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Thermal Cycle Testing of Space Station Freedom Solar Array Blanket Coupons

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Lewis Research Center is presently conducting thermal cycle testing of solar array blanket coupons that represent the baseline design for Space Station Freedom. Four coupons were fabricated as part of the Photovoltaic Array Environmental Protection (PAEP) program, NAS 3-25079, at the Lockheed Missiles and Space Company. The objective of the testing is to demonstrate the durability or operational lifetime of the solar array welded interconnect design within a Low Earth Orbit (LEO) thermal cycling environment. Secondary objectives include the observation and identification of potential failure modes and effects that may occur within the solar array blanket coupons as a result of thermal cycling. The paper presented describes the objectives, test articles, test chamber, performance evaluation, test requirements, and test results for the successful completion of 60,000 thermal cycles.

Introduction

The primary objective of the thermal cycle test is to demonstrate the durability or operational lifetime of the solar array welded interconnect design within a LEO thermal cycling environment. Secondary objectives include the observation and identification of potential failure modes and effects that may occur within the solar array blanket coupons as a result of thermal cycling.

This document describes the objectives, test articles, test chamber, performance evaluation, test requirements, and test results to date for the thermal cycle testing of solar array blanket coupons at NASA LeRC.

Power for Space Station Freedom will be generated by four photovoltaic power modules that each employ two solar array wings. The solar array wings are comprised of two blankets that each are an assembly of active solar panels. An active solar cell panel contains 200 solar cells connected in series. Each solar cell is attached to the underlying circuit interconnects by 10 welded contact points.

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The solar cell to circuit weldments and copper interconnects are subjected to thermally induced stresses as a result of temperature excursions experienced each orbit. Freedom will orbit the earth approximately once every 90 minutes which results in 6,000 thermal cycles a year, or 90,000 thermal cycles for the array over a period of 15 years. This cycling will cause stresses on the blanket materials and will, over time, result in structural fatigue of panel components.

The solar array blanket is a combination of materials with different Coefficients of Thermal Expansion (CTE). Although the copper interconnect and the silver contact points on the solar cell, where the weld is made, have a similar CTE, the adjacent blanket materials, adhesives, and silicon cells do not (Fig. 1). Consequently, the resultant effects at the weld joint, due to mismatches in the adjacent material's CTEs and the composite metallurgical properties of the weld are difficult to predict and warrant the physical testing of a blanket sample.

Test Article Description

The test articles were fabricated as part of the Photovoltaic Array Environmental Protection (PAEP) program, NAS 3-25079, at the Lockheed Missiles and Space Co. (LMSC), Inc., Sunnyvale, California. Four thermal cycle coupons were fabricated using the same design, materials, and manufacturing processes that are presently the baseline for Space Station Freedom (Fig. 3).

Each test coupon contains four 8 cm by 8 cm silicon solar cells with coverglasses. The cells were manufactured as part of an advanced development program, NAS 3-24672, at Spectrolab Inc. The coverglass is bonded to the solar cell with Dow Corning (DC) 93-500 adhesive. The cells are an N-on-P type silicon cell with a boron back surface field and a 10 ohm-cm nominal base resistivity. The back collection grids and the N-type and P-type interconnect contact points are both deposited layers of aluminum, titanium, palladium, and silver. The back side of the cell has six positive and four negative contact points (Fig. 4).

Prior to fabricating the deliverable thermal cycle coupons, the PAEP program completed a weld optimization task using a parallel gap resistance welder. The task determined the voltage, emissivity, and IR sensing settings that are used to control the weld pulse energy and the weld pulse duration on the LMSC production welder. The parallel gap resistance welding utilizes two closely space electrode tips that make contact with the copper interconnect on one side of the array panel. The electrodes pass a current through the copper circuit and underlying solar cell metal contacts causing the metals to join through resistance welding. The welding was performed using a constant voltage power supply that regulates the current during welding to compensate for variations in the resistance occurring in or across the weld. Pull tests, photomicrographs, and illumination tests were used to evaluate the quality of actual solar cell to copper interconnect welds. From this effort a weld schedule was selected that exhibited the statistically highest pull strengths and showed no obvious failure mechanisms such as gross melting, voids, or cracking.

