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# REAL TIME OUTDOOR EXPOSURE TESTING OF SOLAR CELL MODULES AND COMPONENT MATERIALS

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16. Abstract

Plastic samples, solar cell modules and sub-modules have been exposed at test sites in Florida, Arizona, Puerto Rico and Cleveland, Ohio, in order to determine materials suitable for use in solar cell modules with a proposed 20-year lifetime. Various environments have been encountered including sub-tropical, sub-tropical with a sea air atmosphere, desert, rain forest, normal urban, and urban-polluted. The samples have been exposed for periods up to six months. Materials found not suitable were polyurethane, polyester, Kapton, Mylar and UV-stabilized Lexan. Suitable materials were acrylic, FEP-A and glass. The results of exposure of polyvinylidene fluoride were dependent on the specific formulation but several types appear suitable. RTV silicone rubber (clear) appears to pick up and hold dirt both as a free film and as a potting medium for modules. The results indicate that dirt accumulation and cleanability are important factors in the selection of solar cell module covers and encapsulants.

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## INTRODUCTION

Increasing emphasis is being placed on solar energy programs, including solar photovoltaics. With this emphasis, solar cell modules are being produced by different manufacturers for the Energy Research and Development Agency (ERDA) Photovoltaic Program. Since the modules which will eventually be in general use must withstand a variety of environmental conditions, the modules and their components must be tested to determine the effects of outdoor exposure.

In a continuation of real-time testing begun under NASA sponsorship (ref. 1), plastic samples, solar cell modules and sub-modules have been exposed at several test sites with different environments under real-time conditions. The modules were manufactured in 1976 as part of the 46-kW ERDA/Jet Propulsion Laboratory (JPL) Low Cost Silicon Solar Array Project. Plastic samples were provided by manufacturers and the sub-modules were made at NASA-LeRC by Jacob D. Broder. This report covers the recent results of these tests. In some cases, quantitative data is available. For others, only qualitative observations can be reported.

## TEST SITES AND CONDITIONS

Modules, sub-modules and plastic samples have been exposed at the following sites at the given panel inclination angle and under the conditions listed.

1. Desert Sunshine Exposure Tests, Inc., Phoenix, Arizona. South-facing panels, inclined at $45^{\circ}$. Desert conditions.

2. Caribbean Testing, Inc., Caguas, Puerto Rico. South-facing panels inclined at $5^{\circ}$, $18^{\circ}$ and $45^{\circ}$. A fourth panel has its inclination angle changed by $5^{\circ}$ approximately every two weeks to follow the sun. The maximum angle is $40^{\circ}$ and the minimum is $0^{\circ}$. Tropical, rain forest conditions.

3. Solar Testing Service, Inc., Pompano Beach, Florida. South-facing panels inclined at $5^{\circ}$ and $45^{\circ}$. Sub-tropical conditions.

4. Sub-Tropical Testing Service, Miami, Florida. South-facing panels inclined at $5^{o}$ and $45^{o}$. Sub-tropical conditions.

5. South Florida Testing Service, Miami, Florida. South-facing panels inclined at $5^{o}$ and $45^{o}$. Sub-tropical, sea air atmosphere.

6. Air Pollution Control Center, Cleveland, Ohio. South-facing panels inclined at $40^{o}$. A very heavy industrial environment.

7. NASA-Lewis Research Center, Cleveland, Ohio. South-facing panels inclined at $40^{o}$. Ordinary urban environment (commercial business/ residential areas in prevailing upwind direction).

A variety of samples was exposed at each site. The optical transmission samples were 2.54-cm-by-12.7-cm in size supported on a metal or cardboard frame. The sub-modules were two sizes. Some were 2.54-cm by 12.7-cm and consisted of five 2-by-2-cm solar cells connected in series. The rest were 6.50-cm-by-12.7-cm and consisted of two 5.30-cm round cells connected in series.

At Site 1, 7 different plastics and 31 five-cell sub-modules were tested. The plastics were FEP-A, acrylic, perfluoroalkoxy (PFA), Mylar, polyester, Aclar 22A and Tefzel. The sub-modules were covered with FEP-A (heat bonded or glued), FEP-C (heat bonded or glued), acrylic, clear silicons rubber, UV-stabilized Lexan, polyether-sulfone and PFA (heat bonded or glued). A more detailed listing of these samples is given in Tables I and II.

