NASA Technical Memorandum 107197

Mir Cooperative Solar Array Project
Accelerated Life Thermal Cycling Test

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April 1996

National Aeronautics and
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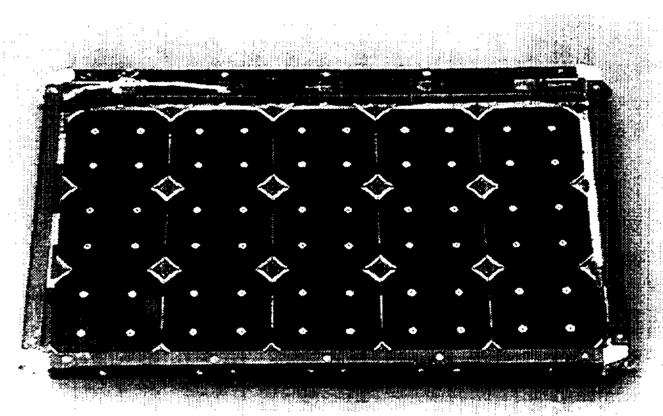
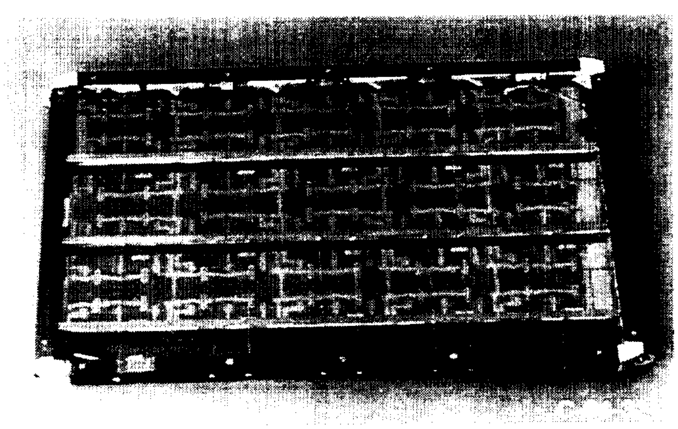
TEST OBJECTIVE

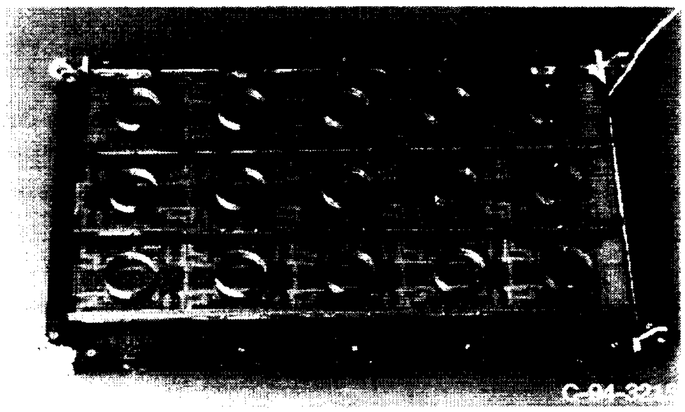
The objective of this test was to place samples of the Mir Cooperative Solar Array (MCSA) through rapid thermal cycling (+80 °C to -100 °C) in order to detect gross design flaws or other weaknesses associated with the integration of the U.S. solar cell modules with the Russian support structure. The primary failure criterion was no detectable power loss over 24,000 thermal cycles, equivalent to four years in low earth orbit (the test equipment can detect a degradation in power of about 2%, or slightly less). A secondary subjective criterion was that any structural or mechanical changes resulting from thermal cycling should not be of such a nature or degree which would compromise the MCSA design life. Two MCSA solar array "mini" panel test articles, one with support rings and one without rings, were simultaneously put through 24,000 thermal cycles. This was considered a development test.

TEST ARTICLES DESCRIPTION

There are two MCSA thermal cycling test articles (RUSA-1 and RUSA-2). Each article contains a U.S.-supplied coupon of 15 series-connected photovoltaic solar cells in a 5 cell x 3 cell matrix with one bypass diode in parallel with 10 of the cells. Each of these two coupons are mounted in a Russian-supplied frame assembly. Test article RUSA-2 also includes the Russian-supplied support rings. Although not present at the beginning of the tests, two resistance temperature devices (RTDs) identical to the type which will be used for taking temperature measurements of the flight array on-orbit were glued to RUSA-2 in order to see if they would stay attached and function properly. As will be the case in the flight design, five solar cells along one edge have been shortened by 5 mm so that the coupon would fit into the existing Russian support frame. However, both thermal cycle test articles deviate from the flight design in that the shortened edges are "pinned" to the frame with a metal clip while the flight articles will have this edge "sewn" to the frame with a composite button and nylon thread. This compromise occurred because of the need to rapidly construct the panels during a U.S. visit to RSC-E in Moscow. The photograph on the left below shows the front of the test article while the back of RUSA-1 is shown on the right.





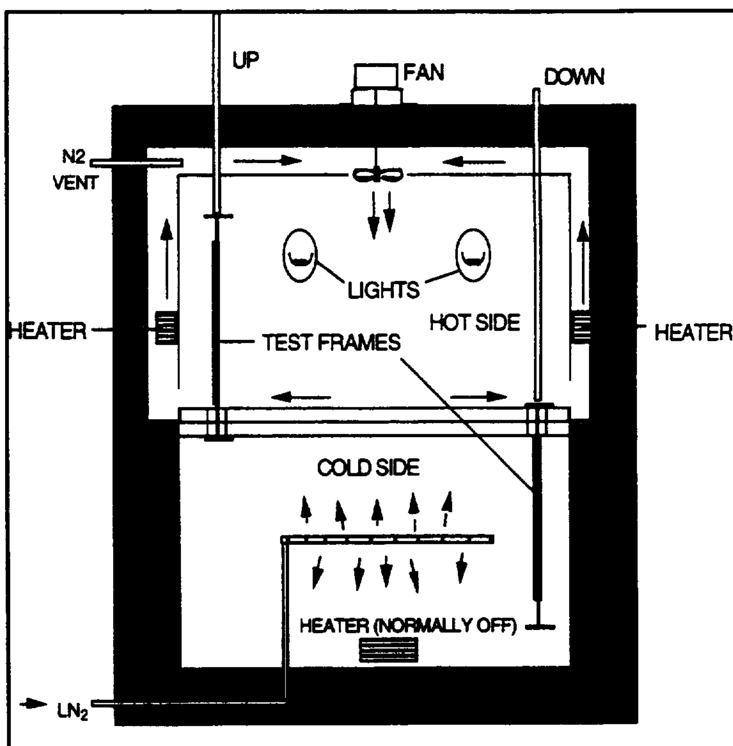


The photograph to the left shows the back side of RUSA-2, giving a view of the support rings. As a result of the development test program, the MCSA team chose to include the support rings in the flight design.

Each test article measures about 10 inches by 18 inches (254 mm by 457 mm).

TEST FACILITY DESCRIPTION

The thermal cycling test chamber was designed and built at NASA Lewis specifically for rapid thermal cycling of solar array test coupons. The intent was to enable rapid cycling of a test coupon as quickly as possible at an affordable cost in order to detect failure modes and gross design flaws due to thermal cycling. Since testing is not performed in a thermal vacuum environment, it is regarded as a development test facility and is not intended to be used for official space qualification.



THERMAL CYCLING CHAMBER

The thermal cycling test chamber is basically an oven on a freezer. Temperatures can be set to range from +120° C down to -190° C (liquid nitrogen). The oven is heated by two 750 Watt convective finned heaters in an outer duct. A low speed fan circulates air downward to minimize any temperature gradient. Two 100 Watt oven bulbs are also present to provide illumination of the coupon for continuity and performance checks during cycling. The freezer is cooled using liquid nitrogen. A fine spray is directed into the chamber and away from the coupons. An exhaust pipe is located near the top of this section to vent excess nitrogen gas. Besides cooling, the nitrogen provides an inert atmosphere for both sections of the chamber. In order to bring the chamber to room ambient temperature quickly (< 2 hours), the oven has a nitrogen gas inlet and the freezer has a 500 Watt heater. Thermocouples centrally located in each chamber section monitor the temperature. The heating and cooling, either on or off, is computer controlled. The nitrogen flow rates can be manually adjusted. Over temperature shutdown protection is also present.

