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INTERCONNECT AND BONDING TECHNOLOGIES FOR LARGE FLEXIBLE SOLAR ARRAYS

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Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER

SSD
SPACE SYSTEMS DIVISION

FINAL REPORT

LOCKHEED MISSILES & SPACE COMPANY, INC.
A SUBSIDIARY OF LOCKHEED AIRCRAFT CORPORATION
SPACE SYSTEMS DIVISION · SUNNYVALE, CALIFORNIA

LMSC-D492654
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FINAL REPORT FOR THE PERIOD
26 AUGUST 1974 - 31 DECEMBER 1975

NAS8-31016

Prepared for

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
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FOREWORD

This final report summarizes the work performed for NASA/Marshall Space Flight Center under Contract NAS8-31016 in the period 26 August 1974 through 31 December 1975. The subject is the development of solar cell interconnect bonding technology and selection of bonding materials and process controls for fabrication of large flexible solar cell arrays. Thermocompression bonding and conductive adhesive bonding were developed and evaluated as methods of joining solar cells to their interconnect circuitry. LMSC has received a contract follow-on to continue the study through 1976.

The MSFC Technical Monitor is George Filip. The LMSC project supervisor is Gene J. Antonides.

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ACKNOWLEDGEMENTS

The author wishes to acknowledge the contributions of the following persons to this effort:

	Technical Area
Paul A. Dillard	Overall technical support, esp. thermo-compression bonding
Richard V. Elms, Jr.	Applicability to large area flexible solar arrays
Walter M. Fritz, Jr.	Manufacturing engineering
George P. Kullberg	Thermocompression bonding and module fabrication
Dan R. Lott	Bonding technology, test module evaluation
Clayton C. May	Conductive adhesive investigation
Chuck F. Schwager	Program controls
Dr. William R. Scoble, Jr.	Thermocompression bonding processes: selection of equipment, materials and schedule

Section 1

INTRODUCTION AND SUMMARY

The purpose of this study is to develop and evaluate thermocompression bonding and conductive adhesive bonding as alternate methods of joining solar cells to their interconnect assemblies, and to select bonding materials and process controls applicable to fabrication of large, flexible substrate solar cell arrays. A bonding method other than soldering is necessary on lightweight, flexible substrate arrays to obtain lifetimes in orbit of 5 years or more, because solders cannot withstand the orbital temperature cycling.

Previous work at LMSC* established that parallel-gap welding is a satisfactory solar cell/interconnect joining technique. There are, however, difficulties and potential problems with parallel-gap welding; namely, tight process control requirements, frequent welding tip cleaning, and possible degradation of the solar cell electrical output. This study is intended to determine whether thermocompression or conductive adhesive bonding could substitute for parallel-gap welding on flexible solar arrays.

The primary potential use of the techniques developed in this study is on the solar array being developed by NASA/MSFC and LMSC for solar electric propulsion (SEP) and Shuttle payload applications. This array is made up of flexible panels approximately 0.7 by 3.4 meters. It is required to operate in space between 0.3 and 6 AU for 5 years with limited degradation. Materials selected must be capable of enduring this space environment, including outgassing and radiation.

The study includes the following:

- Evaluation of 9 conductive epoxies
- Development of optimum thermocompression bonding process parameters
- Comparison of 13 different interconnect materials

*Contract NAS8-28432/Solar Array Flexible Substrate Design Optimization, Fabrication, Delivery and Test Evaluation Program.

- Fabrication of solar array test modules, using best material combinations and both conventional and high-efficiency solar cells
- Temperature cycling and other testing of 3 72-cell modules of different designs
- Shipment of a second set of 3 72-cell modules to MSFC for additional temperature cycling testing

Some of the work is closely related to ongoing Independent Development projects at LMSC. These projects include pull tab tests of conductive epoxies and interconnect materials, and fabrication and test of some 12-cell solar array modules. Pertinent results are included in this report.

The candidate conductive epoxies and interconnect materials were:

Epoxies:

Ablebond 36-2	Epotech H31D
Ablebond 58-1	Epotech H44
DuPont 5504	Transene Ohmex-Ag
Epotech H20E	Transene GE-10
Epotech H21D	

Interconnects:

Copper, 1 oz.*	Moly, 1 mil, silver-plated
Copper, 2 oz.	Moly, 1 mil, gold-plated
Copper, 1 oz, silver-plated	Kovar, 1 mil, silver-plated
Copper, 2 oz, silver-plated	Kovar, 1 mil, gold-plated
Copper, 1 oz, gold-plated	Silver, 1 mil
Copper, 2 oz, gold-plated	Silver, 2 mil
	Invar, 1 mil, silver-plated

*1 oz. = 1.34 mil

Bond strengths were measured by pulling tabs at a 45° angle. Pull strengths for the four most promising epoxy/interconnect material combinations ranged from 113 to 369 grams before temperature cycling and from 91 to 284 grams after 50 temperature cycles from -196 to 150°C. Bond failures were caused predominantly by bond interface separation, although there were some by silicon divoting.

Thermocompression bonding parameters were varied as follows: pressure from 35.7 to 52.1 MN/m^2 (5170 to 7560 psi), temperature from 204 to 538°C (400 to 1000°F) and time from 0.5 to 10 seconds. The optimum parameters, which applied to all the interconnect materials, were 48 MN/m^2 (6960 psi), 450°C (850°F) and 1.1 seconds. Average (of 5 tabs) 45° pull strengths for the 4 best interconnect materials ranged from 573 to over 800 grams before temperature cycling and from 420 to 684 grams after 50 cycles from -196 to 150°C. Bond failures were of several types, in the following order of occurrence: separation at bond interface, divoting of silicon, tearing of pull tab, and peeling of plating on tab.

A total of 10 12-cell test modules were fabricated of these selected materials 4 of which were conductive epoxy bonded and 6 thermocompression bonded. The modules were temperature-cycled from -196 to 150°C in LMSC's Quick-Look Temperature Cycler. The silver-plated molybdenum, DuPont 5504 epoxy-bonded module performed best, losing just one of 48 bonds in 1080 cycles.

Based on the pull tab and 12-cell module testing three interconnect material/bonding combinations were selected as the most promising:

- Silver-plated molybdenum, bonded with DuPont 5504 silver-filled epoxy
- Silver-plated molybdenum, thermocompression bonded
- Gold-plated copper, thermocompression bonded

Six 72-cell solar cell array modules were fabricated, two each of the above. One set of 3 modules was tested in the LMSC Solar Panel Temperature Cycling Facility. The other three modules were shipped to MSFC where they will be similarly temperature cycled.

The modules tested at LMSC were exposed to 604 90-minute cycles from -160 to 150°C, except that during the first 84 cycles they were mistakenly overheated to 325°C, adversely affecting the test results. The conductive epoxy bonded module performed best of the three; 17% of its bonds had failed after 604 cycles. The thermocompression bonded modules, with silver-plated molybdenum and gold-plated copper interconnects, lost 63% and 100% of their bonds, respectively.

The thermocompression bonded modules did not do as well as expected, considering the pull tab testing results. The reason for this may be the polyester adhesive on the substrate film which melted and flowed onto the bond access areas during the bonding process and may have contaminated the bond interface, preventing a good bond. If so, the use of an acrylic adhesive should improve the performance of thermocompression bonded arrays up to the level of the pull tab specimens.

Despite the number of bond failures on the test modules during temperature cycling, both thermocompression bonding and conductive adhesive bonding appear to be viable methods of joining solar cells to their interconnect circuitry. The bond strengths typically are not as high as obtained with parallel-gap welding, but may be sufficient. Compared to parallel-gap welding, conductive epoxy bonding can be applied much more efficiently, using screen printing techniques. But it requires a complicated setup and a curing operation. Thermocompression bonding is accomplished at a lower temperature, allows less exact control of the bonding parameters, and requires less frequent cleaning of the tip. However, the higher bonding pressure presents a greater danger of cell damage and the longer bonding time may cause overheating of parts of the array (such as the substrate adhesive).

Further development and evaluation are necessary, particularly of tooling and fabrication processes, before either bonding method can be accepted on a flight array.

Section 2
THERMOCOMPRESSION BONDING PROCESS DEVELOPMENT

2.1 Introduction

Thermocompression bonding is a process in which two metal surfaces are joined by solid state diffusion under high pressure and an elevated temperature below the melting point. Other names for the process are diffusion welding, thermal diffusion bonding, solid phase welding, and mechanical thermal pulse bonding.

Thermocompression bonding is a two-stage process. First, the two materials are placed together under sufficient pressure to cause plastic deformation of one or both materials. This ruptures and displaces surface films such as oxides which would otherwise interfere with good bonding. It also smooths surface asperities, providing more intimate contact. Second, the combination of high interface pressure and elevated temperature produces a reaction between the two metals, resulting in the bond. The reaction can be one of three kinds: 1) solid state diffusion of the two materials across the bond interface, 2) formation of a eutectic of lower melting point, or 3) formation of an intermetallic compound.

For the maximum possibility of success the interconnect material should be as soft and ductile as possible (such as copper or gold) so that it will readily deform under pressure and come into intimate contact with the silver plating on the solar cell. For corrosion resistance the interconnect should be coated with gold or another corrosion resistant material. Hard materials such as nickel or molybdenum, unless heavily plated with softer materials, are very difficult to bond using this technique. Although the low thermal expansion coefficient of molybdenum is desirable because it matches that of silicon, it creates additional difficulty in achieving a good thermocompression bond.

The advantages of thermocompression bonding over parallel-gap welding are 1) a lower temperature requirement reducing the possibility of cell degradation, 2) less critical surface preparation, and 3) less exacting bond parameters. Potential problems in the use of thermocompression bonding are 1) higher pressures causing cell damage and 2) longer time durations required per bond. These factors were thoroughly investigated.

To obtain successful thermocompression bonds, the bond parameters should be in general as follows:

- Temperature - approximately at one-half the absolute melting point, and above the oxide dissociation temperature

- Pressure - above yield point of material at the interface temperature

- Time - a few tenths of a second minimum. The optimum time must be determined empirically for each set of conditions, since different times may produce different metallurgical results.

The work performed to develop thermocompression bonding for the large area, flexible solar array application was essentially a five-step procedure:

1. Select best bonding equipment.

2. Determine process requirements and optimum bonding parameters for several interconnect materials. Evaluate bond performance, including temperature cycling testing.

3. With 4 best interconnect materials, build 4 12-cell test modules of design similar to SEP array.

4. Temperature cycle and electrically test the 12-cell modules.

5. Select best interconnect materials for fabrication of 72-cell test modules.

A flow chart, describing in detail the work done, is given in Figure 2-1.

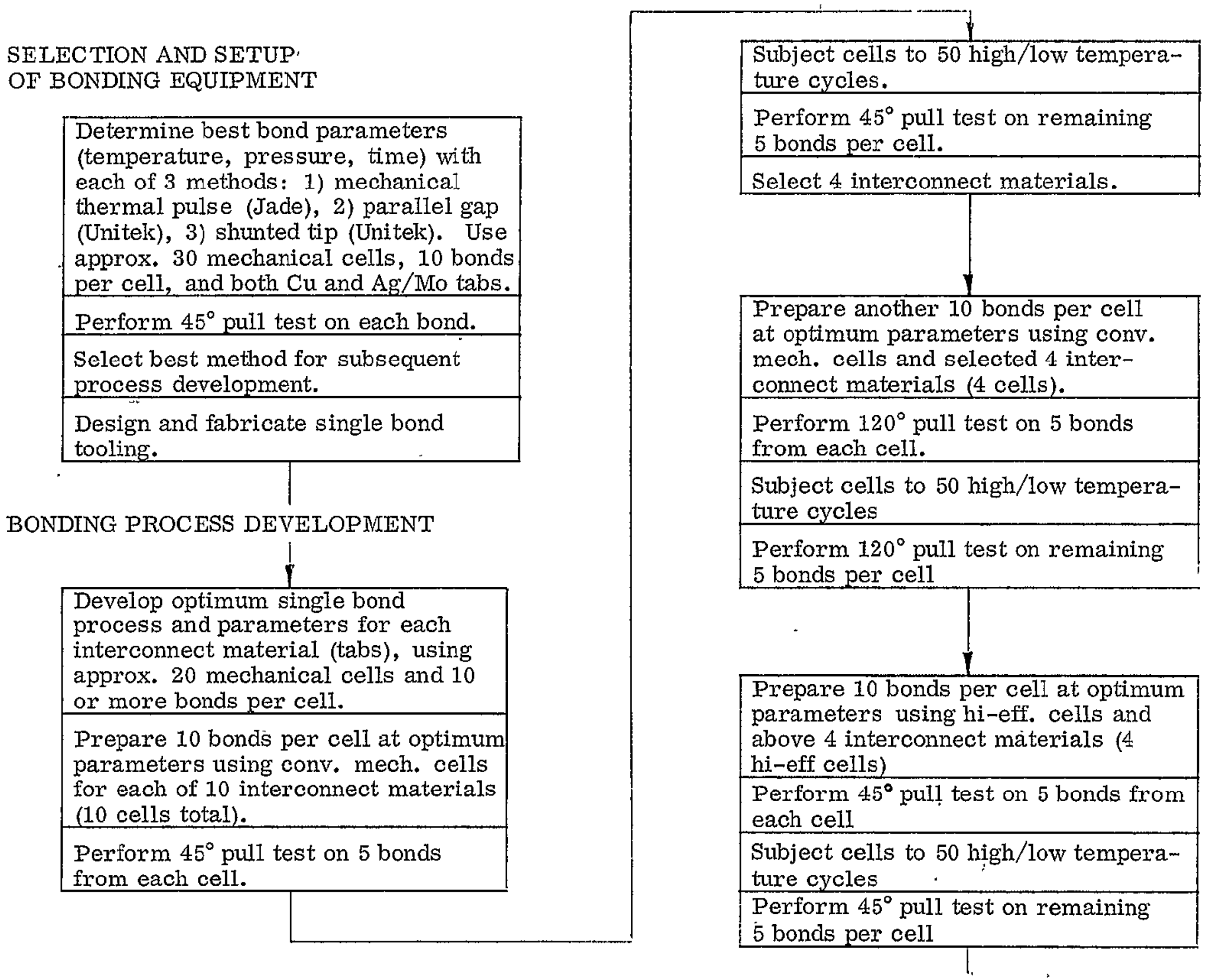


Figure 2-1 Flow Chart for Thermocompression Bonding Development and Testing

Measure electrical performance of 8 conv. and 4 hi-eff. covered cells.

Bond 2 n-contact and 2 p-contact tabs on each cell at optimum parameters for 4 interconnect materials, 2 conv. cells and 1 hi-eff. cell per interconnect material (48 bonds on 12 cells).

Measure electrical resistance of each bond (48 bonds).

Measure electrical performance of each cell (12 cells).

Subject cells to 50 high/low temperature cycles.

Visually inspect all bonds.

Measure electrical performance of each cell.

Measure electrical resistance of each bond.

Perform 45° pull test on all bonds.

12-CELL MODULE FABRICATION

Measure electrical performance of 24 conv. and 24 hi-eff. covered cells.

Fabricate 4 12-cell modules using 4 interconnect materials and 6 conv. and 6 hi-eff. cells per module.

12-CELL MODULE TESTING

Measure electrical performance of 4 12-cell modules

Subject 12-cell modules to 1000 thermal cycles in Quick-Look Tester.

Inspect modules.

Measure electrical performance of 4 12-cell modules after temperature cycling

Perform 45° pull test on minimum of 24 selected bonds

72-CELL MODULE DESIGN SELECTION

Select best interconnect design and material and optimum bond schedule for both conv. and hi-eff. 72-cell modules.

NOTE: All cells used in TC bonding development have covers installed.

Figure 2-1 (continued) Flow Chart for Thermocompression Bonding Development and Testing

Pull tabs, of the dimensions shown in Figure 2-2, were made to test bond strengths. The pull tests were done on a Unitek Micropull Pull Strength Tester, pictured in Figure 2-3.

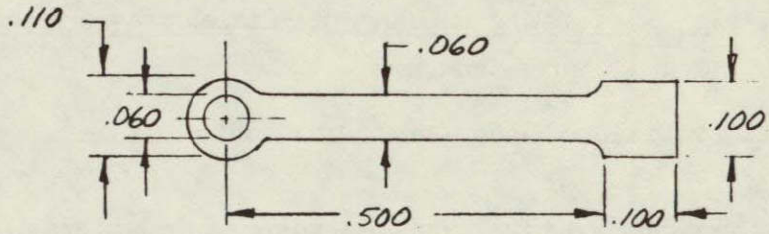


Figure 2-2 Pull Tab for Bonding Development Tests

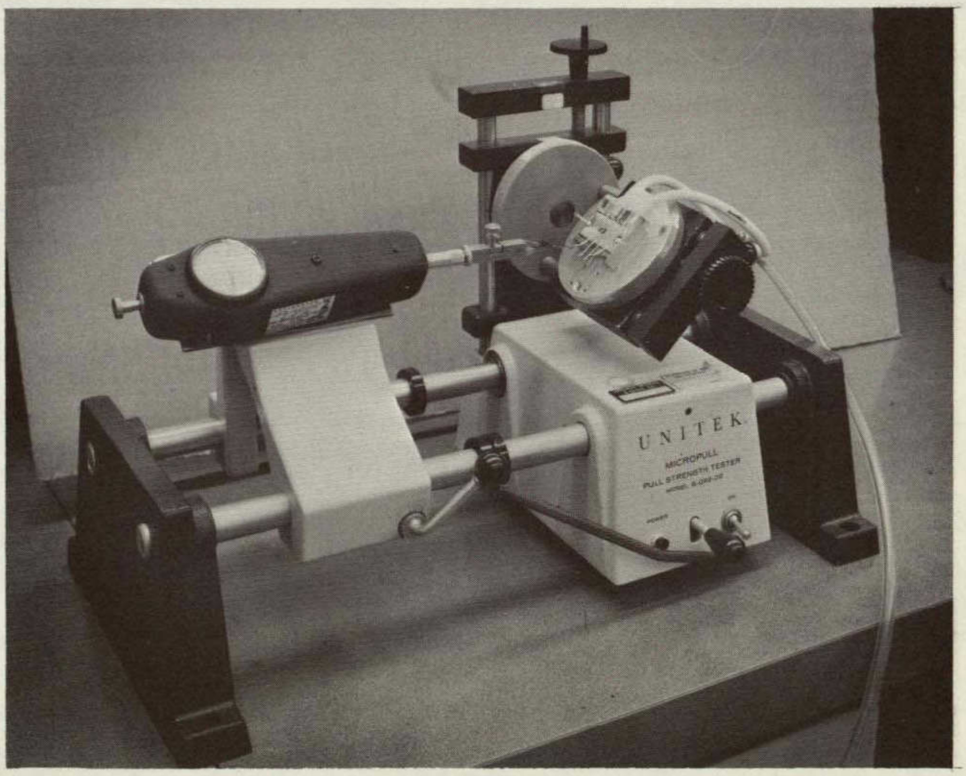


Figure 2-3 Unitek Micropull Tester

2.2 Selection and Setup of Bonding Equipment

Three different types of thermocompression bonding equipment were evaluated, using both bare copper and silver-plated molybdenum pull tabs on covered solar cells:

(1) heated ram (also named mechanical thermal pulse method)

(2) parallel-gap tip, operating at values of voltage, pressure and time which result in thermocompression bonds

(3) shunted tip with closed-loop temperature control

In the heated ram method a relatively massive volume of metal (ram) with a tip chosen to have high thermal conductivity is heated to an accurately controlled temperature. The ram is mechanically pressed against the workpiece with sufficient force to provide low values of thermal resistance between the work parts and the tip. This allows the thermal energy stored in the ram to be rapidly transferred to the work parts by thermal conduction. The heat and pressure at the interface of the workpieces results in a thermocompression bond. For evaluation of this method a Jade Model CA-1 Mechanical Thermal Pulse bonder was used (Figure 2-4). LMSC also has a Model Mark IA bonder, used in microelectronic assembly (Figure 2-5).

The most consistent bond strengths for bare copper and silver-plated molybdenum were obtained at machine settings:

Pressure = 4.5 to 6 kg (10 to 13 lbs.)
Ram Temperature = $500 {}^{+30}_{-15}$ °C
Time = 5 seconds

This gave 90° pull strengths of 75 to 250 gm with an average of 130 gm. Samples for these and all other tests were prepared by abrading oxides from cells and contacts and wiping clean with isopropyl alcohol.

In the parallel-gap tip method, current is passed between two closely-spaced tips through the material to be joined. By reducing the voltage between the tips and increasing the pressure and dwell time over what are normally applied in parallel-gap welding, a solid state diffusion bond (thermocompression bond) can be made.

Figure 2-4 Jade Model CA-1 Mechanical Thermal Pulse Bonder at LMSC

Figure 2-5 Jade Mark IA Mechanical Thermal Pulse Bonder at LMSC

A Unitek Model 1-137-02 welder was used with a tip used previously on parallel-gap welded, solar array test modules (Figure 2-6 and 2-7). Each electrode tip was .38 by .63 mm (.015 by .025 inches), spaced .2 mm (.008 in.) apart.

Bond strengths (90° pull) from 63 grams to 522 grams with an average of 222 grams were obtained with welder settings of:

Force = 1 Kg (2.2 lb)
Voltage setting = 3.6
Time = 10 seconds

The Unitek welder has a foot pedal to apply tip pressure. The welding arm is brought down onto the workpiece by a cable attached to the pedal. Tip pressure is determined by deflection of flexible metal bands in the arm which is limited by a stop in the foot pedal. Thus tip pressure varies with height of the workpiece as well as setting of the stop. Tip force is established using a force gauge under the tip which is located at the same height as the workpiece. Force limits are .45-45 Kg (1 to 10 lbs.). For the Unitek .38 x .63 mm parallel-gap tip this corresponds to a pressure of 9.2 to 92 MN/m^2 (1300-13,000 psi). According to Conti[(1)*], pressure for successful thermocompression bonding should be between 38 and 100 MN/m^2 (5500 to 14,700 psi). The pressure settings on the Unitek welder are considered adequate for this contract, because minimum values are being sought to avoid cell damage and for ease of manufacturing.

The tip force at which current begins to flow is adjustable. Setting the switch to close at just below the final force value will ensure satisfactory pressure through the full dwell time. The technique for bonding is to watch temperature control light while depressing the foot pedal, hold against stop while light is on, and then release.

In the <u>shunted-tip method,</u> a tip similar to that used for parallel-gap welding but with material bridging the end is used. The heat is generated by the electrical resistance of the shunt rather than the resistance of the interconnect and solar cell metalization. With a thermocouple attached to the shunt, the tip temperature can be controlled accurately.

*See Bibliography Reference 1 at end of this Section.

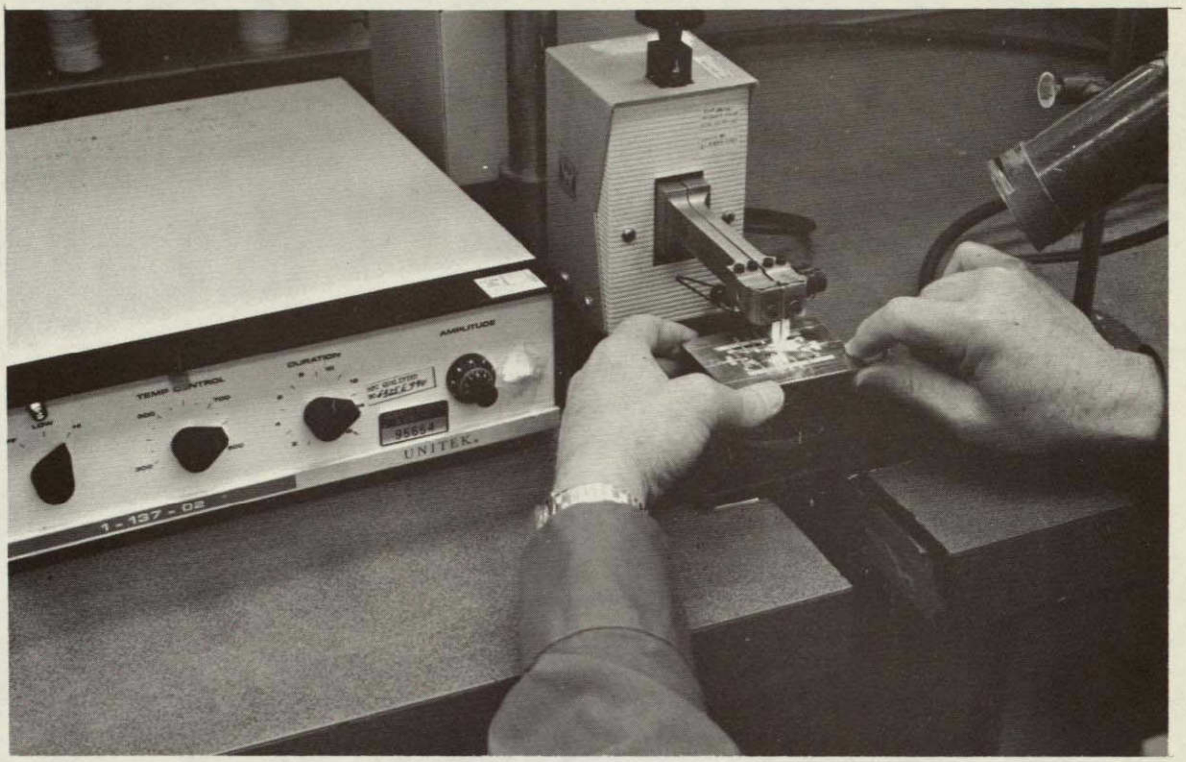


Figure 2-6 Thermocompression Bonder

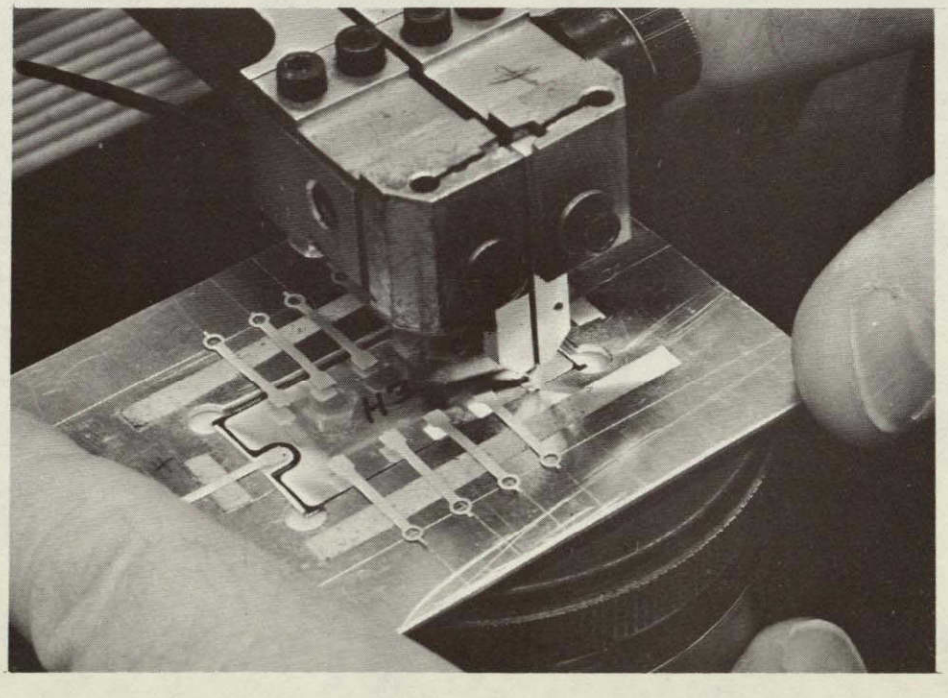


Figure 2-7 TC Bonding of Pull Tab Specimen

The Unitek Model 1-137-02 bonder was used for this evaluation also. Two shunted tip designs were used. The first was a special LMSC design with two tips each made of tungsten carbide and inconel (Figure 2-8). Several good bonds were obtained with

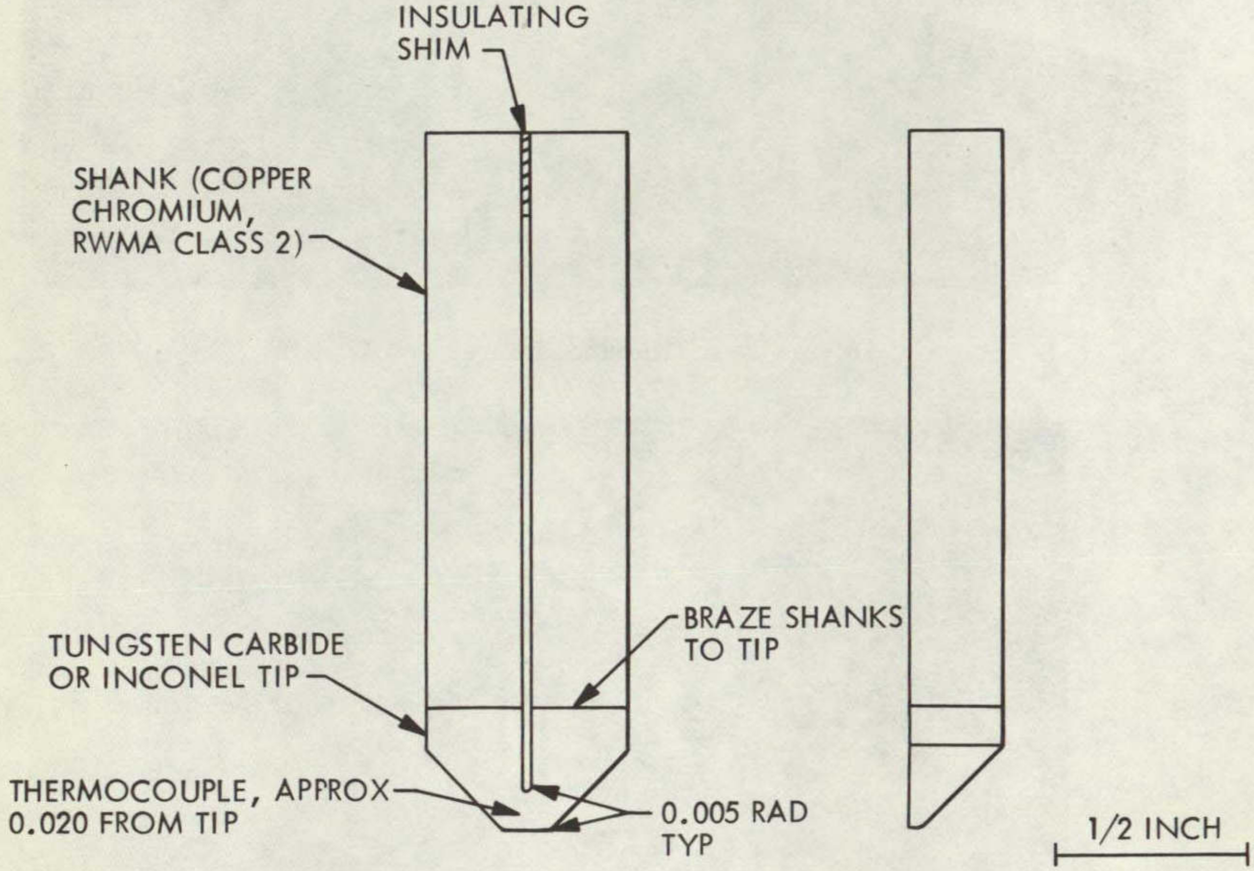


Figure 2-8 Shunted Tip, LMSC Design

the tungsten carbide tips. However, before the optimum bond parameters could be determined, both tips had been broken at the bridge of the tip, due partly to carelessness in mounting the tip in the bonder. Then two more tips were purchased, with a tougher material--inconel--replacing the tungsten carbide.

The inconel bonding tips were tried, but the temperature difference between the thermocouple on the tip and the interface to be bonded was so large that a good bond could not be obtained even at the highest temperature setting (540°C) on the bonder. The thermocouple could have been re-welded closer to where the tip contacts the workpiece. Instead, at this time a standard Unitek shunted tip was obtained.