For the plastic samples, the transmission was measured over the wavelength range 0.35 to 1.20μm before and after testing using a Cary 14 spectrophotometer. For the modules, current-voltage (I-V) traces were made before and after testing and from these, the short-circuit current ($I_{sc}$), open-circuit voltage ($V_{oc}$), maximum power ($P_{max}$), fill factor and efficiency were determined. All of these measurements were made at LeRC. On earlier samples I-V measurements were made using the X-25 solar simulator at air mass zero (AMO) conditions and $25^{o}$ C. On the more recent samples measurements were made at air mass one (AM1) and $28^{o}$ C using a flash simulator since these conditions have been standardized for terrestrial testing.

At Site 2, 97 samples of types described in Table III, numbers 1 through 13, are being exposed along with 9 sub-modules of type number 14. The sub-modules are made using two round cells as described earlier. Initial transmission data (except for the fiberglas samples, numbers 8 and 10) and I-V measurements for the sub-modules have been recorded but since these samples are still on-site, only comments of a qualitative nature will be made.

At Site 3, 54 samples of types 1 - 13 in Table III are being exposed. Again, only qualitative comments can be made for these samples.

At Site 4, 53 samples of types 1 - 13 and 11 sub-modules, type 14, as described in Table III are being exposed.

At Site 5, 61 samples of types 1 - 13 and 13 sub-modules, type 14, as described in Table III are being exposed.

At Sites 6 and 7, modules from four manufacturers have been exposed for approximately two months outdoors. These modules were manufactured in 1976 for the 46-kW purchase of the ERDA/JPL Low Cost Silicon Solar Array Project. The manufacturers are Spectrolab, Sensor Technology, Solar Power and Solarex. The construction of the modules is described in Table IV. For these modules, initial I-V curves were taken using a flash simulator (AM1, 28$^{o}$ C). The curves were again recorded after exposure but before the modules were cleaned. After they were cleaned with detergent and water, another I-V curve was recorded. $I_{sc}$, $V_{oc}$ and $P_{max}$ were determined from the curves. For both power and current measurements, the reproducibility is ±2%.

## RESULTS

The data for the sub-modules exposed at Site 1 are shown in Table I. The first three columns identify and describe each sample. Next is given the exposure time in months and the solar flux in langleys. $I_{sc}$ and $P_{max}$ are given at the initial and final time of the test as is the percentage change in $P_{max}$ ($\Delta P_{max}$) over the course of the test. Finally, the visual observations on the condition of the sub-modules are shown under "Remarks."

The first eight sub-modules listed were made using 2x2-cm cells with front and back contacts. Previous accelerated outdoor exposure of similarly constructed samples (ref. 1) showed that stress-cracking at the interconnect areas occurred. Therefore subsequent samples were made using wraparound contact 2x2-cm solar cells.

Of the 31 sub-modules exposed at Site 1, three showed loss of current after testing, and five had no output at the end of the test. Those with no output had either a broken cell or problems with bubbling of the adhesive around the interconnects which may have caused poor contact. These results point out that, for these limited exposures, darkening of the cover plastic is not a problem.

In general, little change was observed under visual examination for these sub-modules. For a large proportion of the samples, 20 out of 31, the change in maximum power, the parameter of most interest, was less than the experimental error. Same-day and day-to-day variations in current and maximum power measurements of reference cells and modules shows the experimental error to be ±4%.

The sub-modules that degraded the least had covers of heat-bonded FEP-A or FEP-A attached with either GE574 or GE585 adhesive. One acrylic-covered sub-module also did not degrade. Of the six sub-modules whose maximum power decreased, two were covered with UV-stabilized Lexan, one was a potted silicone (XR-63489) sample and one each was covered with heat-bonded FEP-C, heat-bonded PFA and polyethersulfone attached with GE585. Part of the poor performance of these latter samples may be attributed to technique problems in making the sub-modules and the limited sampling.

The results for the plastics exposed at Site 1 are shown in Table II. There was very little transmission loss for any of the samples except Mylar. The losses that did occur were higher in the blue end of the spectrum which could be observed by noting tanning of the samples.

The results from Sites 2, 3, 4 and 5 will be discussed together since the samples at all sites were similar. The results are presented in Table III. The general types of observations which were made were for cracking, tearing, darkening, delamination and physical deterioration of the samples. All of the samples have been exposed for six months but because of different angles of exposure and a different latitude for Puerto Rico, the flux density received by the samples was not the same. This accounts for the occurrence of a particular effect at different times. Also, different observers may judge the same effect differently. For these reasons, the observations from these sites cannot be interpreted more precisely until the first phase of exposure (12 months) is over and transmission is remeasured.

