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Final Report Solar Collector Materials Exposure to the IPH Site Environment

Volume 1

V. L. Morris
Huntington Beach, CA 92647

Prepared by Sandia National Laboratories Albuquerque, New Mexico 87185 and Livermore, California 94550 for the United States Department of Energy under Contract DE-AC04-76DP00789

Printed January 1982

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FINAL REPORT
SOLAR-COLLECTOR-MATERIALS EXPOSURE TO THE IPH SITE ENVIRONMENT

VOLUME 1

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Huntington Beach, California 92467

ABSTRACT

In-situ environmental exposure tests were conducted at nine proposed intermediate-temperature Industrial Process Heat (IPH) sites. Three types of reflector materials were evaluated for survivability at the nine sites: second-surface silvered glass, aluminized acrylic FEK-244 film on aluminum substrate, and Alzak (electropolished aluminum) on aluminum substrate. Black chrome absorber material and low-iron float glass were evaluated for thermal, photochemical, and environmental degradation. The reflector specimens were monitored for decreases in specular and hemispherical reflectance due to soil buildup. The absorber material was evaluated for changes in solar absorptivity and emissivity, and the float glass was monitored for changes in transmissivity. Surface and subsurface defects on all materials were examined microscopically and, where deemed of note, were documented photographically.

Prepared for Sandia National Laboratories under Contract 13-0261.

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ACKNOWLEDGEMENT

This work has been supported by the United States Department of Energy. I appreciate the solar project contractors and site owners for the voluntary cooperation and assistance afforded this effort. Acknowledgments are also due to C. J. Kojima and other McDonnell Douglas Astronautics Company laboratory personnel, who performed over 30,000 measurements on the solar optical material specimens, and to the following Sandia National Laboratory personnel for their assistance and valuable discussions: K. D. Bergeron, D. E. Randall (Project Monitors), R. B. Pettit, L. M. Larsen, E. P. Roth and N. H. Clark.

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PREFACE

This final contract report is being issued in two volumes - Volume I, which is a condensation of all results and conclusions, and Volume II, which contains all data, results, and conclusions. This was deemed necessary because of the large amount of data in Volume II, which is of more interest to persons conducting research in related areas than to the casual reader. The effort described herein was performed by the McDonnell Douglas Astronautics Company for The Sandia National Laboratories, Albuquerque, New Mexico, in accordance with Contract 13-0261.

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SOLAR COLLECTOR MATERIALS EXPOSURE TO
THE IPH SITE ENVIRONMENT

Introduction

In 1976, the Office of Conservation and Solar Applications of The Department of Energy (DOE) undertook the design (Phase I), construction (Phase II), and operation (Phase III) of a series of field experiments to investigate the application of solar thermal energy systems to the industrial process heat (IPH) market. Experience gained from the operational phase of the initial series of field experiments in the hot-water and the drying-dehydration cycles of the IPH program indicated that the environment of the industrial site might interfere with the proper optical functioning of solar collectors. Certain effluents, contaminants, and pollutants characteristic of the industrial environment could seriously degrade the optical properties of solar collector reflector and receiver materials.

During 1979, DOE instituted a test program to provide early indication of serious environmental degradation of the optical properties of reflector and receiver materials at industrial sites selected for future solar IPH experimental projects. Sandia National Laboratories is managing the program, and the McDonnell Douglas Astronautics Company is doing the actual testing. This final report has been prepared to disseminate test results and to describe problem areas encountered at the field experiment sites.

Technical Approach

At the inception of this materials exposure test program, conceptual design studies (Phase I) for seven candidate solar project sites had recently been initiated under the IPH field experiment program. The original design concept for all these project sites was to use concentrating line-focus solar collectors to supply steam at intermediate temperatures (300° to 550°F) to the industrial process at the site. Subsequent cancellation of contracts for construction and installation (Phase II) of two of these seven sites had no effect on the operational philosophy adopted for conducting the materials test program: the number of sites to be monitored during the initial phase was simply reduced to five. Four additional sites were subsequently added to the program. All these sites were candidates for the next cycle of DOE IPH field tests.

The influence that the environment at the industrial site had on collector performance was evaluated by monitoring the change in optical characteristics of typical reflector and receiver material specimens exposed on site. During the exposure period, the specimens were not cleaned, either artificially or intentionally, the only cleaning being that which occurred as a result of natural cleaning forces, e.g., precipitation.

Test Specimen Materials

Initially, three reflector materials were selected for exposure testing. Two of these, electropolished sheet aluminum such as Alzak and the thin aluminized acrylic films such as FEK-244, were chosen as being representative of the near-term trend in reflector materials for concentrating line-focus collectors. The Alzak and FEK-244 reflectors were both bonded to 0.125-in.-thick aluminum substrates to enhance the dimensional stability of the specimen surface. The third group consisted of glass reflectors, on which three different types of rear-surface protective coatings were applied. These were (1) an Imron polyurethane enamel, (2) an adhesive-backed vinyl coating, and (3) a two-layer epoxy system, which used an initial primer coat and a top coat of paint. All reflector specimens were 6x6-in. flat plates.

Receiver test specimens consisted of a 2.5x5.5-in. flat absorber specimen plated with a black chrome coating and a 6x6-in. clear, low-iron, float-glass cover plate representing a receiver envelope.

Appendix A gives a more detailed description of specimen fabrication.

Test Specimen Orientation

Although all the initial series of solar projects used single-axis tracking collectors, it was felt that movable or rotating test specimens represented an unnecessary complication, and that adequate simulation could be achieved by using stationary specimens. Reflector specimens were exposed in three orientations: (1) 45° tilt from the zenith toward the southern horizon, (2) horizontal, faceup, and (3) horizontal, facedown.

Receiver specimens were mounted in an enclosed box structure that contained heating elements encased in an aluminum bar. The absorber specimens were clipped to the bar. The glass covers were mounted in the box lid over the absorbers. This heater box was attached to the exposure test rack so that the full complement of receiver specimens at each site (four absorbers and four glass covers) was oriented in the 45° tilt from the zenith toward the southern horizon.

Exposure and Retrieval Procedures

It was considered desirable, for an initial test program, to provide a 12-month data accumulation phase, with test specimen retrieval spaced over this interval to evaluate seasonal influence as well as the progression of environmental effects. A full complement of 108 mirrors provided monthly retrieval of reflector specimens of each material and from each orientation.

All 108 reflector specimens were mounted on the test rack at the begining of the test. Following 1 month of exposure, a sample of each of the three material types was removed from the three exposure orientations. Each retrieval included nine specimens, which were returned to the contractor for evaluation. Following evaluation, the samples were archived. The second set of samples was removed after 2 months of uninterrupted exposure and was returned to the contractor for evaluation and archiving. This procedure was followed for 1 year, with the 12th retrieval consisting of nine specimens that had been exposed for 12 continuous months.

Figure 1 illustrates the test rack. This design facilitated packaging and shipment to sites disassembled, and provided ease of assembly and erection

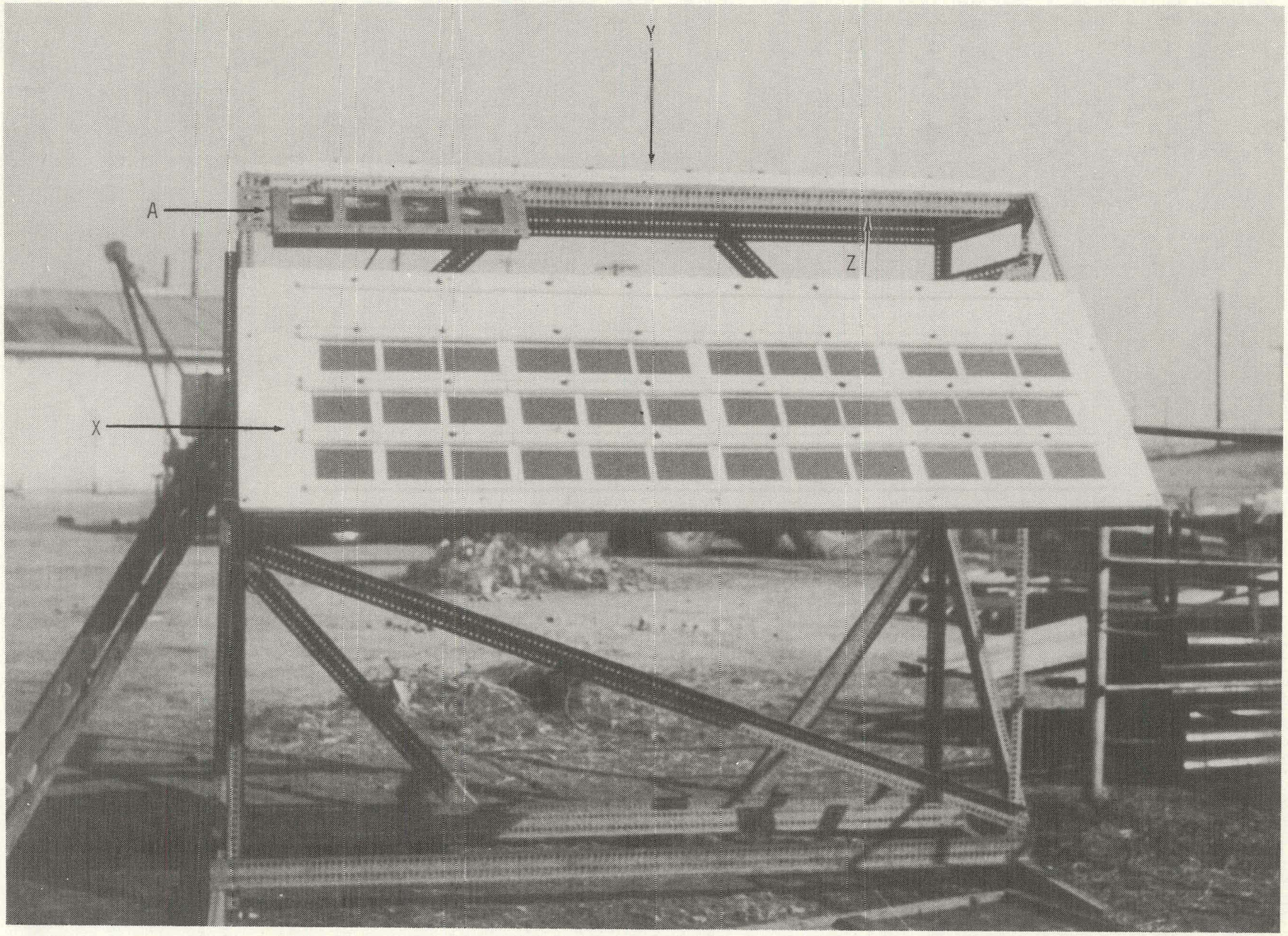


Figure 1. Exposure Rack. Used in environmental degradation study of mirror surfaces. A – Receiver specimen test unit. Reflector exposure planes: X – 45° upward lift; Y – horizontal, faceup; Z – horizontal, facedown.

on site. The project relied upon the voluntary cooperation of the solar project contractor or the site owner or both for the retrieval on schedule and the return of test specimens to the contractor by mail.

As previously described, four black chrome absorber specimens and four glass cover plates were exposed at each site. The absorber specimens were each mounted on a timer-controlled heating element contained within a box structure that attached to the test rack in the 45° tilt orientation. The glass cover plates were mounted in the box lid. The box structure did not form a dust-tight seal, thus it was representative of contemporary nonevacuated-type receivers. Figure 2 illustrates the heater box with specimen complement. A clock-driven timer provided a 12-hour, diurnal, thermostat-controlled heating cycle to 450±50°F for the absorber specimens. Maximum current capability of the heater circuit automatically limited the maximum temperature of the absorber specimens to approximately 520°F. Retrieval of the receiver specimens was scheduled to occur at the end of the 2nd, 6th, 9th, and 11th months following original exposure.

Test Sites

The initial series of exposure test sites was determined by the Phase II awards of the Intermediate-Temperature Steam IPH Solar RFP. These five sites were:

1. Dow Chemical Company
   Dalton, Georgia

2. Lone Star Brewing Company
   San Antonio, Texas

3. Southern Union Refining Company
   Lovington, New Mexico

4. Stauffer Chemical Company
   Henderson, Nevada

5. Ore-Ida Foods, Inc.
   Ontario, Oregon

A second series of experiment sites was used approximately 6 months later. These sites represented the four Phase I projects selected in response

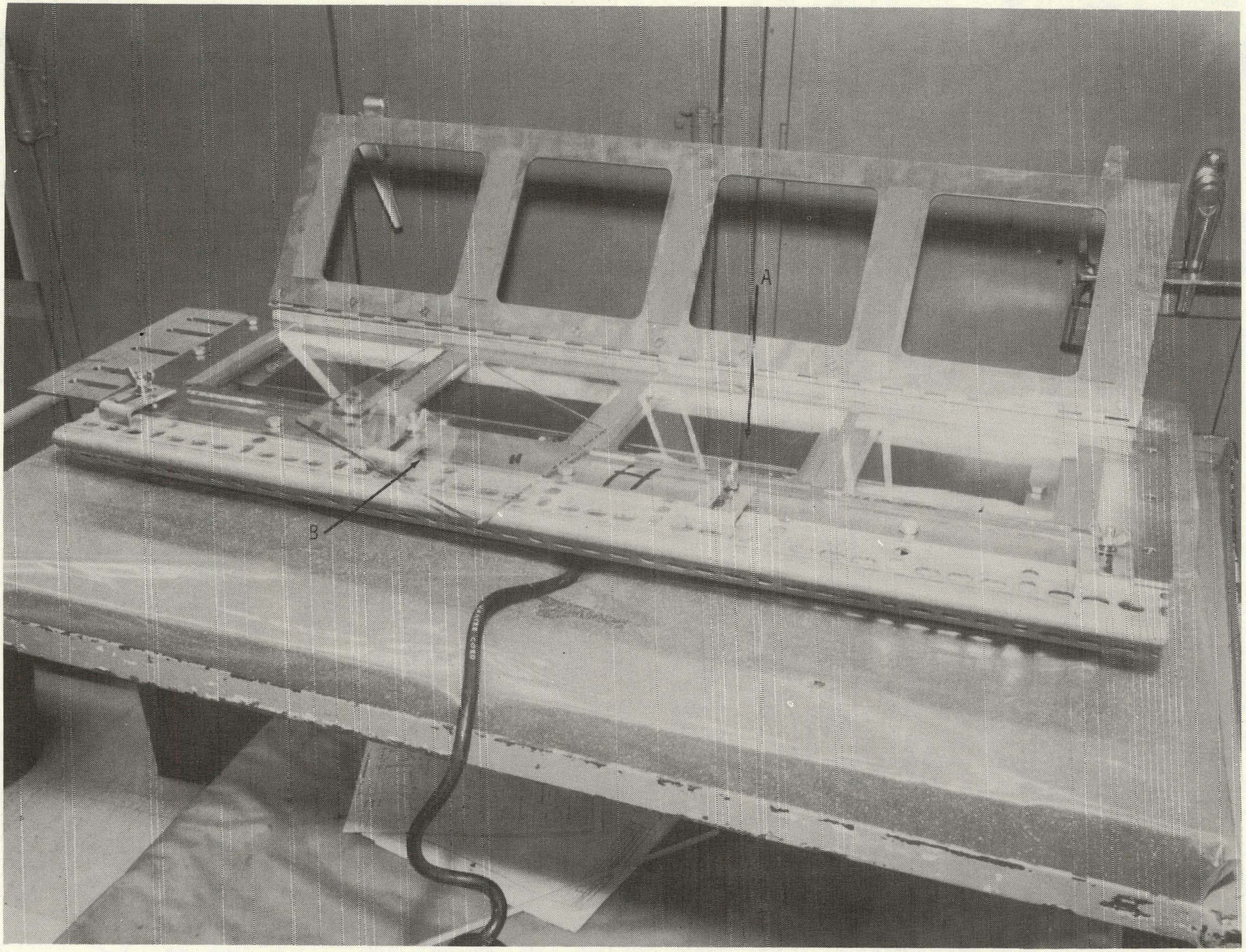


Figure 2. Receiver Specimen Heater. Unit showing placement of receiver specimen (A) and glass panels (B)

to the Intermediate-Temperature, 50 000-ft^2, cost-shared solar thermal system Program Opportunity Notice (PON). These four sites were:

1. Bates Container Company
   Ft. Worth, Texas
2. Caterpillar Tractor Company
   San Leandro, California
3. Hilo Coast Processing Company
   Pepeekeo, Hawaii
4. U. S. Steel Chemical Company
   Haverhill, Ohio

Test Protocol

Environmental degradation effects for the reflector, receiver, and glass cover plate materials were monitored by (1) evaluating changes in specified optical properties, and (2) photomicrographically examining surface and subsurface defects of the candidate materials after exposure to specific environments. Figure 3 shows the test protocol for these cleaning materials, and the specific cleaning and evaluation procedures are described in the following paragraphs.

Specimen Cleaning Procedures

The specimen cleaning procedures specified in the materials test program were selected from the results of a study of cleaning solutions and techniques completed by McDonnell Douglas Astronautics Company - Huntington Beach, (MDAC-HB) for Sandia National Laboratories, Alburquerque (SNLA).[1] The study evaluated the effectiveness of cleaning techniques that could be applicable to solar collector fields. Some techniques studied were barrier coatings, high-pressure sprays of water or detergent solutions or both, ultrasonic cleaning, and low-pressure detergent and rinse washes.

The best cleaning method, primarily because of cost, was a high-pressure water-spray wash. The most effective detergent solution found was McGean

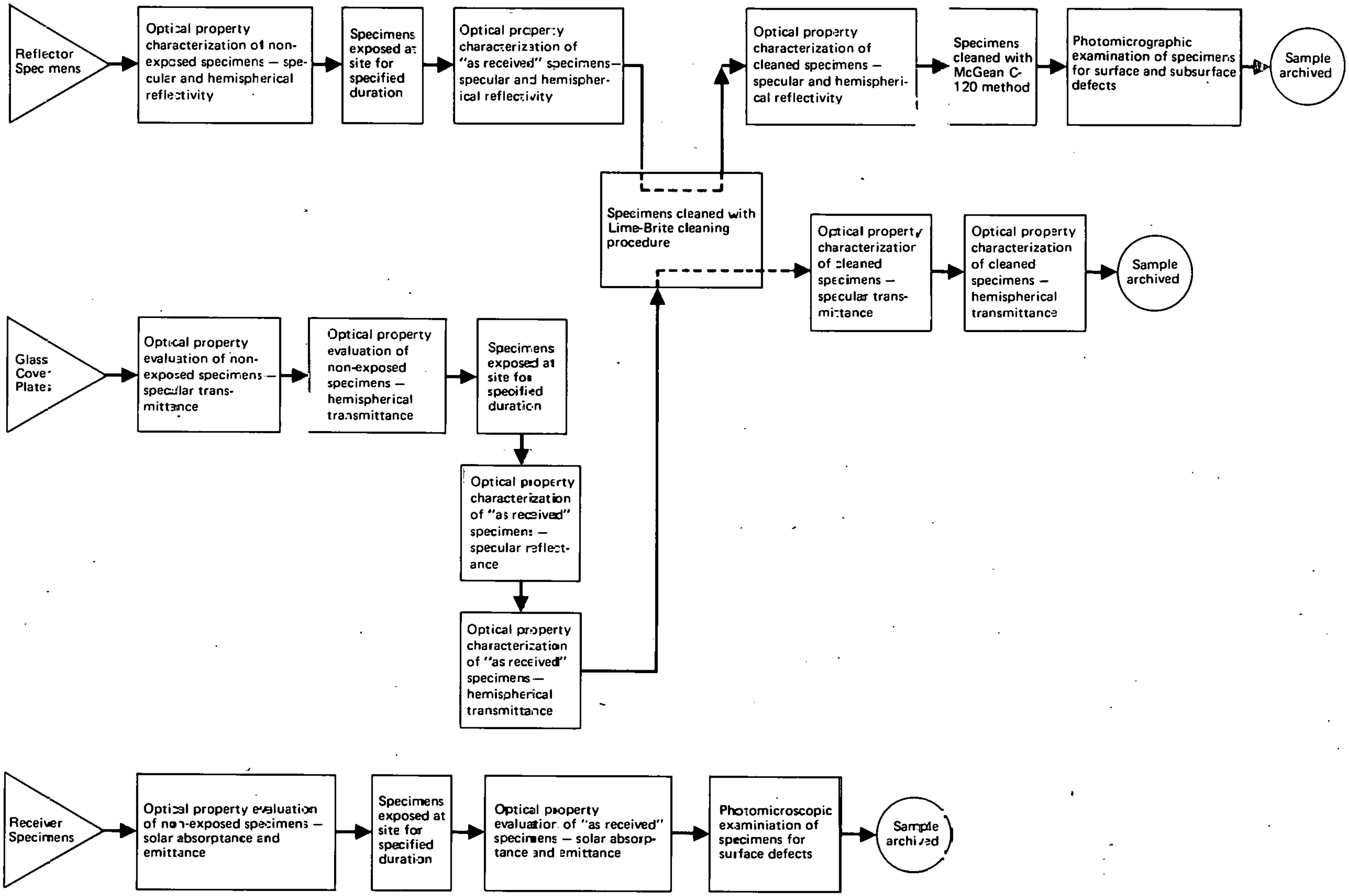


Figure 3. Test protocol used for evaluating candidate solar materials

C-120 detergent; however, this detergent contains low levels of hydrofluoric acid, and could be considered environmentally unacceptable. The next best detergent product studied was Lime-Brite detergent (Vestal Laboratories). While not as effective as the McGean product, it did not contain any potentially hazardous or environmentally unacceptable chemicals.

The high-pressure water spray and the Lime-Brite cleaning methods were found to be approximately equally effective. Consequently, while the high-pressure water spray would be better for field cleaning, the Lime-Brite method was selected for laboratory studies.

Reflector Specimens -- Before being fielded, the newly fabricated specimens were cleaned by spraying spectroscopic-grade methanol onto the specimen surface and gently wiping the surface with non-abrasive, lintless paper. Aqueous cleaning solutions were not used because of the possibility of the water-detergent mixture diffusing into the reflective metal materials and causing premature or non-field-related corrosion. A random selection of reflector specimens was documented photographically for the "before exposure" condition. These specimens were used as controls for subsequent comparison with exposed samples. Photographic evaluations were made at magnifications of 1X, 32X, and 200X.

When the specimens were returned to the laboratory after their prescribed exposure time and were re-evaluated for specular and hemispherical reflectance, they were cleaned by spraying a detergent solution of 6.3% by volume of Lime-Brite detergent in deionized water onto the specimen surface, such that the entire surface was covered with a continuous liquid film. The detergent solution was applied with an aerosol spray bottle at pressures slightly above atmospheric. The solution was left on the specimen for at least 5 minutes. The detergent solution was thoroughly rinsed from the specimen surface with deionized water, and the surface was dried with filtered, compressed air (100 psi).

Following the third and final measurement of the specimens in the cleaned condition for reflectance, both specular and hemispherical, the specimens were cleaned again, using a 6.3% by volume solution of the McGean C-120 detergent in deionized water. The McGean detergent contains 700 ppm hydrofluoric acid at the aforementioned detergent dilution and has been shown to be a very effective glass cleaner;[1] however, questions have been raised as to the acceptability of this cleaner for actual use in the field because of environmental impact considerations and the toxic hazards for personnel using the detergent. Consequently, this detergent was not considered for field use, but was used to remove residual soil from the specimen surface in the laboratory so that the surface and sub-surface defects, e.g., abrasion and corrosion, could be examined using optical microscopic techniques. The procedure for using the McGean C-120 detergent was identical to that described for using the Lime-Brite detergent. (Appendix A contains toxicity data for McGean C-120.)

No dry-form detergents were considered for cleaning in order to avoid any possibility of surface abrasion from insoluble constituents that might be present. Also, for the same reason, only non-contacting cleaning methods were used.

Glass Cover Plates -- The low-iron, float-glass cover plates were cleaned using the same procedures outlined for the reflector materials, with the exception of the final wash with the McGean detergent. The final wash was not used because corrosion and abrasion of the cover plates were not considered to be applicable or significant degradation mechanisms.

Receiver Specimens -- The receiver materials were not cleaned at any time during the course of this program.

Optical Property Evaluation

Reflector Specimens -- Changes in the optical properties of the reflector materials, following field exposure, were monitored by evaluating the specular and hemispherical reflectance. The measurements were made (1) before the specimens were shipped to the site, (2) in the as-received or soiled-specimen condition, and (3) following cleaning of the specimen using the Lime-Brite method.

The specular reflectance values of each test specimen were characterized by the average of five readings over the surface. Hemispherical reflectance was measured at one location in the center of each test specimen. Special mirror specimen holders were fabricated that permitted readings at the same locations to be repeated following retrieval from the field. A Sheldahl portable bidirectional reflectance distribution photometer (PBFDF) was used to measure specular reflectance, and a Gier Dunkle MS-251 solar reflectometer (filter = 0) was used to measure hemispherical reflectance. All hemispherical reflectance values reported are solar averaged, and the specular reflectance values are measured using a broadband tungsten light source with a measurement spectrum of 440 to 600 nm and a maximum of 520 nm.

The results of the specular and hemispherical reflectance measurements of the exposed samples, in both the soiled and cleaned conditions, were plotted as the fraction of the original reflectance versus the duration of environmental exposure in months. The fraction was calculated from the average of the surface readings on the specimen before and after the prescribed exposure interval.

Figure 4 shows an example of a plot of the fraction of the original specular reflectance versus the exposure duration in months. Each data point

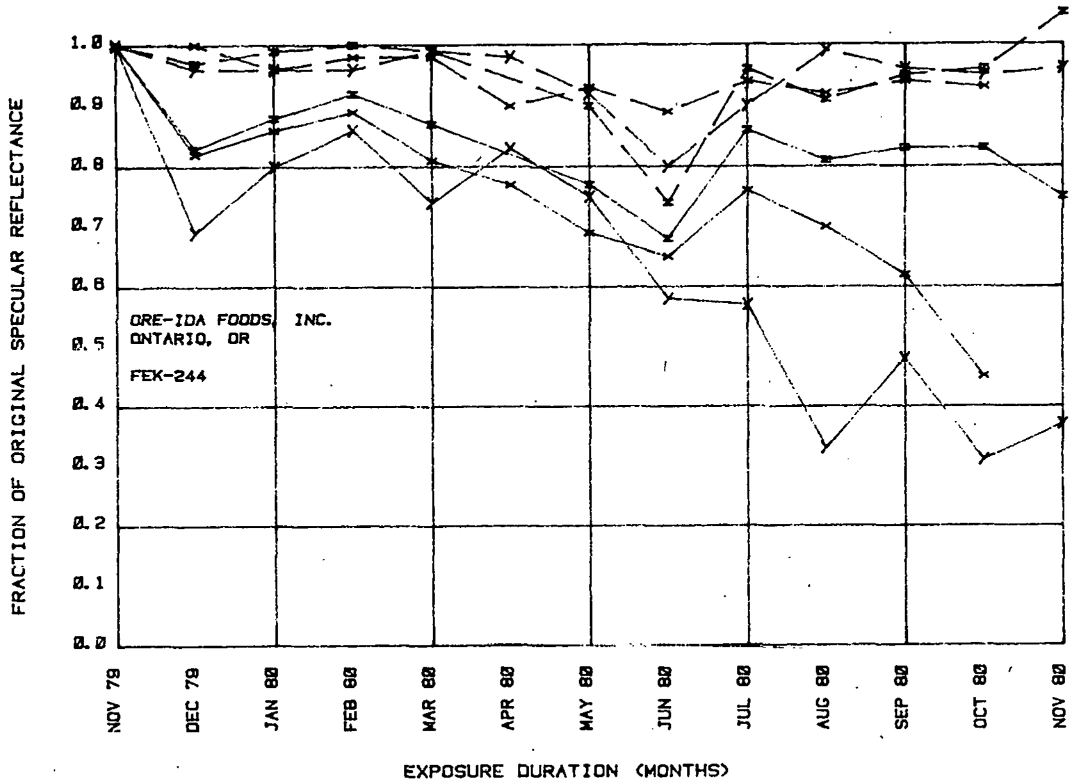


Figure 4. Plot of optical properties of collector specimens vs exposure duration

is designated with a letter -- X, Y, or Z. These letters designate the exposure orientation on the test hardware: (X) 45° upward tilt facing south, (Y) horizontal, faceup, and (Z) horizontal, facedown. The solid lines (——) represent measurements for samples in the as-received or soiled condition, and the dashed lines (----) represent measurements for the cleaned samples. The reflector material type and the location of the exposure test are designated on each plot. The hemispherical reflectance measurement plots are formatted identically.

In addition to the reflectance measurements, optical microscopy was used to evaluate each mirror specimen for degradation effects. To facilitate computerized data management, a code system was devised that described surface and sub-surface defects. An explanation of the code is contained in Appendix C. The reflector specimens were examined microscopically following routine cleaning with the McGean C-120 detergent method. The second evaluation was to determine if a more aggressive detergent would remove any remaining surface soil.

Following the surface characterization, selected specimens were subjected to further analysis to determine the degradation mechanism. Surface contamination and corrosion by-products were investigated using Fourier-transform infrared spectroscopy (FTIR), scanning electron microscopy/energy-dispersive X-ray (SEM-EDAX), and X-ray diffraction techniques.

<u>Receiver Specimens</u> -- Absorber degradation was evaluated from changes in the solar absorptance and emittance characteristics. The solar absorptance was measured with a Gier Dunkle MS-251 solar reflectometer (filter = 0), and emittance measurements were made with a Gier Dunkle DB-100 infrared reflectometer. Both solar absorptance and emittance measurements were made at three locations on each specimen, and the final result was expressed as an arithmetic mean of these three results. The measurements were made on each specimen before exposure and then again, following the specified exposure duration. A combination of alignment marks scribed on the back-side of the specimens and a template were used to replicate the measurement locations for determining the change in solar absorptance and emittance. Optical microscopy was used to evaluate degradation effects on the receiver specimens, and these effects were documented photographically.

A separate experiment was conducted in the laboratory to evaluate exclusively the thermal degradation of the receiver specimens. The control specimens were placed in a heated test assembly identical to the assemblies used in the field tests, and were thermally cycled under the same temperature cycle. The control experiment was conducted in a laboratory environment in the absence of light and environmental pollutants. These control specimens were used to obtain baseline data for the field tests and to ascertain the extent of thermal versus photochemical plus environmental degradation effects for the receiver specimens. These specimens were not cleaned during any portion of the test.

Glass Cover Plate Specimens -- Glass cover plate degradation was determined by changes in the transmittance, both specular (Cary 14 spectrophotometer) and hemispherical (measured by Dr. R. Pettit of Sandia National Laboratories, Albuquerque, New Mexico, using a Beckman 5270 spectrophotometer with an integrating sphere). All transmittance measurements were made over the spectral range of 200 to 800 nm. The specimens were measured before exposure and after exposure, both before and after being cleaned. The Lime-Brite cleaning technique was used. Care was taken, using an instrument sample holder, to replicate the measurement locations for each analysis.

