AD-A015 840

STRESS FREE APPLICATION OF GLASS COVERS FOR RADIATION HARDENED SOLAR CELLS AND ARRAYS

Allen R. Kirkpatrick, et al

Simulation Physics, Incorporated

Prepared for:

Air Force Aero Propulsion Laboratory

June 1975

AFAPL-TR-75-54

296073

STRESS FREE APPLICATION OF GLASS COVERS FOR RADIATION HARDENED SOLAR CELLS AND ARRAYS

SIMULATION PHYSICS, INC.
BURLINGTON, MASS.

AUGUST 1975

TECHNICAL REPORT AFAPL-TR-75-54
INTERIM REPORT FOR PERIOD JANUARY 1974 – JUNE 1975

Approved for public release; distribution unlimited

Reproduced by
NATIONAL TECHNICAL
INFORMATION SERVICE
US Department of Commerce
Springfield, VA. 22151

AIR FORCE AERO PROPULSION LABORATORY
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio 45433

NOTICE

This Interim Technical Report has been submitted by Simulation Physics, Inc. under Contract F33615-74-C-2001. The effort is sponsored by the Air Force Aero Propulsion Laboratory, Air Force Systems Command, Wright-Patterson AFB, Ohio under Project 3145, Task 314519 and Work Unit 31451948 with Capt. John M. Green/POE-2 as Project Engineer. Allen R. Kirkpatrick of Simulation Physics, Inc. was technically responsible for the work.

This report has been reviewed by the Information Office (ASD/OIP) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

John M Green
John M. Green, Capt. USAF

Joseph Wise
Joseph F. Wise/Technical Area Manager
Solar Energy Conversion

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (*When Data Entered*)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS
BEFORE COMPLETING FORM

1. REPORT NUMBER AFAPL-TR-75-54	**2. GOVT ACCESSION NO.**	**3. RECIPIENT'S CATALOG NUMBER**
4. TITLE (*and Subtitle*) STRESS FREE APPLICATION OF GLASS COVERS FOR RADIATION HARDENED SOLAR CELLS AND ARRAYS		**5. TYPE OF REPORT & PERIOD COVERED** Interim Technical Report January 1974 thru June 1975 **6. PERFORMING ORG. REPORT NUMBER**
7. AUTHOR(s) Allen R. Kirkpatrick John A. Minnucci		**8. CONTRACT OR GRANT NUMBER(s)** Air Force Contract F33615-74-C-2001
9. PERFORMING ORGANIZATION NAME AND ADDRESS Simulation Physics, Inc. 41 "B" St. Burlington, MA 01803		**10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS** 31451948
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Aero Propulsion Laboratory Wright-Patterson AFB, Ohio 45433		**12. REPORT DATE** June 1975 **13. NUMBER OF PAGES** 42
14. MONITORING AGENCY NAME & ADDRESS (*if different from Controlling Office*)		**15. SECURITY CLASS.** (*of this report*) Unclassified **15a. DECLASSIFICATION/DOWNGRADING SCHEDULE**

16. DISTRIBUTION STATEMENT (*of this Report*)

Approved for public release; Distribution Unlimited

17. DISTRIBUTION STATEMENT (*of the abstract entered in Block 20, if different from Report*)

D D C

OCT 9 1975

C

18. SUPPLEMENTARY NOTES

19. KEY WORDS (*Continue on reverse side if necessary and identify by block number*)

20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

This report describes the first sixteen months of a two and one half year program to develop a practical integral protective cover for silicon solar cells. The report discusses selection of Corning 7070 borosilicate glass as an optimum cover material and explains the mechanics of the electrostatic field-assisted bonding process used for cover application. Excellent results have been achieved for most solar cell types. Under environmental evaluations and electron and proton irradiation tests integrally

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

SECURITY CLASSIFICATION OF THIS PAGE (*When Data Entered*)

BLOCK #20

covered cells exhibit performance statistically at least equal to that of cells with conventional glued covers.

TABLE OF CONTENTS

Section		Page
I	INTRODUCTION	1
II	INTEGRAL COVER DEVELOPMENT	3
	2.1 SELECTION OF COVER MATERIAL	3
	2.2 BONDING PROCESS	16
	2.3 CELL PERFORMANCE	19
III	ENVIRONMENTAL EVALUATIONS	24
	3.1 GENERAL	24
	3.2 TEMPERATURE-HUMIDITY STORAGE	25
	3.3 THERMAL CYCLING	26
	3.4 VACUUM-ULTRAVIOLET STORAGE	29
	3.5 1 Mev PROTON IRRADIATION	31
	3.6 1 Mev ELECTRON IRRADIATION	31
IV	CONCLUSIONS	37

SECTION I

INTRODUCTION

Over the past decade, the potential technical and economic advantages of integral rather than glued covers for spacecraft solar cells have led to a series of investigations(1-9) of possible integral cover application methods. Prior to the present work, techniques evaluated included molecular deposition by RF sputtering, electron beam evaporation and high vacuum ion beam sputtering and particulate application by frit and fuse methods. Each development effort resulted in unacceptable technical capabilities and/or impractical economics. Technical problems generally related to high stress levels in the deposited cover material, degradation of cell performance by the application process or inferior characteristics of the glass compositions as applied to the cell surface. High cost factors had to be projected because of difficult or low rate application processes, expensive required facilities and significant probabilities of cell losses.

The present new approach to integral cover technology for silicon solar cells which is being developed has none of the disadvantages of earlier methods. The technique involves the use of electrostatic field assisted sealing to permanently attach complete slides of Corning type 7070 borosilicate glass to solar cell surfaces without employing an adhesive interface. Slides of any available thickness can be integrally bonded to solar cells in periods of a few minutes using moderate temperature process conditions that do not degrade performance of most solar cell structures. Integrally covered cells exhibit no evidence of residual mechanical stresses.

Integral covers have been successfully applied to conventional N/P cells with titanium-silver, titanium-palladium-silver and aluminum contacts, with silicon monoxide and tantalum pentoxide antireflective coatings, to high performance violet cells and to lithium doped P/N cells. In general it has been possible to achieve post-covering cell output performance at least equal to that resulting following application of conventional glued fused silica covers.

A series of environmental evaluations has been performed on groups of representative integrally covered cell samples. Tests have included temperature-humidity storage, thermal cycling and ultraviolet exposure under vacuum. Radiation testing under 1 Mev proton and 1 Mev electron environments has been completed. Without exception the integrally covered cells have exhibited excellent, or even superior performance under all conditions.

In addition to offering excellent technical capabilities, the integral process being developed is expected to result in substantially reduced costs for protective covers. The method is fast, reproducible and adaptable to total automation using only moderately complex facilities. Cover costs below \$0.10 per cm^2 are considered feasible.

SECTION II

INTEGRAL COVER DEVELOPMENT

2.1 SELECTION OF COVER MATERIAL

Success or failure of an integral cover development program is dependent upon the choice of cover application process, but experience has shown that the process is in turn strongly limited by the physical characteristics of the cover materials employed. Optical parameters of cover materials are fixed by solar cell requirements. Consequently specification of essential parameters and selection of acceptable candidate materials was the logical starting point for this integral cover program. Considerable integral cover development work which has been conducted to date has demonstrated that very few truly adequate materials are available. As a result of the factors to be discussed, Corning type 7070 borosilicate glass is the cover material being used in the present effort.

Choice of a protective cover material for the silicon solar cell is governed by a series of technical considerations which demand that the material exhibit the characteristics listed below:

(i) The cover material should exhibit essentially 100% transmission of photons over wavelengths between 0.3 and 1.2 micrometers.

(ii) The cover material must resist darkening due to exposure to ultraviolet and ionizing particle radiations.

(iii) The cover material must be stable under ambient atmosphere and space environment conditions.

(iv) For normal thermal control purposes the cover material must be highly emissive for photon wavelengths exceeding 5 microns.

(v) Because of the absence of antireflective coating materials with refractive index above 2.4, the cover material on a silicon solar cell should have refractive index below 1.5.

To this point these requirements are best satisfied by fused silica (amorphous SiO_2) and to varying lesser degrees by alumina (Al_2O_3) and a number of silicate glasses. Fused silica is the most expensive of all glasses but is clearly superior to all other candidate cover materials in many respects. Fused silica would be an optimum material for the integral cover but unfortunately, in addition to satisfying requirements (i) through (v) above, the integral cover material must possess two additional characteristics:

(vi) The material must have thermal expansion coefficient as close as possible to that of silicon (approximately 30×10^{-7} $^{o}C^{-1}$) over a temperature range from well below room temperature up to several hundred degrees centigrade.

(vii) The material must be compatible with some practical integral deposition process which can be accomplished under conditions which do not cause degradation of the solar cell device.

The most important requirements upon an integral cover material which can be deposited by some process are a close match of thermal expansion coefficient to that of silicon, high optical transmission over the solar cell response band and an ability to retain transmission in spite of exposure to ionizing radiation. Fused silica which has an expansion coefficient of approximately 5 x 10^{-7} $^{o}C^{-1}$ is not compatible with requirement (vi) and except to a limited degree not with requirement (vii). Alumina has the same deficiencies and also has too high a refractive index. Certain aluminosilicate glasses are available with some potential for integral cover applications but, because of their alumina content, have expansion coefficients somewhat higher than that of silicon and have refractive indices greater than 1.5. Borosilicate glasses are the least expensive of the potential integral cover materials and certain borosilicate compositions exhibit the best combined characteristics for integral cover use. Several other integral cover development programs(1, 2, 9) have independently identified Corning type 7070 borosilicate glass as an acceptable choice for an integral cover.

Graphs of thermal expansion versus temperature are shown in Figure 1 for silicon, 7070 glass and the glasses which have been used for conventional glued covers. The integral cover must possess an expansion coefficient similar to that of silicon in order to insure stability of the covered cell under the transient space thermal environment and for successful integral deposition of a low residual stress cover. It is obvious from Figure 1 that 7940 fused silica is not compatible with silicon in this essential requirement, nor is 0211 microsheet which has been used as a glued cover for some space applications. Type 7070 glass has expansion characteristic closely matched to that of silicon and, if applied to the cell at a process temperature of approximately 450°C, 7070 can be left without residual stress.

The solar cell cover must transmit to the cell virtually all solar spectrum photons with energy greater than 1.1 eV, the silicon band gap energy.

