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PILOT PRODUCTION AND TESTING OF HIGH EFFICIENCY WRAPAROUND CONTACT SOLAR CELLS

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CONTRACT NAS 3-21270

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1.0 INTRODUCTION

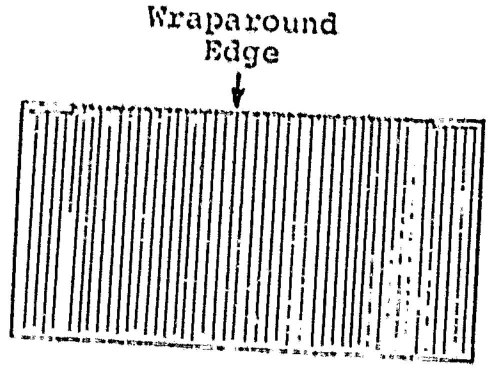
1.1 BACKGROUND

Wraparound contact solar cells with both electrical contacts on the back (see Figure 1) offer several significant advantages when compared with conventional cells. The cell interconnection is simplified, use of automatable interconnect techniques is possible, coverglass application is simplified and grid coverage is reduced increasing illuminated area and efficiency.

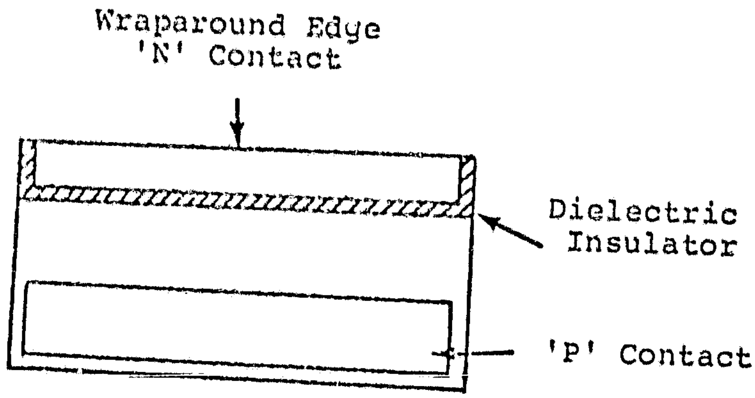
Improvements in wraparound cell performance have been made under Contract NAS 3-20065[1]. This program was designed to develop a processing sequence for fabricating 2 x 4 cm wraparound contact solar cells by combining high efficiency conventional cell technology and low-cost cell technology. Conventional technology includes gaseous diffusion, evaporated contacts and evaporated antireflection coatings. Low-cost technology includes print-on back surface fields and print-on wraparound insulating layers. With these combined technologies, high efficiency wraparound contact (HEWAC) solar cells with air mass zero (AM0) efficiencies as high as 15% had been made on occasion, but only in the laboratory. With further development, this new cell technology has been shown to be ready to be moved through the pilot production stage. This production readiness has been demonstrated under the current program, NAS 3-21270.

1.2 OBJECTIVES

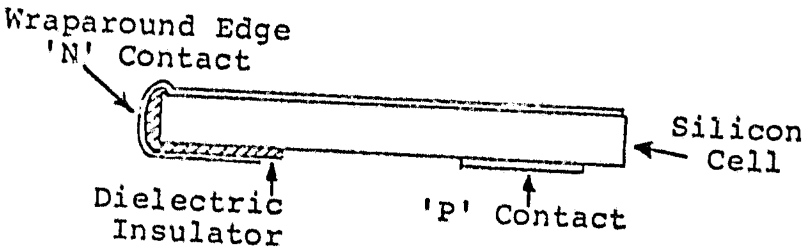
The objectives of this new program were threefold. First was to complete the optimization and refinement of the wraparound cells developed under NAS 3-20065, secondly, to mature and formalize the processing of such cells to a point where cell fabrication



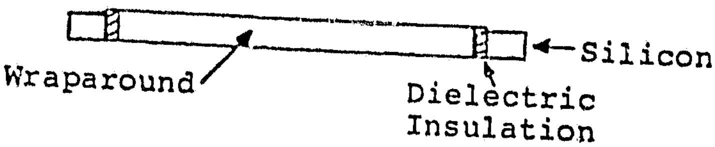
FRONT VIEW OF CELL



BACK VIEW OF CELL



CROSS-SECTIONAL VIEW OF CELL



EDGE VIEW OF CELL

Figure 1

SKETCHES SHOWING VARIOUS VIEWS OF
BASELINE HEWAC CELL

can be carried out by production personnel under operating production line conditions. And finally, pilot production will then manufacture and deliver 1000 acceptable cells (minimum cell performance 13.5%, minimum lot average 14% at AM0, 25°C). Pilot production includes the generation of all required software, tooling and acceptance testing for these devices.

2.0 TECHNICAL DISCUSSION

2.1 PROBLEM IDENTIFICATION

The initial effort on this program was to identify the major problem(s) of the devices made under the previous program, NAS3-20065. Identifying problem areas would give some direction for the development of a test plan to resolve these problems.

The flow chart in Figure 2 shows the baseline process sequence developed under NAS3-20065. Cells produced by this process measure 2 x 4 x 0.02 cm and feature a texturized front surface with Ta_2O_5 AR coating, chromium-palladium-silver contact system and an aluminum back surface field in addition to the wraparound contacts and silica-seal dielectric insulator. A back surface reflector was not utilized. Material used was 'P' type, boron doped, 7-14 ohm-cm silicon with (100) crystal orientation.

One lot of 25 cells was produced following this process to determine what type of problems were to be encountered and which process steps would require further development. The test results of this lot of cells were very similar to the devices made previously. High open circuit voltage (616 mV average) and short circuit current (355 mA average) but poor curve fill factor (0.68 average) and lot yield (52% with at least 13½% efficiency). The loss of curve shape was due primarily to high series resistance (0.24 ohms average) and low shunt resistance (1400 ohms at 500 mV average). Upon close visual examination, several physical discontinuities were noticed on the cells. These discontinuities included cracking of the dielectric material when fired, poor coverage of the dielectric material on the wraparound edge (e.g. voids and seams), poor coverage of the contact metallization on the wraparound edge and puddles and/or lumps on the aluminum back surface field layer.