Test Results and Discussions

Reflector Specimen Evaluation and Site Description

Because the environment at each site was unique, each location was evaluated separately. All meteorological data were obtained, for the exact exposure duration of the reflector specimens, from the Environmental Data and Information Service of the National Oceanic and Atmospheric Administration - National Climatic Center in Asheville, North Carolina.[2] Table 1 presents the data for all the sites.

Stauffer Chemical Company -- Stauffer Chemical Company, which manufactures primarily chlorine and sodium hydroxide, is located in the extreme southern

Table 1 (Page 1 of 2)

Environmental Test Site Descriptions

Site	Location	Industrial Process	Meteorological Conditions	Soil Type	Impacting Site Parameters	Adjacent Industries
Stauffer Chemical Co.	Henderson, Nevada	Chemical plant (Chlorine/ NaOH)	Arid	Red Desert -alkaline	● 6 Cooling towers ● Chlorine/ caustic environment	Kerr-McGee Titanium Refining Co. Small industries (e.g., water heater company)
Southern Union Refining Co.	Lovington, New Mexico	Oil refinery	Semi-arid	Red Prairie -alkaline	● 1 Cooling Tower ● Moisture Cycling ● High Wind Speeds	Refineries; relatively unpopulated area
Lone Star Brewing Co.	San Antonio, Texas	Brewery	Temperate	Rendzina -neutral	● 2 Cooling towers ● Roof mount--tar roof	Junkyard for scrap metal/cars. Heavily industrialized area.
Ore-Ida Foods, Inc.	Ontario, Oregon	Food Manufacturer (frozen foods)	Arid with ice/snow in winter	Gray Desert -alkaline	Roof mount over vent for potato frying vats.	Pasture/crop land. Relatively unpopulated area
Dow Chemical Co.	Dalton, Georgia	Chemical plant (latex polymer)	Warm temperate to tropical humid	Red or yellow Podzol -acid	Solar structure located on hillside away from plant processes. Clean plant.	Vegetation; relatively unpopulated area
U.S. Steel Chemical Corp.	Haverhill, Ohio	Chemical plant (acids, polymers)	Temperate with rain, ice, snow	Sol Brun Acide -acid	● Cooling towers ● Mixing pond ● Plant processes	Heavy industry--steel refining.
Hilo Coast Processing Co.	Pepeekeo, Hawaii	Food Manufacturer (sugar)	Tropical with heavy rainfall	Not Known	Located near ocean	Not Known

Table 1 (Page 2 of 2)

Environmental Test Site Descriptions

Site	Location	Industrial Process	Meteorological Conditions	Soil Type	Impacting Site Parameters	Adjacent Industries
Bates Container Corp.	Ft. Worth, Texas	Cardboard box manufacturer	Warm to moderate	Rendzina -neutral	Construction on site causing blowing soil	School; lumberyard
Caterpillar Tractor Co.	San Leandro, California	Manufacturer of heavy machinery	Cool to warm temperate	Brunizem or prairie -neutral	• Roof mount on paint-sealed roof • Roof venting of degreasing solvents and machining oil	• Kaiser Polymer Plant • Truck farm • In flight path to Oakland Airport • Semi-truck high pressure washing apparatus • Located near ocean

portion of Nevada at Henderson. A survey of the plant facilities showed six cooling towers located at the site, one of which was approximately 60 ft southwest of the environmental test hardware. Adjacent industries were several small companies that contributed little to the overall environment in that area, e.g., a water heater company and the Kerr-McGee Titanium Refining Company. The immediate surrounding area would best be described as semi-rural, the only topographical area of note being Lake Mead, approximately 20 miles to the east.

The U.S.D.A. soil map categorized the soil in the Henderson area as Red Desert, an alkaline soil, which has a carbonate layer that is generally within 1 ft of the surface soil and has a thin organic layer. The area is arid, creosote bush shrubland.[3]

Over the 12-month exposure period, both soil retention and corrosion caused losses in the optical properties of the reflective specimens. The extent of the degradation varied as a function of the material type.

The specimens in the 45° upward tilt (X) and the horizontal, faceup (Y) orientations were more susceptible to soil accumulation, losing between 20 to 100% specular reflectance following 12 months of exposure, with the 100% losses occurring for the samples at the 3- and 9-month retrieval events. The cyclic nature of the plots for the uncleaned specimens was closely related to seasonal variations, with the least soil accumulation occurring during January 1980 (Month 4) to April 1980 (Month 7). This time frame corresponded to climatic periods of the greatest precipitation and highest wind speeds. All material types exhibited essentially the same susceptibility for soil accumulation. However, differences were observed in the ability to clean the surface as a function of material type.

The second surface glass mirrors showed significant reductions in specular reflectance for the soiled specimens. Even though up to 100% specularity was lost due to soil accumulation, cleaning, using the standard Lime-Brite method, returned the specular reflectance to an average of 95% of original. The reflector specimens from all three exposure orientations were cleaned to approximately the same level. Microscopic examinations of the cleaned specimen surfaces (Lime-Brite method) showed the presence of particulate deposits, which were removed when the specimens were cleaned using the McGean method.

The three additional protective backings added to the glass specimens did not prove totally effective in withstanding the micro-climate at this site, particularly along the unprotected edges of the reflector specimen, i.e., those edges not covered by the sample retainers. The paints chipped, blistered, and peeled, and the vinyl sheet lost adhesion around the exposed edges to a depth of 0.50 inch. The silver was corroded in the areas where the protective backing failed on the unprotected edges (Figure 5). Six months of exposure was required to reach the 0.50-inch corrosion depth. However, continued exposure from 6 to 12 months did not produce further degradation of the silver, and corrosion in the center areas of the specimen was not observed. It is not clear whether continued exposure would further degrade the paint backings and allow penetration of the corrosive material into the silver layer, thus resulting in corrosion across the surface of the reflector.

The FEK-244 aluminized acrylic reflector specimens showed soil accumulation profiles similar to those of the glass mirrors, as indicated by their specular reflectance. However, the FEK-244 reflector specimens did not exhibit the same characteristics of high specularity following cleaning.

Laboratory cleaning of the FEK-244 specimens restored the specular reflectance values to an average 15% loss for the first 7 months of exposure, but a decrease in the measured specular reflectance is noted after that time for all specimens except those in the horizontal, facedown (Z) orientation. The surface analysis revealed the acrylic film over the aluminum sheet started becoming cloudy after 2 months, and the cloudy appearance increased as the exposure duration progressed. A SEM-EDAX analysis of the surface of an FEK-244 specimen that had been exposed 12 months was conducted to determine if at least a portion of the loss in specular reflectance was caused by corrosion of the underlying aluminum layer. While only incidental corrosion was found where there was damage to the acrylic film, particulates did appear to be embedded in the soft acrylic top layer

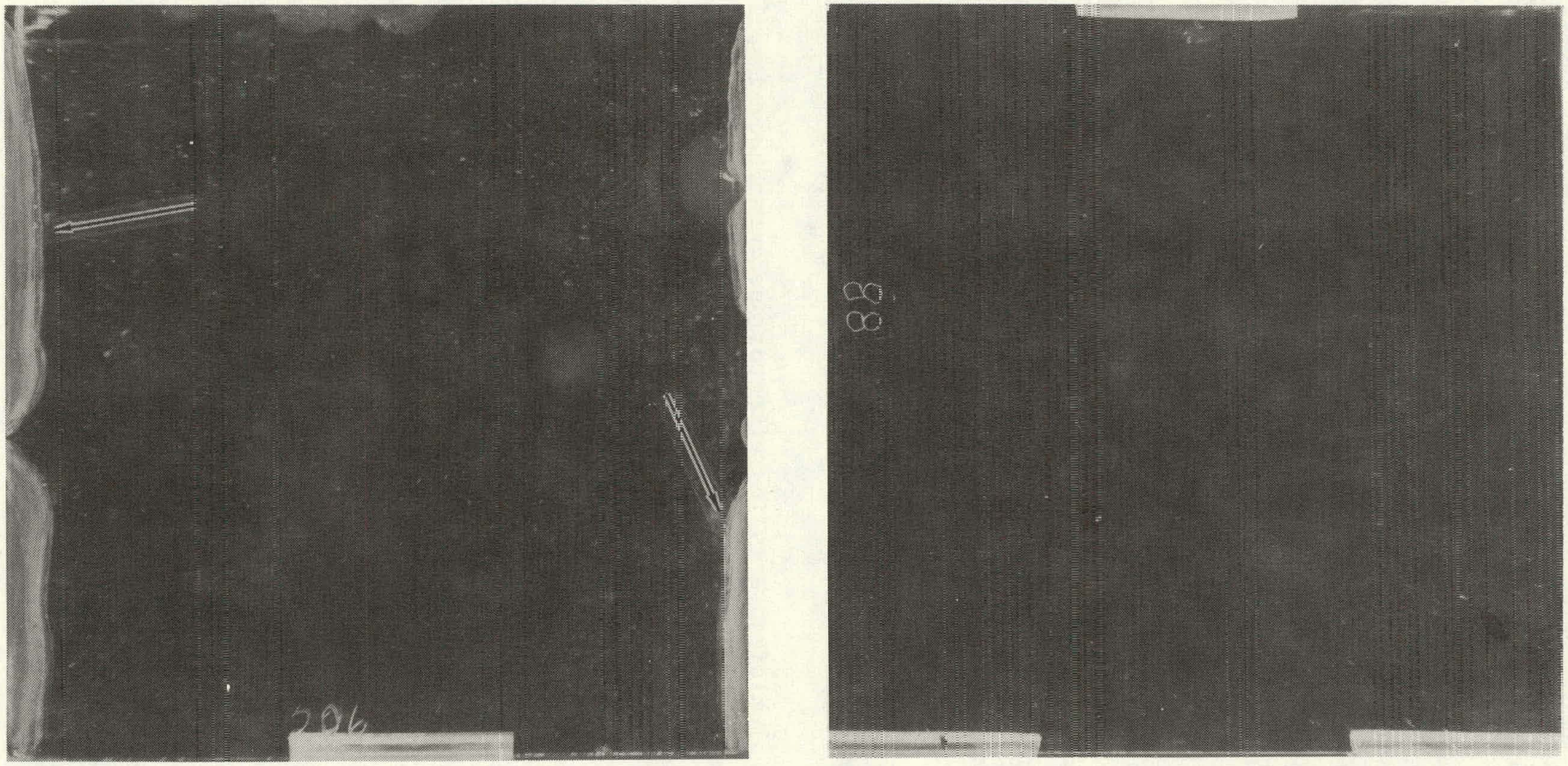


Figure 5. Glass Specimen with Epoxy Backing. Specimen 206 was exposed 6 months, X-plane at Stauffer Chemical Co. Arrows indicate silver corrosion along sample edges. Specimen 88 is a control specimen maintained in a desiccated laboratory environment. Specimen 206 has been cleaned.

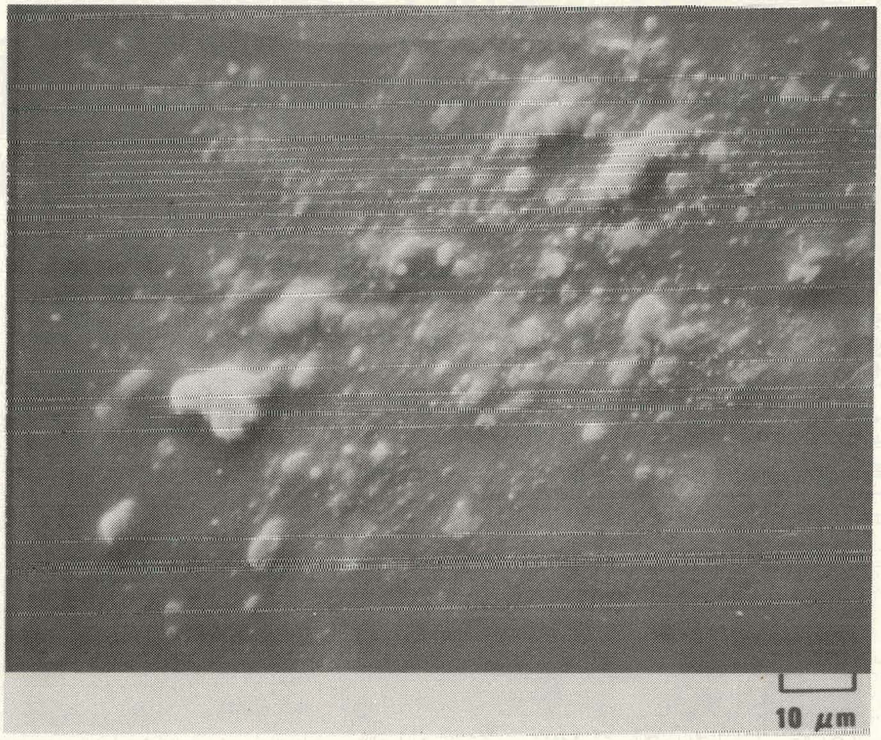
(Figure 6A). It is, however, difficult to say conclusively that this is a true embedment phenomenon, because the high-intensity source of the SEM-EDAX instrument caused the acrylic film to bubble, which tended to obscure the data. EDAX analysis of the soil particles on the specimen surface showed aluminum, silica, sulfur, calcium, and iron, which are typical of most soils, in addition to lead and tin (Figure 6B). One particle was isolated that was composed primarily of lead and tin and was probably airborne from the adjacent Kerr-McGee plant (Figure 7).

The Alzak specimens fared the poorest at this location, with soil accumulation causing losses of up to 100% specular reflectance for 3 months of continuous exposure. Specimens exposed 4 months to 1 year generally showed reflectance losses of 70 to 90% because of corrosion and soiling of the aluminum surface. Figure 8 shows a clean Alzak specimen exposed 7 months in the horizontal facedown (Z) plane, whose surface is uniformly pitted by corrosion. After 5 months, the losses in specular reflectance leveled off, apparently because the soil accumulation passivated the surface and protected the material from further corrosion.

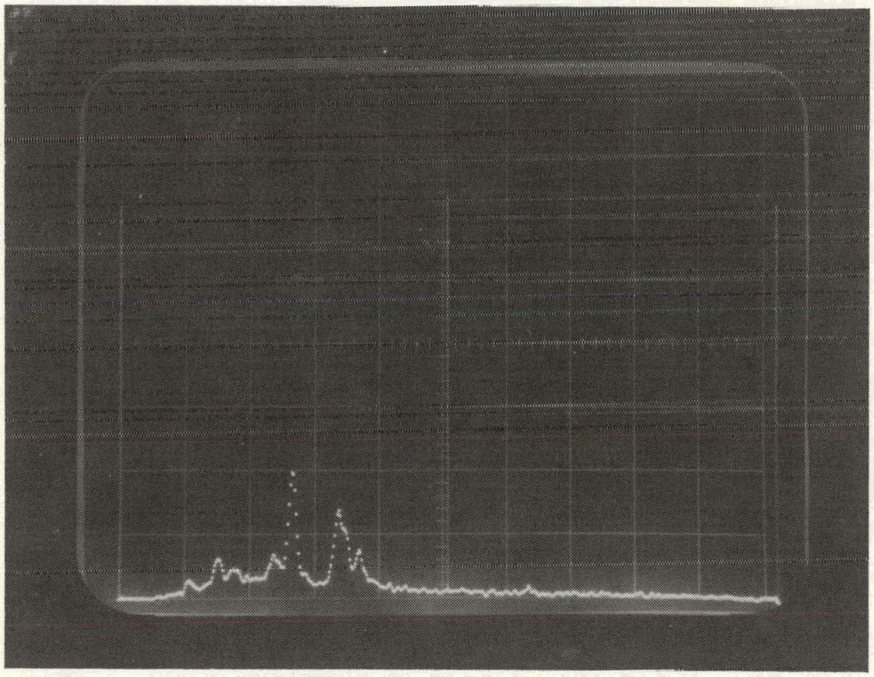
SEM-EDAX and X-ray diffraction analyses of the Alzak surface were conducted. Results from these studies confirmed that degradation of the surface was due to chlorine attack, and also revealed the presence of titanium dioxide, probably as airborne particulate from the adjacent Kerr-McGee plant.

Ore-Ida Foods, Inc. -- Ore-Ida Foods, Inc., located in Ontario, Oregon, manufactures frozen food items; e.g., potatoes and pizza. The area around the Ore-Ida plant is rural, with very little industry. The environmental test hardware was located on a tar-gravel roof near a vent for large frying vats. The climate in the Ontario area is classified as arid, with an annual precipitation of less than 10 inches. The primary vegetation is sagebrush shrubs. The U.S.D.A. soil map categorized the soil as Gray Desert, with a thin organic layer, plus a carbonate layer, which is generally within 1 ft of the surface. The soil has a high degree of alkalinity.[3]

The reflector specimens at the Ore-Ida site were heavily soiled when returned to the laboratory for evaluation, but were easily cleaned. Specular

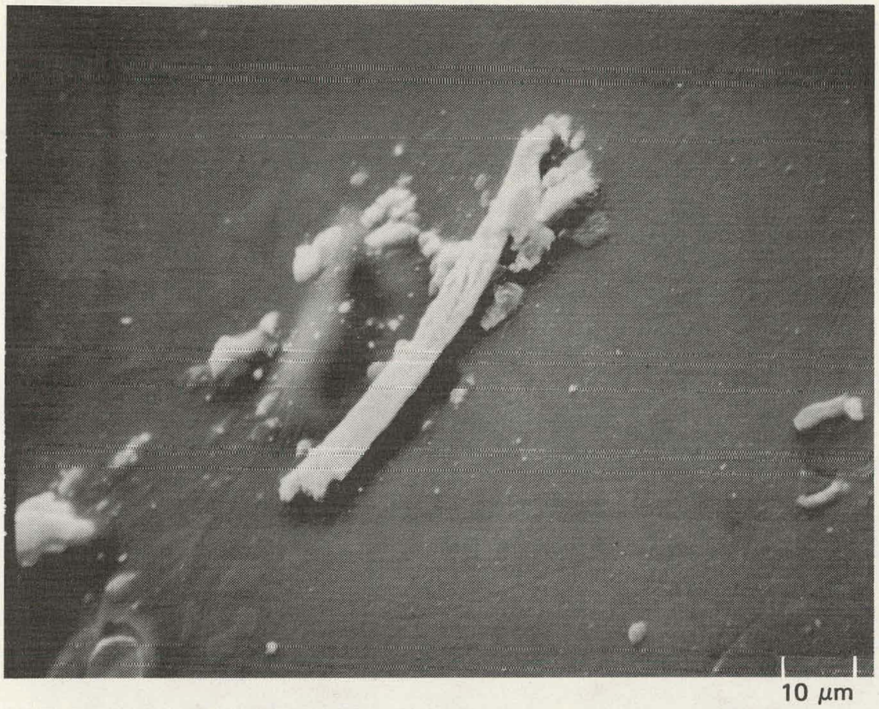


A. FEK-244 specimen (ID 318) exposed 8 months at Stauffer Chemical Co.

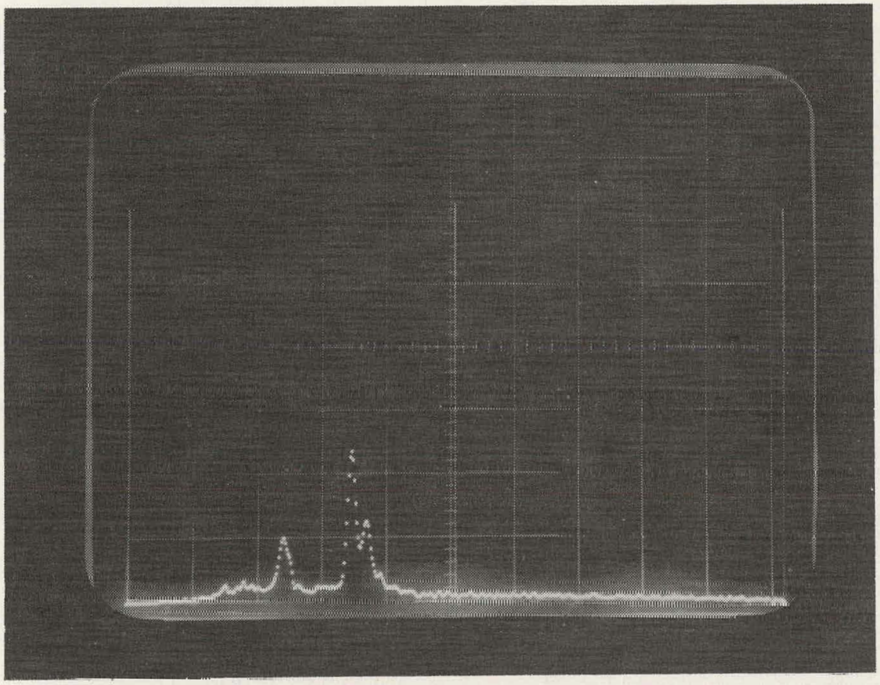


B. EDAX analysis of surface soil showing, respectively, Na, Al Si, Pb, Cl, K, Sn

Figure 6. Soil Embedment. Apparent in acrylic layer of FEK-244 specimen.



A. FEK-244 specimen (ID 318) exposed 8 months at Stauffer Chemical Co.



B. EDAX analysis of discrete particle shown in A. Particle is primarily lead and tin.

Figure 7. Lead-Tin Contaminant. Photomicrograph of reflector specimen from Stauffer Chemical Co.

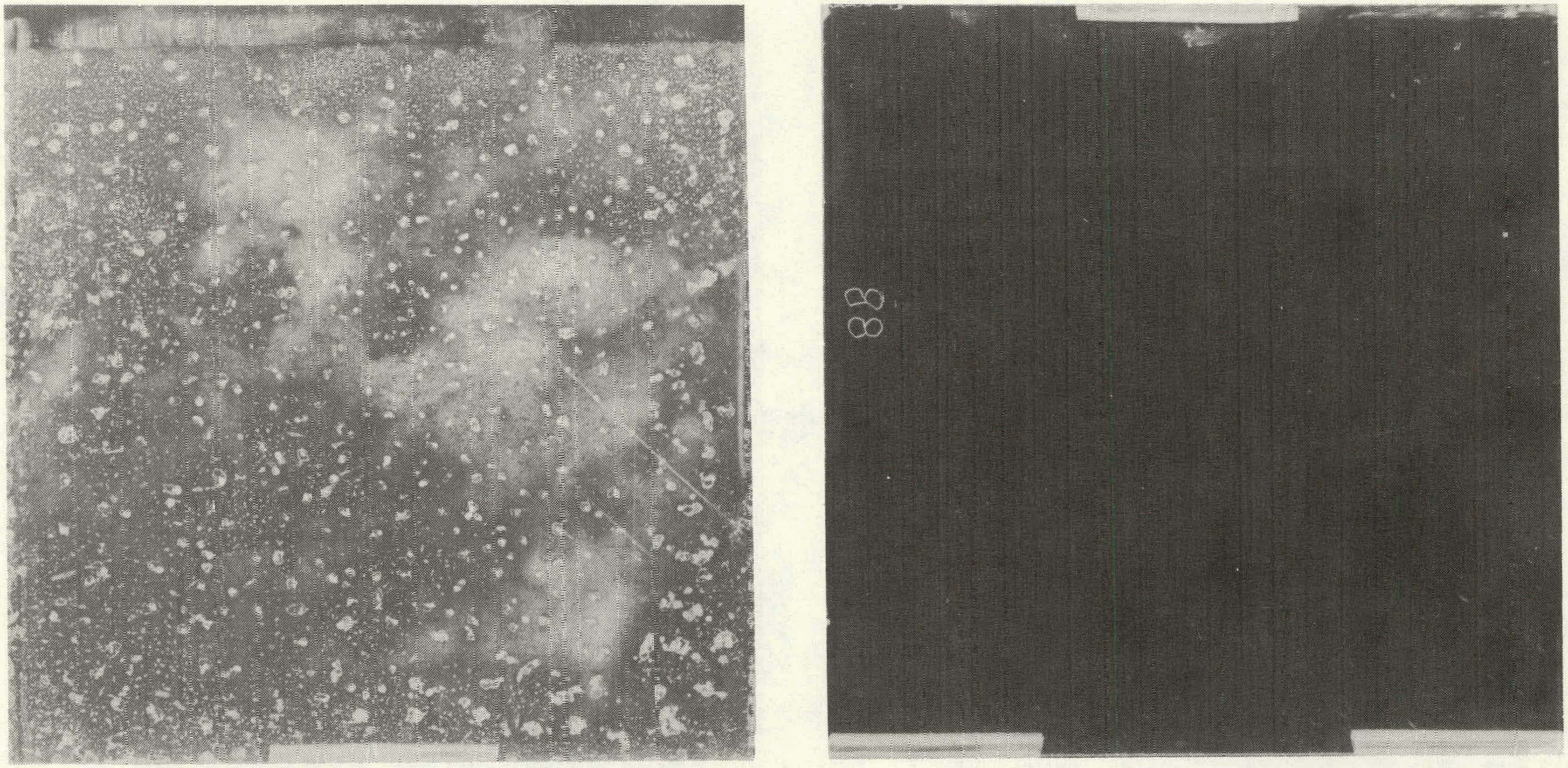


Figure 8. Alzak Corrosion. Specimen 638 (Alzak) exposed 3 months, X-plane, at Stauffer Chemical Co. Specimen 88 is a control maintained in a desiccated laboratory environment. Specimen 638 has been cleaned.

reflectance losses of 20% due to soil accumulation remained fairly constant until the 6th month (May 1980), when the rate of soiling was accelerated. It should be noted that the first major volcanic eruption of Mt. St. Helens occurred May 18, 1980. A sharp decrease in the specularity was observed in the 9th month (August 1980). The glass and FEK-244 specimens had specular reflectance values that returned to 95% of the original value following cleaning. However, following cleaning, the specularity of Alzak specimens was 80% of original reflectance measurements for specimens exposed 12 months. Little apparent corrosion of the metallic components of the reflector specimens or attack on the paint backings was observed. Heavy oil deposits on the reflector surface, probably cooking oil effluent from the roof vents, appeared to be responsible for the heavy soil accumulation.

It was observed only during the summer months that a white waxy material, which could be a component of the cooking oil, was precipitating onto the reflector surfaces. While this material could not be removed with normal cleaning procedures, little effect on the specular reflectance was noted. It is notable that the Alzak specimens in the horizontal, facedown (Z) orientation experienced a significant loss in specularity analogous to the Alzak specimens at the Lone Star Brewing Company site. This loss was believed to be caused by outgassing of the roofing material. However, the decision was made to locate the proposed solar array at this site on a ground-level alternate location. Consequently, the effects of roofing material outgassing and blowoff from roof vents is not anticipated to be a problem, particularly as there are buildings located between the alternate location and the building where the frying is done.

Dow Chemical Company -- The Dow Chemical plant is located in Dalton, Georgia, a mountainous, heavily wooded area with little surrounding industry. The area would best be described as rural. The primary product of the plant is vinyl latex polymer; the surrounding plant structures are clean and well maintained. The only plant structure that could impact the solar optical materials is a boiler house, which vents steam from the side of the building nearest the environmental test hardware.

The U.S.D.A. soil map categorized the soil in this area as Red or Yellow Podzol. This soil is acidic and has a thin, dark-colored organic layer at the surface over a yellow-gray or gray-brown leached layer, covering a darker clayey layer of deposition that grades downward into a brightly colored, deeply weathered parent material. The parent material may be scores of feet deep, while the organic layer, leached layer, and the layer of deposition is commonly 3 to 4 ft deep. The climate is warm temperature to tropical humid, the primary vegetation being mixed broadleaf and pine forest.[3]

The second-surface glass specimens exposed at this site lost 30 to 35% of their specular reflectance due to soil accumulation during exposures of up to 12 months. Cleaning restored these specimens to within 92 to 95% of the original specular reflectance values (Figure B7, Appendix B). No corrosion or other degradation defects were observed, other than a slight chipping of the paint backings along the exposed edges not protected by the sample retainers (Tables C-25 - C36, Appendix C). A microscopic examination of the reflector surfaces showed that routine cleaning with the Lime-Brite detergent removed most of the soil that had accumulated for 6 months. Some particulate buildup was observed from 6 to 12 months of exposure (May to November 1980), but cleaning with the McGean C-120 detergent removed virtually all residually retained soil.

The rate of soil accumulation for the FEK-244 specimens was less than at the other sites, and the samples were easily cleaned to 93 to 95% of the original reflectance values with the Lime-Bright detergent. Particulate deposits began accumulating after the 6th month (May 1980) of exposure, but cleaning with the McGean C-120 detergent did not remove a significant amount of the residual soil remaining on the surface after the standard cleaning procedure.

The Alzak specimens did not respond as well to this environment as did the other two materials. After 6 months of exposure there was a significant increase in the rate of soil accumulation, approximately 20% greater than for the two other materials. Following cleaning, the specular reflectance values were restored to a value 35 to 40% less than the original measurements.

There was a small amount of surface pitting, and the loss in specular reflectance was due primarily to soil accumulation.

Lone Star Brewing Company -- Lone Star Brewing Company, as a beer manufacturer, has the typical clean plant environment usually associated with food manufacturers. The plant, located in San Antonio, Texas, is situated in an industrialized area and is adjacent to a junk yard containing rusting automobiles and metal. The environmental test hardware was mounted on the roof of a two-story structure 60 ft northwest of two cooling towers.

The primary vegetation in this region is oak hickory forest, and the soil, as categorized by the U.S.D.A. soil map, is Rendzina, a neutral pH soil. The Rendzina soil is a dark-gray or black, organic-rich surface soil over a soft, white, calcareous material derived from chalk, soft limestone, or marl. This soil is typically associated with "swellable clay". The climate is variable from moderately warm summers to mild winters and has moderate rainfall.[3]

The reflector specimens exposed at this site were less heavily soiled than those at most sites, losing at most 60% of their specular reflectance due to soil accumulated over a 13-month period. Upon cleaning, the specular reflectance of the glass and FEK-244 specimens was restored to within 85 to 95% of the original values. No corrosion of the glass specimens was observed. The FEK-244 acrylic layer turned cloudy, and abrasion patterns developed. However, these phenomena did not greatly affect the specular reflectance of the reflectors. The only anomalous result at this site was the performance of the Alzak specimens, particularly those in the horizontal, facedown (Z) plane. These specimens lost up to 60% specular reflectance because of accumulated soil. However, cleaning the Alzak specimens still left a loss in reflectance of 10 to 40%. It was theorized that the tar roof was outgassing, thus affecting the Z-plane more severely than the other orientations of exposure, and that these outgassing products served as an adhesive for entrapping particulates. It is not known why the Alzak was more affected by this phenomenon than were the other material types.

