5101-131
Low-Cost
Solar Array Project

DOE/JPL-1012-49
Distribution Category UC-63b

Photovoltaic Module Soiling Studies May 1978 - October 1980

A. R. Hoffman
C. R. Maag

(DOE/JPL-1012-49) PHOTOVOLTAIC MODULE SOILING STUDIES, MAY 1978 - OCTOBER 1980 (Jet Propulsion Lab.) 52 p HC A04/MF A01 CSCL 10C

N81-16580

Unclas
G3/44 41234

November 1, 1980

Prepared for
U.S. Department of Energy
Through an agreement with
National Aeronautics and Space Administration
by
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

(JPL PUBLICATION 80-87)

5101-131
Low-Cost
Solar Array Project

DOE/JPL-1012-49
Distribution Category UC-63b

Photovoltaic Module Soiling Studies May 1978 - October 1980

A. R. Hoffman
C. R. Maag

November 1, 1980

Prepared for
U.S. Department of Energy
Through an agreement with
National Aeronautics and Space Administration
by
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

(JPL PUBLICATION 80-87)

Prepared by the Jet Propulsion Laboratory, California Institute of Technology, for the Department of Energy through an agreement with the National Aeronautics and Space Administration.

The JPL Low-Cost Solar Array Project is sponsored by the Department of Energy (DOE) and forms part of the Photovoltaic Energy Systems Program to initiate a major effort toward the development of low-cost solar arrays.

ABSTRACT

The retention of particulate contamination on the surface of flat-plate photovoltaic devices is adversely affecting electrical performance of outdoor-exposed modules. This report describes the results of an experimental study being performed by the Jet Propulsion Laboratory's Low-Cost Solar Array Project to characterize and understand the effects of outdoor contaminants on sensitive optical surfaces of flat-plate photovoltaic modules and cover materials.

Comparative electrical and optical performance data from photovoltaic modules and materials subjected to outdoor exposure at field test sites throughout the United States have been collected and examined. The results show significant time- and site-dependence. During periods when natural removal processes do not dominate, the rate of particulate contamination accumulation appears to be largely material-independent. The effectiveness of natural removal processes, especially rain, is strongly material-dependent. Glass and acrylic top-cover materials retain fewer particles than silicone rubber does. Side-by-side outdoor exposure testing for long duration is presently the most effective means of evaluating soiling differences between materials. Changes in spectral transmission as a function of time and location and limited scattering data are presented.

ACKNOWLEDGMENTS

This task report presents the results of one phase of research conducted in the Applied Mechanics Division of the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the U. S. Department of Energy (DOE), through an agreement with the National Aeronautics and Space Administration (NASA). Many JPL people have supported these efforts. Special acknowledgement is given to A. Wilson, H. Schneider, W. Neiderheiser, F. Morelli, A. Garcia, W. Carroll, E. Cuddihy, and P. Jaffe. S. Forman, Massachusetts Institute of Technology Lincoln Laboratories (MIT/LL), Lexington MA, and A. Forestieri, NASA Lewis Research Center, have kindly provided field data from their test sites. M. Lind and T. Stewart, Battelle's Pacific Northwest Laboratories, Richland WA, under contract to DOE, have provided reflectance, transmittance, and scattering information on a set of material samples submitted from two test sites. S. Witz and E. Camarena of California's South Coast Air Quality Management District have provided testing sites in Pasadena and Torrance, California, and air pollution information. The following organizations have provided testing stations in their locales: Battelle's Pacific Northwest Laboratories, Sandia Laboratories, Albuquerque NM, MIT/LL, and New York University.

DEFINITIONS OF ABBREVIATIONS

A	Angstrom
GN_2	Gaseous nitrogen
I-V	Current-voltage
I_{sc}	Short-circuit current
JPL	Jet Propulsion Laboratory
LSA	Low-Cost Solar Array Project
P	Power
P_{max}	Maximum power
psig	Pounds per square inch, gauge
RNHT	Relative normal hemispherical transmittance
SCAQMD	South Coast Air Quality Management District (comprises four Southern California counties), a state agency
SEM	Scanning electron microscope
UV	Ultraviolet

CONTENTS

Tables

SECTION I

INTRODUCTION

As part of the national Photovoltaic Energy Systems Program, flat-plate photovoltaic modules have been exposed to outdoor weathering environments at several different application and test sites throughout the country during the last four years. One of the most significant causes of electrical performance degradation during that exposure has been the soiling of optical surfaces by airborne particulate matter, which causes significant optical loss by absorbing and scattering incident light. Performance degradation up to 60% has been reported at some outdoor sites in the United States (Reference 1). Soiling is the most pronounced cause, but it is not the only mechanism that can cause electrical performance loss resulting from the disruption of the light path to the solar cells. Other mechanisms that may contribute to optical-path degradation through the module encapsulant include: absorption of solar ultraviolet radiation, adsorption of moisture, temperature rises or temperature cycling, oxidation, chemical reaction with pollutants, interaction of the cover with dust particles, or two or more of these weathering elements acting synergistically. An earlier task report by A. Gupta (Reference 2) has addressed the photodegradation of encapsulant materials, which may be caused by solar UV acting alone (photolysis), solar UV and oxygen acting together (photooxidation), or solar UV and moisture acting together (photohydrolysis).

This report covers module-soiling investigations performed between May 1978 and October 1980 by the Engineering Area of the Low-Cost Solar Array Project (LSA) of the Jet Propulsion Laboratory (JPL), with the cooperation of LSA's Operations Area and Encapsulation Task, Technology Development Area. The investigations, which are ongoing, have the following objectives:

(1) Compile a data base from field-exposed modules and materials.

(2) Identify key physical properties of optical materials that govern soil retention.

(3) Develop technically sound test methods for evaluation of encapsulant materials.

(4) Develop simple laboratory tests for estimating the soiling affinities of various optical surface materials.

(5) Set preliminary guidelines for selection of materials to be exposed to dirt or dust or both.

This report describes the results of those efforts to date and provides a reference source of available experimental data.

SECTION II

FIELD SOILING EXPERIMENTS: DESCRIPTION AND RESULTS

A. MODULE FIELD DATA

Since 1976 three organizations in the photovoltaic program (NASA Lewis Research Center, Massachusetts Institute of Technology Lincoln Laboratory, and the Jet Propulsion Laboratory) have placed flat-plate modules in outdoor exposure sites throughout the country. Some results of those field experiments have been published (References 3 through 7). Included in these reports were tabulations of the effects of dirt on the electrical performance of the modules. The compilation and analysis of existing photovoltaic soiling data (i.e., development of a data base) were initial efforts in these investigations. The source materials for the data base were the referenced reports and additional information obtained directly from cognizant personnel.

Since the soiling data were obtained from different organizations with various performance measurement and reporting techniques, the information had to be analyzed carefully so that meaningful comparisons and interpretations could be made. Specifically, compilation difficulties resulted from differences in the accuracy of performance measurements and differences in soiling degradation calculations and reporting methods. The technique used to measure electrical performance degradation of a photovoltaic module is to obtain current-voltage (I-V) curves and compare the electrical characteristics, e.g., maximum power (P_{max}), short-circuit current (I_{sc}), open-circuit voltage (V_{oc}), fill factor, etc. with previous conditions. There are two methods commonly used to obtain I-V curves on flat-plate modules: irradiation by solar simulation, specifically large-area pulsed solar simulators (LAPSS), and irradiation by natural sunlight. The majority of the module soiling data utilized in this report is based on I-V curves obtained using solar simulation.

Performance degradation due to soiling is typically reported as a percentage of change from a prior condition. For example, for array subsystem performance evaluation the percentage of change in P_{max} from the initial condition (i.e., before deployment) to that several months after deployment is frequently reported. Some investigators (References 4 through 6) prefer to report the percentage of change in P_{max} or in I_{sc} between pre-cleaning and post-cleaning conditions. Typical cleaning procedures used by these organizations are:

(1) NASA Lewis Research Center:

A solution of Alconox-Tide is prepared and is applied with a scrub cloth; this is followed by light hand scrubbing until the scrub cloth appears clean. The modules are rinsed well with tap water and then dried.

(2) MIT/Lincoln Laboratory:

A solution of Alconox is prepared and is applied with a sponge or a washcloth. (At the Mead NB site it is applied with a soft bristle brush, which is followed by light hand scrubbing.) The modules are rinsed with tap water, using a hose. A squeegee is used for drying.

(3) Jet Propulsion Laboratory:

Modules are thoroughly rinsed with tap water. A cleaning solution of Franklin Formula 707 heavy duty water-based degreaser (62.25 cc per liter of water) is applied with a sponge. For badly soiled modules a bug sponge is used. The modules are then rinsed and dried with a squeegee and thoroughly wiped with a chamois. Modules at the JPL site are washed weekly. Modules at the other sites are washed at the time of physical and electrical inspection.

With certain types of materials (e.g. silicone rubbers), distinguishing among removable dirt, permanently adhered dirt, and material obscuration because of aging is not necessarily straightforward. This has led to the development of the following expressions for calculating the percentage change in I_{sc}:

% Total I_{sc} change before cleaning

$$= \frac{I_{sc}\ \text{DIRTY} - I_{sc}\ \text{INITIAL}}{I_{sc}\ \text{INITIAL}}\ (100)$$

% Total nonrecoverable I_{sc} change after cleaning

$$= \frac{I_{sc}\ \text{CLEAN} - I_{sc}\ \text{INITIAL}}{I_{sc}\ \text{INITIAL}}\ (100)$$

% I_{sc} change by cleaning

$$= \frac{I_{sc}\ \text{CLEAN} - I_{sc}\ \text{DIRTY}}{I_{sc}\ \text{CLEAN}}\ (100)$$

Analogous expressions for maximum power can be obtained by changing I_{sc} to P_{max} in these equations.

I_{sc} is probably more useful in characterizing soiling than is P_{max} because I_{sc} is known to be linear with illumination (for single-crystal silicon cells). I_{sc} is also relatively insensitive to temperature and cell electrical degradation associated with series resistance changes, in marked contrast to P_{max}, which is a strong function of both. This makes I_{sc} less sensitive to cell aging and measurement conditions. Since soiling affects the illumination of the cells by absorption and scattering of incident light, I_{sc} can be used as a direct measure of soiling of linear solar cells, especially when reporting changes between pre- and post-cleaning.

The percentage changes in P_{max} and I_{sc} for various modules at various sites throughout the country are given in Appendix A. From the examination of the tabulated data and of Figures 1 and 2, the following observations are made:

(1) Performance Degradation

Typical average short-term electrical performance degradation of 6 to 7% per month has been observed during rain-free periods in Pasadena CA, independent of surface materials (Figure 1). Over long periods (about 6 mo) the net accumulation, including effects of natural removal, results in measured degradation ranging from 2% for glass-surfaced modules in Arizona to 60% for silicone-surfaced modules in high-pollution city locations (Cleveland and New York City).

(2) Environmental Factors

Contamination effects on performance appear to be strongly dependent on local environmental factors. Significant differences in effects are observed at sites separated by only a few miles (Cleveland), primarily due to local pollution sources (one site was near a steel mill). Although the effect is not as pronounced, modules in lower Manhattan at New York University appear to experience greater performance degradation than do those in upper Manhattan, at Columbia University. Remote mountain sites, such as Mt. Washington NH and Mines Peak CO, as expected, seem to have relatively dust-free environments. Sites that have considerable precipitation throughout the year--resulting in periodic natural cleaning of surfaces--do not experience as great a performance loss as do those with less-frequent rains. Stronger bonds seem to be formed between particles and silicone-rubber module surfaces at sites with high humidity, such as Cleveland and Puerto Rico, than at sites with low humidity (Phoenix). This is manifested in relative differences in electrical characteristics in the total non-recoverable post-cleaning columns in Appendix A.

Local conditions that are likely to affect optical losses include at least some of the following factors (there may be others):

(a) Local airborne particulate matter, including quantity, molecular species, optical properties (absorption coefficient and refractive index), particle size and shape, and adhesion properties (chemical and physical adsorption).

(b) Local meteorology, including type, frequency, and quantity of precipitation; humidity and dew cycles, wind, temperature cycles, and ocean influence (salt nuclei).

(c) Simultaneous or sequential occurrences of various combinations of pollutant and meteorological factors.

