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FINAL RESULTS OF THE ADVANCED PHOTOVOLTAIC EXPERIMENT FLIGHT TEST

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ABSTRACT

The Advanced Photovoltaic Experiment was designed to generate laboratory reference standards as well as to explore the durability of a wide variety of space solar cells. In addition to the cells, it was equipped with an absolute cavity radiometer to measure solar intensity, a spectroradiometer to measure the spectral content of this radiation and a sun angle sensor. Data from the solar cells and various sensors was obtained on a daily basis during the first eleven months of the 69 month flight. In this paper we compare pre-flight and post-flight laboratory measurements with on-orbit calibration data. Pre-flight and post-flight calibration data of the cavity radiometer as well as on-orbit data demonstrated the accuracy and durability of the Eppley instrument flown on APEX.

INTRODUCTION AND EXPERIMENT DESCRIPTION

The Advanced Photovoltaic Experiment (APEX) is a space flight test designed to provide reference cell standards for laboratory photovoltaic performance measurements as well as to investigate the solar spectrum and the effect of long term exposure of solar cells to the space environment. Toward this end, 155 solar cells of the widest available variety of designs and materials were incorporated into the experiment along with sensors to measure total solar irradiance and sun angle. Experimental measurements were made on a daily basis, dependent upon the achievement of proper sun angles, and recorded on an on-board magnetic tape recorder. The experiment was designed around the original flight time of one year, with battery capacity the principal lifetime limiting factor. Useful data was, in fact, obtained for 325 days, at which time the voltage of the batteries supplying the data acquisition system fell below the threshold necessary for calibrated operation. Details of the design and operation of APEX have been previously published [1,2].

When the announcement of opportunity for LDEF experiments was released in 1976, a launch in 1980 was envisioned. As a result, the solar cell samples prepared for APEX represented the state-of-the-art in space cell technology as of 1979, as well as samples of cells in use on a variety of satellites. A Shuttle-caused delay in the launch of LDEF by several years provided both the opportunity and necessity for updating the sample set, to one including the most recent advances in technology. The cell investigators were invited in mid-1982 to submit new cells. Of the 136 calibration cells (120 Isc and 16 IV cells), 69 were replaced. Many of those which were not replaced were either standards previously calibrated by other techniques or representative of cells in use on a variety of satellites. These APEX solar cell investigators and the number of cells each supplied are:

A.F. Wright Aeronautical Laboratory	8
Applied Solar Energy Corporation	14
COMSAT Laboratories	7
European Space Agency	9
Jet Propulsion Laboratory	34
NASA Lewis Research Center	56
NASA Marshall Space Flight Center	11
Solarex Corporation	7
Spectrolab, Inc.	9

Each group provided cells representative of technologies which were either in development or production. The experiment was designed to accommodate a total of 155 such cells, including the silicon cells which were employed as sensors for the spectral radiometer portion of the experiment. All cells were permanently mounted on aluminum plates with a thermistor in contact with the rear of the cell. 139 cells were designated as Isc cells, 120 to be calibrated as reference standards and returned to the investigators, eighteen for use as spectral radiometer sensors and one as a night sensor to signal the data acquisition system that conditions were correct for the requisite periodic calibration of the cavity radiometer. For these cells, the short-circuit current was converted to a voltage through the use of a precision load resistor. In most cases a 0.1 Ω value was used. The remaining sixteen cells were designated IV cells, that is the entire current - voltage characteristic was measured through the loading of the cell by a series of five appropriately sized resistors.

At that time, only silicon cells were in production, with the development of gallium arsenide in its early stages.

This is reflected in the distribution of these semiconductor types in the APEX complement, which is summarized by cell type and size below:

Si:	105	2 x 2 cm	GaAs: 10	2 x 2 cm
	21	2 x 4 cm	1	1.3 x 1.6 cm
	2	5 x 5 cm	11	
	15	5.9 x 5.9 cm		
	1	6 x 6 cm (module)		
	144			

The cells were mounted on 127 aluminum plates of twelve different sizes and configurations. 28 of the mounts each held two 2 x 2 cm cells. Each mount was equipped with a Yellow Springs Instruments Type 16429 thermistor (10,000 Ω @ 25 °C). An additional thermistor monitored the Eppley absolute cavity radiometer.

