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EVALUATION OF INTEGRAL COVERS ON SILICON SOLAR CELLS

JOHN W. FAIRBANKS

SEPTEMBER 1969

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GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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SUMMARY

The integrally coverslipped solar cell promises significant cost reduction and power-to-weight ratio improvement for space power systems. Goddard Space Flight Center has funded three integral coverslip developmental efforts. The initial approach involved fusing a borosilicate glass on the cell surface. In the other approaches, two types of sputtering were developed: Radio Frequency (RF) sputtering and high-vacuum-ion-beam (HVIB) sputtering. Sputtering work was concentrated on fused silica (SiO_2). Cells coverslipped by these three techniques were subjected to solderability, temperature-humidity, and radiation tests. All cells were solderable by conventional techniques. Several RF sputtered coverslipped cells fractured during temperature-humidity testing. Cells with 2 mil sputtered coverslips were protected from 500 keV and 2.0 MeV protons at fluences to 10^{14} protons cm^{-2}. Bare cells with CeO_2 and SiO anti-reflection coatings exposed to the same proton exposures were equally degraded.

Four RF sputter-coated cells were also subjected to hydrogen impregnation to ascertain their compatibility with this process, which is used to shift the effect of radiation induced color defects from the cells' spectral response band to the IR region. These cells exhibited an unexpected 5%-9% increase in short circuit current after impregnation. Three cells of the same type, subjected only to annealing, showed less than 1% improvement. Thus, the increased performance does not appear to be strictly an annealing effect. An explanation of this gain is not available at this time.

Tests indicate that all sputtered SiO_2 coverslips have internal stresses built into the coverslip. These stresses are possibly tolerable in film thicknesses up to 3 mils. Current efforts are directed toward alleviating the problem. Efforts include the use of low temperature annealable glasses with emphasis on Cerium doped material. Additional sputter deposition investigations are proceeding with Al_2O_3, oxynitride films and boric-oxide glasses. Replacement of oxygen in SiO_2 films by nitrogen has been reported to eliminate compressive internal film stresses. Non-sputtering techniques, such as chemical vapor deposition and electric potential bonding, are also being assessed for their integral coverslipping capabilities.

EVALUATION OF INTEGRAL COVERS
ON SILICON SOLAR CELLS

INTRODUCTION

The integral coverslip approach is used to eliminate the need for an optically transmissive adhesive in the conventional solar cell/bonded coverslide composite. The necessity for a multilayer interference filter to protect this adhesive from ultraviolet exposure is also eliminated. Ultraviolet radiation causes optical adhesives to darken. This coverslide adhesive is the "weak link" in solar arrays for many environmental conditions. Manufacture of the conventional coverslide with the necessary multilayer interference filter and its installation on a solar cell involves many time consuming steps. The use of integrally coverslipped cells could eliminate most of these steps, and thus provide a significant reduction in solar-array fabrication cost. In addition, many missions currently flying or in the planning stages operate only in low radiation level regions and solar arrays could perform satisfactorily with only 1 or 2 mils of SiO_2 protective coating in these environments. However, conventional bonded coverslides less than 6 mils thick are difficult to fabricate in quantity and are also difficult to assemble. Thus, weight saving for the integrally coverslipped cell is also significant - particularly so for large area arrays. In order to be used on a flight program, the integrally coverslipped cell must exhibit a significant technical or economic advantage over the conventionally bonded coverslide. This paper describes several of the most promising techniques used in integral coverslip developmental work, delineates the problems encountered, presents evaluation test results, and outlines the direction of current efforts

INTEGRAL COVERSLIPPING TECHNIQUES

A multitude of techniques have been considered for the installation, encapsulation, attachment, or spray-on of transparent radiation protective coverings for solar cells. An early effort was the development in 1963 of a process of powdering a boro-silicate glass which was then dispersed in a slurry and deposited on the solar cell surface in a centrifuge. These particles were then fused to the cell surface at temperatures ranging up to 900°C.

As the fusing temperature was increased up to about 750°C the optical transmission characteristics improved. Above this temperature excessive bubbles formed in the glass, and the electrical performance of the solar cell degraded. The degradation was attributed to metal atoms of the N contact achieving sufficient mobility to penetrate to the shallow diffused P-N junction, thus shorting the cell. This mobility of the contact atoms was utilized in subsequent efforts. The N contacts were deposited on top of a dielectric layer on the cell surface. During the final glass fusion step, the temperature and time were controlled such that the contact atoms penetrated the dielectric sufficiently to make ohmic contact with the diffused layer of the cell, but not deep enough to reach the junction (1). Cells fabricated by this technique exhibited radiation darkening of the glass of a degree comparable to Corning 0211, which is considered tolerable for some missions. However, GSFC decided to investigate several other promising integral coverslipping methods at this stage rather than perfect the fusing process. In particular, developments in sputter desposition of thin films warranted an investigation of the applicability of this technique for the comparatively thick film requirements for integral coverslipping.

A review of the basic sputter processes and the various sputter modes investigated for the unique integral coverslip application is in order to describe the type of integrally coverslipped cells developed and evaluated.

The basic sputtering apparatus consists of a cathode of the material to be sputtered, an anode to provide electrical continuity, and a substrate to be coated enclosed in a vacuum chamber. This substrate, the solar cell in our application, is placed on or adjacent to the anode. Sputtering is performed in a 5×10^{-3} to 500×10^{-3} Torr inert gas atmosphere, usually Argon. A voltage of about 1 to 10 kilovolts applied between the cathode and anode generates a plasma. Positive ions from the plasma are accelerated to the cathode surface by this high potential with sufficient energy to overcome the binding energy of the cathode lattice atoms and dislodge, or "sputter," these atoms by momentum transfer. These bombarding ions also release cathode electrons which are then repelled by the cathode into the plasma, creating additional ions and sustaining an electron-ion regeneration cycle. The sputtered atoms impinge on the substrate, which is positioned on the anode, forming a very uniform film. The high energy of these sputtered atoms makes this film much more adherent to the substrate surface than evaporated films.

So far we have described the DC sputtering process which works successfully with practically all metals and conducting materials. However, if any of the transparent dielectric materials considered for solar cell coverslips are used as cathodes in this process, an insulating positive charge would build up on the cathode surface under the positive ion bombardment. This positive charge buildup would repel additional positive ions and extinguish the plasma - thus stopping the process. A solution to this problem through the application of a radio-frequency (RF) potential to the dielectric target was proposed by Wehner in 1955 (2), but was not pursued until 1961. The RF potential drives a current through the dielectric, which is attached to the cathode, thereby energizing the plasma. The dielectric target is then alternately bombarded with ions and electrons. These electrons neutralize the surface charge for one half of the cycle and the ion bombardment dislodges the dielectric atoms during the other half of the cycle. This is the RF sputtering process (see Figure 1). It can be employed to deposit atoms or molecules of a dielectric target in films that closely resemble the target's structure. Deposition rates as high as 2000 Å/min. have been obtained with RF sputtering.

An external magnetic coil generating an axial magnetic field is used in many sputtering processes to change the linear path of the electron flow into a helical path. This increases the number of ionizing collisions and the increased ion density at the target increases the sputtering rate.

A variation of the basic sputtering process is obtained by introducing reactive gas atoms into the inert gas region. Sputtered atoms from a single element target combine with the reactive gas atoms at the substrate surface and also by collision prior to substrate impact. This technique is appropriately referred to as reactive sputtering and it can be combined with either the DC or the RF sputtering process.

The problems encountered with reactive sputtering stem from backscatter of molecules which collect at the cathode and form discontinuous dielectric regions. Electrical breakdown of these regions can dislodge flakes of SiO_1 or form devitrified SiO_2, both of which can become inclusions in the depositied thick film. These effects significantly impair the optical quality of the film.