The coupon substrate is comprised of two layers of silicon dioxide coated Kapton [ref. 2] with a copper circuit between. The copper circuitry is thermally bonded to the first layer of Kapton with a polyester adhesive. The solar cells are welded to the copper circuitry through access holes in the first layer of Kapton. The second sheet of Kapton is bonded with DC 93-500 to the exposed circuitry, the first sheet of Kapton, and the solar cells through access slots in the first layer of Kapton. The coupons are also configured with aluminum foil covered Kapton hinges and hinge pins. The aluminum foil was determined to be the most effective method of protecting the panel hinges from atomic oxygen.

For thermal cycling, the test articles are mounted to metal frames using springs. The springs maintain a tension that simulates the on orbit solar array assembly conditions and isolates the samples from any adverse affects that may be caused by the frames.

Test Chamber Description

The test chamber (Fig. 2) is designed to cycle a test article between the temperature extremes encountered by spacecraft orbiting the earth. The thermal cycling chamber consists of two smaller chambers that each maintain a constant hot and cold temperature of +85°C and -115°C, respectively. The switching temperatures of the test frames are set at +70°C and -90°C. Once a switching temperature is achieved, the frame and coupon move to the opposite side of the chamber. The typical cycle time for one complete cycle is between 3-4 minutes, depending on the number of test frames in the chamber at a given time.

The thermal cycling chamber is basically an insulated box with an oven and a freezer. The oven is heated electrically using two 500 W resistance heaters which provide radiative and convective heat transfer to the samples. The freezer is cooled using liquid nitrogen which is fed into the chamber through a series of holes in a 1/4 inch copper tube. The liquid nitrogen boils off creating nitrogen gas which cools the chamber and also provides an inert atmosphere. As a result of this, the oven chamber is also provided with a nitrogen environment. Temperatures of the chambers are monitored by centrally located thermocouples interfaced to a computer which turns the heaters and liquid nitrogen on or off as required. The system is capable of temperature extremes as high as +125°C ± 10°C as low as -180°C ± 10°C.

Up to four 8 in.× 8 in.× 1/2 in. solar array test articles can be tested simultaneously. Each test article is mounted to a removable frame which slides between the hot and cold sides of the chamber. Each frame is independently monitored by a thermocouple attached to the test article. Cycle counts are maintained by the computer and printed hourly. The temperature swing of any test article can be plotted graphically against time if desired. Cycling will stop automatically at a predetermined cycle count, at which time, the test frames can be removed from the chamber for performance measurements and visual inspection.

This method of thermal cycling allows for a more rapid cycling than can be achieved in a vacuum chamber with much lower maintenance and operational costs. Both of these issues are rationale for using an inert atmosphere chamber. Atmosphere thermal cycling does tend to be equal or more severe than when cycling in a vacuum [ref. 3].

Test Requirements

Phase I

A test chamber characterization shall be run and recorded to determine the thermal environment and the thermal gradients that exist within each side of the test chamber.

The coupons shall be mounted in a manner that represents the on–orbit tensions of the solar array blanket. Equally tensioned springs should be used along at least one side of the coupon.

The coupons shall be attached to the test fixture frame along the sides of the hinge pins only.

The coupon should be oriented in the test fixture frames so that the largest thermal gradient across the coupon is perpendicular to the longest series run in the copper circuitry. This will minimize the thermal gradients across a single cell's interconnected weldments during the test.

Electrical leads from the coupon shall be attached to the fixture frame such that any forces directly applied to the lead during measurement will not compromise the lead-to-coupon connection or result in any external forces on the coupon.

Phase II

The test chamber shall cycle between -90°C ± 10°C and +70°C ± 10°C.

Both the upper and lower chamber temperatures shall be monitored throughout the test. Coupon temperatures shall be monitored by attaching a thermocouple to a single point on the coupon.

Cycling time shall be between 3 and 5 minutes per cycle.

A record of events that may have occurred shall be kept where the experiment exceeded the experimental design limits.