Solar array cell test coupons are mounted on stainless steel frames which fit into a frame holder in the test chamber. An air-driven rod shuttles the frame between the two chambers while a lip on the top and bottom of the frame seals the chamber. Thermocouples mounted on each test coupon control the switching between the hot and cold sections. Once a predetermined number of cycles or a given date is reached, the coupons are left in the chamber's cold section while the chamber shuts down and reaches room temperature.

The test chamber is controlled with IEEE-488 interfaces to a switch controller and a Digital Volt Meter (DVM). The switch controller operates all solenoids for the heaters, liquid nitrogen valves, thermocouple and voltage channels, and frames. The DVM monitors the power supply voltage, cell output (if desired), and reads all thermocouples. Cycle counts are printed out on an hourly basis. Although temperature data can be printed out for 1 1/2 hour intervals on demand, a complete temperature history is not stored due to limitations in computer memory. The thermocouples are read about every 12-14 seconds. Once operational, the chamber can run seven days a week, 24 hours a day. Chamber operation is controlled by a BASIC computer program which can be modified to accommodate a wide range of requirements, within the overall limits of the equipment.

TEST PROCEDURE

Both MCSA test articles underwent thermal cycling at the same time. Each was independently cycled between the hot and cold chambers when the temperature exceeded the +80° C and -100° C set points as measured by a thermocouple mounted to back of a cell in the center of each test article. These temperature limits were derived from the temperature extremes calculated for Space Station Freedom solar cells, (now the International Space Station Alpha) which are identical to the MCSA solar cells, with 20 °C development test margins included at both extremes. There were no intentional hot or cold temperature soaks. A complete cycle took about 6 minutes on average, leading to 10 cycles per hour. RUSA-2 took slightly longer to cycle due to the higher thermal mass associated with the support rings. Cycle times varied slightly throughout the test because of variations in nitrogen gas leakage and the fluctuation in nitrogen flow rates, among other factors. The test ran automatically with pauses planned at specific intervals when the coupons were removed for electrical performance testing and visual inspection.

Experimental SetUp

Thermocouple:	Type T (Copper Constantine) bonded to backside of center cell.
Additional Connections:	Thermocouple on the frame (middle of short side).

Frame Size:	12 inches x 20 inches Chamber #3, Frames 1 and 3
Switching Temperature:	$\leq$-100° C to $\geq$+80° C (same as Space Station Freedom coupons)
Chamber Temperatures:	Cold Side at a constant -120° C Hot Side at a constant +100° C
Cycle Time:	6 to 8 minutes or 200 per day

Test Measurements

Electrical performance was measured initially at room temperature with the test articles removed from the chamber:

1) Current/Voltage curves on entire 15-cell string using LAPSS100 Flash Simulator.

2) Dark Diode check on bypass diode using TEK 370A curve tracer plotted on paper and stored in files.

Visual inspection/mapping was performed under 1-10X magnification. The following list indicates the type of phenomena which could be detected:

-breaks or cracks in the cell surface
-breaks or cracks in the coverglass
-voids or open areas (lack of adhesive)
-wrinkles in the interconnects or blanket
-evidence of adhesive migration or elongation
-any other nonconformity; bubbles, peeling, delamination.

Photographs were taken at the beginning and end of the test, and at one point in the test where significant physical changes occurred, as will be described later.

Products

Two current/voltage curves (as a consistency check) from the flash test were produced at the completion of each major cycle interval from which the following performance parameters were reported:

Isc Imax Pmax Efficiency Voc Vmax Fill Factor P/Po

For both the front and back sides, a map of flaws found as a result of the visual inspection were updated after the completion of each set of cycles and recorded on a paper image of the test coupon. Brief status reports were written at each major cycle interval.

TEST RESULTS

Summary of Final Results

After 24,000 thermal cycles between +80 °C and -100 °C, no measurable electrical degradation was detected in either test article during room temperature illuminated "flash" tests. Electrical degradation was detected at elevated temperatures in the test article with support rings (RUSA-2), traced to a single cell (#4). This degradation is most likely the result of a combination of deviations of the test article from the flight design and damage from facility-induced shocks experienced in the early phases of testing, and not as a result of thermal cycling. There was degradation in some of the structural aspects of both test articles, again most likely due to the test artifacts just mentioned, but the overall integrity of the solar cell coupon-to-support frame interface was not compromised.

The visual inspection diagrams and "flash" illuminated electrical test results at specific points throughout the test are given at the end of this report.

Review of the Significant Events

RUSA-1 = test article without support rings.
RUSA-2 = test article **with** support rings.

Date	Cycles	Event
4 Aug. '94	0	Testing began. Each test article had cells with cracks prior to testing. 1 cracked cell on RUSA-1 and 2 on RUSA-2
5 Aug. '94	55	Testing suspended - cold chamber refrigerant supply problem.
31 Aug. '94	55	Testing resumed.
7 Sept. '94	750	No room temperature electrical degradation. Short edge pins tear Kapton: 3 places on RUSA-1;1 place on RUSA-2
14 Sept. '94	1,500	Visual inspection revealed a number changes in some of the mechanical PPM/frame attachment points and support structure on both articles. Since most of the significant developments in the test program occurred at this point, a detailed status is given below.

Detailed Status At 1,500 Cycles

RUSA-1

- The remaining three (3) pins tore through the Kapton (i.e. all six pins had now torn through the Kapton).

- The 15-cell coupon had shifted "down" in the frame; from 0 mm on the top left side to 3 mm on the top right.
- The top two of the three T-bars had come loose (lost adhesion) from the C-channel frame.
- Most of the styrofoam spacer inserts in the C-channel had deteriorated.

RUSA-2 (With Rings)

- The remaining five (5) short-edge pins tore through the Kapton; as a result, the top row of cells was no longer under a preload (i.e. since all six pins had torn through the Kapton, the top edge was no longer attached).
- Four of the five cells in the top (pinned) row had cracks in the coverglass (one of these coverglass cracks was present prior to the start of the test); two cells also had cracks in the silicon wafer.
- The 15-cell coupon had shifted "down" in the frame; from 3 mm on the top left side to 4 mm on the top right.
- All three T-bars were still attached; the top T-bar was slightly warped, or "bowed downward".
- A button fell off and the thread was severed. This was probably due to the overall shift in the coupon. The thread securing several other buttons shows increased tension due to the overall shift in the coupon as described above.
- Two support rings in the top row had shifted downward from their original position. This was most likely due to a combination of weak adhesive, loss of preload due to the pin tear-through described above, facility-induced shocks, and gravity.
- There was evidence that the adhesive softened and flowed along the wires.
- Several other rings were loose on at least one of their bond points to the frame wires. However, the preload remained.

In spite of the deterioration described above, the solar cell coupons remained fairly rigidly attached to the frames.

The cause of the changes in the mechanical attachment points were determined to be a combination of mechanical shock induced by the facility (on transfer of the frames between chambers), gravity, thermal cycling, and a faulty mixture of the three components of the epoxy which lead to incomplete curing and consequent weak adhesion.

The status of the thermal cycling test was discussed at the September 16-23, 1994 Mir Cooperative Solar Array Project Technical Interchange Meeting at Lockheed in Sunnyvale, Ca. The team decided that the test should resume after reducing the facility-induced mechanical shock and repairing the torn pin holes. The rationale for repairing the holes was to minimize the difference between the test and flight articles.

The shock that the frames experienced on transfer between hot and cold test chambers was greatly reduced by adjusting the pressure in the air-driven pistons which accomplish this task and by placing a spring at the end of a lever in order to dampen the shock which occurred at the end of the transfer. The six (6) torn pin holes were repaired on each of the frames by means of Kapton tape which had a hole punched in it and secured to the "C-channel" with a loop of stainless steel wire. Although this repair did not restore the preload from the rings on RUSA-2 and it did not duplicate the buttons and thread which would secure this edge in the flight articles, it kept the edge (which is the "top" edge in the vertical experimental set-up) from flopping over and experiencing further damage. Due to the nature of the pin hole tears and the overall shifting of the coupons in each frame, a more significant repair was not considered prudent.

As also agreed at the September '94 meeting, the U.S. developed a contingency plan which described the actions that would have been taken if further "significant" mechanical and/or structural changes occurred, or any electrical degradation occurred. The essence of this contingency plan was as follows.

