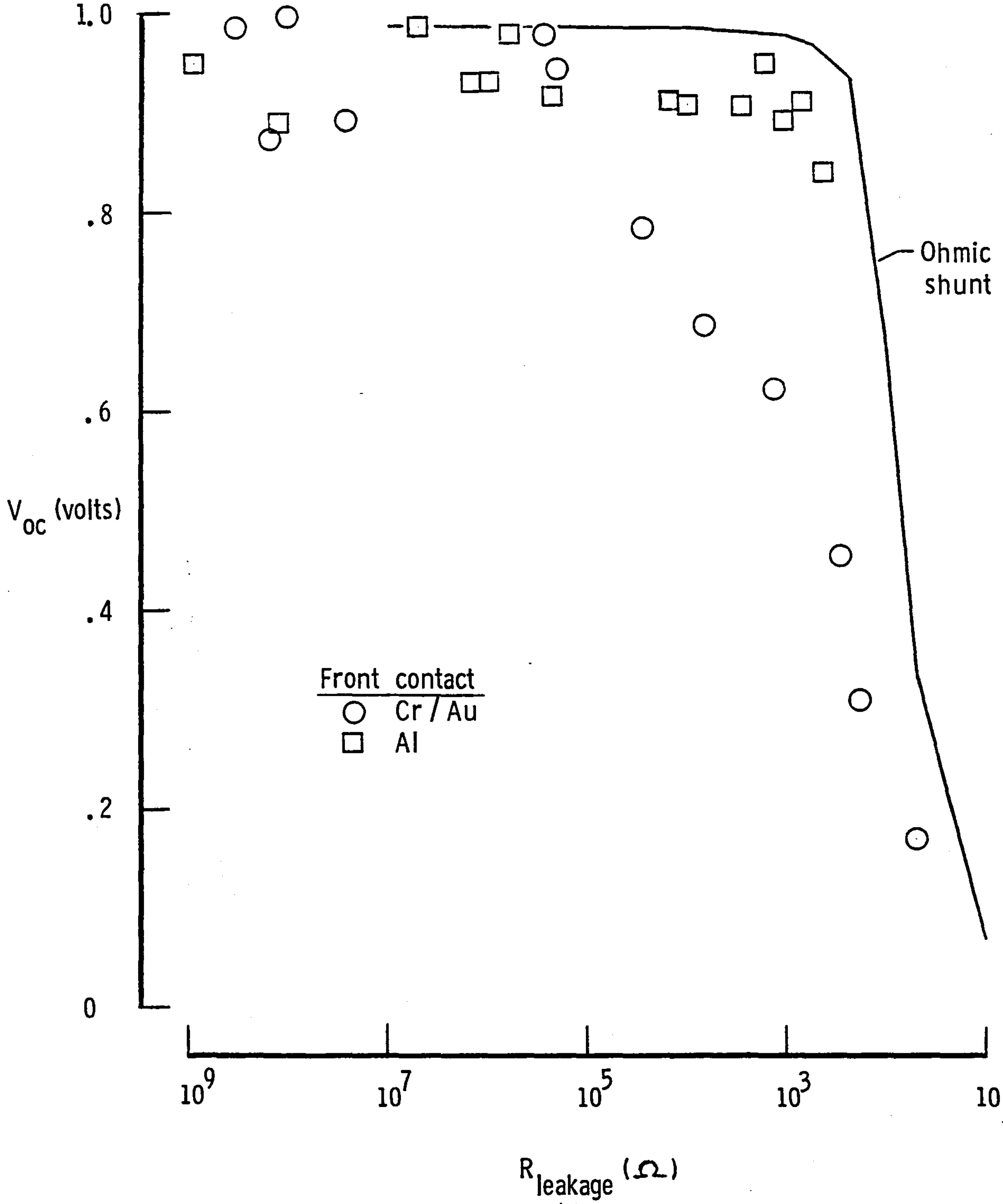

Figure 5.- Open circuit voltage at 1 Sun eqv. and 21°C versus leakage resistance. Solid line indicates the trend for a cell with an external ohmic shunt.

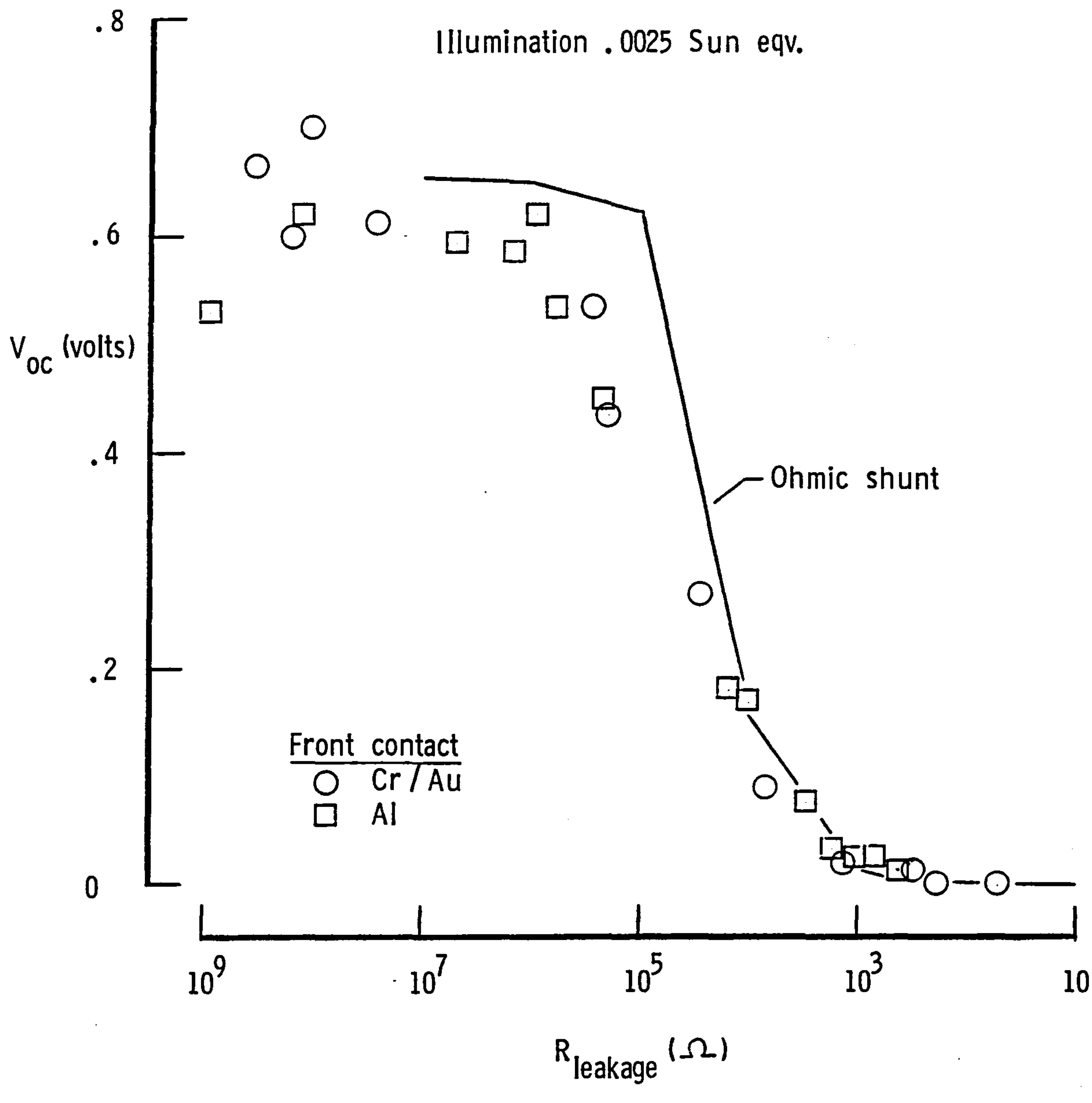

Figure 6.- Open circuit voltage at .0025 Sun eqv. and 21°C versus leakage resistance. Solid line indicates the trend for a cell with an external ohmic shunt.

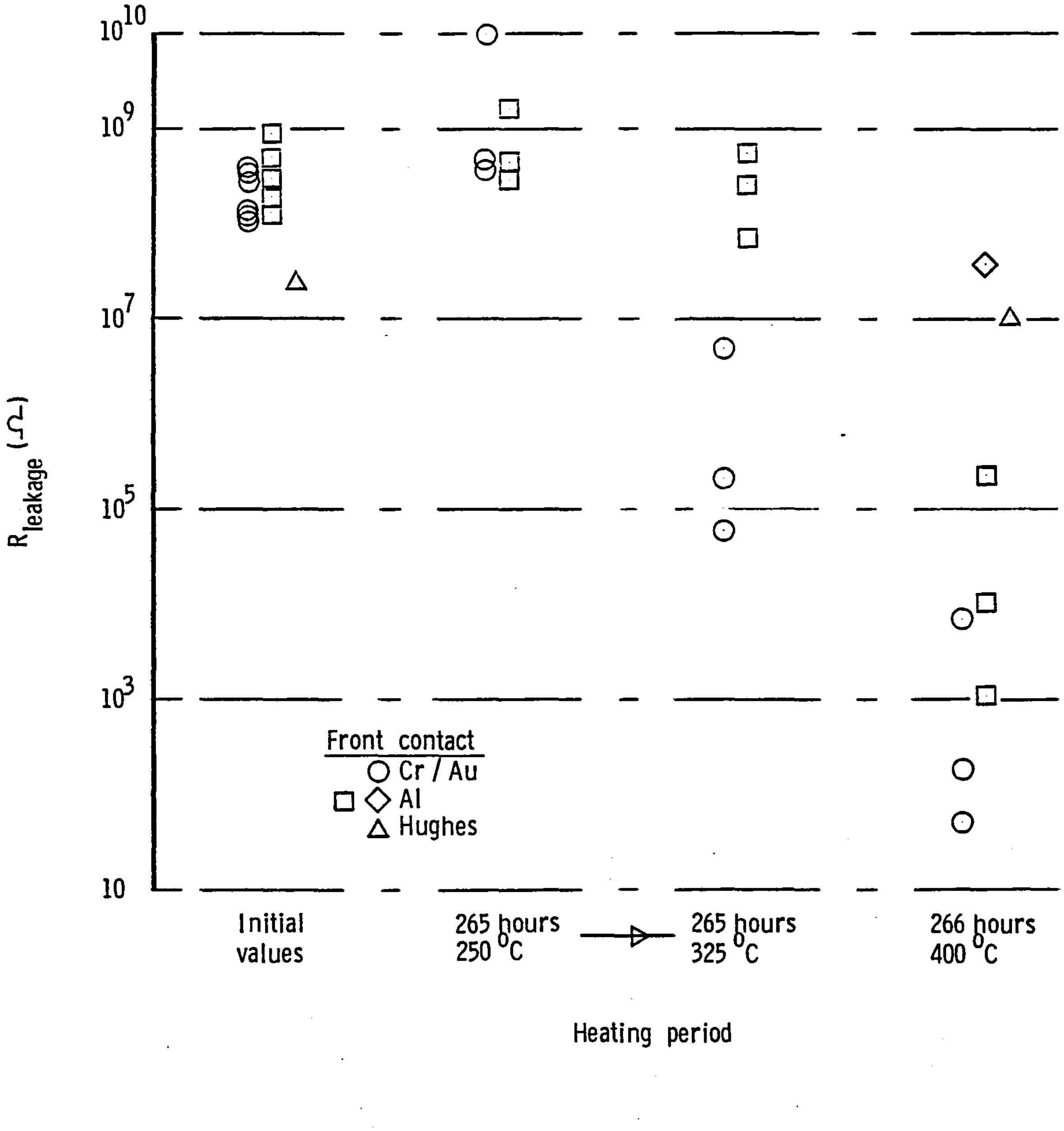

Figure 7.- Leakage resistance after heating to different temperatures for comparable periods.