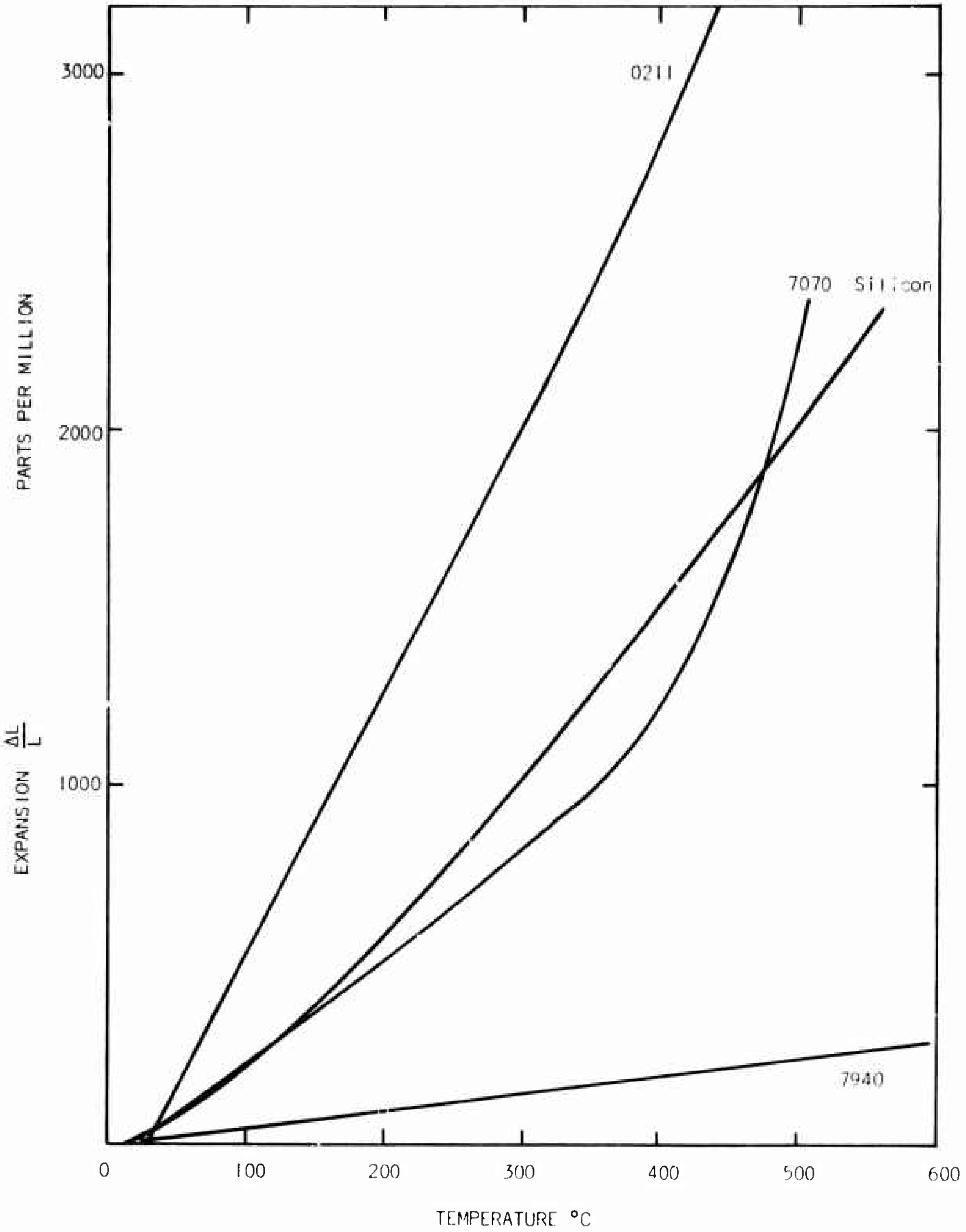


Figure 1. Expansion Curves of Cover Glass Materials.
Source: Corning Glass Material Information.

Figure 2 shows transmittance characteristics of 300 µm thick slides of unirradiated 7940, 0211 and 7070 glasses. While 7940 is measurably better in the shortest wavelengths region, all three materials can be considered to have acceptable initial transmission characteristics.

The cover must protect the solar cell from damaging space (and perhaps nuclear weapon) radiation environments with minimum degradation to its own transmission over the cell response band. Figures 3a and 3b show transmittance of 300 µm slides of 7940, 0211 and 7070 glasses after exposure to 10^{15} and 10^{16} 1 MeV electrons per cm^2. Microsheet and 7070 glasses exhibit sufficiently severe darkening that they might be considered inadequate for certain high radiation environment applications. However another factor must be taken into consideration. Under the ultraviolet component of AMO sunlight, appreciable bleaching of the color centers introduced into some glasses by ionizing radiation can take place. Figure 4 illustrates the effects of exposure of electron irradiated 7070 glass to the approximate equivalent of 12 and 48 hours of the less than 400 nm component of AMO sunlight. Rapid bleaching of the radiation induced darkening results in restoration of preirradiation transmission behavior except at shorter wavelengths where the recovery is less than complete. For purposes of comparison, Figure 5 illustrates that effective UV bleaching behaviour also takes place in irradiated 0211 microsheet.

While ultraviolet illumination can remove darkening of the cover glass material resulting from particle irradiation, the ultraviolet itself can eventually cause a loss of short wavelength transmission of the glass. Figure 6 shows transmittance of 300 µm thick 7070 glass initially and after mercury vapor lamp exposure under vacuum at 30°C approximately equivalent to 600 and 1200 hours of the less than 400 nm component of the AMO spectrum. Comparison of the 600 and

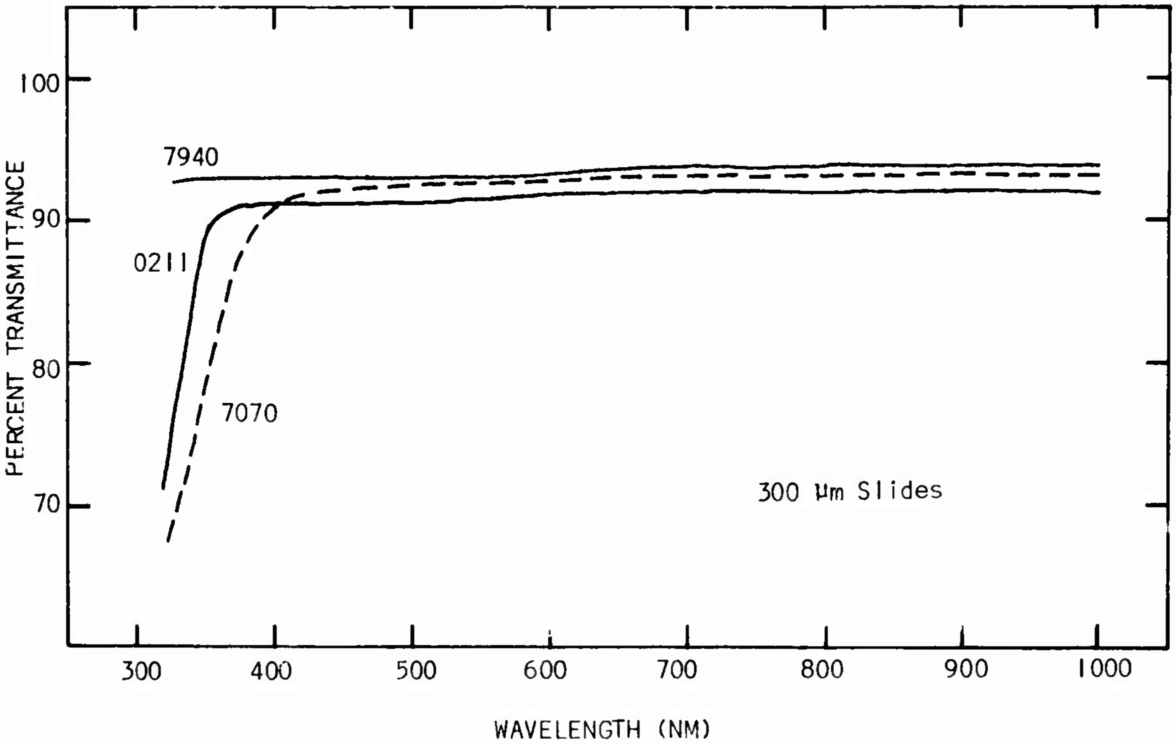


Figure 2. Transmittance of Unirradiated 7940, 0211, and 7070 Glasses.