Repair of either thermal cycle test article during the remainder of the test was to be considered very carefully, and only as a last resort. So as not to introduce complications which may render the overall test results not meaningful or not representative, repair of any future damage had to meet four conditions:

1. Degradation must have occurred as a result of test circumstances or aspects of the test article design which did not represent flight circumstances or the flight article design.

2. The repair could be accomplished without inducing further damage caused by the repair process itself.

3. The repaired test article had to be representative of the flight design.

4. The repair must have been completed in a timely manner in order to support aggressive MCSA schedule.

In order to accommodate potential future repairs consistent with these guidelines, a repair kit containing the epoxy components (and application instructions), buttons and thread was supplied by RSC-Energia.

<u>Test Resumption</u>

6 Oct. '94	1,500	The mechanical shock on transfer of the test frames between chambers was greatly reduced. The loose short-edge of the coupon was stabilized with Kapton tape and wire to prevent further damage. Testing resumed.
14 Oct. '94	3,000	Cracking observed at 1,500 cycles lengthened, but no new cracks were seen. No room temperature electrical degradation.

8 Nov. '94	6,000	Cracks lengthened, but no new cracks were seen. On RUSA-2, although the weld itself was intact, there was fatigue in the copper around a p-weld where the external test leads were connected and the Kapton was bent at a sharp angle because of the C-channel. This was not representative of the flight design. No room temperature electrical degradation. Two thermal sensors (RTDs) were added to RUSA-2. The test lead wires were extended so that IV curves could be obtained while the test articles were in the hot chamber.
11 Nov. '94		After resuming thermal cycling at 6,000 cycles, constant illumination I-V curves were generated while the test articles were in the hot chamber of the thermal cycling facility. A curve tracer was attached to the thermal cycling coupon's test leads and the IV curve was monitored while the temperature rose from - 100 degrees C to +80 degrees C. The overall shape of the IV curve for RUSA-1 showed no anomalies over the entire temperature range. From about -100 to +40 degrees C, the shape of the IV curve for RUSA-2 was normal. However, at temperatures over +40 degrees C, an IV curve with a "double-dip" was observed. The transition from a "normal" to anomalous IV curve was rather abrupt and repeatable at about +40 degrees C. There was about a 50% drop in load current from the 15-cell article. Since no baseline elevated temperature electrical performance tests were done before thermal cycling began and RUSA-2 had coverglass cracks prior to beginning the test as well as damage as a result of facility-induced shocks during the test, it is not possible to unequivocally say what caused the degradation and when it may have first occurred.
21 Nov. '94	7,500	Suspended test in order to perform individual cell elevated temperature tests. The 50% drop in current was attributed only to cell #4 on RUSA-2. Please refer to the section of this report entitled "Elevated Temperature Degradation" for a description of how this was done.
20 Dec. '94	12,000	Some minor delamination detected near outer perimeter welds. No room temperature electrical degradation. Elevated temperature degradation continued on RUSA-2.
9 Feb. '95	18,000	T-beams on RUSA-2 have lost adhesion at all points except one. No room temperature electrical degradation. Elevated temperature degradation on cell #4 on RUSA-2 seemed to occur at slightly higher temperatures (~50°C).
15 Feb. '95		Paused test to view cell #4 of RUSA-2 with IR camera while under a forward bias and also while heated. No anomalies detected.

17 Feb. '95	19,150	Testing resumed.
25 Mar. '95	24,000	Testing completed. A large crack was found in the coverglass of a cell on RUSA-1. Also, copper fatigue was seen in the welds on RUSA-1 along with partial tearing around the perimeter of the weld. This occurred where the edge of the coupon is inside the C-channel. No room temperature electrical degradation. Elevated temperature degradation on cell #4 on RUSA-2 continued to occur, with the onset again occurring at around 40 °C. The "area loss" power degradation seems to be isolated to the "upper half" of the cell. This was discovered by measuring the electrical output of the test article while shading half of cell #4 along with elevating its temperature.

Review of the Significant Findings

1) Problems associated with fastening the short edge of the PPM with "pins" first seen in the development acoustic tests were also experienced in the initial phase of thermal cycling. The effects were made worse by the facility-induced shocks which occurred in the beginning.

2) Problems with softening and flowing of the adhesive illustrated the importance of properly mixing the adhesive and allowing it to fully cure.

3) The "button" falling off sometime prior to 1,500 cycles resulted in RSC deciding to double-tie the buttons and use two coatings of lacquer to seal them.

4) Even though the electrical tabs in the flight design are not attached to wiring in the same way as the thermal test articles, the fatigue in a p-weld observed on RUSA-2 after 6,000 cycles illustrates the need for careful routing of the tabs. In the flight design, the extended electrical tabs will be "looped" underneath the PPM in the C-channel and connected to wiring. Care should be taken to ensure that the radius of curvature in electrical tab loop is not too extreme, especially where it comes off the PPM (near the P-welds).

5) Electrical illumination tests while RUSA-2 was in the hot chamber revealed elevated temperature degradation to occur rather abruptly between 40 - 50 °C. This illustrated the importance of checking for electrical degradation in solar cells over the entire operating range of temperatures. That is, checking for electrical degradation only at room temperature, as traditionally done in the U.S., may not be sufficient after the solar cells have been exposed to environmental stresses.

6) Electrical illumination tests at room temperature performed with one-half of a solar cell shadowed reveal the same IV curve shape as the curve seen at elevated

temperature. This implies that the problem is associated with an "area loss" phenomenon. The cause of this is unknown.

Despite the problems with the frame adhesive and damage induced by the facility shocks, there was no degradation in the electrical performance of RUSA-1 and there was no significant degradation in the integrity of the PPM/structural support interface after 24,000 thermal cycles.

Despite the same problems with the frame adhesive and damage induced by the facility shocks for RUSA-2, there was no significant degradation in the integrity of the PPM/structural support interface after 24,000 thermal cycles. There was no significant delamination due to the force exerted on the cells by the support rings. The degradation in the electrical performance above 40 to 50 °C is most likely not due to thermal cycling effects.

ELEVATED TEMPERATURE DEGRADATION

Background

The accelerated life thermal cycling test reached the 1-year equivalent life point of 6,000 thermal cycles (-100°C to +80°C) on 31 October 1994. Up until this point in the test, room temperature "flash" illumination electrical tests revealed no degradation in the power output of either 15-cell coupon test article. However, since Lockheed (LMSC) confirmed RSC-Energia's report of degraded electrical power output (experienced as a result of Panel #2 development test activity in Russia) in PPM #2 *only at elevated temperatures*, it was decided to perform elevated temperature electrical performance tests on the thermal cycling test articles. This was done on Thursday, November 10, 1994 at a count of about 6,400 cycles.

Full Coupon Elevated Temperature Electrical Tests

The NASA Lewis thermal cycling facility has the capability of obtaining constant illumination electrical performance data (current-voltage or IV curves) while the test articles are in the hot chamber of the facility. Illumination is provided by two 100 watt incandescent light bulbs. Current-voltage characteristics are obtained with a programmable curve tracer via four-wire measurements. Since the intensity and spectrum of the light provided by the incandescent bulbs are not representative of solar insolation conditions on-orbit at air mass zero, the absolute IV measurements are not in themselves meaningful. However, the relative shape of the IV curves can reveal anomalous behavior.

IV curves were obtained for both RUSA-1 and RUSA-2 over a wide range of temperatures (approximately -10°C to +75°C). The IV curves for RUSA-1 showed normal characteristics. However, the IV curves for RUSA-2 showed about a 50% drop in current for temperatures above +40°C. Since these tests were performed while thermal cycling was in progress (the test articles reside for approximately 3 minutes in each chamber, either hot or cold) and an IV curve trace is more or less instantaneous, it was possible to monitor the IV curve through most of the temperature range. The 50% drop in current was rather abrupt and very consistent at the +40°C point.

Failure Isolation: Individual Cell Elevated Temperature Tests

On November 21, 1994 at a cycle count of about 7,500 RUSA-2 was removed from the test facility in order to isolate the cause of the electrical power degradation. The plan was to heat individual cells above +40°C one at a time, perform a flash illumination electrical test (i.e. "flash test"), and look for the "double-dip" or "stairstep" characteristic in the IV curve. This was the same process that LMSC used to isolate the failure on PPM#2.

First, a room temperature (25°C) flash test of the entire 15-cell coupon gave a baseline IV curve. Then each cell was heated to about +80°C, as measured by a thermocouple in surface contact with the coverglass in the middle of the cell. This was done with a small, focussed hot-air heat gun. When the thermocouple read near +80°C, the heat gun was removed and a flash test of the entire 15-cell coupon was quickly performed. The thermocouple reading at the moment of flash was recorded on the IV plots. This process was repeated for all 15 cells.