The Unitek Model 10-128-01 tip, sketched in Figure 2-9, has a short cylindrical shunt which is clamped between two shanks. A thermocouple is welded near the end of the shunt and connects to a control circuit in the power supply, providing closed loop control of the tip temperature.

The principal advantage of the shunted tip method is that the important bonding process parameters--temperature, pressure and time--can be better controlled and known. For this reason, the pulse-heated shunted tip method, using the Unitek bonder and tip, was selected for all subsequent work.

Measurements were made to determine the difference between the shunt temperature as represented by the thermocouple and the actual bond surface temperature. A 3-mil thermocouple was placed on an alumina plate. A piece of interconnect circuit/substrate was placed over them with a bond pad area centered on the thermocouple. The bonding tip then was brought down as if to make a bond, and the maximum thermocouple temperature was recorded. Measurements were made for 3 temperature settings and 3 time settings on the bonder. The results are shown in Figure 2-10. Although there is considerable scatter in the data, it is seen the actual bond interface temperature is from 60°C to 180°C below the bonder setting due to temperature drop between the two thermocouples. The temperature drop is dependent on the thermal conductivity of the substrate (in this case alumina). It would be somewhat larger with a solar cell in place of the alumina. Since all the bonding process data to be presented gives the temperature setting, it must be remembered the actual interface temperature is well below that

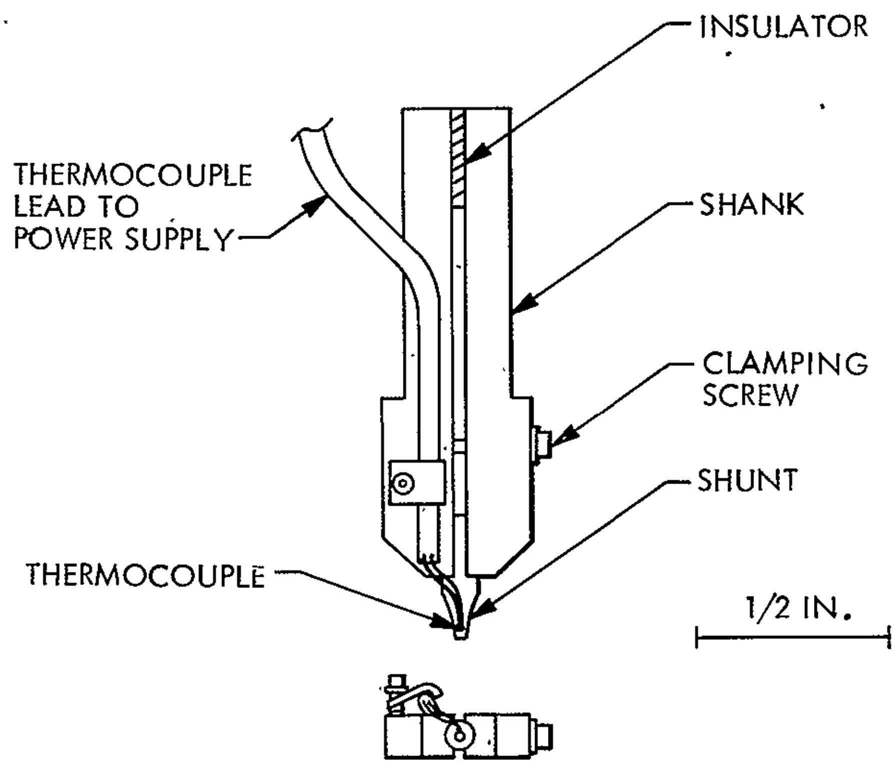


Figure 2-9 Shunted Tip, Unitek Model 10-128-01

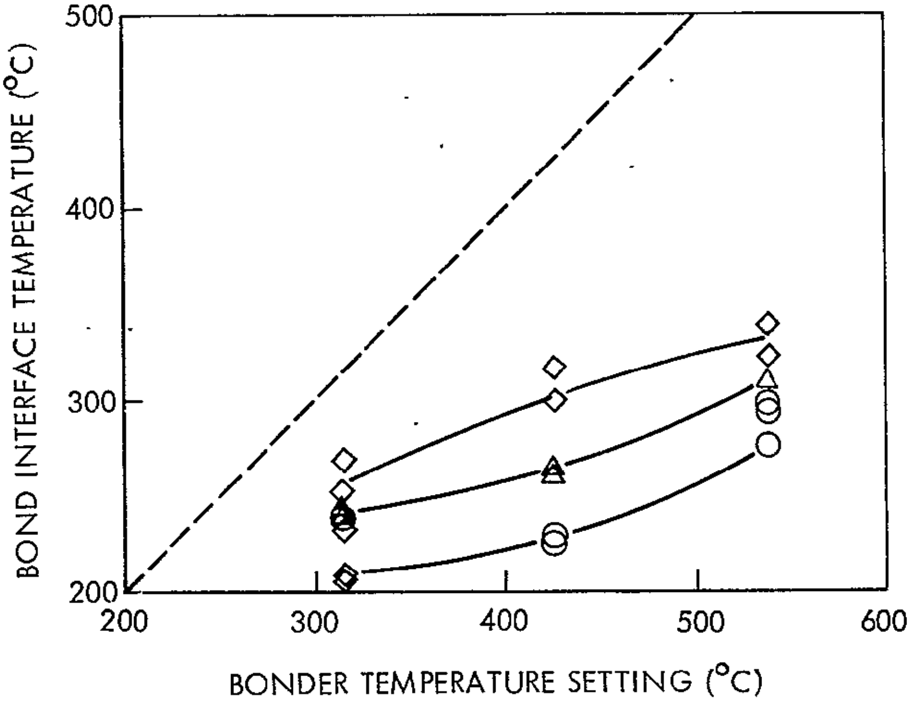


Figure 2-10 Bonder Temperature Setting vs Actual Bond Interface Temperature

value. Also, when using feedback temperature control it is important to have the thermocouple located as close as possible to the end of the tip contacting the workpiece. This will provide the best knowledge and control of bond interface temperature.

2.3 Bonding Process Development

The steps taken in determining the best interconnect metals and optimum bonding parameters (temperature, pressure, time) were summarized in Figure 2-1.

The bond parameters were scanned as follows:

Pressure	35.7 to 52.1 MN/m^2 (5172 to 7559 psi)
Time	.5 to 10 sec
Temperature	204 to 538°C (400 to 1000°F)

Using silver-plated 1 mil molybdenum tabs the optimum pull strengths were obtained at the following parameters (See Table 2-1):

Pressure	48.0 MN/m^2 (6962 psi)
Time	1.7 sec
Temperature	427°C (800°F)

Of all the materials and parameters tested, the minimum parameters which yielded good pull strengths were:

Pressure	35.7 MN/m^2 (5172 psi)
Time	.75 sec
Temperature	371°C (700°F)

The following plan then was executed to establish optimum bond parameters for several interconnect materials by varying pressure, time, and temperature. Bond parameters were compared by evaluating pull strengths at 45°. The materials used were those shown in Table 2-2.

1. Prepare 10 cells which meet mechanical specifications and have similar metalization thickness (mechanical cells) with 12 bonds each (Group I) using optimum bond parameters for silver-plated 1 mil molybdenum.
   - Pull 6 bonds at 45°
   - Temp cycle 50 times (-196°C to 150°C)
   - Pull remaining 6 bonds at 45°

TABLE 2-1

AVERAGE PULL STRENGTHS (gm)

1 mil silver-plated molybdenum bonded at 427°C (800°F)

Tip Pressure MN/m^2(psi)	5 [17]	2.3 [15]	1.7 [14]	1.1 [13]	.75 [12]	.50 [11]	Time (Sec)
52.1 (7559)	288* (3)	227* (29)		74* (2)	198* (4)	49* (2)	
50.7 (7360)		547 (3)	459 (3)				
48.0 (6962)		424 (4)	649 (4)				
45.3 (6564)			442 (2)				
42.5 (6167)			196 (2)				
39.1 (5669)			300 (5)				
35.7 (5172)		241 (7)	234 (3)				

optimum

1 mmDia Tip
45° Pulls
* Force/time not controlled
(i.e., temp turned on before full force was applied)

[ ] machine setting for time
( ) number of samples

2. Prepare 10 mechanical cells with 12 bonds each (Group II) using minimum parameters which yielded good bond strengths.

- Pull 6 bonds at 45°
- Temp cycle 50 times (-196°C to 150°C)
- Pull remaining 6 bonds at 45°

TABLE 2-2
INTERCONNECT MATERIAL CANDIDATES
FOR THERMOCOMPRESSION BONDING

A	-		1 oz. copper
B	-		1 mil silver
C	-	Silver-plated	1 oz. copper
D	-	Silver-plated	1 mil Invar
E	-	Silver-plated	1 mil Kovar
F	-	Gold-plated	1 oz. copper
G	-	Silver-plated	1 mil molybdenum
H	-	Gold-plated	1 mil molybdenum
I	-		2 mil silver
J	-	Gold-plated	1 mil Kovar

3. Prepare 10 mechanical cells at parameters which are selected after evaluating results of Groups I and II.

- Pull 6 bonds at 45°
- Temp cycle 50 times(-196°C to 150°C)
- Pull remaining 6 bonds at 45°

The pull strengths before and after temperature cycling and other data from Groups I, II and III are given in Table 2-3.

4. Select 4 best interconnect materials and their bonding parameters, based on high pull strength (45° pull), low degradation during temperature cycling, and a minimum pull strength of 200 grams. Prepare 4 cells with 12 bonds each (Group IV).

TABLE 2-3

AVG. PULL STRENGTHS (gm at 45°) BEFORE AND AFTER TEMPERATURE CYCLING FOR TEN TAB MATERIALS

GROUP I			GROUP II			GROUP III		
Before TC	After TC	Character	Before TC	After TC	Character	Before TC	After TC	Character
C 800	I 736	s, d	C 569	F 448*	s	D 800	D 684	s
I 711	D 639	s	B 383	D 421*	s	C 800	C 666	s
D 592	E 625	s, d	I 354*	I 400*	s	I 800	E 481	s,d
E 452	C 609	s, d	F 295*	B 398	It	F 769	G 477	s,d
F 419*	F 542*	s, d	D 180*	C 357*	s	G 573	F 420*	sd
B 378*	G 516	s, d	E 113*	E 351	s	E 566*	B 417	It
G 245*	B 371*	It	G 97*	G 338*	s	A 461	I 408*	s,d
A 138*	A 218*	s	A 89*	J 287*	s	B 460	A 367*	s
H 137*	H 181*	s, d	J 86*	H 170*	s	H 454*	H 365	s
J 133*	J 134*	Tm	H 35*	A 140*	s	J 429*	J 336*	s

See Table 2-2 for material code letters

* contains readings below 200 gm

GROUP I
Temp 427°C(800°F) Duration 1.7 sec Pressure 48.0 MN/m^2 (6962 psi)

GROUP II
371°C(700°F) .75 sec 35.7 MN/m^2 (5172 psi)

GROUP III
454°C(850°F) 1.1 sec 48.0 MN/m^2 (6962 psi)

Character of break (after temperature cycling)

d = divot
s = surface bond
It = tab material broke before bond
Tm = tab plating peeled

- Pull 6 bonds at 120°
- Temp cycle 50 times(-196°C to 150°C)
- Pull remaining 6 bonds at 120°

Table 2-4 lists the selected materials and their pull tab strengths before and after temperature cycling from Group III data.

5. Using same materials prepare 4 high-efficiency cells with 12 bonds each (Group V).
   - Pull 6 bonds at 120°
   - Temp cycle 50 times (-196°C to 150°C)
   - Pull remaining 6 bonds at 120°

Table 2-5 gives pull strength data for the 120° pull tests (Groups IV and V).

6. Measure electrical output (I-V) of 8 conventional and 4 high-efficiency cells (covered with 6 mil covers). For each of 4 selected interconnect materials, bond 2 conventional and 1 high-efficiency cells with 2 N-tabs and 2 P-tabs (Group VI).
   - Measure electrical resistance of each bond and electrical output (I-V) of each cell
   - Temp cycle 50 times (-196°C to +150°C)
   - Inspect bonds visually
   - Measure electrical output of each cell and resistance of each bond
   - Pull tabs at 45°

The results of the Group VI electrical tests are given in Table 2-6. The contact resistances increased 0 to 54% due to temperature cycling.

TABLE 2-4

SELECTED MATERIALS FROM GROUP III
BOND STRENGTHS (45° PULL, gm) BEFORE
AND AFTER TEMPERATURE CYCLING

MATL CODE	MATERIAL	BOND STRENGTH* BEFORE TC	AFTER TC
D	Silver-plated 1 mil Invar	800	684
C	Silver-plated 1 oz. copper	800	666
F	Gold-plated 1 oz. copper	769	420
G	Silver-plated 1 mil molybdenum	573	477

*Bond Parameters:

454°C (850°F), 1.1 sec, 48 MN/m^2 (6962 psi)

Temperature Cycling = 50 cycles

-196°C to +150°C

TABLE 2-5

GROUP IV & V
PULL STRENGTHS (120^{o} PULL, gm)
BEFORE AND AFTER TEMPERATURE CYCLING

GROUP	MATERIAL	Silver Plated 1 oz Copper	Gold Plated 1 oz Copper	Silver Plated 1 mil Invar	Silver Plated 1 mil Moly
IV Conven-tional Efficiency	Before TC	293	205	196	150
	After TC	306	294	280	203
V High Efficiency	Before TC	287	225	105	118
	After TC	192	198	141	172

TABLE 2-6

GROUP VI ELECTRICAL PERFORMANCE BEFORE/AFTER TC

45° PULL STRENGTH AFTER TC (grams)				CELL NO.	MATL.	CURRENT AT 470 MV (milliamps)			RESISTANCE OF P-CONTACT AT 25°C (milliohms)							
						CELL BEFORE BOND	AFTER BOND	AFTER TC	AFTER BOND				AFTER TC			
									1	2	3	4	1	2	3	4
800	85	500	800	(VI-H1) HE18	C	244.9	283.4	282.3		1.4	1.4			1.80	1.85	
462	426	265	350	(VI-H2) HE19	D	252.3	280.2	274.3		3.6	4.2			3.6	4.3	
530	143	460	341	(VI-H3) HE21	F	249.6	277.6	275.5		1.8	2.4			2.2	2.5	
245	275	191	X	(VI-H4) HE22	G	238.5	281.4	285.7		1.4	1.7			1.85	2.20	
63	800	800	800	(VI-C1) 393	C	252.5	251.7	248.7		1.7	1.7			1.9	1.9	
123	X	800	800	(VI-C2) 394	C	256.1	230.5	234.7		4.8	3.8			7.4	5.7	
800	800	637	612	(VI-C3) 395	D	255.1	251.8	252.7		1.1	1.0			1.15	1.1	
482	621	800	200	(VI-C4) 396	D	255.1	250.2	245.5		0.9	0.9			1.15	1.25	
35	X	800	630	(VI-C5) 397	F	252.2	---	---		-	3.2			-	4.1	
800	412	473	640	(VI-C6) 398	F	260.1	258.2	260.5		0.9	0.8			1.0	1.05	
346	270	479	202	(VI-C7) 399	G	258.8	248.9	258.1		1.2	1.2			1.3	1.4	
288	395	430	627	(VI-C8) 400	G	254.6	244.7	250.4		4.1	3.0			4.2	3.5	

TC - temperature cycling 50 times from -196°C to +150°C in air

X - bond failed prior to pull test

The effect of cell temperature on bond electrical resistance is shown in Table 2-7. Resistance values, measured at 25°C, -196°C and 150°C, increase significantly with temperature, although they remain too small to affect significantly the electrical output of a solar array. The resistance values at 25°C, before and after temperature cycling, are repeated from Table 2-6. One bond broke before the measurements were started; there were no bonds which failed as a result of either the temperature cycling or handling during resistance measurements.

Several variables were found to affect thermocompression bond quality. These are listed in Table 2-8 below.

TABLE 2-8

VARIABLES AFFECTING THERMOCOMPRESSION BOND QUALITY

Bonding Parameters
- Temperature
- Pressure
- Duration

Tip Geometry

Interconnect
- Material(s) used
- Thickness
- Adherence of plating

Cell Metalization
- Adherence to cell

Cleanliness of Parts

Oxide Formation

Handling Requirements

In summary, the 4 interconnect materials which performed best and were selected for fabrication of 12-cell test modules are:

Silver-plated, 1 mil Invar
Silver-plated, 1 ounce (approx. 1.3 mil) copper
Gold-plated, 1 ounce copper
Silver-plated, 1 mil molybdenum

A single set of bonding parameters was selected for all 4 materials:

TEMP CYCLING EXPOSURE	TEMPERA-TURE (°C)	ELECTRICAL RESISTANCE IN MILLIOHMS							
		Copper, 1 oz., Silver-Plated				Invar, 1 Mil, Silver-Plated			
		Cell No. 393		Cell No. 394		Cell No. 395		Cell No. 396	
		P1	P2	P1	P2	P1	P2	P1	P2
Before	-196	0.5	0.4	1.5	1.3	0.25	0.27	0.25	0.25
	25	1.7	1.7	4.8	3.8	1.1	1.0	0.9	0.9
	150	2.9	3.0	8.2	6.5	2.5	2.2	2.0	2.0
After	25	1.9	1.9	7.4	5.7	1.15	1.1	1.15	1.25

TEMP CYCLING EXPOSURE	TEMPERA-TURE (°C)	ELECTRICAL RESISTANCE IN MILLIOHMS							
		Copper, 1 oz., Gold-Plated				Molybdenum, 1 Mil, Silver-Plated			
		Cell No. 397		Cell No. 398		Cell No. 399		Cell No. 400	
		P1	P2	P1	P2	P1	P2	P1	P2
Before	-196	--	1.0	0.24	0.2	0.3	0.3	1.25	0.96
	25	--	3.2	0.9	0.8	1.2	1.2	4.1	3.0
	150	--	5.6	1.7	1.8	2.4	2.0	6.1	4.8
After	25	--	4.1	1.0	1.05	1.3	1.4	4.2	3.5

P1, P2 refer to the two tabs on P-contact of solar cell
-- = bond failed prior to resistance measurement

TABLE 2-7

ELECTRICAL RESISTANCE IN MILLIOHMS OF THERMOCOMPRESSION BONDS, CONVENTIONAL EFFICIENCY CELLS

TEMP CYCLING EXPOSURE	TEMPERATURE (°C)	ELECTRICAL RESISTANCE IN MILLIOHMS							
		Cu. 1 oz. Silver-Pl		Invar, 1 Mil, Silver-Pl		Cu, 1 oz, Gold-Pl Gold-Pl		Moly, 1 Mil, Silver-Pl	
		Cell No. HE-18		Cell No. HE-19		Cell No. HE-21		Cell No. HE-22	
		P1	P2	P1	P2	P1	P2	P1	P2
Before	-196	0.43	0.44	1.21	1.44	0.63	0.69	0.40	0.60
	25	1.4	1.4	3.6	4.2	1.8	2.4	1.4	1.7
	150	2.3	2.4	4.9	6.0	2.7	3.2	2.2	2.8
After	25	1.80	1.85	3.6	4.3	2.2	2.5	1.85	2.20

P1, P2 refer to the two tabs on P-contact of solar cells

TABLE 2-7 (cont.) ELECTRICAL RESISTANCE OF THERMOCOMPRESSION BONDS, HIGH EFFICIENCY CELLS

450°C (850°F)
1.1 second
48 MN/m^2 (6960 psi)

Bond strengths (45° pull) for these materials after 50 temperature cycles (-196°C to 150°C) were from 420 to 684 grams.

Electrical contact resistance increased 0 to 50% after temperature cycling.

2.4 12-Cell Module Fabrication

Four 12-cell test modules, one of which is shown in Figures 2-11 and 2-12, were made using the thermocompression bonding parameters and 4 interconnect materials selected at the end of the bonding process development task. The design was as much as possible like the SEP solar array baseline design. The solar cells were 2 x 4 cm, 8-mil thick, end tab wraparound cells with a 6-mil fused silica cover. Figure 2-13 shows the flexible printed interconnect circuit configuration, which is made up of the interconnect circuit sandwiched between sheets of 0.5-mil Kapton/ 0.5-mil polyester laminate, the polyester acting as a thermosetting adhesive to hold the 2 layers of Kapton and circuit together. The interconnect circuitry includes 3 terminal pads to permit electrical measurement of each half-circuit (3 cells in parallel by 2 in series) or the full circuit (3 by 4).

The fabrication of the flexible printed circuit was done as follows:

(1) Cut Kapton/polyester laminate film pieces and punch .100 in. dia. holes at 48 bond locations.

(2) Heat-laminate interconnect foil to base film at 350°F, 300 psi for 10 min.

(3) Print and etch interconnect circuit onto foil using KMER resist.

(4) Laminate cover film to base film/interconnect assembly at 350°F, 300 psi for 10 min.

The interconnect bonding was done on the Unitek Model 1-137-02 bonder with Model 10-128-01 tip using the following parameters:

Temperature = 454°C (850°F)

Time = 1.1 seconds

Pressure = 48 MN/m2 (6960 psi)

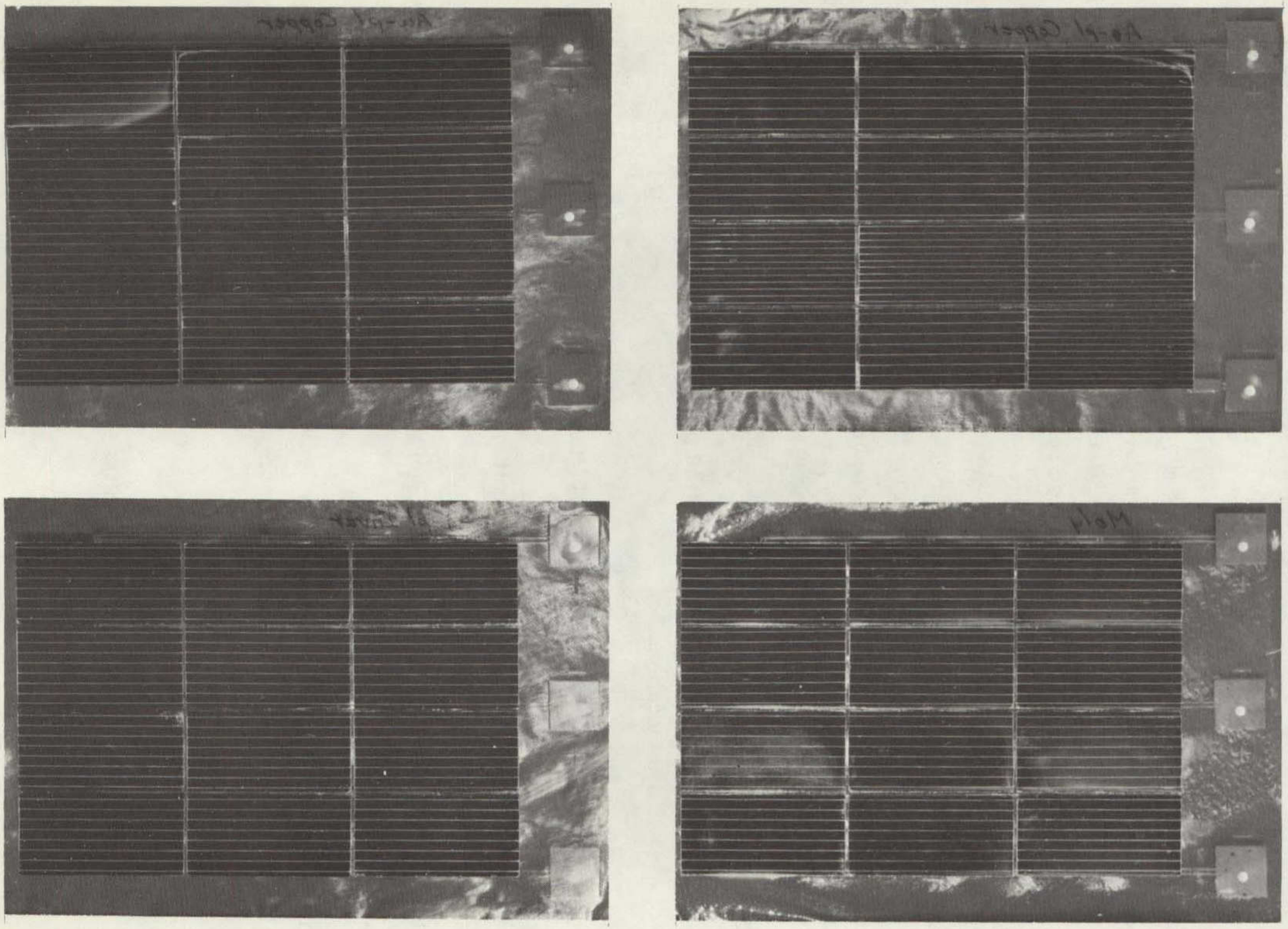


Figure 2-11 12-Cell Test Module, Thermocompression-Bonded - Front Side

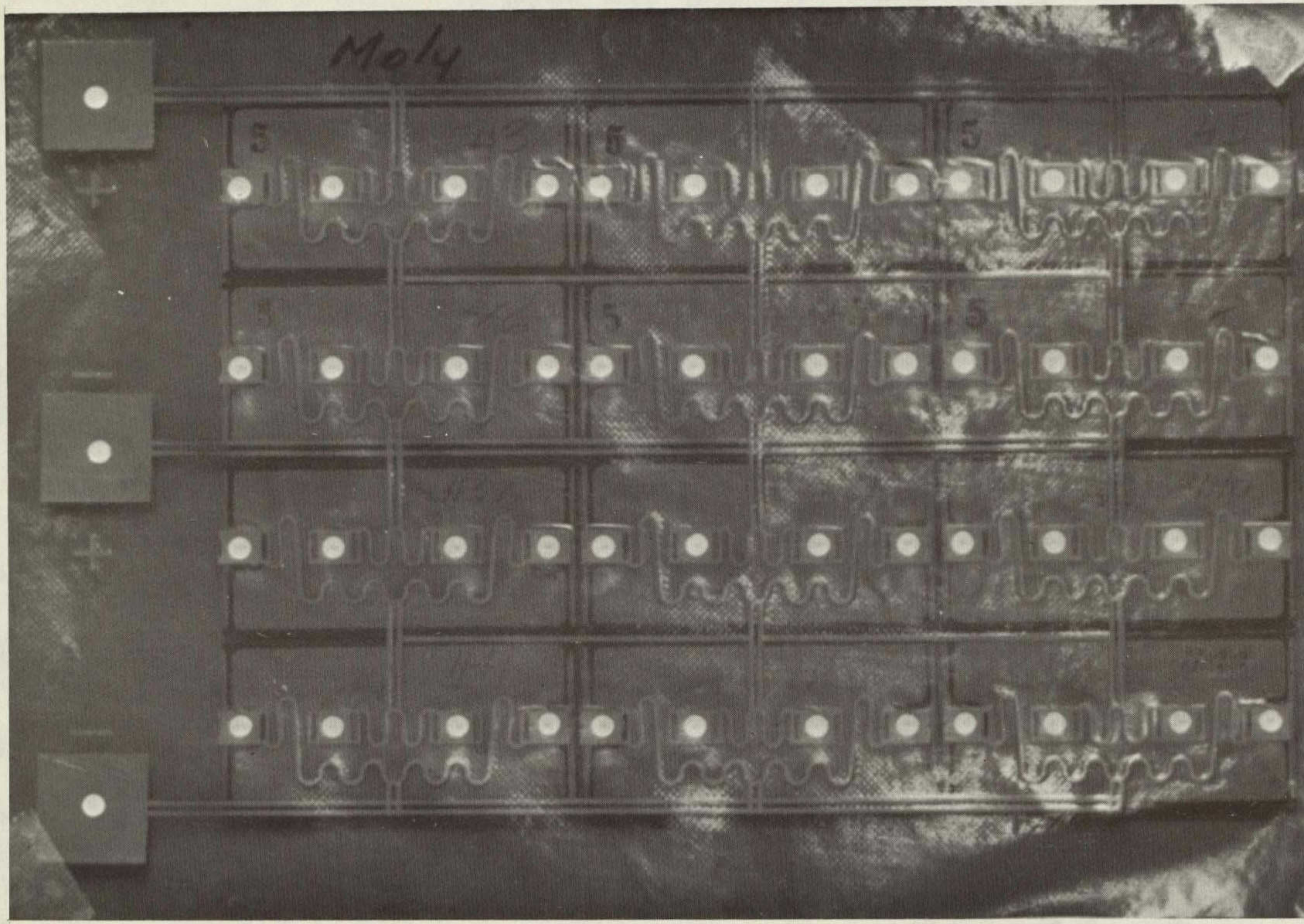


Figure 2-12 12-Cell Test Module, Thermocompression Bonded - Back Side

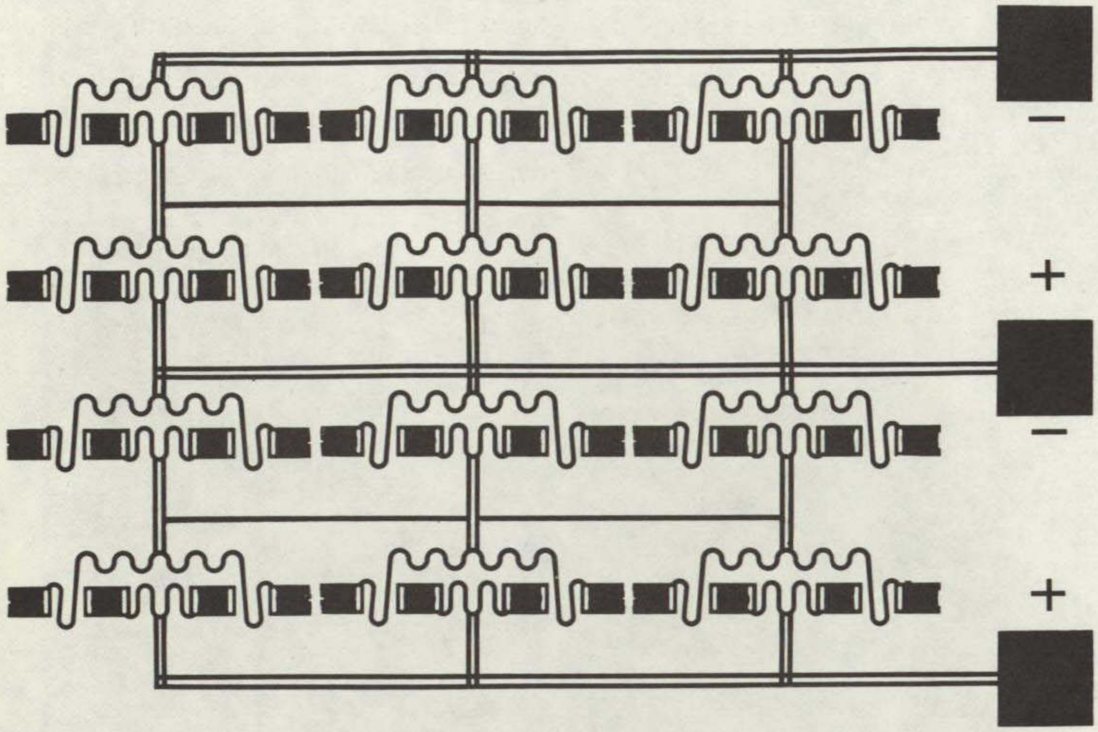


Figure 2-13 Interconnect Circuit, 12-Cell Test Modules

Much difficulty was encountered in making all the bonds hold, especially with the gold-plated copper module. Loose joints were subjected again to the bonding process, and if that did not succeed the entire cell was replaced. In removing a cell, it was always possible to break the good bonds on the cell without damaging the interconnect. Table 2-9 gives data on the number of loose bonds repaired and the number of cells that had to be replaced in repairing those bonds.

