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Heliostat Dust Buildup and Cleaning Studies

Raymond S. Berg

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Abstract

Dirt accumulation on solar energy optical surfaces such as heliostats can cause losses of over 25% after relatively short outdoor exposure. The optical loss is due to absorption and scattering by particulates that collect on the surface. Particulates impinge on the surface through complex fluid mechanical interactions between the dust-laden airstream and the heliostat structure and reflector surface. Initial particle adhesion is dominated by surface energetics. However, condensed water vapor at the particle-surface interface provides a vehicle for soluble components of the surface and dirt to establish very strong chemical and physical bonds between the dirt particle and the surface.

Cleaning effectiveness depends on the technique used, the environmental conditions, and the amount of time the mirror has been exposed. Several continuous and periodic cleaning techniques have shown promise. Continuous cleaning using electrostatic repulsion has been tested in laboratory experiments and was shown to reduce dust accumulation. These experiments were performed in a low velocity (0-25 m/s) atmospheric wind tunnel

fitted with a dust injector capable of injecting 10^4 times as many optically important particles as are present in the normal aerosol. Periodic cleaning using high pressure sprays of up to 10,000 psi have been used to clean dirt from outdoor test samples. Tap water sprays at pressures above 500 psi seem to be equally effective and recover about 95% of the reflectance loss from dirt buildup. Several common detergents have been examined. Detergents with low pressure sprays generally must be used on short intervals, less than two weeks, or they lose their effectiveness.

Measurements on accumulated dirt show that a limited number of measurements are required to characterize the optical loss of a dirty mirror. Weighted reflectivity measurements at 500 nm can be used. The dirt buildup is a very complex function of time and environmental conditions.

Acknowledgment

The author would like to acknowledge the contributions of Dan Arvizu, Roscoe Champion, Jim Freese, and Dick Pettit for their contributions to the cleaning and dirt characterization experiments.

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I. Introduction

Cleaning of accumulated dirt is beginning to be recognized as a major factor in the overall cost performance of most solar energy systems. Dirt accumulation can result in losses of over 25% after relatively short outdoor exposure. Long term effects are not understood and need further study.

The object of this paper is to describe the range of techniques that can be used to reduce dirt accumulation and to discuss some of the corresponding experiments being performed at Sandia. The methodology used was to first study the mechanisms of dirt impingement and adhesion and the time development of adhesion forces. The behavior of adhesion forces leads to restrictions on the periods when dirt is most susceptible to removal and on the potential removal techniques that can be successfully used. Several experiments utilizing a variety of these techniques are being pursued.

II. Deposition Mechanics

The actual dirt deposition rates and bond strengths are functions not only of the type of dirt particles and surface materials, but of numerous factors such as environmental conditions, geographical and site effects, design features, and time effects. However, there are several features to both the impingement and adhesion of particles on the various surfaces that are independent of these variables.

A. Particle Transport

Airborne particles must have a sufficiently low Stokes (terminal) velocity to remain suspended.[1] Stokes velocities of particles as a function of their sizes are shown in Fig. 1. Particles with Stokes velocities greater than wind velocities will tend to fall out by sedimentation. Some particles, such as those arising from industrial and transportation emissions, are active enough, while others, such as water droplets, are volatile enough that they can grow or shrink in the aerosol. Relatively concentrated clouds of particles have been tracked for hundreds of miles downstream from their creation point. Long range particle transport is a factor which can affect siting.

B. Impingement Processes

Particles impinge on a surface because of the complex fluid mechanical interaction of the dirt-laden airstream with the entire heliostat structure. In some cases, such as with a field of heliostats, the structures themselves can interact strongly through their interaction with the airstream. The mechanisms of interaction of an airstream with a structure are listed in Table I.[2] Normal air velocities and heliostat dimensions can result in airflows characterized by Reynolds numbers in the range of 10^5-10^6. For Reynolds numbers $\lesssim 10^5$, laminar streams flowing across a flat surface produce a laminar boundary layer which grows in thickness as it progresses across the surface. This layer is denuded of particles, since particles that enter the boundary layer are rapidly deposited on the surface. Very small particles ($d \lesssim 0.1$ μm) are transported by convective diffusion to the surface where they readily adhere because of their high surface energy/volume ratio. Larger particles which are engulfed by the growing boundary layer fall by sedimentation onto the surface.

For Reynolds numbers $\gtrsim 10^6$, the boundary layer becomes turbulent, with a very thin laminar sublayer. In a turbulent boundary layer, the average air velocity remains high very close to the surface. The air current is thus able to "scrub" the surface, keeping particles in suspension that would normally diffuse or settle out of the airstream.

When the airstream moves over an edge at an angle to the overall direction (such as with a parabola or heliostat facet), turbulent eddies and dead spaces in the airstream are created. In such a case, particles which are not able to follow the eddies impact into the surface. Particles can also be thrown into dead spaces and fall out of the airstream by sedimendation.

C. Adhesion Mechanisms

The adhesion mechanisms holding particles that have fallen onto a surface are shown in Table II.[3] These are affected not just by the materials comprising the surface and dirt, but also by the environmental conditions, particularly the humidity. Because of the nature of these bonding mechanisms, they fall into a regular hierarchy of strength ranges. Under normal dry conditions, the adhesion is dominated by surface energetics.* When high humidities are present, intense physical and chemical bonds can develop.[4] The high energy densities near the particle/surface contact region result in the condensation of water from the atmosphere even when the relative humidity is less than 100%. Thus the distinction between dry and humid conditions may be relatively unimportant, since the nighttime temperatures in geographical regions most suited to solar energy applications (such as Albuquerque, NM, and Barstow, CA) inevitably are below the dewpoint and sufficient water is available almost nightly to condense at the dirt/surface contact zone.

With the presence of water, the bonding mechanism changes because water can leach soluble materials from the dirt, air, and reflector surface. Crushed glass, for example, can lose a large percentage of its weight in the form of water soluble constituents when placed in distilled water. The resulting chemicals can produce intense chemical and physical bonds that are virtually impossible to break without causing damage to the surface.

