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DEVELOPMENT OF INTEGRAL COVERS ON SOLAR CELLS

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July 1971

Final Report for Period June 1970 - June 1971
Contract Number NAS5-21510
Technical Monitor: Luther W. Slifer, Jr.
National Aeronautics and Space Administration
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Greenbelt, Maryland 20771



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<p>The electron-beam technique for evaporating a dielectric material onto N/P solar cells is investigated. A process has been developed which will provide a highly transparent, low stress, 2 mil thick cover capable of withstanding conventional space type qualification tests including humidity, thermal shock, and thermal cycling. The covers have demonstrated the ability to withstand 10^{15} 1 MeV electrons and UV irradiation with minor darkening. Investigation of the cell AR coating has produced a space qualifiable titanium oxide coating which will give an additional 6% current output over similar silicon oxide coated cells when covered by glass.</p>					
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SUMMARY

The objective of this contract is to evaluate the electron-beam technique for evaporating a dielectric shielding material onto N/P solar cells. The deposited covers are to be optimized for high cell efficiency and reliability so that they will meet conventional space type covered solar cell qualification requirements. The program efforts will examine cleaning processes, coating materials, and the evaporation process necessary to provide a transparent, low stress, integral cover capable of surviving space-type environmental qualification testing. This includes humidity, abrasion, U.V. and 1 MeV electron irradiation, plus thermal shock and cycling. The economical manufacturability of the process will be demonstrated through the fabrication of state-of-the-art samples.

During the program efforts TiO_x was shown to be a more desirable cell anti-reflection coating; satisfying space type qualification requirements, and providing approximately 6% more cell output than SiO_x AR coated cells when covered by glass cover materials. Integral cover experiments with #1720 Corning glass showed a deposition rate variation with substrate temperature and an output power loss for substrate temperatures greater than 300°C. Further, initially poor cover performance in humidity, thermal shock and cycling, and transmission tests, were shown to be related to that phase of the evaporation process in which the dielectric material is premelted. Correction here provided significant improvement in the cover transmission (comparable to conventional glued on platelets), resistance to thermal shock and cycling, and humidity. Deposited cover stresses were shown to be dependent upon the electron gun power input to the crucible, with higher power levels providing reduced cover stresses. Consequently the evaporation parameters were adjusted to provide minimally stressed covers. Parameters for providing an optimized cover comparable to conventional platelet systems in performance and environmental stability are reported herein.

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INTRODUCTION

It is the purpose of this contract to examine the electron-beam techniques for evaporating a dielectric material onto N/P solar cells. The deposited covers will be optimized for high cell efficiency and reliability so that they will meet conventional space-type covered solar cell qualification requirements.

The scope of these efforts has included examination of the cell anti-reflection coatings and dielectric material deposition parameters, including cleaning operations, so as to provide a coating system optimized for high cell output. Furthermore, the evaporation process has been examined with the intent of developing cell covers which will meet typical space flight qualification requirements for humidity, thermal shock and cycle, abrasion, and UV and 1 MeV electron irradiation. The study included examining evaporation parameters such as substrate temperature, cell and source cleaning procedures, evaporation and substrate deposition rate, residual atmosphere composition and pressure, and dielectric material.

The efforts undertaken during the contract can be most clearly described in two phases. The first phase, comprising essentially two months of effort, was principally devoted to developing and comparing cell AR coating systems composed of silicon monoxide, titanium oxide, and cerium oxide. The second phase was devoted to examining the process of depositing dielectric materials onto N/P solar cells in order to determine the optimum material and procedure. In each phase electrical output tests were made on samples with an X25 Spectrosun solar simulator (except where noted) to determine space-type performance. Furthermore, environmental tests were conducted in order to demonstrate the covers' compatibility with typical space-type requirements. A summary of each phase is presented in this introduction.

PHASE I. Cell Antireflection (AR) Coating Optimization

Theoretical analysis had indicated that with a dielectric interference coating on silicon solar cells, AR coatings such as CeO_2 and TiO_x

with refractive indices on the order of 2.2 when placed at the cell-cover interface should yield a greater cell output than an SiO_x AR coating with its lower index of 1.85. The results of this investigation showed that indeed both CeO_2 and TiO_x could be deposited with indices of refraction on the order of 2.2. Difficulties with the CeO_2 coatings in environmental qualification testing, specifically soft erasible coatings, led to the choice of TiO_x , which could pass the boil, eraser rub, and humidity tests, as the optimized AR coating. Both CeO_2 and TiO_x AR coated cells showed substantially greater cell efficiency, when a glass cover was placed on the cells, than the SiO_x coated cells. Approximately 6% more power was available from the glass covered TiO_x and CeO_2 cells than from the glass covered SiO_x coated cells. This increase was approximately 3% greater than had been theoretically determined, and spectral analysis indicated that the source of the extra increase was due to the greater transparency of the TiO_x and CeO_2 AR coatings at shorter wavelengths (less than .50 micron).

PHASE II. Integral Cover Evaporation Process Studies

At the beginning of this contract a number of specific problem areas in the electron beam deposition of dielectrics were identified and selected for the major emphasis in the development of a potential flight-qualified integral cover. Of these, excessive optical absorption in the cover, peeling in humidity qualification tests, and high cover stresses were felt to warrant the major research emphasis.

The first area investigated was that of the optical absorption. The effects of substrate temperature, evaporation rate, source preparation, cover thickness, and residual gas pressure were examined to determine the effect on cover transmission. The results clearly indicated that the dominant contribution to the cover absorption was the formation of a cell surface contamination due to the first step in the deposition process in which the source material was pre-melted so as to prevent

subsequent spattering onto the cells. Even though the substrates were shielded from any line of slight deposition during this stage, an absorbing surface layer formed. A number of approaches such as premelting the source in a furnace prior to being placed in the vacuum chamber, and pre-melting the source in the vacuum chamber before placing cells in the chamber provided a significant decrease in the coating absorption. Qualitatively the best evaporated covers fabricated by this improved process were comparable to conventional glued-on platelets with respect to transmission (in the wavelength region 400 m μ to 1200 m μ), with an estimated maximum optical absorption of 0.5% per mil thickness.

As an added benefit of this change in the evaporation procedure, a marked improvement in the cover's ability to withstand severe humidity environments (95% RH, 65°C) and thermal shock and cycling tests was observed.

Additional studies showed that coating thickness decreased as substrate temperature increased for constant electron beam power levels. At substrate temperatures above 300°C the cell curve shape degraded. Both of these results indicated that relatively low substrate temperatures should be maintained. (Due to thermal radiation from the crucible, 200°C was the lowest substrate temperature attainable without major modifications of the vacuum system.)

The third problem area, cover stress, was shown to be dependent upon the electron beam power level. Increasing this parameter caused a reduction in the cover stress and consequently reduced the amount of cell bowing. By tripling the input beam power, a five fold reduction in cover stress was achieved. Tests examining different deposition rates (by altering source-substrate distance) showed that the stress change was not due to deposition rate. Preliminary spectrographic analysis of the deposited cover showed a composition much

different than the raw 1720 glass charge (the deposited cover has a significant reduction in alkali oxides) and might indicate the stress reduction is due to a change in evaporated glass composition produced by the various electron beam power levels in the source. It is felt that the minimum stress covers are quite compatible with present day array fabrication techniques and do not incur excessive stressing in the cell-cover assembly. The results of these studies led to the determination of parameters necessary for providing an optimized cover.

The behavior of the optimized cover in additional environmental tests such as thermal cycle, thermal shock, 1 MeV electron irradiation, and U.V. irradiation, demonstrates that the deposited cover is comparable to conventional glue-on covers in the ability to withstand degradation and of course, the deposited covers will offer the further advantages of complete cell active area coverage, and reduced fabrication cost.

Slight variations in the environmental stability of samples was felt to be due to problems of scheduling which provided only minimum time for thorough cleaning of the evaporation equipment. As with all evaporation processes, system cleanliness must not be minimized and production capability here will require thorough cleaning. The requirement of low substrate temperature and high electron beam power both lead to fast deposition rates and at present, it is possible to deposit 2 mil thick covers in forty minutes using a sample holder containing 25 cells.

2.0

TECHNICAL DISCUSSION

The efforts undertaken during this contract can best be discussed by dividing the work into two phases. Phase I, the initial two months, was principally devoted to developing an anti-reflective (AR) coating for the silicon solar cell which would optimize the efficiency of the solar cell-integral cover system. Phase II consisted in examining parameters

of the cover deposition process so as to optimize the cover with respect to the requirements mentioned in the Introduction (optical transmission, low stress and environmental survival for example). Additional efforts during this phase involved the environmental testing performed to establish the suitability of the covering process to space flight requirements. These include humidity, thermal cycle, thermal shock, U.V. irradiation, and 1 MeV electron irradiation tests.

2.1 SOLAR CELL ANTIREFLECTIVE (AR) COATING

Based upon the optical properties of silicon and coverglass materials, earlier studies had shown that an optimum cell antireflecting coating would need a refractive index somewhat greater than 2.0 and should have little absorptance in the spectral range from 400 to 1100 μ . The most commonly used materials for this purpose are silicon oxide (SiO_x), cerium dioxide (CeO_2) and titanium oxide (TiO_x). The refractive index for SiO_x , the industry standard AR material, is on the order of 1.85 depending on the method of deposition. For CeO_2 and TiO_x , index values in the range 2.0 through 2.4 are all possible, depending upon the evaporation parameters. The object of the AR study was to determine what kind of refractive index could be obtained with the CeO_2 and TiO_x , decide whether the resultant coatings could pass space-type qualification tests, and determine what actual solar cell output current values could be realized.

A brief preliminary analysis was conducted in order to predict the possible magnitude of current change that could be expected through the utilization of the high index AR coatings (TiO_x and CeO_2). This analysis calculated the transmission properties that SiO_x , TiO_x and CeO_2 coatings would provide under air-mass-zero (AM0) sunlight conditions, i.e., extra-terrestrial space sunlight, both for bare cells and glass covered cells. A refractive index of 1.85 was assumed for

SiO_x along with values of 1.50 and 3.45 for the glass and silicon solar cell respectively. Rather than assuming particular values each for TiO_x and CeO₂, calculations were made using indices of 2.1 and 2.3, values which could be expected for either material. The transmission properties of the cover-AR coating cell structure were calculated using the following relations:

$$T = 1 - R \quad (1)$$

$$R = \frac{b_1 \cos^2 a + b_2 \sin^2 a}{b_3 \cos^2 a - b_4 \sin^2 a} \quad (2)$$

with T = transmission at a given wavelength
 R = reflection at a given wavelength

$$b_1 = (\eta_o - \eta_s)^2 \quad b_2 = \left(\eta_1 - \frac{\eta_o \eta_s}{\eta_1} \right)^2$$

$$b_3 = (\eta_o + \eta_s)^2 \quad b_4 = \left(\eta_1 + \frac{\eta_o \eta_s}{\eta_1} \right)^2$$

η_o = refractive index of cover glass

η_1 = refractive index of AR coating

η_s = refractive index of silicon

$$a = \frac{2 \pi \eta_1 t_1}{\lambda}$$

$$t_1 = \text{thickness of AR coating} = \frac{1625 \text{ \AA}}{\eta_1}$$

λ = given wavelength

Following this, the transmission at a given wavelength was multiplied by the amount of incident solar energy in a narrow band centered at that wavelength. This provided a value for the amount of energy in a wavelength band which would then be available to the solar cell. Multiplying this by the spectral response of the cell, at the given wavelength, then provided the amount of cell generated energy in a

narrow bandwidth surrounding the given wavelength. By dividing the spectral region from 400 m μ to 1250 m μ into a continuous series of 50 m μ wide bands and by calculating the solar cell generated energy produced in the bands (according to the above method) a simple summation yielded the total energy theoretically produced by the solar cell under AMO conditions. The relative output values for the various configurations are summarized in Table 1. These values served not only as an indication of the possible cell current change which could be expected through the use of optimized refractive index coatings, but also served as initial guidelines in evaluating the performance of the experimental coatings deposited on actual cells.

2.1.1 Cerium Oxide AR Coatings

The first material examined was CeO₂. Samples were prepared by depositing the CeO₂ by a resistance-heating technique. The effects of the following process variables were examined:

1. Cell substrate temperature: 200°C \longrightarrow 400°C
2. O₂ pressure: $\sim 10^{-6}$ \longrightarrow 8×10^{-4} torr
3. Glow discharge: none, before, and after coating.
4. Source materials:
 - (a) Vendor: Balzers and Sylvania
 - (b) Pre-evaporation bake-out at 1055°C
to remove any water vapor, no bake out
5. Post coating treatment:
 - (a) Sintering in H₂ at 605°C
 - (b) Bake-out in air at 250°C
 - (c) None

The cells obtained from the application of the above variable matrix were all subjected to a number of tests examining cell output and environmental capability. In no instances were consistently hard CeO₂ coatings obtainable, i.e., the standard AR coating erasure test con-

TABLE I

THEORETICAL AR COATING INFLUENCE ON SOLAR CELL PERFORMANCE

<u>AR Coating</u> <u>Reflective Index</u>	<u>Relative Short Circuit Current (AM0)</u>	
	<u>Bare cell</u>	<u>cell with glass cover</u>
1.85(SiO _x)	1.000	1.000
2.1	0.991	1.025
2.3	0.967	1.030

sisting of 20 rubs across the surface with an eraser applied at 2 pounds downward force could remove the coating to some degree. The most consistently hard coatings of CeO_2 were obtained using parameters of 300°C substrate temperature, 5×10^{-4} O_2 pressure, and no glow discharge. These samples received the most extensive measurements of cell output and coating optical parameters.