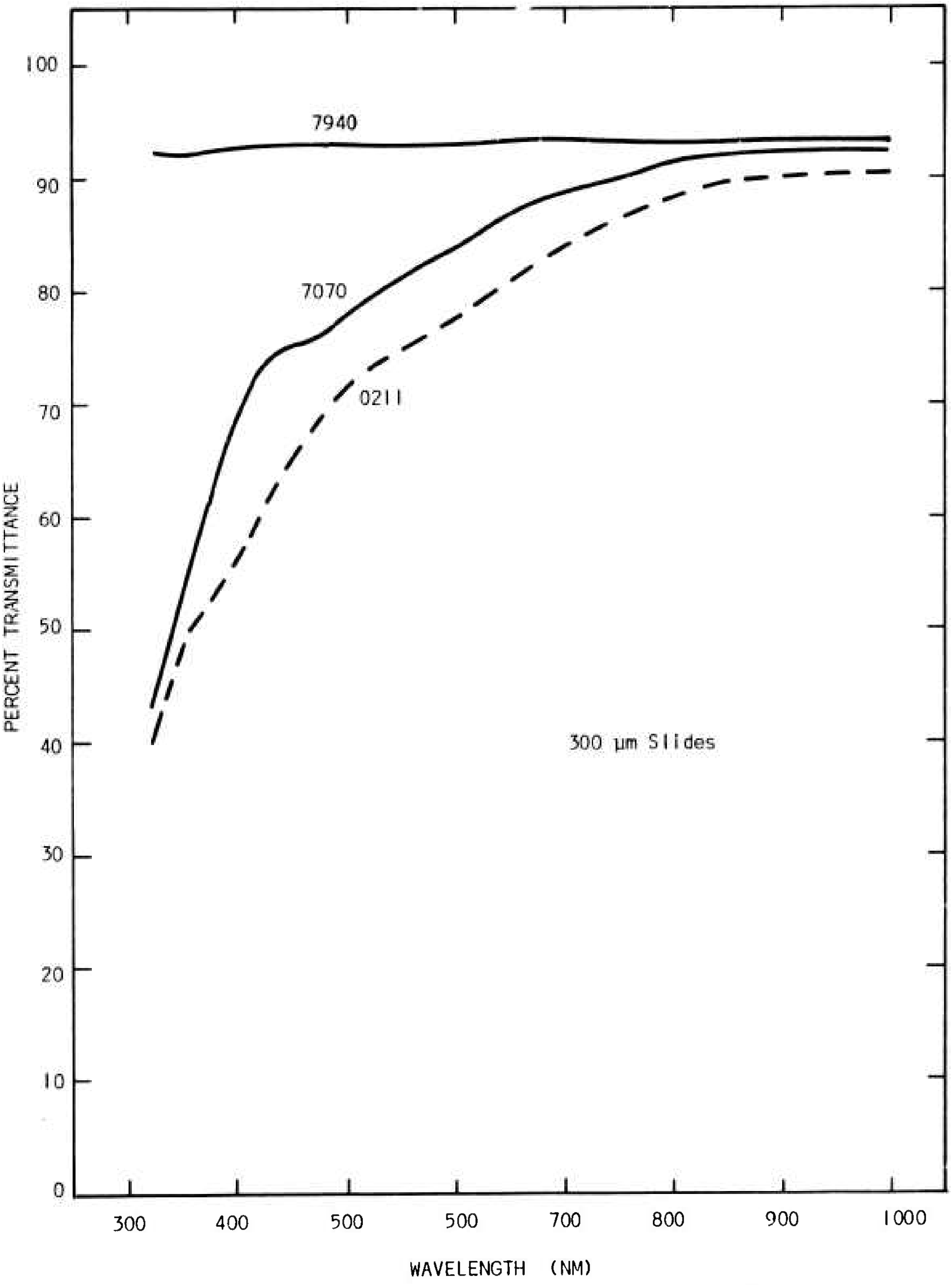


Figure 3a. Transmittance of Glass Slides After 10^{15} cm^{-2} Electron Irradiation.

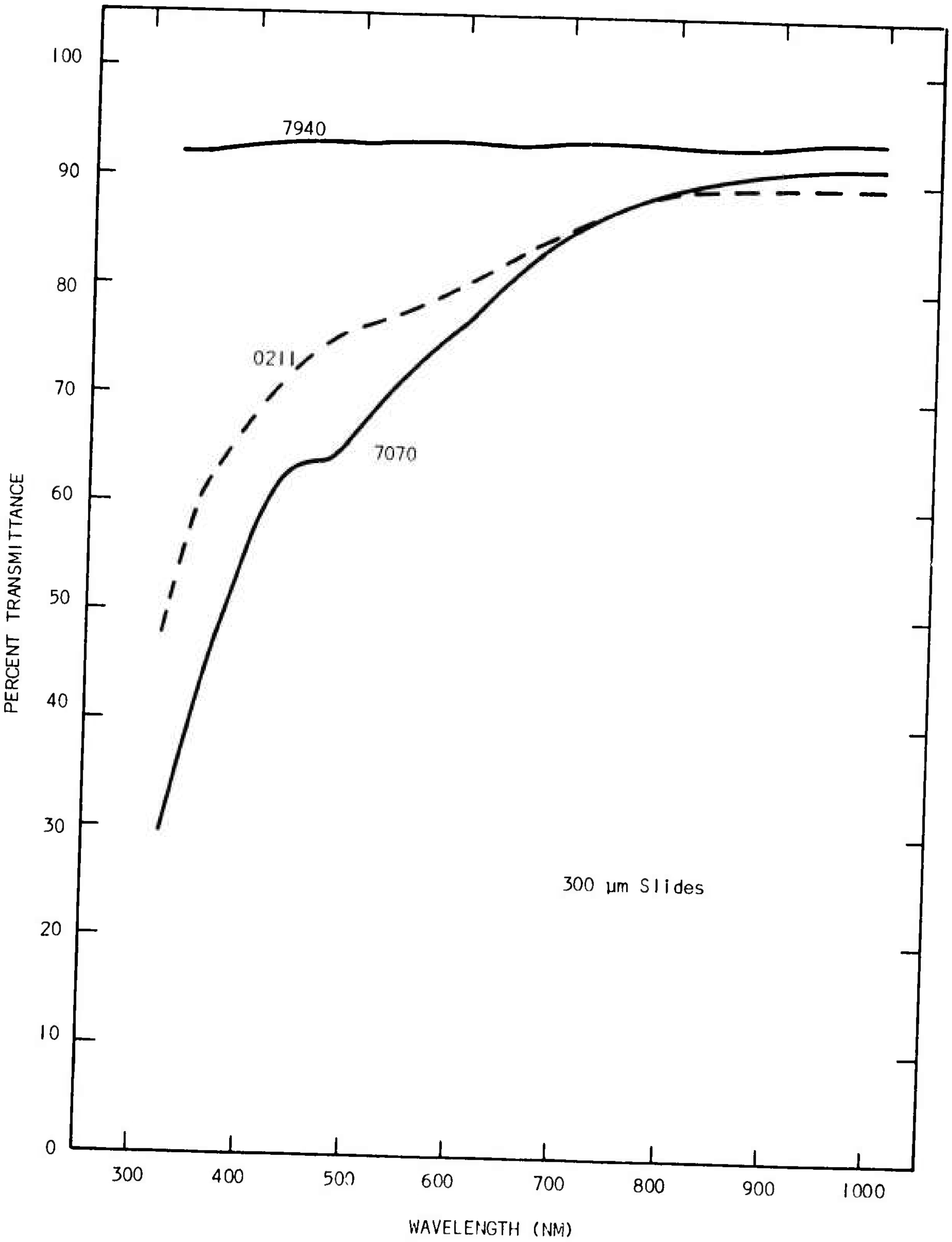


Figure 3b. Transmittance of Glass Slides After 10^{16} cm^{-2} Electron Irradiation.

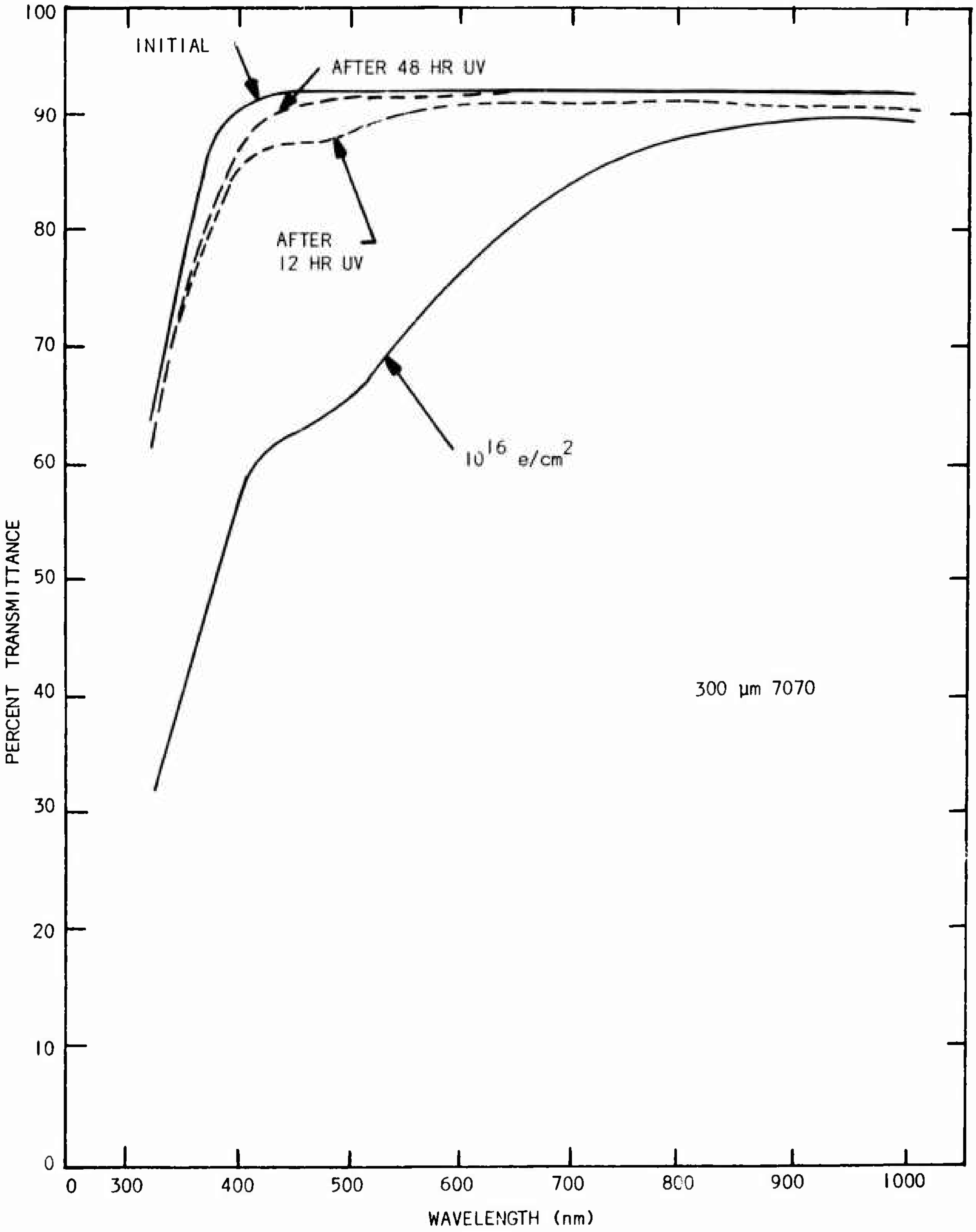


Figure 4. Ultraviolet Bleaching of Irradiated 7070 Glass.