III. Optical Scattering Effects

The optical loss caused by a collection of particles depends on both the particle size distribution and their dielectric properties.[5] In addition, the optics of the col-

*Very clean, low ionic conductivity polymeric materials can exhibit large electrostatic effects. However, the normal aerosol and water contain enough contaminants to insure that the surface soon becomes sufficiently conducting to reduce the electrostatic force to normal levels.

lection system are important. This is best described in terms of the acceptance aperture of the collector. The higher the optical concentration, the smaller the acceptance aperture. Flat plate collectors essentially have a 180^o aperture, while central receiver systems have apertures of 1^o or less. The optics of the collector are also affected by the number of times the sunlight intercepts the reflector surface as well as the reflecting angle with respect to the surface normal. For moderately large angles on mirrors with thick glass, the dust layer interferes with a light ray twice. For front surface or low reflection angle devices, only one scattering event occurs.

The detailed interaction of light with dirt particles is characterized by the particles' wavelength dependent optical absorption and scattering properties. These properties are described by an extinction efficiency which is related to the various cross sections by

$$Q_{ext} = Q_s + Q_a = \frac{\sigma_s}{\sigma_g} + \frac{\sigma_a}{\sigma_g} \quad .$$

σ_s is the scattering cross section, σ_a is the absorption cross section, and σ_g is the projected geometric area of the particle relative to the incident beam direction. Figure 2 shows the extinction coefficient for a typical range of particle characteristics. This curve is valid for $1 \lesssim |m| \lesssim 2$, where m is the complex refractive index. For larger m, the curve begins shifting to the left. In the solar spectral region, very small particles ($d \lesssim 0.1$ μm) have such low extinction coefficients that even when weighted by extremely large-number densities, they do not result in any significant optical loss. For large particles ($d \gtrsim 1$ μm) the extinction coefficient goes to 2. This is due to the fact that the particle intercepts an area in the light beam equal to its projection which causes absorption and large angle scattering by reflection and refraction. In addition, an equal amount of light from outside its projected area is affected by diffraction. The phenomenon of the large particle optical scattering cross section being twice its projected geometric area is called the extinction paradox. For particles larger than 10 μm, the diffracted light is thrown into a narrow forward lobe about 1-10° wide,[6] which is larger than the acceptance angle of concentrating collectors. In the intermediate region (0.1 μm $\lesssim d \lesssim 1$ μm), the scattering has complicated angular distribution and cross sections that can become greater than two times the geometric cross section.

In practical terms, this means that flat plate devices will lose only the amount of light intercepted by the geometric cross section of dust on its surface because of the large acceptance aperture, while (narrow acceptance angle) concentrating devices with large reflection angles can lose over four times the light intercepted by the geometric cross section.

IV. Cleaning

In looking at the mechanics of dust deposition and the time development of the adhesion, it becomes apparent that only certain cleaning strategies will be effective. The strategies can be arranged according to the time scale over which they act. They are:

1. Keep dirt from settling and adhering to the surfaces.
2. Wash off the dirt with low surface energy detergent-type solutions before strong chemical or mechanical bonding can develop.
3. Use chemically or mechanically active cleaning techniques capable of breaking the chemical and mechanical bonds.
4. Modify the surface so that strong bonding cannot develop.

Strategies 2 and 3 are primarily maintenance oriented, while strategies 1 and 4 are materials and design oriented. The problem of reducing dirt accumulation is not strictly a maintenance one, and we feel that the best solution may require some materials and design modifications.

Strategy 1 involves primarily noncontact, continuous techniques which require additional materials and design features. However, they do not generally require labor. Table III lists several techniques which should affect dirt accumulation and are being investigated at Sandia.

Strategy 2 involves frequent washing with detergent-type (low surface energy) water solutions. Used by itself, ordinary washing has the disadvantage that to be most effective, it must be done after only a few humidity cycles (perhaps every 1 to 3 days), since strong particulate bonding can develop very rapidly. Such washing is usually thought to be very labor-intensive. In addition, there are environmental questions concerning the water requirements both for the quality of wash water and quality of dumped waste water.

Strategy 3 involves a number of chemical and mechanical techniques for supplementing the washing. Many of the chemical techniques suffer from both environmental and health problems. Sandia is investigating several automated, high pressure techniques that can conserve water and which mechanically attack particles bonded to the surface by using high pressure spray. This strategy may also involve controlled exposure to frost and snow, which can mechanically wipe a surface.

Strategy 4 involves either surface modifications or the use of a substitute surface. Substitute surfaces may be either permanent coatings to make the surface inert or temporary coatings, such as surfactants, that can be periodically restored as part of a wash cycle. Sandia is also studying some coating possibilities.

The effectiveness of any combination of cleaning techniques is problematic. It is commonly believed that dust buildup levels off after some time and remains at about a constant level thereafter. It is also believed that any cleaning technique results in oscillations about a "steady state" cleanliness level that is presumably better than the steady state uncleaned level. While this behavior is consistent with many of the properties of particulate-surface interactions, it is a hypothesis that remains unproven, particularly for 20-30 year lifetimes desired of solar energy devices. It is possible that after normal outdoor exposures, slow changes are induced in glasses which result in a long term increase in the dirt accumulation. For this reason an additional set of experiments is being performed at Sandia on the long term effects of dirt accumulation and cleaning. This includes measurements of the optical losses from dirt and measurements of the particulate levels in the aerosol.

V. Experimental Investigations

A. Reducing Dust Deposition

The techniques described in Table III are of interest only in regard to their ability to reduce the accumulation of particulates. In order to test these techniques in a controlled laboratory environment, a dust exposure system has been assembled for exposing surfaces to calibrated amounts of a relatively well-defined Arizona Desert Dust. The system consists of a low velocity (0-25 m/s) atmospheric pressure wind tunnel[7] fitted with a dust injector/disburser unit. It is capable of producing particle number densities 10^4 times greater than the number of particles (larger than about 1 μm diameter) present in the normal aerosol. Outdoor dust accumulation levels from 5-6 weeks' exposure in Albuquerque have been simulated in about 10 minutes in the wind tunnel.