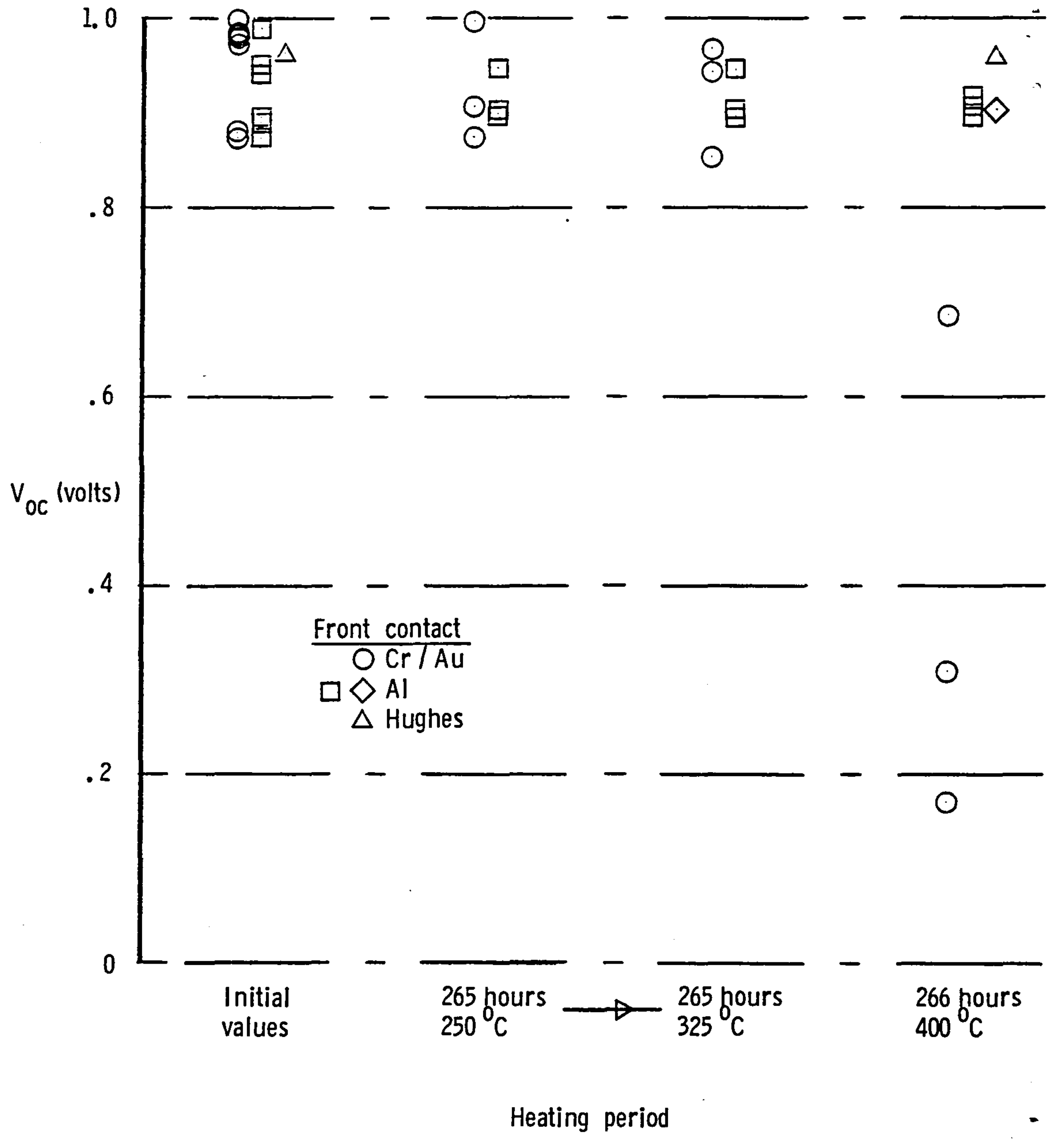

Figure 8.- Open circuit voltage at 1 Sun eqv. and 21°C after heating to different temperatures for comparable periods.

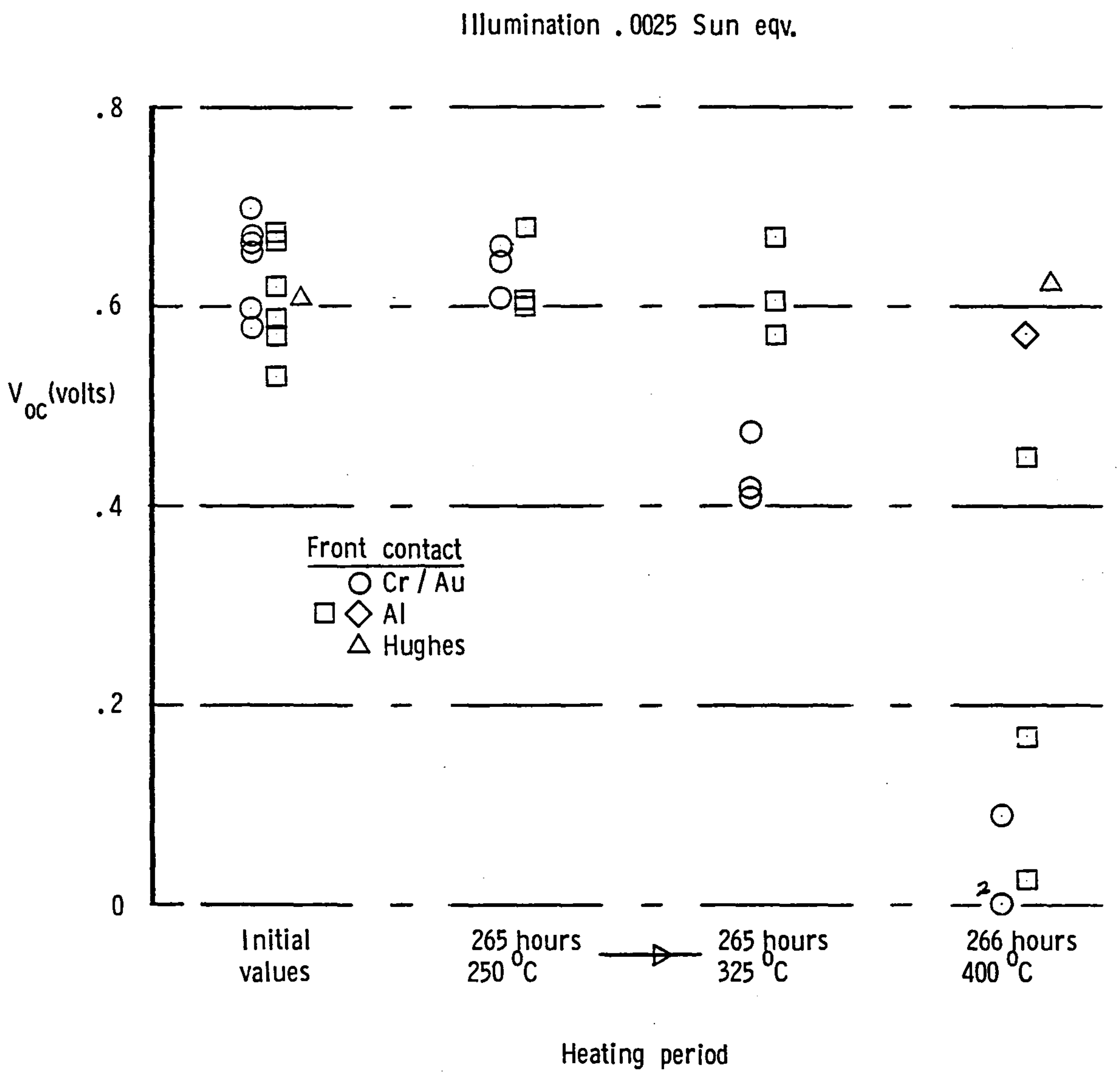

Figure 9.- Open circuit voltage at .0025 Sun eqv. and 21°C after heating to different temperatures for comparable periods.

