SURFACE SOILING: THEORETICAL MECHANISMS AND EVALUATION OF LOW-SOILING COATINGS

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INTRODUCTION

The accumulation of dust, dirt, pollen, and other atmospheric contaminants and particles on the surfaces of solar-energy devices such as solar-thermal collectors and photovoltaic modules results in a loss of performance due to a decrease in transmitted sunlight. This accumulation of a diversity of deposited atmospheric materials, hereafter referred to simply as soil, reduces light transmission by a combined action of absorption and scattering. To minimize performance losses caused by soiling, solar devices should have surfaces or surface coatings that have low affinity for soil retention and a maximum susceptibility to natural cleaning by wind, rain and snow, and are readily cleanable by simple and inexpensive maintenance cleaning techniques.

A review of literature published before 1980 (Reference 1) found no information specifically addressing the chemistry and physics of surface soiling, nor requirements of surfaces or surface coatings that would have natural tendencies for low to zero soil retention or for ready cleanability by natural means. Accordingly, the Flat-Plate Solar Array Project (FSA), managed by JPL for DOE, established a program to investigate natural surface soiling ultimately to establish chemical, physical, and mechanical criteria required for low-soiling surfaces or surface coatings.

The soiling program divided into five activities: (1) measurement as a function of time of the decrease in light transmission resulting from the natural accumulation of soil on the surfaces of a wide variety of glasses and transparent plastic films mounted on outdoor exposure racks at various geographical locations; (2) chemical and physical analysis of the soil on these surfaces; (3) generation of theories and hypothesis as to the chemical and physical requirements of surfaces for low soil retention; (4) investigation of the details of construction of the soil layer on surfaces, and (5) identification and evaluation of candidate low-soiling surface coatings or treatments.

This presentation reports on the progress to date on the evolution of a soiling theory, and on the positive performance of low-soiling coatings after one year of outdoor exposure.

SOILING THEORY

Although the search of published literature for information on prevention of surface soiling was not directly fruitful, several articles (References 2-7) were found, which in combination with the experimental

light transmittance measurements (References 8, 9), resulted in an initial capability of defining theoretically the requirements for low-soiling surfaces or surface coatings, and of assessing the effectiveness of wind, rain, and snow as natural cleaning agents.

With respect to snow, observations have been made (Reference 10) that the surfaces of photovoltaic modules and mirrors are noticeably quite clean after a heavy snow pack has slid off these tilted surfaces. The presumption is that cleaning is accomplished by a combination of abrasive action and the presence of liquid water at the module-surface and snow-pack interface. However, accumulated snow that is eventually removed by melting and not sliding is not effective (Reference 11).

Wind is not an effective cleaning agent. The aerodynamic lifting action of wind can remove particles larger than about 50 m, from surfaces (Reference 4), but is ineffective for smaller particles. Thus, the particle size of soil matter is generally found to be less than 50 m, and predominantly to be less than 5 m (References 12, 13).

Rain is the primary natural cleaning agent, but rain is not necessarily efficient at all times in removing all of the accumulated soil on a surface. In a previous publication (Reference 1), known and speculated mechanisms of soil adhesion to surfaces that result in resistance to soil removal by rain were described, resulting in generation of the following requirements for low-soiling surfaces:

(1) Hardness
(2) Smoothness
(3) Hydrophobicity
(4) Low surface energy
(5) Chemically clean of sticky materials (surface and bulk)
(6) Chemically clean of water-soluble salts and first-period elements (surface and bulk).

In addition, physical examination of soiled surfaces resulted in a theoretical speculation that soil accumulates in a tier of up to three distinct layers. These layers are designated outward from the surface as A, B, and C. Layers A and B, which are resistant to removal by rain, may or may not form, but if they do, they will form in the sequence A followed by B followed by C, or B only followed by C. Layer C forms during dry periods, and is removed during rainy periods. Therefore, refinement of the soiling theory suggests that the six requirements for low-soiling surface listed above are those for preventing the formation of layers A and B, or B alone, but have no influence on layer C. Layer A involves strong chemical attachment, or strong chemisorption of soil on the natural surface. Layer B is physical, consisting of a highly organized arrangement of soil effecting a gradation in surface energy from a high associated with the energetic first layer or natural surface to the lowest possible energy state on the outer surface of layer B. The lowest possible energy state is dictated by the chemical and physical nature of the regional atmospheric soiling materials. Layer C constitutes a settling of loose soil matter, accumulating in dry periods and being removed during rainy periods.