The dust/airstream is presently monitored by total particle counts and a recorder for particle rates. Instrumentation is presently being developed for the particle size histogram both in the airstream and on sample surfaces. This will permit a better understanding of the deposition mechanics and optical losses. Samples are presently analyzed visually and by optical transmission and reflection measurements.

Preliminary tests have been performed on an electrostatic repulsion technique. In this experiment the front surface of a microscope slide was coated with a conducting SnO_2 film and biased up to 1000V negative with respect to ground. A ground reference wire was also placed above the surface for experimental purposes. Dirt particles that contact the surface are charged and repelled with enough force that the airstream can carry them away. The resulting dust accumulation was significantly less than on a control glass slide exposed at the same time. A photographic comparison of the treated and untreated samples is shown in Figure 3a. A more detailed characterization of this technique and small scale field tests are being planned.

Some preliminary testing also has been performed on the use of spoilers which modify the airstream boundary layer by making it turbulent. Wind tunnel tests have indicated that less dust is deposited on regions behind the spoilers. The effect of a spoiler is shown in Figure 3b. Much more extensive work in this area is needed. The other techniques listed in Table III are under study and will be instrumented and tested in wind tunnel experiments.

Some of the dust monitoring instrumentation is being examined for possible use in monitoring field conditions.

In order to design solar devices for lowest dust accumulation, it is important to know more about the dust stream properties such as relative amounts, particle sizes, time dependence, etc.

B. Cleaning Solution Investigations

The usefulness of cleaning detergents is being investigated on reflector materials in parabolic troughs. The initial work was on a second surface FEP teflon mirror, which ordinarily should be much easier to clean than most materials because of its low surface energy. Samples left facing up, which accumulated dirt like a gutter, were completely uncleanable without mechanical wiping, which damaged the surface.[8] Figure 4 shows the effect of cleaning the FEP, as measured on a bidirectional reflectometer. Weathered (as received) materials were obtained from the Sandia Solar Thermal Test Facility (STTF) and were subjected to one of the following four cleaning procedures: (1) high pressure water, (2) Jet-X with detergent, (3) a mist spray of a commercial cleaner (C-120) from the McGean Chemical Co., and (4) hot soapy water with a cloth wipe. All were followed with a deionized water rinse. The clean surface had the same hemispherical reflectance as before exposure, implying that the loss was due to scattering from both residual dirt particles and scratches in the FEP. The effect of mechanical damage can be seen dramatically by comparing the cleaning of FEP, Figure 4, with a similar cleaning on a glass mirror, Figure 5. Vertical displacements of the curves are due to the very broad light scattering by dust particles.

Rinsing with tap water was unacceptable because it left water spots. For this reason a deionizing cartridge was procured. A series of mirrors was rinsed every 3 to 4 days with a deionized water rinse, which removed most of the accumulated dirt. However, there was a steady buildup of residual dirt that had to be removed with a detergent solution every 2 weeks. Criteria for the types of detergents required have been developed. They must be (1) effective in reducing the surface tension, (2) low cost in the mixing ratios used, (3) capable of being handled and mixed in automated equipment, and (4) biodegradable and able to meet EPA standards. In addition, the cleaning agent may have some chemical activity (such as nonneutral pH) which must not result in any long term degradation of the mirror surface.

C. High Pressure Spray Washing

In order to begin establishing a base for cleaning with semiautomated techniques, several tests were performed at the STTF using a high pressure spray of 3 GPM water at 300 psi with several different detergents and solvents. These tests indicated that it was possible to recover 80-90% of the reflectance loss from short term environmental influences. Another test was performed at the Triton Corporation of Houston, TX, consisting of high pressure sprays of 500, 1500, and 10,000 psi tap water streams on dirty mirror samples. Reflectivity tests were performed on samples sprayed at each of the three pressures. All recovered about 95% of the original 0.83 average solar reflectance. Triton has been contracted to supply the STTF with a mirror washing vehicle outfitted with high pressure spray and mixing equipment.

D. Dirt Characterization

Work has also been done on development of statistical methods for evaluating the variations of the reflectivity losses over the solar spectrum and for different positions on the mirror. The technique was developed by R. B. Pettit[9] using the bidirectional reflectometer. This technique allows investigation of both wavelength dependence and specularity of the surface. Dust results in optical loss in the form of scattered light, which shows up in the diffuse component of the reflected beam.[10] The diffuse reflectance as a function of wavelength for four different loss levels is shown in Figure 6 for silvered glass mirrors exposed in Albuquerque. Losses ranged from 6.6% to 24.1% at 500 nm (0.5 μm). Each curve can be normalized by the diffuse reflectance at 500 nm wavelength to yield a "universal" curve. This means that a measurement of the reflectance loss at 500 nm can be used to characterize the loss for the entire solar spectrum for the mirror. The solar-averaged loss has been calculated to be 0.78 ± 0.04 times the loss at 500 nm. Work is also progressing to determine the statistical number of measurements necessary to characterize an entire mirror surface based on measured reflectivity variances and source beam diameters.

The time dependence of the dust deposition and mirror orientation effects are also being studied in roof-top experiments. Samples mounted at 0° (horizontal), 30°, 45°, and 60° accumulated losses that were the same to within experimental errors. An inverted sample and a sample that was brought inside at night and during nonsunny weather periods showed lower accumulation rates. Long periods without rain in Albuquerque afford the opportunity to study short term steady state dirt levels. Figure 7 shows the effect of dirt accumulation on a mirror sample over a several week period. The large improvement after several weeks is due to a rain and snow storm that cleaned the surface.

