JPL NO. 9950 – 1070

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(NASA-CR-175683) NASA WELDING ASSESSMENT PROGRAM Final Test Report (TRW Space Technology Labs.) 31 p HC A03/MF A01 CSCL 13H

N85-25845

Unclas
G3/37 21044

Power and Electronics Hardware Laboratory
Power Sources Engineering Department

NASA Welding Assessment Program

Final Test Report
January 1985

JPL Contract 956042,
"Development of Technologies for Welding Interconnects to Fifty-Micron Thick Silicon Solar Cells."

Document No. 38512-6003-UT-00

Prepared by
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Prepared for
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Pasadena, CA 91103

This work was performed for
Jet Propulsion Laboratory,
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CONTENTS

ILLUSTRATIONS

TABLES

ACKNOWLEDGMENT

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. Ira Allard fabricated the interlayer substrate. Saul Bashin designed the module support fixtures for the thermal cycle test. Belinda Zamora and Suzette Swanson assembled the coupons and modules. Rod Dobson performed the cell and module electrical measurements and performed the module thermal cycle test. John Scott-Monck of JPL and Cosmo Baraona, John Bozek, and Russell Hart, Jr. of NASA Lewis Research Center provided valuable technical review and helpful comments throughout the course of this program.

ABSTRACT

A program was conducted to demonstrate the cycle life capability of welded solar cell modules relative to a soldered solar cell module in a simulated low earth orbit thermal environment. A total of five 18-cell welded (parallel gap resistance welding) modules, three 18-cell soldered modules, and eighteen single cell samples were fabricated using 2 x 4 cm silicon solar cells from ASEC, fused silica cover glass from OCLI, silver plated Invar interconnectors, DC 93-500 adhesive, and Kapton-Kevlar-Kapton flexible substrate material. Zero degree pull strength ranged from 2.4 to 5.7 lbs for front welded contacts (40 samples), and 3.5 to 6.2 lbs for back welded contacts (40 samples). Solar cell cross sections show solid state welding on both front and rear contacts. The 18-cell welded modules have a specific power of 124 W/kg and an areal power density of 142 W/m^2 (both at 28°C). Three welded and one soldered module were thermal cycle tested in a thermal vacuum chamber simulating a low earth orbit thermal environment. Temperature was cycled between 80°C and -80°C in twelve minute intervals. The chamber was opened following 2910, 6550, 9184, 12,180, 18,000, 24,011, and 30,051 cycles. Pre and post visual inspections indicated no significant observable physical degradation on any of the four modules following exposure to 30,051 cycles. Pre and post electrical measurements indicated no significant electrical degradation (less than 2%) following exposure to 30,051 cycles.

1. INTRODUCTION

Soldering has been the exclusive interconnect-to-solar cell joining process for all known earth orbiting solar arrays built in the United States. On the other hand, the Europeans have exclusively used welding as the preferred joining process. An excellent historical review of interconnect-to-solar cell joining is presented in Reference 1. Prior to this project, there did not exist a broad data base for soldered or welded solar cell capability in a low earth orbit thermal environment. It has been speculated that the cycle life capability of soldered solar cells may be limited crystallization process that takes place in solder after exposure to extended thermal cycling, and, consequently, welded solar cells may ultimately provide longer cycle life capability than soldered solar cells. However, the relative capability of welding versus soldering has never been experimentally established as discussed in Reference 2.

With the emergence of Space Station which may require solar arrays to perform from five to ten years in low earth orbit, NASA initiated a solar cell welding program in 1982. Even though the United States built solar arrays are soldered, a number of U.S. companies have welding capability. In recognition of this, NASA awarded three concurrent contracts in 1982 to assess the state-of-the-art of welded solar arrays in the United States and to demonstrate the capability of welding relative to soldering. One of the contracts was awarded to TRW and is described in this report.

The results of this project are extremely significant. For the first time welding and soldering capabilities have been compared experimentally. The results clearly demonstrate both welded and soldered arrays are capable of satisfactorily performing for over five years in low earth orbit. It is recommended that the test be extended to further increase our knowledge of the relative cycle life capability of welded and soldered solar arrays in low earth orbit.

2. TECHNICAL DISCUSSION

2.1 REQUIREMENTS

The total project is summarized in Figure 2.1-1. The major tasks (and requirements) were:

a) The fabrication of five welded and three soldered modules each consisting of eighteen 200 μm thick silicon solar cells in a three (3) parallel by six (6) series configuration.

   i) All module materials shall be capable of withstanding the space environment and shall be readily available on a production, pilot production or advanced development basis.

   ii) The module substrate material shall be a flexible material such as Kapton, fiberglass cloth, etc.

   iii) All modules shall provide at least 140 W/m^2 when measured at 28°C under AMO illumination.

   iv) Welded modules shall be capable of at least 90 W/kg.

   v) State-of-the-art fabrication processes including welding and soldering shall be employed to produce the modules.

b) The performance of pull tests on welded interconnect samples (both p and n contact areas) and the microsectioning of welded interconnects (both p and n contact areas) to determine the chemical reaction that has taken place between the interconnect and the solar cell contact.

c) The performance of thermal cycle testing of one (1) soldered and three (3) welded test modules.

   i) Cycling shall be performed in either dry nitrogen or inert atmosphere from +80°C ± 5°C to -80°C ± 5°C.

   ii) Cycling time shall be less than fifteen minutes per cycle.

   iii) Minimum number of cycles shall be thirty thousand (30,000).

   iv) Inspections consisting of visual examination under 10X magnification, current/voltage measurements at AMO, 28°C and any other NDE techniques shall be made prior to cycling and after five hundred, one thousand, two thousand, four thousand, eight thousand, twelve thousand, eighteen thousand, twenty-four thousand and thirty thousand cycles.