SENSOR RESULTS

A detailed examination and recalibration of the various sensors and instruments on APEX was performed. The Eppley Type HF absolute cavity radiometer was of particular interest in that it is the only radiometer ever returned from an extended stay in space. It is identical to an instrument that has provided over 12 years of data as part of the Earth Radiation Budget experiment on Nimbus 7. After detailed examination at the Eppley Laboratories, it was compared with standards at the World Radiation Center in Davos, Switzerland [3]. As seen in Table I, the 69 months in-orbit had little effect on the radiometer. Its sensitivity was essentially unchanged, as was the its reflectance, in agreement with the results of visual inspections.

A spectroradiometer was included in APEX to measure the spectral content of the extraterrestrial sunlight. After return, it was intended that the instrument be used for calibration of laboratory solar simulators. The spectroradiometer consisted of sixteen identical silicon cells with narrow bandpass optical filters. The wavelength center of the filters ranged from 325 to 1100 nm, with the last filter covering the infrared out to 2000 nm. Figure 1 compares values of solar irradiance from the APEX flight data with the World Meteorological Organization (WMO) standard. A comparison of pre-flight and post-flight transmittance of the first thirteen filters is seen in Figure 2. The drastic change in transmittance in many filters is clearly seen, although there was no major shift in wavelength band. This degradation was, of course, unexpected and has made the instrument unsuitable for further use in the laboratory. An explanation of the effect or its probable cause has not been forthcoming from the filter manufacturer [4].

Table I Cavity Radiometer Tests

	Pre-Flight	Post-Flight	Δ, %
Heater Resist.(Ω)	152.2	152.2	0.00
Thermopile Res. (Ω)	354.4	354.7	0.08
Power Sensitivity (V/W)			
Atmosphere	0.02134	0.02084	-2.34
Vacuum	0.02592	0.02527	-2.51
Ratio, Vac/Atm	1.2146	1.2126	-0.16
Intercomparison with World Radiation Reference			
APEX Instrument		1.00069	
Eppley Reference Instrument		1.00002	
Reflectance Measurement			
APEX Instrument	250±80 ppm		
New Eppley Cavity	270±80 ppm		

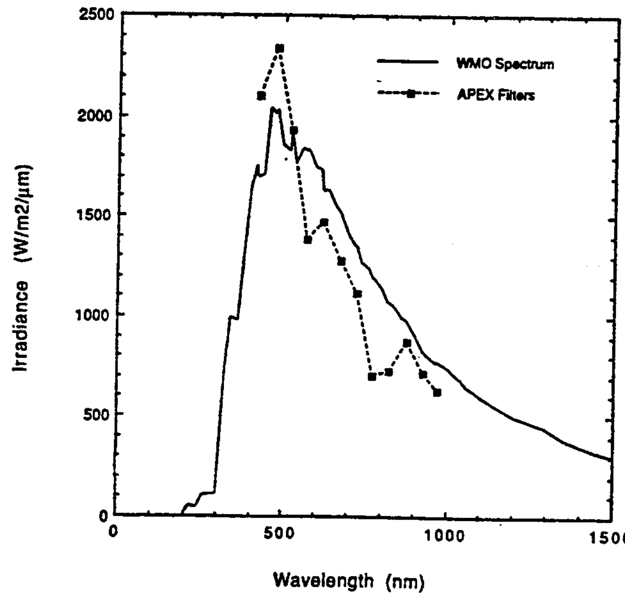

Fig. 1. APEX Spectroradiometer data compared with WMO spectrum.

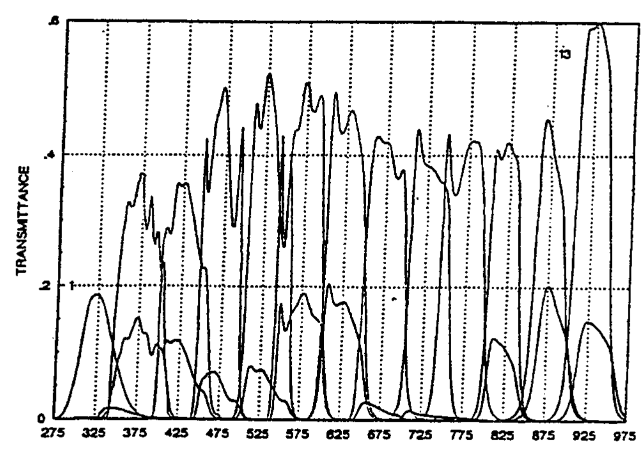

Fig. 2. Pre- and post-flight transmittance of UV-Visible filters.

