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AN OVERVIEW OF THE FIRST RESULTS ON THE SOLAR ARRAY MATERIALS PASSIVE LDEF EXPERIMENT (SAMPLE), AO171

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SUMMARY

Power degradation in experiment solar cells was consistent with the exposure environment and appears to be produced principally by the radiation and atomic oxygen environments. Atomic oxygen erosion was generally as expected; atomic oxygen effects dominated for the most part in materials that were both atomic oxygen and ultraviolet vulnerable. Silicone coatings appear to protect Kapton, and adhesive systems contained under photon opaque materials were surprisingly environmentally resistant. A high density of small micro-meteoroid/space debris impacts were observed on mirrors, protective coatings, paints and composites. New synergistic effects of the space environment were noted in the interaction of atomic oxygen and copious amounts of contamination and in the induced luminescence of many materials.

INTRODUCTION

This paper describes some of the key results of AO171 materials evaluations performed to date. This passive experiment contains about 100 materials and material processes which address primarily solar array materials although other materials of interest to the aerospace industry were included in the experiment complement. Figure 1 shows the experiment after space exposure. The experiment objective was to determine the electrical, mechanical and optical property changes induced by the combined space environments. The space environments in which this experiment were exposed as a result of its location on LDEF row 8 are described in Table I.

Although this experiment was configured for 18 months of exposure, the longer than anticipated exposure of about 70 months generally enhanced the experiment even though most of the thin film polymeric materials were eroded away as a result of atomic oxygen exposure. From an analyses standpoint it is important to consider that well heat sunk, thermally conductive materials on row 8 probably saw no temperature greater than 100°F and that isolated materials of low thermal conductivity, mass and emittance saw wide temperature cycling. Outgassing of materials would have occurred early in the mission, and the atomic oxygen environment was most severe during the last 6 months of the mission.

RESULTS

General Observations

From a molecular contamination standpoint, the experiment was generally considered to be very clean with the exception of one localized area where the materials outgassed as a result of insufficient thermal vacuum bakeout prior to flight. Particulate contamination was wide spread over the experiment presumed, primarily, from disintegrated silicone coatings and metallized films which were transferred during the post retrieval process. Dark deposits were found on the interior sides of the experiment tray at vents to the external environment consistent with the angle of atomic oxygen impingement but not consistent with sun angle. This phenomena suggests a new synergistic effect between atomic oxygen and copious contamination. The chemistry of the deposits has not been fully identified but the unbaked polyurethane paint and primer system on the interior of the LDEF surface are suspected to be the principal contributors of materials exposed to the incoming atomic oxygen at these vent locations. Many phenomena were observed on this experiment that have never been reported on in materials exposure experiments either from flight or in ground based simulations. Some of these phenomena are listed as follows and are described as they apply to various categories of materials evaluations.

1. Organic materials such as polyimides, silicones, and polyurethanes were found to luminesce after flight upon exposure to far UV irradiation.

2. Fiberous "ash" material was observed on carbon fiber based composite materials.

3. Silicone adhesives were found to function surprisingly well after 5.8 years in space.

4. A high density of small (<1mm) micrometeoroid and space debris impacts was obvious on all materials.

5. New synergistic effects were noted where atomic oxygen and copious amount of contamination were interactive.

Solar Cells

Seven separate MSFC photovoltaic (solar cell) test articles were flown on this experiment. They were fabricated for MSFC by Lockheed Missiles and Space Company (LMSC) who also supplied the pre-flight electrical performance test data.

As a result of the longer than planned duration of the flight, all test articles underwent substantial atomic oxygen erosion of their polyimide (Kapton) substrate structures with the result that one module was lost prior to Orbiter rendezvous with LDEF, one came loose and drifted away when LDEF was grappled, and one (M3) was attached at only one corner when LDEF was retrieved. The latter was found on the floor of the cargo bay when LDEF was removed. A description of the solar cell test articles on hand post-flight is found in Table II.