VI. Conclusions

The behavior of dirt and several cleaning strategies has been studied. It was found that:

1. Dirt deposits onto mirrors due to the fluid mechanical interactions of the dirt-laden airstream with heliostat structures and adheres due to the forces from surface energetics.
2. Intense chemical and physical bonds develop due to the interaction of condensed water vapor with the dirt and mirror surfaces.
3. The optical loss is caused by absorption and scattering of light by dirt. The loss can be characterized by a small number of measurements due to the scattering behavior of the dirt. Total solar loss for a second surface glass

mirror exposed in Albuquerque is 0.78 ± 0.04 times the spectral loss at 500 nm.

4. Continuous dust repulsion techniques can be used to reduce the rate at which dust accumulates. Electrostatic repulsion and boundary layer modification techniques have been successfully tested in laboratory wind tunnel experiments.
5. Water and detergent solution rinsing can be effective when used at relatively frequent intervals.
6. High pressure sprays above 500 psi can recover up to 95% of the reflectance loss from dirt accumulation.

Much more work is needed in all areas of dirt characterization and cleaning technology to establish limits on the requirements for and capabilities of cleaning.

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Table I. Mechanisms of Impingement for Wind-Carried Particles

Mechanism	Affected Particles (Size, Stokes Velocity)	Affecting Property
Convective diffusion	$d \lesssim 0.1\ \mu m$	Boundary layer
Impact	$d \gtrsim 1\ \mu m$, $v_s <$ air velocity	Air turbulence
Sedimentation	$d \gtrsim 1\ \mu m$, $v_s >$ air velocity	Air turbulence, dead spaces

Table II. Dust Adhesion Mechanisms for 10-20 μm Particles on a Surface

Mechanism	Relative Force Size	Affecting Material Property	Applications
Gravity	1 g	Mass	
Electrostatic	$\gtrsim 1$ g	Surface (coating) conductivity	Conducting polymers, precipitations
Charge double layer	≈ 100 g	Contact potential or difference in electron affinities	
Surface energy	≈ 100 g	Solid surface relaxation	Surfactants, teflon coating
Capillary force	$\gtrsim 10{,}000$ g	Fluid surface relaxation	Detergents
Chemical/physical	?	Chemical activity	

Table III. Techniques Which Can Affect Dust Accumulation

Action	Comment
Inverting while inactive	Relative importance of sedimentation in particle settling
Aerodynamic streamlining	Prevention of turbulent eddies and dead spots
Electrostatic biasing	Several hundred volts with normal electric field rejects particles
Vibrating the surface	
Thermally induced air currents	Boundary type of phenomenon used on astronomical telescopes
Flowing air	Boundary type of phenomenon used on astronomical telescopes

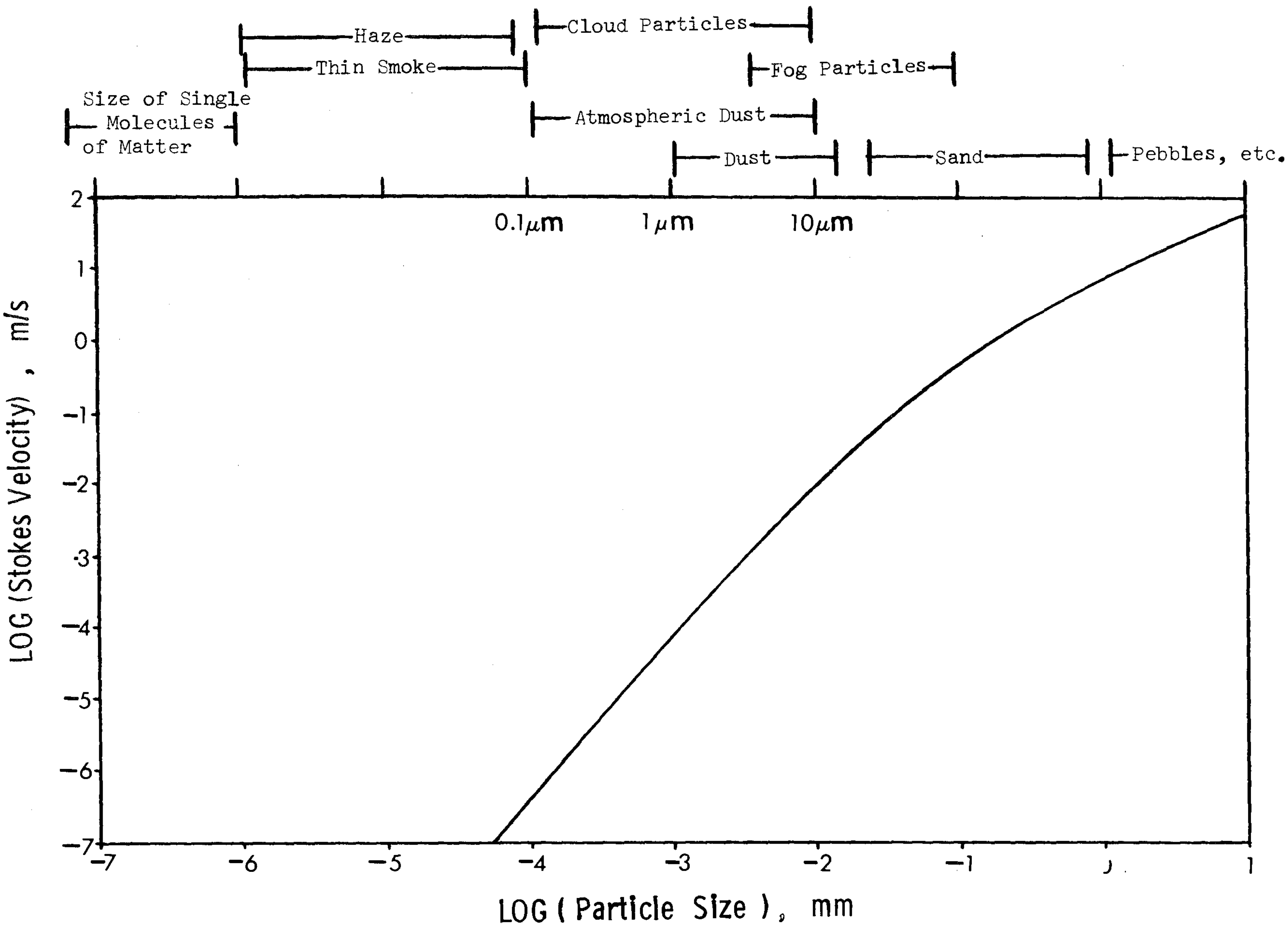

Figure 1. Particle sizes and the corresponding Stokes velocities for particles found in the atmospheric aerosol.