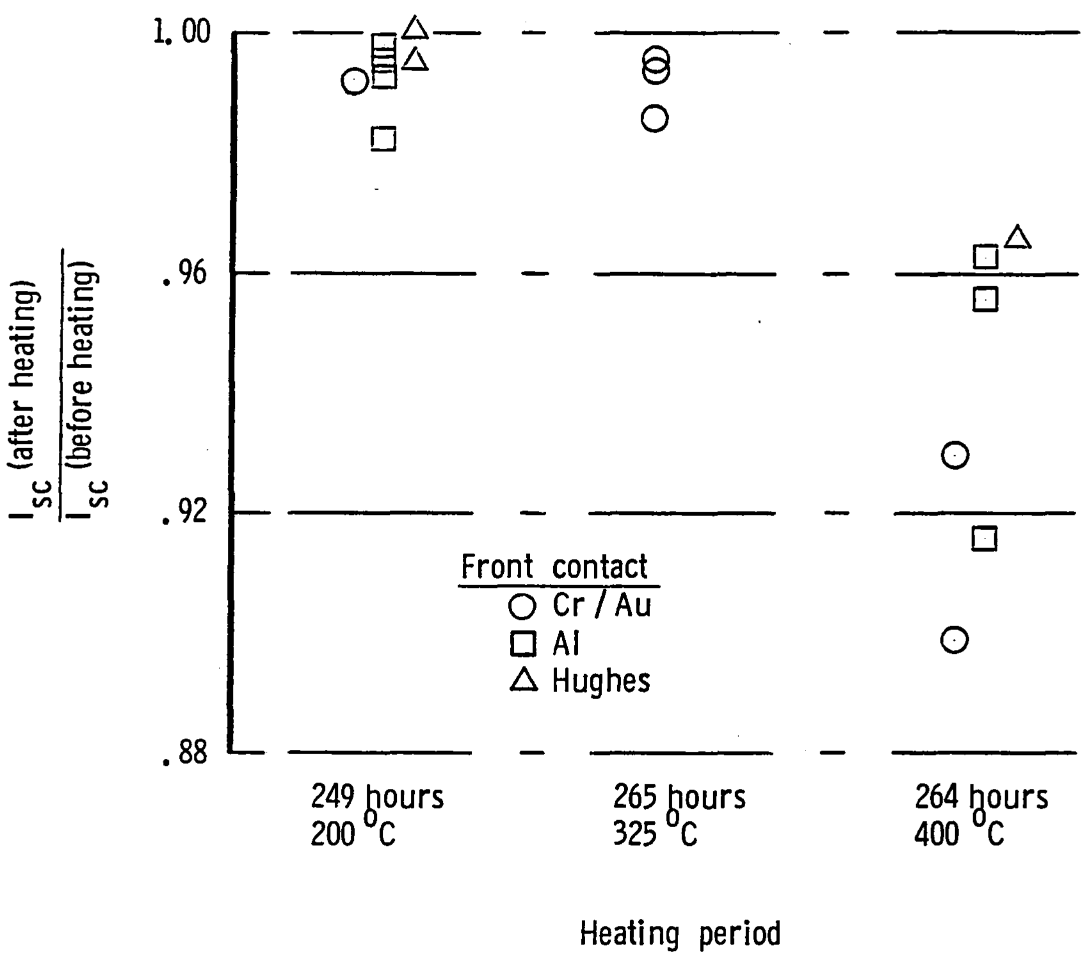

Figure 10.- Normalized value of short circuit current after heating to different temperatures for comparable periods.

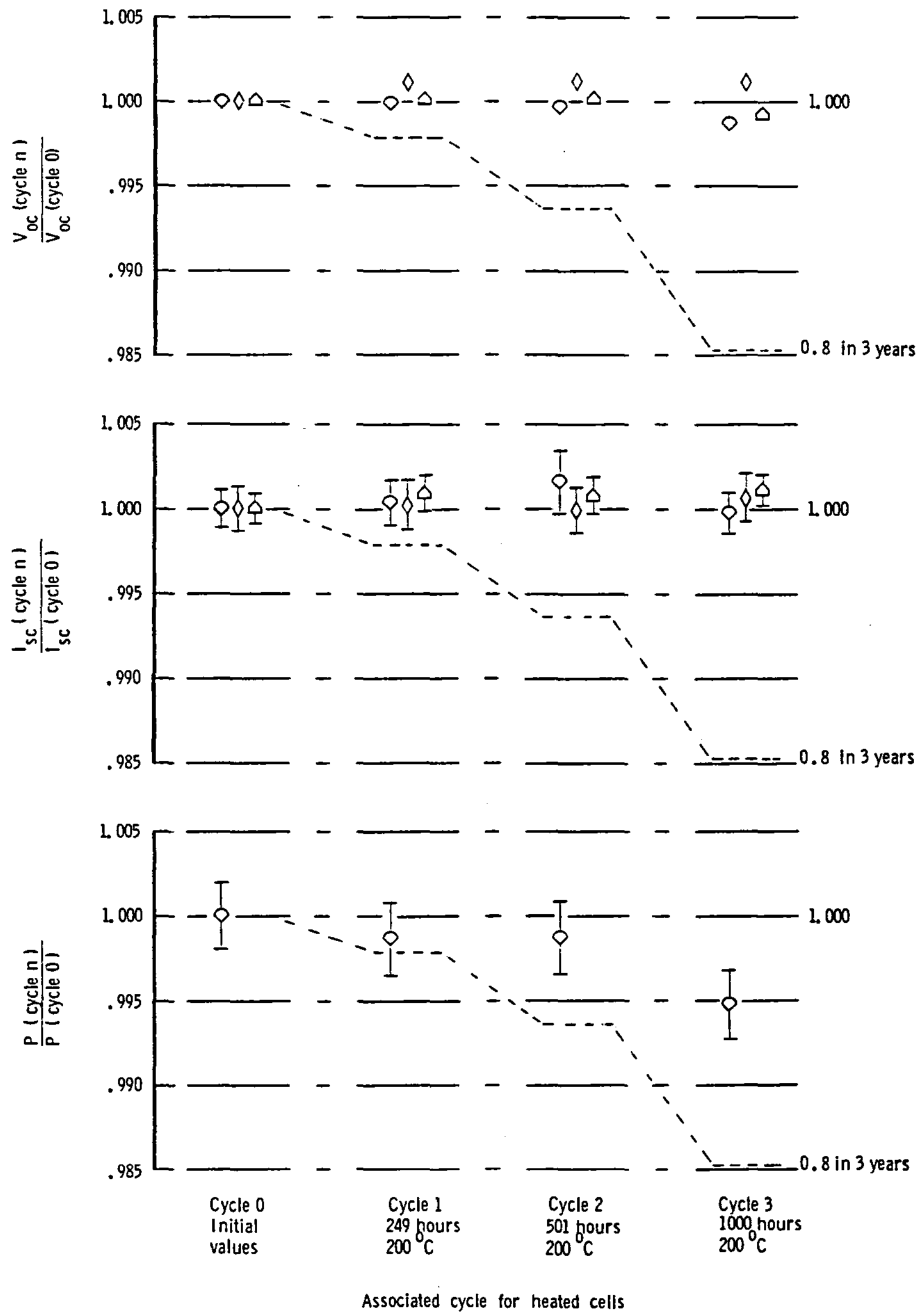

Figure 11.- Normalized values of open circuit voltage, short circuit current and output power at 1 Sun eqv. for unheated Hughes cells measured after each heating cycle.

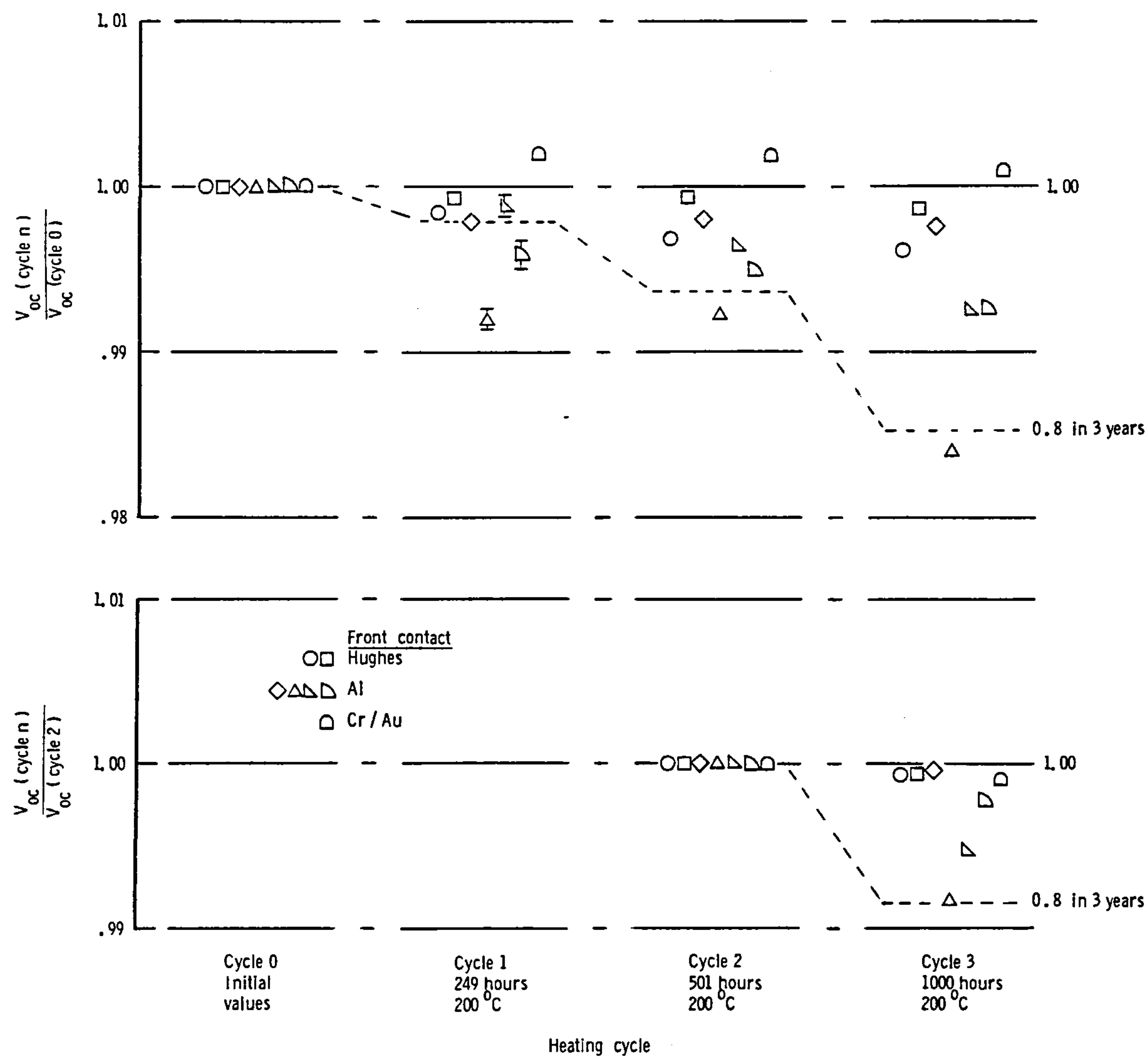

Figure 12.- Normalized values of open circuit voltage at 1 Sun eqv. after successive heating cycles.