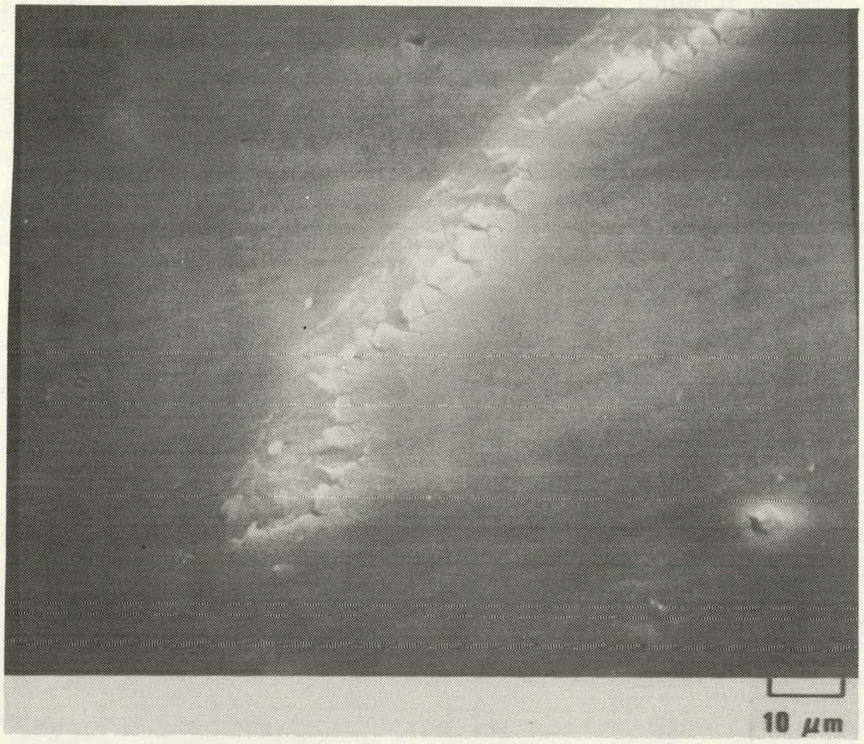
Microscopic surface examination showed particulate deposits on the front surface of all material types, but the Alzak specimens appeared to have the highest density of puddle-shaped particulate formations.

The Lone Star Brewing site was considered to have only a moderate soiling problem over the 13-month exposure time. The FEK-244 and the glass specimens appeared to survive the environment well. However, the long-term impact of outgassing of the tar roof on the specimens is not known at this time. Some rust-like particulate formations were observed on the 45° upward tilt (X), and the horizontal, faceup (Y) plane specimen, possibly from the adjacent junk yard, but they were easily removed with routine cleaning procedures.

Southern Union Refining Company -- Southern Union Refining Company, located in the southeast corner of New Mexico near Lovington, is an independent oil refinery. The site is situated in a rural environment with only agricultural land in a 5-mile radius around the plant. The soil in the area is categorized as Red Prairie, and is alkaline. The soil is brown to red, on the surface covering a clay subsoil layer, and has a large lime carbonate component in the surface soil. The climate is semiarid, with the primary vegetation being short grass.[3]

There was a severe loss in specular reflectance for all reflector materials exposed at this site. The reflectance losses were greater than 90% in the 45° upward tilt (X) and horizontal, faceup (Y) planes after 7 months of exposure. Cleaning by routine cleaning methods, including both the Lime-Brite and McGean C-120 detergents, improved the reflectance values by only a few percentage points. The horizontal, facedown (Z) plane specimens were not as severely soiled and were more easily cleaned.

The microscopic examination of the reflector specimens following cleaning of the surface showed soil adhering to the mirror surfaces in small (up to 0.25 inch) elliptical patterns resembling water droplets. Figure 9A shows soil encrustation along a partial perimeter



A. 1000X magnification of soil encrustation along perimeter of water droplet.

B. 1000X magnification of soil encrustation over entirety of water droplet.

Figure 9. Soiling Patterns. Two Alzak specimens exposed 1 month at Southern Union Refining Co.

of a water droplet, and Figure 9B shows soil encrustation encompassing a water droplet. This phenomenon increased until the surface was totally occluded by the adhered soil (Figure 10). Minor corrosion of the Alzak and the silvered-glass mirrors was observed. Before total surface occlusion by soil, significant abrasion patterns were observed in the FEK-244 acrylic layer.

It was observed during a site visit that, under the proper wind conditions, a spray of water from a cooling tower (approximately 30 ft high) was deposited on the test rack, which was located about 200 ft east of the tower. The spray from the tower is believed to be a critical element in the reflector soiling process.

The surface analyses indicated that the principal components of the soil adhering after washing were alumino silicates, probably clay from the natural environment. Essentially all the ingredients of the additives to the cooling tower makeup water (a very heavily doped solution) were found in smaller amounts. Also seen were magnesium, potassium, sodium, calcium, and carbonates. The latter two are important because calcium carbonate ($CaCO_3$) can serve as an effective cement for clays.[4] It turns out $CaCO_3$ is present both in the makeup of the cooling tower and in the natural environment (as caliche, a local limestone). It is significant (since this is a refinery site) that high levels of hydrocarbons were not seen.

There are two principal types of natural soil in the area: caliche, and a loam ("Kimbrough-Lea complex"), which has a high clay component.[5] The type of bonding mechanism that might be taking place depends to some extent on the clay type (illite, kaolinite, montmorillonite, etc).

In MDAC's first cleaning study for Sandia,[1] the development of a tenacious soil layer after several months of exposure to the natural environment was observed. However, it was responsible for only a 2 to 5% loss in specularity after washing. Over approximately the same exposure period, much less tenacious dirt accumulated in this study because of the low number of wet-dry cycles. At the Lovington site, the number of these cycles is very large because of the cooling tower.

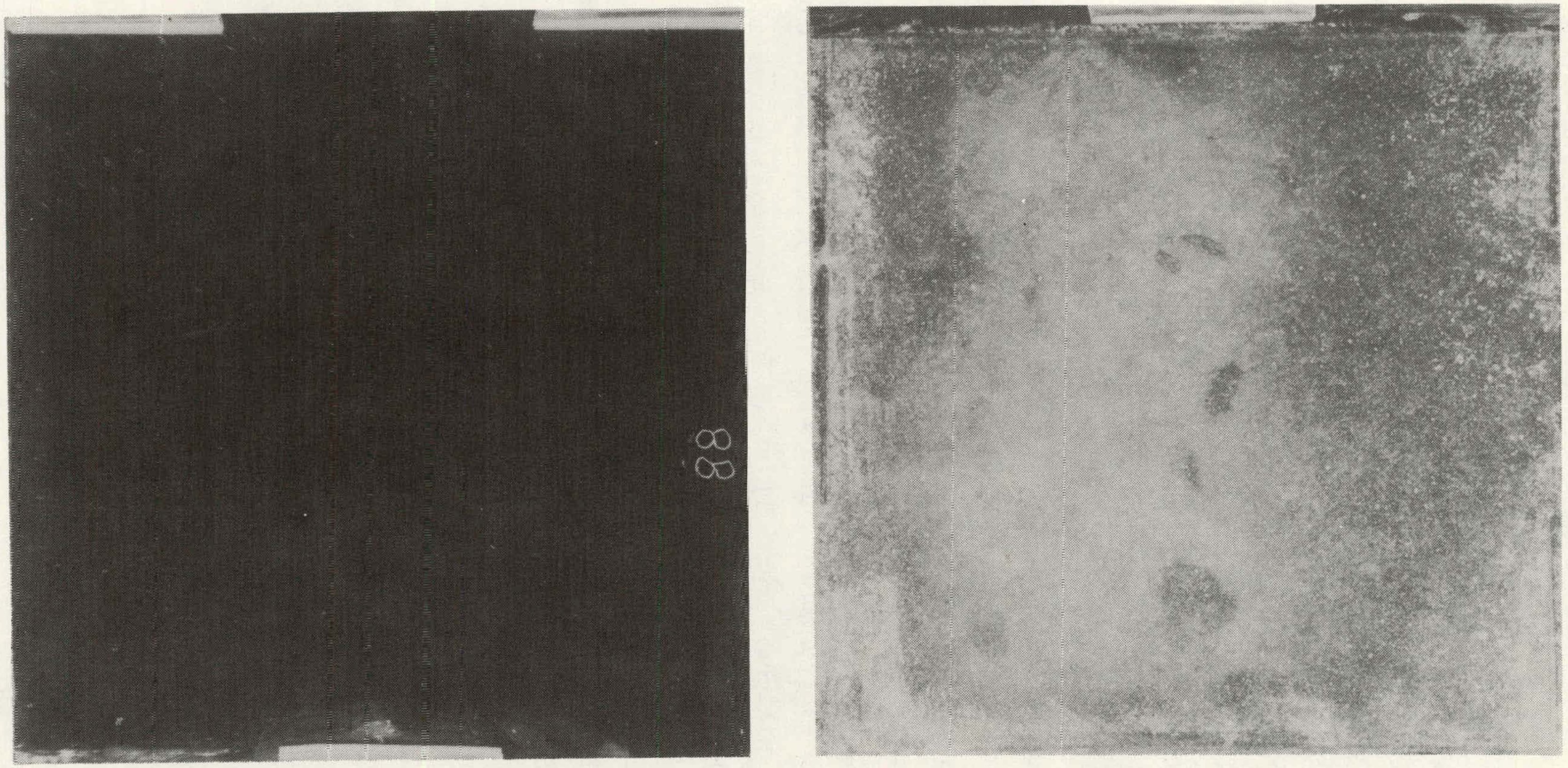


Figure 10. Specimen 470 FEK-244, X-Plane. Specimen 88 is a control specimen maintained in a desiccated laboratory environment. Specimen 470 is a cleaned specimen.

It is probable that a similar process was occurring on the Lovington mirrors, but the rate of growth of tenacious soil on the reflector surface and severity of the reflectivity degradation were orders of magnitude greater because of the spray from the cooling tower. It has often been observed that a large quantity of water (a long soaking rain, for example) tends to clean mirror surfaces, while a small quantity (very little rain, or dew) causes dirt to accrete. At the Lovington test rack, periods during which the wind-borne spray wets the surface lightly alternate with drying periods when the wind shifts to another direction. Thus, the number of wet-dry cycles are greatly increased, and the conditions seemed to be the best possible for the formation of a tenacious soil layer.

The high level of chemical additives in the water being emitted from the cooling tower could also play a role in the soiling process. There are two hypotheses being considered for the mechanism bonding the soil to the reflector surfaces: first, certain types of clay are non-swelling. After a number of wet-dry cycles, the clay particles (typically 2 to 5 μm and planar in shape) could develop a contact area with the reflector, which was optically flat over a significant area. Physical (non-chemical) forces alone (electrostatic or Van der Waals or both) could then exert extremely strong binding forces (up to 100000 psi) in theory.[6] Second, water soluble chemical cements could, over time, seep under the lightly bonded dirt particles and form a strong chemical bond. The dirt particles and the dirt layer would then provide a hermetic seal over the cement layer, preventing water (or other solvents) from reaching and dissolving cement. The most likely candidate for this cement is calcium carbonate, the principal ingredient of Portland cement. Calcium carbonate was an ingredient in the cooling tower makeup water, as were a number of other cement candidates (e.g., sulfates). However, calcium carbonate also exists in abundance in the natural soil. Thus, although the additives in the cooling tower spray may aggravate soil accretion, it is unlikely that the problem can be completely eliminated by a change in the makeup water formula.[7]

Following the initial 7-month exposure, the test was terminated at the initial site and an alternate site, approximately 1000 ft south of the original site was selected. It was believed this location would be less affected by the cooling towers Although the specimens were heavily soiled when returned to the laboratory, the specular reflectance of the specimens, when cleaned, returned to an average 94% of the original value. The glass specimens showed slightly higher reflectance values after cleaning than did the FEK-244 or Alzak specimens. Surface examination showed non-removable particulate deposits on the surfaces of the reflector specimens following 5 months of exposure.

A test plan modification was initiated at the original site near the cooling towers to determine if increased frequency of cleaning would alleviate the rapid loss in specularity. Specimens were successively re-exposed for 1 month periods. After each exposure period, the specimens were returned to the contractor for evaluation. After three successive exposure intervals of 1 month each, it was found that monthly cleaning maintained the specular reflectance values at 95% of their original values; however, surface examination revealed that particulate deposits were building up again. It is suspected that increased frequency of cleaning significantly retards, but probably does not prevent, this tenacious soil layer from developing.

Hilo Coast Processing Company -- Hilo Coast Processing, a manufacturer of sugar products, is located on the east side of the main island of Hawaii, near Hilo. The company is located in a small community called Pepeekeo. The only known adverse environmental parameter that could affect the survivability of the reflector specimens at this site was the proximity of the test hardware to the ocean. Soil-typing information is not available from the U.S.D.A soil maps for the Hawaiian Islands, but the climate is sub-tropical.

All reflector specimens at this site had unusually heavy soil accumulation on the surfaces, which caused a loss of specular reflectance of >90% following 10 months of exposure for specimens in the horizontal, faceup (Y), and a loss of approximately 60% for specimens in the 45° upward tilt (X) planes. Only 10 months of results are reported for this site because the test hardware was vandalized and the final 2 months' specimens were stolen. The glass specimens had approximately 10% greater surface soil accumulation that did FEK-244 or Alzak. This trend became apparent following 3 months (August 1980) of exposure, and continued until termination of the test.

Cleaning the reflector specimens, using the Lime-Brite cleaning method, returned all glass reflectors to within 88% of their original reflectance and all FEK-244 specimens to within 80% of their original reflectance throughout the 10-month test interval. The cleaned Alzak specimens showed continuing loss of specularity until termination of test, losing from 18 to 42% of their original specular reflectance. Both the FEK-244, and even more noticeably, the Alzak specimens had developed particulate deposits on their surfaces following 3 months of exposure. These deposits were not removed by cleaning with the Lime-Brite or the McGean C-120 cleaning method.

Significant corrosion of the silvered reflective layer of the glass mirrors was observed at the Hilo coast site. Small circular corrosion patterns were distributed non-uniformly over the surface of the samples (Figure 11). There was evidence of edge-attack of the silver by the corrosive material and attack through the protective backings to produce corrosion in the center of the glass reflector specimens. Damage appeared to occur where liquid droplets formed on the backside of the reflector, and the corrosive material diffused through the coating to attack the silver layer. It is notable that the vinyl sheet backing was as susceptible to "through-the-backing" attack as were the two paints. Where the corrosion occurred, the backing had blistered and bubbled, but no mechanical damage, e.g., holes or tears, were observed.

Corrosion damage was not observed on the FEK-244 or, surprisingly, the Alzak specimens. While it is postulated that corrosion of silvered glass mirrors resulted from exposure to salt water, no confirmation of this theory has been made at this time.

U. S. Steel Chemical Corporation -- U. S. Steel Chemical Corp., located on the Ohio River in Haverhill, Ohio, manufactures polymers, acids, and other related chemicals. There are a number of adjacent industries along the river, but the areas away from the river are farm and pasture lands. Some of the industries in the area of this site are steel refining plants and other chemical plants. In the immediate area of the environmental test hardware were cooling towers and a mixing pond for waste chemicals.

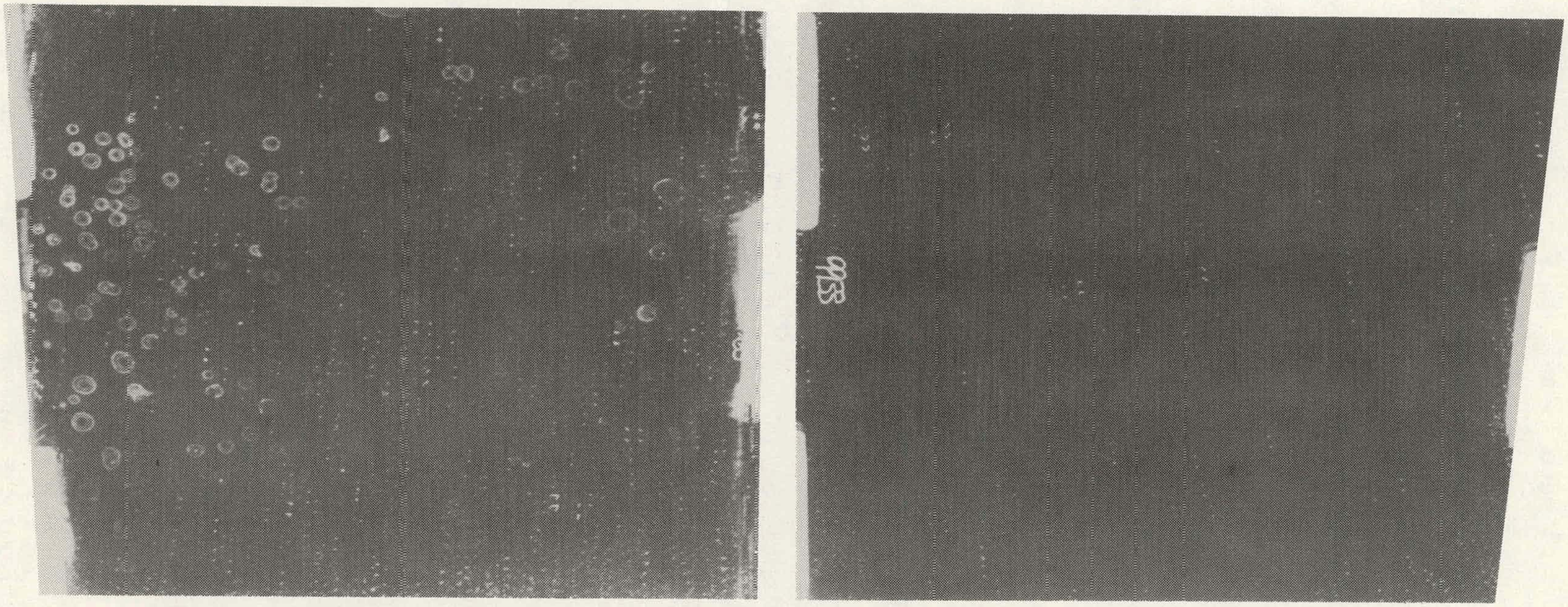


Figure 11. 'Through the Backing' Corrosion. Specimen 84 (glass, DuPont Imron backing) exposed 4 months, X-plane, at Hilo Coast Processing. Arrows indicate corrosion. Specimen 93 is a control specimen maintained in a desiccated laboratory environment. Specimen 84 has been cleaned.

The primary vegetation in this region is deciduous broadleaf (oak, hickory) forest, and the climate is temperate and humid. The soil classified as Sol Brun Acide, which is composed of a surface layer, mostly litter from broadleaf trees, that covers a humus-rich layer containing mineral matter. These layers overlay a brown, leached layer that is primarily clay. This soil type is acidic and rich in carbonate content.[3]

The soil accumulation profiles are fairly typical of a site with a moderate soiling problem, with reflectance losses of 20 to 60% being measured for the soiled specimens. Cleaning restored the specular reflectance to greater than 82% of the original for the glass specimens and to over 85% of the original for FEK-244. Alzak specimens could only be restored, upon cleaning, to 20 to 40% of their original reflectance values.

A large portion of the loss of specular reflectance for the glass specimens was caused by the silver layer corroding and separating from the glass in large circular patterns (Figure 12). The corrosion of the silver was first observed in May 1980 (5 months of exposure), and the separation of the silver backing was observed in October 1980 (9 months of exposure). An examination of the paint backings showed blistering and the appearance of a liquid droplet falling or condensing on the areas where the silver-backing separation occurred. The paint backing was intact, i.e., had not flaked away. There was also a progressive accumulation of surface particulate formation that could not be removed by either the Lime-Brite or McGean C-120 detergents.

The Alzak specimens also showed damage to the surface caused by corrosion. Small pits and microcracking around the pits were observed as early as after 3 months of exposure, and the phenomena increased until the test terminated. These pits were covered with a white crystalline material, which was removed mechanically, i.e., by surgical knife, thus revealing the underlying pits (Figure 13). Cleaning the specimens using both the Lime-Brite and the McGean C-120 methods did not remove the crystalline material.

It was reported in the contract interim report[8] that the FEK-244 specimens had shown corrosion effects, which resulted because of chemical damage to the acrylic top layer. Following a subsequent, more-intensive examination of the

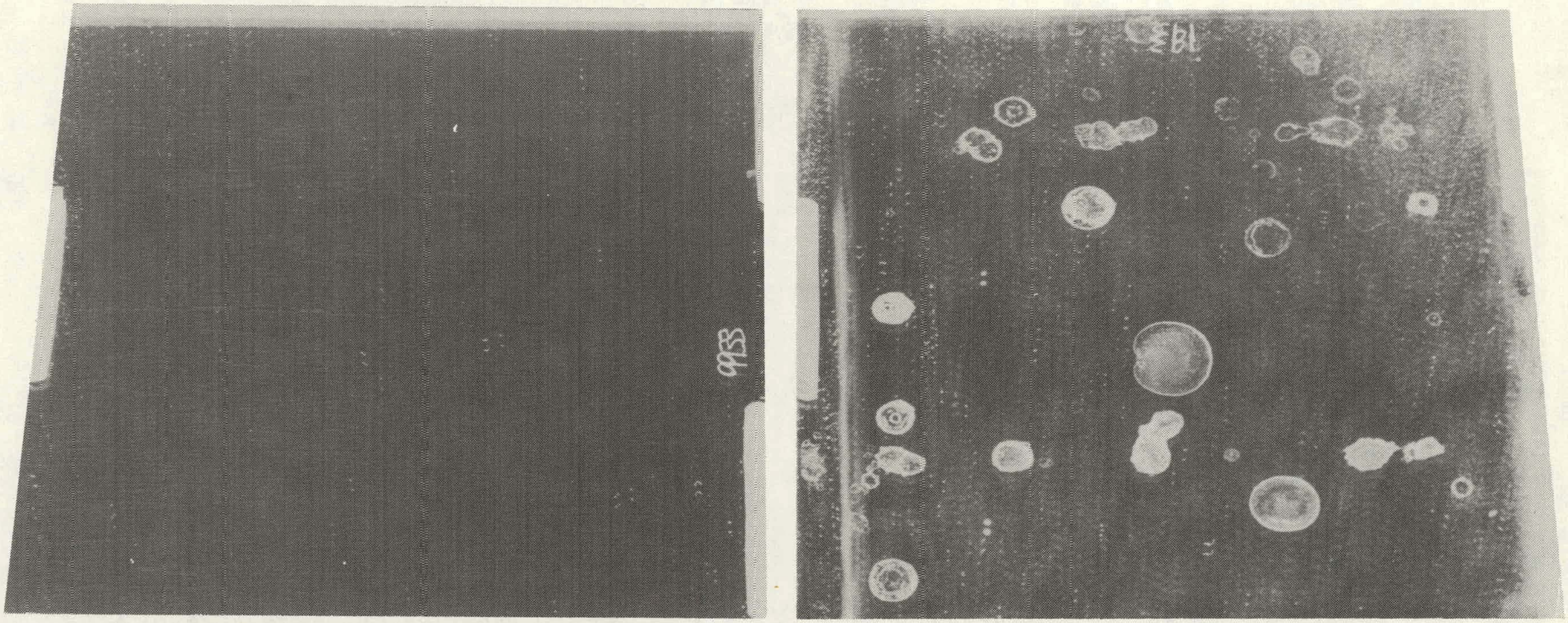
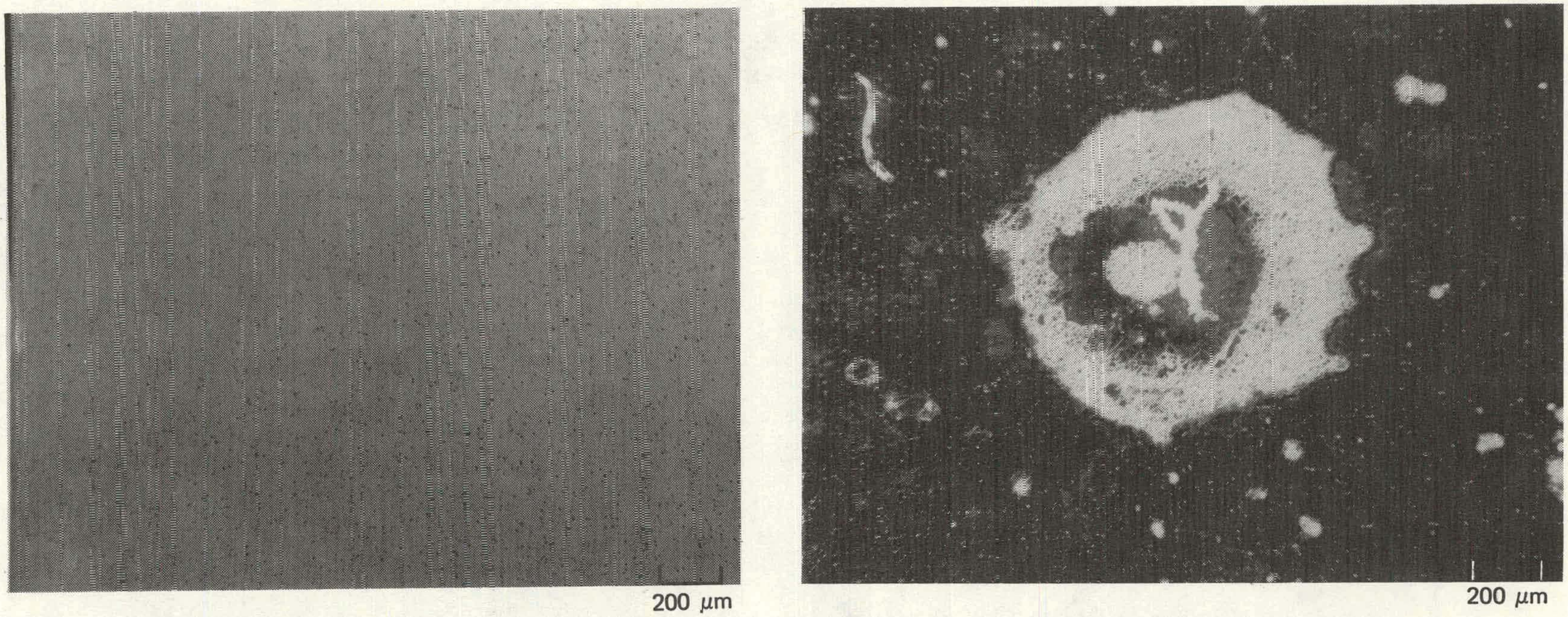


Figure 12. Glass Specimen with Epoxy Backing. Exposed 8 months, Y-Plane, at U.S. Steel Chemical Co. Specimen 93 is a control maintained in a desiccated laboratory environment. Specimen 193 has been cleaned.



A. Control Alzak specimen maintained in a desiccated laboratory environment.

B. Photomicrograph of cleaned Alzak specimen exposed 5 months at U.S. Steel Chemical Co.

Figure 13. Crystalline Deposits. Photomicrograph of enlargement (32X) of deposits covering corrosion pit on cleaned Alzak Specimen.

FEK-244 specimen in question, this was found not to be the case. During the 10th through the 12th month of exposure, the FEK-244 specimens exposed in the horizontal, facedown (Z) orientation developed a unique surface condition, which appeared to result in damage to the acrylic film. The other two exposure orientations, 45° upward tilt (X) and the horizontal, faceup (Y), were unaffected. Damage to the acrylic film of FEK-244 is perceived to be a serious problem, as it would expose the underlying reflective aluminum film to the same corrosive environment that caused corrosion of the silver on the glass and Alzak specimens.

The FEK-244 specimens, when evaluated in the "as-received" condition before any cleaning, had developed what appeared to be 2.5- to 6-in.-long cracks in the acrylic layer. A significant number of these "cracks" originated from localized white, cloudy areas on the specimen surface, and the total specimen surface was involved (Figure 14). There were, however, areas where the "cracks" were more dense. The potential seriousness of acrylic damage prompted an in-depth analysis of the surface phenomena, with contributing analyses by Drs. R. B. Pettit and E. P. Roth of Sandia National Laboratory, Mr. B. A. Benson of 3M Corp., and the McDonnell Douglas Astronatics Company.

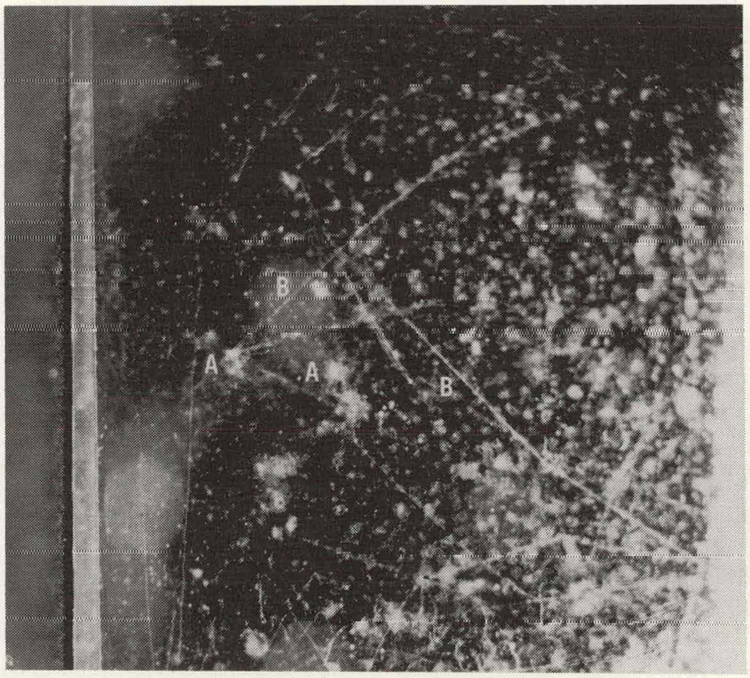


Figure 14. Specimen FEK-244 (ID 488). Exposed 12 months, Z-Plane, U.S. Steel Chemical Co. (A) Localized cloudy areas; (B) Fibers encrusted with siliceous materials (Photo courtesy Dr. R. B. Pettit, SNLA. 1/2 sec., f5.6)

The results of the analysis showed the "cracks" were actually organic fibers, encrusted with a crystalline growth. The fibers, whose origin is unknown, were attached to the mirror surface by the white, cloudy areas, which appeared to be siliceous materials (soil) in an organic matrix. The cloudy areas had the appearance of being a wax-type material. All surface deposits except the waxy material could be removed by a conventional contact detergent cleaning method, high-pressure cold-water spray, or a solution of 50:50% by volume isopropyl alcohol and water. Approximately 50 to 60% of the waxy material was removed using a hot-detergent non-contact cleaning method, and approximately 90% was removed using a hot-detergent contact cleaning method. The contact cleaning method used a cotton swab for cleaning after allowing the cleaning solution to stay on the specimen surface 10 minutes, whereas the non-contact cleaning method used the same procedure without using any physically contacting cleaning procedure. Upon cleaning the FEK-244 surface, no damage to the acrylic film was observed and, subsequently, no corrosion of the reflective aluminum layer was observed. There does, however, remain the problem of developing an effective method for removing the waxy material.