To obtain a qualitative indication of the effects of interaction of climate, pollution, and module top-cover material, I_{sc} data from

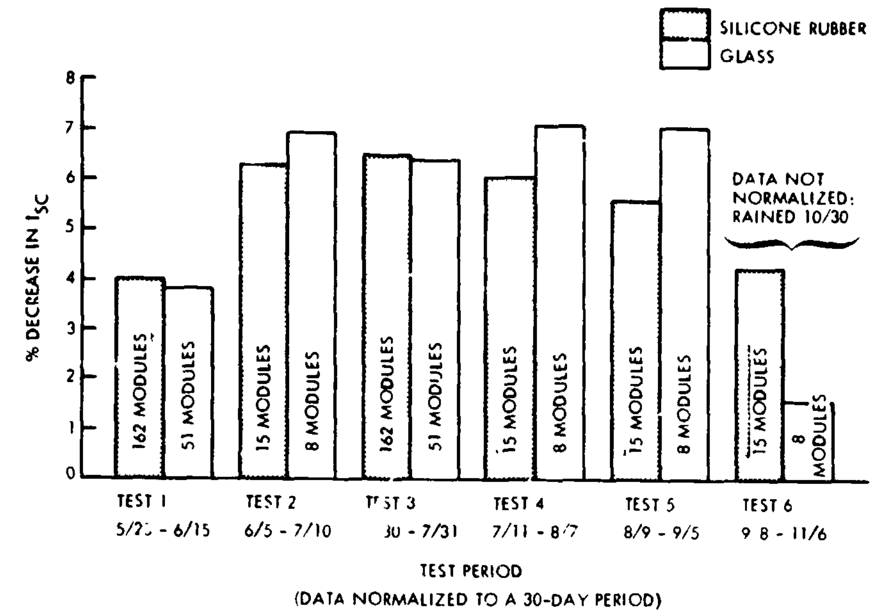


Figure 1. Electrical Performance Degradation of Modules During Rain-Free Periods in Pasadena CA (1978)

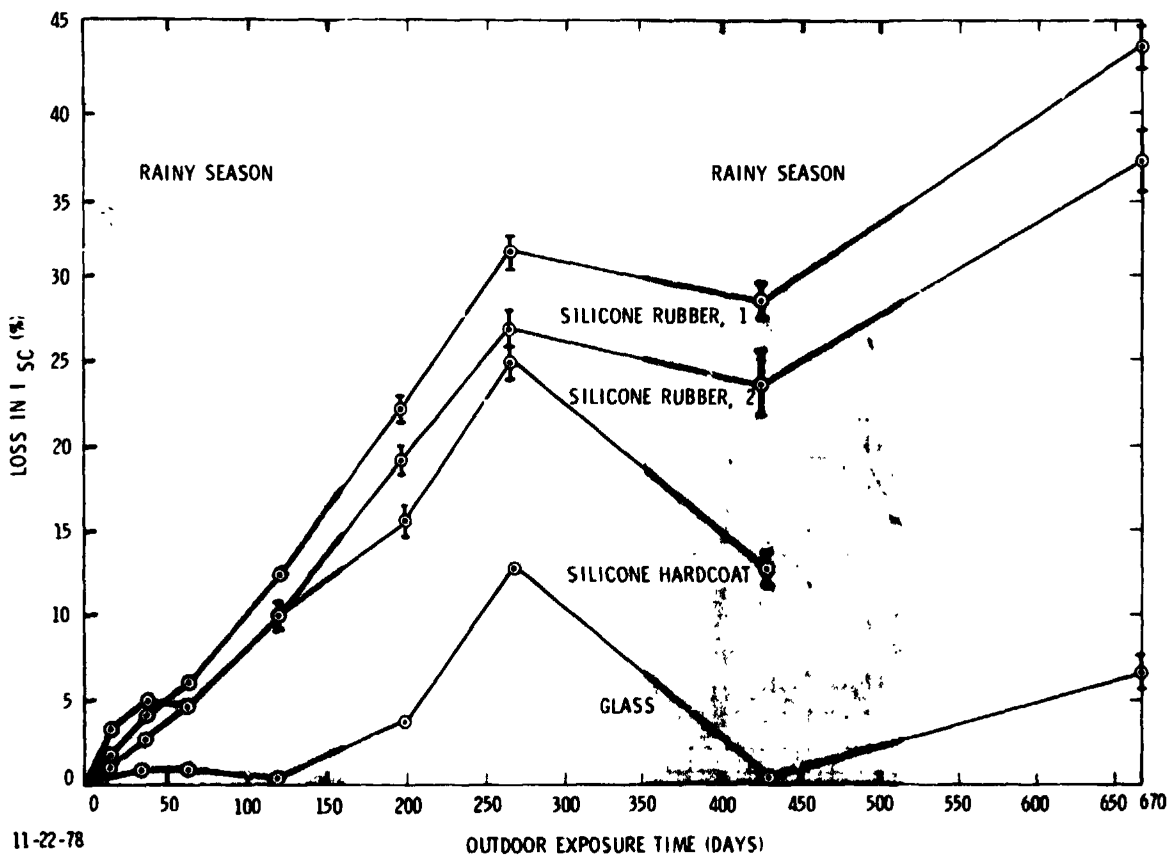


Figure 2. Module Soiling Without Cleaning: Pasadena, CA

modules exposed for extended durations were normalized to a one-month exposure and then ordered as shown in Table 1. As the abundance of airborne contaminants (especially particulates and oily aerosols) increases, the softer top cover materials, such as silicone rubber, appear to retain dirt more tightly. This type of qualitative assessment suggests that low-soiling surfaces should be hard, hydrophobic and oleophobic (i.e., lacking affinity for water and oils). Postulated mechanisms for surface soiling that is resistant to natural removal (by wind and rain, etc.) are described in References 8 and 9.

(3) Load

From the analyzed data, no conclusion could be drawn whether electrical load influences rate of accumulation. It is speculated that, because of the relative low electrical fields induced by the modules in their immediate surroundings, large differences in rates of accumulation on modules, whether open-circuited or loaded, are unlikely. An investigation is in prog ess to determine if high

Table 1. Relationship of the Climatological-Pollution Classification of Various Field Sites to the Performance of Flat-Plate Modules Fabricated With Different Top Covers

Field Sites (increasing oil, contaminants, and RH) ⇩	Climatological Classification *	Pollution Classification	Soft Silicone RTV 615 (⇨ Increasing surface hardness)	Silicone Elastomers Sylg 184	Hard Coat	Glass
Mt. Washington, NH	Dfb: Humid microthermal, humid continental (cool summer) with no dry season	Remote	-	0	-	0
So. Florida	Aw: Tropical savanna, more rain in summer than in winter	Rural, near-urban	~0	~0	~0	~0
Phoenix, AZ vicinity	BWh: Dry climate, desert, tropical-subtropical steppe	Rural	1e	1e	0	0
Mead, NE	Daf: Humid microthermal, humid continental (warm summer) with no dry season	Rural, agricultural				
Ft. Belvoir, VA	Caf: Humid subtropical, no dry season	Rural			1	
Lexington, MA	Dbf	Suburban, undeveloped			1	-
Cleveland, OH near airport	Daf	Suburban, commercial	2	3	2	1
Cambridge, MA	Dbf	Suburban, commercial	2.5	2.5	2	1
Pasadena, CA	Cs: Humid mesothermal, dry summer, subtropical	Suburban, residential	2e	4e	3e	1e
New York City	Daf	Urban, commercial	5e	6e	5e	3
Cleveland, OH near steel mill	Daf	Urban, commercial	8	8	8	2

*Based on Ref. 10
e = estimated

voltages resulting from long series strings for grid-power generation affects the rate of accumulation of dirt on the modules. Three minimodules from each of four manufacturers are used in the experiment. One each has an applied voltage of +1500 V relative to ground, the second from each manufacturer has -1500 V, and the third from each has no applied voltage. Plots showing changes in I_{sc} as a function of time for the three minimodules from each manufacturer are given in Figure 2. Applied voltage effects are indicated by the error bars. The modules have not been artificially cleaned during the test period. Recent observations on differences in rates of dirt accumulation, as measured by I_{sc}, on modules and material samples subjected to high voltage for more than one year are indicating trends that suggest dependence.

B. MATERIALS FIELD DATA

In addition to the studies of outdoor soiling of modules, a series of experiments exposing material samples (candidate encapsulants and top covers) to outdoor environments has been performed as a JPL in-house effort and by contractors for LSA's Encapsulation Task (References 10 and 11). The objectives of these experimental efforts are to determine differences in rates of accumulation and in degree of self-cleaning by natural causes.

The materials exposure investigations developed into two separate time phases. The Phase I investigation was made from May 1, 1978, to April 30, 1979, and is reported here. The Phase II investigation started May 1, 1979, and is continuing. Its preliminary results are also reported here.

The specific objectives of the Phase I materials investigations were:

(1) To develop a data base from field-exposed materials at nearby sites.

(2) To identify physical properties of optical materials that govern soil retention.

(3) To identify key environmental factors that govern soiling levels.

The specific objectives of the Phase II materials investigations are:

(1) To deploy materials for outdoor exposure at several sites throughout the country.

(2) To develop sound test methods for evaluation of encapsulant materials.

(3) To assess dust species, properties and accumulation at various sites.

(4) To develop understanding of soiling mechanisms (retention).

(5) To support the development of preliminary guidelines for selection of materials exposed to dirt or dust or both.

As part of Phase I, an outdoor experiment was performed by JPL with the cooperation of the South Coast Air Quality Management District (SCAQMD), a four-county special district created by the state of California. The experiment consisted of placing material samples at an SCAQMD air-quality monitoring site in Pasadena CA, close to the monitoring equipment (Figure 3). Material samples 5 x 5 cm were placed on fixed rack at a tilt of 45°. The materials included in the study were silicone rubber (RTV 615), soda-lime glass, and Plexiglas. Periodically during the one-year experiment, from April 1978 through April 1979, material samples were retrieved from the site and returned to the laboratory for evaluation of optical transmission. The apparatus used to make this measurement had been specially designed for the purpose; it is pictured in Figure 4. Two matched solar cells are illuminated by a beam splitter from a point source. A control sample is placed over one of the solar cells and the exposed sample over the other. The ratio of I_{sc} measurements is then recorded. This ratio is referred to as the relative normal hemispherical transmittance (RNHT). This apparatus permits relative optical transmission measurements to be made quickly and with good repeatability. Comparisons of these measurements with more sophisticated transmission techniques are being performed in the Phase II investigations.

The results from this study for silicone rubber, glass, and Plexiglas are shown in Figure 5. During the first month and a half the rate of soil accumulation on all materials as measured by the loss of relative transmittance was about 7% per month. The dip at 82 days could not be explained by any meteorological phenomenon, although fog and possible condensation could have caused some cleaning. However, after the first significant rain of the Southern California rainy season the Plexiglas and glass samples were more extensively cleaned than was the silicone rubber. Dirt began to accumulate and the obscuration on all materials increased until another rain occurred. This pattern continued throughout the sampling period. The conclusions drawn from this experiment include the following:

(1) The rate of soil deposition is material-independent; the effectiveness of natural removal by rain is material-dependent.

(2) Average losses in relative transmittance over a one-year period were 16% for silicone rubber, and 7% to 8% for glass and Plexiglas.

(3) If exposed materials are heavily soiled, rain can cause improvements in transmission of 10% to 15% for glass and Plexiglas and 5% for silicone rubber.

An additional objective of this study with the SCAQMD was to determine the feasibility of correlating data on dust accumulation on optical surfaces with data from high-volumetric particulate-matter measurement equipment operated by SCAQMD. If correlation could be established and a dirt accumulation algorithm developed, there is a wealth of data available from the federal Environmental Protection Agency (for example, the newly established Inhalable Particulate Network) and from local communities that would permit an evaluation of site dust accumulations. Based on a preliminary analysis, there is some promise of feasibility, but much more data from many sites would have to be examined and appropriate algorithms developed.

It should be emphasized that the conclusions drawn from the Phase I investigations are related to the data obtained at the Pasadena SCAQMD site; extension of these conclusions to any other sites would be premature.

Figure 3. Material Samples at SCAQMD Air Monitoring Site, Pasadena CA

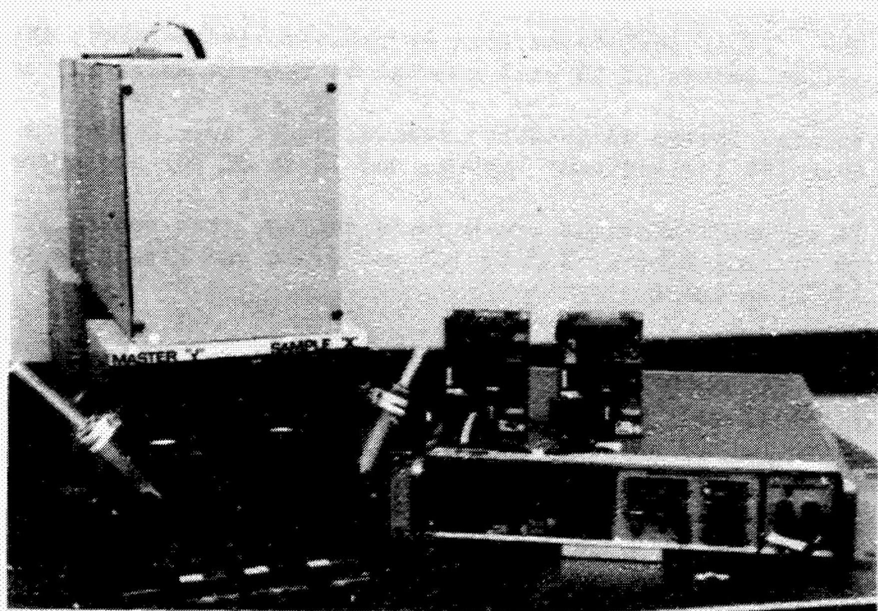


Figure 4. Relative Normal Hemispherical Transmittance Measurement Apparatus

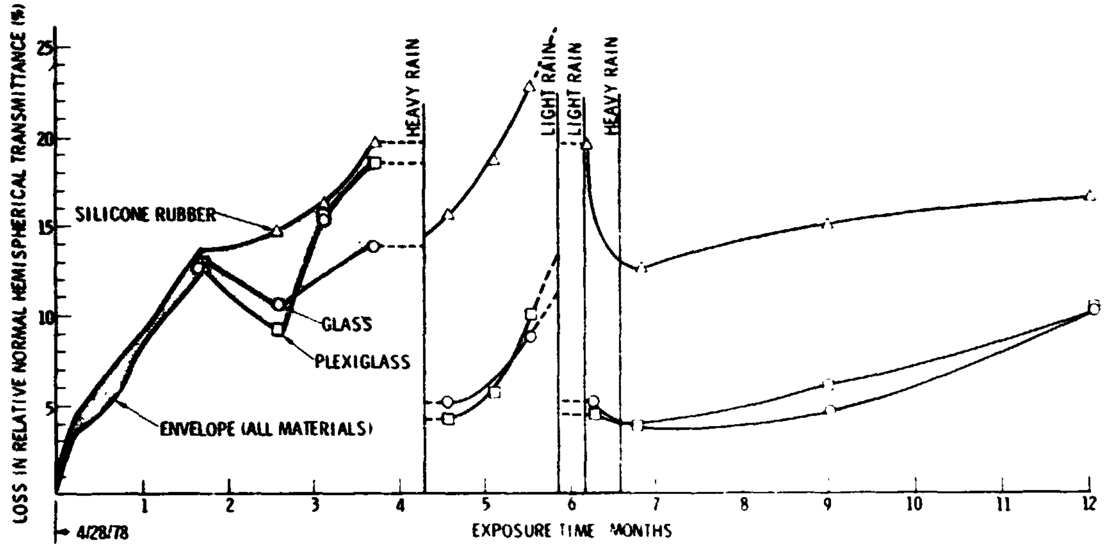


Figure 5. Relative Transmittance of Materials at SCAQMD Site, Pasadena

It was this limitation that led to the Phase II investigations. As shown above, the Phase II program objectives were very ambitious. It became obvious that if any sense were to be made of the overall soiling investigation, a nationwide outdoor exposure program must be established, with attendant geographical considerations. It would be necessary to select cover materials that have been used as covers or as encapsulants, or both, in the Block I and Block II module purchases and to select others in an attempt to anticipate materials that may be considered for future module purchases or that may remain in use until the end of the program. With these considerations in mind, the Phase II program was initiated.