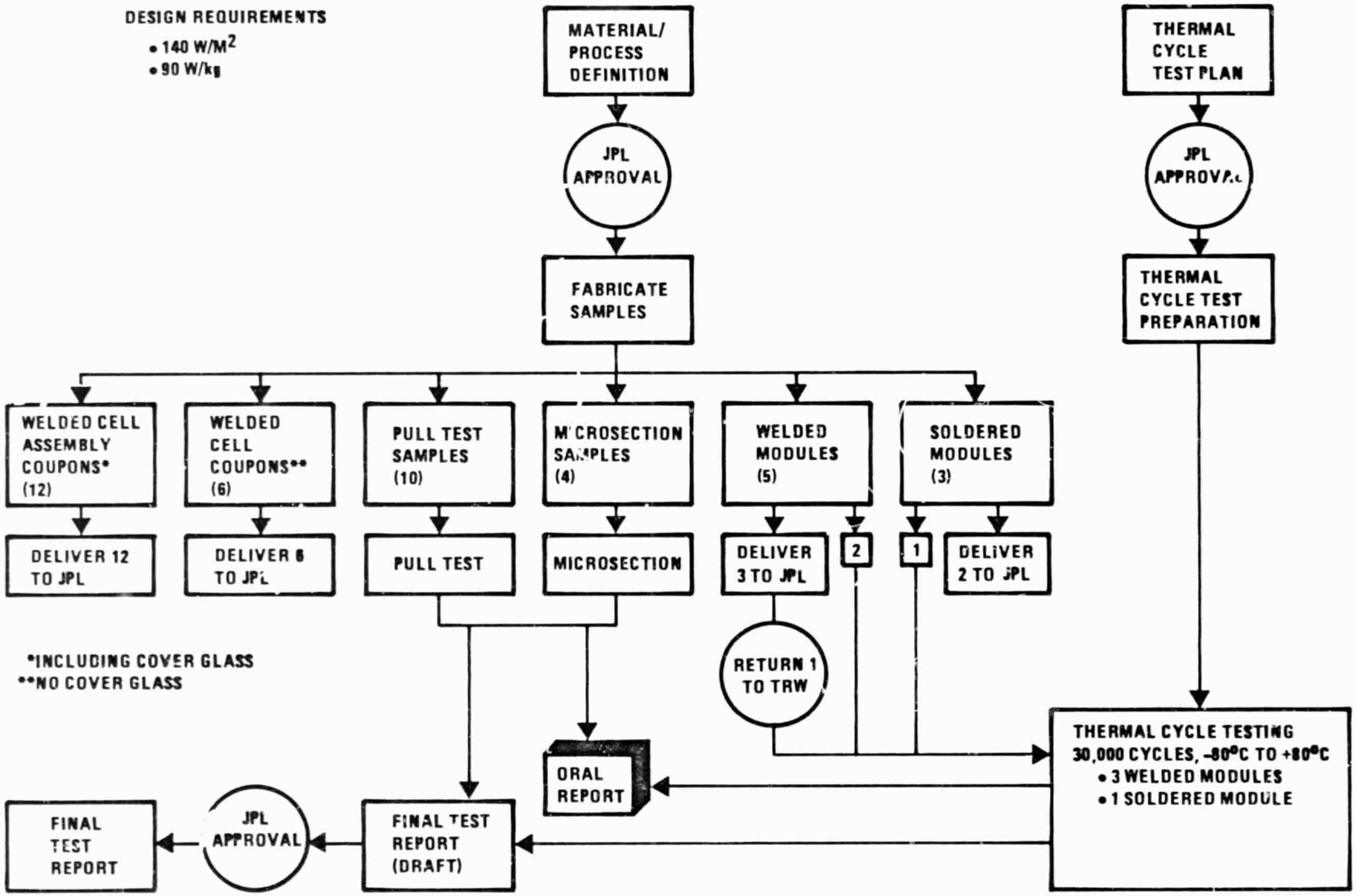


Figure 2.1-1 Work Flow Summary

2.2 HARDWARE FABRICATION

The hardware fabrication effort consisted of producing the following:

a) Five (5) 18-cell welded modules
b) Three (3) 18-cell soldered modules
c) Four (4) microsection samples
d) Ten (10) pull test samples
e) Six (6) welded cell coupons
f) Twelve (12) welded cell assembly coupons.

Identical components were used for each type of hardware with one exception: solderless cells and interconnectors were used in the welded modules and solder coated cells and interconnectors were used in the soldered modules. Summarized hardware component descriptions are presented in Table 2.2-1. The single cell assembly coupons and single cell coupons used components and processes identical to those for the 18-cell modules and are not discussed any further in this report.

2.2.1 Solar Cell

The solar cell physical and electrical nominal characteristics are presented in Table 2.2-2. All characteristics are the same for both welded cells and soldered cells with the exception of solder coating. The solderable cells are pressed solder (SN-62) coated on the N- contact and on a zone of the P- contact.

2.2.2 Cover Glass

The cover glass is 0.15-mm-thick fused silica. The cover has a single layer of interference-type anti-reflection coating on the upper surface, designed to enhance the transmittance of energy to the solar cell in the region of peak response. In addition, the cover has a multilayer interference-type coating on the bottom side (side bonded to the solar cell) designed to provide protection for the adhesive used to bond the covers to the solar cells, and to reject the ultraviolet energy which is not converted to electrical energy.

Table 2.2-1 Hardware Component Summary

COMPONENT	MATERIAL	CONFIGURATION
CELL	SILICON	20.2 x 40.0 x 0.2 MM
COVER	FUSED SILICA	20.4 x 40.4 x 0.15 MM
PARALLEL INTERCONNECTOR	Ag PLATED INVAR	0.05 MM SANDWICH
SERIES INTERCONNECTOR *	Ag PLATED INVAR, Ag CLAD INVAR	0.05 MM SANDWICH
COVER ADHESIVE	DC 93-500	0.05 MM
CELL ADHESIVE	DC 93-500	0.06 MM
SUBSTRATE	KAPTON-KEVLAR-KAPTON	0.15 MM SANDWICH

* IN-PLANE ARE Ag PLATED, OUT-OF-PLANE ARE Ag CLAD

Table 2.2-2 Solar Cell Characteristics

PARAMETER	TYPE/VALUE
TYPE	N ON P HYBRID
MATERIAL	MONOCRYSTALLINE SILICON
RESISTIVITY	10 OHM-CM
PERFORMANCE ENHANCEMENT	BACK SURFACE REFLECTOR
OPTICAL COATING	MULTILAYER ANTI REFLECTIVE COATING
SIZE	20 x 40 MM (NOMINAL)
THICKNESS	0.2 MM (NOMINAL)
CONTACTS	PALLADIUM-TITANIUM-SILVER
SOLDER*	N-CONTACT AND A ZONE OF THE P-CONTACT ARE PRESSED SOLDER COATED (SN-62)
SILVER CONTACT THICKNESS	3 TO 6 μM
CONTACT WAVINESS	3 μM OR LESS
GLASSED CELL AVERAGE POWER OUTPUT (MINIMUM)	284 mA AT 452 $\pm$ 2 mV, 1 AMC, 28^{o}C MINIMUM

*NO SOLDER ON CELLS TO BE WELDED.