Caterpillar Tractor Company -- Caterpillar Tractor Company manufactures precision-machined parts for heavy machinery at San Leandro, California, a location that is approximately 1 mile from the San Francisco bay. The environmental test hardware was mounted on the roof of a three-story structure housing the machining operation. The roof is tar, sealed with a white paint. It was observed during a visit to the test site that the air in the first floor machining area was hazy, apparently because of finely dispersed low-viscosity machine oil. This atmosphere and the effluent from the vapor degreasing area were vented through the roof in the area of the test hardware. Two cooling towers are also located on the roof.

The Caterpillar plant is situated in a heavily industrialized area, immediately surrounded by a polymer manufacturing plant, a vegetable truck farm, and a high-pressure washing station for large trucks. Consequently, there is a high moisture contribution to this area from the proximity of the bay and the truck wash station, and a source of loose, blowing soil from the truck farm. The test site is also located in the flight path for small aircraft traffic for the Oakland Airport. The assumption was made that a high concentration of exhaust fumes from small aircraft could contribute to the air quality in this location.

The soil in the San Leandro area is classified as Brunizem or Prairie Soil with a neutral pH. It is dark brown, mildly acidic surface soil, which overlaps a well-oxidized subsoil. There is no accumulation of lime carbonate in this soil type. The general climate is cool to warm temperature, humid, and has an annual precipitation of 25 to 30 inches. The primary vegetation is southwest broadleaf forest, although the area is in the transition zone for the redwood forest.[3]

As anticipated from the parametric study of the test site and the surrounding industries, the rate of soil accumulation on the reflector specimens was high. Reflectance losses of 20 to 75% due to soil accumulation were reported following 12 months of exposure. Cleaning with the Lime-Brite detergent restored the reflectance values of all material types, except Alzak, to 92 to 95% of their original values. A microscopic surface examination showed a small buildup of residual soil, which was not removed by cleaning with the McGean C-120 detergent.

The metallic elements of all collector specimens exhibited evidence of corrosion to varying degrees. The cleaned Alzak specimens had reflectance values which were 20 to 50% less than the original measurements. This loss was caused by large pits across the entire surface of the mirror sample. A white crystalline material was observed on the Alzak mirror surfaces which, upon removal, was found to cover large pits. The identity of the crystalline material is not known. Minor corrosion of the aluminum on the FEK-244 specimens was observed where damage to the acrylic film had occurred. The damage to the acrylic appeared to be from mechanical rather than from chemical sources. Corrosion of the silver on the glass reflectors appeared primarily along the edges, although some corrosion attack was seen in the center areas of the specimens.

Bates Container Corporation -- Bates Container Corp., located in Ft. Worth, Texas, manufacturers corrugated cardboard boxes by steam pressing sheets of paper interlaced with adhesive. Site documentation revealed no known plant processes that could affect the environmental exposure of the reflector/ receiver materials. Adjacent to the site was a rail line still currently in use by, primarily, freight trains. The rail line was approximately 150 ft from the test hardware. Although the proposed parabolic trough system for this site was planned to be a roof-mounted structure, the test hardware was located on the ground, as the area where the troughs were to be located was under construction and no suitable roof location could be found on other site structures. Subsequently, the system was changed to locate the collectors on the ground because of potential fire hazards. The on-going construction during the duration of the exposure test created temporarily high levels of airborne particulate.

Mesquite and desert grasslands are the primary forms of vegetation in the Ft. Worth area, where the climate is variable, from warm (85°F) summers to moderate (35°F) winters. The soil type is Rendzina, a neutral pH soil, which is a gray or black, organic-rich surface soil over a soft, white calcareous material derived from chalk, soft limestone, or marl. This soil is typically associated with "swellable" clays.[3]

The glass and FEK-244 specimens responded similarly to exposure conditions at this site, with specular reflectance losses for specimens in the X and Y orientations being $\leq$ 40% of the original reflectance values. Cleaning these specimens, using the Lime-Brite procedure, restored the reflectance values to $\geq$ 95% of the original values.

The Alzak specimens showed somewhat greater susceptibility to the accumulation of surface soil. Specular reflectance values were restored to ∿55% of the original values. Cleaning the Alzak specimens (Lime-Brite procedure) restored the values to $\geq$ 50% of original values in the worst case, i.e., Months 5, Z orientation, and to an average of 70% of original values for all orientations.

The surface analysis showed an increase in residual soil buildup for all specimens that was not effectively removed, even with the more stringent McGean C-120 detergent. However, this soil buildup did not significantly affect the specular reflectance measurements during the 1 year of exposure testing, except for the Alzak specimens.

Corrosion of the FEK-244 and glass reflector specimens was not observed. Only very minor corrosion was observed on the Alzak reflector specimens.

Experimental Results for Receiver Materials

The black chrome receiver materials, which were supplied by Dr. R. B. Pettit of SNLA, were evaluated for changes in solar absorptance (α_s) and emittance (ε) following the prescribed exposure conditions and duration at the IPH sites. The glass cover plate specimens were evaluated for changes in specular and hemispherical transmittance. A description of specimen preparation for the black chrome and glass cover plate materials is given in Appendix A. Heated receiver and glass test units were not exposed at Southern Union Refining Co., because of fire hazard, nor at Hilo Coast Processing Co., because of its early withdrawal from consideration as an IPH demonstration site.

Black Chrome Receiver Specimens -- The black chrome receiver materials were subjected to three types of exposure conditions that could cause degradation: (1) thermal cycling (successive exposure of 450±50°F for 12 hours followed by 12 hours of no thermal exposure), (2) photochemical degradation caused by exposure to the sun, and (3) environmental pollutant attack on the material caused by exposure to real industrial environments.

A control experiment was conducted in the laboratory to ascertain the effect of thermal cycling on the black chrome material. Four specimens were subjected to thermal exposure conditions identical to those at the field sites, but in the absence of light and environmental pollutants. These specimens were evaluated for α_s and ε before the thermal cycling test and, again, following 2, 6, and 9 months of thermal exposure.

Figure 15 shows the plot of α_s versus exposure duration for the four specimens from the control experiment. The range of α_s for the specimens before thermal cycling was 0.978 to 0.985. Following 2 months of thermal exposure, α_s for three specimens increased by 0.011 absorptance units. After 6 months of exposure, all specimens showed a decrease from the initial measurement of α_s by an average 0.010 absorptance units. The average α_s of the four specimens following 9 months of thermal cycling was 0.982, as compared to the average of the original α_s values of 0.982.

The average total variation of α_s of the control specimens, over the course of 9 months of test, was 0.979 ± 0.013. The Gier Dunkle solar reflectometer has an instrumental accuracy rating of ±0.015 absorptance units. Consequently, thermal cycling caused essentially no measurable change in the solar absorptance of the black chrome specimens.

Figure 16 shows a similar plot of emittance versus exposure duration for the same four control specimens. Original emittance measurements ranged from 0.136 to 0.166 ($\bar{\varepsilon}_o$ = 0.151 ± 0.009, where $\bar{\varepsilon}_o$ is the average initial emittance measurement). All four specimens showed average increases in ε, following cycling, as follows:

Exposure Duration	Average $(\varepsilon_T - \varepsilon_o)$
2 months	+ 0.008
7 months	+ 0.010
9 months	+ 0.010

where ε_T is the emittance measured at time, T, and ε_o is the original emittance measurement for the specimen. The quantity, $\varepsilon_T - \varepsilon_o$, is calculated for each individual specimen, and the four results for the control specimens were averaged to obtain Average $(\varepsilon_T - \varepsilon_o)$.

The instrumental accuracy rating for the Gier Dunkle infrared reflectometer is ±0.02 reflectance units. The maximum variation in ε for any specimen measured was less than this ±0.02 accuracy rating, indicating that thermal cycling caused no measurable change in the emissivity of the black chrome specimens.

The only observed degradation of the control specimens was the formation of gray spots (approximately 0.1 mm diameter) on the black chrome surface. This phenomenon was observed only after 9 months of thermal cycling.

Figures 17 and 18 show the plots of $\Delta\alpha_s$ versus exposure duration for specimens exposed at the IPH sites. $\Delta\alpha_s$ is calculated as the α_s of the exposed sample minus α_s of the same specimen before deployment. $+\Delta\alpha_s$ represents a decrease in the solar absorptance of the specimens. The lines N--- are the $\Delta\alpha_s$ values of the control specimens, as previously described.

FIGURE 15. PLOT OF ABSORPTANCE VS EXPOSURE DURATION FOR BLACK CHROME CONTROL

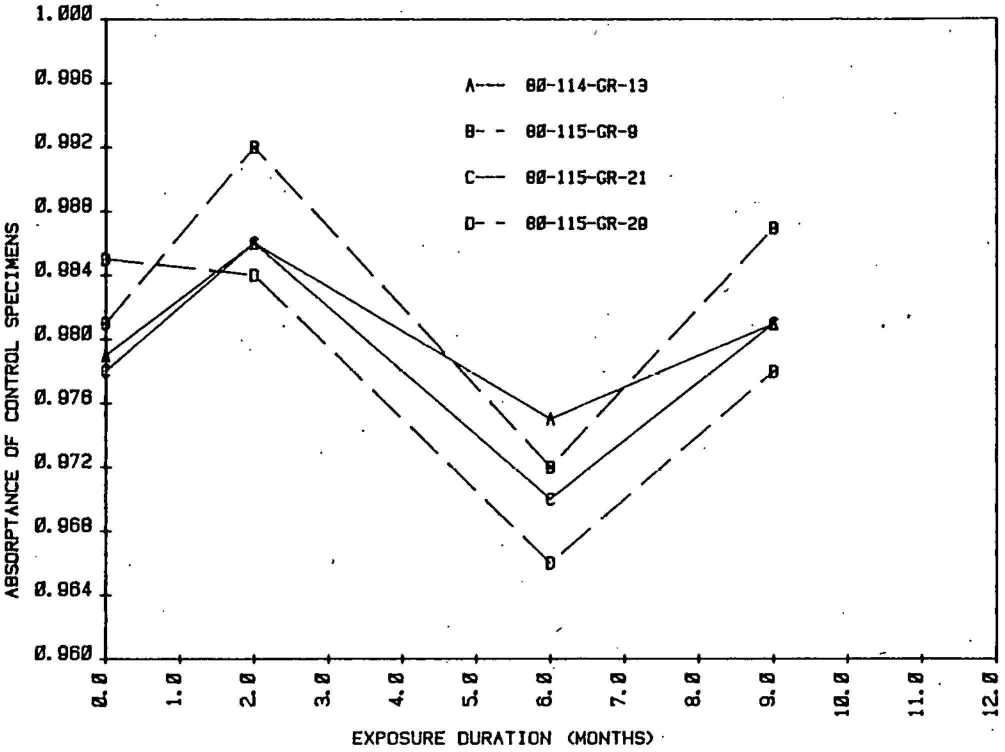


FIGURE 16. PLOT OF EMITTANCE VE EXPOSURE DURATION FOR BLACK CHROME CONTROL

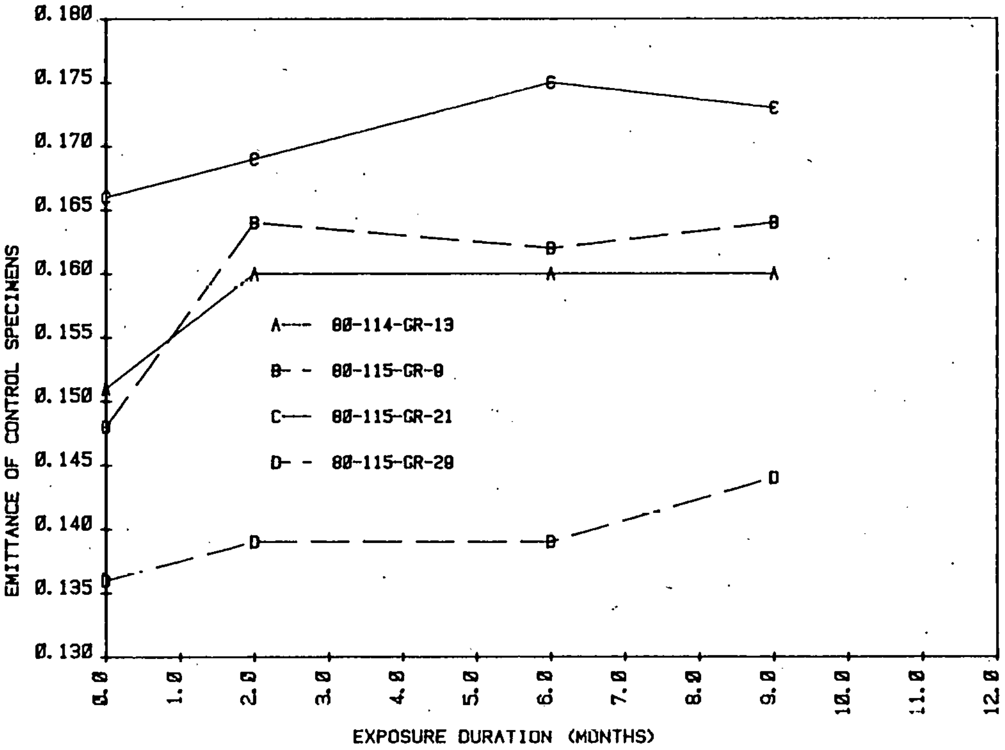


FIGURE 17 . PLOT OF ABSORPTANCE INITIAL - ABSORPTANCE EXPOSED VS EXPOSURE DURATION FOR BLACK CHROME ABSORBER

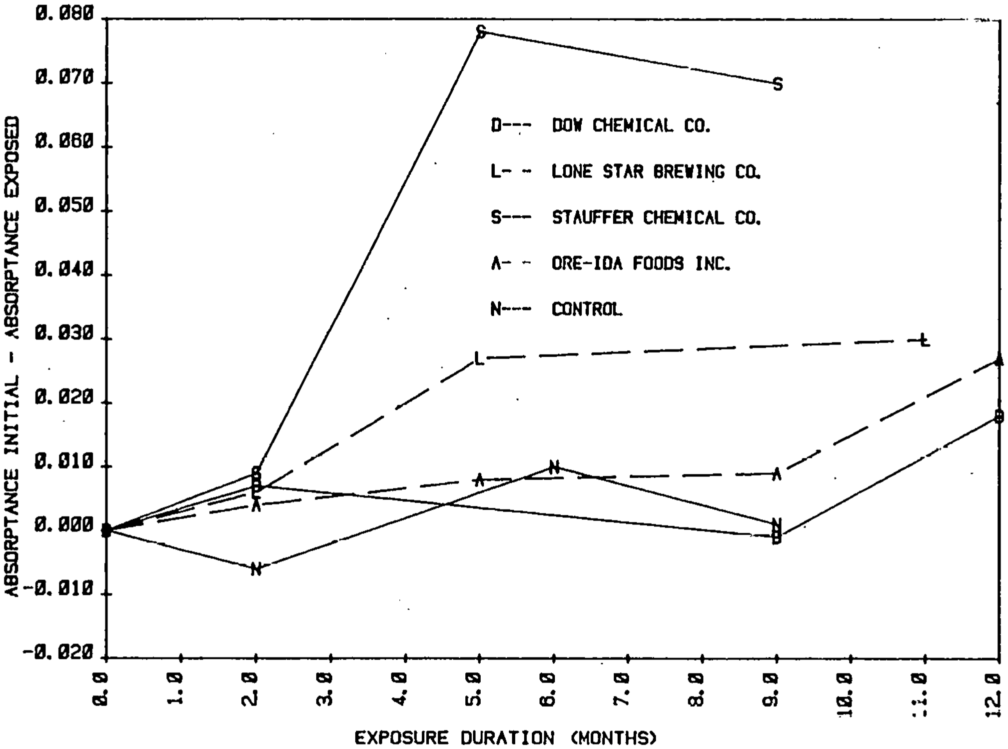
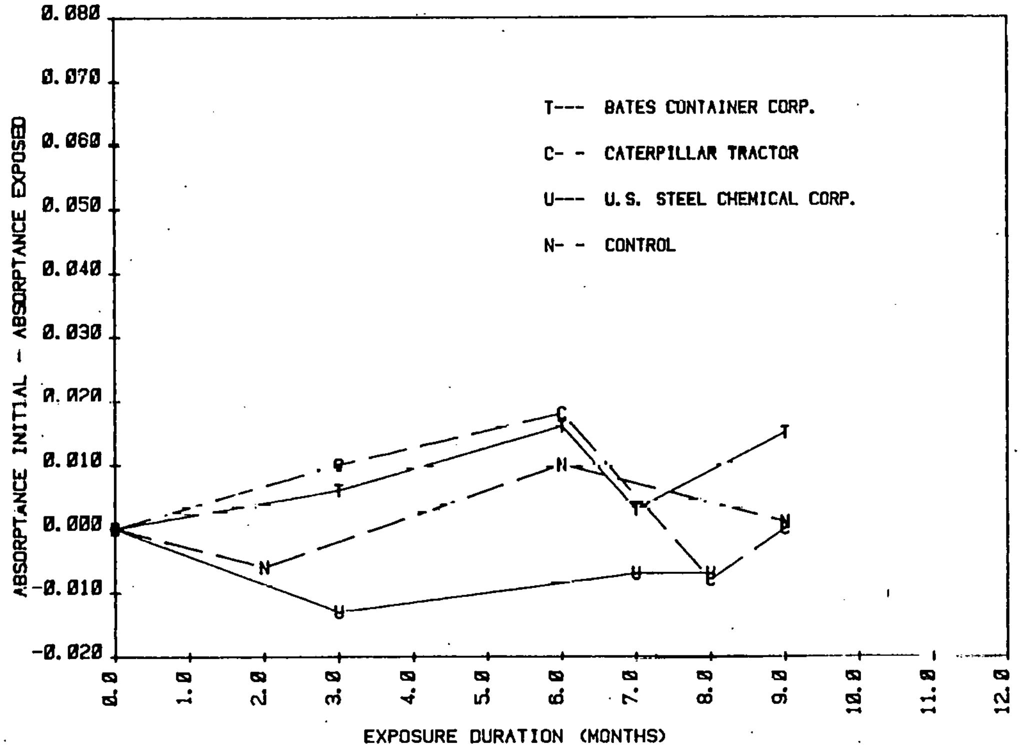


FIGURE 18 . PLOT OF ABSORPTANCE INITIAL - ABSORPTANCE EXPOSED VS EXPOSURE DURATION FOR BLACK CHROME ABSORBER



At three sites (Stauffer Chemical Co., Lone Star Brewing Co., Ore-Ida Foods, Inc.) black chrome specimens had measurable decreases in α_s, within the instrumental error of ±0.015 absorptance units, after 9 months of exposure. Stauffer Chemical Co. had the worst-case specimens, with a $\Delta\alpha_s$ of 0.079 ± 0.015 absorptance units after 6 months and a $\Delta\alpha_s$ of 0.071 ± 0.015 absorptance units after 9 months of exposure. Specimens exposed at Lone Star Brewing Co., had an average $\Delta\alpha_s$ of 0.030 ± 0.015 absorptance units over 6 to 9 months. Specimens from Ore-Ida Foods, Inc., did not show a measurable decrease in α_s until the ninth month of exposure, with a $\Delta\alpha_s$ of 0.029 ± 0.015 absorptance units.

Figures 19 and 20 show the plots of $\Delta\varepsilon$ versus exposure duration for the exposed specimens. $\Delta\varepsilon$ is calculated as the emittance of the exposed specimen minus the emittance of the same specimen before exposure. $+\Delta\varepsilon$ represents an increase in the emissivity of the specimen. The lines designated N--- are the $\Delta\varepsilon$ values of the control specimens, as previously described.

Average $\Delta\varepsilon$ measurements for the control specimens were 0.0 ± 0.02 reflectance units over the 9-month exposure period. Three sites (Dow Chemical Co., Caterpillar Tractor Co., U.S. Steel Chemical Co.) had specimens with $\Delta\varepsilon$ values for the exposed samples which were equal to those of the control specimens, within the measurement error of the instrument. All other sites showed measurable variations in $\Delta\varepsilon$ at 5 to 6 and at 9 months of exposure.

Specimens from Stauffer Chemical Co. had the most dramatic increase in ε, with a $\Delta\varepsilon$ of 0.26 ± 0.02 reflectance units at 6 and 9 months of exposure. Bates Container Corp. specimens had $\Delta\varepsilon$ values 0.05 ± 0.02 reflectance units at 6 months and 0.08 ± 0.02 reflectance units at 9 months. A constant $\Delta\varepsilon$ of 0.06 ± 0.02 reflectance units was reported at 6 to 9 months of exposure for the Lone Star Brewing Co. specimens, and Ore-Ida Foods, Inc., specimens showed measurable increases in ε at 9 months (0.03 ± 0.02 reflectance units) and 12 months (0.07 ± 0.02 reflectance units). The increase in emissivity for these sites generally appears to be progressive with time.

Many black chrome specimens received from the test sites had a number of visual defects, in addition to changes in the emittance and solar absorptance. The specimens were soiled where dust had accumulated on the surfaces and, at some sites, foreign matter (e.g., white crystalline deposits) was observed on

FIGURE 19. PLOT OF EMITTANCE EXPOSED - EMITTANCE INITIAL VS EXPOSURE DURATION FOR BLACK CHROME ABSORBER

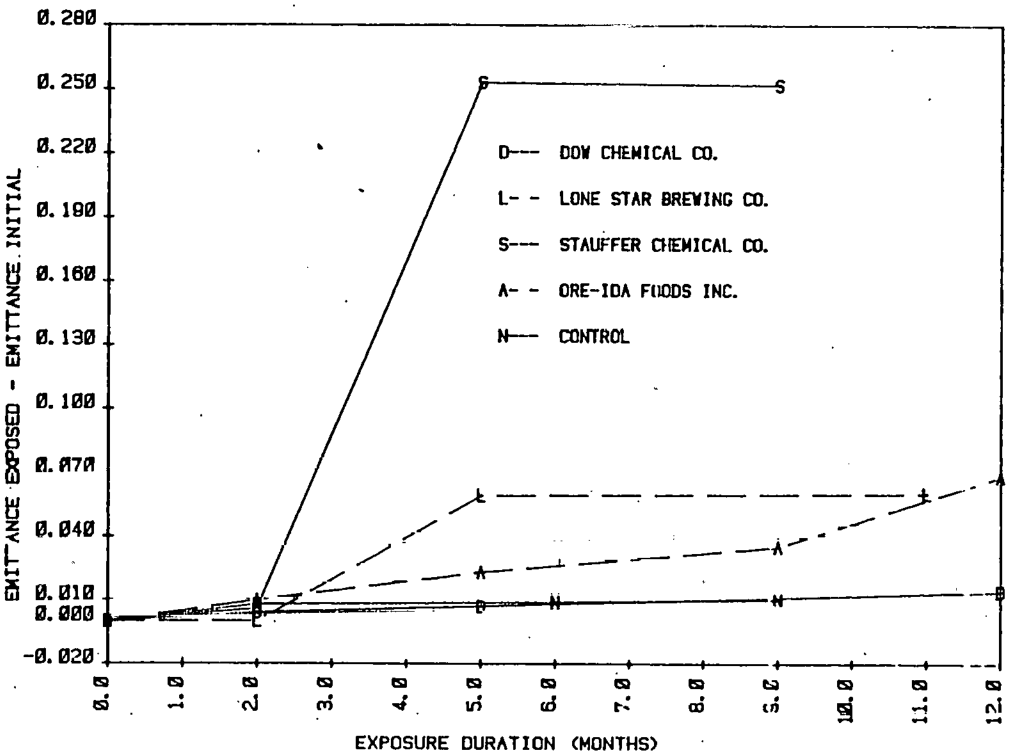
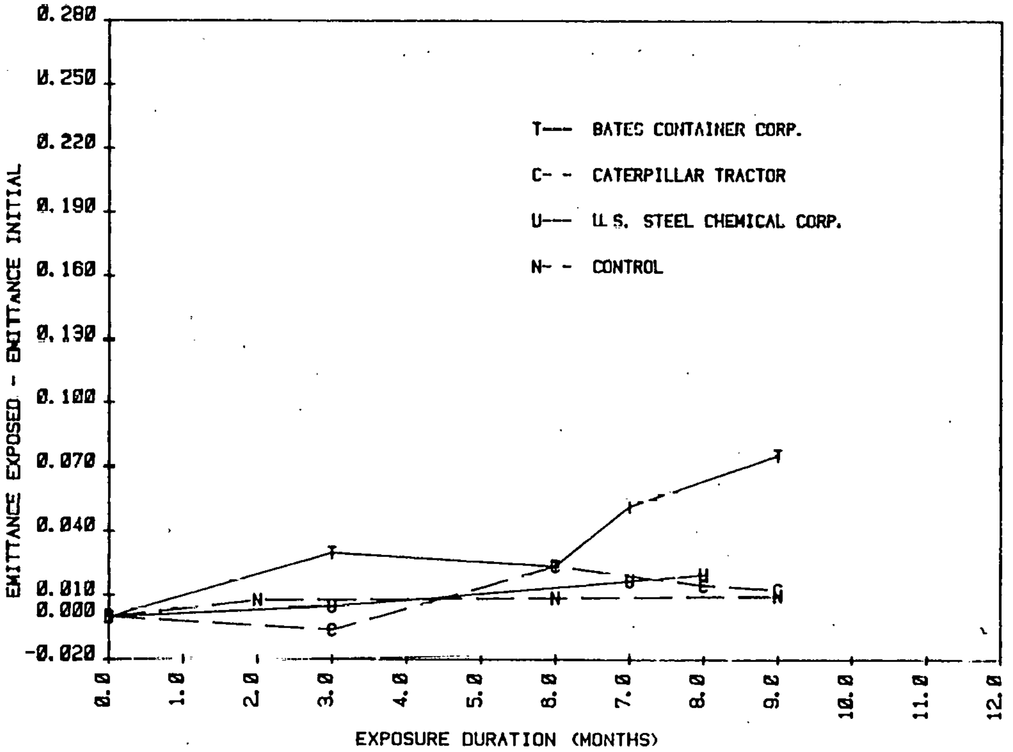


FIGURE 20. PLOT OF EMITTANCE EXPOSED - EMITTANCE INITIAL VS EXPOSURE DURATION FOR BLACK CHROME ABSORBER



the samples. At most sites, cracking of the black chrome plating was observed, and at some sites the rusting nickel support could be seen through holes which had developed in the plating. However, unless these localized defects were in one of three measurement locations on the specimens, they were not reflected in the α_s and ε measurements.

Glass Cover Plate Specimens -- The glass cover plate specimens were subjected to the same three types of field exposure conditions as were the black chrome receiver specimens. A laboratory control experiment for the glass cover plate specimens was conducted concurrently for the black chrome receiver specimens, using the same exposure instrumentation and conditions.

The glass cover plate control specimens were evaluated for specular transmittance (Ts) before the thermal cycling test and also following 2, 6, and 9 months of thermal exposure. Because of programmatic time constraints, hemispherical transmittance (T_H) measurements were not made on the control specimens, but were made on the field-exposed specimens.

Figure 21 shows the results obtained for Ts measurements on the control specimens. The Ts measurements were made (1) before inception of the test, (2) following the prescribed exposure duration for the uncleaned specimen, and (3) following cleaning of the specimen. The Lime-Brite cleaning procedure was used. The test was conducted in the absence of light and in a laboratory environment; consequently, the only soiling which occurred was from normal laboratory dust. The Ts results for the control specimens were the arithmetic mean of four controls.

The data are plotted as follows:

X-axis: Exposure duration, months

Y-axis: fraction of original transmittance, where the fraction is calculated as:

$$\frac{\text{Ts, following exposure}}{\text{Ts, initial}}$$

The solid lines on the plot (——) represent measurements for the cleaned specimens, and the dashed lines (----) represent measurements for the soiled specimens. All glass measurement plots are formatted identically. Incomplete data was available for some of the field-exposed specimens, as some broke during the thermal cycling test.

The glass cover plate control specimens, which had been thermally cycled and not cleaned, showed a continuing loss in Ts from Month 0 to Month 6 (approximately 30% loss in Ts) with an approximate 20% increase in Ts from Month 6 to Month 9. Visual examination of the specimens showed dust accumulated on the surface. Cleaning the specimens restored the Ts to the original value, so thermal cycling of the glass cover plates caused no irreversible degradation.

Figures 22 through 28 show the plots of the fraction of the original transmittance (specular and hemispherical) versus exposure duration for the glass cover plate specimens at the IPH sites. Four sites (Dow Chemical Co., Lone Star Brewing, U.S. Steel Chemical Co., Bates Container Corp.) showed virtually identical T_H measurements for both the soiled and cleaned specimens for the exposure duration and showed total losses in $T_H \leq 5\%$ of the original transmittance. These four sites had Ts values for the soiled samples that were 65 to 85% of the original measurements. Upon cleaning, the Ts was restored to 75 to 95% of the original Ts.

T_H values after 12 months of exposure for the soiled samples of glass cover plates at Ore-Ida Foods, Inc., were approximately 90% of the original T_H, but cleaning the specimens restored the T_H to approximately 1% of original. Soil accumulation on the specimen surfaces caused a sharp decrease in Ts, particularly from Months 6 to 12, but cleaning restored the specular transmittance to approximately 90% of the original values.

Glass cover plates at Caterpillar Tractor Co. and Stauffer Chemical Co. behaved similarly to the Ore-Ida specimens, with losses in transmittance, both T_H and Ts, reported for the soiled specimens. Cleaning restored Ts to within 10% and T_H to within 1% of the original values. $\bar{T}_H$ values for exposed specimens at Stauffer Chemical Co. at 9 months are not available because the specimen was broken after the Ts measurement.