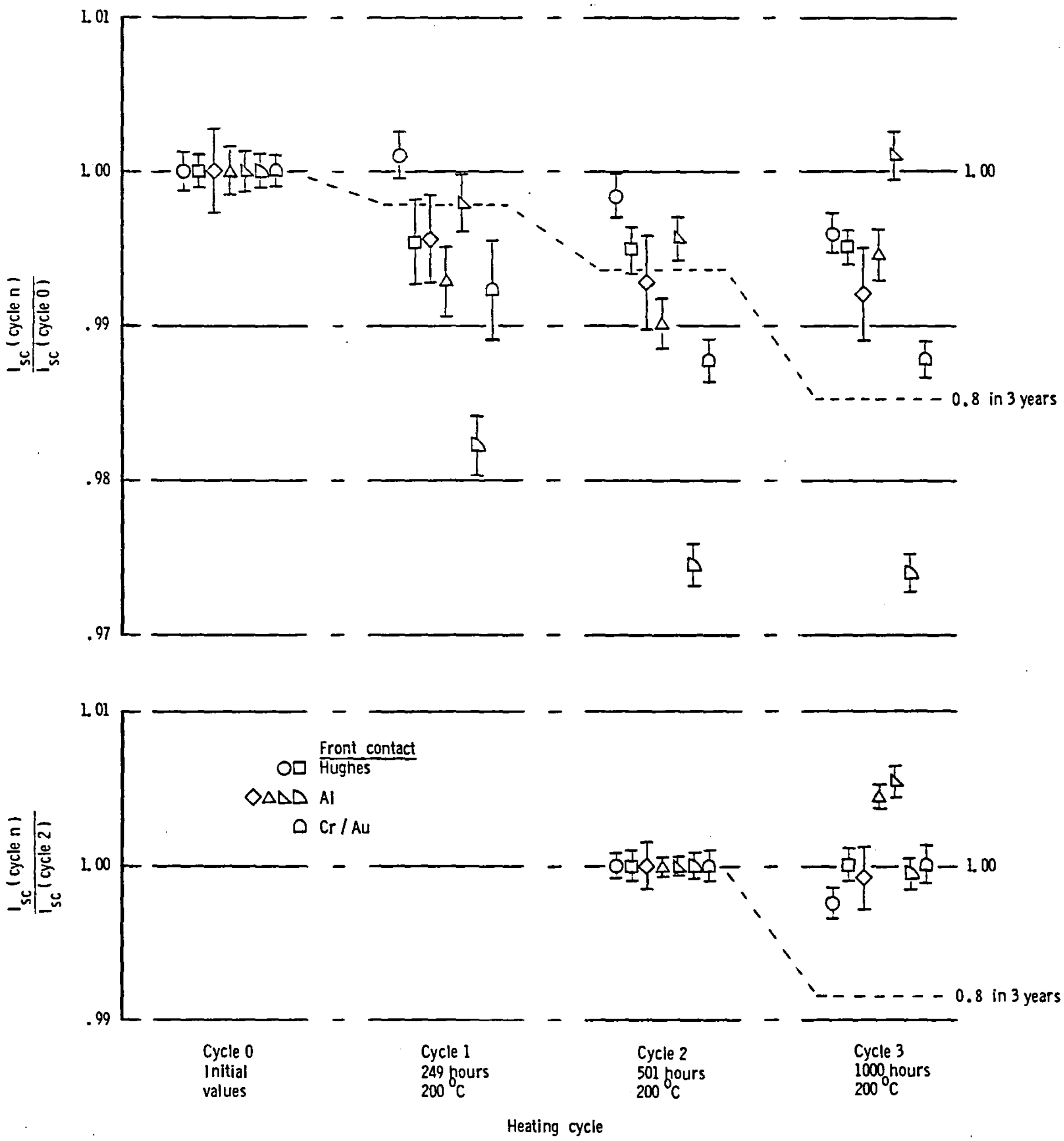

Figure 13.- Normalized values of short circuit current at 1 Sun eqv. after successive heating cycles.

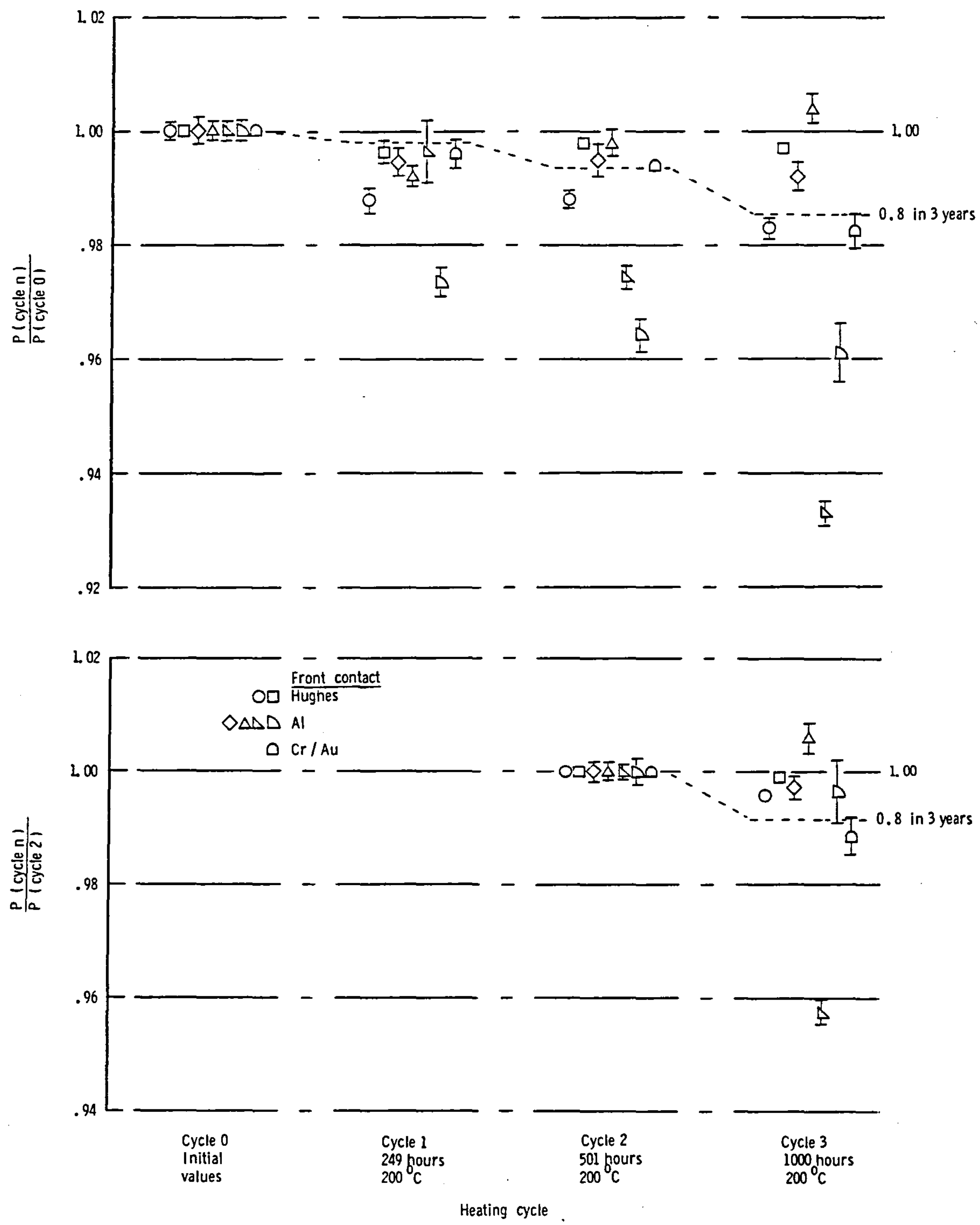

Figure 14.- Normalized values of output power at 1 Sun eqv. after successive heating cycles.

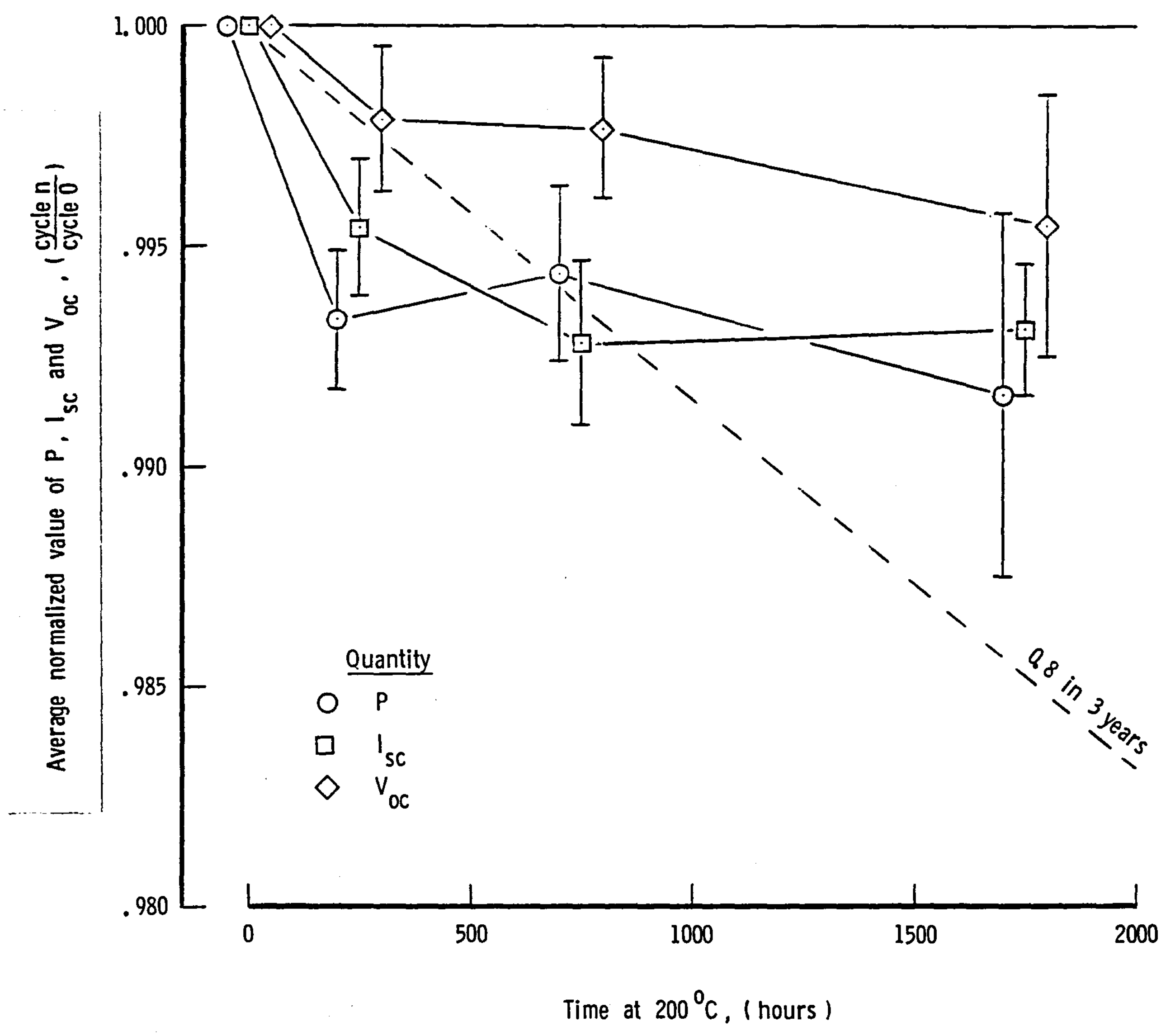

Figure 15.- Average normalized values of output power, short circuit current and open circuit voltage at 1 Sun eqv. Averages for 5 cells which meet criterion for output power after 1750 hours.