TABLE 2-9

BOND REPAIRS ON THERMOCOMPRESSION-BONDED MODULES

MODULE	NO. OF LOOSE BONDS REPAIRED	NO. OF CELLS REPLACED
Silver-Plated Copper	2	2
Gold-Plated Copper	17	9
Silver-Plated Molybdenum	5	3
Silver-Plated Invar	2	2

The cause of the bond failures is evidently due to the addition of the Kapton/polyester substrate, since such failures did not occur with the thermocompression-bonded pull tab specimens. The most likely cause is the polyester adhesive which melts locally during bonding and flows out over the bond access area, potentially contaminating the bond interface.

Two additional 12-cell modules with silver-plated copper and gold-plated copper were made to investigate the poor temperature cycling performance of the first two made of these materials. The bonding parameters were varied on these modules as shown in Figure 2-14.

SILVER-PLATED COPPER:

			427°C (800°F)	538°C (1000°F)
52 MN/m^2 (7560 psi)	1.1 Sec	370°C (700°F)		
	2.3 Sec	315°C (600°F)		
36 MN/m^2 (5170 psi)	1.1 Sec	370°C (700°F)		
	2.3 Sec	315°C (600°F)		

GOLD-PLATED COPPER:

		370°C (700°F)	427°C (800°F)	538°C (1000°F)
36 MN/m^2 (5170 psi)	1.1 Sec			
	2.3 Sec			
52 MN/m^2 (7560 psi)	1.1 Sec			
	2.3 Sec			

NOTE: The blocks represent solar cell locations in the test module

Figure 2-14 Thermocompression Bonding Parameters for Additional 12-Cell Test Modules

2.5 12-Cell Module Testing

The 4 thermocompression-bonded 12-cell test modules with their 4 different interconnect materials were tested electrically under 1 sun using the Spectrolab X-25 simulator. Their outputs are given in Table 2-10, and were satisfactory in all respects.

The modules then were temperature-cycled from -196°C to 150°C in the Quick-Look Tester. The Quick-Look Temperature Cycling Tester, pictured in Figure 2-15, was built to provide preliminary temperature cycling data rapidly, comprehensively and inexpensively. The test chamber uses the boil-off from an open container of liquid nitrogen to provide an inert environment at atmospheric pressure. Heat lamps are installed at the top of the chamber. A drive mechanism automatically cycles the test modules in 10-minute cycles between the lamps and the liquid nitrogen bath. During cooling, the modules were lowered just over the liquid nitrogen surface until they reached -125°C, then they were dunked into the liquid to be certain each sample was cooled to -196°C.

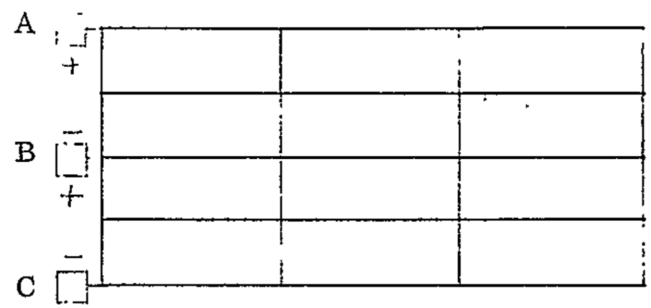
The modules' bond performance during 380 cycles is shown in Figures 2-16 and 2-17. None of the modules performed well, and the gold- and silver-plated copper interconnected modules lost most of their bonds. Consequently, 2 new gold- and silver-plated copper modules were made (ref. Section 2.4) to see whether better performance could be obtained with these materials.

The new modules replaced the old copper modules in the Quick-Look Tester since only 4 modules could be cycled at one time. Also the silver-plated Invar module was replaced by one conductive adhesive bonded module with silver-plated molybdenum interconnects. This was done to get more cycling data on the conductive epoxy module. The silver-plated Invar interconnect was dropped as a candidate because it was outperformed by the silver-plated molybdenum material and it is magnetic. Figures 2-18 and 2-19 give bond failure data for the new copper modules and 2 molybdenum modules. Only one bond failed on the DuPont 5504 conductive epoxy bonded module in 1080 cycles. This failure may have been due more to the probing to count bond failures (over 14 times) than to temperature cycling exposure. On the thermocompression-bonded, silver-plated molybdenum module there were no bond failures from 380 through 1080 cycles.

On the silver- and gold-plated copper modules, the bonds failed very rapidly. The gold-plated copper module withstood long-term temperature cycling somewhat better, perhaps because gold has a lower coefficient of thermal expansion than silver.

TABLE 2-10

ELECTRICAL OUTPUT BEFORE TEMPERATURE CYCLING 12-CELL MODULES, THERMOCOMPRESSION BONDING



INTERCONNECT MATERIAL	A TO B			B TO C			A TO C		
	I_{sc} (amps)	V_{oc} (volts)	I at .94V (amps)	I_{sc} (amps)	V_{oc} (volts)	I at .94V (amps)	I_{sc} (amps)	V_{oc} (volts)	I at 1.88V (amps)
Silver-Plated Copper	.81	1.15	.65	.89	1.16	.68	.84	2.3	.71
Gold-Plated Copper	.79	1.13	.57	.88	1.14	.57	.80	2.3	.63
Silver-Plated Molybdenum	.79	1.14	.56	.89	1.16	.57	.81	2.3	.67
Silver-Plated Invar	.79	1.13	.42	.86	1.16	.45	.82	2.3	.54

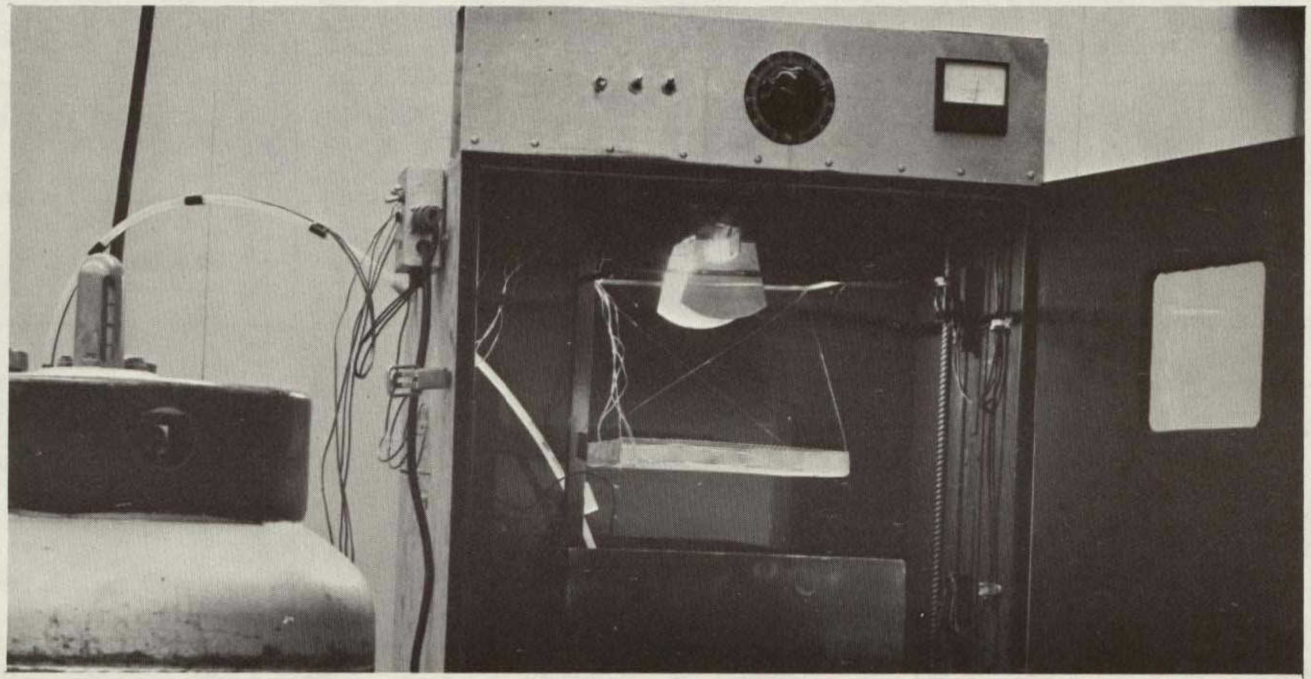


Figure 2-15 Quick-Look Temperature Cycling Tester

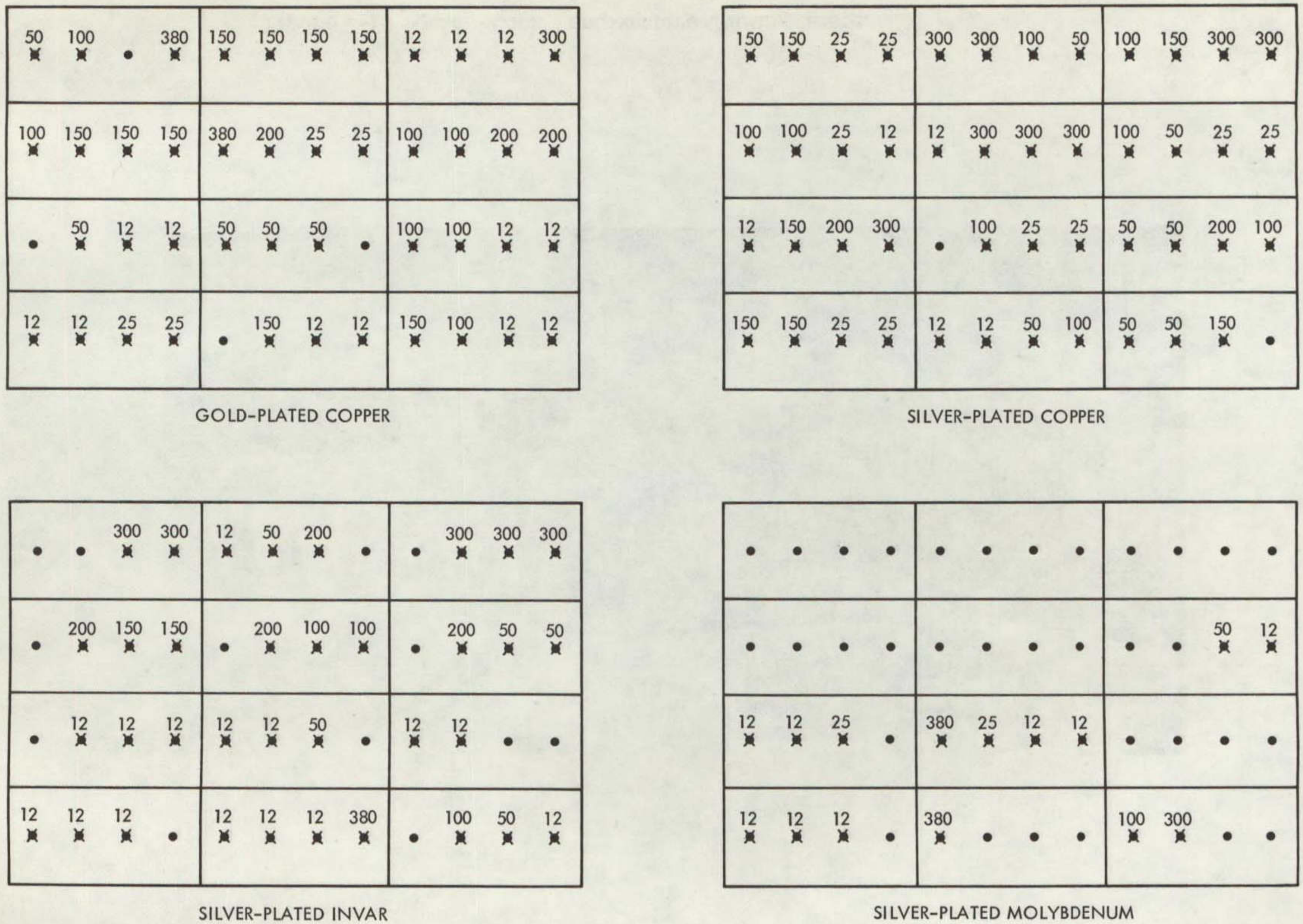


Figure 2-16 Bond Failure Data, 12-Cell Modules, Thermocompression Bonded

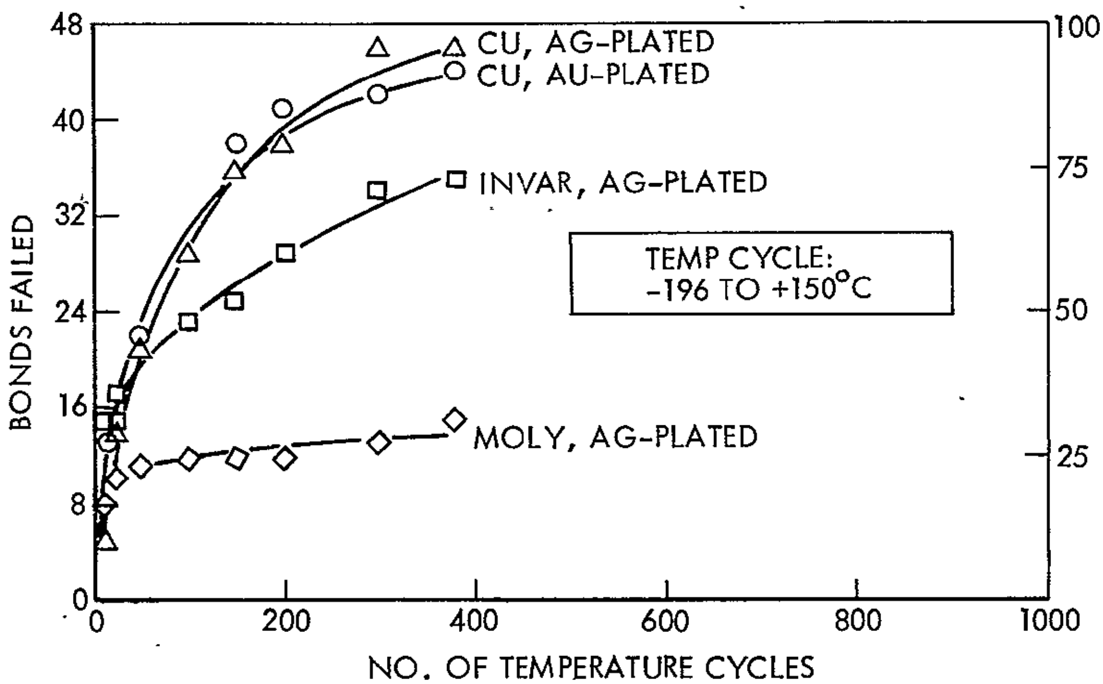


Figure 2-17 Bond Failure Histories, 12-Cell Modules, Thermocompression Bonded

3	3	3	3	17	10	3	3	3	3	10	44
10	10	•	300	980	10	10	10	20	20	100	100
3	3	10	21	50	890	10	3	90	50	20	20
10	10	10	50	3	3	50	700	400	•	•	•

T/C TC/GOLD - PLATED COPPER (NO. 2)

20	20	3	3	200	50	3	3	50	50	300	600
10	10	3	3	44	44	44	44	810	300	100	100
20	10	10	10.	13	13	3	3	20	20	52	52
3	3	3	3	44	44	20	20	100	100	100	600

TC/SILVER - PLATED COPPER (NO. 2)

•	•	•	•	•	•	•	•	•	•	•	•
•	•	•	•	•	•	•	•	•	•	•	•
•	•	•	•	580	•	•	•	•	•	•	•
•	•	•	•	•	•	•	•	•	•	•	•

DUPONT 5504/SILVER - PLATED MOLYBDENUM

•	•	•	•	•	•	•	•	•	•	•	•
•	•	•	•	•	•	•	•	•	•	50	12
12	12	25	•	380	25	12	12	•	•	•	•
12	12	12	•	380	•	•	•	100	300	•	•

TC/SILVER - PLATED MOLYBDENUM

Figure 2-18 Bond Failure Data, 12-Cell Modules, Final Testing

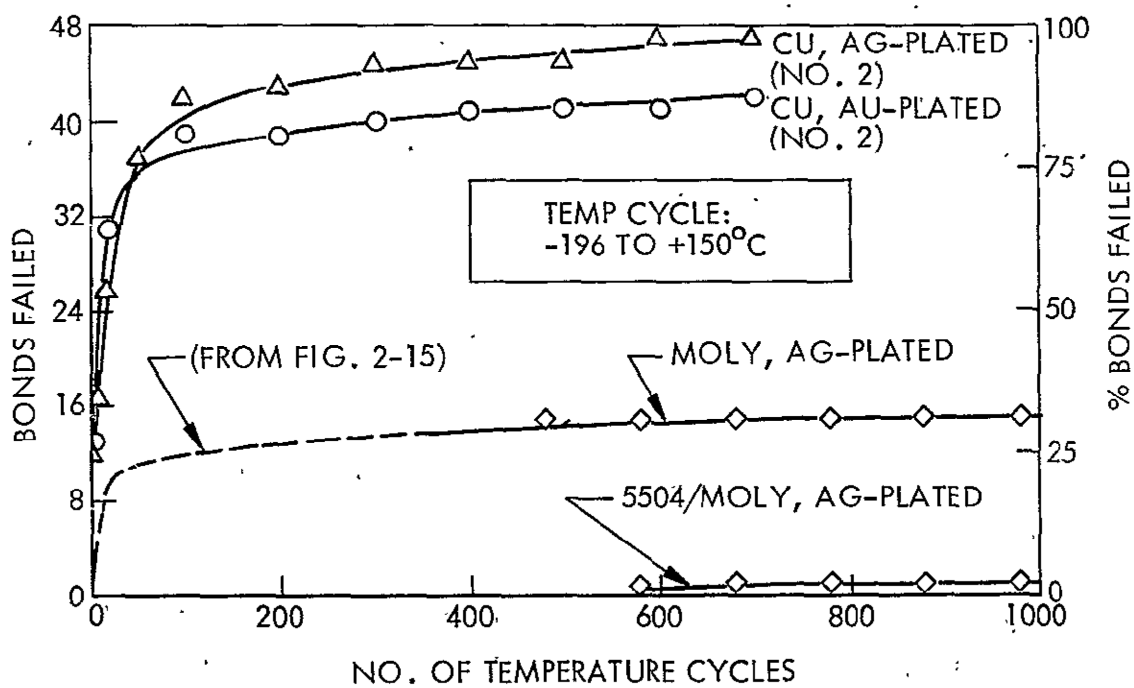


Figure 2-19 Bond Failure Histories, 12-Cell Modules, Final Testing

2.6 72-Cell Module Design Selection

Based on the tests performed and other pertinent data it was decided to build 72-cell modules of 2 different interconnect materials. The silver-plated molybdenum was an obvious selection having performed best in the temperature cycling of 12-cell modules. Copper was still of interest because the baseline SEP array uses a bare copper interconnect, even though copper did not perform well during the 12-cell module temperature cycling. Since the gold-plated copper 12-cell module performed better in temperature cycling than the silver-plated copper, it was selected as the second interconnect material. Gold also does not oxidize and thus requires less preparation than the silver-plated copper before bonding. The silver-plated Invar was eliminated because it did not perform as well as the silver-plated molybdenum, has a relatively high electrical resistance, and is magnetic.

Each module has 36 conventional efficiency cells and 36 high-efficiency cells. The interconnect circuitry has 2 separate 36-cell circuits; thus each cell type can be evaluated independently of the other.

The interconnect configuration and flexible printed circuit are the same as used on the 12-cell modules and conductive epoxy bonded 72-cell modules, except there are no holes through the interconnect at the bond locations.

The bond parameters selected are as established before except a longer duration was chosen based on the final copper module test data.

Temperature	=	454°C (850°F)
Pressure	=	48 MN/m^2 (6960 psi)
Time	=	2.3 seconds

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Section 3
CONDUCTIVE ADHESIVE DEVELOPMENT

3.1 Introduction

Epoxies, silicones and other polymers can be made electrically conducting by blending in metallic or carbon particles in the form of powder, fibers or flakes. To acquire a high conductivity, the particles must be mixed in the polymer in sufficient density to establish contact between a large percentage of them, thus providing continuous electrical pathways through the mixture. Possible conductive materials include silver, gold, palladium and platinum. Metals whose oxides are non-conductive are not desirable.

Electrically conductive adhesives are in common use in microelectronics for the electrical connection of semiconductors, capacitors and resistors. The advantages of adhesives over soldering or welding are:

- lower temperature bonding
- choice of interconnect materials not as critical
- ease of application
- adaptability to automated assembly

Epoxy-based conductive adhesives are favored over silicones and other polymers for the solar array application because of their:

- higher bond strength
- lower cure temperature
- relatively high electrical conductivity

A bibliography on conductive adhesives is included at the end of this Section.

3.2 Initial Screening Tests

A wide variety of conductive adhesives is available from numerous manufacturers. This large number of potential candidates makes it necessary to develop a process for screening them. A group of nine conductive epoxies was selected based on available industry experience and on a comparison of the required properties of electrical conductivity, bond strength, service temperature range, and outgassing. Six of the epoxies were suggested by MSFC and had met outgassing requirements. To these were added 2 Transene epoxies in common use in microelectronics at LMSC and Epotek H20E which the manufacturer stated was superior to H21D or H31D with respect to bond strength and pot life.

These 9 epoxies were put through comprehensive tests which are described in the Flow Chart for Conductive Adhesive Development and Testing, Figure 3-1. Essentially, the screening procedure was first to compare bond strengths of the 9 epoxies before and after temperature cycling, then to evaluate twelve candidate interconnect metals with the 4 best epoxies, and finally to select the four best epoxy/interconnect combinations.

The method of application was the first task undertaken. Sophisticated dot dispensers, available in LMSC's Microelectronics facilities, were tried; and it was verified that this equipment could apply epoxy dots on solar cells satisfactorily. However, because of small quantities of the candidate epoxies purchased and because the dispensers were not equipped to apply large enough dots, the epoxy was applied by hand with a needle for all of the single solar cell specimens. During this application evaluation, it was decided to try a screening technique for the 12-cell test modules because of its obvious potential for high production efficiency.

The test specimens were single solar cells with up to 20 pull tabs bonded on them. A minimum of 5 bonds was made for each test case to obtain statistically meaningful results.

Evaluate adhesive application methods-positive displacement dot, pressure dot, and silk screen-based on application ease, control and suitability for production

↓

Bond 10 bare copper pull tabs on a cell for each adhesive candidate (9 mech. cells)

↓

Perform 45° pull test on 5 bonds from each cell

↓

Subject cells to 50 high/low temperature cycles, -196 to 100°C

↓

Perform 45° pull test on remaining 5 bonds per cell

↓

Bond 10 silver-plated copper pull tabs on a cell for each adhesive candidate (9 mech cells)

↓

Perform 45° pull test on 5 bonds from each cell

↓

Measure electrical resistance of remaining 5 bonds at room temp.

↓

Subject cells to 50 high/low temperature cycles, -196 to 100°C

↓

Measure electrical resistance of remaining 5 bonds at room temp. after temp cycling

↓

Perform 45° pull test on remaining 5 bonds per cell

↓

Select 4 best adhesives, based on pull strength after temp cycling, elect. resist., etc.

↓

With 12 interconnect candidates, each with the 4 selected adhesives, bond 20 pull tabs on each of 24 mech cells to give 10 tabs per adhesive/interconnect combination

↓

Perform 45° pull test on 5 bonds of each combination

↓

Subject cells to 50 high/low temperature cycles, -196 to 150°C

↓

Perform 45° pull test on remaining bonds

↓

Select the 4 best interconnect material/adhesive combinations based on pull strength after temperature cycling, etc.

↓

Prepare another 10 bonds for each of 4 adhesive/interconnects

↓

Perform 120° pull test on 5 bonds

↓

Subject cells to 50 high/low temperature cycles, -196 to 150°C

↓

Perform 120° pull test on remaining 5 bonds

↓

Obtain IV curves of 20 electrical cells with covers

↓

Bond 4 tabs (2+, 2-) to each cell, using 5 cells for each of 4 adhesive/interconnect combinations (20 conv. cells)

↓

Obtain IV curves

↓

Measure electrical resistance of bonds at room temp. and at LN_2 temperature and 150°C

↓

Subject cells to 50 high/low temperature cycles, -196 to 150°C

↓

Measure electrical resistance of bonds at room temp. after temp cycling

↓

Obtain IV curves

↓

Perform 45° pull test on all bonds

↓

Select 4 adhesive/interconnect material combinations

Figure 3-1 ɪow Chart for Conductive Adhesive Screening Tests

The 9 conductive epoxies along with the filler metal and the number of components are listed in Table 3-1 below. The tabs were held in position during cure by the clamp shown in Figure 3-2. Curing was done for several hours, so it would undoubtedly be completed rather than be a variable in the early evaluation of adhesives.

TABLE 3-1

CONDUCTIVE ADHESIVE CANDIDATES

ADHESIVE	FILLER	NO. OF COMPONENTS
Ablebond 36-2	Silver	1
Ablebond 58-1	Gold	1
DuPont 5504	Silver	1
Epo-TekH20E	Silver	2 (1:1)*
Epo-Tek H21D	Silver	2 (10:1)
Epo-TekH31D	Silver	1
Epo-TekH44	Gold	1
Transene Ohmex-Ag	Silver	1
Transene GE-10	Gold	1

*( ) - Mixture ratio

The first set of pull tab specimens, shown in Figure 3-3, was made using copper tabs. After cure, 5 of the 10 tabs were pulled at 45°. The cure times and pull strength data are shown in Table 3-2.

Every bond failed at the copper-adhesive interface. There were several very poor bonds suggesting intermittent weakness due to copper oxidation and that better results would be obtained using silver-plated tabs. Because of the low pull strengths obtained, testing of these specimens was suspended.

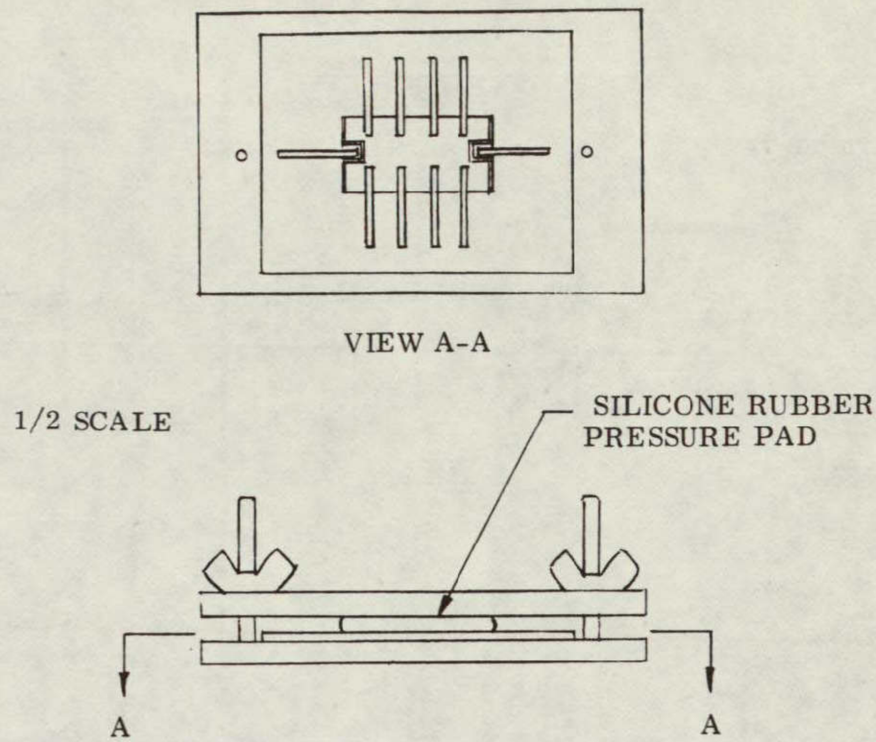


Figure 3-2 Curing Clamp

A second group of 9 solar cells, shown in Figure 3-4, was used to test the 9 conductive epoxies with silver-plated copper pull tabs. This time the end of the pull tab with the .060-inch hole was used to find out whether good bonds could be made by applying adhesive from the outside. The tab was first taped in position, which eliminated the need for clamping during cure. Then the epoxy was applied by hand, wetting the surface of the cell in the hole and covering most of the ring around the hole, thus providing a mushroom-shaped volume of adhesive. Ten (10) tabs were bonded onto a cell for each adhesive. Five (5) of the tabs were pulled at 45°. Then the electrical resistance of the 5 remaining tabs on each cell was measured, the cells were subjected to 50 temperature-cycles from -196°C to +100°C, and the electrical resistance and pull strengths of the remaining bonds were measured. The data obtained are shown in Table 3-3. The primary mode of bond failure during pull testing was the epoxy pulling out of the hole in the tab, followed by failure at the epoxy/cell interface. There also were 4 bonds which failed during temperature cycling or during pull testing afterward by silicon divoting.

