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THE EFFECT OF SUNSHINE TESTING ON TERRESTRIAL SOLAR CELL SYSTEM COMPONENTS

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SUMMARY

FEP encapsulated solar cell samples similar to those used in field applications and transmission samples of FEP, Tedlar, Aclar, and Lexan are being exposed to accelerated sunshine testing and real time testing. The accelerated test gives approximately 8 years of normal exposure time in 1 year. The change in maximum power of the solar cell samples after 7 months of accelerated sunshine exposure (equivalent to almost 5 yr normal exposure) is not significant enough to indicate any major problems due to darkening of the FEP. The tests, however, did reveal some problem areas in the structural integrity of the samples, for example, FEP delamination and cracking. These problem areas are believed to be related to problems in the fabrication of the samples. For the transmission samples, FEP and Aclar have the least loss in transmission after accelerated exposure equivalent to almost 5 and 3 years, respectively.

INTRODUCTION

One of the questions always asked when a solar cell system is designed for terrestrial applications is "How long will it last?" Real time tests are excellent for evaluation purposes, however, it takes a long time to evaluate long lifetime systems. Accelerated sunshine testing has been used as one means to decrease testing time. In this investigation, samples of FEP encapsulated silicon solar cells and various potential encapsulation or cover materials were subjected to both accelerated and real time testing. The testing period was from August 1974 to March 1975 and testing was carried on in the southwestern United States. By measuring changes in solar cell output or optical transmission as a function of exposure the durability of the samples was evaluated.

EQUIPMENT AND TESTS

Real time tests were conducted near Phoenix, Arizona with the samples mounted on a stationary rack tilted at 45° to the horizontal and facing south. FEP encapsulated silicon solar cells and transmission samples of FEP, Tedlar, Aclar, and Lexan were exposed. A calibrated pyranometer set at 45° facing south is used to measure solar insolation. The output of the pyranometer is integrated to give the exposure in langleys.

Similar samples to those exposed on the 45° south racks were tested under concentrated sunshine using a machine with an Equatorial Mount with Mirrors for Acceleration plus a water spray (EMMAQUA*). The accelerating machine is a follow-the-sun rack with 10 mirrors for concentrating the sunlight onto the samples. The 10 mirrors shown in Fig. 1 reflect from 70 to 80 percent of the ultraviolet radiation and about 85 percent of the total. Each machine has a guidance system which keeps the mirrors facing the sun at 90°. Blowers on each machine cool the samples with air so that their surface temperatures are about 10° higher than those being exposed on the stationary racks at 45° facing south. The machine's axis is oriented in the north-south direction and the machines were operated only during periods of bright sunshine to insure a good all-wavelength mix in the radiation. The samples were sprayed for 8 minutes out of each hour of operation with distilled water. A normal incidence pyrheliometer (NIP) is used to measure intensity. This data is then integrated and multiplied by a concentration factor (previously determined) to give NIP langleys. The yearly total exposure on an accelerating machine is about eight times as great as on the stationary racks at 45° facing south. However, it is necessary to realize that the time of year that samples are exposed is an important factor. The amount of ultraviolet radiation below 0.4 μm is significantly greater in the summer months than in the winter months.

The transmission samples used in all the tests were prepared from commercially available materials and were cut into strips 1 by 5 inches in size. The 5-inch dimension was chosen to be compatible with the test plane. A description of the transmission samples is given in Table I(a). The FEP samples were made of two 125-μm thick layers of FEP type A laminated together to simulate FEP as used on solar cell samples. Some samples were made using Kapton as a release material during lamination to produce a glossy surface. Others used skived Teflon (TFE) to produce a matte surface. Three different types of Tedlar were tested. Type 100BG30UT and type 200SG40TR are typical commercially available materials. Type 400XRB145TR was specially chosen for this test because of its optical and laminating properties. All solar cell samples were encapsulated in FEP (1) and were prepared in two different sizes and with two different substrates. The sizes are either 1 by 5 inches or 3 by 5 inches. The cells are connected five in series for the 1-inch wide samples and five in series, three in parallel for the 3-inch wide samples. The substrate is either anodized aluminum or woven fiberglass cloth impregnated with FEP. A description of the solar cell samples is given in Table I(b).

The optical transmission was measured with a Cary model 14 spectrophotometer. Measurements were made in the visible spectrum (0.35 to 0.7 μm) since past experience

*EMMAQUA - Trademark of Desert Sunshine Exposure Tests, Inc., Phoenix, Arizona.