BASELINE PROCESS SEQUENCE
Developed under NAS 3-20065

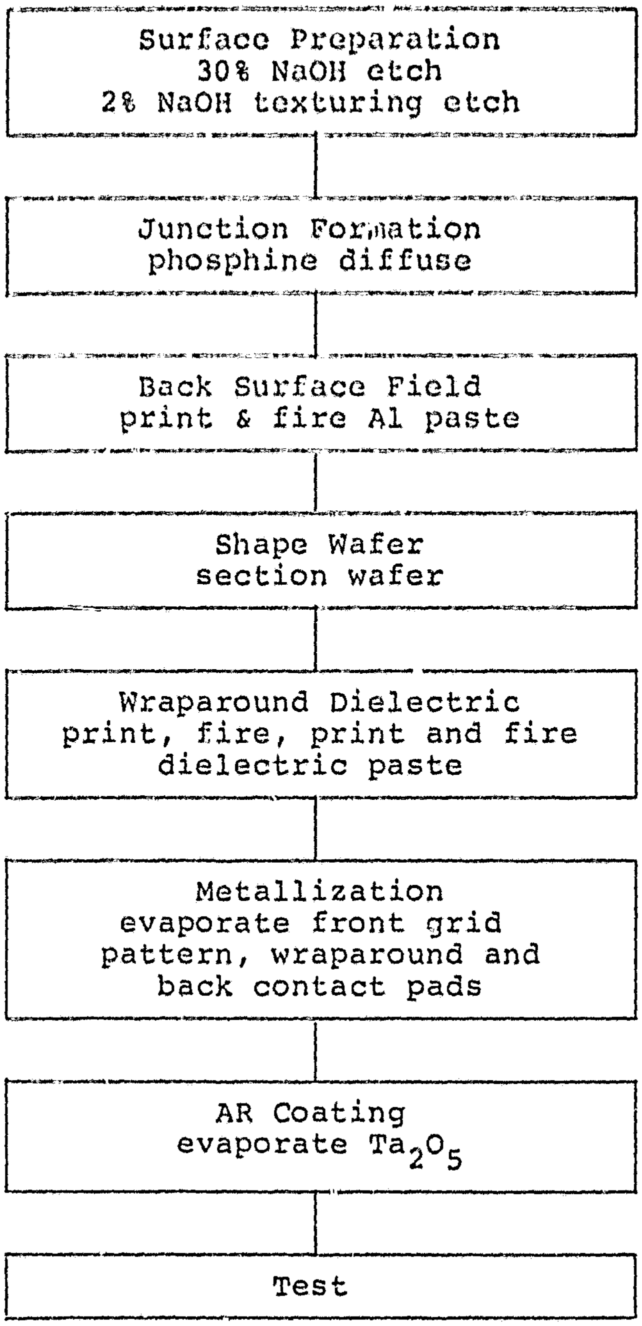


Figure 2

FLOW CHART SHOWING BASELINE
PROCESS SEQUENCE DEVELOPED
UNDER NAS 3-20065

These problems appeared to be the major causes for poor electrical performance on the initial lot of baseline cells. Having identified these problem areas the next step was to devise a thorough test plan designed to isolate the causes of these problems and to resolve them.

2.2 PROCESS MODIFICATIONS

2.2.1 Dielectric Firing Temperature

A test plan was developed and implemented and the aforementioned problems were eliminated one by one.

The problem with the dielectric material cracking when fired was eliminated by simply reducing the firing temperature from 650°C to 575°C. The direct result of this change was an immediate improvement in shunt resistance without any difficulties with the dielectric or its adhesion to the cell.

2.2.2 Contact Evaporation Angle

By changing the cell-to-source angle in the contact evaporator from 60° to 45° (see Figure 3), a more complete wraparound contact was obtained. This resulted in improved series resistance and therefore better cell performance.

2.2.3 Screen Mesh Orientation

The voids and seams found in the dielectric material on the wraparound edge were eliminated by switching to a different mesh orientation in the screen used for the printing of the dielectric. The same size screen and image were used, but the screen was

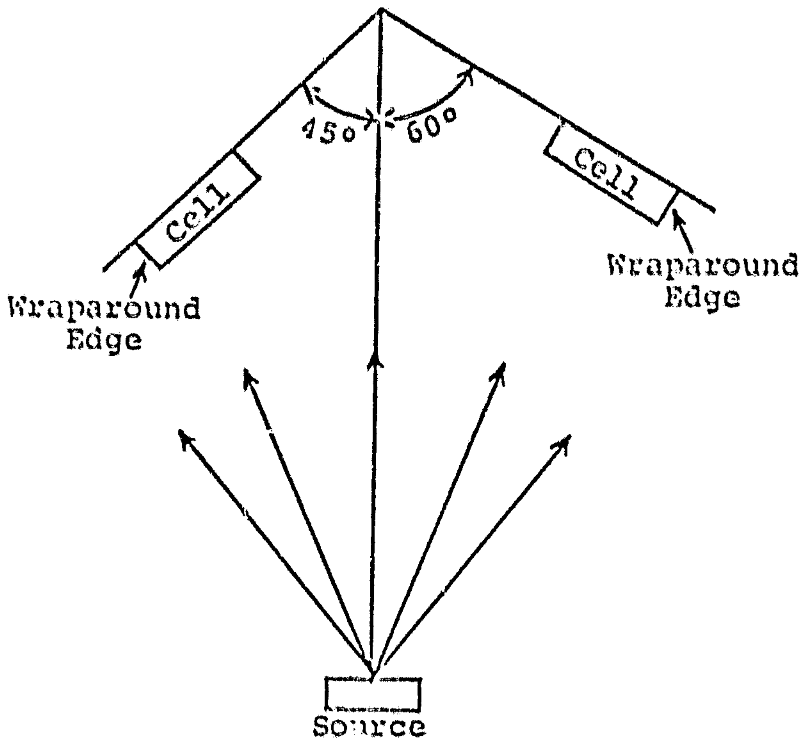


Figure 3

CROSS-SECTIONAL VIEW OF CONTACT EVAPORATOR CELL-TO-SOURCE ANGLES. ANGLE USED FOR METALLIZATION OF THE HEWAC CELLS IS 45° ANGLE ON LEFT SIDE OF FIGURE

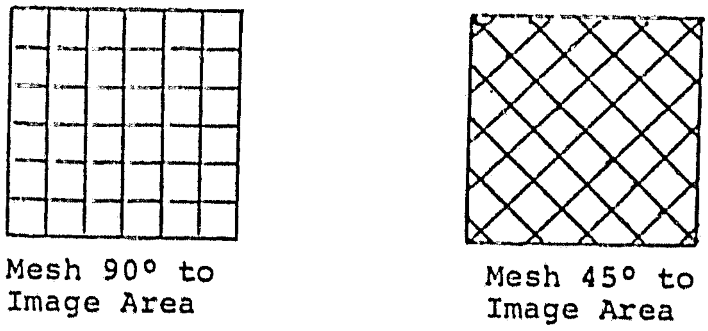


Figure 4

DIELECTRIC SCREEN MESH ORIENTATIONS

rotated so that the mesh was 45° to the image instead of 90° which was used previously (see Figure 4). The cells printed using this screen exhibit a very uniform glass layer with complete coverage of the silicon, even on the edge.

The absence of the voids helps to avoid problems, such as grid-line being broken by a pinhole, or shunting caused by an evaporated metal filling a pinhole and contacting the silicon underneath. This change resulted in an improvement in both shunt resistance and series resistance.

2.2.4 BSF Firing Temperature

After the screen printed aluminum, used to establish the back surface field, was fired, some of the aluminum "puddled" on the back of the cell, leaving lumps of various size and number. These lumps could not be removed by soda rubbing.