Electrical measurements, visual inspections including low power magnification, and any other NonDestructive Evaluation (NDE) techniques shall be made after the following number of cycles: 0, 3000, 6000, 12000, 18000, 24000, 30000, 42000, 60000, 72000, 84000, 90000.

Once the testing has begun, the time taken to measure and inspect the coupons out of the chamber should be kept to an absolute minimum.

All test coupons should be photographed before cycling and at any point during the test that specifically illustrates a failure mode and/or effect.

Solar Cell Performance Evaluation

Performance of the test article is measured by the range of its power output under illumination. This electrical output is characterized as an I-V curve (current vs. voltage). The I-V curve is generated by varying a load resistance on the solar cell or array from 0 to infinity ohms while the cell is under illumination. The illumination is the equivalent sunlight or solar spectrum that would be seen in space. The solar constant or air mass zero (AM0) is 136 mW/cm^2 for the IV flash reference. The following key factors from the IV curve are used in the performance evaluation:

1) I_{sc} short circuit current (AMPS)
2) V_{oc} open circuit voltage (VOLTS)
3) I_{max} maximum power current (AMPS)
4) V_{max} maximum power voltage (VOLTS)
5) P_{max} maximum power ($V_{max}I_{max}$, WATTS)
6) F.F. fill factor, < 1 ($V_{max}I_{max}/P_{max}$)

7) Efficiency peak efficiency P_{max}/(light intensity × cell area)

(The cell area is the surface area of the cell being illuminated).

SSF solar array test articles' I-V curves are obtained by flash testing. Flash testing is performed by using a short burst of light (xenon arc lap) with a normalized AM0 spectrum and ramping an increasing load on the cell during that burst. Using this method a complete I-V curve is generated in about 1.5 milliseconds. This flash test provides curve data with virtually no heat being generated in the cells under test. Under this condition, test repeatability is very good and data comparisons can be made. If a weld failure were detected, series resistance in the cell would increase. Series resistance would most prominently affect the slope of the curve between the P_{max} point and V_{oc}.

Solar Cell Visual Inspection

In addition to performance characteristics, the solar cells undergoing thermal cycling are visually inspected and mapped. This consists of looking at the cell under

10× magnification with incident light at varying angles. Because of the glass and reflective nature of the cell, light angles are varied to detect any notable flaws in the surface of the cell or glass. These flaws are noted in their respective locations on a paper image of the cell. Each flaw is marked with a letter designation and subscripted to indicate the time the flaw was first seen. In the SSF solar array test articles, both the front and back sides are mapped, the front being the cell face and the back having the actual welds and interconnects. The following flaws are noted:

1) B - break/crack in cell surface
2) C - break/crack in cover glass
3) V - void
4) W - wrinkle in copper interconnect
5) A - adhesive (visible lines/bubbles)

6) Any other suspicious or nonconformity in the cell array, i.e., air bubbles, glue, peeling

Visual mapping and subscripted notations are performed for each of the coupons at all scheduled intervals. Ultimately, the visual inspection is used to observe any trends that would lead to the performance degradation in the cells or trace the origin of any possible failures that may have occurred.

Status to Date

All of the four array test articles have completed 60,000 cycles which is approximately 10 years in LEO. All of these samples show no significant signs of electrical degradation or failure.

Electrical performance of the arrays has been unchanged within the accuracy of the test equipment (2%). Measurements were taken at 0, 3000, 6000, 12000, 18000, 24000, 30000, 42000, 48000, and 60000 cycles. The ratio of maximum power over initial maximum power has remained consistent. Any weld failures or catastrophic cracks would cause a significant change in the coupon output.

Visual inspection of the coupons at 10× magnification has revealed very slight changes in the cells. Fine cracks have been detected in the cell and coverglass. Most of the cell and coverglass cracks were observed before cycling and only tended to elongate fractionally during the first 12000 cycles. These changes in the cells are viewed as creating no severe consequence to the integrity of the cells.