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had indicated that only minor changes were usually observed in plastic materials above 0.7 μm. A closely filtered high pressure xenon solar simulator was used to measure current-voltage curves of the solar cell samples. The spectrum was closely matched to AMO and the samples were at $25^{\circ} \pm 2^{\circ}$ C during measurements.

RESULTS AND DISCUSSION

Real Time Tests

Optical transmission. - Percent transmission versus wavelength curves of the transmission samples, taken before and after exposure, were compared. The results are described below and summarized in Table II. Measurement error is ±2 percent. Maximum exposure time on the samples varied because of different test starting dates.

FEP samples. - After exposure to 107 922 langleys (7 months, starting in August 1974) there was no change in the transmission of the FEP samples. The results in Table II are an average of three samples, two with a glossy surface finish and one with a matte surface finish.

Tedlar samples. - Type 100 Tedlar was exposed for 7 months (107 922 langleys) and showed a transmission loss of about 5 to 9 percent. Type 200 was begun on tests later and was exposed for only 2 months (36 545 langleys). The transmission loss for this sample was between 2 and 7 percent. Two samples of type 400 were unchanged within measurement error after 7 months exposure (107 922 langleys) except for a $4\frac{1}{2}$-percent loss in the ultraviolet region (0.35 μm).

Aclar sample. - One sample was exposed for 4 months (59 048 langleys) and remained unchanged within measurement error of about ±2 percent.

Lexan sample. - This sample was exposed for 5 months (71 377 langleys) and showed no change in transmission above 0.5 μm. There was, however, a loss in transmission in the ultraviolet region as seen in Table II. At 0.4 μm the loss was 17 percent and at 0.35 μm the loss was 21 percent.

Solar cell samples. - Table III summarizes the real time exposure test results for the FEP encapsulated solar cells. These solar cell samples show a change in maximum power of between +1 percent and -5 percent after 7 months exposure (107 922 langleys). Variations of about ±2 percent can be expected due to measurement errors. The average change in maximum power suggests that the aluminum substrate samples degrade more than the fiberglass substrate samples. Minor delamination was observed in all samples that experienced a power loss. For all 10 solar cell samples the change in short circuit current was within the ±2 percent measurement error and therefore not considered significant.

Accelerated Tests

The accelerated testing of samples began in August 1974. Some of the samples remained on test since that date and other samples were removed periodically and either replaced with new samples or returned for further exposure after measurements were made.

Optical transmission. - Percent transmission versus wavelength curves of the transmission samples were taken before initial exposure and whenever the samples were removed and returned. Since the testing was done in a sandy region and there were some windy days throughout the test period, samples showed fine scratches on the surface after exposure. These scratches produced a translucent appearance in the samples and tended to scatter the light and contribute to the transmission loss. This transmission loss, however, may not be evident in the solar cell samples since the solar cells can collect the scattered light. The following results are summarized in table IV.

FEP samples. - The sample exposed for 7 months (905 900 langleys) showed a transmission loss varying from 2.6 percent at 0.7 μm to 5.5 percent at 0.35 μm. Samples measured after 5 months exposure (683 200 langleys) indicate that most of the loss had already occurred by then. These results are characteristic for this type of test with plastic materials. Initially there is a high rate of degradation followed by a tapering off and finally a saturation effect. The surface finish did not affect the transmission loss.

Tedlar samples. - Type 100 and type 200 samples were exposed for 2 months (346 200 langleys). Their transmission loss is shown in Table IV. Type 400 was exposed to accelerated sunshine for the entire test period. Two samples were tested. One had 2 months exposure (346 200 langleys) and the other had 7 months exposure (905 900 langleys). The latter sample showed a transmission loss of about 10 percent throughout the measured spectrum, from 0.35 to 0.7 μm.

Aclar samples. - One Aclar sample showed a transmission loss of between 4 and 8 percent after 4 months exposure (461 400 langleys). The larger losses occurred in the ultraviolet region of the spectrum. One other sample was accidently torn before measurements could be made.

Lexan sample. - Two samples of Lexan were exposed for 4 months (435 300 langleys). A definite brown color was observed on these samples. The transmission loss for these samples averaged about 13 percent at 0.7 μm and increased to about 85 percent at 0.35 μm. The maximum difference in observed transmission loss between the two samples was about 6 percent.