The materials considered for placement in the outdoor exposure network are shown in Table 2.

Table 2. Phase II Outdoor Exposure Materials

MATERIAL	MANUFACTURER	TYPE
Poly (dimethyl siloxane)	General Electric	RTV 615
Proprietary Silicone	Dow Corning	Q1-2577
Soda Lime Float Glass	Ford Motor Glass Div.	1/8 inch Window Glass
Borosilicate Glass	Corning Glass	7070
Alumino Silicate Glass	Corning Glass	0317
Polyvinyl Fluoride	Dupont	Tedlar 400 x RS160SE
Acrylic	Xcel Corp.	Korad 212

Outdoor exposure locations used during the Phase II investigations were:

JPL, Pasadena CA
Table Mountain, Wrightwood CA
Goldstone Tracking Station, Barstow CA
Pt. Vicente (U.S. Coast Guard Station), Palos Verdes CA
South Coast Air Quality Management District Facility, Pasadena CA
South Coast Air Quality Management District Facility, Torrance CA
New York University, New York NY
Massachusetts Institute of Technology, Cambridge MA
Sandia Laboratories, Albuquerque NM
Battelle Pacific Northwest Laboratories, Richland WA.

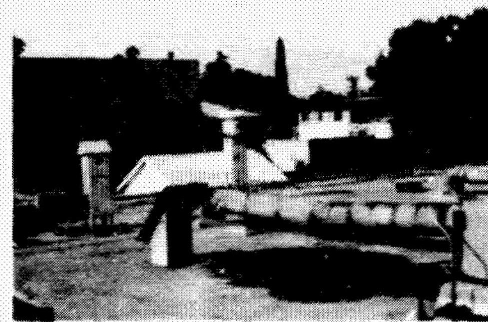
In order to prevent the influence of any factors other than environmental action upon the outdoor materials, a special test rack was constructed and deployed (with materials) at all outdoor exposure sites. The test rack was constructed of No. 316 stainless steel and was coated with Cat-a-Lac black epoxy, a high-quality aerospace (flight quality) black paint. In addition to the all stainless-steel construction hardware used, rain channels were incorporated between rows of materials samples to prevent draining of naturally removed (washed away) dirt over lower samples. The surface of the test rack was painted black for two reasons: to prevent photolysis of the samples from the double pass phenomenon (bare stainless steel has a relatively high spectral reflectance below 4000 A) and to achieve an equilibrium temperature under the samples somewhere near that of an exposed module; the solar absorptance-to-hemispheric emittance ratio (α/ϵ) for the black paint and for the typical solar cell is near unity. Figure 6 shows a sampling of the outdoor exposure sites and one of the test racks.

As noted earlier, one of the objectives of the Phase II investigation was to develop sound test methods for evaluation of encapsulant materials. In order to accomplish this, several optical and non-destructive testing techniques were employed. One such optical measurement technique was the use of RNHT. The merits of this technique were described in the discussion of the Phase I investigation above. Additional optical measurements performed by Lind and Stewart of Battelle Pacific Northwest Laboratories include: spectral transmittance (normal hemispherical and normal); spectral reflectance (normal hemispherical); and scattering (specular transmittance). Scanning electron microscopy measurements are being performed on all RTV 615 samples to identify density and species of deposited particulate matter.

The preliminary results of this investigation (i.e., from those sites that have had at least one year of field exposure) show some interesting trends. Appendix B shows the RNHT values of nine sites in the network. Figure 7 presents a comparison between the "cleanest" and "dirtiest" sites in the Southern California area.

In addition to the RNHT data, Table 3 shows the severity of dust and dirt accumulation, in this case at the Pasadena SCAQMD site. As a direct result of the data presented in Figure 7, new mechanisms for soil accumulation and retention have been postulated, first and foremost by Cuddihy (Reference 12) and second as a lemma by the authors. An interpretation of the retention mechanisms will be published in a future report. Briefly, the data suggests that three distinct layers may form on the surface of the most heavily

Goldstone Site Terrain



SCAQMD Monitoring Site, Pasadena

Jet Propulsion Laboratory Test Site

Test Rack With Material Samples

Figure 6. Some Outdoor Exposure Sites and a Typical Sample Test Rack

contaminated materials as depicted in Figure 8. Layer A is associated with the chemical activity of the surface; i.e., the natural environment reacts with the surface to kill any reactive sites (free radicals) left during the manufacturing process; ergo, a high population of multivalent ions would remain on the surface. This surface would in reality be the bulk material's new surface and would be impossible to remove. As a consequence of the formation of the highly reactive layer A, additional surface contamination will accumulate on layer A until its surface energy has been reduced to a nominal level. Layer B has now been formed and would most likely be susceptible to mechanical removal. Layer C is then the "neighborhood dirt" (geographically differentiated) that accumulates on Layer B. The binding energy of Layer C to Layer B is very low--much weaker than that of rain, thus permitting natural removal. This theory suggests that material would build up on a module or material surface, decreasing power or transmission, respectively; power loss or change in transmission then would level off and, as rain or snow or other natural removal forces dominate, oscillate above this equilibrium value. If mechanical cleaning is inserted in the scenario, i.e.,

Table 3. Severity of Dust and Dirt Accumulation: Pasadena SCAQMD Site

MATERIAL	HEMISPHERICAL TRANSMITTANCE		SPECULAR TRANSMITTANCE
	Day 0	Day 150	Day 150
RTV 615	0.930	0.585	0.303
Q1-2577	0.870	0.564	0.251
Soda Lime Glass	0.870	0.681	0.581
Borosilicate Glass	0.910	0.730	0.613
Alumino Silicate Glass	0.914	0.783	0.642
Tedlar	0.892	0.741	0.585
Korad	0.912	0.718	0.564

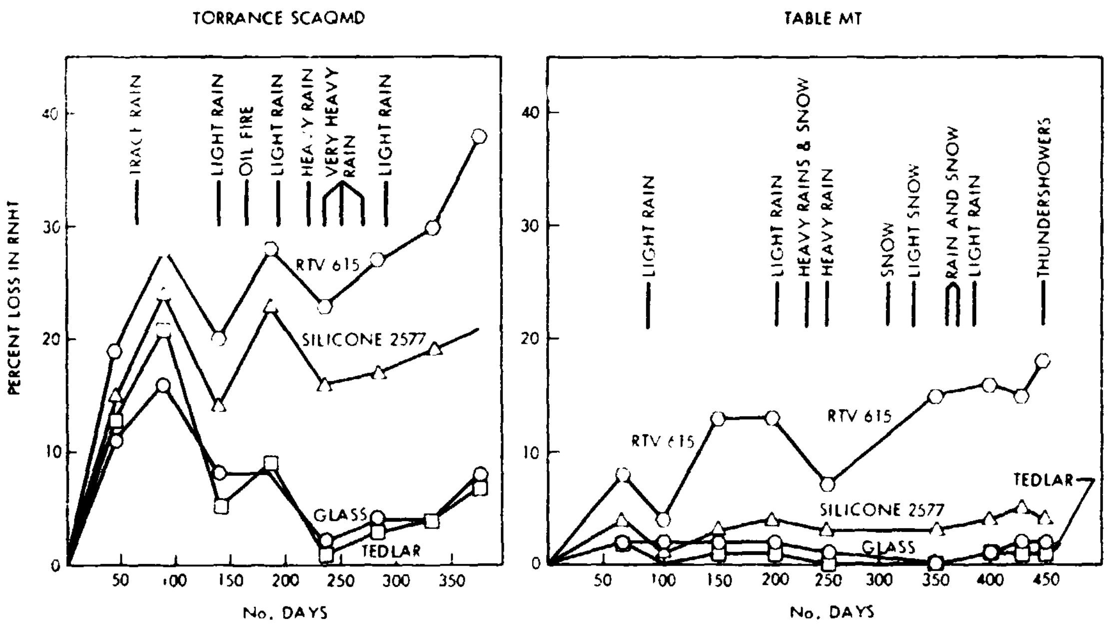


Figure 7. Percentage Loss in RNHT of Materials Exposed at Two Locations

removing Layer B, an almost complete recovery should occur. This is consistent with field observations. Theory also suggests that if no reactive oxidation occurs (i.e., no reactive sites exist), no Layer A can be formed. This appears to be the case for surfaces such as glass and acrylic materials.

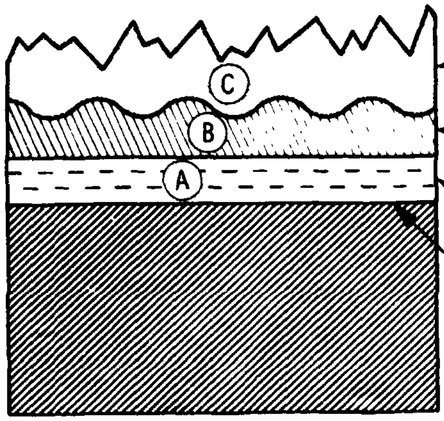


Figure 8. Three-Layer Soiling Mechanism

In summary, the observations made during this phase of the investigation include:

1) The relative transmission of glass, polyvinyl fluoride and acrylic material samples was significantly better than that of silicone rubber and the hardcoat silicone at all sites.

2) Of the three glasses, borosilicate was effected the least by outdoor soiling, followed by aluminosilicate, then soda lime. The maximum transmission loss for all glasses was 16%, with the majority of the readings <5% loss.

3) The maximum measured transmission losses were: silicone rubber, 46%; proprietary silicone, 31%; soda lime glass, 16%; aluminosilicate glass, 14%; borosilicate glass, 13%; polyvinyl fluoride, 21%; and acrylic, 21%. All of these occurred at the Lennox, CA site.

4) At the Southern California sites, where there were washed and unwashed samples, no appreciable differences in relative transmission are noted, especially on the harder materials. Some differences are noted on the softer materials during the rain-free periods.

5) Tilt angle affected soil accumulation more on the softer materials ($\Delta 5\%$) than the harder materials ($\Delta 2\%$). Samples tilted at the local latitude (34°) had slightly more transmission loss than at the nominal test angle (45°).

SECTION III

LABORATORY SOILING EXPERIMENTS: DESCRIPTION AND RESULTS

Early field data showed that there was considerable site-to-site variation in the performance degradation of modules attributable to soiling. Parallel with the assessment of the field data, a series of laboratory experiments was initiated. The objective of these experiments was to simulate contaminant deposition on test surfaces and determine factors affecting module performance.

The initial set of laboratory soiling tests performed at JPL used a set of four Block II minimodules (one from each manufacturer) and standard motor-vehicle air-cleaner test dust (GM #1543094). Although the test dust does not have characteristics identical to those of field dust (e.g., it has no organic constituents), it is well characterized (Reference 13), is available commercially, and has small lot-to-lot variation. These initial tests were performed with and without condensed moisture on the surface of the modules. For the dry test, 50 cc of dust was distributed uniformly over the face of the modules, the module was tapped to remove loose particles, and then the module was measured electrically. For the fogged condition, the modules were refrigerated for 2 h so that moisture would condense on the surface after exposure to room air. Then steps similar to those of the dry test were performed. The test results are compared with field results in Table 4. The results do not correlate well with the field experiments, indicating that simple testing procedures are inadequate.

Table 4. Initial Dust Test Results

MINIMODULE ENCAPSULANT EXTERIOR SURFACE	OUTPUT POWER DEGRADATION (%)		
	Dry	Fogged	Field Data
Float Glass	2	66	2 to 7
Semiflexible Silicone Conformal Coating	4	49	6 to 32
Silicone RTV Rubber Compound Type 1	64	68	11 to 39
Silicone RTV Rubber Compound Type 2	46	52	8 to 36

In a concurrent test to explore dust-removal effects by blowing air, test dust was applied in the same manner as for the dry test. This was followed by blowing with an air hose (100 psig) 5 cm (2 in.) from the modules' surface at an angle of 30°. During the blowing operation, it was observed that dust blows off to a certain point, then no more is removed. This is commonly seen when a fluid under pressure (air, GN_2, or water) is directed at a surface covered with particulates, whether it be a window, a car hood, or a driveway. With the exception of the glass module, which was initially minimally degraded and showed no change, the non-glass covered modules showed a significant improvement in electrical performance. A possible explanation is that the blowing breaks the bonds on the loosely adhered particles, especially the larger ones, which are entrained in the airstream and are blown away from the surface with the smaller-sized particles remaining behind. The net effect is less blockage of incident light, resulting in improved electrical performance of the modules.