Atomic oxygen degradation was obvious from visual examination of the polyimide substrates of the cells. Solar cell to solar cell interconnect bonds withstood the effects of thermal cycling well with no debonding found at the parallel-gap weld of the copper interconnect to the cell contact pads. Thermal analyses have not as yet been performed, but since the solar cell modules were thermally isolated from the LDEF structure by polyurethane foam padding, temperature excursions are expected to be reasonably broad over the orbit. The module that was retrieved from the cargo bay had 5 (of 12) cells that contained cracks in either the solar cell or cell cover. Micrometeoroids/space debris impacts were evident on all the test articles. These ranged from small surface nicks to solar cell coverslide breakage and rather deep penetrations within the cells. At this time no correlation between cell/module electrical performance and impacts has been established.

During post flight electrical performance testing of module M3, it was discovered that an apparent voltage calibration error was made on this module as evidenced by post-flight open circuit voltage higher than that measured pre-flight. For this reason, pre-flight performance for M3 was fabricated by using the pre-flight performance of the single cell C8 and expanding it to the configuration of M3 (4 cells in series by 3 cells in parallel). Cell C8 performance was selected because its short circuit current, when multiplied by 3, was the closest match to the actual M3 module performance. Additionally, there were no other indicators to suggest a current calibration error of any significance. After the overall electrical performance of M3 was established through testing, the module was cut apart to determine individual cell performance.

Solar cell and solar cell module maximum power point (Pmp) degradation ranged from 4.3% to 80% with 76% of the single cells tested having less than 10% degradation, Figure 2. There were 4 cells out of 17 that had Pmp degradation greater than 20%. Three of these were from the module which was retrieved from the cargo bay. The other was the cell (C6) which was flown without a coverslide. Discounting these cells, the average cell Pmp degradation was 6.5% with a standard deviation of 1.75%. The thin cell module (M4), which was retrieved intact but with severe damage to its Kapton substrate degraded 5.2% in Pmp. Four cells had discernible degradation in open circuit voltage (Voc) which is typical of a decrease in cell shunt resistance. Three of these cells were from the module retrieved from the cargo bay with the other being the cell flown without a coverslide. Two of the cells with Voc degradation were from the four which degraded more than 20%. Three cells showed evidence of severe series resistance increases. All three of these were from the cargo bay module. Two are from the four having discernible degradation in Voc. Figure 3 illustrates the differences in current/voltage (IV) characteristics between three poor performance cells and cell C1 that underwent the lowest degradation.

In summary the electrical performance of the cells is consistent with the expected performance for the environment experienced. To date no partition of cell degradation to specific environmental effect has been made. Loss of Kapton substrate from atomic oxygen attack was not a surprise since the materials were in space much longer than planned with no protective coatings. Some portions of the Kapton substrate containing adhesives are still intact and require more evaluation to determine the reasons for their survival in the atomic oxygen environment.

Composites

The carbon fiber and glass fiber composites contained in this experiment are described, along with a summary of their data generated to date, in Table III. The most obvious visible effect noted on these composites is the increased optical diffuseness of the surfaces which is commonly observed in materials exposed to orbital atomic oxygen. All of the carbon fiber composites have a charred appearance and show the fiber direction as a result of preferential atomic oxygen erosion of the matrix material. A porous ash structure formed on the exposed carbon fiber composite surfaces with the greatest concentration being on the polysulfone materials. Micrometeoroid/space debris impacts less than 1 millimeter in diameter were present on all composites. Concentration of these impacts ranged from 2 to 7 impacts per 25 in^2. Non-penetrating splattered contaminents, probably from spacecraft fluid dumps, were also noted on the composites.

