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PREFACE

The work described in this report was performed by the Guidance and Control Division of the Jet Propulsion Laboratory.

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The authors are indebted to Dr. Bruce Anspaugh for performing the irradiations and associated electrical measurements and to Mr. Robert L. Mueller for performing and/or monitoring the environmental tests and associated electrical measurements described in this report.

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ABSTRACT

Results of a previous JPL Lithium-Doped Solar Cell program indicated that such cells can exhibit high efficiencies and radiation tolerance. This report presents the results of an additional effort to determine the technology readiness of lithium-doped silicon solar cells with respect to use in space programs. This effort was comprised of a pilot line fabrication program and an evaluation of the pilot line cells after exposure to environments representative of those presently imposed on state-of-the-art, nonlithium-doped silicon solar cells. A summary of the results of the effort is presented. It is concluded that further process improvements are required, particularly with respect to the P/N junction diffusion and the electrical contacting technique (including solder coating). It is also concluded that lithium-doped cells can be fabricated to exhibit high efficiencies, uniform cell-to-cell recovery characteristics after exposure to 1-MeV electrons, and good stability in most environments investigated (the only exception being the thermal shock environment).

I. INTRODUCTION

On the basis of the results of the JPL Lithium-Doped Solar Cell Program (Ref. 1-23) it was determined that lithium-doped solar cells fabricated from oxygen-rich silicon could present advantages with respect to both radiation hardening and initial cell efficiency. Lithium-doped silicon solar cell lots having average efficiencies of 11.9% and efficiencies as high as 12.8% in an air mass zero spectrum at 28°C had been obtained. Experimental cell design matrices were used in conjunction with analysis of the capacitance-voltage characteristics of the cells to provide information concerning the lithium donor density gradient near the junction as a function of the lithium diffusion schedule (Refs. 1-4). The results of these investigations were used to obtain a high degree of consistency and improvement in cell radiation annealing characteristics.

While a good understanding of the effects of lithium-doped cell design and processing on pre- and postirradiation characteristics was obtained, and a reasonably good understanding of the interaction among lithium, silicon, oxygen, and radiation-induced defects had been built up, there still remained some significant questions. In particular, there were questions about how the cells would behave under space-type environmental conditions, how conditions of temperature cycling and temperature soaks affect the radiation recovery characteristics, and what the effects of contact sintering on cell pre-and postirradiation cell characteristics would be. Moreover, there remained a major question about whether the processes involved in the fabrication of lithium-doped solar cells could be scaled-up to provide an economically viable alternative to the state-of-the-art N/P solar cell, and whether such process modifications could be effected in such a way as to obtain cells with consistent pre- and postirradiation characteristics. To address these questions, two complementary programs were set up by the Jet Propulsion Laboratory. One program was for pilot line production of lithium-doped silicon solar cells, which was awarded to Heliotek, Division of Textron under JPL contract, and the other was an extensive in-house evaluation program of these cells by the Jet Propulsion Laboratory.

II. OBJECTIVES

The objectives of the lithium-doped cell pilot line fabrication program consisted of the following:

(1) Development of processes amenable to large scale production of high-efficiency, radiation resistant, lithium-doped solar cells with emphasis on such factors as reproducibility, reliability, economy, compatibility with state-of-the-art array fabrication requirements, compatibility with space-type environmental requirements, and cell-to-cell uniformity of electrical and mechanical characteristics.

(2) Delivery of 300 cells per month for four months and 3000 per month for one month, the 3000-cell lot being fabricated within a 30-calendar-day time period. Since it was recognized at the outset that this program entailed a significant number of technical problems, JPL decided to standardize with a particular cell design for the life of the program. The choice of cell design is considered to be somewhat arbitrary simply because no true optimum cell design has yet been found; that is, no design was shown to be clearly superior to all other designs, but rather a band of "good" designs was determined encompassing a range of lithium diffusion schedules that appear at this time to be superior to others. To maintain compatibility with the most commonly used solar cell dimensions, the cell dimensions were specified as nominal 2 cm x 2 cm x 0.035 cm. The contact material was specified as titanium-silver with solder coating. A six-grid line top surface contact having a contact bar along one edge of the cell was specified, with an area contact to the bottom surface. Thus, in configuration, the lithium-doped solar cells were quite similar to the Mariner-class solar cells presently used by JPL. The minimum cell efficiency was specified to be no less than 11% on the basis of an area of 3.8 cm^2 as measured in a solar simulator having an AMO spectrum and intensity at a cell temperature of 28 ±1°C. The lithium diffusion schedule was specified as 3 h at 360° C, on the basis of results of previous work in lithium diffusion schedule optimization. This previous work had indicated that the specified

diffusion schedule would result in very uniform postirradiation recovery characteristics and would provide a high degree of recovery at the relatively high 1-MeV electron fluence of 3×10^{15} e/cm^2.

It should be mentioned here that the extent of technical difficulties encountered in scaling-up the lithium-doped cell process, in particular with respect to the P/N junction diffusion operation, was in fact underestimated, and as a result it was impossible to fabricate the 3000-cell lot within the funding constraints of the program. Therefore, a major objective of the program was not achieved. A good deal of valuable information, however, was obtained and several major problem areas were defined. These will have to be resolved before the lithium-doped solar cell can become a viable alternative to the state-of-the-art N/P solar cells (Ref. 24).

The objective of the JPL lithium-doped solar cell test program was to determine the effects of various environments on the performance of both irradiated and unirradiated lithium-doped solar cells. To this end, cells fabricated under the pilot line program were exposed to temperature-humidity soaks, thermal shocks, vacuum-temperature soaks, high-temperature soaks, solder melt soaks, and irradiation by several fluences of 1-MeV electrons. Electron irradiations were performed on solar cells exposed to one or more of the foregoing environments and on cells as received, to determine whether exposure to these environments resulted in significantly different post-irradiation recovery characteristics as a function of annealing at 60°C. The cells exposed to the various environments, as well as representative unexposed cells, were evaluated electrically by means of current voltage characteristics obtained in a solar simulator having a spectrum and intensity representative of air mass zero conditions at a cell temperature of 28 ±1°C. The cells were evaluated mechanically by pull strength tests performed on both N and P contacts. The most important problem area delineated by these tests was associated with the apparent fragility of the lithium-doped solar cell contacts (solder-coated) after exposure to thermal cycling of +100 to -196°C. While solder-coated state-of-the-art N/P solar cell contacts fabricated from evaporated and sintered titanium silver are quite sensitive to this test, the lithium-doped solar cells appear to be even more vulnerable, and further work in improving the resistance of lithium-doped cells to thermal cycle mechanical degradation is indicated if a high degree of reliability is desired.

III. SUMMARY OF RESULTS OF PILOT LINE

A rather complete discussion of the lithium-doped solar cell pilot line practices and pitfalls is given in Ref. 24. For the sake of completeness, a brief discussion of some of the major results will be presented here. Firstly, it should be noted that the average efficiency of the last two lots (Lots 3 and 4) of lithium-doped solar cells was about one efficiency group lower (that is, about 10% lower in power output) than the efficiencies of the cells in the first two lots (Lots 1 and 2). The first two lots yielded 50% of the cells with efficiencies greater than 12%, with efficiencies of the delivered cell ranging from 11 to as high as 12.7%, as measured at AMO spectral and intensity conditions in a solar simulator at a temperature of 28 ±1°C. Lot 4, on the other hand, had delivered cell efficiencies ranging from 11 to only 12.1% which, although certainly competitive with state-of-the-art N/P solar cells, is considerably below the potential efficiencies exhibited by Lots 1 and 2.

The principal reason for this apparent negative progress is to be found in the scale-up of the P/N junction diffusion operation. The P/N junction diffusion technique utilized for the first two lots, and which has been utilized in the past, involves the use of boron trichloride with a nitrogen carrier gas. Because of reactions on the silicon surface, the number of cells that could be diffused simultaneously to yield consistently high-efficiency solar cells was limited. In the past, only 10 to 20 cells per run could be successfully diffused. Over the course of the present contract this number was increased to a maximum of 40 cells per diffusion run. While this is a significant increase percentage-wise, it is still far from competitive with the number of cells that are diffused for fabrication of the state-of-the-art N/P solar cells. Since one of the objectives of this program was to make the lithium-doped solar cell economically competitive with state-of-the-art N/P cells on the basis of dollars per end of mission watt output, and since the lithium-doped cells should be inherently more expensive than nonlithium-doped cells because of the additional operations required to introduce the lithium, it is necessary to make all nonlithium associated operations at least as economically competitive as those used for the N/P cell fabrication. Therefore the major investigative efforts on this program were associated with scaling-up the P/N junction diffusion to allow diffusion of approximately 150 cells or more simultaneously. After a considerable amount of work, a diffusion system using boron trichloride with oxygen rather than nitrogen as the carrier gas was developed; it allowed the simultaneous diffusion of up to 150 cells with good uniformity and reproducibility; however, as observed above, the average power output of the cells was 10% below that of the cells diffused by nitrogen carrier gas system. Clearly, more work is needed in this area to recover this 10% power loss.

Electrical measurements made by the contractor on cell Lot 4 indicated rather large variations in curve shape. Analysis indicated that a combination of series resistance effects and the apparent formation of a metal to semiconductor barrier was the cause of the variations. Measurements of sintered and unsintered cells indicated that the barrier formation effects occurred only in the case of sintered cells. The severity of barrier formation appears to be quite variable and hence might be a result of process variations such as contamination during evaporation, variations in the amount of oxide on the back surface, and variations in bulk resistance and/or lithium concentration at the surface. While the normal sintering schedules consist of exposure for 2 min at 605°C, experiments were performed at 360°C for a series of 5-min cycles. Although some cells did not exhibit barrier formation until exposure to three 5-min heat cycles at 360°C, others exhibited the effect after the first 5-min cycle. The contractor points out (Ref. 24) that the sintering operation tends to optimize the silicon monoxide coating by decreasing light absorption in the short wavelength region, and this normally results in improved short circuit current. Thus, elimination of the sintering to eliminate the barrier formation may have an adverse effect on the short circuit current parameter. Further work is required in this area.

Still another problem was encountered in fabricating Lot 4 of the lithium-doped solar cells, namely the downward trend in short circuit current parameter with each successive lithium diffusion. This amounted to a loss in short circuit current of between 5 and 10 mA somewhere between the boron diffusion and contact evaporations. The loss was traced to the lithium evaporation step. Thorough examination of the evaporation system showed that lithium was present throughout the lower part of the vacuum system(i.e., in the diffusion pump, cold trap, valves, etc.). A thorough cleaning of the entire vacuum system resulted in restoration of the short circuit current. In production, however, this could be a very costly process and it appears that further significant effort is required to circumvent or minimize the necessity of such a time-consuming maintenance procedure.

The lithium diffusion schedule specified by JPL and used for all cells fabricated throughout this contract was based on results previously reported on the correlation between the lithium diffusion schedule and the electrically active lithium density gradient near the junction, and on the correlation between the lithium density gradient near the junction and the resultant solar cell irradiation recovery characteristics (Refs. 1-3). The lithium diffusion schedule of 3 h at 360°C was expected to give both uniform irradiation recovery characteristics and a high degree of radiation-induced defect neutralization after exposure to 1-MeV electrons to a fluence of $3 \times 10^{15} e/cm^2$. This was, indeed, found to be the situation. Capacitance-voltage measurements (Refs. 3, 11, and 15) indicated electrically active lithium donor density gradients near the junction consistent within about a factor of three for all cells measured. Thus, it is felt that the cell design used, while possibly not optimized, is certainly a good one. The period of time required for lithium diffusion, however, appears to be a production rate-limiting step since it is approximately six times that required for the boron diffusion operation. For large production quantities, three lithium diffusion furnaces would be required for each junction diffusion furnace, unless a continuous lithium diffusion furnace is developed or unless a significantly shorter lithium diffusion time can be utilized.

Except for the possibility of requirements for extensive evaporation system cleaning, the lithium introduction operations, that is, lithium evaporation and lithium diffusion, were successfully scaled-up. The P/N junction diffusion operation, while successful in scaling-up the quantities, requires more work to extract the high efficiency potential of lithium-doped solar cells. Also, something must be done to eliminate the variable metal-to-semiconductor barrier formation as a result of contact sintering. Since the sintering appears to be required more for the treatment of the silicon monoxide coating than for the contact itself, perhaps the use of different antireflection coating (e.g., TiO) might allow the elimination of the sintering and the associated problems. The contractor estimates that for lithium-doped cell quantities of 3000 cells per month, the lithium diffusion time of 3 h would not be particularly rate-limiting, but significantly larger production quantities would require some modification.

IV. ENVIRONMENTAL TESTS

As discussed previously, one of the two major programs comprising this effort was to determine the effects of environmental tests, similar to those imposed on state-of-the-art Mariner type N/P solar cells, on the mechanical and electrical characteristics of unirradiated and irradiated lithium-doped solar cells fabricated as a result of the lithium-doped solar cell pilot line. Literally tens of thousands of data points were obtained as a result of this program. A summary of the results are presented in Tables 1 through 51. These tables present data pertinent primarily to Lots 1 and 4, while similar data is available for Lots 2 and 3. The discussion given below will present some conclusions and comparisons that are of particular interest to the author and in no way reflect the number and types of comparisons that can be made by this comprehensive body of data. That is to say, while a vast number of comparative permutations exist, this report has been quite selective and subjective as to the types of comparisons made.

An important question remaining at the end of the previous program was what the effect of the sintering operation would be with respect to pre-and post-irradiation cell characteristics. Lot 1 was of interest because it compared lithium-doped cells fabricated with both sintered and unsintered silver-titanium contacts. This lot also made use of the best P/N junction diffusion process available with respect to resultant cell efficiency.

Lot 4 is of interest because it made use of a P/N junction diffusion that, while not optimized for resultant cell efficiency, did allow the diffusion of large batches of cells simultaneously. Moreover, had funds been available to complete the 3000-cell lot 5 within a 30-day time period, it is basically the junction diffusion processes used on lot 4 that would have been utilized. Consequently, two additional environmental tests were imposed on cells from Lot 4, namely, the vacuum-temperature test, in which the cells were stored at pressures of $1.3 \times 10^{-3} N/m^2$ (10^{-5} torr) or less at a temperature of 125°C for 12 days, and the humidity-temperature test in which cells were stored at a temperature of 80 ±5°C and a relative humidity of 90 ±5% for a period of two weeks. Tests performed on both Lots 1 and 4 consisted of thermal shock in which the cells were subjected to 5 temperature cycles between +100 and -196°C with a 1-min soak at each extreme, a high-temperature soak in which the cells were stored at a temperature of 150°C for 12 days, and a solder melt test in which cells were exposed to a temperature of 215°C for 2 min. Irradiation tests by 1-MeV electrons to fluences of 1×10^{14} and 3×10^{15} e/cm^2 with subsequent annealing at 60°C were also made on environmentally exposed cells as well as unexposed cells.

A. ENVIRONMENTAL TEST TECHNIQUES

1. Solar Simulation

The illumination source used throughout this test program was a Spectrolab Model X25L close-filtered solar simulator. This simulator uses 19 lenticular lenses in the optical system; these lenses filter and uniformly distribute a relatively collimated light beam at specific distances from a 2.5-kW short arc xenon lamp so that the resultant spectral distribution approaches that of space sunlight. The light beam provides a 30.5-cm-diameter beam pattern having a uniformity of approximately ±2% at the test plane and an illumination level of 140 mW/cm^2 (one solar constant). All solar cells measured under the solar simulator were measured at 140 mW/cm^2 and a test temperature of 28 ±1°C. The solar intensity and spectral integrity of the solar simulator were constantly monitored and maintained in conjunction with the NASA/JPL solar cell standardization program.

2. Contact Pull-Strength Test

The tabs used in the performance of the pull-strength tests were fabricated from tin-plated, photo-etched Kovar (iron, nickel, and cobalt alloy), having a thickness of 0.1 mm. Each test tab was bent in a forming fixture at a 90-deg angle before being soldered to the cell. The soldering operation was accomplished semiautomatically by use of a Sippican RS-333 Reflow Soldering System[1]. A solder preform was added to all nonsolder-coated solar cells; its composition was 62% tin, 36% lead, and 2% silver.

The area on the cell contact to which the tabs may be soldered was carefully defined to eliminate extraneous effects and to enhance the uniformity of cell-to-cell contacts. After soldering, the tab was inspected to ensure its location within the area allowed, as shown in Fig. 1, and to determine that the

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[1] Sippican Corp., Industrial Products Division, Mattapoisett, Mass.

joint itself was acceptable. The solder joint area, assuming an additional area of about 10% for the solder fillet, was calculated to be 3.42 mm^2. Tab-cell joints that exhibited excessive solder, incomplete solder, or an incomplete solder joint were rejected and not tested. It was found that many apparent inconsistencies in contact pull-strength results were the result of improper tab soldering techniques and that strict adherence to the solder joint inspection criteria was mandatory if meaningful results were to be obtained.

A second major source of anomalous pull-strength test results was found to be the result of variations in the soldering technique, and the precise control associated with the following technique described has served to greatly minimize such variations. To minimize electrode heating during the soldering reflow operation, the solder time-temperature profile or heat cycle was pulsed twice at a reduced voltage to obtain consistent and uniform soldering. An applied electrode load of 3.3 kg was used, and a total elapsed time of about 4 s for each soldering operation was maintained. This operator-independent soldering technique was developed to minimize the effects of variations in the soldering operation.

