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Electrical Power Systems Laboratory
Power Sources Engineering Department

Development of Technologies for Welding Interconnects to Fifty-Micron Thick Silicon Solar Cells

Interim Report
May 14, 1981 to December 1982

JPL Contract 956042

TRW No. 38512.000

Prepared by
R.E. Patterson

December 1982

Prepared for
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91103

NF02586

This work was prepared for
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ILLUSTRATIONS

ILLUSTRATIONS (Continued)

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ACKNOWLEDGEMENT

The author wishes to acknowledge the greatly appreciated support from TRW personnel who made key contributions to this program. George Mesch, Head of the Advanced Manufacturing Process Development Section, directed all weld schedule development and hardware fabrication and contributed his vast welding experience to this program. Charles Gibson, Senior Staff Engineer, developed test methods and directed all cell characterization testing. Belinda Zamora assembled the coupons and modules. Rod Dobson performed the cell and module electrical measurements.

1. ABSTRACT

A program was conducted to develop technologies for welding interconnects to 50-μm thick, 2 by 2 cm solar cells obtained from Spectrolab, Solarex, and Applied Solar Energy Corporation (ASEC). The cells were characterized with respect to electrical performance, cell thickness, silver contact thickness, contact waviness, bowing, and fracture strength. Weld schedules were independently developed for each of the three cell types and were coincidentally identical. Thermal shock tests (100 cycles from 100°C to -180°C) were performed on 16-cell coupons for each cell type without any weld joint failures or electrical degradation. Three 48-cell modules (one for each cell type) were assembled with 50-μm thick cells, frosted fused silica covers, silver clad Invar interconnectors, and Kapton substrates.

2. INTRODUCTION

JPL-developed advanced solar array blanket designs offer the potential for providing beginning-of-life (BOL) specific powers in the range 180 to 660 W/kg (Reference 1). These designs use the thin silicon solar cell developed under the auspices of the NASA Office of Aeronautics and Space Technology, use welding as the cell-to-interconnector attachment process, and use cell covers $\leq$50-μm thick. TRW performed a development program (Reference 2) directed toward incorporation of the OAST thin cell into solar array blankets for space applications. As a continuation to this effort, TRW was awarded the program that is the subject of this report, JPL Contract 956042, with the objective of developing technologies for welding interconnects to 50-μm thick silicon solar cells.

The basic approach of the program was to characterize cells with respect to those parameters that are thought to have significant influence on welded cell performance, to build and test coupons to verify material compatability and assembly processes, and to build test hardware for thermal cycle testing. Results of the thermal cycle testing (not yet performed) will be correlated with the cell characterization data.

This development activity is of significant importance for several reasons. Ultralightweight arrays will not only increase the available spacecraft mass allocated to the payload, but they will in some cases enable missions that otherwise would not be possible with conventional arrays. Also, welding enables solar arrays to survive high temperature exposures that cannot now be accommodated by conventional soldered arrays.

3. TECHNICAL DISCUSSION

3.1 REQUIREMENTS

The basic contract requirement was to conduct a program to develop technologies for welding interconnects to 50-μm thick, 2 by 2 cm solar cells from three solar cell suppliers. The program is summarized in Figure 3.1-1 and consisted of:

1) An evaluation of cell characteristics that have significant impact on welding and weld/cell performance of spacecraft solar arrays.

2) The selection of a baseline interconnect design.

3) An evaluation of the compatibility of 50- to 150-μm thick covers with 50-μm thick solar cells.

4) The development of weld schedules for cells obtained from each of three suppliers.

5) The fabrication of 48-cell welded coupons from cells from each of three suppliers based on results obtained from 1, 2, 3, and 4 above.

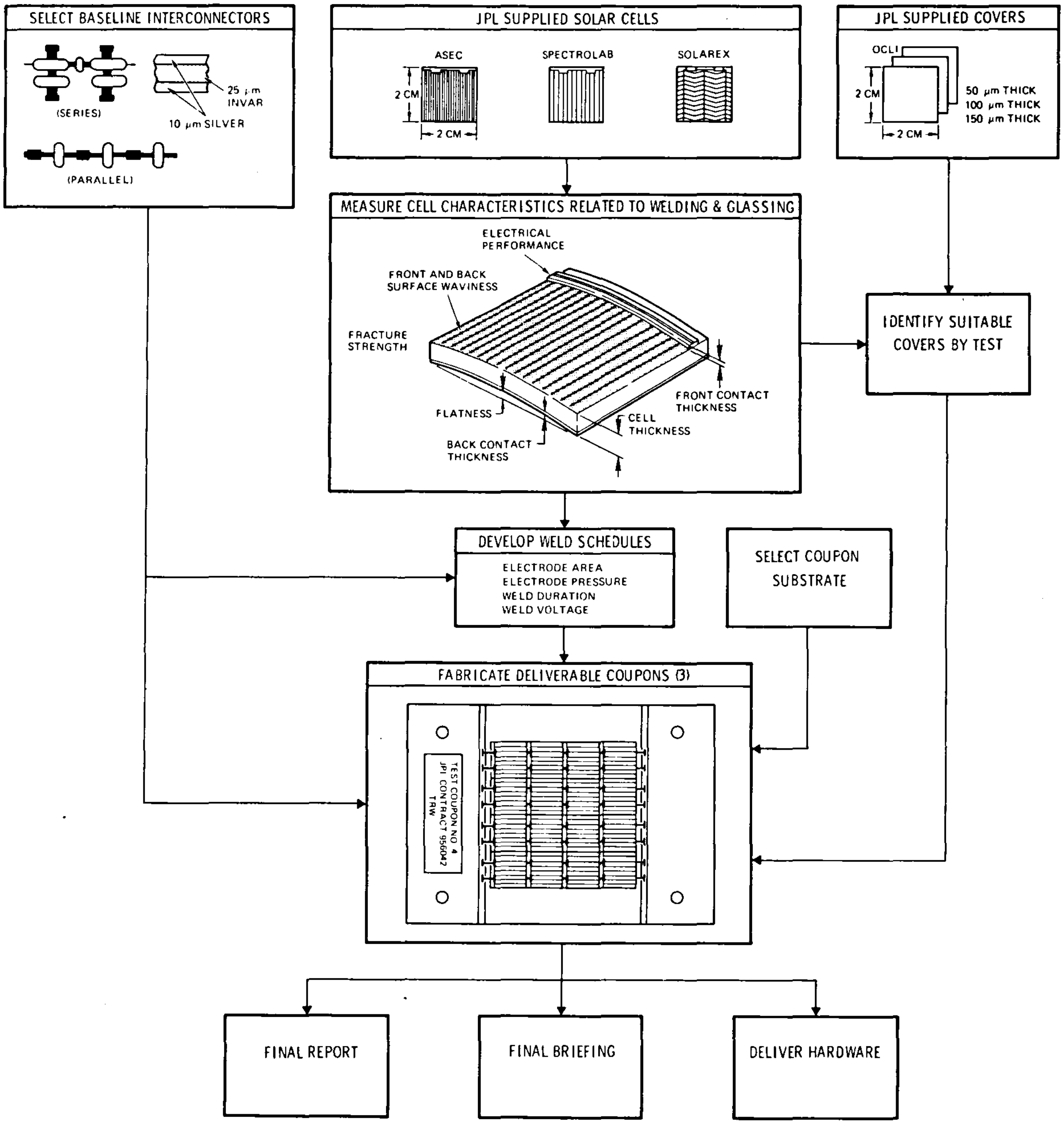


Figure 3.1-1. Weld Study Work Flow Summary

3.2 EVALUATION OF CELL CHARACTERISTICS

JPL furnished a total of 600 solar cells in equal quantities (200) obtained from Solarex, Spectrolab, and ASEC. Cell parameters were evaluated that have significant impact on welding and weld/cell performance of spacecraft solar arrays. This section discusses the cell characteristics evaluation.

3.2.1 Cell Electrical Performance

Initial cell electrical performance measurements were made on approximately 25 cells each from ASEC, Spectrolab, and Solarex. The cells were measured under an X-25 solar simulator which has an 18- by 36-cm illuminated area at one solar constant with a closely filtered air mass zero (AMO) spectrum. The uniformity was maintained within ± 0.5 percent over the single cell test area.

The electrical characteristics are presented in Table 3.2-1 and indicate similar performance of the cells from the three different suppliers. Additional electrical performance measurements were made to support weld schedule development (3.4.1), test coupon fabrication (3.4.4), and deliverable hardware fabrication (3.5), and are discussed in the indicated sections.

3.2.2 Cell Thickness

Cell thickness measurements were made using a dial gauge indicator. The cells were placed back side facing down on a flat glass surface and slid under the arm of a dial gauge indicator. The arm had a spherical contact which was positioned between grid lines on the solar cell top surface. Thus, the measurement included the back contact thickness but did not include front contact thickness. All measurements were made in the center area of each cell. The spring force of the dial gauge was of sufficient magnitude to flatten bowed cells. This was verified visually and by measuring bowed cells with additional weight placed on top of the cells. The additional weight had no influence on the thickness measurements. Results of the thickness measurements are presented as histograms in Figure 3.2-1 and are summarized in Table 3.2-2.

Table 3.2-1. Solar Cell Electrical Characteristics

ELECTRICAL MEASUREMENT		ASEC	SPECTROLAB	SOLAREX
SHORT CIRCUIT CURRENT	SAMPLE SIZE	26	23	25
	MEAN, mA	151	154	147
	STANDARD DEVIATION, mA	1.8	2.0	2.7
OPEN CIRCUIT VOLTAGE	SAMPLE SIZE	26	23	25
	MEAN, mV	597	579	594
	STANDARD DEVIATION, mV	5.3	10.0	4.8
CURRENT AT 460 mV	SAMPLE SIZE	26	23	25
	MEAN, mA	146	146	142
	STANDARD DEVIATION, mA	1.3	2.5	3.8

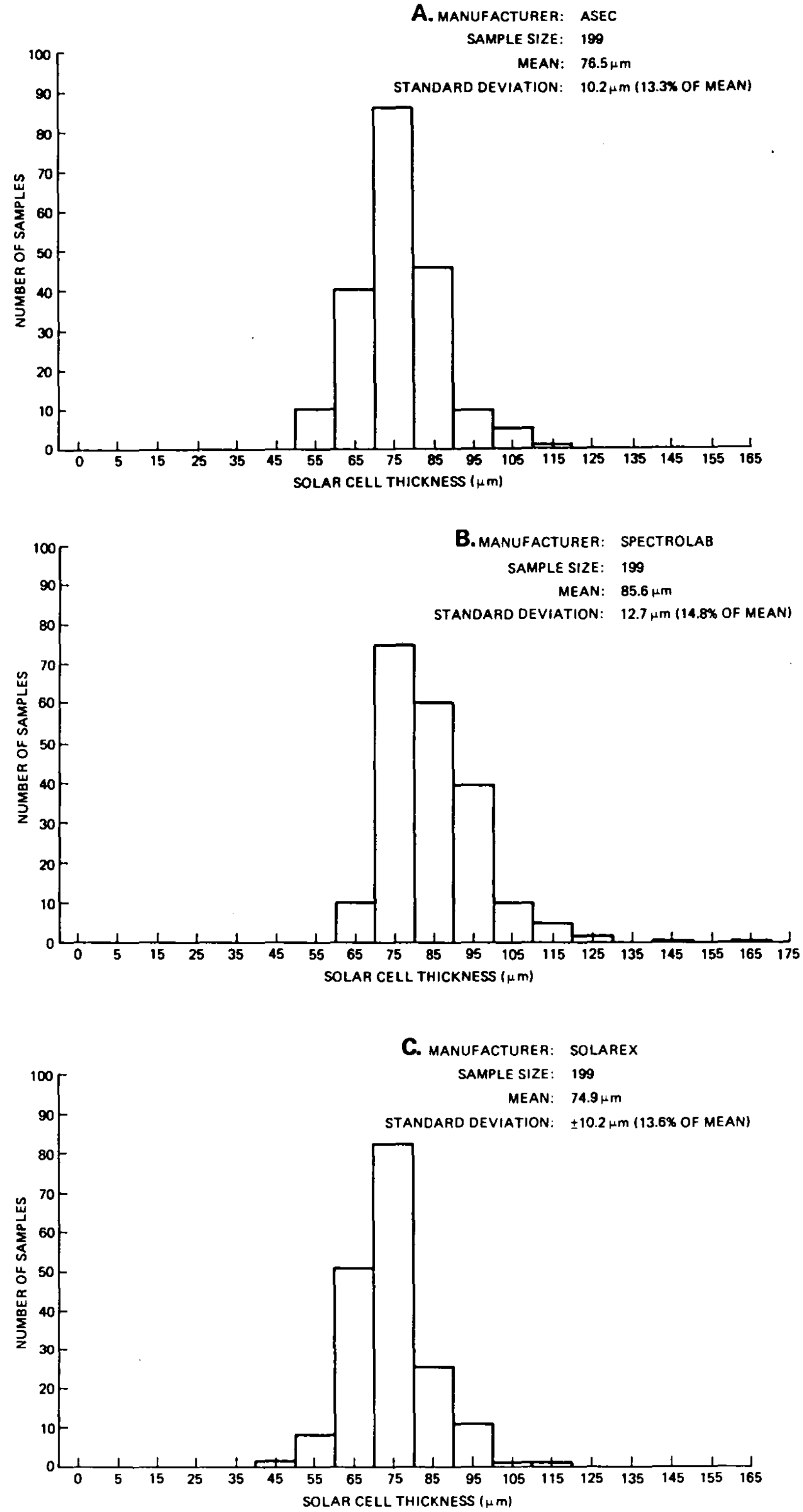


Figure 3.2-1. Thickness Measurements on Nominal 50-μm Thick Solar Cells

Table 3.2-2. Thickness Measurement Summary on Nominal 50-μm Thick Solar Cells

Thickness Measurement	ASEC	Spectrolab	Solarex
Mean, μm	77	86	75
Low, μm	51	66	46
High, μm	112	163	112
Standard Deviation, μm	10	13	10
Sample Size	199	199	199

3.2.3 Cell Silver Contact Thickness

3.2.3.1 Front Contact Thickness Results

Front surface contact thickness measurements were made on cells from each of the three vendors using an Alpha-Step profiler manufactured by Tencor Intruments. A 0.5-μm radius stylus was used to scan the profile of the front contact pads (or bar) on each test article. The magnified profiles were recorded on a continuous 50-mm wide strip chart with each 1-mm spaced grid line corresponding to 0.5 μm in contact thickness. All plots were read to the nearest gridline; consequently, all measurements were reported in 0.5-μm increments.

Figure 3.2-2 shows a typical profiler plot in relationship to a front contact pad. The step in the profile plot corresponds to the edge of the contact and, consequently, the magnitude of the step corresponds to the contact thickness at the edge of the contact. The assumption is that the thickness at the edge of the contact is representative of the average contact thickness.

Results of the contact thickness measurements are presented in histograms in Figures 3.2-3, 3.2-4, and 3.2-5 for the ASEC, Spectrolab, and cells, respectively. Solarex edge thickness measurements are probably not as representative of average contact thickness as are the ASEC and Spectrolab edge thickness measurements because the Solarex cell contacts were electroplated whereas, the ASEC and Spectrolab contacts were vacuum deposited. Electroplated contacts are frequently thicker at the perimeter that in the center.

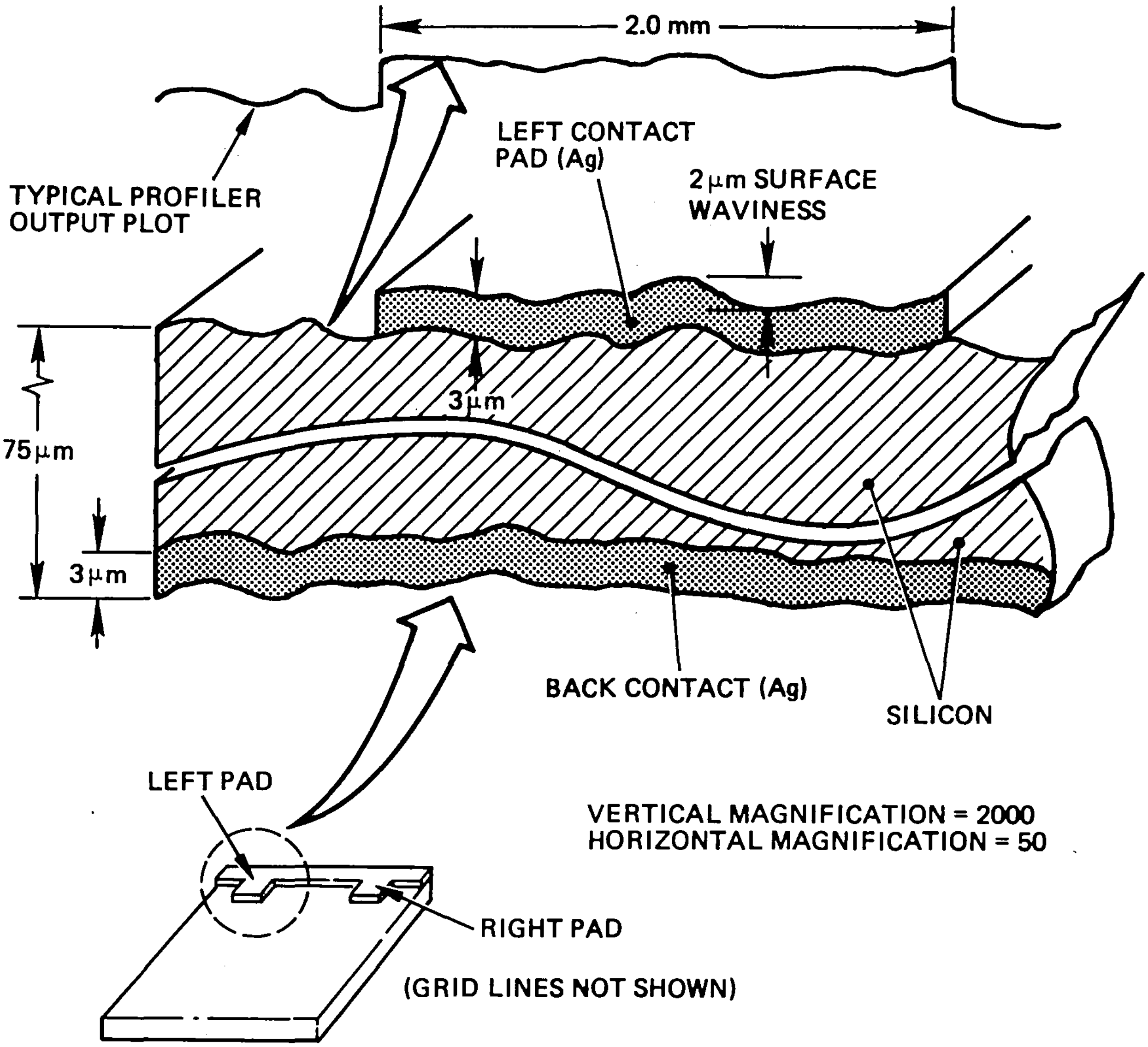


Figure 3.2-2. Typical Profiler Plot of Solar Cell Front Contact Pad

MANUFACTURER: ASEC

SAMPLE SIZE: 122

MEAN: 4.2 μm

STANDARD DEVIATION: 1.0 μm (23.4% OF MEAN)