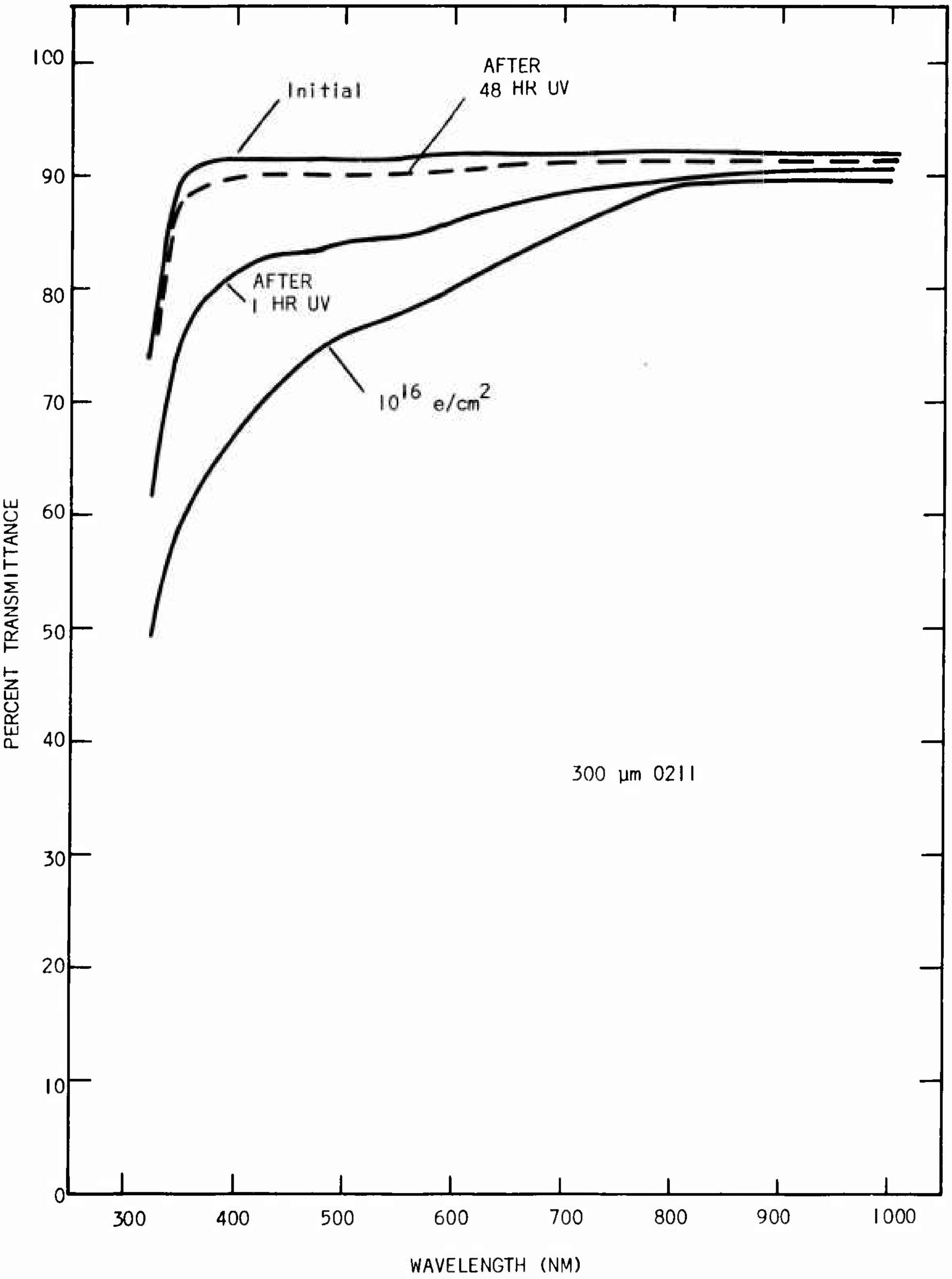


Figure 5. Ultraviolet Bleaching of Irradiated 0211 Glass.

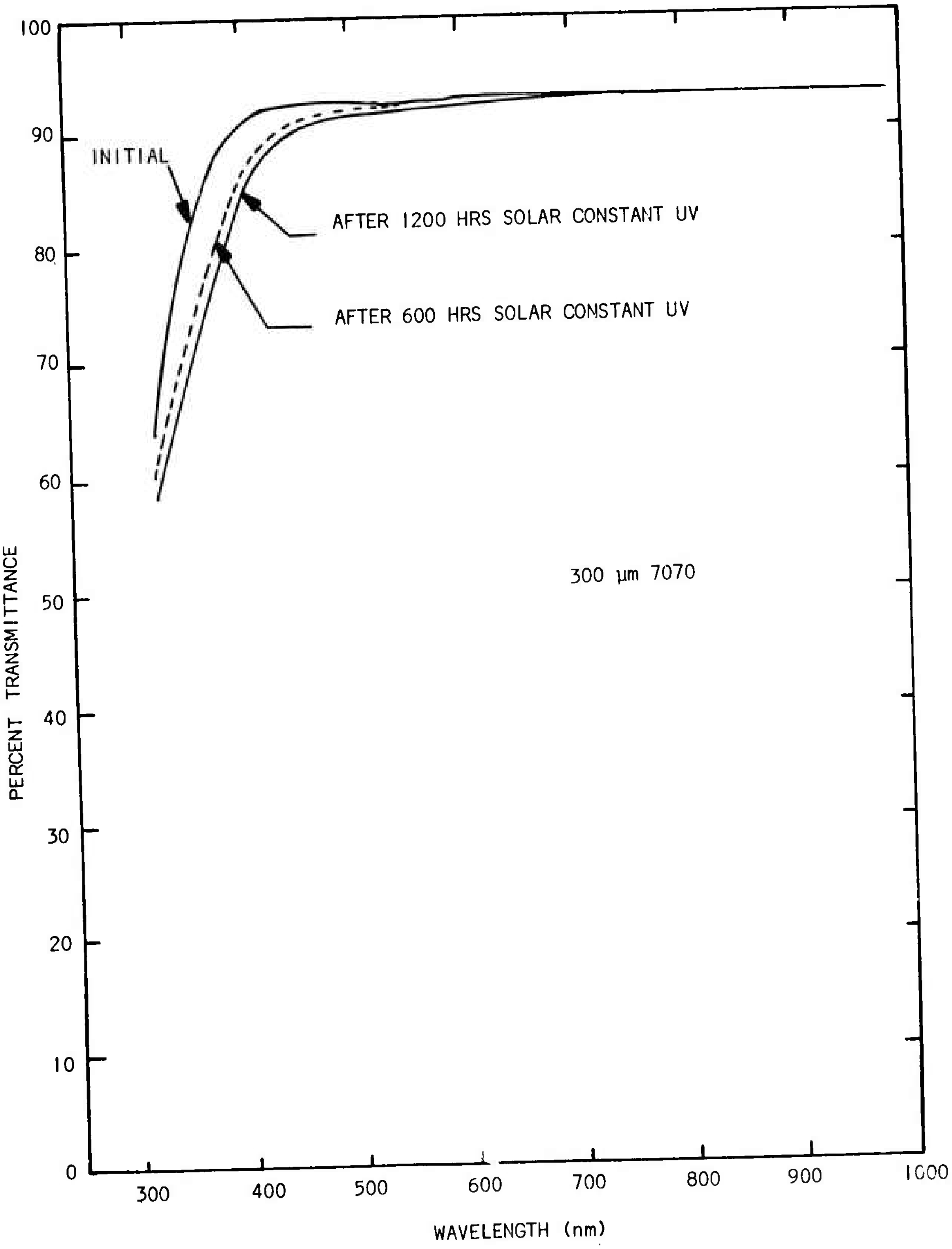


Figure 6. The Effect of Ultraviolet Illumination on 7070 Glass.

1200 hour curves suggests a saturation of this darkening effect. Further comparison with the Figure 4 transmission curves of the UV bleached electron irradiated 7070 glass indicates that the portion of the lost initial transmission under electron irradiation which is not restored by UV bleaching occurs in the spectral region sensitive to ultraviolet induced darkening. While the effects of ultraviolet irradiation on the short wavelength transmission properties of 7070 glass are not insignificant, it must be considered that in the case of nonintegral cover cells an interference filter must be employed to reject shorter wavelengths so that they do not degrade the optically transparent adhesive used to attach the cover. In addition to rejecting wavelengths below cut-on, the multilayer filter can also be sensitive to alteration by ionizing particle or UV radiations. Figure 7 shows the effects of 1200 hours of the equivalent of the AMO spectrum below 400 nm upon a 7940 slide with 400 nm cut-on filter.

In addition to exhibiting adequate characteristics in the tests of this program from which the above results have been extracted, some flight test data does exist for cells with integral 7070 glass covers. Flight data is from earlier integral covers applied by ion beam sputtering(2, 13), but does confirm acceptability of 7070 material for space use. Cells with 75 μm thick 7070 covers on the ATS-6 flight experiment show "excellent stability" after exposure to synchronous orbit for 247(14) and 321(15) days. After 30 months in circular orbit at 31 earth radii, cells with 75 μm thick 7070 covers on IMP-H continue to perform similarly to cells with conventional glued covers(16).

