CO_2 LASER ANNEALING OF 50- μm-THICK SILICON SOLAR CELLS

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SUMMARY

A test program is currently being conducted to determine thin solar cell annealing effects using a laser energy source. A CO_2 continuous-wave (CW) laser has been used in annealing experiments on 50- μm-thick silicon solar cells after proton irradiation. Test cells were irradiated to a fluence of 1.0×10^{12} protons/cm^2 with 1.9 MeV protons. After irradiation, those cells receiving full proton dosage were degraded by an average of 30% in output power. In annealing tests laser beam exposure times on the solar cell varied from 2 seconds to 16 seconds reaching cell temperatures of from 400°C to 500°C. Under those conditions annealing test results showed recovery in cell output power of from 33% to 90%.*

INTRODUCTION

Past investigations have shown positive annealing effects when radiation damaged silicon solar cells were heated to above 400°C for longer than 10 minutes (ref. 1 and 2). More recently, manufacturing process induced defects in semiconductors have been annealed using directed beam energy to obtain the desired annealing time and temperature (ref. 3). The coherent beam of a laser may provide an ideal energy source for solar cell annealing space applications

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where annealing ovens or array enclosures (ref. 4) might not be practical. A laser provides the added benefit of directing the annealing beam to any portion of a large array when required (such as a Solar Power Satellite). This would allow the annealing device to scan the array continuously without disrupting panel power generation as only a small segment of the array is affected. In-situ annealing of solar arrays in space has been a topic of technical scrutiny for some time.

BACKGROUND

Preliminary laser annealing studies were conducted to determine feasibility of laser annealing principles as applied to the annealing of radiation damage in silcon solar cells.* These studies showed positive annealing results for uncovered solar cells annealed with a scanned DC electron beam (fig. 1) and with a pulsed Nd:YAG laser (fig. 2). Glass covered solar cells with electrostatically bonded (ESB) Corning 7070 cover glasses were annealed using a CO_2 laser (fig. 3). These early solar cell laser annealing tests involved exposure periods of from 10 μsec for the electron beam to 2 sec for the CO_2 laser. No attempt was made to optimize beam parameters or to determine what effect, if any, the short duration, high intensity laser exposure had on the cell or the annealing process (ref. 5).

LASER ANNEALING OF THIN CELLS

Further testing of solar cell annealing using a CO_2 laser has been conducted to address the questions of laser beam effects on solar cells and reproducibility of laser annealing in an individual cell. In particular, 50-μm-thick solar cells were tested as a low mass advanced cell with potential for application in the development of large space power generating systems. Solar cell types used in the annealing tests are described in table 1.

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*This work was performed by Spire Corp., Bedford, MA, under contract to Boeing Aerospace Company, Seattle, WA.

Initial laser annealing test parameters were derived from thermodynamic analysis of a 50- μm-thick silicon solar cell with a 50- μm-thick integral-glass cover. This steady state thermodynamic model shows in figure 4 the laser beam energy density required to maintain a desired annealing temperature. The amount of time required for a laser beam to raise the temperature of a solar cell, as a function of laser beam energy density, from room temperature (28°C) to an annealing temperature of 500°C is plotted in figure 5. Although early theoretical analysis was done for a 50- μm-thick cell with 50-μm-thick integral-glass cover, unglassed 50- μm-thick solar cells were used in these annealing tests as integral-glass covers on thin cells are not completely developed.

TEST PROCEDURES

Figure 6 shows schematically the test set-up. A CO_2 laser capable of greater than 150 watts CW was used as the laser source. A mechanical shutter was used which utilizes two knife edge shutter leaves and a light emitting diode, photo cell to generate a pulse of laser radiation and an electrical timing pulse, respectively. The electrical pulse was measured with a counter to determine the exact laser beam pulse length. With the shutter held open, a sampling mirror was placed in the beam to deflect the beam into the reference power transducer which was used to measure the total raw beam power as a reference.

A zinc selenide lens with a 5.0 inch focal length was used to spread the beam. Distance C in figure 6 was adjusted to give the required power density at the test plane.

The beam travels through a motor-driven mirror arrangement which was computer controlled and can be used for aligning and centering the beam and for scanning the beam across the aperture plate (2mm aperture) to provide power density profile maps of the beam. The laser test facility and Coherent Optics, Everlase 150 laser with the test set-up on the work table above the laser cabinet are pictorially illustrated in figure 7.

Electrical parameters of each cell are measured before and after every test to provide comparative test parameters. A Spectrolab X-25 Mark II solar simulator provides illumination on the test cell during electrical measurements.

Each cell is electrically degraded by irradiation of 1.9 MeV protons to a fluence of 1.0×10^{12} protons/cm^2 at Boeing's Radiation Effects Laboratory.

EVALUATION OF ELECTRICAL DEGRADATION IN UNIRRADIATED TEST CELLS DUE TO LASER EXPOSURE

Before formal laser annealing tests began, 50- µm-thick solar cell test specimens were subjected to various laser intensities and exposure durations to determine the mechanical effects of thermal shock during laser irradiation. Unglassed 50-µm-thick solar cells were found to physically deform in an unpredeterminable fashion above 300°C when subjected to a laser beam. Upon measuring electrical characteristics (figs. 8 and 9) of test cells after a 5 second, 100 watt CO_2 laser exposure that raised the cell temperature to 500°C, no reduction in the solar cells' electrical characteristics was apparent within measurement tolerances.

RESULTS AND DISCUSSION

Figures 10 through 16 illustrate laser annealing of charged-particle irradiated Solarex and O.C.L.I. 50- µm-thick solar cells. Each cell was to be irradiated with 1.9 MeV protons to a fluence of 1.0×10^{12} protons/cm^2; however cells No. 18, 19, 31 and 32 did not receive full irradiation fluence due to a malfunction of the proton source during the irradiation portion of the test sequence. Cells No. 18 and 32 had reduced outputs after the laser anneal portion of the test due to cell damage. Cell No. 18 was broken and 25% of the cell was lost. Cell No. 31 curled during laser exposure to such an extent that accurate measurement in our solar simulation test facility was not possible.

The average cell degradation in output power due to irradiation was 30%. Recovery of output power as measured at the maximum power point varied from 33% to 90% after laser annealing. Cells that were moderately degraded appeared to recover more completely than those more severely damaged. There was some indication that longer exposure to the annealing temperature was beneficial.

Figure 17 illustrates repeated annealing under the same test conditions as applied to those solar cells depicted in figures 10 through 16. Note that this cell did not recover as completely after the second annealing as it did after the first.

Figure 18 is a summary of output power variations, at the maximum power point, after each step of the annealing test sequence for all cells except cells No. 18 and 32 which were damaged during laser exposure.

Test cells were exposed to temperatures greater than 500°C for various time periods; however, no annealing data was obtained as cells tested above 500-600°C were broken as a result of severe mechanical deformation of the cell. The suspect cause of this effect is thermal expansion differences between the silicon of the cell and the metal of the cell back contact. This back contact covers the entire back of the cell having a greater effect than the metal grid on the front cell surface.

CONCLUSIONS

Laser annealing of thin cells shows promise; however, basic design alterations are required to minimize thermal shock effects of short duration, high intensity laser pulses on the 50- μm-thick solar cell. Further studies of annealing temperature and duration of laser annealing on thermo-mechanically stable thin cells are suggested.