Therefore, soiling theory suggests that the rain-resistant layers A and B will not form on surfaces that are chemically nonreactive with regional atmospheric soil materials, and that have surface energies lower than that of the regional atmospheric soil materials. In addition, there are experimental indications that the quantity of layer C soil on flat surfaces decreases as the tilt angle increases toward vertical.

LOW-SOILING COATINGS

The six theoretically derived requirements for low-soiling surfaces suggest that surfaces or surface coatings should be based on fluorocarbon chemistry. A list of candidate fluorocarbon coating materials identified to date is given on p. 393. Two of the materials, L-1668 and E-3820, have chemically reactive functional groups for chemical attachment to surfaces, but FC-721 and FC-723 do not. Testing showed that FC-721 and FC-723 readily dissipated from surfaces, and therefore could not be used. The two chemically attachable fluorocarbon coatings were tested on the surfaces of outer cover materials that are being evaluated for photovoltaic modules: Sunadex (ASG) soda-lime glass, and Acrylar (3M) and Tedlar (Du Pont) UV-screening plastic films (Reference 14). The fluorocarbon coatings L-1668 and E-3820 will attach chemically to the surfaces of these three outer cover materials, but it was found (Reference 11) that the chemical attachment of E-3820 to Acrylar and L-1668 to Tedlar was weak. Therefore, for these specific coatings, the surfaces of the plastic films were treated with ozone to generate polar groups for enhanced chemical reactivity and therefore enhanced chemical attachment. This technique worked, and although not indicated as needed in trial testing, L-1668 was also applied to an ozone-treated Acrylar surface, and E-3820 was also applied to an ozone-treated Tedlar surface.

The positive performances of the L-1668 and E-3820 fluorocarbon coatings on the glass and plastic films after 1 year of outdoor exposure are shown on pp. 393 and 394. In all cases, the fluorocarbon-coated samples retained less soil compared with uncoated controls. The fluctuations observed in the soiling data curves are associated with the accumulation and removal of layer C in sequence with local rain patterns.

The concept of using chemically attachable fluorocarbon coating materials for low-soiling application is strongly supported by this one year's experimental data. Research directed toward achieving further improvements in soil-reducing fluorocarbon coatings is being planned.

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JET PROPULSION LABORATORY

E.F. Cuddihy

Theoretical Considerations of Soil Retention

Achieve a fundamental understanding of soiling behavior:

(1) Soil-surface interactions

(2) Chemical and physical details of soil layer construction

(3) Mechanisms resulting in resistance of soil to natural removal by wind, rain, and snow

Derive from a fundamental understanding of soiling behavior, chemical, physical, and mechanical properties of surfaces required for:

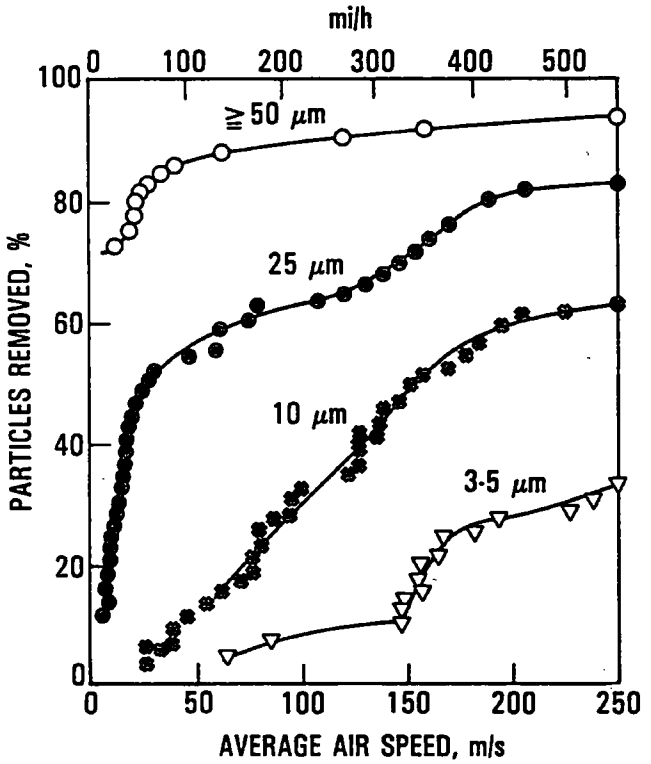
(1) Minimum accumulation of soil

(2) Maximum susceptibility to natural cleaning by wind, rain, and snow

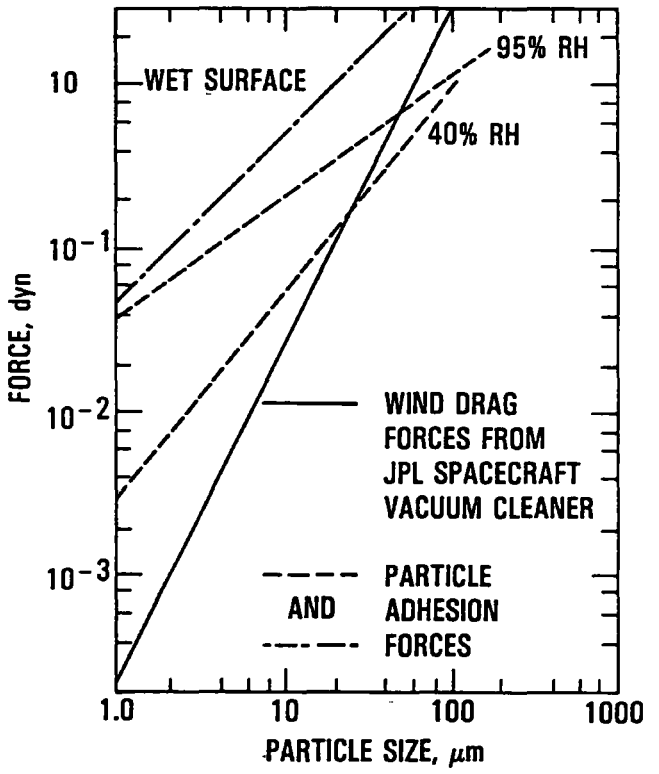
(3) Cleanability by simple and inexpensive maintenance cleaning techniques

Particle-Surface Attraction

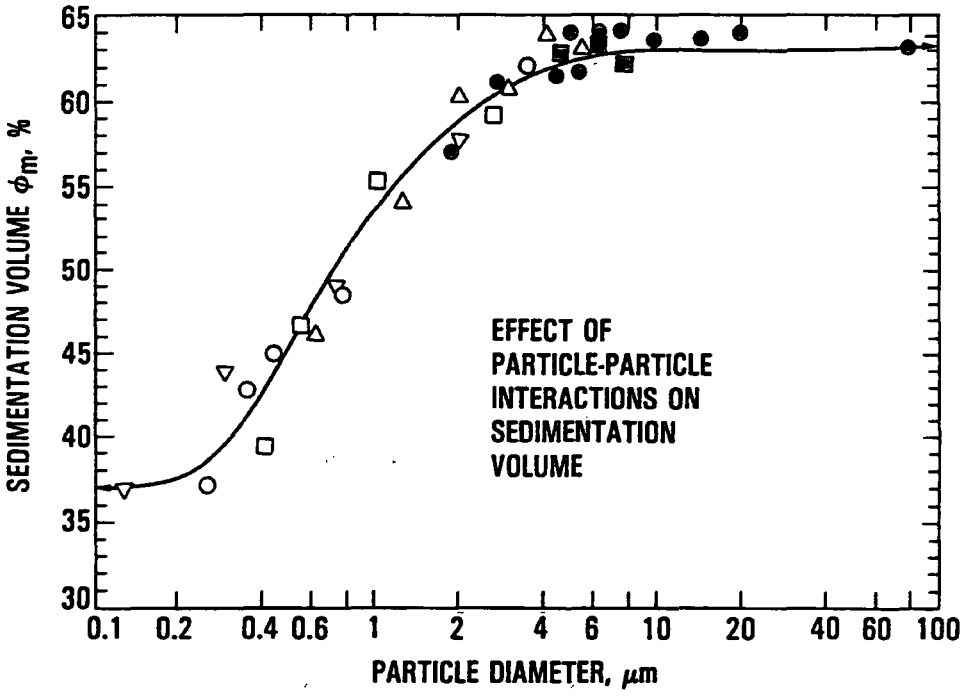
REMOVAL BY WIND OF DUST PARTICLES FROM THE SURFACE OF A CLEAN, OIL-FREE GLASS SLIDE (40% RH)