The solution was that of firing the cells for a longer time period, but at a lower temperature. The old parameters of 875°C and 20 seconds were replaced with 850°C and 30 seconds. This change was very successful in reducing the lumps and makes for a much flatter, better looking surface finish on the back of the cell. Also, the removal of the aluminum oxide layer after firing was made easier with the lower temperature. Electrical tests on cell lots fired in this manner showed that the back surface field had retained its effectiveness as V_{oc} remained high. Another positive result of eliminating the lumps was that fewer cells were broken when handled during processing, increasing yield.

2.2.5 Modifications Summary

All of these modifications were incorporated into the baseline process sequence. The resultant device was one of high performance and good yield. The next section, 2.3 EXPERIMENTS, describes work using this improved process as the baseline. The final baseline process modification was incorporated after the experiments were completed. This change was that of switching from a texturized, Ta_2O_5 AR coated surface to a polished front surface with a dual AR coating.

The change was made for two reasons. First was to help reduce the breaking of cells during processing known to be a common problem with cells having a texturized surface. Secondly, was because cells with a planar surface have a lower thermal alpha than texturized cells, meaning that they operate at a lower temperature in space. The only penalty sustained is a slight drop in short circuit current.

2.3 EXPERIMENTS

2.3.1 Wraparound vs Conventional Cells

Following the improvement of the baseline process through process modifications, several experiments were conducted in an attempt to gain a better understanding of the dielectric wraparound and to further improve the baseline process.

In the first experiment all of the cells in one lot were made using the baseline process sequence, except that a standard ohmic bar was evaporated on the 'N' contact in addition to the wraparound feature. The cells were electrically tested as wraparound to 0.11 ohms. This same test was repeated on other cells, with the same results, therefore isolating the series resistance problem. The obvious course of action was to eliminate the edge rounding step because there was not time available to develop a satisfactory edge rounding process.

2.3.4 Aluminum Removal After BSF Formation

Experiments 4 and 5 were conducted in an attempt to investigate variations in the structure of the rear of the cell. The fourth experiment involved the removal of the aluminum layer remaining after back surface field formation. The standard baseline method consists of a gentle soda rub which removes the excess aluminum oxide layer from the back surface after firing. Following the removal of this layer, a dull aluminum underlayer is exposed, which provides for a suitable base for subsequent printing of the dielectric wraparound and the 'P' contact pad. In this experiment, both the oxide layer and the aluminum layer were removed using a concentrated HCl boil. This process leaves only the silicon rich aluminum-silicon eutectic region, which forms the back surface field. The removal of the aluminum layer proved to be unsuccessful. When the print-on dielectric glass insulation was fired, it did not adhere to the eutectic region. Subsequently it cracked and peeled off the surface. The same procedure was repeated, with the same results. There was insufficient time in the program to investigate this lack of dielectric adhesion to the eutectic region.

2.3.5 Full Back Contacts

The previous experiment (2.3.4) failed because the dielectric insulator would not adhere to the regrowth area on the back of the cell. As an alternative, another experiment was attempted whereby the aluminum is again removed, but a full back contact system is evaporated prior to the screen printing of the dielectric insulation. By this method the dielectric material does not have to stick to the regrowth layer, but to the silver of the back contact. A cell of this type would be very much like a standard space cell, as the aluminum layer would be removed, a full back contact would be employed, and an evaporated aluminum back surface reflector could be used. A disadvantage would be the extra processing steps involved, as the front surface and wraparound edge would have to be contacted in a separate step from the back contact. Two lots of cells (25 wafers each) were processed in this experiment. The results of the initial experiment were not good. Only three cells of the 25 started achieved the minimum efficiency of 13.5%. This is a lot yield of only 12%. Open circuit voltage and short circuit current were up to par, but the curve shape was very poor due to high series resistance and low shunt resistance. This was due to poor adhesion of the dielectric to the back contact, resulting in peeling and cracking of the dielectric insulation.

The second attempt yielded much better results. Special attention was paid to the cleanliness of the back contact prior to the dielectric application, and this resulted in much better adhesion of the dielectric to the back, and therefore better test results. The data showed a lot yield of 80%, fill factor of 0.78 and average cell efficiency of 14.3%. Average open circuit voltage is a bit low (614 mV), but did not have any effect on overall cell performance.

One lot of cells is hardly conclusive, but this experiment does show promise as being a possible alternative to the present baseline cell.

2.3.6 Cells With Evaporated BSR

One of the requirements of NAS3-21270 was that the cells produced have a back surface reflector under the Cr-Pd-Ag back contact pads. It was suspected, however, that the firing of the dielectric may break down an aluminum reflector. The reasoning behind this is that the temperature used to fire the dielectric material ($575^{\circ}C$) is very close to the eutectic temperature of aluminum and silicon ($577^{\circ}C$). The number of firings (two) as well as the time involved in each firing (ten minutes) may also be detrimental to the effectiveness of an evaporated aluminum BSR. The fifth experiment was designed to find out if this was true.

One lot of cells was divided into three groups. Group A cells had an evaporated aluminum BSR and were given the following heat treatment: 10 minutes at $125^{\circ}C$ followed by 10 minutes at $575^{\circ}C$, then each was repeated. Then two, 10 minute steps at $125^{\circ}C$ were done to simulate the drying of the dielectric after printing. Group B cells had a BSR without heat treatment, and the cells in Group C were used as control cells. They had neither a BSR nor a heat treatment. All cells in the lot were made as conventional non-wraparound 2 x 4 cm cells because extra steps would have to be added to the process and the tooling used for contact metallization would have to be modified to apply a BSR to wraparound cells.

The BSR cells with and without heat treatment, Groups A and B respectively, do not differ appreciably in any of the electrical measurements. The control cells, on the other hand, exhibit a drop in current when compared to the BSR cells. Average I_{sc} and I_{mp} are down about 10 mA each, and that makes for a small loss in average cell efficiency (about 0.3%). The results were not conclusive as to the effect of a BSR after the firing of the dielectric. Some of the cells in each group from this lot had reflectance measurements taken on them for additional information.

2.3.7 Experiment Summary

Although the experiments performed displayed some very interesting possibilities, it was decided that the cell design to be used for the pilot production would be the original baseline cell. These other cell types have not been made in large enough numbers to be considered reliable at this time. The following conclusions can be made on the basis of these experiments. First, the efficiency reduction due to the wraparound is about 0.5% and is not due to the dielectric or the dielectric process. Secondly, edge rounding and full back contacts may improve performance if they can be done controllably and reproducibly. Finally, making the dielectric adhere to the Al-Si eutectic region and the use of an evaporated BSR require further investigation. Perhaps some of these other techniques could be investigated and/or utilized on a future dielectric wraparound cell.