A third major source of anomalous pull-strength test results was found associated with variations in the pull rate, and careful control of the pull rate minimized variations in pull strength. The contact pull-strength tests were performed with an Instron Universal Material Test Machine, Model TM-1.[2] A special test fixture was used, which adapted to cells of varying dimensions so that the cells could be mounted and properly aligned perpendicular to the direction of the applied load. The contacts were pulled at a constant rate of 0.084 ±0.008 cm/s, which corresponds to 5.04 cm/min, until complete separation occurs. The resultant contact strength was recorded on a strip chart recorder in the form of a stress-strain characteristic curve. After separation, the test specimens were reinspected and analyzed for the interfacial characteristics that led to the separation (e.g., solder failure, contact delamination, broken cells, defective tabs, etc.). By careful control of the materials, processes, techniques, and inspections involved in performing the contact pull-strength tests, the effects of extraneous variables on the test results were minimized and the validity of the test results greatly enhanced. Further details are given in Ref. 25.

[2] Instron Engineering Corp., Long Beach, Calif.

3. <u>150°C Storage for 12 Days</u>

The tests were conducted in a self-contained Missimers Model FT10-100X500 temperature oven capable of operating at set-point temperatures from -73 to 260°C (-100 to 500°F). To minimize temperature gradients throughout the workspace (0.28 m^3), air was recirculated by employing the use of an internally mounted corrosion-resistant blower. A vapor-sealed shaft assembly was used to couple an externally mounted motor to the blower through the insulated wall of the test chamber to assure long trouble-free operation and maintain test validity. The workspace was 76 cm wide × 61 cm deep × 61 cm high and was heated by rapid-response electric air heaters mounted so that radiant heat energy would not be directly transmitted to the test specimens. The heaters were cycled by heavy-duty magnetic contactors. To prevent an excessively high temperature, a safety thermostat was also included in the control circuit. Temperatures within the workspace were monitored and controlled by a Brown thermocouple potentiometer instrument. The system has a 30-cm diameter circular chart for recording oven temperature and a circular cam that is preshaped for programming temperature. The temperature control assembly is said to have an accuracy of ±0.25% and sensitivity of 0.03% or better of full scale. Besides having the feature of a thermocouple break protection circuit, temperature control was provided by a time-proportional control instrument.

The normal procedure used for these long-term temperature storage tests was to cycle the liquid refrigerant (CO_2) and/or hot gas and bypass the solenoid valves, thereby permitting the compressor to run continuously to eliminate short cycling, which would result in compressor overheating due to frequent starting. Heat balance, which depends on set-point temperature, is provided by the radiant heat source and two cascaded mechanical refrigeration systems.

For handling of solar cells to and from the Missimers oven, a 28 × 41-cm aluminum tray lined with an 0.317-cm-thick Teflon sheet was used. The test cells were laid with the sensitive surface facing upward in the tray. Power for the oven was never reduced or turned off. The mass of the steel tray and teflon sheet caused some lag in cell temperature rise or decay rates when they were placed or removed from the temperature oven, thereby minimizing and/or reducing thermal stresses resulting from shock. For additional details see Ref. 26.

4. Thermal Shock

The thermal shock tests were accomplished by manually and rapidly cycling the cells through baths of boiling distilled water (+100° C) and liquid nitrogen (-196° C). To facilitate handling of the cells during cycling and to eliminate the possibility of cells striking one another, the cells were loaded in a specially fabricated teflon coated cage, designed to restrict cell motion. The cells, before immersion in either of the baths, were lowered, in the cage, to a region just above the surface of the bath fluid and held for one minute before complete immersion was effected. After immersion in the fluid, the cells were again held just above the surface for one minute. A copper-constantan thermocouple attached to one cell was used to ascertain the time-temperature profile by means of the millivolt output of the thermocouple.

5. Temperature-Humidity Tests

The temperature-humidity environmental tests described in this report were conducted in a Conrad Model FD 32-5-S test chamber, which produces a humid condition by means of a stream-generating system in which moisture is admitted to the chamber in the form of low-pressure steam. A relative humidity of 95% was maintained by a programmable cam in which both the dry bulb temperature and wet bulb temperature were independently controlled from cam disks cut to produce a predetermined succession of temperatures. As these two cams rotate, at any one moment a dry bulb temperature is produced concurrently with a wet bulb temperature in the test chamber, which yields the desired relative humidity. The test specimens (solar cells) were placed on Teflon-coated metal screen cages adjacent to the wet bulb and dry bulb humidity instruments. To minimize water condensation on the test samples, an inverted V-shaped shield was installed between the test specimens and the top of the chamber. The temperature of 80 ±2° C was maintained by using a proportional temperature controller and was monitored by means of Leeds and Northrup Model Speedomax G temperature strip chart recorders. The test specimen heat source was provided by Inconel-sheathed electrical heaters. The dehumidifying operation was controlled to minimize water condensation on the test specimens by employing a refrigeration coil, which was located under the work deck at the floor of the chamber. This coil is fed refrigerant when the dehumidifying solenoid is in the open mode. When the coil cools below the dew point in the chamber, moisture condenses onto the coil. As the coil is brought below the freezing point of water, the moisture is trapped or collected on the cooled coil as frost. When the dehumidifying period is completed, the frost is melted off the coil and the precipitated water is then drained out of the chamber. Additional details are given in Ref. 27.

6. Vacuum-Temperature Test, 125°C for 12 Days

The vacuum chamber utilized for these tests was a modified CEC chamber, the modifications including replacement of mechanical valves by pneumatic valves activated by an external control unit automated to insure maintenance of specified pressure levels. The system utilizes a Welch, Model 1397 mechanical roughing pump and a high-vacuum diffusion pump. The temperature source consists of a cylindrical container 40.6 cm (16 in.) high and 21.6 cm (8.5 in.) in diameter. Ten 250-W Chromalux strip heaters are mechanically mounted to the exterior of the cylinder with metal bands, with parallel attachments to the heaters by means of copper interconnectors. The heat input is varied by means of a dual-type V20-20A Variac, with fine voltage control achieved through the control circuit within a Leeds and Northrop Speedomax H strip chart recorder, which also serves to monitor the temperature. The test specimens (cells) were mounted on five separate circular aluminum plates (17.8 cm in diameter, 0.08 cm thick), which were stacked with a spacing of 5 cm within the cylinder.

7. Solder-Melt Test, 215°C for 2 min.

The test articles (cells) were mounted on an aluminum test plate having dimensions of 5 cm (2 in.) × 11.45 cm (5 in.) × 0.16 cm (0.062 in.), which in turn was mounted on a Model SP-A-1025B temperature-controlled hot plate. The temperature was monitored by means of a copper-constantan thermocouple attached to the center of the solar cell mounting plate in conjunction with a Leeds and Northrop Millivolt Potentiometer, Model 8690. The temperature was adjusted utilizing the test plate upon which were mounted dummy cells. The test fixture was designed to accommodate a total of 8 cells having dimensions of 2 cm × 2 cm. The variation of temperature from specified temperature was found to be no greater than ±3°C. Approximately 1.5 min were required to achieve the desired temperature, after which the cells (on the test plate) were allowed to remain on the hot plate for 2 min. The test plate was then removed from the hot plate and allowed to cool, with particular attention given to minimize disturbance of the cells while the solder was molten.

8. Electron Irradiation

The radiation laboratory is built around a 3-MeV Dynamitron accelerator manufactured by Radiation Dynamics Inc. This machine produces a useful electron beam in the range of energies between 0.6 and 2.3 MeV at electron currents up to 2 mA. This high current capability makes this machine ideal for the irradiation of large areas with high flux rates. The electron beam can be directed (horizontally) down a beam transport system into either one of two experimental areas. Patch panels installed in each area allow routing of signals to a central data area near the accelerator control console.

One experimental area is devoted to a semipermanent installation of a vacuum chamber designed for measuring radiation effects in solar cells. An Aerospace Controls Model 302 Solar Simulator is coupled into the vacuum chamber for producing a beam of light on a 5-in.-square test plane. The simulator beam closely approximates solar radiation at one astronomical unit in both intensity and spectrum. All optics are ground from 7940 fused silica for maximum resistance to radiation darkening. The target area is a temperature controlled block with a set point variable between -150°C and +150°C. Provision is made for the simultaneous irradiation of up to 14 solar cells on this target plane with subsequent *in situ* measurement of their electrical parameters using the solar simulator and a remote test console. A thin aluminum or copper scattering foil is used to spread the electron beam uniformly over the target area. A small Faraday cup is mounted in the center of the target area for measuring the electron exposure level. All areas struck by the beam are water cooled (including the scattering foil). A liquid nitrogen shroud in the chamber is used during solar cell radiations to trap diffusion and fore-pump oil (even though the pumping system is LN_2 trapped), and to cryopump the chamber.

B. ENVIRONMENTAL TEST RESULTS

1. Lot 1 Cells

a. Cells Environmentally Exposed Prior to Irradiation. These results can be neatly described after the 12-day test at 150° C and the 2-min test at 215° C, for both sintered and unsintered contact cells, by stating simply that there was essentially no electrical degradation in any of the electrical characteristics as a result of these two tests as shown in Table 52.

Table 52 also shows, however, that cells exposed to thermal shocks (5 cycles of +100 to -196° C) suffered very severe degradation of the electrical characteristics. The short circuit current was degraded by only about 2% for the sintered contact cells but around 12% for the unsintered contact cells. The open circuit voltage was degraded also by about 2% for the sintered contact cells and by about 5% for the unsintered contact cells. The maximum power degradation was very severe for both sintered and unsintered cells, and was degraded about 12% in the former case and 27% in the latter case. Thus, the maximum power degradation for the sintered cells was due primarily to curve shape degradation while for the unsintered cells it was primarily due to both curve shape degradation and short circuit current degradation. While the power loss was unacceptably high for both sintered and unsintered cells, the loss in nonsintered cell maximum power was about twice as great as that for the sintered cell power loss. It should be noted that this test is a particularly severe one, and not necessarily applicable to most missions; however, it is quite apparent that the panel designer who considers using lithium-doped cells fabricated to the same design used on this pilot line must carefully test the cells with respect to the particular thermal cycling and/or shock requirements appropriate to the mission for which the cells are being considered. It is unknown at this time what effect a large number of shallower temperature excursions would have on the cell operating characteristics; however, this might also be a problem area. In addition, for mission qualification of thermal cycling capabilities, the cells should be tested after mounting to a sample substrate and interconnected in the manner appropriate to the final design of the array, rather than tested as individual cells. If however, as in the case here, one wishes to determine whether the cell should be considered at all, it is appropriate to first test the cells alone under the thermal cycling conditions appropriate to the mission, since, if the cells alone cannot stand the environment, it is pretty well assured that the cells mounted and interconnected to form an array would be even less likely to survive. It should be noted that the cells tested here were solder coated, and it is not known whether the elimination of solder coating would mitigate the degradations associated with thermal shock tests or, indeed, if similar results would not be obtained with nonlithium-doped P/N cells fabricated in a similar manner.

b. 12-Day Soak at 150°C. As shown in Tables 1 and 2, prior to irradiation to a fluence of 1×10^{14} e/cm^2, the sintered and unsintered lithium-doped cells had approximately the same short circuit current and open circuit voltage as one another. The maximum power, however, of the sintered cells was 2 to 3 mW higher than the unsintered cells. After irradiation by 1-MeV electrons to 1×10^{14} e/cm^2, the average short circuit current and open circuit voltage of sintered and unsintered cells were similar to one another and the maximum power difference was now less than 2 mW due to an approximate 1% lower degradation rate after annealing of the unsintered cells. As shown in Tables 9 and 10, prior to 1-MeV electron irradiation to 3×10^{15} e/cm^2, the sintered cells had an approximate 3-mA lower short circuit current and 5-mW higher open circuit voltage than the unsintered cells, while the maximum power was still 2 mW higher for the sintered cell than for the unsintered cell. Since the selection of cells for the two different fluences was random, the differences in short circuit current and open circuit voltage between sintered and unsintered cells reflect the normal spread of possible values, whereas the maximum power seems to be approximately 2 mW higher for the sintered cells than for the unsintered cells in both cases. After exposure to and recovery from a 1-MeV electron fluence of 3×10^{15} e/cm^2, the short circuit current difference between sintered and unsintered cells is reduced to 1.5 mA, as opposed to the 3-mA difference prior to irradiation. The open circuit voltage of the sintered cells was now 13 mV higher than the unsintered cell, and the maximum power now 3 mW higher than the unsintered cells. In the case of the higher fluence exposures, the unsintered cells exhibited a 2% higher degradation rate than the sintered cells, whereas at the lower fluence, the unsintered cells exhibited a slightly lower degradation rate. It is not known whether this is a real effect or simply due to normal variations in the cells. In any case, the differences are not large.

c. <u>Cells Exposed for 2 min at 215°C (Solder Melt).</u> As shown in Tables 3 and 4, prior to irradiation, the sintered cells exhibited the 2- to 3-mW higher average maximum power than the unsintered cells, as was observed in the previous test. The degradation rate of the electrical parameters after recovery from exposure to 1×10^{14} e/cm^2 was not significantly different between the sintered and unsintered groups. As shown in Tables 11 and 12 after recovery from exposure to 3×10^{15} e/cm^2, the maximum power of the unsintered cells appear to degrade at a rate 3% slower than sintered cells, so that the recovered maximum power of both sintered and unsintered cells were similar. This can be contrasted with the results of the previous test in which the maximum power advantage of the sintered cells was maintained after exposure to this higher fluence.

d. <u>5 Cycles from +100 to -196°C (Thermal Shock).</u> The effects of this test on the performance of the lithium-doped solar cells were disastrous, and indicate a major weakness of solder-coated lithium-doped solar cells with titanium-silver contacts. Severe mechanical damage, consisting basically of silicon fracture as shown in Fig. 2, was observed on many cells subjected to this test. This not only adversely affected the mechanical strength of the contacts, but the electrical characteristics of the cells exposed to this environment as well. Most cells, whether exposed to environments or not, exhibited short circuit currents in the range of 140 to 145 mA, whereas cells exposed to thermal shock ranged from 129 to 144 mA. Open circuit voltages normally ranged between 590 and 620 mV and maximum power ranged normally between 60 and 67 mW. In constrast, as shown in Tables 5, 6, 13, and 14, cells exposed to the thermal shock exhibited values ranging between 579 and 610 mV and 46 and 65 mW for open circuit voltage and maximum power, respectively. Thus, it can be seen that while some cells exposed to the thermal shock environment suffered little electrical degradation, others exhibited very large degrees of electrical degradation. This is reflected in the larger 95% confidence limits associated with the thermal shock exposed cells, which were found to be usually 2 to 4 times as great as cells either not exposed to any environment or to cells exposed to the other environments. For cells exposed to this thermal shock test, a very decided difference was observed between the results of the cells with sintered contacts (Tables 5 and 13) and those with unsintered contacts (Tables 6 and 14). Whereas for unexposed cells and cells exposed to the other environments, very little difference was observed between the behavior of sintered and unsintered cells (in most cases the 95% confidence limits overlapped one another for sintered and unsintered cells), a very significant difference in all electrical parameters was observed between the sintered (Tables 5 and 13) and unsintered (Tables 6 and 14) cells exposed to the thermal shock. The electrical parameters of the sintered cells were invariably and significantly higher than those of the unsintered cells. As shown in Table 5, prior to exposure to 1-MeV electron irradiation at 1×10^{14} e/cm^2, the sintered group of cells showed average short circuit currents 14 mA higher, open circuit voltage 20 mV higher, and maximum power 11 mW higher than the average unsintered groups, shown in Table 6. Similar results were observed with respect to the 3×10^{15} e/cm^2 irradiation, with the average short circuit current, open circuit voltage, and maximum power of the sintered cells being 11 mA 20 mV, and 10 mw higher than the unsintered group (Tables 6 and 14 respectively). It is mentioned above that the 95% confidence limits of the unsintered group were approximately 2 to 4 times as large as those of the sintered group. After irradiation by 1-MeV electrons to 1×10^{14} e/cm^2, the recovered short circuit current, open circuit voltage, and maximum power of the sintered groups were, respectively, 11 mA, 21 mV, and 10 mW higher than the unsintered groups. After exposure to 1-MeV electrons to a fluence of 3×10^{15} e/cm^2, the recovered short circuit current, open circuit voltage, and maximum power of the sintered group were 9 mA, 12 mV, and 6 mW higher than for the unsintered group. It can be seen that the maximum power parameter after recovery from the high fluence (Tables 13 and 14) exhibits a somewhat smaller difference between sintered and unsintered cells than that after recovery from the preirradiation condition, due to a 2% slower degradation rate for the unsintered cells after recovery from this fluence.

e. Lot 1 Cells not Environmentally Exposed. The average initial electrical characteristics of the group of cells to be exposed to 1-MeV electrons at a fluence of 1×10^{14} e/cm^2 were very similar for both sintered and unsintered cells as shown in Tables 7 and 8, respectively. After recovery from exposure to this fluence, the electricial characteristics of both sintered and unsintered groups were also similar, indicating a similar degradation rate associated with the sintered and unsintered cell types. As shown in Tables 15 and 16, the group of cells selected for exposure to 1-MeV electron fluence of 3×10^{15} e/cm^2 show what is believed to be a quirk of selection in that the short circuit current of the sintered cells averaged 10 mA higher than that of the unsintered cells. This is not believed to be a "real" difference but rather the "luck of the draw" in selecting the samples for this test. The maximum power of the sintered cells shown in Table 15, averaged 2 mW higher than the unsintered cells prior to exposure. After recovery from exposure to this fluence, the short circuit current of the sintered cells appeared to average 7 mA higher while the open circuit voltage averaged 10 mV lower than the unsintered cells shown in Table 16. The recovered maximum powers were essentially similar for sintered and unsintered cells, indicating a 3% lower degradation rate for the unsintered cells. It is of interest to note that the short circuit current of the sintered cells prior to irradiation was unusually high compared with the other groups of preirradiation cells, having a short circuit current of 149 mA as opposed to the normal spread of 140 to 145 mA. In contrast, the unirradiated, unsintered cells were at the lower end of this range at about 139 mA. This gave rise to the 10-mA difference in short circuit current between sintered and unsintered cells. After irradiation, however, the recovered average short circuit difference was only 7 mA, indicating a lower degradation rate of recovered short circuit current for the unsintered cells, which coincidentally had lower starting short circuit current averages. While the maximum power of the sintered cells prior to irradiation to the high fluence was 2 mW higher on the average than for the unsintered cells (Tables 15 and 16 respectively), the maximum power averages for the sintered and unsintered cells after recovery from exposure to this fluence were essentially similar because of a 3% lower degradation rate in the maximum power parameter (composed of about a 1% lower degradation rate for short circuit current and a 2% lower degradation rate for open circuit voltage) applicable to the unsintered cells.