REFERENCES

1. Fang, P. H.: Thermal Annealing of Radiation Damage in Solar Cells. Astronautica Acta, Vol. 13, No. 2, pg 147-157, 1967

2. Faraday, B. J., Statler, R. L., and Tauke, R. V.: Thermal Annealing of Proton-Irradiated Silicon Solar Cells. Proceedings of the IEEEE, Vol. 56, No. 1, pg 31-37, January 1968

3. Young, R. T., and Narayun, J.: Laser Annealing of Diffusion-Induced Imperfections in Silicon. Appl. Phys. Lett., 33(1), pg 14-15, 1 July 1978

4. Fang, P. H., Meszaros, G.; and Gdula, W. G.: Recovery of Radiation Damaged Solar Cells Through Thermal Annealing. Patent No. 3,597,281, Aug. 3, 1971

5. Minucci, J. A.; Matthei, K. W.; Kirkpatrick, A. R.; and Oman, H.: In-Situ Annealing of Space Radiation Damage. Thirteenth IEEE Photovolatic Specialists Conference, pg 586-589, 1978

6. Walker, F. E.: Silicon Solar Cell Annealing Test. NASA Report No. D180-25037-4 under Contract NAS9-15636, 1979

MANUFACTURER	THICKNESS (μm)	CELL DIMENSIONS (cm)	SURFACE FINISH	BASE RESISTIVITY	JUNCTION DEPTH	A. R. COATING	BACK SURFACE FIELD	ELECTRICAL CONTACTS	MEASURED MEAN EFF. (%)
SOLAREX	50	2 x 2	Chemical Etch	2Ωcm	2-3μm	Ta_2O_5	Compensated Back Surface Field	Ti-Pd-Ag Chevron	10.22
O.C.L.I.	50	2 x 2	Chemical Etch	2Ωcm	2-3μm	OCLI Multi-layer Coating	Back Surface Field	Ti-Pd-Ag Grid	10.28

Table 1 ; Test Sample Description

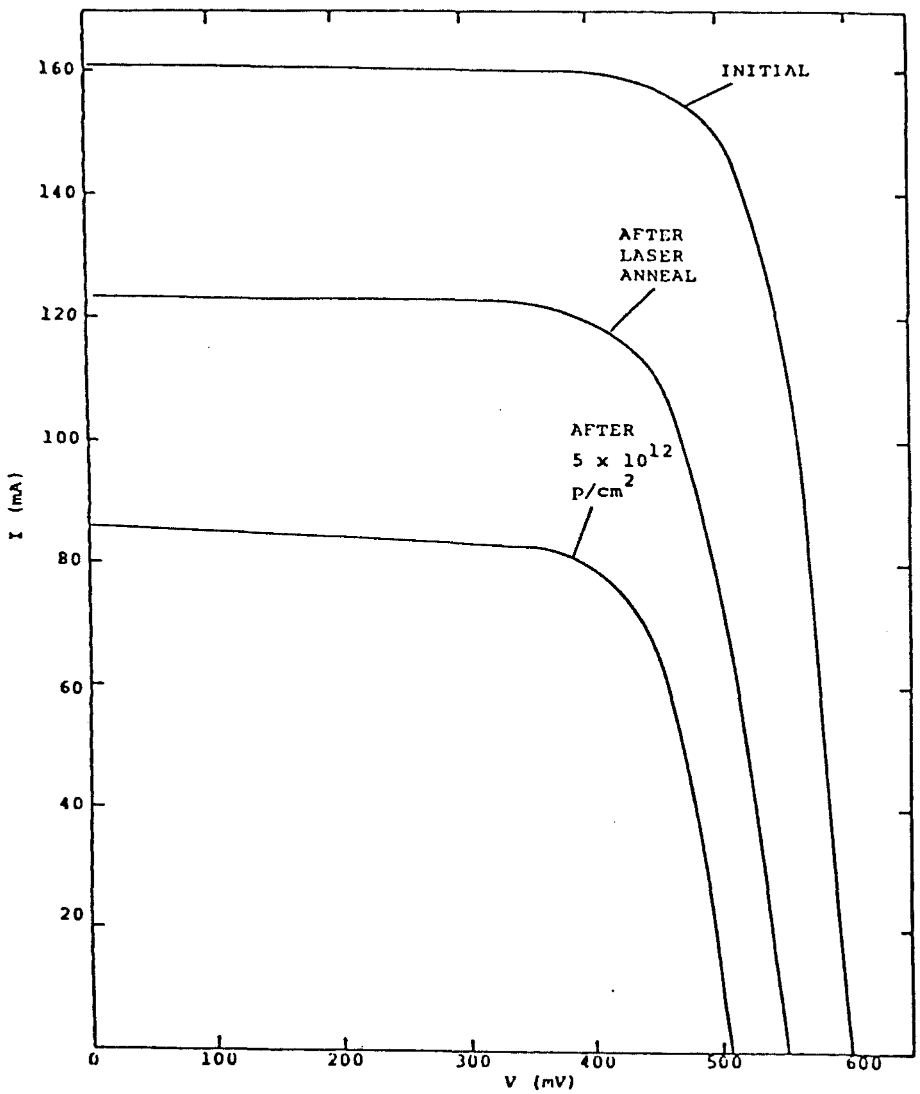

Figure 1 ; The Effect of Pulsed Laser Anneal on Violet Cell 12E

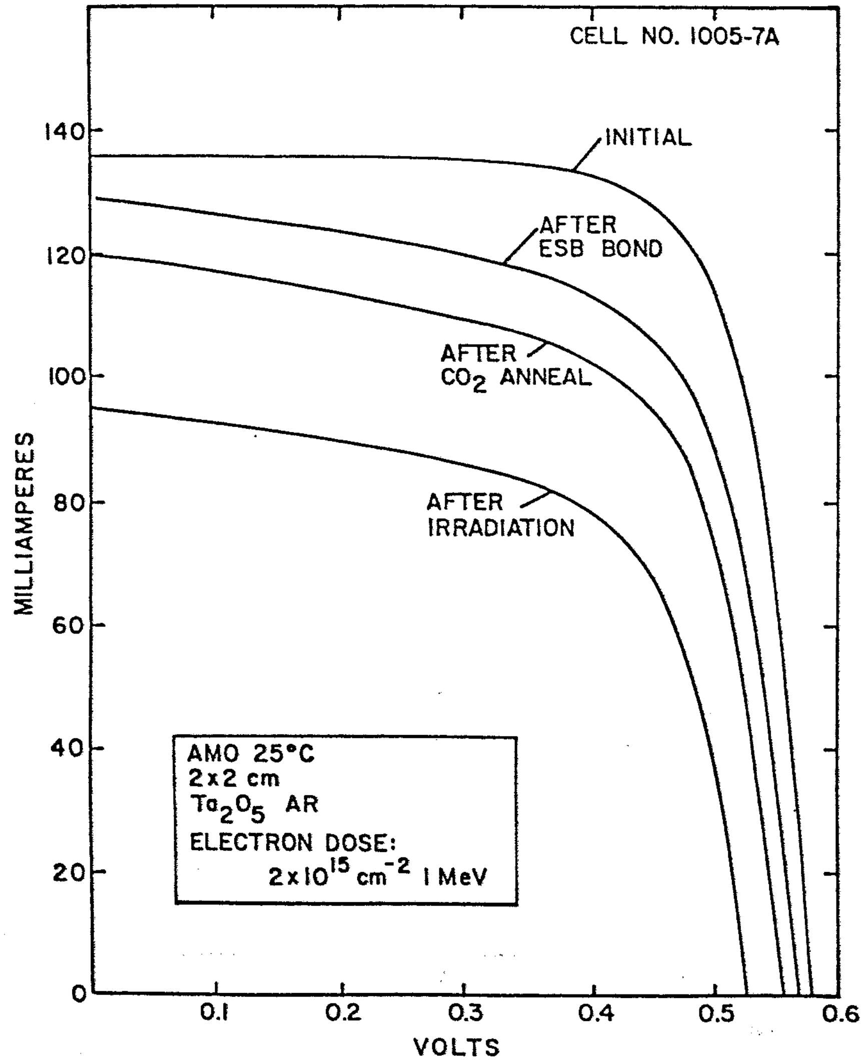

Figure 2: I-V Characteristics of Cells with ESB 7070 Coverglass After Electron Irradiation and After CO_2 Laser Anneal