The backside of the coupon or interconnect side has exhibited a change in the copper interconnects, Kapton, and adhesive layers. Within the first 12000 cycles a movement of the copper and Kapton was observed. The copper went from being flat to having a large number of ripples. This out of plane rippling, resulting from initial thermal stresses, has actually become a stress relief path for subsequent thermal cycling. Depending on how the copper was applied, more ripples occurred in some areas than in others. Rippling of the copper interconnects has run up to some of the weld connections on the cells.

The adhesive also appears to have become elongated. This elongation is exhibited by round voids in the adhesive that have become oval in shape. After 12000 cycles all of the motion in the copper, Kapton, and adhesives stabilized and does not appear to have affected the weld joints. After 48000 cycles some of the rippling appeared to have decreased in size and the adhesive looks as if crystallization has taken place in some localized areas. The adhesive bonds within the coupons will be carefully watched for any delaminations or bonding failure that might occur as a result of cycling.

Table 1 contains flash test results to date for the four thermal cycle coupons; SSFSA–1, SSFSA–3, SSFSA–4, and SSFSA–5. All of the data indicates that the performance has been unchanged throughout the cycling. At this time, the achievement of the 90000 thermal cycle goal appears to be feasible.

References

[1.] Jet Propulsion Laboratory: Solar Cell Array Design Handbook Volume II. NASA, October 1976, pp. 7.11–4,5.

[2.] Kapton is a registered trademark of E.I. DuPont de Nemours and Co., Inc.

[3.] Rauschenbach, H.S.: Solar Cell Array Design Handbook. Van Nostrand Reinhold Company. 1980. pp.402–403.

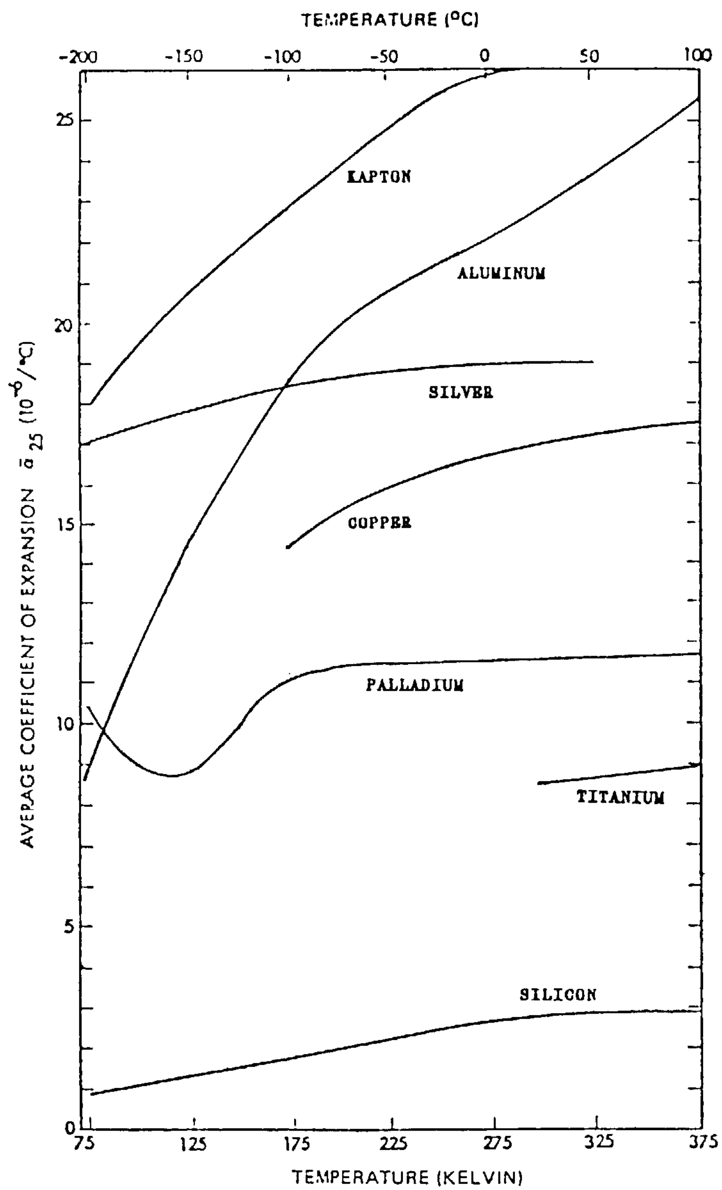


Fig. 1 CTE (Coefficient of Thermal Expansion) Versus Temperature for Materials Used on SSf Array[1]