In summarizing the results of the cells exposed to the 1-MeV electron radiation fluences but not to the environmental tests, it can be seen that after recovery from the lower fluence (1×10^{14} e/cm^2), the average short circuit currents, open circuit voltages, and maximum powers, as well as the recovered degradation rates of these parameters, were similar for both the sintered and nonsintered cells. At the higher 1-MeV electron fluence (3×10^{15} e/cm^2), the average degradation rate of short circuit current, open circuit voltage, and maximum power appear to be lower for the unsintered cells than for the sintered cell. The results of the 12-day exposure to 150°C environment indicated an approximate 1% lower recovered maximum power degradation rate for the unsintered cells, which agrees pretty well with the nonenvironmentally exposed test results. At the higher fluence, however, the short circuit current, open circuit voltage, and maximum power indicated a higher, rather than lower degradation rate for the unsintered cells. (Unsintered cells exhibited a 2% higher maximum power degradation rate for environmentally exposed cells vs a 3% lower degradation rate for unsintered cells for the nonenvironmentally exposed cells). For exposures at 215°C for 2 min, the degradation rates after recovery of all parameters appear to be similar for the sintered and unsintered cells after exposure to the lower fluence, which agrees with the results of the test on the nonenvironmentally exposed cells. After exposure to the higher 1-MeV electron fluence, the recovered maximum power of the unsintered cells appears to degrade approximately 2% slower than sintered cells, which is in agreement with nonenvironmentally exposed sintered cells at this fluence level, which indicated an approximate 3% slower power degradation rate. For the group of cells exposed to 5 cycles of thermal shock (+100 to -196°C), degradations were so catastrophic and 95% confidence limits were so large that probably not much confidence can be placed on the degradation rates, which, unexpectedly, agree rather well with the degradation rates obtained for the cells not exposed to environments at both lower and higher 1-MeV electron fluences. The electrical parameters of sintered and unsintered cells exposed to the thermal shock (Tables 5, 6, 13, and 14) have confidence limits considerably larger than those associated with the other tests; however, the unsintered cell confidence limits were 2 to 3 times larger than the sintered cell confidence limits for all electrical parameters recorded after the thermal shock test.

f. Summary of Radiation Results on Lot 1 Cells. It is of interest to note that subjecting Lot 1 Lithium-doped cells to the various environments did not greatly affect the percentage degradation of the electrical characteristics after recovery from exposure to 1-MeV electron fluences of 1×10^4 and 3×10^{15} e/cm^2. At the lower fluence the short circuit currents degraded between 7 and 9%, the open circuit voltages degraded between 2 and 4%, and the maximum power degraded between 7 and 9%. At the higher fluence the short circuit currents degraded between 22 and 25%. The open circuit voltage degraded between 16 and 21%, and the maximum power degraded between 35 and 40%. The cells not environmentally exposed fell within these ranges, and in fact, appeared to be towards the upper edge of the degradation, that is, the cells exhibited somewhat higher degradation. In general, the unsintered recovered cell maximum powers degraded at an equal or slightly slower rate than the sintered cells except at the 3×10^{15} e/cm^2 exposure after 12 days at 150°C. There was not, however, a great deal of difference between the behavior of the sintered and unsintered cells, except in the case of the thermal shock environment where the sintered cells appeared to be significantly better than the unsintered cells (but they were all terrible).

g. Pull Strength Test Results on Lot 1 Cells

(1) 12 Days at 150°C. The pull strength for both N and P sintered and unsintered contacts all appeared to be between 1069 and 1198 g for exposure to this environment as shown in Tables 28 through 31; that is, they were all very similar to one another. The largest variation in 95% confidence limits was for the N contact on the unsintered cells. In comparison with the unexposed N contact for the unsintered cells the percentage degradation for the exposed cells seems rather high, but if one examines the unexposed absolute strength it appears to be higher (1499 g) than most other values obtained, so that the absolute value after exposure is still quite high (1198 g).

(2) Lot 1 Cells Exposed to 215°C. The N contacts of the sintered cells appear to be significantly lower in average contact strength than the N contacts of the unsintered cells or than the P contacts of both the sintered and unsintered cells, as shown in Tables 33 and 35 respectively. The loss in N-contact pull strength for the sintered cells represents an approximate 25% reduction in pull strength over the unexposed case. It should be noted, however, that the 811 g associated with the N contact of the sintered cell is still significantly above the minimum 500 g pull strength presently specified for Mariner-type solar cells.

(3) Lot 1 Cells Exposed to Thermal Shock (5 Cycles +100 to -196°C. As discussed previously, many cells that underwent this environmental exposure suffered catastrophic failure. As it made little sense to perform pull tests on obviously fractured cells, the 10 samples selected for the pull test were examined, and only cells exhibiting little or no silicon fracture were actually tested. Thus the pull test results on these cells were not randomly selected as was the case for the other cells. The average pull strengths (with

respect to cells exposed to the other environments) of the selected cells (as shown in Tables 36 through 39) is of great interest because it clearly indicates that the degradations experienced in contact strength are not an inherent mechanism in this cell type. It is rather apparent that the observed severe silicon fracture is associated with process variables, and that by properly controlling the process, very high pull strengths can be achieved. This is to be seen for example in the fact the the N contact of the (screened) sintered cells had an average pull strength of better than 1600 g as shown in Table 37, even more impressive when one notes that the plus or minus values associated with the 95% confidence limits was 873 g. The situation, then, with respect to the thermal shock environment appears to indicate an area that at the moment is quite disturbing, but that is clearly treatable with a reasonable amount of effort devoted to process improvement.

2. Thermal Shock (+100 to -196° C) Test Performed on Lots 2 and 3

Because of the significant degradations experienced as the result of exposure to this environment by the Lot 1 cells, similar tests were performed on Lot 2 and 3 cells. Since this problem did not become apparent until after Lot 2 had been fabricated, the cells from Lot 2 were essentially of the same design as Lot 1. After being advised of the sensitivity of the lithium-doped solar cells delivered in Lot 1 to thermal shock exposure and the fact that previous JPL investigations indicated that nonuniform solder coating tended to increase the severity of the silicon fracture that occurs as a result of the thermal shock (Refs. 25, 26, and 28) the contractor increased attention to insuring a uniform, thin solder coating in Lot 3.

Results of the electrical measurements of the Lot 2 cells shown in Table 17 indicated results similar to those obtained for the Lot 1 cells. The short circuit current decreased from about 142 to 126.2 mA, or a degradation of about 12% after exposure to this environment. The open circuit voltage decreased from about 611 mV to 518 mV, for a degradation of about 15%, and the maximum power decreased from 63.3 mW to 41.7 mW or a degradation of about 44%. The mechanical pull strength tests of Lot 2 sintered cells shown in Tables 40 and 41 indicated a 29% and a 2% degradation for the P and N contacts, respectively. The standard deviations obtained for the P-contact pull strengths were similar for exposed and unexposed cells, whereas the standard deviation was almost twice as large for the exposed N-contact cell as for the unexposed N contacts.

The majority of cells fabricated for Lot 3 utilized the boron trichloride with oxygen carrier gas junction diffusion technique rather than the nitrogen carrier gas technique used for Lots 1 and 2. Twenty samples of Lot 3 cells fabricated with the oxygen carrier gas junction diffusion and five cells fabricated with the nitrogen gas junction diffusion were exposed to the thermal shock environment. There appeared to be little significant difference between the electrical results obtained on the cells fabricated by means of the two P/N junction diffusion techniques as shown in Tables 18 and 19. It should be noted, however, that the short circuit currents of even the unexposed cells for both types of diffusion were considerably below the normal range of short circuit currents for the cells of Lot 1. The average cell maximum power of the two diffusion techniques were similar to one another (59.4 for the oxygen system versus 59.6 for the nitrogen system) but were at the lower edge of the band of normal maximum powers obtained for the Lot 1 cells (which ranged between 60 and 67 mW).

After exposure to the thermal shock environment, a higher percentage degradation was observed in the short circuit current parameter after environmental exposure with respect to the nitrogen system cells (Table 19) than for the oxygen system cells (Table 18). The short circuit currents of the latter cells were similar to the percentage degradations experienced for the Lot 1 cells. The percentage degradation of the maximum power parameter was also greater for the nitrogen-diffusion cells than the oxygen-diffusion cells (12% versus 7%), so that from a percentage maximum power degradation viewpoint, the oxygen-diffusion cells looked somewhat better than the Lot 1 cells, which had experienced a 12% degradation, similar to the nitrogen-diffusion cells of Lot 3. The absolute values of maximum power after exposure were, however, lower for the oxygen-diffusion and nitrogen-diffusion cells of Lot 3 (55.4 and 52.6 mW, respectively) than for the sintered nitrogen-diffusion cells of Lot 1 (58.4 mW). It thus appears that the electrical quality of the cells fabricated for Lot 3 were somewhat inferior to these fabricated for Lot 1. In view of the lower absolute maximum power of Lot 3 cells after environmental exposure, as compared with the Lot 1 cells, the apparent improvement in maximum power percentage degradation of the oxygen-diffusion cells might be of dubious benefit.

The pull strength of cells from Lot 3 unexposed to the thermal cycle environment was also found to be considerably below that of the sintered cells from Lot 1. Whereas the average pull strength for either P or N contacts for the Lot 1 sintered cells were approximately 1100 g or better, pull strengths of unexposed cells of Lot 3 were never much higher than 900 g. This is the case for both cells diffused in the oxygen and nitrogen carrier gases. On a more positive note, the pull strengths of both oxygen and nitrogen-diffusion cells of Lot 3 did not appear to undergo degradation as a result of exposure to the thermal shock environment, and therefore these cells greatly exceeded the 500-g pull strength minimum specified for Mariner-type solar cells. These results indicate that further work must be done with respect to cell contacting and solder coating in order to preserve the electrical characteristics after exposure to the thermal shock environment.

3. Comparison Between Environmental Tests on Lot 4 and Lot 1 Cells

The cells for Lot 4 were fabricated utilizing the boron tricholoride with oxygen carrier gas technique for P/N junction diffusion and utilized sintered titanium-silver solder coated contacts. As discussed previously, cell power output cells from this lot were on the average 10 to 15% below those achieved for Lots 1 and 2.

For the 12-day soak at 150°C ambient laboratory conditions, it was found that the average short circuit current of Lot 4 was about 14 mA lower than was observed for Lot 1. The open circuit voltage of Lot 4 cells was about 25 mV below Lot 1 and the maximum power was about 9 mW below those of Lot 1 cells. No significant electrical degradation was observed in the electrical characteristics for either Lot 1 or Lot 4 cells. The lower postexposure short circuit current, open circuit voltage, and maximum power for the lot of 4 cells were simply a result of the lower preexposure values of these cells. The 95% confidence limits associated with the Lot 1 and Lot 4 cells were similar to one another for each of the electrical parameters investigated. Similar results were obtained with respect to the electrical characteristics of Lot 4 and 1 cells exposed to 215°C for 2 min (solder melt tests). The short circuit current, open circuit voltage, and maximum power of Lot 4 cells were lower than those of the Lot 1 cells by 14 mA, 15 mV and 8.5 mW, respectively. Again, no electrical degradation was observed as a result of the tests for either Lot 4 or Lot 1 cells, and the 95% confidence limits associated with the parameters were similar for the cell Lots 1 and 4.

After exposure to 5 thermal cycles of +100 to -196°C, the short circuit current and open circuit voltage of Lot 4 cells were lower than those of Lot 1 cells by 13 mA and 13 mV, respectively. The average maximum power, however, of the Lot 4 cells was lower by approximately 4.5 mW than the Lot 1 cells, in contract to the 9-mW difference observed in the previous two environmental tests. Hence, for this test, the Lot 4 cells appear to preserve their curve shape somewhat better than the Lot 1 cells. This can further be seen by examining the percentage degradation associated with the two cell lots. The Lot 4 cells degraded 1.5% in short circuit current as opposed to 2% for the Lot 1 cells. Both the Lot 4 and Lot 1 cells degraded about 2% in open circuit voltage. In contrast, the average maximum power of the Lot 4 cells degraded only 8% as opposed to the 12% degradation observed for the Lot 1 cell average maximum power. Thus, the efforts to control the solder thickness appear to have resulted in some improvement in the electrical curve shape after the thermal shock test, although the spread in maximum power, indicated by the 95% confidence limits, was quite similar for the two lots, indicating little improvement in cell-to-cell variability.

Contact pull strength tests performed on Lot 4 cells exposed to the above environments as shown in Tables 44 through 47 indicated that while unexposed P- and N-contact pull strengths were similar, averaging 876 and 744 g respectively, in general, the P contacts after exposure were 200 to 300 g higher than the N-contact pull strengths. After environmental tests the contact pull strength of Lot 4 appeared to vary between 800 and 1000 g and the N-contact strength varied between 500 and 700 g. This can be compared with pull strengths for Lot 1 cells that exhibited N- and P-contact strengths between 1070 and 1200 g. Thus, the absolute final pull strengths of cells from Lot 4 were considerably below those observed for the Lot 1 cells.

After an exposure of 12 days at a temperature of 150°C the Lot 4 cells exhibited average P-contact strength of about 962 g and N-contact strength of about 600 g as shown in Tables 46 and 47, respectively. This can be contrasted with cells from Lot 1, which exhibited average P-contact strength of 1183 g and N-contact strength of 1072 g as shown in Tables 28 and 29. Thus, the cells from Lot 1 exhibited similar P- and N-contact strengths whereas the cells from Lot 4 exhibited an almost 400-g difference between the P- and N-contact strengths. The average P-contact strength of Lot 4 cells was about 200 g lower than the Lot 1 cells and the average N-contact strength of Lot 4 cells was about 600 g lower than the N-contact strength of the Lot 1 cells. The 95% confidence limits indicated that the variation in pull strengths of the P contact is about twice as large for the Lot 1 cells as for the Lot 4 cells (523 g vs 176 g). The Lot 4 cells exhibited essentially no degradation in average pull strength of the P contact and a more than 18% degradation in N-contact pull strength, as opposed to a 7% degradation P-contact pull strength for Lot 1 cells and a 2% degradation in pull strength of the N contact for the Lot 1 cells. Thus the N contact of the Lot 4 cells appears to be significantly inferior to those of the Lot 1 cells from the point of view of absolute contact strength and percentage degradation after exposure to 150°C for 12 days.

Cells from Lot 4 exposed to a temperature of 215°C for 2 min exhibited an average P-contact strength of 930 g and an N-contact strength of 687 g. This can be contrasted with results from Lot 1 cells similarly exposed, which exhibited an average P-contact strength of 1156 g and an average N-contact strength of 811 g. Hence, the absolute contact strengths of the P and N contacts of the Lot 4 cells were lower than those of the Lot 1 cells by 200 g. The P-contact pull strengths of the Lot 4 cells exhibited essentially no degradation resulting from exposure to the environment, and an 8% degradation in average N-contact strength. The Lot 1 cells had exhibited a 9% degradation of P-contact strength and a 26% degradation in N-contact strength as a result of this environment. It therefore appears that from a percentage degradation basis, the Lot 4 cells were superior to the Lot 1 cells in contact pull strength, but not on an absolute contact strength basis.

With respect to the pull strength tests on the cells exposed to the thermal shock environment, it is difficult to really interpret the results of the tests. This is because, as discussed previously, these cells were visually selected to ensure that cells having experienced silicon fracture would not be pull tested, whereas cells having undergone the other environmental exposures were randomly selected for pull strength tests. Bearing this in mind, the following discussion considers only the actual numbers obtained, but does not imply that this would be the situation for a randomly selected sampling production lot. The P-contact strength of both Lots 1 and 4 (Tables 36 and 44, respectively) were similar at a value of about 1100 g. The average N-contact strength of the Lot 4 cells (Table 45) was significantly below that of the Lot 1 cells (694 g vs 1607 g, respectively). The spread in values as indicated by the 95% confidence limits was much greater for the Lot 1 cells (873 g) than for the

Lot 4 cells (190 g) for the N contact, while the 95% confidence limits were similar for both lots with respect to the P contact.