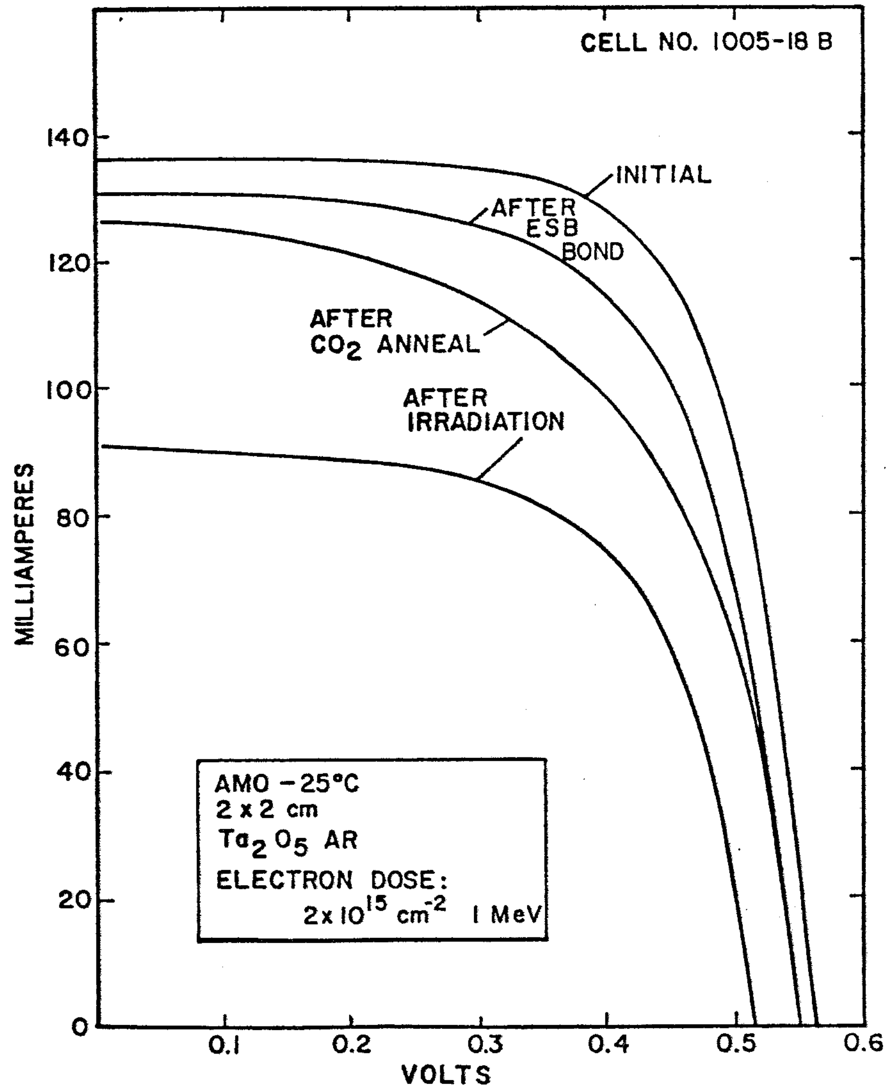

Figure 3; I-V Characteristics of Cell with ESB Coverglass After Electron Irradiation and After CO_2 Laser Anneal

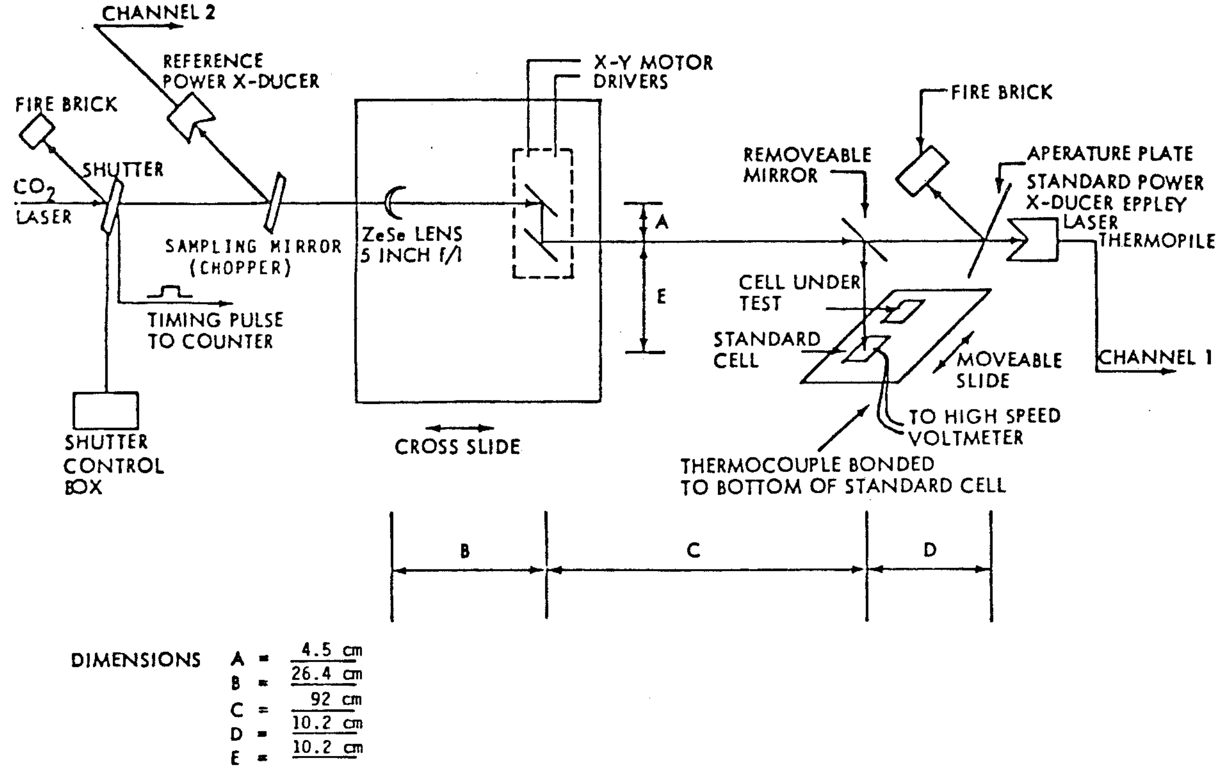

Figure 4; Laser Annealing of Solar Cells — Test Schematic

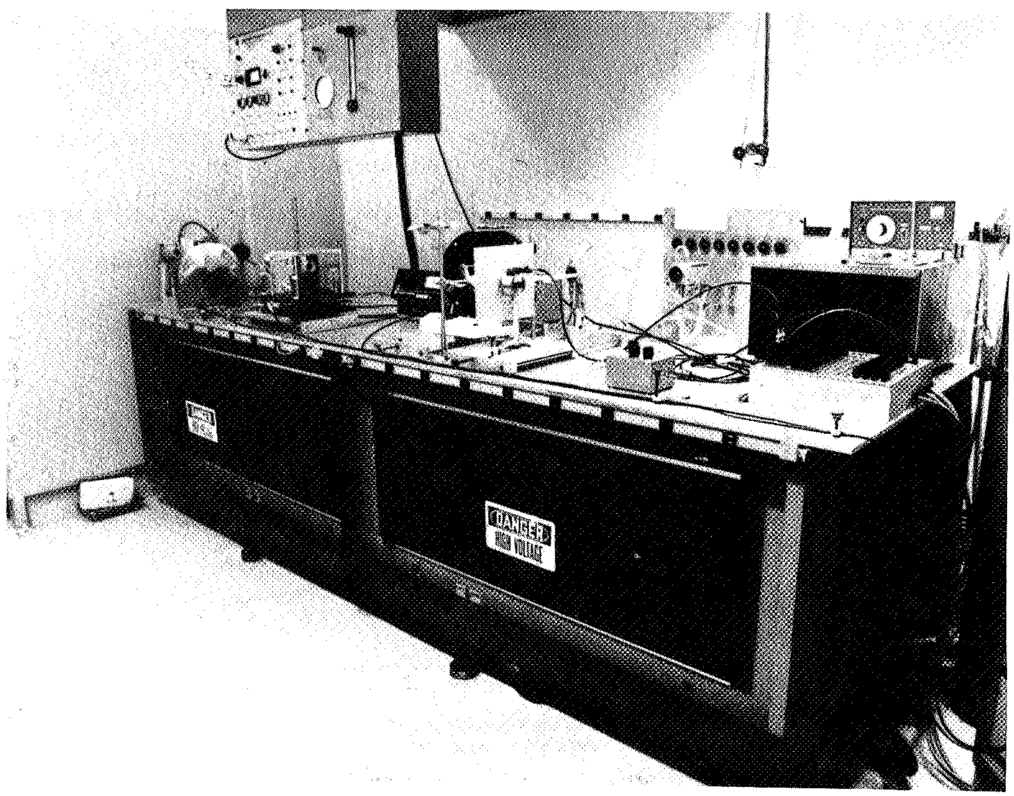

Figure 5; Laser Annealing Test Setup With Coherant Optics Everlase 150 CO_2 Laser