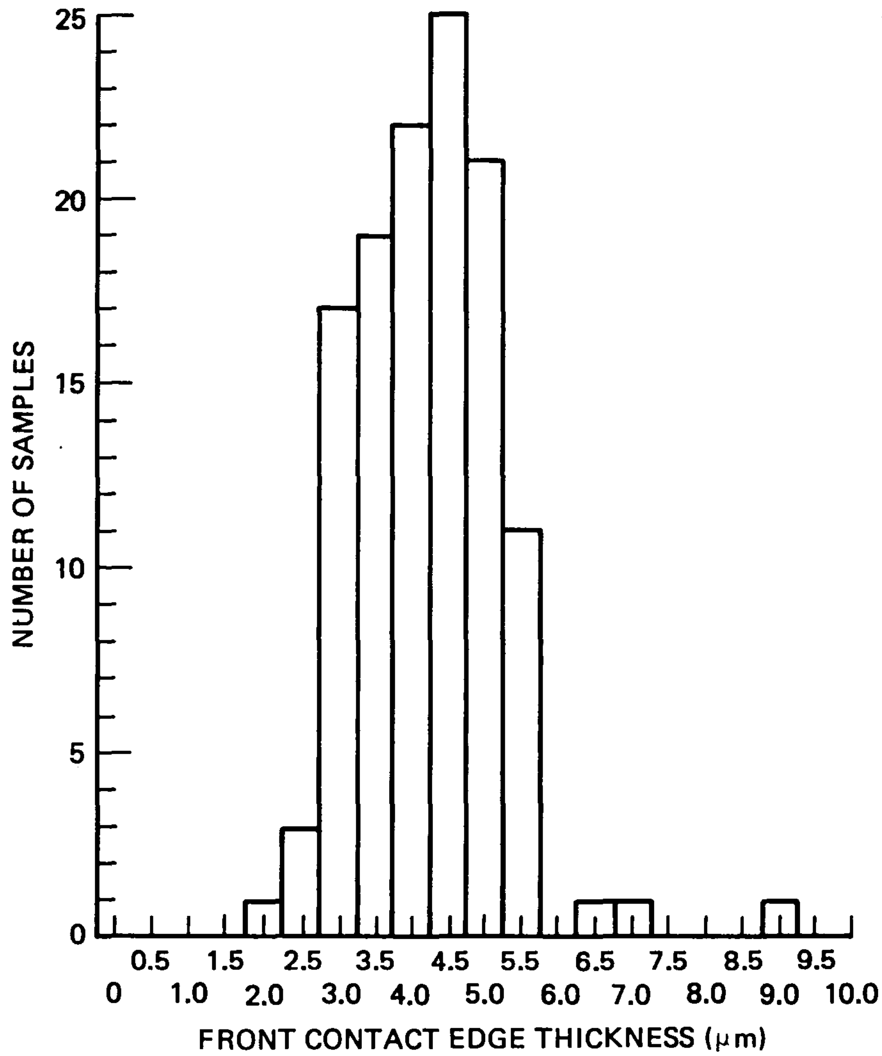


Figure 3.2-3. ASEC Cell Front Contact Pad Edge Thickness Measurements Using a Profiler

MANUFACTURER: SPECTROLAB
SAMPLE SIZE: 124
MEAN: 2.8 μm
STANDARD DEVIATION: 1.0 μm (35.8% OF MEAN)

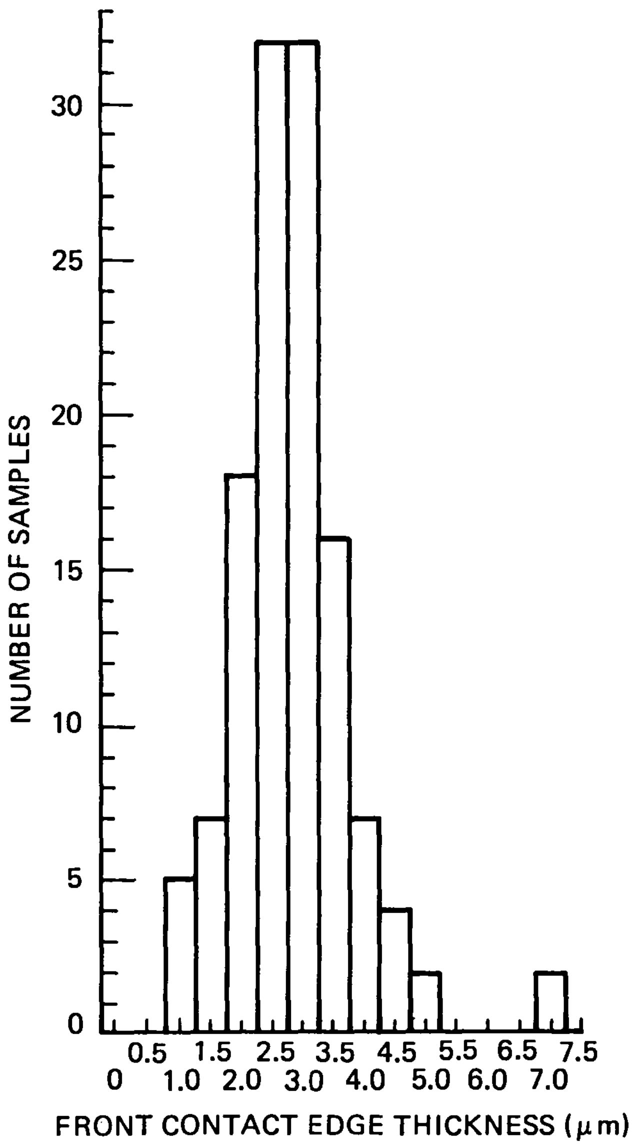


Figure 3.2-4. Spectrolab Cell Front Contact Pad Edge Thickness Measurements Using a Profiler

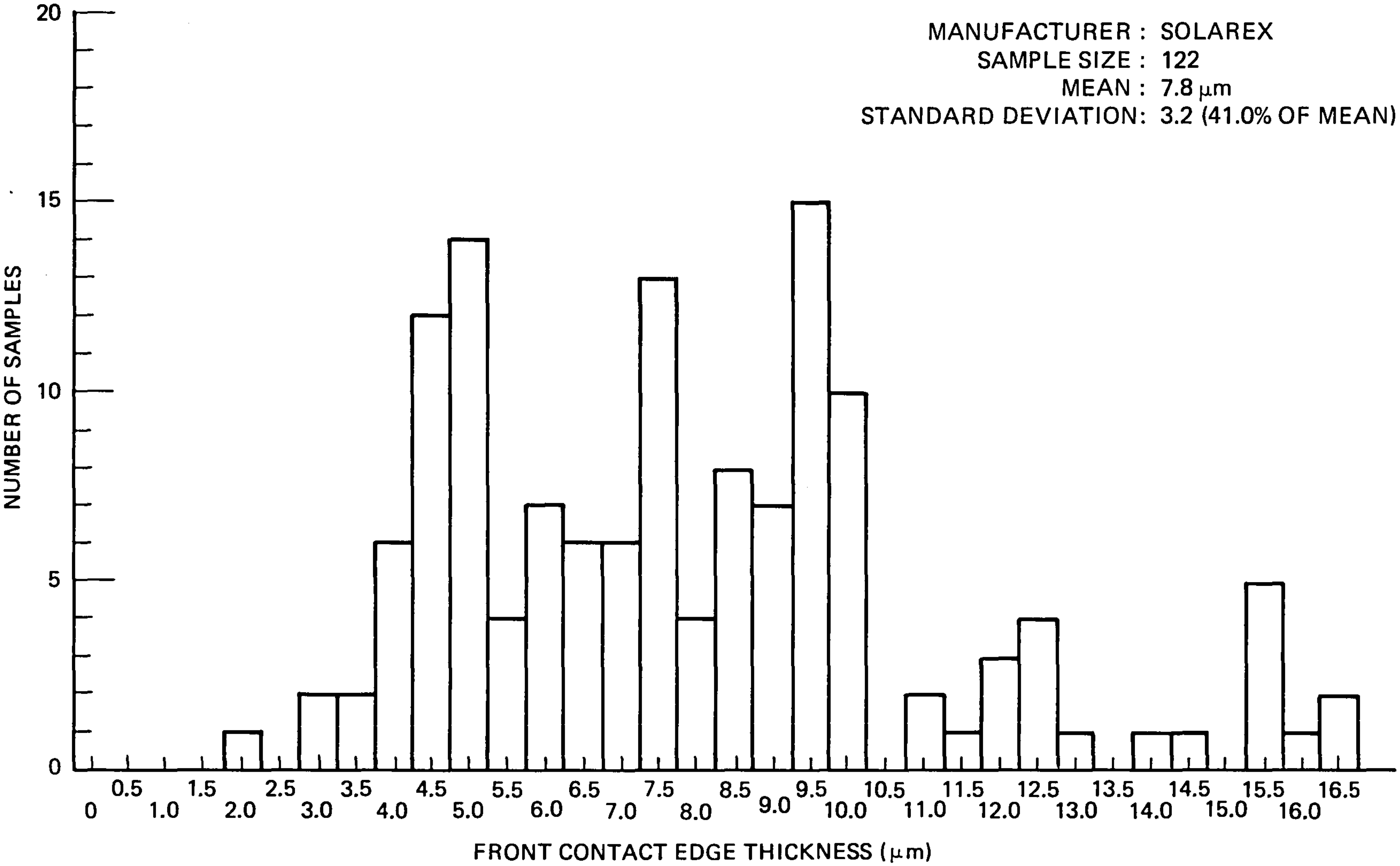


Figure 3.2-5. Solarex Cell Front Contact Pad Edge Thickness Measurements Using a Profiler

3.2.3.2 Back Contact Thickness Results

Back contacts were measured using a Memoderm Model MP-95 Digital Direct Reading Thickness Gauge manufactured by UPA Technology, Inc., Syossett, New York. The probe was a No. TL-37474 which has Thallium-204 as a radiation source and is equipped with a 0.040- by 0.125-inch rectangular mask which defines its active probe area.

The Memoderm provides a nondestructive method for measuring relative contact thicknesss. However, it is necessary to calibrate the Memoderm with "standards" representative of each cell type. The Memoderm measurements were calibrated using Ion Mass Microprobe Analyzer (IMMA) measurements on a few selected cells from each of the three suppliers. The IMMA sputters away the contact within a small area (0.008 by 0.008 in^2). A mass analyzer captures the specimen atoms as they are sputtered off the cell contact. The mass analyzer makes accurate determinations of the contact materials and mass. Thickness is computed using the IMMA mass measurements and an assumed density.

Results of the back contact thickness measurements are presented in histograms in Figures 3.2-6, 3.2-7, and 3.2-8 for the ASEC, Spectrolab, and Solarex cells, respectively.

3.2.3.3 Contact Thickness Measurement Discussion

Two different methods were used for front and back contact thickness measurements. Back contact thickness could not be measured using a profiler with the present configuration of the back contacts since the contacts cover the entire back surfaces of the cell and there are no "steps" for the profiler to measure. Front contacts could not be measured using the Memoderm because the active probe area is larger than the front contact pads.

Back contact thickness was considerably less than front contact thickness for each of the three cell types. A few cells were microcross-sectioned in order to verify results of the nondestructive profiler (front contacts) and Memoderm (back contacts). Typical cross sections are shown in Figures 3.2-9, 3.2-10, and 3.2-11 for the Spectrolab, Solarex, and ASEC

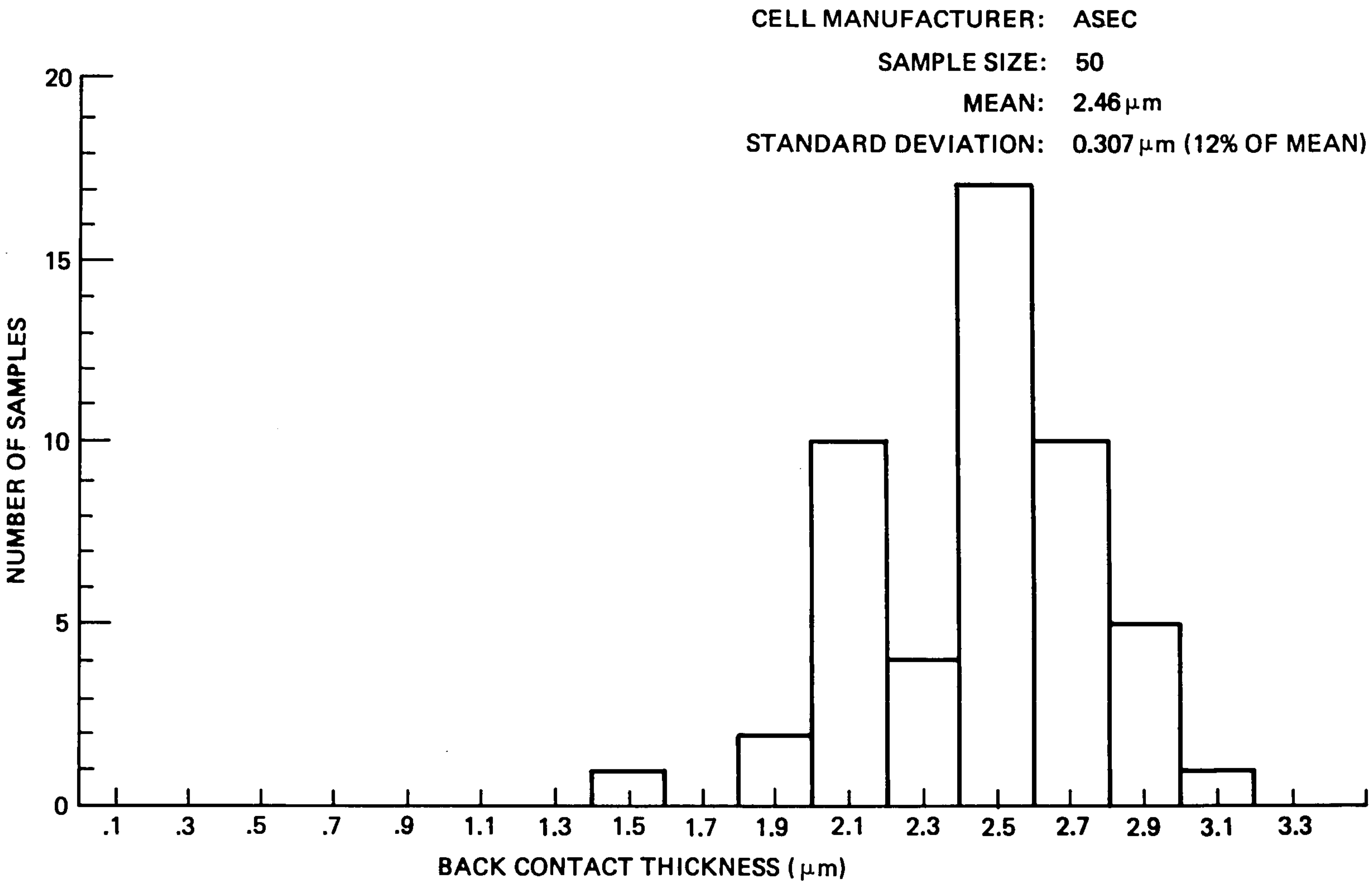


Figure 3.2-6. ASEC Cell Back Contact Thickness Measurements Using a Betascope

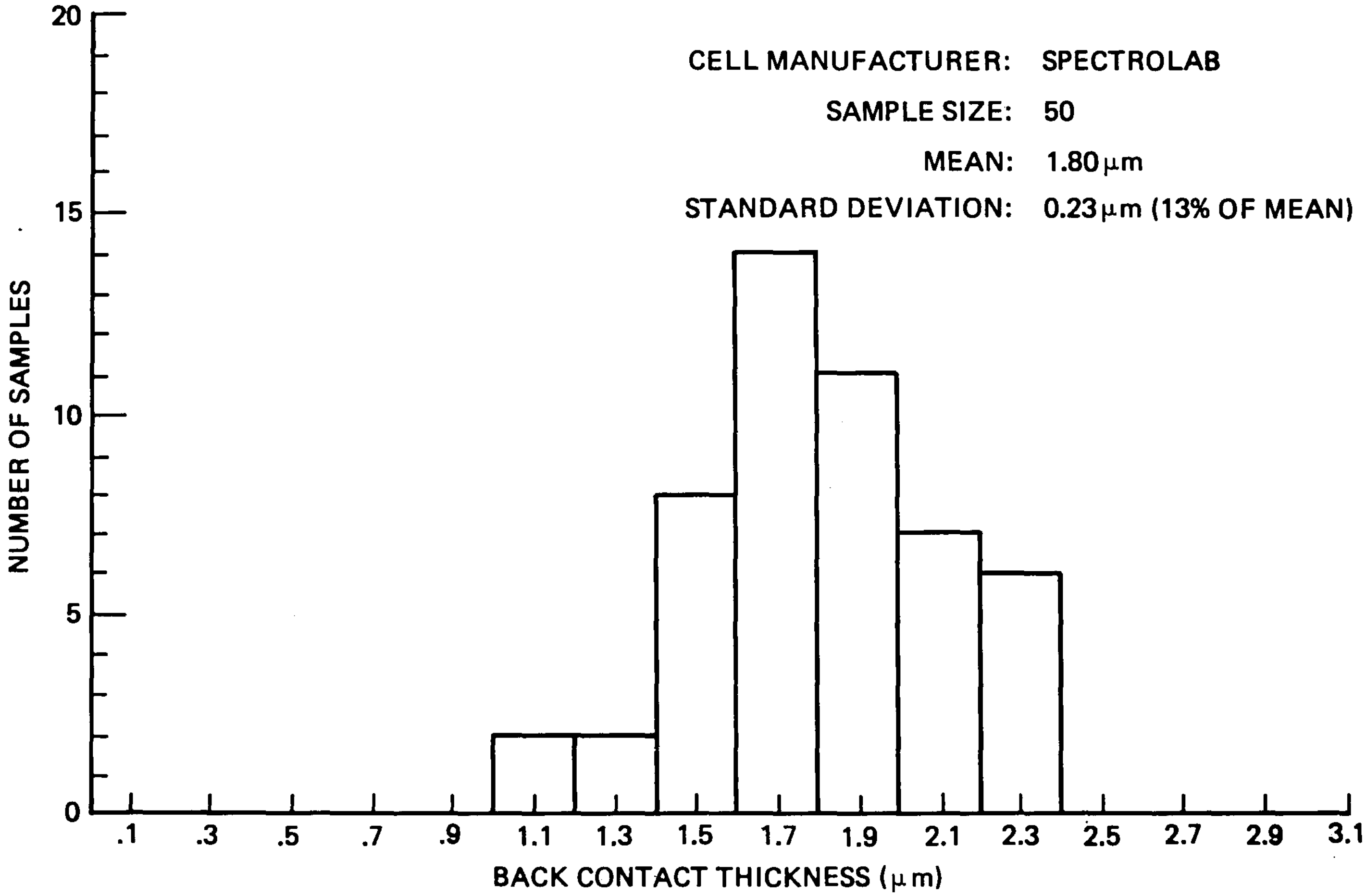


Figure 3.2-7. Spectrolab Cell Back Contact Thickness Measurements Using a Betascope