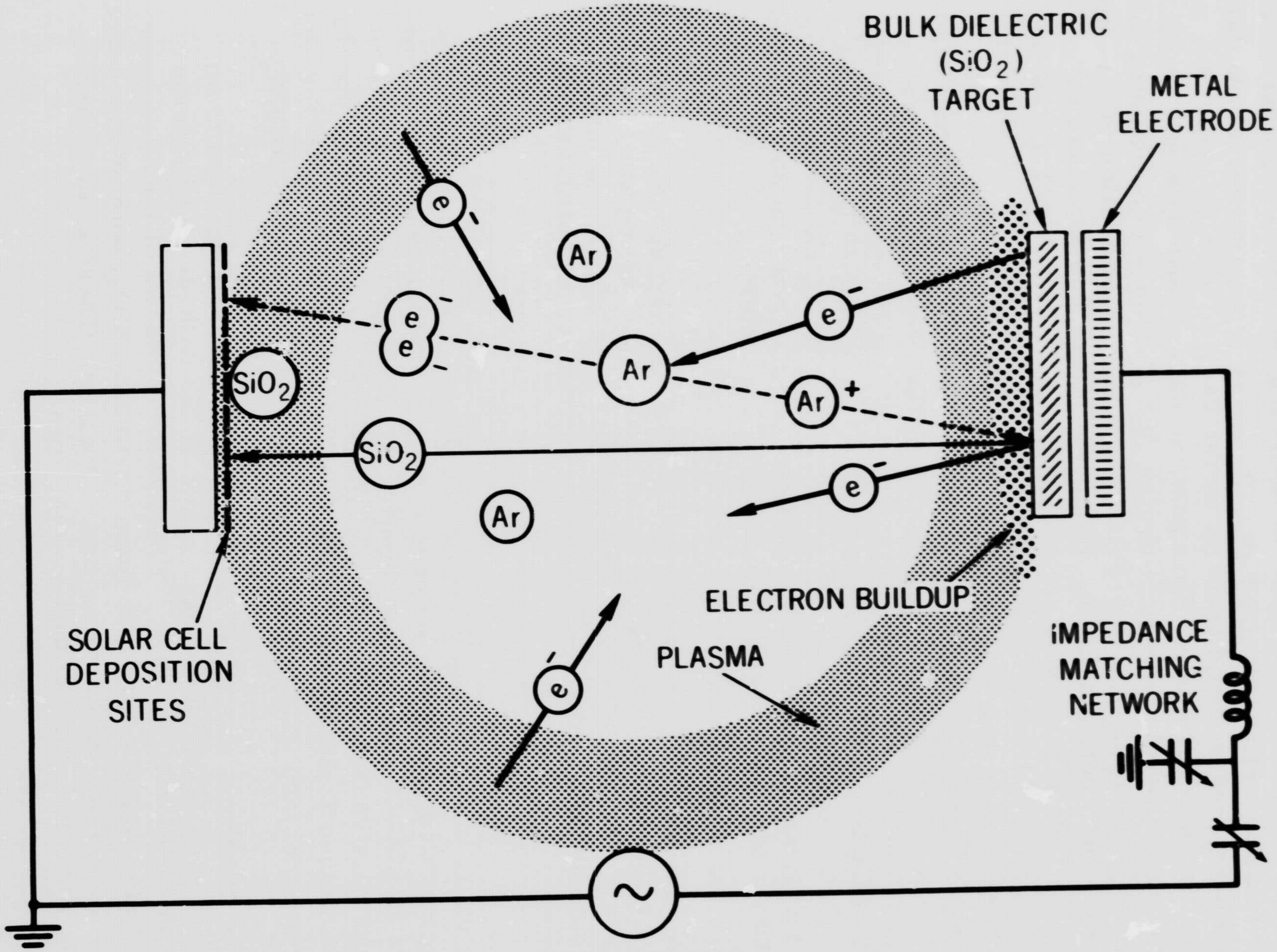

Figure 1–RF Sputtering Schematic

A high-vacuum-ion beam (HVIB) sputtering apparatus developed specifically for integral coverslipping solar cells is schematically illustrated in Figure 2. This system uses an ion source physically separated from the target to generate a 35 to 50 keV focused ion beam. Separation is effected because the source plasma fills the lens aperture. This separation allows the ion source to operate in a relatively poor vacuum (approximately 10^{-3} Torr), where it is efficient while deposition takes place in a high vacuum (10^{-6} Torr) space. High vacuum between the target and the solar cells provides a mean free path of the sputtered molecules which greatly exceeds the target-to-cell spacing. Theoretically, the sputtered molecules reach the cells without collision and at maximum energy, which enhances their surface penetration, resulting in a strongly bonded coating (3). The focused ion beam is directed at the target at a grazing incidence since the sputtering yield (number of sputtered atoms per incident ion) increases with the more oblique incidence of the ions. Electrons are boiled off a filament adjacent to the target to prevent charge build-up. Solar cells are mounted along the periphery of a rotating drum, which enables eight hundred cells to be coated simultaneously. Deposition rates by HVIB sputtering are typically 200 A/min. of SiO_2. Thus, it takes about 21 hours to deposit one mil of SiO_2 on one hundred 1 X 2 cm cells with the drum in a fixed position. When sputtering is accomplished with the drum rotating, it takes about 80 hours to deposit a one-mil film on eight hundred cells.

A comparative evaluation of five modes of sputtering and electron beam evaporation was conducted to assess their integral coverslipping capability. Sputtering methods evaluated included: reactive DC, RF diode, RF triode, combined RF and DC reactive, and HVIB. Thick films deposited by reactive DC sputtering of silicon in an oxygen partial pressure were characterized by physical and optical inhomogeneity which was considered excessive for the integral coverslip application. These reactive sputtered film had a frothy white appearance not indicative of an SiO_x material. RF sputtered films were of good optical quality although they incorporated significant internal stresses. High initial costs of RF triode sputtering equipment precluded it from this investigation. HVIB sputtering produced thick films with similar characteristics as those of RF sputtered films. Thick films produced by electron beam evaporation of SiO_2 were of poor optical quality which was attributed to evaporation of devitrified SiO_2 (3).

In view of these results, it was decided to concentrate efforts on RF sputtering and HVIB sputtering with two independent investigators.

