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

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USED IN TERRESTRIAL APPLICATIONS

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

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SUMMARY

The Lewis Research Center has been actively engaged in transferring the FEP encapsulated solar cell technology developed for the space program to terrestrial applications. FEP encapsulated solar cell modules and arrays have been designed and built expressly for terrestrial applications. Solar cell power systems have been installed at three different land sites, while individual 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 corrected. The results confirm the inherent utility of FEP encapsulated terrestrial solar cell systems.

INTRODUCTION

Photovoltaic power systems for terrestrial applications 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 solar 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 terrestrial applications to encourage and stimulate expansion 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 Oceanographic and Atmospheric Administration (NOAA) requested that we support them in the design, fabrication and installation of a solar cell power supply for their Remote Automatic Meteorological Observation Stations (RAMOS). Similar arrangements were made with other government 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. Batteries 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 budgeting of the energy requirements of the load and a good estimate of the sunshine available. For most applications the load profile can be easily defined. The 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 generate enough ampere-hours to satisfy the total annual load requirements, including battery charging inefficiencies. 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 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 better definition of battery requirements and losses. The daytime continuous load is generally assumed to be supplied 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 inclination 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 application.

System sizing combines the compilations of the load requirements and the solar cell outputs to determine the number of solar cells, the optimum array inclination 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 independent function of battery charging voltage and maximum solar cell operating temperature.

The optimum inclination angle is not just a function 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 gasing 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.

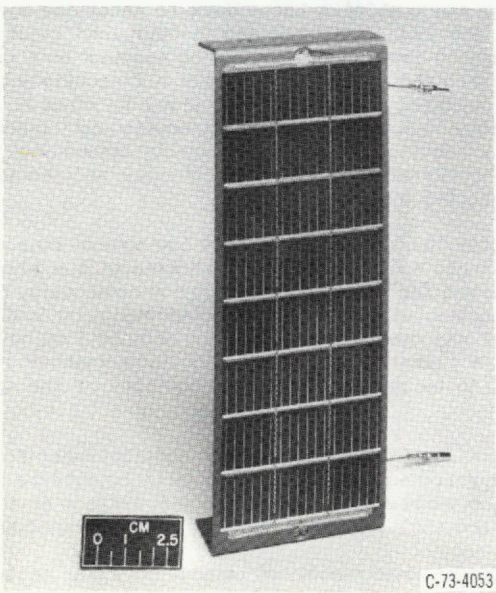

Fig. 1 - A 1-watt aluminum substrate FEP encapsulated module

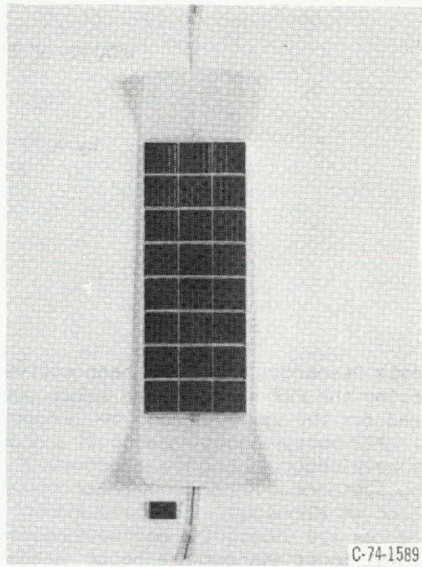

Fig. 2 - A 1-watt fiberglass cloth substrate FEP encapsulated module

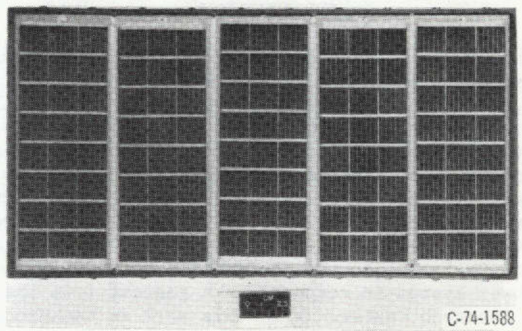

Fig. 3 - A 12-volt module of five 1-watt FEP encapsulated modules

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).