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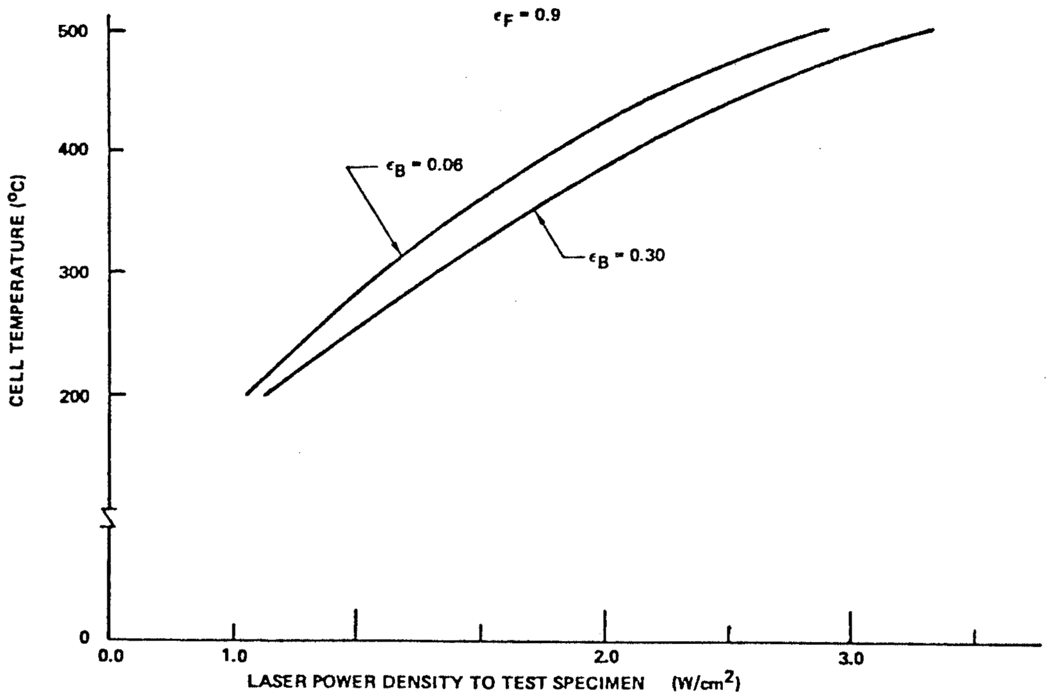

Figure 6; Steady State Temperature Resulting From Different Energy Densities in a 50-µm-Thick Solar Cell With 50-µm-Thick Integral Glass Cover

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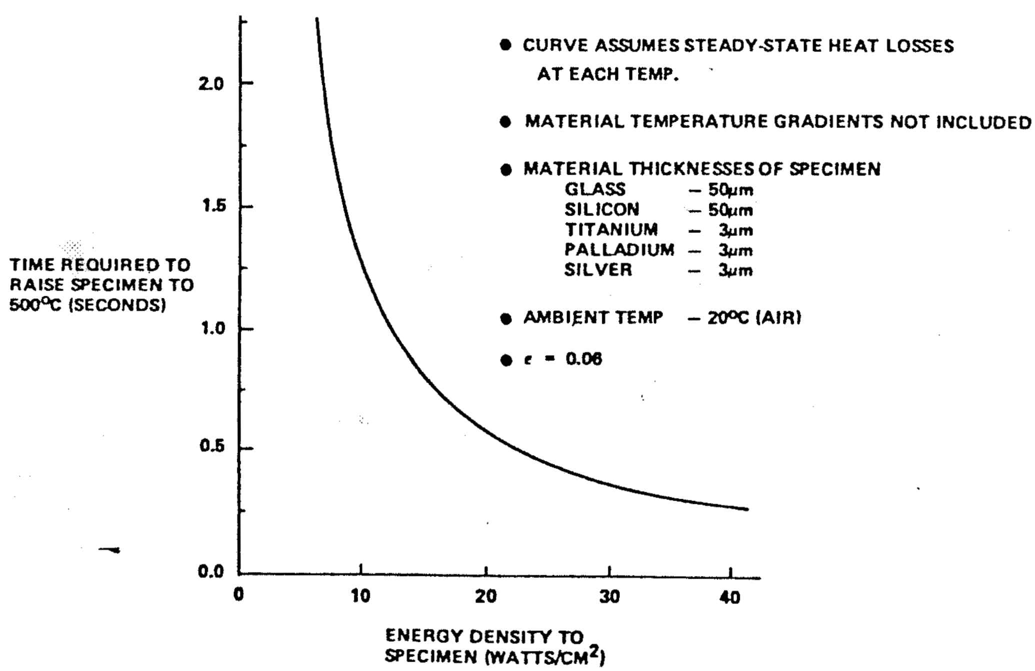

Figure 7; Time to Temperatore (500°C) Curve For Different Energy Densities In A 50-µm-Thick Silicon Solar Cell With 50-µm-Thick Integral Glass Cover

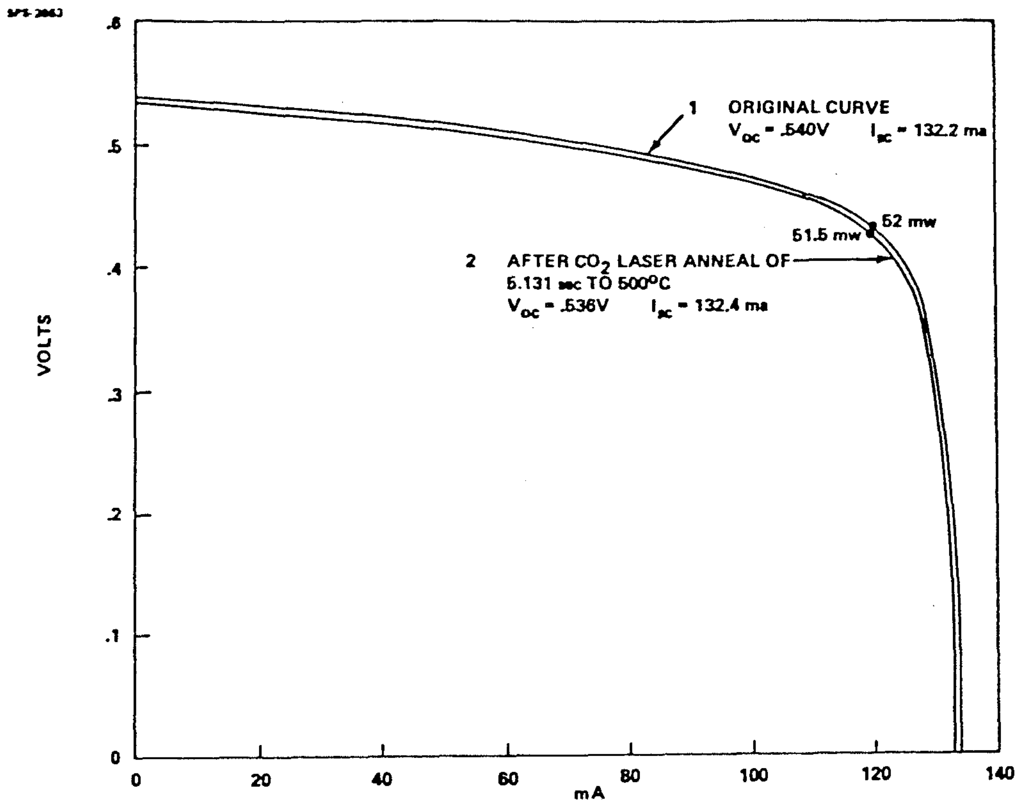

Figure 8 ; CO_2 Laser Annealed Solar Cell Without Coverglass, Solarex Cell No. 44