SOLAR CELL RESULTS

The overall condition of the cell sample set was excellent. A contaminating film seen over much of LDEF was present to a varying degree on APEX, the thickness of the layer dependent upon location. No loss of cell coverglass nor significant changes in color or appearance was observed. Several of the cells were cratered from micrometeoroid and/or debris impacts, with the range of damage spanning from microscopic craters in the coverglass surface to penetration of the coverglass and cell and cratering of the underlying aluminum mounting plate. However, even the few cells in which the cratering extended into the solar cell itself, or caused a crack in the coverglass and cell, electrical continuity was maintained. Loss in current proportional to the damage area and decrease in fill factor due to cell cracking was observed. The electrical leads from the mounting plate feedthrough to the cell front and rear contacts were found to open in six cells. A silver ribbon of about 3 mil thickness was used for these cells. Where the flat portion of the ribbon faced the ram direction, the ribbon was severely eroded, creating an open circuit. In most cases the ribbon twisted through 90° at the feedthrough so that the narrow (3 mil) edge faced the ram direction; here the silver ribbon remained intact. Examination of the flight data indicates that the erosion did not occur to any extent that would affect cell performance during the data recording portion of the flight, the first eleven months. Post-flight performance testing of these cells was accomplished by direct probing of the cell contacts, no significant change from pre-flight performance was seen.

The first post-flight electrical test performed was measurement of the short-circuit current utilizing the precision load resistor mounted on each cell for the flight. The resistors were soldered to the cell mounting plate electrical feedthroughs on the underside of the cell mounting plates. These measurements, as well as subsequent current-voltage (I-V) tests, were carried out in the Solar Cell Evaluation Laboratory at Lewis Research Center using a Spectrolab X-25L solar simulator. This simulator employs a short-arc xenon lamp as the light source and provides uniform, collimated illumination. The intensity of the simulator was set using an aircraft calibrated silicon standard which is identical to the standard used at Eppley Laboratory for pre-flight testing, where a xenon arc lamp simulator was also utilized. Cell temperature was monitored using the flight thermistors. One thermistor was found to be open. An examination of the flight data showed abnormal readings from it, indicating that the failure occurred before launch. With this sole exception, all of the thermistors functioned properly, providing values in close agreement with a temperature sensor used in controlling the laboratory test fixture. The short-circuit current values obtained in these test are useful in comparison with both pre-flight performance and flight data. The values obtained were in most cases in good agreement with pre-flight values, with the exception of those cells without a coverglass.

Upon completion of the measurement of short-circuit current, the load resistor was removed from the circuit by cutting one of its two leads. If LDEF had been retrieved on schedule and the value of the cells as calibration standards was retained, the load resistors could not have been removed. However, the absence of data from the last five years on-orbit negates their usefulness as standards. The complete I-V characteristic of all cells were then measured at 25 °C and recorded. Table II compares flight data with pre- and post-flight simulator data for a small representative sampling of the silicon cells. All data presented here is corrected to 25 °C and one AM0 sun (136.7 mW/cm^2). All of these cells are n-p type, as were most of the silicon cells flown. Also included is the value of short-circuit current as measured on-orbit.

The loss in voltage and current in the unglassed cells (cells ISC 63 and ISC 83) was consistent with the proton radiation flux of the 250 nm, 28° inclination orbit. The variation in pre-flight to post-flight Isc for the last four cells of Table II is typical of the entire cells set; the variation