Examination of glass witnesses in a Beckman DK-2A spectrophotometer showed that the deposited CeO_2 coating's refractive index was on the order of 2.2. However, not all witnesses had measurable refractive index values due to AR coating inhomogeneity. Rather than behaving as a single quarter wave thickness, the deposited material behaved similar to a multilayer coating, consisting of extremely thin layers with slightly differing refractive indices. This was due to fluctuations in the evaporation rate of the source during the deposition process. For samples with inhomogenous coatings, no accurate refractive index measurement could be obtained.

Electrical measurements on all coated cells did show, however, the expected change; i.e., whereas typically an SiO_x AR coated cell will maintain or decrease slightly its I_{sc} (short circuit current) upon being covered with a coverglass, the CeO_2 AR coated cell exhibited average increases of 3.1% (the average I_{sc} of a group of 24 cells increased from 141.1 mA to 145.5 mA upon covering with glass - see Table II). In these tests, differences in the transmission properties of individual glass platelets were eliminated by using the same cover on each cell. This procedure is accomplished by using an uncured adhesive layer between the cell and platelet. In this way the platelet can be removed from the cell after testing, and placed on another cell with adhesive (uncured). The refractive index of the uncured adhesive is close to its cured value of 1.4 and prevents the occurrence of any large reflection losses that would occur if an air gap existed between the cell and the glass. This same technique was applied throughout

CELL NUMBER	SHORT CIRCUIT CURRENT BARE	SHORT CIRCUIT CURRENT COVERED (GLUE-ON PLATELET)
1	138.8 mA	143.5 mA
2	142.9	146.5
3	140.0	144.5
4	140.2	145.3
5	140.8	144.6
6	138.9	144.7
7	142.2	148.2
8	142.7	145.1
9	damaged	
10	143.5	147.7
11	138.6	142.4
12	137.7	143.8
13	139.1	144.8
14	143.0	148.2
15	142.4	145.7
16	142.5	147.1
17	143.1	146.7
18	142.1	146.3
19	139.2	144.6
20	140.0	144.7
21	142.0	146.3
22	139.1	145.4
23	142.4	146.1
24	142.8	146.3
25	<u>141.9</u>	<u>147.3</u>
Average	141.1	145.5

Table II
CeO₂ AR Coating Performance

the AR coating testing programs whenever the effect of a coating on electrical properties was required. It provides accurate electrical output values that would be equivalent to a cured flight-ready platelet-cell system with the advantage of allowing for the recovery of the cell-AR coating for other tests.

The CeO₂ AR coating study did indicate that a significant cell efficiency increase could be affected through the use of the higher index material. However, due to the relative softness of the particular coating, efforts at hardening it were delayed so as to examine the TiO_x system and determine its merits.

2.1.2 Titanium Oxide AR Coatings

In contrast to the CeO₂ coatings, the TiO_x coatings readily satisfied the environmental requirements for space qualifiable coatings. In particular, after a parameter test sequence similar to that for CeO₂ the following deposition parameters:

Substrate temperature	200°C + 20°C
O ₂ pressure	5x10 ⁻⁴ torr
Evaporation rate	~500Å/min
Source material	TiO

provided coatings which satisfied the following specifications:

humidity	65°C, 95% RH, for one month
boil in H ₂ O	1/2 hour
abrasion	20 rubs across surface with 2 lbs. downward force

Optically, refractive indices on the order of 2.1 were measured with less than 0.5% absorptance (measurement accuracy) in the region from 400 mμ to 1200 mμ.

The cell electrical output performance measurements consisted of two sequences. In the first, approximately 200 N/P cells were obtained from Heliotek production line prior to the AR coating process and randomly separated in two groups; one for TiO_x AR coatings and one for SiO_x coatings. The SiO_x cells were coated using the conventional production process and the TiO_x cells were coated using the process described above. Comparison of bare cell outputs at 28°C, AMO conditions showed the average output of the TiO_x cells to be 1.5% higher than the SiO_x cell average. When covered by placing adhesive and a 12 mil glass cover on the cells (as described in Section 2.1.1), the short circuit current (I_{sc}) of the SiO_x coated cells decreased on the average by 1.3% while the I_{sc} of the TiO_x coated cells increased by 3.3%. Consequently the glass covered TiO_x coated cells showed a 6.2% higher output than similarly covered SiO_x coated solar cells from the same population of cells. (See Table III.)

Since solar cell outputs within a group will possess some distribution, it would be necessary to use prohibitively large samples for determining confidently the output effects of various parameters. To avoid this, the second series of tests was designed and conducted so that identical individual cells would be measured both with SiO_x and TiO_x AR coatings. This necessitated the removal of one AR coating and the subsequent deposition of the other coating. In order to account for any AR coating removal degradations that might have been biased towards one coating system, the cells were divided into two groups (approximately 20 cells each) which were processed through the following coating sequences:

GROUP I	SiO_x	$\xrightarrow{\text{remove}}$	TiO_x	$\xrightarrow{\text{remove}}$	SiO_x
GROUP II	TiO_x	$\xrightarrow{\text{remove}}$	SiO_x	$\xrightarrow{\text{remove}}$	TiO_x

It was felt that this procedure would identify and account for any cell output degradations due to coating removal. These results showed that on the average each bare cell would produce 1.7% greater power with a TiO_x coating, and when glass covered, 6.0% greater power with a TiO_x coating than with an SiO_x AR coating. (See Table III.) This is in agreement with the previous tests on the two 100 cell groups.

Recalling the theoretical calculations in Section 2.1 above which concluded that bare TiO_x cells should be lower in output than SiO_x cells (experimentally they were not) and when covered with glass should be approximately 3% higher than the SiO_x cells, these above listed empirical values indicate a discrepancy which appears to be due to a characteristic optical absorption in SiO_x films at short wavelengths. Transmission curve measurements of coatings on glass witnesses indeed do exhibit absorption at wavelengths below 500 m μ in varying amounts for the conventional SiO_x AR films (Figure 1). The increased performance of the covered TiO_x coated cells then is due to both the better refractive index match and the nonabsorbing film characteristics.

These experiments showed that TiO_x AR coatings can be applied to silicon solar cells in such a manner that they could pass typical space type AR coating qualification tests and also provide a substantial increase in power (approximately 6% when covered) over similar SiO_x AR coated cells.

The strong environmental and electrical performance capabilities of the TiO_x AR coatings lead to its selection as a state-of-the-art optimized coating for the coverglass-cell system. No further efforts were expended on the CeO_2 coatings inasmuch as no clear benefit over TiO_x appeared to be evident.

2.2 INTEGRAL COVER INVESTIGATIONS

During this program Corning glass #1720 was utilized in the majority of the cover evaporation tests. This aluminosilicate glass had proven

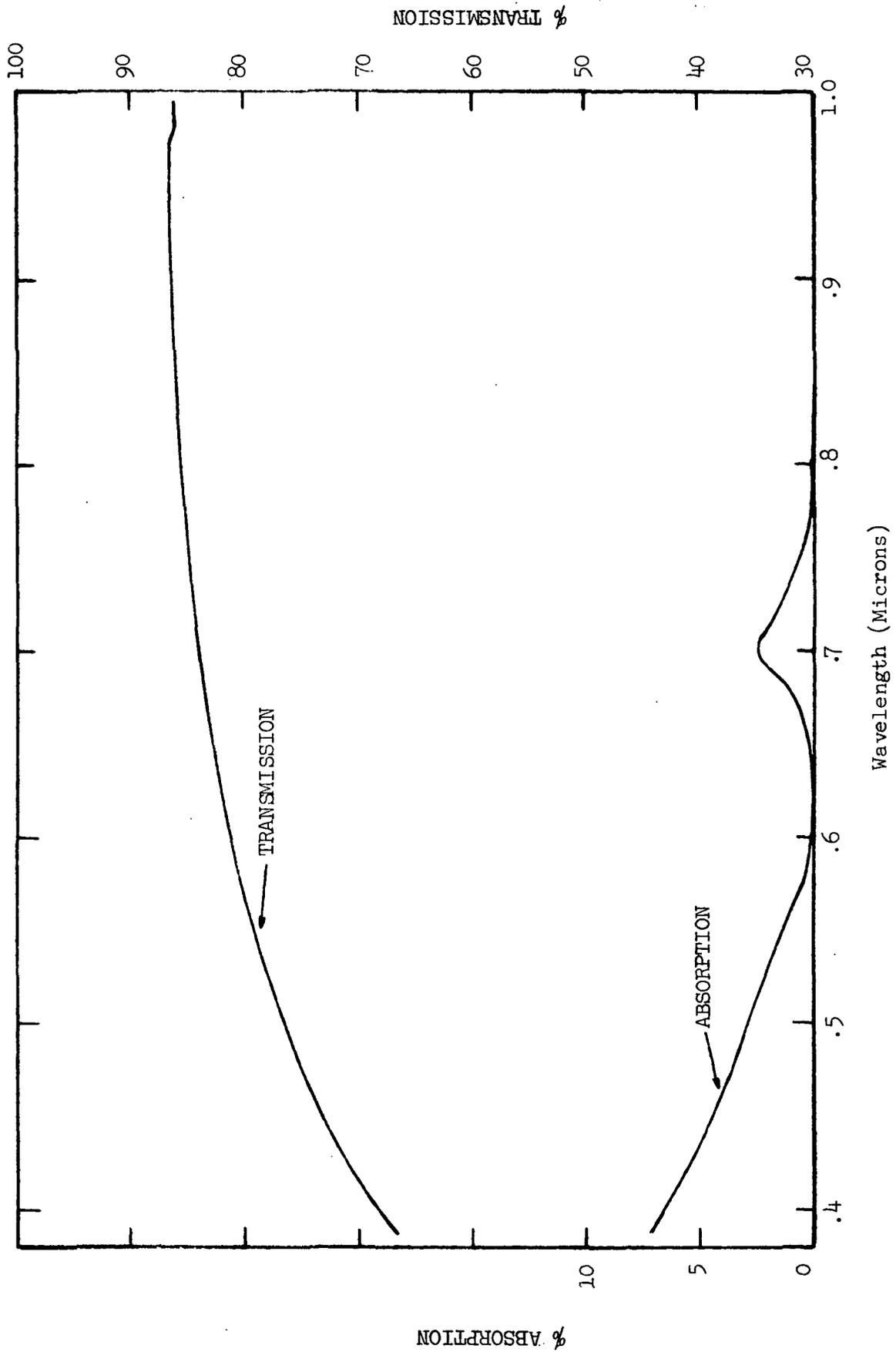


Figure 1. SiO AR Coating Transmission Curve
(SiO on glass witness)

COATING	NUMBER OF CELLS	AVERAGE SHORT CIRCUIT CURRENT (mA)		CURRENT CHANGE (%)
		BARE CELLS	GLUE-ON PLATELET COVERED CELLS	
SiO _x	96	134.7	132.9	-1.2
TiO _x	114	136.7	141.2	3.3

Comparison of SiO_x and TiO_x Coated Cells

Cell Group #1 (14 cells)

COATING	AVERAGE I _{sc} BARE (mA)	AVERAGE I _{sc} COVERED (mA)	CURRENT CHANGE (%)
SiO _x	140.3	139.3	-0.7
TiO _x	138.7	142.5	+2.7
SiO _x	136.0	137.0	+0.7

Cell Group #2 (23 cells)

COATING	AVERAGE I _{sc} BARE (mA)	AVERAGE I _{sc} COVERED (mA)	CURRENT CHANGE (%)
TiO _x	137.3	141.5	+3.1
SiO _x	133.0	129.0	-3.0
TiO _x	136.8	139.6	+2.3

Comparison of SiO_x and TiO_x Coatings on Same Cells

Table III

SiO_x and TiO_x AR Coating Comparison

(refer to text for test description)

to be the most promising during Heliotek's earlier survey work and consequently was employed as a base line system for this contract. However, some work was also conducted with #7070 Borosilicate glass and 7070-1720 mixtures.

The first experimental tests conducted examined the effect of substrate temperature during the evaporation process. Although the substrate temperature could conceivably affect any of the three major problem areas, the specific task was to determine at what temperature cell degradation might occur (electrical) and what qualitative cover effects could be observed. As will be shown below, this test sequence led directly into the examination of cover absorption. The electron beam evaporation equipment is shown in Figure 2.