2.2.3 Solar Cell Interconnector

Electrical interconnection of the solar cells is accomplished using 0.001-inch-thick, silver-plated Invar interconnectors. Interconnectors for soldering contain an additional outer coating of solder (SN-62). The interconnector selected is the configuration now used on the Tracking and Data Relay Satellite (TDRS) solar arrays.

Two interconnectors are parallel gap welded (or reflow soldered) to the negative contacts of each 2 by 4-cm cell; they are parallel gap welded (or reflow soldered) to the positive contacts of the next cell in series. Each interconnector has two weld (solder) joints for both the front and back solar cell contact areas providing redundant cell-to-cell connections.

2.2.4 Adhesive

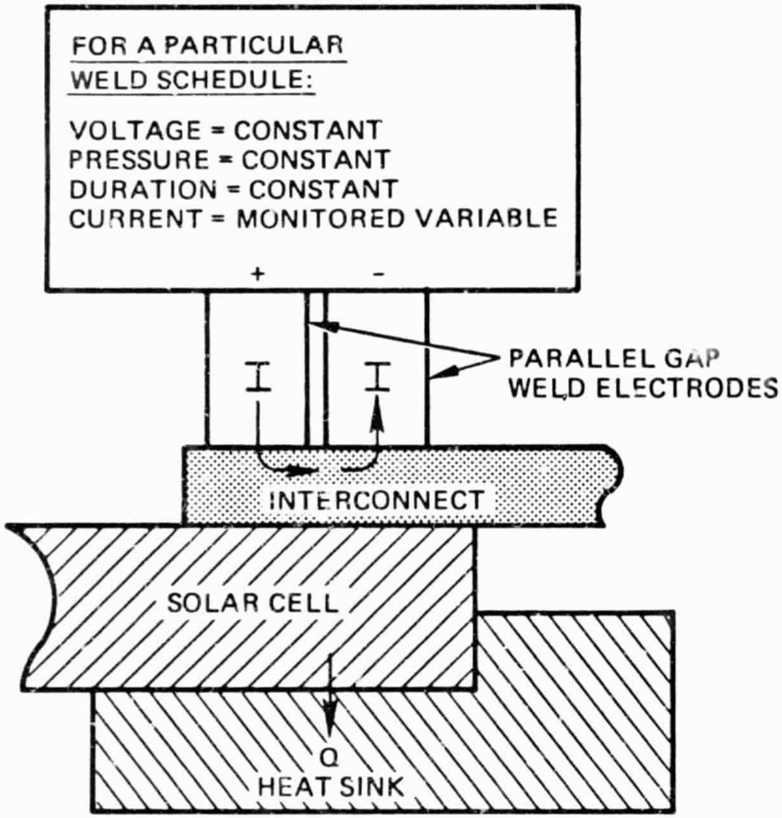
The cover glass adhesive is Dow Corning (DC) 93-500. This adhesive is currently used on TDRS, FSC, and DSP assemblies. DC 93-500 is also used for cell to substrate bonding.

2.2.5 Substrate

The baseline substrate is a flexible laminate consisting of a 0.005 inch Kevlar interlayer sandwiched between two layers of 0.001 inch Kapton.

2.2.6 Interconnect to Cell Welding

Front and back contact parallel gap resistance welding was performed with 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. Weld electrodes were cleaned after every twelfth weld joint using an aluminum oxide chip. Each weld joint was monitored by recording the time-integrated weld current. Front and back contact weld schedules are presented in Figures 2.2-1 and 2.2-2, respectively. Zero degree pull test results are also presented in these figures. A cross-sectioned weld joint is shown in Figure 2.2-3 and indicates that a solid state weld has been produced.

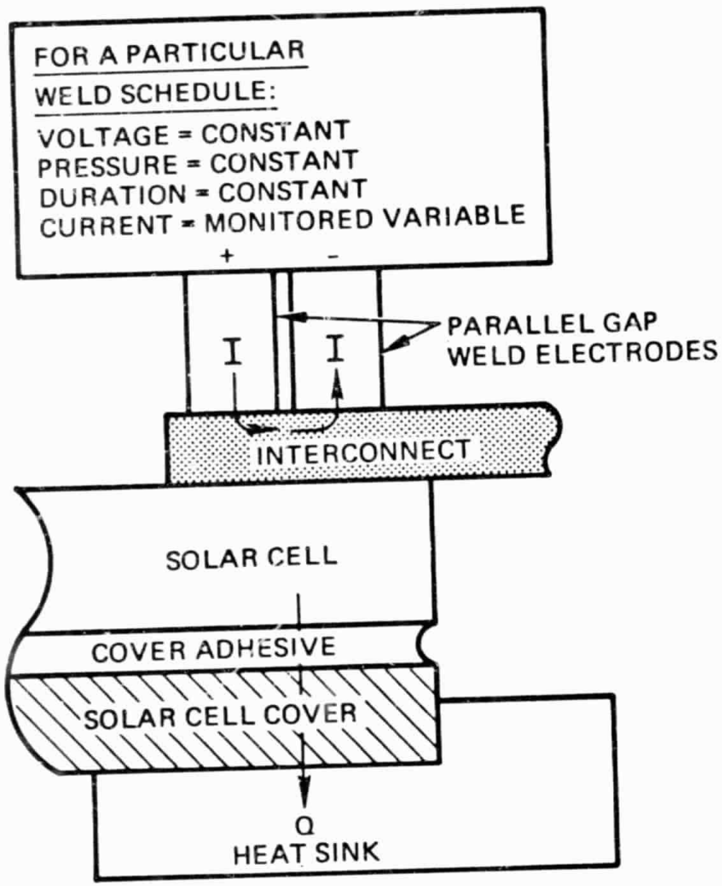


- WELD EQUIPMENT REQUIREMENTS
  - DELIVER WELD SCHEDULE
  - SUPPORT AND INDEX CELL AND INTERCONNECTOR
  - MAINTAIN ELECTRODE CLEANLINESS
- FRONT CONTACT WELD SCHEDULE PARAMETERS