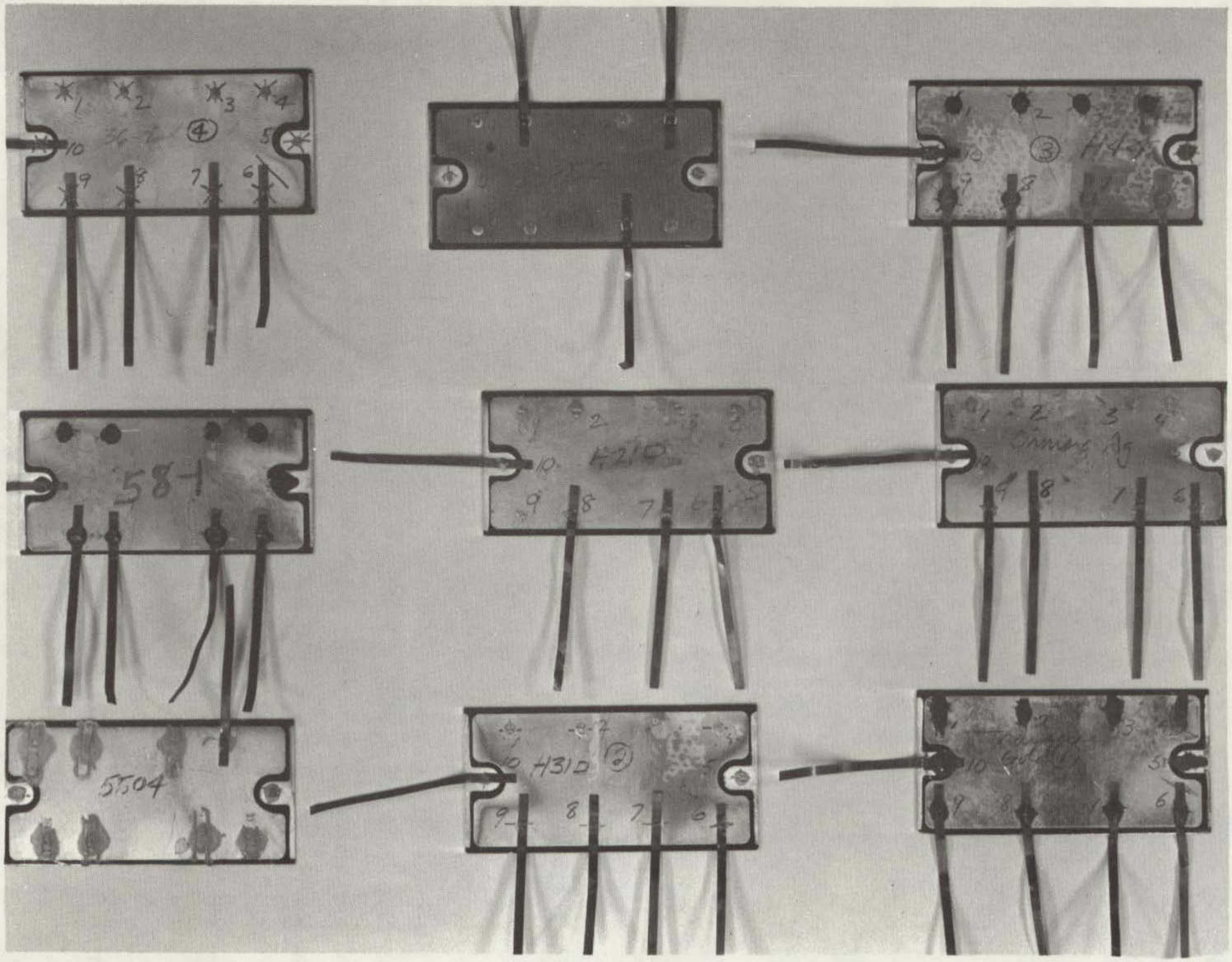


Figure 3-3 Copper Pull Tab Specimens

TABLE 3-2

INITIAL SCREENING OF CONDUCTIVE ADHESIVES, COPPER PULL TABS

Adhesive	Filler	Cure Temp (°C)	Cure Time (Hrs)	Pull Strength in Grams (5 Bonds)
Ablebond 36-2	Silver	150°	2.5	186, 95, 59, 45, 41
" " (2nd sample)	"		17.0	127, 64, 54, 14, 0
Ablebond 58-1	Gold		17.0	168, 118, 100, 73, 54
DuPont 5504	Silver		17.0	45, 45, 5, 0, 0
Epo-Tek H20E	Silver		15.0	36, 27, 9, *, *
Epo-Tek H21D	Silver		17.0	86, 73, 50, 50, *
Epo-Tek H31D	Silver		5.0	104, 73, 41, 32, 9
Epo-Tek H44	Gold		3.5	191, 145, 118, 100, 68
Transene Ohmex-Ag	Silver		16.5	227, 145, 109, 73, 59
Transene GE-10	Gold		16.0	408, 363, 313, 159, 104

*Tab lost during diasssembly, before pull test

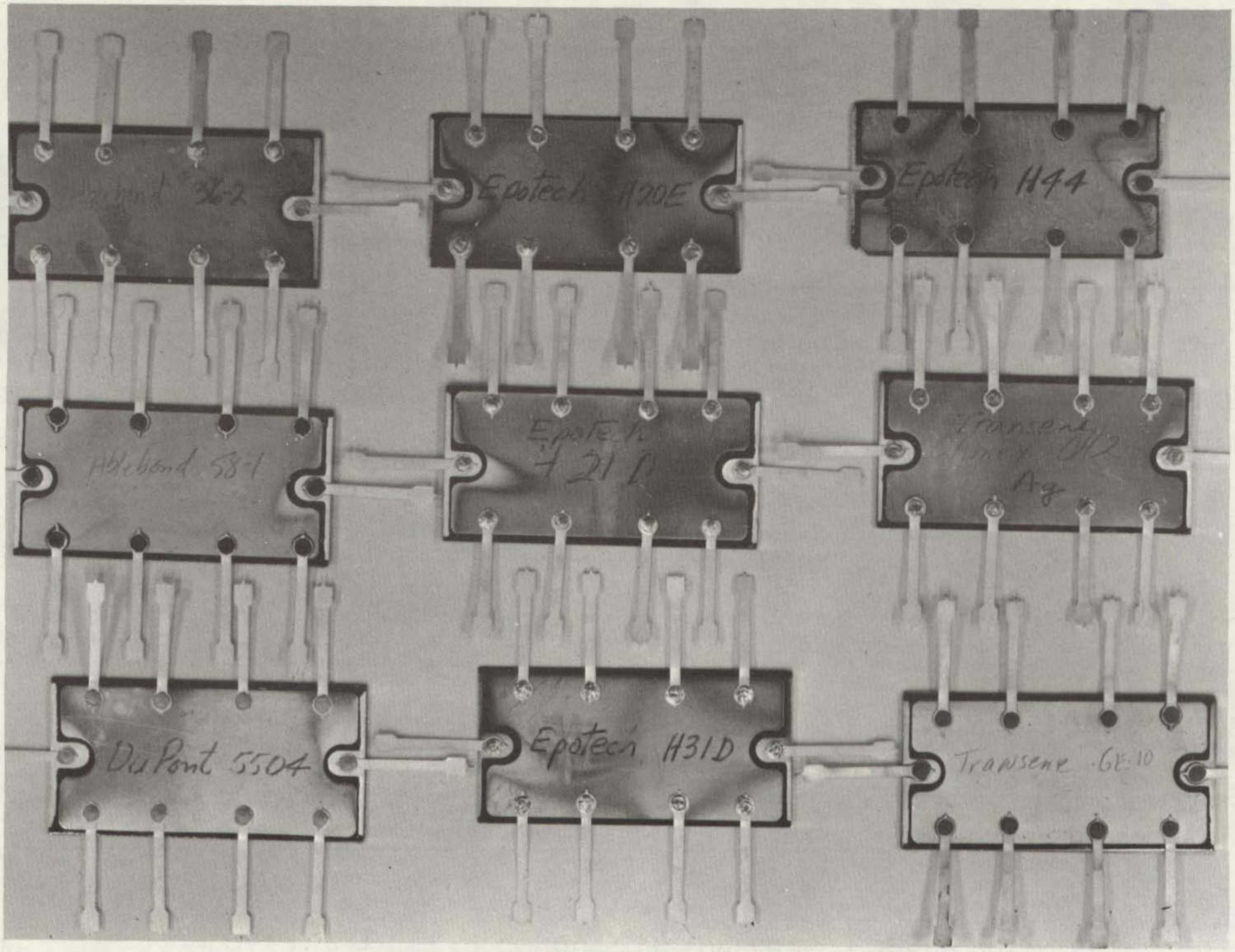


Figure 3-4 Silver-Plated Copper Pull Tab Specimens

TABLE 3-3

PERFORMANCE OF 9 CONDUCTIVE EPOXY CANDIDATES SILVER-PLATED 2 OZ. COPPER TABS

ADHESIVE	(1)	45° PULL STRENGTH IN GRAMS					ELECTRICAL RESISTANCE IN MILLIOHMS				
		1(2)	2	3	4	5	1(2)	2	3	4	5
36-2	B	599	422	363	363	358	5.0	5.0	6.0	6.5	8.0
	A	167	0	0	0	0	6.0	$>10^6$	(4)		
58-1	B	494	408	318	195	172	5.0	5.5	5.5	6.0	6.5
	A	541	343	218	91	31	13	37	49	94	249
5504	B	372	358	281	249	222	2.5	3.0	3.0	3.0	3.2
	A	346	113	99	60	45	2.9	3.5	3.5	3.7	4.0
H20E	B	748	508	540	404	145	4.0	5.0	5.0	6.0	8.0
	A	128	60	0	0	0	4.5	34			
H21D	B	472	381	358	41	36	4.0	5.0	5.0	5.5	6.0
	A	284	238	71	0	0	5.0	6.0	26		
H31D	B	721	490	404	277	191	6.0	6.5	8.5	8.5	18.5
	A	794	638	550	0(3)	0(3)	7.8	8.5	17	20	38
H44	B	812	308	227	177	145	3.5	4.5	5.0	5.2	6.3
	A	819	814	802	369	298	4.3	4.8	5.9	6.4	6.5
Ohmex-Ag	B	404	222	145	127	77	3.5	4.5	5.0	5.2	6.3
	A	0	0	0	0	0					
GE-10	B	494	413	308	277	268	2.3	4.8	5.2	7.0	9.7
	A	652	445	252	232	128	5.0	6.5	11.0	13.5	14.5

(1) B - Before temperature-cycling
A - After temperature-cycling
(2) Data listed 1-5 from best to worst
(3) Tab broke loose by divoting silicon after temperature cycling. Adhesive was not downgraded because of this result.
(4) Blank spaces represent broken-off tabs

TABLE 3-4

SELECTION OF BEST CONDUCTIVE EPOXIES

Adhesive	Pull Strength 10*	Electrical Resistance 7	Weight 3	Cost of Adhesive 3	Ease of Application 3	Total Score	Rank
36-2	0	0	24	24	21	69	7
58-1	70	14	12	6	21	123	5
5504	60	63	24	24	15	186	3
H20E	0	0	24	24	18	66	8
H21D	0	7	24	24	9	64	9
H31D	100	42	24	24	27	217	1
H44	100	56	12	6	27	201	2
Ohmex Ag	0	0	24	24	27	75	6
GE-10	90	49	12	6	21	178	4

*Weighting Factor

The temperature cycling of all the pull tab specimens was done by heating them under a lamp, then cooling them first by holding them over liquid nitrogen and then, when at -125°C, dunking them in the LN_2.

The 9 adhesive candidates were ranked as shown in Table 3-4 on the basis of pull strength data (particularly that after temperature cycling), electrical resistance, weight (density), cost of adhesive, and ease of application. Each adhesive was scored from 1 to 10 for each criterion, and this number was multiplied by the weighting factor to obtain the numbers shown. The ranking resulted in the selection of the following 4 adhesives for further investigation:

Epo-Tek	H31D	silver-filled
Epo-Tek	H44	gold-filled
DuPont	5504	silver-filled
Transene	GE-10	gold-filled

A third group of solar cells was used to test 12 different interconnect materials each with the 4 best adhesives. Twenty (20) pull tabs were bonded onto each of 24 cells giving a total of 480 tabs, or 10 tabs per adhesive/interconnect combination (providing a good statistical sampling). Five (5) tabs of each adhesive/interconnect combination were pulled at 45°. The cells were then subjected to 50 temperature cycles from -196°C to 150°C (note the higher maximum temperature), and the pull strengths of the remaining bonds were measured. The 12 interconnect materials and the pull strength data obtained are shown in Tables 3-5(a) and3-5(b). The square end of the tab was used in this group of cells. The predominant bond failure mode was epoxy/cell interface separation. There also were a few failures by silicon divoting.

Table 3-6 shows the 8 adhesive/interconnect combinations which yielded the highest pull strengths and ranks them on the basis of that pull strength, electrical resistance, weight of interconnect, ease of application, and cost of adhesive. The gold-plated 2 mil copper was derated 20 points (in pull strength column) because one bond failed by divoting of the silicon. Divoting appears to be a serious problem with the 2-mil copper and silver because of the relatively high coefficient of thermal expansion of these materials and the higher stress due to material thickness.

Next, 2 pull tab specimens were made using the 4 adhesive/interconnect combinations selected in Table 3-6, and pull-tested at 120°. Ten (10) tabs of each combination were prepared. In addition, on a third solar cell, the GE-10 and 5504 adhesives were interchanged, providing also the combinations of GE-10/gold-plated copper and 5504/bare copper. The 120° pull strength results are given in Table 3-7.

To determine the electrical performance of conductive epoxy bonded cells, 20 electrical cells each were bonded with 4 pull tabs at the 2 negative (end tabs) and 2 positive locations. The four selected adhesive/interconnect combinations were included, and 5 samples of each combination were made to provide a good statistical sample. The test sequence was as follows:

1. IV data of covered cells before bonding
2. IV data of cells with pull tabs bonded
3. Electrical resistance of all P-bonds at room temperature, LN_2 temperature (-196°C) and 150°C
4. Temperature cycling from -196°C to 150°C for 50 cycles
5. Electrical resistance of P-bonds at room temperature

TABLE 3-5(a)

PULL STRENGTHS AND RANKINGS OF 12 INTERCONNECT MATERIALS WITH 4 SELECTED ADHESIVES

Interconnect Material	(1)	DuPont 5504 Pull Strength in Grams 1(2)	2	3	4	5	Rank(3)	Transene GE-10 Pull Strength in Grams 1	2	3	4	5	Rank
Cu, 1 mil	B	210	119	119	0	0	11	414	320	315	295	252	1
	A	79	71	57	23	6		329	320	275	247	139	1
Cu, 2 mil	B	247	238	235	71	40	9	318	241	108	108	28	6
	A	119	77	23	23	(4)		142	133	113(D)	94(D)	51	
Cu, 1 mil Ag-plated	B	326	261	252	247	122	8	193	150	142	128	108	8
	A	122	113(D)	77	34	.6		159	106	71	54	14(D)	
Cu, 2 mil Ag-plated	B	264	213	187	170	164	10	119	99	85	82	20	12
	A	71	65	28	28	20		28	23	0	0		
Cu, 1 mil Au-plated	B	369	340	252	204	173	4	312	221	159	139	125	4
	A	241	204	125	91	91	8	150	111	108	102	102	7
Cu, 2 mil Au-plated	B	369	326	323	320	125	1	227	210	51			7
	A	465	249	196	181	113(D)	2	142	139	136	74	26	
Mo, 1 mil Ag-plated	B	329	281	232	230	130	3	96	88	54	34	34	11
	A	284	210	196	142	136	4	60	43	28	28	0	
Mo, 1 mil Au-plated	B	122	111	65	48	48	6	91	85	74	62	54	10
	A	125	108	105	102	51		99	68	43	37	14	
Kovar, 1 mil Ag-plated	B	196	167	164	159	57	5	207	204	170	156	147	2
	A	232	125	105	82	54		198	193	187	156	102	5
Kovar, 1 mil Au-plated	B	193	181	159	136	113	2	150	136	113	94	65	3
	A	284	215	187	147	142	3	210	198	187	111	99	6
Ag, 1 mil	B	184	173	162	147	139	12	266	258	247	227	170	5
	A	139	9	6	0	0		184	108	99	88	79	
Ag, 2 mil	B	536	519	459	425	405	7	238	235	198	133	71	9
	A	221	150(D)	96	79(D)	20(D)		170(D)	85(D)	51	37(D)	28(D)	

(1) B - Before temperature-cycling
A - After temperature-cycling

(2) Data listed 1-5 from best to worst

(3) Upper number - ranking for 1 adhesive
Lower, circled number - ranking for all 4 adhesives

(4) Blank spaces represent broken-off tabs

(D) Tab broke off leaving divot in silicon

TABLE3-5(b)

PULL STRENGTHS AND RANKINGS OF 12 INTERCONNECT MATERIALS WITH 4 SELECTED ADHESIVES

Interconnect Material	(1)	Epo-Tek H31D Pull Strength in Grams 1[2]	2	3	4	5	Rank[3]	Epo-Tek H44 Pull Strength in Grams 1	2	3	4	5	Rank
Cu, 1 mil	B	170	142	102	43	31	4	369	252	210	201	170	7
	A	57	57	40	28	11		20	0				
Cu, 2 mil	B	111	85	62	31	20	1	258	227	184	111	105	8
	A	99	65	62	51	23							
Cu, 1 mil Ag-plated	B	85	79	77	54	51	7	71	28	14	9	0	8
	A	34	34	20	(4)								
Cu, 2 mil Ag-plated	B	136	113	77	71	60	12	82	60	31	31	26	8
	A	0						0					
Cu, 1 mil Au-plated	B	128	99	74	71	51	11	689	686	516	490	247	2
	A	6	0					343	85	0			
Cu, 2 mil Au-plated	B	139	116	113	77	51	9	845	720	675	675	388	1
	A	14	6	6	0	0		179	65(D)	26			
Mo, 1 mil Ag-plated	B	28	6	0			5	57	57	34	28	14	4
	A	48	48	28	28	14		43	34	20			
Mo, 1 mil Au-plated	B	54	40	28	26	11	6	51	31	28	20	0	8
	A	48	43	28	28	9							
Kovar, 1 mil Ag-plated	B	85	85	68	60	57	3	71	34	34	28	20	5
	A	85	68	48	34	6		11	6	6			
Kovar, 1 mil Au-plated	B	96	77	62	60	40	2	71	51	37	6	0	3
	A	60	48	40	40	28		128	74	0	0	0	
Ag, 1 mil	B	173	139	130	119	113	8	159	85	85	60	57	6
	A	28	23	6	0	0		14	9	0	0		
Ag, 2 mil	B	156	145	99	62	28	10	318	204	196	139	119	8
	A	68											

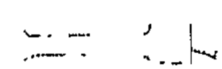
(1) B - Before temperature-cycling
A - After temperature-cycling

(2) Data listed 1-5 from best to worst

(3) Upper number - ranking for 1 adhesive
Lower, circled number - ranking for all 4 adhesives

(4) Blank spaces represent broken-off tabs

(D) Tab broke off leaving divot in silicon



Bonded Area

TABLE 3-6

SELECTION OF BEST ADHESIVE/INTERCONNECT COMBINATIONS

Interconnect Material	Adhesive	Pull Strength 10*	Electrical Resistance 7	Weight of Interconnect 3	Ease of Application 3	Cost of Adhesive 3	Total Score	Rank
Cu, 1 mil	GE10	100	49	30	21	6	206	3 **
Cu, 2 mil, Au-plated	5504	70	63	9	15	24	181	6
Kovar, 1 mil, Au-plated	5504	90	63	24	15	24	216	1 **
Mo, 1 mil, Ag-plated	5504	90	63	24	15	24	216	1 **
Kovar, 1 mil, Ag-plated	GE10	85	49	24	21	6	185	5
Kovar, 1 mil, Au-plated	GE10	80	49	24	21	6	180	7
Cu, 1 mil, Au-plated	GE10	75	49	24	21	6	175	8
Cu, 1 mil, Au-plated	5504	70	63	24	15	24	196	4 **

Pull strength used is that after temperature cycling

*Weighting factor

**Preliminary selections

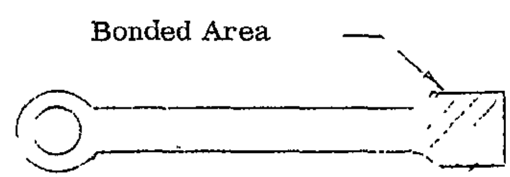
TABLE 3-7

120° PULL STRENGTHS OF SELECTED ADHESIVE/INTERCONNECT COMBINATIONS

ADHESIVE	INTERCONNECT	(1)	120° PULL STRENGTHS IN GRAMS					
			1(2)	2	3	4	5	Avg
GE-10	Copper, 1 oz. Unplated	B	96	60	57	48	0	52
		A	85	79	65	51	23	61
5504	Copper, 1 oz. Gold-plated	B	105	99	96	60	51	82
		A	65	62	54	51	28	52
	Molybdenum, 1 mil Silver-plated	B	122	68	48	43	37	64
		A	204	91	57	48	37	87
	Kovar, 1 mil Gold-plated	B	130	105	85	74	74	94
		A	136	65	37	34	34	61
GE-10	Copper, 1 oz. Gold-plated	B	60	60	57	57	37	54
		A	57	48	43	43	17	42
5504	Copper, 1 oz. Unplated	B	28	14	11	6	0	12
		A	14	0	0	0	0	3

(1) B - Before temperature cycling
A - After temperature cycling

(2) Data listed 1-5 from best to worst



6. IV data
7. 45° pull test on all bonds

The electrical output was measured using an OCLI Model 31 solar simulator. The test results are presented in Tables 3-8(a), 3-8(b), and 3-9.

In Table 3-8(a) it is seen that the GE-10/unplated copper combination had poor electrical resistance after temperature cycling. Consequently, additional tests were run replacing unplated copper with gold-plated copper tabs. At the same time, it was decided to include unplated copper again for a more direct comparison, and to look at another gold-filled epoxy, Epotech H44, which had exhibited some high bond strengths in earlier testing. The pull strengths and electrical resistance data obtained are shown in Tables 3-10 and 3-11. It is clear that GE-10/gold-plated copper is the best choice among these four (4) combinations. Therefore, it was chosen to replace GE-10/unplated copper as one of the final 4 selections.

On the basis of these comprehensive screening tests, the following 4 adhesive/interconnect material combinations were selected.

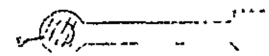
INTERCONNECT MATERIAL	ADHESIVE
Kovar, 1 mil, gold-plated	DuPont 5504
Molybdenum, 1 mil, silver-plated	DuPont 5504
Cu, 1 mil, gold-plated	Transene GE 10
Cu, 1 mil, gold-plated	DuPont 5504

TABLE 3-8 (a)

ELECTRICAL RESISTANCE OF CONDUCTIVE ADHESIVE BONDS

COPPER, 1 MIL, UNPLATED; GE10

BONDED AREA --



TEMP CYCLING EXPOSURE	TEMP (°C)	ELECTRICAL RESISTANCE IN MILLIOHMS									
		CELL NO. C2		C3		C4		C5		C6	
		P1	P2	P1	P2	P1	P2	P1	P2	P1	P2
BEFORE	25			250	340	150	210	150	150	47	36
	-196			2300	230	118	165	113	118	39	31
	150			52	600	132	460	330	255	640	80
AFTER 50 CYCLES	25	21,000	6,500	>10^5	76,000	60,000	>10^5	1050	2700	20,000	>10^5

COPPER, 1 MIL, GOLD-PLATED; 5504

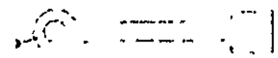
TEMP CYCLING EXPOSURE	TEMP (°C)	ELECTRICAL RESISTANCE IN MILLIOHMS									
		C7		C8		C9		C11		C12	
		P1	P2	P1	P2	P1	P2	P1	P2	P1	P2
BEFORE	25	Broke	1.0	1.5	1.5	Broke	Broke	1.0	1.0	2.9	2.6
	-196	--	0.3	Broke	0.0	--	--	0.0	0.4	Broke	0.0
	150	--	2.0	--	Broke	--	--	2.9	1.85	--	Broke
AFTER 50 CYCLES	25	--	1.6	--	--	--	--	2.1	1.9	--	--

NOTE: P1 and P2 refer to the two tabs on P contact of solar cell.

TABLE 3-8 (b)

ELECTRICAL RESISTANCE OF CONDUCTIVE ADHESIVE BONDS

KOVAR, 1MIL, GOLD-PLATED; 5504

BONDED AREA 

TEMP CYCLING EXPOSURE	TEMP (°C)	ELECTRICAL RESISTANCE IN MILLIOHMS									
		C13		C14		C15		C16		C17	
		P1	P2	P1	P2	P1	P2	P1	P2	P1	P2
BEFORE	25	1.2	1.7	3.0	3.1	2.0	2.5	1.8	--	3.7	3.6
	-196	0.51	0.67	2.31	1.13	0.86	0.45	0.57	--	0.97	1.11
	150	3.3	3.8	Broke	8.0	6.9	5.3	4.2	--	7.5	7.9
AFTER 50 CYCLES	25	2.8	2.9	--	5.4	4.8	3.4	2.8	--	6.1	4.9

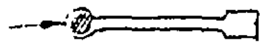
MOLYBDENUM, 1 MIL, SILVER-PLATED; 5504

TEMP CYCLING EXPOSURE	TEMP (°C)	ELECTRICAL RESISTANCE IN MILLIOHMS									
		C18		C19		C20		C21		C22	
		P1	P2	P1	P2	P1	P2	P1	P2	P1	P2
BEFORE	25	1.2	1.5	2.3	2.5	1.0	1.3	1.1	1.6	1.6	1.9
	-196	0.52	0.54	1.78	1.15	0.40	0.41	0.61	0.83	1.55	1.69
	150	4.4	3.1	12.4	5.2	2.8	4.7	4.5	Broke	3.5	8.5
AFTER	25	3.6	4.1	--	4.8	2.6	2.6	3.5	--	6.8	6.7

NOTE: P1 and P2 refer to the two tabs on P-contact of solar cell.

TABLE 3-9

45° PULL STRENGTHS AFTER TEMPERATURE CYCLING CONDUCTIVE ADHESIVE BONDS, IN GRAMS

Bonded Area 

COPPER, 1 OZ., UNPLATED: GE10

CELL NO.	TAB NO.			
	N1	N2	P1	P2
C2	17	6	71	62
C3	65	0	45	23
C4	14	9	51	57
C5	43	34	74	82
C6	3	31	40	37

KOVAR, IMIL, GOLD-PLATED; 5504

CELL NO.	TAB NO.			
	N1	N2	P1	P2
C13	60	54	187	99
C14	119	122	26	--
C15	51	232	54	3
C16	48	85	--	196
C17	184	173	54	88

COPPER, 1 OZ., GOLD-PLATED; 5504

CELL NO.	TAB NO.			
	N1	N2	P1	P2
C7	96	85	--	0
C8	65	0	--	--
C9	57	17	--	--
C11	20	0	34	0
C12	0	23	--	--

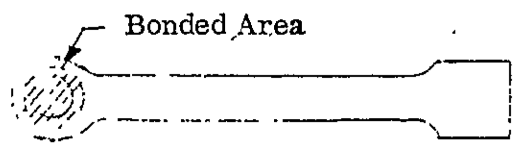
MOLYBDENUM, 1 MIL, SILVER-PLATED; 5504

CELL NO.	TAB NO.			
	N1	N2	P1	P2
C18	79	201	0	6
C19	301	133	122	0
C20	34	--	0	6
C21	0	85	--	14
C22	156	91	0	0

NOTE: N1, N2, P1 and P2 refer to location on N-contact and P-contact of solar cell.

TABLE 3-10

45° PULL STRENGTHS OF ADDITIONAL SELECTED ADHESIVE/INTERCONNECT COMBINATIONS



ADHESIVE	INTERCONNECT	(1)	45° PULL STRENGTH IN GRAMS					
			1 (2)	2	3	4	5	AVG.
GE-10	COPPER, 1 oz. UNPLATED	B	312	286	232	227	119	235
		A	360	232	193	133	26	189
	COPPER, 1 oz. GOLD-PLATED	B	437	278	227	215	190	269
		A	320	278	227	215	77	223
H44	COPPER, 1 oz. UNPLATED	B	337	264	225	207	150	243
		A	94	0	R	TC-13	TC-10	19
	COPPER, 1 oz. GOLD-PLATED	B	448	380	326	318	303	355
		A	147	68	34	23	0	54

(1) B - Before temperature cycling
A - After temperature cycling

(2) Data listed 1-5 from best to worst

R - Tab broke loose during elec. resist. meas. after temp. cycling

TC-XX - Tab broke loose during temp. cycling at Cycle XX

TABLE 3-11

ELECTRICAL RESISTANCE OF ADDITIONAL SELECTED ADHESIVE/
INTERCONNECT COMBINATIONS

ADHESIVE	INTERCONNECT	(1)	ELECTRICAL RESISTANCE IN MILLIOHMS										
			1	2	3	4	5	6	7	8	9	10	AVG
GE-10	COPPER, 1 oz. UNPLATED	B	17.8	25.2	30.5	30.0	16.5	36.3	121	18.0	94.0	13.7	40.3
		A						5,650	10,000	1,320	$>10^5$	570	$>10^4$
	COPPER, 1 oz. GOLD-PLATED	B	1.60	2.25	1.76	1.91	2.26	[illegible].42	1.56	1.48	2.18	0.74	1.72
		A						2.30	2.95	2.75	4.10	0.85	2.59
H44	COPPER, 1 oz. UNPLATED	B	3.50	2.95	2.82	3.00	3.21	1.75	2.15	2.45	3.20	1.90	2.69
		A						TC*	2,200	70	TC	44	—
	COPPER, 1 oz. GOLD-PLATED	B	1.67	2.40	1.92	1.54	1.62	1.85	1.92	1.42	1.84	1.56	1.77
		A						5.15	1.40	7.00	6.75	2.40	4.54

*Tab broke loose during temperature cycling

3.3 12-Cell Module Fabrication

Four 12-cell test modules, one of which is shown in Figures 3-5 and 3-6, were fabricated using the 4 selected epoxy/interconnect combinations. The flexible printed interconnect circuits were fabricated in the same way as for the thermocompression bonded 12-cell modules, as described in Section 2.3. The interconnect circuit design is identical (see Figure 2-9), except that .050 in. holes have been added in the bond areas so that epoxy can be applied after the circuit and cells are assembled into place.

The epoxy was applied to the module assembly as pictured in Figure 3-7, using a Presco Model 150 screen printer. A 48-hole bond pattern was photo-developed on a 200-mesh stainless steel screen which subsequently was mounted horizontally on the printer. The 12 solar cells were placed active side down on a vacuum fixture, shown in Figures 3-7 and 3-8. The flexible printed circuit was laid in place over the cells, the vacuum holding it. The fixture with the module components was positioned under the hole pattern and 1-2 mm from the screen. The printing operation was then performed in which the squeegee is forced pneumatically down and over the hole pattern, pressing the screen against the module assembly and squeezing epoxy through the holes onto the interconnect circuit and solar cells. The assembly, still under vacuum, finally was put in an oven to cure at 150°C for 15 hours.

3.4 12-Cell Module Testing

The 4 12-cell modules using conductive epoxies were tested according to the following procedure:

(1) Attach thermocouples, 1 on each module
(2) Measure IV data at 28°C, using X-25 solar simulator
(3) Mount modules in Quick Look Tester, connect thermocouples, set cycle counter, etc.
(4) Start 10-min temperature cycles, +150°C to -196°C
(5) Inspect modules periodically for bond failures, and record observations
(6) After cycling, repeat IV measurements

The 4 modules were put through 380 cycles. Counts of loose bonds were made at 11, 86, 100, 125, 175, 200, 212, 229, 250 and 380 cycles.