Mass loss was consistent with thickness loss with the carbon fiber based composites losing approximately 1 ply. Atomic oxygen reactivity numbers are not inconsistent with those generated for carbon composites but no short term data is available currently for comparison of short and long term reactivity numbers for these specific composites. Another factor to consider is that short term exposure data probably would not be correlatible to the long term exposure data since the composite surfaces are matrix material rich. Aluminized tape was effective in protecting the composites from atomic oxygen erosion although penetrations of the protective aluminized tape were made by small impacts. The silicone adhesives on these tapes were well preserved and as effective as the controls. Further evaluations of the tapes are planned.

Thin Films

A cursory assessment of metallized and thin polymeric films is provided in Table IV which is a summary of post-flight visual observations of the films. No analyses other than a SEM examination of the white Tedlar have been made to date. Visually, the white Tedlar appears intact but the inert particles in the material are basically the only remaining component of the material. The intact Kapton protected by the silicone coatings provide some promise that silicones can furnish long term protection for Kapton against atomic oxygen attack. However, the extent of the effectiveness of their protection remains to be quantified. Thin films of Kapton, Mylar and Teflon which were aluminized with the aluminum surface exposed appear to have been protected from atomic oxygen erosion.

Paints

During the post-flight examination of this experiment under black light illumination, it was discovered that various types of materials were luminescing (fluorescing). Among these fluorescing materials were the polyurethane and silicone based paints. The intensity and wavelength dependence of this fluorescence varies with material and are the subject of a separate report.

Upon exposure, specular paints became diffuse and diffuse paints became more diffuse - a phenomena which is known from short term exposures and results principally from atomic oxygen induced surface texturing and also from preferential atomic oxygen attack of diffuse paint constituents. Inert particles in the paint accumulate on the paint surface as it erodes thereby providing more shielding of the underlying surface with increased exposure. Atomic oxygen erosion is, as observed from these results and those from the STS flight, non-linear in time in those paints subject to this preferential attack so their mass loss cannot be used to predict erosion rates. Optical properties and mass loss of these paints, Table V, are compared to data from control paints prepared at about the same time as the flight samples. As noted by the data, exposure of pigments in white and yellow diffuse paints tend to decrease absorptivity. S13GLO silicone paint which resists atomic oxygen attack showed darkening, presumably from ultraviolet/particulate irradiation. One of the more interesting effects noted in the paints is that atomic oxygen effects dominate in those paints which are both ultraviolet and atomic oxygen vulnerable. Without evaluating this phenomena in great detail, it would appear that any synergism, if it exists, between atomic oxygen and irradiation effects under these exposure conditions for these paints is minimal.

Metals

Metals flown on this experiment include aluminum, titanium, silver (disk and cold rolled ribbon), niobium, magnesium, copper (disk and cold rolled ribbon), molybdenum, tantalum, and Tophet-30, HOS-875 and Ni-Cr alloys in the as received condition and preoxidized. Several other combination of metals and coatings were also flown but are not part of this report. All of these metals gained weight from interaction with atomic oxygen except the preoxidized alloys which showed a slight mass loss. Macroscopic atomic oxygen effects were observed on silver and copper. Of all the metals silver was the most affected, as expected, and tantalum was the least affected. Accommodation of atomic oxygen in silver ranged from one atom per 1000 incident atoms in disk samples which were well heat sunk to 7 atoms per 1000 incident atoms in cold rolled stressed ribbon samples which were thermally isolated from the base structure. Mass increase in these materials, total incident fluence of atomic oxygen and the assumption that the highest oxidation state of the oxide was achieved, were used to generate these accommodation numbers.

Other Polymers

Materials including RTV-511, Halar and the PEEK resin, configured into tensile, shear and miscellaneous rectangular samples, and TFE Teflon washers comprised the majority of structural polymers on the experiment. The RTV-511 materials received an insufficient thermal vacuum bakeout (for contamination control) prior to flight resulting in outgassing with deposition on the near adjacent experiment area.