FIGURE 21. PLOT OF TRANSMITTANCE VS EXPOSURE DURATION FOR GLASS COVER PLATES

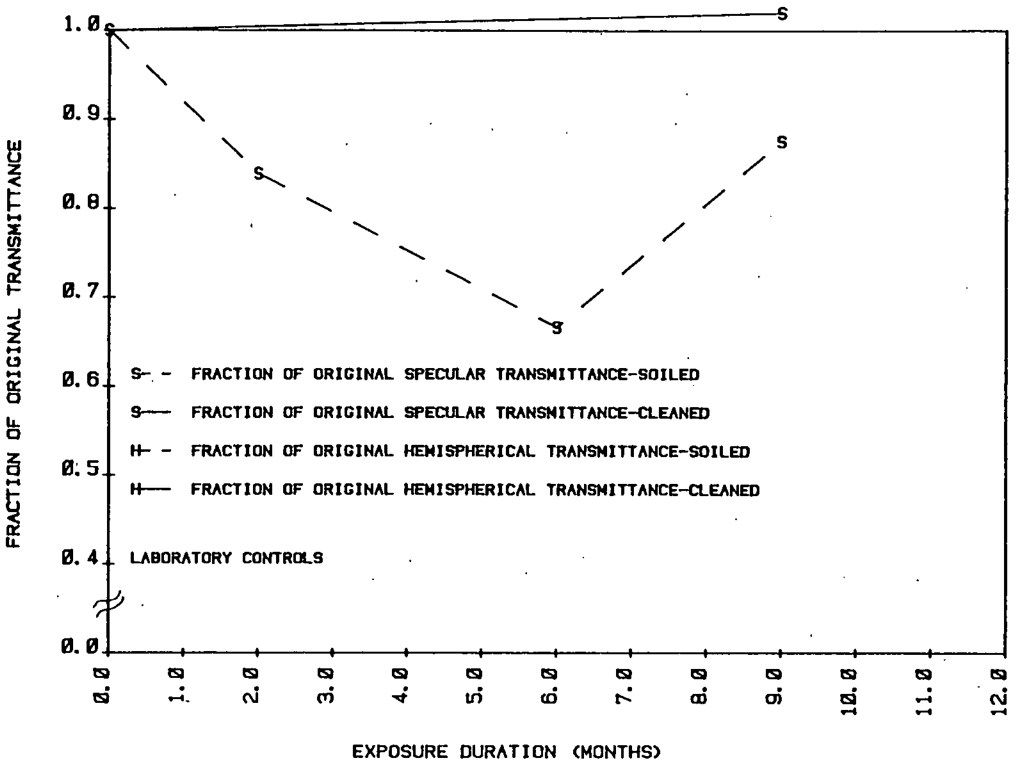


FIGURE 22. PLOT OF TRANSMITTANCE VS EXPOSURE DURATION FOR GLASS COVER PLATES

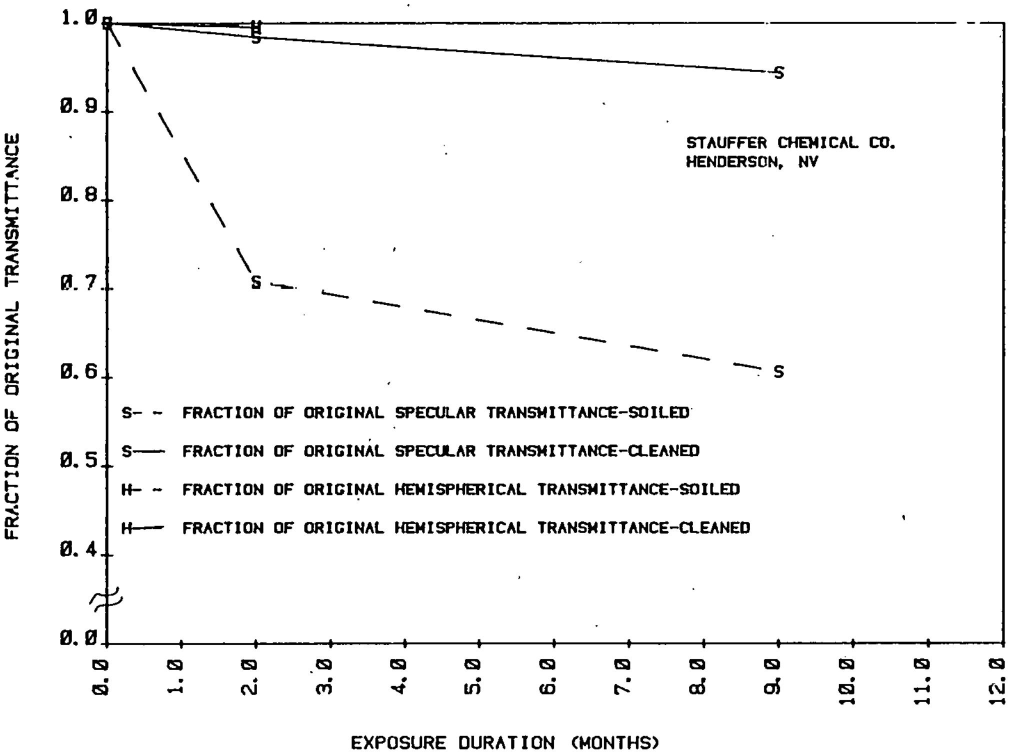


FIGURE 23. PLOT OF TRANSMITTANCE VS EXPOSURE DURATION FOR GLASS COVER PLATES

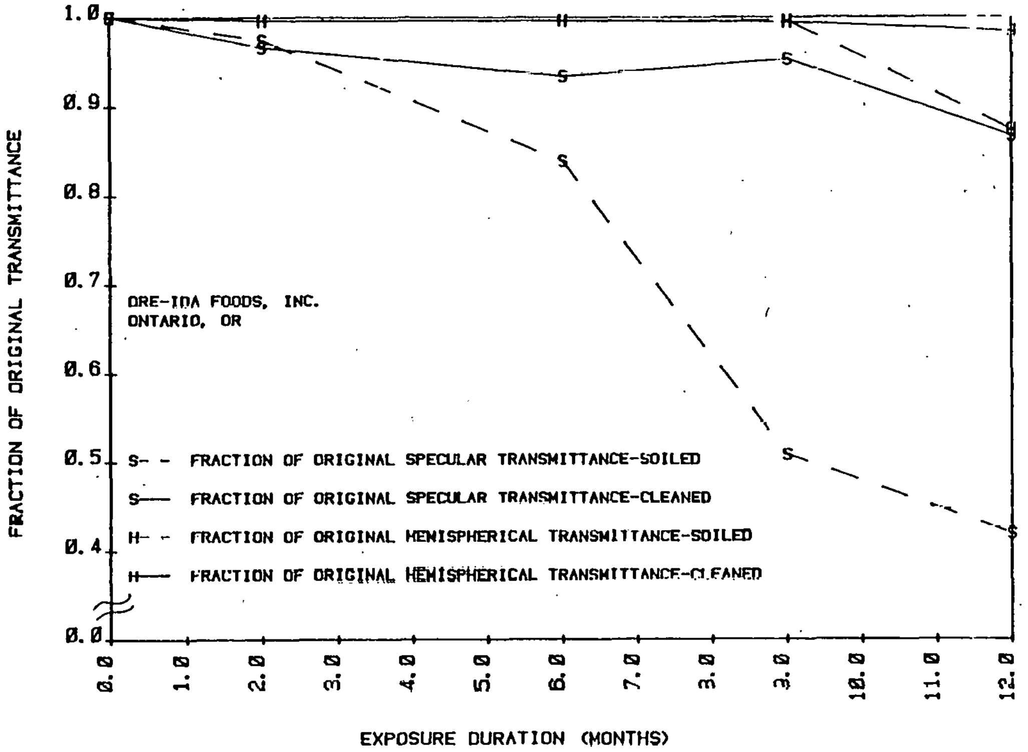


FIGURE 24. PLOT OF TRANSMITTANCE VS EXPOSURE DURATION FOR GLASS COVER PLATES

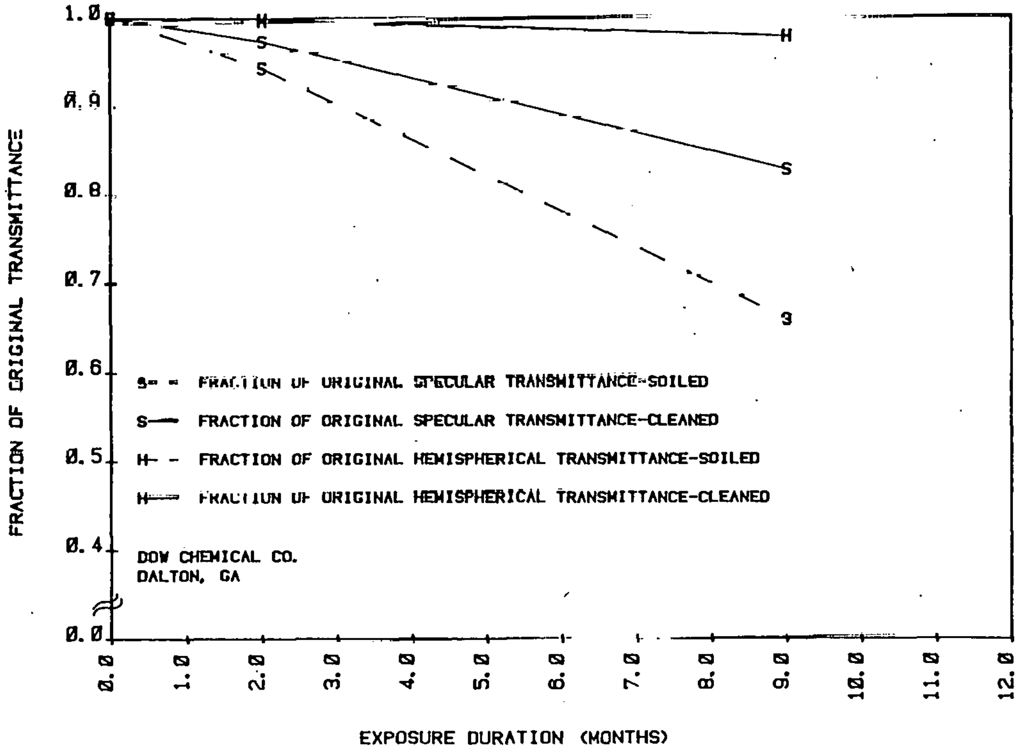


FIGURE 25. PLOT OF TRANSMITTANCE VS EXPOSURE DURATION FOR GLASS COVER PLATES

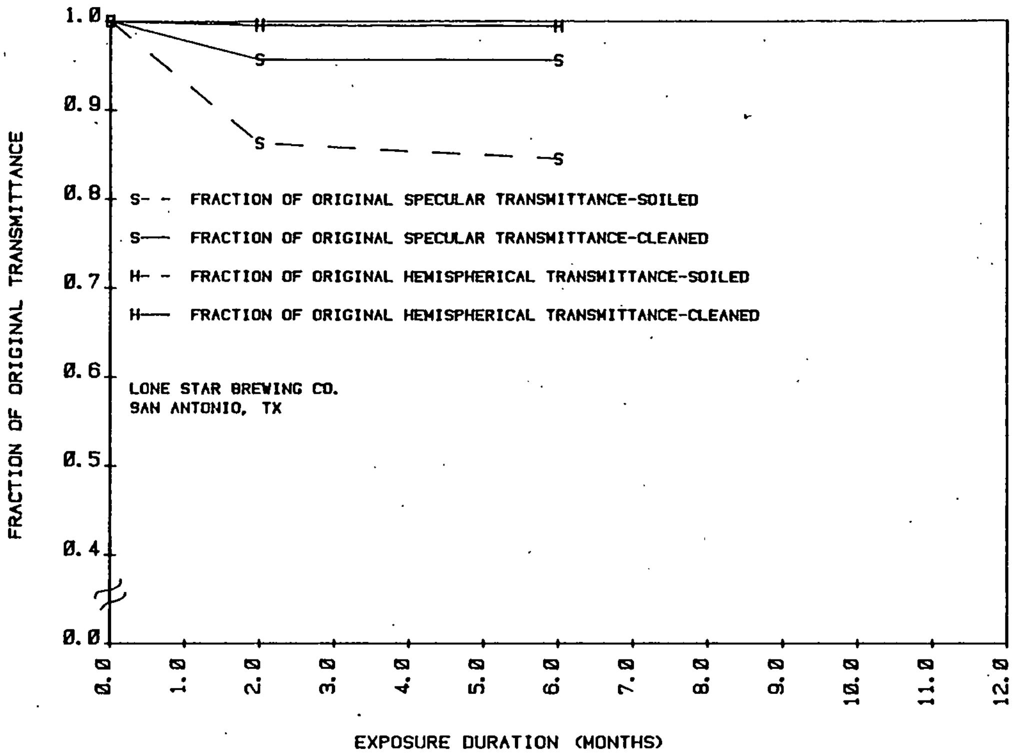


FIGURE 26 . PLOT OF TRANSMITTANCE VS EXPOSURE DURATION FOR GLASS COVER PLATES

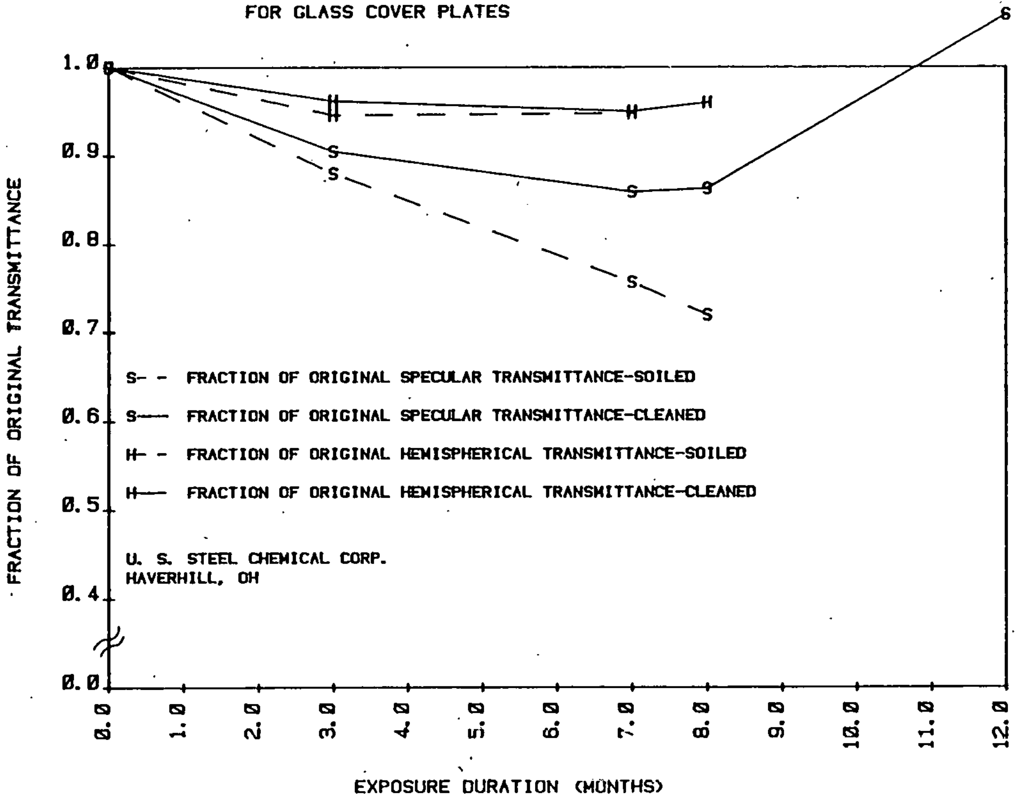


FIGURE 27. PLOT OF TRANSMITTANCE VS EXPOSURE DURATION FOR GLASS COVER PLATES

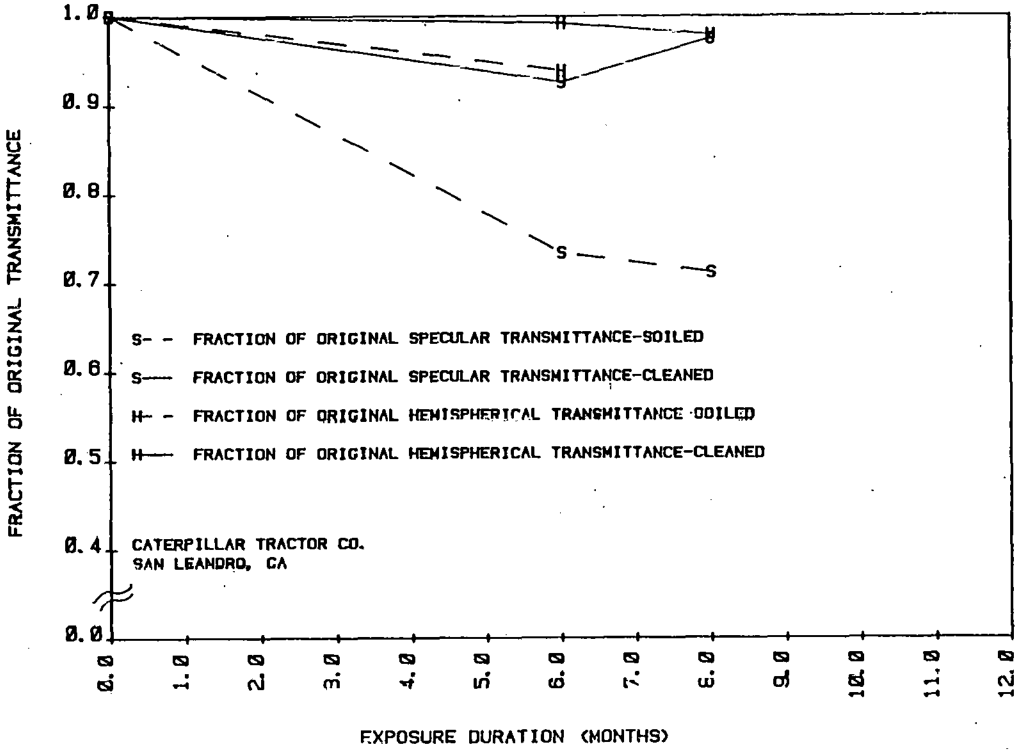
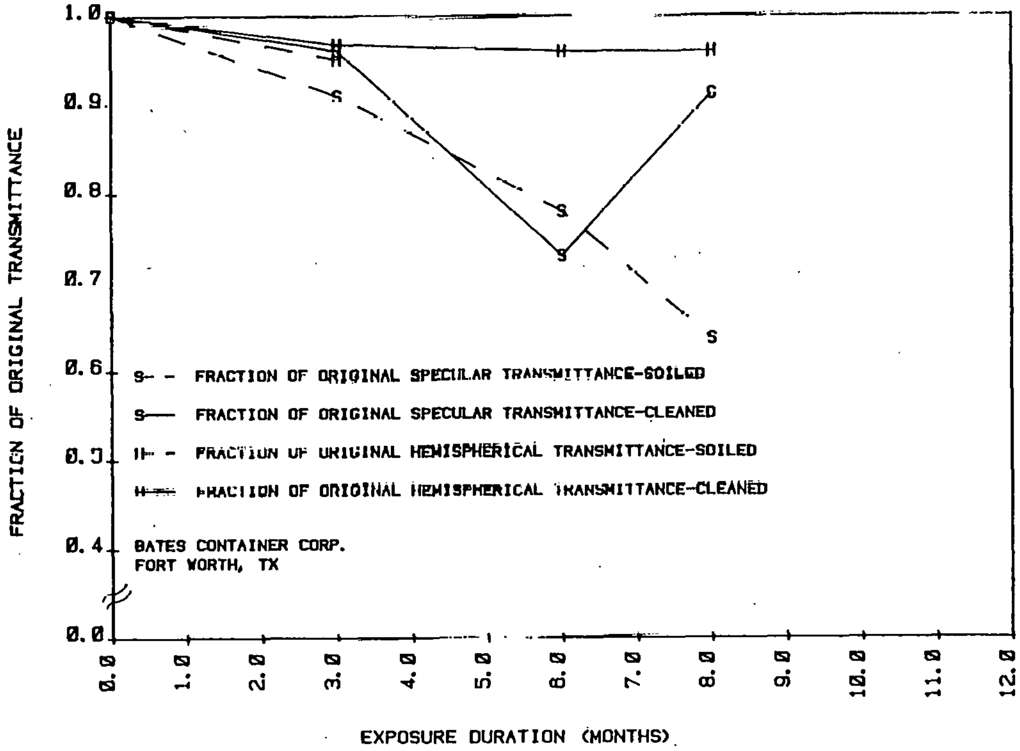


FIGURE 28. PLOT OF TRANSMITTANCE VS EXPOSURE DURATION FOR GLASS COVER PLATES



Statistical Analysis of Specular Reflectance of the Reflector Specimens

During the course of this study, answers were sought to the following questions: (1) were there differences in the susceptibility of the three reflector materials to soiling, and (2) were the three materials equally responsive to cleaning?

These questions were investigated by constructing bar plots of all data generated during this study for each specific material. The graphs were constructed by plotting the relative population of specimens of one material (as a fraction of the total number of samples) which had lost a discrete value of specular reflectance. A plot was constructed for the soiled and the cleaned samples. The measurements are shown for all specimens evaluated in this program, and consideration is not given separately to site location, cooling towers, soil type, or any other impacting parameters. The bar plots show relative trends for the reflector specimens. All subsequent calculations in this section were done using actual numerical values.

Figures 29 through 31 show the bar plots of the specular reflectance values for the soiled samples. The plots for the glass (Figure 29) and the FEK-244 (Figure 30) specimens show that the two materials have very similar susceptibilities for surface soil accumulation, with 70% of the sample population density losing 40% or less specular reflectance after 1 to 12 months of exposure.

The remaining 30% of the samples were fairly uniformly distributed from reflectance losses of 41 to 100%. The Alzak specimens had a different profile (Figure 31), with approximately 70% of the specimens losing between 0 to 54% specular reflectance. Thus, the Alzak material appears to be slightly more susceptible to soiling.

However, the real differences in the reflector materials become apparent in the specular reflectance measurements for the cleaned specimens (Figures 32 through 34). Approximately 8% more of the silvered-glass specimens could be restored to 96% of the original specular reflectance values than could the FEK-244 specimens. As these reflectance measurements for the cleaned speci-