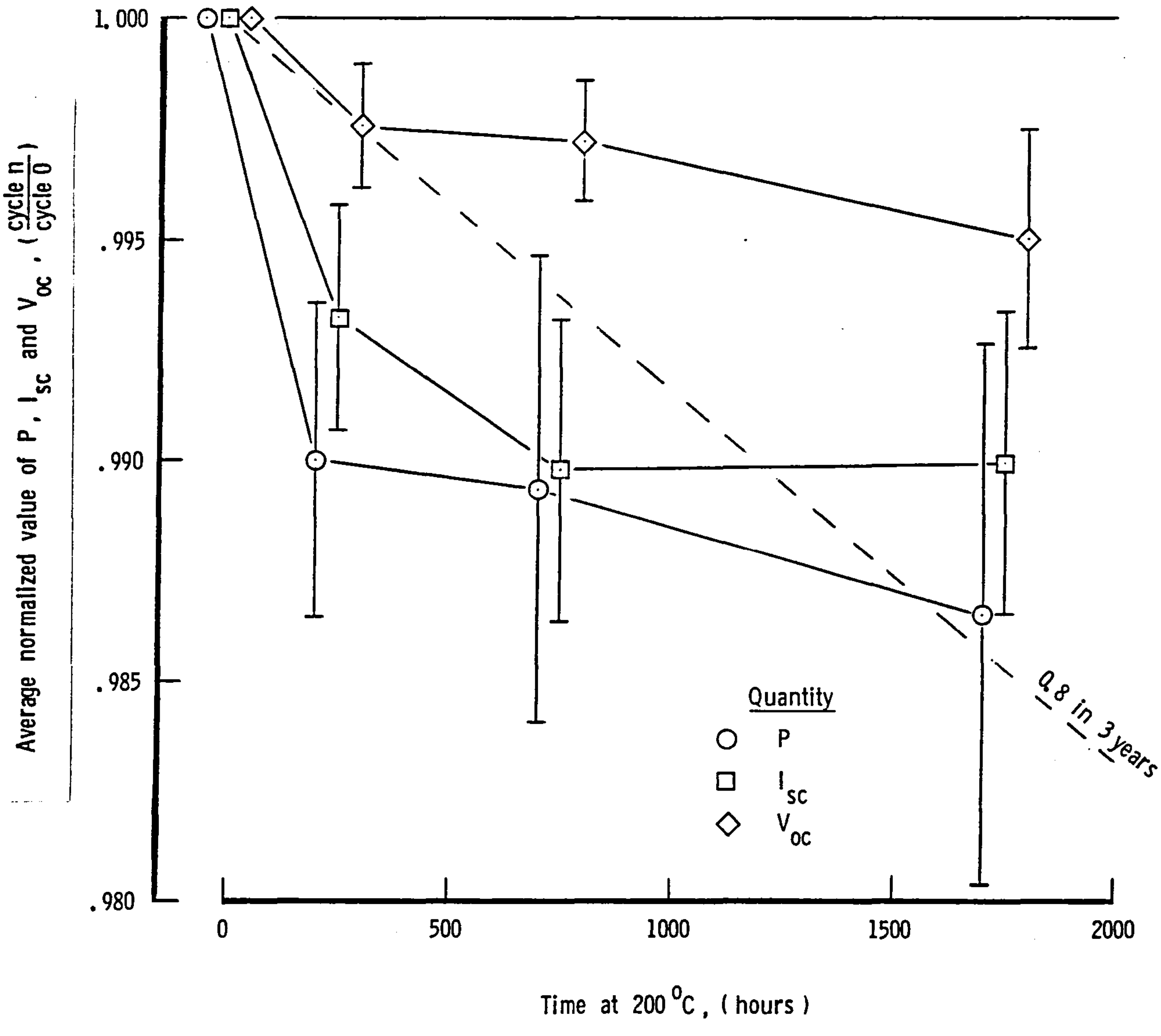

Figure 16.- Average normalized values of output power, short circuit current and open circuit voltage at 1 Sun eqv. Averages for 6 cells which meet criterion for output power when considering only the last 1000 hours of heating.

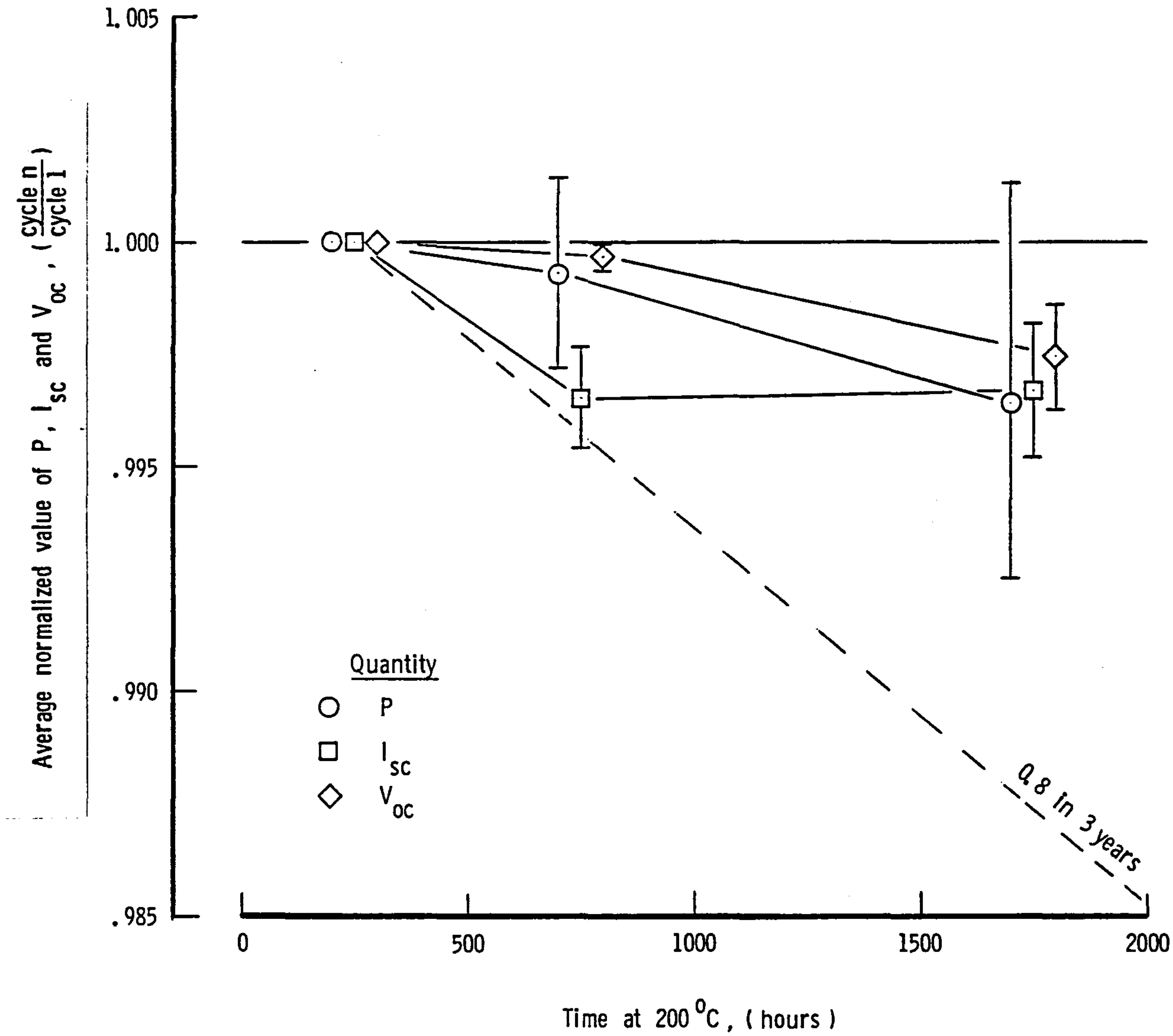

Figure 16.- Continued.

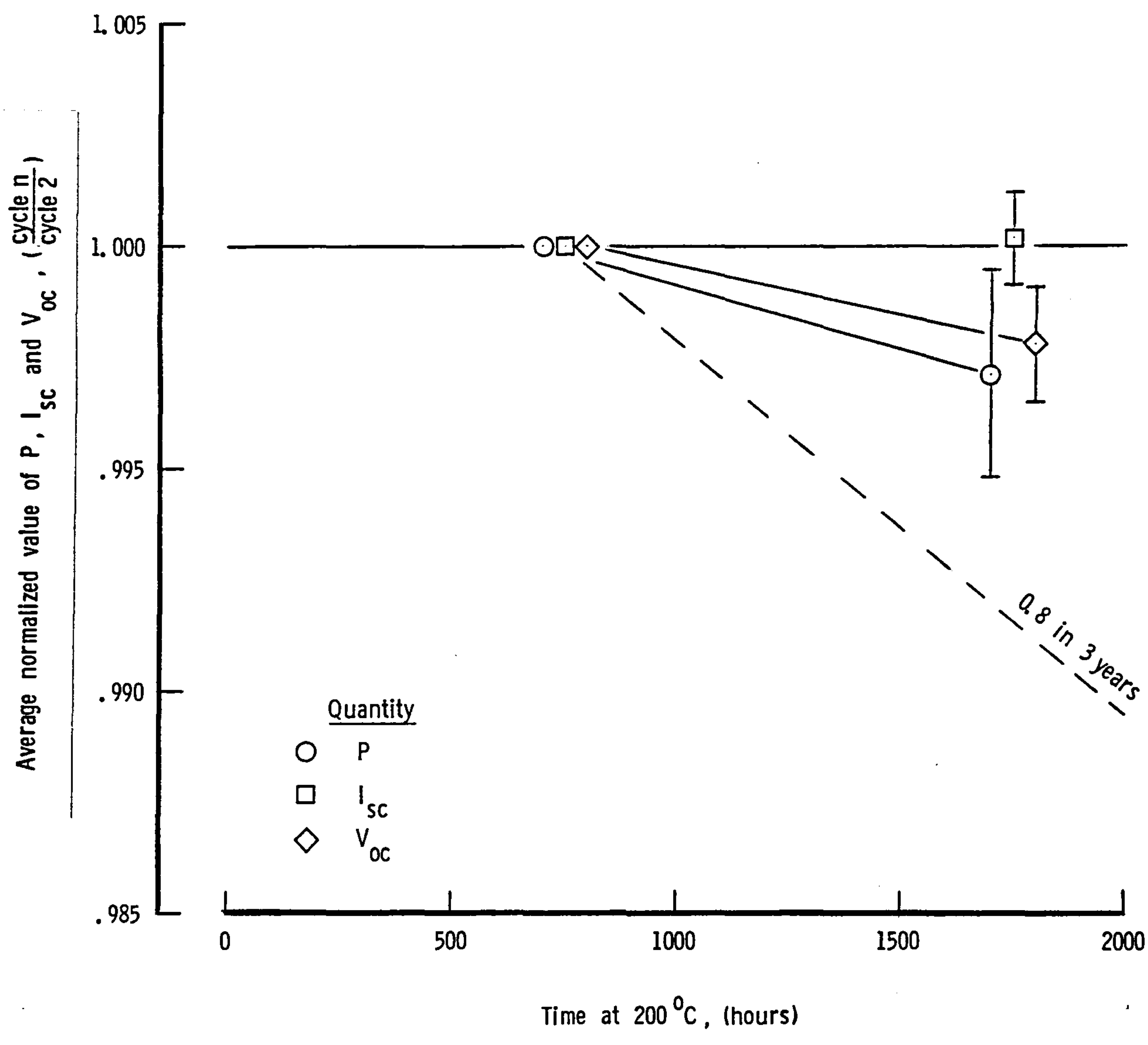

Figure 16.- Concluded.