The current-limiting phenomenon was isolated to one of the shortened cells along the top pinned edge of the coupon: the fourth cell from the left (cell #4). All other cells had normal I-V curves.

Flash tests were performed over a range of temperatures for cell #4. The onset of degradation begins near +40°C with a "softening" of the IV curve. Softening of the curve continued at +50°C while the current limiting effects began to be seen at +60°C and were most pronounced at +70°C.

As for the physical condition of cell#4, inspection with an unaided eye from a number of different angles revealed at least two fairly large cracks in the coverglass. A portion of one of the cracks appeared also to be in the silicon wafer itself. A detailed visual inspection revealed many cracks, both in the coverglass and the silicon wafer. Also, this row of cells was no longer under any preload due to the pins having torn through the Kapton.

After the testing described above, RUSA-2 was placed back into the test facility and thermal cycling was resumed on both articles on November 21, 1994. High temperature IV curves were obtained while the test articles were in the hot chamber prior to removing them from the facility for routine inspections at the 12,000, 18,000 and 24,000 cycle points. In addition, individual cell elevated temperature tests were performed on RUSA-2 for comparison with the baseline obtained at the 7,500 cycle point.

At this point, it was decided by the MCSA U.S. IPT to alter the "failure criterion" for RUSA-2. Since the damage to cell #4 was most likely caused by a combination of test article deviations (i.e. the pinned edge tear-through and glue softening) and facility problems not related to thermal cycling, the team decided to monitor the performance of only the bottom two rows of cells (10 total) on RUSA-2 for the remainder of the test.

Possible Causes

NASA Lewis has discussed various types of solar cell degradation phenomena in a memo entitled "Thermal Cycling of RUSA-2 (rings) 15 Cell Solar Array Coupon: Loss of Power/Current at Elevated Temperature" by Dave Scheiman dated 13 January 1995. This memo was distributed to the MCSA Integrated Product Team in February 1995. Since we believe the elevated temperature degradation results from artifacts of the test not related to thermal cycling effects, only the highlights of this discussion will be given here.

Supplemental testing at NASA Lewis has shown that the observed anomaly appears to be due to a loss of area in the cell rather than a change in shunt or series resistance alone. The evidence for this will be present below.

Electrical output of a solar cell is defined by a current vs. voltage (IV) curve. The parameters of the curve, all affected by cell quality, are listed below.

I_{sc} = Short Circuit Current (0 volts); Related to cell area and illumination intensity
V_{oc} = Open Circuit Voltage (0 amps); Related to cell material (bandgap).
P_{max} = Maximum Power (Knee of Curve); Related to series and shunt resistances.
I_{max} = Current at Maximum Power
V_{max} = Voltage at Maximum Power
F.F. = Fill Factor; Defines the "squareness" of the curve, 1 is ideal. $P_{max} / (V_{oc} \cdot I_{sc})$
Efficiency= (Power Out / Power In)

A solar cell is equivalent to a large area diode. It has a thin negative (N) top layer, a thick positive (P) bottom layer, capacitance, series resistance, and shunt resistance. The solar cells used in the MCSA have 6 P welds and 4 N welds and extensive grid lines on both the front and back sides of the cell. Physical damage to a cell could affect its electrical output in different ways, from no effect at all to various degrees:

1) No effect at all: Cracks that break a cell cleanly do not cause any performance loss provided there is an unchanged current path to a front and back contact. The cells used in the MCSA could easily be broken into 4 smaller cells (quadrants) in parallel. The loss in power would be negligible.

2) Increased Series Resistance: Cracks in a cell which prevent proper current flow to the nearest contact (weld) pad tend to increase series resistance. A crack of this type must not only be through the cell but also sever the grid lines. Grid lines are optimized to compromise series resistance and shadowing (blockage). They are also optimized to direct current to a contact pad. Because all the grids are connected, loss of a contact pad (weld) will result in increased current at another contact pad, limiting the power loss

from the entire cell. Below are the results of testing done by Spectrolab showing power loss vs. number of contact pads lost.

Pads Lost	Power Lost (%)	
1 N	6%	
2 N (diagonal)	11%	
2 N (adjacent)	20%	
2 N + 2P	22%	
3 N	32%	(.8% loss in I_{sc})

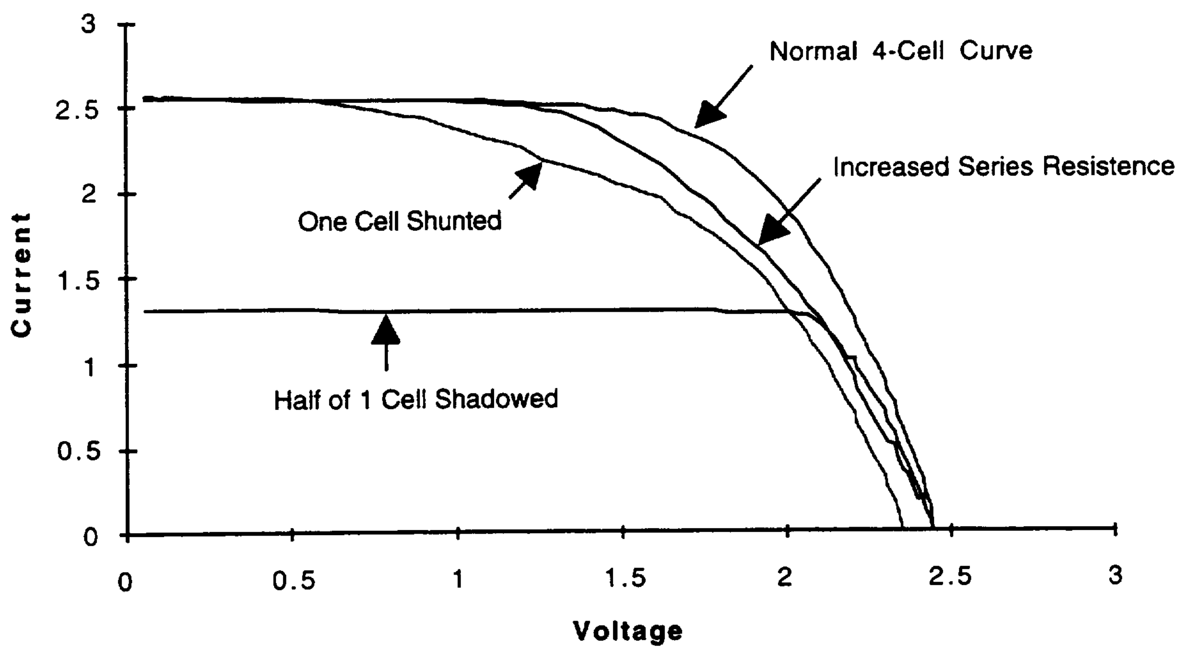
3) Decreased Shunt Resistance: This is caused by localized shorting in the cell. A crack in a cell causes the N top layer to contact the P bottom layer. In most cases, cracking results in a slight separation of the cell at the crack which would prevent any kind of shunting. Natural shunts occur in the cell fabrication and therefore are apparent at the cell measurement. Poor welding techniques will also cause shunting, excessive heat during welding will tend to cause the contact to burn through the thin N top layer and short the cell. Large area cells have inherently lower shunt resistance.

4) Loss of Current: Short circuit current is directly proportional to cell area and illumination intensity. A loss in current would be directly related to a loss in area (intensity being constant). Extreme cases of high series resistance and/or shunting will also cause a loss in short circuit current. Micrometeoroid impacts that go cleanly through the cell will result in a loss of current proportional to the loss in area. Shadowing will also cause a loss of current. This is intensity related, a 50% loss in light will produce 50% loss in current. Cracking in the cell would have to eliminate any electrical connection to the rest of the cell resulting in a loss of area.

