STATUS OF FEP ENCAPSULATED SOLAR CELL MODULES
USED IN TERRESTRIAL APPLICATIONS

by A. F. Ratajczak and A. F. Forestieri
Lewis Research Center
Cleveland, Ohio 44135

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NASA-Lewis Research Center
Cleveland, Ohio

SUMMARY

The Lewis Research Center has been actively engaged
in transferring the FEP encapsulated solar cell technol-
ogy developed for the space program to terrestrial ap-
lications. FEP encapsulated solar cell modules and
arrays have been designed and built expressly for ter-
restrial applications. Solar cell power systems have
been installed at three different land sites, while in-
dividual modules are undergoing marine environment tests.
Four additional power systems are being completed for
installation during the summer of 1974. These tests
have revealed some minor problems which have been cor-
crected. The results confirm the inherent utility of
FEP encapsulated terrestrial solar cell systems.

INTRODUCTION

Photovoltaic power systems for terrestrial applica-
tions have been in use, both in this country and
abroad, for about ten years. Even though solar cell
arrays are relatively high cost items ($25-$50/watt),
the total cost of a solar cell power system for remote
locations over a lifetime of ten years or so can be
considerably lower when one has to consider the cost of
fuel, transportation, etc. for alternate power sources.
Late in 1970 the Solar Cell Branch at the NASA-Lewis
Research Center began the design of a terrestrial solar
cell power system in response to a request from the NASA
Flight Research Center. With this work as background
we began rooftop tests of some of our latest space type sol-
ar cell module designs using FEP (fluorinated ethylene
propylene) encapsulation (ref. 1). The rooftop tests
indicated that this type of module was well suited for
terrestrial applications.

The LeRC then initiated a program on near-term ter-
restrial applications to encourage and stimulate expan-
sion of markets for solar cells. The main thrust of the
program was to demonstrate that terrestrial solar cell
power systems could be useful and economical. As part
of this program government agencies were contacted that
had a need for small power systems at remote sites. The
Equipment Development Laboratory of the National Ocean-
ographic and Atmospheric Administration (NOAA) requested
that we support them in the design, fabrication and in-
stallation of a solar cell power supply for their Remote
Automatic Meteorological Observation Stations (RAMOS).
Similar arrangements were made with other govern-
ment agencies.

This report will discuss the solar cell array and
system design and results obtained during operation of
the applications noted above.

ELECTRICAL POWER SYSTEM DESIGN

Power output from a solar cell array is limited by
the amount of sunshine (insolation) available. Batter-
ies are therefore used in conjunction with the solar
cells to supply power during periods of low insolation,
nighttime, and for peak load requirements. The sizing
of the array and batteries depends upon careful budget-
ing of the energy requirements of the load and a good
estimate of the sunshine available. For most applica-
tions the load profile can be easily defined. The a-
available sunshine, on the other hand, is uncertain and
must be predicted on the basis of past insolation data,
which are not as complete as desired. Therefore the
design of solar cell systems cannot be precise and must
be on the conservative side.

Our approach to power system design is to size a
system on the basis of an annual ampere-hour budget.
That is, the array, over the course of a year, must gen-
erate enough ampere-hours to satisfy the total annual
load requirements, including battery charging ineffi-
ciencies. The design objective is to end up with the
smallest, least expensive system that will reliably
meet the load requirements.

The sizing of array and batteries entails three
operations: calculating monthly load ampere-hour re-

requirements, calculating monthly solar cell ampere-hour
output, and combining these data to determine system
size. For each month the ampere-hour load requirement
is computed for the prescribed or assumed load profile.
Loads supplied by the battery are differentiated from
those supplied directly by the array to provide a bet-
ter definition of battery requirements and losses.
The daytime continuous load is generally assumed to be sup-
plied by the array while the nighttime and peaking loads
are supplied by the battery.

From local insolation data the ampere-hour output of
a single solar cell or a unit area of the array is
calculated for each month and for several array inclina-
tion angles. The mean daily solar radiation and mean
monthly sky cover data for these calculations are taken
from the Climatic Atlas (ref. 2) for a weather station
judged to be representative of the site of the applica-
tion.

System sizing combines the compilations of the
load requirements and the solar cell outputs to deter-
mine the number of solar cells, the optimum array in-
cination angle, and the battery storage capacity.

The minimum number of paralleled solar cells is
determined from the total load requirements and cell
output. The number of series solar cells is an inde-
pendent function of battery charging voltage and maxi-
imum solar cell operating temperature.