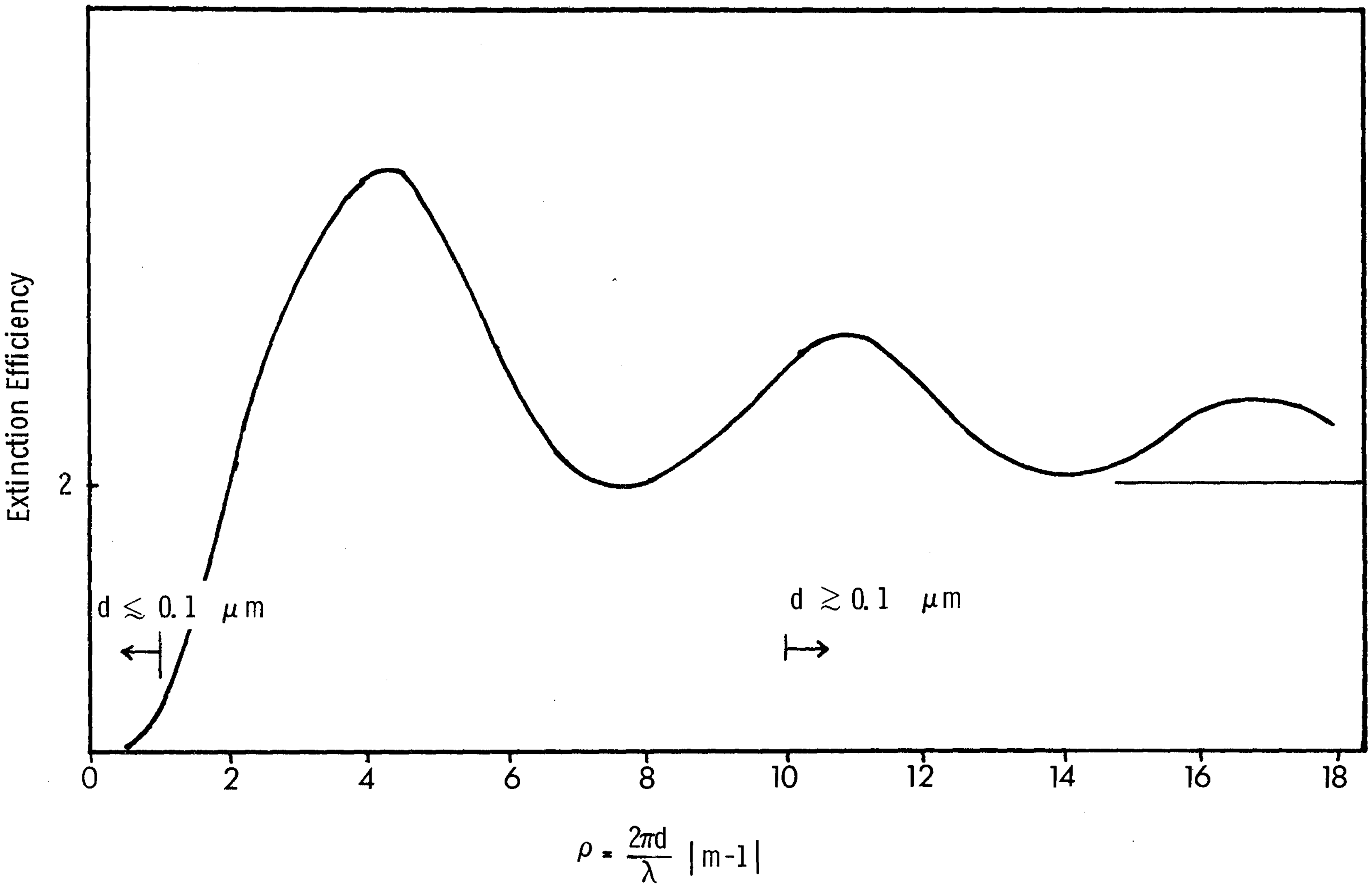

Figure 2. Extinction coefficients for various sizes and types of particles.