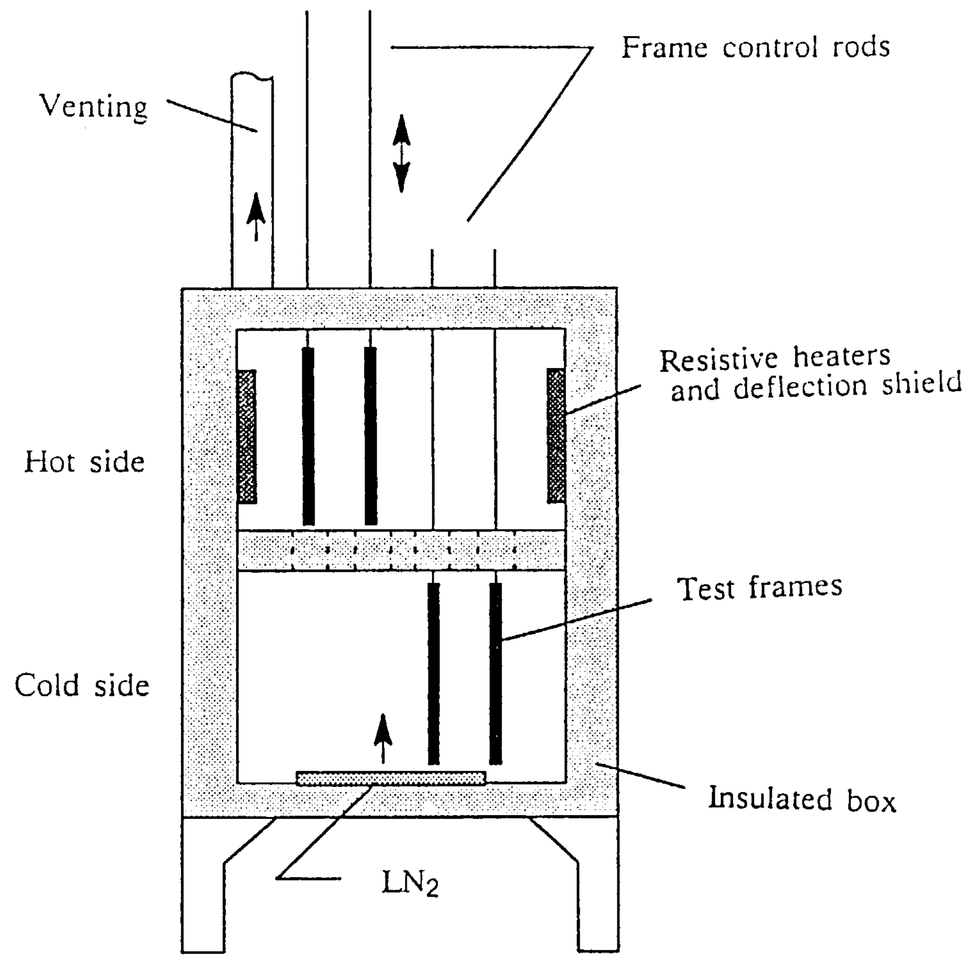