None of the existing data relating to 7070 glass indicate that this specific composition cannot be adequate, perhaps even superior, for spacecraft solar cell integral cover purposes. Ultimately it may be determined that some additional optimization can be achieved by variation of the constituent ratios

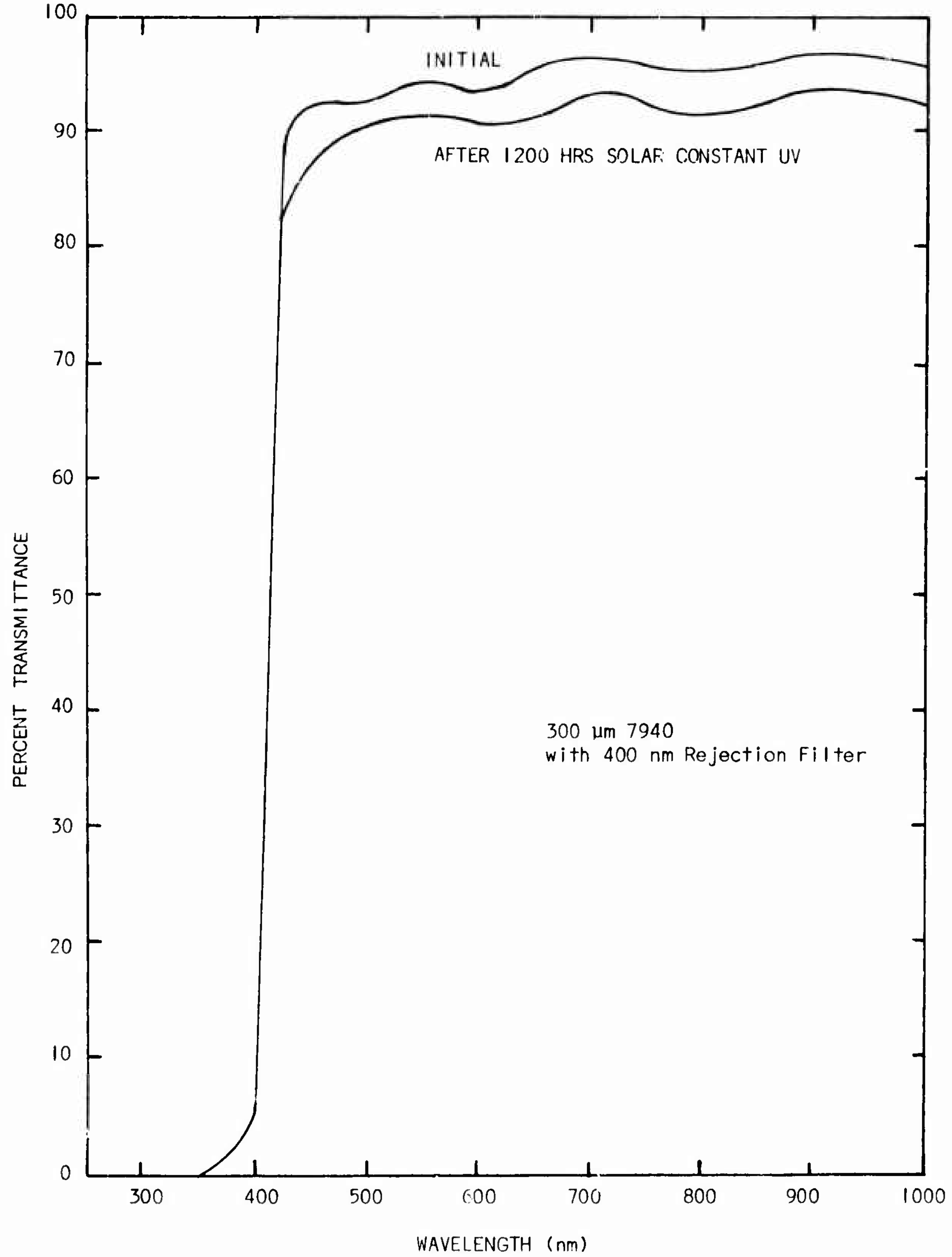


Figure 7. The Effect of Ultraviolet Illumination on Fused Silica With UV Rejection Filter.

or by addition of ceria to improve resistance to radiation induced darkening. But at present these changes are not considered to be necessary.

2.2 BONDING PROCESS

Unlike previous approaches to applying integral covers onto solar cells, the processes being developed start with a slide of cover glass exactly as in the case of the conventional glued cover and then attach the slide to the cell without employing an adhesive interface. The method is based upon a field-assisted glass to metal sealing technique(10). The cover glass is positioned upon the solar cell surface, the temperature is raised and an electric field is used to produce the bonding effect. The elevated temperature, usually above 400°C but always well below the softening point of the glass, is used to create mobile alkali ion species from dissociation of Na_2O and Li_2O(11). Initially the glass and cover make direct contact only at a few points. When a voltage is applied so as to move positive ions away from points of contact at the glass-cell interface, a shallow layer in the glass at touching positions becomes depleted of available positive ions. Almost all of the applied voltage, many hundreds of volts, appears across this polarized layer. Immediately adjacent to points of contact between glass and cell, most of the applied voltage is supported by the gap and strong electrostatic forces proportional to the square of the field in the gap act to close the interface. Spreading from the points of initial contact, the entire cell-glass interface is forced together in a period of seconds. The bond is then completed as oxygen ions in the glass interact with the solar cell surface. Total process times of the order of a few minutes are required.

Excellent bonds have been demonstrated of several different glasses to silicon and to SiO_x and Ta_2O_5 antireflective coatings. The bonding process is not reversible and once formed the bond cannot be released. Strength of the bond exceeds the yield stress of silicon. Figure 8 shows the result of bonding a slide of 0211 microsheet to a silicon wafer and allowing the integral pair to return to room temperature. As cooling takes place the microsheet tries to contract more than the silicon but the interface cannot yield and consequently high stresses are created which increasingly distort the bonded materials during cooling until the yield stress of silicon is reached and a layer of silicon is torn from the wafer and remains bonded to the still distored glass slide. The importance of using expansion coefficient matched materials is clear. Integral 7070 glass covers on silicon cells exhibit no evidence of residual stress upon returning to room temperature.

The constraints upon thickness of 7070 glass which can be integrally bonded to a solar cell are very minor. In fact, limits are apparently to be defined by availability of glass in slide form. Conventional glued covers have usually been employed with minimum thickness in the range of 100 to 150 μm because of practical problems in preparing and handling thinner slides. Similar lower limits can be assumed for the integral process for the same reasons. In the upper extreme it is probably possible to bond almost any thickness of cover material. Experimental work to date has involved thickness from 150 to more than 3000 μm with equal ease.

An important requirement of the bonding process is that the surfaces to be bondad must be reasonably flat and able to mate properly. For the most part development work has involved application of lapped and polished glass slides onto chemically-mechanically polished silicon solar cell surfaces.

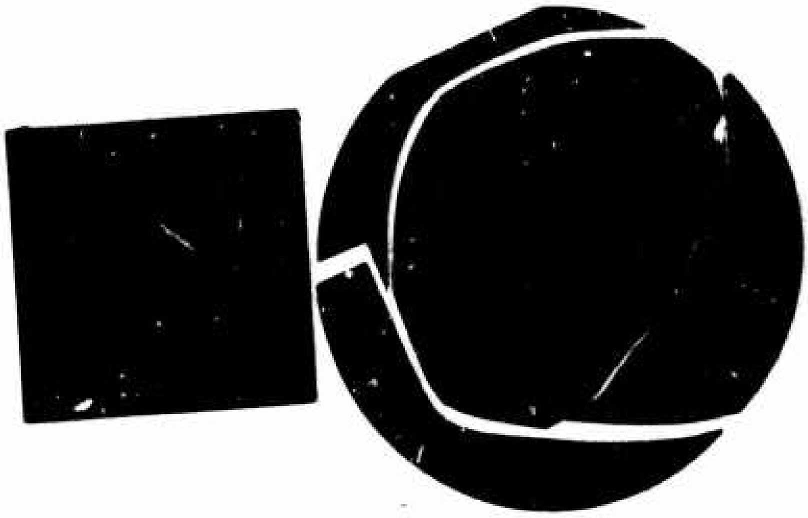


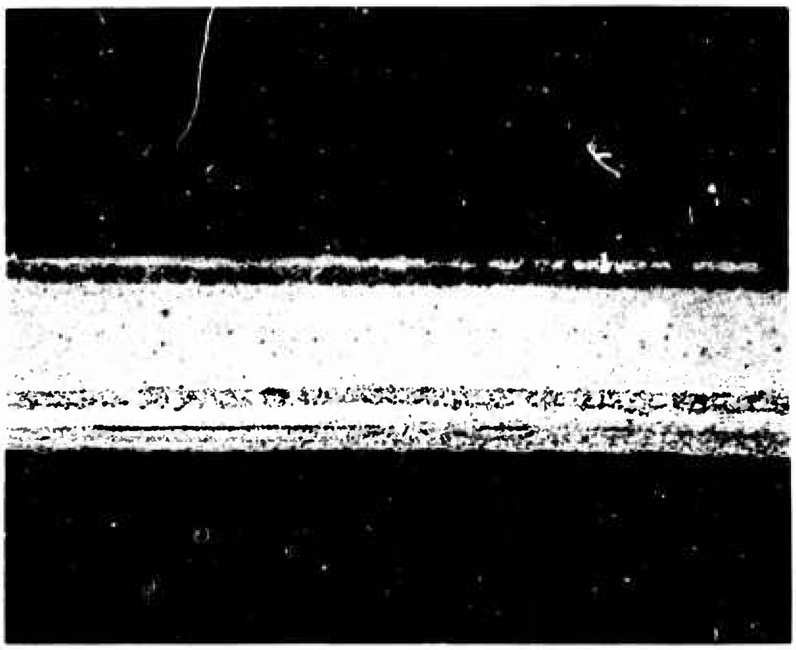
Figure 8. 0211 Microsheet Slide Bonded to Silicon Wafer with Slide and Silicon Surface Torn from Wafer Due to Stresses Upon Return to Room Temperature.

However abrading either the glass or silicon surface with 1 μm lapping grit does not prevent bonding.

The solar cell front contact grid metallization pattern can be accommodated by either of two approaches which have been successfully employed in this program. A method which can be used for almost any cell structure involves scoring shallow grooves into the glass cover slide such that the grooves accept the grid pattern. Cover glasses with narrow grooves approximately 25 μm deep are prepared using a micrometer indexed vacuum table in conjunction with a 150 μm wide diamond scoring blade. The second solution to the problem presented by the grid metal is to utilize the strong forces generated by the bonding process itself to cause plastic flow deformation of the cover glass around the grid pattern. This plastic deformation method requires the process to be performed above the 450°C strain point of 7070 glass while grooved covers can be bonded at minimum temperatures of 400°C or even less. Figure 9 shows magnified views of cell finger regions for the cases of plastically deformed and mechanically grooved covers.

2.3 CELL PERFORMANCE

Development effort under this program has involved a number of solar cell types purchased from OCLI, fabricated by Simulation Physics and supplied by AFAPL. At the present time integral covers have been successfully applied to most cell structures which have been considered and it is possible to apply covers to the following available cell types without causing cell performance degradation:



200 X

a. Plastically Deformed Cover

200 X

b. Grooved Cover

Figure 9. Magnified View of Finger Regions on Plastically Deformed and Grooved Cover Cells.