Considerable darkening of all elastomers occurred as a result of exposure and a 10% increase in Shore A hardness was noted in RTV 511. Halar, which is both ultraviolet and atomic oxygen susceptible, appears to be dominated by irradiation effects but further evaluations are required to identify and quantify these effects. Mass loss in these materials ranged up to 7% of their initial weight. Thirty six TFE washers were examined for atomic oxygen erosion and an atomic oxygen reactivity number of $(1.9 \pm .4) \times 10^{-25}$ cm^3/atom generated for this material.

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TABLE I. - EXPERIMENT AO171 EXPOSURE CONDITIONS

•	High Vacuum	-	10^{-5} - 10^{-7} Torr (estimated)
•	UV Radiation	-	10,041 ESH
•	Proton Fluence	-	$10^{9} p^{+}/cm^{2}$(.05 - 200 MeV)
•	Electron Fluence	-	(10^{12} - 10^{8}) e-/cm^{2} (.05 - 3.0 MeV)
•	Atomic Oxygen	-	*7.68 x 10^{21} atoms/cm^{2}
•	Micrometeoroid/ Space Debris	-	2 to 7 impacts per composite, $<$1mm
•	Thermal Cycles	-	$\simeq$ 32,000 cycles (temp TBD)

*This number was derived for Row 8 from the JSC provided number of 9.75 x 10^{21} atoms/cm^{2} for total atomic oxygen fluence on the RAM surface. All reactivity and accommodation numbers provided in this paper are based on this number.

TABLE II. - SOLAR CELL TEST ARTICLES

M3 ASEC 12 Cell Module

- Applied Solar Energy Corp. (ASEC) 200 micron, 2 cm x 4 cm silicon N on P, 2 ohm-cm, back-surface reflector cells
- Chemically Vapor Deposited (CVD) dielectric, wrap-around contacts
- 150 micron microsheet coverslides with UV filters and AR coatings
- Rear surface of module facing space

M4 ASEC 6 Cell Module

- ASEC 50 micron, 2 cm x 4 cm silicon N on P, 10 ohm-cm back-surface field cells
- Wrap-around contacts with wrap-around junction
- 2 each 50 micron, 4.7 cm x 6.7 cm coverslides
- Cells mounted facing space

Cells C6 through C10 - ASEC cells same as M3 but with coverslides as follows:

- C6 - None
- C7 - 150 micron microsheet with AR coating
- C8 - 150 micron microsheet with UV filter and AR coating
- C9 - 150 micron frosted fused silica with UV filter and AR coating
- C10 - 150 micron fused silica with UV filter and AR coating

Note: Each test article has a copper interconnect system laminated between 2 sheets of Kapton that comprise the structural substrate for the solar cells.

TABLE III. - ATOMIC OXYGEN EFFECTS IN AO171 COMPOSITE SAMPLES

Composite Materials (No. of Specimens)	Average Thickness Loss (Mils)	Atomic Oxygen Reactivity 10^{-24} cm/Atom	General Observations
HMF 322/P1700/±45° (5)	4.7 to 11.5*	(1.6 - 3.8)	Materials (1-5) "blacker", i.e., more diffuse. "S" glass- epoxy much darker - probably from UV effects.
HMS 934/0° (5)	2.5**	0.8	
HMS 934/90° (6)	2.7	0.9	
P75S/934/90° (6)	2.7	0.9	Fibers evident in materials (1-6). Closer observations show micrometeoroid/ space debris hits on all specimens.
P75S/934/0° (5)	2.8	0.9	
"S" Glass-epoxy (3)	0.36***	0.11	
Thermal Control Aluminized Taped "S" Glass-epoxy (3)	Indeterminate	--	Material (7) shows unexplained corrugated features on aluminum tape.