2.4 TEST RESULTS

2.4.1 Electrical Tests

Having refined the baseline process to a point where the major problem areas had been eliminated, the next step was to determine the feasibility of the process. This was accomplished by processing numerous lots of cells without changing the process. Six lots of cells were produced in this manner. Three were started with 25 wafers, and three with 50 wafers. The electrical characteristics of one of the better lots are given in Figure 5. The average electrical data for the six lots are as follows:

PLANAR SURFACE - DUAL AR COATING - 25 WAFER LOT

STD 1050; 25^{o}C @ AMO

92% Lot Yield

Lot/ Cell	V_{oc} mV	I_{sc} mA	V_{mp} mV	I_{mp} mA	P_{max} mW	CFF	EFF %	R_{sh} ohm @ 500 mV	R_s ohm
1	626	342	521	301	156.8	0.732	14.5	12,500	0.16
2	629	343	517	322	166.5	0.772	15.4	12,500	0.07
3	630	349	525	325	170.6	0.776	15.8	12,500	0.10
4	630	344	529	315	166.6	0.768	15.4	16,666	0.12
5	629	344	510	306	146.1	0.722	14.4	833	0.17
6	630	345	502	317	159.1	0.732	14.7	50,000	0.18
7	631	346	520	323	167.9	0.769	15.5	50,000	0.09
8	634	351	521	333	173.5	0.780	16.0	50,000	0.09
9	630	345	518	312	161.6	0.744	14.9	5,000	0.11
10	629	347	481	306	147.2	0.674	13.6	3,125	0.27
11	630	350	517	327	169.0	0.766	15.6	12,500	0.10
12	628	342	522	318	166.0	0.773	15.3	50,000	0.07
13	632	241	-	-	-	-	-	6,250	-
14	630	346	528	321	169.5	0.777	15.6	50,000	0.08
15	630	343	519	320	166.1	0.768	15.3	-	0.10
16	631	348	520	325	169.0	0.769	15.6	50,000	0.10
17	630	345	513	316	162.1	0.745	14.9	16,666	0.17
18	631	344	502	315	158.1	0.728	14.6	1,616	0.18
19	630	348	473	320	151.3	0.690	13.9	25,000	0.27
20	630	344	494	304	150.1	0.692	13.8	50,000	0.28
21	631	344	519	324	168.1	0.774	15.5	16,666	0.09
22	629	345	529	323	170.8	0.787	15.7	12,500	0.07
23	631	343	519	324	168.1	0.774	15.5	50,000	0.09
24	632	353	499	326	162.7	0.729	15.0	16,666	0.20
25	613	285	-	-	-	-	-	10,000	-
AVE	630	345	513	318	163.3	0.751	15.1	24,203	0.14

Figure 5

TEST DATA FROM A GOOD LOT OF HEWAC BASELINE CELLS, EXHIBITING BOTH HIGH EFFICIENCY AND PROCESS YIELD

Open circuit voltage	623 mV
Short circuit current	340 mA
Maximum power	159.8 mW
Curve fill factor	0.752
Efficiency	14.8%
Lot yield	∿ 65%

All electrical data are at AM0 @ 25°C.

It is apparent from the test results that high efficiency wrap-around cells can be produced with acceptable yields. The average efficiency for these six lots of 14.8% is well above the contract goal set at 14.0%. The next step was to determine how the devices hold up under in-process tests (tape peel) and environmental testing (humidity, temperature cycling).

2.4.2 In Process Tests

One of the requirements of a production device is that it be capable of passing a group of in-process mechanical tests. The first is a tape peel test which is performed on both surfaces of the cell. Scotch Brand Magic Transparent Tape No. 810 was pressed down firmly over the cell to remove any air bubbles and to completely cover the cell surface. The tape was then stripped from the cell at a 90° angle to the cell surface. Contacts, when inspected under 10 power magnification, had no imperfections exceeding the following limits:

Delamination - None allowed

Voids - The main component of the metallization shall be continuous and shall cover a minimum of 95 percent of the back contact area.

The next in-process mechanical test was a Contact Strength Test. Pull tabs made of silver plated molybdenum were soldered to the 'N' and 'P' contacts using Sn62 solder alloy per latest revision of QQ-S-571 (Federal Specifications QQ-S-571 governs solder alloy compositions). The tabs were pulled to failure at an angle of 90 ± 5 degrees to the surface of the cell. Average failure loads for the HEWAC devices were 680 grams for the wraparound or 'N' contact and 1000 grams for the 'P' contact. These values easily exceeded the contact strength requirements of 500 grams minimum.

The final in-process test performed on these devices was an AR Coating Adherence Test. The cells were immersed in boiling, distilled water for 15 minutes, and then exposed to direct water vapor for an additional 15 minutes. The cells were then dried and rubbed with an eraser (Pink Pearl No. 101). The eraser was rubbed across the surface of the cell on the same path each time for a total of 20 complete cycles and with a continuously applied force of from 120 to 147 kilo Newtons per square meter (174 to 213 PSI). When each cell was examined, there was no evidence of complete removal or delamination of the antireflection coating visible to the unaided eye.

2.4.3 Environmental Tests

Having passed the in-process mechanical tests, the HEWAC cells were then submitted for some environmental testing which, although limited in nature, did provide some idea as to how well the cells would hold up under some typical environments.

The first test was a Thermal Cycle Test, whereby the cells were exposed to 100 cycles at temperature extremes of $-170^{\circ}C$ to $+75^{\circ}C$. A $14^{\circ}C$/min. rate was used for heating and cooling, with a two minute dwell at each extreme. The cells had test tabs soldered to the contact pads and were electrically tested prior to the cycling test. Upon completion of 100 cycles, the cells were visually inspected and then retested electrically. The dielectric showed no evidence of peeling or cracking when inspected under 10 power magnification, and when retested the cells showed an average current output degradation (at 480 mV cell test voltage) of less than 2% for a 20 cell sample.

The second environmental test performed on the cells was a Humidity Test whereby the cells were exposed to 90% relative humidity at 45°C for a period of 30 days. Per the temperature cycle test, the cells were electrically tested before and after the test, and a visual inspection was performed. The average current output degradation (at 480 mV cell test voltage) was less than 1.5% for a six cell sample.

The last environmental test involved the Thermal Shocking of the HEWAC devices. The cells were exposed to a temperature extreme of -195°C for one minute by dipping them in LN_2. The cells were then allowed to return to ambient temperature and were then exposed to a temperature extreme of +100°C for one minute by placing them on a hot plate. Again the cells were allowed to return to ambient. Two cycles were performed on each cell. A visual examination was performed on each cell as well as pre- and post-electrical testing. The average current output degradation (at 500 mV cell test voltage) was approximately 1.7% for a ten cell sample.

On the basis of the in-process and environmental tests performed on these devices, the HEWAC cell has shown its ability to withstand these tests with an acceptable amount of output degradation (less than 2%).