Cell	Contacts	AR Coating	Cover Type
OCLI N/P	TiAg or TiPdAg	SiO_x or Ta_2O_5	Grooved or Plastically Deformed
Simulation Physics, N/P	TiAg or Aluminum	SiO_x or Ta_2O_5	Grooved or Plastically Deformed
OCLI Violet	Ag-Cr-Au	Ta_2O_5	Grooved
Simulation Physics P/N Lithium	Aluminum	SiO_x	Grooved

Among cell types considered under the program, only OCLI aluminum contact cells (N/P and P/N with lithium) and Ion Physics Corporation cells with CeO_2 antireflective coatings could not be acceptably integrally covered. OCLI cells with aluminum contacts exhibited electrical degradation due to junction shunting as a result of the covering process. Similar cells fabricated by Simulation Physics with aluminum contacts deposited by modified processing show no shunting problems. Cerium oxide coated cells were not integrally covered because bonding conditions could not be established which would result in cover adherence to the cell.

A representative I-V characteristic showing lack of cell performance degradation as a result of the bonding process is shown in Figure 10. A test was conducted to compare performance changes caused by application of integral 7070 covers to changes resulting in identical cells to which were applied several types of glued covers. The results are summarized in Table I. All integral covers in this particular test were grooved to accept the contact grids. Examination of the data given in the table indicates that post covering air mass zero performance of integral covered cells should be equal or superior to performance of cells with glued covers and ultraviolet rejection filters.

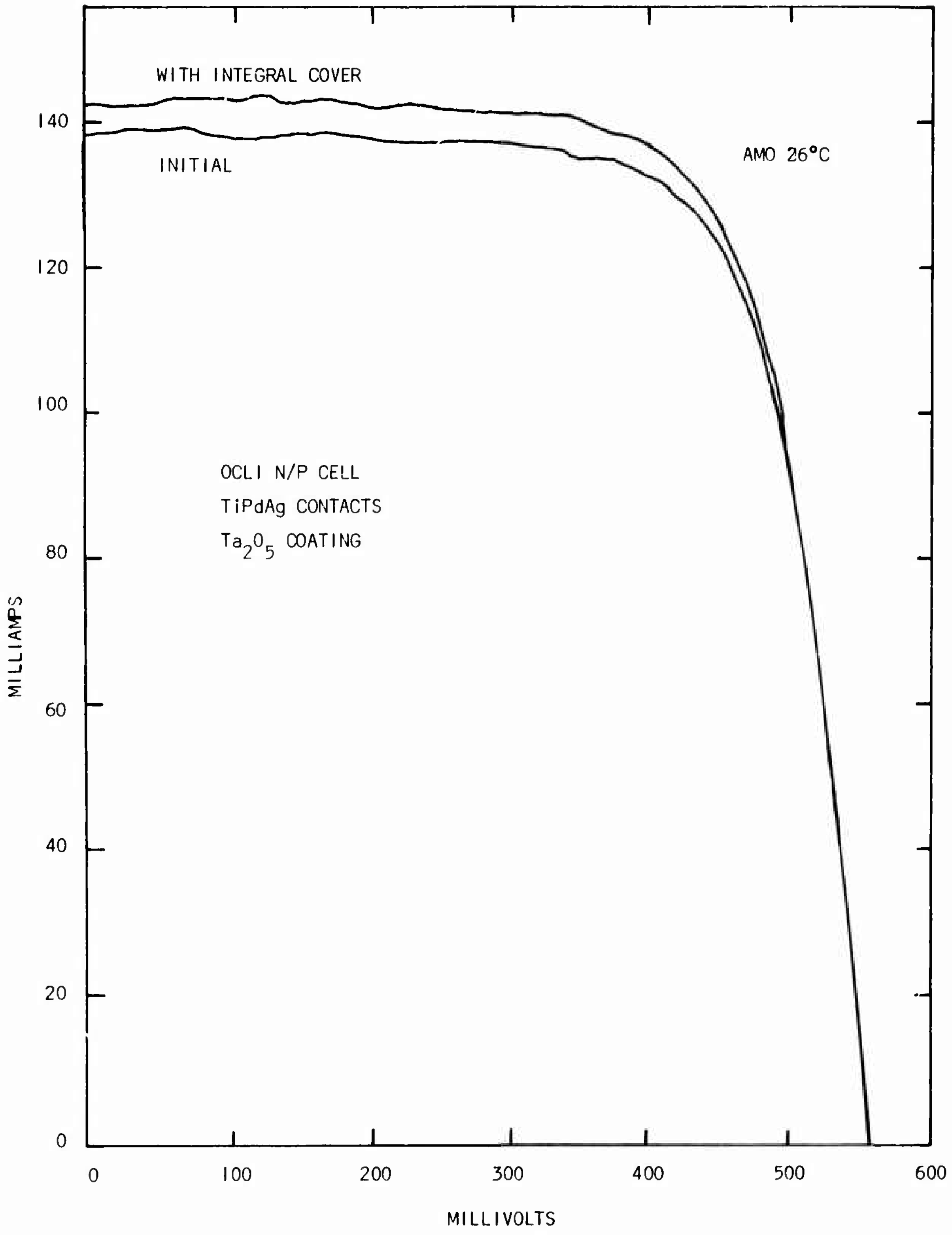


Figure 10. I-V Characteristics of Integral Cover Cell.

TABLE I

SUMMARY OF CELL PERFORMANCE CHANGES RESULTING FROM APPLICATION OF INTEGRAL AND GLUED COVERS

CELL TYPE	COVER MATERIAL	COVER THICKNESS	NO. OF CELLS	% CHANGE AFTER COVERING	
				I_{sc}	P_{max}
TiAg - SiO_x	Integral 7070	300 μm	5	-0.7	-0.8
TiAg - SiO_x	Glued 7070	300	2	-3.6	-3.8
TiAg - SiO_x	Glued 7940	300	1	-1.4	-2.1
TiAg - SiO_x	Glued 7940 w/UV Filter	175	2	-3.4	-3.5
TiAg - SiO_x	Glued 0211 w/UV Filter	150	1	-2.2	-2.8
TiPdAg - SiO_x	Integral 7070	300 μm	4	-1.3	-2.9
TiPdAg - SiO_x	Glued 7070	300	2	-4.3	-3.1
TiPdAg - SiO_x	Glued 7940	300	1	-1.4	-2.4
TiPdAg - SiO_x	Glued 7940 w/UV Filter	175	2	-2.9	-3.5
TiPdAg - SiO_x	Glued 0211 w/UV Filter	150	1	-1.4	-2.4
TiAg - Ta_2O_5	Integral 7070	300 μm	4	+0.7	-0.2
TiAg - Ta_2O_5	Glued 7070	300	2	+0.7	+0.2
TiAg - Ta_2O_5	Glued 7940	300	1	+2.9	+0.9
TiAg - Ta_2O_5	Glued 7940 w/UV Filter	175	2	0	-0.4
TiAg - Ta_2O_5	Glued 0211 w/UV Filter	150	1	0	-3.2
TiPdAg - Ta_2O_5	Integral 7070	300 μm	4	+2.6	+1.3
TiPdAg - Ta_2O_5	Glued 7070	300	2	+2.2	+1.6
TiPdAg - Ta_2O_5	Glued 7940	300	1	+2.2	+2.3
TiPdAg - Ta_2O_5	Glued 7940 w/UV Filter	175	2	+1.4	+0.2
TiPdAg - Ta_2O_5	Glued 0211 w/UV Filter	150	1	+0.7	0

All cells OCLI 10 Ω-cm N/P

Glued Covers attached with Sylgard 182 and Sylgard Primer

Test Conditions: AMO 26°C

SECTION III

ENVIRONMENTAL EVALUATIONS

3.1 GENERAL

A series of environmental tests has been performed upon integral cover cells, glued cover cells, control cells and samples of cover materials. Tests performed have included:

(i) Temperature - humidity storage
(30 days at 45°C, 95% relative humidity)

(ii) Thermal Cycling
(300 cycles from -150°C to +150°C

(iii) Vacuum - ultraviolet storage
(3 months at $<10^{-5}$ torr, 30°C under total ultraviolet exposure of 14 watt-hrs/cm^2)

(iv) Proton Irradiation
(1 Mev protons to 10^{13} cm^{-2})

(v) Electron Irradiation
(1 Mev electrons to 10^{16} cm^{-2})

Temperature-humidity storage and thermal cycling tests were performed in facilities at Acton Environmental Test Corporation, Acton, MA. Vacuum-ultraviolet storage was conducted using a test stand assembled by Simulation Physics. Proton irradiations were performed using a Van de Graaff Accelerator Facility at KSW Electronics, Burlington, MA and electron irradiations were carried out using a Dynamitron at Air Force Cambridge Research Laboratory, Bedford, MA. Throughout these tests all electrical data were measured using a Spectrosun X-25 MK II AMO solar simulator. Each cell sample was inspected microscopically before and after envionmental exposure.

3.2 TEMPERATURE-HUMIDITY STORAGE

In each environmental test, the effects of the test environment upon the physical and electrical characteristics of the cells, particularly the integral cover cells, are important. In the case of 30 day storage at 45°C and 95% relative humidity the physical effects included weathering of cover glass materials and oxidation of contacts. Weathering was more pronounced on 7070 glass than on 0211 microsheet and did not occur to a visible degree on 7940 fused silica. Optical measurements on glass samples and electrical measurements on covered cells indicate that the weathering, which is a surface corrosion effect, causes some scattering of incident light but does not measurably reduce total transmission. Oxidation of contacts was largely cosmetic in the case of titanium-silver and titanium-palladium-silver contact cells but was sufficiently severe to prevent post test electrical measurements on cells with aluminum metallization. One cell with aluminum contacts was treated with potassium hydroxide solution to make measurement possible and confirmed essentially initial output characteristics.

Among 15 cells in the test with integral 7070 glass covers, only one showed any evidence of local physical change in or near the cell-cover interface as a result of the test environment. The single exception was an OCLI N/P cell with SiO_x antireflective coating and integral cover applied using plastic deformation around the titanium silver contact grid. The cell developed small area (1 mm diameter) separations under the cover at the extreme ends of 5 of its 6 grid fingers. The separations are metallic in appearance indicating that the SiO_x antireflective coating had detached from the silicon surface. No other test cells showed any similar effect even on a microscopic scale.