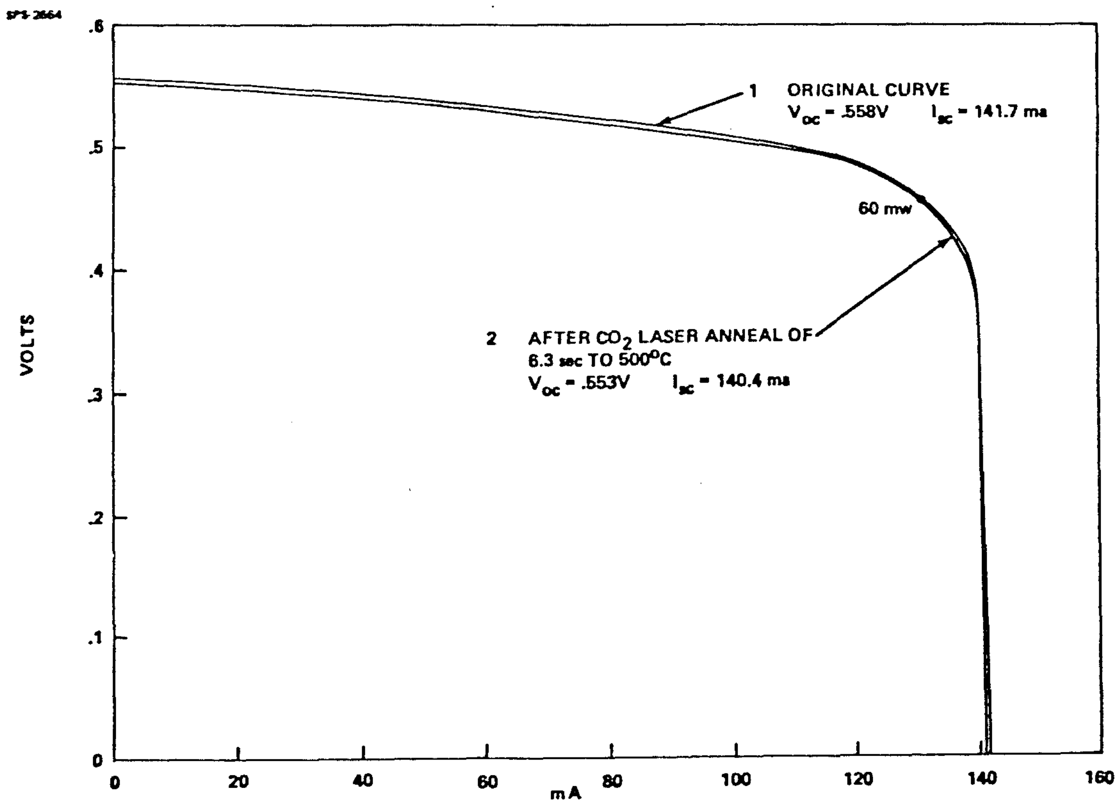

Figure 9 ; CO_2 Laser Annealed Solar Cell Without Coverglass, Solarex Cell No. 45

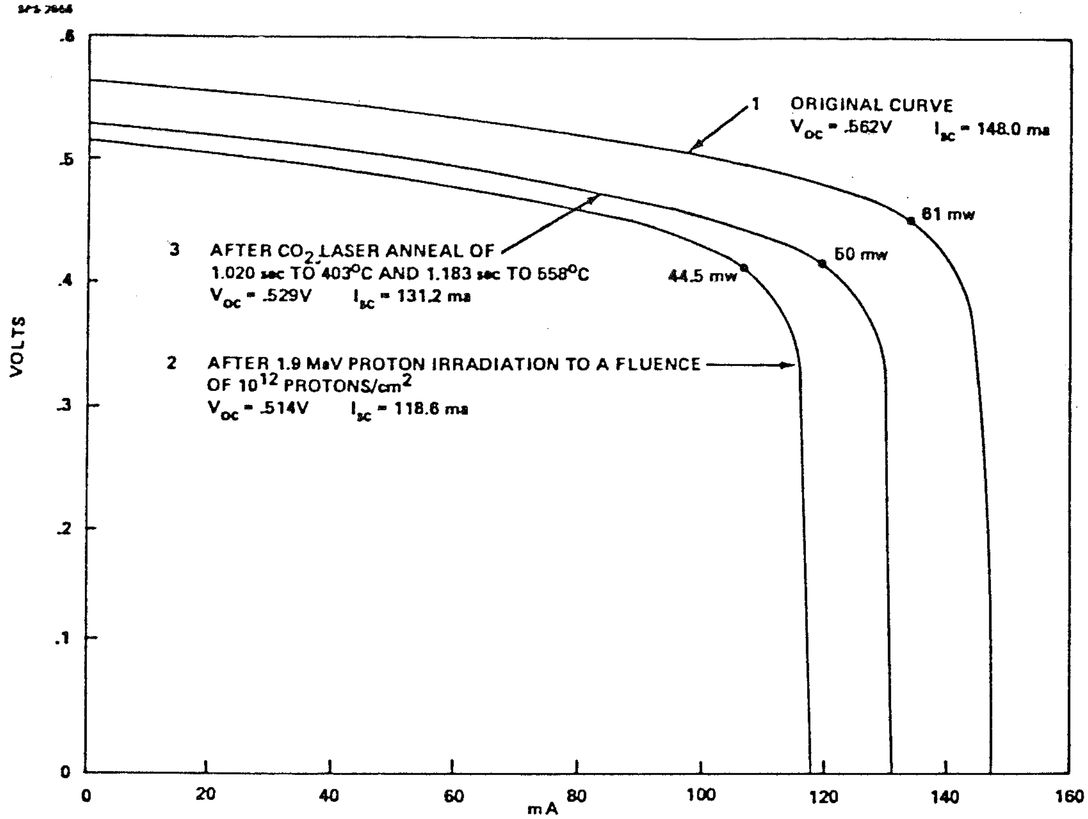

Figure 10; CO_2 Laser Annealed Solar Cell Without Coverglass, Solarex Cell No. 16