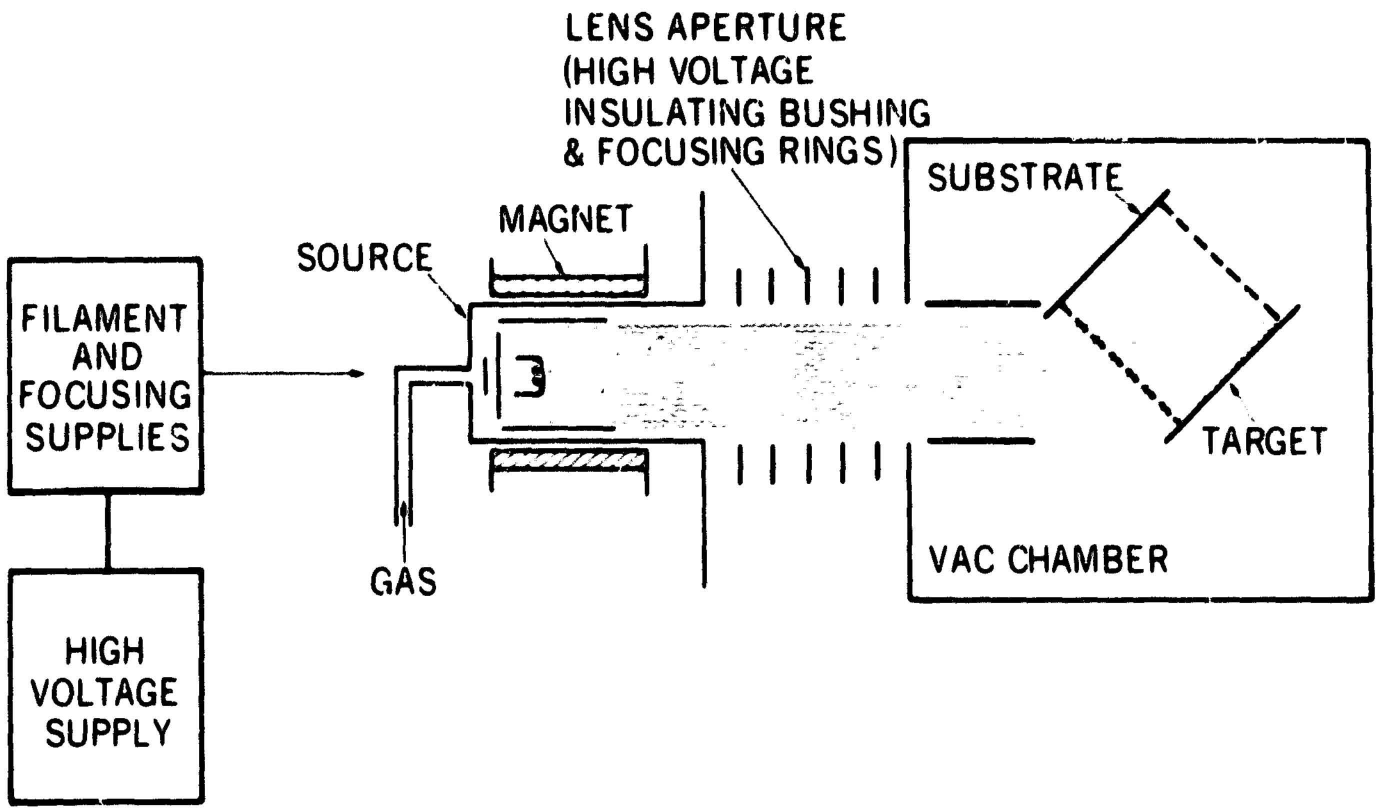

Figure 2–Ion Physics Ion Beam High Vacuum Sputtering System Schematic

Techniques were developed to uniformly sputter thick film coverslip materials onto the thin film anti-reflection (AR) layer which is evaporated directly to the active cell surface. (It should be noted that the sputtering molecules penetrate this AR film, which is approximately 800A-thick, to form a bond. As there is no apparent change in the AR optical characteristics, it is reasonable to assume that most of the sputtered molecules do not penetrate to the cell surface. Bond strength at either the cell-AR coating or the AR coating interfaces has not been a problem.)

ANTI-REFLECTION COATINGS FOR INTEGRAL COVERSLIPPED CELLS

The silicon monoxide (SiO) anti-reflection (AR) coating conventionally applied to silicon solar cell surfaces is not the optimum coating for use with integral coverslips. Ideally, the AR coating should eliminate reflection of all energy, in the cell's spectral response bandwidth, incident to the cell's surface. Theoretically, this ideal condition of total optical absorption at the cell's surface, which produces the maximum possible cell performance, occurs when reflections from the upper and lower surfaces of the AR layer are equal in amplitude and opposite in phase at specific wave lengths. This condition requires that the AR coating thickness be an odd integral multiple of quarter-wave lengths and that the refractive indices, n, maintain the relationship:

$$n_{(coating)} = \sqrt{n_{(coverslip)} \times n_{(silicon)}}$$

Since $n_{(coverslip)} = 1.45$ and $n_{(silicon)} = 4.0$ in the cell response region, the optimum AR coating for an SiO_2- coverslipped Si cell is 2.42. The conventionally applied SiO coating has a refractive index of 1.95. However, a CeO_2 anti-reflective coating with a considerably more ideal refractive index of 2.35 was chosen for integral coverslip application. CeO_2 is more difficult to deposit than SiO, but the techniques are compatible with quantity production. It should be noted that bare cells with CeO_2 will reflect more energy in the cell's response bandwidth than SiO in air, which has a refractive index of unity. That is to say, the "ideal coating" for bare cell measurements in air would have an index of refraction of 2.0. However, since essentially all space applications require a coverslipped cell, the meaningful cell measurements should be made with installed coverslips. The performance gains achieved with CeO_2 coatings on integrally coverslipped cells have been less than theoretically predicted, but are still gains compared to similar units with SiO coated cells. A group of five cells with CeO_2 evaporated coatings was tested before and after the deposition of 3 mils of SiO_2 ion-beam-sputteredintegral coverslip. The coverslipped cells showed a 2 milliamp average increase (a 1-1/2% gain) in short circuit current (I_{sc}), a 1 milliamp gain at the maximum power (a 3/4% gain) and a 10 millivolt average decrease (about 2% loss) in open circuit voltage (V_{oc}) compared to their precoverslipping output. By comparison, solar cells with an SiO AR coating degrade about 3% from their bare cell performance when covered with a conventionally bonded SiO_2 coverslide. This degradation is primarily a current loss.

COVERSLIP MATERIALS

Many materials have been investigated for use as solar cell coverslides. The primary requirements are that the material must have a very high optical transmission characteristic over the cell's spectral response bandwidth and show little sensitivity to ultraviolet and particle radiation exposure at levels encountered by spacecraft. Three materials are used as adhesive-bonded solar cell coverslides. These are sapphire (Al_2O_3); Corning 0211, commonly referred to as Microsheet, which is a treated drawn, fire-polished silica glass with a low melting point; and Corning 7940, a synthetic fused silica manufactured by a vapor deposition method with less than 0.2 ppm impurities and a high melting point. The latter material is by far the most widely used for coverslipping because of its capability of withstanding very high radiation exposure with minimal transmission degradation. Since there have been no significant solar array problems attributable to this fused silica, it was chosen as logical material to start with for sputter depositing integral coverslips.

Deposition of fused silica by various sputtering modes has always produced highly stressed films when the thickness is built up to the coverslip range. This stress is sufficient to produce curvature in 15-mil-thick solar cells. While this compressive stress level is possibly tolerable up to 3 mils, it is much too severe at thicknesses in the 6- to 8-mil range. For example, cells with 6-mil thick sputtered coverslips have fractured in shipping containers within 4 weeks of delivery. In addition, special handling of these highly stressed 6 mil coverslipped cells is mandatory as some have shattered when dropped from a 6-inch height.

This stress-produced coverslip curvature, which is characteristic of sputtered fused silica, decreases with increasing temperature. However, when the solar cell has been removed by etching from the coverslip, curvature still persists. Thus, the major portion of the stress is built into the sputtered film during deposition and is not primarily a result of thermal mismatch. Fused quartz has been sputtered onto cells whose temperatures have been controlled from -196°C to 300°C. The magnitude of cell curvature was independent of substrate temperature. Typically, the films deposited on the very low temperature cells were very porous, of low density, and of poor optical quality. Thick films deposited onto substrates maintained above 0°C by RF sputtering exhibit the desired optical quality; however, the density and porosity although markedly improved may still be a problem as discussed in the temperature-humidity testing section. Films sputtered onto cells at 30°C and at 300°C appeared physically identical although the deposition rate was about 30% higher with the 30°C cells (4). Additional evidence of the built-in stress preponderance was obtained with sputter deposition of 2 mil fused silica films on fused silica slides. Theoretically, these sputtered film-bulk slides have no stresses attributable to thermal mismatch, as the two materials are identical. However, a compressive stress of 2490 psi was measured on these units, which was in excellent agreement with the stress levels measured with similar integral cover-slips on Si solar cells. This intrinsic compressive stress is the major obstacle to flight utilization of sputter-deposited, fused silica integral coverslips.

Several approaches are being considered to alleviate or circumvent this stress problem. These methods include annealing the sputtered film, sputtering new materials and electric potential bonding. Unfortunately, the melting point of fused silica is 1100°C thereby eliminating heat-treatment as a method for stress relief. However, materials with melting points below 600°C can be considered heat-treatable without affecting conventional silicon solar cell performance. Various boric-oxide silica glasses appear to be prominent candidates for integral coverslipping. In the event that sputtered films of these materials incorporate the compressive stresses experienced with fused silica, they can be annealed. These boric-oxide silica glasses have been previously considered questionable as coverslide material because of their degradation due to radiation. This degradation involves optical absorption in the photovoltaic spectral response region.

Two particular , interesting methods of reducing coverslip optical absorption are currently being developed. One method consists of impregnating the coverslip with hydrogen under very high pressures at elevated temperatures. Apparently the hydrogen atom reacts with a damage site caused by particle radiation, resulting in a shift of the absorption band to the IR region. Four cells with RF sputtered cover-slips were subjected to the hydrogen impregnation process to ascertain compatibility. The cells showed an increase in short-circuit current of between 5% and 9% after impregnation. (See Figure 3.)