WELD VOLTAGE:	0.76 V
WELD DURATION:	100 ms
ELECTRODE DIMENSIONS:	0.015 x 0.025 INCH PER ELECTRODE
ELECTRODE FORCE:	3.3 LB PER ELECTRODE PAIR

- FRONT CONTACT PULL STRENGTH (0°) RANGE 2.4 TO 3.7 LB (40 SAMPLES)

Figure 2.2-1 Front Contact Weld Schedule Summary



- WELD EQUIPMENT REQUIREMENTS
  - DELIVER WELD SCHEDULE
  - SUPPORT AND INDEX CELL AND INTERCONNECTOR
  - MAINTAIN ELECTRODE CLEANLINESS
- BACK CONTACT WELD SCHEDULE PARAMETERS

WELD VOLTAGE:	0.74 V
WELD DURATION:	100 ms
ELECTRODE DIMENSIONS:	0.015 x 0.025 INCH PER ELECTRODE
ELECTRODE FORCE:	3.3 LB PER ELECTRODE PAIR

- BACK CONTACT PULL STRENGTH (0^{o}) RANGE 3.5 TO 6.2 LB (40 SAMPLES)

Figure 2.2-2 Back Contact Weld Schedule Summary

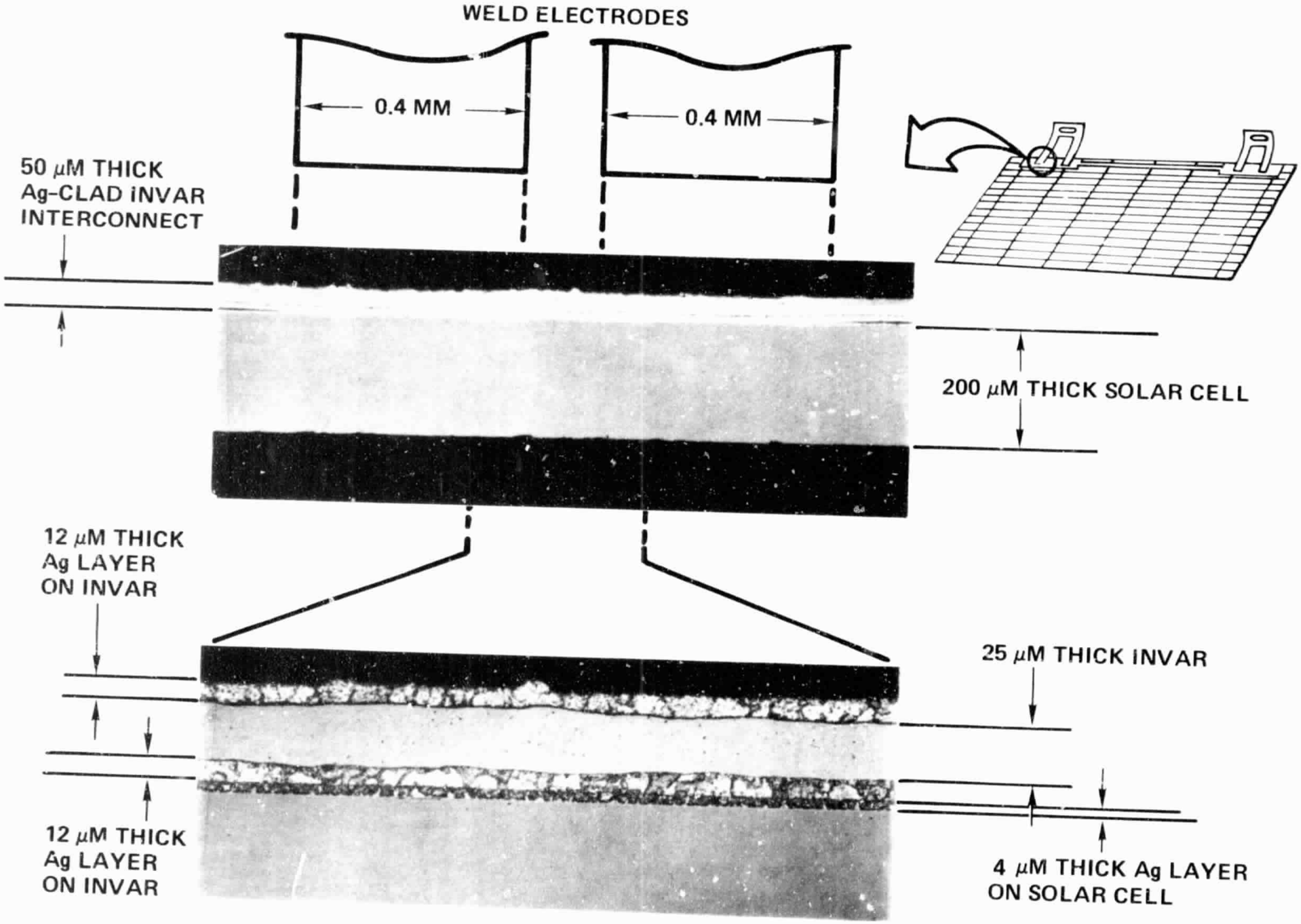


Figure 2.2-3 Solar Cell Cross Sections Showing Solid State Welding

2.2.7 Interconnect to Cell Soldering

Interconnect to cell soldering was performed using standard TRW production equipment.

2.2.8 Eighteen Cell Module Assembly

The configuration of the 18-cell modules is shown in Figure 2.2-4. The production sequence was to interconnect to the solar cell front contact, place the covers on the interconnect-cell subassembly, match cells for electrical performance, interconnect the subassemblies into 18-cell assemblies, and then bond the 18-cell assemblies to the substrates to produce the 18-cell modules. A cross-section schematic of a welded module is shown in Figure 2.2-5. A photograph of the four 18-cell modules used in the thermal cycle test is shown in Figure 2.2-6.

2.3 MODULE AREAL AND SPECIFIC PERFORMANCE

Welded module mass properties are summarized in Table 2.4-1. Total mass of one 18-cell welded module is 17.73 g. Welded module areal and specific performance are summarized in Table 2.4-2. Actual areal and specific performance of 142 W/m^2 and 124 W/kg, respectively, exceeds the contract design requirements of 140 W/m^2 and 90 W/kg, respectively.