Solar cell samples. - Exposure of FEP encapsulated solar cell samples varied between 161 600 and 905 900 langleys. The maximum exposure of 905 900 langleys on the accelerated test is equivalent to almost 5 years of exposure on the real time test at 45° facing south. Current-voltage curves made before and after exposure show a change in maximum power of between +2 percent and -5 percent (Fig. 2). These results are not substantially different from those on the real time test. Again, changes in short circuit (generally less than 2 percent) could not account for changes in maximum power since in some cases where power decreased the current increased and vice versa. A number of samples indicated some delamination but the delamination did not appear to be the cause of short circuit loss. Generally, however, the samples that delaminated exhibited a power loss. Also, the aluminum substrate samples degraded slightly more than the fiberglass substrate samples. Four control samples were kept in storage at the Lewis Research Center and not exposed to sunshine. The change in maximum power of these samples after 7 months was within the measurement accuracy. These results are shown on the zero exposure line of Fig. 2. The samples shown at 107 922 langleys exposure are those from the real time test.

Of nine samples that were removed, measured, and put back on test, six increased in maximum power and three decreased in maximum power. Short circuit current changes did not correlate with maximum power changes. These nine samples are identified in Fig. 2 by small case letters next to the data points.

Photographs taken before the solar cell samples were removed for the last measurement indicated delamination was occurring. On examination at the Lewis Research Center, the samples showed that delamination was taking place primarily at the interconnect areas and along the sample edges. Cracking of the FEP in these areas was also observed and is shown in Figs. 3 to 5. Figure 3 shows cracking along one edge of the solar cell. As a result of the lamination process the FEP is thinner in this region. It is believed that the cracking occurs as a result of high stresses in the thinner FEP. Figure 4 shows cracking of the FEP above the cell interconnect. It is known from stress analysis of the laminated structure that a region of high stress occurs at the edge of the interconnect and can cause fatigue of the FEP after severe temperature cycling (2). Figure 5 shows another sample with cracked FEP at the cell interconnect. In addition the light circular spot in the center shows delamination.

Although the delamination and cracking did not seriously affect the cell output in this test, such exposure of the cell to the elements is expected to result eventually in substantial reduction in cell output. Previous experience (3) with similarly encapsulated cells did not show such failures after exposure to the natural environment for over 2 years. Investigation of the fabrication process used for the present samples revealed that the adhesion promoter had become contaminated. The resulting poor bond led to delamination and to high local stresses that caused the cracking. Proper storage of the adhesion promoter and some other revisions to the fabrication process are expected to eliminate the problems. The accelerated tests proved to be a valuable method to disclose the problems quickly.

The major objectives of the accelerated tests are to save time, reduce costs, and also to correlate with results of real time tests. For the transmission samples there is no disagreement in the results of the two types of tests. However, there has been no overlap in the exposure yet and more real time testing is needed to confirm the results. For the solar cell samples the correlation of power loss was confused by delamination of the samples. However, there was correlation to the degree that delamination occurred in samples on both real time and accelerated tests.

CONCLUSIONS

FEP encapsulated solar cell samples and possible cover or encapsulation materials were exposed for 7 months in a real time test and for an equivalent exposure of almost 5 years in an accelerated sunshine test. The results show that

(1) FEP and Aclar perform well under these conditions. The transmission loss in FEP is not evident when the FEP is used as a solar cell encapsulant.

(2) Tedlar samples exhibit a higher transmission loss but may be suitable when used as a solar cell cover.

(3) The transmission loss in Lexan was substantially higher and does not appear to be suitable.

(4) FEP encapsulated solar cells performed well in spite of delamination and cracking of the FEP. It appears that the cause of the problems is in the fabrication process and can be remedied.