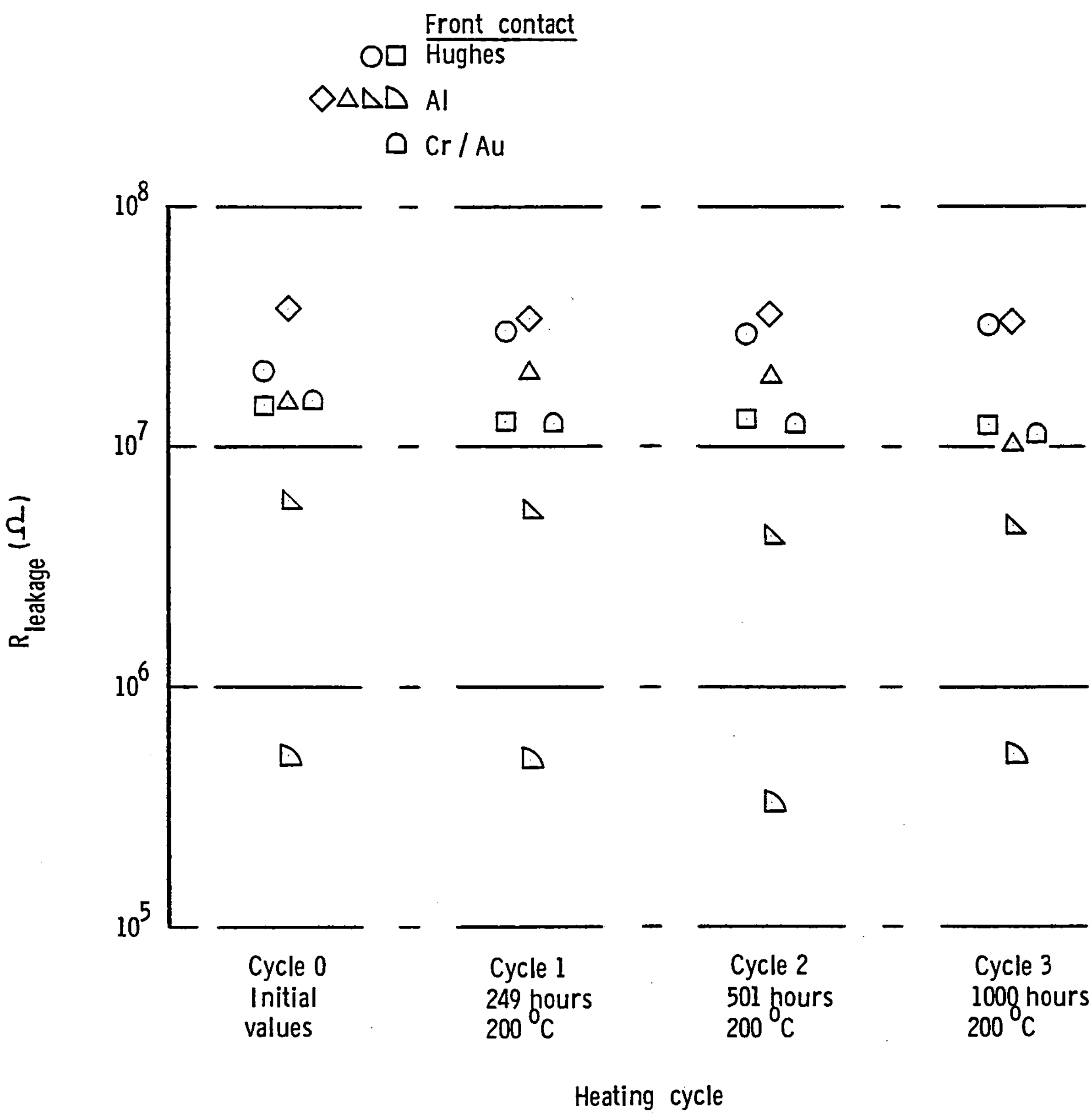

Figure 17.- Leakage resistance after successive heating cycles.

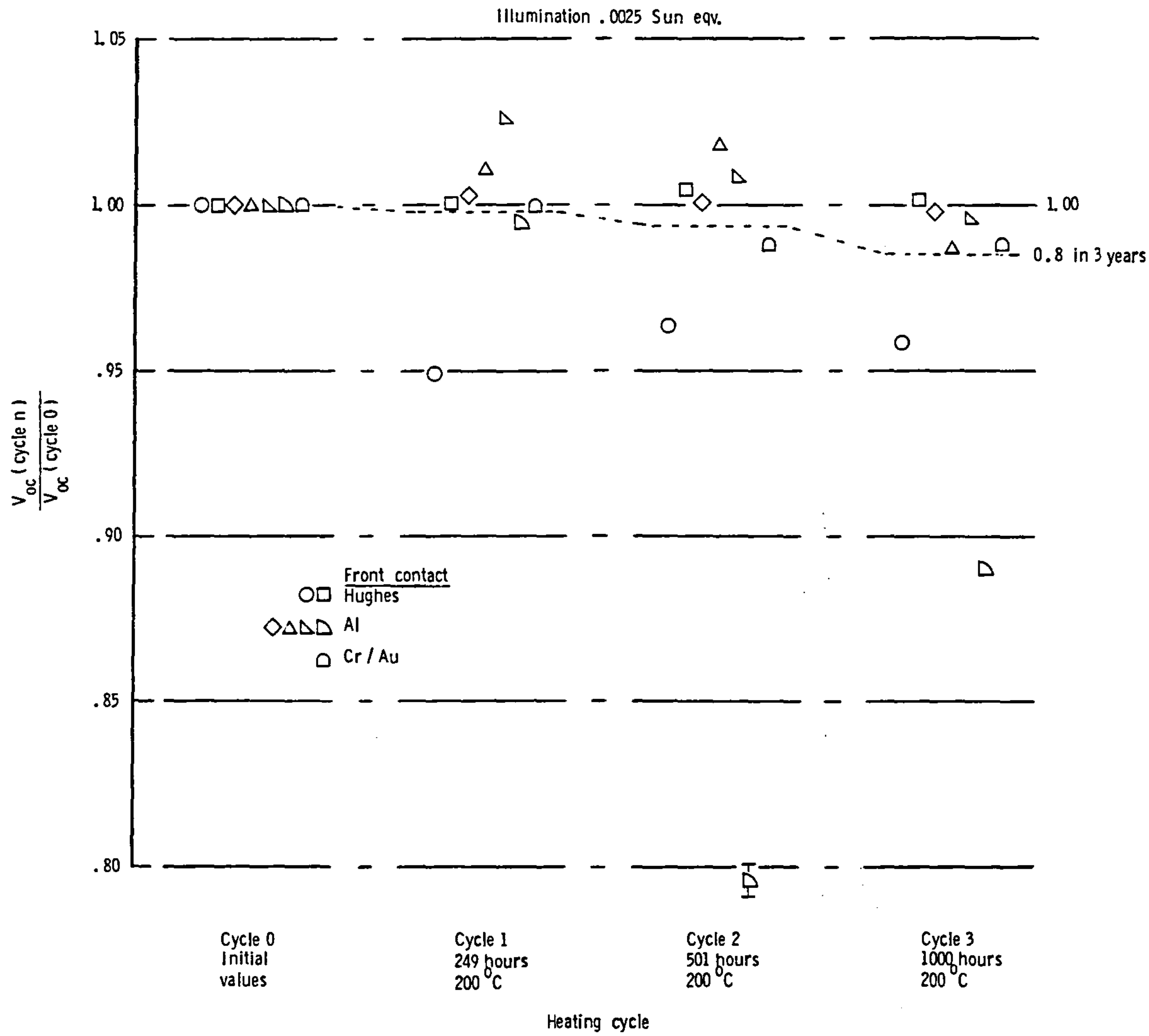

Figure 18.- Normalized values of open circuit voltage at .0025 Sun eqv. after successive heating cycles.

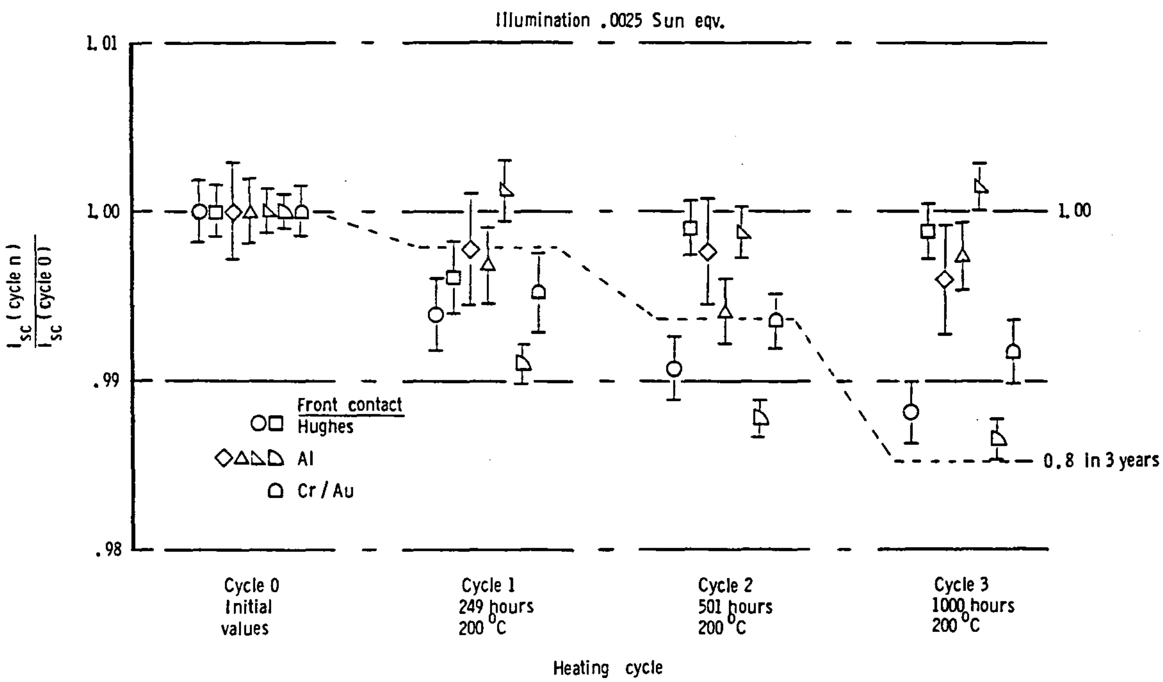

Figure 19.- Normalized values of short circuit current at .0025 Sun eqv. after successive heating cycles.