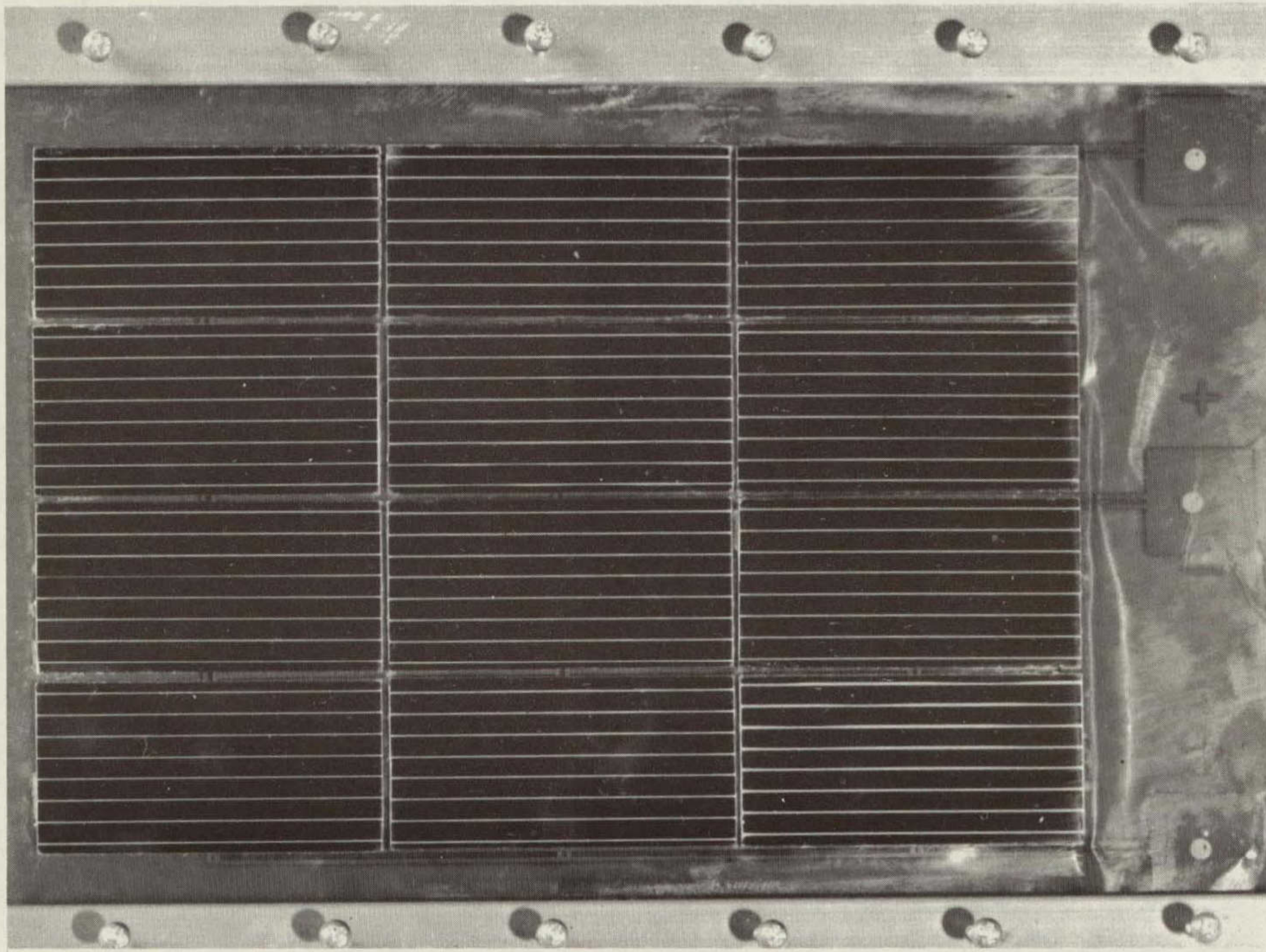


Figure 3-5 12-Cell Test Module, Conductive Adhesives - Front Side

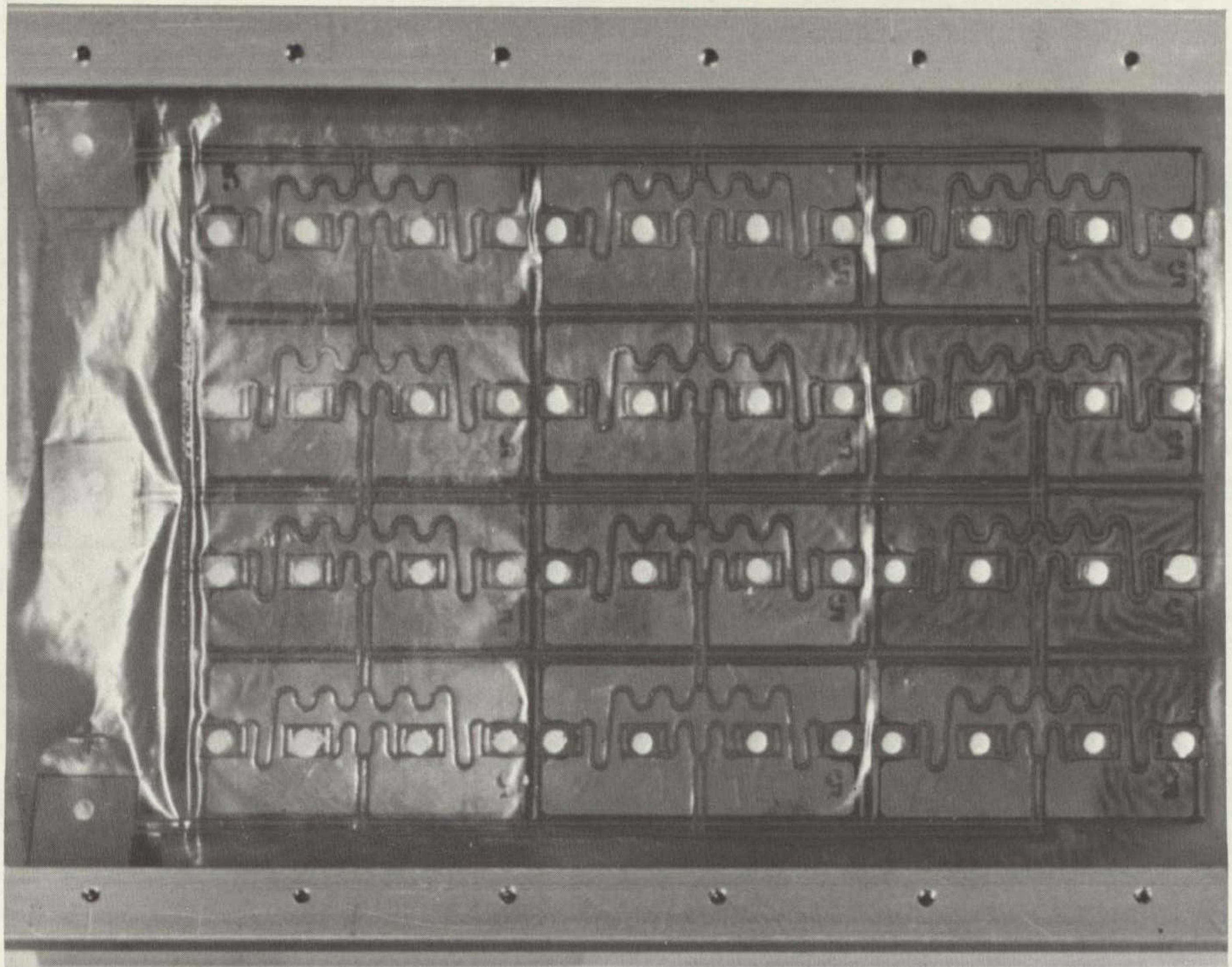


Figure 3-6 12-Cell Test Module, Conductive Adhesives - Back Sides

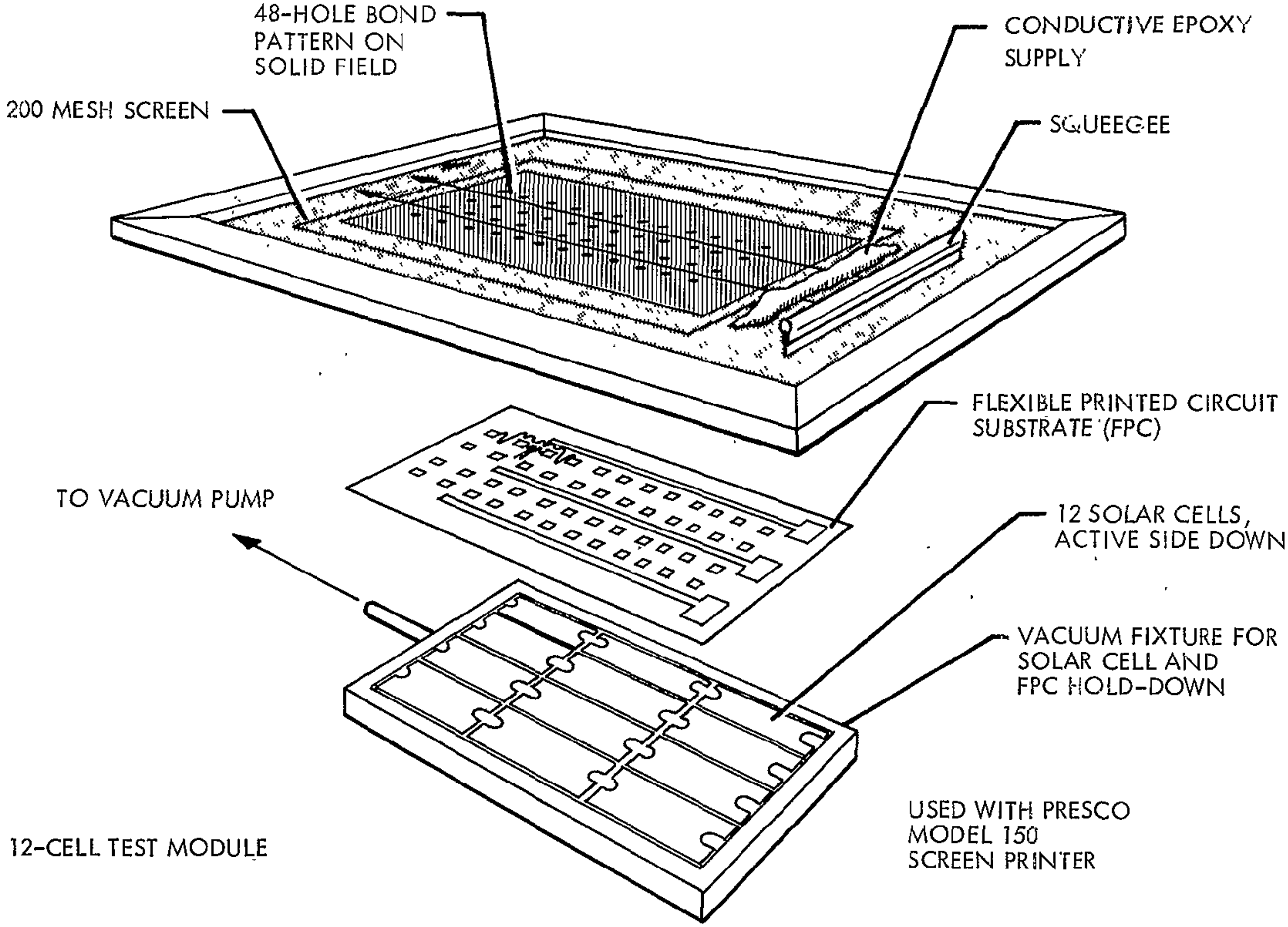


Figure 3-7 Conductive Epoxy Bonding by Screen Printing

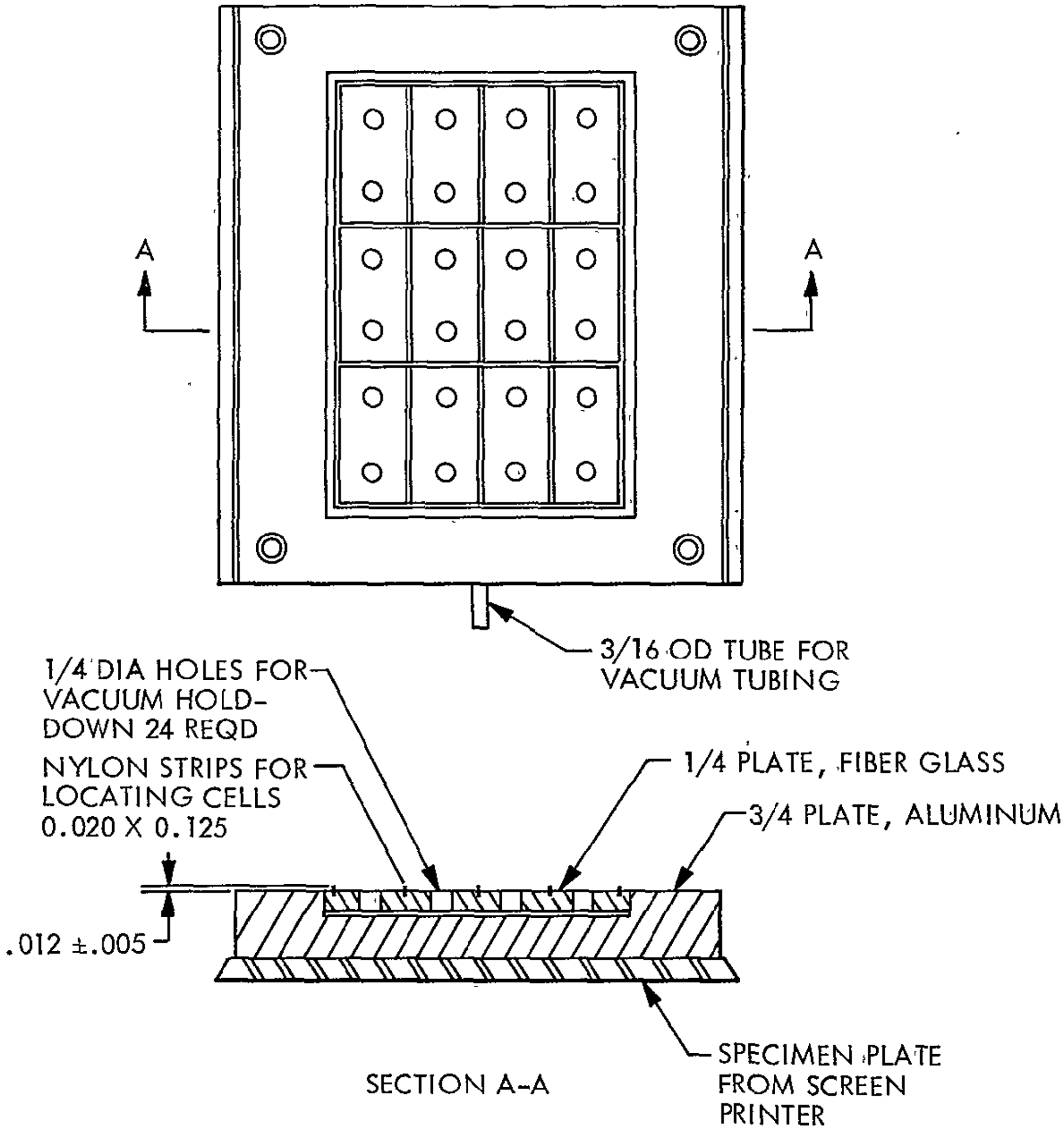


Figure 3-8 12-Cell Module Assembly Fixture

Figure 3-9 presents bond failure data on each module, showing each bond that failed and the cycle number at which the failure was observed.

Bond thermal stresses occur two ways. First, the epoxy/solar cell interface and the epoxy/interconnect interface are stressed due to the different thermal expansion coefficients of the materials. Second, stresses are caused by contraction during cool-down of the FPC between bonds. In this second case, the end-tab wraparound cell is expected to have higher stress at the N-tabs (outside contacts) than at the P-contacts, because with 4 bonds in line there are forces at the inside bonds in both directions, counter balancing each other.

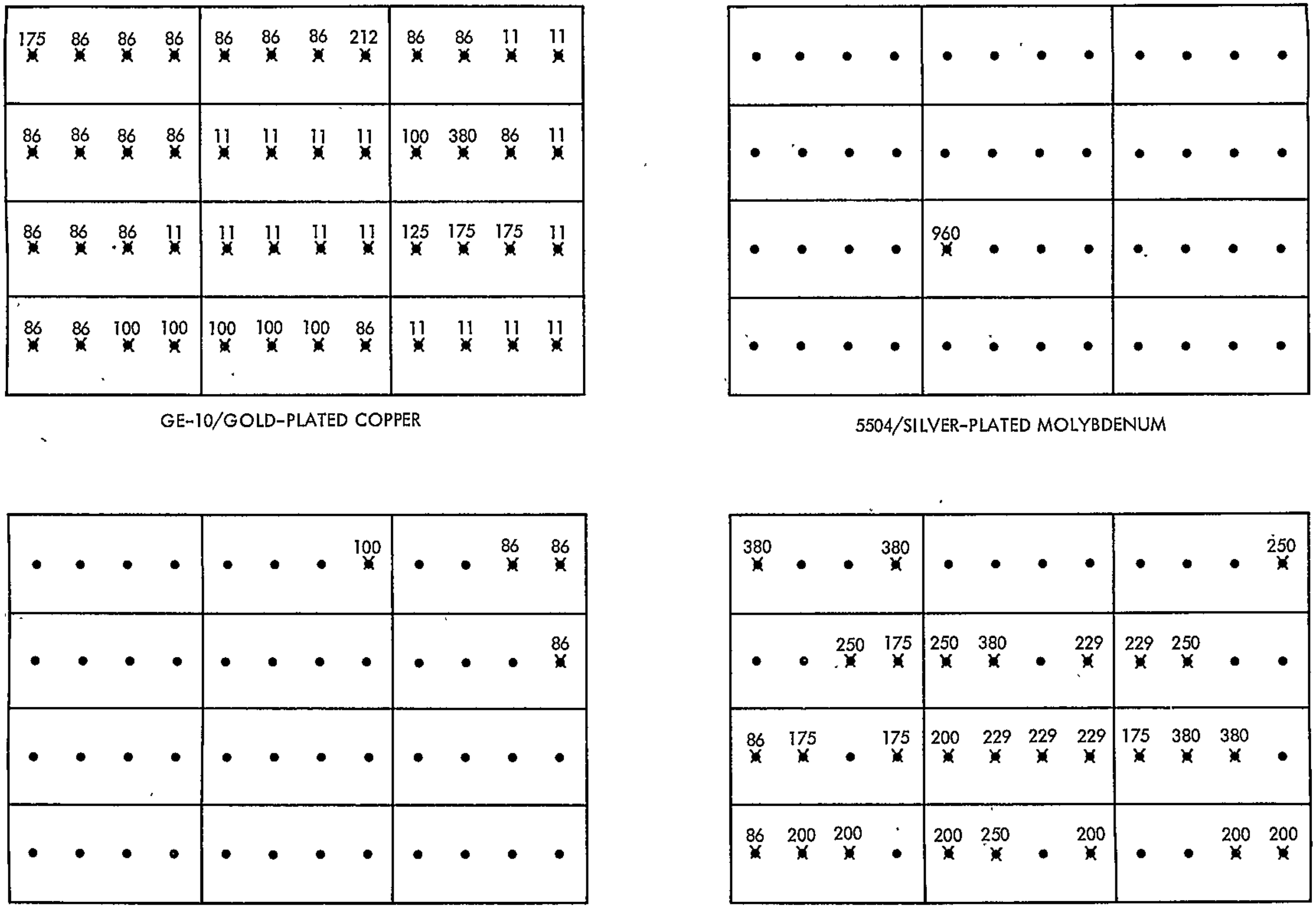
Bond failures on the 5504/gold-plated copper module appear to demonstrate this latter phenomenon, as shown in Figure 3-10. The N-bonds tend to fail first, but are followed later by P-bond failures. Also, looking again at Figure 3-9 for this module, it is seen that on no cell did a P-bond failure precede failure of the adjacent N-bond.

Bond failures on the GE-10/gold-plated copper module did not show this effect as much, as shown in Figure 3-10. Evidently on this module the bonds were weaker and failed rapidly at both N-bonds and P-bonds, making the effect less noticeable.

A plot of bond failures vs number of temperature cycles is given in Figure 3-11 for the 4 modules.

The test module with DuPont 5504 epoxy and silver-plated molybdenum interconnect circuit was later resubmitted to temperature cycling, and after 1080 cycles had lost only one bond.

The electrical performance of the 4 modules is given in Table 3-12. A Spectrolab X-25 solar simulator was used. The open circuit voltage was low on both sub-modules of the 5504/Ag-pl moly module; it is believed this was caused by accidental shorting of two cells with epoxy between the end tab and the P-surface metallization. Note that both this module and the gold-plated Kovar module show very little electrical degradation due to temperature cycling. On the Kovar module, the measurements of I_{SC} and I (at .94 v.) between points A and B show a decrease after temperature cycling. However, the overall (A to C) module output did not show degradation. This could be due to intermittent opening of a loose bond.



GE-10/GOLD-PLATED COPPER

5504/SILVER-PLATED MOLYBDENUM

5504/GOLD-PLATED KOVAR

5504/GOLD-PLATED COPPER

Figure 3-9 Bond Failure Data, 12-Cell Modules, Conductive Adhesives

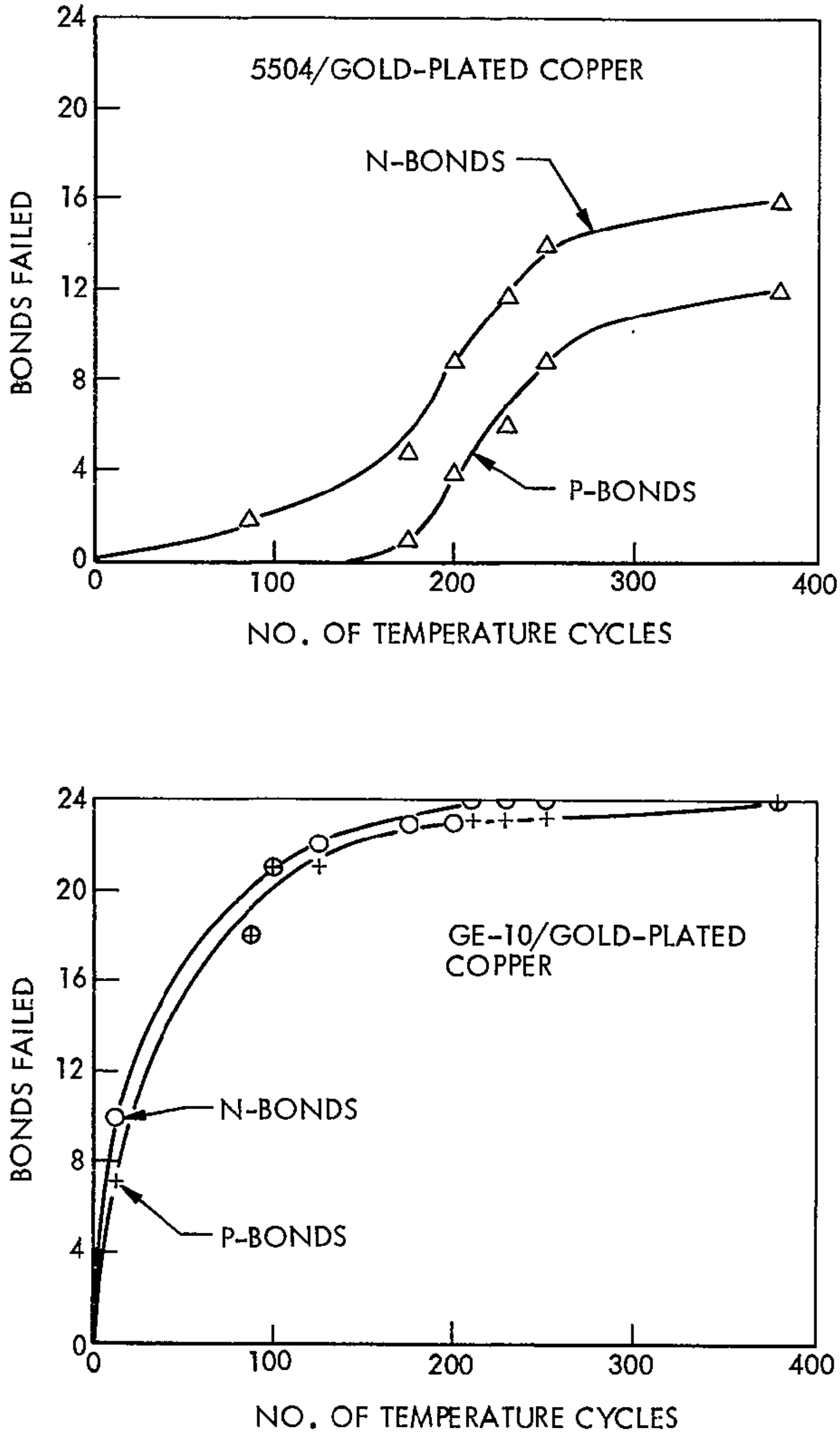
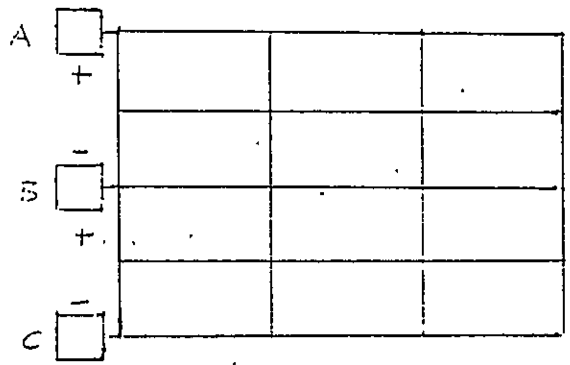


Figure 3-10 Comparison of N-Bond and P-Bond Failures

TABLE 3-12

ELECTRICAL OUTPUT BEFORE AND AFTER TEMPERATURE CYCLING
12-CELL TEST MODULES, CONDUCTIVE ADHESIVE BONDING



Adhesive/Interconnect Combination	(1)	A TO B I_{sc} (amps)	A TO B V_{oc} (volts)	A TO B I at .94v (amps)	B TO C I_{sc} (amps)	B TO C V_{oc} (volts)	B TO C I at .94v (amps)	A TO C I_{sc} (amps)	A TO C V_{oc} (volts)	A TO C I at 1.88v (amps)
GE-10	B	.75	1.13	.30	.78	1.15	.32	.80	2.28	.42
Cu, 1 oz, Au-Plated	A	--(2)	--	--	--	--	--	--	--	--
5504	B	.81	1.14	.63	.81	1.14	.62	.82	2.28	.67
Cu, 1 oz, Au-Plated	A	--	--	--	--	--	--	--	--	--
5504	B	.73	.66	(3)	.72	.68	(3)	.80	1.33	(3)
Moly, 1 mil, Ag-Pl	A	.70	.76	(3)	.69	.69	(3)	.79	1.44	(3)
5504	B	.81	1.14	.45	.75	1.14	.27	.79	2.28	.39
Kovar, 1 mil, Au-Pl	A	.76	1.13	.33	.74	1.12	.26	.79	2.25	.39

(1) Before (B) or after (A) 380 temperature cycles

(2) -- = no output

(3) Specified voltage was greater than V_{oc}, so no data could be obtained.

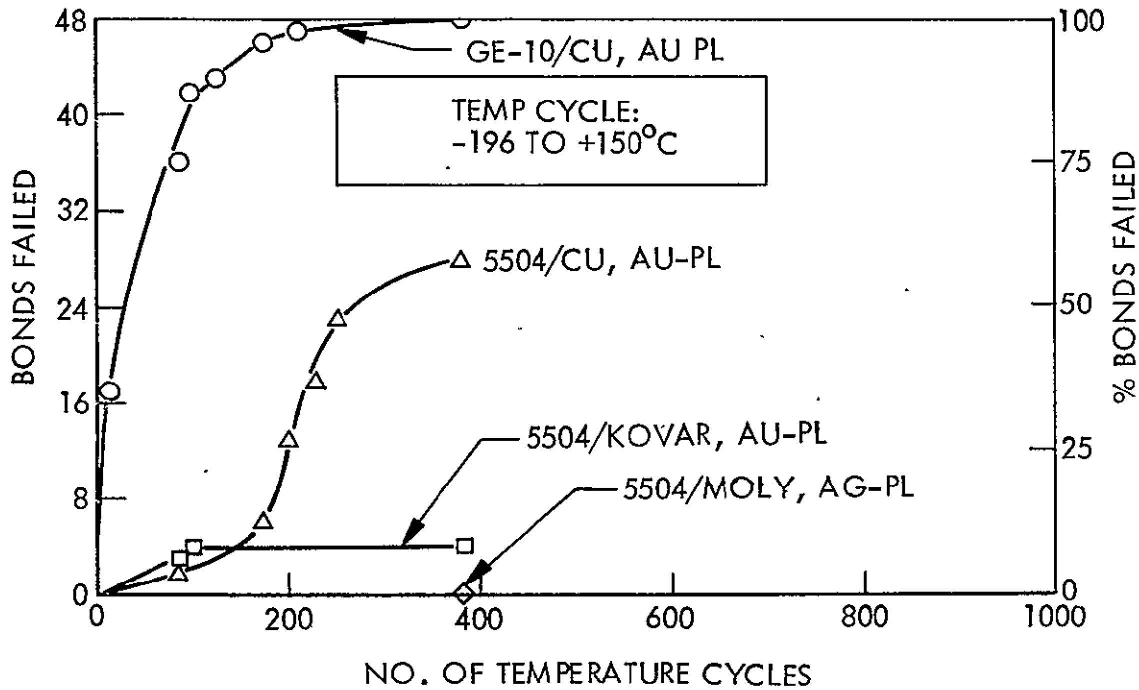


Figure 3-11 Bond Failure Histories, 12-Cell Test Modules, Conductive Adhesives

3.5 72-Cell Module Design Selection

The excellent performance of the DuPont 5504 bonded, silver-plated molybdenum interconnected 12-cell module in temperature cycling made it the clear choice for fabrication of a 72-cell module using conductive adhesives. The module with gold-plated Kovar interconnects also performed well, but not as well. Also, Kovar is a magnetic material and thus is less desirable on large area solar arrays because of the array torquing that can occur with changes in array current.

The screen printing method of applying the conductive epoxy was successfully demonstrated on the 12-cell modules. Because of this and the potential for high efficiency production of large area arrays by this method, screen printing was selected for the 72-cell module design.

The interconnect circuit design selected is the same as used on the 12-cell modules, including the holes in the bond areas for application of the epoxy.

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Section 4
72-CELL TEST MODULE FABRICATION

4.1 Detailed Module Design

The detailed design of the 72-cell test module is shown in Figure 4-1. The left and right sides are independent electrical circuits of 36 cells each. The cells in each half-module are connected 3 in parallel by 12 in series. The solar cells are 8 mil, wraparound N-tab silicon cells with 6-mil fused silica covers attached with Dow Corning 63-489 silicone adhesive. The flexible printed circuit (FPC) is similar to the SEP array design and consists of the photoetched interconnect circuitry sandwiched between 2 layers of 1/2-mil Kapton/1/2-mil polyester laminated film. The films are heat-laminated together, with the polyester acting as the adhesive. There are access holes in both layers of the film at the solar cell/interconnect bond locations.

Three different materials were tested as adhesives for the Kapton film--FEP Teflon, polyester, and acrylic. The polyester was selected because the Kapton/adhesive did not shrink during laminating as happened with both the FEP and acrylic adhesives.

The interconnect circuit pattern, shown in Figure 4-2, is similar to the SEP solar array design and the electrical test modules made during the Flexible Substrate Design Optimization Program (NAS8-28432).

The interconnect materials are:

- 1 mil molybdenum with .4-.7 mil silver plating on both sides
- 1 oz. (approx. 1.3 mil) copper with .2-.4 mil gold plating on both sides

These materials were selected based on results from the conductive adhesive and thermocompression bonding development work and following consultation with the NASA/MSFC Technical Monitor.