* Matrix erosion much greater than fiber

** Average of rates from 2 ends of sample; contamination likely on forward end

*** Fibers uneroded and become protective after initial matrix mass loss

TABLE IV
POST FLIGHT ASSESSMENT OF
METALLIZED AND POLYMERIC FILMS

	Materials/Configuration (Exposed ⇒ inner material)	Post Flight Condition
1.	DC-2577 Coated Kapton	Intact
2.	RTV-670 Coated Kapton	Intact
3.	1.0 mil Kapton H	Eroded away
4.	Sandwich configuration of 1/2 mil Kapton, 1 mil Black Kapton/2 mil Kapton	Eroded away
5.	Aluminized Mylar	Intact
6.	5 mil Kapton H	Eroded away
7.	Aluminized Teflon	Intact
8.	Kapton F	Eroded away
9.	1/2 mil Teflon	Eroded away
10.	1.0 mil White Tedlar	Still white but matrix eroded away
11.	Aluminized Kapton	Intact
12.	Aluminized tape on composite	Intact, surface fatigue, adhesive good

TABLE V. - PROPERTY DATA ON PAINTS ON AO171 EXPERIMENT

PAINT	MASS LOSS *(MG/cm^2)	SOLAR ABSORPTIVITY Unexposed	SOLAR ABSORPTIVITY Exposed
A-276 (White diffuse)	1.00	.284	.237
401-C10 (Black diffuse)	1.13	.990	.995
Z-853 (Yellow diffuse)	0.94	.491	.428
Z-306 (Black diffuse)	1.60	.978	.973
Z-302 (Black specular)	4.06	.973	.974
S13GLO (White)	Negligible	.186	.319

*Inert pigments in diffuse paints tend to retard atomic oxygen produced erosion.
Specular Z-302 was eroded to the metal substrate