In general, the following comments can be made about these samples. Several formulations of polyvinylidene performed less well than the rest. Information from the manufacturer indicated that these formulations were slightly changed relatively frequently and further characterization was not possible. The material might be a good cover material but sub-modules constructed using a specific formulation would have to be exposed to assure quality.

For some materials, effects appeared at some site but not at others. Included in this group are PFA, acrylic, TVP, FEP-A, FEP-C, UV-stabilized Lexan and the silicone. Other materials were affected at all sites. These were three of the polyvinylidene formulations, polyester and Kapton which all disintegrated to some degree. The free fiberglas samples had a tendency to ravel but were unaffected otherwise. The polyurethane-covered sub-modules darkened at all sites and in some cases eroded away.

The results from the modules exposed at Sites 6 and 7 are presented in Table V. Listed are $I_{sc}$ and $P_{max}$. $\Delta I_{sc}$ and $\Delta P_{max}$ are also shown. Three values are listed for each module; the initial data, the data measured on the modules after exposure and prior to cleaning, and that measured after cleaning with detergent and water. Comparing the data

for similar modules, one can immediately see the effect of heavy industrial pollution. Most of this was solid material which can be removed by washing. However, the surface of the module is very important. Note that Spectrolab modules, which are glass-covered, are much less affected by outdoor dirt. This probably occurs because rain or snow can carry off some of this material which apparently does not adhere tightly to glass. The other three modules, whose surface is a softer silicone, tend to hold the dirt more tightly and, in fact, the dirt may actually imbed in the surface and not wash off easily. Differences in formulation of this silicone rubber layer may account for the higher losses in Solar Power modules after cleaning.

## CONCLUSIONS

Limited real time outdoor exposure has shown that some materials are not suitable for solar cell module construction. These are polyurethane, polyester, Kapton, Mylar and UV-stabilized Lexan. Polyvinylidene fluoride may be suitable, but because different formulations are available, each must be evaluated. Acrylic, FEP-A and glass appear to be good candidates for module covers. RTV silicone rubber (clear) appears to pick up and hold dirt both as a free film and as a potting medium for modules. These results indicate that dirt accumulation and cleanability are important factors in the selection of solar cell modules covers and encapsulants.

## REFERENCE

1. Americo F. Forestieri and Evelyn Anagnostou: The Effect of Sunshine Testing on Terrestrial Solar Cell System Components. NASA TM X-71722, May 1975.

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TABLE I

EFFECT OF REAL TIME EXPOSURE ON SOLAR CELL SUB-MODULES EXPOSED AT DESERT SUNSHINE EXPOSURE TESTS, INC., PHOENIX, ARIZONA. PANELS FACING SOUTH AT 45° INCLINATION