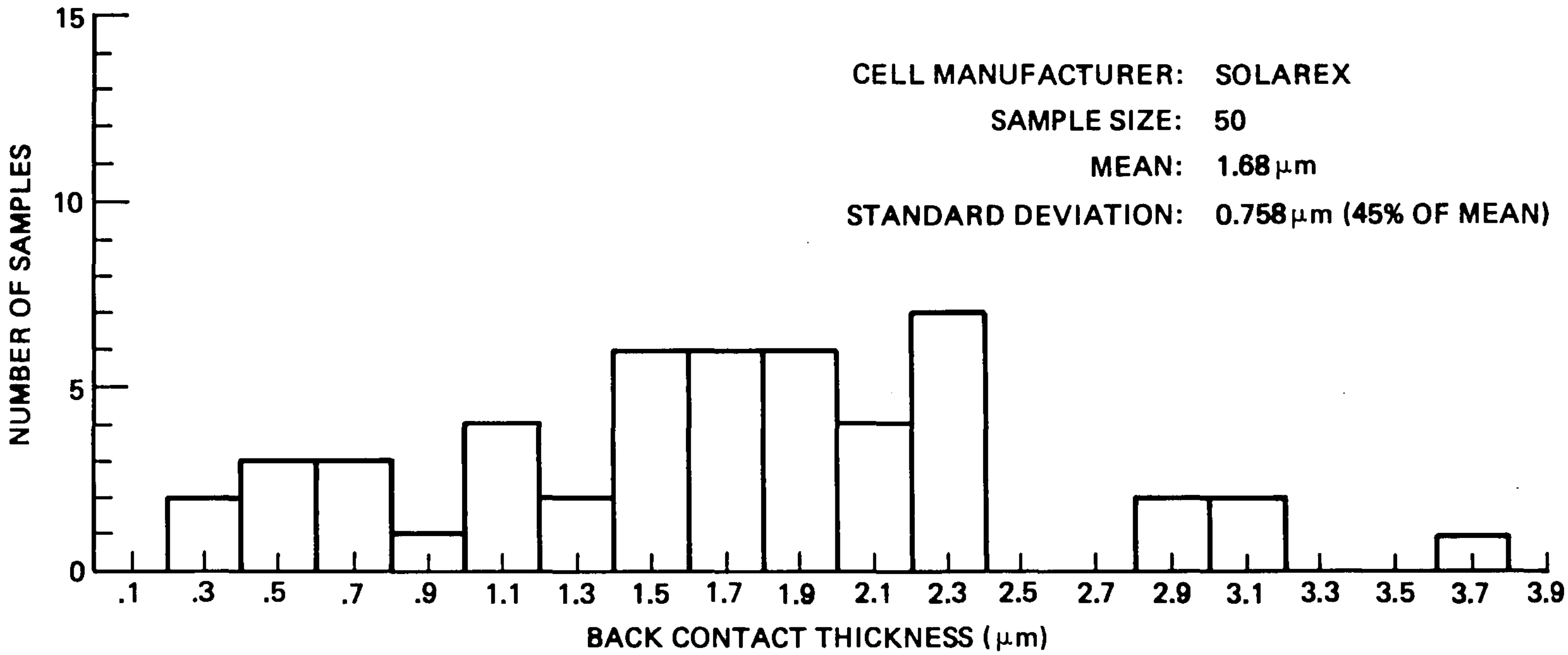


Figure 3.2-8. Solarex Cell Back Contact Thickness Measurements Using a Betascope

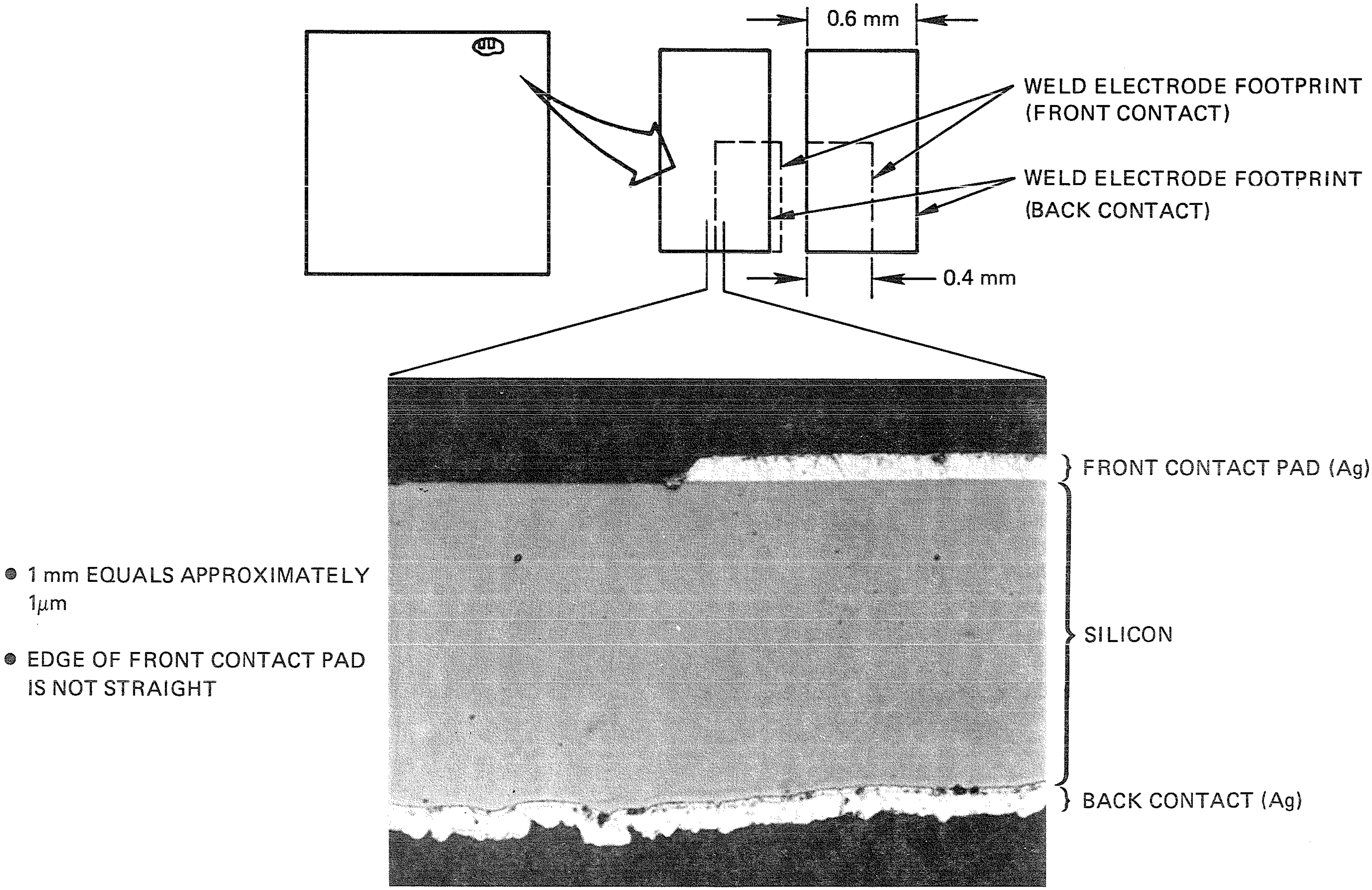
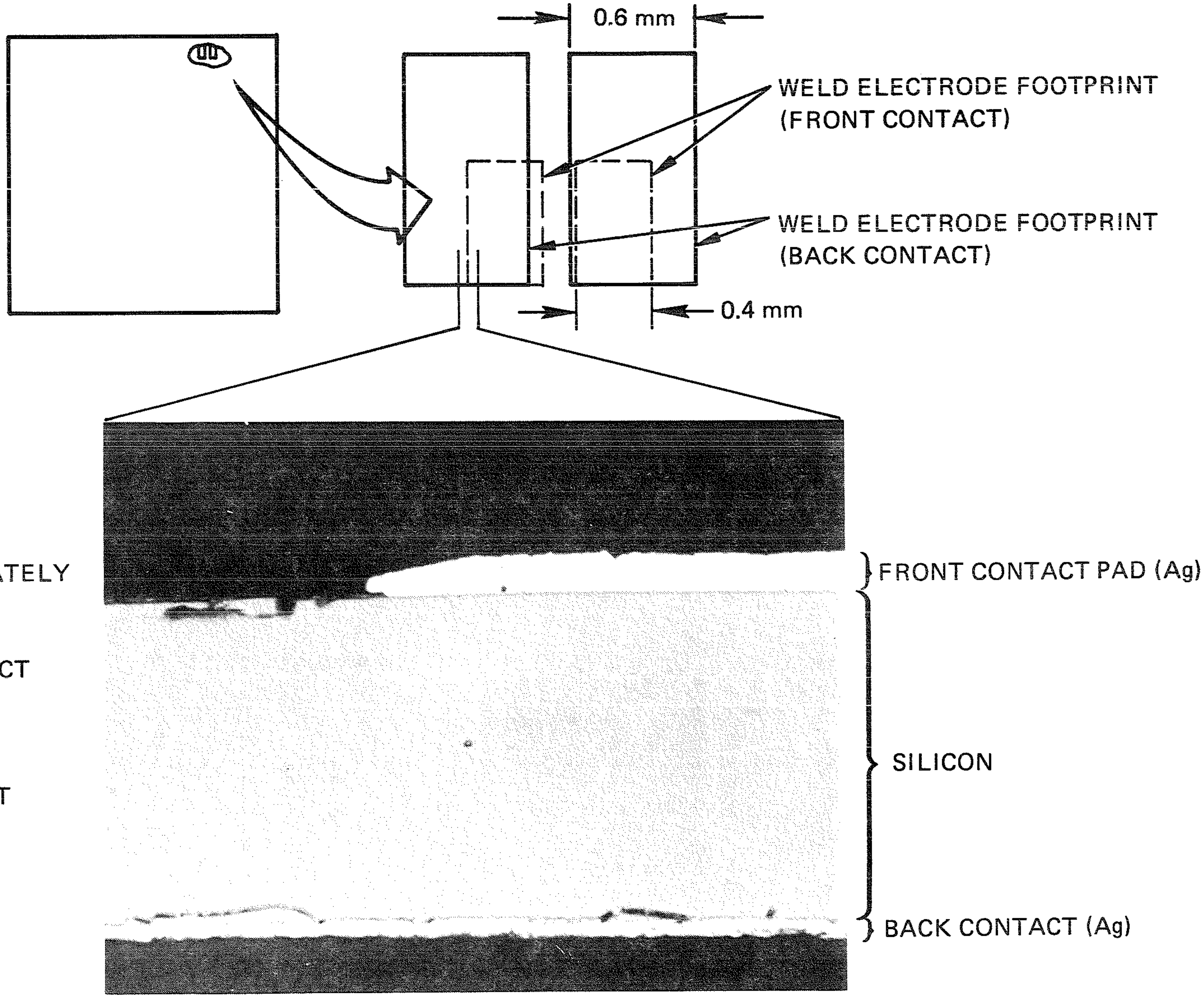


Figure 3.2-9. Spectrolab Cell Cross Section (∿1000X Magnification)



- 1 mm EQUALS APPROXIMATELY 1μm
- FRONT AND BACK CONTACT THICKNESSES ARE NOT EQUAL
- EDGE OF FRONT CONTACT PAD IS NOT STRAIGHT

Figure 3.2-10. Solarex Cell Cross Section (~1000X Magnification)

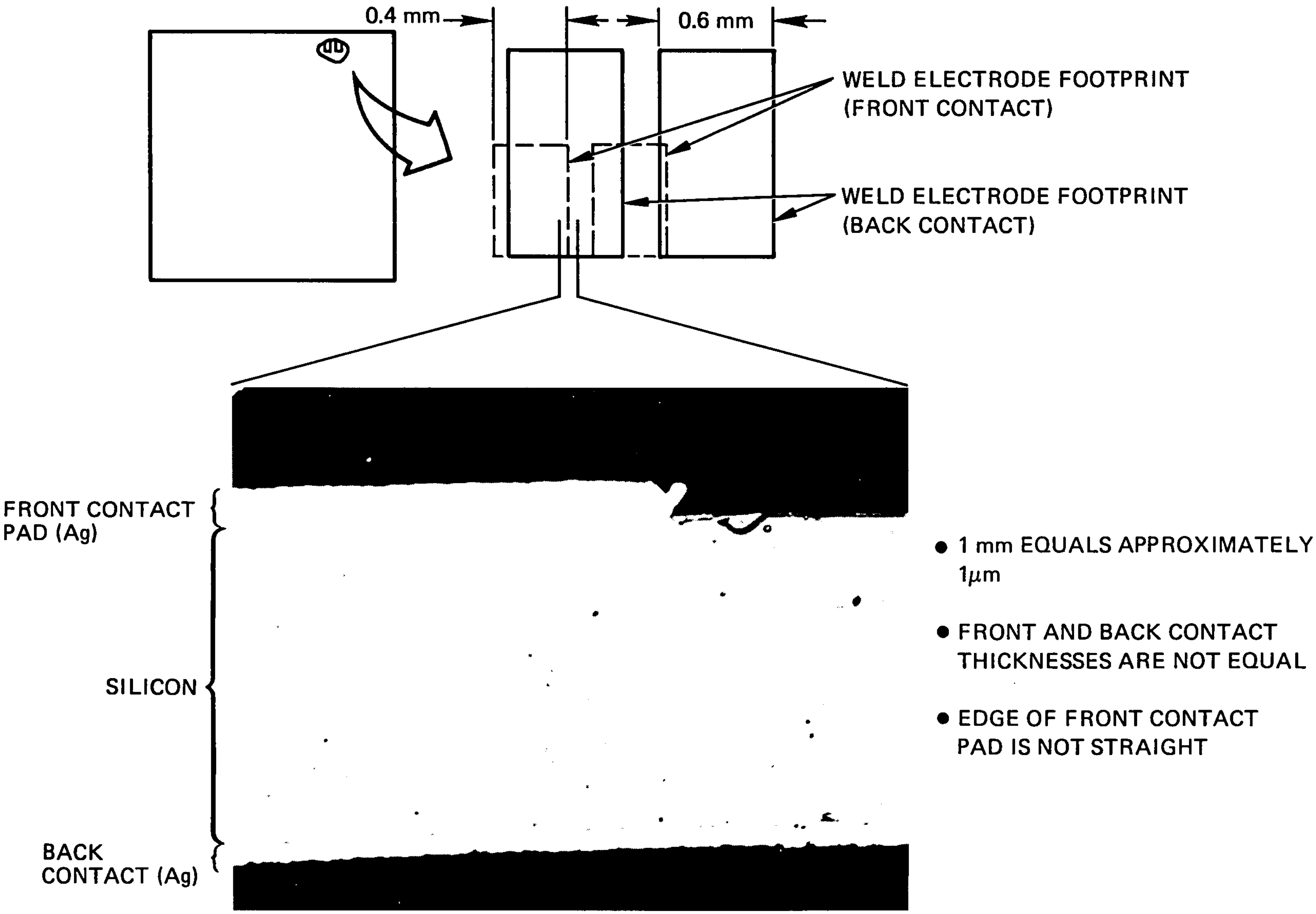


Figure 3.2-11. ASEC Cell Cross Section (~1000X Magnification)

cells, respectively. The microcross sections confirmed that back contacts were consistantly thinner than front contacts and showed that edge contact thickness is not always representative of average contact thickness.

A Scanning Electron Microscope (SEM) was used to examine contact edges. Figure 3.2-12 shows a typical SEM photograph which visually reveals variation in contact pad edge thickness.

The four techniques used to measure contact thickness on this program are compared in Table 3.2-3.

3.2.4 Cell Contact Waviness

Surface waviness was measured concurrent with the front contact measurements using the Alpha-Step profiler. A 0.5-μm radius stylus was used to scan the surface of the front contact pads and the back surface on each test article. A typical front contact profiler plot was shown previously in Figure 3.2-1. In this figure, a surface waviness of 3 μm is indicated and is a measure of the maximum peak-to-valley vertical distance that occurs across the contact surface. Surface roughness is a measure of the local surface irregularities on the larger scale surface waves.

Typical front contact profiles plots are shown in greater detail in Figure 3.2-13. This figure shows the relationship between typical waviness periods (peak-to-peak distance) and weld contact areas. Parallel gap electrode tip areas are shown relative to typical profile plots. Note that it is possible for the contact area to bridge across two waviness peaks with weld voids occurring in between. It is therefore desirable to minimize contact waviness to maximize welded contact area. This is particularly true when using a relatively noncompliant interconnect material such as Invar. However, the Invar is clad with 10 μm of silver and can accommodate some degree of surface waviness.

Front contact surface waviness results are presented in Table 3.2-4. All three cell types had an average front contact waviness of approximately 3 μm. The waviness is primarily caused by the KOH etching process required to reduce cell thickness to produce the thin cells. SEM photographs of ASEC, Spectrolab, and Solarex front cell surfaces are shown in Figures 3.2-14, 3.2-15, and 3.2-16, respectively. Each of the photographs shows

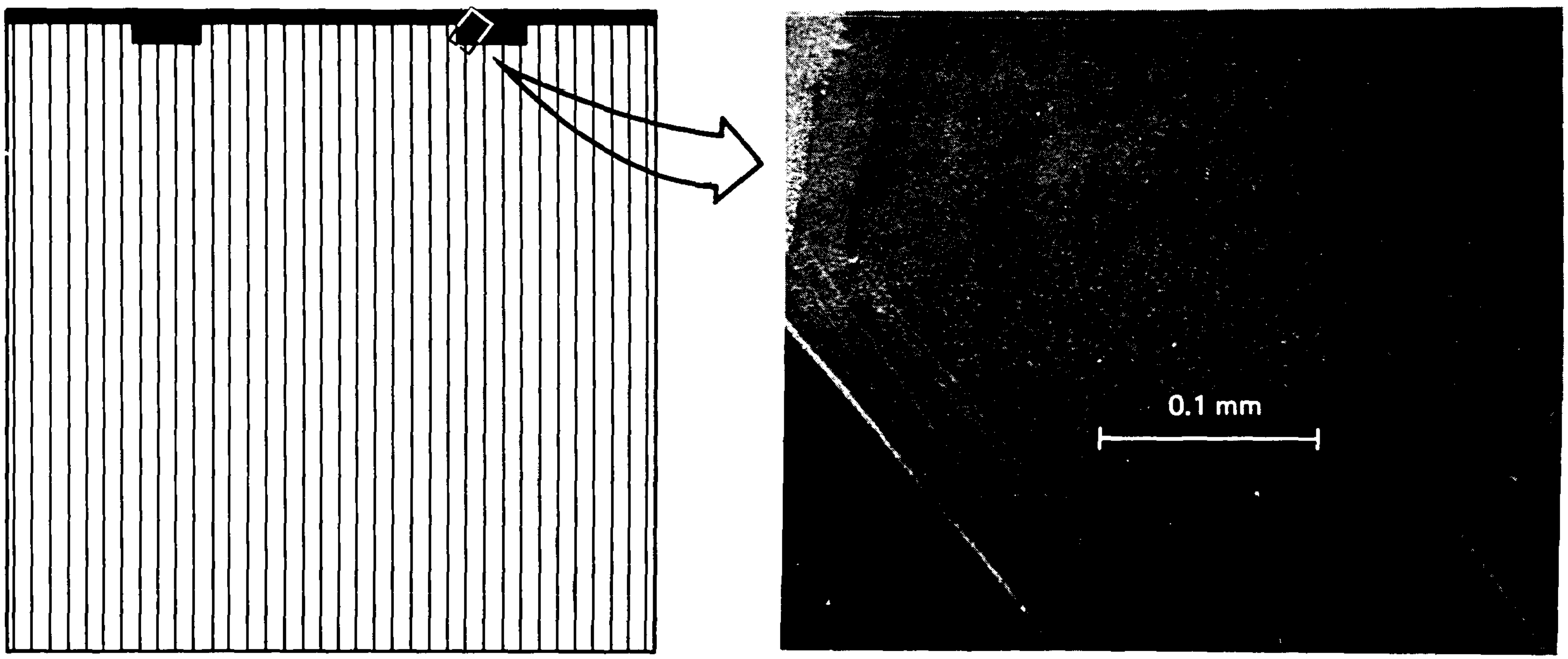


Figure 3.2-12. Variation in Front Contact Pad Edge Thickness (SEM at 300X)