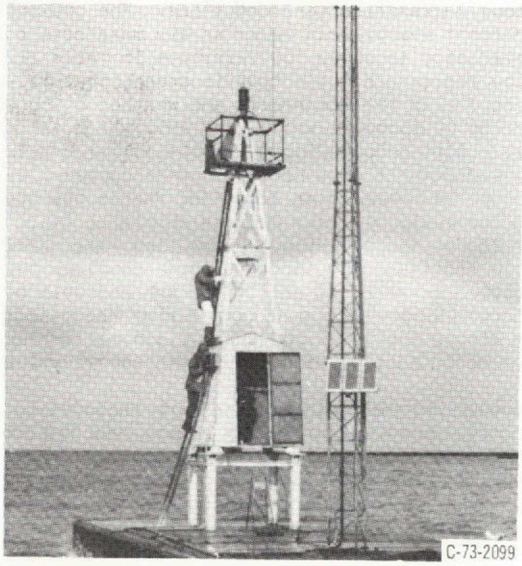

Fig. 4a - Solar cell array powered weather station at Cleveland lakefront

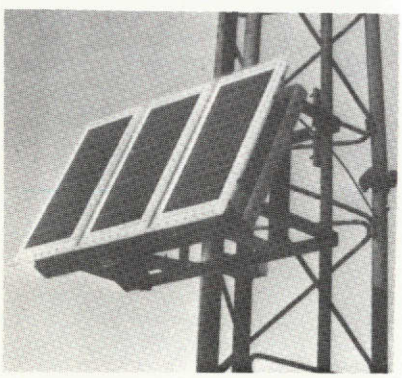

Fig. 4b - Lucite covered solar cell array at Cleveland lakefront

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.

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

NAME AND LOCATION	DATE INSTALLED	VOLTS	CURRENT		NO. OF 1-WATT MODULES	BATTERY CAPAC.
			CONTIN.	PERIODIC		
RAMOS, MAMMOTH MTN, CA	NOV 1973	12	46 mA	6.3 A, 6 SEC/HR	20*	60 AH
		24	83 mA	0.556 A, 6 SEC/HR	40*	100 AH
RAMOS, STERLING, VA	OCT 1973	12	46 mA	6.3 A, 6 SEC/HR	10	60 AH
		24	83 mA	0.556 6 SEC/HR	30	80 AH
NOAA BUOY, GULF OF MEXICO	JUN 1974+	12	24 mA	2.35 A, 6 SEC/HR	5	40 AH
REPEATER INYO NAT'L FOREST	JUL 1974+	8.5	20 mA	1.9 A VARIABLE	16	45 AH
BACK-PACK, INYO NAT'L FOREST	JUL 1974+	13	25 mA	0.31 A, VARIABLE	SPECIAL DESIGN	1 AH
NASA-LEWIS ROOF, OHIO	APR 1974	12	39 mA	3.31 A, 6 SEC/HR	10	40 AH

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

+PLANNED

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.

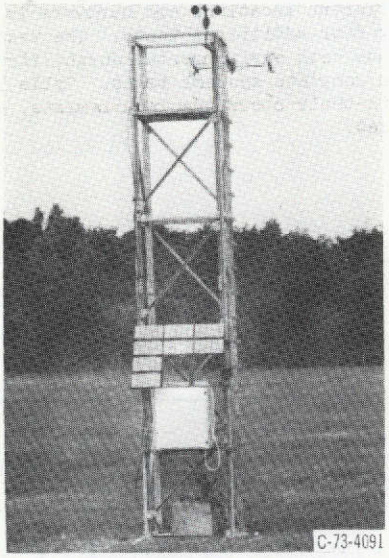

Fig. 5 - Solar cell powered RAMOS Weather Station, Sterling, VA.

TABLE II

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

DATE	SHORT-CIRCUIT CURRENT MA		SKY CONDITIONS
	12-V ARRAY	24-V ARRAY	
OCT 11, 1973	123	183	OVERCAST
NOV 8, 1973	82	122	OVERCAST
DEC 6, 1973	560	850	CLEAR, SCATTERED CLOUDS
JAN 3, 1974	8	12	OVERCAST, DARK CLOUDS
FEB 1, 1974	360	470	OVERCAST, BREAKS IN DARK CLOUDS
MAR 7, 1974	380	470	OVERCAST, DARK CLOUDS
APR 13, 1974	355	600	HIGH, THIN OVERCAST
	840	1260	AIR MASS ZERO SOLAR SIMULATOR

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 (AMO) simulator is shown for reference in Table II. The AMO value represents the output in space, that is, with no losses due to the atmosphere and weather. The December current measurement was 67% of AMO, 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.

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 11053-foot-high peak, it has experienced winds in excess of 92 mph and severe rime ice 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).