FIGURE 29. PLOT OF FRACTION OF TOTAL IN EACH COMPOSITION VS PERCENTAGE LOSS IN SPECULAR REFLECTIVITY

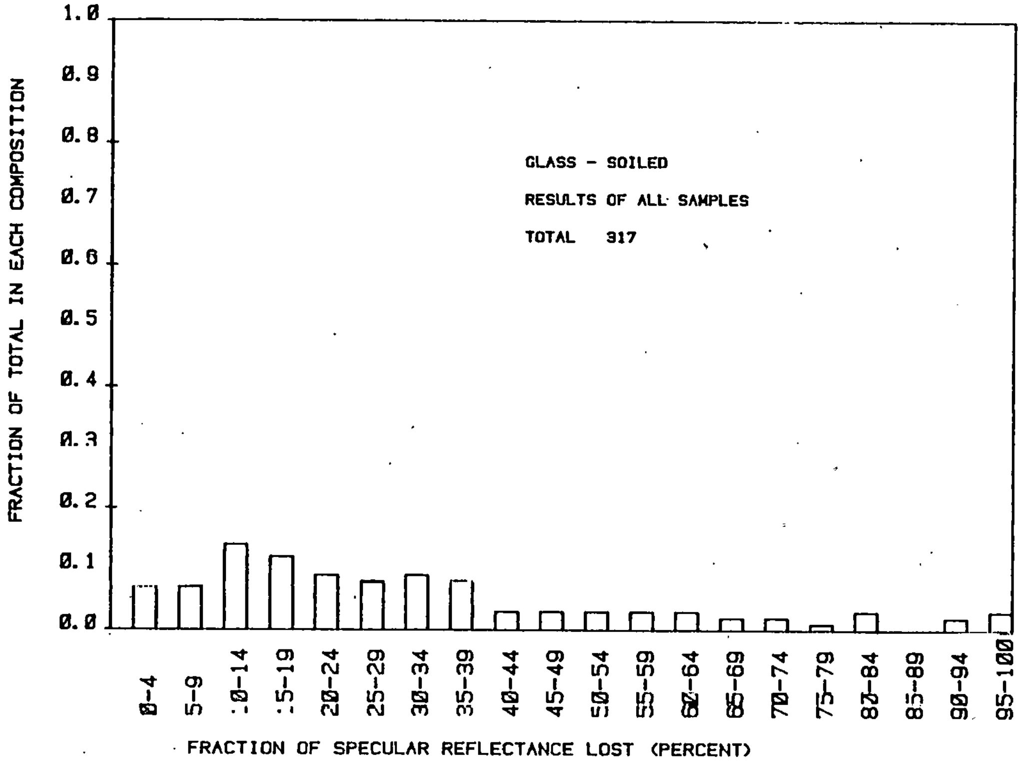


FIGURE 30. PLOT OF FRACTION OF TOTAL IN EACH COMPOSITION VS PERCENTAGE LOSS IN SPECULAR REFLECTIVITY

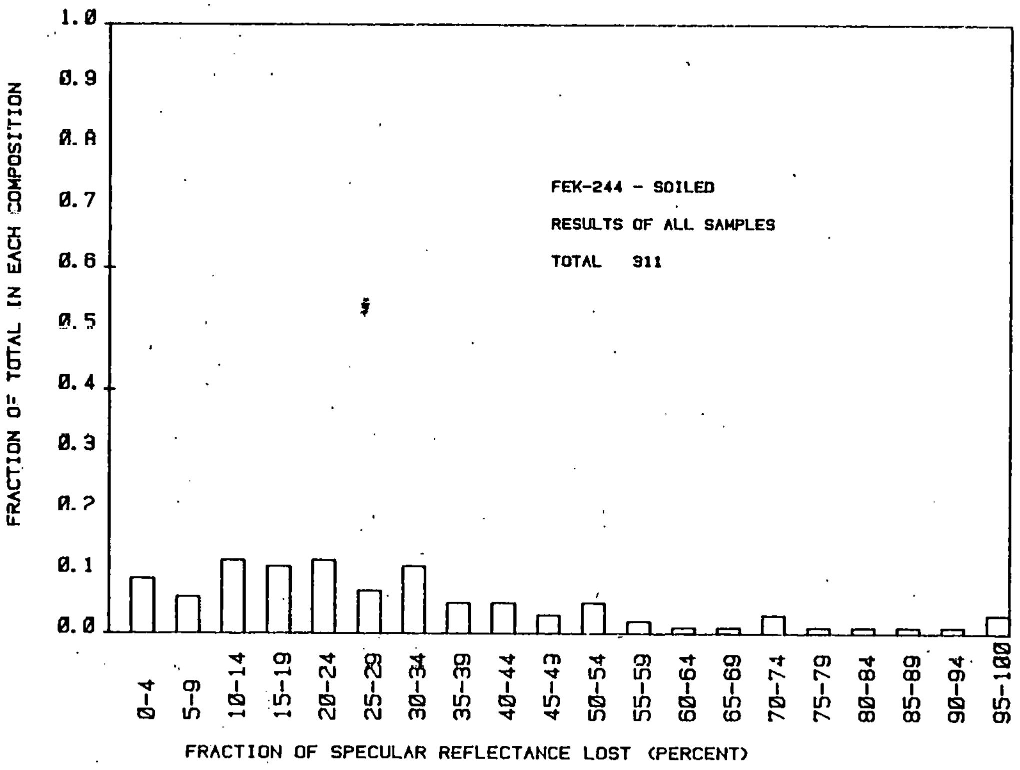


FIGURE 31. PLOT OF FRACTION OF TOTAL IN EACH COMPOSITION VS PERCENTAGE LOSS IN SPECULAR REFLECTIVITY

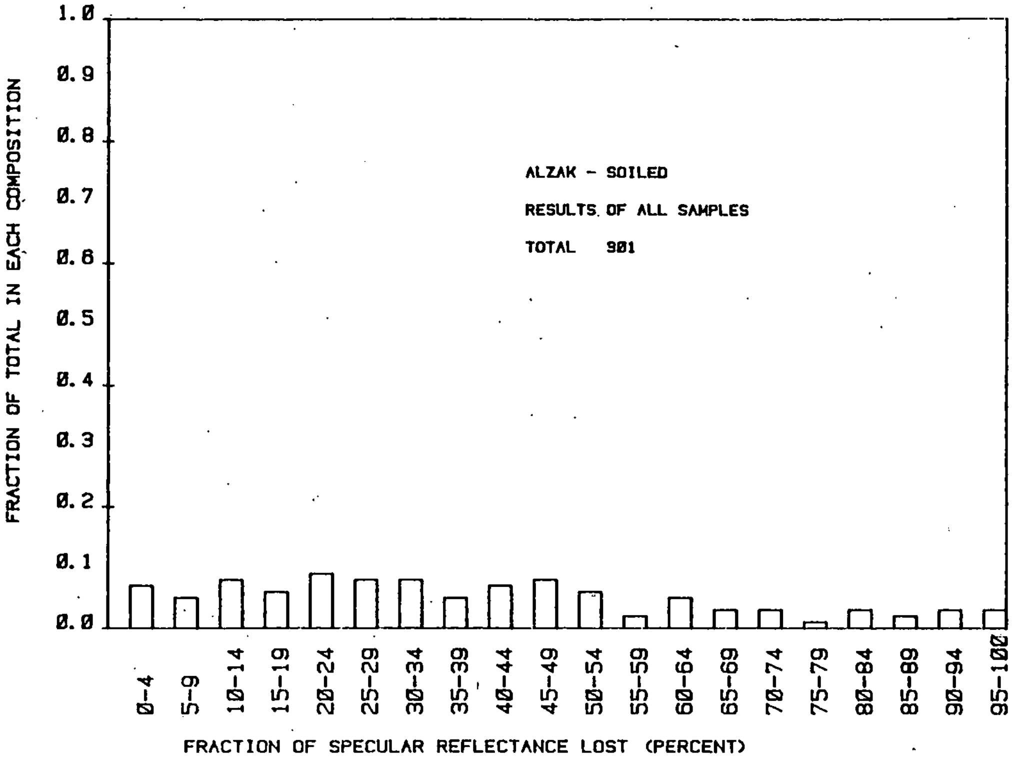


FIGURE 32. PLOT OF FRACTION OF TOTAL IN EACH COMPOSITION VS PERCENTAGE LOSS IN SPECULAR REFLECTIVITY

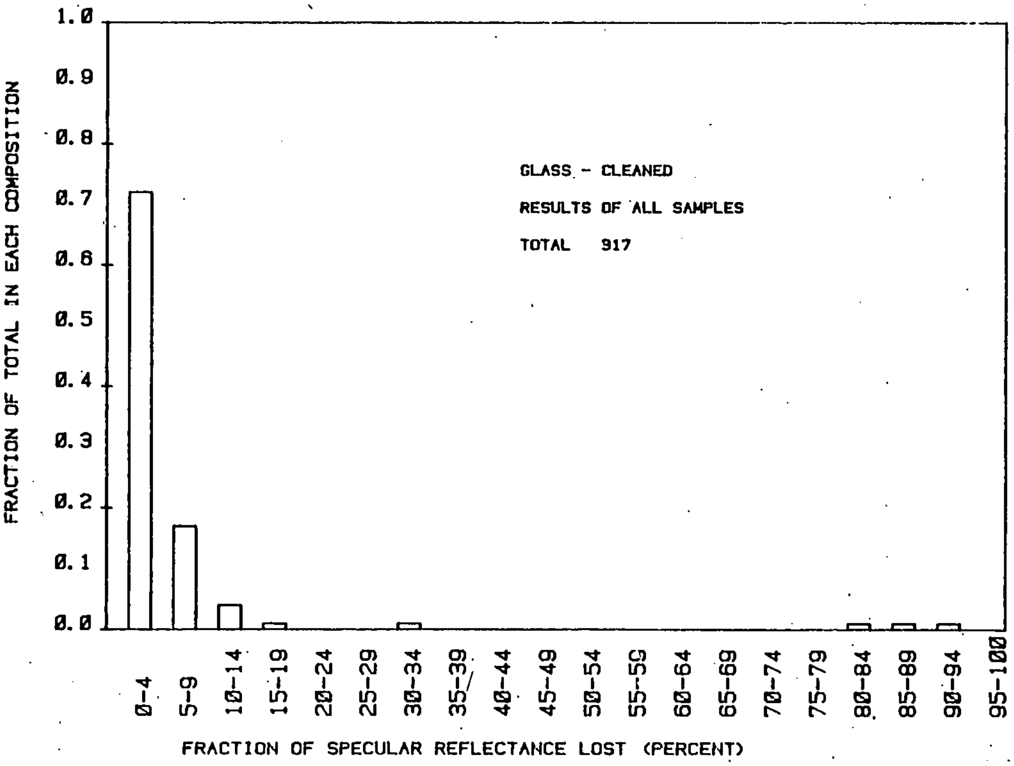


FIGURE 33 . PLOT OF FRACTION OF TOTAL IN EACH COMPOSITION VS PERCENTAGE LOSS IN SPECULAR REFLECTIVITY

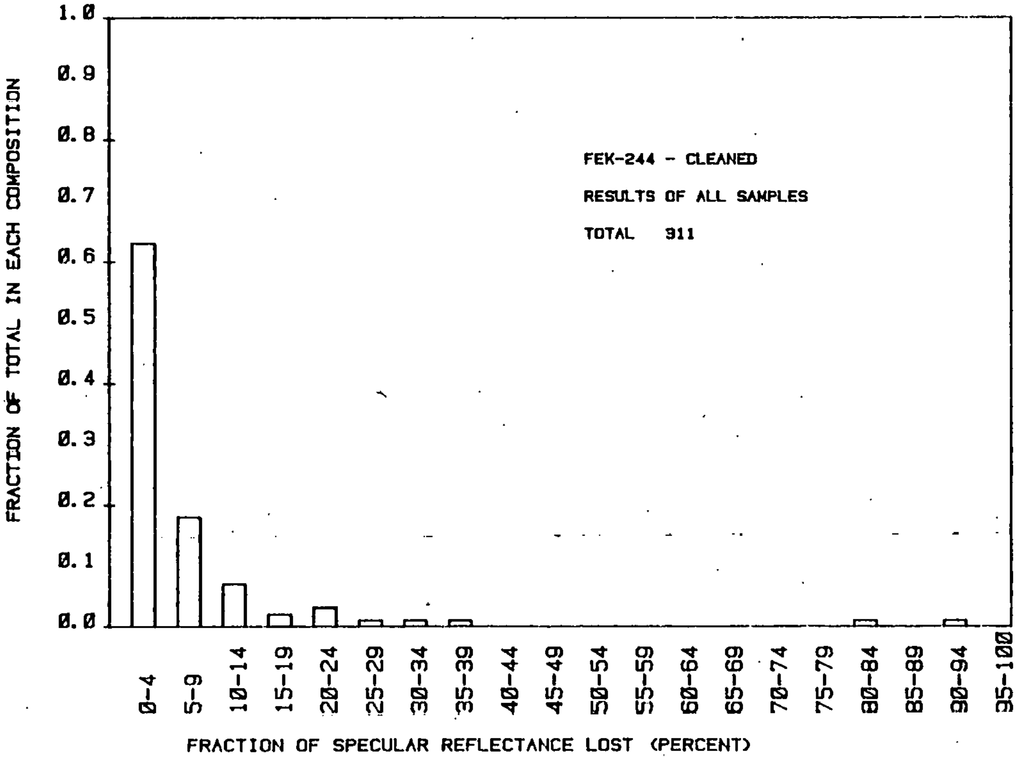
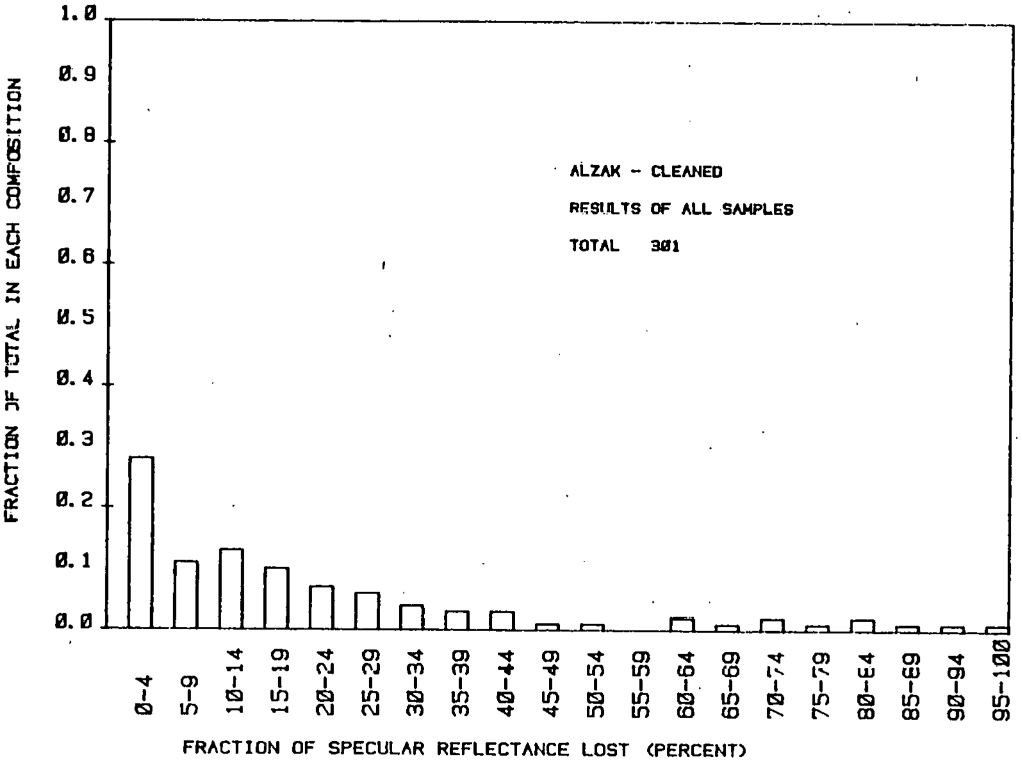


FIGURE 34. PLOT OF FRACTION OF TOTAL IN EACH COMPOSITION VS PERCENTAGE LOSS IN SPECULAR REFLECTIVITY



mens represent reflectance losses caused both by corrosion and soiling, it is believed that the 8% figure should be higher since the FEK-244 specimens did not corrode as significantly as did the silvered-glass specimens. The most significant losses in specular reflectance were for the Alzak specimens. These measurements, again, reflect both corrosion and residual soil retention. A large contributor to the low specular reflectance values for Alzak was its low resistance to corrosion. However, the optical microscopic evaluation of the reflector specimens revealed that the Alzak specimens also had higher levels of residual soil retention than did the other two materials.

Figures 35 through 52 show the reflector material population that was exposed 1, 6, and 12 months as a function of percent specular reflectance loss for both the soiled and cleaned specimens. These plots show that increased duration of exposure shifts the population of the reflector specimens to the larger percentage of specular reflectance loss. The ability of the specimens to be cleaned also decreases with exposure duration, with glass reflectors having the greater ability to be cleaned over FEK-244, followed then by Alzak.

Degradation Mechanisms of Reflector Specimens

In situ environmental exposure tests comprise a complex matrix of parameters, e.g., meteorological, industrial plant process and resultant air quality, and soil chemistry, which could affect the optical properties of the materials under investigation. Because of the potential for site-specific degradation mechanisms, each site was documented photographically (when permission was obtained) and a description of plant structures and processes and surrounding industries is given in Table 1. Each site had to be evaluated independently because the environment at each location was unique.

As anticipated, the environment at each of the nine sites produced different degradation mechanisms for the reflector specimens and varying degrees of degradation. Two primary degradation mechanisms were observed: (1) corrosion of the metallic elements of the samples, and (2) a tenacious layer of surface soil, which could not be removed by routine cleaning procedures using both the Lime-Brite and the more chemically aggressive McGean C-120 detergent. A third