The significantly larger spread in results, indicated by the 95% confidence limits, for the N-contact pull strength of Lot 1 cells, coupled with the above mentioned nonrandom selection of the cells, may, in fact, mean that there is no real difference in the contact strength between Lot 1 and Lot 4. Therefore, one can say with only a reasonable amount of certainty that the Lot 4 cells exhibited less curve shape degradation as a result of this test than did the Lot 1 cells, and that in this respect, more careful control in the solder thickness has been beneficial.

4. Humidity-Temperature and Vacuum-Temperature Tests on Lot 4 Cells

Cells from Lot 4 were exposed to a relative humidity of 95% for 14 days at a temperature of 80°C. As shown in Table 27 no degradation in cell electrical characteristics was observed as a result of this test. As indicated in Table 50 the P-contact pull strength of these cells after exposure averaged 822 g vs 876 g for tests performed on unexposed cells, representing a degradation of about 6%. The 95% confidence limits of the exposed group indicate a spread of 232 g vs a spread of 67 g for the unexposed group. As shown in Table 51, the N-contact strength after exposure was about 300 g below that of the P-contact strength and averaged 555 g. This can be compared with an N-contact strength for the unexposed group of 744 g, or a degradation of about 25%. The 95% confidence limits were 147 g for the exposed group vs 99 g for the unexposed group. The N-contact strength after this test was the lowest observed for all environmental exposure conditions, but was not vastly different from the 12-day exposure to 150°C test, which gave an average pull strength of 600 g. In this test, as for the others performed on Lot 4 cells, it appears that the absolute pull strength of the N contact is considerably below that of the P contact.

Cells from Lot 4 were also exposed to the 125°C temperature soak in vacuum for a period of 12 days. The cells exhibited a slight (2%) degradation in short circuit current and maximum power as shown in Table 22. Pull strength tests performed on exposed cells indicated an average pull strength of 987 g for the P contact and 587 g for the N contact, as shown in Tables 48 and 49 respectively, a difference of about 300 g between the P and N contact. As in the other environmental tests performed on Lot 4 cells, the N contact had a significantly lower absolute pull strength than the P contact. These results can be compared to the unexposed cell pull strength of 876 g and 744 g for the P and N contacts, respectively. The confidence limits for the exposed cells were 214 g and 186 g for the P and N contacts, respectively, as opposed to 67 g and 99 g for P and N contacts, respectively, of the unexposed group, indicating a wider variation in pull strength as a result of exposure to this environment.

Cells having undergone the vacuum-temperature test were exposed to 1-MeV electron fluences of 1×10^{14} and 3×10^{15} e/cm^2 and annealed for 720 h at 60°C. The results are shown in Tables 23 and 24, respectively. At the lower fluence the recovered short circuit current, open circuit voltage, and maximum power exhibited a net degradation of 4%, 3%, and 7%, respectively. This can be compared with Lot 4 cells exposed to the radiation environment but not to the vacuum temperature environment shown in Tables 20 and 21, which indicated recovered short circuit current, open circuit voltage, and maximum power degradations of 6%, 3%, and 9%, respectively. At the higher fluence the net degradation after recovery of the short circuit current, open circuit voltage, and maximum power of the vacuum-temperature exposed cells were 19%, 18%, and 35%, respectively. This can be compared with irradiated cells not exposed to the vacuum temperature environment, which exhibited recovered short circuit current, open circuit voltage, and maximum power of 29%, 17%, and 35%. Thus, it can be seen that exposure to the vacuum-temperature environment does not affect the recovery characteristics of these cells. Furthermore, there was not much difference in the 95% confidence limits between the higher and lower fluences, although the limits were slightly larger for the higher fluence.

V. CONCLUSIONS

Further work on improvement of the P/N-junction diffusion technique is clearly needed to improve the economics of fabrication of high-efficiency, lithium-doped silicon solar cells. Also work is needed to improve the thermal shock capabilities of cells having solder coated titanium-silver contacts. More careful control of the contact solder thickness of the Lot 4 cells resulted in less electrical degradation as a result of exposure to thermal shocks than observed for cells in earlier cell lots that had more variable solder thickness.

Even for the Lot 4 cells, however, significant electrical and mechanical (silicon fracture) occurred during thermal shock. There are indications of possible problem areas with respect to cleaning requirements of the lithium evaporation system, and formation of a metal-semiconductor barrier in sintered cells.

The cell design utilized in the pilot-line gave uniform cell-to-cell lithium donor density gradients and, consequently, uniform irradiation recovery characteristics. The cells appeared to be stable after recovery from exposure to 1-MeV electron irradiations. Cells having very high efficiencies, in the upper 12% range, were fabricated during the course of this program. Exposure to the various environments discussed in this report did not appear to adversely affect the cell recovery characteristics after exposure to electrons having an energy of 1 MeV.

The major conclusions are that the lithium-doped cell is not, at the present time, technologically ready for space applications, that further engineering improvements are required, and that high-efficiency, radiation-tolerant, stable, lithium-doped cells can be reproducibly manufactured.

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Table 1. Lot 1 cell parameters prior to and as a function of time at 60° C after irradiation by 1-MeV electrons to 1×10^{14} e/cm^2; cells previously exposed to 150° C for 12 days — sintered contacts

TIME (hrs.)		ISC (MA)	VOC (MV)	IMP (MA)	VMP (MV)	PMAX (MW)
	AVERAGE	144.9000	612.3200	130.9800	505.6000	66.2351
.0	95 P.C. CONF. LIMITS	6.1399	6.3606	6.4714	6.8337	3.7993
	STANDARD DEVIATION	4.9457	5.1235	5.2127	5.5045	3.0603
	AVERAGE	108.9800	534.7200	99.8900	446.9000	44.9203
.6	95 P.C. CONF. LIMITS	6.6685	1.9220	6.5851	2.8656	3.0725
	STANDARD DEVIATION	5.3714	1.5482	5.3043	2.3083	2.4749
	AVERAGE	111.6800	537.4200	102.0000	447.1000	45.6568
24.0	95 P.C. CONF. LIMITS	5.8564	2.5319	6.7102	4.0569	2.7239
	STANDARD DEVIATION	4.7173	2.0395	5.4051	3.2677	2.1941
	AVERAGE	133.0800	568.0600	121.8000	467.6000	57.0278
48.0	95 P.C. CONF. LIMITS	5.7714	4.6197	6.4928	4.3145	2.8346
	STANDARD DEVIATION	4.6489	3.7211	5.2299	3.4754	2.2833
	AVERAGE	134.5600	580.4800	121.1000	484.6000	58.7425
168.0	95 P.C. CONF. LIMITS	6.2516	2.9850	6.8626	5.1637	3.4052
	STANDARD DEVIATION	5.0357	2.4044	5.5278	4.1593	2.7429
	AVERAGE	133.0800	591.7000	121.9200	494.2000	60.3405
720.0	95 P.C. CONF. LIMITS	6.0287	2.8293	6.4445	6.3822	3.2544
	STANDARD DEVIATION	4.8562	2.2790	5.1910	5.1408	2.6214

Table 2. Lot 1 cell parameters prior to and as a function of time at 60°C after irradiation by 1-MeV electrons to 1×10^{14} e/cm^2; cells previously exposed to 150°C for 12 days – unsintered contacts

TIME (hrs.)		ISC (MA)	VOC (MV)	IMP (MA)	VMP (MV)	PMAX (MW)
	AVERAGE	143.3800	612.6600	128.4000	496.4000	63.7230
.0	95 P.C. CONF. LIMITS	4.5909	2.4752	3.2986	15.0161	1.6874
	STANDARD DEVIATION	3.7785	1.9937	2.6571	12.0955	1.3592
	AVERAGE	106.7800	532.8200	97.8000	434.1000	42.7471
1.0	95 P.C. CONF. LIMITS	3.5436	1.2317	1.9657	10.7606	.6232
	STANDARD DEVIATION	2.8543	.9922	1.5834	8.6676	.5020
	AVERAGE	117.2200	542.1000	106.7800	439.0000	46.9105
24.0	95 P.C. CONF. LIMITS	2.4476	3.1704	1.8106	12.7560	1.3871
	STANDARD DEVIATION	1.9716	2.5538	1.4585	10.2750	1.1173
	AVERAGE	131.6800	569.0200	119.0200	459.1000	54.7337
48.0	95 P.C. CONF. LIMITS	3.1473	4.0401	2.8481	15.2972	1.7742
	STANDARD DEVIATION	2.5352	3.2543	2.2942	12.3219	1.4291
	AVERAGE	134.0000	580.3400	119.5000	472.6000	56.5308
168.0	95 P.C. CONF. LIMITS	3.6921	2.5310	2.2457	15.2705	1.4360
	STANDARD DEVIATION	2.9740	2.0387	1.8089	12.3004	1.1567
	AVERAGE	133.4200	592.8600	121.5800	481.8000	58.6633
720.0	95 P.C. CONF. LIMITS	3.5677	2.1391	2.4212	12.8763	1.1797
	STANDARD DEVIATION	2.9737	1.7230	1.9503	10.3718	.9502

Table 3. Lot 1 cell parameters prior to and as a function of time at 60° C after irradiation by 1-MeV electrons to 1×10^{14} e/cm^2; cells previously exposed to 215° C for 2 min – sintered contacts

TIME (hrs.)		ISC (MA)	VOC (MV)	IMP (MA)	VMP (MV)	PMAX (MW)
.0	AVERAGE	147.3000	619.4600	133.9900	506.2000	67.8275
	95 P.C. CONF. LIMITS	3.6163	9.9636	3.4543	9.1397	2.5195
	STANDARD DEVIATION	2.9129	7.9451	2.7825	7.3621	2.0294
.7	AVERAGE	110.9000	535.1200	102.1400	442.6000	45.4560
	95 P.C. CONF. LIMITS	4.2255	6.9070	3.5427	5.7731	1.4896
	STANDARD DEVIATION	3.4037	5.5636	2.8536	4.6503	1.1998
24.0	AVERAGE	112.9600	537.3400	103.4400	445.7000	46.1574
	95 P.C. CONF. LIMITS	3.4755	9.2409	3.4790	10.9555	1.8661
	STANDARD DEVIATION	2.7995	7.4435	2.8023	8.8247	1.5032
48.0	AVERAGE	133.4000	567.6600	122.5200	465.1000	57.0904
	95 P.C. CONF. LIMITS	4.7445	18.8373	4.9266	14.8756	3.8147
	STANDARD DEVIATION	3.9217	15.1735	3.9684	11.9823	3.0728
168.0	AVERAGE	136.6000	581.4400	123.0200	481.2000	59.2406
	95 P.C. CONF. LIMITS	2.9393	11.4470	3.1929	10.2999	1.7739
	STANDARD DEVIATION	2.3676	9.2206	2.5639	8.2885	1.4289
720.0	AVERAGE	135.5200	592.5600	124.8200	491.3000	61.3783
	95 P.C. CONF. LIMITS	3.4591	8.7455	3.0591	10.5216	1.4574
	STANDARD DEVIATION	2.7863	7.0445	2.4641	8.4751	1.1740

Table 4. Lot 1 cell parameters prior to and as a function of time at 60°C after irradiation by 1-MeV electrons to 1×10^{14} e/cm^2; cells previously exposed to 215°C for 2 min – unsintered contacts

TIME (hrs)		ISC (MA)	VOC (MV)	IMP (MA)	VMP (MV)	PMAX (MW)
	AVERAGE	143.5400	619.3200	128.2600	499.8000	64.1066
.0	95 P.C. CONF. LIMITS	4.6456	4.2804	4.5399	8.6190	2.6295
	STANDARD DEVIATION	3.7420	3.4478	3.6569	6.9426	2.1180
	AVERAGE	105.0000	538.8000	96.1600	442.0000	42.8039
1.1	95 P.C. CONF. LIMITS	4.1250	5.1253	4.1736	5.0319	1.4208
	STANDARD DEVIATION	3.3227	4.1284	3.3619	4.0532	1.1444
	AVERAGE	116.5000	551.2200	106.1400	449.2000	47.6288
24.0	95 P.C. CONF. LIMITS	3.8472	11.1322	2.7123	9.2279	2.0051
	STANDARD DEVIATION	3.0989	8.9670	2.1847	7.4330	1.6151
	AVERAGE	129.7200	576.5800	117.9800	467.2000	55.2205
48.0	95 P.C. CONF. LIMITS	3.4353	9.5624	3.0219	7.5080	1.3529
	STANDARD DEVIATION	2.7671	5.8970	2.4341	6.0477	1.0897
	AVERAGE	131.0800	585.3400	117.6000	477.8000	56.2572
168.0	95 P.C. CONF. LIMITS	4.4757	3.8365	4.5550	7.7231	2.0173
	STANDARD DEVIATION	3.6052	3.0903	3.6691	6.2209	1.6249
	AVERAGE	130.2400	595.8400	119.3800	498.1000	58.3715
720.0	95 P.C. CONF. LIMITS	4.6072	2.9098	4.4039	7.0094	1.6511
	STANDARD DEVIATION	3.7111	2.3439	3.5473	5.6461	1.3300

Table 5. Lot 1 cell parameters prior to and as a function of time at 60° C after irradiation by 1-MeV electrons to 1×10^{14} e/cm^2; cells previously exposed to 5 cycles of +100 to -196° C — sintered contacts

TIME (hrs)		ISC (MA)	VOC (MV)	IMP (MA)	VMP (MV)	PMAX (MW)
	AVERAGE	142.4600	599.6600	123.2800	466.0000	57.4340
.0	95 P.C. CONF. LIMITS	7.1136	9.0092	7.3606	17.6664	3.6029
	STANDARD DEVIATION	5.7300	7.2569	5.9289	14.2302	2.9021
	AVERAGE	105.9000	534.4600	93.6600	429.3000	40.5290
.8	95 P.C. CONF. LIMITS	4.3033	6.2325	5.0217	15.4226	1.9871
	STANDARD DEVIATION	3.4663	5.0203	4.0450	12.4229	1.6006
	AVERAGE	110.8000	540.1600	97.5600	431.6000	42.1872
24.0	95 P.C. CONF. LIMITS	4.5552	10.9039	4.4801	12.4874	2.7849
	STANDARD DEVIATION	3.5692	8.7830	3.6087	10.0586	2.2433
	AVERAGE	130.7600	570.5800	114.7600	450.1000	51.7742
48.0	95 P.C. CONF. LIMITS	4.6457	11.2680	5.5181	14.7195	2.6160
	STANDARD DEVIATION	3.7421	9.0764	4.4449	11.8566	2.1072
	AVERAGE	131.9400	578.4600	114.4200	458.8000	52.5810
168.0	95 P.C. CONF. LIMITS	5.2507	8.8089	5.3091	16.2911	2.7003
	STANDARD DEVIATION	4.2295	7.0956	4.2765	13.1225	2.1751
	AVERAGE	130.4800	587.5200	114.5600	466.0000	53.5467
720.0	95 P.C. CONF. LIMITS	5.8087	8.2332	6.0434	15.8159	3.0305
	STANDARD DEVIATION	4.5789	6.6318	4.8680	12.7397	2.4411

Table 6. Lot 1 cell parameters prior to and as a function of time at 60° C after irradiation by 1-MeV electrons to 1 × 10^{14} e/cm^2; cells previously exposed to 5 cycles of +100 to -196° C — unsintered contacts

TIME (hrs.)		ISC (MA)	VOC (MV)	IMP (MA)	VMP (MV)	PMAX (MW)
	AVERAGE	128.9400	579.1800	105.5600	432.8000	45.9381
.0	95 P.C. CONF. LIMITS	14.8225	17.4173	18.8316	32.7450	11.0262
	STANDARD DEVIATION	11.9396	14.0297	15.1688	26.3761	8.9816
	AVERAGE	94.2400	518.1200	78.3000	397.0000	31.7774
1.3	95 P.C. CONF. LIMITS	15.2469	9.8882	19.0700	29.8191	9.1638
	STANDARD DEVIATION	12.2814	7.9650	15.3609	24.0193	7.3814
	AVERAGE	102.5000	526.4800	84.0800	403.2000	34.2340
24.0	95 P.C. CONF. LIMITS	18.1680	12.6262	23.2329	29.4929	11.0978
	STANDARD DEVIATION	14.6343	10.1704	18.7141	23.7565	8.9393
	AVERAGE	115.4400	543.5000	94.8000	416.2000	40.0415
48.0	95 P.C. CONF. LIMITS	20.3027	13.3902	25.5077	32.7304	12.9359
	STANDARD DEVIATION	16.3538	10.7777	20.5465	26.3643	10.3393
	AVERAGE	118.6600	555.9400	97.0400	422.6000	41.5071
168.0	95 P.C. CONF. LIMITS	20.8942	14.6989	25.3860	33.8239	13.0304
	STANDARD DEVIATION	16.8303	11.8399	20.4484	27.2452	10.4959
	AVERAGE	119.8400	566.3800	99.1400	434.8000	43.7780
720.0	95 P.C. CONF. LIMITS	21.3496	14.7903	25.4475	35.3290	13.4973
	STANDARD DEVIATION	17.1963	11.9136	20.4979	28.4575	10.8721

Table 7. Lot 1 cell parameters prior to and as a function of time at 60° C after irradiation by 1-MeV electrons to 1×10^{14} e/cm^2; no prior environmental exposure – sintered contacts