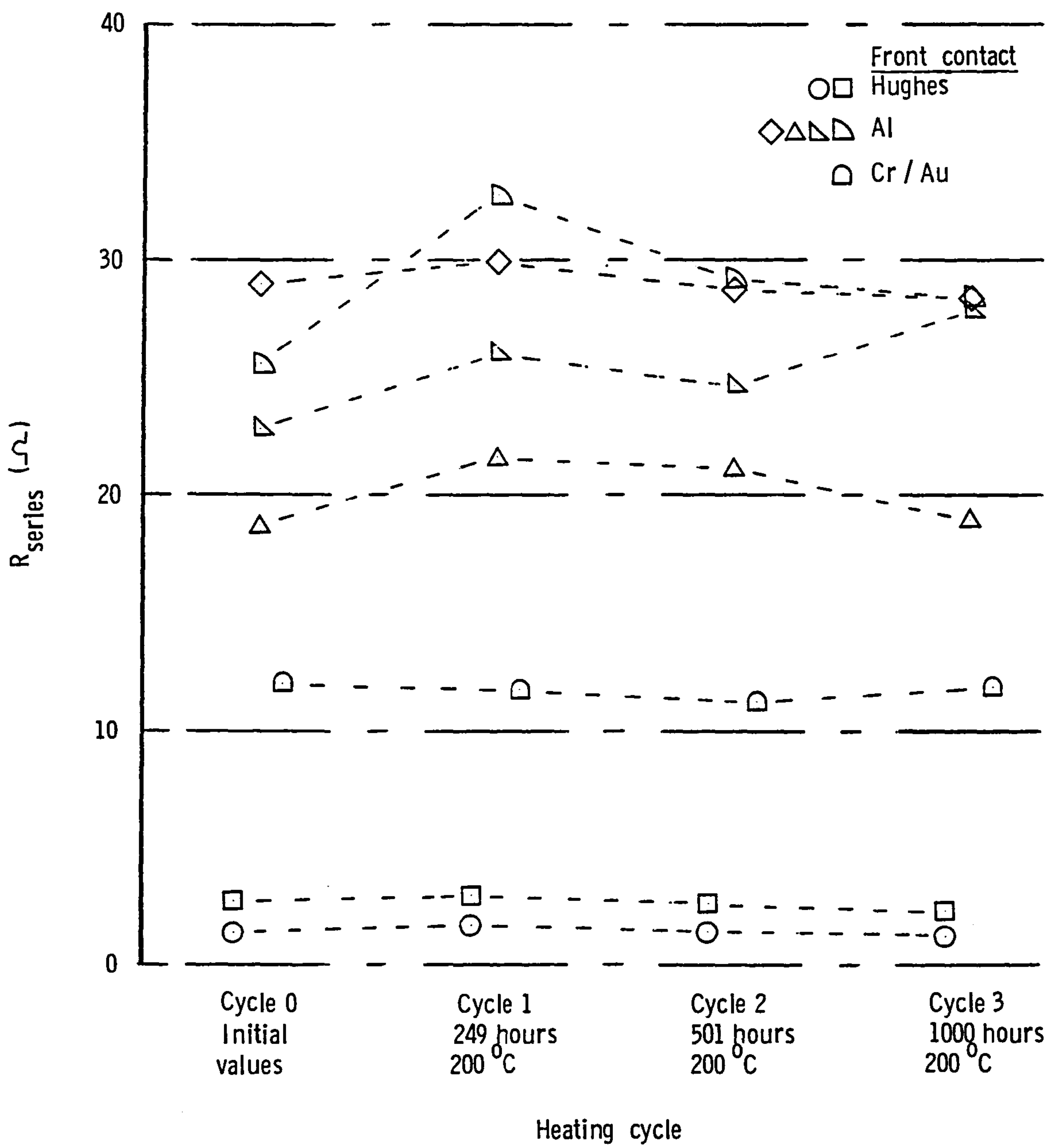

Figure 20.- Series resistance after successive heating cycles.

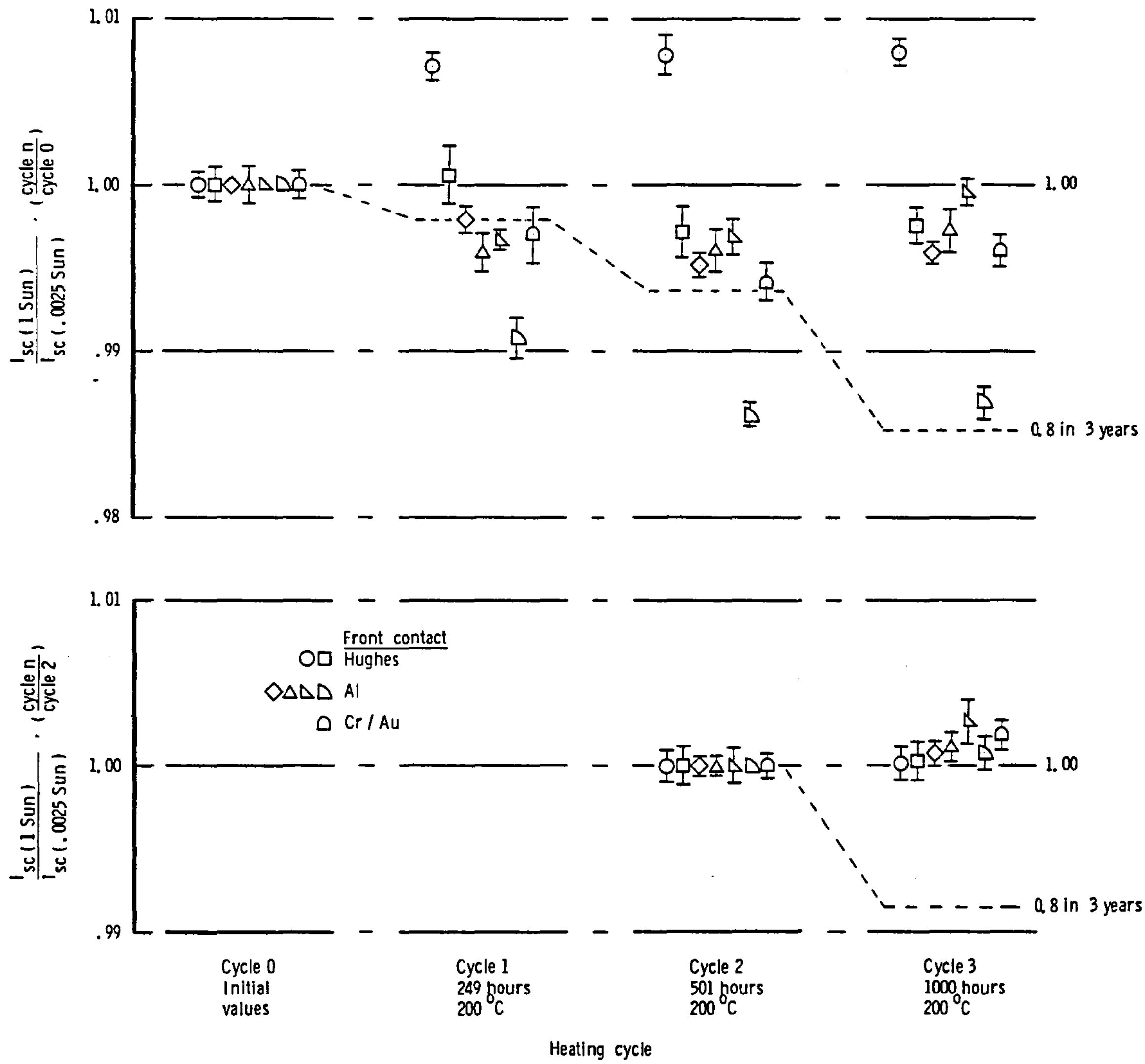

Figure 21.- Normalized value of the ratio of the short circuit current at 1 Sun eqv. to the short circuit current at .0025 Sun eqv. after successive heating cycles.