The optimum inclination angle is not just a func-
tion of latitude, but depends on the load profile and
the monthly variations in insolation and sky cover. The
angle selected is that which gives the smallest monthly
array ampere-hour output deficit and which requires the
fewest number of solar cells and the smallest battery
storage capacity.
The batteries are sized to maintain continuous systems operation. They must have adequate capacity to absorb peaking loads, nighttime operation, and array output deficits during winter or cloudy months. The calculated capacity may require adjustment to account for specific knowledge of local weather conditions, and any peculiarities of the load profile. A conservative battery size is generally used to provide margin for lower-than-expected insolation, and temperatures. It also minimizes gassing problems during periods of high charging rates caused by high array outputs. A voltage regulator is always included in the power system design to prevent battery overcharge.

ARRAY MECHANICAL DESIGN

The array mechanical design is based on a modular approach so as to be adaptable to a variety of applications and provide ease of transportation and field assembly and repair. The basic element is a 1-watt module composed of 2x2 cm cells with 3 cells in parallel and 8 cells in series (figures 1 and 2). This size is convenient for designing for different system voltages and currents. Five modules connected in series (fig. 3) form a nominal 12-volt module, i.e. one capable of charging a 12-volt battery. Since many systems run on 12 or 24 volts, the 12-volt module becomes a second level building block.

Protection of the solar cells from the environment is provided by encapsulation of the 1-watt modules in FEP plastic film. The electrically interconnected cells are laminated under heat and pressure between 5-mil sheets of FEP. Details of the lamination procedure are given in ref. 1. A second lamination process is used to mount the encapsulated cells to the substrate, with the FEP acting as the adhesive. This process provides complete encapsulation of the cells and a smooth surface on the top of the module. This smooth FEP surface is easily cleansed by rain, melting snow, or snow sliding off the array.

Two types of modules are presently made. One type (fig. 1) uses an aluminum substrate and is used where high strength is required. The other (fig. 2) uses a less expensive fiberglass cloth substrate. Either type of module can be used in the frame which forms the 12-volt module.

The main array structure is a welded framework of anodized aluminum angle. The 1-watt modules are bolted to welded, anodized aluminum frames to constitute 12-volt modules, which are bolted to the main framework.
POWER SYSTEMS DESCRIPTIONS AND OPERATIONAL RESULTS

In 1970, a solar cell power system was designed and built by NASA-Lewis Research Center (LeRC) for the NASA-Flight Research Center (FRC) to power remote radar beacons. Program changes at FRC precluded the originally intended use, so the solar cell modules were used instead to power a weather station on the shore of Lake Erie in Cleveland, Ohio (fig. 4a and 4b).

Although this type of solar cell module operates satisfactorily in a terrestrial environment, it is heavier, bulkier, and more expensive than the FEP-encapsulated solar cell modules.

At the present time there are FEP modules on test at five different locations and hardware is being fabricated for four additional tests. The tests in progress include both environmental durability of single modules and complete systems tests. Table I lists the systems with their operating requirements, and array and battery sizes.

### Table I

**SUMMARY OF FEP-ENCAPSULATED SOLAR CELL POWERED SYSTEMS TESTS**

<table>
<thead>
<tr>
<th>NAME AND LOCATION</th>
<th>DATE INSTALLED</th>
<th>CURRENT</th>
<th>NO. OF 1-WATT MODULES</th>
<th>BATTERY CAPAC.</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAMOS, MAMMOTH MTH, CA</td>
<td>NOV 1973</td>
<td>12 46 mA 6.3 A, 6 SEC/HR</td>
<td>20*</td>
<td>60 AH</td>
</tr>
<tr>
<td></td>
<td></td>
<td>24 83 mA 0.596 A, 6 SEC/HR</td>
<td>40*</td>
<td>100 AH</td>
</tr>
<tr>
<td>RAMOS, STERLING, VA</td>
<td>OCT 1973</td>
<td>12 46 mA 6.3 A, 6 SEC/HR</td>
<td>10</td>
<td>60 AH</td>
</tr>
<tr>
<td></td>
<td></td>
<td>24 83 mA 0.596 A, 6 SEC/HR</td>
<td>30</td>
<td>80 AH</td>
</tr>
<tr>
<td>NOAA BUOY, GULF OF MEXICO</td>
<td>JUN 1974+</td>
<td>12 26 mA 2.35 A, 6 SEC/HR</td>
<td>5</td>
<td>40 AH</td>
</tr>
<tr>
<td>REPEATER INTO NAT'L FOREST</td>
<td>JUL 1974+</td>
<td>8.5 20 mA 1.9 A VARIABLE</td>
<td>16</td>
<td>45 AH</td>
</tr>
<tr>
<td>BACKPACK INTO NAT'L FOREST</td>
<td>JUL 1974+</td>
<td>13 23 mA 0.31 A, VARIABLE SPECIAL DESIGN</td>
<td>1 AH</td>
<td></td>
</tr>
<tr>
<td>NASA-LEWIS ROOF, OHIO</td>
<td>APR 1974</td>
<td>12 39 mA 3.31 A, 6 SEC/HR</td>
<td>10</td>
<td>40 AH</td>
</tr>
</tbody>
</table>