A second series of dust deposition-removal experiments was performed in an attempt to achieve better correlation between field results and test results. These tests were performed using Block II minimodules, standard air cleaner dust, and an experimental particulate deposition chamber (Figure 9). The test sequence is depicted in Figure 10. The front surface of each test specimen was preconditioned to one of the following states before dust deposition: dried, fogged, misted with a simulated smog, or a combination of these. A chill step was applied to those minimodules for which a moisture layer was desired on the surface (i.e., fogged condition). Three repetitions of a dusting-tapping-vacuuming step were necessary to increase the density of smaller-diameter particles ($<10\,\mu m$) retained by the surface. (The tapping and vacuuming steps removed loosely adhered larger particles.) Figures 11 and 12 depict these steps. The simulated smog fluid was composed of several organic compounds blended in proportion by volume based on an analysis of air pollution performed in Europe. A thin layer of the fluid was deposited on the appropriate modules using an artist's airbrush and a fume hood (Figure 13). The intent of this conditioning step was to explore the extent to which the organic film enhanced the formation of stronger bonds between the test dust and the module surface.

The results are given in Table 4. In the absence of moisture on the surface of the test item (i.e., dry condition), few particles adhered to the surface, whether glass or silicone rubber. This result was consistent with the field results in dry locations such as Phoenix. When moisture was present on the surface, the number of particles retained was significantly greater, though variable, with glass generally retaining the least. When an oily film was applied to a dry surface and then artificially dusted, the number of particles retained was greater than for the dry condition but smaller than for the fogged condition. The smogged and fogged conditions retained more particles than the smogged condition alone. When several smog-dust layers were applied to the module, the number of particles retained was not appreciably different from that for the single smog layer condition.

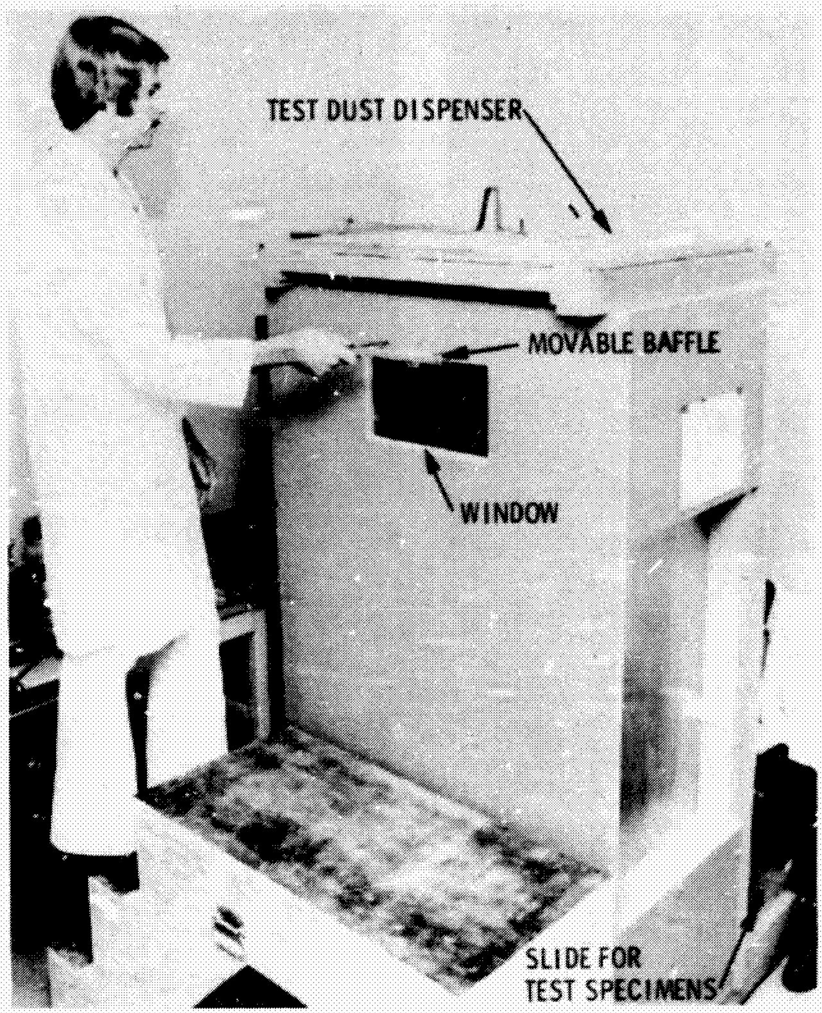


Figure 9. Experimental Particle Deposition Chamber

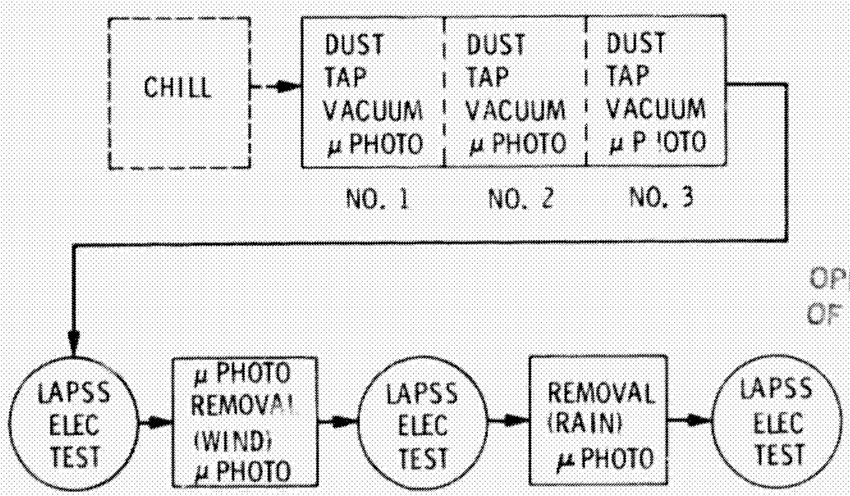


Figure 10. Laboratory Minimodule Dust Test Sequence

Figure 11. Tapping Step

Figure 12. Vacuuming Step

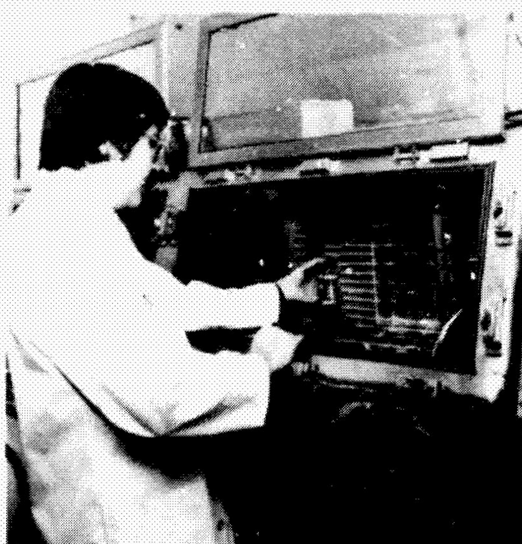


Figure 13. Smogging Step

Figure 14. Wind-Removal Simulation

After soiling deposition and electrical measurement, a wind-removal simulation was performed. This consisted of placing the minimodule in a specially designed vacuum box in which the standoff distance at the entry orifice was controlled to produce steady air speeds of 27 m/s (60 mph) (Figure 14) near the knife edge of the orifice. The simulated wind removal seems to result in very little improvement in electrical performance. This is probably attributable to the paucity of loosely adhered particles present on the surface at the conclusion of the deposition procedure that concluded with a vacuuming. In the field, winds could remove loosely adhered particles deposited on the module surfaces. However, the amount of improvement in performance in a field array could be minimal because of the complex aerodynamics of the field, especially if barrier fences were placed to reduce wind loads on array structures. Aerodynamics of field arrays are being analytically and experimentally investigated by Sandia Laboratories and JPL contractors; see References 14 and 15.)

After electrical measurement, the minimodules were subjected to simulated rain removal. The rate simulated a moderate rain (36 mm/h) and was performed for 15 min. The post-rain electrical performance tests indicate improvements in I_{sc} ranging from 0% to 9%. This degree of improvement is similar to what has been seen in the field on modules and materials immediately after a rain. However, the degree of improvements noted in both laboratory and field results depend on how heavily soiled the items were before the rain.

When the relative retention of the artificially dusted test samples are compared (Figure 14) with the field "by cleaning" data in Appendix A, the laboratory results envelop the field data, except for urban areas with high pollution. The absolute percentage changes are different, but the trends appear to be similar.

In summary, test results from laboratory procedures developed to date provide only fair correlation with field experiments. Side-by-side outdoor exposure testing for long durations at a variety of sites is presently the most effective means of evaluating soiling differences between candidate materials.

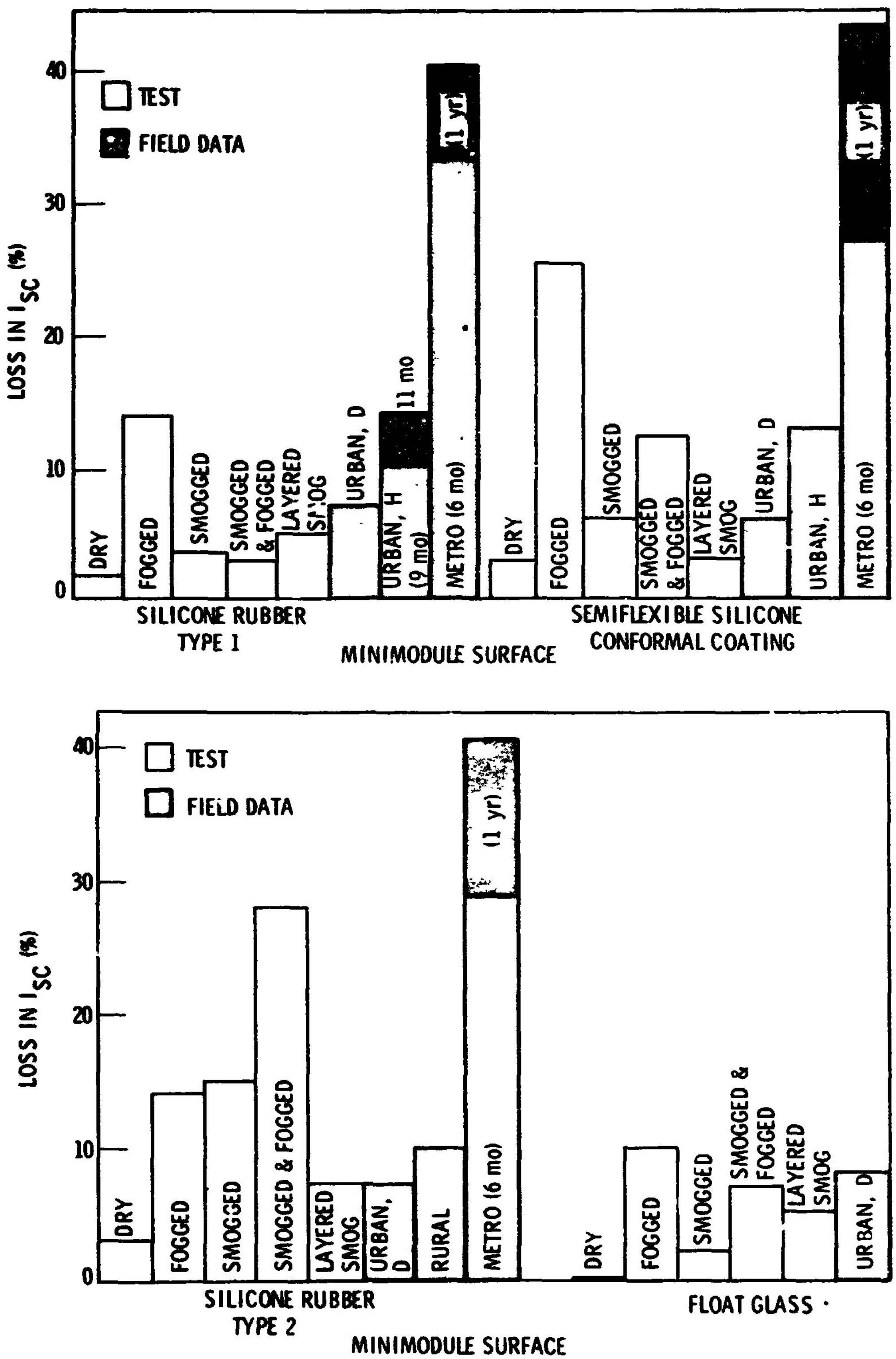


Figure 15. Relative Retention of Particles on Module Surfaces in Laboratory and Field Tests

SECTION IV

DUST ASSESSMENT STUDIES

An assessment of dust species and of the properties of dust accumulating on modules and materials was initiated during the period.

The first efforts involved the review of two reports relevant to dust constituents, prepared by government agencies for different purposes.

An Environmental Protection Agency report (Reference 16) gives the results of an effort to characterize the various components and types of particles that compose ambient suspended particulate matter in urban areas. The results are summarized in Table 5. These results give quantitative and qualitative indications of the types of dirt that could be deposited on modules if placed in representative urban areas in the United States.