Particle Adhesion and Wind Drag Force vs Particle Size



Particle Energetics



Natural Cleaning by Wind

(1) Essentially ineffective for particles smaller than 50 μm

(2) Probably acts to limit retained soil to smaller particle sizes

Retained Soil Concept

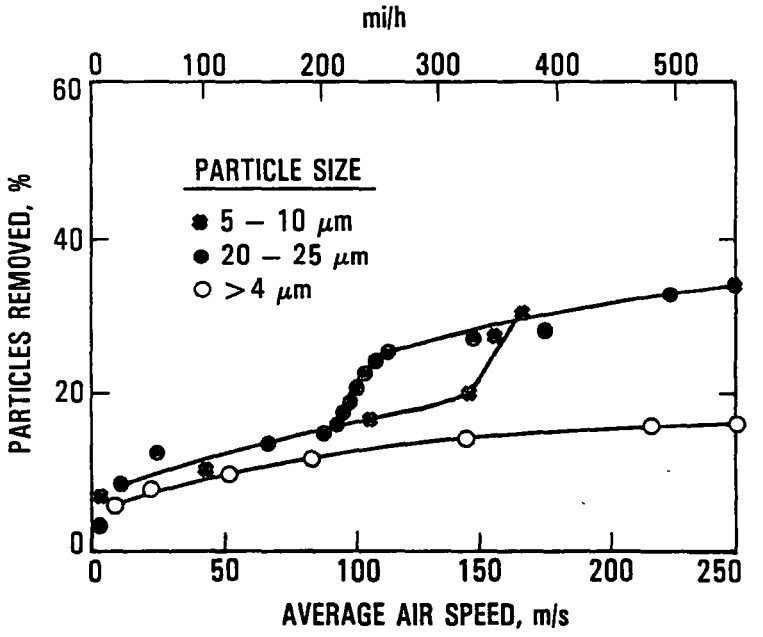
Permanent soil on surfaces is considered to be:

(1) Composed of particles smaller than 50 μm

(2) Retained by mechanisms that result in resistance to natural removal by rain

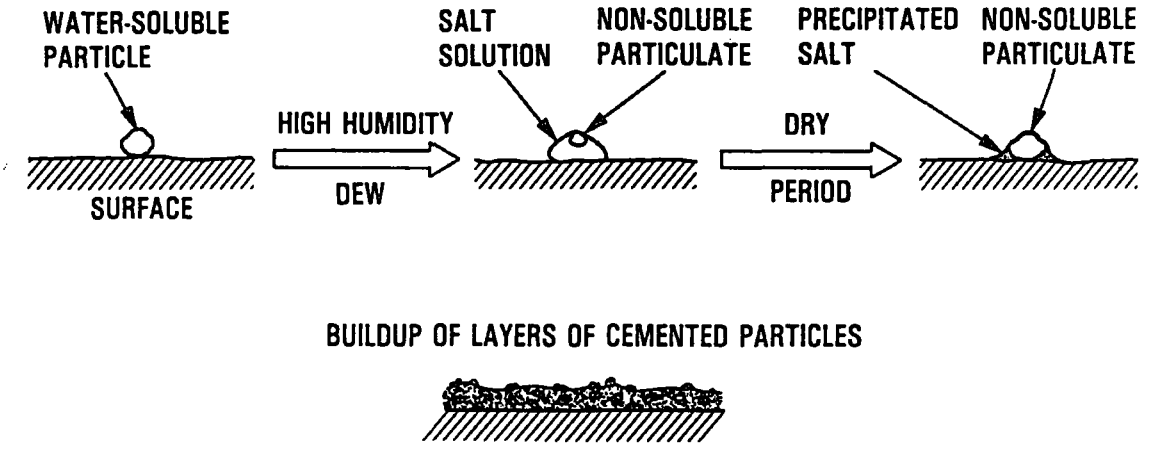
Effect of One Dew Cycle

REMOVAL BY WIND OF DUST PARTICLES FROM A GLASS SLIDE SURFACE AFTER ONE DEW CYCLE

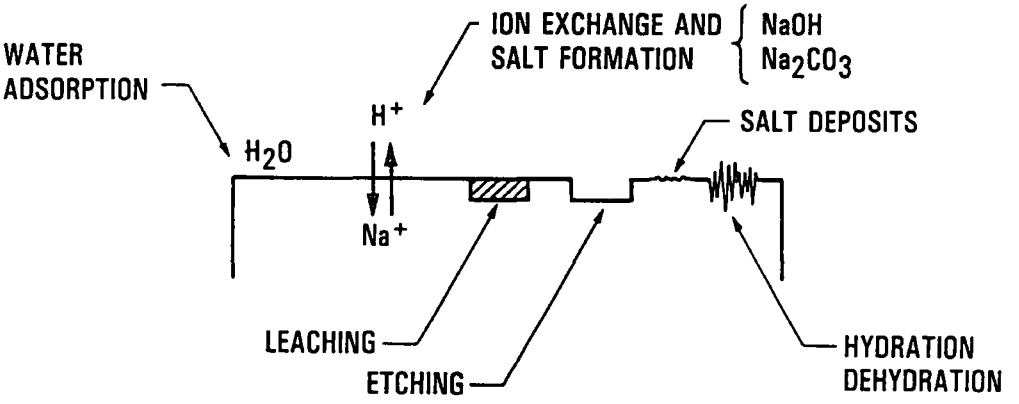


Cementation Process

A NATURAL MECHANISM OF SOIL RETENTION



Weathering of Soda-Lime Glass



Outdoor Soiling Experience of PV Modules Fabricated With Different Surfaces

LEVEL OF SURFACE SOILING INDICATED BY POWER RECOVERY AFTER CLEANING, %

(Months of exposure before cleaning)