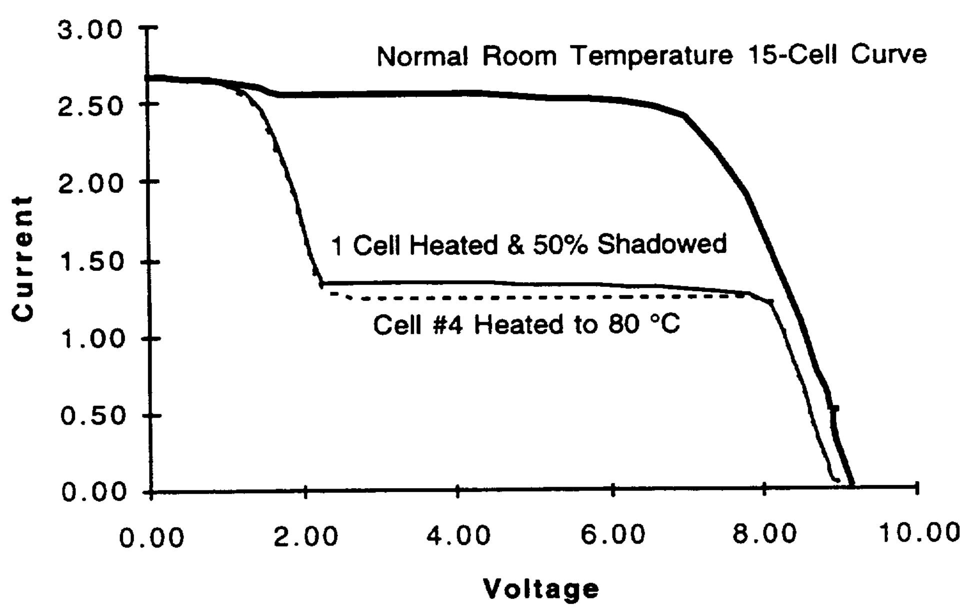
The above information is characteristic of a single cell. An array of cells has additional considerations that also affect its electrical output. Cells connected in series and parallel will have different effects on the overall array output. Connected in series, each cell adds voltage while current is limited to that which is produced by the weakest cell. Connected in parallel, each cell adds current while voltage is limited to the weakest performing cell's voltage. Bypass diodes and blocking diodes are yet another consideration. Bypass diodes sacrifice voltage for current in array strings. The shape of a solar array IV curve will reveal the nature of any damage.

Changes in series and shunt resistance affect the knee of the IV curve and can best be shown graphically. Damage resulting in an increase in series resistance changes the IV curve slope from the maximum power point to the open circuit voltage point. Damage resulting in a decrease in shunt resistance affects the slope from the short circuit current point to the maximum power point. Extreme changes in these resistances will affect both the short circuit current and open circuit voltage.

In order to illustrate these various effects, damage to an array of four MCSA-type solar cells connected in series was simulated. First, one cell was shunted while the other three cells were left untouched. Second, series resistance was added to the 4-cell string to show the effect of losing contact weld pads. Last, half of one cell was covered, or "shadowed" to simulate a loss of area within the cell. The figure below shows the results as compared to a normal 4-cell IV curve.



It is interesting to compare the shape of these IV curves to the curves generated for thermal cycle test article RUSA-2.



A normal IV curve for the 15-cell series-connected RUSA-2 thermal cycle test article is shown in the figure on the bottom of the previous page. The slight hump in the IV curve near I_{sc} is due to the bypass diode. The bypass diode is across 10 cells, which includes 5 cut cells shortened to 7.5 x 8 cm. instead of the normal full 8 x 8 cm. The cut cells limit the maximum current through most of the IV curve. Once the bias voltage drops below the voltage of the final row of cells, the bypass diode operates, eliminating 10 cells form the circuit, and the current is only supplied by the remaining 5 uncut cells and rises up to the full area value.

The dashed line labelled "Cell #4 Heated to 80 °C" shows the IV curve shape which resulted after heating the bad cell (cell 4) in RUSA-2. Notice the current is limited to nearly 50% of the baseline. This curve is nearly identical to the result obtained after one-half of one cell was covered, or shadowed, so that it only produced half of its full area current capability, labelled "1 Cell Heated & 50% Shadowed". The very obvious similarity in these two IV curves indicates that a loss of area in cell #4 is one possible explanation of the current drop seen at elevated temperatures. Note the IV curve shape reveals no shunting or increased series resistance characteristics, which would seem to rule out explanations using those phenomenon by themselves.

Further evidence that an area loss is the most likely cause can be seen by examining the IV curves taken while the coupon was in the thermal cycling chamber. While the light intensity of the flash testing is 1 sun, the intensity of the illumination in the thermal cycling chamber is only 1/3 sun. However, the IV curves have the same overall shape at both intensities. The fact that the percentage current reduction and curve shapes are identical for two different intensity levels eliminates series resistance or shunting problems as the sole source of the degradation. Had the cause been related to series resistance, the current loss would have been less at the lower intensity due to lower series voltage losses.

Summary

The evidence gathered from the experiments described above indicate that the current loss in the RUSA-2 test coupon appears to be due to a loss in cell area. The underlying cause of the area loss is more difficult to explain. Although cracks are visible on the cells, the areas lost do not visibly appear to be separated from reaching any of the 10 contact pads (they are still contributing to cell performance). As with most cell cracking and fatigue damage, as thermal cycling progresses, the condition should tend to worsen. The effect noted above did not worsen as cycling continued, but remained unchanged.

Finally, an illuminated electrical test while heating the bad cell and shadowing different areas of the cell allowed us to determine that "upper half" is the "bad area" of the cell.

CONCLUSION

In eight months time, this test successfully demonstrated the equivalent of four years of low earth orbit thermal cycling, a total of 24,000 cycles, on two samples of the Mir Cooperative Solar Array. As a result of this test, changes were made to improve some aspects of the solar cell coupon-to-support frame interface. It is unfortunate that the test's validity was somewhat compromised due to deviations in the test articles and the initial difficulties with the test facility. However, most of the physical changes and the electrical degradation at elevated temperatures was most likely due only to these initial problems, not related to thermal cycling. Since there was no significant degradation in the structural integrity of the test articles and no electrical degradation (not including the one cell damaged early and removed from consideration), it can reasonably be concluded from the results of this test that the integration of the U.S. PPMs with the Russian support structure will be able to withstand at least 24,000 thermal cycles (4 years on-orbit).

Cooperative Array Thermal Cycling Test Data

Coupons: 15 cells in series 5 x 3 pattern (5 cells cut 5 mm.) RUSA1 and RUSA2 (rings)

	SSF-2	I_{sco}=	151.2					
date	7-15-94	9-7-94	9-16-94	10-14-94	11-04-94	12-21-94	2-9-95	3-30-95
I_{sc} (mA)	151.33	151.16	151.30	151.33	151.17	151.2	151.06	151.2
V_{oc} (mV)	574.81	571.78	571.99	577.45	571.08	576.51	583.7	575.94
I_{max} (mA)	134.76	135.93	136.12	133.84	139.76	137.54	137.72	138.36
V_{max} (mV)	446.82	454.25	449.30	411.37	435.68	457.64	466.87	453.42
P_{max} (mW)	60.216	61.745	61.161	55.057	60.892	62.942	64.3	62.738
F.F.	.692	.714	.707	.630	.705	.722	.729	.720
Eff. (%$_{AMO}$)	11.00	11.28	11.18	10.06	11.13	11.5	11.76	11.47
I_{sc}/I_{sco}	1.0008	0.9997	1.0007	1.0009	0.9998	1.0000	.9991	1.0000

	RUSA1					
# of cycles	0	0	7-15-94 Avg	750	750	9-7-94 Avg
I_{sc} (mA)	2584.4	2613.8	2599.1	2612.7	2611.1	2611.9
V_{oc} (V)	9.360	9.325	9.343	9.256	9.246	9.251
I_{max} (mA)	2365.3	2394.8	2380.1	2415.9	2413.7	2414.8
V_{max} (V)	6937.6	6863.1	6900.4	6734.0	6719.1	6726.6
P_{max} (W)	16.409	16.436	16.423	16.269	16.218	16.244
F.F.	.678	.674	.676	.673	.672	.6725
Eff. (%$_{AMO}$)	13.08	13.10	13.09	12.97	12.93	12.95
P/P_o			1.000			0.998

	RUSA1					
# of cycles	1500	1500	9-16-94 Avg	3000	3000	10-14-94 Avg
I_{sc} (mA)	2627.3	2627.5	2627.4	2628.7	2629.1	2628.9
V_{oc} (V)	9.254	9.273	9.263	9.33	9.319	9.324
I_{max} (mA)	2432.5	2371.4	2401.9	2386.7	2370.8	2378.8
V_{max} (V)	6729.0	6907.8	6818.4	6887.7	6917.7	6902.7
P_{max} (W)	16.368	16.381	16.375	16.439	16.40	16.420
F.F.	.673	.672	.6725	.670	.669	.6695
Eff. (%$_{AMO}$)	13.05	13.06	13.055	13.10	13.07	13.085
P/P_o			0.997			0.9998