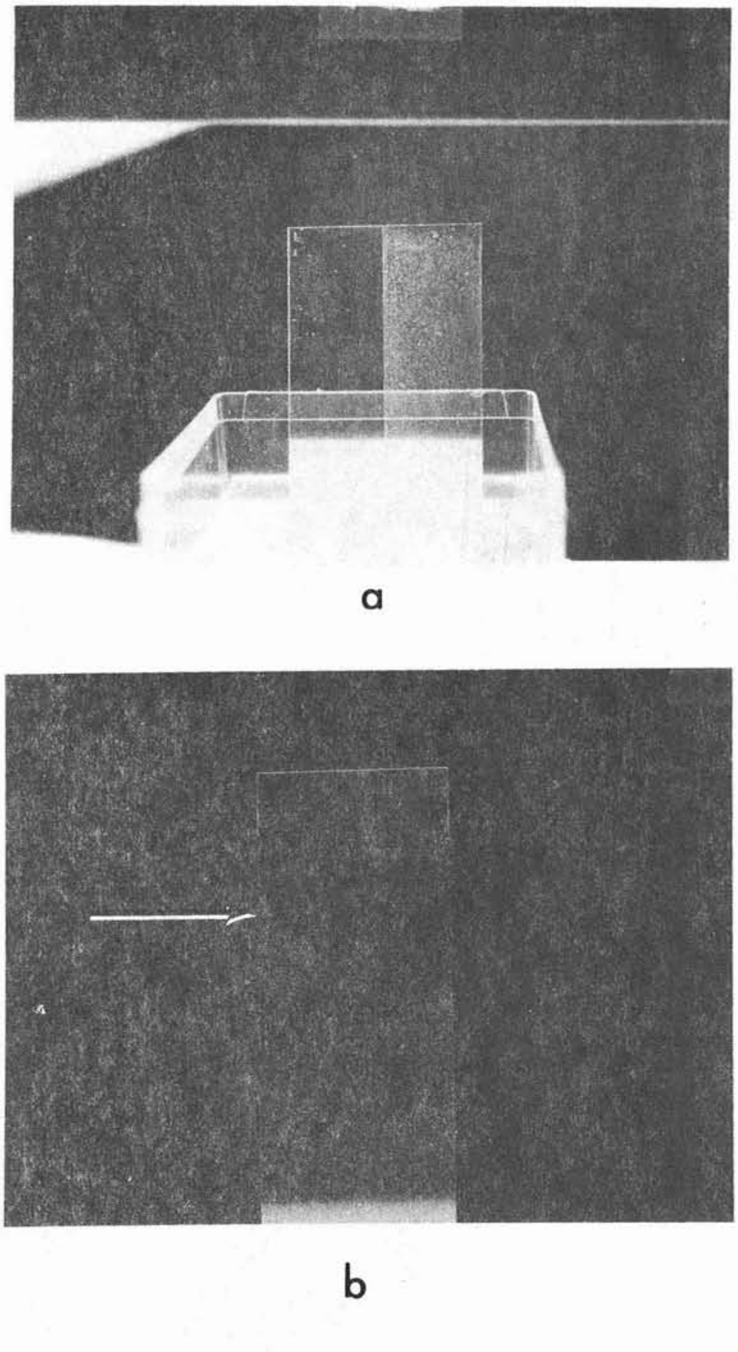

Figure 3. Wind tunnel experiments showing (a) electrostatic repulsion of dust from a SnO_2 coated microscope slide; the slide on the right is an uncoated control sample; and (b) a spoiler-type boundary layer modification with the spoiler at the arrow.

Figure 4. Dirt Accumulation and Cleaning of Aluminized FEP Teflon.

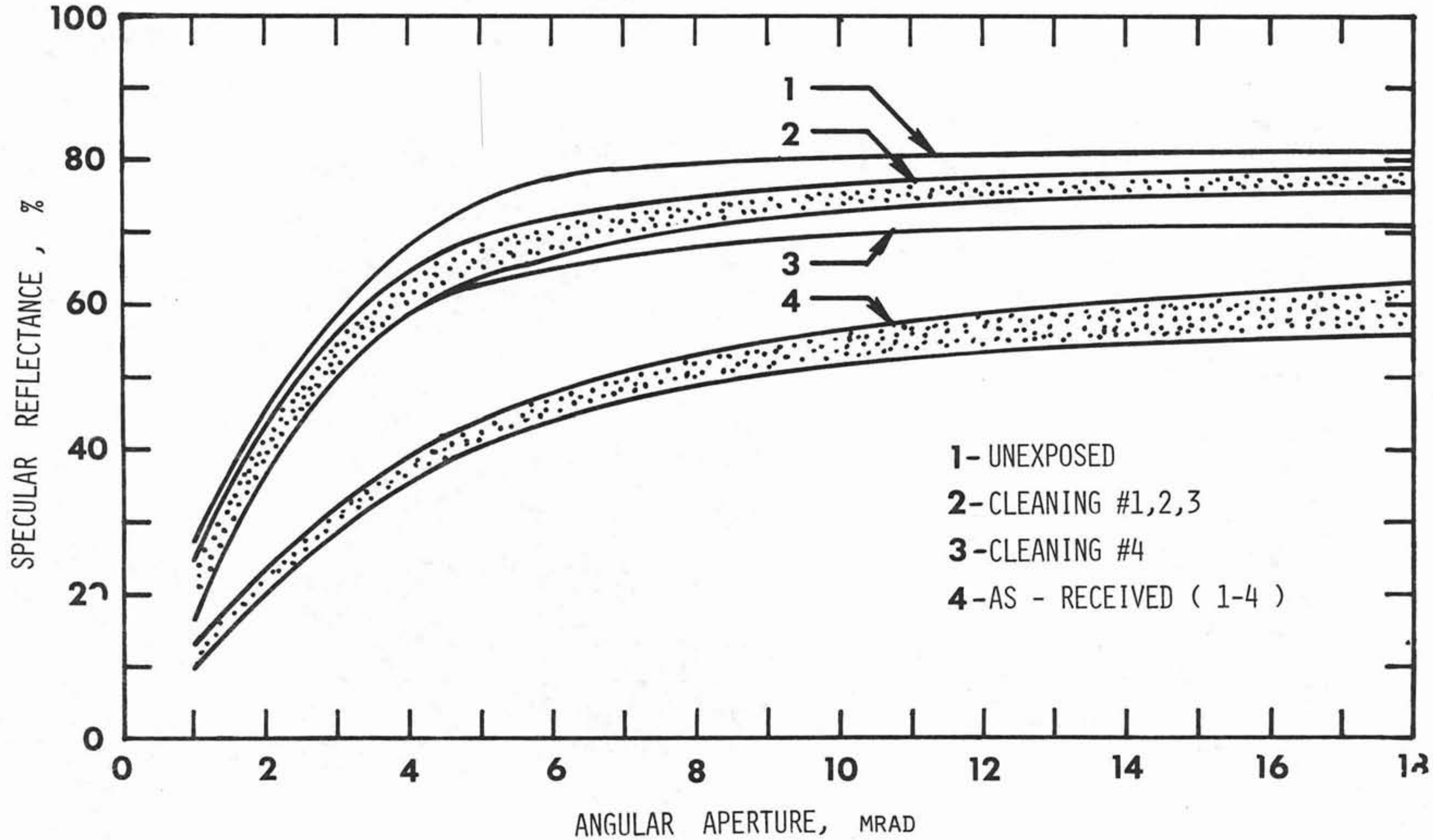

Figure 4. Dirt accumulation and cleaning of aluminized FEP Teflon.