TIME (hrs.)		ISC (MA)	VOC (MV)	IMP (MA)	VMP (MV)	PMAX (MW)
	AVERAGE	143.5400	615.1200	129.3400	498.8000	64.5373
.0	95 P.C. CONF. LIMITS	6.5036	9.0582	4.4670	20.7440	4.2125
	STANDARD DEVIATION	5.2386	6.4909	3.6143	16.7093	3.3931
	AVERAGE	107.0000	535.6200	97.7200	440.7000	43.3681
.9	95 P.C. CONF. LIMITS	5.0253	3.7770	3.8542	14.3537	2.3022
	STANDARD DEVIATION	4.0479	3.0424	3.1046	11.5619	1.8544
	AVERAGE	109.9000	539.1800	100.3800	439.9000	44.2353
24.0	95 P.C. CONF. LIMITS	4.4795	5.7250	4.1819	15.6580	2.9021
	STANDARD DEVIATION	3.6074	4.6115	3.3685	12.6125	2.3377
	AVERAGE	132.4000	572.0800	120.5000	461.8000	55.7574
48.0	95 P.C. CONF. LIMITS	4.3602	8.8680	3.9537	20.6218	3.6797
	STANDARD DEVIATION	3.5122	7.1432	3.1847	16.6109	2.9640
	AVERAGE	133.8000	582.9000	120.2800	475.0000	57.2018
168.0	95 P.C. CONF. LIMITS	4.9752	6.8288	3.3851	19.2927	3.0502
	STANDARD DEVIATION	4.0075	5.5006	2.7267	15.5403	2.4570
	AVERAGE	132.4000	592.2600	121.0200	486.4000	59.9708
720.0	95 P.C. CONF. LIMITS	5.7106	7.1459	4.3588	20.7859	3.4778
	STANDARD DEVIATION	4.5999	5.7560	3.5110	16.7430	2.8013

Table 8. Lot 1 cell parameters prior to and as a function of time at 60°C after irradiation by 1-MeV electrons to 1 × 10^{14} e/cm^2; no prior environmental exposure — unsintered contacts

TIME (hrs.)		ISC (MA)	VOC (MV)	IMP (MA)	VMP (MV)	PMAX (MW)
	AVERAGE	144.3600	610.5400	129.1400	493.6000	63.7475
.0	95 P.C. CONF. LIMITS	2.7881	7.4901	2.3763	11.1248	2.1058
	STANDARD DEVIATION	2.2459	6.0332	1.9141	8.9610	1.6962
	AVERAGE	106.1200	533.0200	97.5800	437.5000	42.9903
1.4	95 P.C. CONF. LIMITS	1.9697	5.3280	1.3542	5.4720	.5334
	STANDARD DEVIATION	1.5866	4.2917	1.0908	4.4077	.4296
	AVERAGE	114.5600	541.1800	104.5800	440.1000	46.0849
24.0	95 P.C. CONF. LIMITS	4.8365	9.0550	4.6893	9.6703	2.7318
	STANDARD DEVIATION	3.8958	7.2938	3.7772	7.7894	2.2004
	AVERAGE	129.7800	565.4000	116.4600	457.7000	53.4515
48.0	95 P.C. CONF. LIMITS	4.9311	13.2452	5.8438	11.7990	3.8710
	STANDARD DEVIATION	3.9720	10.6690	4.7072	9.5041	3.1181
	AVERAGE	132.3400	576.0800	119.9200	469.2000	55.8669
168.0	95 P.C. CONF. LIMITS	1.5019	7.7470	1.6010	9.9859	1.3914
	STANDARD DEVIATION	1.2097	6.2402	1.2896	8.0436	1.1209
	AVERAGE	132.0200	586.5800	121.0000	478.9000	58.0504
720.0	95 P.C. CONF. LIMITS	1.4411	6.4217	.8263	7.1670	.9350
	STANDARD DEVIATION	1.1608	5.1726	.6656	5.7731	.7532

Table 9. Lot 1 cell parameters prior to and as a function of time at 60° C after irradiation by 1-MeV electrons to 3 × 10^{15} e/cm^2; cells previously exposed to 150° C for 12 days — sintered contacts

TIME (hrs.)		ISC (MA)	VOC (MV)	IMP (MA)	VMP (MV)	PMAX (MW)
	AVERAGE	143.1800	612.4400	129.3800	501.9000	64.9465
.0	95 P.C. CONF. LIMITS	6.1846	12.0352	5.4670	19.0596	4.4037
	STANDARD DEVIATION	4.9817	9.6944	4.4037	15.3525	3.5472
	AVERAGE	92.6200	463.7200	75.7800	380.3000	29.4199
.8	95 P.C. CONF. LIMITS	4.3725	3.2787	4.0689	5.6789	1.7863
	STANDARD DEVIATION	3.5221	2.6410	3.2775	4.5744	1.4389
	AVERAGE	87.9000	462.5400	79.3000	380.0000	30.3651
24.0	95 P.C. CONF. LIMITS	1.4062	2.5395	1.1083	4.5323	.4849
	STANDARD DEVIATION	1.1327	2.0456	.8927	3.6508	.3905
	AVERAGE	94.8600	464.9000	85.3000	378.3000	32.5709
48.0	95 P.C. CONF. LIMITS	1.9922	2.1357	1.1928	4.8002	.4125
	STANDARD DEVIATION	1.6047	1.7203	.9608	3.8665	.3323
	AVERAGE	105.5400	475.1000	93.9000	384.4000	36.3025
168.0	95 P.C. CONF. LIMITS	1.5961	3.7707	1.5441	4.9347	.4557
	STANDARD DEVIATION	1.2857	3.0373	1.2438	3.9749	.3670
	AVERAGE	110.3000	493.0200	101.8400	396.8000	40.7260
720.0	95 P.C. CONF. LIMITS	3.2429	3.4140	2.7550	9.1819	1.0233
	STANDARD DEVIATION	2.6122	2.7500	2.2192	7.3959	.8243

Table 10. Lot 1 cell parameters prior to and as a function of time at 60°C after irradiation by 1-MeV electrons to 3×10^{15} e/cm^2; cells previously exposed to 150°C for 12 days – unsintered contacts

TIME (hrs.)		ISC (MA)	VOC (MV)	IMP (MA)	VMP (MV)	PMAX (MW)
	AVERAGE	146.3400	607.1000	129.3400	481.0000	62.2552
.0	95 P.C. CONF. LIMITS	3.7396	8.2892	6.8352	14.5575	4.9789
	STANDARD DEVIATION	3.0122	6.6769	5.5057	11.7260	4.0105
	AVERAGE	86.6400	460.2400	77.3200	371.0000	29.2946
1.9	95 P.C. CONF. LIMITS	2.8438	1.6670	3.0186	9.7200	1.5661
	STANDARD DEVIATION	2.2906	1.3428	2.4314	7.8294	1.2615
	AVERAGE	89.9200	457.5200	78.8400	369.6000	29.4100
24.0	95 P.C. CONF. LIMITS	6.5147	4.2933	6.9320	11.5930	3.3968
	STANDARD DEVIATION	5.2476	3.4582	5.5837	9.3382	2.7361
	AVERAGE	95.7600	459.6000	85.0600	361.8000	31.1501
48.0	95 P.C. CONF. LIMITS	9.2124	6.9970	9.7844	10.9784	4.4284
	STANDARD DEVIATION	7.4206	5.6361	7.8813	8.8431	3.5671
	AVERAGE	105.0600	466.2800	91.7400	364.2000	33.7166
168.0	95 P.C. CONF. LIMITS	9.6114	11.3689	9.9958	15.9807	5.0334
	STANDARD DEVIATION	7.7420	9.1576	8.0516	12.8725	4.0544
	AVERAGE	111.3800	480.3200	99.7600	375.2000	37.9441
720.0	95 P.C. CONF. LIMITS	5.8140	10.3745	7.0509	17.7719	4.2867
	STANDARD DEVIATION	4.6832	8.3567	5.6795	14.3153	3.4529

Table 11. Lot 1 cell parameters prior to and as a function of time at 60° C after irradiation by 1-MeV electrons to 3×10^{15} e/cm^2; cells previously exposed to 215° C for 2 min – sintered contacts

TIME (hrs.)		ISC (MA)	VOC (MV)	IMP (MA)	VMP (MV)	PMAX (MW)
	AVERAGE	145.9200	623.7200	132.8600	513.8000	68.2832
.0	95 P.C. CONF. LIMITS	3.2368	5.0657	3.8089	11.2214	3.3253
	STANDARD DEVIATION	2.6072	4.0804	3.0681	9.0398	2.6785
	AVERAGE	81.7800	469.5800	75.0200	386.5000	29.5838
1.1	95 P.C. CONF. LIMITS	4.3669	2.7279	4.1066	4.9929	1.6429
	STANDARD DEVIATION	3.5175	2.1973	3.3079	4.0218	1.3233
	AVERAGE	94.8200	476.7800	85.4200	390.9000	33.5225
24.0	95 P.C. CONF. LIMITS	7.5385	11.4630	6.5895	8.7720	3.2422
	STANDARD DEVIATION	6.0722	9.2334	5.3078	7.0659	2.6116
	AVERAGE	102.3200	481.5600	91.9800	394.5000	36.5762
48.0	95 P.C. CONF. LIMITS	6.1860	12.0674	5.0933	11.5962	2.9696
	STANDARD DEVIATION	4.9828	9.7203	4.1027	9.3408	2.3920
	AVERAGE	109.8400	493.7400	97.4400	401.8000	39.3478
168.0	95 P.C. CONF. LIMITS	3.4834	10.5067	2.9269	11.6922	1.9092
	STANDARD DEVIATION	2.8059	8.4632	2.3576	9.4181	1.5379
	AVERAGE	111.2600	511.5600	101.7200	418.2000	42.8502
720.0	95 P.C. CONF. LIMITS	3.7614	10.6071	3.5685	12.7017	1.8976
	STANDARD DEVIATION	3.0298	8.5440	2.8744	10.2312	1.5285

Table 12. Lot 1 cell parameters prior to and as a function of time at 60°C after irradiation by 1-MeV electrons to 3 × 10^{15} e/cm^2; cells previously exposed to 215°C for 2 min – unsintered contacts

TIME (hrs.)		TSC (MA)	VOC (MV)	IMP (MA)	VMP (MV)	PMAX (MW)
	AVERAGE	144.2200	621.8500	130.1400	505.8000	65.8284
.0	95 P.C. CONF. LIMITS	2.1403	4.6024	2.0297	10.9784	1.9995
	STANDARD DEVIATION	1.7240	3.7073	1.6349	8.8431	1.6025
	AVERAGE	80.6000	469.1400	72.9400	386.4000	28.7849
2.0	95 P.C. CONF. LIMITS	1.4779	2.4771	1.9110	3.6198	.7209
	STANDARD DEVIATION	1.1904	1.9953	1.4598	2.9157	.5906
	AVERAGE	96.1400	476.0200	96.4000	386.4000	33.6158
24.0	95 P.C. CONF. LIMITS	7.5234	8.9789	6.2761	11.2969	3.3445
	STANDARD DEVIATION	6.0601	7.2325	5.0554	9.0996	2.6940
	AVERAGE	104.5900	483.3400	94.0400	390.0000	36.9577
48.0	95 P.C. CONF. LIMITS	5.2521	9.6431	4.4185	11.1040	2.7649
	STANDARD DEVIATION	4.2305	7.7675	3.5591	8.9443	2.2271
	AVERAGE	111.1200	495.7600	99.7000	396.2000	39.6901
168.0	95 P.C. CONF. LIMITS	1.8816	7.8428	1.7762	11.8233	1.8567
	STANDARD DEVIATION	1.5156	6.3174	1.4308	9.5237	1.4956
	AVERAGE	111.6000	511.5900	102.4800	414.6000	42.9014
720.0	95 P.C. CONF. LIMITS	1.4442	9.0476	1.9186	10.9996	1.7035
	STANDARD DEVIATION	1.1633	7.2978	1.5454	8.8602	1.3722

Table 13. Lot 1 cell parameters prior to and as a function of time at 60°C after irradiation by 1-MeV electrons to 3×10^{15} e/cm^2; cells previously exposed to 5 cycles of +100 to -196°C — sintered contacts

TIME (hrs.)		ISC (MA)	VOC (MV)	IMP (MA)	VMP (MV)	PMAX (MW)
	AVERAGE	146.3600	603.3000	127.5600	477.2000	60.9393
.0	95 P.C. CONF. LIMITS	3.0695	13.4037	6.3984	26.7199	6.0075
	STANDARD DEVIATION	2.4725	10.7967	5.1539	21.5221	4.9390
	AVERAGE	81.8000	465.8400	73.1000	375.1000	28.0496
1.2	95 P.C. CONF. LIMITS	4.4808	6.1359	5.7299	11.1093	2.4220
	STANDARD DEVIATION	3.6093	4.9425	4.6147	8.9486	1.9509
	AVERAGE	94.6800	471.5000	83.7000	376.4000	31.7750
24.0	95 P.C. CONF. LIMITS	7.8741	12.4271	8.8595	15.1439	4.4199
	STANDARD DEVIATION	6.3426	10.0100	7.1363	12.1984	3.5602
	AVERAGE	101.9600	476.2200	89.4800	377.8000	34.1591
48.0	95 P.C. CONF. LIMITS	8.5147	14.4399	9.5178	15.4099	4.7662
	STANDARD DEVIATION	6.8586	11.6313	7.6666	12.4127	3.8392
	AVERAGE	109.9200	482.3800	94.5600	380.2000	36.2161
168.0	95 P.C. CONF. LIMITS	6.3518	18.9215	6.9950	19.1805	4.1909
	STANDARD DEVIATION	5.1163	15.2413	5.6345	15.4499	3.3758
	AVERAGE	110.8600	503.3400	98.8200	396.2000	39.5409
720.0	95 P.C. CONF. LIMITS	4.4372	16.1525	6.5818	19.6411	3.9434
	STANDARD DEVIATION	3.5742	13.0108	5.3016	15.8209	3.1764

Table 14. Lot 1 cell parameters prior to and as a function of time at 60°C after irradiation by 1-MeV electrons to 3×10^{15} e/cm^2; cells previously exposed to 5 cycles of +100 to -196°C — unsintered contacts

TIME (hrs.)		ISC (MA)	VOC (MV)	IMP (MA)	VMP (MV)	PMAX (MW)
	AVERAGE	135.3600	583.9800	113.3800	449.2000	50.3925
.0	95 P.C. CONF. LIMITS	7.3607	10.9771	8.1316	19.2006	4.8509
	STANDARD DEVIATION	5.9290	8.8420	6.5500	15.4661	3.9074
	AVERAGE	78.5800	479.5600	67.9200	364.8000	25.4627
2.1	95 P.C. CONF. LIMITS	6.4339	55.4734	6.2841	10.4092	2.5591
	STANDARD DEVIATION	5.1825	44.6839	5.0618	8.3846	2.0614
	AVERAGE	86.6800	459.7800	73.9000	361.0000	26.9672
24.0	95 P.C. CONF. LIMITS	5.0570	7.2336	6.3214	12.3962	3.1239
	STANDARD DEVIATION	4.0734	5.8267	5.0919	9.9851	2.5163
	AVERAGE	94.6200	465.0200	90.8000	361.6000	29.5895
48.0	95 P.C. CONF. LIMITS	4.8597	9.2015	6.9047	12.8298	3.3946
	STANDARD DEVIATION	3.9145	7.4118	5.5617	10.3344	2.7343
	AVERAGE	103.9000	476.0200	86.5600	367.0000	32.0565
168.0	95 P.C. CONF. LIMITS	4.5766	10.8095	8.3347	13.7965	3.9856
	STANDARD DEVIATION	3.6865	8.7070	6.7136	11.1131	3.2104
	AVERAGE	101.7200	491.3800	87.6400	379.7000	33.6816
720.0	95 P.C. CONF. LIMITS	16.1538	10.1841	18.9406	18.7067	7.4840
	STANDARD DEVIATION	13.0119	8.2033	15.2566	15.0692	6.0283

Table 15. Lot 1 cell parameters prior to and as a function of time at 60°C after irradiation by 1-MeV electrons to 3×10^{15} e/cm^2; no prior environmental exposure– sintered contacts

TIME (hrs.)		ISC (MA)	VOC (MV)	IMP (MA)	VMP (MV)	PMAX (MW)
.0	AVERAGE	149.1000	615.2200	132.7200	488.9000	64.9788
	95 P.C. CONF. LIMITS	3.0711	8.7538	5.7480	17.2336	3.9139
	STANDARD DEVIATION	2.4738	7.0512	4.6300	13.8816	3.0721
1.4	AVERAGE	84.1200	464.8400	75.7600	374.1000	28.9507
	95 P.C. CONF. LIMITS	3.1918	3.5100	4.2443	5.9147	1.7084
	STANDARD DEVIATION	2.5710	2.8273	3.4188	4.7643	1.3761
24.0	AVERAGE	90.1800	465.1200	80.1800	372.4000	30.0840
	95 P.C. CONF. LIMITS	4.5024	4.7335	5.0030	7.9421	1.9060
	STANDARD DEVIATION	3.6267	3.8128	4.0299	6.3974	1.5353
48.0	AVERAGE	97.9400	468.6200	86.9200	372.3000	32.6621
	95 P.C. CONF. LIMITS	5.2048	5.8160	5.8055	9.5520	2.2907
	STANDARD DEVIATION	4.1925	4.6847	4.6763	7.6942	1.8452
168.0	AVERAGE	109.7800	480.1200	95.8800	374.2000	36.0769
	95 P.C. CONF. LIMITS	3.8490	6.7693	4.6699	12.3960	2.0102
	STANDARD DEVIATION	3.1004	5.4526	3.7616	9.9850	1.6192
720.0	AVERAGE	114.1200	497.5800	103.4200	385.9000	40.2232
	95 P.C. CONF. LIMITS	2.5468	5.6470	3.2604	14.1044	1.9989
	STANDARD DEVIATION	2.0514	4.5487	2.6262	11.3611	1.5296