2.4.4 Thermal Alpha Measurements

In an effort to further understand the HEWAC device and its characteristics, Thermal Alpha (α) Measurements were made on some of the various wraparound cells made during the development phase of the program. Some average values are given below:

Cell Type	Al BSR Type	α
Baseline, planar surface, Ta_2O_5 AR	Residual Paste	.743
Baseline, planar surface, Dual AR	Residual Paste	.812
Baseline, textured surface, Ta_2O_5 AR	Residual Paste	.912
Full Back Contact (Section 2.3.5), planar, Ta_2O_5 AR	Evaporated	.792

The decision to switch from a textured front surface to a planar front surface was made on the basis of the lower α value of the planar surface cell.

The full back contact cell from Section 2.3.5 was included to compare its α value to that of the baseline, planar surface, Ta_2O_5 cell. The baseline device retains the residual aluminum remaining after BSF formation and does not have an evaporated BSR. The full back contact cell has the residual aluminum removed and does utilize an evaporated BSR. The lower α value for the baseline cell type indicates that the residual aluminum could be a better reflector than the evaporated aluminum, although the reason for this is not yet known.

All of the alpha measurements were made at the Hughes Aircraft Co. test facility in Culver City, CA.

2.5 PILOT PRODUCTION READINESS

2.5.1 Tooling

At this point in the program, a satisfactory baseline process had been realized. This process had produced wraparound cells of high performance and process yield while being compatible with most production processes and equipment to ensure a smooth transition from the lab to pilot production. But before pilot production could begin, a few items had to be completed.

First was the design and procurement of new contact evaporation tooling to be used for the pilot production run. The tooling used for the development of the HEWAC cell was left over from the previous contract (NAS 3-20065). Due to limitations in the size of the evaporater used and the amount of tooling on hand, only 12 cells could be contacted at one time, and because the tooling was made in the Spectrolab machine shop, the quality and precision was not of suitable calibre to be used in production. Slight modifications in the contact configuration became necessary because of a problem of holding the cell in the new tooling. The old tooling utilized magnets to hold the cell in place during contact deposition. These magnets could not be used for pilot production because of the method of operation of the carousel coater to be used. The changes made to the front and back of the cell were truly minimal, and did not affect cell performance. The new tooling made it possible to contact 192 cells at one time, using the production facilities.

2.5.2 Software

The other item that had to be taken care of before the start of pilot production was the preparation of production-suitable software and quality control elements. Because the pilot production was to be performed by production personnel under production line conditions, it was necessary to implement a complete software file. This included an MCD (Manufacturing Control Document) listing all of the process steps and Q.C. (Quality Control) inspection stages, and an ATP (Acceptance Test Procedure) which defines the procedures used for the acceptance testing. Additionally, the procedures had to be written for each of the process steps that differed from standard production processes, and Engineering Line Instructions (ELI) and Lot Trackers had to be developed.

2.6 RECONFIGURED BACK CONTACT

2.6.1 Approach

Prior to the start of pilot production, the need for a reconfigured back contact system was identified. An alternate back contact configuration was required for the HEWAC cell to make the devices more suitable for some panel manufacturers designs. Although the baseline wraparound design does simplify cell interconnecting compared to standard space cells, a back contact configuration utilizing the centerline of the cell for both 'N' and 'P' contacts would simplify cell interconnection even further, and the weaker 'N' contact points (680 grams vs >1000 grams for the 'P' contacts, see Section 2.4.2) would be located inboard of the 'P' contact points, where stress is less. A sketch of the reconfigured design is shown in Figure 6.

The approach used in the development of the reconfigured back contact HEWAC cell was as follows:

First the design and procurement of new tooling was necessary. This tooling included screens to be used in the dielectric

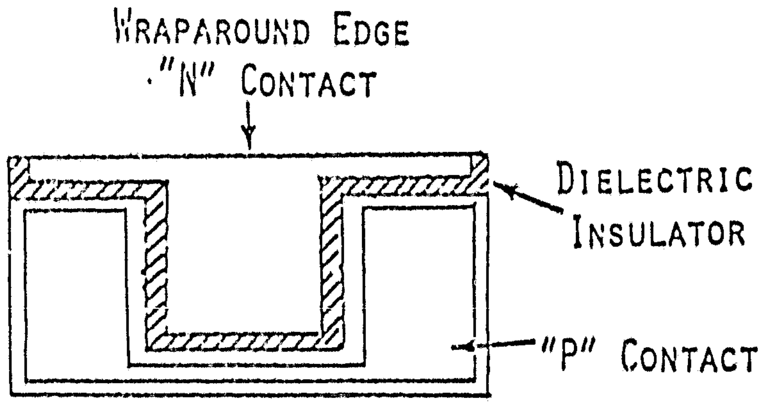


Figure 6

SKETCH SHOWING BACK CONTACT CONFIGURATION
OF ALTERNATE BACK CONTACT HEWAC CELL

print-on step, masks for the contact evaporation step, and a new electrical test fixture. Secondly, test lots were made and evaluated until a satisfactory process was achieved. And finally, the pilot production software was revised to reflect the alternate back contact cell. It was decided to amend the program requirements for the contract and make the 1000 deliverable devices include 500 baseline type cells, and 500 alternate back contact cells. All electrical performance requirements and acceptance test requirements would be the same for both cell types.

2.6.2 Problems/Solutions

Problems not common to those of the baseline cell design, were encountered and resolved with the reconfigured back contact. In the initial experiments, the same size (200 mesh) screens were used to print the dielectric insulation onto the ABC (alternate back contact) cells as were used on the baseline cells. This caused what proved to be the major stumbling block in the development of this cell type. By comparing the sketches of the two cell designs in Figures 1 and 6, it is obvious that the ABC cell (Figure 6) has much more of its back surface area (approximately 39%) covered with insulation material than does the baseline device (approximately 21%). The additional insulation caused unacceptable bowing of the cells when the insulation layer was fired.

Several experiments were conducted employing different combinations of screen types and mesh sizes. Some cells were processed using a single layer of insulation, instead of the standard double-layer method used on the baseline cell. (Double-layer insulation minimizes the chances of pinholes which could lead to shunting of the cells.) Others were processed using double-layer insulation, but with finer mesh screens (325 mesh). The combination which was found to be acceptable from all aspects was the use of a fine mesh screen (325 mesh) for the initial print-on step, followed by a standard mesh screen (200 mesh) for the second print-on step. The single layer experiment failed because of shunting due to pinholes. The double-layer, fine mesh screen experiment failed because an inadequate amount of insulation was being applied to the wrap-around edge of the cell, and the edges of the silicon were protruding from beneath the insulation layer, therefore causing shunting and poor cell performance.

2.6.3 Results

The flow chart in Figure 7 shows the process sequence used in the manufacturing of the baseline cell type. To the right, opposite its respective process step are listed the changes required to make a HEWAC cell utilizing the alternate back contact. It is apparent that the ABC cell type can be made using the same process as the baseline cell, with a minimum of changes.