| SUB-MODULE ID NO. | SUB-MODULE COVER | CONSTRUCTION SUBSTRATE | TEST TIME & EXPOSURE | SHORT CIRCUIT CURRENT Isc, AMPS INITIAL | SHORT CIRCUIT CURRENT Isc, AMPS FINAL | MAXIMUM POWER Pmax, WATTS INITIAL | MAXIMUM POWER Pmax, WATTS FINAL | ΔPmax,% | OBSERVATIONS |
|---|---|---|---|---|---|---|---|---|---|
| 84 | FEP-A, heat bonded[a] | aluminum | 6 months; | .128[b] | .130[b] | .266[b] | .268[b] | + .7 | slight delamination at end interconnect |
| 85 | | | 97,652 langleys | .131 | .134 | .277 | .282 | +1.8 | some edge delamination |
| 105 | | | | .128 | .127 | .276 | .280 | +1.4 | discolorated |
| 114 | | | | .128 | .131 | .270 | .274 | +1.5 | edge delamination |
| 117 | | | | .131 | .136 | .276 | .278 | + .7 | some edge delamination |
| 126 | | fiberglas | | .136 | .138 | .280 | .279 | - .4 | good appearance |
| 116[c] | | aluminum | 2 months; | .128 | .134 | .227 | .234 | +3.1 | edge delamination |
| 121[c] | | fiberglas | 34,612 langleys | .130 | .128 | .253 | .266 | +5.1 | interconnects cut through |
| 195 | .159 cm acrylic sealed at the edges | | | .136 | .134 | .231 | .232 | + .4 | good appearance; some milkiness at edge |
| 199 | cast XR-63489 (clear silicone) | | | .143 | .140 | .251 | .225 | -10 | dulled surface |
| 201 | UV stabilized Lexan | polystyrene | | .127 | .106 | .220 | .099 | -55 | good appearance |
| 202 | FEP-A, heat bonded, no primer attached with Mystak tape | aluminum | | .139 | .144 | .255 | .170 | -33 | one cell delaminated |
| 206 | FEP-C, att. w/Mystik tape | aluminum | | .121[d] | .122[d] | .201[d] | .183[d] | -8.9 | delaminated |
| 211 | FEP-C, GE 585 adhesive | aluminum | | .123 | .124 | .223 | .225 | + .9 | bubbling at cell edges |
| 214 | UV stabilized Lexon with GE 585 adhesive | aluminum | | --- | --- | --- | --- | --- | broken cell; delamination, bubbles |
| 217 | Polyether sulfone with GE 585 adhesive | aluminum | | .123 | .110 | .235 | .192 | -18 | yellow, brittle, pulling off at edges |
| 222 | PFA, heat bonded | fiberglas | | .120 | .075 | .243 | .142 | -42 | some delamination where bubbled; interconnects are white |
| 223 | FEP-A with GE 585 adhesive | aluminum | | .126 | .128 | .240 | .234 | -2.5 | delamination at edges and interconnects |
| 226 | FEP-A with GE 585 adhesive | Formica | | .124 | .127 | .243 | .245 | + .8 | bubbled at cell edges |
| 229 | PFA with GE 585 adhesive | Formica | | .134 | .130 | .237 | .234 | -1.3 | bubbled at cell edges and on one cell |
| 234 | FEP-A with GE 585 adhesive | aluminum | | .132 | .128 | .241 | .234 | -2.9 | unstuck at cell edges |
| 237 | FEP-A with GE 585 adhesive | Kapton | | .127 | .128 | .251 | .251 | 0 | slight bubbling at several cell corners |
| 250 | FEP-A with GE 574 adhesive | aluminum | | .124 | .130 | .247 | .249 | + .8 | edges unstuck |
| 252 | FEP-A with GE 574 adhesive | Kapton | | .121 | .124 | .201 | .204 | +1.5 | cracked cell; bubbles at cell edge |
| 253 | FEP-C with GE 574 adhesive | Kapton | | .128 | --- | .239 | --- | --- | bubbling at interconnects |
| 259 | FEP-A with GE 574 adhesive | fiberglas | | .122 | .124 | .224 | .224 | 0 | some discoloration on cell back |
| 260 | FEP-C with GE 574 adhesive | fiberglas | | .129 | --- | .191 | --- | --- | good appearance |
| 267 | FEP-A with GE 574 adhesive | " & Kapton | | .129 | .132 | .207 | .207 | 0 | good appearance; some discoloration on cell back |
| 271 | PFA with GE 574 adhesive | Kapton | | .127 | --- | .191 | --- | --- | good appearance; some discoloration on cell back |
| 276 | PFA with GE 574 adhesive | fiberglas | | .125 | .132 | .187 | .183 | -2.1 | good appearance; some discoloration on cell back |
| PFA-X | PFA with GE 585 adhesive | aluminum | ✓ | .126 | --- | .222 | --- | --- | delamination at several areas; lead tab off |

(a) These sub-modules were made using front and back contact cells. All others had wraparound contact cells.

(b) These parameters through sample number 202 were measured at AMO, 25° C.

(c) Samples were placed on real time test after four months of accelerated exposure. Initial parameters are those measured prior to real time test.

(d) These parameters for this and all subsequent samples measured at AM1, 28° C.

TABLE II. - TRANSMISSION EFFECTS ON PLASTIC SAMPLES EXPOSED UNDER REAL TIME EXPOSURE AT DESERT SUNSHINE EXPOSURE TESTS, INC., PHOENIX, ARIZONA ON SOUTH-FACING PANELS INCLINED AT 45°

TOTAL EXPOSURE, 30161 LANGLEYS

| Sample | Number of Samples | Transmission Loss 0.35μm | 1.2μm |
|---|---|---|---|
| FEP-A, 2 layers, heat bonded | 2 | 3% | 3% |
| Acrylic | 1 | 1 | 0.5 |
| Perfluoroalkoxy (PFA) | 2 | 9 | 1 |
| Mylar | 2 | 25 | 4 |
| Polyester (Scotchpar) | 1 | 4 | 1 |
| Aclar 22A | 1 | 3 | 0 |
| Tefzel | 2 | 4 | 2 |