Three cells with RF-sputtered coverslips, which were from the same manufacturing run as those subjected to hydrogen impregnation, were annealed at 400°C for 30 minutes. Two of these cells exhibited virtually the same current-voltage characteristic as obtained before annealing. However, the third cell showed an I_{sc} gain of 0.6 milliamps which is about a 1% improvement. Later impregnation work with bare cells did not duplicate the increased performance obtained with integrally coverslipped cells. Thus, the performance gain obtained with hydrogen impregnation does not appear to be primarily an annealing or an optical transmission improvement phenomenon. Although the mechanism responsible for the increased performance remains to be identified, it is believed to be an effect associated with hydrogen enrichment at the

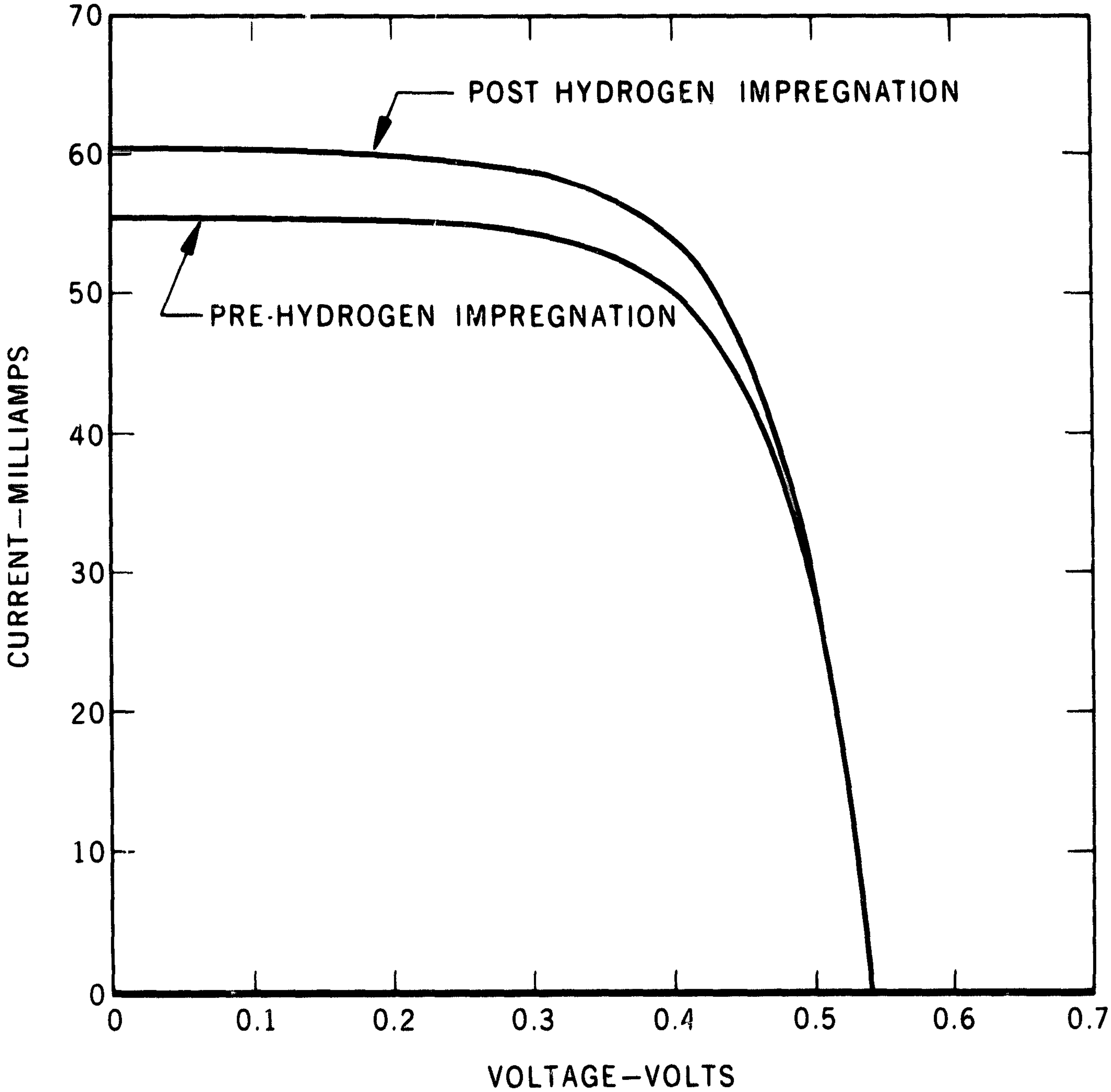

Figure 3—Hydrogen Impregnated RF Sputter Coated Solar Cell (for Parameters see Table 1)

cell surface. Clearly hydrogen diffusion through the integral coverslip must be investigated.

The impregnation level in this preliminary work, which was approximately a 20,000 psi at 250°C for 15 hours, restricts the technique to solderless cells. Recent work by Gereth (5) indicates that the major problem with solderless cells, which is contact degradation in a humid environment, can be solved.

Cells with HVIB sputtered fused quartz covers have shown an increase in electrical performance after being subjected to a short anneal cycle (6). Tests were conducted on five randomly selected 2 X 2 cm cells with Al contacts and SiO antireflective coatings. An average of 6 milliamps short circuit current (I_{sc}) recovery was measured after a 20-minute 300°C anneal cycle. It should be noted that these same cells averaged a 10 milliamp I_{sc} loss as a result of the integral coverslip deposition process. The net loss of these cells from the bare cell performance through integral coverslip deposition and annealing is 4 milliamps. This loss is consistent with the theoretical loss after coverslip deposition due to mismatch of refractive indices on a cell having an SiO antireflective coating. These results indicate that annealing improves the optical transmission characteristics of integrally covered cells which have degraded during the HVIB sputtering deposition of fused quartz covers.

Significant improvement of the optical transmission in resistance to particle radiation has been achieved by doping glasses with small percentages of Cerium (8). An investigation is being conducted to determine whether a thick film can be sputtered reproducing the cerium dopant concentration and dispersal. If this work is successful, cerium doping could greatly increase the number of candidate materials for integral coverslipping. This new latitude in material selection for thick film sputtering should provide an annealable coverslip with little radiation sensitivity.

Recent work at Bell Labs indicates that varying the concentrations of oxygen and nitrogen in oxynitrides produces either tensile or compressive stresses in chemically vaporized films. When 12%-13% of the oxygen atoms in SiO_2 films were replaced by nitrogen the film stress was essentially eliminated (7). This effect will be investigated with the HVIB sputtering process. Oxynitride films will be sputter deposited with a nitrogen gas pressure maintained at the cell substrate. The immediate objective of this effort will be to determine the nitrogen pressure which produces a neutral stress in the sputtered coverslip. An alternate approach will be to use multiple targets rather than maintaining a gas bleed to the cell surfaces during sputtering.

Table I

Types of Integrally Coverslipped, N/P, 1 × 2 cm Silicon Solar Cells Tested

Mfgr.	Base Resistivity (Ω-cm)	Nominal Cell Thickness (mils)	Cell AR Coating	Integral Coverslip Material	Deposition Technique	Approximate Deposition Rate	Nominal Coverslip Thickness (mils)	Date of Mfgr.
Centralab	10	16	SiO	Boro-Silicate Glass	Fused	N/A	1	Sept. '65
Ion Physics	10	15	CeO_2	SiO_2	High Vacuum Ion Beam Sputtered	~200Å/min	2	Mar. '68
Texas Instr.	10	13	CeO_2	SiC_2	RF Sputtered	~1600Å/min	2	Mar. '68

Additionally, existing techniques will be used to sputter deposit Al_2O_3. Since the density of Al_2O_3 is greater than SiO_2 by a factor of 1.32, sputtered Al_2O_3 of 1/3 less thickness than SiO_2 provides equivalent radiation protection. Current efforts are being conducted to determine the thick-film characteristics of sputtered Al_2O_3.

An exploratory investigation of electric potential bonding of thick coverslips directly to the cell or to a thin-film integral coverslip will also be conducted.

INTEGRAL COVERSLIP EVALUATION

Evaluation testing of integral coverslip cells is currently being conducted at GSFC. Cells with integral coverslips of fused borosilicate glass, RF-sputtered and high-vacuum-ion-beam (HVIB) sputtered thick films of fused quartz were tested. The significant manufacturing parameters for these integrally coverslipped cells are identified in Table I. Evaluation tests to date include solderability, temperature-humidity exposure and proton irradiation.

SOLDERABILITY

The only problems experienced in the solderability tests were on a few of the fused borosilicate glass coated cells. These cells required selection as the glass had coated a portion of the cell contact strip on some cells. However, cells of all three types described in Table I were successfully soldered at GSFC to expanded silver mesh interconnectors with conventional soldering techniques.