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TABLE I

SAMPLE DESCRIPTION

(a) TRANSMISSION SAMPLES

FEP TYPE A, GLOSSY SURFACE, 2-125 μM THICK LAYERS LAMINATED TOGETHER

FEP TYPE A, MATTE SURFACE, 2-125 μM THICK LAYERS LAMINATED TOGETHER

TEDLAR TYPE 100BG30UT, 25 μM THICK

TEDLAR TYPE 200SG40TR, 50 μM THICK

TEDLAR TYPE 400XRB145TR, 100 μM THICK

ACLAR TYPE 22A, 37 μM THICK

LEXAN, 0.16 CM THICK

(b) SOLAR CELL SAMPLES

ALL ENCAPSULATED IN FEP TYPE A

1 CELL BY 5 CELLS, GLOSSY SURFACE, FIBERGLASS SUBSTRATE

1 CELL BY 5 CELLS, MATTE SURFACE, FIBERGLASS SUBSTRATE

1 CELL BY 5 CELLS, GLOSSY SURFACE, ALUMINUM SUBSTRATE

1 CELL BY 5 CELLS, MATTE SURFACE, ALUMINUM SUBSTRATE

3 CELLS BY 5 CELLS, GLOSSY SURFACE, ALUMINUM SUBSTRATE

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TABLE II

CHANGE IN TRANSMISSION OF SELECTED PLASTICS AFTER EXPOSURE TO SUNSHINE AT 45 DEG TILT FACING SOUTH

LOSS IN TRANSMISSION, %

SAMPLE TYPE		TEDLAR-100	TEDLAR-200	TEDLAR-400	ACLAR	LEXAN	FEP
EXPOSURE	LANGLEYS	107 922	36 545	107 922	59 048	71 377	107 922
	MONTHS	7	2	7	4	5	7
SAMPLES		1	1	2	1	1	3
WAVELENGTH, μM							
0.7		4.9	2.3	0	0	0	0
.65		5.7	2.4	0	0	0	0
.6		6.9	2.9	0	0	0	0
.55		7.4	3.3	0	0	0	0
.5		8.1	3.5	0	0	1.5	0
.45		8.7	3.8	0	0	4.5	0
.4		8.6	4.7	0	0	17	0
.35		8.7	6.5	4.5	0	21	0

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TABLE III

CHANGE IN MAXIMUM POWER AND SHORT CIRCUIT CURRENT OF FEP ENCAPSULATED SOLAR CELLS AFTER EXPOSURE TO SUNSHINE AT 45 DEG TILT FACING SOUTH

TOTAL EXPOSURE, 107 927 LANGLEYS

	ALUMINUM SUBSTRATE		FIBERGLASS SUBSTRATE	
	ΔP_{MAX}, %	ΔSCC, %	ΔP_{MAX}, %	ΔSCC, %
	-1.4	-2.2	+1.1	-1.4
	-2.5	+1.5	+.7	-.7
	-3.1	-.7	+.4	+.8
	-5.2	-1.5	-1.5	+1.5
	-5.3	+.8	-5.1	0
AVERAGES	-3.5	-.4	-1.0	-.2

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TABLE IV

CHANGE IN TRANSMISSION OF SELECTED PLASTICS AFTER ACCELERATED SUNSHINE EXPOSURE

LOSS IN TRANSMISSION, %

SAMPLE		TEDLAR-100	TEDLAR-200	TEDLAR-400	TEDLAR-400	LEXAN	ACLAR	FEP	FEP
EXPOSURE LANGLEYS		346 200	346 200	346 200	905 900	435 400	461 400	683 200	905 900
MONTHS	ACTUAL	2	2	2	7	4	4	5	7
	EQUIV NATURAL EXPOSURE	16	16	16	56	32	32	40	56
WAVELENGTH, μM									
0.7		7.5	5.6	7.2	9.5	13	4.0	2.4	2.6
.65		8.5	5.5	8.3	9.7	14	4.0	2.5	3.0
.6		9.1	6.0	8.0	10.1	15	4.5	2.6	3.3
.55		9.7	6.2	8.0	11.3	18	4.5	2.6	3.7
.5		10.3	6.4	8.0	10.0	22	5.5	2.4	4.3
.45		10.7	6.7	7.9	10.3	30	6.5	2.0	4.7
.4		10.6	7.1	7.4	9.7	52	6.0	1.8	5.0
.35		10.0	6.8	8.5	8.1	85	7.5	0	5.5

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of 1000 is desirable for cost effectiveness although future developments may dictate the use of lower concentration or unconcentrated light. At such high intensities (1000 AM1), the series resistance of the cell, R_s, becomes a serious performance limiting parameter. Presently obtainable values of R_s in conventional cells must be reduced by about two orders of magnitude for efficient operation. This paper has examined the design considerations needed to achieve low values of R_s and concludes that for the conventional solar cell at 1000 AM1 substantial design modifications are needed to reduce R_s to such low values and these involve tradeoffs with performance or with cost or require technology advancement.