TABLE III. - QUALITATIVE EFFECTS OF REAL TIME EXPOSURE IN FLORIDA AND PUERTO RICO

TOTAL TIME, 6 MONTHS

| Sample Group Identification Number | Sample Description | Number of Samples | Observations |
|---|---|---|---|
| 1 | Eight formulations of polyvinylidene fluoride (Pennevalt) | 64 | Three formulations showed darkening or disintegration after 3 months; others showed no effects. |
| 2 | Perfluoroalkoxy (PFA), (DuPont) | 10 | One sample showed some darkening. |
| 3 | Two quartz cover slips cemented with GE585 | 10 | Unaffected. |
| 4 | Acrylic (Lucite) | 10 | Showed some buckling in Puerto Rico. Others unaffected. |
| 5 | TVP - a laminate of UV stabilized Tedlar, plastic grid (Vexar) and UV inhibited polyethylene | 6 | " " " |
| 6 | Polyester (Scotchpar, 3M), 2 thicknesses | 30 | Samples disintegrated after 2 months in all cases. |
| 7 | RTV, XR 63489 cast at Lewis Research Center | 10 | Appeared to be picking up dirt or possibly mildew. |

TABLE III (Continued)

| Sample Group Identification Number | Sample Description | Number of Samples | Observations |
|---|---|---|---|
| 8 | Fiberglas | 15 | Ravelling |
| 9 | Kapton (DuPont) | 14 | Buckles and tears and eventually breaks up. |
| 10 | FEP-A and fiberglas, heat-bonded together | 20 | Unaffected |
| 11 | FEP-A | 32 | Some samples in Puerto Rico curling and slightly yellow. |
| 12 | FEP-C | 24 | " " " |
| 13 | UV stabilized Lexan | 17 | Buckling and cracking of several samples. |
| 14 | Polyurethane covered sub-modules | 33 | Darkening and some flaking of coating (also noted in earlier DSET tests). |

TABLE IV. - DESCRIPTION OF MODULES SUPPLIED TO THE ERDA/JPL LOW COST SILICON SOLAR ARRAY PROJECT

(46 kW PURCHASE, 1976)

| | |
|---|---|
| Spectrolab | Aluminum backed; 2" diameter cells completely encapsulated in silicone; covered with glass sheet ∿1/8" thick. |
| Sensor Tech | Aluminum backed; 2" diameter cells completely encapsulated in silicone. |
| Solarex | Fiberglas-epoxy composite backed; 3" diameter cells completely encapsulated in silicone. |
| Solar Power | Fiberglas-epoxy composite backed; 3" diameter cells completely encapsulated in silicone. |

## TABLE V. - EFFECT OF DIRT ON MODULE PERFORMANCE

| | | $I_{sc}$, $\Delta I_{sc}$ amps, % | | | | | $P_{max}$, $\Delta P_{max}$ watts, % | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Start | Removed from Site | | Cleaned | | Start | Removed from Site | | Cleaned | |
| | | $I_{sc}$ | $I_{sc}$ | $\Delta I_{sc}$% | $I_{sc}$ | $\Delta I_{sc}$% | $P_{max}$ | $P_{max}$ | $\Delta P_{max}$ | $P_{max}$ | $\Delta P_{max}$ |
| Spectrolab | A* | 0.625 | 0.640 | +2.4 | 0.638 | +2.1 | 5.08 | 5.17 | +1.8 | 5.08 | 0 |
| | B* | 0.596 | 0.570 | -4.4 | 0.615 | +3.2 | 5.07 | 4.78 | -5.7 | 5.16 | +1.8 |
| Sensor Technology | A | 0.525 | 0.484 | -7.8 | 0.521 | -0.8 | 5.65 | 5.17 | -8.5 | 5.60 | -0.9 |
| | B | 0.540 | 0.355 | -34.3 | 0.526 | -2.6 | 5.61 | 3.65 | -34.9 | 5.39 | -3.9 |
| Solarex | A | 1.470 | 1.362 | [illegible] | 1.478 | +0.5 | 9.54 | 8.60 | -9.8 | 9.34 | -2.1 |
| | B | 1.473 | 1.075 | -27.0 | 1.460 | -0.9 | 9.73 | 7.02 | -27.8 | 9.43 | -3.1 |
| Solar Power | A | 1.528 | 1.375 | -10.0 | 1.475 | -3.5 | 13.85 | 12.64 | -8.7 | 13.41 | -3.2 |
| | B | 1.450 | 0.980 | -32.4 | 1.362 | -6.1 | 13.52 | 9.27 | -31.4 | 12.35 | -8.6 |

*Site A - NASA-Lewis, 74 days exposure. (Average daily total suspended particulates, 45)
*Site B - Air Pollution Control Center, 81 days exposure. (Average daily total suspended particulates, 135)