TEMPERATURE-HUMIDITY EXPOSURE

Ten cells of each of the three types represented in Table I were subjected to a 2-week 95% relative humidity exposure at 70°C. Five of the RF sputtered cells fractured catastrophically (see Figure 4) and one additional cell exhibited an extensive milky coloring, which is indicative of delamination, within the coverslip. The other two types did not exhibit either mechanical degradation observable under microscopic (30x) inspection or electrical degradation in current-voltage (I-V) testing. The observed cell fracturing is believed to be either a coverslip porosity problem, in which the SiO_2 molecules have not had sufficient time to

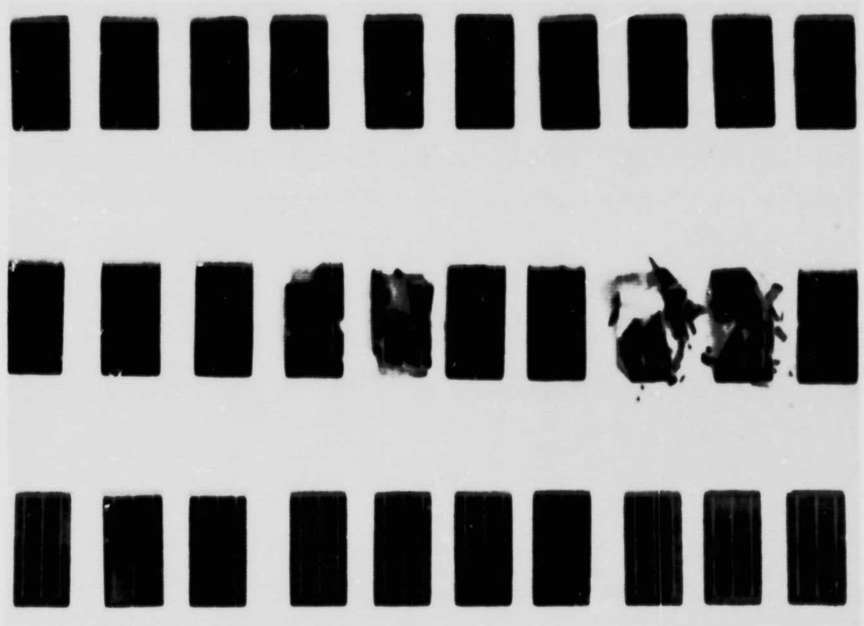

Figure 4-Integrally Coverslipped Cells After Temperature-Humidity Test Toprow-HVIB Sputter Coated Cells, Middlerow-RF Sputter Coated Cells Bottomrow-Fused Glass Coated Cells.

find their closest packing before being locked in by subsequent layers, or a heterogeneous layer deposition problem. Additional RF sputtering work is needed to investigate the films for inclusions and to measure coverslip density as a function of deposition rate and substrate temperature. Obviously, this accelerated humidity exposure cannot be extrapolated to real-time, relatively low-humidity exposure; however, it does indicate a significant problem area.

PROTON IRRADIATION TESTING

The major purpose for the integral coverslip, other than increasing thermal emissivity, is to protect the solar cell from particle radiation protection. If an integral coverslip cannot adequately shield the solar cell without significantly degrading its optical transmissive properties in the process, it cannot be considered for space power application. The effectiveness of shielding solar cells from low energy protons (below 5 MeV) is difficult to assess because an adequate analytical method for predicting the effects of the protons is not yet available (9). Thus, the most meaningful evaluation test for the integral coverslip is the low-energy proton exposure.

Low-energy proton bombardment tests were conducted at the GSFC Radiation Test Facility on integral coverslipped cells with 500 keV and

2 MeV protons. Bare cells with SiO AR coatings were included in the tests as controls to verify the measured exposure level by providing data for direct comparison with previous data. Cells with CeO_2 AR coatings and cells with conventional 6-mil Corning 7940 bonded cover-slides were also tested for comparative purposes. (See Table II).

All irradiation testing was conducted in a 4×10^{-5} Torr vacuum. The proton source was a 2-MeV Van de Graaff accelerator. The beam was defocused through a magnetic field such that only atomic mass number = 1 particles were bent towards the target wheel as a 3-inch diameter collimated beam. Beam uniformity was checked prior to each test. A Faraday Cup, traceable to Bureau of Standards calibration, was mounted on the test wheel's surface at the test sample radius and a Cu target was installed 180 degrees further along the same circumference. Flux was continually monitored with an integrating current meter. An aluminum bar covered the N-contact of each cell under test.

A description of the types and quantities of cells subjected to the 500 keV and the 2.0 MeV proton irradiations is shown in Table II. Cells with CeO_2 AR coatings became available for the 2.0 MeV irradiation test and were included to provide data concerning susceptibility of CeO_2 coatings to proton bombardment. This test also provided comparative data for both the SiO and the CeO_2 AR coatings. In addition, this data was necessary in the event differences were measured in the radiation damage susceptibility of the integrally coverslipped cells.

Before and after every decade of exposure, from 10^{11} and 10^{14} protons/cm^2, current-voltage (I-V) characteristics were measured in air with an X-25 solar simulator. The simulator output was checked with a "balloon flight" standard cell prior to measurements at each decade. Cell temperatures were controlled at 30°C ± 1°C. I-V curve measurement accuracy is considered to be within ±3% for this test.

The normalized values of I_{sc}, V_{oc} and maximum power (P_{max}) as functions of fluence for 500 keV proton irradiation are shown in Figures 5, 6, and 7 respectively. Data are plotted for the three types of integrally coverslipped cells, bare cells, and conventionally bonded 6-mil cells subjected to 500 keV proton bombardment. Bare cell degradation is in general agreement with other investigations, indicating the validity of the fluence values. There was essentially no I_{sc} drop on any of the integrally coverslipped cells. A 6% V_{oc} loss was measured after 10^{14} protons cm^{-2}. The normalized P_{max} loss which "summarizes" the cell degradation was slightly more severe than anticipated, but tolerable

Table II
Number of Cells Tested at Each Fluence

Proton Energy Level	Cell Type	Cell AR Coating	10^{11} protons/cm^2	10^{12} protons/cm^2	10^{13} protons/cm^2	10^{14} protons/cm^2
500 keV	RF Sputtered	CeO_2	8	6	4	2
	HVIB Sputtered	CeO_2	8	6	4	2
	Fused Borosilicate	SiO	8	6	4	2
	Bonded 7940 (6 mil)	SiO	8	6	4	2
	Bare	SiO	2	2	2	2
2.0 MeV	RF Sputtered	CeO_2	7	6	4	2
	HVIB Sputtered	CeO_2	7	6	4	2
	Fused Borosilicate	SiO	7	6	4	2
	Bonded 7940 (6 mil)	SiO	3	3	3	3
	Bonded 7940 (6 mil)	CeO_2	3	3	3	3
	Bare	SiO	4	4	4	4
	Bare	CeO_2	3	3	3	3

for some missions. Proton straggling at this energy level might be involved in the degradation. Data points represent average measured values of matched cells and are consistent, with the exception of fused-glass coated cells, where difference in coverslip thickness is a known factor and differences in contact application and treatment may also be a factor.

The normalized values of I_{sc}, V_{oc}, and P_{max} are shown in Figures 8, 9, and 10 respectively as functions of fluence for the 2.0 MeV irradiation test. Again, bare SiO-coated ce. degradation is in general agreement with other investigations. The RF-sputtered and HVIB-sputtered integrally coverslipped cells were practically undegraded. However, the fused-glass coated cells degraded between 15 and 45 percent in maximum power, with an average of 28% degradation after 10^{14} protons cm^{-2}. The wide spread in the fused-glass cell data is indicative of variation in the nominal 1-mil coverslip thickness, composition and/or contact degradation.

This data verifies the capability of sputtered integral SiO_2 coverslips to shield solar cells effectively from both 500 keV and 2-MeV protons. Thus, the sputtered SiO_2 film apparently retains the radiation characteristics of the bulk material. The bare CeO_2 cells and bare SiO coated cells exhibited similar degradation from 2 MeV protons. Both types were essentially degraded about 50% in I_{sc} at 10^{13} protons cm^{-2} and were degraded about 84% at 10^{14}. Since the bare cell data indicates no signficant difference between SiO and CeO_2 coatings, differences in the data for the shielded cells are not considered attributable to the coatings.