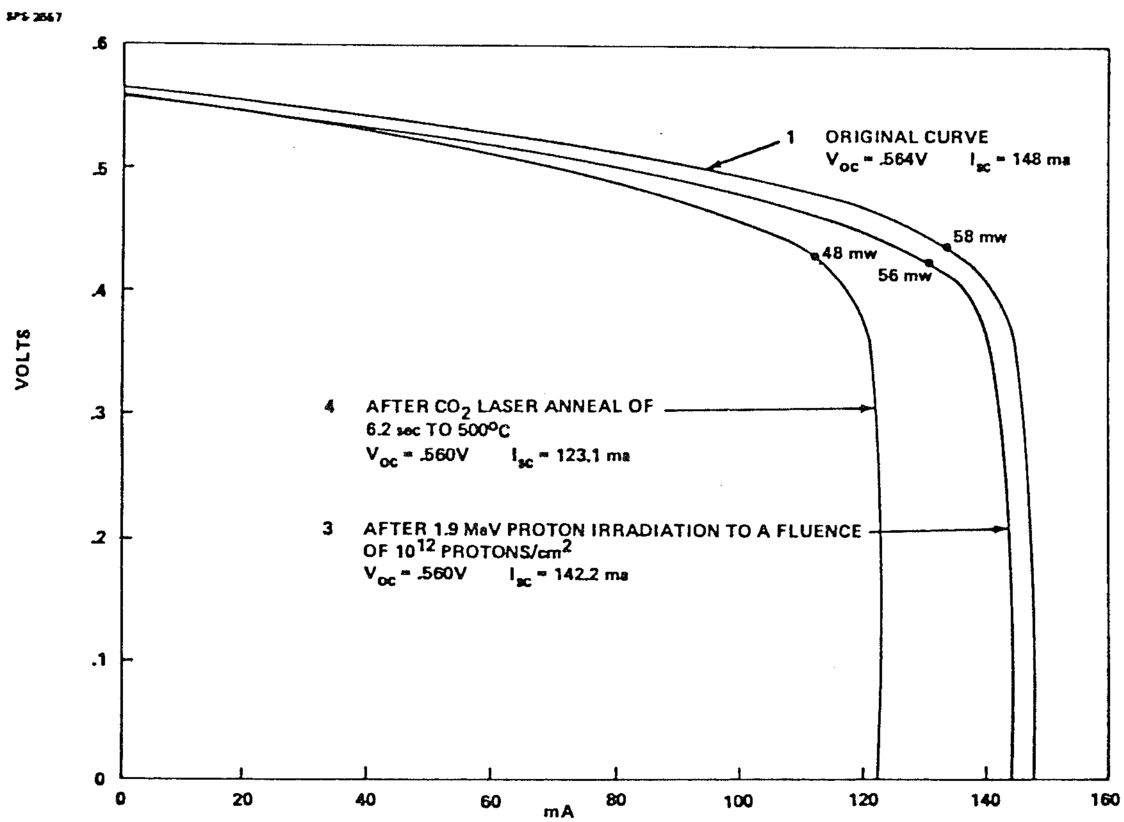

Figure 11; CO_2 Laser Annealed Solar Cell Without Coverglass, Solarex Cell No. 18

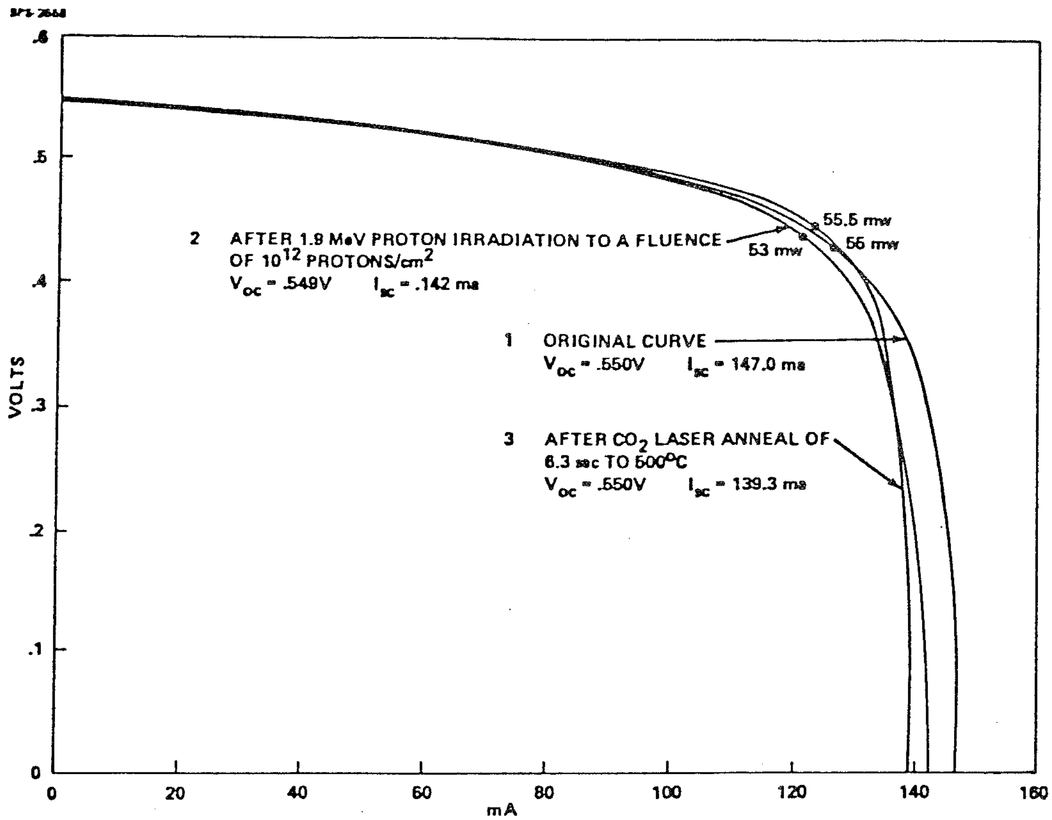

Figure 12 ; CO_2 Laser Annealed Solar Cell Without Coverglass, Solarex Cell No. 19

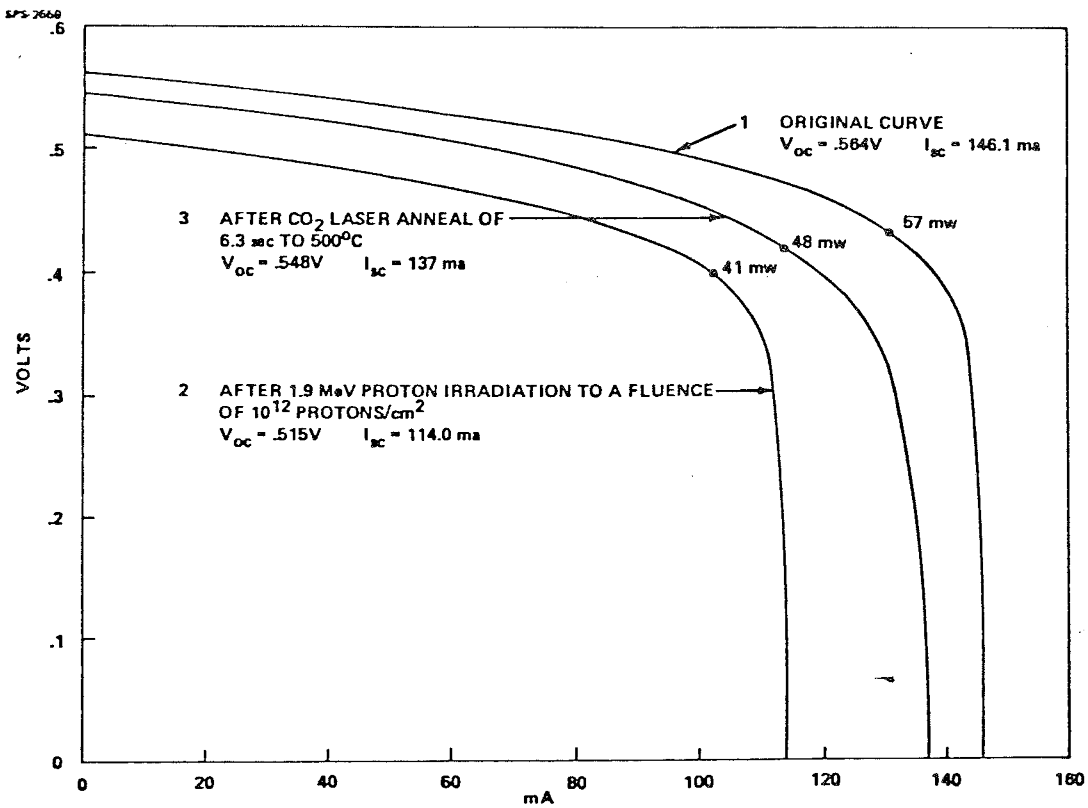

Figure 13 ; CO_2 Laser Annealed Solar Cell Without Coverglass, Solarex Cell No. 20