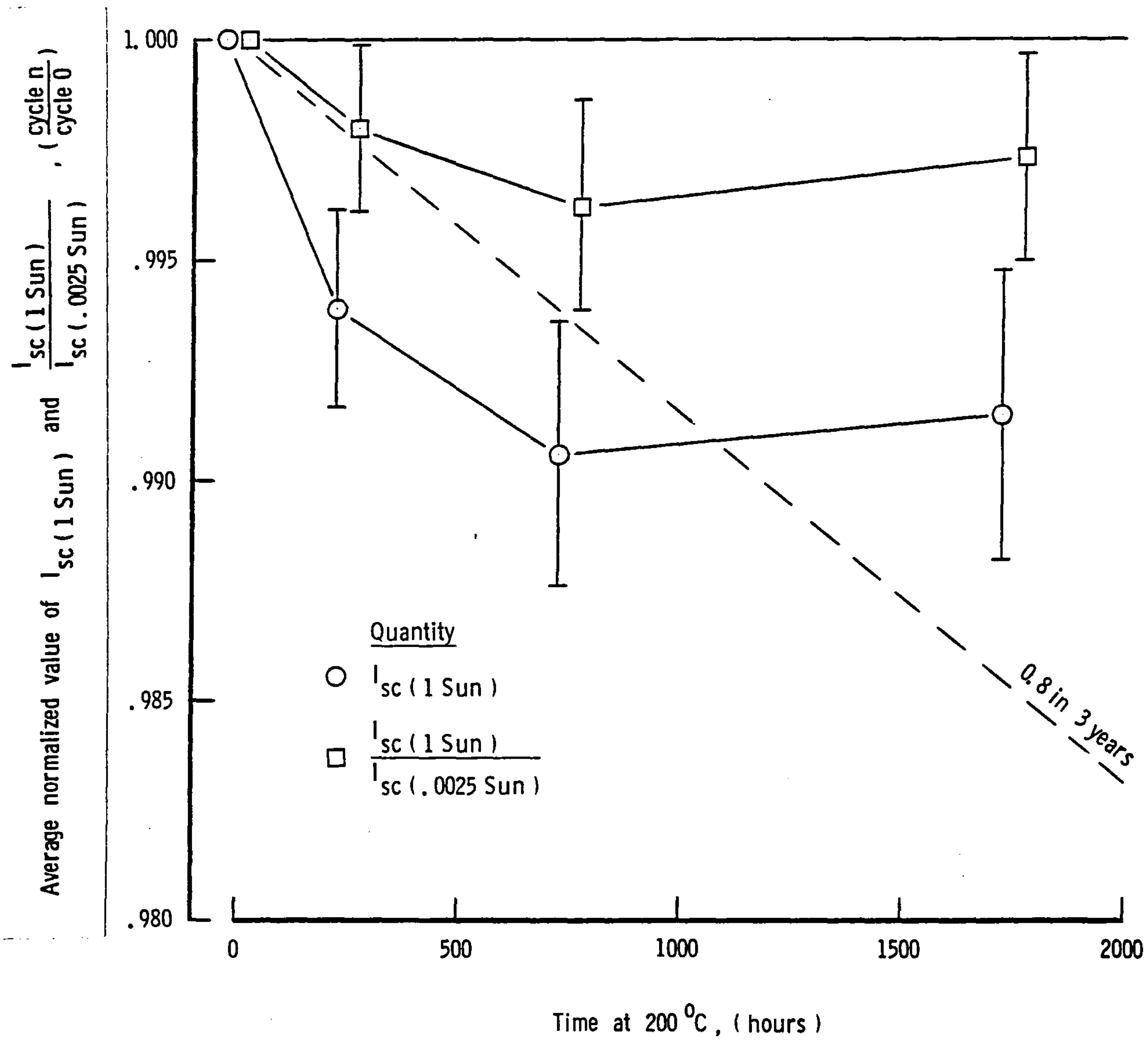

Figure 22.- Average normalized values of the short circuit current at 1 Sun eqv. and the ratio of the short circuit current at 1 Sun eqv. to the short circuit current at .0025 Sun eqv. Averages for 7 cells.

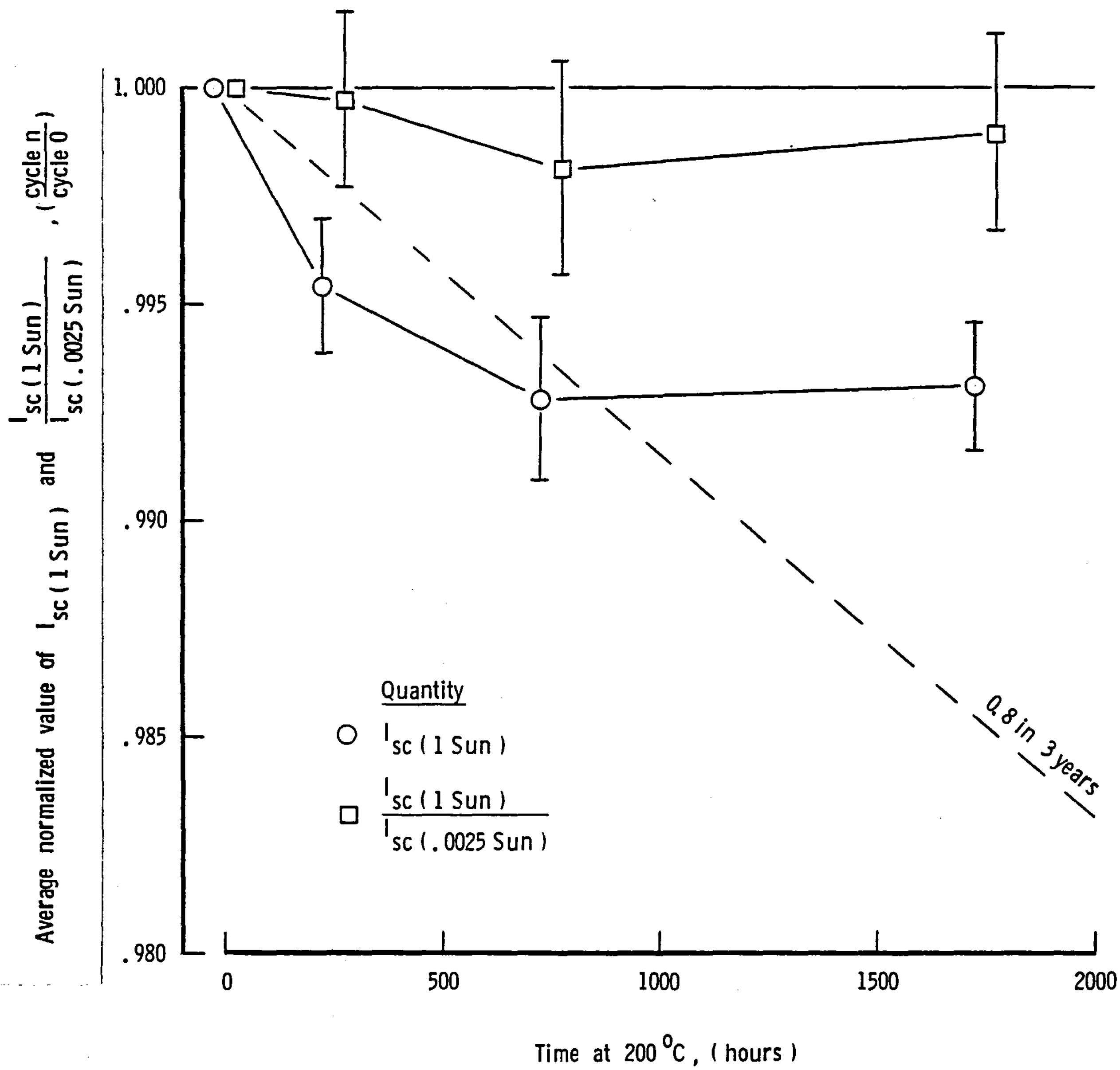

Figure 23.- Average normalized values of the short circuit current at 1 Sun eqv. and the ratio of the short circuit current at 1 Sun eqv. to the short circuit current at .0025 Sun eqv. Averages for 5 cells which meet criterion for output power after 1750 hours.

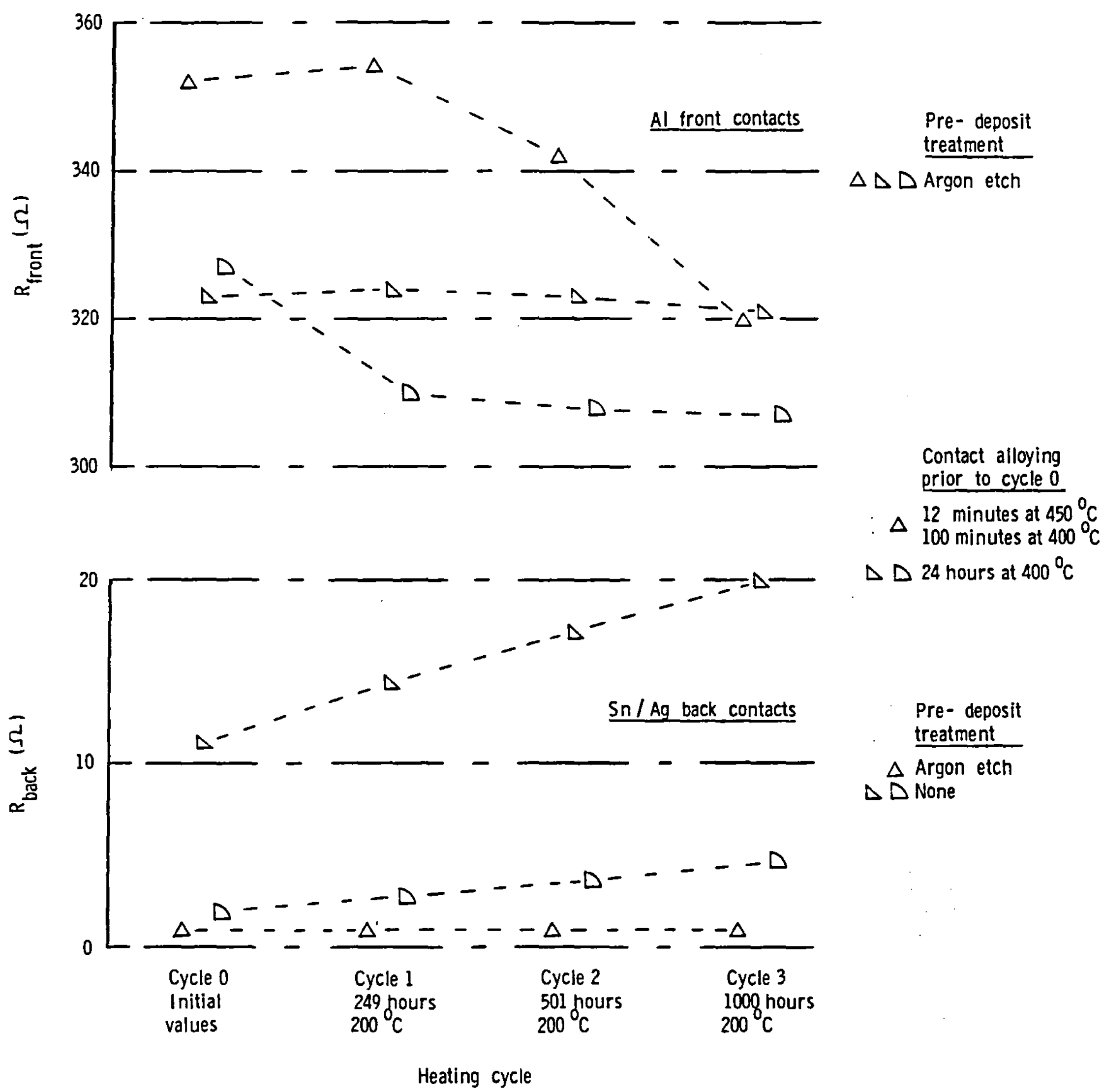

Figure 24.- Resistance between front contacts and resistance between back contacts after successive heating cycles.

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15. Supplementary Notes

16. Abstract

$GaA\ell As/GaAs$ heteroface solar cells used in space offer advantages of higher operating temperatures and recovery from radiation damage using thermal annealing. Experiments were conducted to examine the effects on the room temperature photovoltaic properties of cells due to heating in a vacuum at temperatures encountered in radiation damage annealing. Some degradation of photovoltaic properties was observed for all the cells that were heated. The lifetime, due to heating, for a 20-percent degradation in output power was estimated for cells heated at 200° C and 400° C. The results for cells that were heated at 200° C for 1750 hours indicate a lifetime of at least 3 years. The results for cells that were heated at 400° C for 264 hours indicate that lifetimes in the range of 350 hours to 1400 hours may be expected. The results indicate that for cells that must be heated at 400° C the selection of fabrication techniques and materials is particularly important.

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