CONCLUSIONS

There was essentially no difference between the power out of bare cells with SiO and CeO_2 AR coatings after 2.0 MeV proton irradiation of fluences up to 10^{14} protons-cm^2.

Cells with fu[illegible] borosilicate glass degraded severely under proton irradiation. Appa[illegible]ently this integral coating was non-uniform with respect to composition and thickness. The complexities involved in perfecting this process are significantly greater than those encountered in sputter deposition of thick films.

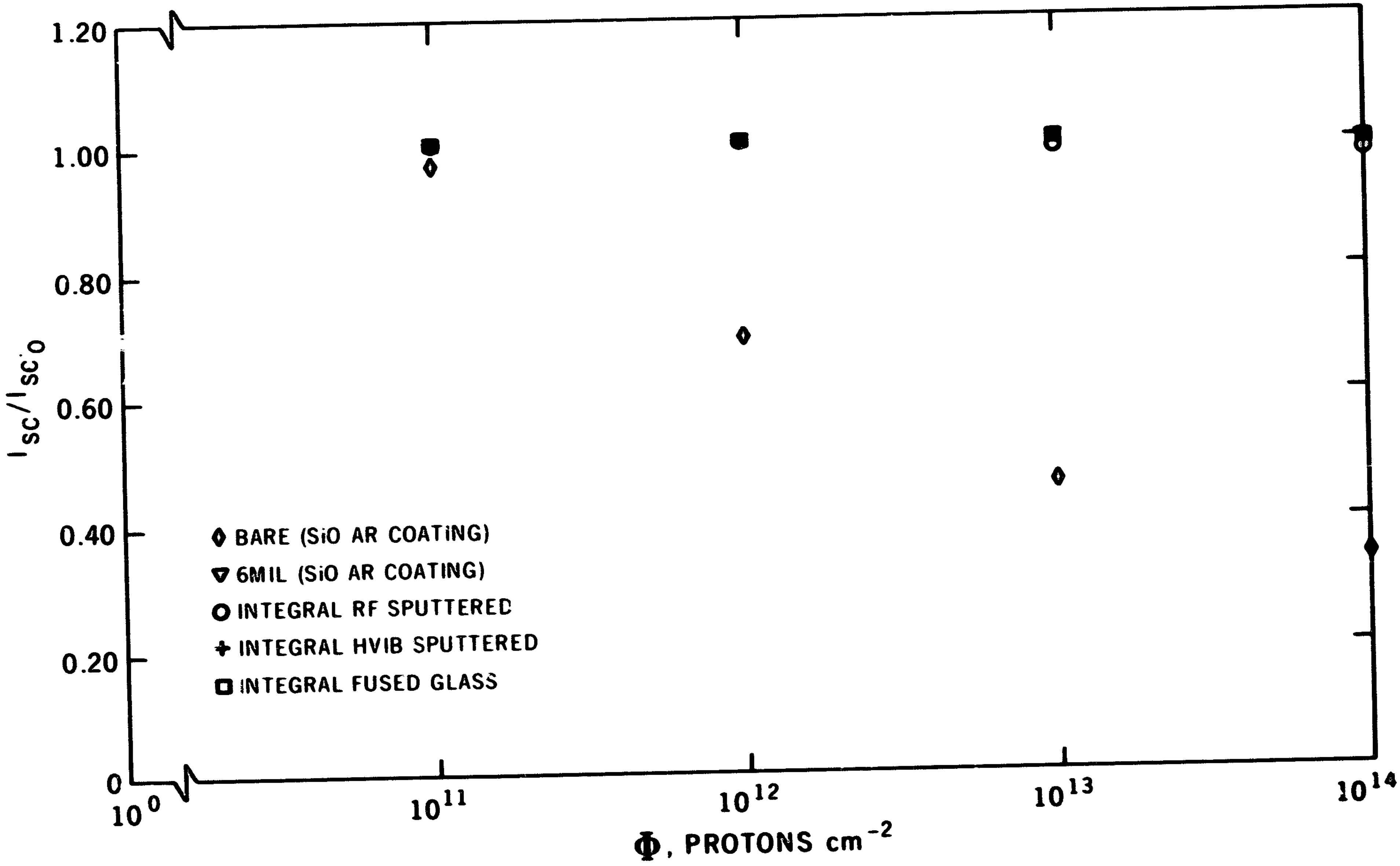

Figure 5–Normalized Short Circuit Current Degradation under 500 Kev Protons

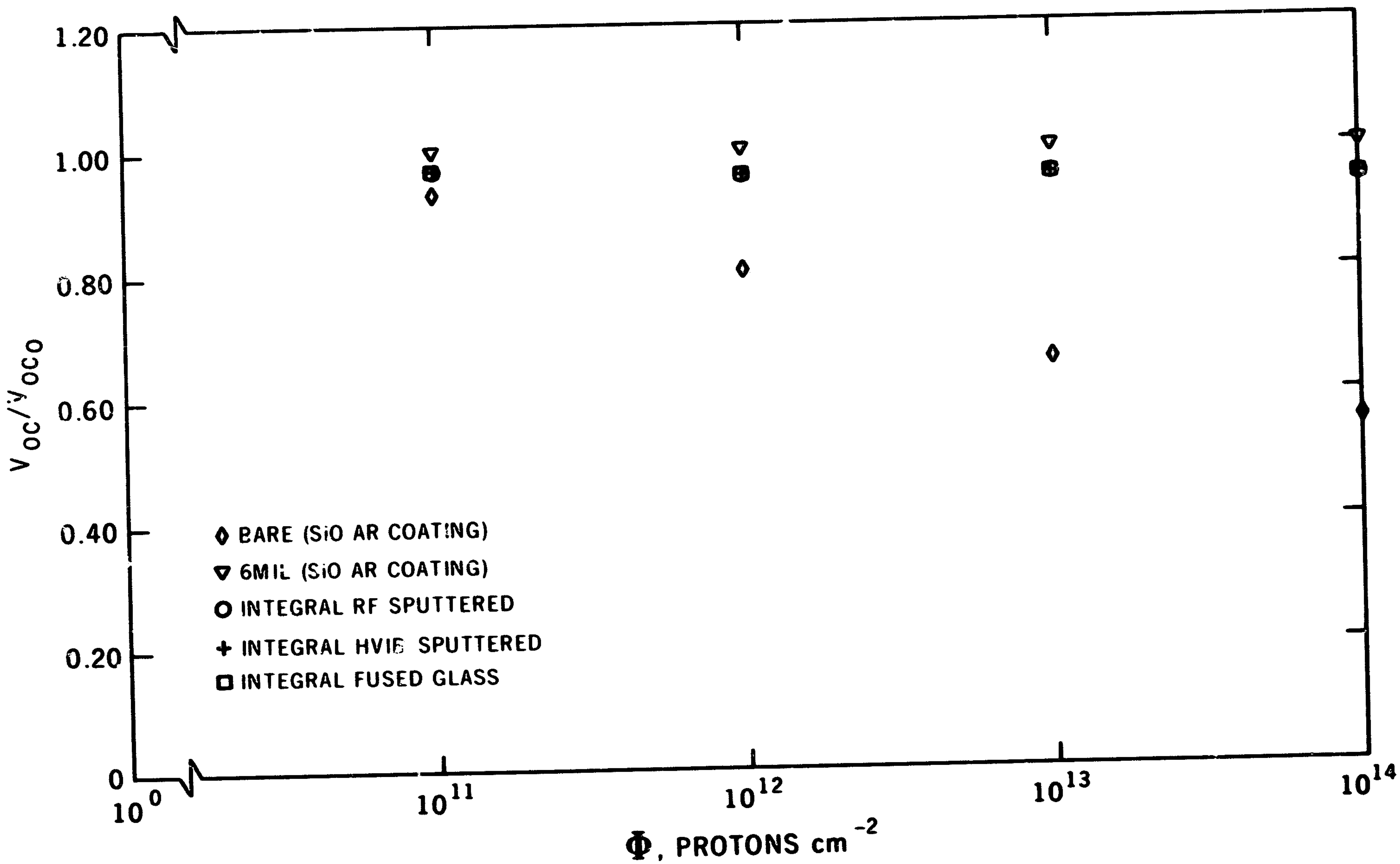

Figure 6–Normalized Open-Circuit Voltage Degradation under 500 Kev Proton Fluence