Table 16. Lot 1 cell parameters prior to and as a function of time at 60°C after irradiation by 1-MeV electrons to 3×10^{15} e/cm^2; no prior environmental exposure — unsintered contacts

TIME (hrs.)		ISC (MA)	VOC (MV)	IMP (MA)	VMP (MV)	PMAX (MW)
	AVERAGE	139.3600	614.1000	125.5400	498.2000	62.5407
.0	95 P.C. CONF. LIMITS	5.3222	8.2833	3.7805	15.8110	2.5645
	STANDARD DEVIATION	4.2870	6.6722	3.0452	12.7358	2.0657
	AVERAGE	78.5600	467.6200	70.5800	386.6000	27.9016
2.2	95 P.C. CONF. LIMITS	3.3099	2.8479	2.3066	5.9149	.9471
	STANDARD DEVIATION	2.6661	2.2940	1.8580	4.7645	.7629
	AVERAGE	90.9400	473.3000	81.2600	387.4000	31.7442
24.0	95 P.C. CONF. LIMITS	7.4586	9.4018	7.3291	12.4952	3.7232
	STANDARD DEVIATION	6.0079	7.5732	5.9036	10.0649	2.9990
	AVERAGE	98.9600	478.8400	89.0600	386.6000	34.7553
48.0	95 P.C. CONF. LIMITS	6.8517	11.1382	6.6305	14.1712	3.7029
	STANDARD DEVIATION	5.5191	8.9718	5.3409	11.4149	2.9827
	AVERAGE	106.1800	492.2000	94.8200	394.4000	37.6226
168.0	95 P.C. CONF. LIMITS	4.8635	9.8043	4.7400	14.8094	2.8944
	STANDARD DEVIATION	3.9176	7.8974	3.8181	11.9290	2.3314
	AVERAGE	107.4200	507.6000	98.4600	410.1000	40.7319
720.0	95 P.C. CONF. LIMITS	4.2832	10.2761	3.7082	18.1877	2.5447
	STANDARD DEVIATION	3.4501	8.2774	2.9870	14.6502	2.0498

Table 17. Lot 2 cell parameters prior to and after exposure to 5 cycles of +100 to -196°C

TIME (hrs.)		ISC (MA)	VOC (MV)	IMP (MA)	VMP (MV)	PMAX (MW)
	AVERAGE	142.5850	611.2800	128.5500	492.5000	63.3106
.0	95 P.C. CONF. LIMITS	1.7947	3.2579	1.3040	5.8896	.9894
	STANDARD DEVIATION	3.8348	6.9612	2.7863	12.5845	2.1141
	AVERAGE	126.2000	517.6000	108.0250	384.2500	41.6682
5.0	95 P.C. CONF. LIMITS	1.7915	34.7386	1.9662	36.6696	4.3701
	STANDARD DEVIATION	3.8279	74.2263	4.2012	78.3522	9.3376

Table 18. Lot 3 cell parameters prior to and after exposure to 5 cycles of +100 to -196°C; junction diffusion with O_2 carrier gas

TIME (hrs.)		ISC (MA)	VOC (MV)	IMP (MA)	VMP (MV)	PMAX (MW)
	AVERAGE	135.3450	607.9550	120.5700	492.8500	59.4297
.0	95 P.C. CONF. LIMITS	1.9977	3.4366	1.7625	5.8252	1.2017
	STANDARD DEVIATION	4.2685	7.3431	3.7659	12.4468	2.5677
	AVERAGE	133.6600	598.7250	115.8750	476.9000	55.3504
5.0	95 P.C. CONF. LIMITS	1.7078	10.8132	2.1673	16.5052	2.5738
	STANDARD DEVIATION	3.6491	23.1047	4.6309	35.2669	5.4996

Table 19. Lot 3 cell parameters prior to and after exposure to 5 cycles of +100 to -196°C; junction diffusion with N_2 carrier gas

TIME (hrs.)		ISC (MA)	VOC (MV)	IMP (MA)	VMP (MV)	PMAX (MW)
	AVERAGE	137.7200	603.6600	122.0400	487.8000	59.5544
.0	95 P.C. CONF. LIMITS	7.2056	10.4957	5.8590	12.3102	3.9669
	STANDARD DEVIATION	5.8041	8.4543	4.7194	9.9159	3.1954
	AVERAGE	131.5100	586.2300	113.8900	462.0000	52.5975
5.0	95 P.C. CONF. LIMITS	7.7622	23.4947	6.2065	34.9572	5.3840
	STANDARD DEVIATION	6.2524	18.9250	4.9993	28.1580	4.3368

Table 20. Lot 4 cell parameters prior to and as a function of time at 60°C after irradiation by 1-MeV electrons to 1×10^{14} e/cm^2; no prior environmental exposure

TIME (hrs.)		ISC (MA)	VOC (MV)	IMP (MA)	VMP (MV)	PMAX (MW)
	AVERAGE	133.3100	599.6000	119.3800	484.4000	57.830
.0	95 P.C. CONF. LIMITS	2.4601	4.6736	1.7992	6.9736	1.274
	STANDARD DEVIATION	3.4392	6.5337	2.5153	9.7491	1.781
	AVERAGE	102.5600	532.3700	92.5900	433.7500	40.340
.7	95 P.C. CONF. LIMITS	2.3177	2.6607	1.9033	4.8021	.634
	STANDARD DEVIATION	3.2402	3.7197	2.6608	6.7134	.886
	AVERAGE	122.1200	561.7200	109.8200	453.7000	49.892
24.0	95 P.C. CONF. LIMITS	1.8905	6.3307	1.7491	9.0026	1.291
	STANDARD DEVIATION	2.6430	8.8503	2.4452	12.5857	1.804
	AVERAGE	124.3000	569.8200	110.9400	459.5500	51.019
48.0	95 P.C. CONF. LIMITS	1.7630	5.2752	1.5384	7.7923	.943
	STANDARD DEVIATION	2.4647	7.3747	2.1506	10.8937	1.319
	AVERAGE	125.6800	578.1400	112.8700	465.6000	52.609
168.0	95 P.C. CONF. LIMITS	1.9413	3.4162	1.3590	5.8272	.733
	STANDARD DEVIATION	2.7139	4.7758	1.8999	8.1464	1.024
	AVERAGE	125.7600	581.4200	112.1900	470.2500	52.806
720.0	95 P.C. CONF. LIMITS	1.8544	3.0974	1.4883	7.2983	.861
	STANDARD DEVIATION	2.5924	4.3301	2.0807	10.2031	1.204

Table 21. Lot 4 cell parameters prior to and as a function of time at 60°C after irradiation by 1-MeV electrons to 3×10^{15} e/cm^2; no prior environmental exposure

TIME (hrs.)		ISC (MA)	VOC (MV)	IMP (MA)	VMP (MV)	PMAX (MW)
	AVERAGE	133.8100	600.3100	120.5800	487.1500	58.7295
.0	95 P.C. CONF. LIMITS	3.0544	4.4473	2.5071	8.1837	1.3237
	STANDARD DEVIATION	4.2700	6.2174	3.5049	11.4408	1.8505
	AVERAGE	76.6700	462.9000	67.3100	374.0000	25.4451
1.2	95 P.C. CONF. LIMITS	2.7098	3.3215	2.3438	7.1436	.7799
	STANDARD DEVIATION	3.7882	4.6434	3.2767	9.9867	1.0904
	AVERAGE	86.6700	469.7700	76.4600	377.2500	29.0784
24.0	95 P.C. CONF. LIMITS	3.6288	5.3696	3.2900	6.5234	1.3782
	STANDARD DEVIATION	5.0731	7.5067	4.5994	9.1197	1.9267
	AVERAGE	94.2300	475.3700	83.4500	380.0000	32.0059
48.0	95 P.C. CONF. LIMITS	3.7353	5.9649	3.4538	7.5948	1.4627
	STANDARD DEVIATION	5.2220	8.3390	4.8284	10.6176	2.0449
	AVERAGE	104.6500	489.2900	92.9100	385.8500	36.0809
168.0	95 P.C. CONF. LIMITS	3.0337	6.1997	2.4885	8.9471	.9242
	STANDARD DEVIATION	4.2411	8.6671	3.4789	12.5081	1.2920
	AVERAGE	106.6200	499.3100	95.0300	396.4500	37.8875
720.0	95 P.C. CONF. LIMITS	2.7362	6.4915	2.0513	10.2514	.8530
	STANDARD DEVIATION	3.8251	9.0751	2.8677	14.3314	1.1925

Table 22. Lot 4 cell parameters prior to and after exposure to 12 days at 125°C in vacuum

TIME (hrs.)		ISC (MA)	VOC (MV)	IMP (MA)	VMP (MV)	PMAX (MW)
.0	AVERAGE	131.3675	600.3524	118.3350	492.1250	58.233
	95 P.C. CONF. LIMITS	1.1593	1.6980	.9542	2.3127	.518
	STANDARD DEVIATION	3.6660	5.3694	3.0174	7.3133	1.638
288.0	AVERAGE	129.8350	596.3599	116.9975	488.2750	57.139
	95 P.C. CONF. LIMITS	.9755	1.8873	.9158	2.2053	.496
	STANDARD DEVIATION	3.0848	5.9683	2.8959	6.9738	1.568

Table 23. Lot 4 cell parameters prior to and as a function of time at 60°C after irradiation by 1-MeV electrons to 1×10^{14} e/cm^2; cells previously exposed to 12 days at 125°C in vacuum

TIME (hrs.)		ISC (MA)	VOC (MV)	IMP (MA)	VMP (MV)	PMAX (MW)
.0	AVERAGE	127.6400	593.8700	115.5500	484.6500	56.0046
	95 P.C. CONF. LIMITS	2.2485	5.6773	1.8419	4.3967	1.1233
	STANDARD DEVIATION	3.1434	7.9369	2.5750	6.1466	1.5704
.4	AVERAGE	100.9700	530.8500	92.0100	435.0000	40.0433
	95 P.C. CONF. LIMITS	1.4590	2.3441	1.4994	3.1632	.5756
	STANDARD DEVIATION	2.0398	3.2770	2.0961	4.4222	.8047
24.0	AVERAGE	118.8900	556.9500	108.2800	452.9000	49.0328
	95 P.C. CONF. LIMITS	2.3739	4.3306	1.8340	3.3306	1.0277
	STANDARD DEVIATION	3.3187	6.0542	2.5639	4.6562	1.4368
48.0	AVERAGE	120.8500	564.4300	109.5000	458.8500	50.2215
	95 P.C. CONF. LIMITS	1.8641	4.3412	1.6006	3.7522	.8402
	STANDARD DEVIATION	2.6060	6.0690	2.2377	5.2456	1.1746
168.0	AVERAGE	122.0100	573.8400	110.2700	466.1000	51.4034
	95 P.C. CONF. LIMITS	1.6633	3.7445	1.3581	3.1495	.6579
	STANDARD DEVIATION	2.3253	5.2348	1.8986	4.4030	.9197
720.0	AVERAGE	122.2900	578.4100	110.6500	470.0000	52.0049
	95 P.C. CONF. LIMITS	1.6623	3.4114	1.2855	2.6778	.5794
	STANDARD DEVIATION	2.3239	4.7691	1.7971	3.7435	.8099

Table 24. Lot 4 cell parameters prior to and as a function of time at 60°C after irradiation by 1-MeV electrons to 3 × 10^{15} e/cm^2; cells previously exposed to 12 days at 125°C in vacuum

TIME (hrs.)		ISC (MA)	VOC (MV)	IMP (MA)	VMP (MV)	PMAX (MW)
	AVERAGE	128.2000	595.0800	115.3200	486.4000	56.0898
.0	95 P.C. CONF. LIMITS	2.1468	3.6423	2.5321	4.5108	1.2968
	STANDARD DEVIATION	3.0012	5.0919	3.5399	6.3061	1.8129
	AVERAGE	77.2800	461.2900	67.8900	376.8000	25.5393
.9	95 P.C. CONF. LIMITS	2.2965	1.6558	2.3265	2.6152	.8899
	STANDARD DEVIATION	3.2105	2.3148	3.2524	3.6560	1.2440
	AVERAGE	84.0000	465.2200	74.2800	374.0500	27.7173
24.0	95 P.C. CONF. LIMITS	3.7273	3.2145	3.6426	3.2034	1.2948
	STANDARD DEVIATION	5.2107	4.4938	5.0923	4.4783	1.8102
	AVERAGE	90.3900	468.7500	79.7400	378.6500	30.2341
48.0	95 P.C. CONF. LIMITS	4.0468	3.9203	3.5948	3.8235	1.4259
	STANDARD DEVIATION	5.6575	5.4805	5.0255	5.3453	1.9935
	AVERAGE	101.5400	480.8200	90.0600	383.0000	34.5301
168.0	95 P.C. CONF. LIMITS	2.8720	4.4136	2.5457	3.6629	1.0897
	STANDARD DEVIATION	4.0150	6.1703	3.5589	5.1208	1.5234
	AVERAGE	104.9200	492.2700	93.9200	391.0000	36.7523
720.0	95 P.C. CONF. LIMITS	3.1209	4.6034	2.4283	6.1715	.9756
	STANDARD DEVIATION	4.3630	6.4356	3.3948	8.6278	1.3639

Table 25. Lot 4 cell parameters prior to and after exposure to 5 cycles of +100 to -196°C

TIME (hrs.)		ISC (MA)	VOC (MV)	IMP (MA)	VMP (MV)	PMAX (MW)
.0	AVERAGE	133.4800	600.3050	120.4950	486.7500	58.6531
	95 P.C. CONF. LIMITS	1.6454	2.1239	1.3097	5.2580	.9357
	STANDARD DEVIATION	3.5158	4.5381	2.7984	11.2349	1.9993
5.0	AVERAGE	131.4350	589.6200	114.7050	469.2250	53.9240
	95 P.C. CONF. LIMITS	1.5657	10.3367	1.9752	16.2460	2.3455
	STANDARD DEVIATION	3.3455	22.0866	4.2204	34.7129	5.0117

Table 26. Lot 4 cell parameters prior to and after exposure to 12 days at 150°C

TIME (hrs.)		ISC (MA)	VOC (MV)	IMP (MA)	VMP (MV)	PMAX (MW)
.0	AVERAGE	131.5767	599.4966	119.0700	488.7667	58.1873
	95 P.C. CONF. LIMITS	1.5809	1.9282	1.2066	3.4183	.5870
	STANDARD DEVIATION	4.2341	5.1644	3.2318	9.1555	1.5723
288.0	AVERAGE	131.2200	592.9300	118.1067	486.6833	57.4852
	95 P.C. CONF. LIMITS	1.4628	6.7769	1.1756	2.6190	.5544
	STANDARD DEVIATION	3.9179	18.1508	3.1488	7.0146	1.4849

Table 27. Lot 4 cell parameters prior to and after exposure to 14 days at 80°C and 95% relative humidity

TIME (hrs.)		ISC (MA)	VOC (MV)	IMP (MA)	VMP (MV)	PMAX (MW)
.0	AVERAGE	131.7800	598.3850	119.3300	490.0750	58.4817
	95 P.C. CONF. LIMITS	1.8722	3.0380	1.4612	5.3406	.9760
	STANDARD DEVIATION	4.0003	6.4913	3.1222	11.4113	2.0855
336.0	AVERAGE	131.9850	597.6450	119.1350	489.4250	58.3092
	95 P.C. CONF. LIMITS	1.7487	3.0294	1.6270	5.3358	.9801
	STANDARD DEVIATION	3.7365	6.4730	3.4764	11.4011	2.0942

Table 28. P-contact pull strength prior to and after exposure to 150°C for 12 days; Lot 1 cells – sintered contacts

```
P/N, 20 OHM-CM, 2X2X.0360 CM

SIL SOLAR CELLS,      AG-TI,  SOLDERCOAT,
  P-CONTACT
CELL MANUFACTURER   HEK

150 DEG C FOR 288 HOURS, HIGH TEMP
PULL WIRES SOLDERED AFTER ENVIR TEST

EXPOSURE TIME (HOURS)               .0    288.0



CONTACT STRENGTH (GRAMS)        1166.0  1765.0
                                 708.0   699.0
                                1134.0  1025.0
                                 875.0  1447.0
                                1306.0   980.0
                                2232.0      .0
                                1356.0      .0
                                 966.0      .0
                                1950.0      .0
                                 998.0      .0

AVERAGE                         1269.1  1183.2

95 P.C. CONF. LIMITS             342.6   522.6

STANDARD DEVIATION               478.9   421.0

PER CENT CHANGE                     .0    -6.8
(REF. INITIAL TIME)
```