The HI cell design characteristics were also examined in this paper and it was noted that this cell has several advantages over the conventional solar cell, especially at high intensities. In addition to providing a more suitable high output voltage, having a better spectral response in the violet and infrared portions of the solar spectrum, and needing no ohmic back contact, the HI cell has the further demonstrated or expected major advantages that: 1) its series resistance has nosheet resistance components, 2) R_s decreases with increasing intensity due to conductivity modulation, 3) a much higher value of R_s is tolerable due to a lower peak power current, 4) acceptable values of R_s are obtainable by using high resistivity, high carrier lifetime material, 5) it has better thermal characteristics and can more easily be provided with reflecting back surface, 6) it has better cost breakdown features and will require fewer new plant outlays for high level power output production and 7) it has a better energy payback ratio than a conventional cell operating under unconcentrated light.

Although much additional work remains to be performed on improving HI cell efficiencies and on demonstrating the performance and economics of a HI cell solar system operating at 1000 AM1 at $\eta \geq 10\%$, it appears that residential sized HIS systems should be possible for less than $1000/KWe with substantial amounts of thermal energy being available for heating and cooling of houses. It appears that the HI cell and the HIS system are worthy of further research and development effort and with such effort, they may perhaps become the key to low cost terrestrial photovoltaic power generation.

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Figure 1. - Emmaqua accelerated testing machine.

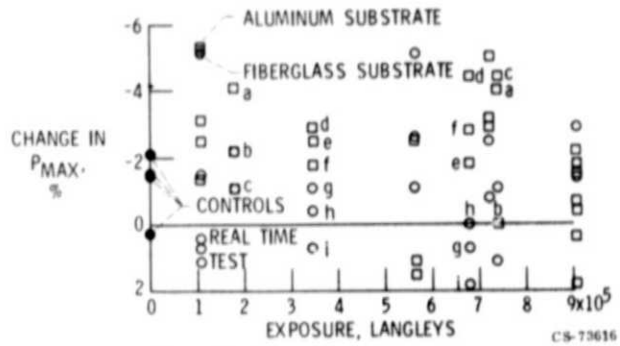

Figure 2. - Change in maximum power as function of sunshine exposure.

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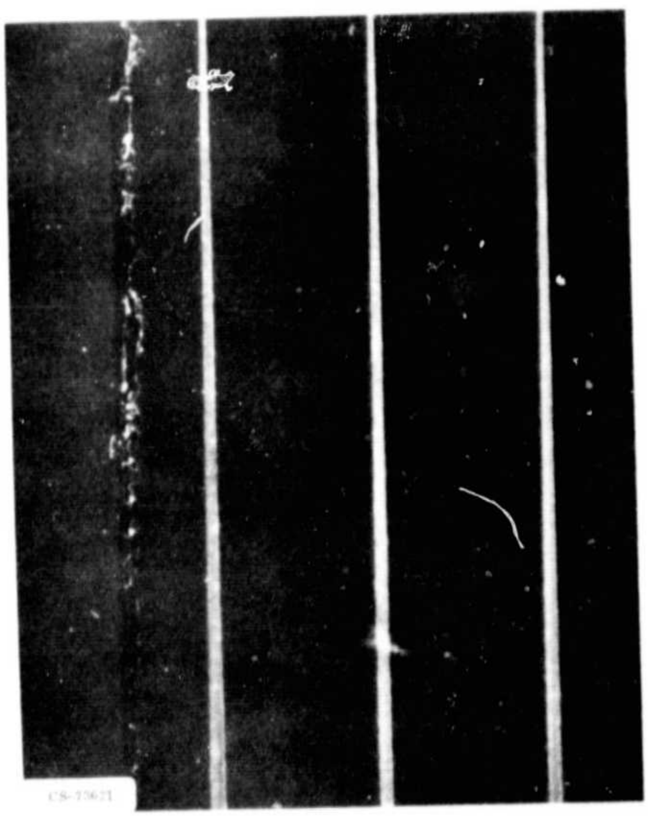

Figure 3. - FEP encapsulated solar cell showing cracking and delamination.

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TABLE 1
BREAKDOWN OF MANUFACTURING COST FACTORS

COST FACTORS	CONV CELLS, %	HI CELLS, %
MATERIAL SILICON	10.5	33.1
MATERIAL OTHER	10.5	2.9
DIRECT LABOR	25	14
INDIRECT LABOR	25	27
OVERHEAD COSTS	18	5
G & A	11	18
	100	100

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TABLE 2
HIGH INTENSITY SOLAR SYSTEM COST ANALYSIS
(PER KW_e)

SUBSYSTEMS	CELL η		
	10%	15%	20%
CONCENTRATOR & TRACKING	\$588.00	\$392.00	\$294.00
HI CELLS	250.00	167.00	125.00
COOLING SYSTEM	100.00	90.00	80.00
SYSTEM TOTAL/KW_e PEAK	\$938.00	\$649.00	\$499.00