Electrical measurements from OCLI N/P cells with TiPdAg and TiAg contacts and SiO_x and Ta_2O_5 antireflective coatings have been combined for each cover type and are summarized in Table II. The data suggest absence of significant degradation mechanisms for the integral cover in the temperature-humidity test environment.

3.3 THERMAL CYCLING

A total of 300 cycles from -150°C to +150°C were completed at a rate of approximately one cycle per hour using low temperature nitrogen gas to reduce test chamber temperature to the lower extreme and electrical heaters to return to the higher temperature. Atmosphere in the unsealed chamber was mainly residual nitrogen but did include some air which resulted in a degree of contact oxidation and minor moisture marking of exposed surfaces.

None of 17 integrally covered cells included in the test developed any physical defects involving their covers. Some cells with glued covers developed regions of cell-cover delamination. Glass samples exhibited no changes in optical transmittance.

Electrical performance data are summarized in Table III. Aluminum contacted cells are not included in the tabulated data because of measurement

TABLE II

TEMPERATURE-HUMIDITY TEST DATA SUMMARY

AFTER 30 DAYS AT 45°C, 95% RELATIVE HUMIDITY

COVER TYPE	NO. OF CELLS	AVERAGE % CHANGE		
		I_{sc}	V_{oc}	P_{max}
Integral 7070 - grooved	10	+0.3	-0.4	-1.2
Integral 7070 - deformed	2	+1.5	0	-0.5
Glued 7070	3	-1.7	-0.4	-2.0
Glued 7940	4	-1.1	+0.7	0
None	8	-0.4	0	-1.3

All Cells OCLI N/P

TiAg or TiPdAg Contacts

SiO_x or Ta_2O_5 AR Coatings

AMO 26°C

TABLE III

THERMAL CYCLE TEST DATA SUMMARY

AFTER 300 CYCLES FROM -150°C to +150°C

COVER TYPE	NO. OF CELLS	AVERAGE % CHANGE		
		I_{sc}	V_{oc}	P_{max}
Integral 7070 - grooved	9	-1.0	-0.2	-1.7
Integral 7070 - deformed	3	-0.5	-0.2	-1.8
Glued 7070	4	-1.5	-1.5	-2.6
Glued 7940	4	0	-0.8	-1.9
None	8	-1.1	-0.1	-1.9

All Cells OCLI N/P

TiAg or TiPdAg Contacts

SiO_x or Ta_2O_5 AR Coatings

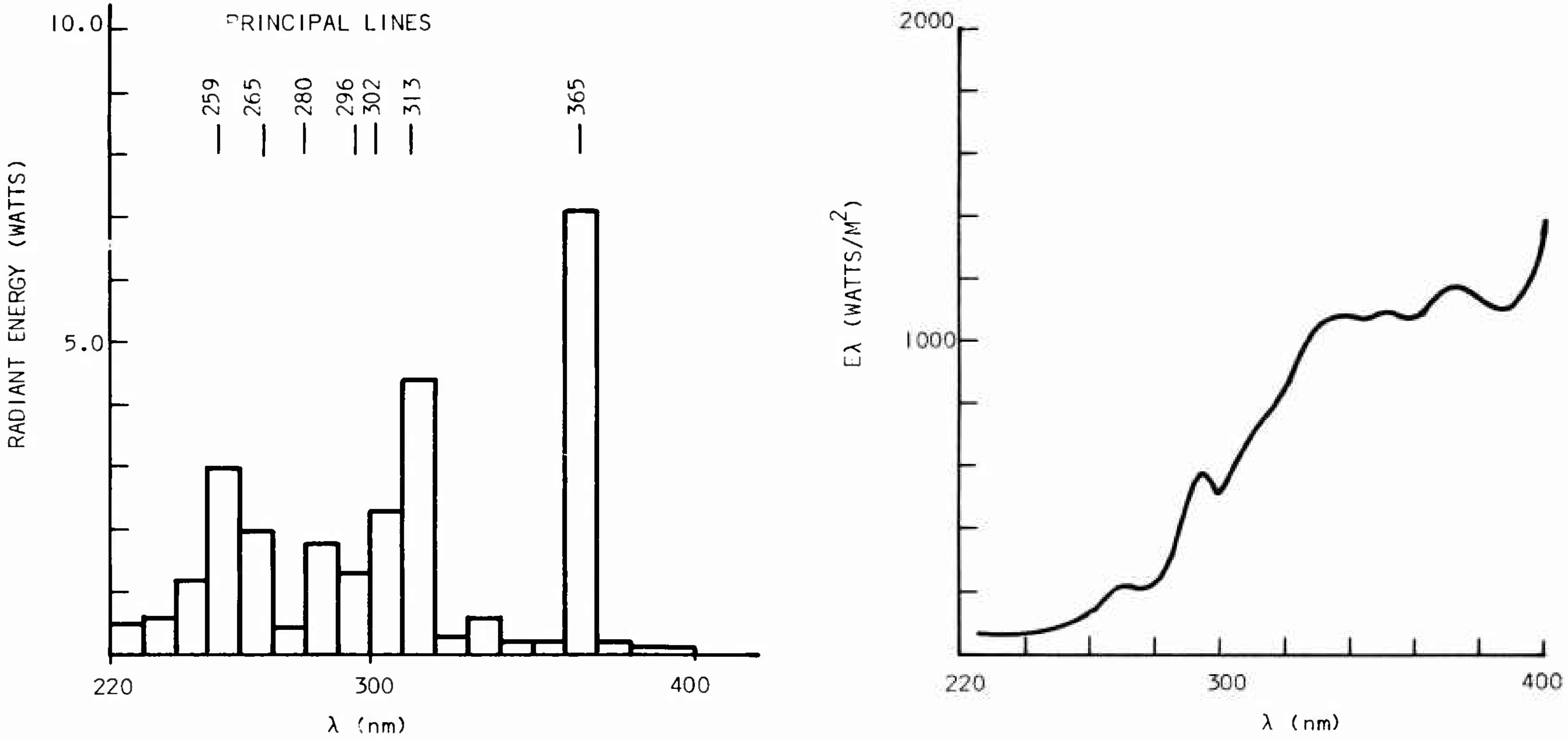
AMO 26°C

problems involving contact oxidation. The integrally covered cells show no performance deficiencies through the cycling test.

3.4 VACUUM-ULTRAVIOLET STORAGE

The vacuum-ultraviolet storage test was performed in a water cooled vacuum system which allowed samples under test to temperature stabilize at 30°C. An oil diffusion pump system with liquid nitrogen cooled baffle maintained continuous vacuum well below 10^{-5} torr. An automatic liquid nitrogen refill control maintained baffle temperature to minimize backstreaming of diffusion pump oil. A General Electric UA-2 250 watt mercury vapor lamp was mounted outside the vacuum system and samples under test were illuminated through a 6 inch diameter fused silica window. Actual ultraviolet intensity at the test location was measured using an Eppley thermopile in conjunction with a set of filters. Ultraviolet intensity upon test samples was measured to be 10.3 mW/cm^2 between 220 and 440 nm with total spectral irradiance of 53 mW/cm^2. The one solar constant AMO spectrum includes 11.8 mW/cm^2 of ultraviolet below 400 nm(12) so that this ultraviolet exposure test came close to approximating real time. Figure 11 compares the spectral distribution of the Thekaekara AMO curve in the ultraviolet to manufacturer's data on the mercury vapor lamp distribution. The ultraviolet exposure test was interrupted for sample measurements after the corrected equivalent of 600 hours of AMO UV exposure and the test was terminated after the equivalent of 1200 hours.

None of the solar cells or cover glass samples showed any visible changes after 600 hours. After 1200 equivalent hours, some minor yellowing of 7070 glass slides was evident. Optical transmission data from the 7070 and filtered 7940 glasses were given as Figures 6 and 7 respectively of Section 2.1 above.



UA-2 Hg Lamp Spectrum

AMO Solar STD Curve
Reference 12

Figure 11. Comparison of Mercury Lamp and AMO Spectral Distributions in 220 - 400 nm Band.

Table IV summarizes electrical performance averages after 600 and 1200 equivalent hours. All of the integral cover samples in this test had titanium-silver or titanium-palladium-silver contacts but glued cover samples were all of similar OCLI N/P cells with aluminum contacts. Bare cell data are included for both contact types. It can be seen that the integrally covered cells showed appreciably less degradation than cells with glued 7940 fused silica covers which included 400 nm cut-on filters. Glued 7070 glass covers which did not include ultraviolet rejection filters allowed lamp UV to reach the Sylgard 182 silicone resin adhesive and the cells involved exhibited large current losses.

3.5 1 Mev PROTON IRRADIATION

Proton irradiations were performed on groups of integrally covered cells. All covers were 300 µm thick 7070 glass. Each sample was irradiated to only a single fluence step. Uncovered cell front contact bars were protected with 75 µm thick aluminum foils during irradiations. Test data are summarized in Table V. Any cell exhibiting performance change greater than reproducibility of the AMO measurement was found under microscopic inspection to involve small exposed surface area due to cover misalignment. The 7070 glass covers are judged to provide completely adequate protection against proton damage.

3.6 1 Mev ELECTRON IRRADIATION

Cells and glass samples were subjected to 1 Mev electron fluences of 3×10^{14}, 1×10^{15}, 3×10^{15} and 1×10^{16} cm^{-2}. Each sample was exposed to all levels. Samples with glued 0211 microsheet covers were included in this test.