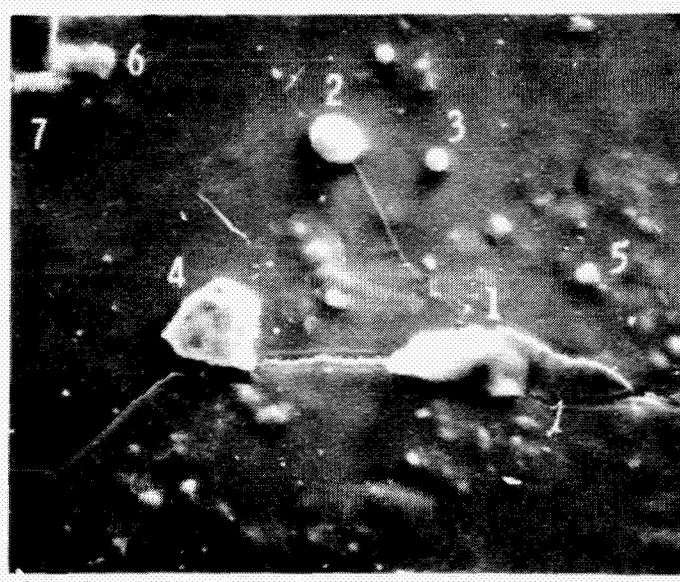
Table 5. Representative Percentages of Total Suspended Particulate Matter in Urban Areas

	MASS QUANTITY (%)		AVERAGE SIZE (μm)	
Constituents	Commercial Industrial Residential	Undeveloped	Mean	Range
Minerals	65	90	8	1-62
SiO_2 (quartz)	29	32		
$CaCO_3$ (calcite)	21	40		
Al silicates	5	3		
Fe_2O_3 (hematite)	10	15		
Other	1	1		
Combustion Products	25	8	5	1-58
Soot	17	7		
Fly ash	8	1		
Misc.	1	1		
Biological Material	3	1	24	5-82
Misc. (mostly rubber from tires)	7	1	43	13-135

Source: Reference 16

The Naval Weapons Center report (Reference 17) describes the techniques of sampling and analyses of worldwide soil samples (not airborne particulate matter). Characterization of soil samples from 43 sites is given in Table 6. This data can be of some interest to module soiling investigators because soils can be made airborne by wind or vehicular traffic and can be transported across large distances with subsequent deposition on modules. From the table, the most noteworthy data is the wide range of average particle size (4 to 188 μm) and the variety of composition evident at the various sites.

Identification of particles on a material sample (silicone rubber) cut from a module exposed at Cleveland, using SEM and energy-dispersive spectroscopy, was made. The results are depicted in Figure 16.



Cleveland: NASA Lewis Research Center 500x

Particle No.	Identification
1	Contains Si, S, Cl, K, Br
2	Pollen?
3	Clay
4	Quartz
5	Paint
6	Water Scale
7	Water Scale

Figure 16. Particle Identification Using Scanning Electron Microscopy and Energy-Dispersive Spectroscopy

As mentioned above, non-destructive tests are being performed on all RTV 615 samples. Complete data will be presented in a forthcoming test report; presented here are the results to date. Figures 17a through 17e show 400x magnification of particulate matter deposited on the RTV 615 after 200 days at each of the five California sites. Figure 16f, 1000x, shows the same, clearly revealing the presence of pollen (probably conifer) and diatomaceous earth. An initial assessment tends to indicate that the predominant contaminating species in the Southern California locale is kaolinite.

This material was observed even at Table Mountain (2,250 m), showing the ubiquity of airborne particulate matter in the Southern California area.

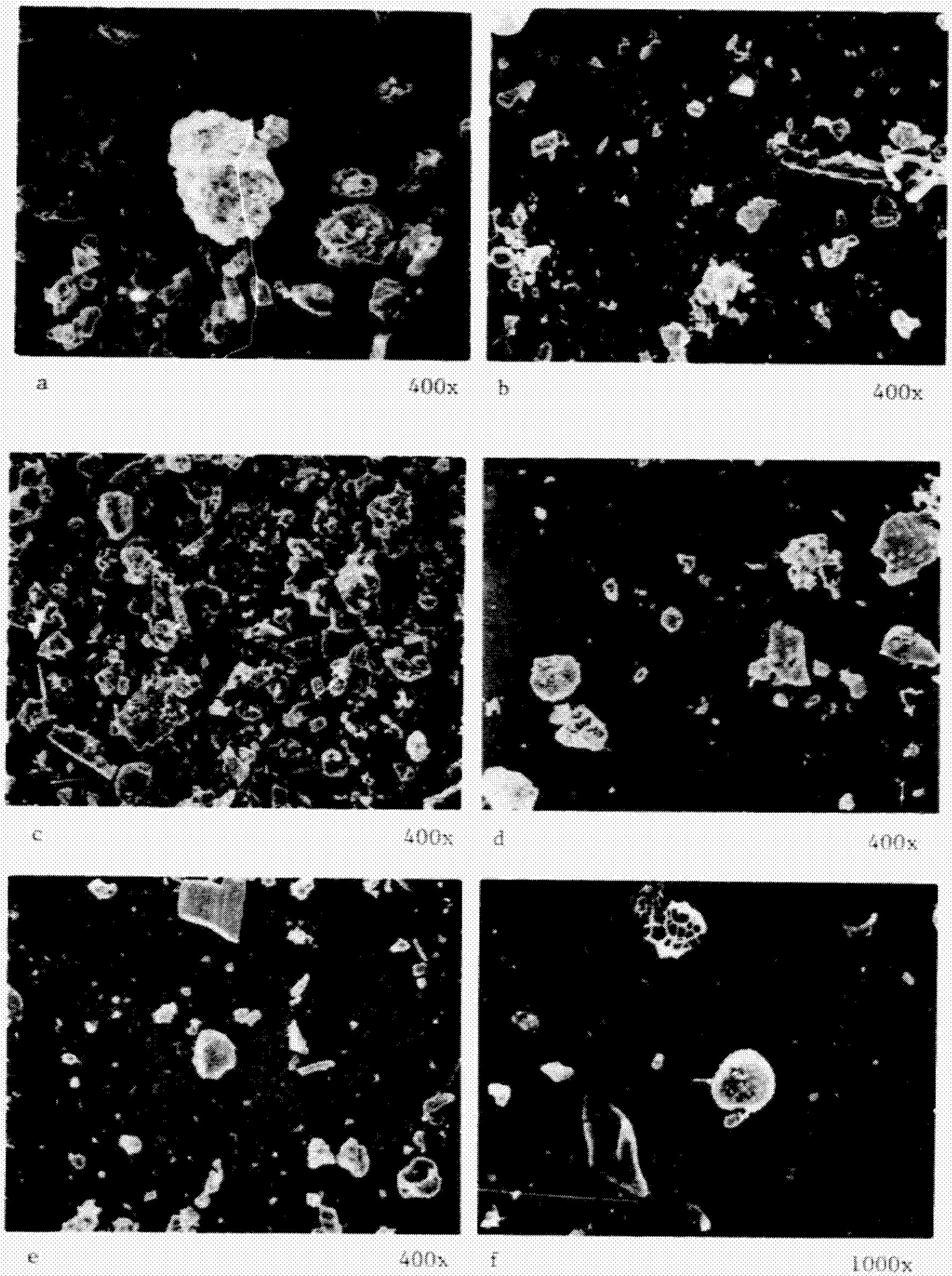


Figure 17. SEM Photographs of Particles Deposited on RTV 615 Samples

Table 6. Characterization of Soil Samples (Source: Reference 17)

Location	Composition (percent by weight)[a] SiO_2	Al_2O_3	Fe_2O_3	TiO_2	MnO	CaO	MgO	K_2	Na_2O	Ignition[b] loss %	Density g/cm³	Average particle size µm
USA												
Sea-Tac, Washington	66.60	14.12	3.70	0.73		0.58	3.17			8.30	2.543	34
China Lake, California	69.50	13.22	3.97	c		5.47	1.15			2.58	2.685	61
Sierra Nevada (Fish Creek), California	54.57	18.85	10.37	c		6.71	3.20			3.00	2.796	36
Yuma, Arizona	82.07	5.80	1.30	0.28		4.84	1.55			2.75	2.646	47
Flagstaff, Arizona	54.28	18.31	10.57	c		4.33	2.44			5.38	3.274	—
Four-State Corners, U.S.	83.01	6.22	1.37	c		2.00	0.65			2.87	2.777	>25
Providence, Rhode Island	76.83	11.41	2.23	c		1.64	0.43			4.75	2.718	20
Harrisburg, Pennsylvania	68.41	13.22	5.35	1.10		1.10	1.63			7.46	2.711	10
Fairfax, Virginia	65.18	16.16	7.28	1.37		2.28	1.35			6.39	2.735	19
Eglin AFB, Florida	95.18	1.94	0.31	c		0.49	0.52			1.10	2.644	52
Oahu, Hawaii	31.71	21.73	26.32	c		0.60	0.94			14.62	4.546	13
Adak #1, Alaska	54.27	25.49	1.80	c		11.45	4.37			0.40	2.899	188
Adak #2, Alaska	31.09	13.79	2.30	c		2.86	0.49			44.78	2.072	22
Anchorage, Alaska	64.94	15.84	5.69	0.70		0.70	1.86			4.19	2.728	35
Kodiak, Alaska	57.06	16.39	6.66	c		1.98	1.54			11.34	2.387	10
Tanana Valley, Alaska	81.43	7.15	3.37	0.63		1.80	1.44			1.52	2.690	45
Caribbean and Central America												
Guatemala City, Guatemala	42.74	20.07	7.41	c		5.45	1.15			17.99	2.796	19
Ft. Clayton, Panama	36.73	25.86	16.71	c		0.37	0.44			12.23	4.239	11
Coco Solo, Panama	44.50	24.55	10.08	c		0.21	0.99			12.38	4.500	12
Bermuda	2.11	1.75	0.79	c		50.05	0.95			42.46	2.699	26
Ramey AFB, Puerto Rico	36.53	7.10	3.33	0.28	0.08	25.43	0.75	0.57	0.67	24.20	2.93	7
Australia												
Innisfail, Queensland, Aust.	32.81	28.32	22.69	2.85	0.13	0.75	0.55	0.05	0.15	12.06	3.08	5
South Pacific												
Agana, Guam	14.09	26.75	15.37	c		12.28	0.40			27.31	3.239	17
Fiji Island	43.99	23.01	12.23	0.93	0.14	3.76	2.98	0.27	2.33	7.63	3.03	4
Moorea, Tahiti	15.69	2.15	1.93	0.33	0.03	35.58	2.22	0.33	0.77	36.69	2.93	8
Pago Pago, American Samoa	13.25	6.08	6.29	0.93	0.10	39.23	3.65	0.29	0.65	28.63	3.20	7
Wake Island	0.13	Nil	0.99	—		51.12	1.23			44.54	2.780	36
Midway Island	29.95	22.16	21.37	c		2.88	0.91			16.57	3.391	15
Southeast Asia												
Iwakuni, Japan	67.94	16.17	4.85	c		2.92	0.89			2.16	2.626	32
Atsugi, Japan	32.56	26.45	15.40	c		1.02	1.96			13.97	5.128	d
Sasebo, Japan	69.83	12.46	5.72	c		0.31	0.63			6.93	2.700	22
Da Nang, Vietnam	80.21	7.61	8.69	0.60			0.08			3.35	2.735	20
Korat, Thailand	77.37	8.90	3.97	0.67			0.29			6.93	2.654	28
Subic Bay, Philippine Islands	39.07	29.22	15.36	1.70			0.20			13.27	2.851	14
Hong Kong	74.75	11.94	2.59	0.40	0.06	0.84	0.13	3.30	0.88	5.00	2.70	9
Naha, Okinawa	67.59	12.15	4.59	c		5.37	1.46			6.41	2.731	21
Canada and Europe												
Alcan Highway (Dawson Creek-Delta Junction)	56.70	14.51	6.40	0.85		7.75	3.65			7.91	2.744	8
White Horse, Yukon	68.14	13.22	3.13	0.60		5.66	1.88			3.96	2.476	20
Argentia, Newfoundland	14.73	9.79	3.49	0.48	0.06	1.39	1.19	1.10	1.81	63.88	1.34	19
Heyford, England	69.77	7.60	4.99	0.47	0.14	4.42	0.48	1.61	0.42	8.34	2.97	8
Other												
Keflavik, Iceland	31.34	23.86	15.25	c		3.09	1.27			15.99	3.368	6
Ross Island, Antarctica	44.17	14.36	13.89	3.55	0.22	9.27	8.61	1.83	2.86	0.79	3.09	12
Taylor Valley, Antarctica	60.77	12.96	7.00	1.08	0.12	5.61	4.76	2.25	2.95	2.11	2.98	10

NOTE: Absence of data in composition section does not mean oxides were not present; depends on testing technique.

[a] All metals reported as oxides.
[b] Ignition loss: 1 hour at 1292°F.
[c] Any minor ~~amount of~~ TiO_2 would be included in the Al_2O_3 value.
[d] Porosity too high, out of range. Particles are large fused agglomerates which crush to micron size particles.

SECTION V

CONCLUSIONS

The following conclusions have been drawn from these soiling investigations:

(1) Electrical performance degradation of photovoltaic modules resulting from accumulation of particulate matter on optical surfaces shows significant time- and site-dependence ranging from 2% to 60% power loss.

(2) During periods when natural removal processes do not dominate, the rate of particulate-matter accumulation appears to be largely material-independent.

(3) The effectiveness of natural removal processes, especially rain, is strongly material-dependent. Thus, natural removal mechanisms must be addressed when determining differences in soil retention between candidate materials for optical surfaces.

(4) Top cover materials of glass, polyvinyl fluoride, and acrylic retain fewer particles than does silicone rubber. Silicone hardcoat does not appear to decrease particle retention of uncoated silicone rubbers (RTV 615 and Sylgard 184) significantly.

(5) High voltages relative to ground may affect the rate of accumulation of dirt on some modules and top cover materials after extended exposure.

(6) Test results from laboratory procedures developed to date have provided only fair correlation with field experiments. Side-by-side outdoor exposure testing for long durations at a variety of sites is presently the most effective means of evaluating soiling differences between candidate materials.