2.2.1 Effects of Substrate Temperature

In examining the effect of substrate temperature on the integral cover, the following deposition parameters were maintained for all tests:

Source to substrate distance	16 inches
Heating source	Quartz infrared lamp
E Gun Current, Voltage	100 mA, 6K volts
Chamber pressure	2×10^{-5} torr
Evaporation Time	1 hour

These tests indicated that varying the substrate temperature from a low of 200°C to a high of 400°C had no observable effect on the integral covers' adherence or environmental stability. All substrate temperature values provided good adhering covers which were stable at ambient storage conditions for periods of at least one month. Yet, all sample covers could be peeled off after a half-day exposure at high temperature, high humidity conditions typical of cell space-type qualification tests (65°C, 95% R.H.).

In contrast, a quite pronounced relation between substrate temperature and coating thickness was identified as is evident in Figure 3. The slight flattening in the curve between 200°C and 300°C might be real,



Figure 2 Electron Beam Evaporation Apparatus

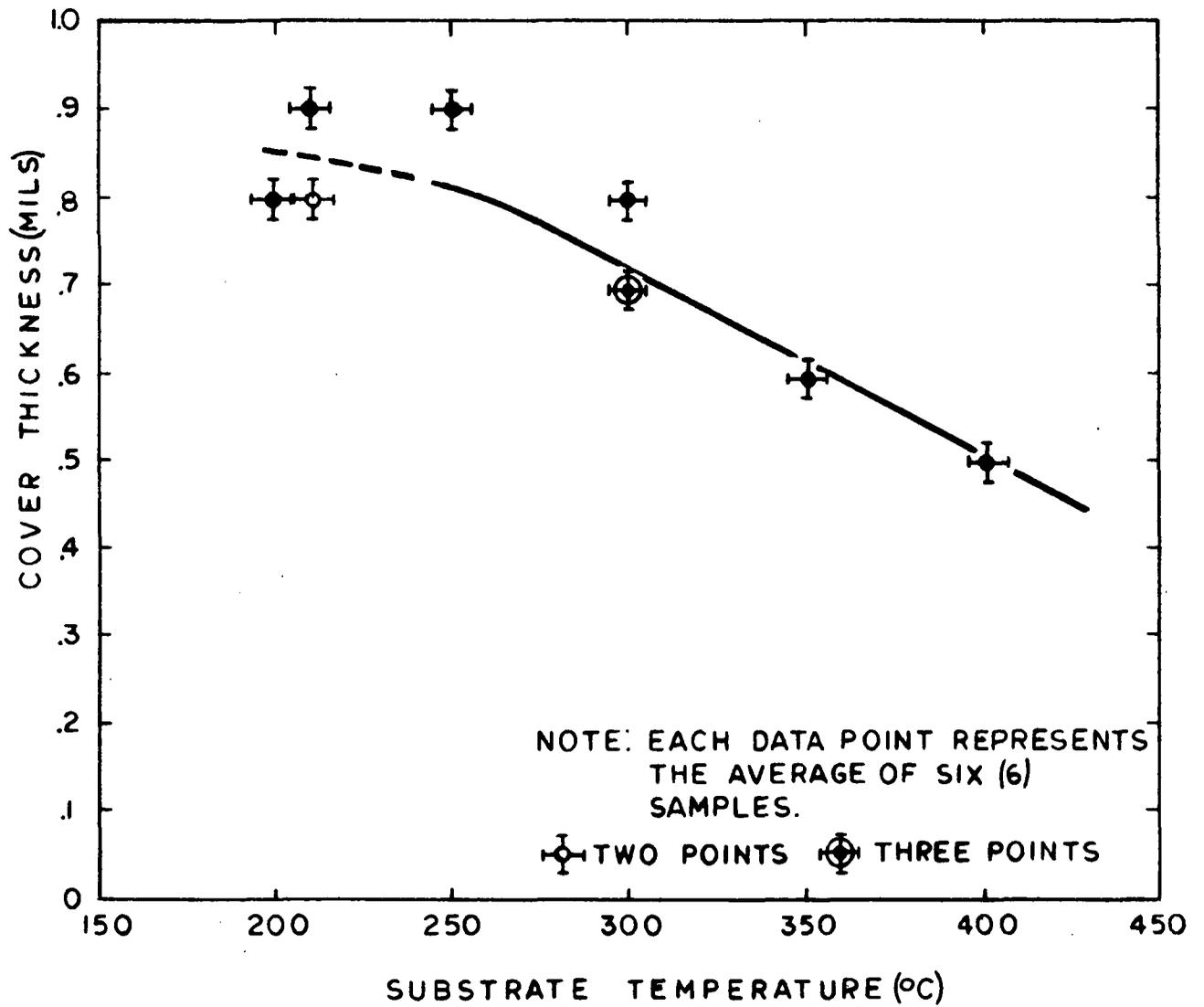


Figure 3. Deposited Cover Thickness vs Cell Substrate Temperature.

indicating some sort of threshold region at 250°C. Such behavior could be understood in terms of the sticking coefficient. In view of the relatively low melting point of the glass (approximately 1190°C compared to greater than 1500°C for most common evaporated materials) and the 200-400°C substrate temperatures, it is quite reasonable to expect that a significant number of impinging particles could retain sufficient energy to be re-emitted. It would be expected that quite different behavior would occur at substrate temperatures substantially lower. However, limitations in the present evaporation system prohibit obtaining substrate temperatures below 200°C. The strong relationship observed does indicate the requirement of maintaining temperature stability during evaporation runs, if only to obtain predictable coating thicknesses. Similar testing conducted by Heliotek under Wright-Patterson Contract F33615-70-C-1619 has also shown this same behavior, although curve flattening begins at 300°C. In both series of tests a curve slope of 0.2 mil per 100°C is observed. The samples obtained in the above described tests were then measured electrically and compared to the uncovered cells' electrical values.

In Figure 4 the rectangular data points show the cell short circuit current change as a function of substrate temperature. The spread in data does not directly indicate any specific relationship other than that which might be expected to be associated with the different cover thicknesses.

Also plotted in Figure 4 is the cell current change (uncovered to covered) at load (445 mV) as a function of substrate temperature (ovals). Here, again, scatter in the data pattern is observed due to the associated thickness change explained earlier. If the output changes are merely a matter of coating absorption, then the short circuit and load current changes would all exhibit the same percentage changes versus substrate temperature (as related to coating thickness). For substrate temperatures less than 300°C, this is

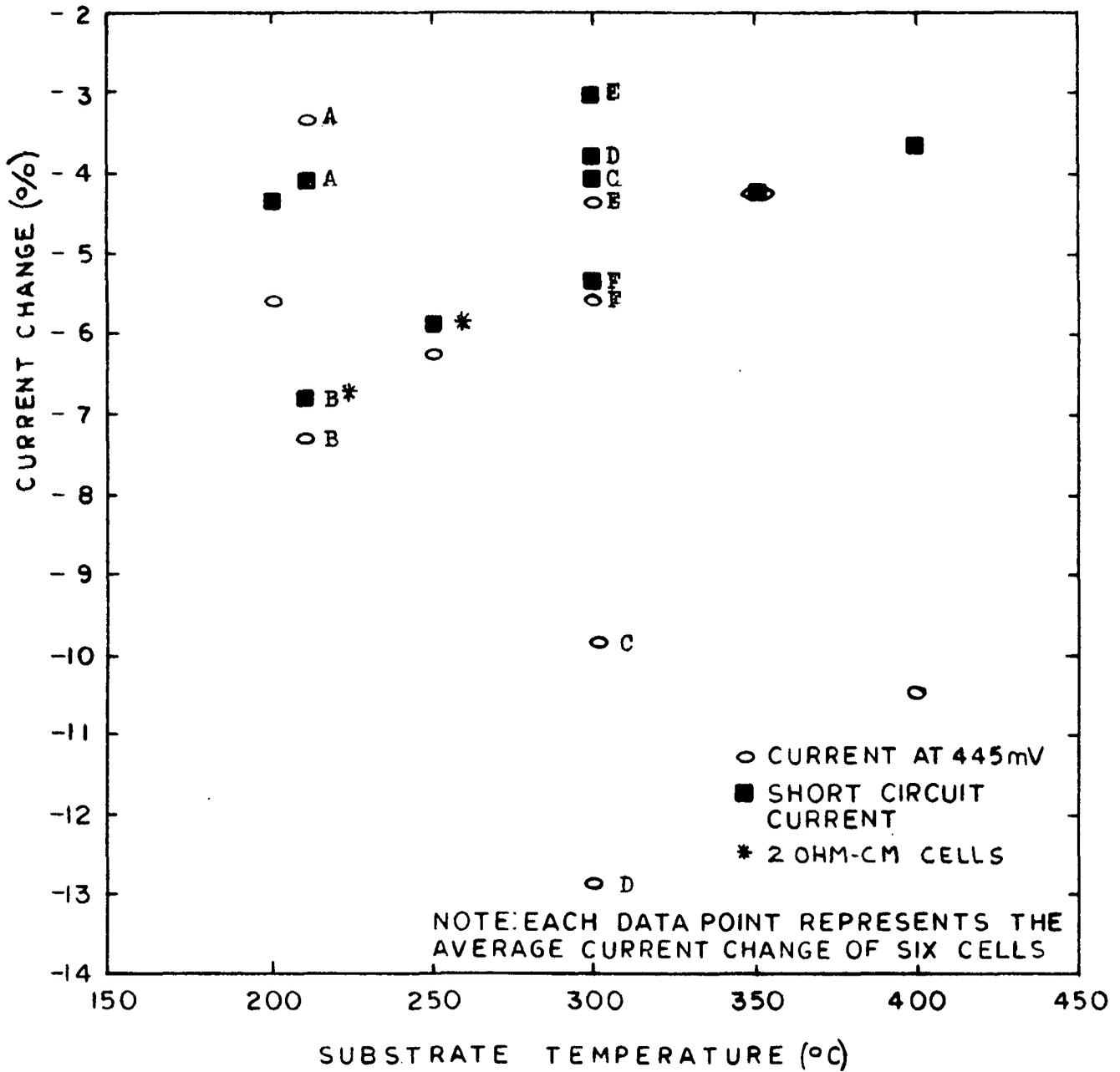


Figure 4. Covered Cell Current Change vs. Cell Substrate Temperature

evidently so; however, at 300°C and above the load current exhibits significantly greater losses than the short circuit current indicating cell degradation due to possible shunting. For this reason all subsequent evaporations will keep the substrate temperature below 300°C during the coating desposition.

2.2.2 Integral Cover Absorption Versus Cover Thickness, Cell Resistivity

Following up the substrate temperature study, a sequence of tests was conducted in which various integral cover thicknesses were obtained by varying the deposition time, and not, as done previously, by varying the substrate temperature. This eliminates any possible substrate temperature-induced absorption effects. Due to the observation in the previous experiments that high substrate temperatures ($\geq 300^\circ\text{C}$) were related to unusually high load point current losses, the substrate temperature was maintained at 250°C for all tests in this new series of experiments. The deposited cover thickness ranged from 0.2 mils to 2.0 mils.

The results of the first sequence of tests are shown in Figure 5 where the short circuit current losses are presented as a function of coating thickness. For a cover system, the short circuit loss will depend on the glass absorption (a function of cover thickness), and reflection losses (thickness independent). Consequently, subtracting the constant amount of 6.2% from the losses presented in Figure 5 leaves what would be expected as the glass absorption contribution to the total short circuit current loss. Assuming an absorption of the form $I(1 - e^{-At})$ where I is the incident intensity, A is the cover absorption constant, and t is the cover thickness, the slope of the short circuit current loss is then identified with the absorption coefficient for the glass. This value, as determined from Figure 5, is 0.5% absorption per one mil of coating thickness. Consequently, a 6 mil cover might be expected to exhibit 2% more short circuit current loss (absorption) than a 2 mil cover.