2.4 THERMAL CYCLE TEST AND RESULTS

2.4.1 Test Hardware Preparation

One additional cell was bonded to each of the four modules with a thermocouple sandwiched between the cell and the module for monitoring module temperature during test. Connectors were attached to each module to enable continuity measurements during the thermal vacuum test and to provide convenient electrical access to the test cells during performance testing. Each module was carefully inspected under 10X magnification. "Roadmaps" were prepared for each of the four modules denoting location and type of observed abnormalities (cracked covers, cracked cells, etc). Each of the four modules were mounted inside of a frame. Current voltage measurements were performed just prior to mounting the frame (with test hardware attached) to the thermal vacuum test equipment.

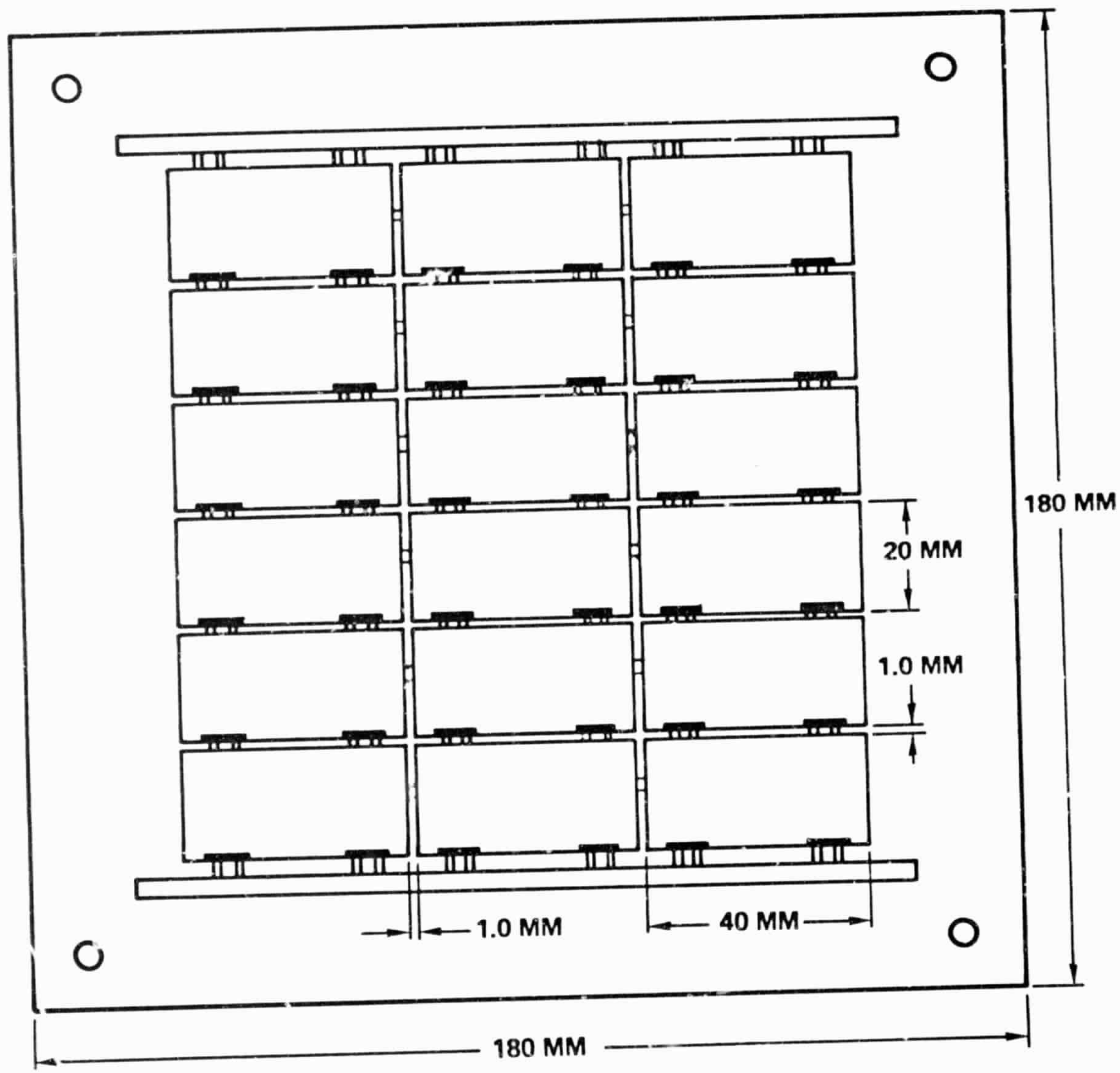


Figure 2.2-4 Eighteen-Cell Module Configuration

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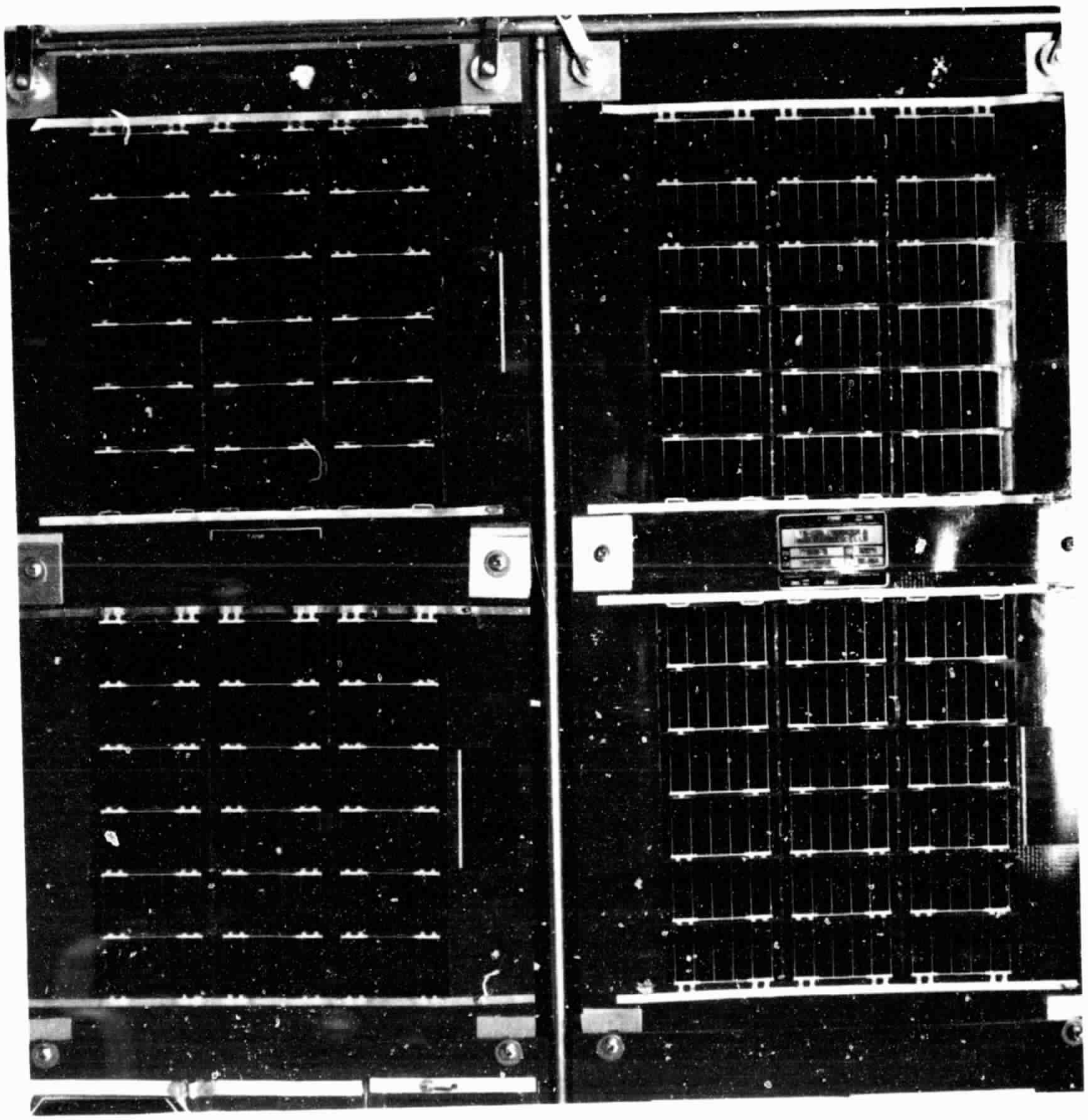