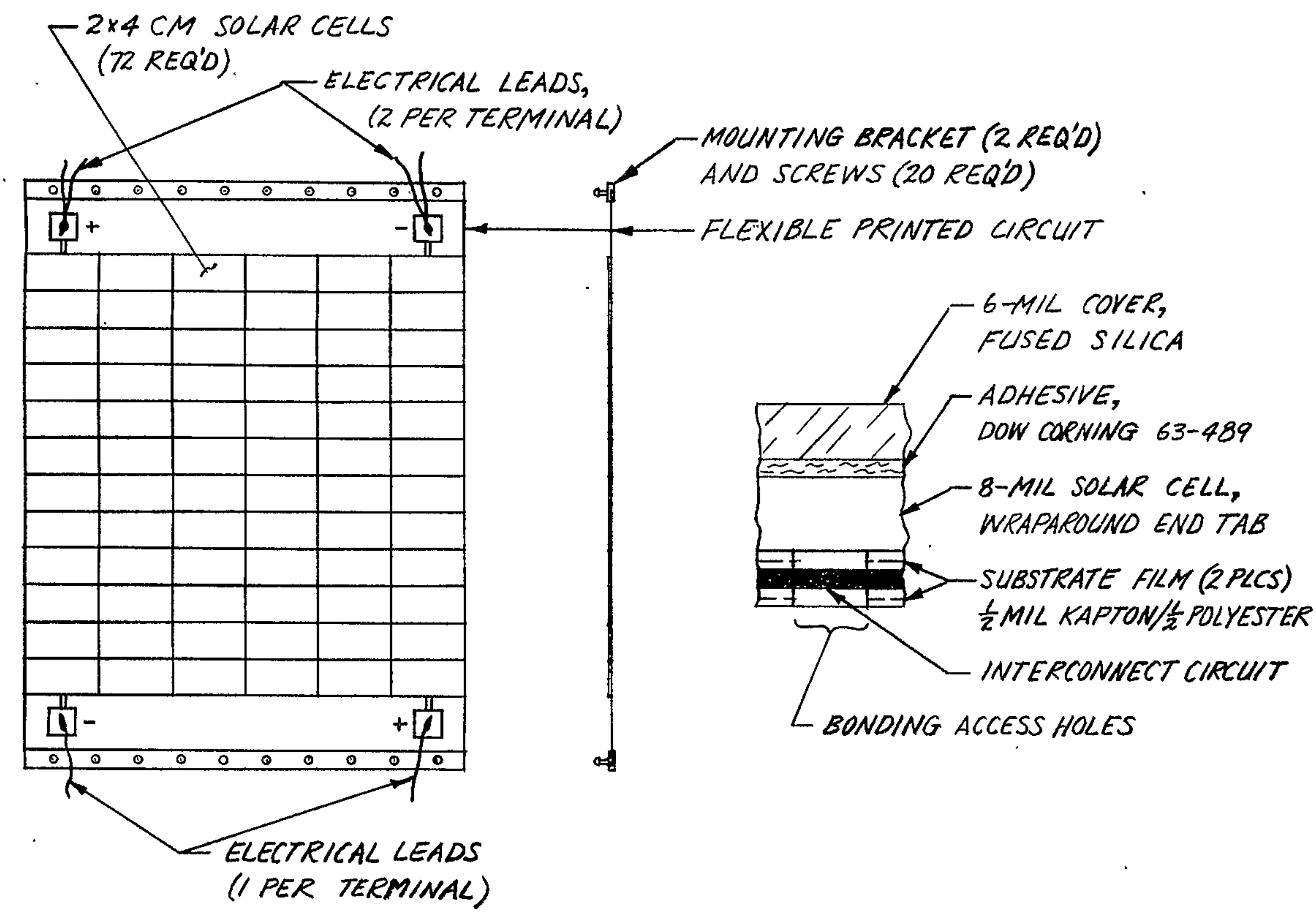

Figure 4-1 72-Cell Test Module Design

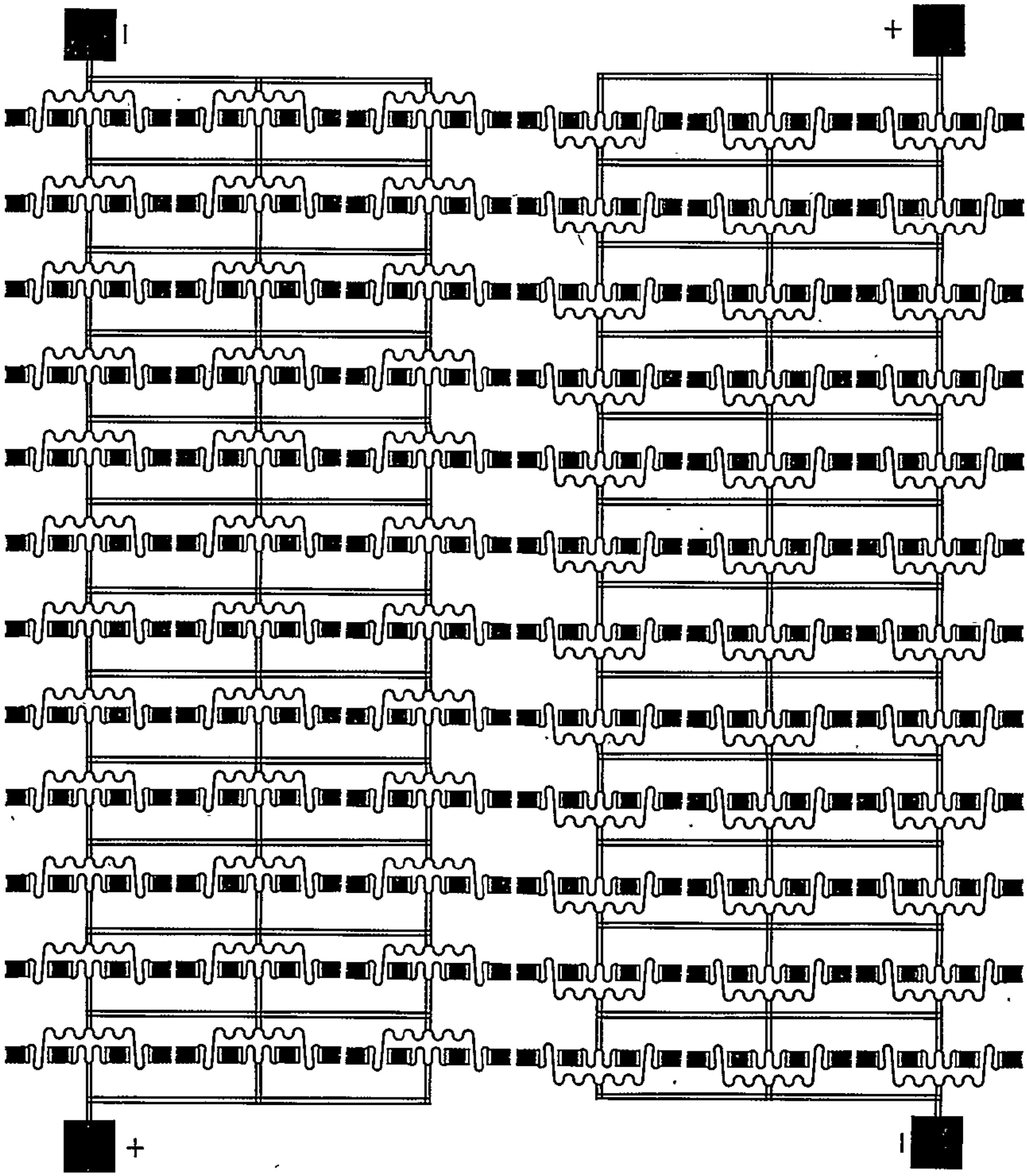

Figure 4-2 Interconnect Circuit of 72-Cell Test Module

Modules employing both conductive adhesives and thermocompression bonding were chosen. The conductive epoxy bonded module has silver-plated molybdenum interconnect bonded with DuPont 5504 silver-filled epoxy. The thermocompression bonded modules have one each of the above 2 interconnect materials.

The thermocompression bonding schedule, as established in the bonding development work, is:

Temperature	- 454°C (850°F)
Pressure	- 48 MN/m^2 (6960 psi)
Time	- 2.3 seconds

In selecting design features, certain guidelines were followed. Departures from the baseline design of the Solar Electric Propulsion (SEP) array were avoided whenever feasible, because the SEP array is the most immediate potential application of the technology developed. All techniques and processes utilized are compatible with scaling up to large area arrays.

Except possibly for the conductive epoxy, all of the solar cell module materials are proven for long-term service in the space radiation environment. The problem of degradation of adhesives has been carefully assessed, and it is believed that in a solar cell assembly the adhesive bond would be effectively shielded by the solar cell/cover assembly on one side and partly by the FPC on the other side. Therefore, failure of the epoxy bonds due to space radiation is not expected to occur.

4.2 Fabrication of Modules

A total of 6 72-cell test modules were built. These included 2 each of the following:

- DuPont 5504 bonded, silver-plated molybdenum interconnects
- Thermocompression bonded, silver-plated molybdenum interconnects
- Thermocompression bonded, gold-plated copper interconnects

One set of 3 modules was temperature-cycled at LMSC; the other set was delivered to NASA/MSFC for temperature cycling testing.

Fabrication and assembly of the modules was performed by experienced individuals in the same LMSC organizations that manufacture other solar arrays.

The process steps used in fabricating the interconnect circuit/substrate assemblies for Modules 1 through 4 were as follows:

1. Cut Kapton/polyester film and punch bond access holes
2. Plate copper and molybdenum foils
3. Print interconnect circuit on both sides of foil using KMER resist
4. Etch foils on both sides to remove silver and gold plating. Remove resist.
5. Laminate one film to each etched foil, aligning holes with circuit.
6. Print interconnect circuit again on foil side using KMER. Coat film side with resist to protect circuit at bond access holes.
7. Etch copper and molybdenum foils. Remove resist.
8. Laminate second film to etched circuits, aligning holes with circuit.

For the last two circuit/substrate assemblies (Modules #5 and 6), KMER resist was not used because it was difficult to remove. Instead the following steps were substituted:

- For the gold plated copper circuit:

  3. Print non-circuit areas on both sides of copper foil using Riston resist.

2 and 4. Plate circuit with 0.3 mil gold. Remove resist.

5. Laminate one film to plated foil.

6. and 7. Etch copper with ferric chloride. Gold protects circuit from etchant on both sides of foil.

- For the silver-plated molybdenum circuit:

  3. Print circuit both sides with Shipley AZ-1350J resist.

  4. Etch foil to remove silver. Remove resist.

  5. Same

  6. Print circuit with Shipley AZ-1350J resist.

  7. Etch molybdenum with ferric chloride. Remove resist.

These revised procedures produced better circuit/substrate assemblies with less effort.

A fixture was made for positioning the solar cells during the bonding operation (Figure 4-3). A vacuum line was installed on the edge of the fixture to evacuate the space between the plate and frame. This provided a vacuum hold-down for the cells and substrate which was used for the conductive epoxy bonded modules during application and cure of the adhesive.

The equipment and materials used during the bonding operation included:

- For all modules:

  72 solar cells, covered
  Flexible printed circuit
  72-cell module fixture
  Tweezers
  Eraser
  Isopropyl alcohol
  Cotton swabs

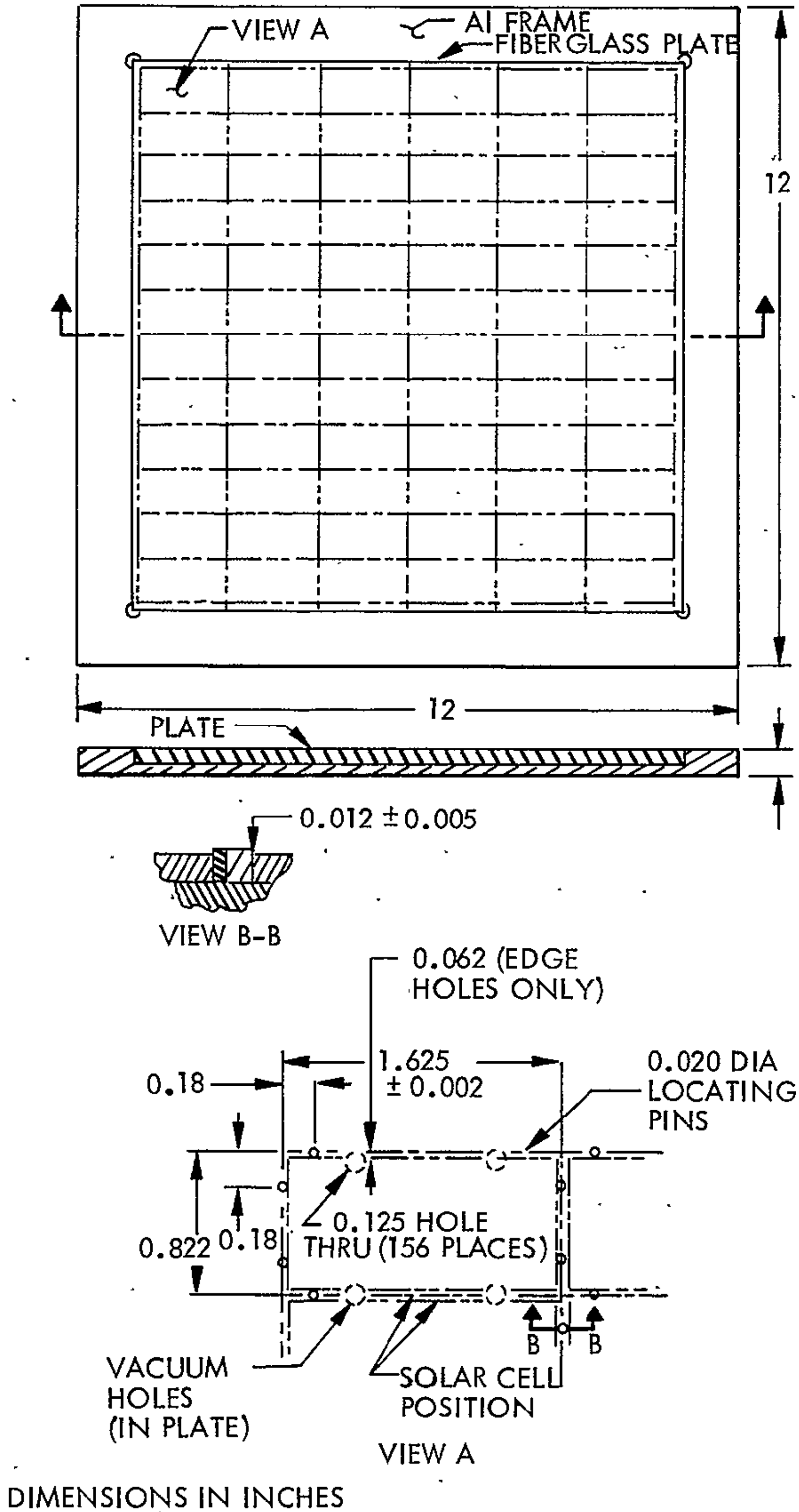

Figure 4-3 72-Cell Module Fixture

- For thermocompression bonded modules:

  Bonder, Unitek Model 1-37-02
  Shunted tip, Unitek Model 10-128-01
  Kapton tape (to hold FPC in place)

- For conductive epoxy bonded modules:

  Screen printer, Forslund Model FCP-1224, with 200 mesh stainless steel screen
  DuPont 5504 silver-filled epoxy
  Vacuum pump and tubing
  Curing oven (150°C)
  Silicone grease
  Extension cord (to permit transfer of fixture from screen printer to curing oven while holding vacuum)

During bonding of cells to the substrate, several difficulties were encountered. The fixture provided a very tight fit for the cells, especially when the cell covers were not precisely located on the cells. Also, the locating pins in the fixture, being only about .012 inches high, did not always keep the cells in position securely. Consequently, several cells were damaged during the bonding operation by cracking of the cover or chipping the cover edge.

When bonding with conductive epoxies, the fixture vacuum system, designed to hold down the cells and substrate, was inadequate to prevent the cells from sticking to the epoxy printer screen when epoxy was applied directly to the cell back. This was due partly to the very high viscosity of the DuPont 5504 adhesive. The problem was circumvented by applying silicone grease between the cells and the fixture to help hold down the cells. Many of the cells/covers were slightly warped and tended to lift up when the wiper blade pressed on one end.

The screen printer used lacked good control of pressure of the wiper blade. The result was that epoxy application was somewhat non-uniform, and some 18 of the 288 bonds on one module (on 17 different cells) required touch-up by hand.

These problems point out the need for a larger investment in process development and tooling before conductive epoxy or thermocompression bonding can be properly considered for use on a flight solar array.

4.3 Electrical Output Tests

The electrical output of the 6 modules was measured in LMSC's Large Area Pulsed Solar Simulator facility (Figure 4-4). The LAPSS provides a uniform, spectrally balanced pulse of light to a test object and simultaneously electronically loads the module and conditions and stores the output data. The data are automatically corrected for differences in module temperature and pulse lamp intensity from the desired values. The stored data then can be recorded by printing values on tape or plotting an IV curve.

The IV curves are shown in Figures 4-5(a) and (b). There was a major anomaly in the right-side half-circuit of the conductive epoxy bonded module (#1), possibly due to a short between N and P cell contacts from adhesive.

Photographs of the 6 72-cell modules are given in Figures 4-6 through 4-11.

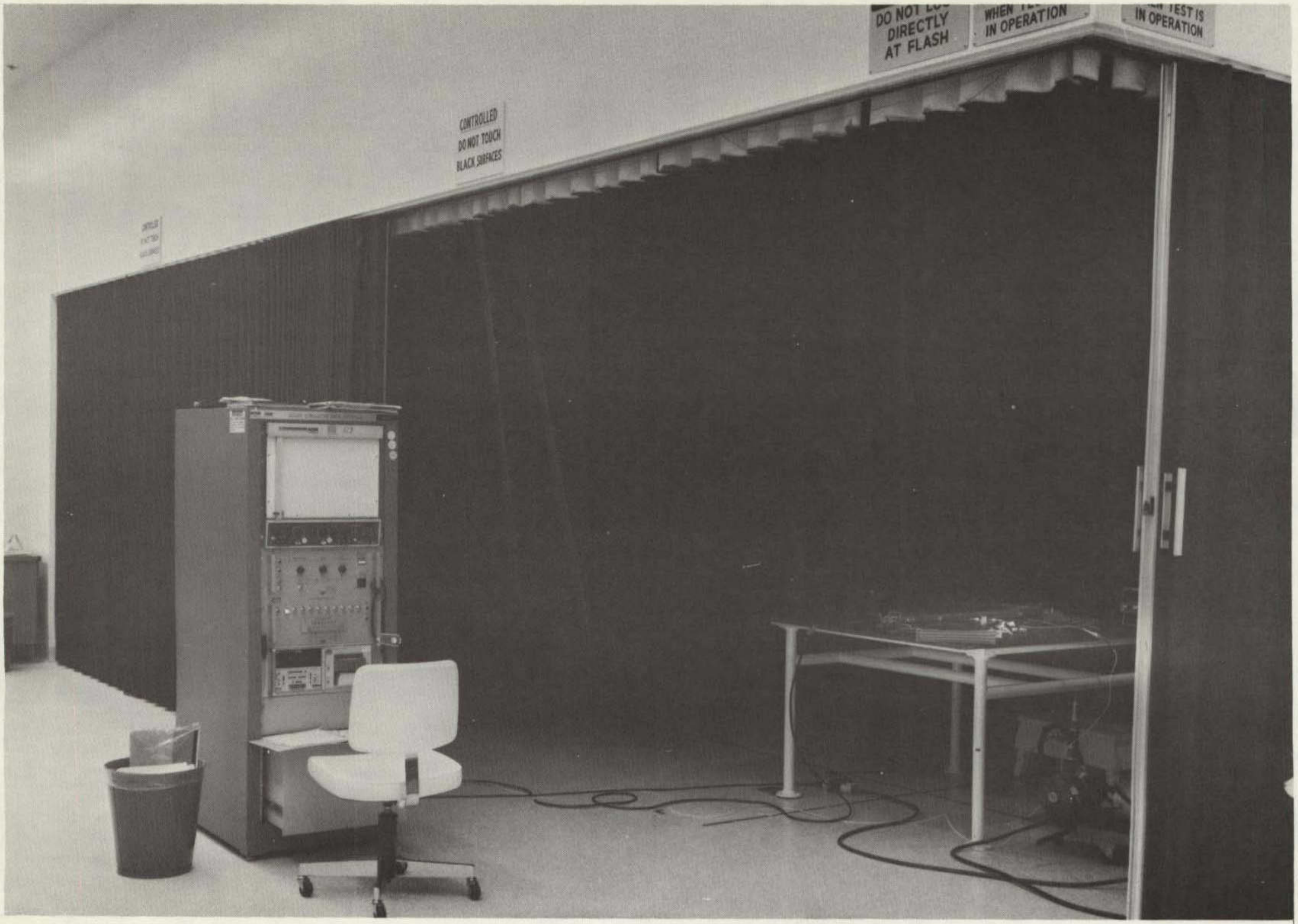

Figure 4-4 Large Area Pulsed Solar Simulator Facility

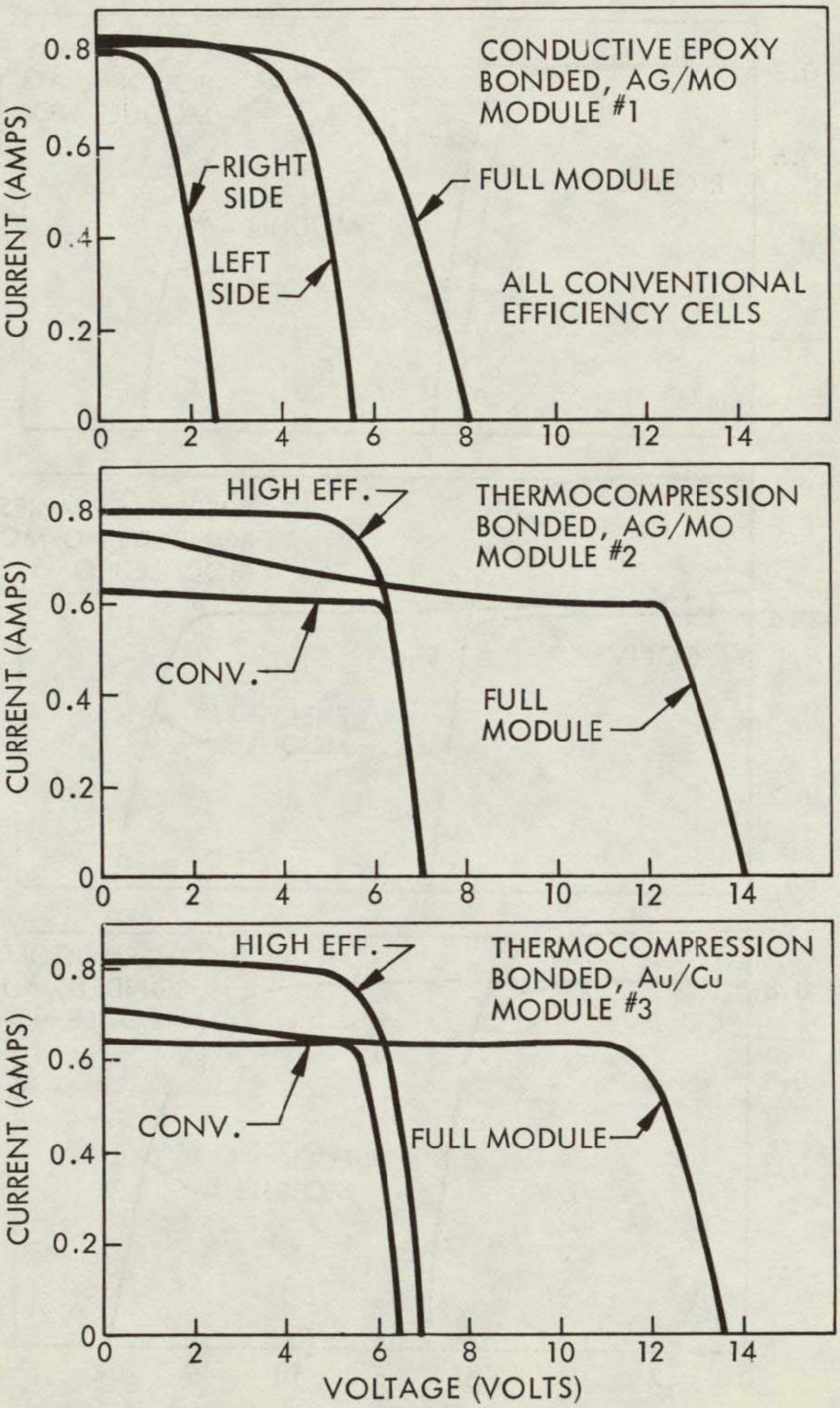

Figure 4-5(a) Electrical Output Data (Before Start of Cycling) Modules 1, 2, and 3

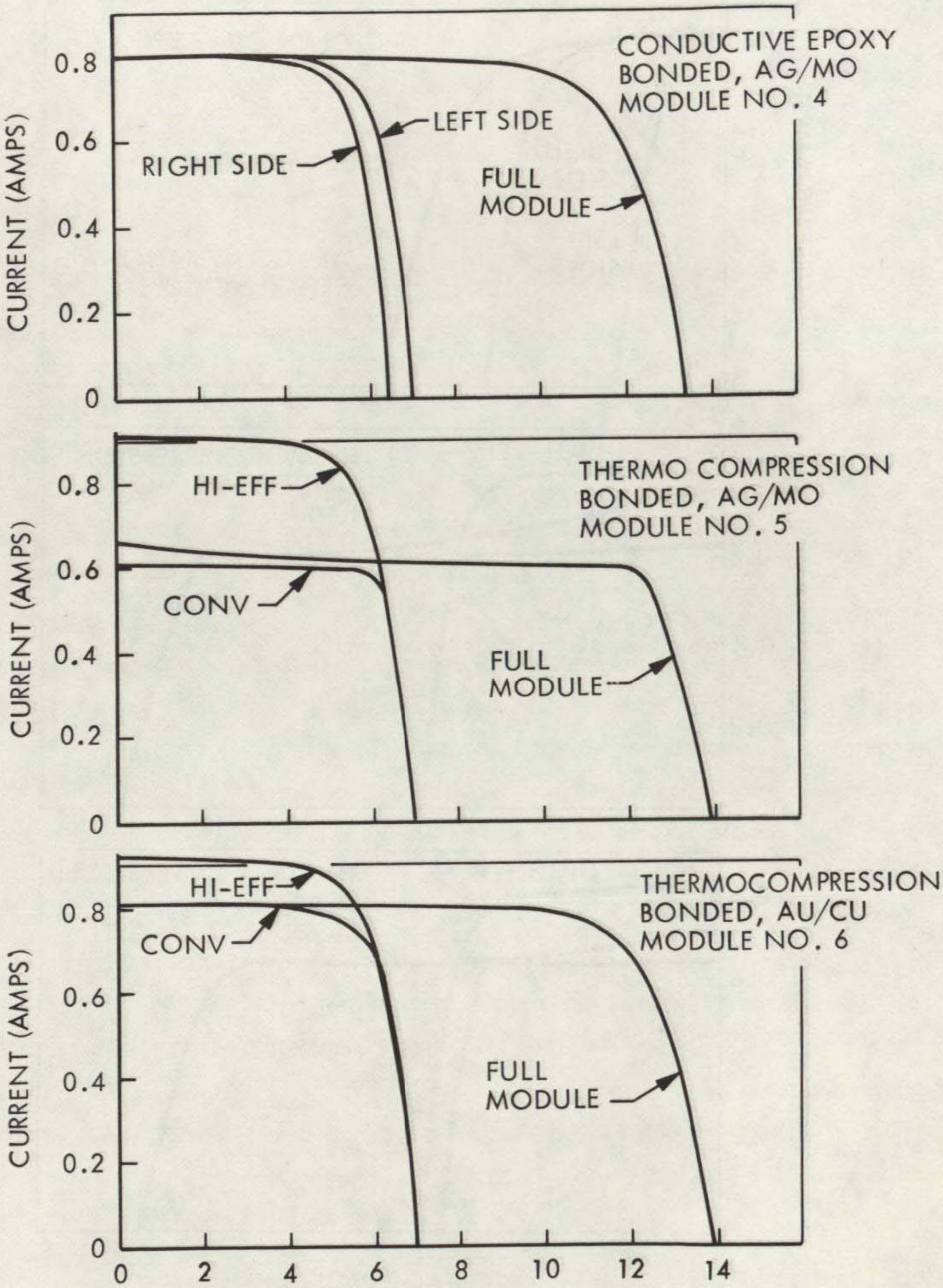

Figure 4-5(b) Electrical Output Data (Before Start of Cycling)
Modules 4, 5 and 6

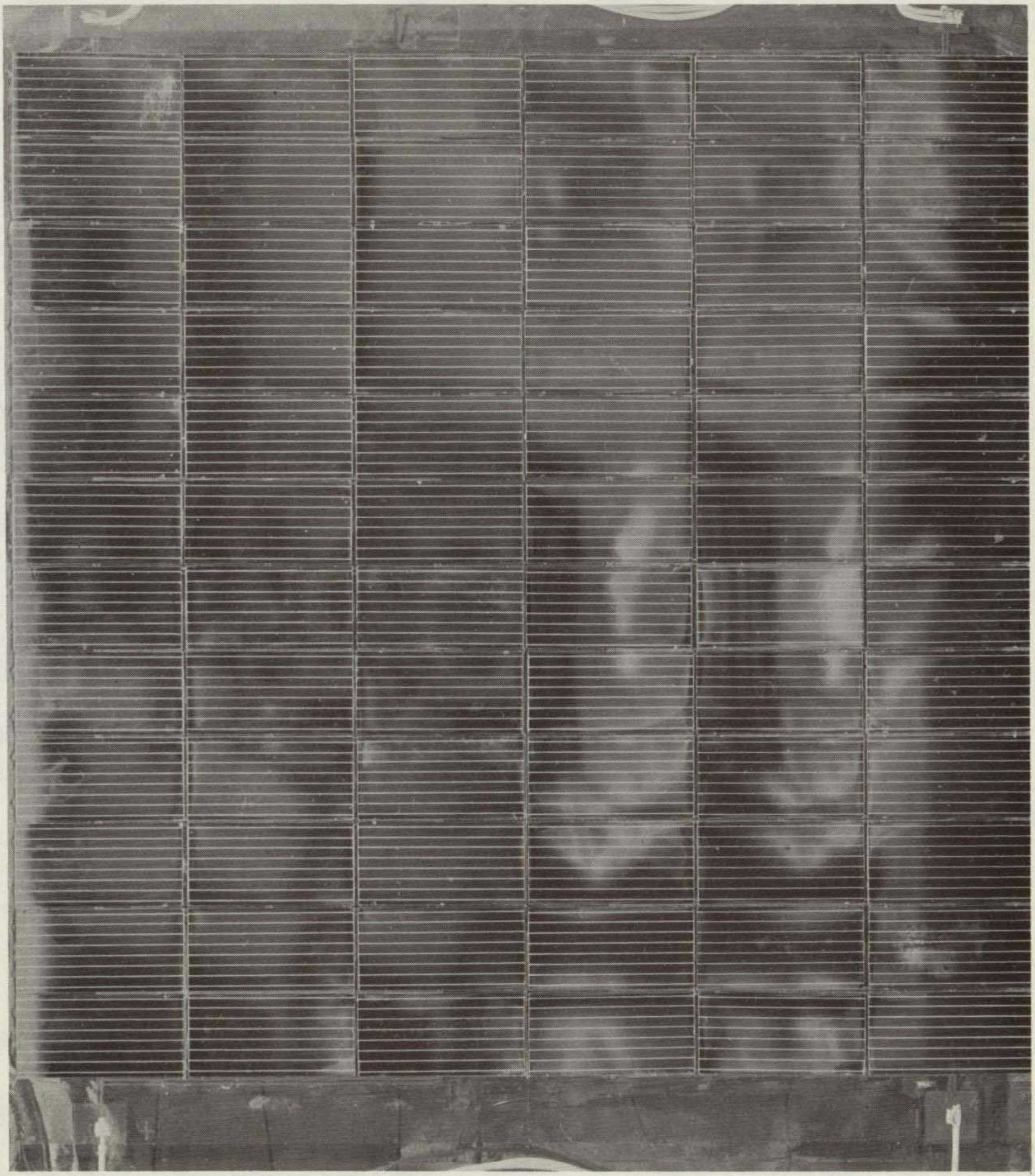

Figure 4-6 72-Cell Module No. 1, Conductive Epoxy Bonded, Silver-Plated Molybdenum Interconnect, Front Side

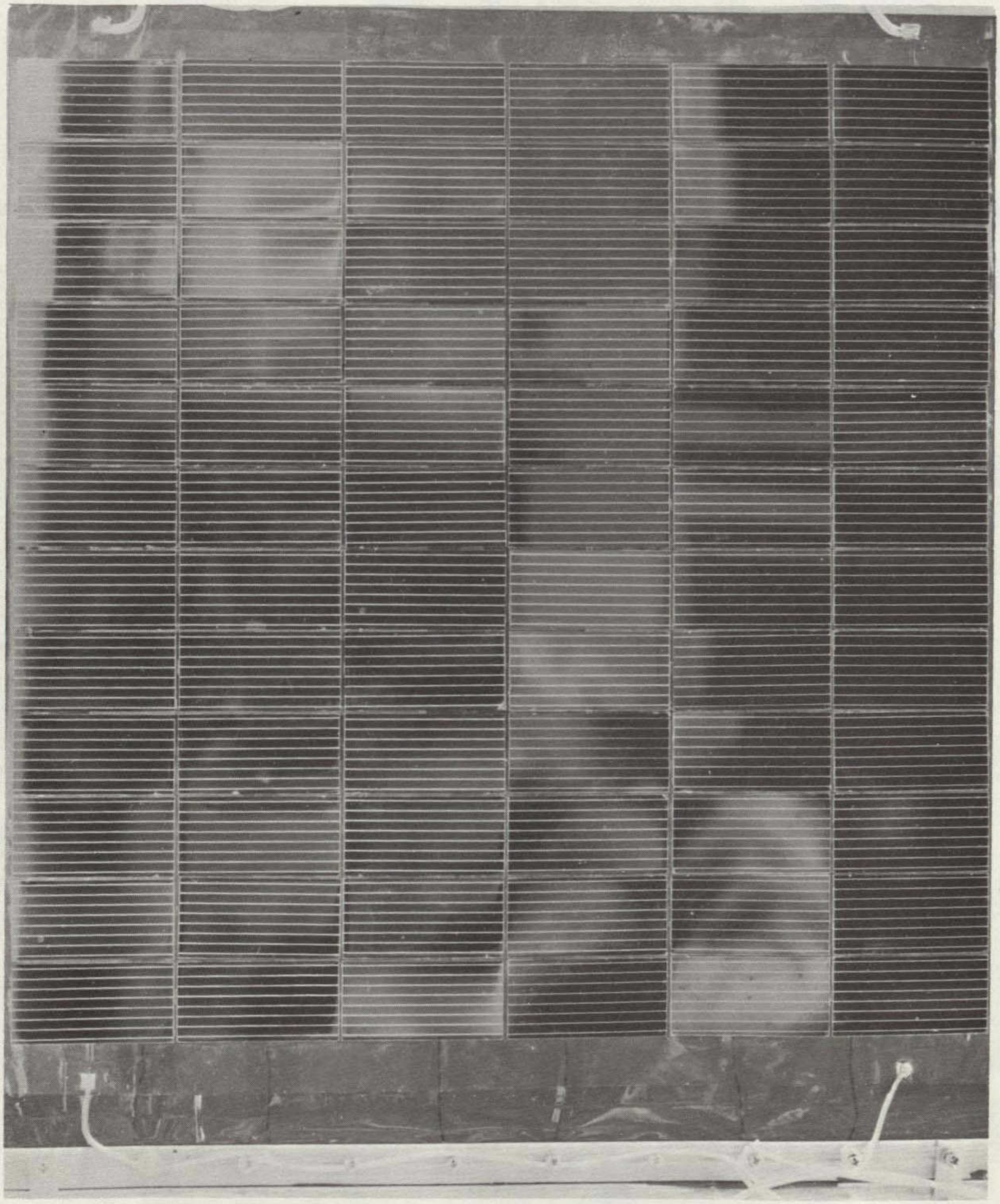

Figure 4-7 72-Cell Module No. 2, Thermocompression Bonded, Silver-Plated Molybdenum Interconnect, Front Side