	SOFT SILICONE ELASTOMERS		SILICONE HARD COAT	GLASS
	RTV615	SYLG. 184		
DSET (DRY)	+9	+9	+4	+1
KEY WEST (WET)	+9	+9	0	+2
MIT	+13 (5)	+14	+10 (5)	+6 (5)
NYU	+23 (6) +33 (12)	+29 (5) +38 (12)	+22 – 26	+11
COLUMBIA U.	+21 (6) +29 (12)	+22 (6) +33 (12)	–	+12 (6)

DECREASING AIRBORNE ORGANICS

INCREASING SURFACE HARDNESS

Evolving Requirements for Low-Soiling Surfaces

(1) Hard

(2) Smooth

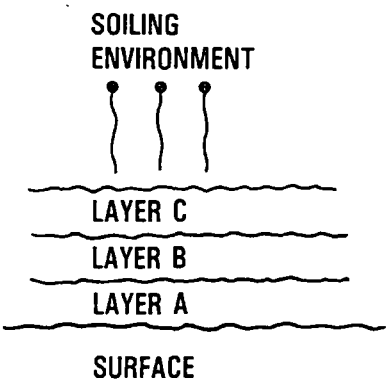
(3) Hydrophobic

(4) Low surface energy

(5) Chemically clean of sticky materials (surface and bulk)

(6) Chemically clean of water-soluble salts (surface and bulk)

The Three Soil Layers

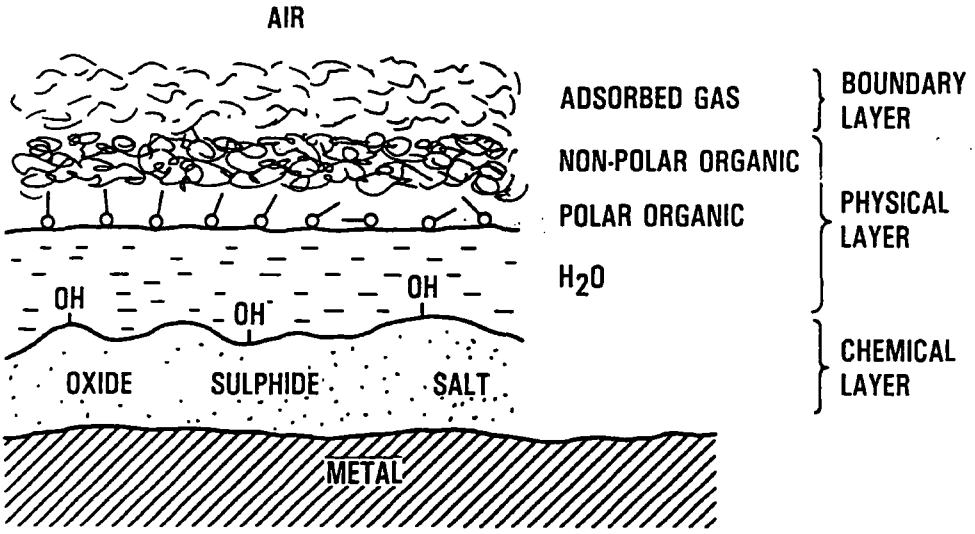


Layer A: Tenacious, primary surface layer of soil, resistant to removal by rain, adhesive tape, and hand washing

Layer B: Secondary surface layer of soil, resistant to removal by rain, but readily removed by adhesive tape and hand washing

Layer C - top surface of loose soil, easily removed by rain

Hierarchy of Spontaneously Adsorbed Layers on a Metal Surface*



*Dr. Robert L. Patrick, Rockwood Systems, Inc., "Water and Adhesive Bonding," presented at a short course on adhesion technology, Kent State University, June 16-20, 1980

Description of the Soil Layers

Layer A: (1) A chemical layer formed by chemical reactions between soil materials and chemically reactive surface sites

(2) A "flypaper" layer; soil particles adhere strongly to a soft, sticky and/or tacky surface

Layer B: A physical layer, effecting a transition from high surface energy to low surface energy

PHYSICAL CONSTRUCTION OF LAYER B:

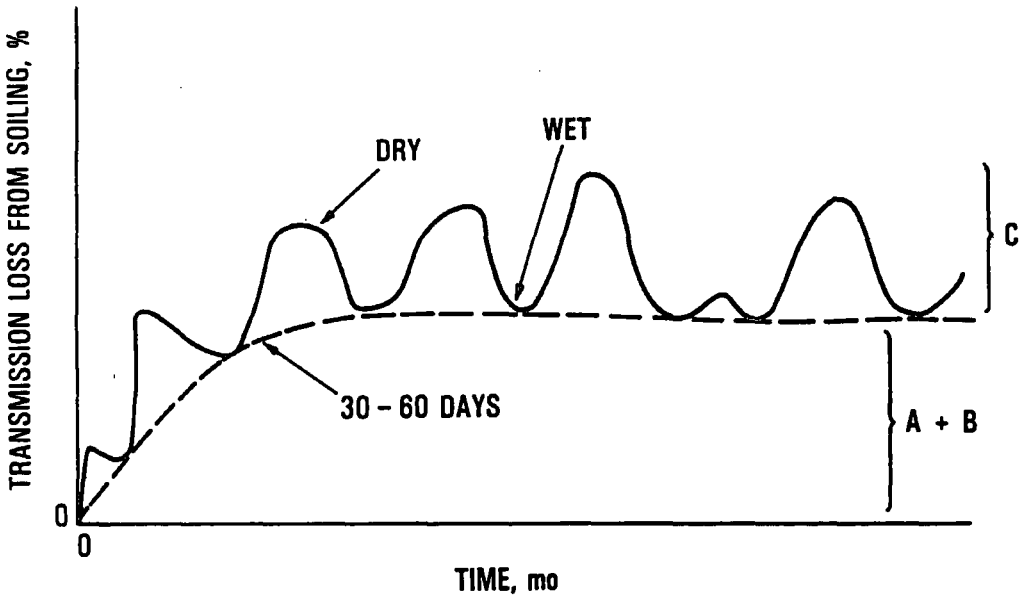
The layer is formed by cementation, spatially achieving:

(1) Energetic gradient in particle size distribution, from fines at the interface with layer A to coarse particles at the interface with layer C

(2) Energetic gradient in particle chemistry, from polar inorganics at the interface with layer A to non-polar organics at the interface with layer C

Layer C: The outer layer, a loose, weakly adhering layer of soil residing on the surface of layer B, readily removable by rain