	RUSA1					
# of cycles	6000	6000	11-4-94 Avg	12000	12000	12-21-24 Avg
I_{sc} (mA)	2632.1	2629.1	2630.6	2635.5	2618.9	2627.2
V_{oc} (V)	9.261	9.244	9.253	9.260	9.266	9.263
I_{max} (mA)	2410.2	2413.3	2411.8	2427.3	2406.7	2417.0
V_{max} (V)	6788.6	6788.6	6788.6	6758.8	6803.5	6781.2
P_{max} (W)	16.362	16.383	16.373	16.405	16.374	16.390
F.F.	.671	.674	.6725	.672	.675	.674
Eff. ($\%_{AMO}$)	13.04	13.06	13.05	13.08	13.05	13.07
P/P_0			0.997			0.998

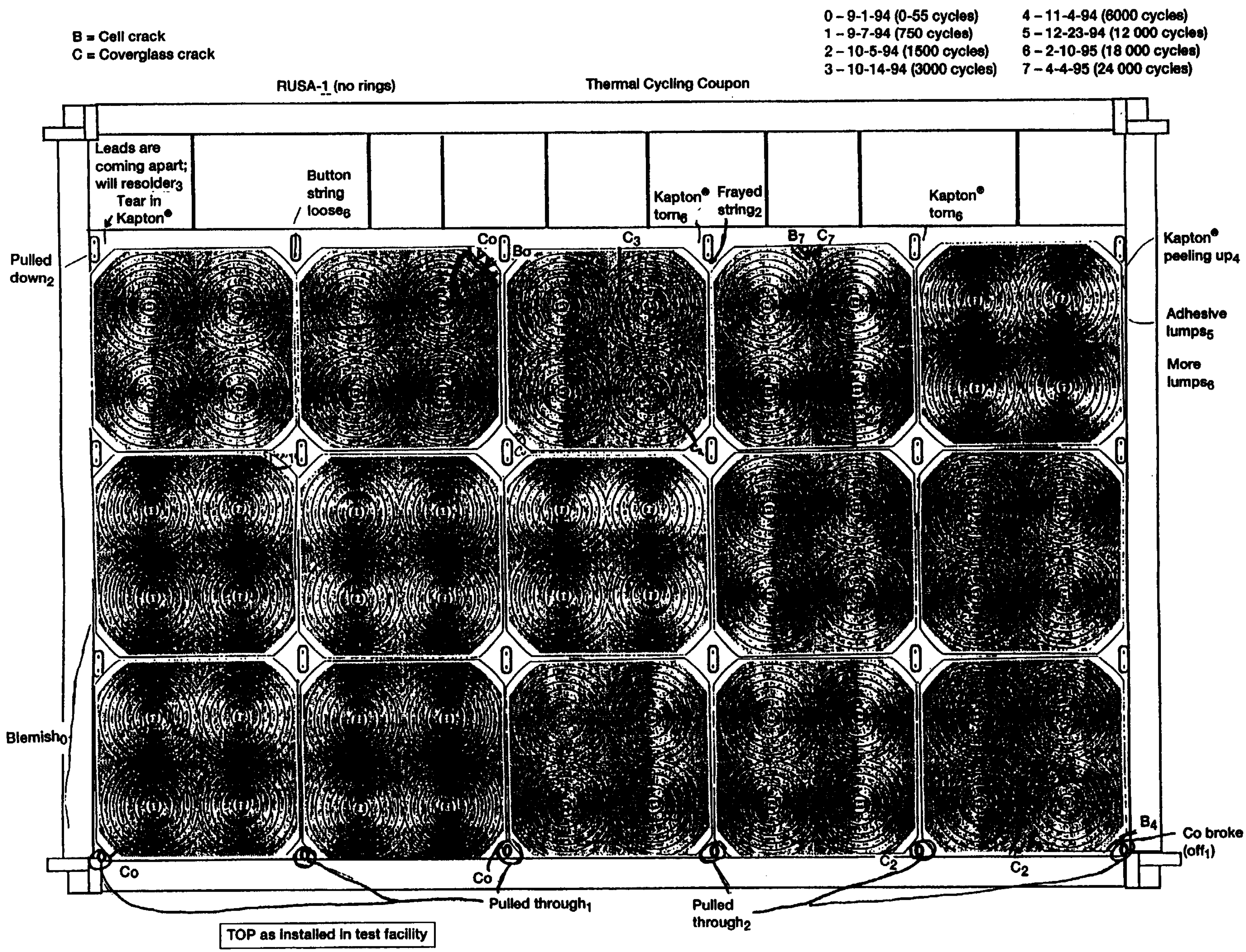
	RUSA1					
# of cycles	18000	18000	2-9-95 Avg	24000	24000	3-30-95 Avg
I_{sc} (mA)	2617.1	2614.5	2615.8	2647.8	2674.4	2661.1
V_{oc} (V)	9.357	9.373	9.365	9.466	9.331	9.398
I_{max} (mA)	2378.6	2375.7	2377.2	2383.9	2401.1	2392.5
V_{max} (V)	6940.7	6930.7	6935.7	6880.9	6831.1	6856.0
P_{max} (W)	16.509	16.465	16.487	16.404	16.402	16.403
F.F.	.674	.672	.6730	.654	.664	.659
Eff. ($\%_{AMO}$)	13.17	13.14	13.16	13.09	13.08	13.08
P/P_0			1.004			0.999

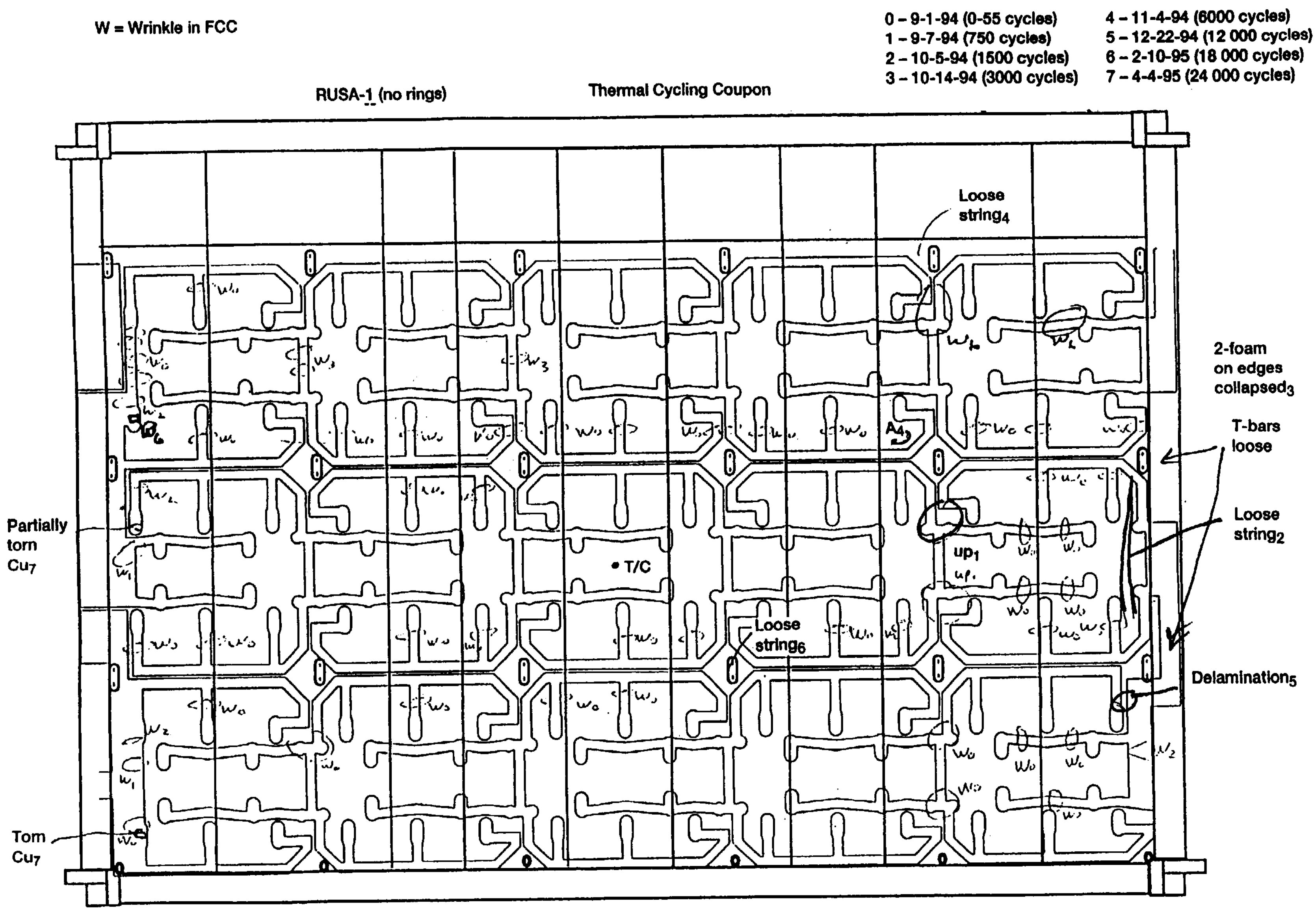
	RUSA2					
# of cycles	0	0	7-15-94 Avg	750	750	9-7-94 Avg
I_{sc} (mA)	2637.8	2631.0	2634.4	2618.7	2617.6	2618.2
V_{oc} (V)	9.275	9.271	9.273	9.274	9.280	9.277
I_{max} (mA)	2368.5	2382.2	2375.4	2340.8	2345.7	2343.3
V_{max} (V)	6912.7	6838.3	6875.5	6912.7	6902.8	6907.8
P_{max} (W)	16.373	16.290	16.332	16.181	16.192	16.187
F.F.	.669	.668	.6685	.666	.667	.6665
Eff. ($\%_{AMO}$)	13.05	12.99	13.02	12.90	12.91	12.91
P/P_0			1.000			0.991