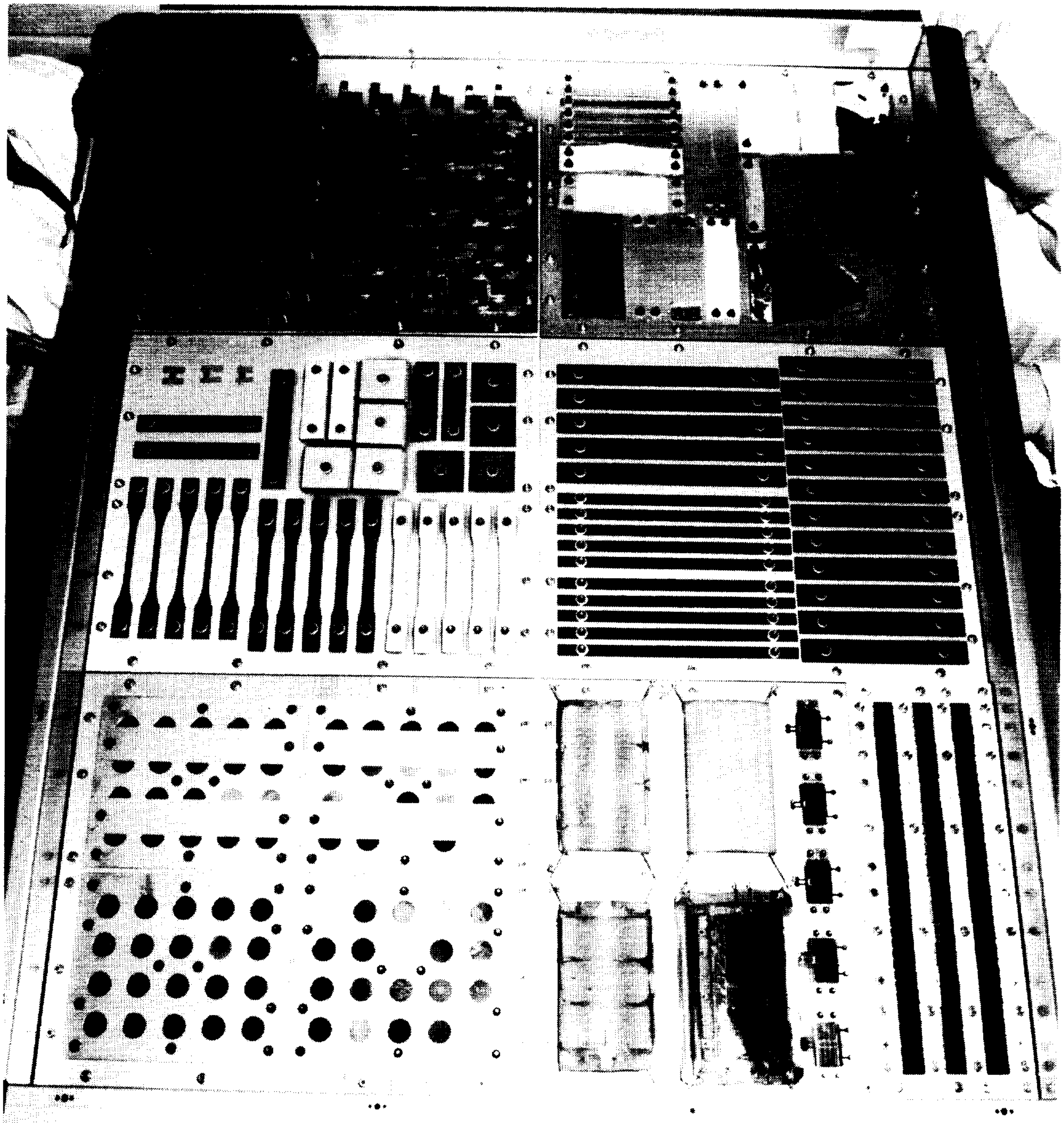

Figure 1. AO171 Experiment After 5.8 Years Exposure in LEO

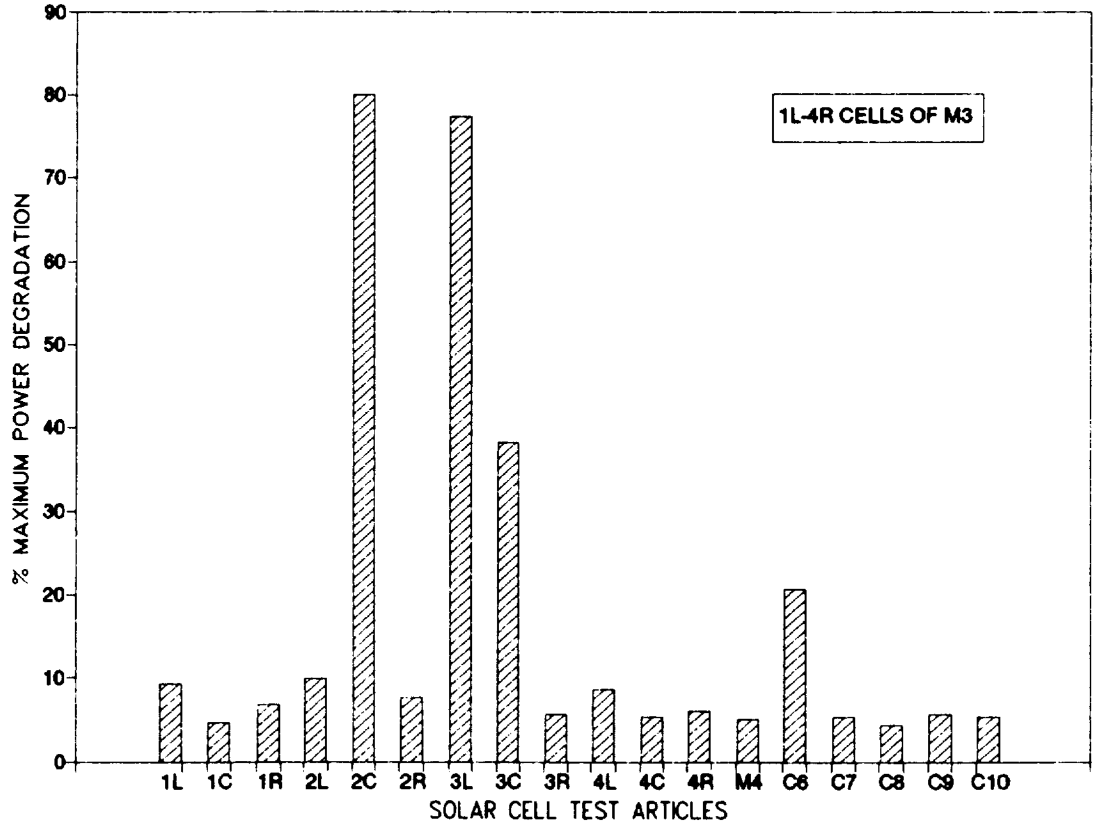

Figure 2. Percent Degradation in Solar Cell