*DESIGN REQUIREMENTS SAME AS FOR STERLING, VA WITH ADDITION OF UNSCHEDULED OPERATION. ADDITIONAL MODULES ADDED TO ACCOMMODATE LATTER REQUIREMENT.

**Fig. 4a** - Solar cell array powered weather station at Cleveland lakefront

**Fig. 4b** - Lucite covered solar cell array at Cleveland lakefront

In this system uncovered solar cell modules are in an O-ring-sealed compartment with a clear acrylic window (ref. 3). The system has been in place for a year and a half and there have been no signs of solar array deterioration. There has been a failure of the power cable from the array due to inadequate weatherproofing and malfunctions in the electronics associated with the weather station, but none of these problems detract from the inherent utility of this type of solar cell array.
The first FEP-covered solar cell power system installation was for a NOAA RAMOS weather station at the NOAA test facility at Sterling, Virginia (fig. 5). This 40-watt array has both 12-volt and 24-volt sections and the 1-watt modules all have aluminum substrates. Short-circuit current readings were taken monthly by NOAA personnel and are listed in Table II. Unfortunately the sky conditions were reasonably good only for the December measurement. Because instrumentation simultaneously measuring insolation was not included in these tests, strong conclusions cannot be drawn from these data. Definitive evaluation of array degradation will have to await remeasurement under the controlled conditions of a solar simulator facility.

Nevertheless, the data in Table II could indicate if serious degradation were occurring. The pre-installation current measurement under an air mass zero solar (AM0) simulator is shown for reference in Table II. The AM0 value represents the output in space, that is, with no losses due to the atmosphere and weather. The December current measurement was 67% of AM0, which is not an unreasonable winter value for that site. The outputs of the 12- and 24-volt array sections were compared to see whether one was damaged or degrading faster than the other. The ratio of their outputs should be 1.5. For most of the readings, including the clear-day reading, the ratio was 1.5. For the last three readings the ratio varied between 1.2 and 1.7, which may well be due to variation in the sky condition during the measurements. Within the limits of these field measurements, there is no indication of serious array degradation.

Mercury column coulombmeters were included in the Sterling system to measure array ampere-hour output. NOAA personnel reported irregular coulombmeter operation shortly after installation. Following this initial problem, coulombmeter operation appeared to be normal. Attempts to correlate measured array output with predicted output, design insolation data, and monthly measured insolation, later proved unsuccessful. In mid-April 1974, NOAA installed digital ampere-hour meters to measure array output. At this writing, there is not sufficient data available to establish a correlation between predicted and measured output.

TABLE II
SHORT-CIRCUIT CURRENT READINGS OF RAMOS SYSTEM AT STERLING, VIRGINIA

<table>
<thead>
<tr>
<th>DATE</th>
<th>SHORT-CIRCUIT CURRENT MA</th>
<th>SKY CONDITIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>12-V ARRAY</td>
<td>24-V ARRAY</td>
</tr>
<tr>
<td>OCT 11, 1973</td>
<td>123</td>
<td>183</td>
</tr>
<tr>
<td>NOV 8, 1973</td>
<td>82</td>
<td>122</td>
</tr>
<tr>
<td>DEC 6, 1973</td>
<td>560</td>
<td>850</td>
</tr>
<tr>
<td>JAN 3, 1974</td>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td>FEB 1, 1974</td>
<td>360</td>
<td>470</td>
</tr>
<tr>
<td>MAR 7, 1974</td>
<td>380</td>
<td>470</td>
</tr>
<tr>
<td>APR 13, 1974</td>
<td>355</td>
<td>600</td>
</tr>
<tr>
<td></td>
<td>840</td>
<td>1260</td>
</tr>
</tbody>
</table>

Fig. 5 - Solar cell powered RAMOS Weather Station, Sterling, VA.

Fig. 6 - Solar cell powered RAMOS weather station on Mammoth Mountain, CA.