Table II Silicon Cell Results

Cell Number		Description	Coverglass	Short-Circuit Current (mA)		
				Pre-Flight	Flight	Post-Flight
ISC 63	NA-10	Solarex, BSR/BSF	No Cover	146.9	144.6	133.5 (ΔVoc = - 65 mV)
ISC 83	B-21R	LeRC Aircraft Standard	No Cover	150.1	152.0	145.4 (ΔVoc = - 46 mV)
ISC 86	B2SOF	COMSAT, Intelsat 5	6 mil Fused Silica	288.2	300.9	292.3
ISC 95	M-5	ASEC, Large Area W//A	6 mil Fused Silica	1199.0	881.3	1195.0
ISC 112	B-2R	COMSAT Blue Response	30 mil V-groove	160.0	178.6	163.7
ISC 114	B-4R	COMSAT Non-Reflecting	12 mil Fused Silica	193.1	202.7	189.3

was within about ±2% It is believed that this variation was due to inherent differences is the LeRC simulator and data acquisition system used for post-flight testing and those at Eppley Labs used for pre-flight testing. Pre-flight testing was not performed at LeRC as it was expected that the APEX cells would be used as calibrated reference cells; the evolution of the experiment into a long term durability test was neither expected nor ever contemplated. The I-V characteristic of 16 cells was measured by first recording the open-circuit voltage and then switching in five load resistors and recording cell current and voltage for each. The excellent agreement of the on-orbit I-V data (black squares) with the post-flight laboratory data of a Solar Maximum Mission cell in shown (Figure 3).

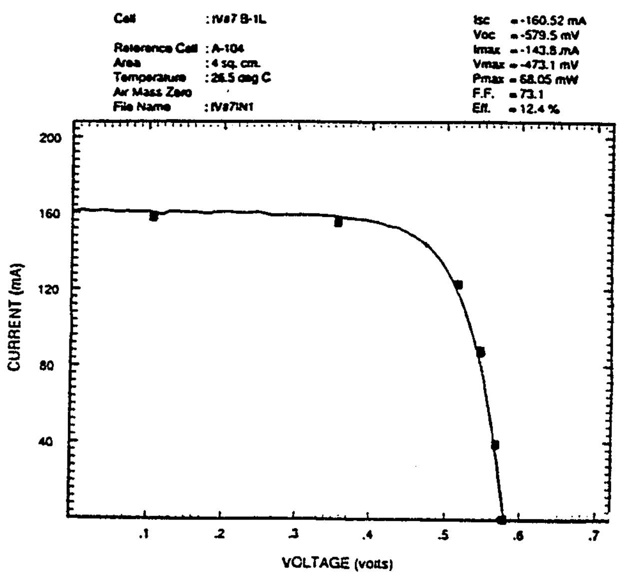

Fig. 3. I-V curve of Solar Maximum Mission cell.

A summary of results from GaAs cells is shown in Table III. Of the eleven GaAs cells flown, ten were made by Hughes Research Laboratory using liquid phase epitaxy, the only type of GaAs cells then available. These cells had junction depths of either 0.35 µm or 0.50 µm and were flown with either a 12 mil fused silica coverglass or unglassed. The performance degradation, particularly in open-circuit voltage, of the uncovered cells is consistent with the known radiation characteristics of these cells and the mostly proton flux of the orbit. The eleventh GaAs cell was a metal-oxide-semiconductor design which was under study at that time as a low fabrication cost alternative to epitaxial growth for III-V compounds. It has a very thick coverglass of unknown thickness and material and degraded significantly in short-circuit current. The accuracy of the pre-flight Isc value is suspect.

Detailed discussion of other cells in the set, particularly those which sustained physical damage from micrometeoroids/debris, can be found in ref. 2 and 5.

CONCLUSION

The solar cells and sensors flown on APEX survived well their nearly six years in low earth orbit. Post-flight testing of the Eppley cavity radiometer shows that it is essential unchanged from its pre-flight condition. The solar cell set survived equally well, with no evidence of electrical or physical changes except in those cases where debris or micrometeoroids cratered the cells. Pre-flight and post-flight performance measurements are in good agreement.

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Table III Gallium Arsenide Cell Results

Cell Number	Description	Coverglass	Short-Circuit Current (mA) Pre-Flight	Flight	Post-Flight
ISC 71 NB-15L	Hughes, Dj = 0.5 µm	12 mil Fused Silica	122.5	116.1	108.0 (ΔVoc = + 10 mV)
ISC 76 NB-29R	HRL, Dj = 0.5 µm	No Cover	117.2	111.6	95.5 (ΔVoc = - 65 mV)
ISC 77 NB-29L	HRL, Dj = 0.35 µm	No Cover	117.3	113.1	93.6 (ΔVoc = - 85 mV)
ISC 111 A-2	JPL, AMOS	Unknown	17.6	33.6	22.0

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