Figure 2.2-5 Four 18-Cell Modules for Thermal Cycle Testing

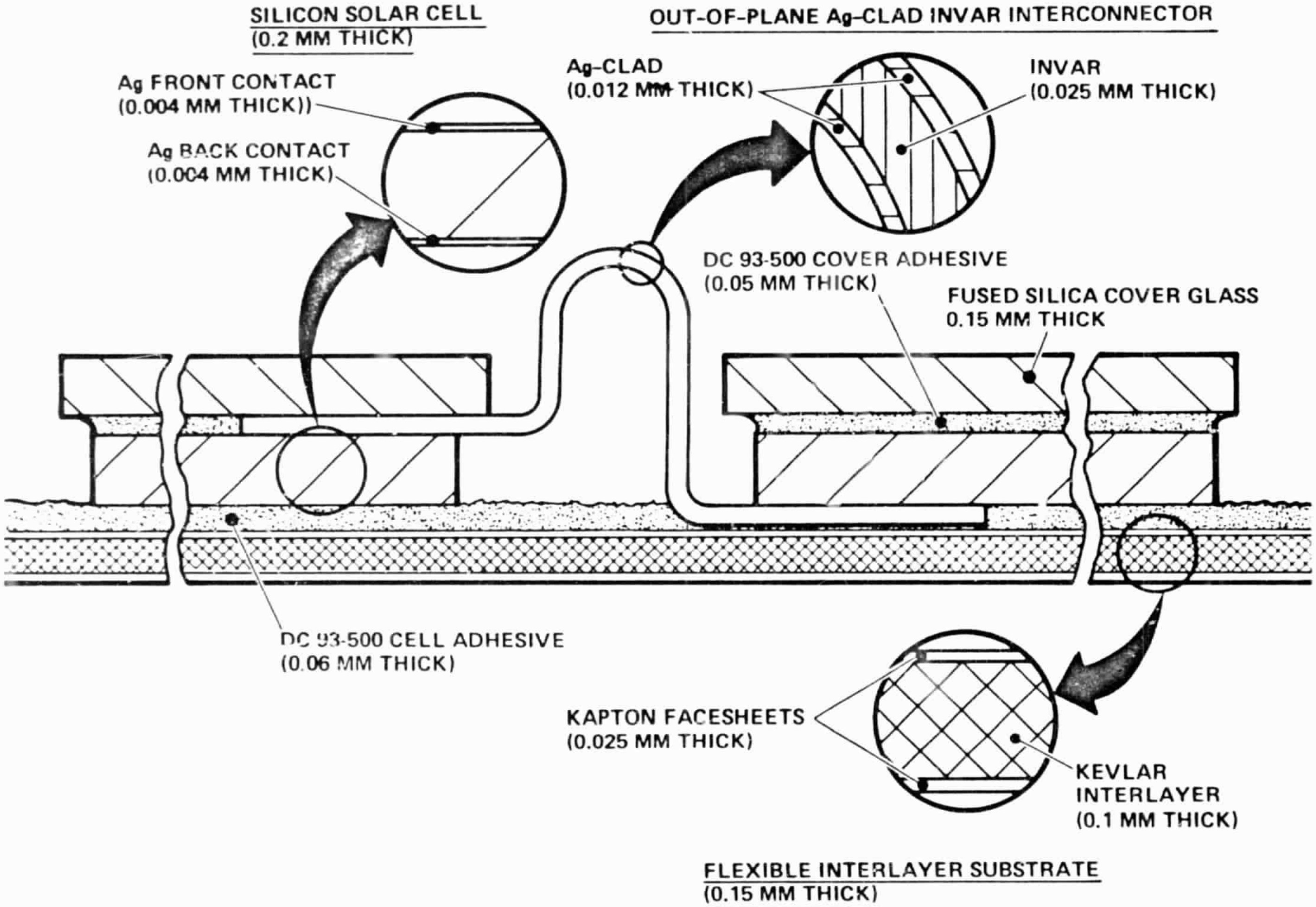

Figure 2.2-6 Cell Stack Cross Section

Table 2.4-1 Welded Module Mass Summary

COMPONENT	CONFIGURATION	QUANTITY PER MODULE	UNIT MASS (g)	MODULE MASS (g)
SOLAR CELL	(SILICON) 20.0 x 40.0 x 0.2 MM	18	0.415	7.470
COVER	(FUSED SILICA) 20.4 x 40.4 x 0.15 MM	18	0.275	4.950
PARALLEL INTERCONNECTOR	(Ag-INVAR) 0.05 MM	6	0.060	0.360
SERIES INTERCONNECTOR	(Ag-INVAR) 0.05 MM	36	0.010	0.360
COVER ADHESIVE	(DC 93-500) 0.05 MM	18	0.043	0.774
CELL ADHESIVE	(DC 93-500) 0.06 MM	18	0.054	0.972
SUBSTRATE*	(KAPTON-KEVLAR-KAPTON) 123 x 126 x 0.15 MM	1	2.837	2.837
TOTAL MODULE MASS				17.723

* INCLUDES 0.5 MM BORDER ALLOWANCE FOR CELL SPACING

Table 2.4-2 Welded Module Performance at 28°C

PARAMETER	ACTUAL VALUE	DESIGN REQUIREMENT
MODULE POWER	2.20 W	NA
MODULE AREA*	0.0155 M^2	NA
MODULE MASS**	17.723 G	NA
SPECIFIC POWER	124 W/KG	90 W/KG
AREAL POWER DENSITY	142 W/M^2	140 W/M^2

* INCLUDES 0.5 MM BORDER ALLOWANCE FOR CELL SPACING

** DOES NOT INCLUDE OVERSIZED TERMINATION STRIPS THAT WERE USED FOR TEST PURPOSES.

2.4.2 Test Chamber Description

The test chamber was a liquid nitrogen-cooled vacuum chamber. The four test specimens were suspended from an aluminum frame using four springs for each specimen attached at the corners of the specimens. The spring force was approximately 0.5 lb per spring. The frame with samples attached was mounted with stand-offs to one face of a liquid nitrogen cooled rectangular fixture which rotates cyclically 90 degrees about its central axis such that the test specimens alternately face a cold wall and then tungsten filament heaters. All cooling walls and heaters were maintained at constant temperature. Thermal cycling was achieved by rotating the rectangular fixture back and forth from the cold wall to the heaters. The test chamber set up is shown in Figure 2.4-1.

2.4.3 Test Start-up

Four samples (three welded and one soldered) were mounted in the thermal vacuum chamber. The chamber was pumped down to 10^{-5} torr. Heaters were turned on and the samples were heated to 80°C ± 5°C for one hour. The samples were then cycled with adjustments to heater power and cycle time until one complete cycle from 80°C to -80°C and back to 80°C was achieved in twelve minutes. The cooling portion was set at eight minutes and the heating portion was set at four minutes.

After setting the cycle profile, cycling commenced at the rate of 120 per day. Continuity and temperature were continually monitored on each of the four panels.

2.4.4 Test Results

The chamber was opened after completion of 2910, 6550, 9184, 12,180, 18,000, 24,211, and 30,051 cycles. No open circuit was indicated at any time throughout the test by the continuity monitor. All modules were inspected and current/voltage measurements were performed prior to cycling and after each chamber opening.

Results of the visual inspections are presented in Table 2.4-3. Modules were examined for broken cells, cover cracks, cover voids, and weld/solder joint failures. Relative to the pre-thermal cycle inspection,