A second solar cell powered RAMOS weather station is on Mammoth Mountain, California (fig. 6). Installed in November 1973 on the 11,053-foot-high peak, it has...
experienced winds in excess of 92 mph and severe rime conditions. This array, which also contains all aluminum substrate modules, generates a total peak power of approximately 60 watts.

The NOAA chose Mammoth Mountain as a test sight for their RAMOS because of its severe climatic conditions. Forest Service personnel at Mammoth have courteously provided photographs of the station following one of their not-too-severe storms in December 1973 (fig. 7).

They have observed that the rime ice does not appear to form directly on the FEP covered modules. Rather, it appears to build up on the tower and array support structure. Gradually, it emerges through the openings between modules and then builds up over the array (fig. 8). Typically, storms last 1 to 4 days and are followed by periods of clear weather. The black anodizing of the array frame plus the high absorptivity of the solar cells absorbs enough heat so that the array quickly clears itself of rime ice accumulations.

The exceptionally severe winter just past has resulted in malfunctions of the RAMOS equipment which disrupted both load and generating profiles. It has not been possible, therefore, to correlate electrometer readings from the array with predicted power system performance. The weather has also resulted in damage to the array from chunks of rime ice falling from the tower following an early spring storm. Forest Service personnel report several bent modules and modules containing cracked cells and cut FEP.

Short-circuit current readings taken by Forest Service personnel when weather permitted, indicate the extent of the damage (table III). Noting that the 12- and 24-volt array sections have the same number of parallel cells, the damage from the falling ice can be seen in the May 3 readings. Both array sections have been damaged. The very high outputs on November 4 (92 to 96% of AMO output) are indicative of the high output possible at high altitudes with thin clouds that significantly increase incoming radiation.

<table>
<thead>
<tr>
<th>DATE</th>
<th>SHORT-CIRCUIT CURRENT MA</th>
<th>SKY CONDITIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>12-V ARRAY</td>
<td>24-V ARRAY</td>
</tr>
<tr>
<td>NOV 4, 1973</td>
<td>1510</td>
<td>1536</td>
</tr>
<tr>
<td>DEC 19, 1973</td>
<td>1568</td>
<td>1482</td>
</tr>
<tr>
<td>JAN 24, 1974</td>
<td>1100</td>
<td>1100</td>
</tr>
<tr>
<td>JAN 29, 1974</td>
<td>320</td>
<td>320</td>
</tr>
<tr>
<td>FEB 14, 1974</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>MAY 3, 1974</td>
<td>1680</td>
<td>1680</td>
</tr>
</tbody>
</table>

The array was originally to have been mounted near the top of the tower to minimize the possibility of such damage. High winds and lack of sufficient personnel during installation, however, mandated its present position. It will be repaired and raised to the top of the tower during the summer of 1974.
be used as a communications link for all mobile and personal transmitter/receivers in the National Forest. Its load profile is a function of the season, the weather, number of visitors/day, and other undefinables.

The backpack modules are special items to be used with portable radios. Back-country guards are often dispatched to wilderness areas for up to 2 weeks at a time. The batteries for the portable radios carried with them often become severely depleted. The small special design modules will either be carried on the guard's backpack or hung on a tree at a wilderness campsite.

The Langley drift buoy project entails building small solar cell arrays for each of three different drift buoys which will be used to trace ocean and river currents off Norfolk, Virginia. These very low profile buoys will use aluminum substrate modules and will have the arrays mounted on the deck of the buoy and in one case about 12'' above the deck. Their deployment is planned for the summer of 1974, but because their designs are being modified at the time of this writing, they are not listed in Table 1.

In addition to these system tests, the LeRC has single FEP module environmental tests in progress in cooperation with the Coast Guard and the NASA Langley Research Center. The test with the Coast Guard involves 3 aluminum substrate modules mounted about 8 feet above the water on a navigation buoy in Boston Harbor. One module is mounted on the buoy permanently. (fig. 10). Two other modules are alternately mounted on the buoy and returned to LeRC for measurements. The modules were installed on January 10, 1974. One has been returned to LeRC for examination after being on the buoy for 3 months. It showed no evidence of mechanical degradation and little evidence of salt or dirt accumulation.

A fully instrumented solar cell powered simulated RAMOS 12-volt system has been installed on a laboratory roof at the LeRC (fig. 9). This array contains both aluminum and fiberglass substrate modules. The solar cell modules were installed on the roof in early March 1974, but were not connected to the system loads until mid-April. Since then, the array has experienced three relatively severe storms with hail and winds to 67 mph. Neither the fiberglass cloth nor aluminum substrate modules have shown any mechanical or electrical degradation. This system has not been in operation long enough to yield correlation data.