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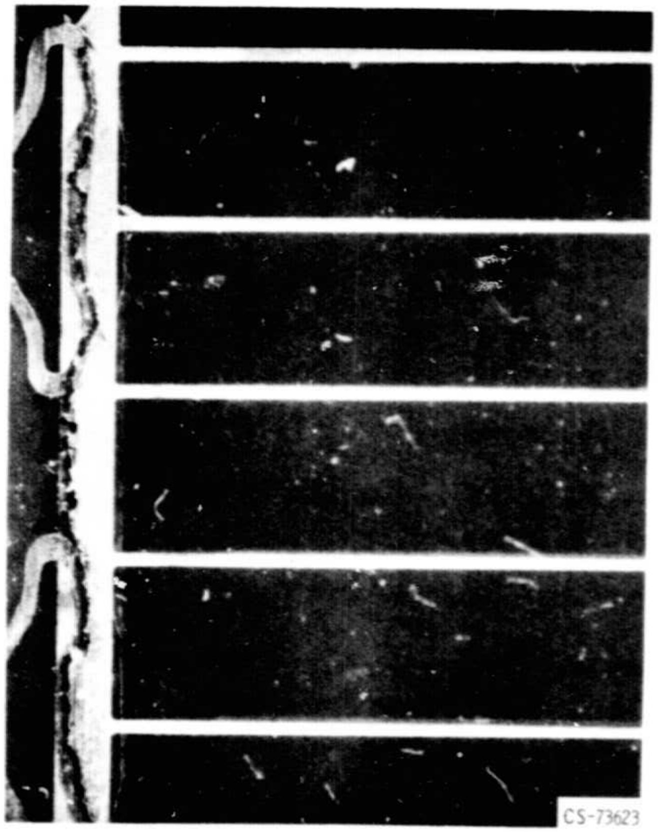

Figure 4. - FEP encapsulated solar cell showing cracking above cell interconnect.

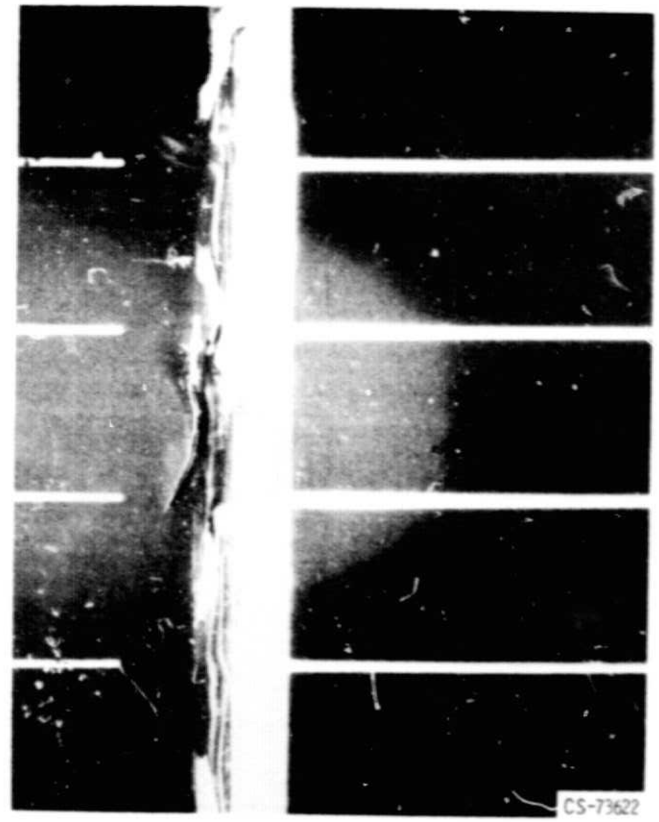

Figure 5. - FEP encapsulated solar cell showing cracking and delamination.

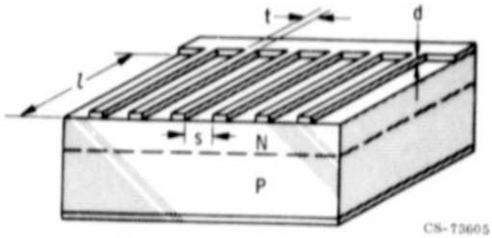

Figure 1. - Conventional solar cell.