Table 3.2-3. Contact Thickness Measurement Technique Review

METHOD	COMMENT
PROFILER	• NON-DESTRUCTIVE, RELATIVELY INEXPENSIVE • CAN BE USED FOR FRONT CONTACT ONLY UNLESS REAR CONTACT HAS A FRAME OR STEP • RESULTS CAN BE MISLEADING BECAUSE OF VARIATION IN CONTACT EDGE THICKNESS
MEMODERM	• NON-DESTRUCTIVE, MODERATELY EXPENSIVE, SCHEDULE DIFFICULTIES • CAN BE USED FOR REAR CONTACT ONLY BECAUSE OF LARGE PROBE APERTURE AREA • REQUIRES ALTERNATE MEASUREMENT (IMMA) FOR CALIBRATION
ION MASS MICROPROBE ANALYZER	• DESTRUCTIVE, VERY EXPENSIVE, SCHEDULE DIFFICULTIES • CAN BE USED FOR BOTH FRONT AND REAR CONTACTS • METHOD DETERMINES MASS.THICKNESS DETERMINED BY ASSUMING DENSITY • METHOD ALSO CAN DETECT PRESENCE OF OTHER METALS
MICROCROSS-SECTION	• DESTRUCTIVE, VERY EXPENSIVE, SCHEDULE DIFFICULTIES • CAN BE USED FOR BOTH FRONT AND REAR CONTACTS • SECTIONING PROCESS CAN DISTORT CONTACT PROFILES

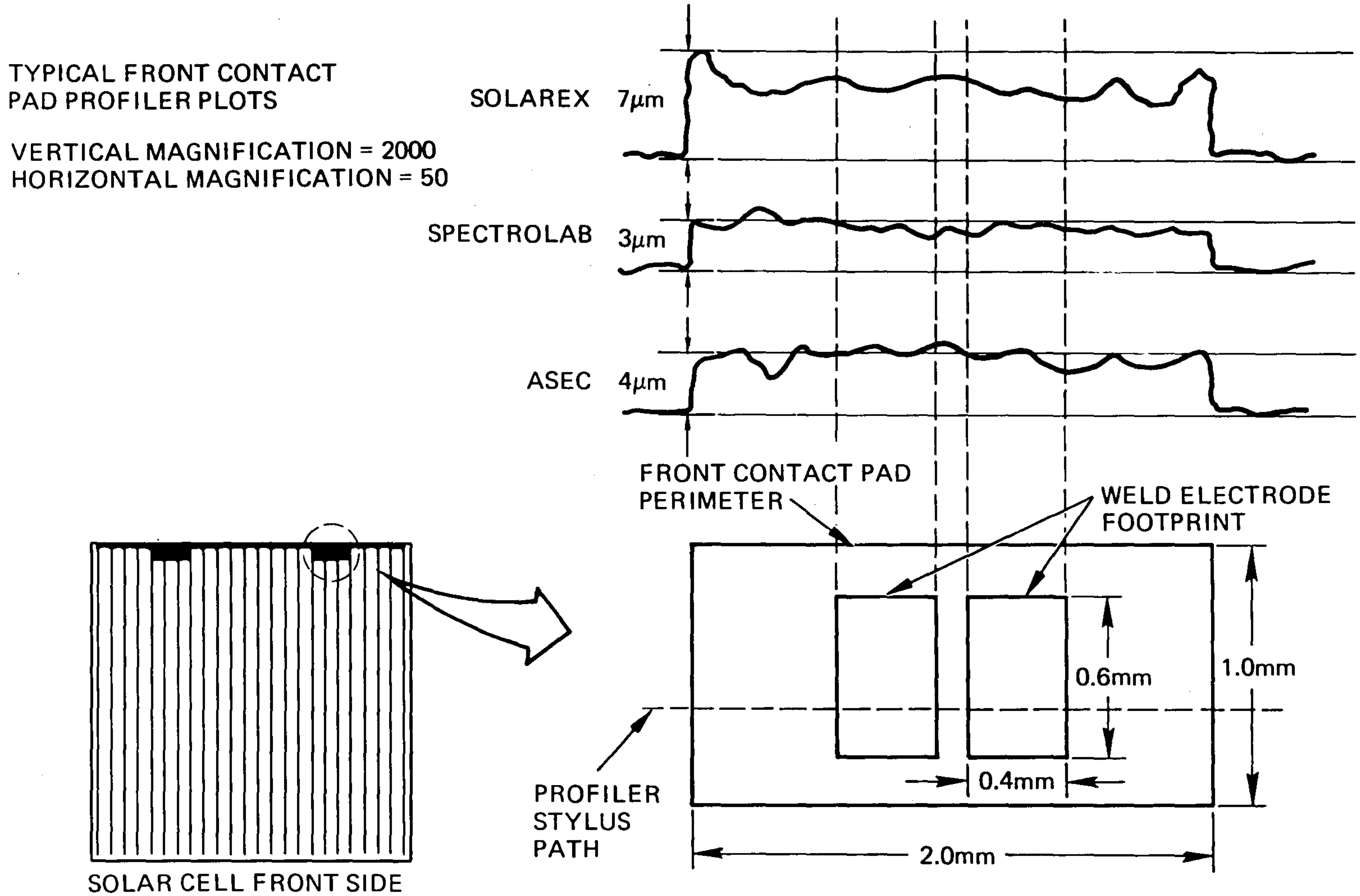
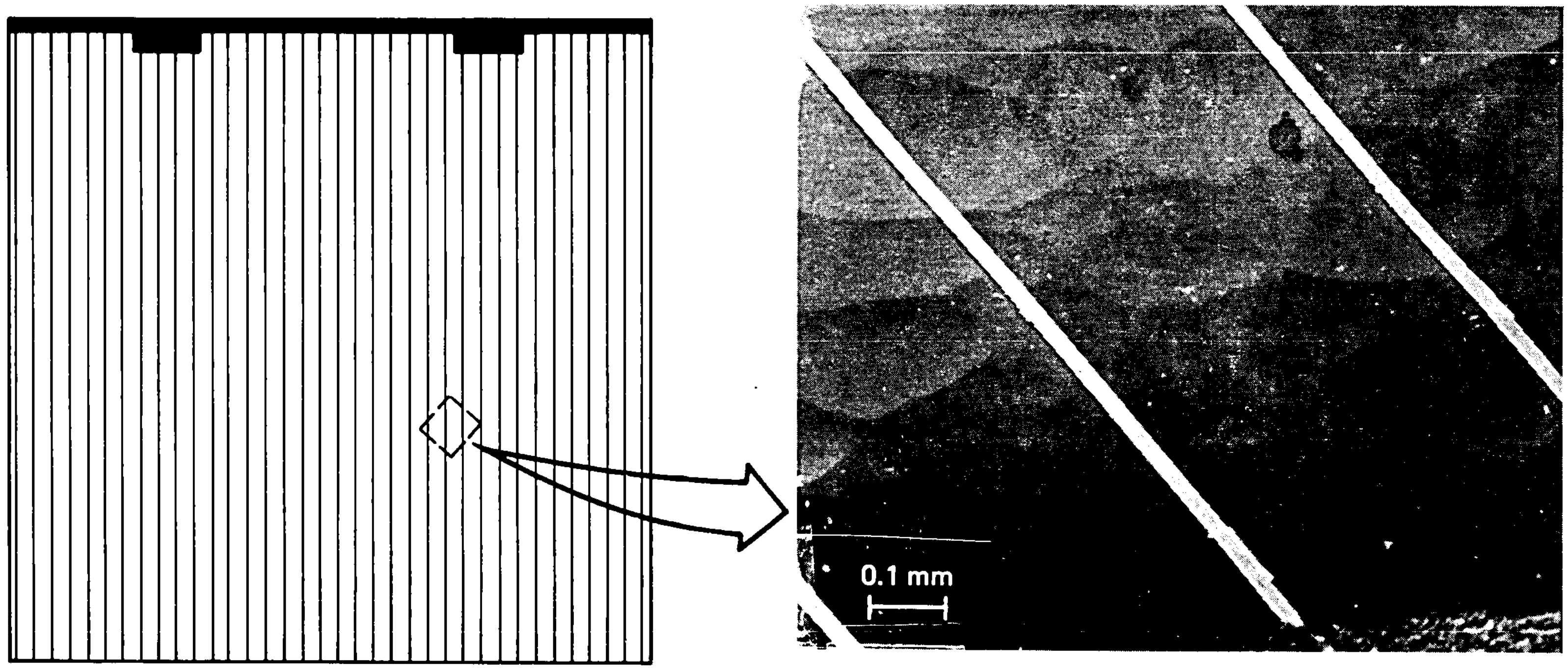


Figure 3.2-13. Front Contact Pad Surface Profile Comparison

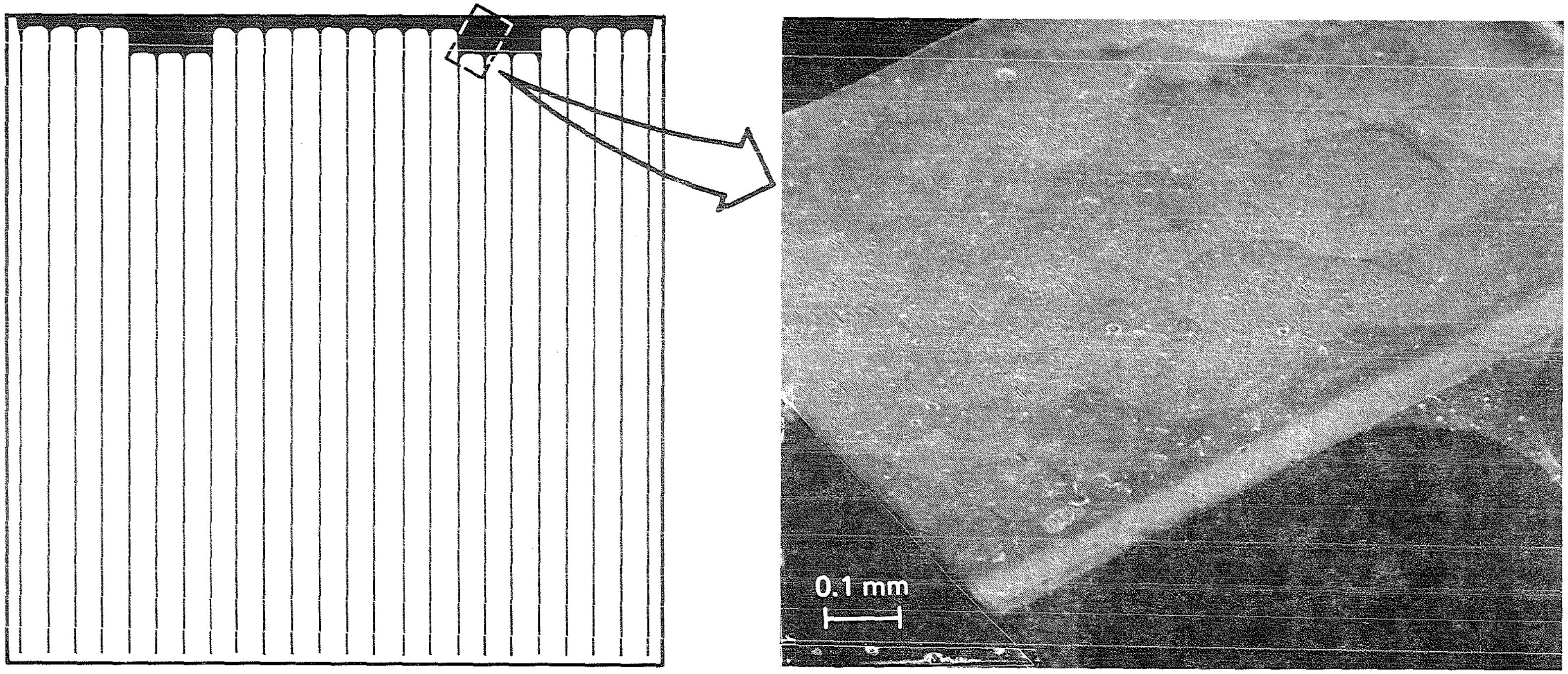
Table 3.2-4. Surface Waviness Results Summary

SURFACE WAVINESS	ASEC		SPECTROLAB		SOLAREX	
	FRONT	BACK	FRONT	BACK	FRONT	BACK
MEAN, μm	3.0	3.1	3.2	5.9	3.1	5.2
STANDARD DEVIATION, μm	1.2	1.0	1.3	2.1	1.3	1.6
SAMPLE SIZE	20	10	22	11	41	16



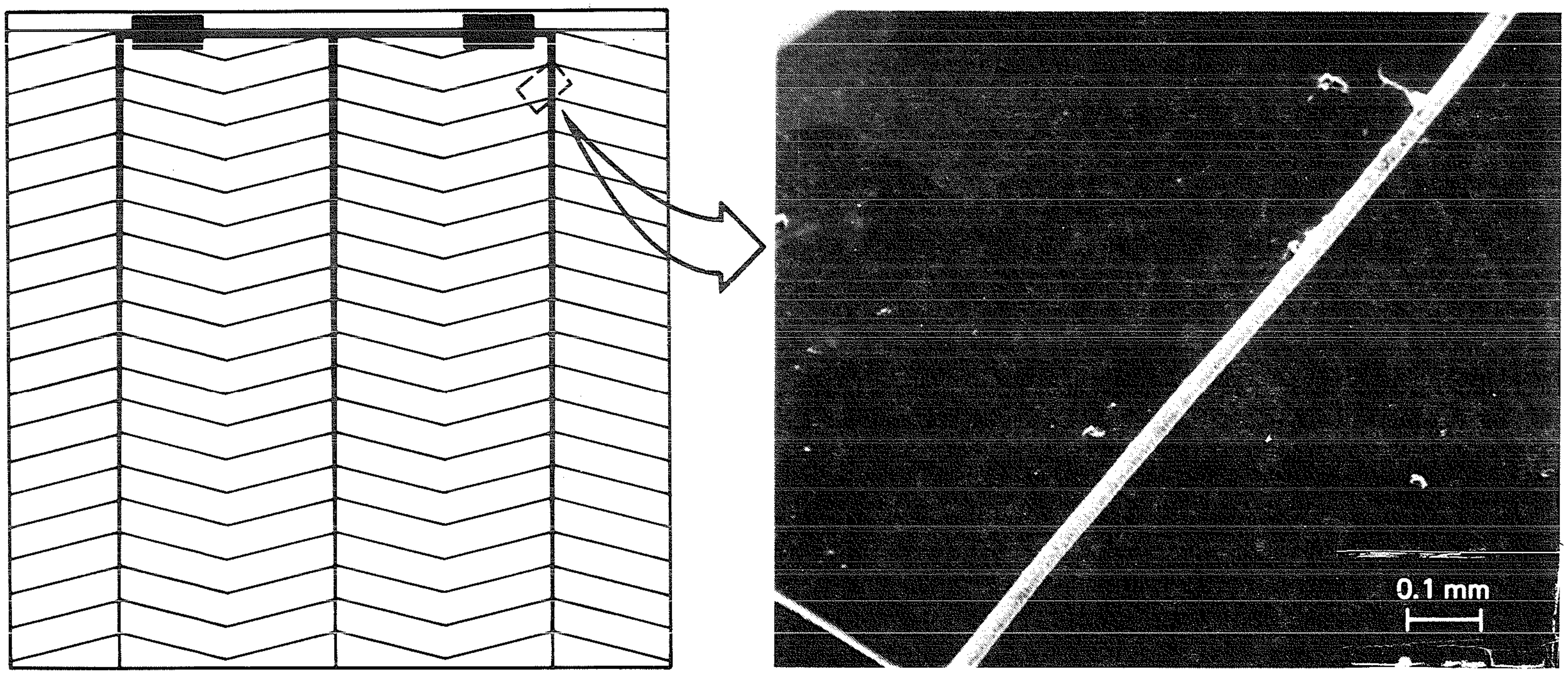
(A-135)

Figure 3.2-14. Scanning Electron Microscope Photo at 100X Shows Craters on ASEC Cell Cell Front Surface



(S-42)

Figure 3.2-15. Front Contact Pad Surface Follows Contour of Silicon Surface Below on Spectrolab Cell (SEM Photo at 100X)



(X-153)

Figure 3.2-16. Scanning Electron Microscope Photo at 100X Shows Craters on Solarex Cell Front Surface

surface cratering. The waviness shown in Figure 3.2-13 is caused as the stylus moves in and out of craters shown in Figures 3.2-14, 3.2-15, and 3.2-16. Figure 3.2-15 shows the front contact area and Figures 3.2-14 and 3.2-16 show noncontact areas. By comparing these figures it was concluded that the waviness on the contact outer surface is a duplication of the waviness of the silicon surface directly below.

Typical back contact profile plots are shown in Figure 3.2-17. Also shown in this figure is the surface profile of an interconnect which is considerably less irregular than any of the cell surfaces. Back contact waviness results were presented in Table 3.2-3. The ASEC cells' front and back surfaces are similar. Both the Spectrolab and the Solarex cell back surfaces are considerably more irregular than the front surfaces. This greater irregularity is caused by the aluminum paste process used to produce the back surface field in the Spectrolab and Solarex cells. The boron process used by ASEC produces a much more regular surface. This point is further illustrated in Figure 3.2-18 which compares the back surfaces of the three cell types using SEM photographs.

3.2.5 Cell Bowing

Cell bowing was determined by placing the cells back side facing down on a machinist's flat and then measuring the maximum thickness of the bowed cell with a dial indicator micrometer height gauge. Using the micrometer the dial gauge was lowered until initial contact with the cell. The process was viewed through a 7X microscope to assure minimal deflection of the cell. In all cases the bowing was convex with respect to the front surface. Cell thickness was subtracted from the measured values to give the bowing parameter, H, defined in Figure 3.2-19. Results of the bowing measurements are summarized in Table 3.2-5. The Solarex cells are significantly less bowed than the ASEC and Spectrolab cells. The measured bowing for all cell types is undesirable because it complicates cell glassing and automated cell handling, and it indicates that there are significant shear forces between the contact and the silicon cell after contact formation.