Another solar cell powered simulated RAMOS 12-volt system has been built and will be installed in late May on a Coast Guard/NOAA buoy moored in the Gulf of Mexico 60 miles east of New Orleans. The array in this case consists of a single 12-volt module made up of 2 aluminum and 3 fiberglass cloth substrate modules. It will be mounted horizontally atop the buoy superstructure which will put the array about 30' above the water. In addition to the five modules making up the 12-volt module, a module has been added which contains two groups of 6 cells each. One group of cells, operating at open-circuit voltage, will be used to measure solar cell operating temperature. The other group of cells, operating at short-circuit current, will be used as an independent insolation monitor.

Three other power system projects are in various stages of completion, two for the Forest Service at the Inyo National Forest in California and one for drift buoys for the NASA Langley Research Center.

The two projects for the Inyo National Forest, shown in Table I, are power supplies for a mountain top voice repeater station and for a backpack charger for portable transmitter/receivers for Forest-Service back-country guards. The voice repeater station will
At the NASA-Langley Research Center, an aluminum substrate module was mounted flush into the top of a small styrofoam buoy which was designed so that the surface of the module would be just barely awash. The buoy was tethered between two docks in a boat slip at Langley for two weeks after which it was returned to Lewis for examination. It showed some mechanical degradation and was covered with a blotchy layer of dried slime. This module was one which used silver mesh as a cell interconnect material. During fabrication of the module, some of the ends of the cut mesh legs were bent upward and protruded through the FEP following lamination. Exposure to sea water induced corrosion of the mesh legs at these protrusion sites. The effect of the salt water continued down the mesh leg, to the cell contacts, and down the cell grid lines. FEP delamination occurred in these areas. This was the only delamination observed after this short test but points out the importance of complete encapsulation of the active module elements. This module has been returned to Langley for an additional exposure, but this time the module will be completely submerged.

Electrical measurements were taken on the same day of both the Coast Guard buoy and Langley buoy modules after their initial salt water exposures. The modules were measured in an as-received condition, after a fresh deionized water rinse, and after a wash (rubbing a finger over the FEP) and rinse. The results of these measurements are shown in Table IV. Considering the differences in appearance in the as-received condition of the two modules, it is interesting to note that the Langley buoy module does not show significantly lower current output. The meaning of the approximate 2.5% loss in short-circuit current for both modules cannot be assessed at this time since this difference is near the level of reproducibility of short-circuit current measurements. Longer exposures in the ocean environment are necessary to establish whether or not electrical degradation is occurring.

### Table IV

**Output of FEP-Encapsulated Modules After Exposure to Marine Environment**

<table>
<thead>
<tr>
<th>Short-Circuit Current, 10 R-Load Current, MA</th>
<th>Coast Guard Buoy</th>
<th>NASA Langley Buoy</th>
<th>Coast Guard Buoy</th>
<th>NASA Langley Buoy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-Exposure</td>
<td>410</td>
<td>417</td>
<td>366</td>
<td>365</td>
</tr>
<tr>
<td>As-Received</td>
<td>395</td>
<td>385</td>
<td>360</td>
<td>355</td>
</tr>
<tr>
<td>Post-Rinse</td>
<td>397</td>
<td>390</td>
<td>363</td>
<td>360</td>
</tr>
<tr>
<td>Post-Wash</td>
<td>399</td>
<td>406</td>
<td>366</td>
<td>368</td>
</tr>
</tbody>
</table>

**Exposure Periods:**
- Coast Guard Buoy, 3 months
- NASA-Langley Buoy, 2 weeks

### Conclusions

The Solar Cell Branch at the NASA-LeRC has designed, built, and installed three terrestrial solar cell power systems using FEP encapsulated solar cell modules. Additional systems are being completed for installation during the summer of 1974. Results from 6 months of operation in Sterling, VA indicate that the system is meeting its electrical design requirements. No mechanical degradation has been reported at the Virginia installation. Falling rime ice has damaged the array on Mammoth Mountain. A rooftop test at the LeRC is operating satisfactorily, albeit for only a short time. Results of marine environment tests on single modules have shown that the electrically active elements of the module must be completely sealed by the FEP. Interconnect protrusions through the FEP or cuts in the FEP which allow salt water access to the electrically active components induce FEP delamination. Based on the limited test data available, the FEP encapsulated solar cell module appears well suited to terrestrial applications.

### References