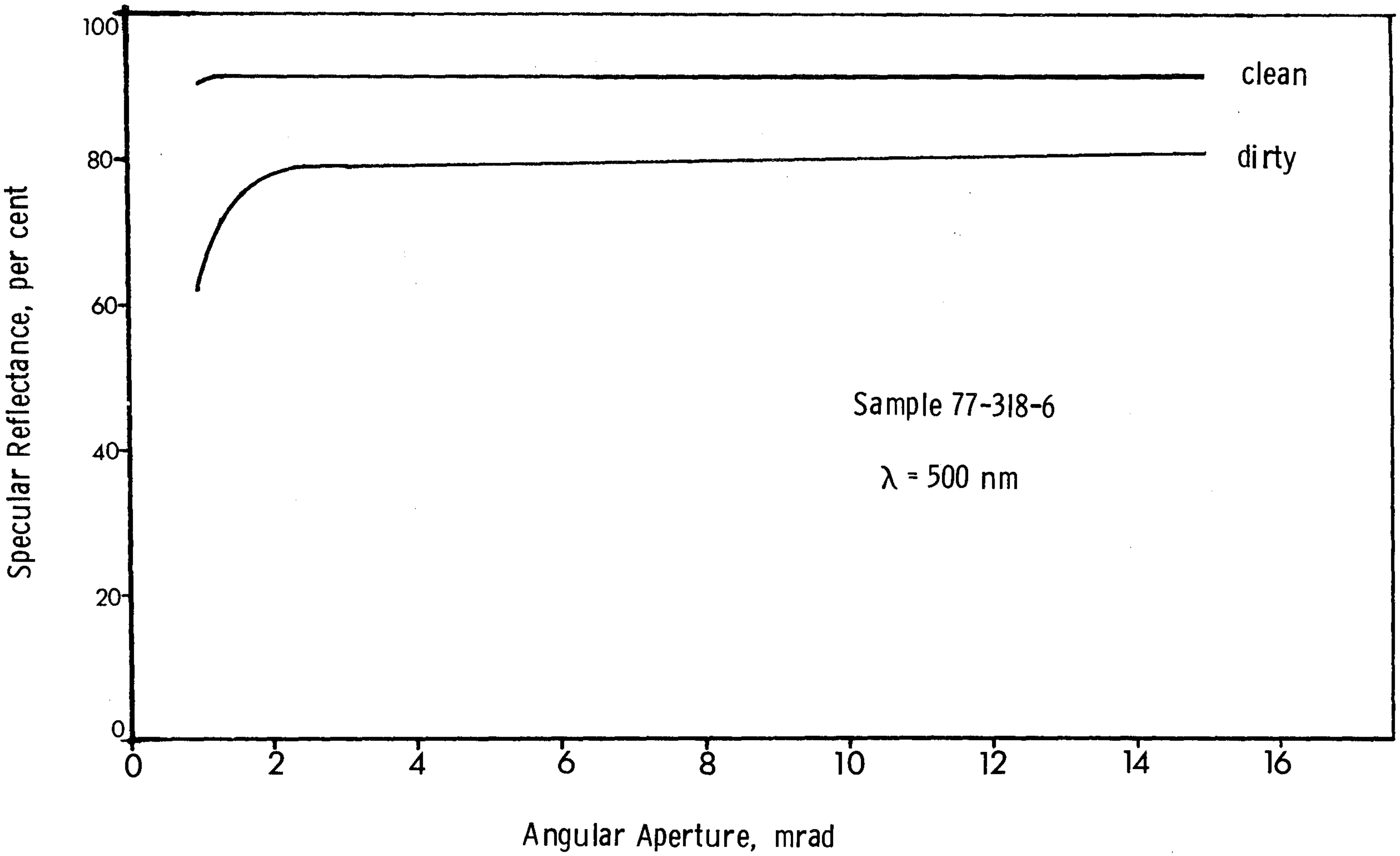

Figure 5. Dirt accumulation on silivered glass.