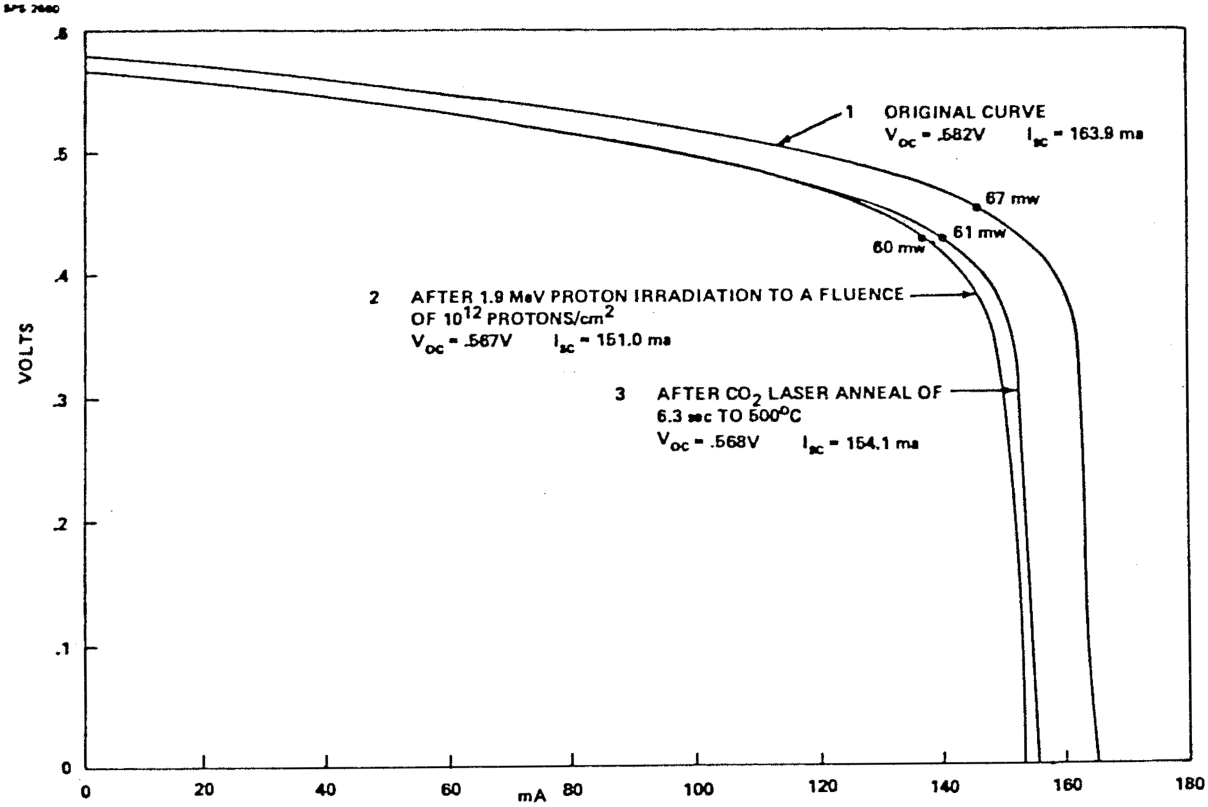

Figure 14; CO_2 Laser Annealed Solar Cell Without Coverglass, O.C.L.I. Cell No. 31

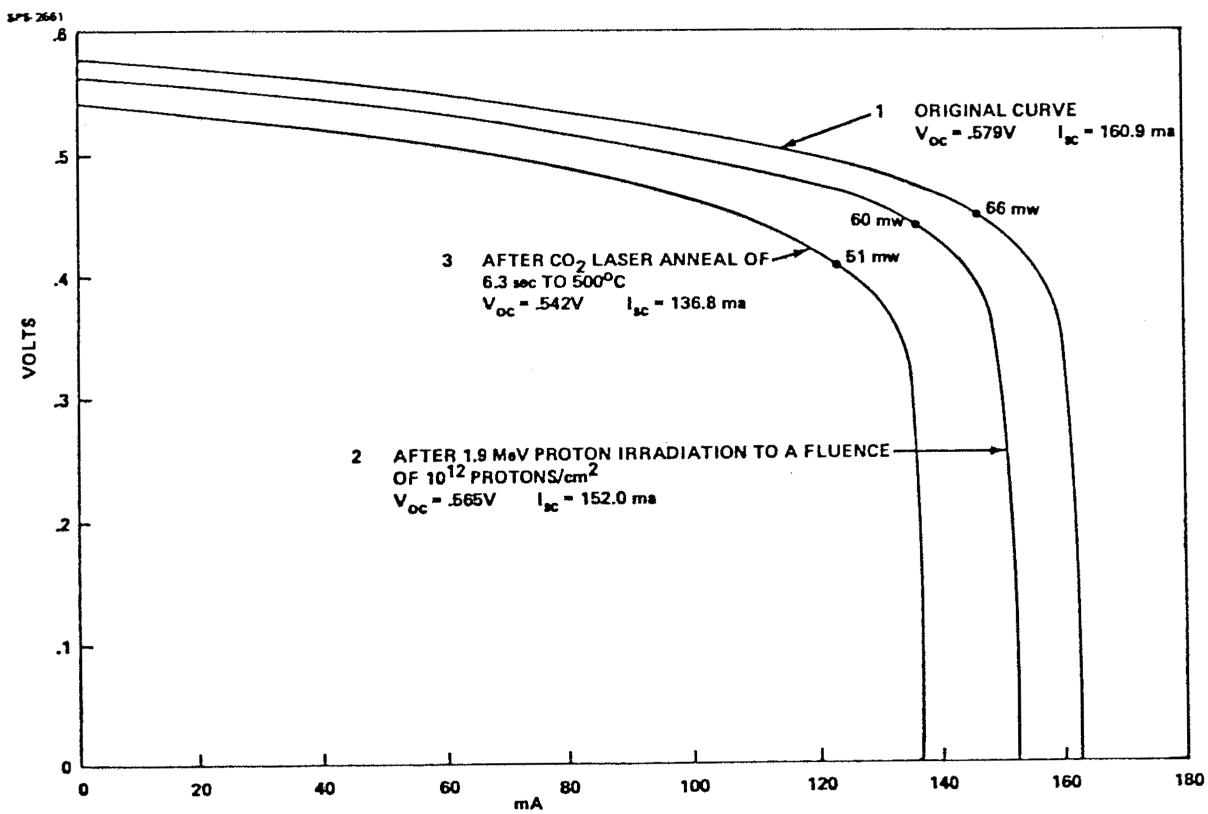

Figure 15; CO_2 Laser Annealed Solar Cell Without Coverglass, O.C.L.I. Cell No. 32