JPL Soiling Data

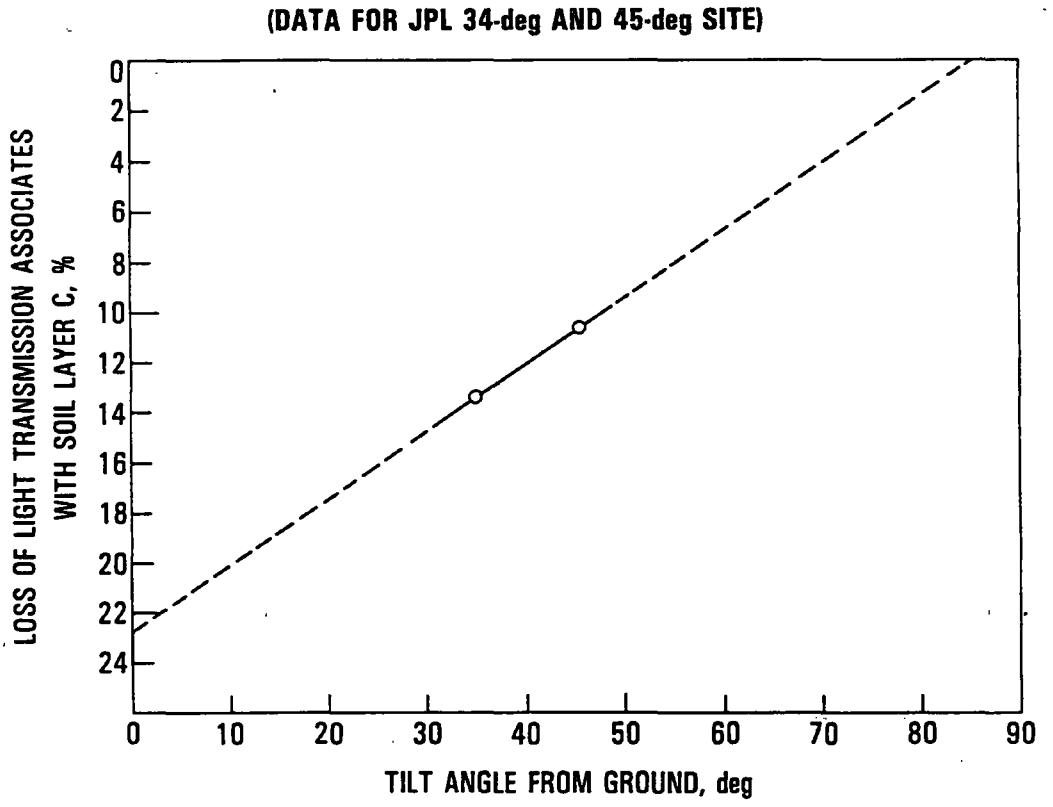


REDUCTIONS IN SHORT-CIRCUIT CURRENT FROM SOILING LAYERS, %

Materials	Torrance		Pt. Vicente		Goldstone		Table Mt.		Pasadena SCAQMD	
	A+B	C	A+B	C	A+B	C	A+B	C	A+B	C
Soft silicone, RTV 615	20	10	?	?	?	?	?	?	25	8
Semi-hard silicone, Q1-2577	14	8	5	2	6	2	1	3	17	15
Acrylic film, Korad 212	3	8	0	8	1	2	2	1	5	14
Fluorocarbon film, Tedlar	1	8	0	5	0	2	0	2	3	13
Soda-lime glass	2	6	1	4	2	2	0	2	3	9
Alumino-silicate glass	1	12	1	5	0	2	0	2	2	12
Borosilicate glass	0	7	0	5	0	2	0	2	1	11
Average for layer C		8.2		4.8		2		2		12.3

Materials	34-deg Site		45-deg Site	
	A+B	C	A+B	C
Soft silicone, RTV 615	24	6	24	7
Semi-hard silicone, Q1-2577	16	12	15	8
Acrylic film, Korad 212	3	13	3	11
Fluorocarbon film, Tedlar	1	16	2	12
Soda-lime glass	4	12	3	9
Alumino-silicate glass	2	13	2	11
Borosilicate glass	1	15	1	13
Average for layer C	13.5		10.6	

Effect of Tilt Angle on Accumulation of Soil Layer C



Evolving Requirements for Surfaces Having Resistance to A and B Soil Layer Formation

(1) Hard

(2) Smooth

(3) Hydrophobic

(4) Low surface energy

(5) Chemically clean of sticky materials (surface and bulk)

(6) Chemically clean of water soluble salts (surface and bulk)

(7) Weather-stable (resistance against oxidation, hydrolysis, UV reactions)

Candidate Fluorocarbon Antisoiling Coatings

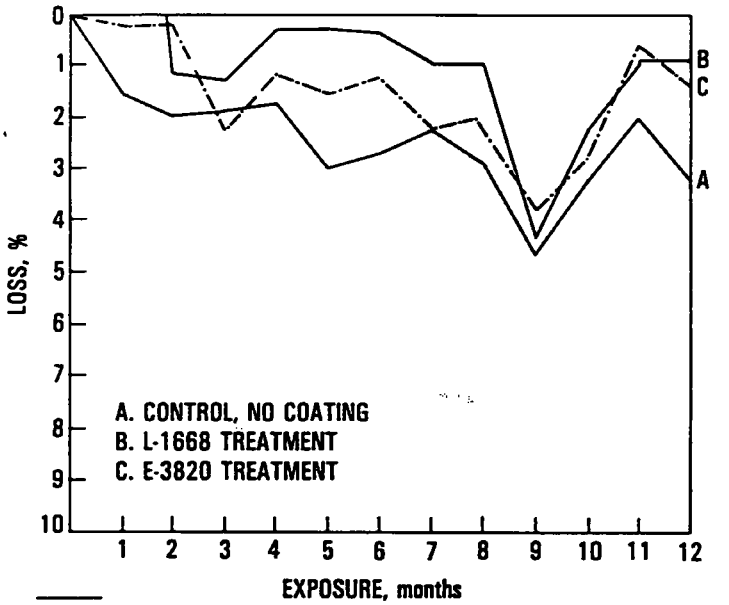
(1) Fluorinated silane, L-1668 (3M)

(2) FC-721 and FC-723, fluorinated acrylic polymer (3M)

(3) Perfluorodecanoic acid with chemical coupling primer (E-3820, Dow Corning)