(7) Mechanisms based on surface energy considerations have been postulated on the accumulation of surface contamination adherance to module surfaces. A three layer model has been suggested.

SECTION VI

RECOMMENDATIONS

1. Electrical performance degradation should be reported in terms of changes in I_{sc}.

2. Follow-on soiling investigations should include the following considerations:

   (a) Rates of dirt accumulation on various materials at several sites throughout the country should be gathered and analyzed carefully. Analysis should include spectral transmittance measurements and correspondence of results with local meteorology and pollution data.

   (b) Effects of particulate constituents and particle size on spectral transmittance loss should be determined; e.g., what kinds of particles cause significant absorption and scattering of incident light for flat-plate photovoltaics?

   (c) A small effort in laboratory soiling test apparatus should be continued with the objective of developing a design and materials screening test. Principal problems to be addressed center on the lack of correlation currently found between laboratory results and field results. Facets of this problem likely include test dust constituents (i.e., an appropriate test dust mixture); the moisture condition of the test dust; the test chamber, and the test surface and the technique of dust deposition (gravity settling vs impingement).

   (d) The feasibility of using EPA's newly established Inhalable Particulate Network results as a data source for developing algorithms for site-dependent dirt accumulation should be determined.

   (e) Surface treatments for inhibiting the adhesion of particulate matter to a surface (e.g. by reducing surface energy) should be investigated.

3. Cleaning economics for distributed systems (especially residential) should be studied. It is not obvious how much cleaning effort a typical user could be expected to perform as well as what techniques could be applied. An initial effort in this area has been completed recently (Reference 18).

REFERENCES

1. "Progress Report 1 for the Period May 1979 to August 1979 and Proceedings of the 12th Project Integration Meeting," LSA Project Document 5101-112, Jet Propulsion Laboratory, Pasadena, California (internal document).

2. Gupta, A., "Photodegradation of Polymeric Encapsulants of Solar Cell Modules," LSA Project Task Report 5101-77, Jet Propulsion Laboratory, Pasadena, California, August 10, 1978 (internal document).

3. Anagnostou, E., and Forestieri, A., "Endurance Testing of First Generation (Block I) Commercial Solar Cell Modules," Thirteenth IEEE Photovoltaics Specialists Conference, 1978, pp. 843-846.

4. Forman, S., "Field Testing and Evaluation of Photovoltaic Module Performance," Thirteenth IEEE Photovoltaics Specialists Conference, 1978, pp. 41-46.

5. Murphy, E., and Forman, S., "Measuring Dirt on Photovoltaic Modules," MIT/LL COO-4094-37, 12 March 1979.

6. Forman, S., and Themelis, P., "Physical and Electrical Degradation of Photovoltaic Modules After Exposure in Terrestrial Environments," 14th Intersociety Energy Conversion Engineering Conference, August 5-10, 1979, pp. 225-229.

7. Jaffe, P., "LSA Field Test Annual Report, August 1977-August 1978," LSA Project Task Report 5101-85, Jet Propulsion Laboratory, Pasadena, California, September 15, 1978 (internal document).

8. Sheratte, M., "Cleaning Agents and Techniques for Concentrating Solar Collectors," MDC G8131 (Sandia Albuquerque Contract Report), McDonnell Douglas Astronautics, Huntington Beach, California, September 1979.

9. Cuddihy, E., "Encapsulation Materials Status to December 1979," LSA Project Task Report 5101-144, Jet Propulsion Laboratory, Pasadena, California, January 15, 1980 (internal document).

10. "Investigation of Test Methods, Material Properties, and Processes for Solar Cell Encapsulants, Annual Report," DOE/JPL-954527-78/8 (JPL Contract Report), Springborn Laboratories, Inc., Enfield, Connecticut, June 1978.

11. "Develop Silicone Encapsulation Systems for Terrestrial Silicon Solar Arrays, Fifth Quarterly Progress Report," DOE/JPL-954995-79/5 (JPL Contract Report), Dow Corning Corp., Midland, Michigan, July 1979.

12. Cuddihy, E., personal communication, June 1980.

13. Johnston, P. R., "The Particle-Size Distribution in AC Fine Test Dust," Journal of Testing and Evaluation, Vol. 6, No. 2, March 1978, pp. 103-107.

14. Poreh, M., Peterka, J. A., Cermak, J. E., "Wind Tunnel Study of Wind Loads on Photovoltaic Structures," Colorado State University, Ft. Collins, Colorado (to be included as part of Bechtel Contract Report #05-6195).

15. Miller, R., and Zimmerman, D., "Wind Loads on Flat Plate Photovoltaic Array Fields," DOE/JPL 954833-79/2 (JPL Contract Report), Boeing Engineering and Construction Co., Seattle, Washington, September 1979.

16. "National Assessment of the Urban Particulate Problem: Volume II --Particle Characterization," EPA-450/3-76-025, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, July 1976.

17. Kuletz, E., and Schafer, H., "Survey of and Study on Sand and Dirt," NWC TP 5170, Naval Weapons Center, China Lake, California, August 1971.

18. "Operation and Maintenance Cost Data for Residential Photovoltaic Modules/Panels," DOE/JPL 955614-80/1, (JPL Contract Report), Burt Hill Kosar Rittlemann Associates, Butler, Pennsylvania, July 1980.

APPENDIX A

MODULE SOILING DATA

The percentage of change in P_{max} and I_{sc} for various modules at various sites across the country is tabulated in this Appendix. The information is organized by manufacturer code (A, B, C, or D); top-cover material (silicone rubber, glass, or silicone hardcoat) and a block-purchase designator indicating module generation (I, off-the-shelf module type, 1976; II, modules fabricated to meet a uniform set of design and test requirements, 1977). Also indicated in the table are the number of modules on which the performance data is based, the field site location, a climatological and pollution classification of the site, tilt of the modules from horizontal, whether or not the modules were providing power to a load, the duration of the exposure, and the percentage of change in I_{sc} and P_{max}. The change percentages were calculated using the expressions given in Section II. The current-voltage characterizations (I-V curves) on which these calculations were based contain measurement inaccuracies due to such causes as differences in spectral content of the light sources, differences in reference standards (e.g., air mass and temperature), and operator error. The raw data measurements have not been corrected for these inaccuracies.

Table A-1. Effects of Field Soiling on Module Performance (Mfr A; Outer Cover, Float Glass)

Generation (Block Number)	Number of Modules	Field Site	Classification	Tilt	Load	Exposure Duration	Date of Exposure	Change in I_{sc} (%): Total Before Cleaning	Change in I_{sc} (%): Total Nonrecoverable Post-cleaning	Change in I_{sc} (%): By Cleaning*	Change in P_{max} (%): Total Before Cleaning	Change in P_{max} (%): Total Nonrecoverable Post-cleaning	Change in P_{max} (%): By Cleaning*
I	3	DSET Phoenix, AZ	Desert, Open	34°	OC	161 d	05/77 - 11/77	-	-	-	-3	-2	+1
I	1	NASA Lewis Cleveland, OH	Suburban near Airport	40°	OC	74 d	10/76 - 01/77	+2	+2	0	+1	0	-1
						83 d	03/77 - 05/77	-3	+3	+6	-5	+1	+6
						32 d	06/77 - 07/77	0	0	0	-1	-3	-1
						54 d	07/77 - 09/77	+3	+3	0	0	-2	-2
						57 d	09/77 - 11/77	+1	+2	+1	-1	+1	+2
						230 d	03/77 - 11/77	-	-	-	-7	-	-
I	1	Air Pollution Ctr Cleveland, OH	Industrial near Steel Mill	40°	OC	81 d	10/76 - 01/77	-4	+2	+6	-6	+2	+7
						90 d	03/77 - 06/77	-4	+2	+6	-5	0	+5
						30 d	06/77 - 07/77	-2	-1	+1	-4	-4	0
						54 d	07/77 - 09/77	-1	+2	+3	-4	-3	+1
						58 d	09/77 - 11/77	-5	0	+5	-6	-1	+5
						230 d	03/77 - 11/77	-	-	-	-7	-	-
I	1	Subtropical Testing Miami, FL	Subtropical	5°	OC	1 yr	09/76 - 09/77	+1	+2	+1	-1	+1	+3
I	1	So. Florida Testing Miami, FL	Subtropical	5°	OC	1 yr	10/76 - 10/77	-1	+1	+2	-5	-6	-1
I	1	Solar Testing Pompano Beach, FL	Subtropical	45°	OC	1 yr	09/76 - 09/77	+3	+3	0	-1	-1	0

* % Improvement from soiled condition determined by obtaining performance data before and after cleaning using techniques listed on Page 2

OC = Open Circuit

Table A-1. Effects of Field Soiling on Module Performance (Mfr A; Outer Cover, Float Glass) (Continuation 1)

Generation (Block Number)	Number of Modules	Field Site	Classification	Tilt	Load	Exposure Duration	Date of Exposure	Change in I_{sc} (%): Total Before Cleaning	Change in I_{sc} (%): Total Nonrecoverable Post-cleaning	Change in I_{sc} (%): By Cleaning*	Change in P_{max} (%): Total Before Cleaning	Change in P_{max} (%): Total Nonrecoverable Post-cleaning	Change in P_{max} (%): By Cleaning*
I	1	Carib. Testing Caguas, PR	Tropical	5°	OC	1 yr	09/76 - 09/77	+1	+3	+1	-6	-2	+3
I	12	Sci. & Ind. Museum Chicago, IL	Metropolitan	45°	Yes	10 mo	07/77 - 05/78	-3	-1	+2	-7	-4	+3
I	9	MIT/LL Lexington, MA	Suburban	45°	OC	7 mo	05/77 - 12/77	-	-	-	-	-	+2
I	2	NYU NYC, NY	Metropolitan	45°	OC	6 mo	01/78 - 06/78	-12	-2	+10	-12	-2	+10
	2					5 mo	07/78 - 12/78	-2e	+6e	+8	-7e	0e	+7
	2					6 mo	01/79 - 06/79	-49e	-8e	+45	-30e	-20e	+13
I	2	Columbia U NYC, NY	Metropolitan	45°	OC	6 mo	01/78 - 06/78	-11	+3	+13	-12	0	+12
I	2	Mt. Washington NH	Mountain, Open	45°	OC	8 mo	10/77 - 06/78	-	-	-	-	-	+2
	2					1 yr	10/77 - 10/78	-1e	0	+1	-1	0	+1
I	2	MIT Cambridge, MA	Metropolitan	45°	OC	5 mo	08/77 - 01/78	-14	-7	+8	-15	-9	+6
	2					6 mo	01/78 - 06/78	-6e	-1e	+4	-10e	-7	+3
	1					6 mo	06/78 - 01/79	-6e	-1e	+5	-20e	-15e	+6

* % Improvement from soiled condition determined by obtaining performance data before and after cleaning using techniques listed on Page 2

OC = Open Circuit

e = estimated by comparing field module and reference module I-V curves

Table A-2. Effects of Field Soiling on Module Performance (Mfr B; Outer Cover, RTV 615)

Generation (Block Number)	Number of Modules	Field Site	Classification	Tilt	Load	Exposure Duration	Date of Exposure	Change in I_{sc} (%) Total Before Cleaning	Change in I_{sc} (%) Total Nonrecoverable Post-cleaning	Change in I_{sc} (%) By Cleaning*	Change in P_{max} (%) Total Before Cleaning	Change in P_{max} (%) Total Nonrecoverable Post-cleaning	Change in P_{max} (%) By Cleaning*
I	3	DSET Phoenix, AZ	Desert, Open	34°	OC	161 d	05/77 - 11/77	-	-	-	-11	-2	+9
I	1	NASA Lewis Cleveland, OH	Suburban near Airport	40°	OC	74 d	10/76 - 01/77	-8	-1	+7	-8	-1	+8
						83 d	03/77 - 05/77	-14	-7	+8	-15	-7	+9
						32 d	06/77 - 07/77	-10	-8	+1	-11	-10	+1
						54 d	07/77 - 09/77	-8	-8	0	-9	-9	0
						57 d	09/77 - 11/77	-11	-10	+2	-11	-10	+1
						230 d	03/77 - 11/77	-	-	-	-11	-	-
I	1	Air Pollution Ctr Cleveland, OH	Industrial near Steel Mill	40°	OC	81 d	10/76 - 01/77	-34	-3	+32	-35	-4	+32
						90 d	03/77 - 06/77	-31	-11	+23	-34	-14	+23
						30 d	06/77 - 07/77	-21	-15	+7	-23	-17	+7
						54 d	07/77 - 09/77	-21	-14	+8	-23	-17	+8
						58 d	09/77 - 11/77	-28	-17	+13	-29	-17	+14
						2[illegible] d	03/77 - 11/77	-	-	-	-39	-	-
I	1	Subtropical Testing Miami, FL	Subtropical	5°	OC	1 yr	09/76 - 09/77	-11	-10	+2	-12	-9	+3
I	1	So. Florida Testing Miami, FL	Subtropical	5°	OC	1 yr	10/76 - 10/77	-13	-11	+2	-13	-9	+4
I	1	Solar Testing Pompano Beach, FL	Subtropical	45°	OC	1 yr	09/76 - 09/77	-8	-6	+2	-9	-8	+2
I	1	Carib. Testing Caguas, PR	Tropical	5°	OC	1 yr	09/76 - 09/77	-25	-20	+6	-20	-13	-8

* % Improvement from soiled condition determined by obtaining performance data before and after cleaning using techniques listed on Page 2

OC = Open Circuit

Table A-2. Effects of Field Soiling on Module Performance (Mfr B; Outer Cover, RTV 615) (Continuation 1)