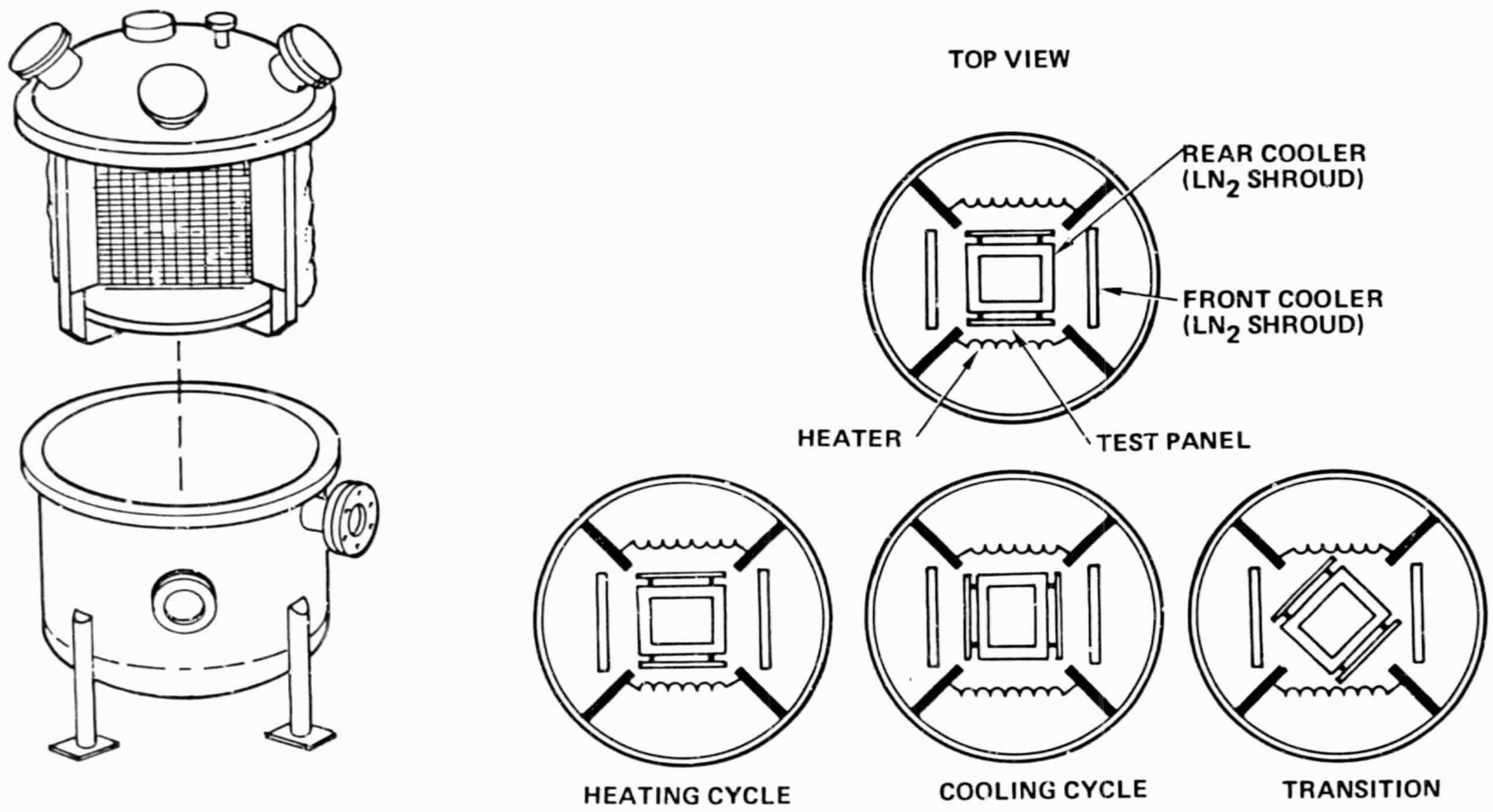

Figure 2.4-1 Thermal Vacuum Test Chamber Concept Description

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Table 2.4-3 Visual Examination Results During Thermal Cycle Test (80°C to -80°C)

SAMPLE	PRE-THERMAL CYCLE	AFTER 2910 CYCLES	AFTER 6550 CYCLES	AFTER 9184 CYCLES	AFTER 12,180 CYCLES	AFTER 18,000 CYCLES	AFTER 24,211 CYCLES	AFTER 30,051 CYCLES
WELDED MODULE 001	1 COVER VOID	1 COVER VOID	1 COVER VOID	1 COVER VOID	1 COVER VOID	1 COVER VOID	1 COVER VOID	1 COVER VOID
WELDED MODULE 002	2 COVER CRACKS	2 COVER CRACKS	2 COVER CRACKS	3 COVER CRACKS	4 COVER CRACKS	4 COVER CRACKS	4 COVER CRACKS	4 COVER CRACKS
WELDED MODULE 003	2 COVER CRACKS 1 COVER VOID	2 COVER CRACKS 1 COVER VOID	2 COVER CRACKS 1 COVER VOID	2 COVER CRACKS 1 COVER VOID	5 COVER CRACKS 1 COVER VOID	5 COVER CRACKS 1 COVER VOID	5 COVER CRACKS 1 COVER VOID	5 COVER CRACKS 1 COVER VOID
SOLDERED MODULE 001								

soldered module number 001 and welded module number 001 experienced no additional flaws following exposure to 30,051 thermal cycles. Two additional cover cracks were observed on welded module number 002 and three additional cover cracks were observed on welded module number 003 following thermal cycling. There was no significant observable (by visual inspection) physical damage on any of the four test modules induced by exposure to 30,051 thermal cycles.

Current/voltage data was taken on each of the four modules prior to cycling and after each chamber opening using the Large Area Pulsed Solar Simulator (LAPSS). The maximum power point was determined for each current voltage measurement and was compared with the corresponding maximum power point prior to thermal cycling (pre-environmental). The estimated accuracy of the LAPSS and measurement system is ± 2%. Table 2-4-4 presents the pre-environmental maximum power point for each of the four modules and the change in maximum power after each chamber opening. These results indicate that there was no significant electrical degradation in any of the four modules after exposure to 30,051 thermal cycles.

Table 2.4-4 Maximum Power During Thermal Cycle Test (80°C to -80°C)