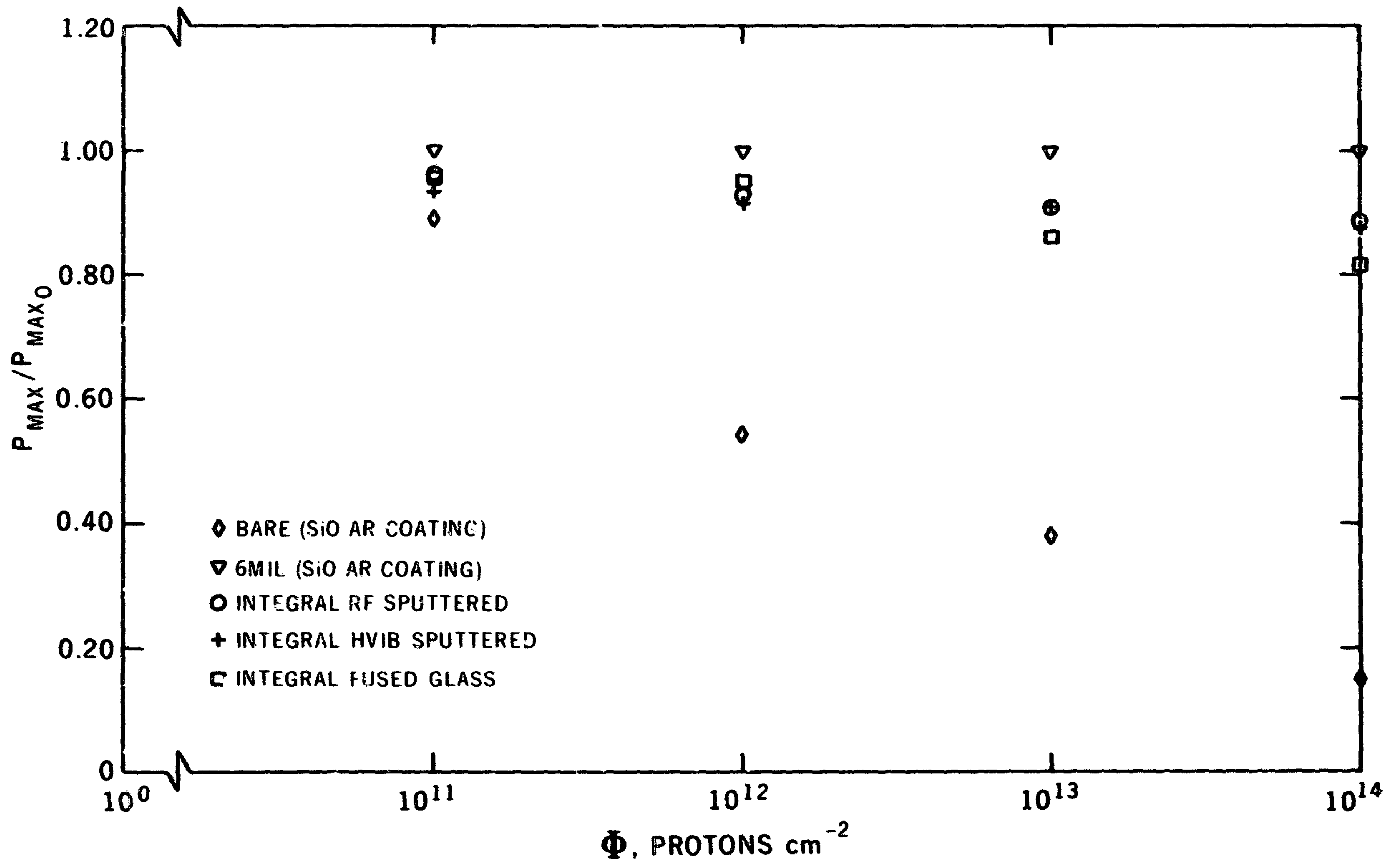

Figure 7—Normalized Maximum Power Degradation under 500 Kev Protons

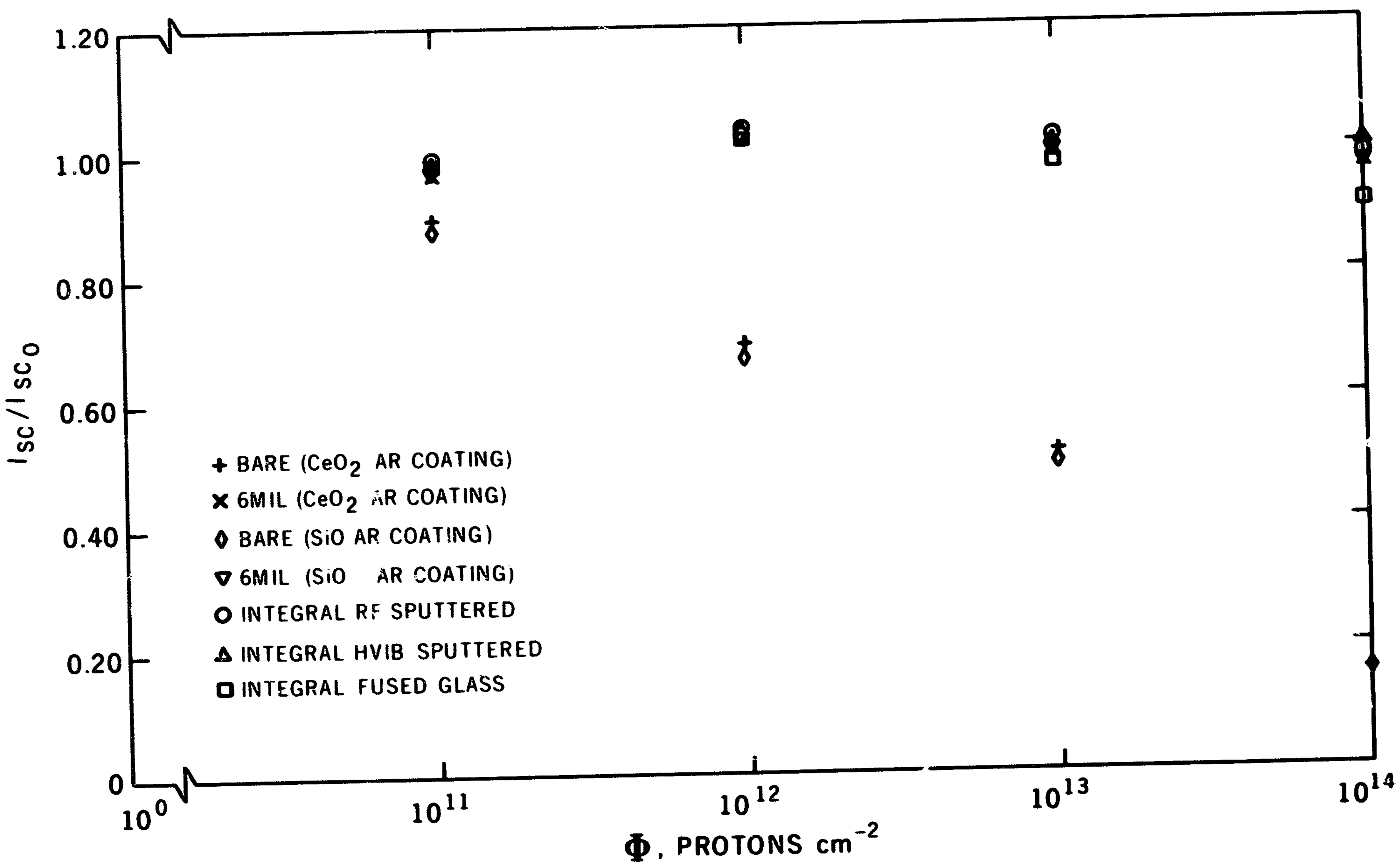

Figure 8—Normalized Short Circuit Current Degradation under 2.0 Mev Protons

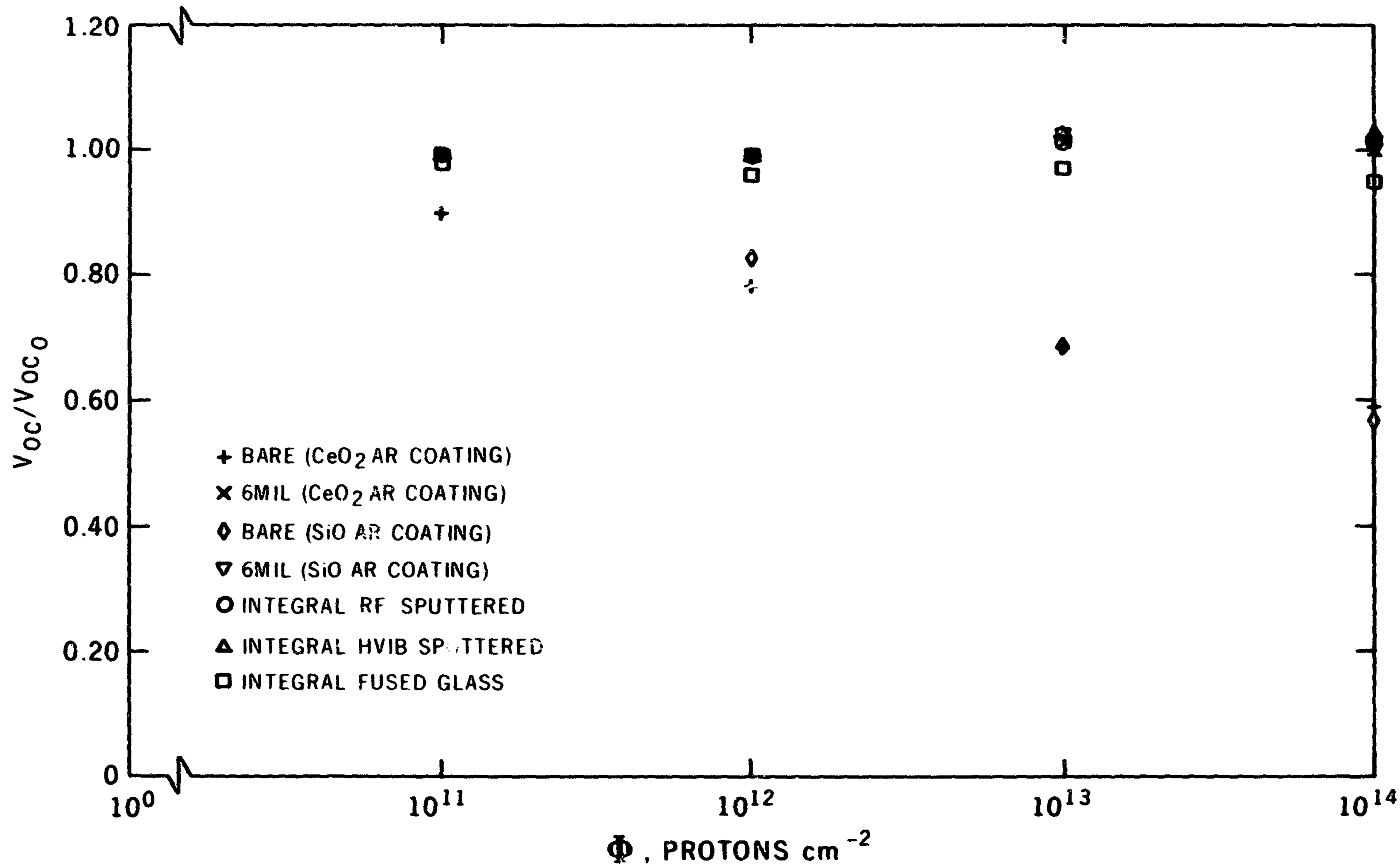

Figure 9—Normalized Open Circuit Voltage Degradation under 2.0 Mev Protons

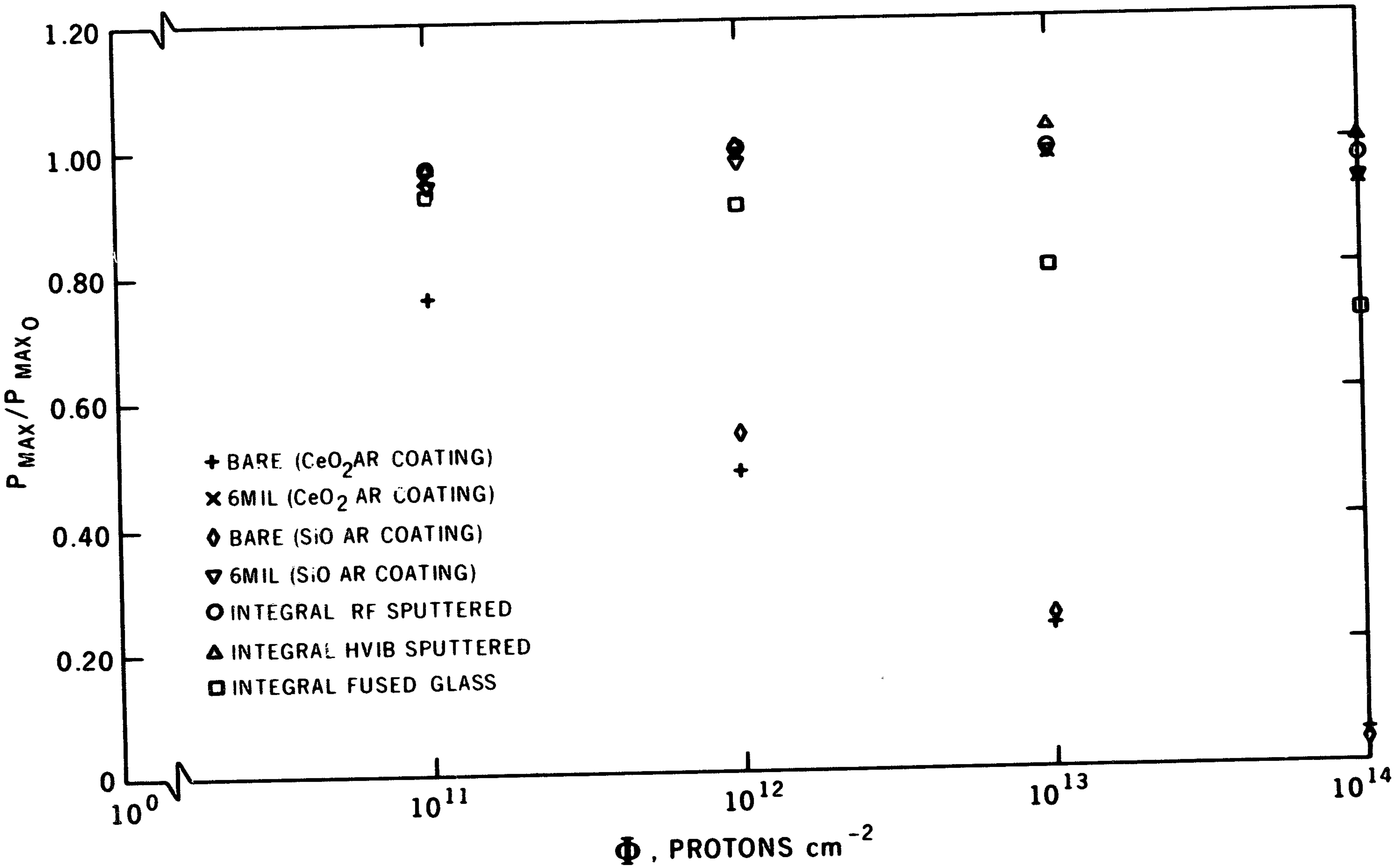

Figure 10—Normalized Maximum Power Degradation under 2 Mev Proton

Sputtering techniques have been developed to integrally deposit SiO_2 coverslips on solar cells in thicknesses which can effectively shield the cells against low-energy protons. However, all thick SiO_2 films sputtered so far exhibit severe compressive stresses. The 3-mil sputtered SiO_2 integrally coverslipped cell could be considered a candidate for certain flight projects; however, additional flight qualification testing is mandatory. The definitive integral coverslipping technique has not yet been developed, primarily because of the stress problem. Circumvention of these internal stresses by sputtering glasses which have low annealing temperatures and which are, or can be made, reasonably radiation resistant is the current objective. Additionally, alternate techniques to achieve the desired integral coverslip are being investigated. These methods include electric potential bonding, sputter deposition of films with an oxynitride polymer structure and chemical vapor deposition.

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