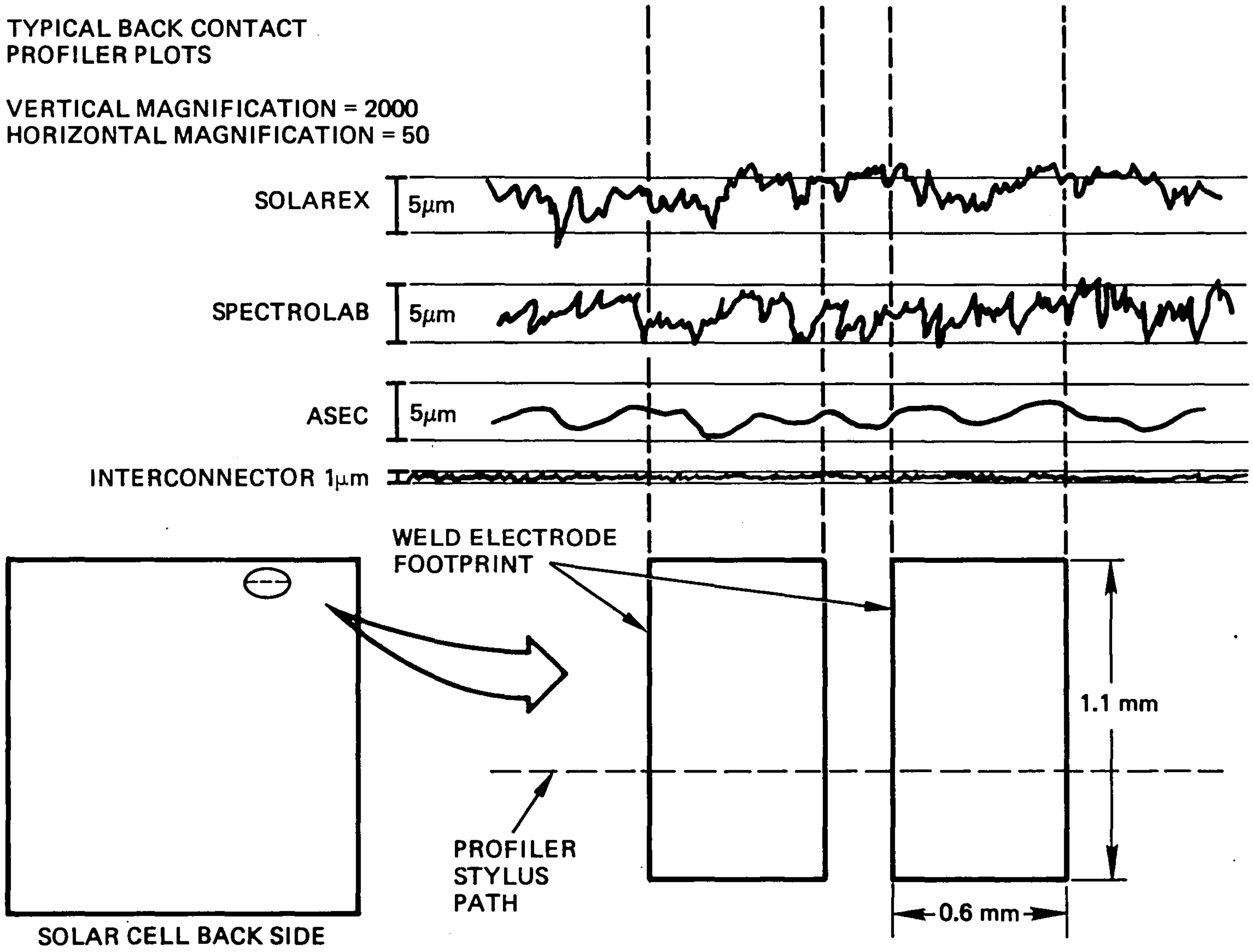
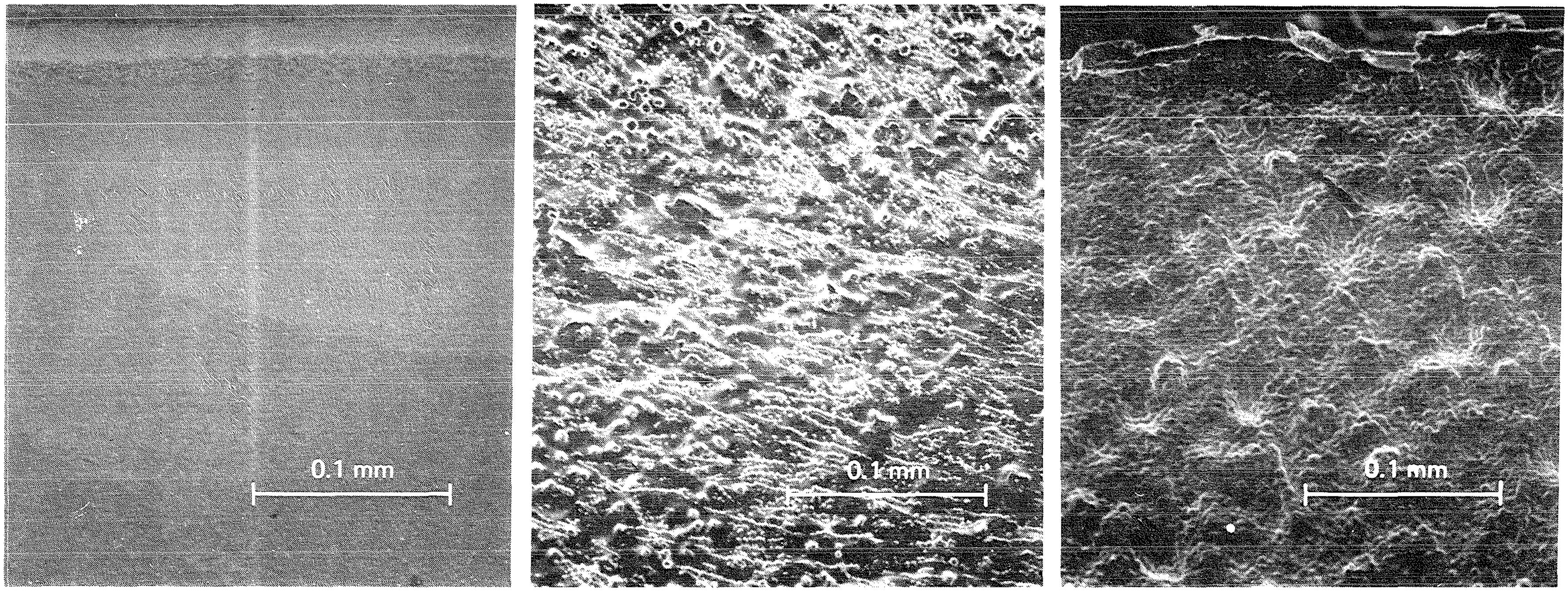


Figure 3.2-17. Back Contact Surface Profile Comparison



ASEC CELL NUMBER 135
- VACUUM DEPOSITED Ag CONTACT
- B DIFFUSION BSF PROCESS

SPECTROLAB CELL NUMBER 42
- VACUUM DEPOSITED Ag CONTACT
- Aℓ PASTE BSF PROCESS

SOLAREX CELL NUMBER 153
- PLATED Ag CONTACT
- Aℓ PASTE BSF PROCESS

Figure 3.2-18. Solar Cell Back Contact Surface Comparison (SEM at 300X)

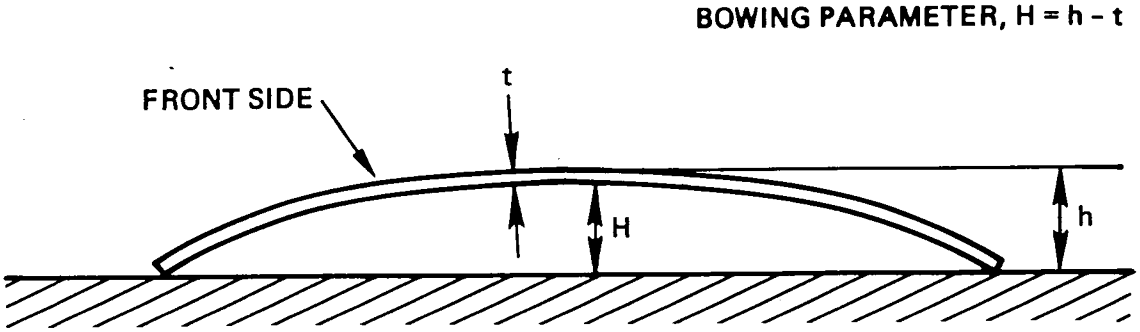


Figure 3.2-19. Definition of Bowing Parameter

Table 3.2-5. Bowing of 50-μm Thick Solar Cells

BOWING, H	ASEC	SPECTROLAB	SOLAREX
SAMPLE SIZE	20	20	20
MEAN, μm	304.8	228.6	127.0
STANDARD DEVIATION, μm	142.2	50.8	25.4

3.2.6 Cell Fracture

Cell fracture strength measurements were performed using the cylindrical bending method developed by JPL (Reference 3). A drawing of the test fixture is shown in Figure 3.2-20. Cell orientations during test are shown in Figures 3.2-21 and 3.2-22 for bare and glassed cells, respectively. The cells were loaded at the rate of 0.1 in/min. A strain gauge was used to monitor the force applied to the test article. A discontinuity appeared in the force versus time recording at the point of cell fracture for the bare cell case and at the point of either cell or cover fracture for the glassed cell case. For the latter case the test article was examined to determine whether the cell or cover had fractures and the test was then resumed to fracture the other component.

Fracture strength data for bare and glassed cells are presented in Tables 3.2-6 and 3.2-7, respectively. No significant difference was observed in the fracture strength of the three cell types. The glassed cells did not have significantly higher fracture strengths than the bare cells. It appeared that in most cases the covers fractured first well below the fracture strength of the bare cells, and then the glassed cell assemblies with fractured covers fractured under about the same force as did the bare cells. This result contradicts the intuitive conclusion reached as a result of handling bare and glassed cells. Glassed cells "feel" less fragile than bare cells. Perhaps cylindrical bending results are not a good indicator of handling characteristics.

3.3 INTERCONNECT SELECTION

Acceptable interconnector/solar cell weld joint fatigue life must be achieved to enable successful solar array design. Weld joint fatigue is primarily the result of thermally induced stresses in the weld joint as the solar array undergoes thermal cycles. The stresses come from two sources:

1) The actual differential expansion or contraction of the weld materials themselves

2) The forces applied to the weld by the interconnector.

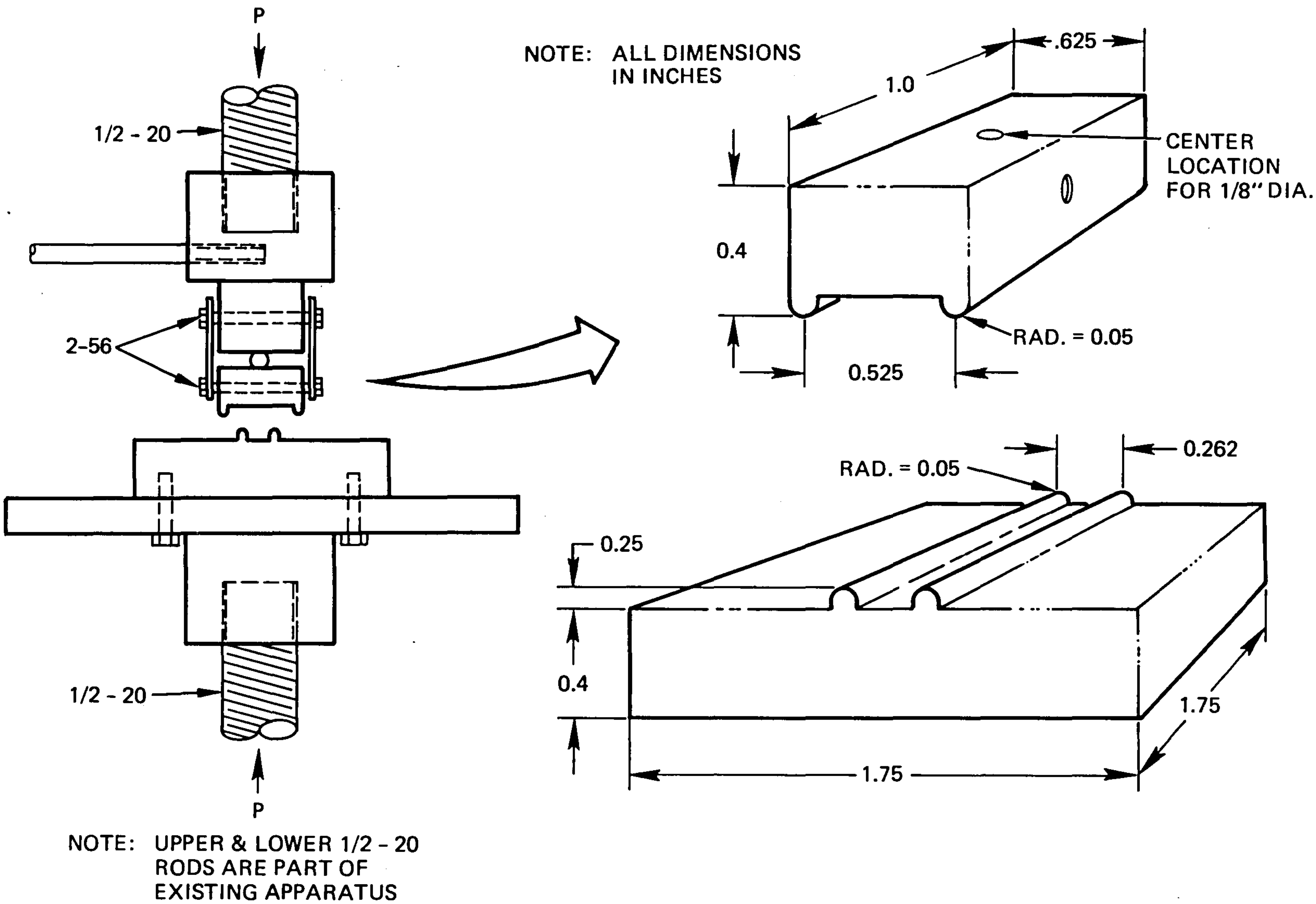


Figure 3.2-20. Solar Cell Fracture Test Fixture

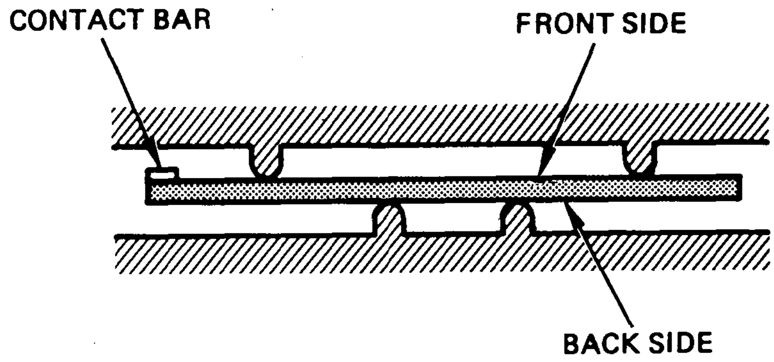


Figure 3.2-21. Bare Cell Orientation During
Cell Fracture Test

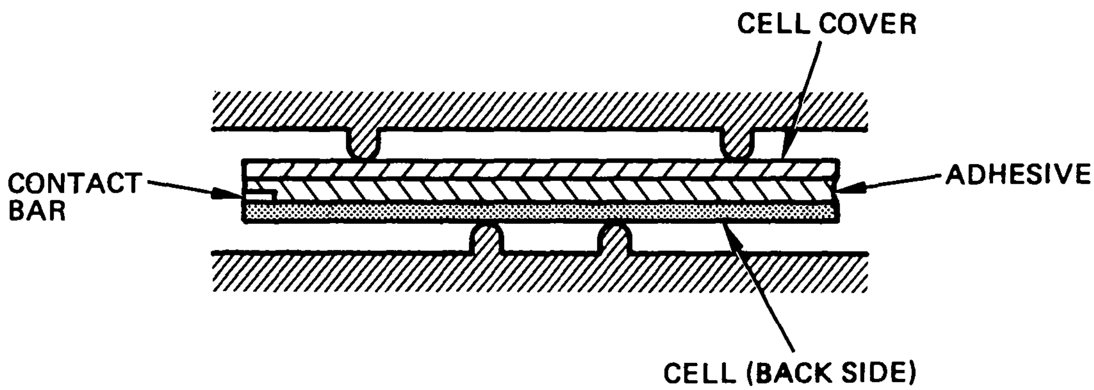


Figure 3.2-22. Glassed Cell Orientation During Fracture Test

Table 3.2-6. Fracture Strength of Bare 50-μm Thick Cells

CELL NUMBER	CELL THICKNESS (IN X 10^{-3})	FRACTURE* FORCE (LB)	RELATIVE DEFLECTION AT FAILURE (IN)
A-155	2.6	0.680	0.054
A-1	2.8	0.505	0.034
A-2	3.0	0.810	0.044
A-52	3.2	0.810	0.032
A-181	3.4	0.580	0.022
S-174	2.6	0.610	0.038
S-147	2.8	0.440	0.032
S-149	3.0	0.950	0.052
S-152	3.2	1.010	0.050
S-153	3.6	0.650	---
X-103	2.0	0.160	0.031
X-112	2.4	0.580	0.049
X-114	2.8	0.580	0.029
X-161	3.2	0.345	0.024
X-22	3.6	0.195	0.013

* (0.1 IN/MINUTE LOADING RATE)

A = ASEC
S = SPECTROLAB
X = SOLAREX

Table 3.2-7. Fracture Strength of Glassed 50-μm Thick Cells

CELL NUMBER	THICKNESS (IN X 10^{-3})				FRACTURE FORCE* (LB)		RELATIVE DEFLECTION AT FAILURE (IN)	
	CELL	COVER	STACK	ADH.	COVER	CELL	COVER	CELL
A-30	2.7	3.0	7.0	1.3	0.355	0.680	0.008	0.022
A-32	2.8	3.0	6.5	0.7	0.415	0.755	0.008	0.030
A-44	2.8	3.0	6.5	0.7	0.740	0.670	0.014	0.029
S-70	2.7	3.0	7.0	1.3	0.575	0.530	0.011	0.022
S-106	2.8	3.0	7.5	1.7	0.300	0.430	0.007	0.015
S-107	2.7	3.0	7.5	1.8	0.675	0.410	0.012	0.015
X-60	2.8	3.0	7.7	1.9	0.880	0.880	0.015	0.015
X-67	2.8	3.0	7.3	1.5	1.180	1.180	0.020	0.020
X-86	2.8	3.0	7.3	1.5	0.460	0.470	0.014	0.036

A = ASEC
S = SPECTROLAB
X = SOLAREX

* (0.1 IN/MINUTE LOADING RATE)

The interconnector-applied force is the product of interconnector stiffness and the intercell thermal displacement. The interconnector design problem is to select materials and configurations which:

a) Minimize weld joint differential expansion or contraction-induced stress

b) Minimize interconnector stiffness.

The interconnector selection process was greatly aided by work accomplished under a previous weld development program (JPL Contract 955139, Reference 2). On that program, a development task was performed which verified by analysis and test the suitability of a silver plated, 25-μm thick, rounded box loop, in-plane stress relief interconnector design for thin-cell coupons. The basic methodology used for evaluating the interconnector designs is summarized in Figure 3.3-1. Based on a review of this previous work, the rounded box loop interconnector shown in Figure 3.3-1 was selected as the baseline interconnect design.

3.4 PROCESS DEVELOPMENT

This section discusses process development which was performed prior to fabrication of the three 48-cell deliverable modules. Weld schedules were developed independently for each of the three cell types. Compatibility of frosted covers with 50-μm thick solar cells was evaluated. Test hardware was fabricated and thermal shock tested to verify the integrity of the baseline hardware design.

3.4.1 Weld Schedule Development

Front and rear contact weld schedules for parallel gap resistance welding were developed. The weld equipment used throughout this study is shown in Figure 3.4-1, consisted of a model MCW-550 constant voltage power supply and a model VTA-66 variable tip weld head, both manufactured by Hughes Aircraft Company. Constant voltage was maintained at the weld electrodes by varying the current during the weld cycle to compensate for variations in resistance occurring in or across the weld. The weld electrodes were made of molybdenum.