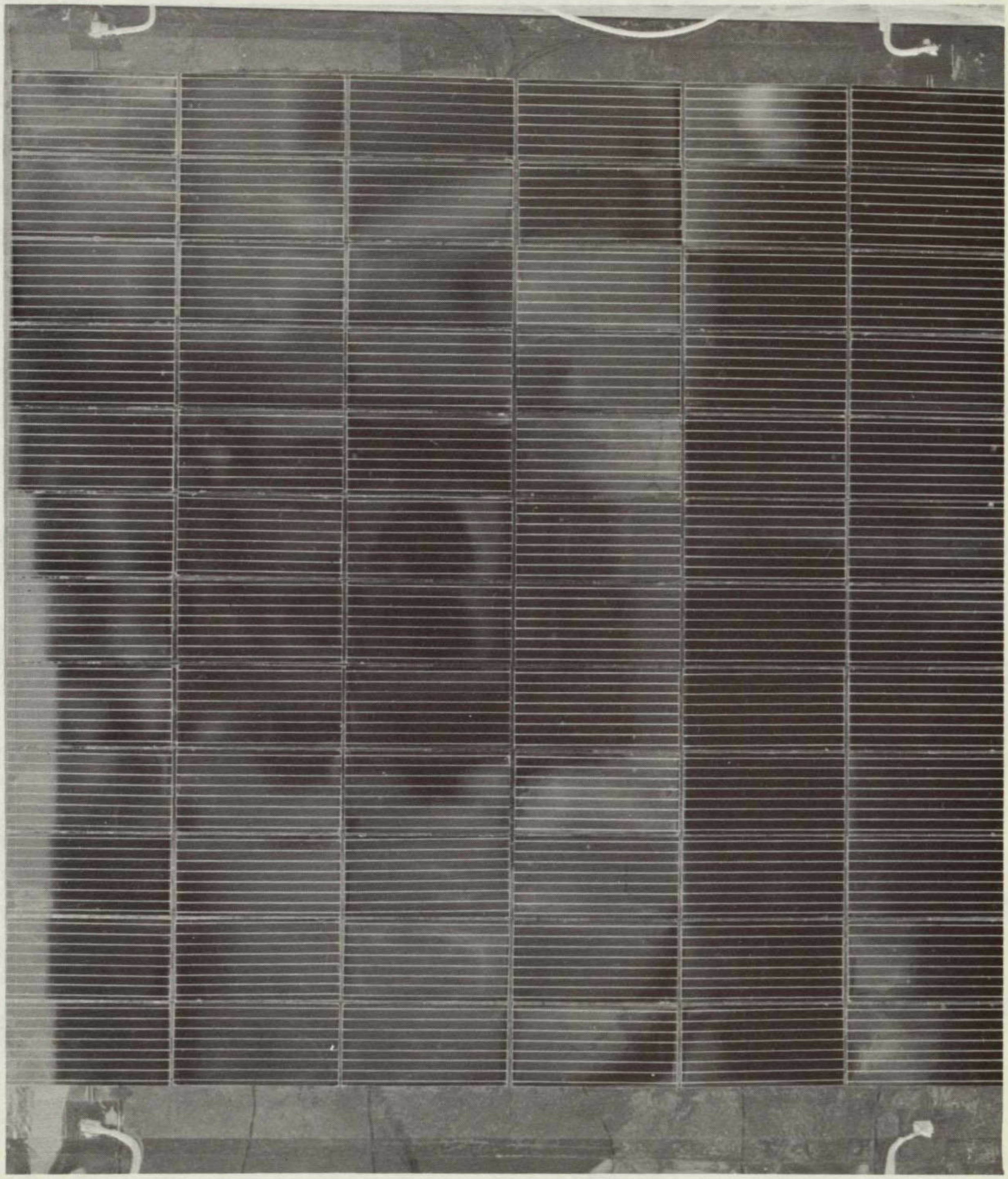

Figure 4-8 72-Cell Module No. 3, Thermocompression Bonded, Gold Plated Copper Interconnect, Front Side

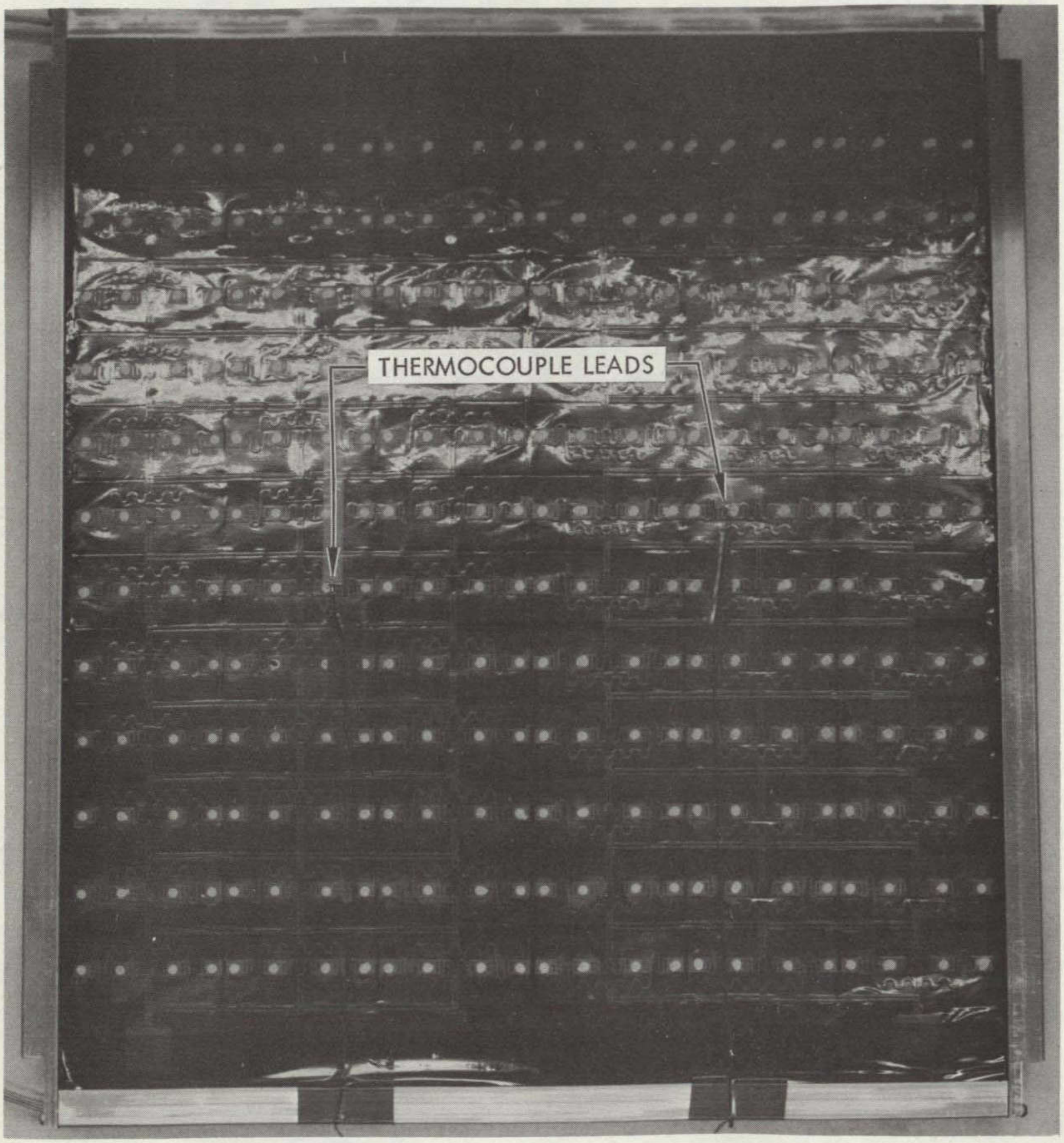

Figure 4-9 72-Cell Module No. 4, Conductive Epoxy Bonded, Silver-Plated Molybdenum Interconnect, Back Side

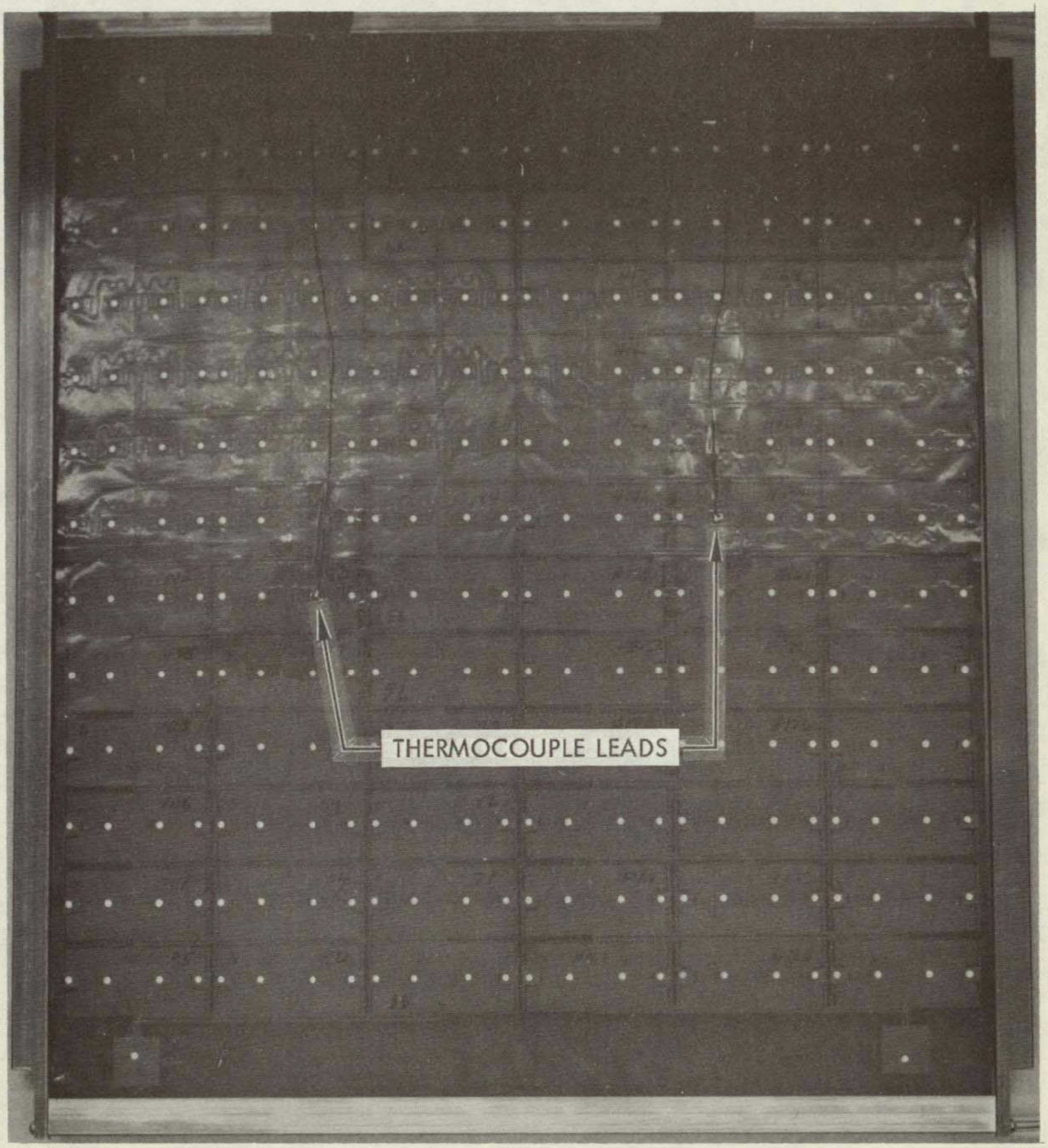

Figure 4-10 72-Cell Module No. 5, Thermocompression Bonded, Silver-Plated Molybdenum Interconnect, Back Side

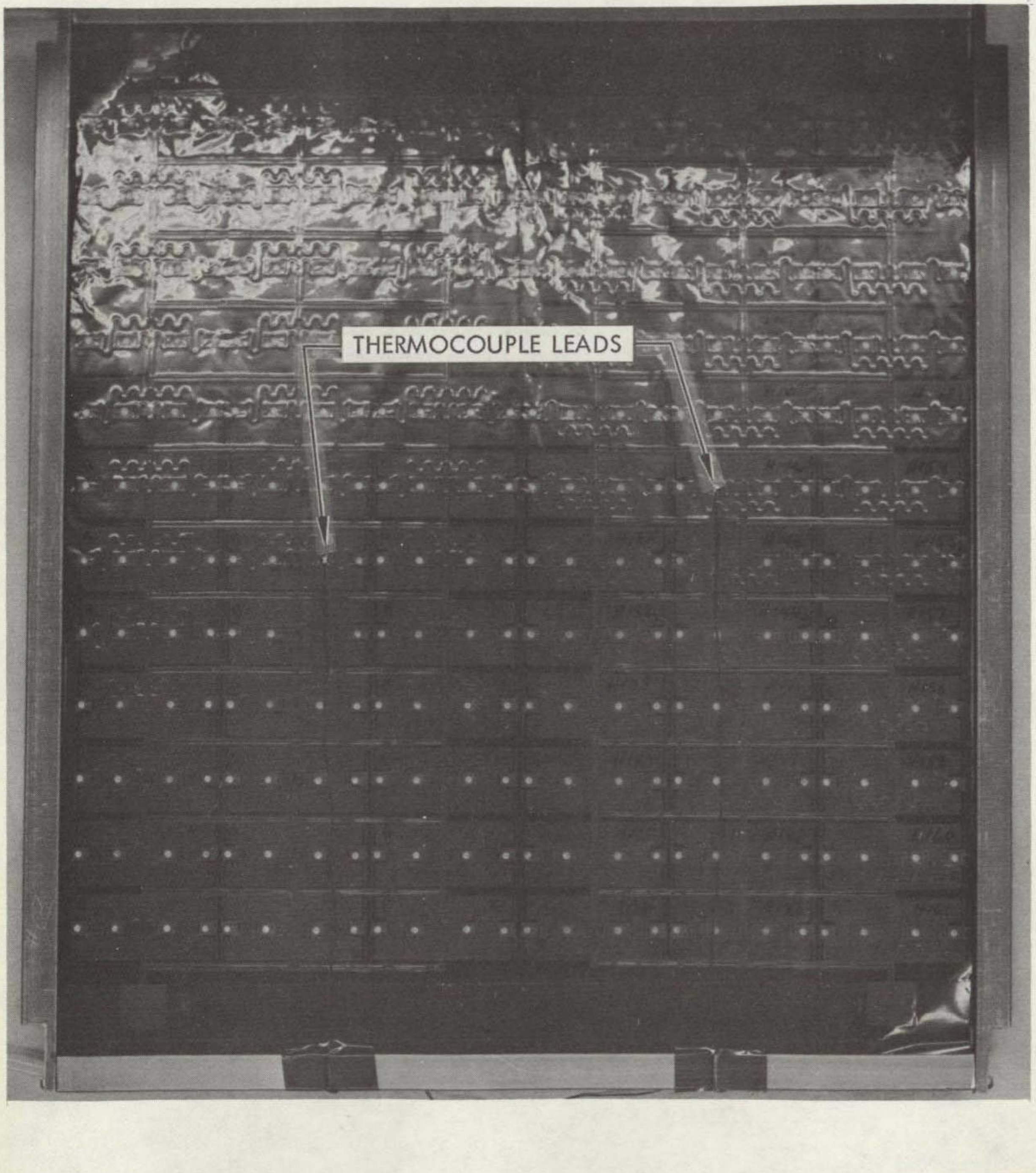

Figure 4-11 72-Cell Module No. 6, Thermocompression Bonded, Gold-Plated Copper Interconnect, Back Side

4.4 Quality and Reliability Assurance Provisions

An LMSC Product Assurance Program Representative (PAPR) acted as central point of contact for the product assurance activities required by the contract. The PAPR performed visual inspections of the deliverable 72-cell modules for proper workmanship and damage before shipment to MSFC, and generated detailed inspection records which were shipped with the modules.

There were two inspections of the modules. The first was done just after fabrication and before the electrical output tests. Following shipment, MSFC technical personnel observed several loose bonds. These evidently failed due to handling between the time of the inspection and shipment. The modules were returned to LMSC and the bonds repaired. The second inspection then occurred just prior to packing the modules for re-shipment to MSFC.

The electrical output measurements were made on LMSC's production solar simulator by an electronics inspector of the Product Assurance organization. All test instrumentation used is kept in calibration.

The plywood shipping container was inspected for design and construction, and the packaging of the container for shipment was selected by LMSC's Material Services organization to insure safe transit to MSFC.

Reliability considerations in the module design were based on existing technology and failure analyses of similar designs. Redundancy in the interconnections was acquired by having 2 N-bonds and 2 P-bonds per cell and by using double traces in the interconnect circuit. At one time two joints were made at each bond location on the cell for additional redundancy. However, experience showed this reduced reliability due to the high stresses between the two joints.

Section 5

TEMPERATURE CYCLING TESTING

Three 72-cell test modules (Modules No. 1, 2 and 3 pictured in Figures 4-6 through 4-8) were temperature-cycled for 604 cycles in LMSC's Solar Panel Temperature Cycling Facility, Figure 5-1. This test facility has two identical systems, each having a vacuum chamber with a test volume 24 inches in diameter by 42 inches high. Two 9-inch diameter quartz windows on one side of the bell jar permit irradiation of smaller solar array modules by a Spectrolab X-25 solar simulator to measure electrical output. Tungsten filament lamps are installed inside the chamber to provide uniform radiant heating. A liquid nitrogen cooled shroud completely surrounds the test volume and includes movable shutters for the quartz windows. At the center of the chamber there is a box, or "target", 7.5 inches square by 21 inches high on which the test modules were mounted. The box also is cooled with liquid nitrogen to provide the cold space environment on the back side of the modules.

The vacuum system consists of a 400 liter per second differential ion pump and initial roughing equipment which includes a carbon vane mechanical pump and a two-stage sorption pump. The ion pumping, together with some cryopumping by the liquid nitrogen shroud system, yielded a vacuum level of approximately 10^{-8} torr. Temperature cycles were obtained by adjusting the radiant lamp intensity and turning the lamps on and off automatically. A 40-channel digital recorder gave both test module temperatures and electrical output data. Automatic cycle control and data acquisition equipment were utilized to provide round-the-clock, unattended facility operation.

The interconnect materials and bonding methods on the test modules were:

Module No.	Bonding Method	Interconnect Material
1	DuPont 5504 epoxy	Molybdenum, silver-plated
2	Thermocompression	Molybdenum, silver-plated
3	Thermocompression	Copper, gold-plated

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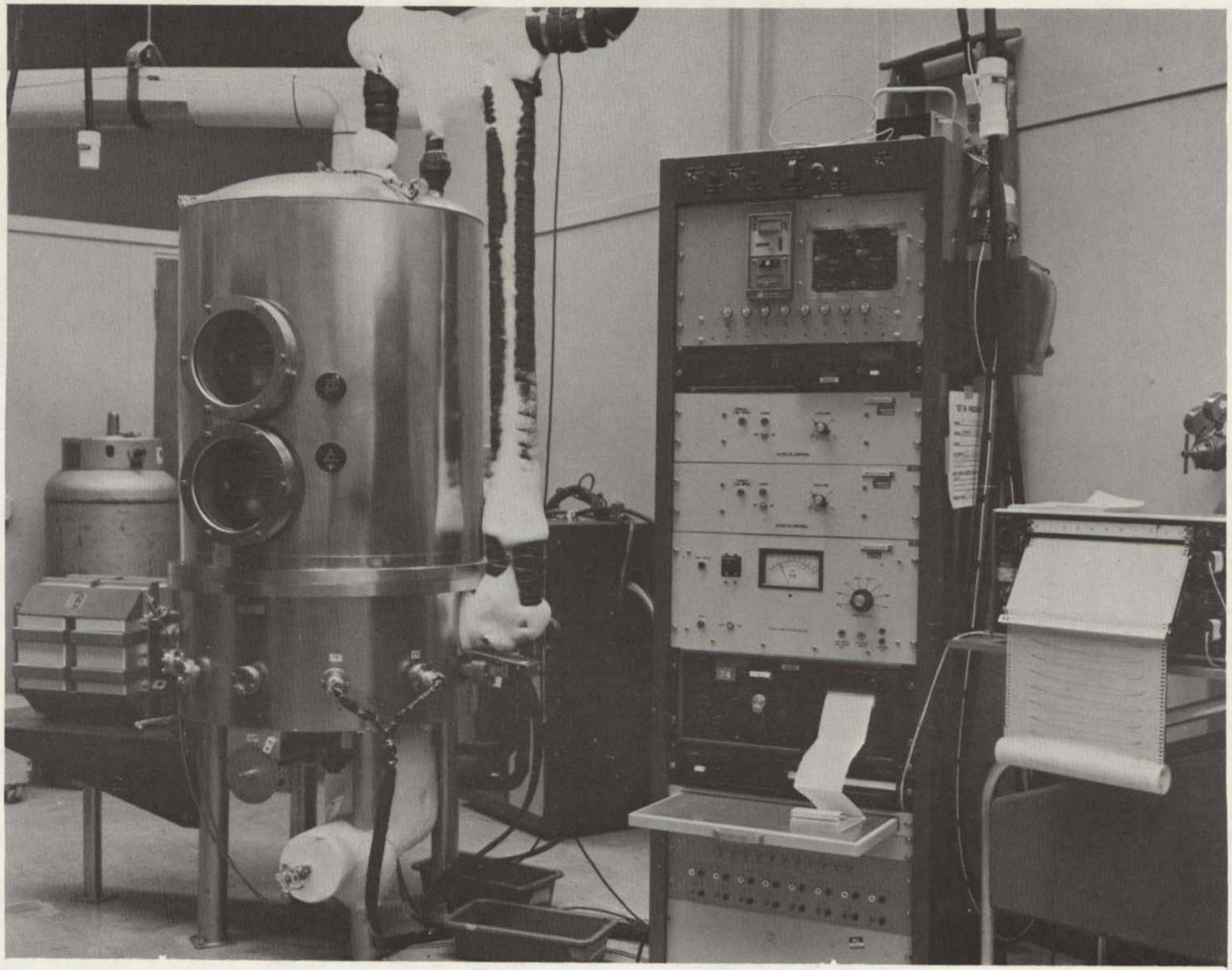

Figure 5-1 System B of Solar Panel Temperature Cycling Facility

The test included the following:

- Visual inspection
- IV measurement
- Installation of electrical leads and thermocouples
- Installation of modules in chamber
- IV measurement, just before putting on bell jar
- Cycling 604 times, -160°C to +150°C at approx. 1×10^{-8} torr
- Measurement of temperature and I_{sc} at maximum and minimum temperature of every cycle
- Interruption of test periodically to count bond failures
- IV measurement and visual inspection after 604 cycles

Six (6) electrical leads were attached to the 4 contact pads on each module as shown in Figure 4-1. The leads were used prior to and after temperature cycling to obtain IV data on the left and right halves and on the whole module. The IV curves of the test modules before cycling were given in Figure 4-5(a). During cycling the lower leads were connected together, and the upper two pairs of leads were wired to the test console to permit measurement of open circuit voltage (V_{oc}) and short circuit current (I_{sc}) of the full module.

Six (6) thermocouples were installed on each module at the locations shown in Figure 5-2. They were 5 mil copper/constantan thermocouples, bonded on the back surface of the Kapton substrate between adjacent N and P bonds. These bonds are approximately 10 mm apart, so the thermocouples were located about 5 mm away from a bond.

The installation of the modules in the vacuum chamber is diagrammed in Figure 5-2. Four lamps with 5-inch tungsten filaments were mounted in front of each module.

The temperature profile experienced during cycling is shown in Figure 5-3. It approximates the profile predicted for the SEP solar array design.

Cycling was interrupted periodically to count the number of failed bonds. This was done by applying pressure at appropriate points near every bond on the back of each module

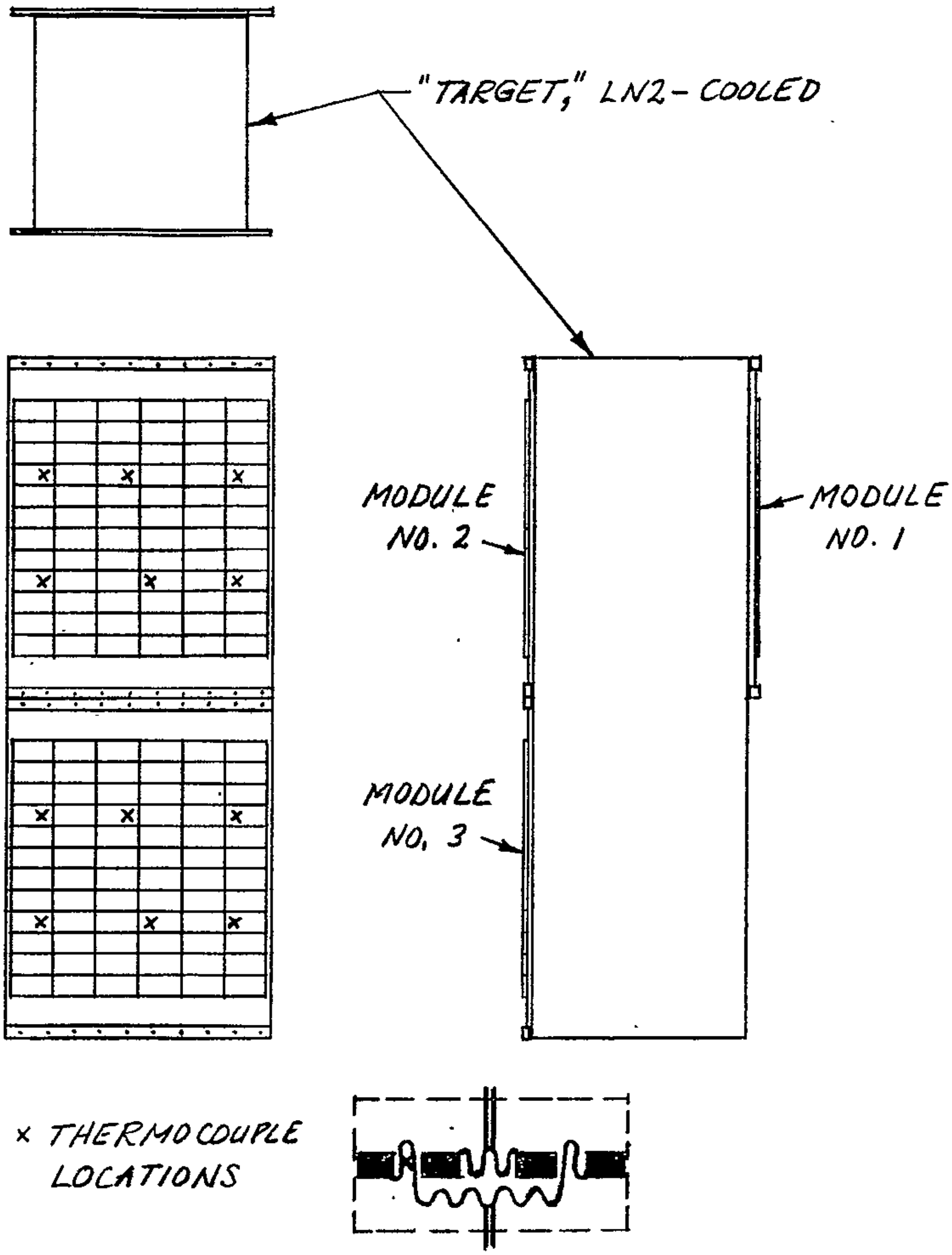

Figure 5-2 Module Installation in Vacuum Chamber

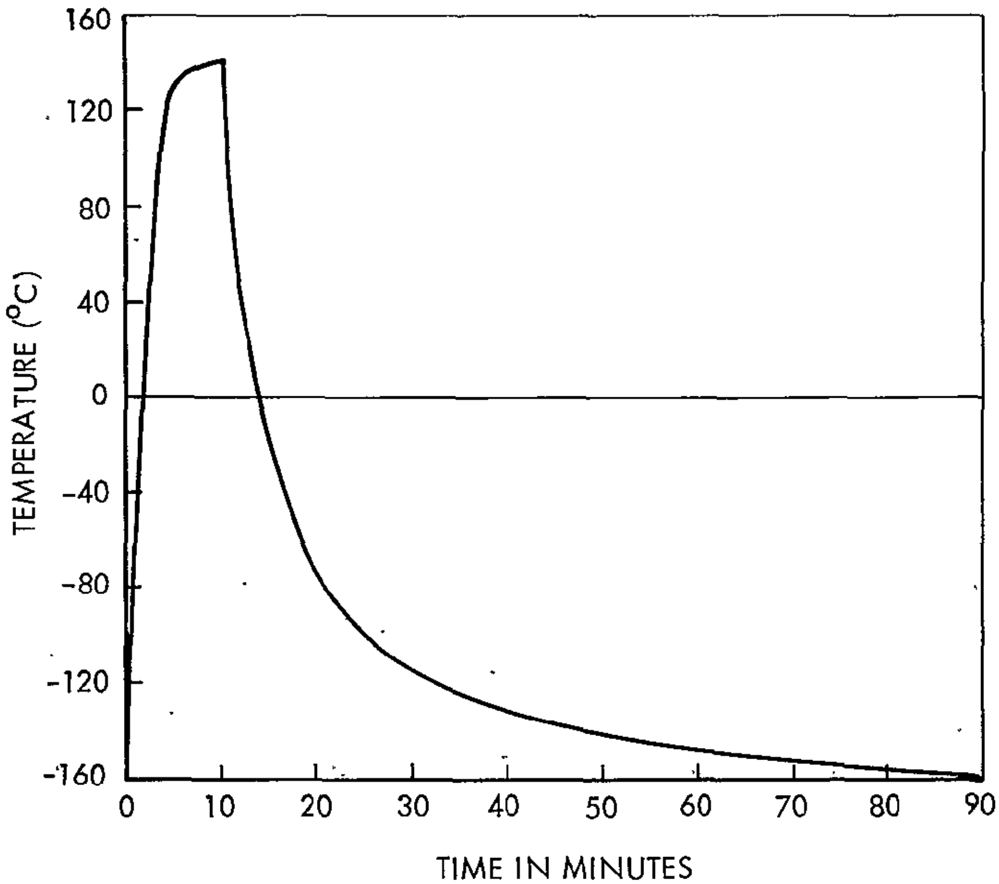

Figure 5-3 Representative Temperature Profile, 72-Cell Test Module

and observing whether the cell separated from the interconnect circuit. Originally, two such bond inspections were planned. At the request of MSFC, the number was increased from 2 (at 10 and 100 cycles) to 5 (at 20, 100, 200, 300 and 500 cycles), and the number of cycles to be performed would be reduced to a number sufficient to establish the failure trend. A total of 604 was performed. Bond failures were counted also at the start and completion of temperature cycling.