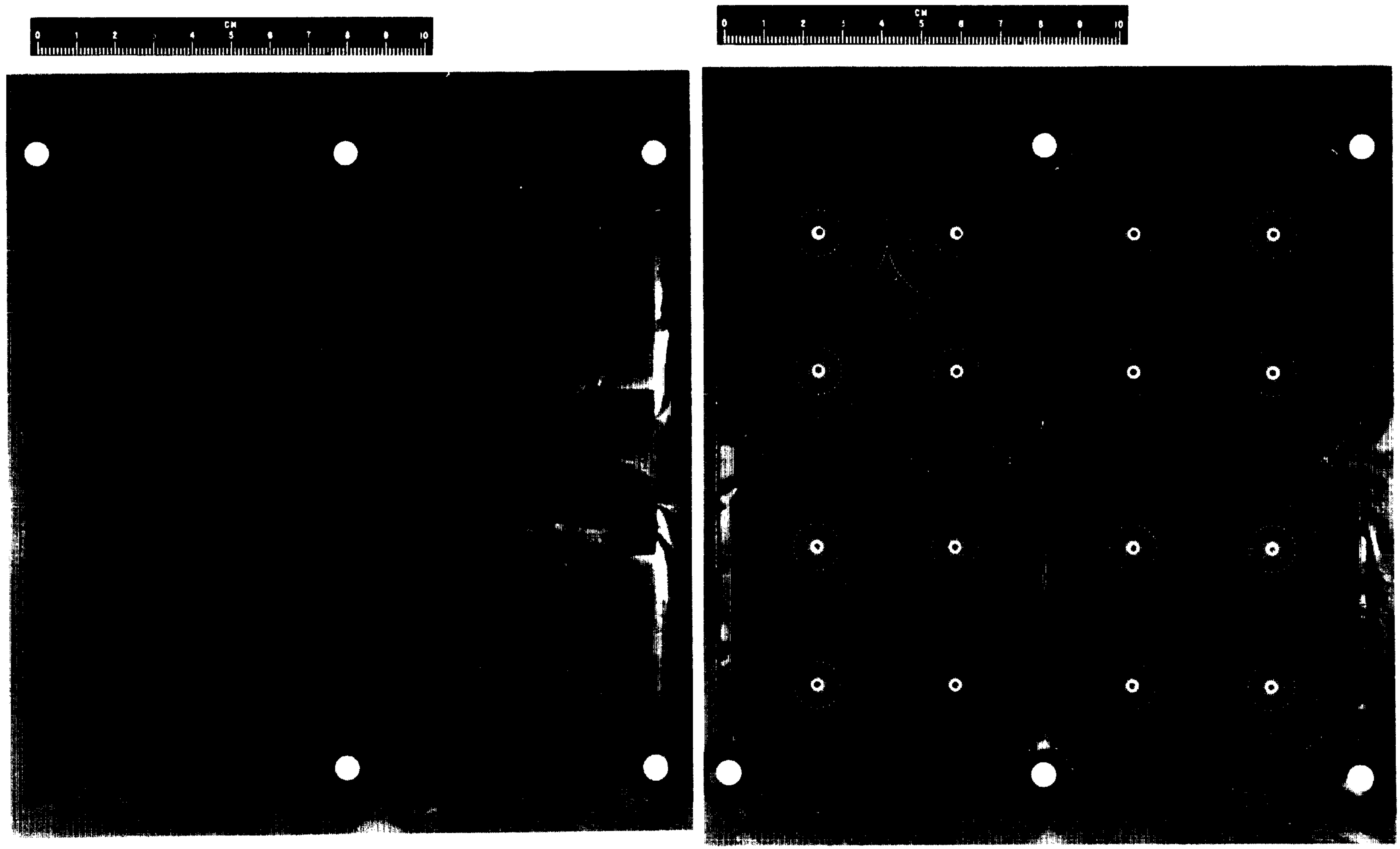