Since only a few process changes had to be made to produce the alternate back contact cell, it would seem logical that the electrical characteristics of the device would also remain very similar to the baseline cell type. This was found to be the case. Figure 8 shows a cell performance comparison of the baseline cell and the reconfigured contact cell. Note that both cell types in this comparison have only a single-layer antireflection coating, which explains the low short-circuit current (I_{sc}) and I_{mp} values. Also note that the reconfigured contact cells were tested at 28°C instead of 25°C. The change from 25°C to 28°C was made for two reasons. First, 28°C conforms more closely to the cell test temperature called out in Section 3.4.1 of the Standard Specification for Silicon Solar Cells and Cell Covers (CASH CAT. NO. 3001). This requirement is 25 $^{+5°}_{-0°}$C. Secondly, 28°C is the test temperature most commonly used by Spectrolab Production for the testing of cells.

HEWAC BASELINE PROCESS SEQUENCE	BASELINE PROCESS CHANGES REQUIRED FOR ALTERNATE BACK CONTACT HEWAC CELLS
Surface Preparation 33% NaOH etch 3-1-2 polishing etch	
Junction Formation Phosphine Diffuse	
Back Surface Field Formation Screen Print & Fire Al Paste	
Wraparound Dielectric Insulation Screen Print, Fire, Screen Print, Fire Dielectric Paste	Change screen pattern and mesh size. Inspect wraparound edge
Contact Deposition Evaporate Front Grid Pattern, Wraparound Edge & Back Contact	Change back contact mask
AR Coating Evaporate Dual AR Coating	
Test	Change testing fixture

Figure 7

FLOW CHART AT LEFT SHOWS PROCESS SEQUENCE USED TO MANUFACTURE BASELINE HEWAC CELL. TO THE RIGHT, OPPOSITE THEIR RESPECTIVE PROCESS STEPS ARE LISTED THE CHANGES REQUIRED TO MAKE A HEWAC CELL UTILIZING THE ALTERNATE BACK CONTACT.

Figure 8

BASELINE/RECONFIGURED CONTACT
CELL PERFORMANCE COMPARISON

	V_{oc} mV	I_{sc} mA	V_{mp} mV	I_{mp} mA	P_{max} mW	EFF %	CFF –	Yield %
BASELINE HEWAC CELL @ 25°C (Average based on 4 cell lots)	623	326	514	302	155.2	14.3	0.764	71
RECONFIGURED CONTACT HEWAC CELL @ 28°C (Average based on 2 cell lots)	612	324	504	302	152.3	14.0	0.767	70

Both cell types have single-layer AR Coating

TOTAL CELL DEVELOPMENT EFFORT

Baseline - 23 Lots (25 cells per lot)

Reconfigured Contact - 13 Lots (25 cells per lot)

In general, a 2.2 mV/$^{\circ}$C penalty in open circuit voltage (V_{oc}), and a -0.07 mW/cm^2-$^{\circ}$C (0.6%/$^{\circ}$C) power penalty can be employed in comparing 10 ohm-cm cells tested at 25°C versus those tested at 28°C.(2)

2.7 PILOT PRODUCTION

2.7.1 Trial Run

With the completion of development of the reconfigured back contact cell, proofing of the evaporation tooling and finalization of the production software, the Pilot Line was ready to begin. The material to be used was grown, slabbed, and sliced into approximately 1150 wafers, 1.70" x 1.70" x 0.14" thick. (During processing, each wafer was diced into two 2 x 4 cm cells, thereby providing for a maximum of 2300 cells.) These wafers were divided into 12 lots of 96 wafers each (one lot had only 94 wafers). Six of these lots were used to make the baseline cells, and the other six lots for the alternate back contact type cell. All twelve lots went through the 30% NaOH etch, 3-1-2 polishing etch and phosphine diffusion steps together. At this point a trial run was initiated before the actual pilot line. Two lots (one for each cell type) were run through the manufacturing process by production line personnel. This was done in an effort to determine what problems, if any, would be encountered by switching the process from the laboratory to the production line.

These two lots did run into some difficulty. Besides a few small problems which only required some minor adjustments to remedy, one large problem was ultimately responsible for the loss of both lots.

Shortly before the start of pilot production, OSHA banned the use of trichloroethylene, one of the solvents widely used at Spectrolab in the cleaning of cells. A substitute solvent (1,1,1-trichloroethane) was incorporated into the Spectrolab production process after it was found suitable for cleaning conventional cells. 1,1,1-trichloroethane simply replaced trichloroethylene in the previously established cleaning sequence. Although this cleaning procedure with the new solvent worked satisfactorily on standard space cells, it failed on the HEWAC devices.

The cleaning procedure and solvent used was not designed for cells which had a dielectric insulation layer screen printed onto the cell. The surfaces onto which the insulation layer was printed were not adequately prepared to allow for good adhesion between substrate and insulation. Therefore, when tape peel tests were run on these cells, they exhibited excessive peeling of the dielectric insulation from the substrate.

Experiments were conducted in an attempt to develop a new solvent and/or cleaning procedure to be used in the pilot production of the HEWAC cells. Many combinations of solvents and procedures were tried. The pass/fail criteria used in these experiments were visual inspection and tape pull test. It was found that the most successful combination tried involved the use of the same 1,1,1-trichloroethane that Spectrolab production uses, but the cleaning procedure had to be changed. These changes included the insertion of a boiling 1,1,1-trochloroethane step and several ultrasonic cleaning steps. After it was determined by visual inspection and tape pull testing that this new procedure worked well, the software was changed.

Another problem, although not as severe, was the return of the lumps on the back of the cell after BSF formation. As reported earlier, this problem was initially resolved by lowering the firing temperature (from 875^{o}C to 850^{o}C) and increasing the time (20 seconds to 30 seconds). This time tests were conducted on the aluminum paste (Al_2O_3 content), the method of applying the paste (screen printer parameters), and the equipment used to apply the paste (screen printer, screens). The problem, however, was traced to the furnace used to fire the paste onto the cells.

Apparently, some sort of shift occurred in the furnace. This shift resulted in a change in the heat zone of the furnace. The cells were being exposed to a higher firing temperature because of this, and the lumps resulted. The furnace was recalibrated, and it was decided to reduce the firing temperature of the HEWAC devices to 825°C. Experiments showed no loss in the effectiveness of the BSF by using the lower temperature. Software changes were made, and to eliminate a recurrence of this type of incident, a daily furnace temperature surveillance step was inserted into the BSF formation procedure.

2.7.2 Start

Having developed a cleaning procedure which resulted in adequate adherence of the dielectric insulation to cell substrate, and again resolving the BSF firing problems, the formal pilot line was set to begin.

The cells moved through pilot production slowly and cautiously, thereby eliminating any major errors due to unfamiliarity of production line personnel with the new cell type. A few minor problems came up, but nothing that had a serious impact on the outcome. For example, the dual AR coater malfunctioned during one of the runs, and about sixty cells came out with a green AR coating. The only effect this had on the cells, besides the green color, was a small drop in I_{sc}.