In the early testing the number of bond failures was greater than expected considering results from the 12-cell module testing in the Quick-Look Temperature Cycler; therefore, after 84 cycles an investigation was made to determine whether the solar cell/interconnect bonds were being heated to a temperature higher than indicated by the thermocouples. Two new thermocouples were added on the front surface of solar cells on two panels. The measured front surface temperatures were extremely high as shown below from data from one of the panels.

Back-Surface Thermocouples (°C)		New Front-Surface Thermocouples (°C)
153.3	157.5	327.7
151.4	150.3	324.8
146.2	148.7	

The question then was whether the large temperature difference was across the cell to the bond or between the bond and the thermocouple location on the substrate, since the objective was to temperature cycle the bonds to +150°C. Another two thermocouples were added to the back of each module by soldering them directly to the interconnect metal immediately adjacent to a bond. This was not done originally because it was felt it would adversely affect bond performance. At this time the heating lamp intensity was decreased to prevent further overheating. The temperatures obtained then from the one panel were:

Front-Surface Thermocouples (°C)	Bond Area Thermocouples (°C)
157.6, 152.9	157.8, 162.3

Thus the temperature of the bond is close to the front surface temperature, and the large temperature drop was between the bond and the original thermocouple location. For the first 84 cycles the modules were being heated up to approximately 325°C. Subsequently, the thermocouples adjacent to a bond were used to monitor temperatures.

Figures 5-4, 5-5 and 5-6 present detailed data on when individual bonds failed on each module. Figure -7 gives curves of bond failures vs number of temperature cycles.

The module which performed best was the conductive epoxy-bonded module with silver-plated molybdenum interconnect circuit (Module No. 1). This module lost 17% of its bonds after 604 cycles.

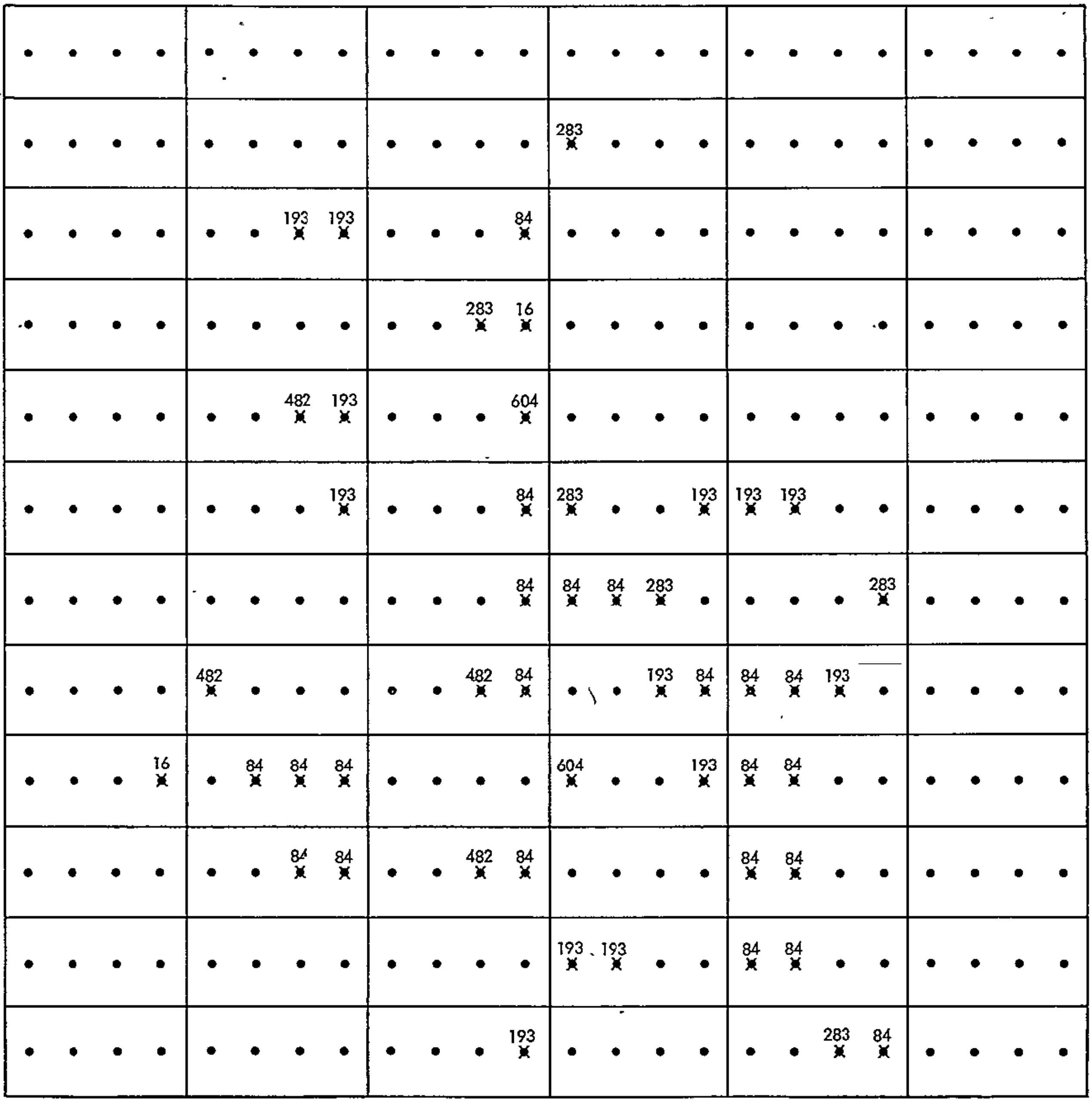

Figure 5-4 Bond Failure Data, 72-Cell Module No. 1

• • • •	• • 482✱ 482✱	84✱ 283✱ • •	283✱ 283✱ 482✱ •	0✱ 84✱ 482✱ •	0✱ • 283✱ 16✱
283✱ 283✱ 283✱ •	• • • •	• • • 193✱	• 84✱ 84✱ 84✱	84✱ 84✱ • 193✱	• • 283✱ 16✱
• • • •	• • • 84✱	16✱ • • o	84✱ • 283✱ 16✱	84✱ 84✱ • 193✱	16✱ 16✱ • 193✱
• 193✱ 84✱ 84✱	16✱ 193✱ • •	• 193✱ 84✱ 16✱	604✱ 16✱ 16✱ 16✱	• • 84✱ 16✱	84✱ 604✱ • 0✱
• 193✱ 84✱ 84✱	• • 482✱ 84✱	• 482✱ 283✱ 193✱	16✱ 16✱ 84✱ •	16✱ 16✱ 16✱ 84✱	193✱ • 84✱ 16✱
16✱ 84✱ 193✱ •	193✱ 193✱ 193✱ •	• • • 193✱	• 16✱ 16✱ 16✱	16✱ 16✱ 84✱ •	84✱ 84✱ 193✱ •
283✱ 482✱ • •	• 193✱ 193✱ 193✱	• 16✱ 16✱ 16✱	• 16✱ 16✱ 16✱	• 16✱ 16✱ 16✱	• 84✱ 84✱ 16✱
• 604✱ 193✱ 16✱	283✱ 16✱ 193✱ •	• 16✱ 16✱ 16✱	16✱ 16✱ 84✱ •	84✱ 283✱ • 84✱	16✱ 16✱ • 193✱
• 84✱ 84✱ 84✱	• 193✱ 16✱ 16✱	• 283✱ 283✱ 283✱	16✱ 16✱ 16✱ •	16✱ 16✱ 84✱ 84✱	16✱ 84✱ • •
84✱ • • 193✱	• 16✱ 16✱ 16✱	• 283✱ 283✱ 193✱	• 84✱ 84✱ 84✱	193✱ • 16✱ 16✱	• • • 0✱
• • • •	• • • •	193✱ 193✱ • •	• 84✱ 16✱ 16✱	193✱ 193✱ 283✱ •	• • 16✱ 16✱
• • • •	16✱ 193✱ • •	84✱ 193✱ 84✱ •	84✱ 604✱ 16✱ 16✱	193✱ 283✱ 283✱ 193✱	283✱ 283✱ 16✱ 16✱

Figure 5-5 Bond Failure Data, 72-Cell Module No. 2

84 84 16 16	84 84 84 16	16 84 84 0	84 84 84 84	84 84 84 84	84 84 84 84
16 84 84 84	16 16 84 84	16 84 84 84	84 84 84 84	0 16 84 84	84 84 84 84
16 84 84 84	84 84 84 16	84 84 84 16	84 84 84 84	84 84 84 84	84 84 84 84
193 283 84 16	84 84 84 84	84 84 16 16	84 84 84 84	84 84 84 84	84 84 84 283
193 283 16 16	84 16 16 16	84 84 84 84	84 84 84 84	84 84 84 84	16 16 84 193
16 193 193 84	16 84 84 84	16 16 16 16	84 84 84 84	84 84 84 84	84 84 84 84
84 84 16 16	84 84 84 84	16 16 84 84	16 84 84 84	84 84 84 84	193 193 84 84
193 283 84 16	0 84 283 16	84 84 84 16	16 84 84 84	84 84 84 84	84 84 84 84
84 84 16 16	84 84 84 16	84 84 84 84	16 16 84 283	84 84 84 16	84 193 193 193
16 193 283 193	16 283 283 283	84 84 84 16	16 84 84 84	16 84 84 84	16 84 283 84
16 193 283 16	84 84 84 16	84 84 84 16	16 16 84 84	84 84 84 84	84 84 283 384
84 84 84 84	84 283 283 84	84 84 84 84	84 193 283 283	84 84 84 84	84 84 283 283

Figure 5-6 Bond Failure Data, 72-Cell Module No. 3

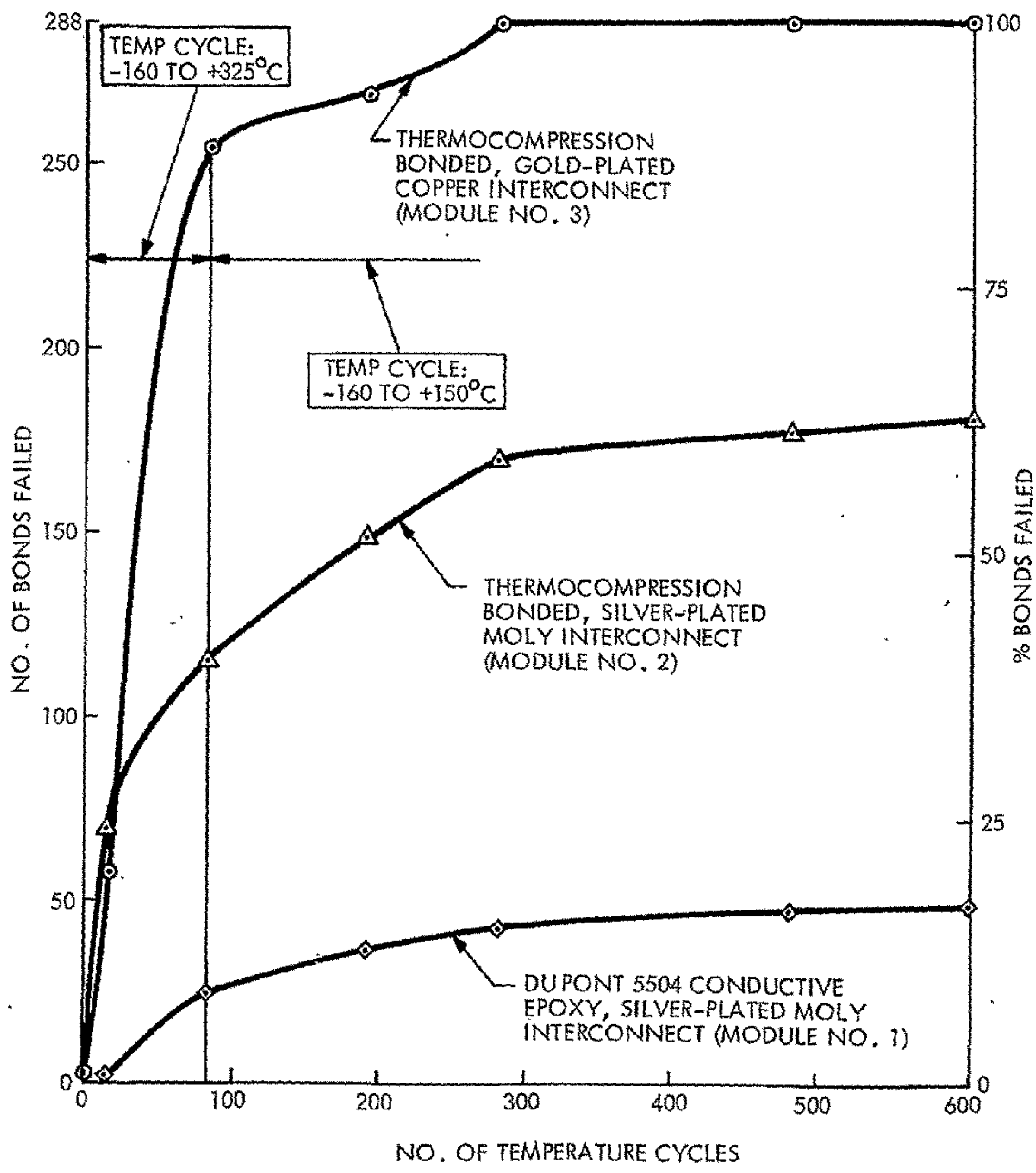

Figure 5-7 Temperature Cycling Performance of 72-Cell Test Modules

The performance of the thermocompression-bonded modules, both 12-cell and 72-cell, was poor compared with the pull tab specimens. At first it was thought this might be due to a high stress riser around the periphery of the bond compared with parallel-gap welding where material melting results in a smoother contour at the periphery. This sharp edge, combined with the added thermal stress of the substrate film when cold, then would cause bond failure. It is now thought more likely the poor performance is due to the polyester adhesive on the Kapton substrate, which melts and flows out over the bond access area during the bonding operation. It is expected this contamination would be avoided by using an epoxy or acrylic (thermoset) adhesive instead of polyester or FEP (thermoplastics).

A comparison of percent bond failures between the 12-cell and 72-cell modules is shown in Figure 5-8. For each module type, the 72-cell module bonds failed more rapidly than the 12-cell module bonds. On the gold-plated copper, 72-cell module, it appears that the over-temperature stress through the 84th cycle resulted in a more rapid bond failure rate, since there is a sharp decrease in slope of the curve after the 84th cycle. On the silver-plated molybdenum, 72-cell modules, there is no sharp knee. However, the poorer performance of these 72-cell modules also is believed to be a direct result of the higher temperatures encountered in the first 84 cycles.

The electrical output from the thermocompression-bonded modules after temperature cycling was zero due to the many bond failures (Module 3 had no cells left on the substrate). The output from the conductive epoxy bonded module before and after cycling is shown in Figure 5-9. After temperature cycling, the current of the right half was down one-third due to bond failures. The left side of the module performed satisfactorily before temperature cycling, but after cycling the current was down by two-thirds. The open circuit voltages across the right side and the full module, which were low before temperature cycling, were higher afterward. This could be due to deterioration of adhesive which had caused a short between N and P contacts on a cell.

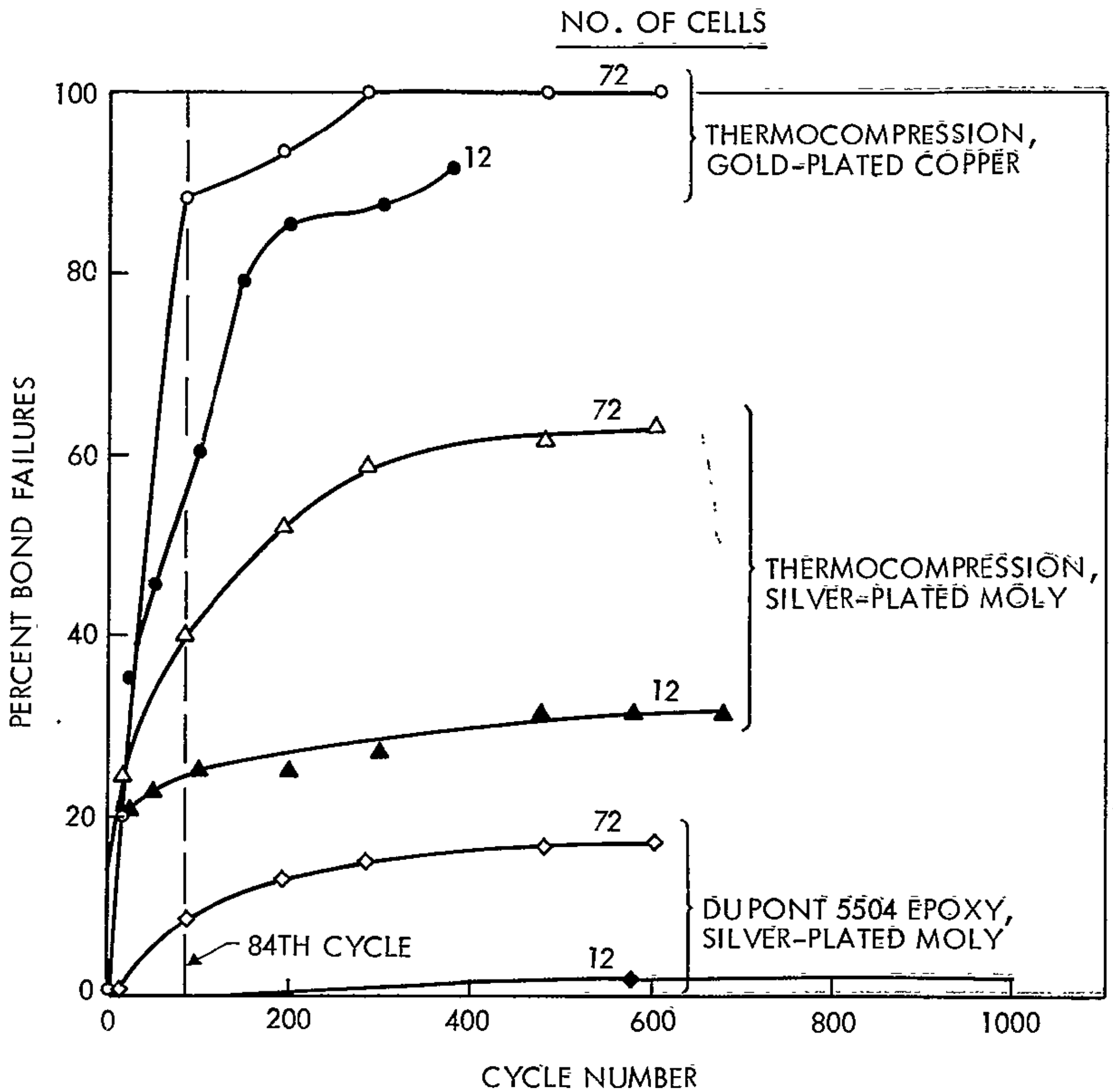

Figure 5-8 Comparison of Percent Bond Failures, 12-Cell and 72-Cell Modules

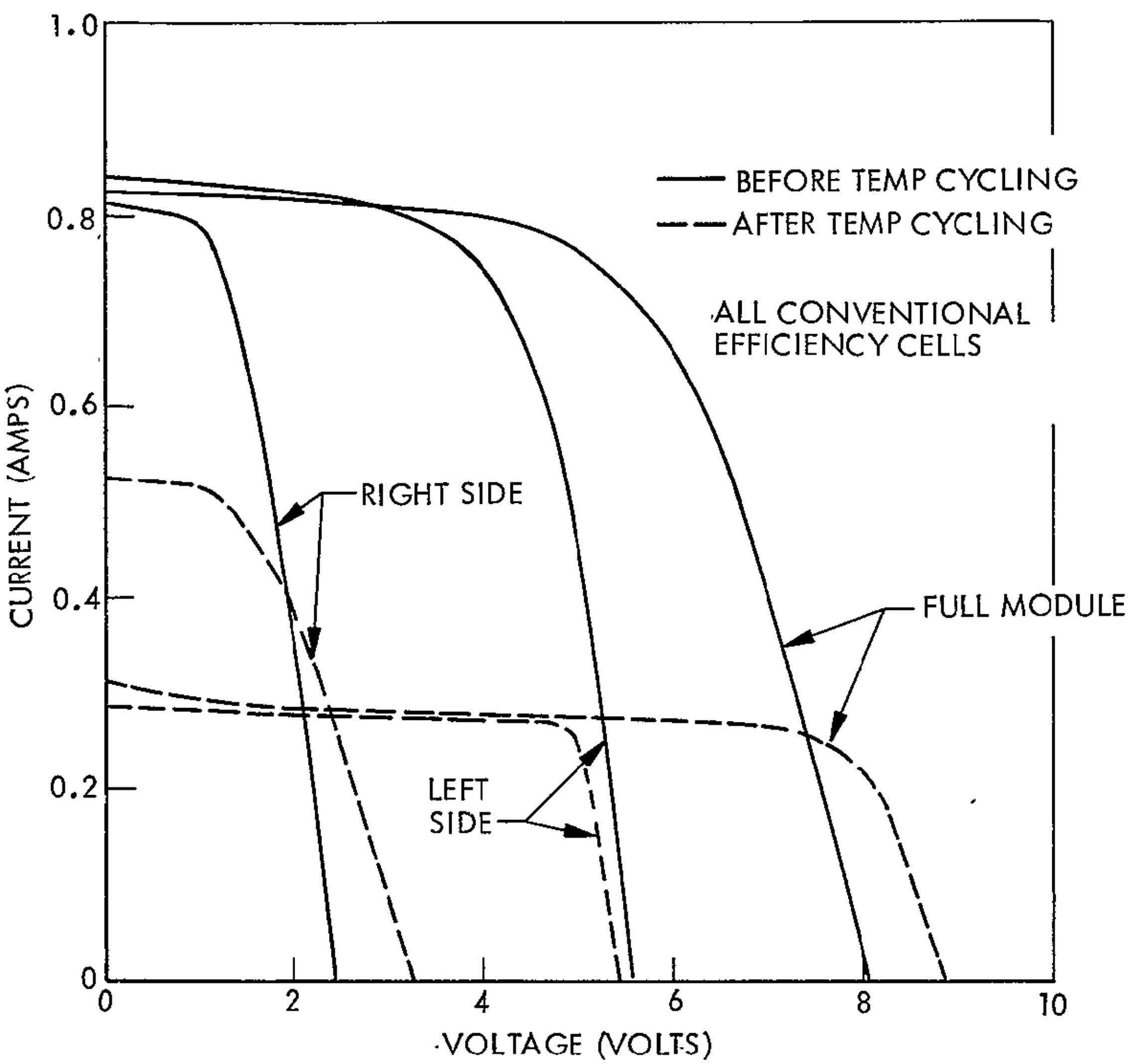

Figure 5-9 Electrical Output Before and After Temperature Cycling, Module No. 1

Section 6
CONCLUSIONS AND RECOMMENDATIONS

Several conclusions were drawn from the work done in the Interconnect Bonding Study. These are applicable to large, flexible substrate solar arrays and, in particular, to solar arrays for Solar Electric Propulsion (SEP) and Shuttle payload applications.

Both thermocompression bonding and conductive adhesives were shown to be viable methods of joining solar cells to the interconnect circuit. Each has advantages and disadvantages compared with parallel-gap welding, so the best bonding method will depend on the application. However, a larger investment must be made in process development and tooling before either method can be considered for a flight array.

The screening testing was successful in demonstrating which of the interconnect metals, conductive epoxies and thermocompression bonding parameters are best for the flexible substrate solar array application.

Thermocompression bonding worked very well and better than the conductive epoxies on pull tab specimens, but performed poorly on solar array test modules. The cause may be the polyester adhesive on the Kapton substrate, which melts and flows onto the bond areas during the bonding operation.

With respect to thermocompression bonding:

- Variables affecting bond quality, in addition to the bonding schedule, are tip geometry, interconnect material, thickness and adherence of plating, cell metalization adherence, cleanliness of parts, oxide formation, and handling requirements.

- Bond quality is less sensitive to the bonding parameters than in parallel-gap welding, thus reducing the chance of a poor bond caused by changed conditions (e.g., oxidized tip).

- The effect of the substrate adhesive on bond quality should be determined.

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With respect to conductive epoxy bonding:

- The DuPont 5504 silver-filled epoxy performed best of the 9 candidates. Of the hundreds of conductive adhesives available commercially, probably only a few would be acceptable. However, better products could be developed readily if the performance requirements were known to the manufacturers. Candidate compositions must be tested thoroughly to determine bond strength and electrical resistance during and after environment exposure.

- Conductive epoxy bonding would be most advantageous in large scale production, using screen printing techniques. Its disadvantages are the relatively complicated set-up and the time required in the curing operation.

- A significant amount of process development is required to improve the ease and control of application of conductive adhesives, to acquire good fixtures to hold the cells and substrate during application and curing, and to demonstrate the potential for automated assembly.

The silver-plated molybdenum interconnect performed best in temperature cycling for both conductive epoxy and thermocompression bonding.

A copper interconnect circuit must be plated to reliably get satisfactory thermocompression or conductive epoxy bonds. Otherwise, copper oxide may form at the bond, seriously degrading the bond strength and/or electrical conductivity. Similar results can be expected from other unplated interconnect metals which form oxides, such as molybdenum and Kovar.

Solar cell electrical output was not degraded by either the conductive epoxy or thermocompression bonding process.

The high-efficiency cells did not present any new problems compared with the conventional efficiency cells.

New interconnect designs should be developed to give lower bond stresses during temperature cycling than the circuit used in this study.

APPENDIX A
MATERIALS PROCUREMENT

The materials used in this study are listed in Figure A-1. The solar cells were all spacecraft quality 8-mil, end-tab-wraparound, 2 x 4 cm cells with Ag-Ti contacts, but were of three kinds. For the initial work, electrical reject cells were used. These were cells that had been manufactured for the SEP contract but failed to meet the output requirement. Consequently they were immediately available at low cost.

The second kind of cell used was the "conventional" efficiency, SEP cell, per LMSC Development Specification 9000300, dated 31 January 1974. These were provided as Government-furnished equipment from extra cells purchased for the SEP contract (NAS8-30315).

The third type of cell was a high efficiency cell, included to evaluate the effect of conductive epoxy and thermocompression bonding on the performance of a shallower junction cell.

The purchase of the high-efficiency solar cells was the most significant procurement activity. A visit to OCLI and Heliotek was made to investigate their capabilities to produce higher-efficiency cells. OCLI (then Centralab) had a license to manufacture violet cells but at the time were not producing end-tab-wraparound violet cells. Thus it became necessary to purchase a so-called improved efficiency cell, which derives its greater output from a shallower junction (but not as shallow as in the violet cell), P^+ field on the back surface, and a tantalum pentoxide antireflective coating. Quotations were requested and received from both companies for 208 cells with a minimum output of 263 ma at 470 mv (minimum efficiency of 11.3%). The cells were purchased from OCLI because it had proposed a shallower junction (0.2 μm vs 0.3-0.4 μm by Heliotek).

The pull tabs used during the conductive adhesive and thermocompression bonding development were etched from foil and plated at LMSC. Except for the silver foil, all materials were taken from existing stock.

ITEM	DESCRIPTION	QTY	SOURCE
1	Solar Cells Hi-eff (263 ma at 470 mv) 8 mil, end tab wraparound	118	OCLI City of Industry, CA
2	Solar Cells Same as above except 257 ma	90	OCLI
3	Solar Cells Electrical Rejects	224	OCLI
4	Solar Cells Conventional Eff, 8 mil, end tab wraparound	489	GFE, from NAS8-30315
5	Solar Cell Covers 6 mil fused silica, AR coating only	244 725	GFE, from NAS8-30315 LMSC-supplied
6	Silver Foil, .001 in.	2 in. x 8 ft.	The Wilkinson Company Westlake Village, CA
7	Silver Foil, .002 in. Comm. pure, annealed	3 in. x 1 ft.	The Wilkinson Company
8	Molybdenum Foil .001 mil	As Req'd	LMSC stock
9	Copper Foil, 1 and 2 oz.	As Req'd	LMSC stock
10	Kovar Foil, .001 in.	As Req'd	LMSC stock
11	Invar Foil, .001 in.	As Req'd	LMSC stock
12	Silver for plating	As Req'd	LMSC stock
13	Gold salts for plating	As Req'd	LMSC stock
14	Kapton/polyester laminate, 1/2 mil/1/2 mil	18 in. x 65 ft.	Left over from NAS8-30315 Made by Circuit Mat'ls Co. Hoosick Falls, N.Y. 12090
15	Conductive epoxy, silver Epotek H20E	Sample	Epoxy Technology, Inc. Watertown, MA 02172
16	Conductive epoxy, silver Epo-tek H21D	1 oz.	Epoxy Technology, Inc.

Figure A-1 Materials Used

ITEM	DESCRIPTION	QTY	SOURCE
17	Conductive epoxy, silver Epo-tek H31D	1 oz.	Epoxy Technology, Inc.
18	Conductive epoxy, gold Epo-Tek H44	1/2 oz.	Epoxy Technology, Inc.
19	Conductive epoxy, silver Ablebond 36-2	1 oz.	Ablestik Laboratories, Inc., Gardena, CA 90248
20	Conductive epoxy, gold Ablebond 58-1	2 gr.	Ablestik Laboratories
21	Conductive epoxy, silver DuPont 5504	350 gr.	E. I. DuPont de Nemours Wilmington, DE 19898
22	Conductive epoxy, silver Ohmex-Ag	As Req'd	LMSC stock. Made by Transene Company, Inc. Rowley, MA 01969
23	Conductive epoxy, gold GE-10	As Req'd	LMSC stock. Made by Transene Company, Inc.
24	Thermocompression Bonding Tip.Tungsten Carbide	2	Small Precision Tools San Rafael, CA 94903
25	Thermocompression Bonding Tip.Inconel	2	Small Precision Tools
26	Adhesive, solar cell cover Dow Corning 63-489	As Req'd	LMSC stock
	Misc. Materials for Tools, Fixtures, Packaging, Testing	As Needed	LMSC stock
	Liquid Nitrogen, during Temp. Cycling Testing	5400 gal.	From LMSC bulk storage

Figure A-1 (cont'd.) Materials Used

Two batches of pull tabs were prepared. A total of about 700 tabs were made in the first batch. When these were used up, a second, larger supply was made consisting of the following:

MATERIAL	NO. OF TABS
1 oz. copper	234
2 oz. copper	208
Silver-plated 1 oz. copper	312
Silver-plated 2 oz. copper	208
Gold-plated 1 oz. copper	312
Gold-plated 2 oz. copper	208
Silver-plated 1 mil Kovar	104
Gold-plated 1 mil Kovar	104
Silver-plated 1 mil Molybdenum	312
Gold-plated 1 mil Molybdenum	156
Silver-plated 1 mil Invar	104
Gold-plated 1 mil Invar	130
1 mil silver	156
2 mil silver	208
TOTAL	2756

Gold-plated Kovar and molybdenum were added to the required materials since our experience indicated that gold is a superior surface material for thermocompression bonding. Silver- and gold-plated Invar also were added because Invar has a low thermal expansion coefficient.

Foils made for the 12-cell module interconnect including extras, were:

Copper, 1 oz., unplated	6 pcs.
Copper, 1 oz., gold-plated	6 pcs.
Copper, 1 oz., silver-plated	3 pcs.
Molybdenum, 1 mil, silver-plated	6 pcs.
Kovar, 1 mil, gold-plated	4 pcs.
Invar, 1 mil, silver-plated	4 pcs.

The Invar foil was obtained by chem-milling existing 3 mil foil down to 1 mil in ferrous chloride. This provided a very uniform thickness foil for the circuit.