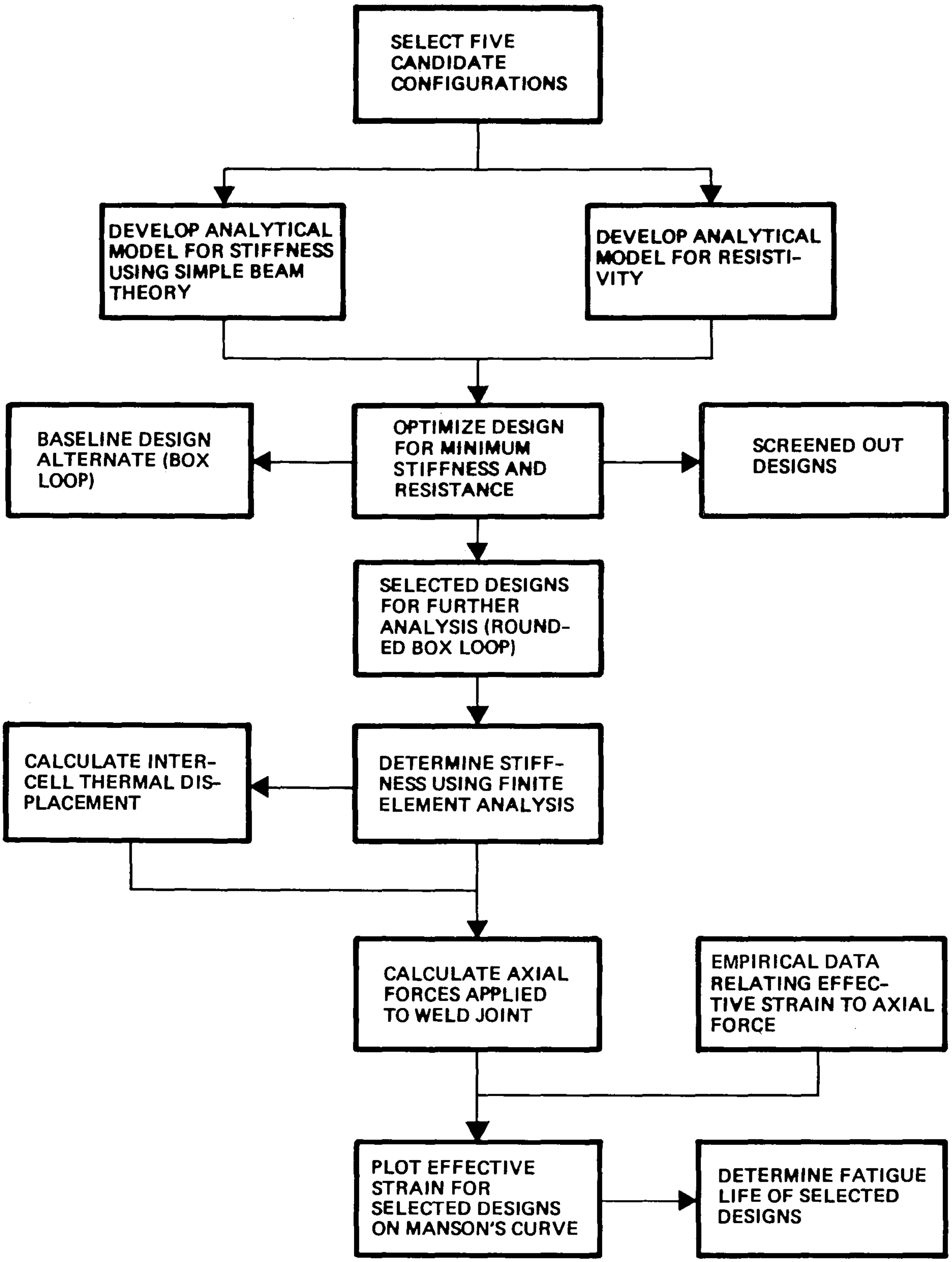


Figure 3.3-1. Interconnector Evaluation Methodology

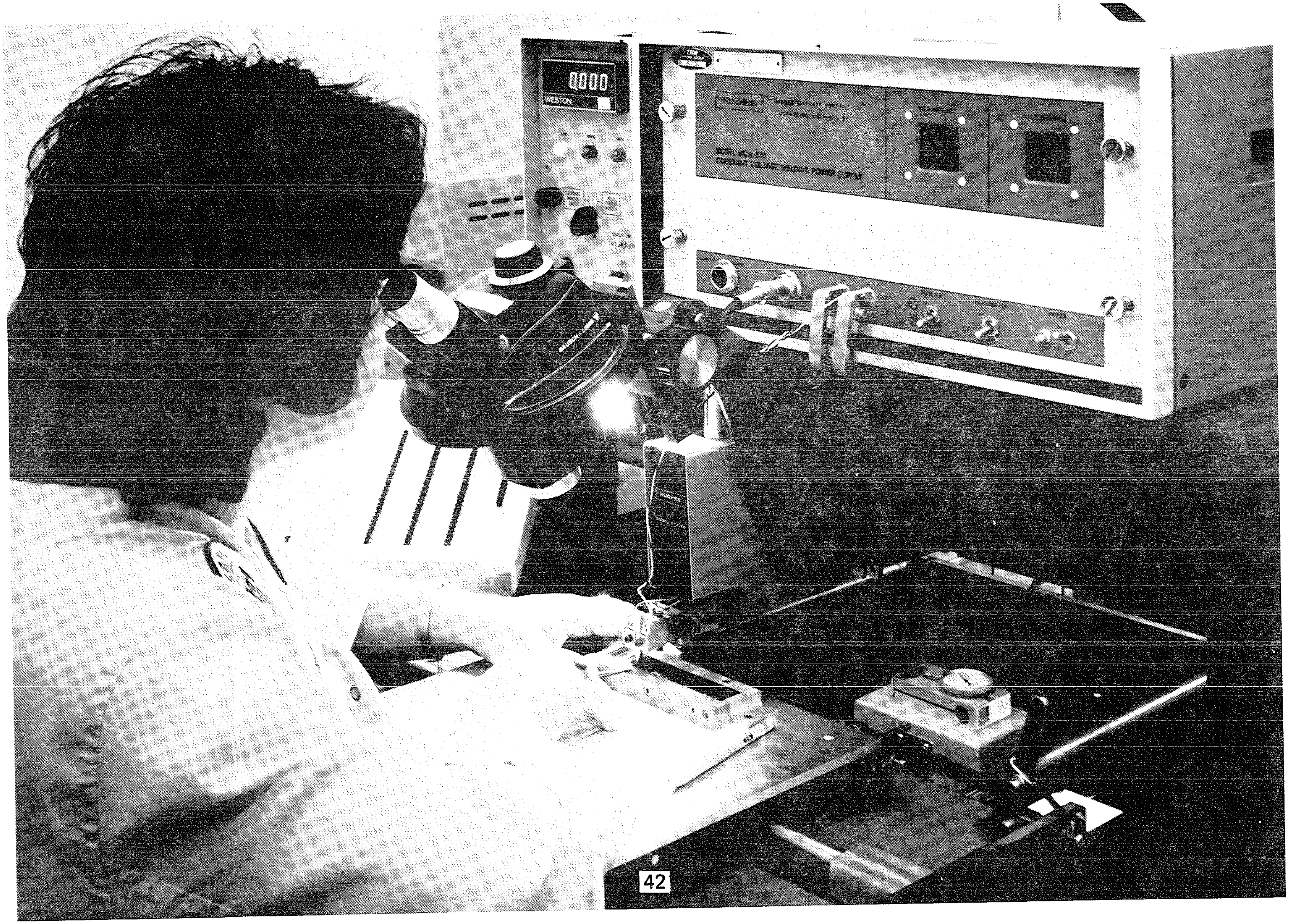


Figure 3.4-1. Weld Station Used for Welding Interconnects to 50-μm Thick Solar Cells

In developing weld schedules, 0-degree pull strength data was used as a measure of joint integrity. The equipment for performing zero pull strength testing consisted of a Unitek Micropull Tester and is shown in Figure 3.4-2.

3.4.1.1 Cell Front Contact

The weld schedule development process for front contacts is summarized in Figure 3.4-3. Electrical characteristics of unglassed solar cells were measured. Interconnects were welded to the front contacts and post welding electrical characteristics were measured. Contact pull strength was measured to determine weld joint integrity.

Weld electrode dimensions for front contact welding were 0.015 by 0.025 in (0.38 by 0.64 mm). Two weld electrode pressures were evaluated: 2933 lb/in^2 (1 kg force on two 0.38 by 0.64 mm electrodes) and 4400 lb/in^2 (1.5 kg force on two 0.38 by 0.64 mm electrodes). Weld duration was held constant at 100 ms. Corresponding pull strength and electrical degradation data were obtained with weld voltage as a variable. The voltage range 0.61 to 0.76 V was covered in 10- to 20-mV increments with two samples at each weld voltage. Figure 3.4-4 presents solar cell electrical degradation at a function of weld and shows the onset of electrical degradation to occur around 0.7 V for each of the three cell types. Weld schedule voltages were then defined by selecting a voltage 100-mV below the onset of electrical degradation.

Front contact weld schedule data are summarized in Table 3.4-1 and is shown to be identical for each of the three cell types. No statistically significant difference was observed in the weld strengths obtained for weld pressures of 2.2 and 3.3 pounds. Consequently, the lower of the two pressures was selected since reducing pressure reduces the probability of cracking cells during the welding operation.

3.4.1.2 Cell Back Contact

The weld schedule development process for back contacts is summarized in Figure 3.4-5. Interconnects were welded to the back contacts of glassed solar cells. The cell was then inspected for cover adhesive delamination and interconnect melting between electrode contact areas. Pull tests were then performed to determine joint integrity.

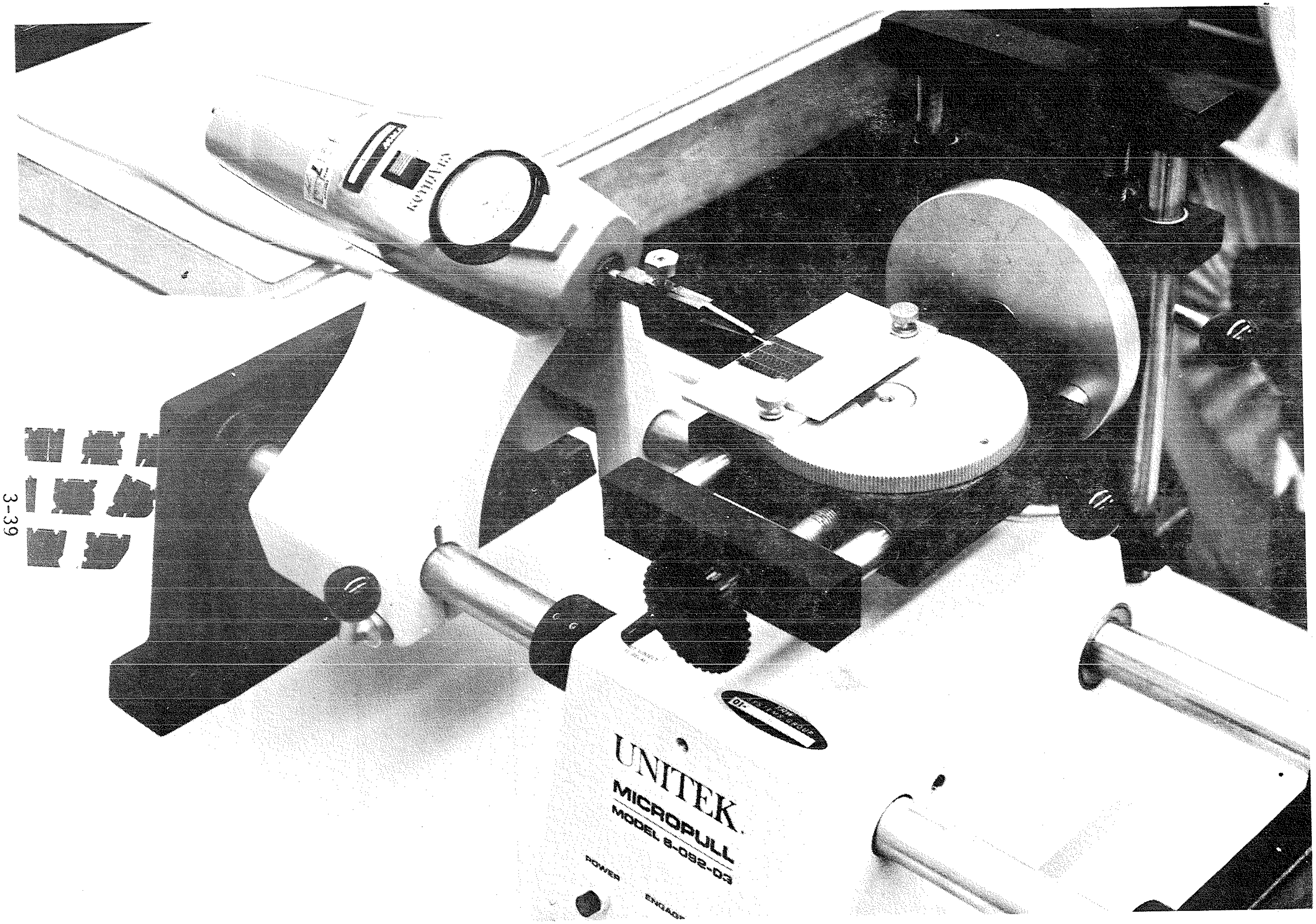
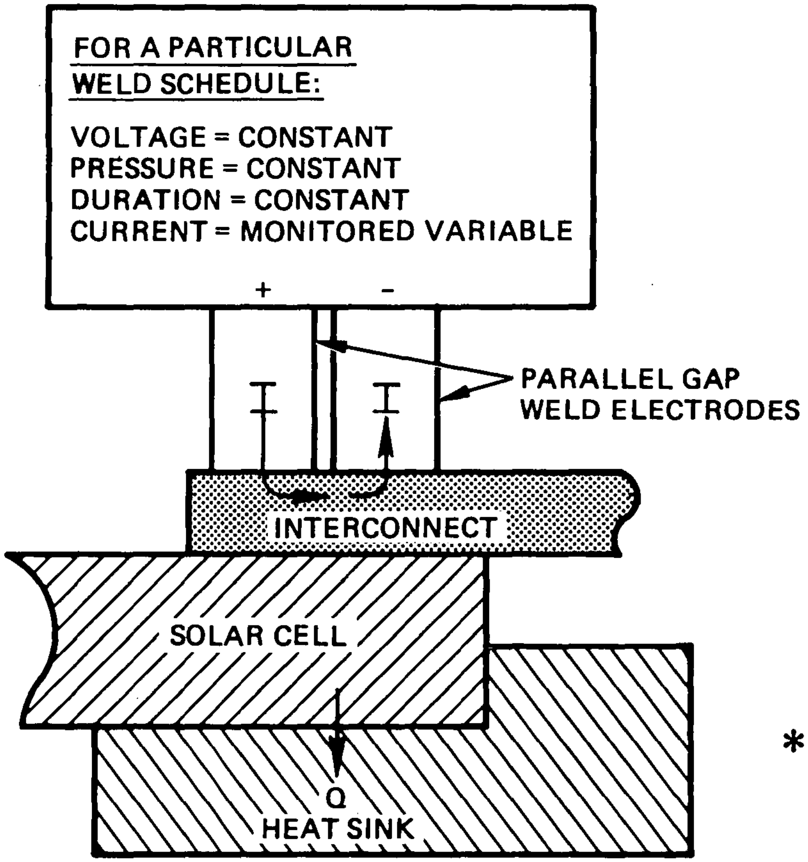


Figure 3.4-2. Test Equipment For Zero-Degree Pull Tests Performed On Solar Cell Weld Joints



- WELD EQUIPMENT REQUIREMENTS
  - DELIVER WELD SCHEDULE
  - SUPPORT AND INDEX CELL AND INTERCONNECTOR
  - MAINTAIN ELECTRODE CLEANLINESS
- WELD SCHEDULE SELECTION GUIDELINES
  - ACHIEVE ACCEPTABLE PULL STRENGTH * (APPROXIMATELY 1 LB)
  - MINIMIZE ELECTRODE PRESSURE
  - AVOID ELECTRICAL DEGRADATION

* PRECISE PULL STRENGTH VALUES ARE DIFFICULT TO OBTAIN AS CELLS FREQUENTLY CRACK BEFORE WELD JOINTS FAIL DURING PULL TESTING

Figure 3.4-3. Front Contact Parallel Gap Weld Schedule Development Summary

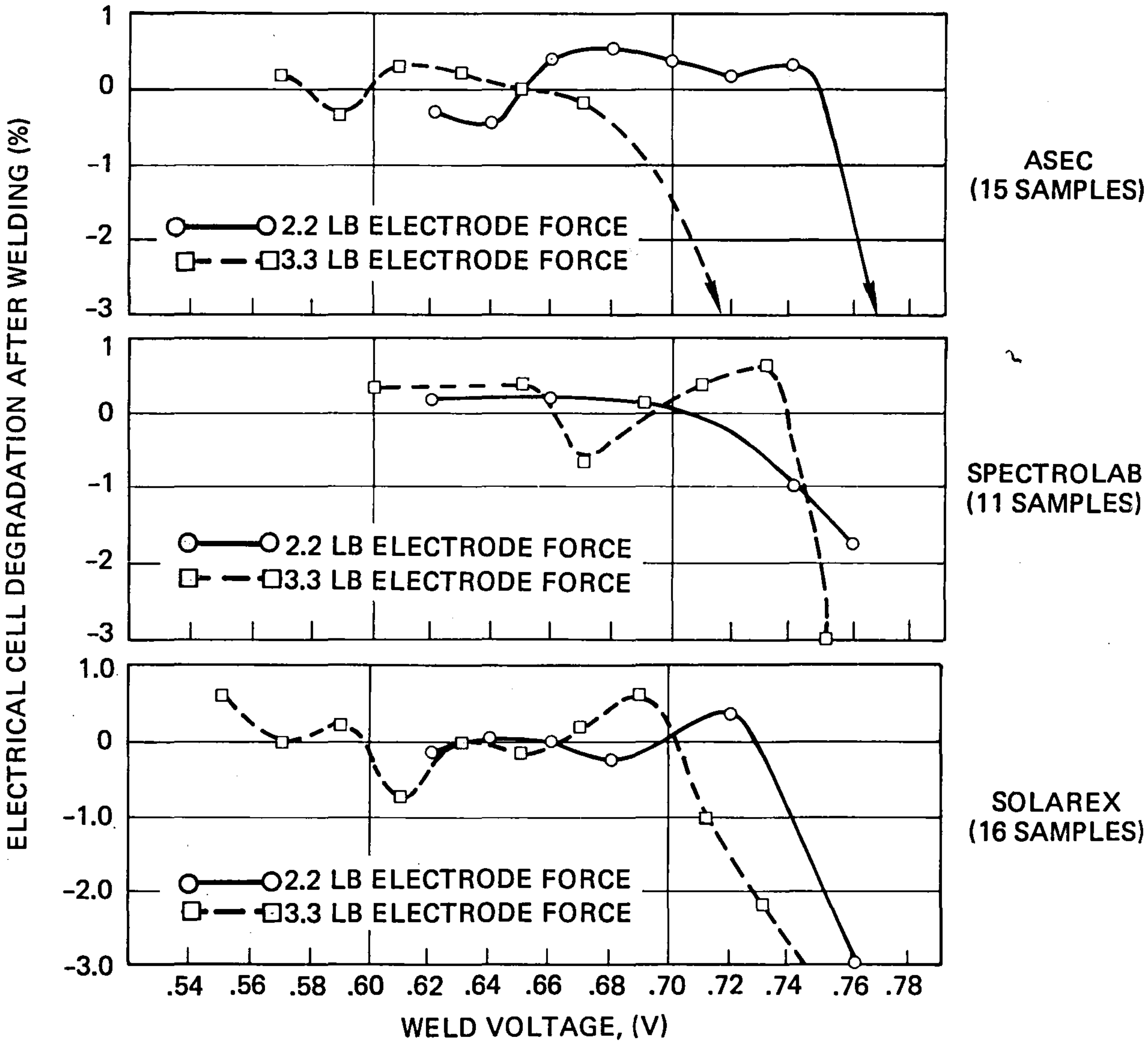
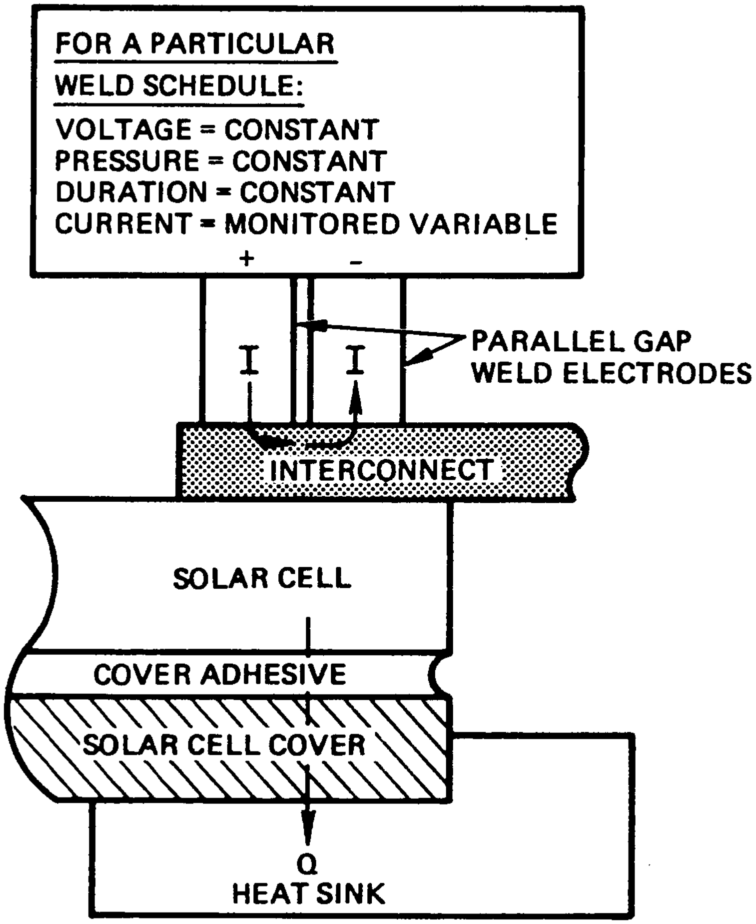