Table 29. N-contact pull strength prior to and after exposure to 150°C for 12 days; Lot 1 cells–sintered contacts

```
P/N, 20 OHM-CM,  2X2X.0360 CM

SIL SOLAR CELLS,      AS-TI,  SOLDERCOAT,
  N-CONTACT
CELL MANUFACTURER   HEK

150 DEG C FOR 288 HOURS, HIGH TEMP
PULL WIRES SOLDERED AFTER ENVIR TEST

EXPOSURE TIME (HOURS)            .0     288.0



CONTACT STRENGTH (GRAMS)     1325.0    1043.0
                              490.0     866.0
                              826.0    1139.0
                             1379.0    1261.0
                             1315.0    1052.0
                             1066.0        .0
                              739.0        .0
                             1225.0        .0
                             1302.0        .0
                             1261.0        .0

AVERAGE                      1092.9    1072.2

95 P.C. CONF. LIMITS          217.9     179.8

STANDARD DEVIATION            304.6     144.8

PER CENT CHANGE                  .0      -1.9
(REF. INITIAL TIME)
```

Table 30. P-contact pull strength prior to and after exposure to 150° C for 12 days; Lot 1 cells – unsintered contacts

```
P/N, 20 OHM-CM,   2X2X.0360 CM

SIL SOLAR CELLS,      AS-TI,  SOLDERCOAT,
  P-CONTACT
CELL MANUFACTURER   HEK

150 DEG C FOR 288 HOURS, HIGH TEMP
PULL WIRES SOLDERED AFTER ENVIR TEST

EXPOSURE TIME (HOURS)              .0    288.0



CONTACT STRENGTH (GRAMS)        894.0   1030.0
                                907.0    830.0
                               1166.0   1107.0
                               1987.0   1393.0
                                944.0    989.0
                                953.0       .0
                                812.0       .0
                               1111.0       .0
                                345.0       .0
                               1247.0       .0

AVERAGE                        1036.6   1069.8

95 P.C. CONF. LIMITS            297.0    257.0

STANDARD DEVIATION              415.2    207.0

PER CENT CHANGE                    .0      3.2
 (REF. INITIAL TIME)
```

Table 31. N-contact pull strength prior to and after exposure to 150° C for 12 days; Lot 1 cells – unsintered contacts

```
P/N, 20 OHM-CM,  2X2X.0360 CM

SIL SOLAR CELLS,      AG-TI,  SOLDERCOAT,
  N-CONTACT
CELL MANUFACTURER    HEK

150 DEG C FOR 288 HOURS, HIGH TEMP
PULL WIRES SOLDERED AFTER ENVIR TEST

EXPOSURE TIME (HOURS)              .0     288.0



CONTACT STRENGTH (GRAMS)       2241.0     599.0
                                730.0    1121.0
                               1052.0     925.0
                               1080.0    2041.0
                               1025.0    1302.0
                               3139.0        .0
                                984.0        .0
                               2268.0        .0
                               1619.0        .0
                                853.0        .0

AVERAGE                        1499.1    1197.6

95 P.C. CONF. LIMITS            570.2     668.8

STANDARD DEVIATION              797.2     538.7

PER CENT CHANGE                    .0     -20.1
(REF. INITIAL TIME)
```

Table 32. P-contact pull strength prior to and after exposure to 215°C for 2 min; Lot 1 cells—sintered contacts

```
P/N, 20 OHM-CM,  2X2X.0360 CM

SIL SOLAR CELLS,      AG-TI,  SOLDERCOAT,
  P-CONTACT
CELL MANUFACTUPER   HEK

215 DEG C FOR 2 MINUTES, SOLDER MELT
PULL WIRES SOLDERED AFTER ENVIR TEST

EXPOSURE TIME (MINUTES)              .0      2.0


CONTACT STRENGTH (GRAMS)         1166.0    830.0
                                  708.0    857.0
                                 1134.0    944.0
                                  875.0   2109.0
                                 1306.0   1039.0
                                 2232.0       .0
                                 1356.0       .0
                                  966.0       .0
                                 1950.0       .0
                                  998.0       .0

AVERAGE                          1269.1   1155.8

95 P.C. CONF. LIMITS              342.6    669.3

STANDARD DEVIATION                478.9    539.1

PER CENT CHANGE                      .0     -8.9
 (REF. INITIAL TIME)
```

Table 33. N-contact pull strength prior to and after exposure to 215°C for 2 min; Lot 1 cells—sintered contacts

P/N, 20 OHM-CM, 2X2X.0360 CM

SIL SOLAR CELLS, AG-TI, SOLDERCOAT, N-CONTACT

CELL MANUFACTURER HEK

215 DEG C FOR 2 MINUTES, SOLDER MELT

PULL WIRES SOLDERED AFTER ENVIR TEST

EXPOSURE TIME (MINUTES)	.0	2.0
CONTACT STRENGTH (GRAMS)	1325.0	853.0
	490.0	1057.0
	826.0	835.0
	1379.0	735.0
	1315.0	576.0
	1066.0	.0
	739.0	.0
	1225.0	.0
	1302.0	.0
	1261.0	.0
AVERAGE	1092.8	811.2
95 P.C. CONF. LIMITS	217.9	218.5
STANDARD DEVIATION	304.6	176.0
PER CENT CHANGE (REF. INITIAL TIME)	.0	-25.8

Table 34. P-contact pull strength prior to and after exposure to 215°C for 2 min; Lot 1 cells—unsintered contacts

P/N, 20 OHM-CM, 2X2X.0360 CM

SIL SOLAR CELLS, AG-TI, SOLDERCOAT, P-CONTACT
CELL MANUFACTURER HEK

215 DEG C FOR 2 MINUTES, SOLDER MELT
PULL WIRES SOLDERED AFTER ENVIR TEST

EXPOSURE TIME (MINUTES)	.0	2.0
CONTACT STRENGTH (GRAMS)	894.0	1397.0
	907.0	1111.0
	1166.0	1706.0
	1987.0	1470.0
	944.0	1320.0
	953.0	.0
	812.0	.0
	1111.0	.0
	345.0	.0
	1247.0	.0
AVERAGE	1036.6	1400.8
95 P.C. CONF. LIMITS	297.0	269.5
STANDARD DEVIATION	415.2	217.1
PER CENT CHANGE (REF. INITIAL TIME)	.0	35.1

Table 35. N-contact pull strength prior to and after exposure to 215° for 2 min; Lot 1 cells — unsintered contacts

```
P/N, 20 OHM-CM, 2X2X.0360 CM

SIL SOLAR CELLS,      AG-TI,  SOLDERCOAT,
  N-CONTACT
CELL MANUFACTURER   HEK

215 DEG C FOR 2 MINUTES, SOLDER MELT
PULL WIRES SOLDERED AFTER ENVIR TEST

EXPOSURE TIME (MINUTES)              .0      2.0



CONTACT STRENGTH (GRAMS)         2241.0   1320.0
                                  730.0   1202.0
                                 1052.0   3030.0
                                 1090.0    898.0
                                 1025.0   1043.0
                                 3139.0       .0
                                  984.0       .0
                                 2268.0       .0
                                 1619.0       .0
                                  853.0       .0

AVERAGE                          1499.1   1498.6

95 P.C. CONF. LIMITS              570.2   1081.1

STANDARD DEVIATION                797.2    870.8

PER CENT CHANGE                      .0      -.0
(REF. INITIAL TIME)
```

Table 36. P-contact pull strength prior to and after exposure to 5 cycles of +100 to -196°C; Lot 1 cells — sintered contacts

P/N, 20 OHM-CM, 2X2X.0360 CM

SIL SOLAR CELLS, AG-TI, SOLDERCOAT, P-CONTACT

CELL MANUFACTURER HEK

5 CYCLES, LN2 TO BOILING WATER SHOCK

PULL WIRES SOLDERED AFTER ENVIR TEST

CYCLES	0.0000	5.0000+00
CONTACT STRENGTH (GRAMS)	1166.0	1206.0
	708.0	1111.0
	1134.0	812.0
	875.0	1288.0
	1306.0	966.0
	2232.0	.0
	1356.0	.0
	966.0	.0
	1950.0	.0
	998.0	.0
AVERAGE	1269.1	1076.6
95 P.C. CONF. LIMITS	342.6	236.3
STANDARD DEVIATION	478.9	190.3
PER CENT CHANGE (REF. INITIAL CYCLE)	.0	-15.2

Table 37. N-contact pull strength prior to and after exposure to 5 cycles of +100 to -196°C; Lot 1 cells — sintered contacts

P/N. 20 OHM-CM, 2X2X.0360 CM		
SIL SOLAR CELLS, AG-TI, SOLDERCOAT, N-CONTACT		
CELL MANUFACTURER HEK		
5 CYCLES, LN2 TO BOILING WATER SHOCK		
PULL WIRES SOLDERED AFTER ENVIR TEST		
CYCLES	0.0000	5.0000+00
CONTACT STRENGTH (GRAMS)	1325.0	1910.0
	490.0	2155.0
	826.0	780.0
	1379.0	2268.0
	1315.0	925.0
	1066.0	.0
	739.0	.0
	1225.0	.0
	1302.0	.0
	1261.0	.0
AVERAGE	1092.8	1607.6
95 P.C. CONF. LIMITS	217.9	873.0
STANDARD DEVIATION	304.6	703.2
PER CENT CHANGE (REF. INITIAL CYCLE)	.0	47.1

Table 38. P-contact pull strength prior to and after exposure to 5 cycles of +100 to -196°C; Lot 1 cells — unsintered contacts

P/N, 20 OHM-CM, 2X2X.0360 CM

SIL SOLAR CELLS, AG-TI, SOLDERCOAT, P-CONTACT

CELL MANUFACTURER HEK

5 CYCLES, LN2 TO BOILING WATER SHOCK

PULL WIRES SOLDERED AFTER ENVIR TEST

CYCLES	0.0000	5.0000+00
CONTACT STRENGTH (GRAMS)	894.0	799.0
	907.0	454.0
	1166.0	1429.0
	1987.0	1352.0
	944.0	1479.0
	953.0	.0
	912.0	.0
	1111.0	.0
	345.0	.0
	1247.0	.0
AVERAGE	1036.6	1100.6
95 P.C. CONF. LIMITS	297.0	565.3
STANDARD DEVIATION	415.2	455.4
PER CENT CHANGE (REF. INITIAL CYCLE)	.0	6.2

Table 39. N-contact pull strength prior to and after exposure to 5 cycles of +100 to -196°C; Lot 1 cells — unsintered contacts

P/N, 20 OHM-CM, 2X2X.0360 CM

SIL SOLAR CELLS, AG-TI, SOLDERCOAT, N-CONTACT

CELL MANUFACTURER HEK

5 CYCLES, LN2 TO BOILING WATER SHOCK

PULL WIRES SOLDERED AFTER ENVIR TEST

CYCLES	0.0000	5.0000+00
CONTACT STRENGTH (GRAMS)	2241.0	1352.0
	730.0	758.0
	1052.0	767.0
	1090.0	1080.0
	1025.0	916.0
	3139.0	.0
	994.0	.0
	2268.0	.0
	1619.0	.0
	853.0	.0
AVERAGE	1499.1	974.6
95 P.C. CONF. LIMITS	570.2	308.5
STANDARD DEVIATION	797.2	248.5
PER CENT CHANGE (REF. INITIAL CYCLE)	.0	-35.0

Table 40. P-contact pull strength prior to and after exposure to 5 cycles of +100 to -196°C; Lot 2 cells -- sintered contacts

P-CONTACT STRENGTH, LITHIUM LOT 2 SOLAR CELLS,
AFTER ENVIR TEST

P/N, 20 OHM-CM, 2X2X.0360 CM

SIL SOLAR CELLS, AG-TI, SOLDERCOATED, HEK

5 CYCLES, LN2 TO BOILING WATER SHOCK
PULL WIRES SOLDERED AFTER ENVIR TEST

CYCLES	0.0000	5.0000+00
CONTACT STRENGTH (GRAMS)	1157.0	676.0
	762.0	1329.0
	989.0	921.0
	1243.0	726.0
	1084.0	1043.0
	2018.0	572.0
	1034.0	567.0
	953.0	789.0
	2173.0	1175.0
	1306.0	916.0
	930.0	
	635.0	
	1043.0	
	1379.0	
	957.0	
	1542.0	
	1134.0	
	1070.0	
	939.0	
	2327.0	
AVERAGE	1233.7	871.4
95 P.C. CONF. LIMITS	212.9	182.2
STANDARD DEVIATION	454.8	254.7
PER CENT CHANGE (REF. INITIAL CYCLE)	.0	-29.4

Table 41. N-contact pull strength prior to and after exposure to 5 cycles of +100 to -196°C; Lot 2 cells — sintered contacts

N-CONTACT STRENGTH, LITHIUM LOT 2 SOLAR CELLS, AFTER ENVIR TEST

P/N, 20 OHM-CM, 2X2X.0360 CM

SIL SOLAR CELLS, AG-TI, SOLDERCOATED, HEK

5 CYCLES, LN2 TO BOILING WATER SHOCK
PULL WIRES SOLDERED AFTER ENVIR TEST

CYCLES	0.0000	5.0000+00
CONTACT STRENGTH (GRAMS)	1383.0	1184.0
	1261.0	1084.0
	567.0	1406.0
	912.0	930.0
	712.0	1706.0
	1102.0	862.0
	957.0	1461.0
	953.0	472.0
	2018.0	1021.0
	953.0	912.0
	1447.0	
	1034.0	
	1202.0	
	903.0	
	1334.0	
	1388.0	
	776.0	
	1465.0	
	962.0	
	1238.0	
AVERAGE	1128.3	1103.8
95 P.C. CONF. LIMITS	153.9	252.3
STANDARD DEVIATION	328.8	352.7
PER CENT CHANGE (REF. INITIAL CYCLE)	.0	-2.2

Table 42. P-contact pull strength prior to and after exposure to 4 cycles of +100 to -196°C; Lot 3 cells — sintered contacts

```
P-CONTACT STRENGTH, LITH LOT 3 CELLS WITH OXYGEN
  DIFF, POST ENVIR TEST

P/N, 20 OHM-CM,  2X2X.0360 CM

SIL SOLAR CELLS,     AG-TI,  SOLDERCOATED,  HEK

5 CYCLES, LN2 TO BOILING WATER SHOCK
PULL WIRES SOLDERED AFTER ENVIR TEST

CYCLES                          0.0000       5.0000+00



CONTACT STRENGTH (GRAMS)         998.0         1193.0
                                1252.0         1197.0
                                 943.0          798.0
                                 980.0          626.0
                                 472.0         1266.0
                                 916.0          789.0
                                 626.0          839.0
                                1166.0         1025.0
                                1066.0         1107.0
                                 866.0         1061.0
                                1184.0
                                 912.0
                                 880.0
                                 975.0
                                 812.0
                                1111.0
                                 957.0
                                 957.0
                                 794.0
                                 467.0

AVERAGE                          916.7          990.1

95 P.C. CONF. LIMITS              98.3          153.2

STANDARD DEVIATION               210.1          214.2

PER CENT CHANGE                     .0            8.0
(REF. INITIAL CYCLE)
```

Table 43. N-contact pull strength prior to and after exposure to 5 cycles of +100 to -196°C; Lot 3 cells — sintered contacts

N-CONTACT STRENGTH, LITH LOT 3 CELLS WITH OXYGEN DIFF, POST ENVIR TEST

P/N, 20 OHM-CM, 2X2X.0360 CM

SIL SOLAR CELLS, AG-TI, SOLDERCOATED, HEK

5 CYCLES, LN2 TO BOILING WATER SHOCK
PULL WIRES SOLDERED AFTER ENVIR TEST

CYCLES	0.0000	5.0000+00
CONTACT STRENGTH (GRAMS)	630.0	1048.0
	1061.0	590.0
	517.0	1067.0
	662.0	1084.0
	644.0	744.0
	1021.0	465.0
	581.0	658.0
	971.0	1039.0
	699.0	1102.0
	603.0	744.0
	712.0	
	590.0	
	948.0	
	590.0	
	1243.0	
	708.0	
	685.0	
	844.0	
	857.0	
	626.0	
AVERAGE	759.6	855.1
95 P.C. CONF. LIMITS	92.0	167.9
STANDARD DEVIATION	196.6	234.7
PER CENT CHANGE (REF. INITIAL CYCLE)	.0	12.6

Table 44. P-contact pull strength prior to and after exposure to 5 cycles of +100 to -196°C; Lot 4 cells — sintered contacts

P-CONTACT STRENGTH, LITHIUM LOT 4 SOLAR CELLS, AFTER ENVIR TEST

P/N, 20 OHM-CM, 2X2X.0360 CM

SIL SOLAR CELLS, AG-TI, SOLDERCOATED, HEK

5 CYCLES, LN2 TO BOILING WATER SHOCK
PULL WIRES SOLDERED AFTER ENVIR TEST

CYCLES	0.0000	5.0000+00
CONTACT STRENGTH (GRAMS)	934.0	948.0
	862.0	1057.0
	1134.0	1293.0
	835.0	1007.0
	798.0	1719.0
	1034.0	703.0
	726.0	1284.0
	839.0	816.0
	1125.0	948.0
	821.0	998.0
	835.0	
	1080.0	
	930.0	
	807.0	
	785.0	
	948.0	
	780.0	
	590.0	
	694.0	
	962.0	
AVERAGE	875.9	1077.3
95 P.C. CONF. LIMITS	66.9	207.1
STANDARD DEVIATION	142.9	289.5
PER CENT CHANGE (REF. INITIAL CYCLE)	.0	23.0

Table 45. N-contact pull strength prior to and after exposure to 5 cycles of +100 to -196°C; Lot 4 cells — sintered contacts