Generation (Block Number)	Number of Modules	Field Site	Classification	Tilt	Load	Exposure Duration	Date of Exposure	Change in I_{sc} (%) Total Before Cleaning	Change in I_{sc} (%) Total Nonrecoverable Post-cleaning	Change in I_{sc} (%) By Cleaning*	Change in P_{max} (%) Total Before Cleaning	Change in P_{max} (%) Total Nonrecoverable Post-cleaning	Change in P_{max} (%) By Cleaning*
II	1	JPL Pasadena, CA	Suburban	34°	OC	1 yr	12/77 - 12/78	-26	-	-	-28	-	-
II	1	MIT Cambridge, MA	Metropolitan	45°	OC	5 mo	08/77 - 01/78	-12e	+2e	+13	-	-	+13
	2					6 mo	01/78 - 06/78	-26e	-13e	+16	-30e	-16e	+16
	1					6 mo	06/78 - 01/79	-27e	-17e	+12	-35e	-32e	+5
II	15	MIT/LL Lexington, MA	Suburban	45°	OC	2 mo	05/77 - 07/77	-3e	0e	+2	-	-	+3
	15					9 mo	07/77 - 04/78	-8e	-5e	+4	-	-	+8
	17					11 mo	05/77 - 04/78	-12e	-3e	+9	-	-	+10
II	1	NYU NYC, NY	Metropolitan	45°	OC	5 mo	06/77 - 12/77	-25e	-3e	+23	-	-	+[illegible]9
	1					5 mo	01/78 - 06/78	-34e	-14e	+24	-41e	-24e	+23
	1					1 yr	06/77 - 06/78	-41e	-14e	+31	-43e	-15e	+33
	2					5 mo	07/78 - 12/78	-30e	-8e	+23	-34e	-12e	+2[illegible]
						6 mo	01/79 - 06/79	-	-	-	-	-	+4[illegible]
II	1	Columbia U NYC, NY	Metropolitan	45°	OC	5 mo	06/77 - 12/77	-25e	0e	+25	-	-	+21
	1					5 mo	01/78 - 06/78	-32e	-12e	+23	-34e	-16e	+21
	1					1 yr	06/77 - 06/78	-39e	-12e	+31	-42e	-19e	+29
	2					6 mo	01/79 - 06/79	-47e	-8e	+40	-61e	-33e	+43
II	8	Irrigation Project Mead, NE	Agricultural	seas. 15° to 60°	YES	5 mo	07/77 - 12/77	-7e	+3e	+10	-	-	+7
	25					7 mo	07/77 - 02/78	+2e	+10e	+8	-	-	+11
	28					9 mo	07/77 - 04/78	-11e	-4e	+7	-16e	-10e	+6
	28					12 mo	07/77 - 07/78	-	-	-	-	-	7 to 11
	28					14 mo	07/77 - 09/78	-	-	-	-	-	9 to 16

*Late Block I, All Block II, III
e = Estimated

Table A-3. Effects of Field Soiling on Module Performance (Mfr C; Outer Cover, Sylgard 184)

Generation (Block Number)	Number of Modules	Field Site	Classification	Tilt	Load	Exposure Duration	Date of Exposure	Change in I_{sc} (%): Total Before Cleaning	Change in I_{sc} (%): Total Nonrecoverable Post-cleaning	Change in I_{sc} (%): By Cleaning*	Change in P_{max} (%): Total Before Cleaning	Change in P_{max} (%): Total Nonrecoverable Post-cleaning	Change in P_{max} (%): By Cleaning*
I	3	DSET Phoenix, AZ	Desert, Open	34°	OC	161 d	05/77 - 11/77	-	-	-	-11	-2	-9
I	1	NASA Lewis Cleveland, OH	Suburban near Airport	40°	OC	74 d	10/76 - 01/77	-7	0	+8	-10	-2	+8
						83 d	03/77 - 05/77	-13	-4	+10	-16	-6	+10
						32 d	06/77 - 07/77	-6	-4	+3	-9	-10	-1
						54 d	07/77 - 09/77	-6	-5	+2	-12	-9	+4
						57 d	09/77 - 11/77	-11	-6	+5	-11	-9	+2
						230 d	03/77 - 11/77	-	-	-	-14	-	-
I	1	Air Pollution Ctr Cleveland, OH	Industrial near Steel Mill	40°	OC	81 d	10/76 - 01/77	-27	-1	+26	-28	-3	+26
						90 d	03/77 - 06/77	-26	-5	+23	-29	-8	+23
						30 d	06/77 - 07/77	-19	-8	+12	-17	-11	+6
						54 d	07/77 - 09/77	-16	-7	+9	-20	-14	+7
						58 d	09/77 - 11/77	-23	-10	+14	-24	-12	+26
						230 d	03/77 - 11/77	-	-	-	-36	-	-
I	1	Subtropical Testing Miami, FL	Subtropical	5°	OC	1 yr	09/76 - 09/77	-9	-5	+4	-9	-1	+8
I	1	So. Florida Testing Miami, FL	Subtropical	5°	OC	1 yr	10/76 - 10/77	-3	+1	+4	-10	-6	+5
I	1	Solar Testing Pompano Beach, FL	Subtropical	45°	OC	1 yr	09/76 - 09/77	-11	-6	+4	-15	-12	+3
I	1	Carib Testing Caguas, PR	Tropical	5°	OC	1 yr	09/76 - 09/77	-14	-6	+9	-14	-5	+9

* % Improvement from soiled condition determined by obtaining performance data before and after cleaning using techniques listed on Page 2
OC = Open Circuit

Table A-3. Effects of Field Soiling on Module Performance (Mfr C; Outer Cover, Sylgard 184) (Continuation 1)

Generation (Block Number)	Number of Modules	Field Site	Classification	Tilt	Load	Exposure Duration	Date of Exposure	Change in I_{sc} (%): Total Before Cleaning	Change in I_{sc} (%): Total Nonrecoverable Post-cleaning	Change in I_{sc} (%): By Cleaning*	Change in P_{max} (%): Total Before Cleaning	Change in P_{max} (%): Total Nonrecoverable Post-cleaning	Change in P_{max} (%): By Cleaning*
II	2	Mt. Washington NH	Mountain, Open	45°	OC	1 yr	10/77 - 10/78	-13e	-12e	+1	-1e	0e	+[illegible]
II	1	MIT, Cambridge, MA	Metropolitan	45°	OC	5 mo	08/77 - 01/78	-21	-8	+15	-22	-9	+14
						6 mo	01/78 - 06/78	-19	-5	+15	-9	-8	+16
						6 mo	06/78 - 01/79	-19e	-5e	+14	-27e	+10e	+34
II	1	NYU NYC, NY	Metropolitan	45°	OC	5 mo	06/77 - 12/77	-25e	-2e	+24	-	-	+20
	1					5 mo	01/78 - 06/78	-34e	-11e	+26	-26e	+5e	+29
	1					1 yr	06/77 - 06/78	-41e	-12e	+34	-37e	+1e	+38
	2					5 mo	07/78 - 12/78	-23e	-3e	+21	-8e	+15e	+20
	2					6 mo	01/79 - 06/79	-69e	-1[illegible]	+64	-60e	-17e	+5[illegible]
II	1	Columbia U NYC, NY	Metropolitan	45°	OC	5 mo	06/77 - 12/77	-17e	0e	+20	-	-	+12
	1					5 mo	01/78 - 06/78	-25e	-12e	+22	-18e	+8e	+25
	1					1 yr	06/77 - 06/78	-39e	-12e	+33	-33e	+6e	+37
	2					6 mo	01/79 - 06/79	-48e	-8e	+43	-57e	-16e	+49
II	12	Irrigation Project Mead, NE	Agricultural	seas. 15° to 60°	YES	3 mo	07/77 - 10/77	-7e	-3e	+4	-	-	+5
	6					5 mo	07/77 - 12/77	-4e	+4e	+8	-	-	+7
	12					7 mo	07/77 - 08/78	-1e	+8e	+6	-	-	+7
	12					9 mo	07/77 - 04/78	-10e	-5e	+5	-	-	+5

*Late Block I, All Block II III
e = Estimated

Table A-4. Effects of Field Soiling on Module Performance (Mfr D; Outer Cover, Dow Corning X1-2577)

								Change in I_{sc} (%)			Change in P_{max} (%)		
Generation (Block Number)	Number of Modules	Field Site	Classification	Tilt	Load	Exposure Duration	Date of Exposure	Total Before Cleaning	Total Nonrecoverable Post-cleaning	By Cleaning*	Total Before Cleaning	Total Nonrecoverable Post-cleaning	By Cleaning*
I	3	DSET Phoenix, AZ	Desert, Open	34°	OC	161 d	05/77 - 11/77	-	-	-	-6	-2	-4
I	1	NASA Lewis Cleveland, OH	Suburban near Airport	40°	OC	74 d	10/76 - 01/77	-10	-3	+7	-9	-3	+6
						83 d	03/77 - 05/77	-17	-9	+9	-18	-10	+9
						32 d	06/77 - 07/77	-11	-11	0	-12	-15	-3
						54 d	07/77 - 09/77	-9	-7	+2	-10	-10	0
						57 d	09/77 - 11/77	-12	+10	+3	-12	-8	+4
						230 d	03/77 - 11/77	-	-	-	-10	-	-
I	1	Air Pollution Ctr Cleveland, OH	Industrial near Steel Mill	40°	OC	81 d	10/76 - 01/77	-32	-13	+28	-31	-9	+25
						90 d	03/77 - 06/77	-30	-12	+20	-32	-13	+22
						30 d	06/77 - 07/77	-18	-14	+10	-20	-17	+4
						54 d	07/77 - 09/77	-20	-13	+12	-22	-16	+7
						58 d	09/77 - 11/77	-26	-14	+13	-25	-14	+12
						230 d	03/77 - 11/77	-	-	-	-32	-	-
I	1	Subtropical Testing Miami, FL	Subtropical	5°	OC	1 yr	09/76 - 09/77	-11	-8	+4	-10	-9	+2
I	1	So. Florida Testing Miami, FL	Subtropical	* 5°	OC	1 yr	10/76 - 10/77	-6	-3	+4	-7	-4	+4
I		Solar Testing Pompano Beach, FL	Subtropical	45°	OC	1 yr	09/76 - 09/77	-12	-6	+6	-20	-7	+14
:	1	Carib. Testing Caguas, PR	Tropical	5°	OC	1 yr	09/76 - 09/77	-12	-7	+5	-20	-18	+3

* % Improvement from soiled condition determined by obtaining performance data before and after cleaning using techniques listed on Page 2
OC = Open Circuit

Table A-4. Effects of Field Soiling on Module Performance (Mfr D; Outer Cover, Dow Corning X1-2577) (Continuation 1)

Generation (Block Number)	Number of Modules	Field Site	Classification	Tilt	Load	Exposure Duration	Date of Exposure	Change in I_{sc} (%): Total Before Cleaning	Change in I_{sc} (%): Total Nonrecoverable Post-cleaning	Change in I_{sc} (%): By Cleaning*	Change in P_{max} (%): Total Before Cleaning	Change in P_{max} (%): Total Nonrecoverable Post-cleaning	Change in P_{max} (%): By Cleaning*
II	1	Meradcom Ft. Belvoir, VA	Suburban	seas. 15° to 62°	YES	2 yr	04/77 - 04/79	-	-	+15	-	-	+15
II	1	MIT Cambridge, MA	Metropolitan	45°	OC	5 mo	08/77 - 01/78	-12e	+1e	+13	-14e	-4e	+10
	2					6 mo	01/78 - 06/78	-14e	-8e	+7	-23e	-18e	+6
	1					6 mo	06/78 - 01/79	-16e	-6e	+11	-31e	-20e	+3
II	3	MIT/LL Lexington, MA	Suburban	45°	OC	5 mo	01/78 - 05/78	-13e	-10e	+4	-8e	-5e	+3
II	2	NYU NYC, NY	Metropolitan	45°	OC	6 mo	01/78 - 06/78	-31e	-11e	+23	-31e	-10e	+24
	3					5 mo	07/78 - 12/78	-25e	-8e	+19	-48e	-18e	+17
	3					6 mo	01/79 - 06/79	-57e	-23e	+47	-41e	-26e	+20

*Late Block I, All Block II, III
e = Estimated

APPENDIX B

MATERIALS SOILING DATA

Transmission loss for seven representative top-cover materials subjected to soiling conditions at five sites in Southern California and four sites in the rest of the country is tabulated in this appendix. In Table B-1, the unwashed samples are identical samples of the same material placed in the sample rack at the same time with one being retrieved at the appropriate sampling interval. The sample is stored for subsequent analysis and studies. The washed samples (Southern California sites only) are retrieved, measured, washed using a standard soap and water procedure, and returned to the field. Transmission measurements were made using the apparatus shown in Figure 4. In Table B-2, transmission loss for seven top cover materials as a function of the applied voltage (±1500 V, 0) to the materials rack is tabulated.