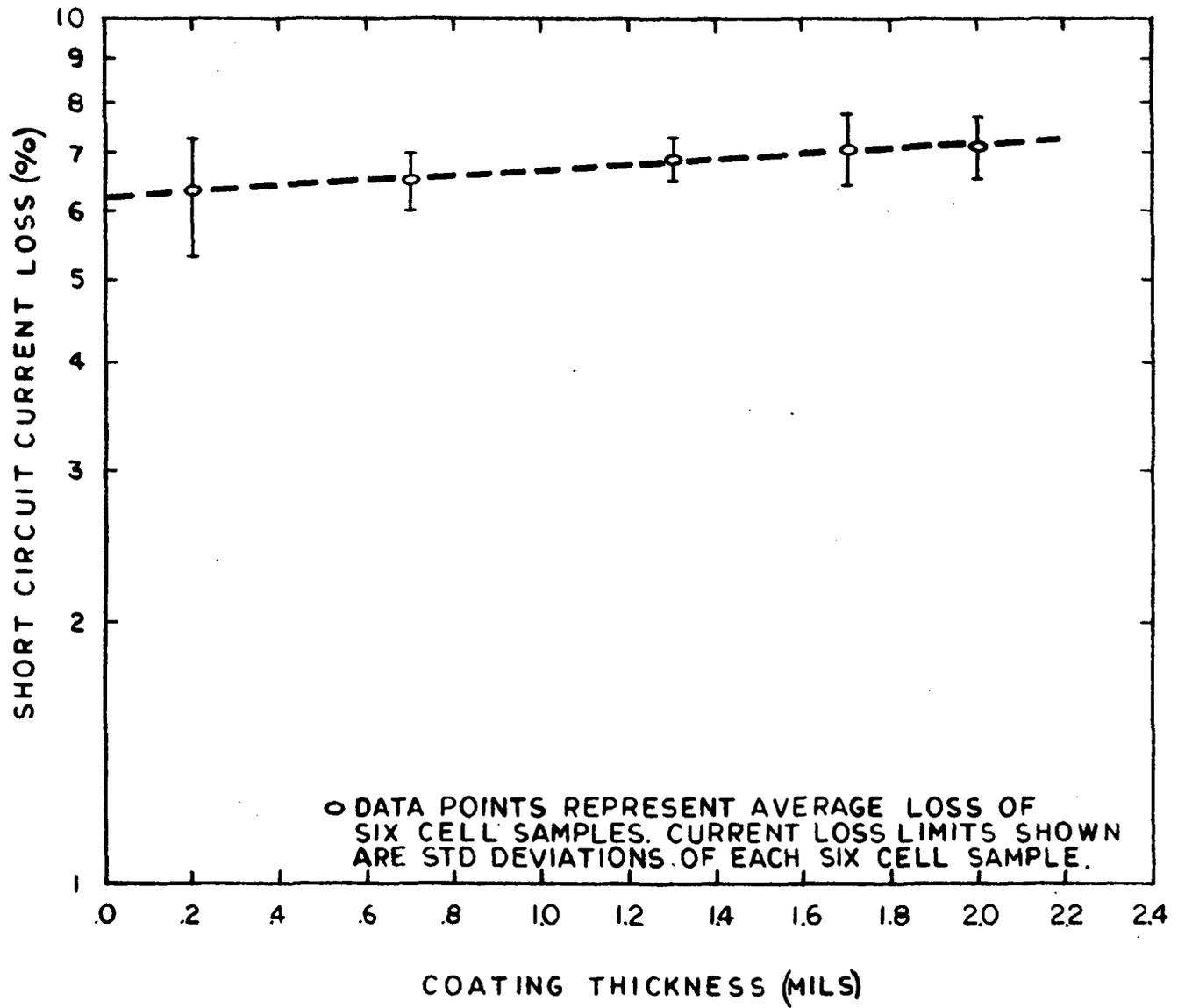


Figure 5. Cell Short Circuit Current Loss vs Cover Thickness.
(2 ohm-cm cells)

This interpretation, although consistent with the known short circuit current loss mechanisms, does introduce an extremely large constant loss value of 6.2%. It has already been shown that theoretical considerations indicate that because of the SiO_x cell AR coating refractive index mismatch, and because of the lack of a cover front surface AR coating, it would be reasonable to expect a thickness independent current drop of 3 to 4% when covering. The observed 6.2% drop requires some other loss mechanism (other than surface reflection) to be present, and it must also be thickness independent. The most likely possibility postulated was absorption at either the cell surface or cover surface due to some contamination during the deposition process. This theory was consequently investigated and the source of this loss was determined and is discussed in Section 2.2.3.

Again, recalling the current losses observed in the substrate temperature experiments discussed previously, the average short circuit current loss observed for 10 ohm-cm cells ranged from 3.0% to 5.3% for cover thicknesses up to 0.9 mils. In contrast the average loss values observed during the thickness effect tests, which were conducted on 2 ohm-cm cells entirely, varied from 6.2% to 7.1%. The increase in current losses posed a serious question as to a possible cause, without, however, any apparent significant changes in the deposition process or materials. Comparison of the loss distribution for individual covered cells showed that not only were 2 ohm-cm cells exhibiting greater losses on the average, but that the maximum and minimum current losses exhibited by the 2 ohm-cm group ran higher than the 10 ohm-cm cells maximum and minimum losses in all comparable cases (i.e., similar cover thicknesses). Consequently the absorption versus cover thickness sequence of experiments was repeated, this time employing 10 ohm-cm cells.

In Figure 6, the short circuit current loss versus cover thickness is presented for the tests on 10 ohm-cm cells. By comparing Figure 6 with Figure 5 it is apparent that at any given cover thickness the average

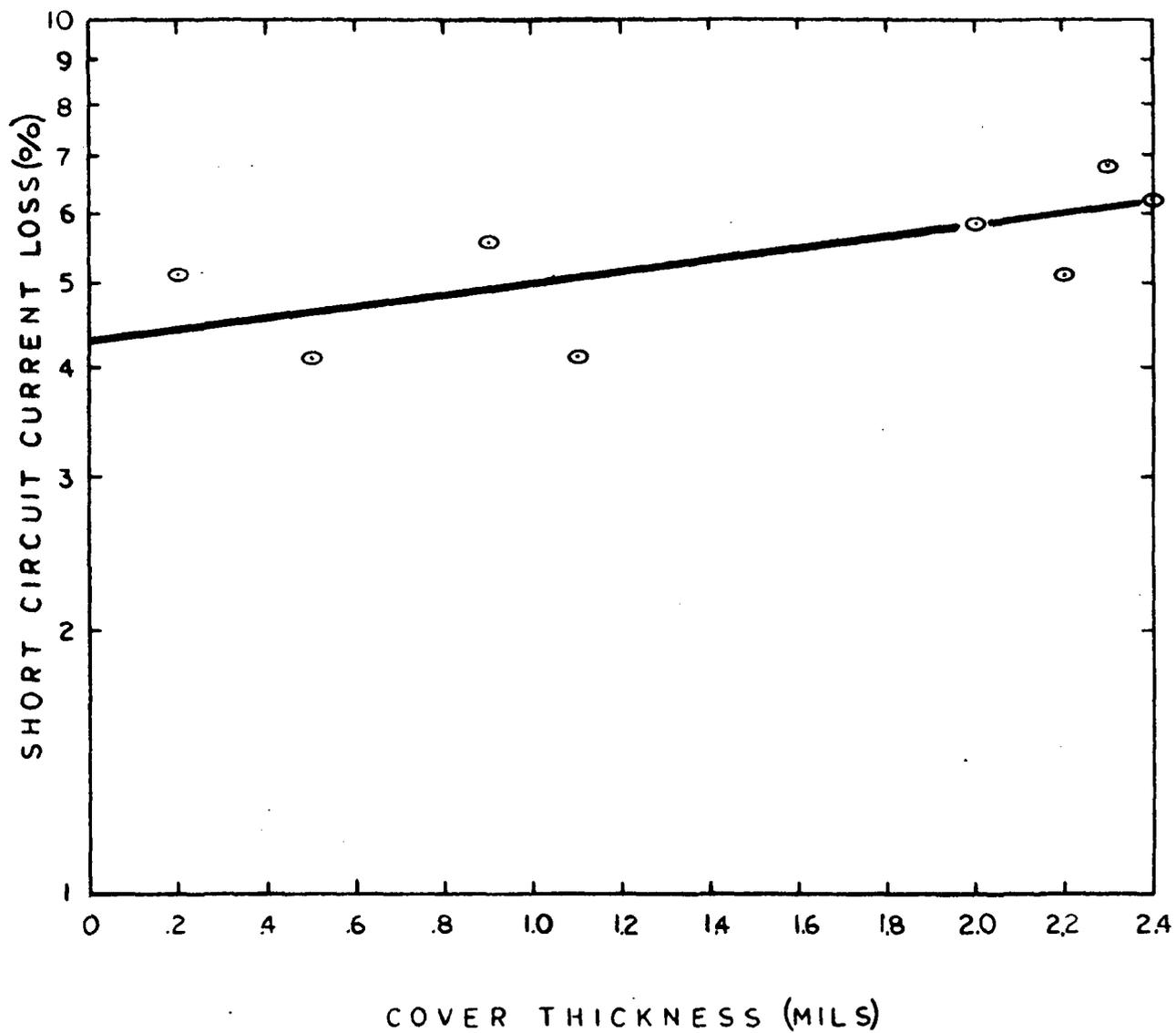


Figure 6. Cell Short Circuit Current Change vs Cover Thickness.
 (10 ohm-cm cells)

current loss in 10 ohm-cm cells is less than in 2 ohm-cm cells. In fact, by examining the distribution of all 10 ohm-cm cell losses observed during all tests (substrate temperature, thickness, etc.) and of all 2 ohm-cm cell losses observed, the 10 ohm-cm distribution exhibits a maximum loss, a minimum loss, and an average loss of 1-1/2 to 2% smaller than the corresponding 2 ohm-cm cell losses. Clearly there exists a current loss mechanism dependent in some manner on the cell resistivity. An examination of the manufacturing process for each cell resistivity shows only a few subtle differences in cleaning procedure plus the principle difference of material dopant levels. Brief tests comparing the spectral response of 2 and 10 ohm-cm cells did not show any major differences which would explain the differences in short circuit current losses. It is possible that a comprehensive sequence of spectral response tests could provide sufficient data for explaining the difference behavior; however, such a task is well beyond this program's scope.

2.2.3 Source pre-melting and Cover Absorption

An examination of the coating process indicated that the most likely occurrence of surface contamination would be during the source pre-melting stage. This is a process step whereby the ground glass is heated with the electron beam until it has been melted down to a molten charge in order to drive off volatiles that make the glass spatter. During the pre-melting process a shutter is closed between the source crucible and sample substrates to prevent spatter from impinging upon the cells. The cells are not, however, shielded to the extent that they would be isolated from escaping gases and/or glass material from secondary scattering. In order to examine the effect of the pre-melting stage on cell performance, a number of cells were tested by subjecting them to the glass evaporation procedure up to and including the pre-melting step and then terminating the process. These cells were subsequently measured to determine if any short circuit current losses did in fact occur during the process

step. Using six solar cells in two pre-melting tests, an average current loss of $5.1\% \pm 1.3\%$ was measured. This value was quite a significant loss and was very close to the high and unaccounted for, thickness-independent loss observed earlier. See Table IV, experiment A.

This particular test was conducted prior to the observation that different amounts of current loss could occur for 2 ohm-cm and 10 ohm-cm cells. Consequently the 5.1% loss is only for 2 ohm-cm cells. With the possibility existing that since pre-evaporation losses were the major loss source for the cells, pre-melting could also manifest different losses for 2 ohm-cm and 10 ohm-cm cells, a pre-melting test was conducted using cells of both resistivities.

The results of this test showed a clear difference in cell losses, with the 10 ohm-cm cells experiencing an average 5.5% current loss and the 2 ohm-cm cells an average loss of 6.8% . This 1.3% loss difference between the two compares well to the 1.5% to 2.0% difference in total covered cell current loss observed between the total lot of 2 ohm-cm and 10 ohm-cm cells. (See the preceding Section 2.2.2.) See Table IV, experiment B.

The ensuing series of tests then consisted of depositing a cover on cells without exposing them to any pre-melting step. In the first approach, the crushed glass charge was pre-melted in a furnace set at 1055°C (N_2 atmosphere). Thus when the evaporation procedures were initiated on test cells, evaporation of the source began immediately after pump down. For a run consisting only of 2 ohm-cm cells an average current loss of 5.3% was measured (6 cells). Although still relatively high, it was approximately 1 to 2% less loss than had been observed in the previous covered 2 ohm-cm cell tests. See Table IV, experiment C.

A second test series tried a different approach at avoiding the pre-melting loss by reusing a charge from a previous evaporation. In the first run which was conducted with the normal pre-melting phase, 2 ohm-cm and 10 ohm-cm cells lost an average I_{sc} of 7.2% and 5.1%

A. Effect of Pre-melting exposure (six 2 ohm-cm cells)

Average cell I_{sc} before pre-melt	Average I_{sc} after pre-melt exposure - no cover	Average I_{sc} change (percent)	Standard deviation
137.4 mA	130.4 mA	-5.1%	$\pm 1.5\%$

B. Comparing pre-melting effect on 2 ohm-cm and 10 ohm-cm cells

Type	Quantity	Average I_{sc} before pre-melt	Average I_{sc} after pre-melt	Average I_{sc} change	Standard deviation
2 ohm-cm	3	135.9 mA	126.7 mA	-6.8%	$\pm 0.2\%$
10 ohm-cm	3	137.1	129.6	-5.5%	$\pm 0.6\%$

C. Fused source experiment (six 2 ohm-cm cells)

Average I_{sc} before covering	Average I_{sc} after covering	Average I_{sc} change	Standard deviation
138.0 mA	130.7 mA	-5.3%	$\pm 0.6\%$

D. Single charge - Double evaporation experiment

<u>With pre-melting</u>	Cell Type	Qty	Average I_{sc} Before covering	Average I_{sc} after covering	Average I_{sc} change	Deviation
	2 ohm-cm	2	134.8 mA	125.1 mA	-7.2%	$\pm 0.2\%$
	10 ohm-cm	3	138.2	131.1	-5.1	± 0.4
<u>Second evaporation</u>	2 ohm-cm	3	134.0 mA	126.1 mA	-5.9%	$\pm 1.6\%$
<u>No pre-melting</u>	10 ohm-cm	2	137.5	133.2	-3.1	± 0.5

Table IV
Pre-melting Influence on Cover
Absorption - Four Experiments

respectively. Replacing those test cells with new cells and again evaporating the same source (no pre-melting) both 2 ohm-cm and 10 ohm-cm cell groups exhibited reduced I_{sc} losses of 5.9% and 3.1% respectively. See Table IV, experiment D.