FIGURE 35 . PLOT OF FRACTION OF TOTAL IN EACH COMPOSITION VS PERCENTAGE LOSS IN SPECULAR REFLECTIVITY

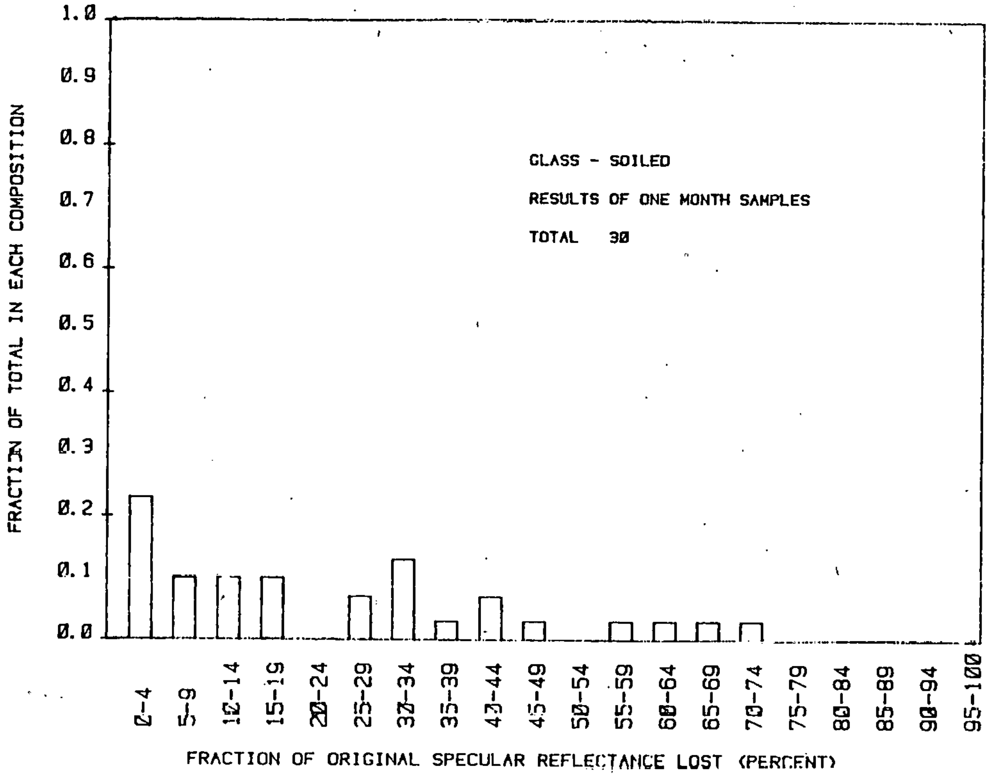


FIGURE 36 . PLOT OF FRACTION OF TOTAL IN EACH COMPOSITION VS PERCENTAGE LOSS IN SPECULAR REFLECTIVITY

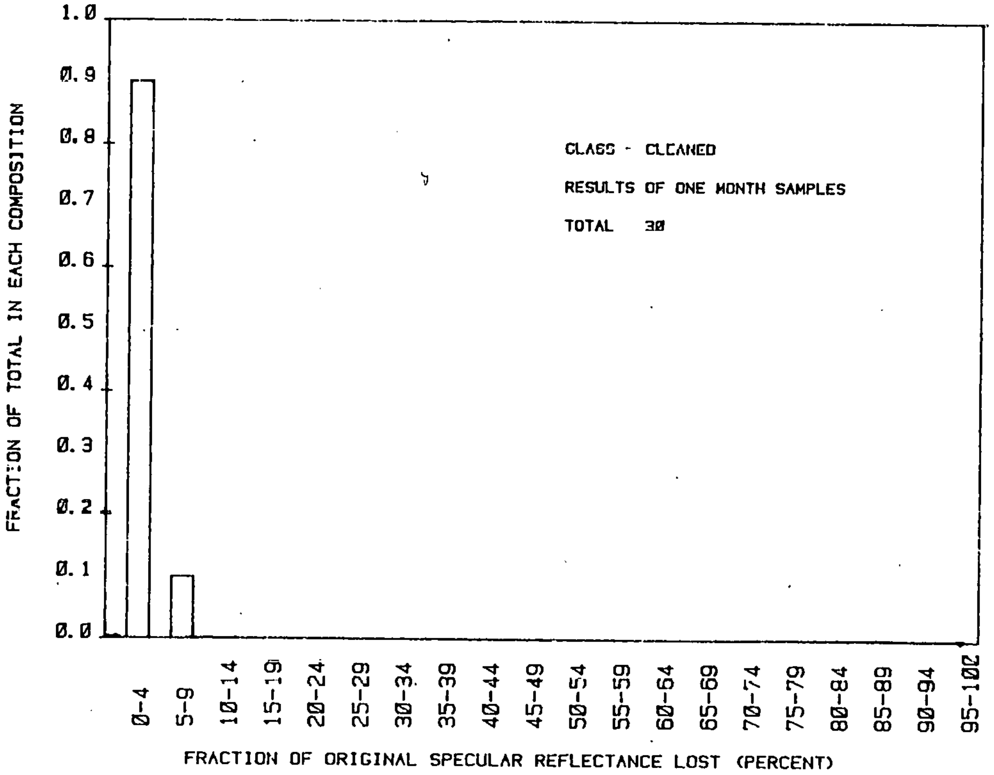


FIGURE 37 . PLOT OF FRACTION OF TOTAL IN EACH COMPOSITION VS PERCENTAGE LOSS IN SPECULAR REFLECTIVITY

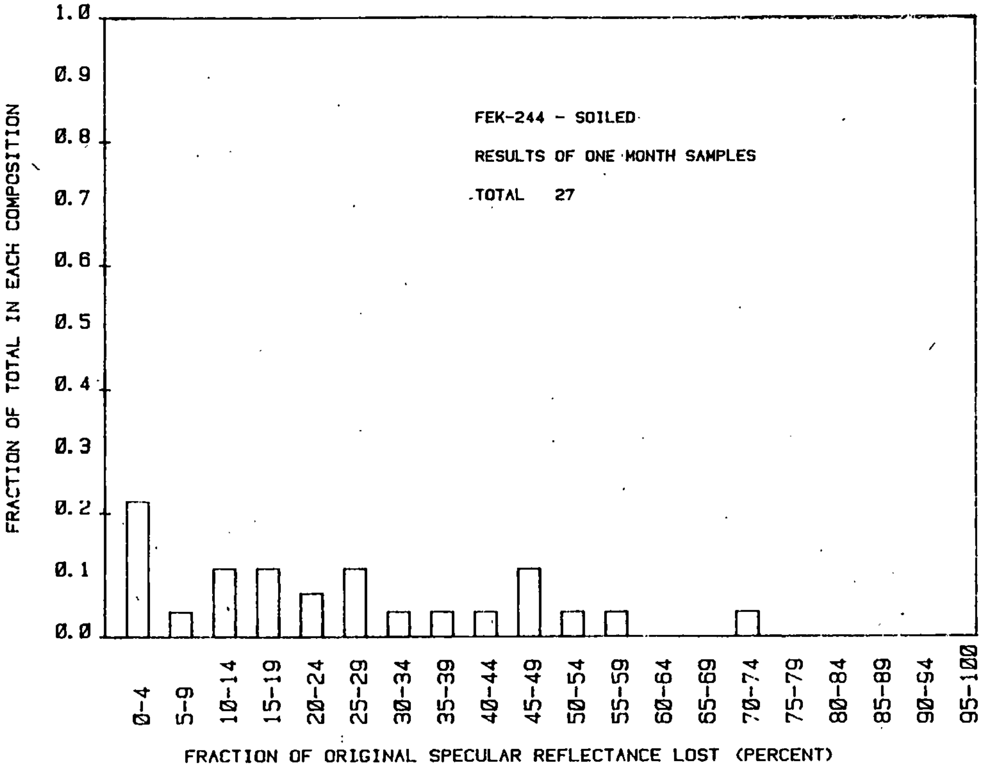


FIGURE 38 . PLOT OF FRACTION OF TOTAL IN EACH COMPOSITION VS PERCENTAGE LOSS IN SPECULAR REFLECTIVITY

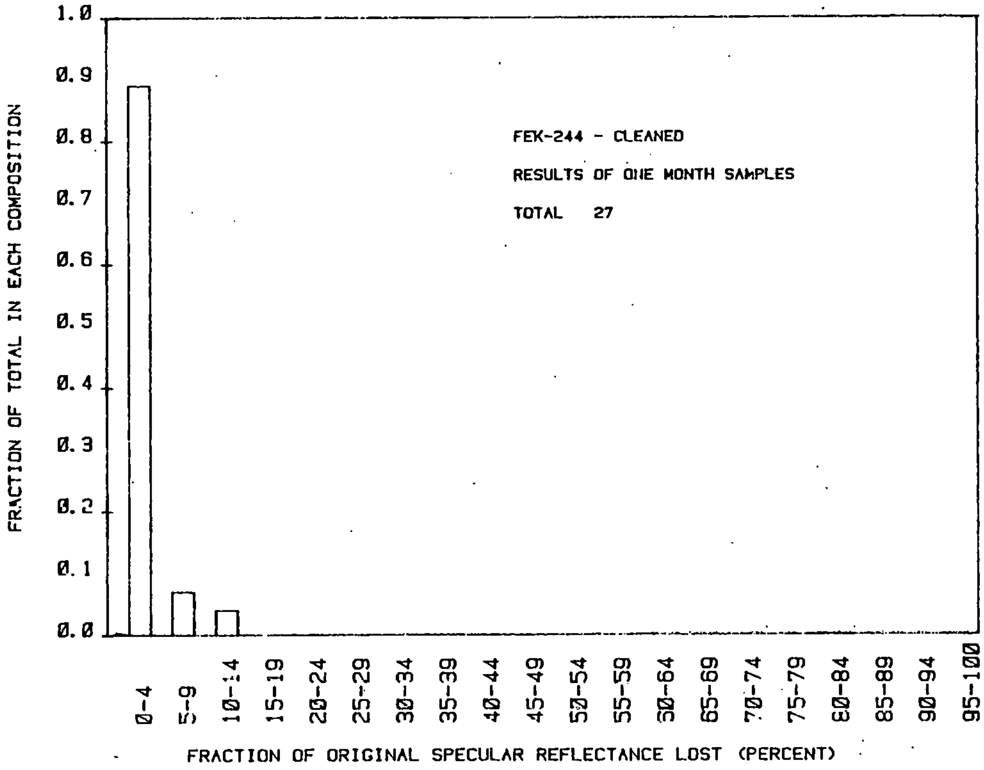


FIGURE 39 . PLOT OF FRACTION OF TOTAL IN EACH COMPOSITION VS PERCENTAGE LOSS IN SPECULAR REFLECTIVITY

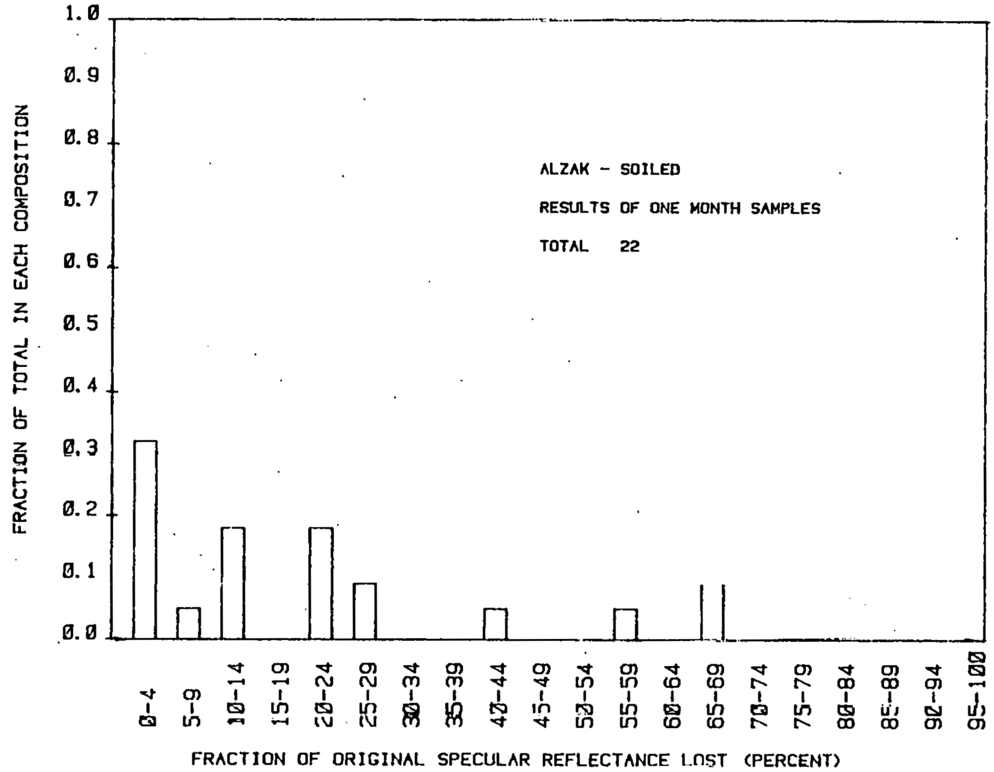


FIGURE 40 . PLOT OF FRACTION OF TOTAL IN EACH COMPOSITION VS PERCENTAGE LOSS IN SPECULAR REFLECTIVITY

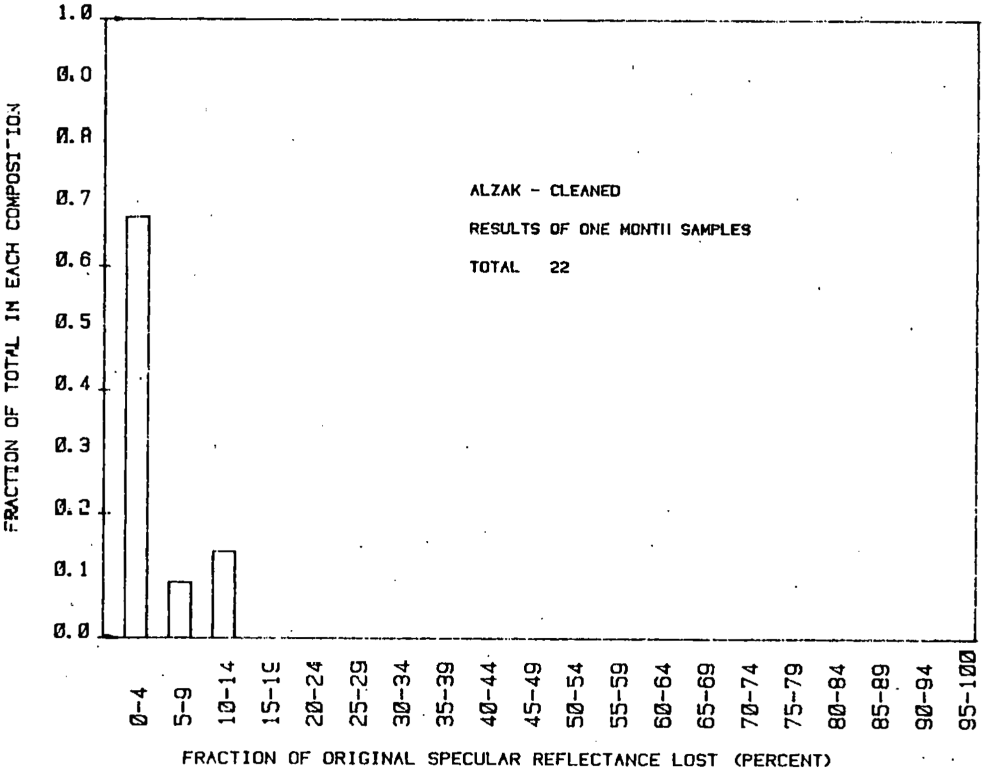


FIGURE 41 . PLOT OF FRACTION OF TOTAL IN EACH COMPOSITION
VS PERCENTAGE LOSS IN SPECULAR REFLECTIVITY

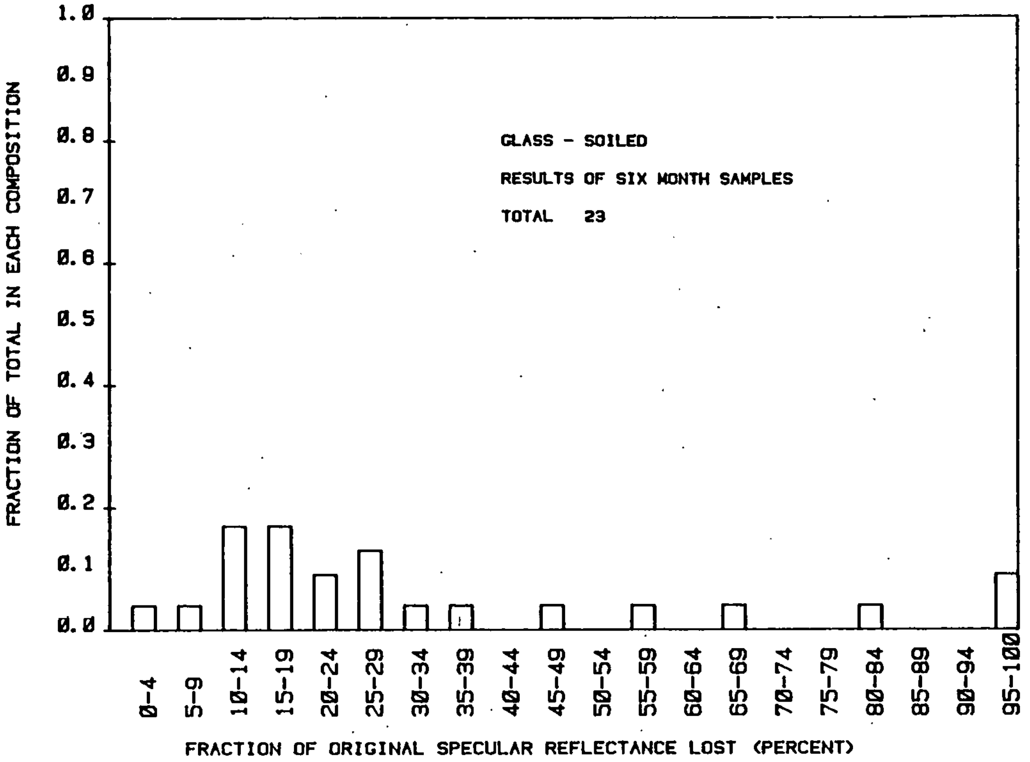


FIGURE 42 . PLOT OF FRACTION OF TOTAL IN EACH COMPOSITION
VS PERCENTAGE LOSS IN SPECULAR REFLECTIVITY

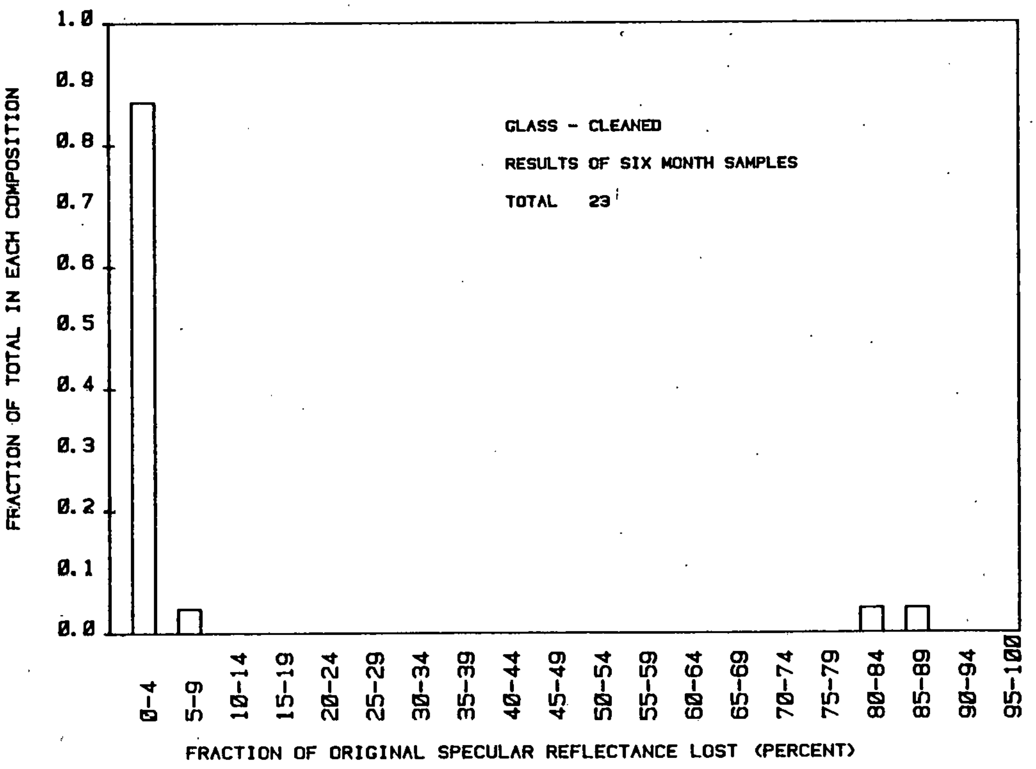


FIGURE 43 . PLOT OF FRACTION OF TOTAL IN EACH COMPOSITION VS PERCENTAGE LOSS IN SPECULAR REFLECTIVITY

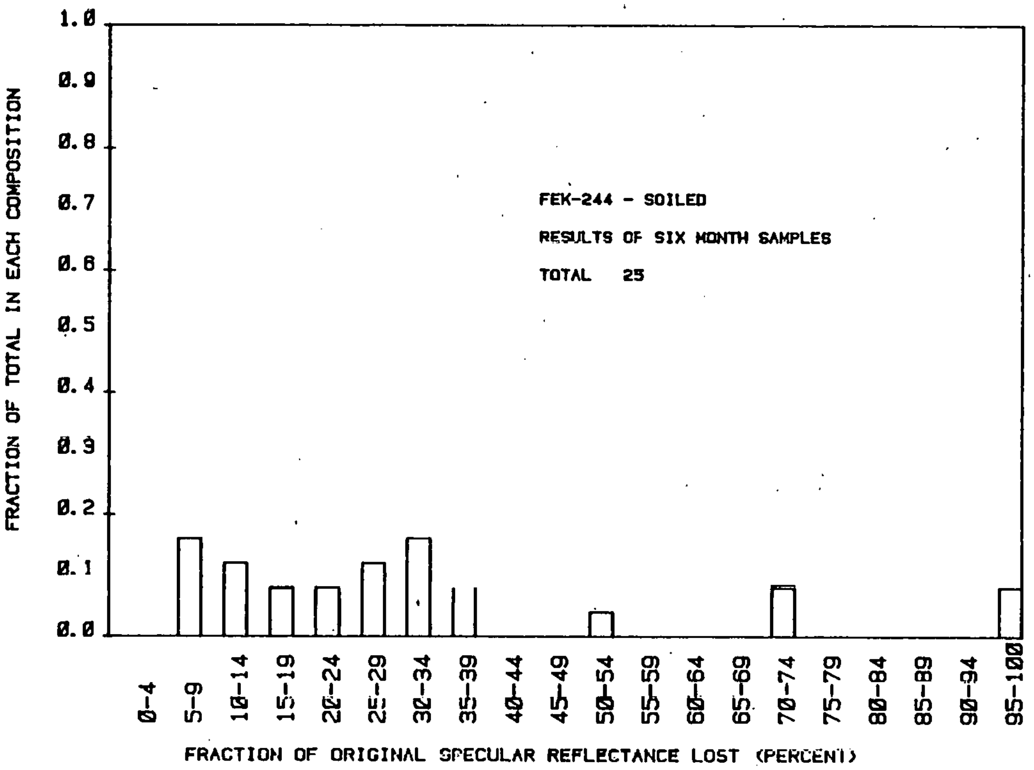


FIGURE 44 . PLOT OF FRACTION OF TOTAL IN EACH COMPOSITION VS PERCENTAGE LOSS IN SPECULAR REFLECTIVITY

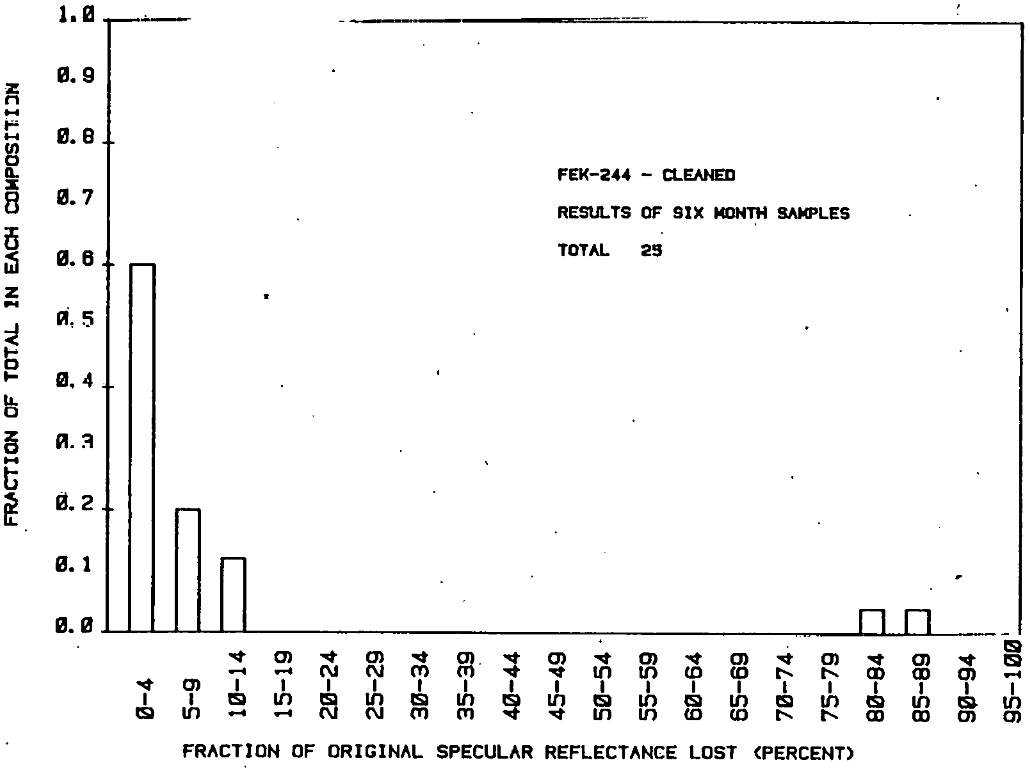


FIGURE 45 . PLOT OF FRACTION OF TOTAL IN EACH COMPOSITION
VS PERCENTAGE LOSS IN SPECULAR REFLECTIVITY

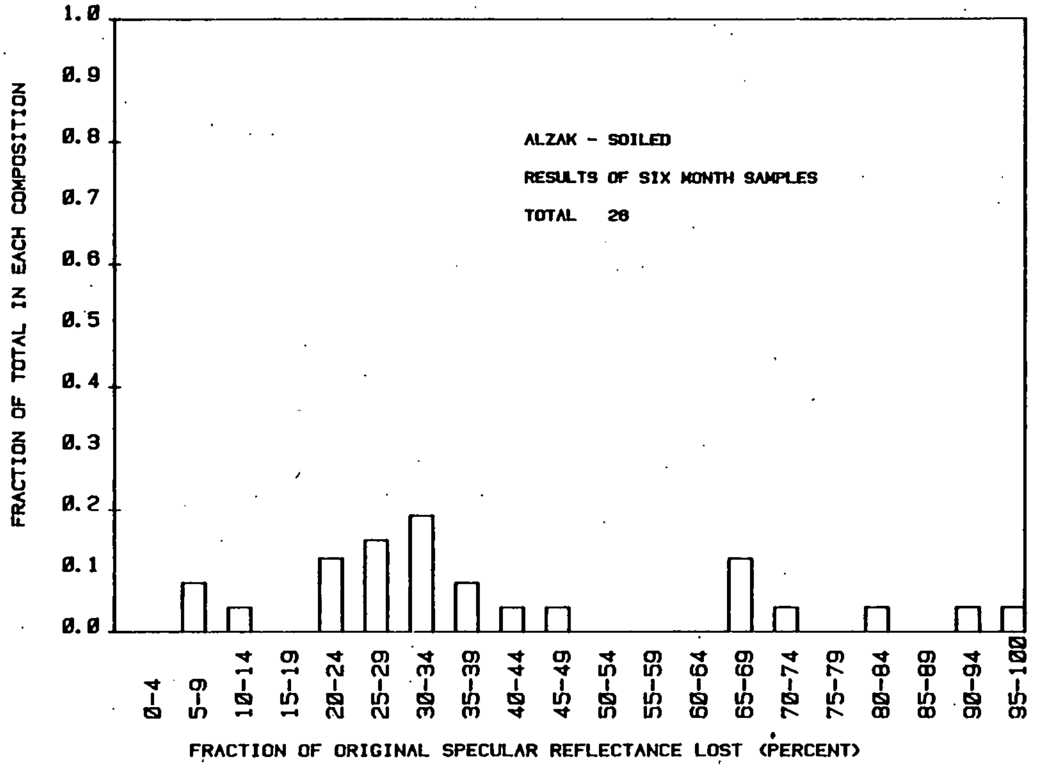


FIGURE 46 . PLOT OF FRACTION OF TOTAL IN EACH COMPOSITION
VS PERCENTAGE LOSS IN SPECULAR REFLECTIVITY

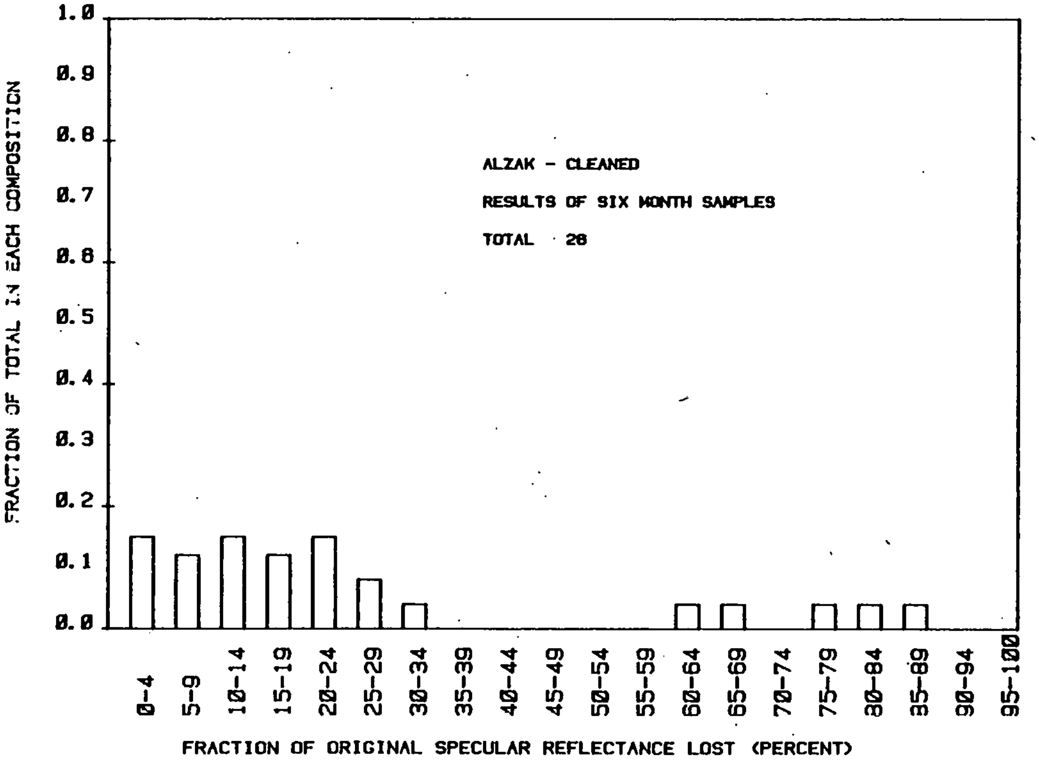


FIGURE 47 . PLOT OF FRACTION OF TOTAL IN EACH COMPOSITION
VS PERCENTAGE LOSS IN SPECULAR REFLECTIVITY

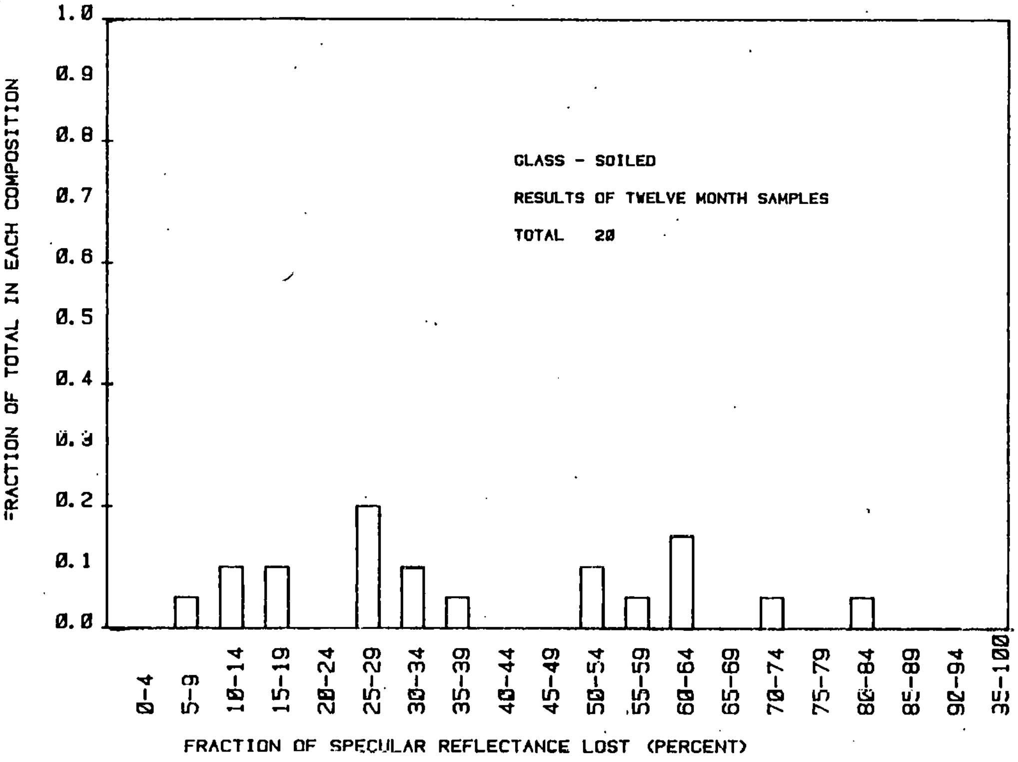


FIGURE 48 . PLOT OF FRACTION OF TOTAL IN EACH COMPOSITION
VS PERCENTAGE LOSS IN SPECULAR REFLECTIVITY

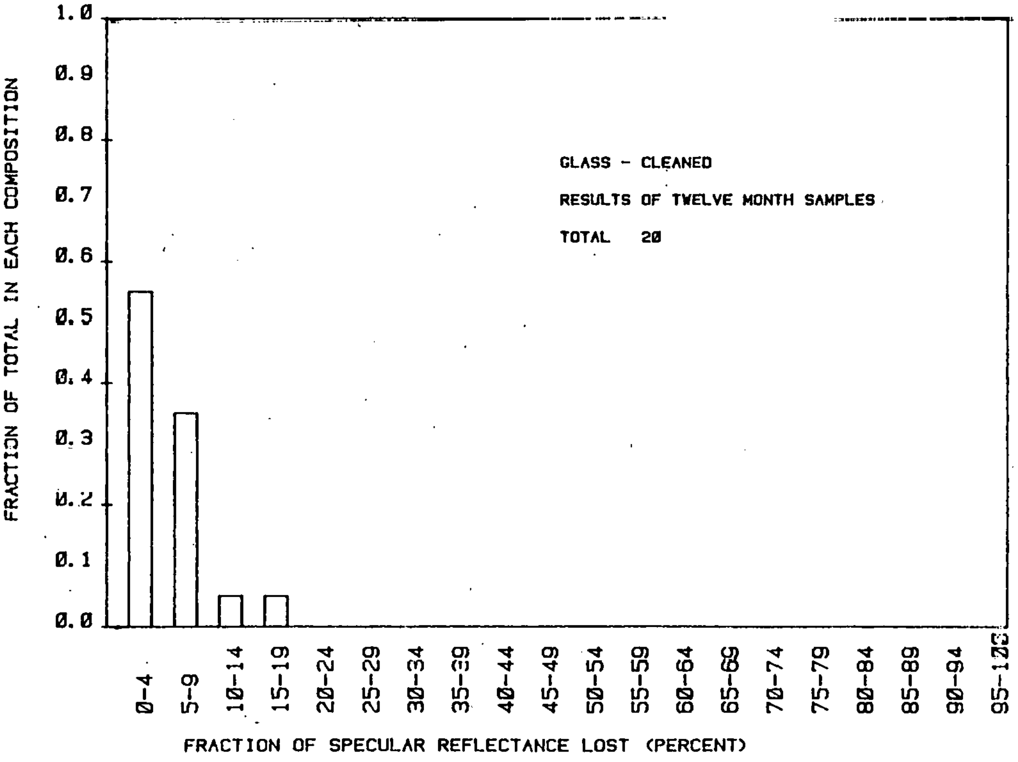


FIGURE 49 . PLOT OF FRACTION OF TOTAL IN EACH COMPOSITION VS PERCENTAGE LOSS IN SPECULAR REFLECTIVITY

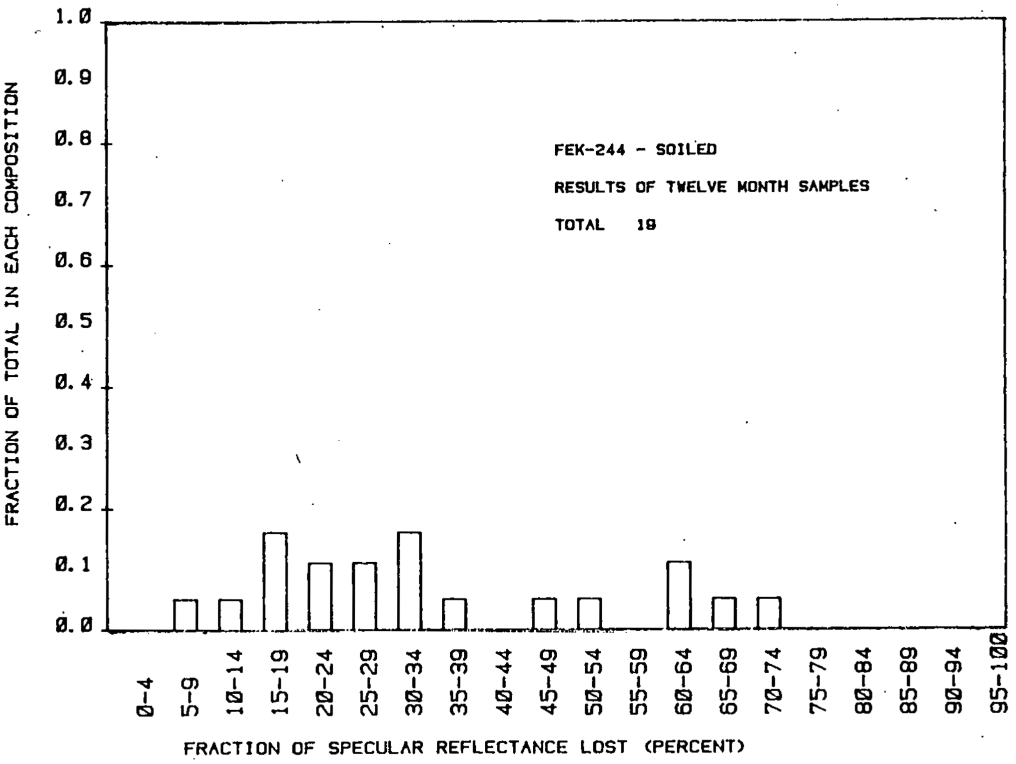


FIGURE 50 . PLOT OF FRACTION OF TOTAL IN EACH COMPOSITION VS PERCENTAGE LOSS IN SPECULAR REFLECTIVITY

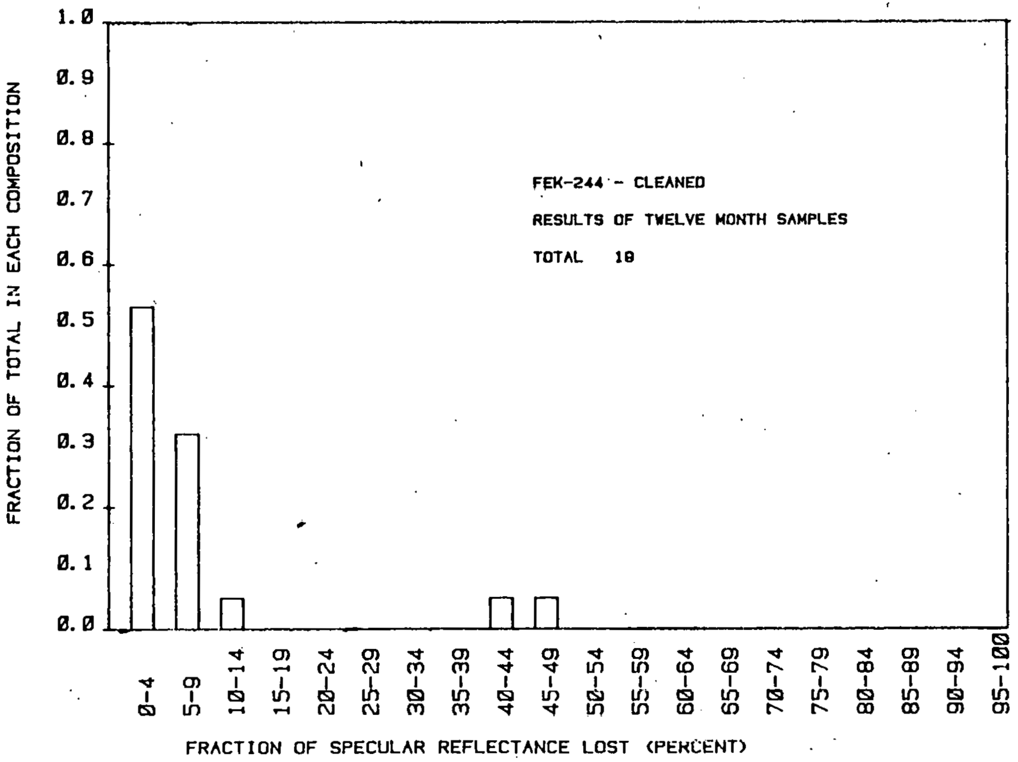


FIGURE 51 . PLOT OF FRACTION OF TOTAL IN EACH COMPOSITION VS PERCENTAGE LOSS IN SPECULAR REFLECTIVITY

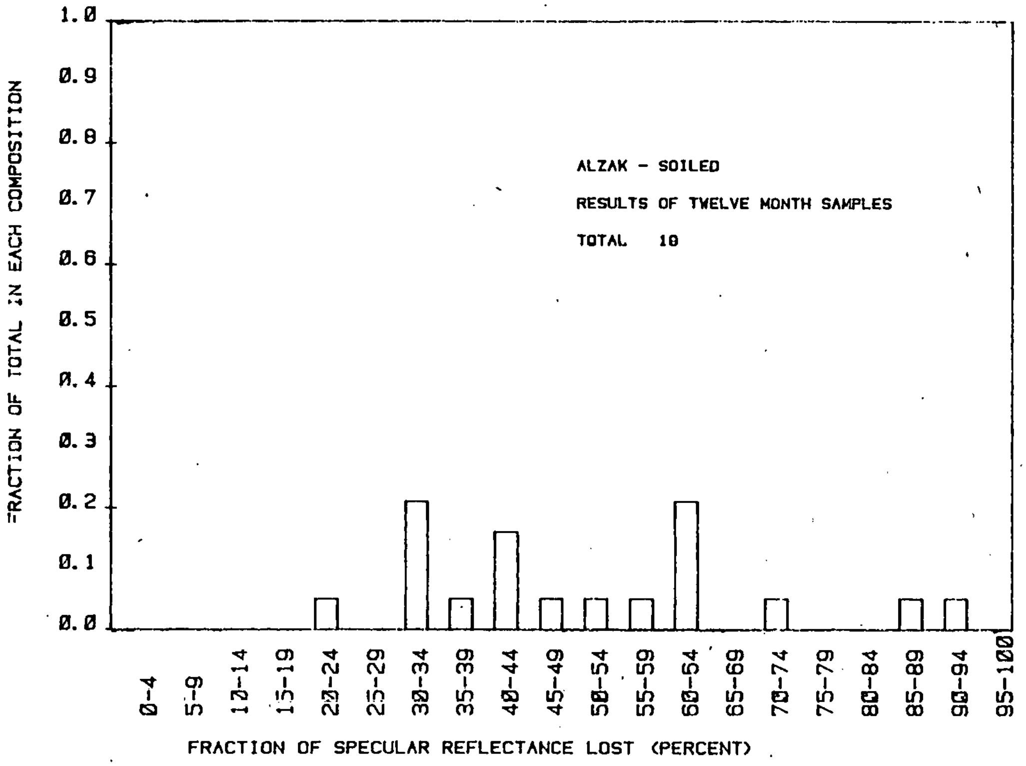
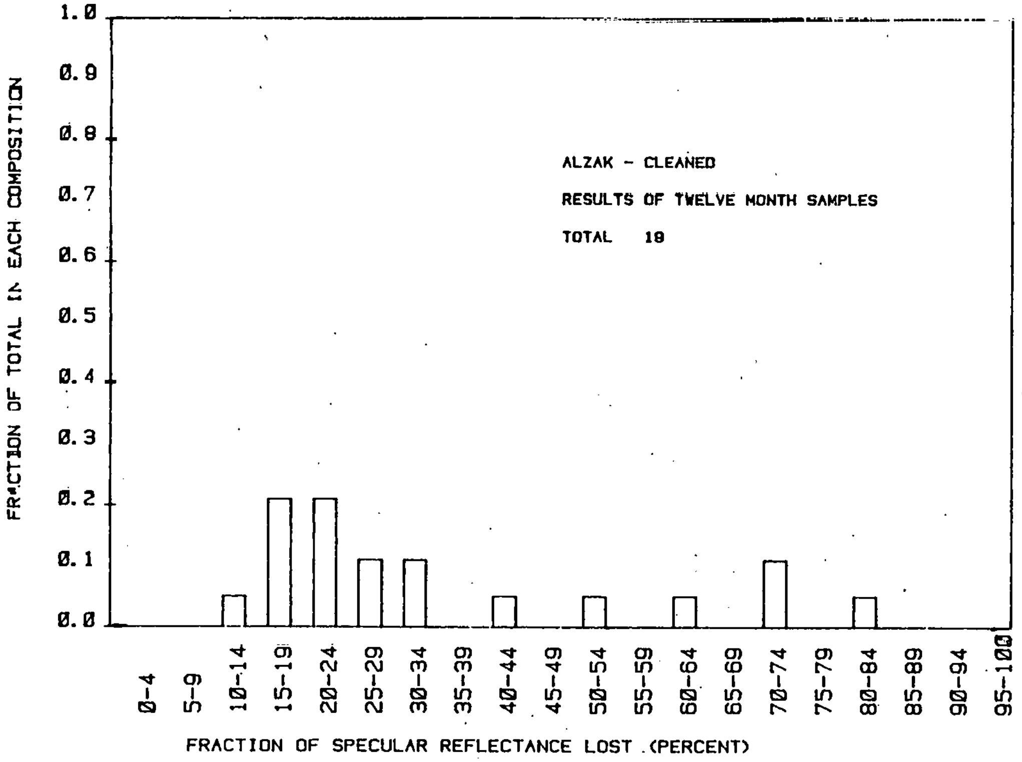


FIGURE 52 . PLOT OF FRACTION OF TOTAL IN EACH COMPOSITION VS PERCENTAGE LOSS IN SPECULAR REFLECTIVITY



degradation mechanism, which was observed but which had considerably less impact on the optical properties of the reflector specimens, was abrasion of the softer material surfaces.

Corrosion Degradation Mechanism -- Corrosion occurs on the reflective metallic portion of the reflector specimen as a result of a chemical reaction between the corrosive material and the metal. The corrosive material is usually a liquid or gas and is easily transported as an airborne contaminant to the reflector specimens exposed on the test racks. Water obtained from any conventional water supply, although seemingly innocuous, can act as a corrosive material for metallic species. However, when a strongly oxidizing material, e.g., chlorine, becomes dissolved in the water, the solution becomes even more aggressive as a corrosive agent. Chemically oxidizing species are naturally present as an airborne species in trace amounts in most environments, as shown in Table 2. Over a period of years, these materials alone can significantly corrode some metals. When the chemical oxidizing capability of these materials is enhanced by either increasing the concentration of the active species or by adding other oxidizing species to the environment, then corrosion becomes a more critical problem. Urban environments with high concentrations of photochemical smog, and the subsequent generation of ozone (O_3), have strong oxidizing atmospheres. Some industrial processes that generate oxidizing species as a byproduct of their process are an additional source. A natural source of a strong oxidizing atmosphere is the salt component of coastal waters.

Corrosion effects were observed on all the reflector specimen material types, but not at all sites. FEK-244 aluminized acrylic was the most corrosion-resistant reflector material in this study. Corrosion of the underlying aluminum layer was observed only when the acrylic film was damaged, usually the damage being mechanical, e.g., tearing or puncturing the film by sharp objects. However, many specimens could not be examined closely for corrosion effects, as the surface was heavily soiled and the soil could not be removed by a razor blade or knife because of the soft acrylic overlayer. This technique was employed for examining the glass reflector specimens. Difficulty was also experienced trying to use SEM-EDAX to analyze for corrosion byproducts, because the instrument source bubbled the acrylic film and obscured some of the data.

Table 2

Composition of Precipitation of Aerosols, Southwestern Desert Area

	Constituent	Concentration	References
1. Precipitation (pH $\simeq 6$)	Cl-	0.2-0.3 mg l^{-1}	9
	F^-	$\simeq$ 0.02	10
	Br^-	0.003	11
	I^-	0.001	12
	NO_3^-	1.3	12
	NH_4^+	0.1	12
	$SO_4^=$	2.0	12
	Na^+	0.8	12
	K^+	0.2	12
	Ca^{++}	1.5	12
	$H_2CO_3, HCO_3^-, CO_3^=$ (mostly as H_2CO_3 and HCO_3^-)	$\simeq$ 1.0	
2. Aerosols (Death Valley)[13]	Cl	0.42 µg m^{-3} Air	
	S	0.31	
	K	0.24	
	Na	0.21	
	Si	0.41	
	Ca	0.44	
	Ti	0.08	

The second-surface silver/glass mirrors did show corrosion effects at several of the exposure sites. There were two primary modes of corrosive attack on the silver reflective layer. The first mode was "edge attack", where the corrosive material would diffuse into the silver layer from the edges of mirror (Figure 5). This phenomenon occurred primarily along the unprotected edges of the reflector specimen (i.e., those edges not covered by sample retainers on the test hardware) and appeared to be self-regulating. The corrosion penetrated to a maximum depth of 0.5 in. Further exposure did not produce continued penetration depth of the corrosion. The second mode of corrosive failure for the silvered glass mirrors (second-surface) was "through the backing" attack. In this failure mode, the corrosive material would diffuse through the permeable paint or vinyl sheet mirror backings and attack the silver in discrete circular patterns (Figure 11). These patterns usually corresponded to bubbling or blistering of the protective backings, which appeared to be caused by liquid droplets falling or condensing on these backings and diffusing through. Figure 53 shows a 17X magnification of one of the circular corrosion patterns on the reflector specimen shown in Figure 11.

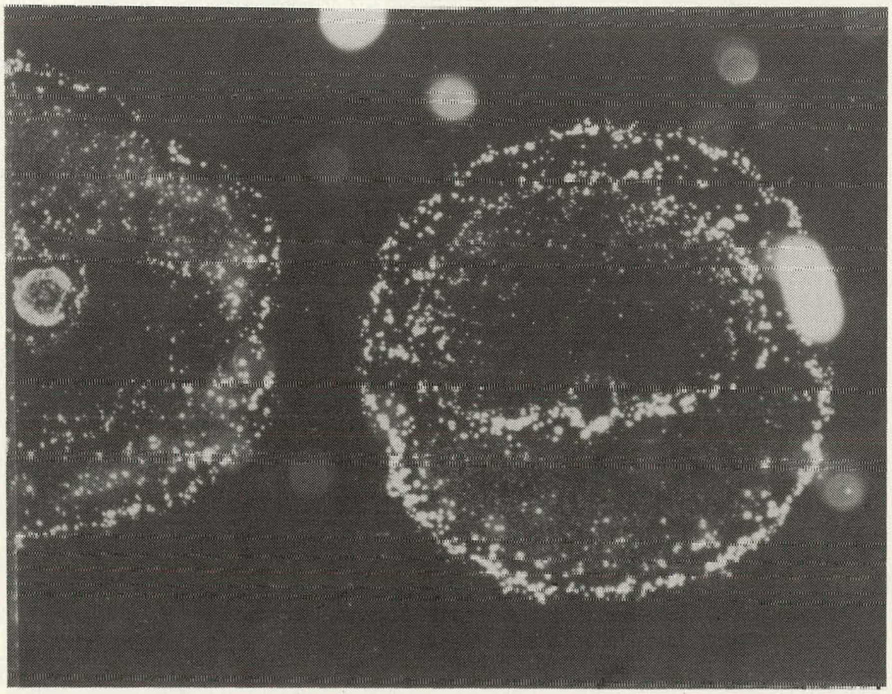


Figure 53. Circular Corrosion Pattern (17X magnification). Specimen 84, (glass, Dupont Imron backing), X-Plane, exposed 4 months at Hilo Coast Processing. Specimen 84 has been cleaned.