Table B-1. Materials Soiling Data, Nationwide Exposure Sites: Percentage Transmission Loss

Site	Retrieval Date	Exposure Duration days	Accum. Exposure Duration days	Silicone Rubber (RTV 615) W(%)	Silicone Rubber (RTV 615) U(%)	Proprietary Silicone (QI-2577) W(%)	Proprietary Silicone (QI-2577) U(%)	Glass (Soda Lime) W(%)	Glass (Soda Lime) U(%)	Glass (Alumino-silicate) W(%)	Glass (Alumino-silicate) U(%)	Glass (Boro-silicate) W(%)	Glass (Boro-silicate) U(%)	Polyvinyl Fluoride (Tedlar) W(%)	Polyvinyl Fluoride (Tedlar) U(%)	Acrylic (KORAD 212) W(%)	Acrylic (KORAD 212) U(%)
	6-8-79	33	33	9	11	7	8	3	3	3	4	2	3	4	3	5	5
	7-24-79	46	79	17	20	13	17	9	11	8	11	9	12	10	4	13	14
	8-28-79	35	114	15	25	13	23	5	16	7	15	6	16	7	17	10	16
JPL	10-12-79	45	159	19	30	15	27	5	12	5	10	5	10	5	12	7	12
Pasadena, CA	11-27-79	46	205	21	28	12	19	4	4	2	4	3	4	3	4	6	6
Tilt: 34°	1-10-79	44	249	24	24	12	16	4	4	3	3	2	2	2	1	3	3
Placement:	2-25-79	46	295	31	26	15	17	4	4	4	3	2	3	1	2	4	4
5/7/79	4-9-79	44	339	32	28	16	17	3	4	1	2	0	1	1	3	4	5
	5-23-80	44	383	36	lost	20	18	4	5	2	3	1	1	4	4	7	7
	6-18-79	35	35	9	8	6	7	2	3	2	2	1	2	3	3	4	5
	7-24-79	37	72	13	15	9	14	5	9	5	9	4	10	7	11	9	12
	8-28-79	35	107	12	19	10	18	5	12	5	13	3	14	7	14	7	14
JPL	10-12-79	45	152	14	25	12	23	3	10	4	6	3	8	6	11	6	8
Pasadena, CA	11-27-79	46	198	15	24	10	17	2	3	2	3	2	3	3	3	4	5
Tilt: 45°	1-10-79	44	242	16	24	10	16	3	3	2	3	1	2	1	2	3	3
Placement:	2-25-80	46	288	23	29	12	15	6	5	2	2	2	4	4	3	4	3
5/15/79	4-9-80	44	332	24	27	14	17	4	3	2	2	0	1	3	3	3	3
	5-23-80	44	376	28	31	18	20	6	5	5	3	1	2	7	4	8	6
	5-31-79	30	30	8	9	5	6	4	6	4	5	4	5	6	7	7	8
	7-5-79	37	67	11	14	9	12	5	6	5	6	5	5	5	7	8	8
	8-14-79	40	107	14	21	10	17	6	8	6	12	6	11	6	11	9	13
SCAQMD	9-28-79	45	152	16	31	11	27	7	12	6	14	8	12	8	16	11	19
Pasadena, CA	11-12-79	45	197	15	26	10	20	3	3	2	3	3	4	3	4	6	6
Tilt: 45°	12-27-79	45	242	16	26	10	19	3	3	3	3	2	1	3	4	5	5
Placement:	2-12-80	54	288	25	33	16	32	6	6	6	5	3	3	6	5	7	6
5/1/79	3-27-80	43	331	23	25	13	17	4	3	4	2	1	1	3	3	5	5
	5-12-80	45	376	28	33	15	20	6	4	5	4	5	6	3	4	7	6

NOTE:
W: Washed
U: Unwashed

Table B-1. Materials Soiling Data, Nationwide Exposure Sites: Percentage Transmission Loss (Continuation 1)

Site	Retrieval Date	Exposure Duration days	Accum. Exposure Duration days	Silicone Rubber (RTV 615) W(%)	Silicone Rubber (RTV 615) U(%)	Proprietary Silicone (QI-2577) W(%)	Proprietary Silicone (QI-2577) U(%)	Glass (Soda Lime) W(%)	Glass (Soda Lime) U(%)	Glass (Alumino-silicate) W(%)	Glass (Alumino-silicate) U(%)	Glass (Boro-silicate) W(%)	Glass (Boro-silicate) U(%)	Polyvinyl Fluoride (Tedlar) W(%)	Polyvinyl Fluoride (Tedlar) U(%)	Acrylic (KORAD 212) W(%)	Acrylic (KORAD 212) U(%)
	7-23-79	46	46	16	19	12	15	10	11	9	11	9	10	12	13	12	15
	9-4-79	43	89	14	28	11	24	8	16	7	13	6	13	7	21	8	21
SCAQMD	10-22-79	48	137	9	20	8	14	2	8	1	1	0	0	1	5	3	3
Lennox, CA	12-10-79	49	186	23	28	14	23	7	8	6	13	6	[illegible]	7	9	4	11
Tilt: 45°	1-28-80	49	235	23	23	9	16	3	2	1	1	1	1	1	1	3	3
Placement:	3-7-80	49	284	26	27	9	17	4	4	3	3	4	3	2	3	4	5
6/7/79	5-5-80	49	333	29	30	11	19	3	4	2	3	2	2	3	4	6	5
	6-23-80	58	381	33	38	16	21	10	8	7	8	6	6	7	7	6	6
	8-11-80	49	430	39	46	19	31	12	15	12	14	12	13	15	16	10	16
	6-14-79	28	28	4	4	3	2	2	3	1	2	1	2	1	3	4	4
	7-23-79	39	67	6	8	4	4	4	5	3	4	2	3	3	5	6	6
USCG	9-4-79	43	110	6	11	3	6	3	4	3	6	1	3	2	5	4	8
Pt. Vicente, CA	10-23-79	49	159	7	13	4	6	1	2	3	4	0	0	0	0	2	3
Tilt: 45°	12-10-79	48	207	14	23	6	7	4	4	4	4	4	4	4	5	4	5
Placement:	1-28-79	49	256	19	15	5	5	2	1	1	1	1	5	0	0	1	0
5/17/79	3-17-80	49	305	21	18	4	6	1	2	2	2	2	2	0	0	1	1
	5-6-80	50	355	26	24	7	7	2	3	2	2	1	0	1	4	2	4
	6-18-80	43	398	34	lost	9	9	5	5	4	5	3	3	4	6	5	7
	7-17-79	68	68	2[a]	8	2[a]	4	1[a]	2	2[a]	2	1[a]	2	2[a]	2	2[a]	3
	8-22-79	37	105	2	4	2	1	1	2	0	1	1	1	0	0	2	2
Table Mountain	10-8-79	49	154	8	13	3	3	1	2	2	2	2	2	1	1	2	2
Wrightwood, CA	11-26-79	49	203	12	13	3	4	2	2	2	2	2	2	1	1	2	2
Tilt: 45°	1-14-80	49	252	19	7	3	3	1	9	2	2	0	1	0	0	2	2
Placement:	4-22-80	99	351	16	15	3	3	0	0	0	0	0	0	1	0	4	2
5/10/79	6-10-80	49	400	16	16	3	4	1	1	1	1	1	0	1	1	1	3
	7-8-80	28	428	17	15	6	5	2	2	1	1	0	1	2	1	4	4
	7-28-80	20	448	16	18	3	4	1	2	0	0	0	0	1	1	3	4
	5-30-79	21	21			1	1	2	2	1	1	1	1	1	2	3	3
	7-8-79	39	60			4	4	1	2	1	1	1	8	4	1	2	3
Goldstone, CA	8-27-79	50	110			3	5	2	2	2	2	1	0	1	1	2	2
Tilt: 45°	10-15-79	49	159	(b)		4	6	2	2	1	2	0	0	0	1	2	3
Placement:	12-3-79	49	208			5	8	3	4	2	2	0	1	2	2	3	3
5/9/79	1-21-80	49	257			5	6	2	2	2	2	1	2	1	1	2	2
	3-10-80	49	306			4	6	2	3	1	2	1	0	1	0	1	1
	4-28-80	49	355			4	8	0	2	0	0	0	0	1	0	0	2
	6-18-80	51	406			7	8	2	3	2	3	0	1	3	2	3	4

NOTE:
W: Washed
U: Unwashed

ORIGINAL PAGE IS OF POOR QUALITY

Table B-1. Materials Soiling Data, Nationwide Exposure Sites: Percentage Tiansmission Loss (Continuation 2)

Site	Retrieval Date	Exposure Duration days	Accum. Exposure Duration days	Silicone Rubber (RTV 615) W(%)	U(%)	Proprietary Silicone (QI-2577) W(%)	U(%)	Glass (Soda Lime) W(%)	U(%)	Glass (Alumino-silicate) W(%)	U(%)	Glass (Boro-silicate) W(%)	U(%)	Polyvinyl Fluoride (Tedlar) W(%)	U(%)	Acrylic (KORAD 212) W(%)	U(%)
NYU	8-10-79	21	21	-	6	-	5	-	1	-	2	-	1	-	1	-	3
New York City, NY	9-15-79	36	57	-	10	-	6	-	3	-	4	-	1	-	2	-	5
Tilt: 45°	11-7-79	53	110	-	18	-	13	-	8	-	7	-	5	-	6	-	9
Placement:	2-25-80	110	220	-	30	-	22	-	11	-	9	-	5	-	8	-	9
7/20/79	6-17-80	113	333	-	43	-	25	-	10	-	8	-	6	-	8	-	8
MIT	8-20-79	30	30	-	3	-	3	-	1	-	1	-	1	-	2	-	3
Cambridge, MA	10-29-79	70	100	-	12	-	6	-	3	-	4	-	1	-	3	-	5
Tilt: 45°	2-25-80	119	219	-	32	-	11	-	5	-	4	-	2	-	4	-	6
Placement:	6-17-80	113	332	-	22	-	16	-	8	-	7	-	4	-	7	-	6
7/21/79																	
Sandia																	
Albuquerque, NM	6-11-80	176	176	-	20	-	3	-	1	-	1	-	0	-	1	-	2
Tilt: 45°																	
Placement:																	
12/8/79																	
Battelle																	
Richland, WA	2-8-80	53	53	-	7	-	1	-	0	-	0	-	0	-	0	-	1
Tilt: 45°	4-30-80	82	135	-	12	-	5	-	1	-	0	-	0	-	0	-	2
Placement:																	
12/17/79																	

(a) Initial retrieval of washed samples on 5-28-80 after an exposure of 19 days.

(b) Original RTV 615 samples at Goldstone destroyed by birds. New samples placed on 7/20/79 retrieved on following dates:

Retrevial Date	Exposure Days	Accum. Days	Washed	Unwashed
8-27-80	38	38	5	4
10-5-79	49	87	8	6
12-3-79	49	136	11	7
1-14-80	49	185	12	8
3-10-80	49	234	13	8
4-28-80	49	283	14	12
6-18-80	51	334	16	16
8-4-80	47	381	12	13
9-22-80	49	430	14	19

Table B-2. High-Voltage at JPL, Pasadena, CA (45° Tilt); % RNHT Loss

MATERIAL (Initial Placement 5/17/79)	VOLTAGE (Relative to Ground)	RETRIEVAL DATE 2/11/80 D = 271 D_a = 366	5/16/80 D = 95 D_a = 366	7/16/80 D = 61 D_a = 427	10/28/80 D = 104 D_a = 531
		% RNHT LOSS			
Silicone Rubber (RTV 615)	+1500	25	32	36	60
	-1500	25	30	33	47
	0	24	31	35	51
Proprietary Silicone Q1-2577	+1500	19	19	24	49
	-1500	19	19	23	30
	0	19	19	24	36
Glass (Soda Lime)	+1500	9	11	13	26
	-1500	9	11	14	21
	0	7	5	10	18
Glass (Alumino-silicate)	+1500	6	8	11	19
	-1500	8	12	15	27
	0	6	4	7	15
Glass (Boro-silicate)	+1500	6	9	13	21
	-1500	9	11	17	39
	0	5	6	6	15
Polyvinyl Fluoride (Tedlar)	+1500	9	12	15	29
	-1500	10	15	16	40
	0	4	5	7	21
Acrylic (Korad 212)	+1500	9	15	16	35
	-1500	10	17	17	33
	0	6	7	7	23

NOTE: D = Exposure Duration Since Previous Retrieval Date (days)
D_a = Accumulated Exposure Duration (days)

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. JPL Pub 80-87	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle PHOTOVOLTAIC MODULE SOILING STUDIES - May 1978 - October 1980		5. Report Date November 1, 1980
		6. Performing Organization Code
7. Author(s) A.R. Hoffman, C.R. Maag		8. Performing Organization Report No.
9. Performing Organization Name and Address JET PROPULSION LABORATORY California Institute of Technology 4800 Oak Grove Drive Pasadena, California 91109		10. Work Unit No.
		11. Contract or Grant No. NAS 7-100
12. Sponsoring Agency Name and Address NATIONAL AERONAUTICS AND SPACE ADMINISTRATION Washington, D.C. 20546		13. Type of Report and Period Covered JPL Publication
		14. Sponsoring Agency Code

15. Supplementary Notes Also sponsored by U.S. Department of Energy under Interagency Agreement EX-76-A-29-1012; identified as JPL Project Document 5101-131 and DOE/JPL-1012-49

16. Abstract

The retention of particulate contamination on the surface of flat-plate photovolatic devices is adversely affecting electrical performance of outdoor-exposed modules. This report describes the results of an experimental study being performed by the Jet Propulsion Laboratory's Low Cost Solar Array Project to characterize and understand the effects of outdoor contaminants on sensitive optical surfaces of flat-plate photovoltaic modules and cover materials.

Comparative electrical and optical performance data from photovoltaic modules and materials subjected to outdoor exposure at field test sites throughout the United States have been collected and examined. The results show significant time- and site-dependence. During periods when natural removal processes do not dominate, the rate of particulate contamination accumulation appears to be largely material-independent. The effectiveness of natural removal processes, especially rain, is strongly material-dependent. Glass and acrylic top-cover materials retain fewer particles than silicone rubber does. Side-by-side outdoor exposure testing for long duration is presently the most effective means of evaluating soiling differences between materials. Changes in spectral transmission as a function of time and location and limited scattering data are presented.

17. Key Words (Selected by Author(s))	18. Distribution Statement
Conversion Techniques Energy Storage	Unlimited - Unclassified

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	53	