Although insufficient time was available for an in-depth examination of the actual degradation process and its peculiar resistivity-dependent behavior, a number of observations are readily available. First, the loss difference between 2 ohm-cm and 10 ohm-cm cells appears to occur during the pre-melting phase. This finding could relate to the different material dopant levels or different cleaning procedures for the two resistivities. Second, the loss value for the best 10 ohm-cm cells, at 3.2%, is equal to the loss that would be expected by a platelet system with no MgF_2 AR coating, i.e., essentially no optical absorption; just front surface reflection.

Consequently, preliminary efforts at avoiding a pre-melting stage in which the cells are subject to exposure has significantly reduced the cover absorption. In fact, examination of Figures 5 and 6 which show the I_{sc} loss versus cover thickness for 2 ohm-cm and 10 ohm-cm cells, respectively, indicate the elimination of the pre-evaporation loss mechanism leaves a cover system with, at most, 0.5% absorption per mil thickness.

2.2.4 Cover Stresses

Two techniques have presently been utilized in measuring cover stresses. Both require the measurement of the amount of bending a substrate-cover system exhibits after the glass deposition. The bending is then related to the stresses in the cover glass by one of the following relations (1).

(1) Chopra, Kasturi L. "Thin Film Phenomena" McGraw-Hill, New York, 1969

$$S = \frac{ED^2}{6rt(1-\nu)} ; \text{ used when } t < D \quad (1)$$

$$S = \frac{\sigma ED^2}{3L^2t(1-\nu)} \left(1 + \frac{et}{ED} \right) \quad (2)$$

where

S = film stress

D = substrate thickness

t = coating thickness

E = Young's moduli of substrate $\approx 6.1 \times 10^{11}$ dynes/cm² for quartz
 9.5×10^{11} dynes/cm² for silicon

ν = Poissons ratio for substrate ≈ 0.25

L = free length of substrate

σ = deflection of the substrate

r = radius of curvature of bent substrate

e = Young's modulus of glass deposit $\approx 8.9 \times 10^{11}$ dynes/cm²

For slightly bent substrates, equation (2) is employed; however, for severely bent substrates it is much easier to measure the radius of curvature and use equation (1).

Typically, glass witnesses 1.5 to 6.0 mils thick have been employed for test substrates.

Preliminary experiments had indicated that the stresses in the deposited glass covers were related to the electron beam power level, and that higher power levels produced lower stressed covers. At the same time, it appeared that covers produced with high power levels also exhibited high absorption (approximately 20%). Figure 7 plots cover stress versus electron beam power level. Clearly cover stresses have been reduced by increasing the beam power.

Defining a safe maximum stress level is a difficult procedure requiring considerable knowledge of the material properties and environmental conditions which will be experienced by the integral cover-solar cell

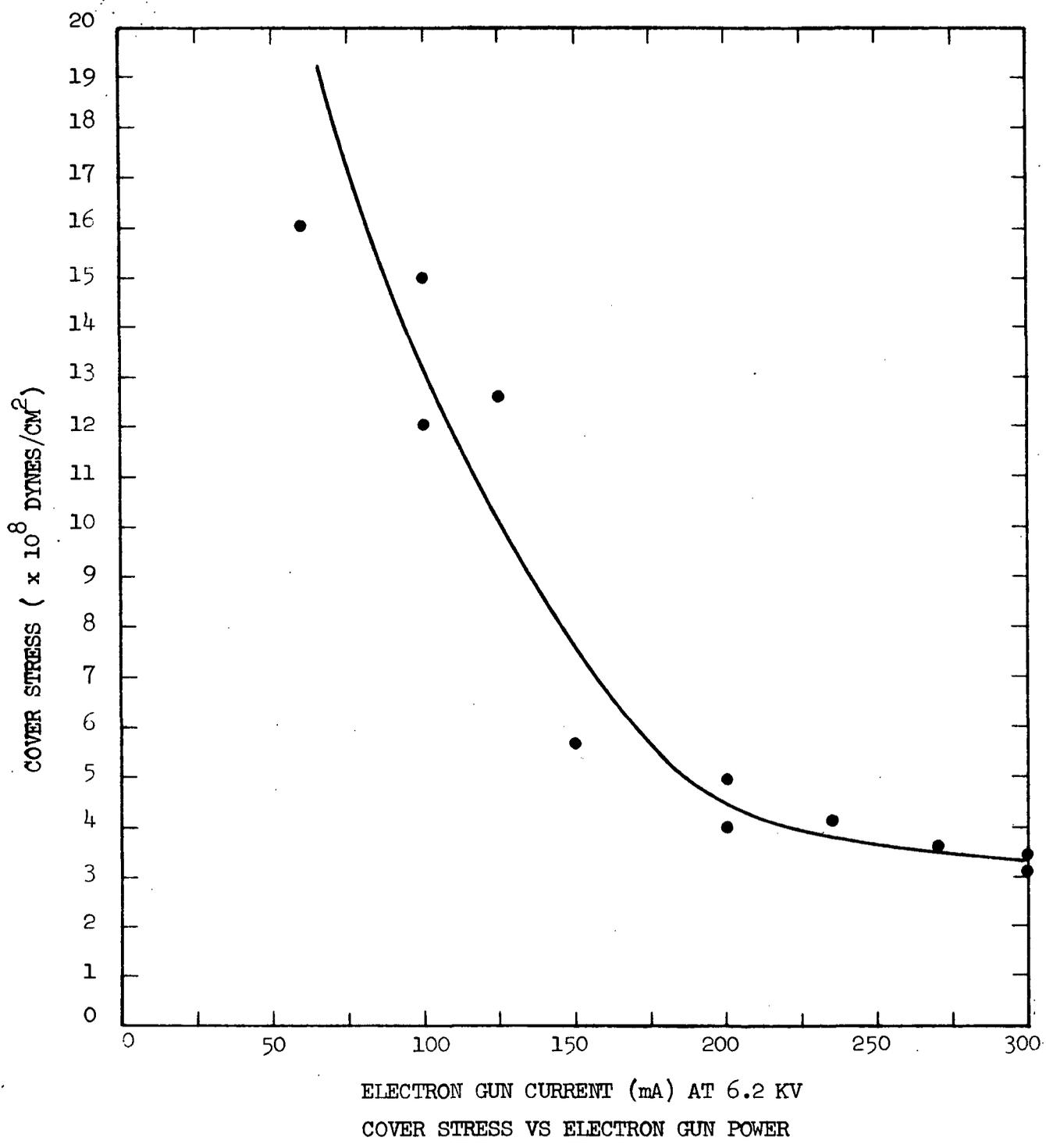


FIGURE 7

system. Consequently Heliotek attempted to incorporate all techniques for minimizing the cover stress without incurring any significant loss in given environmental stability and transmission. As a reference position, all covers fabricated previous to this study phase have used an electron beam setting of 100 mA and 6.2 kV. This was found to correspond to a stress level of approximately 1.4×10^9 dynes/cm². These covers have shown the ability to withstand severe thermal shock and cycling tests, and high humidity exposures without damage or degradation. Such a stress level has not been found to be detrimental to the cover-cell system. Consequently by utilizing beam power levels necessary to give cover stresses on the order of 4×10^8 dynes/cm² a safety factor of 3 is obtained. A possible explanation for the stress versus beam power level dependence is discussed in Section 2.4.

A second set of data obtained in the stress versus power level experiments is the cover absorption versus power values exhibited in Figure 8. Although there appears to be a slightly greater amount of absorption with the higher power level covers, it is not so significant as the amounts observed in the preliminary experiments which indicated losses on the order of 20%. The absorption values plotted are obtained by measuring the solar cell short circuit current loss when the cover is deposited. A constant loss of 3% is subtracted from the current loss values to account for first surface cover reflection and cell AR coating mismatch (inasmuch as these cells were coated with SiO_x). Consequently, the remaining current loss should be equivalent to the cover absorption.

The data in Figure 8 does indicate some increase in absorption for high power levels. However, a number of power level independent possibilities exist which can affect absorption enough to explain the small losses observed in Figure 8. One absorption source is

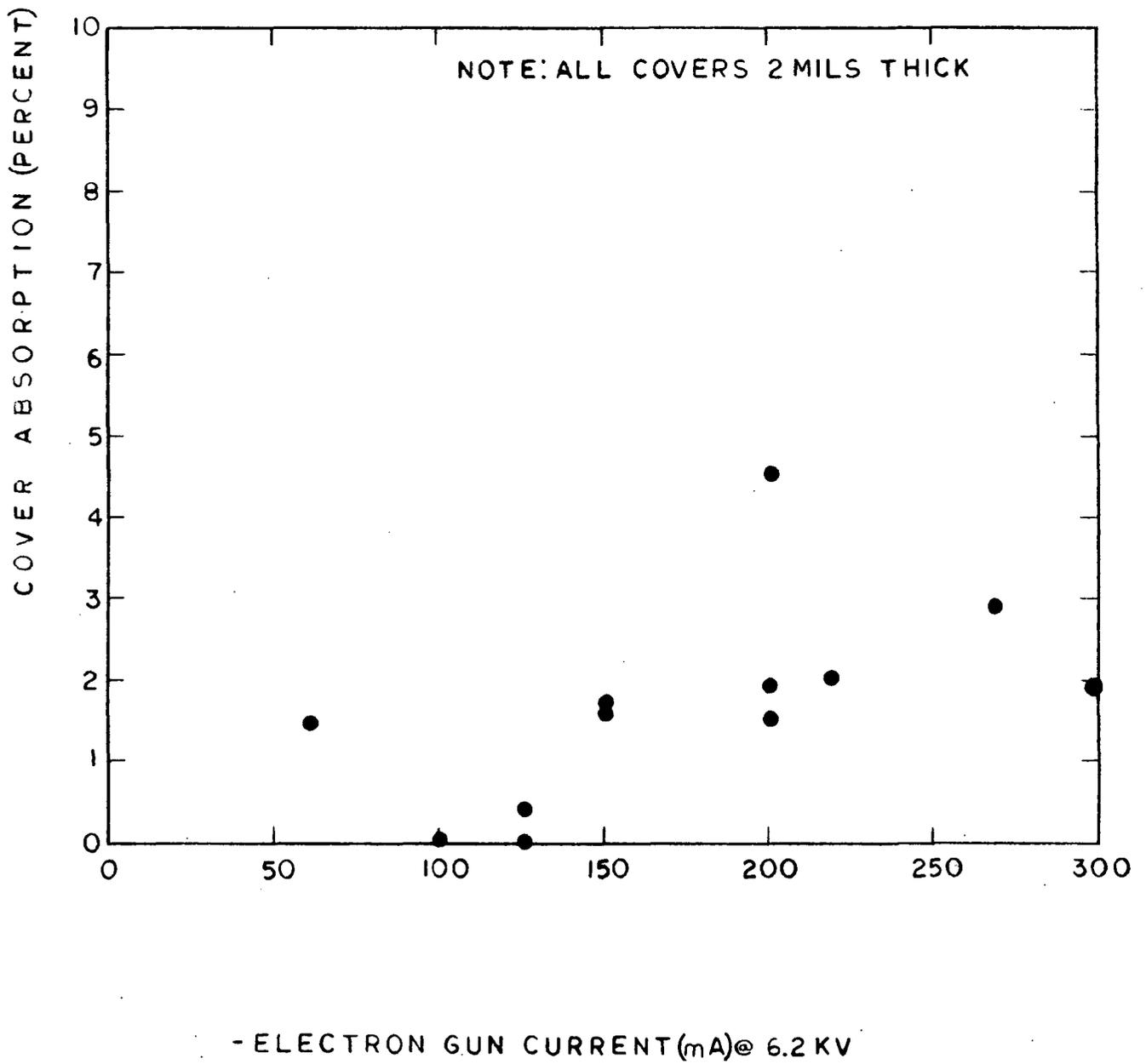


Figure 8. Cover Absorption vs. Electron Beam Power

associated with the proximity of the substrate to the source. It is felt that stray electrons can impinge upon the substrate-glass samples possibly producing low energy defects and causing the deposit to have a brown coloring. This is evident from a number of tests wherein fixed evaporation parameters of 200 mA at 6.2 kv were used. Samples at 6 inches source-to-substrate distance exhibited 10-12% short circuit current loss and samples at 11 inches exhibited 5-6% short circuit current loss (including glass reflection losses in both cases). Furthermore, the preliminary tests which exhibited near 20% loss were conducted at approximately 6 inches source-substrate distance. Consequently, the larger distances are desirable. Of course, more source material and evaporation time is required to offset the inverse square loss.