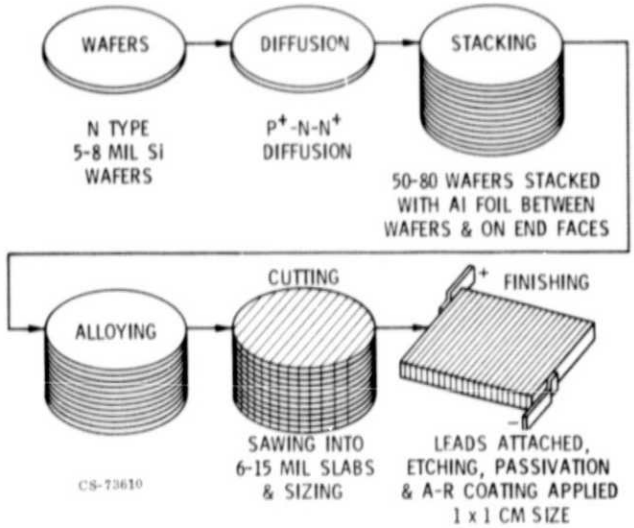

Figure 2. - HI cell fabrication processes.

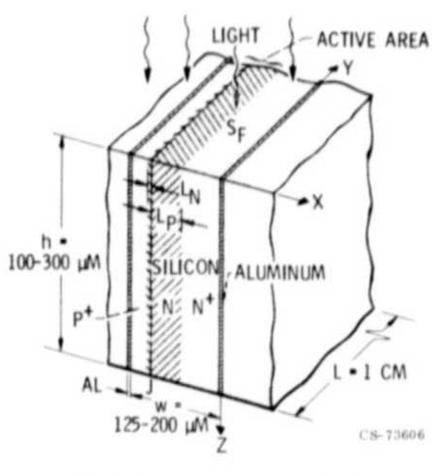

Figure 3. - Unit cell of the HI cell.

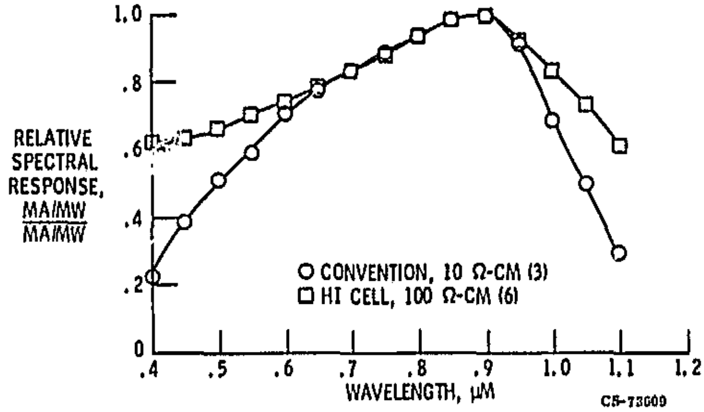

Figure 4. - Relative spectral responses of conventional and HI cells.

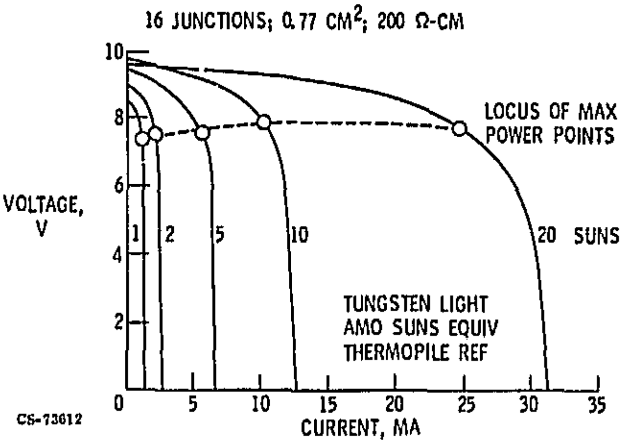

Figure 5. - HI cell I-V characteristics at various intensities.

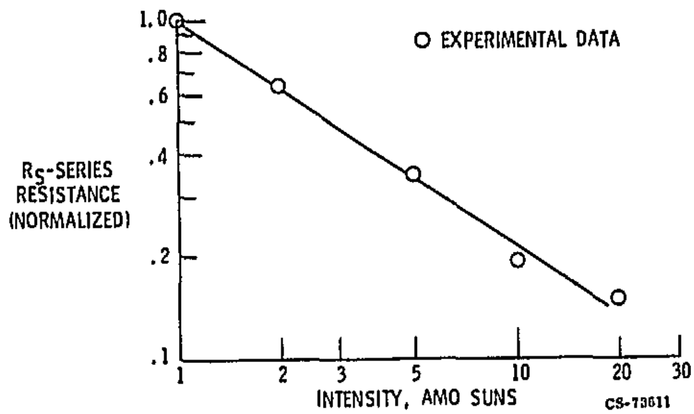

Figure 6. - HI cell series resistance normalized vs. intensity.