Test Article Maximum Power Output

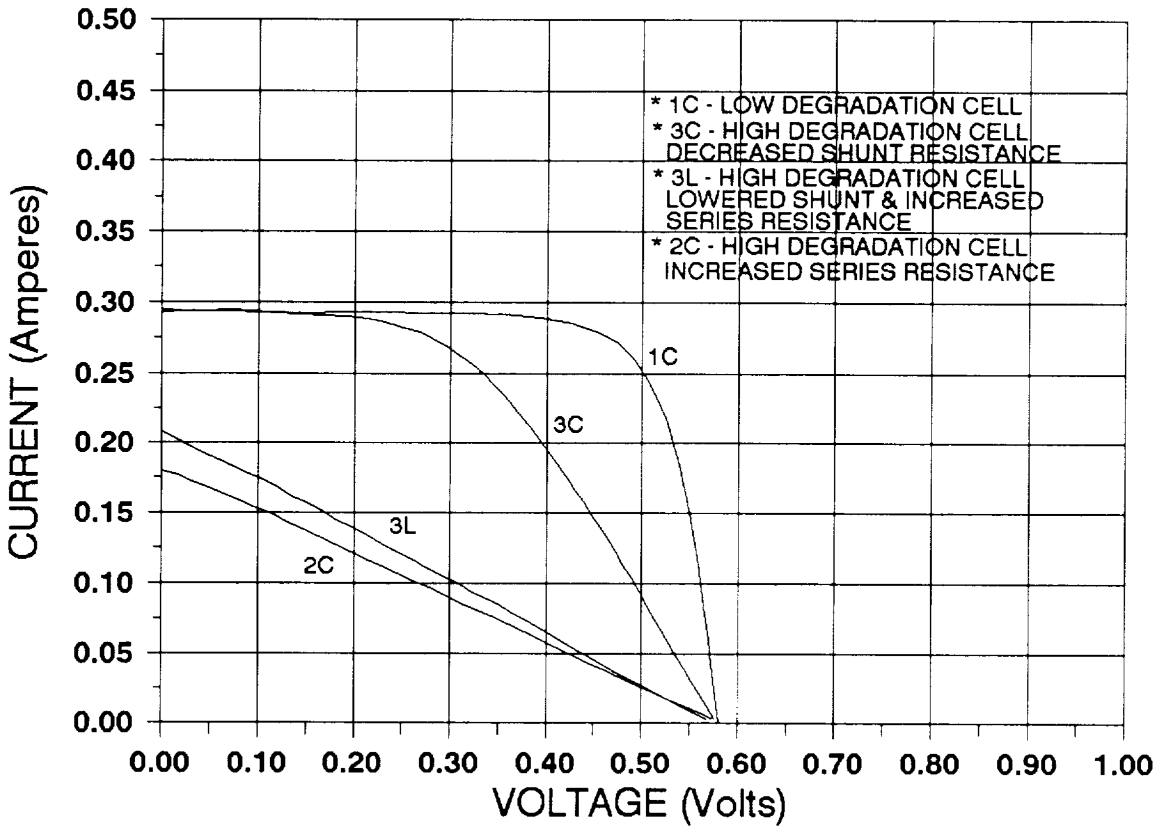

Figure 3. Variations in Current/Voltage Characteristics of Poor Performance Cells and Best Performing Cell C1