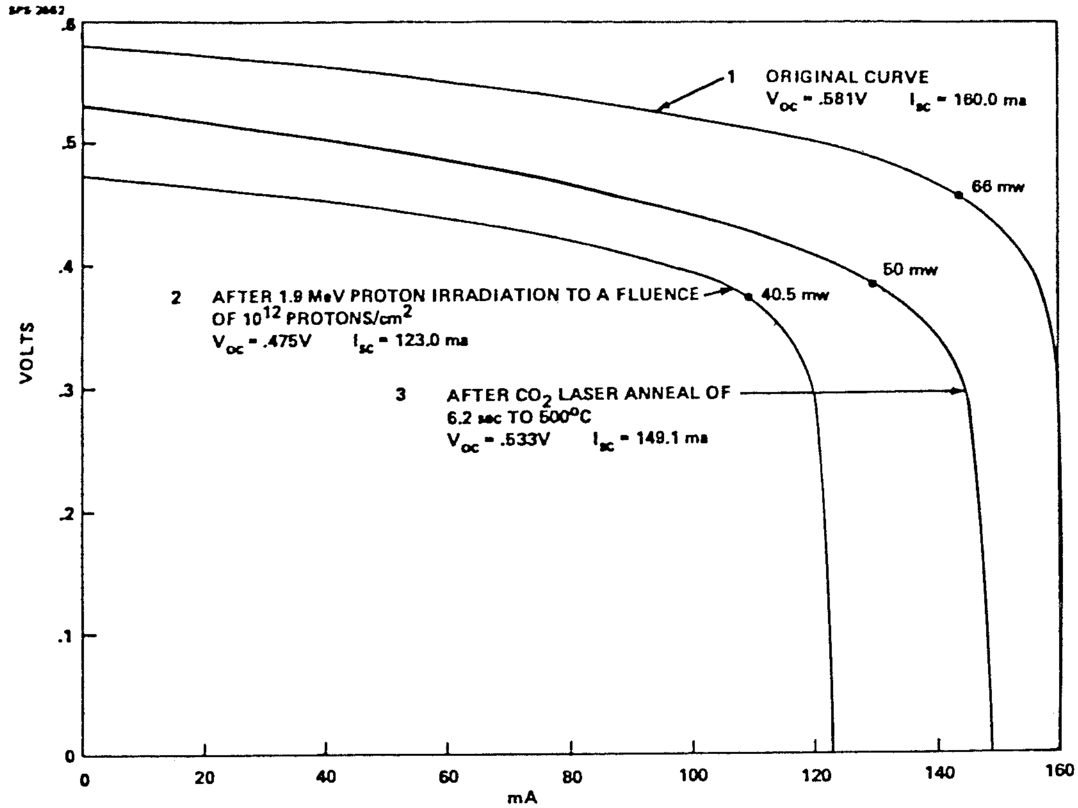

Figure 16; CO_2 Laser Annealed Solar Cell Without Coverglass, O.C.L.I. Cell No. 33

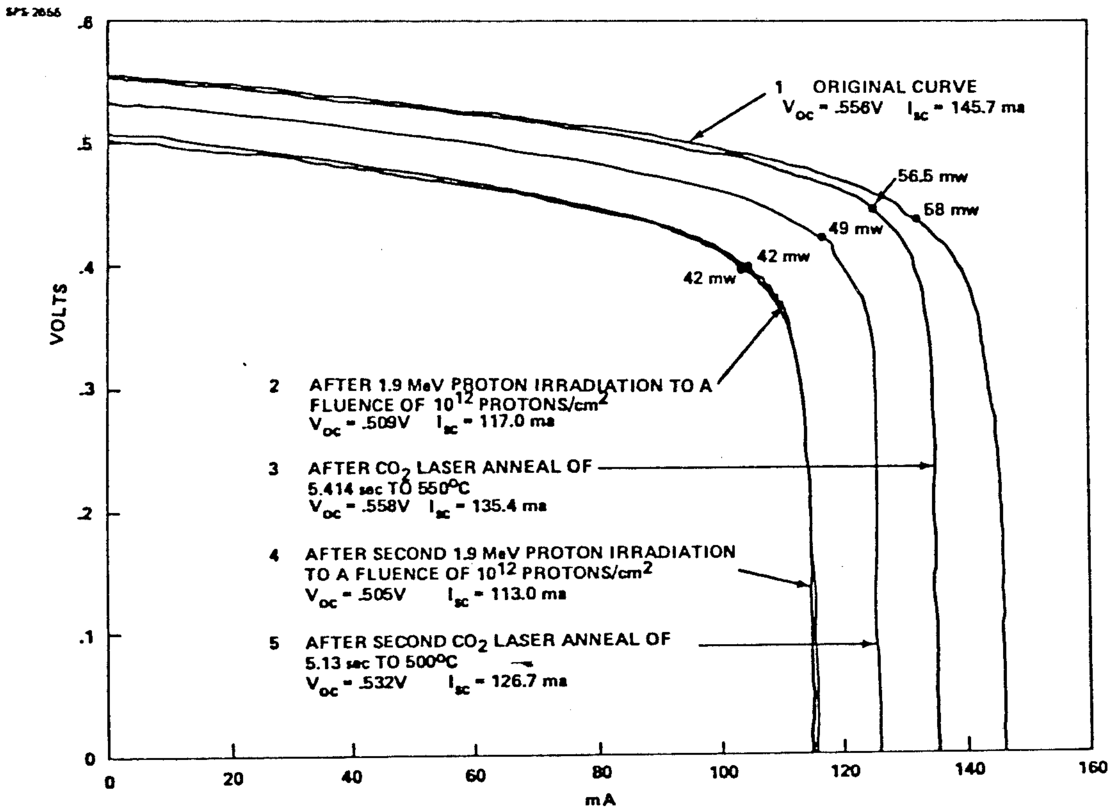

Figure 17; CO_2 Laser Annealed Solar Cell Without Coverglass, Solarex Cell No. 13

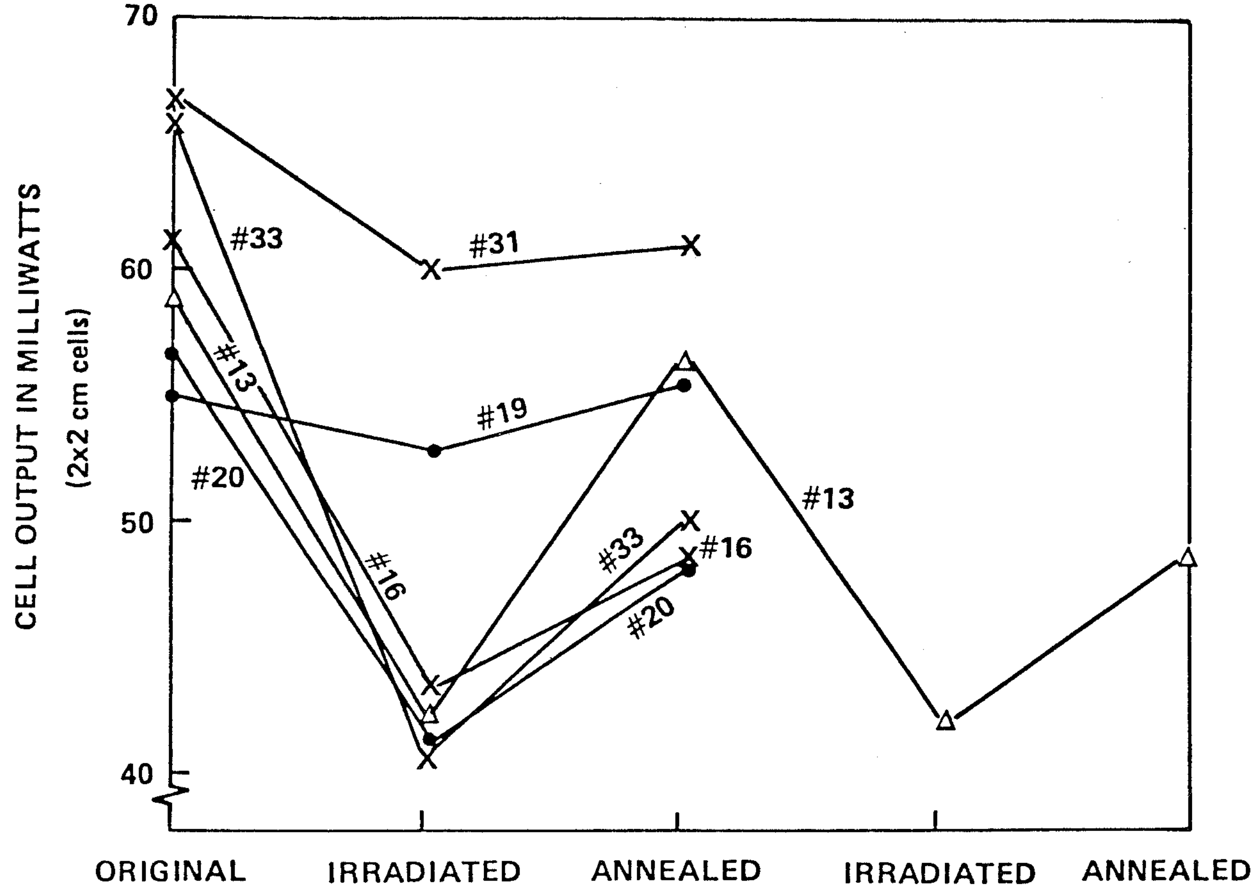

Figure 18; Degradation and Recovery of Maximum Power for Laser Annealed Solar Cells