A second loss mechanism appears to lie in the contamination of the lower levels of the source material, possibly due to glass falling back into the crucible from regions of the bell jar interior. The evidence for this phenomenon arises from tests using fixed source to substrate distances and fixed electron gun parameters. Generally, all evaporations taking some time duration "t" or less will exhibit 5% short circuit current loss, whereas a slight lengthening of the evaporation time will be marked by significantly higher current losses. The threshold time appears to correspond to a utilization of approximately 70% of the source material. In these situations, up to 100% greater cover absorption can be obtained by evaporating only 12% longer. Consequently, the absorption doesn't appear to be related to cover thickness, but rather is related to the amount (percentage) of source material used. It is felt that either through the use of crucible reloaders, larger crucibles, or multiple crucibles, longer evaporation times can be obtained without contaminating the covers.

A third possibility also exists for affecting cover absorption. This is cleanliness of the bell jar interior. With the work schedule imposed by the contract tasks, the length of time to completely clean the bell

jar interior of glass deposits prohibited cleaning between each evaporation. Experience indicated that two cleanings per week were sufficient in preventing any gross contamination of the cover system. It is not impossible, however, that in some instances a small amount of contamination might occur.

This problem is compounded by the use of TiO_x AR coatings. TiO_x has clearly been shown to enhance the covered solar cells output current. However, due to scheduling it is necessary to perform the TiO_x AR coating in the same chamber in which the glass cover is deposited. During the preparation of state-of-the-art sample cells, it was observed that cells covered after the chamber had been utilized for TiO_x AR coating showed particularly large current losses. Further tests do indicate the TiO_x provides a major contaminant source for the cover process and unless sufficient time is allowed for cleaning, AR coating and glass covering must be accomplished in separate systems.

Consequently, all present loss mechanisms, since they appear predictably in relation to the situations mentioned above, should be considered matters of equipment design and scheduling. It is important to realize that the best covered cells compared favorably to conventional platelet covered cells in transmission, and environmental testing (see Section 2.3).

The efforts aimed at reducing cover stresses have provided a cover system with an acceptable low stress. Initial thermal and humidity tests showed that the high stress covers (1.4×10^9 dynes/cm²) could withstand typical space-type requirements. The low stress cells (typically having a third to a fourth the stress of the high stress covers) have performed as well in these tests and would be expected to have a greater margin of stability because of the lower stresses.

2.2.5 OPTIMIZED 1720 GLASS COVER SUMMARY

With the completion of the work on minimizing cover stresses, a cover system exhibiting high transmission, humidity stability, and low stress has been produced. High evaporation rate samples have low stresses and high transmission and have shown the ability to withstand humidity and thermal shock environments in preliminary tests (environmental test results are in following sections). The major process parameters of the optimized 1720 glass integral cover system are summarized below.

- A. AR Coating.- TiO_x has provided the highest output cells with integral covers. In order to facilitate coating reproducibility the electron gun technique is being utilized for evaporations rather than the resistance heating method used earlier in this contract.

- B. Dielectric Cover.- The evaporated 1720 glass has exhibited an excellent combination of humidity and thermal shock and cycle endurance along with good transparency and low cover stresses. The following evaporation parameters have been determined to be near optimum and will be used for fabricating covers for further environmental testing.

Substrate Temperature	200°C - 275°C
Source to Substrate Distance	11"
Electron Gun Power	225 - 275 mA at 6.2 kvolts
Bell Jar Pressure	2×10^{-5} to 5×10^{-4} torr
Evaporation Time	Approximately 35 minutes for 2 mil thickness.

The source to substrate distance and electron gun power level were chosen to minimize the cover darkening mechanisms described earlier,

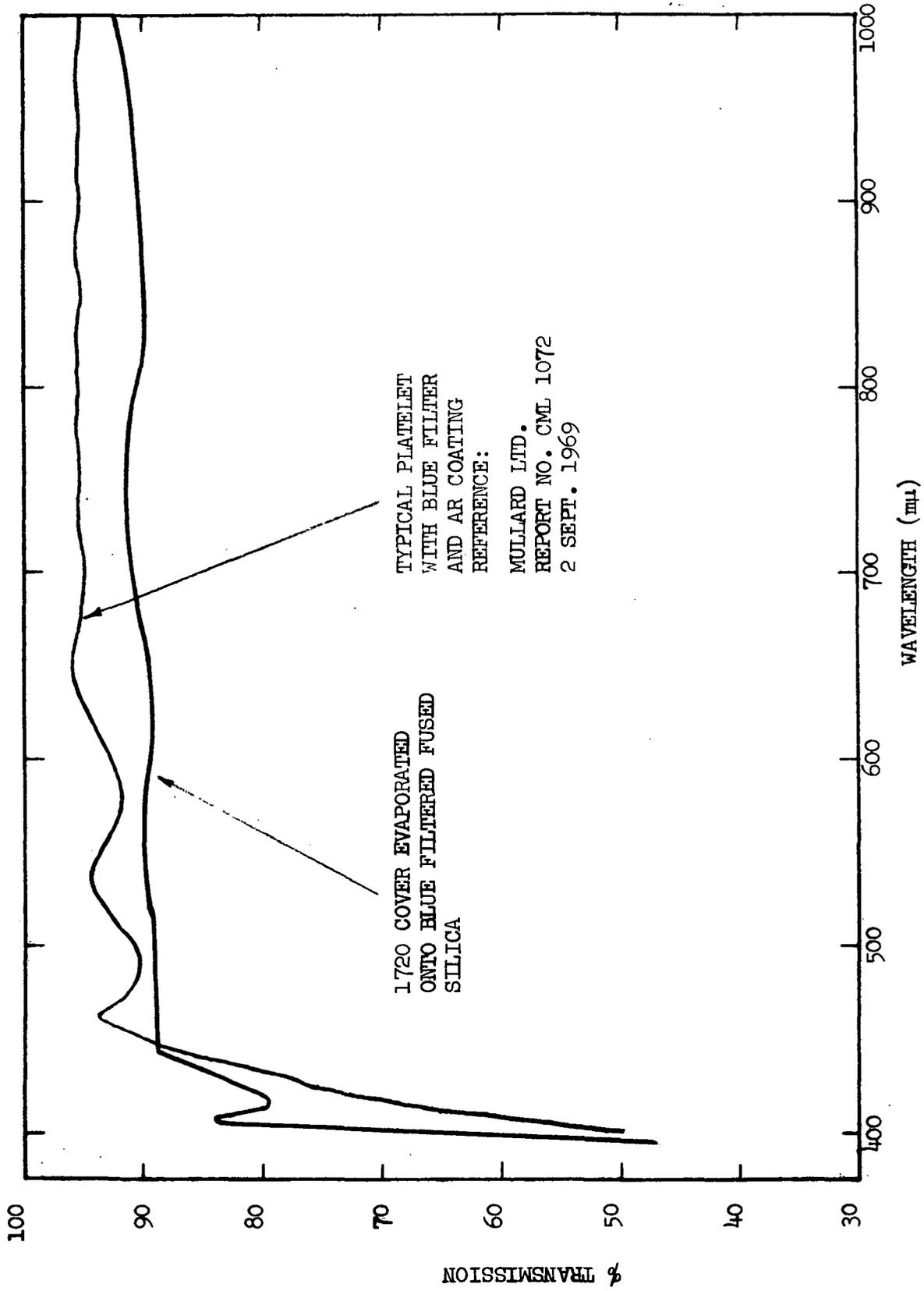
provide a constrollable and repeatable evaporation rate, and allow a reasonably short evaporation time for attaining 2 mil thick covers. The cleanliness requirements of the deposition process unfortunately prohibit the use of a one-step AR coating-glass cover deposition procedure. It has been found necessary to thoroughly clean the interior of the bell jar between AR coating depositions and glass cover depositions to prevent excessive cover absorption (approximately 6-10%). Consequently, a two-step evaporation is utilized. A transmission curve for a typical optimized 1720 cover evaporated onto a blue-filtered 12 mil thick quartz substrate is shown in Figure 9. No AR coating has been applied to the cover's top surface or witness' rear surface. Such coatings would provide approximately 4% increase in transmission. A typical platelet with blue reflecting filter and AR coating is presented for comparison. Typical cells with optimized 1720 evaporated covers are shown in Figure 10.

2.3 ENVIRONMENTAL TESTS

2.3.1 Humidity and Thermal Testing

A beneficial side-effect of the investigation of pre-melting and cover absorption was the improvement in the cover's ability to withstand high humidity, thermal shock, and thermal cycle environments. Throughout the entire testing period a few cells from each test group (substrate temperature tests, cover thickness tests, etc.) have been placed in a humidity chamber set at 95% RH, 65°C conditions. The solving of humidity problems is one of the program's major goals and, consequently, and improvements made here would provide the basis for a series of experiments designed to solve the humidity problem.

Typically for all systems in which cells were exposed to a pre-melting step four to six hours of exposure in the severe humidity environment caused peeling of 80% to 100% of the cover. The examination of different cell substrate temperatures, cover thicknesses, cell resistivities, and AR coatings, all proved to have no significant impact



TRANSMISSION OF OPTIMIZED 1720 COVERS
 1.5 MILS 1720 EVAPORATED ONTO 12 MILS FUSED SILICA (WITH BLUE FILTER)
 NO AR COATING

FIGURE 9

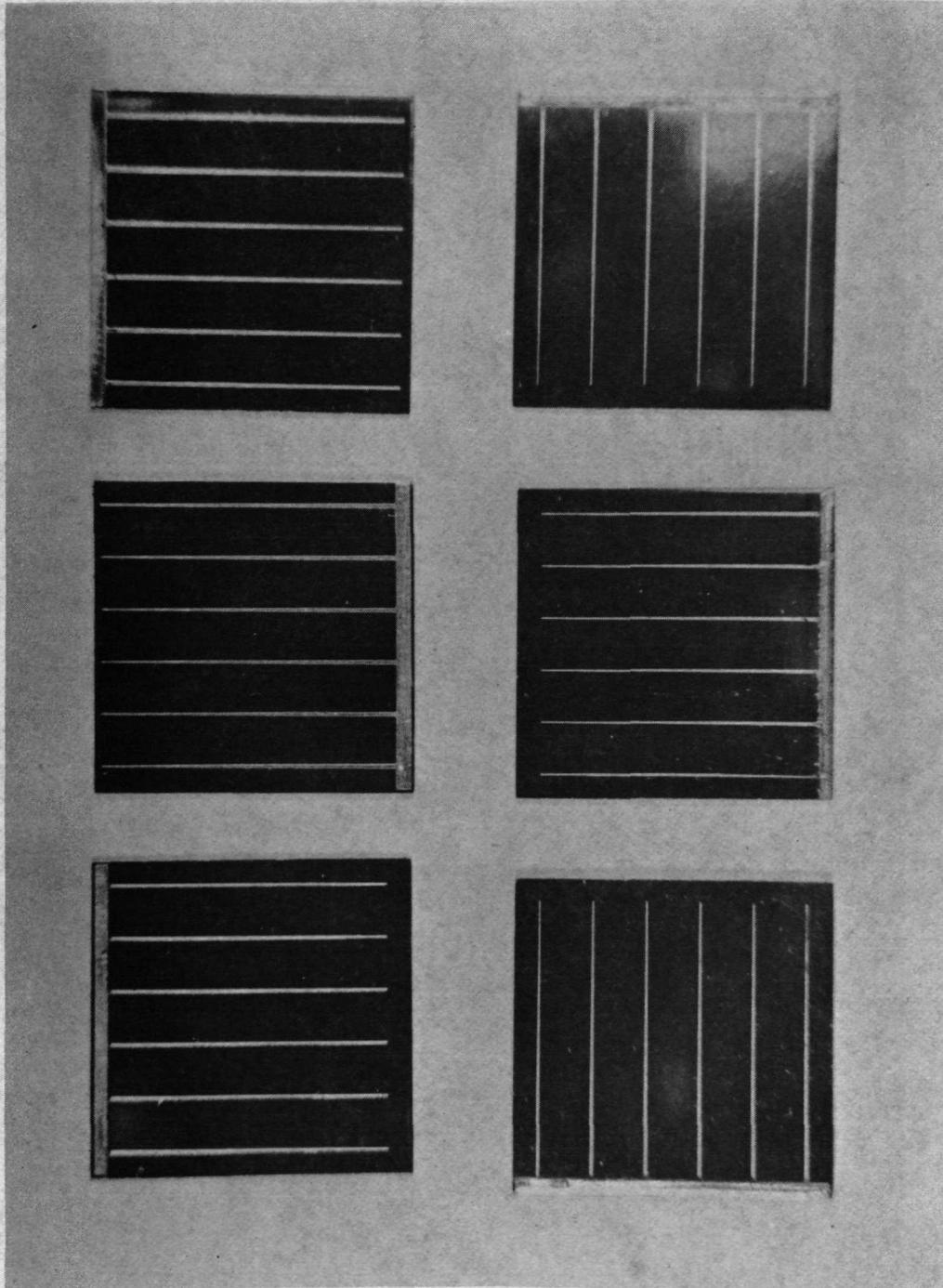


Figure 10. Typical Cells with 1720 Integral Glass

on the cover's humidity resistance. In sharp contrast, cells that have been covered without exposure to the pre-melting step have exhibited marked improvement in humidity resistance as described below.