Figure 3.4-4. Front Contact Electrical Degradation Data

Table 3.4-1. Front Contact Weld Schedule Data Summary

WELD SCHEDULE PARAMETER/DATA	ASEC	SPECTROLAB	SOLAREX
ELECTRODE DIMENSION	0.015 x 0.025 IN (0.38 x 0.64 mm)	0.015 x 0.025 IN (0.38 x 0.64 mm)	0.015 x 0.025 IN (0.38 x 0.64 mm)
ELECTRODE FORCE	2.2 LB PER PAIR	2.2 LB PER PAIR	2.2 LB PER PAIR
ELECTRODE PRESSURE	2933 $LB/IN.^2$	2933 $LB/IN.^2$	2933 $LB/IN.^2$
WELD DURATION	100 ms	100 ms	100 ms
WELD VOLTAGE	0.6V	0.6 V	0.6V



- WELD EQUIPMENT REQUIREMENTS
  - DELIVER WELD SCHEDULE
  - SUPPORT AND INDEX CELL AND INTERCONNECTOR
  - MAINTAIN ELECTRODE CLEANLINESS
- WELD SCHEDULE SELECTION GUIDELINES
  - ACHIEVE ACCEPTABLE PULL STRENGTH* (APPROXIMATELY 2 LB)
  - MINIMIZE ELECTRODE PRESSURE
  - AVOID EXCESSIVE INTERCONNECT MELTING BETWEEN WELD ELECTRODES
  - AVOID COVER ADHESIVE DELAMINATION ABOVE WELD AREA

* PRECISE PULL STRENGTH VALUES ARE DIFFICULT TO OBTAIN AS CELLS FREQUENTLY CRACK BEFORE WELD JOINTS FAIL DURING PULL TESTING

Figure 3.4-5. Back Contact Parallel Gap Weld Schedule Development Summary

Two electrode sizes for rear contact welding were evaluated: 0.025 by 0.045 in (0.64 by 1.14 mm) and 0.035 by 0.055 in (0.86 by 1.38 mm). Two weld electrode pressures for each of the two electrode sizes were evaluated: 978 and 1467 lb/in^2 (1.0 and 1.5 kg) for the 0.025 by 0.045 in (0.64 by 1.14 mm) electrodes and 571 and 857 lb/in^2 (1.0 and 1.5 kg) for the 0.035 by 0.055 in (0.86 by 1.38 mm) electrodes. Weld duration was held constant at 100 ms. Weld voltage was a variable with corresponding pull strength data (two samples) taken at each weld voltage over the range 0.55 to 0.62 V in 10- to 20-mV increments. All samples were glassed in order to properly simulate a production configuration and to determine the influence of back contact welding on coverglass adhesive. For all three cell types, cover adhesive delamination was observed at the high end of the weld voltage range and, consequently, back contact weld voltage was limited to values below which the delamination was observed. Pull strength data was in most cases limited by the fracture strength of the thin silicon since most of the weld joints failed due to cell breakage (with the welds still intact) during pull strength testing.

The resulting selected values for rear contact weld schedule parameters are presented in Table 3.4-2.

3.4.2 Bonding Thin Covers to Cells

JPL provided 450 frosted fused silica covers from Optical Coating Laboratories, Inc. (OCLI) in Santa Rosa, California. Thickness measurements on 200 randomly selected covers indicated a cover thickness range from 25 to 150 μm.

The frosted covers were bonded to the 50-μm thick cells using DC 93-500 adhesive. A 12 g mass was placed on the glassed cell assembly to eliminate cell bowing and to minimize adhesive bondline thickness (approximately 50 μm). The following observations were made with respect to the use of frosted covers:

- Manual cover cleaning is approximately three times as time consuming for frosted covers than for smooth covers.
- There is essentially no difference in handling or application between thin and thick frosted covers with the exception of adhesive bleed-through on some of the thinner covers. The bleed-through occurred because of microscopic pinholes in some of the thinner covers.

Table 3.4-2. Back Contact Weld Schedule Data Summary

WELD SCHEDULE PARAMETER/DATA	ASEC	SPECTROLAB	SOLAREX
ELECTRODE DIMENSION	0.025 x 0.045 IN (0.64 x 1.14 mm)	0.025 x 0.045 IN (0.64 x 1.14 mm)	0.025 x 0.045 IN (0.64 x 1.14 mm)
ELECTRODE FORCE	2.2 LB PER PAIR	2.2 LB PER PAIR	2.2 LB PER PAIR
ELECTRODE PRESSURE	978 LB/IN^2	978 LB/IN^2	978 LB/IN^2
WELD DURATION	100 ms	100 ms	100 ms
WELD VOLTAGE	0.55V	0.55V	0.55V

- Frosted covers make it difficult to detect cracks in glassed cells.

3.4.3 Cell-to-Substrate Bonding

DC 93-500 adhesive, together with 92-023 primer, was used for cell-to-substrate bonding. The primer was applied to the back surfaces of the cells and to the Kapton (50- m thick) substrate. Approximately 12 mg of DC 93-500 was applied to the rear side of each cell. After cell-substrate positioning, light pressure was applied through a thin foam sheet for about 30 minutes.

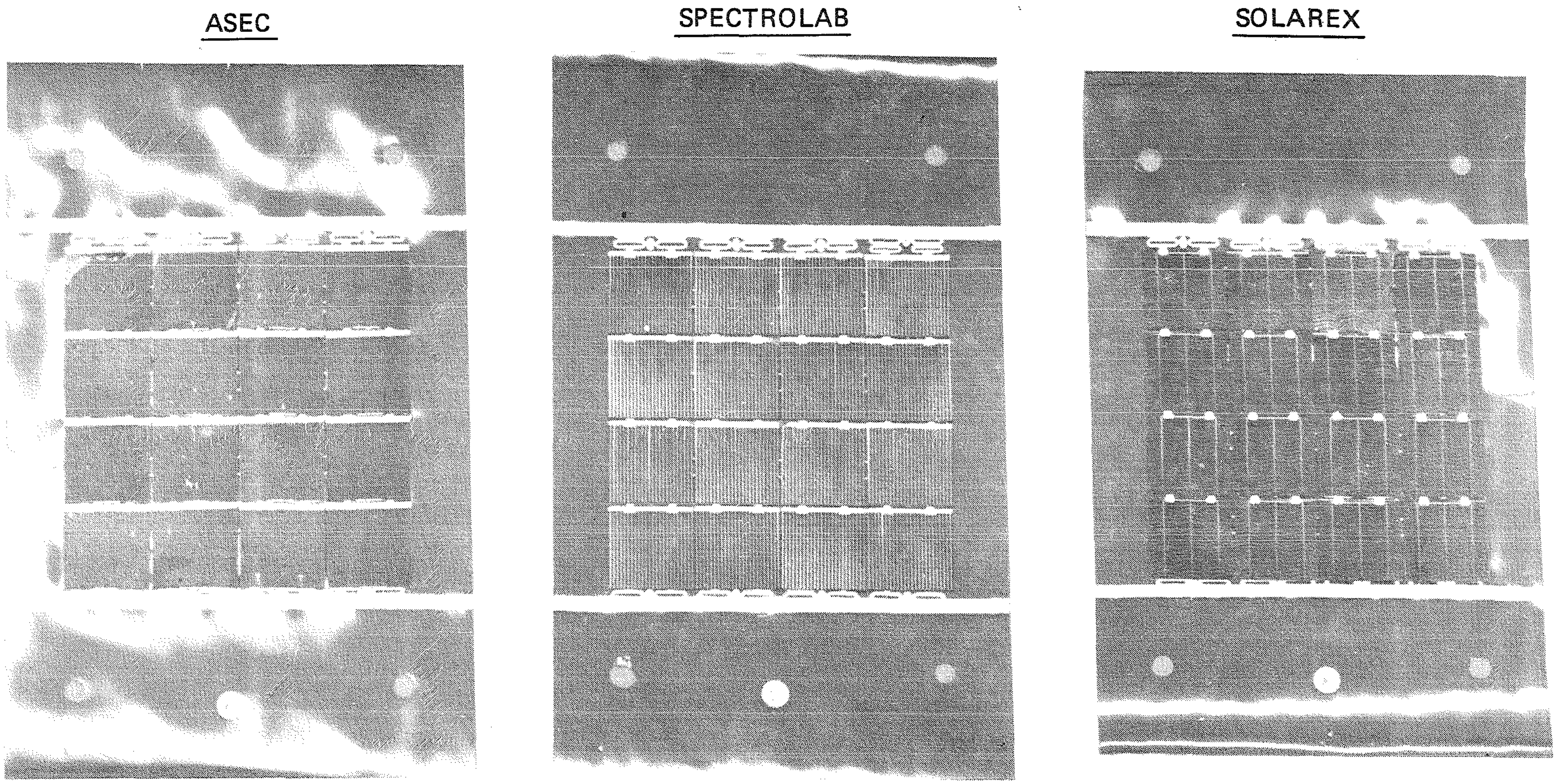
3.4.4 Test Coupon Fabrication and Test

Three 16-cell modules were assembled and thermal shock tested. The modules were designated "ASEC," "Spectrolab," and "Solarex" corresponding to the cell type contained in each module. All cells were covered with either 50-, 100-, or 150-μm thick frosted fused silica covers from OCLI. DC 93-500 adhesive was used for glassing as well to bond the cells to the module substrates (50-μm thick Kapton). Covers of each of the three thicknesses are contained in each module. Series and parallel interconnectors were etched from 25-μm thick Invar plated with 10- m Ag on each side. Welding, glassing, and cell-to-substrate bonding processes were performed as previously described in Sections 3.4.1, 3.4.2, and 3.4.3, respectively. The three test coupons are shown in Figure 3.4.6. Following assembly, each module was subjected to thermal shock testing. The test sequence and summary results are presented in Table 3.4-3. No weld joint failures and no electrical degradation was observed following 100 thermal shock cycles from -180° to 100°C. Cracked covers were observed. These results verify the compatibility of the coupon components and indicate that each of the three cell types are weldable using the weld schedules developed on this program as discussed in Section 3.4.1.

3.5 DELIVERABLE HARDWARE

3.5.1 Module Description

Three 48-cell modules were assembled. The modules are designated "ASEC," "Spectrolab," and "Solarex" corresponding to the cell type contained in each module. All cells were covered with either 50-, 100-, or 150-μm thick frosted glass covers from OCLI. DC 93-500 adhesive was used



CELLS	SOLAREX, SPECTROLAB, ASEC (75μm THICK)
COVERS	FROSTED GLASS FROM OCLI (50μm TO 150μm)
COVER ADHESIVE	DC 93-500 (50μm BONDLINE)
CELL ADHESIVE	DC 93-500 WITH DC 92-023 PRIMER (50μm BONDLINE)
INTERCONNECTORS	Ag PLATED INVAR (50μm THICK)
SUBSTRATE	KAPTON (50μm THICK)

Figure 3.4-6. Sixteen-Cell Coupons Fabricated for Thermal Shock Testing

Table 3.4-3. Coupon Evaluation Test Sequence and Results Summary

EVENT. NO.	TEST	CONDITIONS	RESULTS SUMMARY
1	ELECTRICAL PERFORMANCE	1 SUN, AMO, 28°C	ESTABLISHED BASELINE PERFORMANCE
2	PRE-THERMAL SHOCK INSPECTION	X 10 MAGNIFICATION	ASEC: 2 INITIAL COVER CRACKS SPECTROLAB: 8 INITIAL COVER CRACKS SOLAREX: 1 INITIAL COVER CRACK
3	INITIAL THERMAL SHOCK TEST	50 SHOCKS FROM -180°C TO +100°C (1 MINUTE DWELL AT EACH EXTREME)	
4	MID-POINT THERMAL SHOCK INSPECTION	X 10 MAGNIFICATION	ASEC: 3 ADDITIONAL COVER CRACKS, NO WELD JOINT FAILURES SPECTROLAB: 5 ADDITIONAL COVER CRACKS, NO WELD JOINT FAILURES SOLAREX: 3 ADDITIONAL COVER CRACKS, NO WELD JOINT FAILURES
5	FINAL THERMAL SHOCK TEST	50 SHOCKS FROM -180°C TO +100°C (1 MINUTE DWELL AT EACH EXTREME)	
6	POST THERMAL SHOCK ELECTRICAL PERFORMANCE	1 SUN, AMO, 28°C	ASEC: NO ELECTRICAL DEGRADATION SPECTROLAB: NO ELECTRICAL DEGRADATION SOLAREX: NO ELECTRICAL DEGRADATION
7	POST THERMAL SHOCK INSPECTION	X 10 MAGNIFICATION	ASEC: 2 ADDITIONAL COVER CRACKS, NO WELD JOINT FAILURES SPECTROLAB: 1 ADDITIONAL COVER CRACK, NO WELD JOINT FAILURES SOLAREX: 0 ADDITIONAL COVER CRACKS, NO WELD JOINT FAILURES

for glassing as well as to bond the cells to the module substrates (50-μm thick Kapton). Covers of each of the three thicknesses are contained in each module. Series and parallel interconnectors were etched from 25-μm thick Invar plated with 10-μm Ag on each side. A matrix showing cell serial number, cell thickness, and cover thickness by location in the 48-cell module in shown for the ASEC, Spectrolab, and Solarex modules in Figure 3.5-1. The three modules are shown in Figure 3.5-2.

3.5.2 Module Electrical Performance

The electrical configuration of each module is 16 series cells by four cells in parallel. Cells were matched for the modules by (1) finding the average current at 0.46 V for each cell type, (2) multiplying the average current by 4 (four parallel cells) to establish the cell matching design point, and (3) selecting four cells to be parallel interconnected whose individual currents at 0.46 V sum to the cell matching design point.

The electrical output of each module was measured using a TRW Xenon Large Area Pulsed Solar Simulator (LAPSS) and its accompanying data acquisition system. Current voltage curves for each module are shown in Figures 3.5-3, 3.5-4, and 3.5-5. The cell matching design point is shown on each figure and is in excellent agreement with actual performance for each of the three modules.

48-CELL MODULE
ASEC CELLS
4 PARALLEL X 16 SERIES
CELL MATCHING DESIGN POINT:
582 MA @ 0.46V

A69 3.3 5.3	A64 2.7 5.0	A81 3.0 5.5	A170 2.9 4.3
A79 2.6 5.2	A168 2.8 4.5	A166 3.2 5.4	A163 3.4 5.3
A160 3.1 4.9	A156 2.5 5.6	A157 2.9 5.5	A158 3.3 4.3
A08 3.1 2.5	A153 3.1 4.8	A154 3.0 5.0	A199 2.4 5.7
A161 3.3 5.0	A151 2.8 4.6	A143 3.1 5.3	A197 3.0 4.7
A193 3.2 4.4	A192 3.1 6.0	A191 2.8 4.6	A190 3.0 5.1
A198 3.8 5.4	A194 3.0 5.4	A180 3.0 3.6	A179 2.7 3.7
A186 3.0 4.7	A109 2.9 5.2	A72 3.0 1.7	A175 3.0 4.2
A187 3.4 4.4	A182 3.3 5.6	A177 3.1 4.5	A174 2.4 4.4
A176 2.6 4.8	A200 3.3 4.9	A173 3.0 4.2	A95 3.1 2.8
A91 3.1 3.3	A83 3.3 3.2	A88 3.4 1.3	A89 3.1 1.7
A100 3.3 3.2	A96 3.7 3.2	A103 2.9 3.4	A66 3.0 3.7

CELL SERIAL NO.
CELL THICKNESS (IN. x 10^{-3})
COVER THICKNESS (IN x 10^{-3})

48-CELL MODULE
SOLAREX CELLS
4 PARALLEL X 16 SERIES
CELL MATCHING DESIGN POINT:
573 MA @ 0.46V

X180 2.5 4.6	X28 3.8 5.6	X131 2.5 4.5	X132 2.8 5.5
X29 3.3 5.0	X138 3.0 5.1	X136 2.0 5.2	X142 2.0 4.6
X133 2.9 5.0	X110 2.8 6.0	X113 2.8 5.0	X199 2.7 5.5
X109 3.0 4.7	X149 2.9 5.2	X106 2.4 4.9	X163 3.0 4.0
X134 3.2 4.5	X140 2.9 5.1	X145 3.0 5.3	X157 2.1 4.5
X139 2.4 5.5	X118 3.4 4.5	X120 2.9 5.4	X193 3.1 3.0
X194 3.1 3.6	X191 3.6 3.2	X159 3.1 1.8	X189 2.5 2.7
X183 2.3 3.0	X116 2.7 2.9	X115 2.8 3.1	X117 3.2 3.5
X188 2.7 3.5	X187 2.8 1.5	X184 3.3 3.0	X121 2.6 3.3
X181 3.4 3.2	X126 2.5 2.7	X14 3.8 1.1	X197 3.5 3.0
X128 2.9 1.3	X123 2.5 2.5	X20 2.7 1.1	X39 3.7 2.3
X42 3.2 1.0	X175 3.0 2.9	X171 2.5 3.0	X170 2.9 3.3