Fig. 2 **Thermal Cycle Test Chamber**



BACK FACE

FRONT FACE

Fig. 3 Test Article Solar Array Blanket Coupons

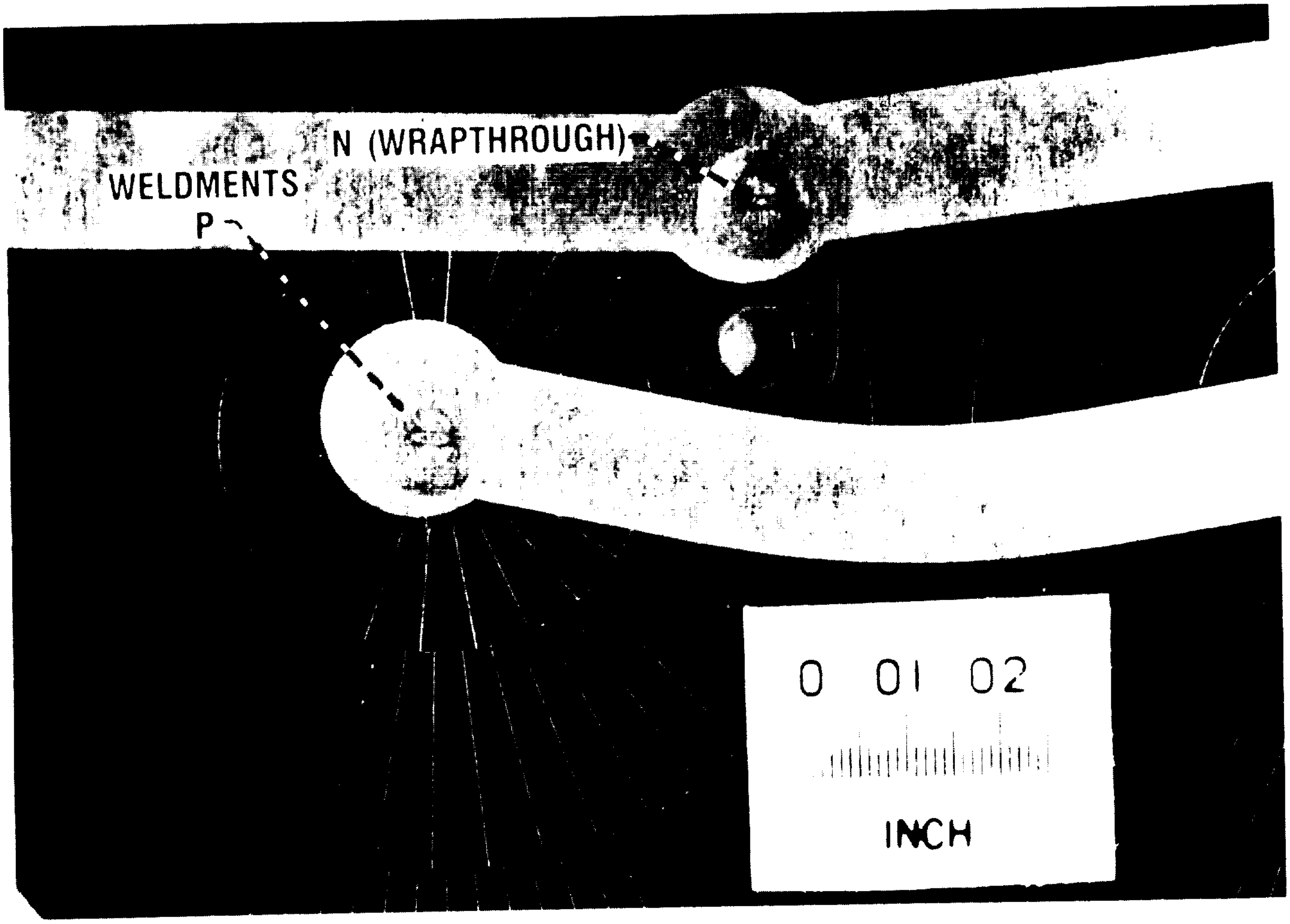


Fig. 4 Close-up view of copper interconnect weld contact points, shown is one P-weld and one N-weld contact.

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Space Station Thermal Cycling Modules

Table I: I-V Data 4-cells in series arrays.

A-51 (standard reference cell AMO I_{SC}= .1518 Amps)

Date	3/02/89	4/06/89	4/24/89	5/08/89	5/24/89	6/09/89	7/09/89	7/25/89	8/21/89
Isc	0.1529	0.1519	0.1514	0.1517	0.1518	0.1519	0.1520	0.1518	0.1517
Isc/Isc0	1.0072	1.0007	0.9974	0.9993	1.0000	1.0007	1.0013	1.0000	0.9993