Cell covers were 2 mils thick with the exposed contact regions covered with solder. These samples are representative of the cells submitted to Goddard as state-of-the-art items and include TiO_x AR coatings. Of five cells tested for a period of one month, two have exhibited no visible peeling or other cosmetic changes, and three have exhibited approximately 5% peeling. These samples are significantly more humidity resistant than samples prepared at the beginning of this contract. For the peeled cells, all cover loss occurred during the first week of exposure.

It is felt that the slight peeling (5%) was due to incomplete system cleaning prior to evaporation. The sensitivity to the pre-melting exposure points out the requirement for clean cell surfaces and contamination free vacuum systems in order to provide good integral covers.

The second environmental aspect examined was thermal shock-thermal cycle behavior. This test used covered cells both from groups which had experienced pre-melt exposure and groups without pre-melt exposure. The cells were subjected to a number of test sequences, with the low temperature limit of $-196^{\circ}C$ provided by immersion in LN_2 . As summarized in Table V, the cells not exposed to pre-melting showed up substantially better than the cells subjected to pre-melting contamination.

2.3.2 Ultraviolet Radiation Degradation

Experiments conducted at Heliotek indicate that evaporated 1720 covers are not significantly degraded by ultraviolet radiation.

TABLE V
Glass Cover Thermal Shock and Cycling Test Results

Number of Cells in Test	Test Conditions			Test Observations
	Evaporation Conditions	Number of Cycles	Temperature Range	
4	Pre-melt exposure	25	-195°C → 100°C	All cells show 25% to 35% cover peeling.
2	No pre-melt ex- posure; source melted in furnace	25	-195°C ↔ 100°C	Slight peeling (~ 5%)
		25	-195°C ↔ 100°C	Increased peeling (~ 10%)
		25	-195°C ↔ 250°C	No further change
		25	-195°C ↔ 300°C	No further change
2	No pre-melting exposure; source premelted in vacuum chamber without cells	25	-195°C ↔ 100°C	No measurable peeling
		25	-195°C → 200°C	
		25	-195°C ↔ 250°C	
		25	-195°C → 300°C	

In these experiments an ellipsoidal Shannon luminescence reflector, with a 1000 watt mercury arc was used to radiate samples in air. The G.E. BH6 quartz bulb lamp was air cooled while the samples were cooled to 30°C by mounting them on a water cooled aluminum block.

Measurements were taken of the covered cell assemblies with a model 1206 Spectrosun solar simulator. In these measurements the short circuit current was recorded.

The sample radiation dosage can be estimated by computing the total incident power for various bandwidths, comparing these with the corresponding power for the Johnson curve and then multiplying by the total exposure time.

These lamp-Johnson curve comparisons are exhibited in Table VI where λ_{\max} indicates the high end of the included band. The lower limits can be taken as approximately 0.25 microns for all.

All covers consisted of 0.002 inch evaporated #1720 glass. Figure 11 exhibits the resulting degradation for samples versus lamp exposure time. The asymptotic degradation for the samples was approximately 1.4% in short circuit current which is comparable to glue-on platelet systems.

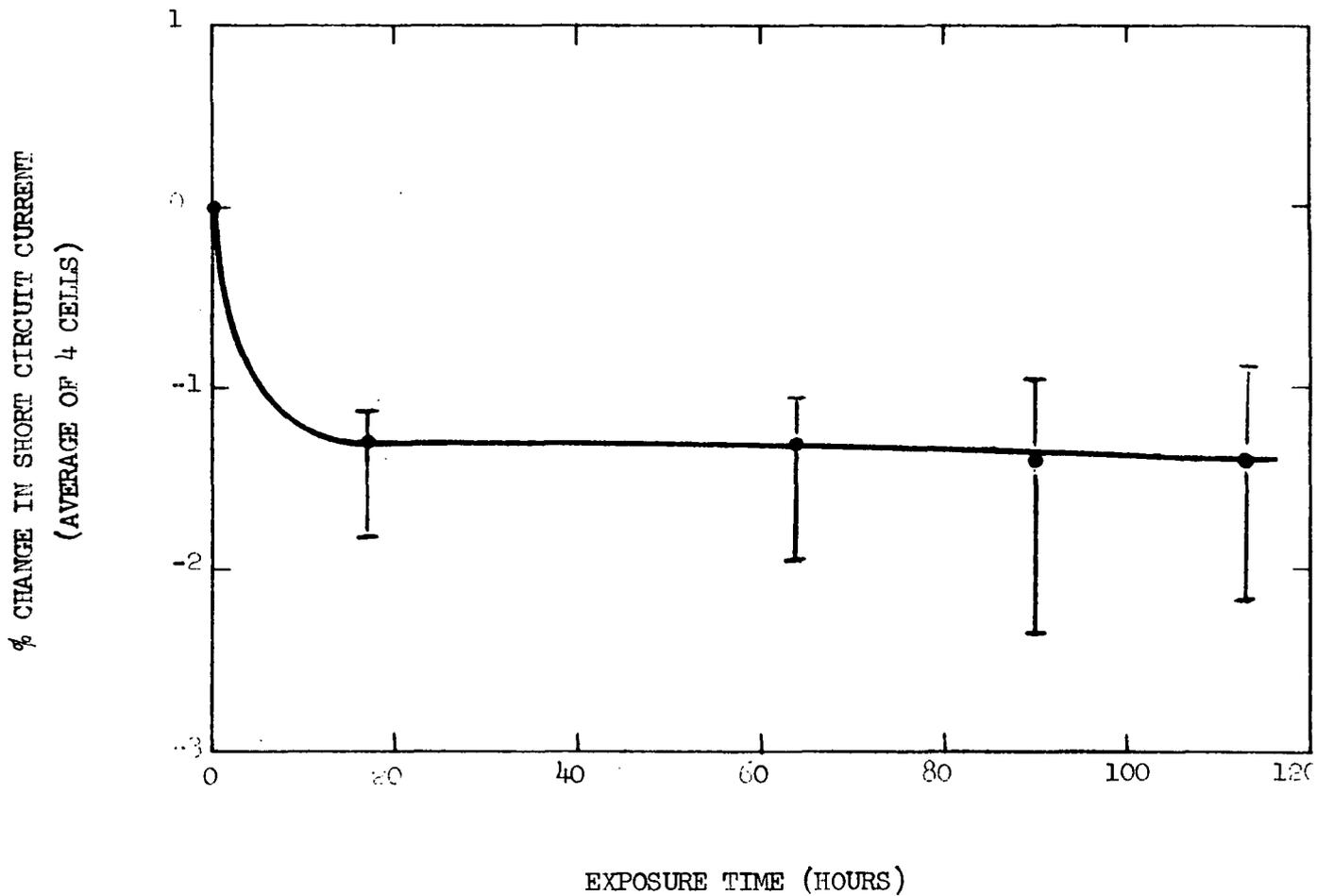
2.3.5 1 MEV Electron Radiation Tests

The purpose of conducting electron radiation tests on integral coverslips was to establish what effect this environment would have on the optical transmission (i.e. darkening or absorption). A high voltage Van de Graaff generator was used to produce the 1 MEV electrons and a Faraday cup to count and integrate the electron flux. The solar cells and coverslip samples were mounted on a rotating wheel behind a shield which had a cut-out portion upon which the electron beam was focused.

λ Max (Microns)	Solar Energy mw/cm^2 (Johnson)	Lamp Radiant Energy at Specimen Position mw/cm^2	Equivalent Sun AMO
0.45	22	220	10
0.40	12	158	13
0.32	4	74	19

COMPARISON OF SOLAR RADIATION AND
G.E. BH6 MERCURY LAMP RADIATION

TABLE VI



EXPOSURE TIME (HOURS)

UV RADIATION DEGRADATION TO SOLAR CELLS
WITH 2 MIL THICK EVAPORATED
1720 GLASS COVERS

FIGURE 11

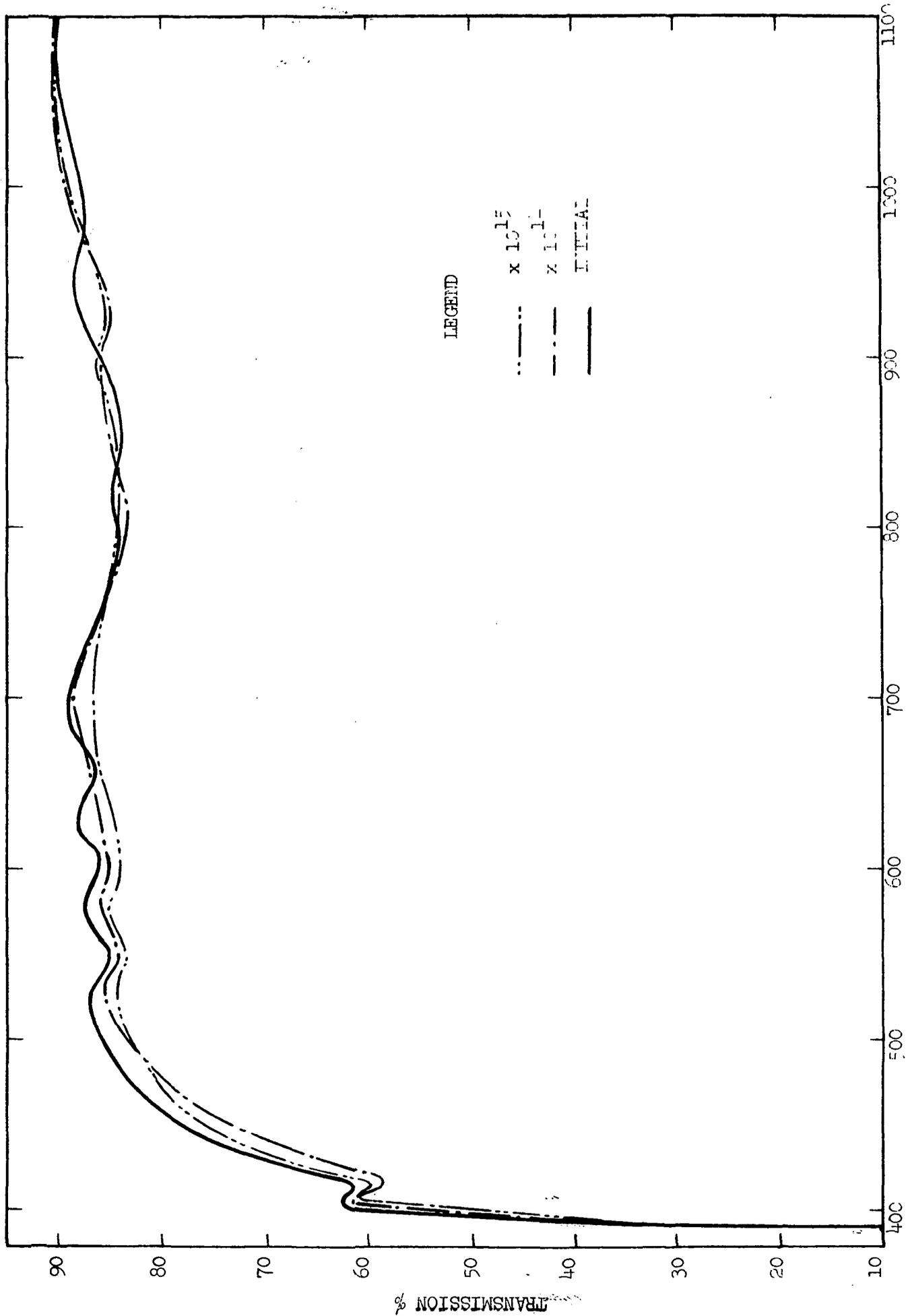
As the samples rotated into the cut-out, each received its radiation dosage and subsequent shielding while each of the other samples were irradiated. The samples were mounted on a copper heat sink so that a test temperature of $\sim 30^{\circ}\text{C}$ was maintained.

The samples consisted of glass covers, 2 mils in thickness, evaporated onto 6 mil thick blue-filtered quartz platelets. Transmission curves were obtained for all samples prior to irradiation. These samples were subjected to 10^{14} 1 MeV electrons, after which transmission curves were obtained. Following this, an additional exposure to 9×10^{14} 1 MeV electrons was performed followed by a third series of transmission measurements.