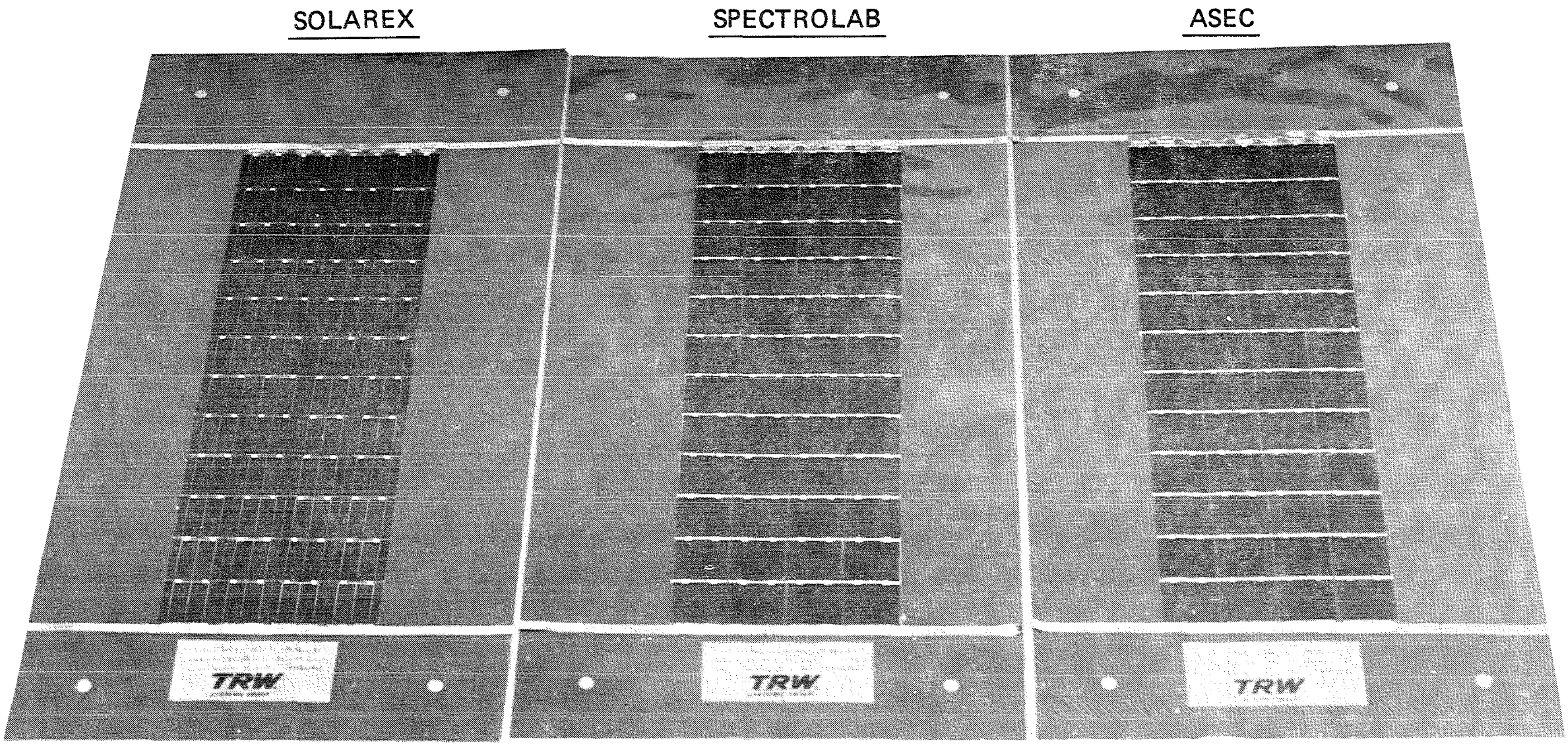
CELL SERIAL NO.
CELL THICKNESS (IN x 10^{-3})
COVER THICKNESS (IN x 10^{-3})

48-CELL MODULE
SPECTROLAB CELLS
4 PARALLEL X 16 SERIES
CELL MATCHING DESIGN POINT:
600 MA @ 0.46V

S175 3.8 3.0	S187 2.9 4.5	S171 3.2 3.2	S178 3.6 2.6
S170 3.2 2.5	S179 3.9 2.4	S145 3.0 2.5	S180 3.6 2.1
S181 3.7 2.6	S182 3.4 3.1	S185 3.6 3.7	S169 3.3 2.0
S129 3.6 3.4	S128 3.6 3.4	S146 2.9 6.0	S148 2.9 6.0
S133 3.3 2.6	S140 3.4 3.0	S120 2.9 5.4	S122 3.3 5.1
S134 3.4 2.9	S135 3.4 2.2	S137 2.9 2.6	S10 3.4 4.4
S141 3.4 4.4	S151 2.8 4.8	S154 3.0 5.9	S125 3.0 4.8
S158 4.3 5.3	S121 3.5 5.4	S114 2.9 5.3	S117 3.0 4.6
S144 3.3 2.8	S157 3.7 4.9	S66 3.0 4.4	S119 4.3 5.5
S127 3.4 3.1	S160 3.1 5.6	S7 3.7 4.6	S167 3.2 4.5
S124 3.6 5.3	S115 2.9 5.4	S166 2.9 5.3	S163 2.9 5.3
S165 2.9 5.4	S164 3.0 4.9	S67 3.2 4.6	S162 3.1 5.0

CELL SERIAL NO.
CELL THICKNESS (IN x 10^{-3})
COVER THICKNESS (IN x 10^{-3})

Figure 3.5-1. Forty-Eight Cell Module Layouts



CELLS	SOLAREX, SPECTROLAB, ASEC (75μm THICK)
COVERS	FROSTED GLASS FROM OCLI (50μm TO 150μm)
COVER ADHESIVE	DC 93-500 (50μm BONDLINE)
CELL ADHESIVE	DC 93-500 WITH DC 92-023 PRIMER (50μm BONDLINE)
INTERCONNECTORS	Ag PLATED INVAR (50μm THICK)
SUBSTRATE	KAPTON (50μm THICK)

Figure 3.5-2. Forty-Eight Cell Modules Fabricated for Thermal Cycle Testing

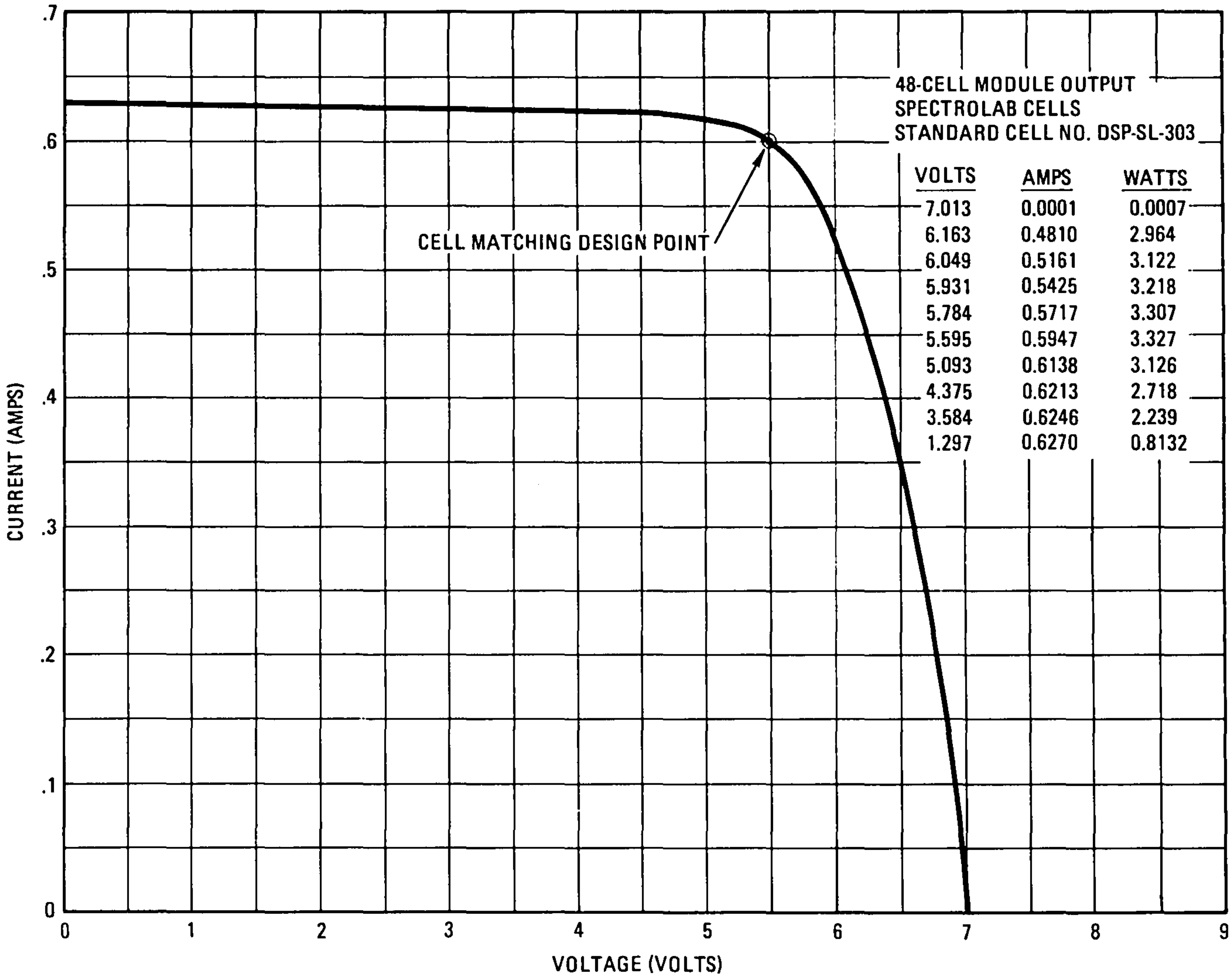


Figure 3.5-3. Spectrolab 48-Cell Module Electrical Characteristics at 28°C

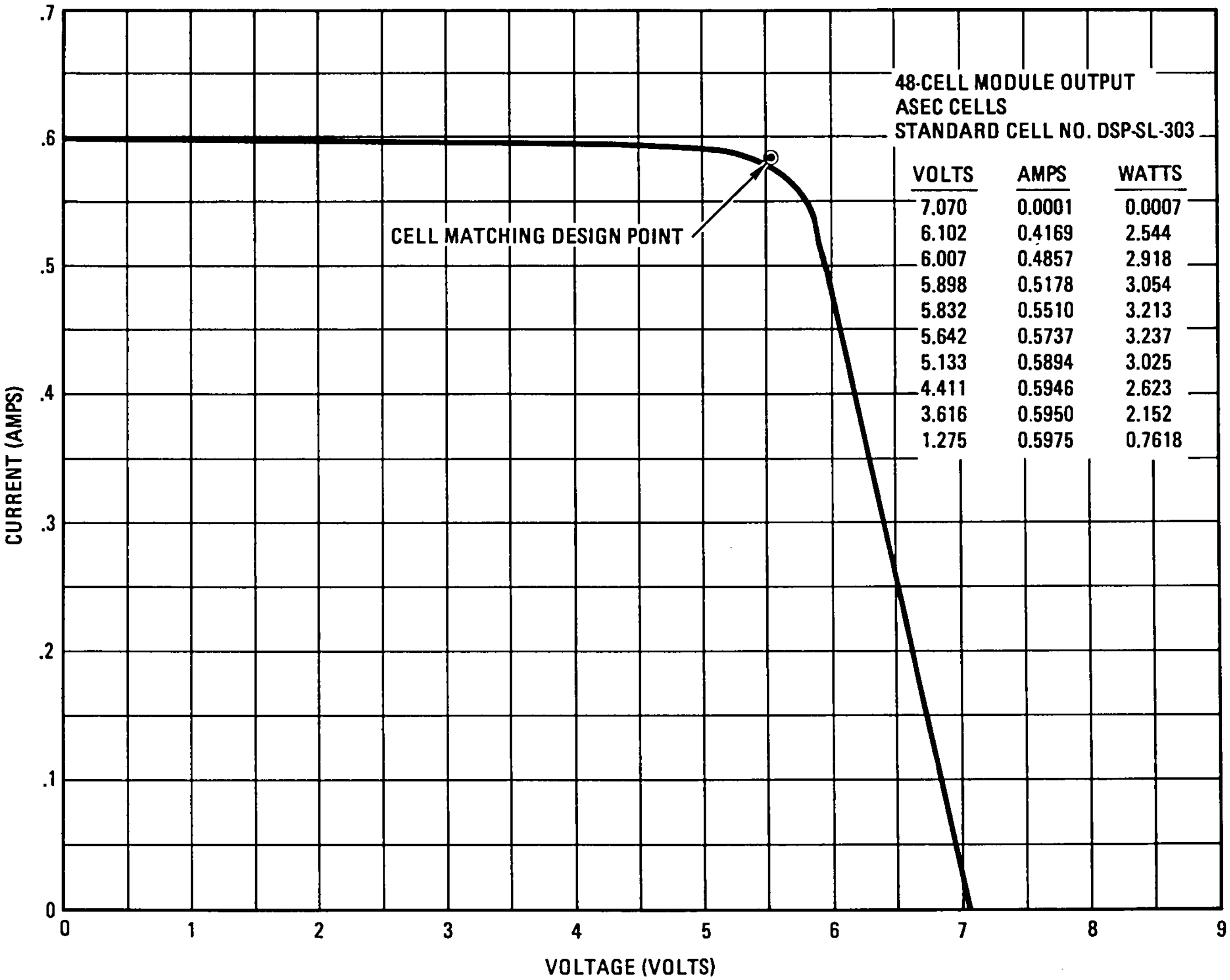
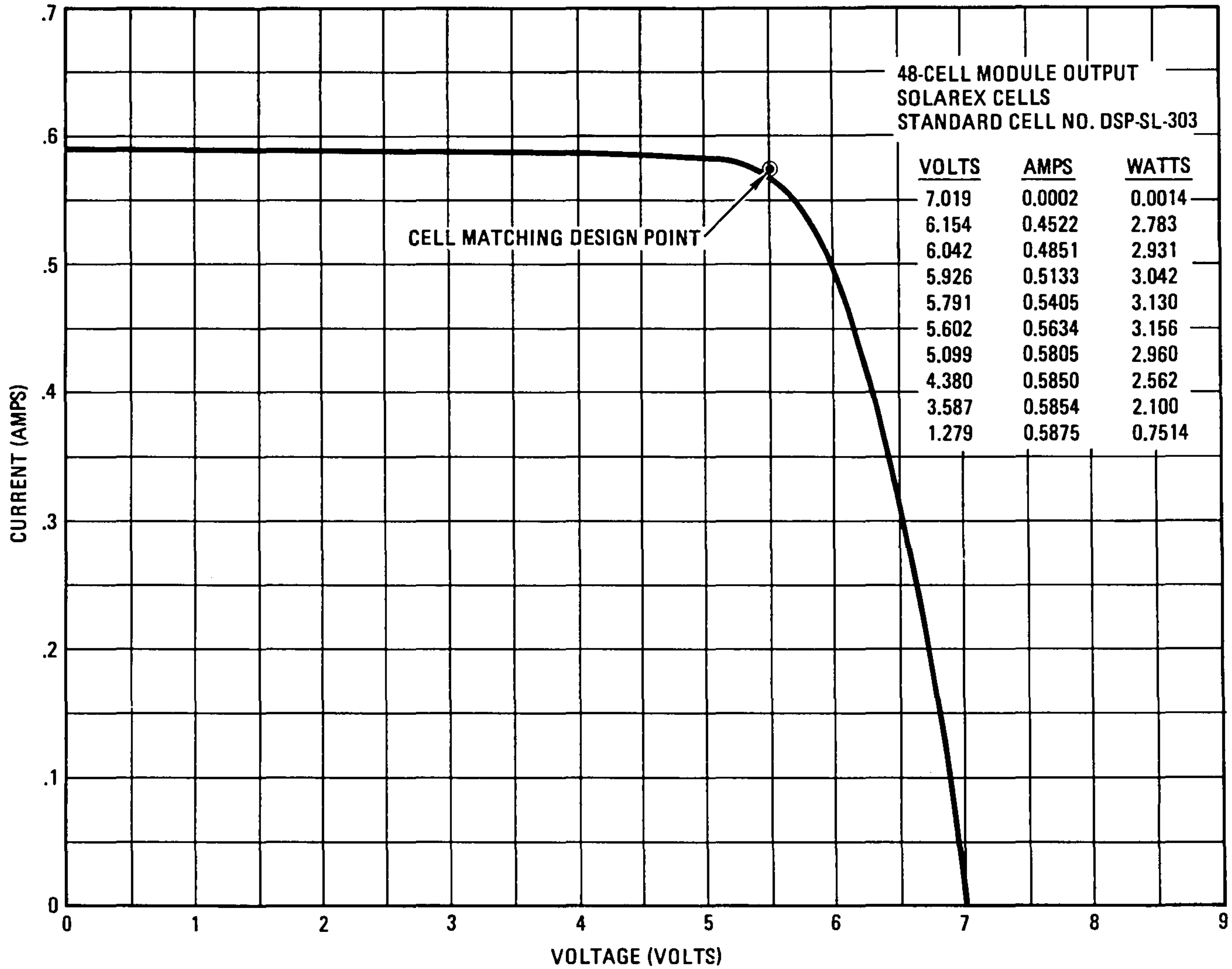


Figure 3.5-4. ASEC 48-Cell Module Electrical Characteristics at 28°C



VOLTS	AMPS	WATTS
7.019	0.0002	0.0014
6.154	0.4522	2.783
6.042	0.4851	2.931
5.926	0.5133	3.042
5.791	0.5405	3.130
5.602	0.5634	3.156
5.099	0.5805	2.960
4.380	0.5850	2.562
3.587	0.5854	2.100
1.279	0.5875	0.7514

Figure 3.5-5. Solarex 48-Cell Module Electrical Characteristics at 28°C

4. CONCLUSIONS

The following conclusions are based on the results obtained on this program which include thermal shock testing (100 cycles) but do not include thermal cycle testing:

- Cell characterization testing indicates that the 50-μm cells from ASEC, Solarex, and Spectrolab are comparable with the following exceptions:
  - Front contact edge thickness variation and mean value are greater for Solarex cells than for ASEC or Spectrolab cells.
  - Solarex cells are less bowed than are ASEC or Spectrolab cells.
  - Back contacts of Spectrolab and Solarex cells with aluminum paste back surface fields are considerably more textured than ASEC back contacts with boron diffused back surface fields.
- Weld schedule development indicates that the ASEC, Spectrolab, and Solarex cells are comparable in weldability. Identical weld schedules were independently developed for each of the three cell types.
- Frosted glass covers as thin as 50-μm can be handled and assembled into blanket modules with minimal breakage.
- Small area welded modules using present generation 50-μm thick solar cells from ASEC, Spectrolab, and Solarex can be assembled and handled.

5. RECOMMENDATIONS

Results presented in this report indicate that work should continue for developing technologies for welding interconnects to 50-μm thick solar cells. It is recommended that:

- The elimination of cell bowing be investigated to provide flat cells more compatible with standard tooling and automated processing.
- Process control over contact thickness be developed to assure contact thickness and uniformity specifications be met with only minimal verification testing required.
- The front contacts on the ASEC and Spectrolab cells be recessed from the edge of the cell. In their present configurations, the front and back contacts are separated by the 50-μm silicon substrate thickness and are vulnerable to edge shorting during welding.
- A reliable nondestructive method be developed for determining weld joint integrity.
- The 48-cell modules be thermal cycled for sufficient duration to create weld joint failures and that the resultant cycle life data be correlated with solar cell characterization data.
- Additional modules be fabricated and thermal cycle tested using substrate materials, configurations, and support structures representative of flight hardware.

6. NEW TECHNOLOGY

No items of new technology have been identified by TRW Space and Technology Group under this contract.

7. REFERENCES

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3. C. P. Chen, "Fracture Strength of Silicon Solar Cells," JPL Publication 79-102, October 15, 1979.

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