TABLE IV

ULTRAVIOLET-VACUUM STORAGE TEST DATA SUMMARY

AFTER 600 AND 1200 EQUIVALENT AMO HOURS AT 30°C, $<10^{-5}$ TORR

COVER TYPE	NO. OF CELLS	AVERAGE % CHANGE 600 HRS.			AVERAGE % CHANGE 1200 HRS.		
		I_{sc}	V_{oc}	P_{max}	I_{sc}	V_{oc}	P_{max}
Integral 7070 - grooved	7	-0.2	0	-0.3	-2.1	-0.7	-3.1
Integral 7070 - deformed	2	-0.4	0	-0.2	-2.3	-0.6	-3.3
Glued 7070*	2	-8.2	-0.2	-7.2	-14.9	-1.1	-14.0
Glued 7940 with 400 nm cut-on filter*	2	-4.6	0	-3.5	-5.7	-0.6	-5.6
None	3	-0.8	0	-0.9	-1.3	-0.5	-2.1
None*	2	0	0	+0.4	-1.1	-0.9	-2.9

All cells OCLI N/P

TiAg or TiPdAg Contacts, except *Aluminum

SiO_x or Ta_2O_5 AR Coatings

AMO 26°C

TABLE V

I MEV PROTON IRRADIATION DATA SUMMARY FOR INTEGRAL COVER CELLS

I Mev PROTON FLUENCE	GROOVED INTEGRAL COVERS			DEFORMED INTEGRAL COVERS		
	NO. OF CELLS	% CHANGE		NO. OF CELLS	% CHANGE	
		I_{sc}	P_{max}		I_{sc}	P_{max}
10^{10} cm^{-2}	3	0	-0.1	2	0	0
10^{11}	3	0	-0.1	1	0	0
10^{12}	3	-0.2*	-0.6*	2	0	0
10^{13}	3	0	-0.5	2	-0.4*	-1.2*

All cells OCLI N/P

TiAg or TiPdAg Contacts

SiO_x or Ta_2O_5 AR Coatings

*Included cell or cells with small unprotected surface areas due to cover misalignment

AMO 26°C

Both 7070 and 0211 glasses showed significant darkening under the electron irradiation. Transmittance curves were presented previously as Figures 3a and 3b. At lower fluences darkening of the 7070 glass was less than that of the 0211 microsheet. However the microsheet darkening saturated then decreased slightly so that at higher fluences 7070 losses were approximately comparable to those in 0211. As was discussed in Section 2.1, both glasses showed rapid, effective bleaching when exposed to ultraviolet illumination following irradiation. As was shown in Figures 4 and 5, transmittances were restored to almost pre-irradiation levels by the equivalent of approximately 48 hours of AM0 solar constant ultraviolet.

As a result of darkening of the 7070 glass, cells with integral 7070 covers degraded under electron irradiation more rapidly than did similar bare or glued fused silica covered cells. Averaged normalized I_{sc} and P_{max} data are presented in Table VI. Following the final irradiation step, half of the cells with integral 7070 covers were exposed to the equivalent of 14 hours of solar constant UV (~150 mW-hrs/cm^2 of <400 nm) under vacuum at 30°C and were then retested. Output performance exhibited increase to approximately the bare cell level. Normalized maximum power data averages are plotted in Figure 12.

TABLE VI

1 MEV ELECTRON IRRADIATION DATA SUMMARY

NORMALIZED I_{sc} AND P_{max}

COVER TYPE	NO. OF CELLS	I_{sc}/I_{sc_o}			
		3×10^{14} e/cm^2	1×10^{15}	3×10^{15}	1×10^{16}
None	4	0.90	0.83	0.79	0.71
Glued 7940	4	0.90	0.84	0.78	0.70
Glued 0211	3	0.85	0.79	0.75	0.68
Integral 7070	10	0.87	0.80	0.74	0.64
Integral 7070 after UV	5				0.71

COVER TYPE	NO. OF CELLS	P_{max}/P_{max_o}			
		3×10^{14}	1×10^{15}	3×10^{15}	1×10^{16}
None	4	0.85	0.76	0.69	0.60
Glued 7940	4	0.86	0.76	0.68	0.56
Glued 0211	3	0.80	0.72	0.66	0.56
Integral 7070	10	0.82	0.73	0.65	0.54
Integral 7070 after UV	5				0.59

AMO 26°C

All Cells OCLI N/P

TiAg or TiPdAg Contacts

SiO_x or Ta_2O_5 AR Coatings

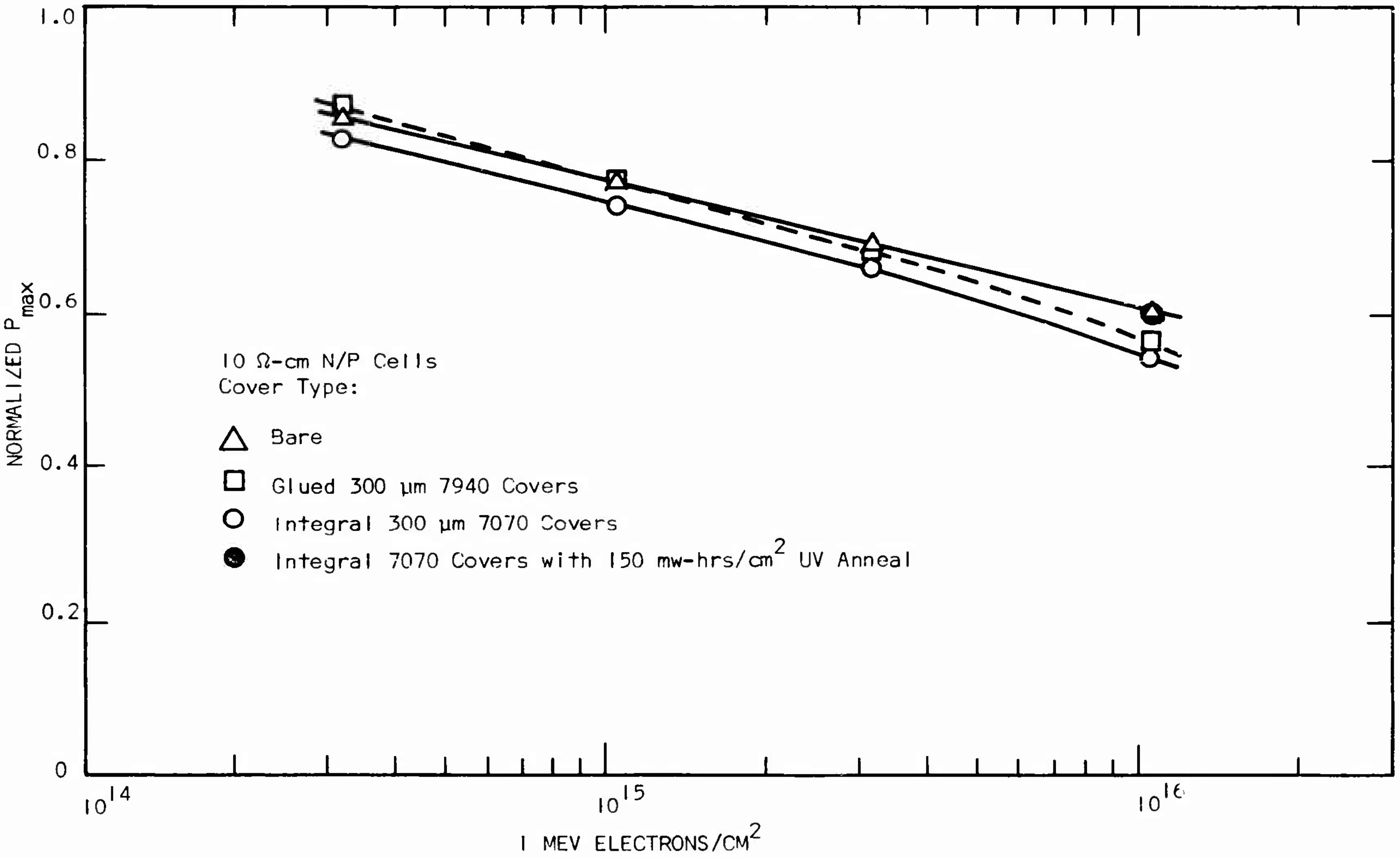


Figure 12. Normalized Maximum Power vs. Electron Fluence.

SECTION IV

CONCLUSIONS

Integrally bonded glass covers for silicon solar cells are being developed. Corning type 7070 borosilicate glass has been selected because of good compatibility with the solar cell and the bonding process combined with resistance to permanent radiation induced darkening. Cells with any thickness of integral 7070 glass covers are left in a physically unstressed condition.

Development to date has concentrated upon several types of cells with polished front surface. The cell front metallization grid is accommodated with good success by plastic deformation of the glass around the grid or by appropriate grooving of the glass. Covers have been successfully bonded to cell types able to withstand minimum processing of at least 400°C for a few minutes. Output performance of an integrally covered cell equals or exceeds that expected from a similar cell with glued cover.

Integrally covered cells have exhibited stability under a range of environmental exposures and particle irradiations. Moderate darkening of the 7070 glass with corresponding loss of cell output as a result of 1 MeV electron irradiation has been observed but is found to be effectively eliminated by bleaching by the AMO ultraviolet component for short periods of time.

REFERENCES

(1) NASA Contract NAS5-3857, Hoffman Electronics.

(2) NASA Contract NAS5-10236, Ion Physics Corporation.

(3) NASA Contract NAS5-10319, Texas Instruments.

(4) NASA Contract NAS5-21510, Heliotek.

(5) Air Force Contract F33615-67-C-1158, Ion Physics Corporation.

(6) Air Force Contract F33615-68-C-1198, Heliotek.

(7) Air Force Contract F33615-70-C-1619, Heliotek.

(8) Air Force Contract F33615-71-C-1656, General Electric

(9) ESRO Contracts 810/69/AA, 1407/71/AA, Electrical Research Association, England.

(10) Wallis, G., "Direct - Current Polarization During Field - Assisted Glass - Metal Sealing", 71st Annual Meeting, American Ceramic Society, Washington, DC, May 1969.

(11) Weyl, W. A. and Marboe, E. C. "The Constitution of Glasses", Vol. III, Pt. 2 P. 893, John Wiley & Sons, New York, 1967.

(12) Thekaekara, M. P., "Extraterrestrial Solar Spectrum, 3000-6000 Å at 1 - Å Intervals", Appl. Optics, 13, No. 3, 518, March 1974.

(13) Kirkpatrick, A. R., Tripoli, G. A. and Bartels, F. T. C., "Low Stress Integral Covers", P. 176, Record of Eighth Photovoltaic Specialists Conference, August 1970.

(14) Goldhammer, L. J. and Corrigan, J. P., "Early Results of the ATS-6 Solar Cell Flight Experiment", Record of the Eleventh Photovoltaic Specialists Conference, Phoenix, May 1975

(15) Private Communication, L. J. Goldhammer, Hughes Aircraft Company, May 1975.

(16) Private Communication, L. W. Slifer, Goddard Space Flight Center, May 1975.