After 10^{15} 1 MeV electrons, approximately 2.5% transmission loss was observed in the region 400 to 700 $\text{m}\mu$ with approximately 1.5% loss from 700 $\text{m}\mu$ through 1100 $\text{m}\mu$, including darkening in the quartz substrate. This degradation is considered to be quite reasonable and will allow 1720 glass covers to be excellent candidates for lightweight array utilization. Transmission curves for a typical sample are shown in Figure 12. This particular cover is slightly more absorbing than the best covers achieved during this program, but does represent the type and extent of radiation darkening observed.

2.4 INTREPRETATION OF #1720 GLASS PERFORMANCE

Major findings under this study include the critical nature of the source pre-melting phase on cover absorption and humidity resistance and the reduction of cover stresses with increasing electron beam power. The first finding can be understood in terms of cell surface contamination. The original evaporation process step which pre-melted the source at the same time shielded cells were present in the vacuum system most likely deposited an absorbing amorphous layer on the cell surface. Altering the pre-melting procedure essentially solved



COVER TRANSMISSION AS FUNCTION OF 1 MEV ELECTRON EXPOSURE
 2 MIL THICK 17°C COVER OF 1.5 MIL THICK FUSED QUARTZ

FIGURE 12

problems of cover absorption and humidity induced peeling.

The second finding is not as well explained. In order to gain more information, samples of the raw #1720 glass, source residue and deposited glass cover were subjected to a spectrographic analysis in order to determine if any composition change had occurred. Although time was not available to run extensive analyses against various process parameters, such as beam power, it is evident that the deposited glass differs significantly from the raw glass and source residue. The spectrographic analysis shows that the deposited cover has much lower concentrations of alkali oxides (< 1%) and is higher in silicon oxides. The results of the heavy metal analysis are shown in Table VII. It is assumed that in addition to these elements listed, the remaining composition is primarily oxygen. This finding is quite compatible with the results of this program's radiation test results. It would normally be expected that large quantities of alkali oxides in a glass would lead to severe darkening under electron and U.V. irradiation. The performance of the deposited covers being quite to the contrary would then be explained by the low occurrence of the alkali oxides. In view of the change in glass composition during the evaporation, it is quite reasonable to expect the deposited glass composition, and hence cover stress, could be a function of the electron beam power. During this program insufficient time was available for running correlations between these two items, but this could prove to be a worthwhile aspect of further investigations in the near future.

2.5 EVAPORATION OF 7070 GLASS AND 1720-7070 GLASS MIXTURES

Since 7070 Glass has been considered a radiation resistant cover, experiments were conducted in evaporating #7070 Glass. Starting with the evaporation parameters initially used for evaporating 1720 Glass (100 mA at 6.2 kvolts), the electron-gun current levels were varied in a number of evaporations so as to observe any effects on the

	MANU- FACTURER'S DATA	RAW GLASS	SOURCE RESIDUE	DEPOSITED COVER
Si	26.6	23. %	21. %	46. %
Al	14	11.	13.	0.025
Ca	4.9	7.2	8.2	0.0098
Mg	2.6	10.	9.9	0.068
Na	0.7	1.2	0.95	Nil
Fe	--	0.19	0.16	0.052
Zr	--	0.15	0.18	Nil
B	0.17	0.37	0.31	0.029
Mn	--	0.0063	0.0072	Nil
Pb	--	0.0082	0.021	Nil
Ga	--	Trace	Trace	Nil
Cu	--	0.0017	0.0055	0.00015
Ti	--	0.0090	0.012	0.031
Co	--	0.0029	0.0026	Nil
Sr	--	0.026	0.024	Nil
Cr	--	0.0082	0.0071	0.0021
Ag	--	Nil	Nil	Trace

HEAVY METAL ANALYSIS OF #1720 GLASS

TABLE VII

cover. Electron beam current levels were varied from 60 to 200 mA. In all cases glass fibers are deposited on the solar cells producing high short circuit current losses. Cell current losses for 2 mil thick covers were typically on the order of 10%. In those regions where fibers were not deposited, visual inspection did indicate a highly transparent glass cover. However, this finding is merely academic unless fiber formation can be eliminated. In most instances these fibers did not appear to affect the cover's mechanical integrity, although for thin covers (approximately 0.5 mils) the fibers could be removed by rubbing with an eraser, leaving the cell uncovered by glass immediately underneath the fiber's original position. Humidity tests of the 7070 cover (65°C 95% RH) show this material to have good humidity resistance, comparable to the best 1720 covers. A number of the 7070 samples evaporated at 100 mA beam current were also measured so as to determine cover stresses. The results were quite comparable to the 1720 glass with stresses found to be on the order of 1.3×10^9 dynes/cm². (See Figure 7.) Typical cells with evaporated 7070 glass are shown in Figure 13.

In a second sequence of tests, a number of mixtures of 7070 and 1720 glass were evaporated which did provide a transparent and adherent cover. The evaporating source characteristically exhibited properties of both materials. For instance, the small surface bubbles of 7070 glass and the spitting and larger bubbling of 1720 glass were both evident. Mixtures of 7070 glass in 1720 glass ranging from 33% to 75% by weight, although reducing the formation of fibers (no fiber formation is observed where 7070 glass constitutes approximately 60% of the mixture or less), did provide deposited covers having high stresses (1.6×10^9 dynes/cm² for the 70% 7070-30% 1720 glass mixture). In lieu of the above described work it is felt that the 7070 glass does not compare favorably to the 100% 1720 glass covers and further work with 7070 was discontinued.

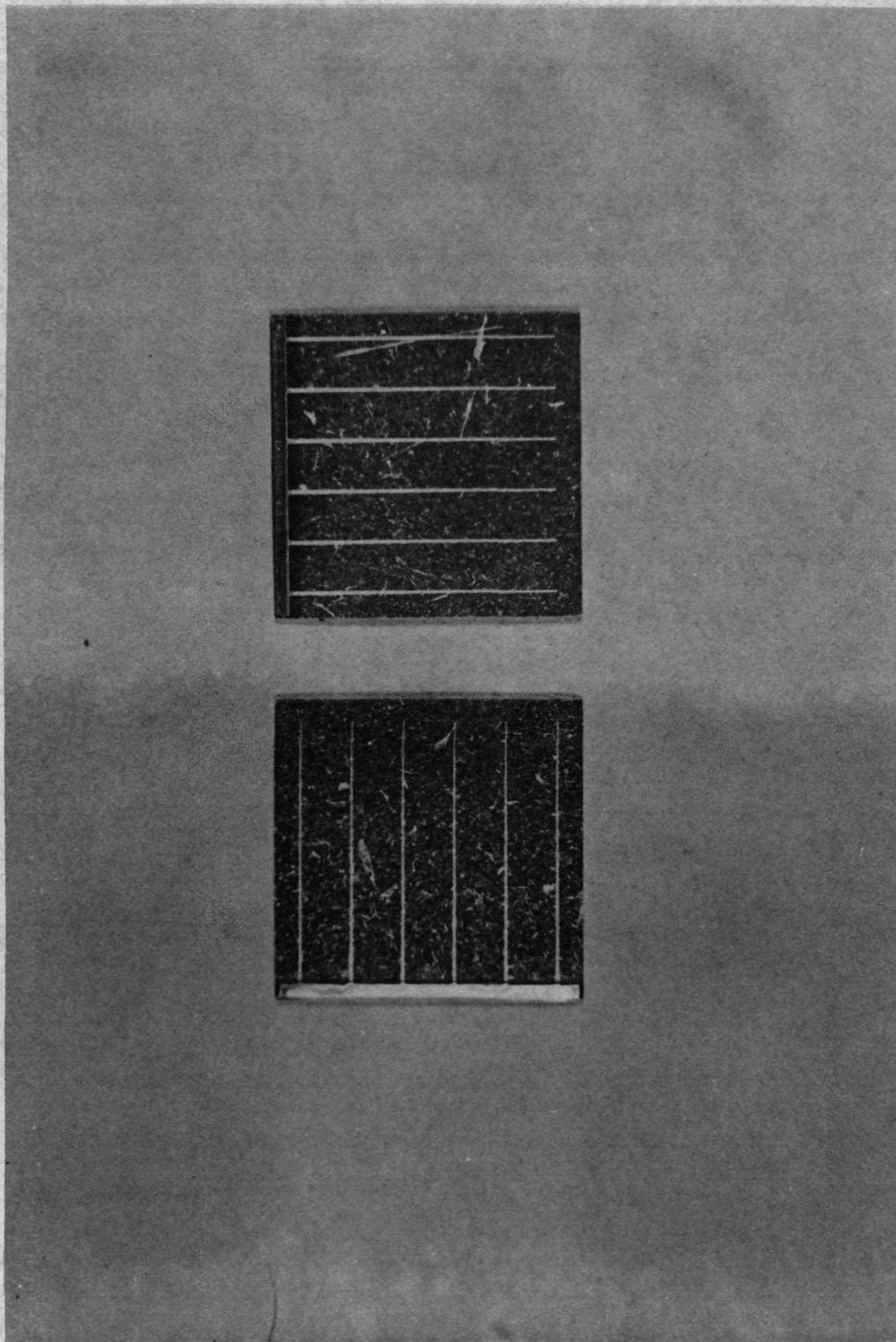


Figure 13. Typical Cells with 7070 Integral Glass

3.0 NEW TECHNOLOGY

- A. Integrally glassed cell of improved efficiency through the use of TiO_x cell AR coating.
- B. Optimized parameters for electron evaporated integral shields on solar cells.

4.0 CONCLUSIONS

In the study of cell AR coatings, TiO_x was shown to be a more desirable solar cell antireflection coating than CeO_2 or SiO_x . Both CeO_2 and TiO_x AR coatings provided significantly more cell output (up to 6%) than SiO_x AR coated cells, when covered by cover glass materials. CeO_2 coatings, however, were not capable of surviving space-type qualification requirements, in particular, abrasion tests.

Evaporation of TiO_x coatings was observed to be a potential glass cover contamination source when a single vacuum system is employed for both evaporations, necessitating a two step process with a thorough system cleaning between AR and glass depositions.

For the evaporated dielectric coating part of the program efforts, three major problem areas were defined for investigation. These were high cover absorption, poor humidity resistance and high cover stress. The cover absorption and humidity resistance problems have been corrected with the identification of a degradation mechanism occurring during the pre-melting phase of the cover evaporation. Correction of this situation provides covers which exhibit no more than 0.5% absorption per mil thickness with greatly improved humidity resistance. Furthermore, this improvement has been manifested in improved thermal shock-thermal cycling results.

The cover stress has been shown to decrease with increasing beam power level. This is thought to be due to a slight change in the chemical composition of the deposited glass. Spectrographic analysis has shown that the deposited glass differs significantly from the raw glass in that the deposited cover has a higher percentage of silicon oxides and

very small amounts of alkali oxides (<1%). Cover stresses obtained by optimizing the beam power were considered sufficiently low to be acceptable for space-type hardware use ($\sim 4 \times 10^8$ dynes/cm²).

Evaporation parameters for optimized covers were determined, and samples so prepared were subjected to environmental tests. The covered samples survived humidity, thermal cycles, and thermal shock tests with no peeling in most cases. Some partial failures were noted in humidity testing, although this was felt to be attributable to contamination of the vacuum chambers. Minimal cover darkening was noted in 1 MeV electron and U.V. irradiations tests. At 10^{15} 1 MeV electron irradiation levels, approximately 2-3% cover darkening was noted and U.V. degradation appeared to plateau at a total loss of 1.4%. These are all reasonable levels.

Additionally, investigation of the effect of the cell substrate temperature during cover deposition showed a strong relationship between coating deposition rate and temperature with faster coating buildup occurring for lower substrate temperatures. A power point degradation at substrate temperatures of 300°C and greater was also observed, so that all present covering is done at lower temperatures.

Results of those efforts indicate that the electron beam evaporation of 1720 glass can provide space qualifiable cell covers. They should offer the significant advantages, over glue-on platelets, of complete cell active area coverage and low cost.

Random poorer performance of covers in electrical and environmental tests appears to be attributable to contamination of the vacuum system by materials during the TiO_x AR coating of cells, indicating that the vacuum system be thoroughly cleaned between AR coating and glass evaporation or that, even better, separate systems be employed.

Cells using 7070 glass or 7070/1720 glass mixtures showed no advantages over the 1720 glassed cell and, in fact, were of poorer quality.

5.0

RECOMMENDATIONS

- A. It is recommended that the source of the occasional cover contamination noted within be further investigated so that procedures can be determined for elimination of the problem.
- B. It is recommended that analysis of the glass composition be extended and the effects of various operational parameters, such as electron beam power level and substrate temperature, be so examined.
- C. The examination of the electron beam technique for evaporating dielectric covers should be extended so that a large quantity of covered cells can be fabricated over a period of time in order to do a comprehensive qualification test of the system. This step should follow after steps A and B above.
- D. Since a large number of space missions are in high radiation environments where thick shielding is required, the work should be extended to cover thicknesses greater than 2 mils.