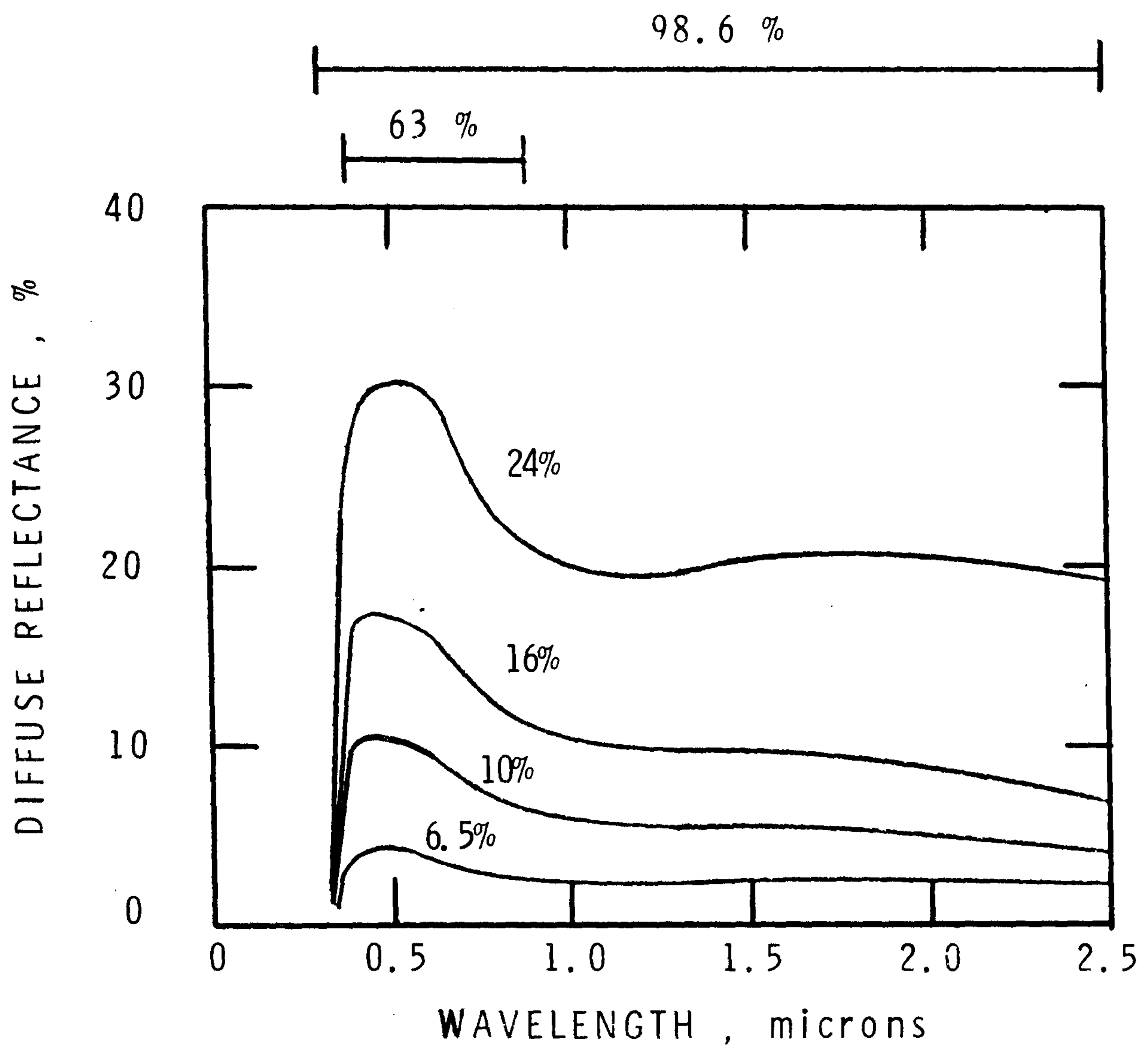

Figure 6. Diffuse reflectance of various amounts of dirt accumulated on silvered glass mirrors.

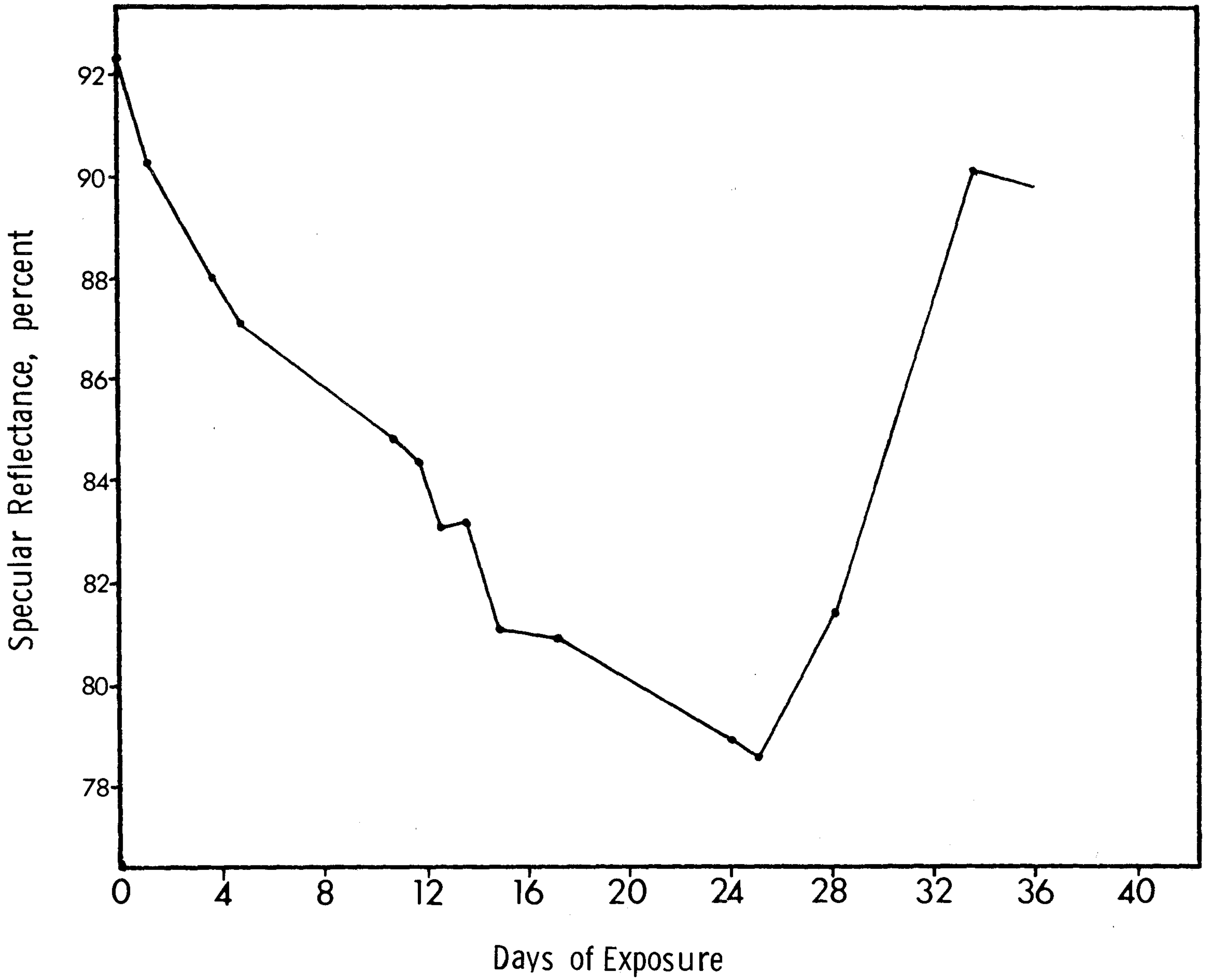

Figure 7. Specular reflectance loss and natural cleaning of a silvered glass mirror over an 8 week period in Winter 1977-78.

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