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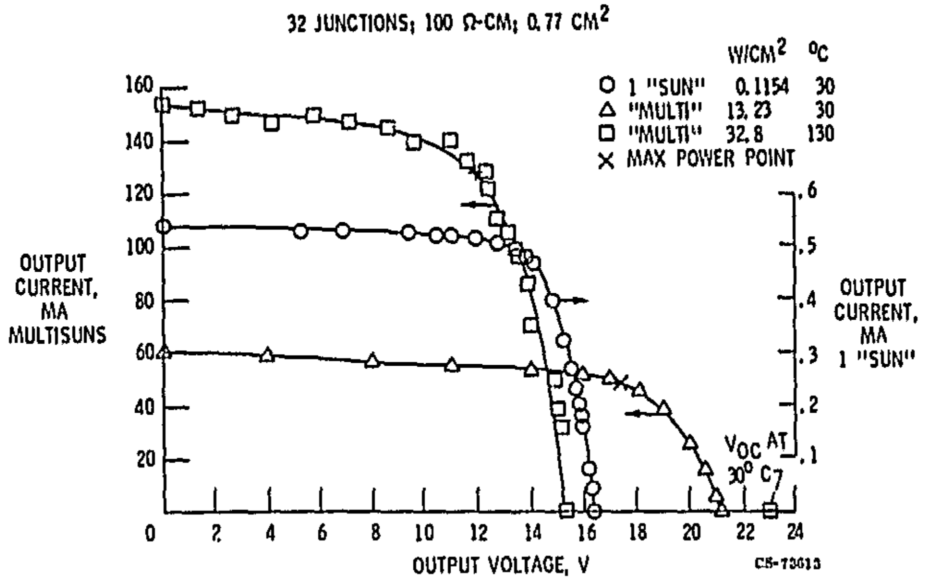

Figure 7. - I-V characteristics of HI cells at various intensities.

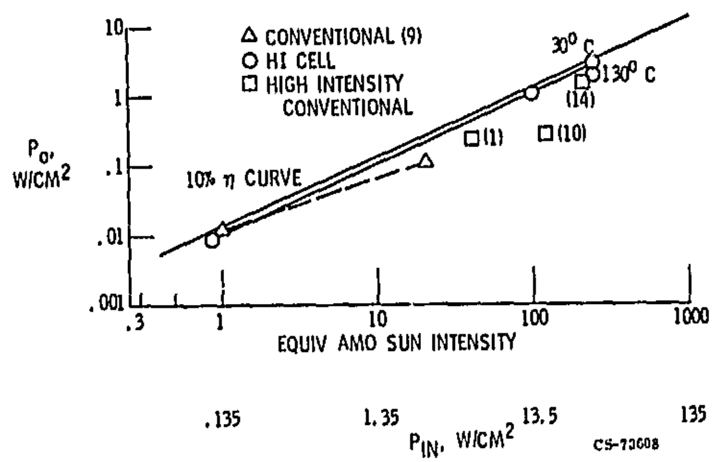

Figure 8. - Power output density at various intensities.

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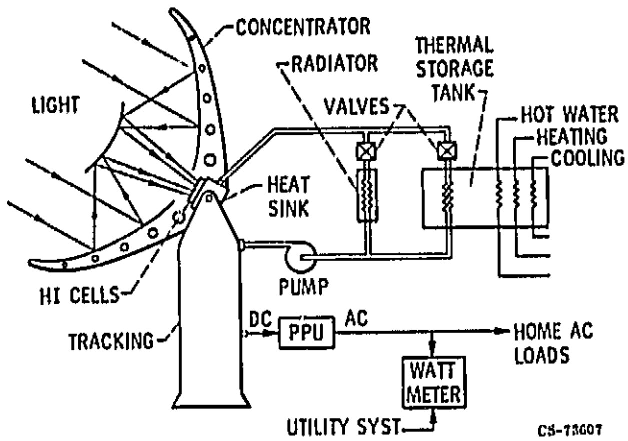

Figure 9. - High intensity solar system.

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