MODULE	PRE-ENVIRONMENTAL MAXIMUM POWER POINT*			CHANGE IN MAXIMUM POWER* RELATIVE TO PRE-ENVIRONMENTAL						
	VOLTAGE (V)	CURRENT (A)	POWER (W)	AFTER 2910 CYCLES	AFTER 6550 CYCLES	AFTER 9184 CYCLES	AFTER 12,180 CYCLES	AFTER 18,000 CYCLES	AFTER 24,211 CYCLES	AFTER 30,051 CYCLES
WELDED 001	2.621	0.8417	2.207	-1.4%	-1.9%	-2.2%	-1.0%	-0.4%	-1.5%	-0.0%
WELDED 002	2.613	0.8500	2.221	-0.3%	-1.4%	-1.5%	-0.4%	-0.6%	-2.5%	-0.0%
WELDED 003	2.611	0.8538	2.230	-0.5%	-0.4%	-0.9%	-1.4%	0.0%	-1.2%	0.0%
SOLDERED 001	2.607	0.8802	2.295	-0.5%	-1.3%	-1.5%	-1.1%	-0.7%	-1.7%	-0.8%

* Large Area Pulsed Solar Simulator (LAPSS) and Measurement System Accuracy is ± 2%. All data has been corrected to 28°C.

3. CONCLUSIONS

The following conclusions are based on the results obtained during this project:

1. The TRW parallel gap resistance welding process results in solid state welds between silicon solar cells and silver plated Invar interconnectors (both front and back contacts).

2. Zero degree pull strengths in excess of 2.4 lbs can be achieved on both front and rear cell contacts using parallel gap resistance welding.

3. Welded module specific performance of 124 W/kg (at 28°C) and 142 W/m^2 (at 28°C) can be achieved using 2 x 4 cm silicon solar cells and a flexible Kapton-Kevlar-Kapton sandwich substrate.

4. Both welded and soldered modules using flexible Kapton-Kevlar-Kapton substrate material will perform satisfactorily (insignificant electrical degradation and observable physical damage) for over five years (30,000 cycles) in a low earth orbit thermal environment (+80°C to -80°C).

4. RECOMMENDATIONS

It is recommended that thermal cycle testing of the modules be continued to establish a design data base for both welded and soldered solar cell cycle life capability in a low earth orbit environment.

5. NEW TECHNOLOGY

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

6. REFERENCES

1. P.M. Stella, "U.S. Welding Technology - Constraints to Space Implementation", 17th IECEC Conference Proceedings, Los Angeles, CA, 1982, pp 1584-1588.

2. H.S. Rauschenbach, "Solar Cell Array Design Handbook", p 273, Van Nostrand Reinhold Company, New York, NY, 1980.