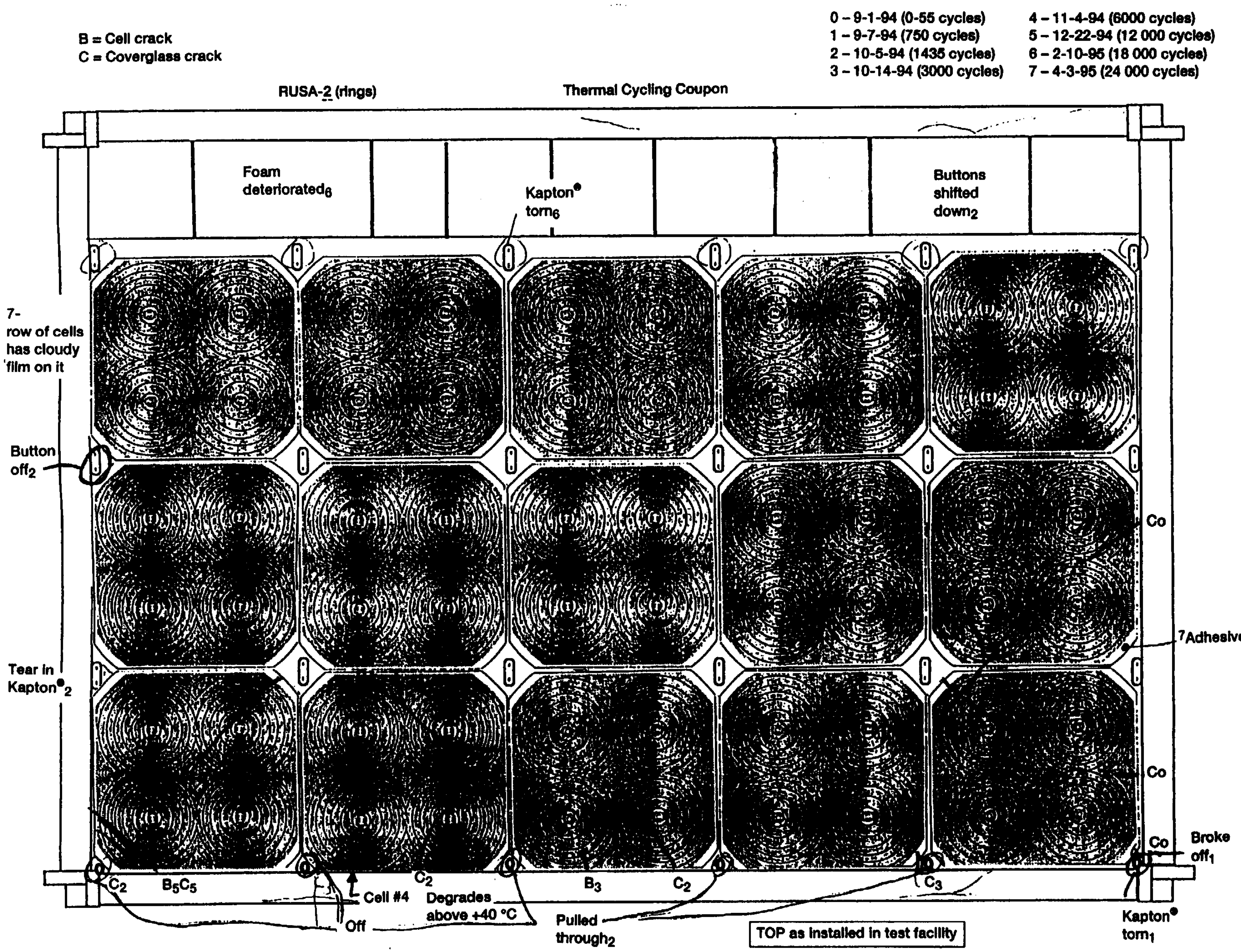
	RUSA2					
# of cycles	1435	1435	9-16-94 Avg	3000	3000	10-16-94 Avg
I_{sc} (mA)	2637.4	2644.0	2640.7	2633.9	2634.7	2634.3
V_{oc} (V)	9.285	9.264	9.275	9.317	9.323	9.32
I_{max} (mA)	2356.4	2336.5	2345.5	2366.2	2386.4	2376.3
V_{max} (V)	6942.5	6947.5	6945.0	6878.0	6818.4	6848.2
P_{max} (W)	16.359	16.233	16.296	16.275	16.272	16.274
F.F.	.668	.663	.6655	.663	.662	.6625
Eff. ($\%_{AMO}$)	13.04	12.94	12.99	12.97	12.97	12.97
P/P_o			0.998			0.996

	RUSA2					
# of cycles	6000	6000	11-4-94 Avg	12000	12000	12-21-94 Avg
I_{sc} (mA)	2637.3	2634.2	2635.8	2644.0	2644.5	2644.3
V_{oc} (V)	9.315	9.283	9.299	9.266	9.254	9.260
I_{max} (mA)	2402.4	2399.4	2400.9	2361.2	2414.6	2387.9
V_{max} (V)	6843.2	6828.3	6735.8	6917.7	6753.8	6835.8
P_{max} (W)	16.440	16.384	16.412	16.334	16.308	16.321
F.F.	.669	.670	.6695	.667	.666	.6665
Eff. ($\%_{AMO}$)	13.11	13.06	13.09	13.02	13.00	13.01
P/P_o			1.005			0.999