During the processing of these cells it was decided to run the Tape Peel Test after the electrical testing, or in other words, after the pilot line operations were completed. The previous experience with the trial run was the reason for this decision. The trial run cells were tape peel tested before electrical testing, and because the cells displayed excessive peeling the electrical testing was useless. This made it impossible to determine if the cells were good electrically or not. Although a recurrence of the excessive peeling of these cells was doubtful (due to the new cleaning procedure), it was still a possibility. And in the event that it did recur, at least electrical data will have already been collected. Aside from this one change, the pilot production traveller was followed and the results will now be discussed.

2.7.3 Electrical Test Results

Up to this point the two cell types run through pilot production (baseline and alternate back contact) have been treated as one. This was due to the fact that the processing of the two cell types was identical except for the screens used in the dielectric print-on step and the back mask used in the contact evaporation step. For the electrical test and yield results, however, the two cell types have been split up and will be reported on separately.

The data in Figures 9 and 10 provide the breakdown for each lot of each cell type after electrical testing. The values given are based on measuring the cells at a load point of 485 mV @ AM0, 28°C. As shown, nine of the ten cell lots surpass the contract goal of 14.0% lot average. The one low lot is the lot that contains the cells with the poor AR coating. Had these cells had a proper AR coating, this lot would also have surpassed the contract goal.

Figures 11, 12 and 13 show histograms plotting power (at 485 mV) vs. number of cells of the total pilot production, the baseline cell type and the alternate back contact cell type, respectively. The total production and alternate back cell histograms look very good. The baseline cell type histogram is not very good, due again to the cells with green AR coating.

Figure 9

ELECTRICAL PERFORMANCE @ 28°C, AMO
HEWAC BASELINE CELL DESIGN

Lot	I_L @ 485 mV (mA)	Power @ 485 mV (mW)	η %
2	315.2	152.9	14.1
4	319.8	155.1	14.3
5	315.3	152.9	14.1
6	310.4	150.5	13.9 *
7	321.0	155.7	14.4
AVE	316.3	153.4	14.2

* AR Coater malfunction

Figure 10

ELECTRICAL PERFORMANCE @ 28°C, AMO
HEWAC ALTERNATE BACK CONTACT CELL DESIGN

Lot	I_L @ 485 mV (mA)	Power @ 485 mV (mW)	η %
10	320.7	155.5	14.4
11	316.9	153.7	14.2
12	313.9	152.3	14.1
13	314.5	152.5	14.1
14	313.9	152.2	14.1
AVE	316.0	153.3	14.2

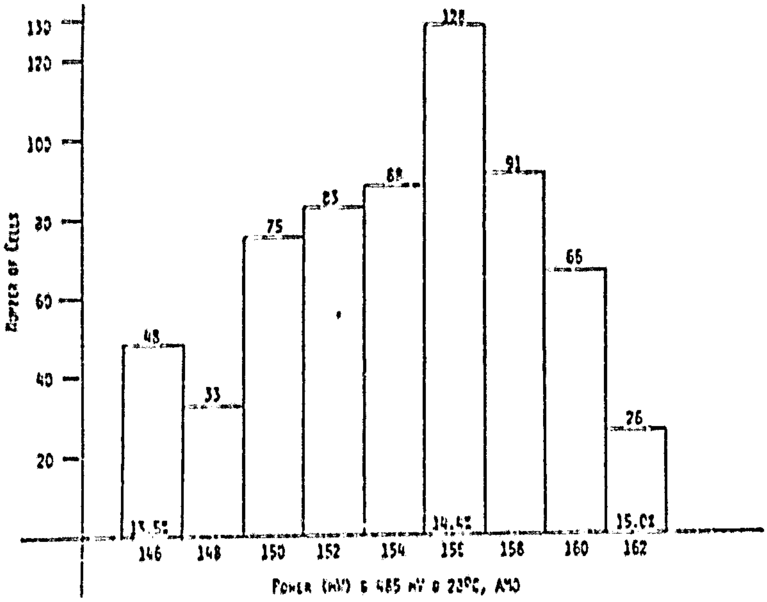


Figure 11
POWER DISTRIBUTION HEWAC PILOT LINE
630 Total Cells

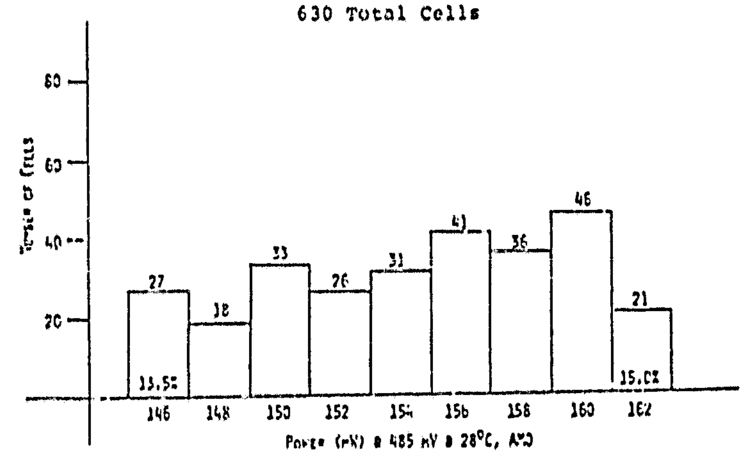


Figure 12
POWER DISTRIBUTION HEWAC BASELINE CELL DESIGN
284 Total Cells

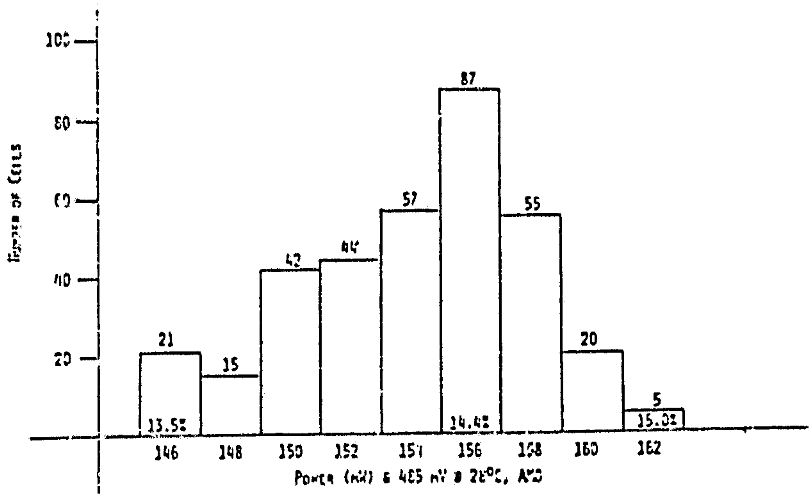


Figure 13
POWER DISTRIBUTION HEWAC ALTERNATE
BACK CONTACT CELL DESIGN
346 Total Cells

Measuring the electrical performance of cells using a load point is only an approximation of the actual values. To get a better idea of the actual performance of these cells, as well as measured values for open circuit voltage and short circuit current, I-V curves were run on a sample of the total. Cells were taken at random from each current grouping and tested. A total of 90 cells (45 each cell type) were tested, and the average values are given in Figure 14. These data show that the two cell types are almost identical performance-wise, and the average efficiency is a little better than the "load point" data. Judging from the electrical data, the HEWAC pilot production was very successful.