Evaluation of Fluorocarbon Antisoiling Coatings on Sunadex* Soda-Lime Glass

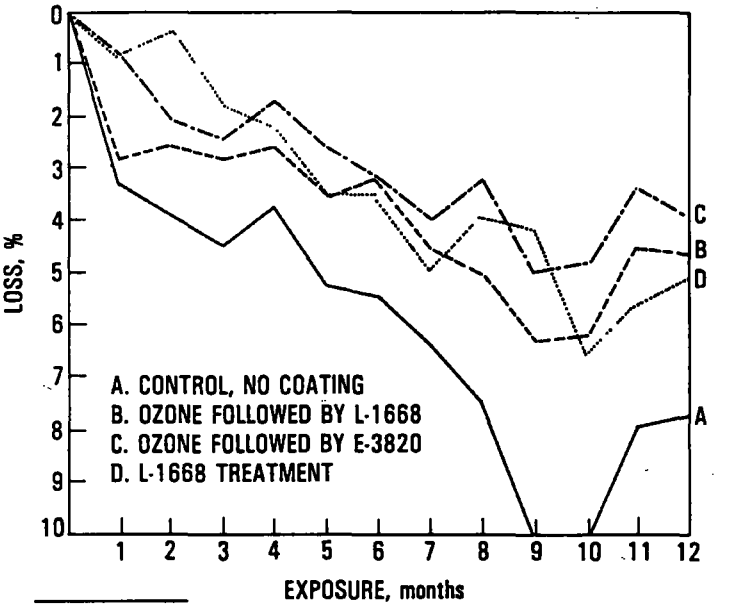
% LOSS OF SOLAR-CELL SHORT-CIRCUIT CURRENT VS TIME



*ASG

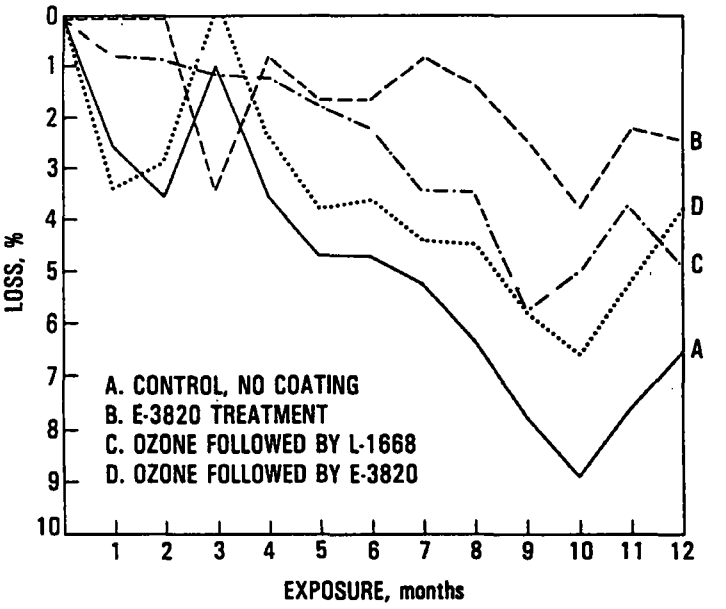
Evaluation of Fluorocarbon Antisoiling Coatings on Acrylar* (Acrylic) Plastic Film

% LOSS OF SOLAR-CELL SHORT-CIRCUIT CURRENT VS TIME



*X-22417, 3M

Evaluation of Fluorocarbon Antisoiling Coatings on Tedlar* Plastic Film



*100 BG-30-UT, Du Pont

Evolving Considerations for Cleaning Strategies and Techniques

(1) Water washing of surfaces while wet with dew

(2) Washing with detergent and/or surfactant solutions selected for specific organic deposits

(3) Washing with solvent-water mixtures for both deposited organics and inorganic salt "cements"

(4) Resurfacing of wind-damaged surfaces

(5) Replenishment of low-soil surface materials during routine washing (car-wash principle)

Evolving Requirements for Low-Soiling Environments

(1) Low to zero airborne organic vapors

(2) Frequent rains, or generally dry (dew, RH)

(3) Pattern of few dew cycles and high RH occurrences between rain periods

DISCUSSION

D'AIELLO: As a matter of interest, I notice that of the three tests that were done at Enfield, the first showed the least change. Only about a 2% or 3% change even for the uncoated samples. Was there a big difference between the modules?

CUDDIHY: Well, these aren't modules. These are just individual samples. The one you are referring to is a glass surface, which runs low even without a coating, as compared with plastic films. The reduction in soil, though real, is therefore smaller on a glass surface than on a plastic film surface. This is not related to any differences in modules.

D'AIELLO: My other question relates to glasses: were there any differences you noted in soiling characteristics among commercially available glasses?

CUDDIHY: Yes, as illustrated in the experimental data for aluminosilicate glass, borosilicate glass and regular window glass, where soiling levels increased in this same order, being highest on window glass.

D'AIELLO: What about side-to-side differences with soda-lime float glass, there being a side that was exposed to tin during manufacturing, and the other side that was facing the air? Do they exhibit similar natural soiling behavior?

CUDDIHY: We haven't studied this yet.