Date Cycles	3/02/89 0	4/06/89 6000	4/24/89 12000	5/08/89 18000	5/24/89 24000	6/09/89 30000	7/09/89 42000	7/25/89 48000	8/21/89 60000
SSFSA-3									
I_{sc}	2.7080	2.6855	2.7361	2.6446	2.6698	2.6733	2.7272	2.6893	2.6772
V_{oc}	2.4530	2.5073	2.4917	2.4885	2.4829	2.5162	2.4803	2.5136	2.5192
I_{max}	2.4290	2.3754	2.4744	2.3466	2.4095	2.3829	2.4292	2.4131	2.4038
V_{max}	1.8480	1.9066	1.8582	1.9140	1.8520	1.9264	1.8892	1.9239	1.9140
P_{max}	4.4880	4.5287	4.5979	4.4875	4.4624	4.5904	4.5893	4.6425	4.6008
F.F.	0.676	0.673	0.674	0.677	0.673	0.682	0.678	0.687	0.682
Effic.	13.2	13.3	13.63	13.2	13.2	13.5	13.5	13.7	13.6
P/P_0	1.0000	1.0091	1.0245	0.9999	0.9943	1.0228	1.0226	1.0344	1.0251
SSFSA-4									
I_{sc}	2.7070	2.6703	2.7331	2.6612	2.6519	2.6654	2.7274	2.6886	2.6759
V_{oc}	2.4470	2.4559	2.4783	2.4774	2.4722	2.5127	2.4724	2.5058	2.5097
I_{max}	2.4740	2.4228	2.4337	2.4027	2.3405	2.3993	2.4336	2.4148	2.4368
V_{max}	1.8360	1.8669	1.9152	1.8842	1.9152	1.9289	1.9053	1.9450	1.9115
P_{max}	4.5430	4.5230	4.6610	4.5272	4.4827	4.6279	4.6368	4.7038	4.6580
F.F.	0.686	0.690	0.688	0.687	0.684	0.691	0.688	0.698	0.694
Effic.	13.4	13.3	13.7	13.3	13.2	13.6	13.7	13.9	13.7
P/P_0	1.0000	0.9956	1.0260	0.9965	0.9867	1.0187	1.0206	1.0354	1.0253

Date Cycles	3/02/89 0	5/23/89 6000	6/09/89 12000	7/10/89 24000	7/24/89 30000	8/21/89 42000	9/25/89 54000	10/23/89 66000
SSFSA-1								
I_{sc}	2.6870	2.6571	2.6752	2.7133	2.6983	2.6611	2.6463	2.6493
V_{oc}	2.5125	2.4910	2.5294	2.4865	2.5179	2.5247	2.4960	2.4928
I_{max}	2.3790	2.3990	2.4083	2.4354	2.4212	2.3978	2.3820	2.3927
V_{max}	1.9115	1.8756	1.9276	1.9090	1.9363	1.9425	1.9053	1.9028
P_{max}	4.5475	4.4994	4.6422	4.6493	4.6882	4.6577	4.5385	4.5528
F.F.	0.674	0.680	0.686	0.689	0.690	0.693	0.687	0.689
Effic.	13.4	13.3	13.7	13.7	13.8	13.7	13.4	13.4
P/P_0	1.0000	1.9894	1.0208	1.0224	1.0309	1.0242	0.9980	1.0012
SSFSA-5								
I_{sc}	2.6776	2.6643	2.6809	2.7156	2.7026	2.6828	2.6516	2.6561
V_{oc}	2.4766	2.4767	2.5097	2.4769	2.5087	2.5152	2.4851	2.4827
I_{max}	2.3782	2.3966	2.3704	2.4599	2.3994	2.3991	2.3670	2.3324
V_{max}	1.8756	1.8446	1.9202	1.8520	1.9289	1.9140	1.8892	1.9214
P_{max}	4.4605	4.4206	4.5516	4.5559	4.6281	4.5919	4.4717	4.4815
F.F.	0.673	0.670	0.676	0.677	0.683	0.681	0.679	0.680
Effic.	13.1	13.0	13.4	13.4	13.6	13.5	13.2	13.2
P/P_0	1.0000	0.9911	1.0204	1.0214	1.0376	1.0295	1.0025	1.0047