N-CONTACT STRENGTH, LITHIUM LOT 4 SOLAR CELLS,
AFTER ENVIR TEST

P/N, 20 OHM-CM, 2X2X.0360 CM

SIL SOLAR CELLS, AG-TI, SOLDERCOATED, HEK

5 CYCLES, LN2 TO BOILING WATER SHOCK
PULL WIRES SOLDERED AFTER ENVIR TEST

CYCLES	0.0000	5.0000+00
CONTACT STRENGTH (GRAMS)	826.0	404.0
	848.0	653.0
	1111.0	667.0
	708.0	934.0
	544.0	962.0
	934.0	703.0
	789.0	472.0
	558.0	948.0
	866.0	218.0
	426.0	980.0
	721.0	
	354.0	
	1025.0	
	744.0	
	844.0	
	689.0	
	513.0	
	544.0	
	1116.0	
	730.0	
AVERAGE	744.5	694.1
95 P.C. CONF. LIMITS	99.5	190.5
STANDARD DEVIATION	212.6	266.3
PER CENT CHANGE (REF. INITIAL CYCLE)	.0	-6.8

Table 46. P-contact pull strength prior to and after exposure to 150°C for 12 days; Lot 4 cells — sintered contacts

P-CONTACT STRENGTH, LITHIUM LOT 4 SOLAR CELLS, AFTER ENVIR TEST

P/N, 20 OHM-CM, 2X2X.0360 CM

SIL SOLAR CELLS, AG-TI, SOLDERCOATED, HEK

150 DEG C FOR 288 HOURS, HIGH TEMP
PULL WIRES SOLDERED AFTER ENVIR TEST

EXPOSURE TIME (HOURS)	.0	288.0
CONTACT STRENGTH (GRAMS)	934.0	1451.0
	862.0	680.0
	1134.0	1256.0
	835.0	703.0
	798.0	962.0
	1034.0	939.0
	726.0	753.0
	839.0	1093.0
	1125.0	885.0
	821.0	898.0
	835.0	
	1080.0	
	930.0	
	807.0	
	785.0	
	948.0	
	780.0	
	590.0	
	694.0	
	962.0	
AVERAGE	875.9	962.0
95 P.C. CONF. LIMITS	66.9	175.8
STANDARD DEVIATION	142.9	245.8
PER CENT CHANGE (REF. INITIAL TIME)	.0	9.8

Table 47. N-contact pull strength prior to and after exposure to 150°C for 12 days; Lot 4 cells – sintered contacts

N-CONTACT STRENGTH, LITHIUM LOT 4 SOLAR CELLS, AFTER ENVIR TEST

P/N, 20 OHM-CM, 2X2X.0360 CM

SIL SOLAR CELLS, AG-TI, SOLDERCOATED, HEK

150 DEG C FOR 288 HOURS, HIGH TEMP
PULL WIRES SOLDERED AFTER ENVIR TEST

EXPOSURE TIME (HOURS)	.0	288.0
CONTACT STRENGTH (GRAMS)	826.0	245.0
	848.0	544.0
	1111.0	426.0
	708.0	862.0
	544.0	880.0
	934.0	680.0
	789.0	222.0
	558.0	853.0
	866.0	844.0
	426.0	440.0
	721.0	
	354.0	
	1025.0	
	744.0	
	844.0	
	689.0	
	513.0	
	544.0	
	1116.0	
	730.0	
AVERAGE	744.5	599.6
95 P.C. CONF. LIMITS	99.5	185.4
STANDARD DEVIATION	212.6	259.3
PER CENT CHANGE (REF. INITIAL TIME)	.0	-19.5

Table 48. P-contact pull strength prior to and after exposure to 125°C for 12 days in vacuum; Lot 4 cells — sintered contacts

P-CONTACT STRENGTH, LITHIUM LOT 4 SOLAR CELLS, AFTER ENVIR TEST

P/N, 20 OHM-CM, 2X2X.0360 CM

SIL SOLAR CELLS, AG-TI, SOLDERCOATED, HEK

125 DEG C FOR 288 HOURS, VACUUM-TEMP
PULL WIRES SOLDERED AFTER ENVIR TEST

EXPOSURE TIME (HOURS)	.0	288.0
CONTACT STRENGTH (GRAMS)	934.0	957.0
	862.0	599.0
	1134.0	830.0
	835.0	930.0
	798.0	798.0
	1034.0	767.0
	726.0	1696.0
	839.0	1066.0
	1125.0	1098.0
	821.0	1125.0
	835.0	
	1080.0	
	930.0	
	807.0	
	785.0	
	948.0	
	780.0	
	590.0	
	694.0	
	962.0	
AVERAGE	875.9	986.6
95 P.C. CONF. LIMITS	66.9	213.8
STANDARD DEVIATION	142.9	298.8
PER CENT CHANGE (REF. INITIAL TIME)	.0	12.6

Table 49. N-contact pull strength prior to and after exposure to 125°C for 12 days in vacuum; Lot 4 cells — sintered contacts

N-CONTACT STRENGTH, LITHIUM LOT 4 SOLAR CELLS, AFTER ENVIR TEST

P/N, 20 OHM-CM, 2X2X.0360 CM

SIL SOLAR CELLS, AG-TI, SOLDERCOATED, HEK

215 DEG C FOR 2 MINUTES, SOLDER MELT
PULL WIRES SOLDERED AFTER ENVIR TEST

EXPOSURE TIME (MINUTES)	.0	2.0
CONTACT STRENGTH (GRAMS)	826.0	630.0
	848.0	526.0
	1111.0	635.0
	708.0	458.0
	544.0	1234.0
	934.0	340.0
	789.0	417.0
	558.0	1315.0
	866.0	898.0
	426.0	413.0
	721.0	
	354.0	
	1025.0	
	744.0	
	844.0	
	689.0	
	513.0	
	544.0	
	1116.0	
	730.0	
AVERAGE	744.5	686.6
95 P.C. CONF. LIMITS	99.5	249.0
STANDARD DEVIATION	212.6	348.1
PER CENT CHANGE (REF. INITIAL TIME)	.0	-7.8

Table 50. P-contact pull strength prior to and after exposure to 14 days at 80°C; 95% relative humidity; Lot 4 cells — sintered contacts

P-CONTACT STRENGTH, LITHIUM LOT 4 SOLAR CELLS, AFTER ENVIR TEST

P/N, 20 OHM-CM, 2X2X.0360 CM

SIL SOLAR CELLS, AG-TI, SOLDERCOATED, HEK

80 C FOR 336 HRS,95 PCT REL HUMIDITY
PULL WIRES SOLDERED AFTER ENVIR TEST

EXPOSURE TIME (HOURS)	.0	336.0
CONTACT STRENGTH (GRAMS)	934.0	581.0
	862.0	118.0
	1134.0	971.0
	835.0	726.0
	798.0	1034.0
	1034.0	1311.0
	726.0	753.0
	839.0	1084.0
	1125.0	885.0
	821.0	757.0
	835.0	
	1080.0	
	930.0	
	807.0	
	785.0	
	948.0	
	780.0	
	590.0	
	694.0	
	962.0	
AVERAGE	875.9	822.0
95 P.C. CONF. LIMITS	66.9	232.5
STANDARD DEVIATION	142.9	325.0
PER CENT CHANGE (REF. INITIAL TIME)	.0	-6.2

Table 51. N-contact pull strength prior to and after exposure to 14 days at 80°C; 95% relative humidity; Lot 4 cells — sintered contacts

N-CONTACT STRENGTH, LITHIUM LOT 4 SOLAR CELLS, AFTER ENVIR TEST

P/N, 20 OHM-CM, 2X2X.0360 CM

SIL SOLAR CELLS, AG-TI, SOLDERCOATED, HEK

80 C FOR 336 HRS,95 PCT REL HUMIDITY
PULL WIRES SOLDERED AFTER ENVIR TEST

EXPOSURE TIME (HOURS)	.0	336.0
CONTACT STRENGTH (GRAMS)	826.0	440.0
	848.0	835.0
	1111.0	481.0
	708.0	376.0
	544.0	562.0
	934.0	649.0
	789.0	249.0
	558.0	794.0
	866.0	794.0
	426.0	372.0
	721.0	
	354.0	
	1025.0	
	744.0	
	844.0	
	689.0	
	513.0	
	544.0	
	1116.0	
	730.0	
AVERAGE	744.5	555.2
95 P.C. CONF. LIMITS	99.5	146.9
STANDARD DEVIATION	212.6	205.3
PER CENT CHANGE (REF. INITIAL TIME)	.0	-25.4

Table 52. Electrical characteristics of Lot 1 cells environmentally exposed but not irradiated[a]

Environmental Test	Contact	I_{sc},[b] mA	I_{sc}/I_{sc0} [c]	V_{oc}[d], mV	V_{oc}/V_{oc0}[e]	P_{max}[f], mW	P_{max}/P_{max0}[g]
12 days at 150°C	Sintered	144.8	0.990	614.2	1.000	65.7	1.010
12 days at 150°C	Unsintered	145.7	1.00	609.3	0.992	63.0	0.996
5 cycles from +100 to -196°C	Sintered	144.1	0.982	603.1	0.977	58.4	0.878
5 cycles from +100 to -196°C	Sintered	129.4	0.882	597.5	0.947	46.9	0.731
2 min at 215°C	Sintered	146.9	0.998	616.0	1.002	67.1	1.013
2 min at 215°C	Unsintered	144.7	1.004	615.3	1.005	64.3	1.003

[a] Average of 20 cells.

[b] I_{sc} = short circuit current, postexposure.

[c] I_{sc0} = short circuit current, preexposure.

[d] V_{oc} = open circuit voltage, postexposure.

[e] V_{oc0} = open circuit voltage, preexposure.

[f] P_{max} = maximum power output, postexposure.

[g] P_{max0} = maximum power output, preexposure.

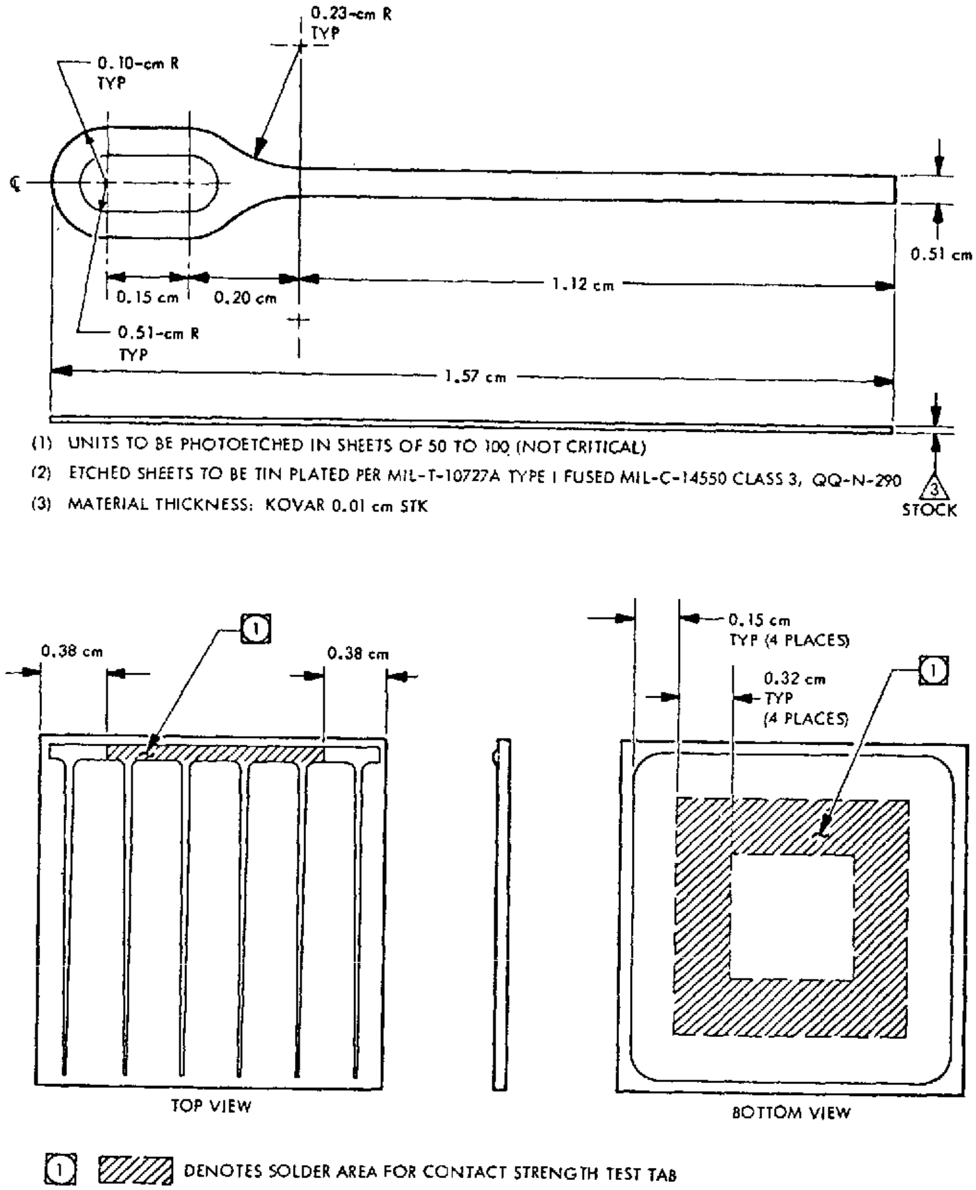

Fig. 1. Definition of pull-test tab and allowable area for soldering

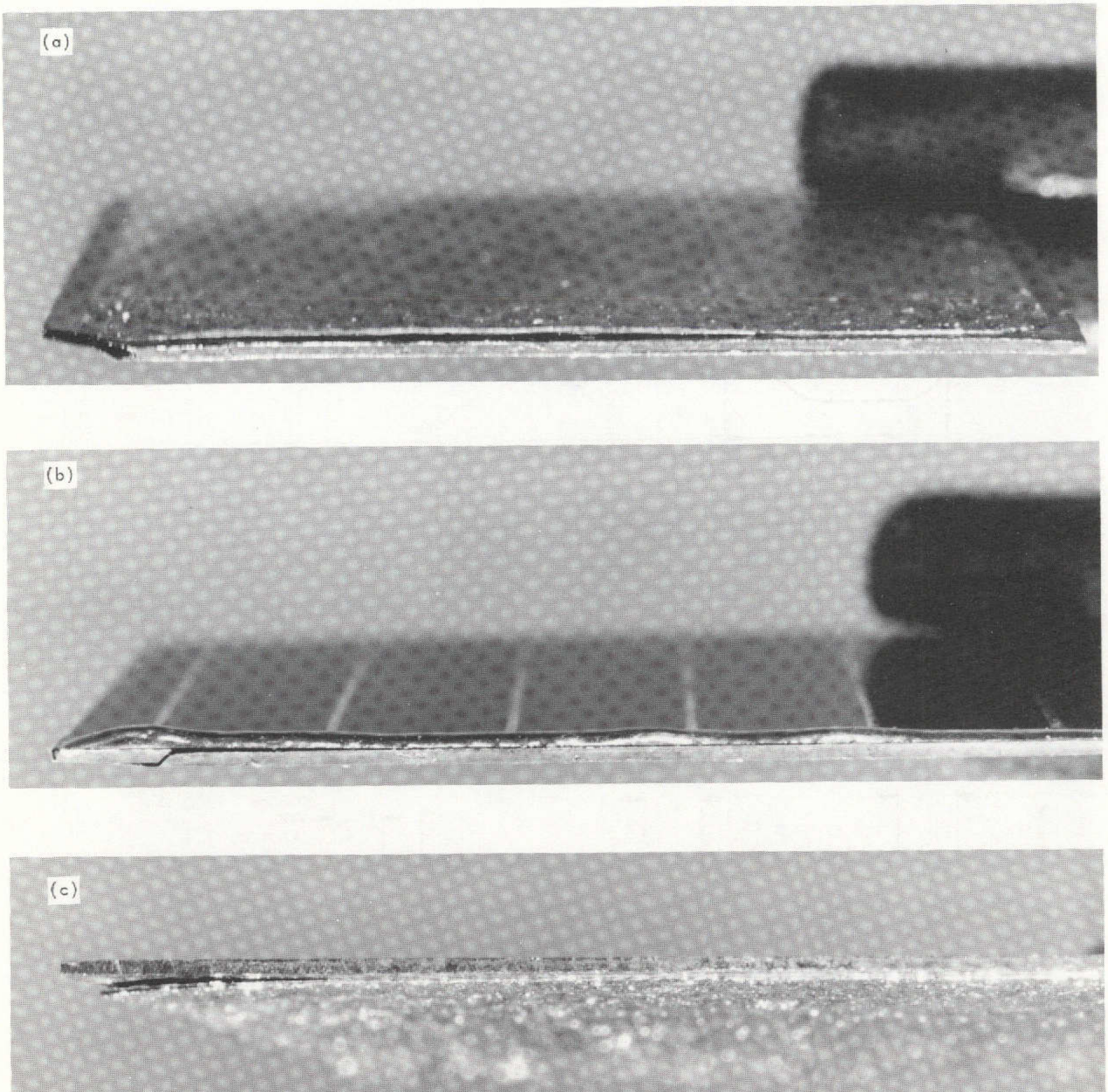

Fig. 2. Silicon solar cell fractures resulting from thermal cycling and shock test: (a) delamination between the back solder-coated contact and silicon wafer; (b) excessive solder along top contact; (c) delamination between back contact and silicon; (d) extensive delamination between contact and silicon