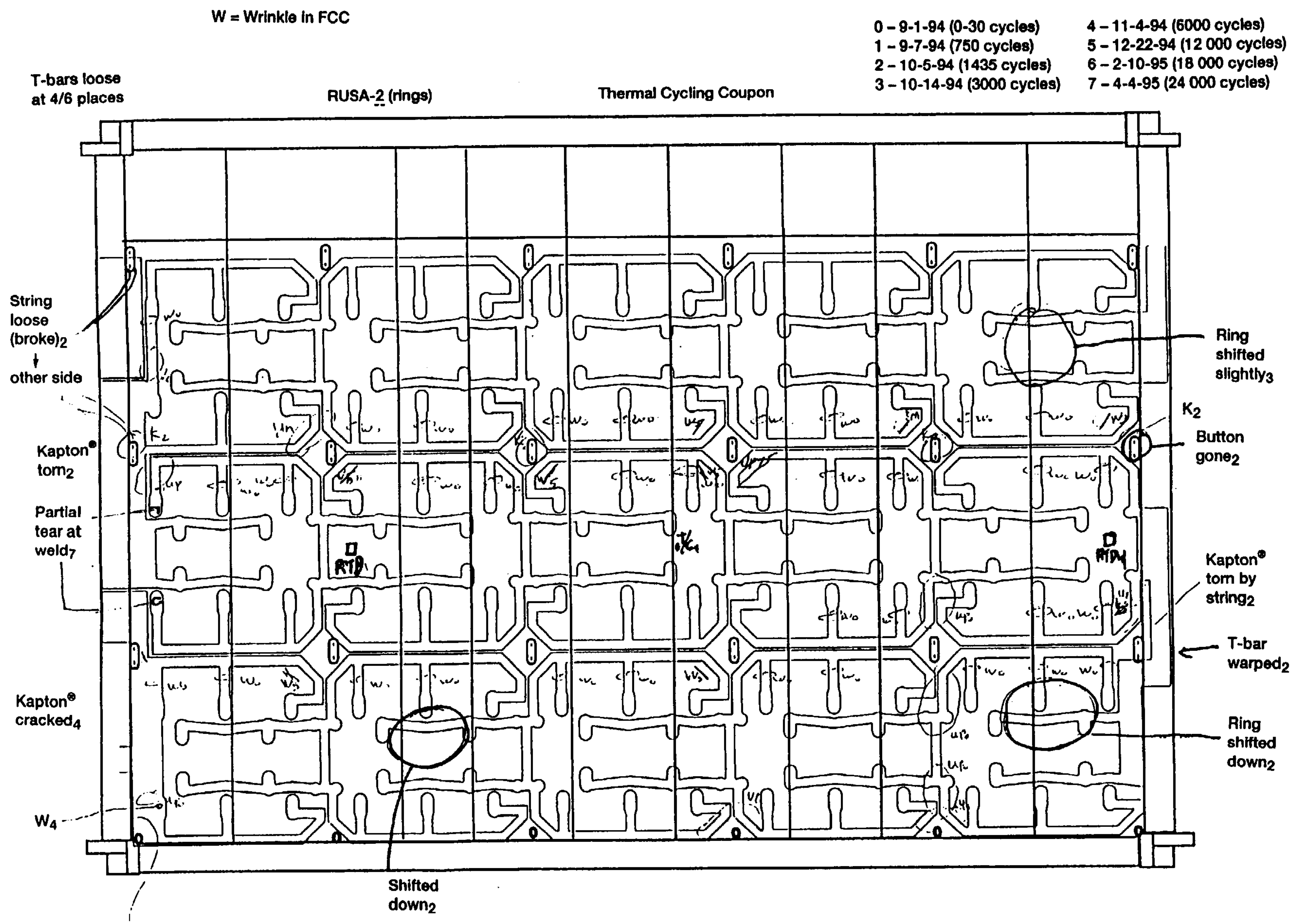
	RUSA2					
# of cycles	18000	18000	2-9-95 Avg	24000	24000	3-30-95 Avg
I_{sc} (mA)	2632.1	2634.7	2633.4	2666.9	2659.5	2663.2
V_{oc} (V)	9.361	9.366	9.364	9.335	9.368	9.352
I_{max} (mA)	2370.5	2378.5	2374.5	2377.3	2383.7	2380.5
V_{max} (V)	6935.7	6960.6	6948.2	6875.9	6875.9	6875.9
P_{max} (W)	16.441	16.556	16.498	16.346	16.390	16.368
F.F.	.667	.671	.669	.657	.658	.658
Eff. ($\%_{AMO}$)	13.12	13.21	13.17	13.04	13.08	13.06
P/P_o			1.010			1.002


B = Cell crack
C = Coverglass crack
RUSA-1 (no rings)
Thermal Cycling Coupon
0 – 9-1-94 (0-55 cycles)
1 – 9-7-94 (750 cycles)
2 – 10-5-94 (1500 cycles)
3 – 10-14-94 (3000 cycles)
4 – 11-4-94 (6000 cycles)
5 – 12-23-94 (12 000 cycles)
6 – 2-10-95 (18 000 cycles)
7 – 4-4-95 (24 000 cycles)
Leads are coming apart; will resolder$_3$
Tear in Kapton®
Button string loose$_6$
Kapton® torn$_6$
Frayed string$_2$
Kapton® torn$_6$
Kapton® peeling up$_4$
Adhesive lumps$_5$
More lumps$_6$
Pulled down$_2$
Co
Bo
C$_3$
B$_7$ C$_7$
Blemish$_0$
Co
Co
Pulled through$_1$
Pulled through$_2$
C$_2$
C$_2$
B$_4$
Co broke (off$_1$)
TOP as installed in test facility


W = Wrinkle in FCC
RUSA-1 (no rings)
Thermal Cycling Coupon
0 – 9-1-94 (0-55 cycles)
1 – 9-7-94 (750 cycles)
2 – 10-5-94 (1500 cycles)
3 – 10-14-94 (3000 cycles)
4 – 11-4-94 (6000 cycles)
5 – 12-22-94 (12 000 cycles)
6 – 2-10-95 (18 000 cycles)
7 – 4-4-95 (24 000 cycles)
Loose string4
2-foam on edges collapsed3
T-bars loose
Loose string2
Delamination5
up1
• T/C
Loose string6
A4
Partially torn Cu7
Torn Cu7



B = Cell crack
C = Coverglass crack
0 – 9-1-94 (0-55 cycles)
1 – 9-7-94 (750 cycles)
2 – 10-5-94 (1435 cycles)
3 – 10-14-94 (3000 cycles)
4 – 11-4-94 (6000 cycles)
5 – 12-22-94 (12 000 cycles)
6 – 2-10-95 (18 000 cycles)
7 – 4-3-95 (24 000 cycles)
RUSA-2 (rings)
Thermal Cycling Coupon
Foam deteriorated6
Kapton® torn6
Buttons shifted down2
7- row of cells has cloudy film on it
Button off2
Tear in Kapton®2
Co
7Adhesive
Co
Co
Broke off1
Kapton® torn1
C2
B5C5
Cell #4
Off
C2
Degrades above +40 °C
B3
C2
Pulled through2
C3
TOP as installed in test facility



W = Wrinkle in FCC
0 – 9-1-94 (0-30 cycles)
1 – 9-7-94 (750 cycles)
2 – 10-5-94 (1435 cycles)
3 – 10-14-94 (3000 cycles)
4 – 11-4-94 (6000 cycles)
5 – 12-22-94 (12 000 cycles)
6 – 2-10-95 (18 000 cycles)
7 – 4-4-95 (24 000 cycles)
T-bars loose at 4/6 places
RUSA-2 (rings)
Thermal Cycling Coupon
String loose (broke)2 other side
Kapton® torn2
Partial tear at weld7
Kapton® cracked4
W4
Shifted down2
Ring shifted slightly3
K2
Button gone2
Kapton® torn by string2
T-bar warped2
Ring shifted down2
RTD

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	April 1996	Technical Memorandum

4. TITLE AND SUBTITLE

Mir Cooperative Solar Array Project
Accelerated Life Thermal Cycling Test

5. FUNDING NUMBERS

WU-478-12-10

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135-3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E-10177

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, D.C. 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM-107197

11. SUPPLEMENTARY NOTES

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12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Categories 18 and 20

This publication is available from the NASA Center for AeroSpace Information, (301) 621-0390.

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

The Mir Cooperative Solar Array (MCSA) project was a joint U.S./Russian effort to build a photovoltaic (PV) solar array and deliver it to the Russian space station *Mir*. The MCSA will be used to increase the electrical power on *Mir* and provide PV array performance data in support of Phase I of the International Space Station. The MCSA was brought to *Mir* by space shuttle *Atlantis* in November 1995. This report describes an accelerated thermal life cycle test which was performed on two samples of the MCSA. In eight months time, two MCSA solar array "mini" panel test articles were simultaneously put through 24,000 thermal cycles. There was no significant degradation in the structural integrity of the test articles and no electrical degradation, not including one cell damaged early and removed from consideration. The nature of the performance degradation caused by this one cell is briefly discussed. As a result of this test, changes were made to improve some aspects of the solar cell coupon-to-support frame interface on the flight unit. It was concluded from the results that the integration of the U.S. solar cell modules with the Russian support structure would be able to withstand at least 24,000 thermal cycles (4 years on-orbit). This was considered a successful development test.

14. SUBJECT TERMS	15. NUMBER OF PAGES
Photovoltaic; Thermal cycling; Mir	26
	16. PRICE CODE
	A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	