2.7.4 Yields

The yields discussed in this section are not the total yields for the pilot production. This data was compiled before the tape peel test and acceptance testing were performed on the cells. This data should, however, provide some idea as to the success of the process sequence under production line conditions. Figures 15 and 16 show the lot by lot breakdown for each cell type, showing the maximum number of cells possible, the number of cells from each lot which went through mechanical inspection, and the number of cells from each lot that achieved an electrical performance of at least 13.5% at AM0, 28°C. The combined (both cell types) average processing yield was about 50%, and the combined average electrical yield was about 33%.

Although well below the project goals of 60% overall yield, these numbers are respectable for a cell being introduced to production for the first time. Past experience at Spectrolab has shown that new cell types start off at about a 30% yield, and as more cells are processed and the operators become familiar with them, the yield goes up. Judging from the HEWAC experience an overall yield of 50% does not seem out of line.

Figure 14

BASELINE/ALTERNATE BACK CONTACT
PILOT PRODUCTION CELL PERFORMANCE COMPARISON (FULL I-V CURVES)
(AM0, 28^{o}C)

	V_{oc} mV	I_{sc} mA	V_{mp} mV	I_{mp} mA	I_L @ 485mV mA	P_{max} mW	P_L @ 485mV mW	CFF -	EFF %
BASELINE CELL (Average based on 45 cells)	603	350	492	317	322	156.0	156.2	0.739	14.4
ALTERNATE BACK CONTACT CELL (Average based on 45 cells)	602	350	493	318	320	156.8	155.2	0.744	14.5

Load Point Data (I_L and P_L) are shown for comparison

Figure 15

HEWAC BASELINE CELL DESIGN
PILOT PRODUCTION YIELDS
(Through Mechanical Inspection)

Lot	Starts	Complete (thru Mech. Insp.)	Performance (13½% min. 28°C, AM0)
2	192	79	35
4	188	83	71
5	192	107	64
6	192	80	42
7	192	88	72
	956	437 (46%)	284 (30%)

Figure 16

HEWAC ALTERNATE BACK CONTACT CELL DESIGN
PILOT PRODUCTION YIELDS
(Through Mechanical Inspection)

Lot	Starts	Complete (thru Mech. Insp.)	Performance (13½% min. 28°C, AM0)
10	192	95	77
11	192	132	84
12	192	113	68
13	192	99	57
14	192	79	60
	960	518 (54%)	346 (36%)

2.7.5 Acceptance Tests

Acceptance tests as defined in the Standard Specification for Silicon Solar Cells and Cell Covers (CASH CAT. NO. 3.001), Appendix A, section 4.4, were performed on the HEWAC devices. The Lot Tolerance Percent Defective (LTPD) method, defined in section 6.4, was used to verify the requirements of the Acceptance Tests. The acceptance testing consisted of four categories: identification of product (sample size 45 cells); visual examination (sample size 32 cells; dimensions and weight (sample size 32 cells); and electrical output and spectral response (sample size 45 cells). The total sample was not the sum of the sample sizes in each category, but a number specified in the LTPD method, 85 cells in this case. Each cell subjected to any test in the sequence had to have been previously subjected to all prior tests in the sequence. Because the two cell types were treated as two different cells, the sample size indicated (85 cells) was pulled from lots of each cell type.

Because no requirement had been determined for cell weight and spectral response, this information was simply recorded and cells would not be rejected on that basis. The data in Figure 17 shows the results of the acceptance testing. Both cell types failed three of the four tests. These results would normally cause some concern, but it should be noted that the LTPD method is very tight, much tighter than the method Spectrolab usually uses on space cells. The method used by Spectrolab is per MIL-STD-105D, Inspection Level II, Table II-A. Under this method a sample size of 32 cells is allowed two rejects, and a sample size of 45 cells is allowed three rejects. Using this method the HEWAC cells would have passed three of four tests, and because the cells are in a pilot production, in that they have never been made in production before, the results would seem to be acceptable for a first time through device.

Figure 17

RESULTS OF ACCEPTANCE TESTS

Test	Sample Size (# of Cells)	# Rejects Allowed (LTPD/ MIL-STD-105D)	# Rejects (Baseline)	Disposition (LTPD/ MIL-STD-105D)	# Rejects (Alternate)	Disposition (LTPD/ MIL-STD-105D)
Identification of Product	45	0/3	0	Pass/Pass	0	Pass/Pass
Visual Inspection	32	0/2	3	Fail/Fail	4	Fail/Fail
Dimension and Weight	32	0/2	2	Fail/Pass	1	Fail/Pass
Electrical and Spectral Response	45	0/3	2	Fail/Pass	3	Fail/Pass

2.7.6 Pilot Line Summary

Based on the results of pilot production, it is fair to state that the HEWAC cell does show promise of being a successful large scale production-made device. Although yields were not as high as expected, performance was better than expected. Recalling past experience, yields would improve with more cell processing as the bulk of losses were due to breakage during handling.

The LTPD method for acceptance testing was too tough for a new device to be subjected to, but the same cell was reasonably successful using the more common (at Spectrolab) MIL-STD-105D method. In general, only two process steps would require more work before a future large scale production run should be attempted. These processes are the cell dicing and dielectric print-on steps. The cell dicing was done using a dicing saw to cut the 2 x 4 cm wafers out of the larger one, but this process was very slow and time consuming. Using a laser scribe to do the cell dicing would be better, if the rough edge left after laser scribing could be removed so that the dielectric could be printed over the edge successfully. Something should probably be done to speed up the dielectric print-on step. Developing a new dielectric material that required only one printed layer, or used a shorter firing time would help. With the incorporation of these refinements in the baseline process, future large scale production of the HEWAC device should result in less processing time, higher yields, and an even more successful production made device.

3.0 CONCLUSIONS

This program has evolved a production made dielectric wraparound cell of high efficiency and typical "first-run" yields. The tests and experiments implemented in the development phase of the program helped tremendously in understanding this cell and solving the processing problems associated with making it. Although there were problems in transferring the processing sequence to the production line, these problems were solved with minimal impact on the design and performance of the device. The test data show that this cell can be made in a production environment with good results. And, the cells successfully survived some preliminary environmental tests, including temperature cycling, humidity and thermal shock.

The only two areas of this process that require further work are the cell dicing step and the dielectric print-on step. Should these steps be simplified and the processing time reduced, the HEWAC cell could be an even better production device.

In addition, the development of the wraparound cell utilizing the alternate back contact design will make the device more suitable for some panel manufacturers.

4.0 REFERENCES

1. Thornhill, J.W., "Development of Improved Wraparound Contacts for Silicon Solar Cells", Final Report, NASA Contract No. NAS 3-20065, December, 1979.

2. Carter, J. R., Jr., and Tada, H. Y., "Solar Cell Radiation Handbook", JPL Publication 77-56, November, 1977, page 3-39.