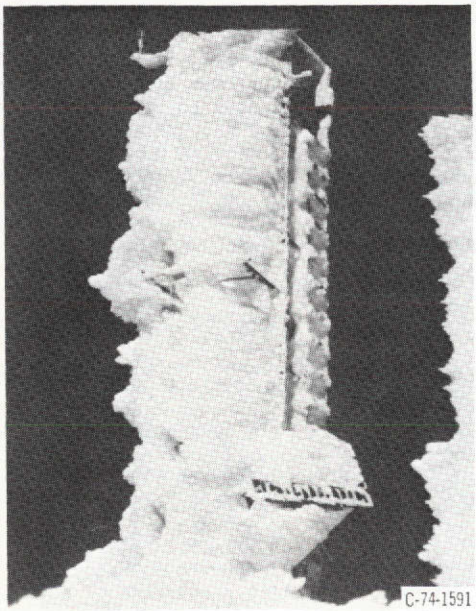

Fig. 7 - Mammoth Mountain Installation following a winter ice storm.

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 out 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 coulombmeter 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.

Fig. 8 - Detail of rime ice build up on Mammoth Mountain array.

TABLE III

SHORT-CIRCUIT CURRENT READINGS OF RAMOS SYSTEM ON MAMMOTH MOUNTAIN, CALIFORNIA

DATE	SHORT-CIRCUIT CURRENT MA		SKY CONDITIONS
	12-V ARRAY	24-V ARRAY	
NOV 4, 1973	1610	1556	CLEAR, VERY THIN CLOUDS
DEC 19, 1973	1568	1482	CLEAR
JAN 24, 1974	1100	1100	CLEAR (SOME ICE ON ARRAY)
JAN 29, 1974	320	320	OVERCAST
FEB 14, 1974	600	600	OVERCAST
MAY 3, 1974	465	1005	CLEAR
	1680	1680	AIR MASS ZERO SOLAR SIMULATOR

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.

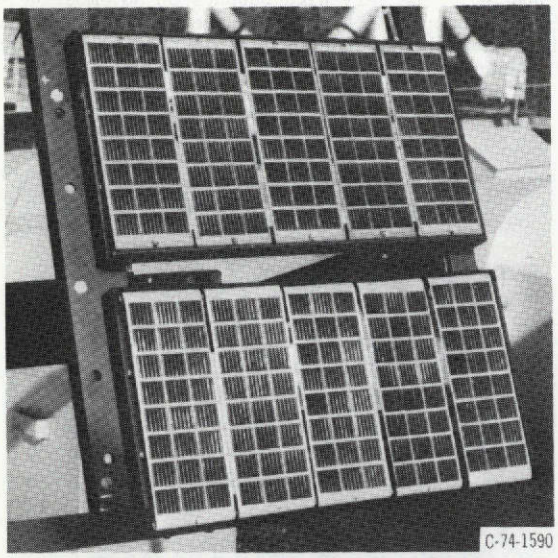

Fig. 9 - Solar cell power system experiment on NASA-LeRC laboratory roof. Upper 12-volt module contains aluminum substrate modules. Lower 12-volt module contains fiberglass cloth substrate modules.

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 is 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 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 co-operation 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.

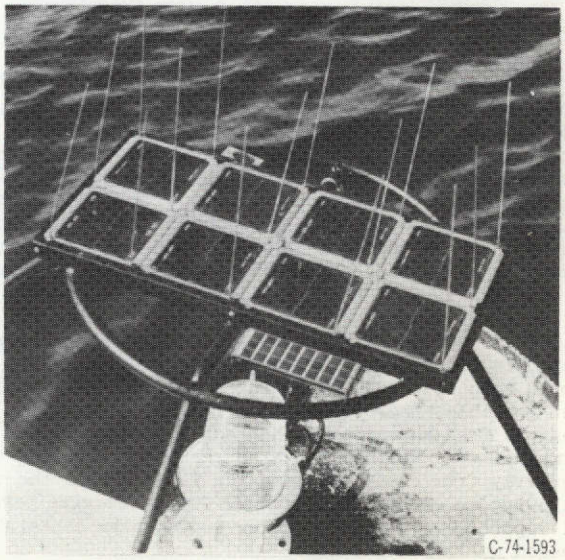

Fig. 10 - A 1-watt FEP encapsulated module mounted on a Coast Guard Buoy, Boston Harbor, Massachusetts.

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 shown 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

	SHORT-CIRCUIT CURRENT, MA		10 Ω-LOAD CURRENT, MA	
	COAST GUARD BUOY	NASA-LANGLEY BUOY	COAST GUARD BUOY	NASA-LANGLEY BUOY
PRE-EXPOSURE	410	417	366	365
AS-RECEIVED	395	385	360	355
POST-RINSE	397	390	363	360
POST-WASH	399	406	366	368
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.

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