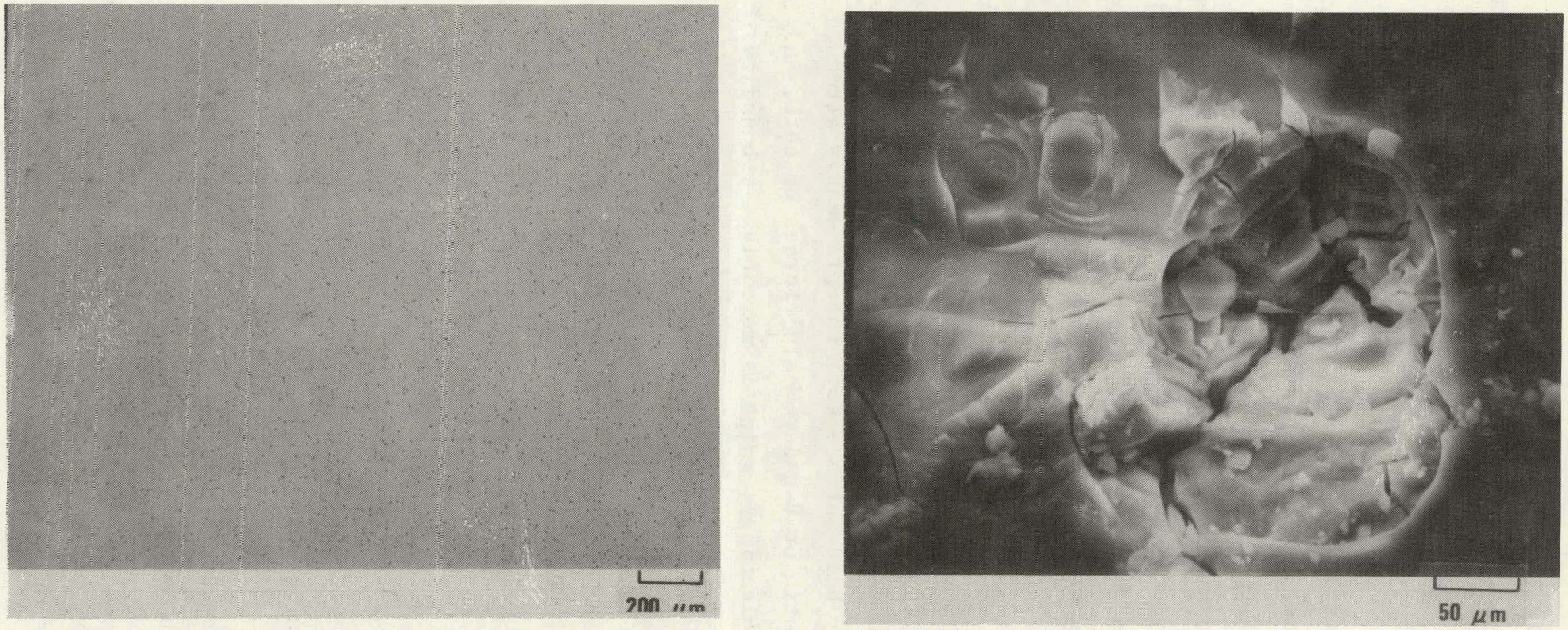
In the more severe cases of corrosion, the silver/backing layers delaminated or separated from the glass surface, thus producing an air pocket between the glass and reflective layer (Figure 12).

The Alzak specimens were the most susceptible to corrosive environments. The corrosion effects were usually exhibited as small pits in the reflector surface, usually surrounded by microcracks. As the exposure time in the corrosive environment increased, the pits became progressively larger (Figure 54) and more numerous, until the total reflector surface was covered (Figure 8). In some cases, a crystalline material was seen on the Alzak surface and, when this was removed by a razor blade, a corrosion pit was observed below the contaminant (Figure 13).

It is of interest that when the residually retained soil, which remains after the reflector is cleaned, reaches a high level, the corrosion of the Alzak reflector is inhibited, as the corrosive material can no longer reach the surface. This is not, however, suggested as a viable corrosion inhibition technique for solar reflective materials.

The Alzak reflector is a front-surface mirror, and corrosion occurred on both the front reflective surface and the rear backup material. With the glass reflectors, which are second-surface mirrors, corrosive attack occurred through the edge seals and the backing materials. No apparent degradation of the glass front surface was observed. The FEK-244 specimens are also second-surface reflectors, and corrosion only occurred when the top-surface acrylic film was damaged. No edge attack was observed, but the aluminum backup material was degraded.

Soiling Degradation Mechanism -- Soil deposition on solar reflector surfaces is a serious problem because of the related loss in optical efficiency, caused by losses in reflectivity, and the subsequent cost of cleaning. Many studies have been conducted on reflectivity losses for solar reflectors as a function of their exposure in benign environments, where benign environments are defined as a typical solar use environment without the impact of industrial processes.[1 14 15 16 17 18] This study adds the industrial environment to the test matrix.



A. Control Alzak reflector specimen maintained in a desiccated laboratory environment

B. Photomicrograph of cleaned Alzak specimen exposed 12 months at Stauffer Chemical Co. Deep corrosion pits are partially filled with soil deposits.

Figure 54. Corrosion Pit on Alzak Specimen. Photomicrograph of enlargement (32X).

Illustrations used for describing the residual soiling mechanism were taken from worst-case situations. The residual soil problem was observed at all sites, but to varying degrees, with the average sites reporting losses of specular reflectance for the cleaned reflector materials of 5 to 15%.

As observed in previous studies for the benign environments, solar reflective surfaces may become heavily soiled when exposed 30 days or more to "real" environments (Figure 55). The extent of the soiling is quite dependent upon the frequency and amount of natural precipitation, the concentration of airborne particulates, the duration of exposure, and its location. However, upon cleaning with conventional cleaning procedures, e.g., high-pressure water spray or use of detergent solutions, the specular reflectance could be returned to a value near the original reflectance.[1 15 17] In some cases, small specularity losses of 2 to 5% after cleaning were reported for reflectors exposed for up to 1 year.

The soil attached to the reflector surfaces was divided into two categories: (1) a loosely held surface soil that is weakly attached to the surface, probably by electrostatic or Van der Waals' forces or both, and (2) a residually retained soil (after cleaning), which is more tightly bound to the surface. The loosely held soil is easily removed by conventional cleaning techniques, but the residual soil represents a potential problem for which no clear solution has been determined.

One hypothesis of the mechanism for attachment of the residual soil to the reflector surface is as follows: the reflector surface is wetted with water from natural or man-made sources, e.g., cooling towers, evaporation ponds, liquid sources. The soil is transported as airborne particulate to the reflector surface and is entrapped in the liquid matrix. As the liquid evaporates, contaminants precipitate or settle out, including the soil, carbonates and sulfates from natural sources, and dopants and contaminants in the man-made liquid sources. Carbonates and sulfates are known to be natural, water-soluble cements and, hence, cement the soil to the surface. If the soil is planar in shape, does not absorb moisture to swell, and is cemented onto the surface in an overlapped manner, then a soil layer seemingly impervious to cleaning solutions is formed, as the aqueous cleaning solution cannot penetrate the soil

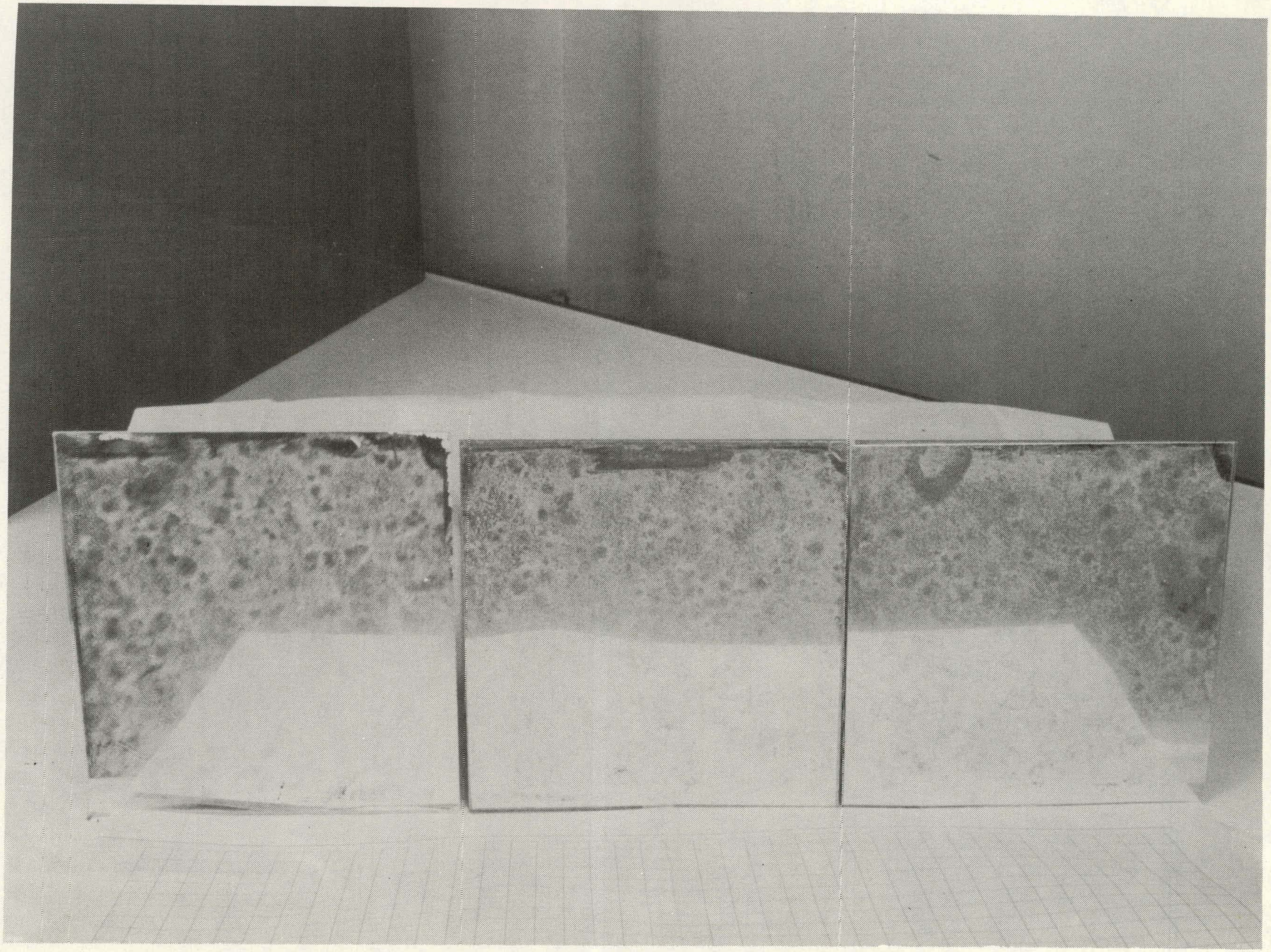
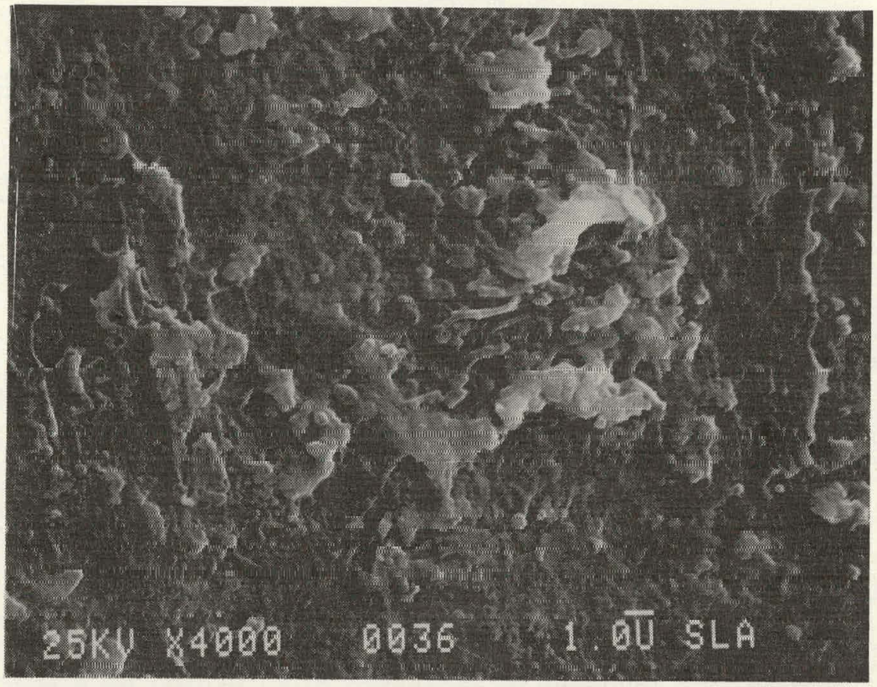


Figure 55. Second-Surface Silvered Glass. FEK-244 and Alzak Specimen "as received" following 1 month exposure at Lone Star Brewing Site.

layer to dissolve the cement layer.[1] If the soil particles swell, the liquid has a better chance of penetrating the soil layer to dissolve the cement. When the reflector surface is allowed to undergo a number of thermal cycles, i.e., elevated temperatures of hot days to cool night temperatures with subsequent condensation, the layers of the residual soil build up to create an even more tenacious residual soil layer as the layers overlap (Figure 56A). Continuous buildup of the soil layers results in a specimen whose condition can be seen in Figure 56B.

The soil type believed to be the most damaging in this phenomenon is a clay-type soil. Analyses of the residual soil layer have shown that the particles adhering to the surface are small ($\leq$ 10-μm diameter). These are known to adhere more strongly than larger particles.[1 19] The three most prevalent clay soils found in alkaline desert soils are: kaolinite clay (5 to 20% of southwestern desert clay-sized materials), illite (35 to 70%), and montmorillonite (35 to 70%). Montmorillonite is the only clay of the three listed above that has the capability to swell significantly.[20]

The types of clay that appear to be the most deleterious in the soiling mechanism are non-swellable clays, which are extremely small in size and are cemented to the reflector surface in an overleaf fashion to create a soil layer seemingly impervious to existing cleaning methods. The primary non-swellable clays are illite and kaolinite and are found in large concentrations in alkaline desert environments. Table 3 shows the breakdown of soil types at the different sites and the related specular reflectance losses for FEK-244, the only material whose reflectance losses are due almost entirely to soiling, not corrosion. The results from the nine sites show that sites with acidic soils have generally the lowest specular reflectance losses, followed by the neutral soils, with the highest losses in specular reflectance being reported at sites with alkaline soils. The Lone Star Brewing and U.S. Steel Chemical sites have other mechanisms in addition to soil type and moisture entrapment, which cause them to fall somewhat out of the trend. Cooling towers accelerated results at some sites. Organic contaminants also entrapped soil particles. It is theorized that contaminant entrapment of soil particles played a substantial role at many sites but could not be clearly isolated from the liquid entrapment phenomenon. Effluent from industrial solvent towers, spraying of agricultural chemicals, and effluents from surrounding industries, etc., were also suspected.



A. 4000X magnification of residual soil layer of a cleaned specimen exposed 6 months at Southern Union Refining Co.

B. 100X magnification of residual soil layer of a cleaned specimen exposed 12 months at Stauffer Chemical Co.

Figure 56. Residual Soil Buildup. Examples on Alzak specimen.

Table 3

Effect of Soil Type on Specular Reflectance Losses

Site	Soil Type	Soil pH	Average Percent Loss in Specular Reflectance of Cleaned FEK-244 (12-Month Exposure, X-orientation)
Southern Union Refining Co.	Red Prairie	Alkaline (pH >7)	100% - near cooling tower $\sim$12% - 1000 ft. S. cooling tower
Stauffer Chemical Co.[1]	Red Desert	Alkaline (pH >7)	>15%
Ore-Ida Foods[2,3]	Gray Desert	Alkaline (pH >7)	15%
Caterpillar Tractor[1]	Brunizem	Neutral (pH $\cong$ 7)	5-8%
Lone Star Brewing[1,2] Co.	Rendzina	Neutral (pH $\cong$ 7)	5-15%
Bates Container Co.	Rendzina	Neutral (pH $\cong$ 7)	5%
Dow Chemical Co.	Red or Yellow Podzol	Acid (pH <7)	5-7%
U.S. Steel[1,3] Chemical Co.	Sol Brun Acide	Acid (pH <7)	15%
Hilo Coast Processing Co.	Not known	Not known	2-20%

[1] Cooling towers were located on the site.

[2] Additional soil entrapment by outgassing of tar roofs. Caterpillar Tractor Co. was also a roof mount but roofing material was sealed with white paint.

[3] Unique soiling problem, i.e., white waxy deposits.

Chemically, the clay minerals are best described as hydrous aluminum silicates, with the general formula $H_xAl_ySi_zO_r \cdot m(H_2O)$. Many clays will contain other metals in addition to the aluminum (Al), particularly magnesium (Mg) and iron (Fe). Actual compositions are never simple but show variations in the silicone (Si):Al ratio, a variable quantity of water, and usually considerable amounts of magnesium, iron, calcium (Ca), and the alkali metals. Clay minerals are phyllosilicates, which are silicates with continuous sheet structures, and the characteristic structure is made up of alternating layers of two kinds. One layer consists of the ions Al^{+3}, O^{-2}, and OH^{-1}; the negative ions form octahedra around Al^{+3}. This pattern is called the "gibbsite" or the octahedral sheet. The second layer is made up of Si^{+4}, O^{-2}, and OH^{-1} ions, with each Si^{+4} in the center of a tetrahedron of oxygen ions; the tetrahedra all face the same direction, and the oxygens at their bases are linked to form hexagonal rings. This sheet is the silica sheet of the clay structure. The complete clay structure consists of several possible combinations of the octahedral and tetrahedral sheets.[21] The spacing between the consecutive sheets is 7 to 10 angstroms for illite and kaolinite and 10 to 17.5 angstroms for montmorillonite. The larger the spacing, the greater the swelling capability the clay has.[4] The clay minerals are then best described as water-insoluble layers, which overlap to form flat particles of very small sizes.

Water, the second element in the residual soil mechanism, can be obtained from natural or man-made sources. Natural sources include rain, condensation, dew, etc. Heavy rains prove beneficial, as they clean the reflector surfaces. Light rains, having no runoff from specimen surfaces, appear to be the most damaging. Man-made sources include blowoff from solvent towers, evaporation and mixing ponds, and cooling towers. The cooling towers are probably the single most deleterious moisture source, as the water is doped with chemicals (carbonates, sulfates, polymers), which serve as cements for soil particles. Many of the intermediate-temperature IPH sites have cooling towers associated with their process.

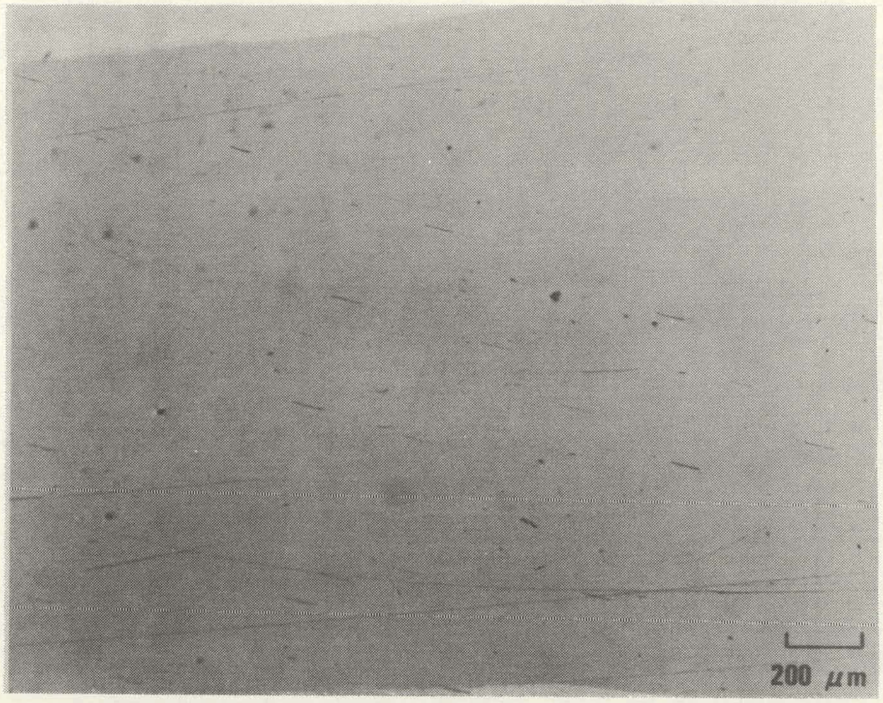
The impact of wet cooling towers was obvious at the Southern Union Refining Company site, where the test hardware was located 200 ft from the tower. Persons standing near the test rack could feel the effluent, a heavy mist, from the tower. A microscopic examination of the reflector surfaces deployed 1 month at this site showed soil that had precipitated along the perimeter of a water droplet (Figure 9A) and soil that had encrusted over the entire area of a water droplet (Figure 9B). With the constant moisture source from the tower, this process continued until the entire reflective surface was covered with the soil and the specular reflectance had decreased to 0. It is believed that the soiling phenomena at the Southern Union Refining site is an extremely rapid acceleration of the natural soiling found in more benign environments, the acceleration being caused by a continuous, low-level source of moisture.

In some sites, an additional mechanism of soil attachment was observed in addition to the liquid method. At sites where the environmental test hardware was located on a roof, some types of roofing material would outgas and contaminate the reflector surfaces with sticky organic materials. These organics also entrapped soil particles. It is theorized that contaminant entrapment of soil particles played a substantial role at many sites, but it could not be clearly isolated from the liquid entrapment phenomenon. Effluent from industrial solvent towers, spraying of agricultural chemicals, and effluents from surrounding industries, etc., are also suspected.

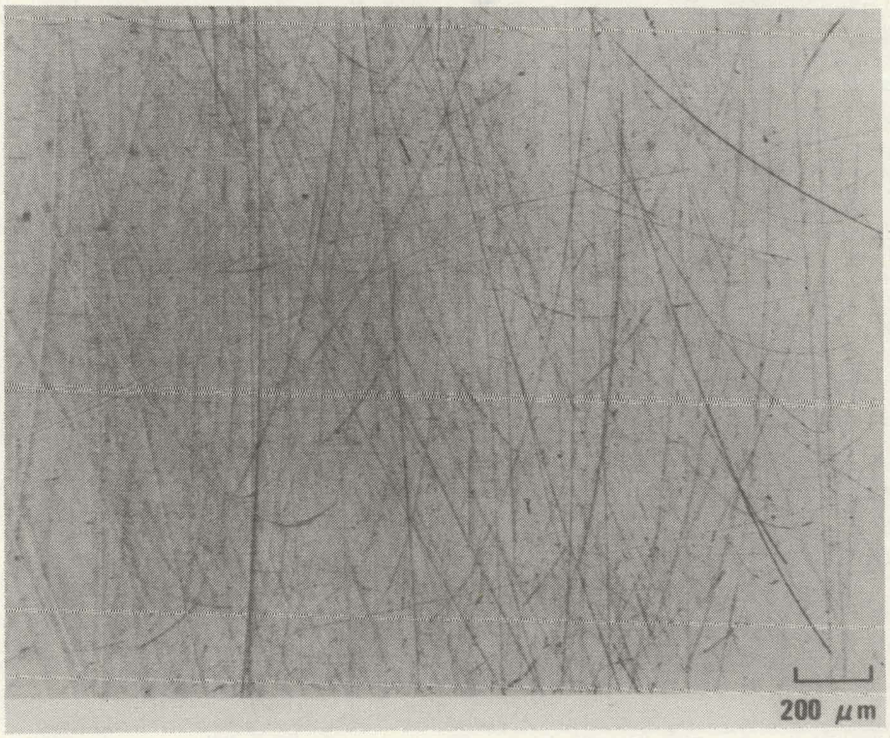
Abrasion Degradation Mechanism -- Abrasion of the solar reflective surfaces was observed on the softer surfaces, i.e., Alzak, and particularly, FEK-244. The abrasion phenomenon was documented by photographing an enlargement of 20 randomly selected specimens of each material type, before fielding, and rephotographing them following their field exposure. In many cases, abrasion was difficult to document because of the advanced stage of soil retention in the latter period of the test.

Abrasion was observed on virtually all the FEK-244 specimens that were exposed at the test sites (Figure 57). The abrasion patterns were usually linear from side to side of the exposed specimen (i.e., east to west or conversely, as arranged on the exposure rack). Abrasion was also observed on many of the Alzak specimens, as noted in Appendix C.

Degradation of reflector surfaces by abrasion, although it does not appear to significantly decrease the specular reflectance values, is of concern, particularly for FEK-244 specimens. Figure 58 shows an FEK-244 specimen where the acrylic film has been damaged, and the subsequent corrosion of the underlying aluminum film. If, over a long period of time, the acrylic layer is sufficiently damaged by abrasion, corrosion may then become a problem for this material.

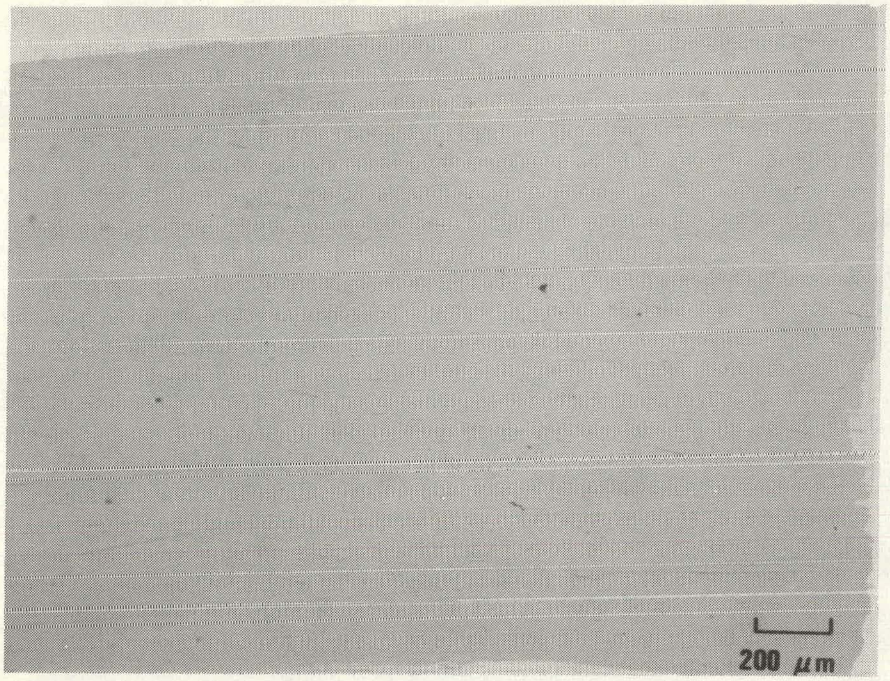


A. Control FEK-244 aluminized acrylic sample maintained in a desiccated laboratory environment

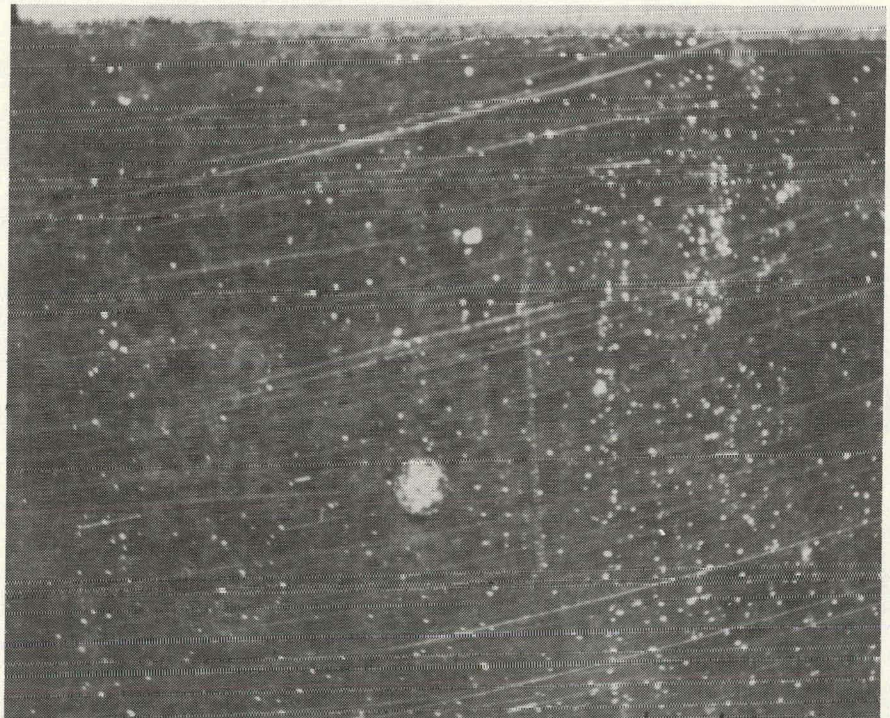


B. FEK-244 aluminized acrylic specimen exposed 1 month, X-Plane, at Stauffer Chemical Co.

Figure 57. Abrasion Degradation. FEK-244 aluminized acrylic specimen.



A. Control FEK-244 aluminized acrylic specimen maintained in a desiccated laboratory environment



B. FEK-244 aluminized acrylic specimen exposed 8 months, X-plane, at Stauffer Chemical Co.

Figure 58. Abrasion and Subsequent Corrosion. Underlying aluminum layer of FEK-244 aluminized acrylic specimen.

Summary and Conclusions

Results obtained from the in situ exposure of solar optical materials in "real" industrial environments show that some serious problems have been encountered. For many sites, the projections for 30-year life expectancies for the reflector and receiver materials evaluated in this program cannot currently be supported, as a number of degradation mechanisms were observed for which easy-fix solutions did not appear to be available. However, as this test matrix used accumulated exposure results, the long-term implications of the degradation mechanisms are difficult to predict.

Two primary degradation mechanisms for solar collector materials were observed: (1) a residual layer of soil adhering to the cleaned mirror surfaces, which accounted for 5 to 15% loss in specular reflectance at all sites, and a 90% loss at one site, after 12 months of exposure; and (2) corrosion of metallic components of the reflector specimen at four of the nine industrial sites. A less serious degradation mechanism, abrasion of Alzak and FEK-244 specimen surfaces, did not appear to cause as large a loss in specular reflectance.

The impact of the soil retention problem on existing and proposed full-scale solar structures could be considerable. All test sites have shown evidence, in varying degrees of severity, that this problem could shorten the useful life of the reflector in field use unless appropriate corrective actions are taken. It is theorized that a combination of low levels of moisture and particular soil types, (specific types of clay), when subjected to thermal cycling (Figure 59) will create ideal conditions for the formation of the tenacious layer of soil that is not removable by non-contact cleaning methods. Although an extensive systematic evaluation of cleaning methods was beyond the scope of this effort, a variety of solvents and cleaning agents were tried (chelating agents, acidic and basic cleaning agents, organic solvents), using both contact and non-contact cleaning methods, on glass mirror surfaces. There was no significant improvement in the specular reflectance measurements using these cleaning methods. The two methods that did finally remove the soil layer, an acid wash (36.5% by volume HCl, which consumed all but the glass portion of the mirror, and the use of a surgical knife to scrape the soil off), showed

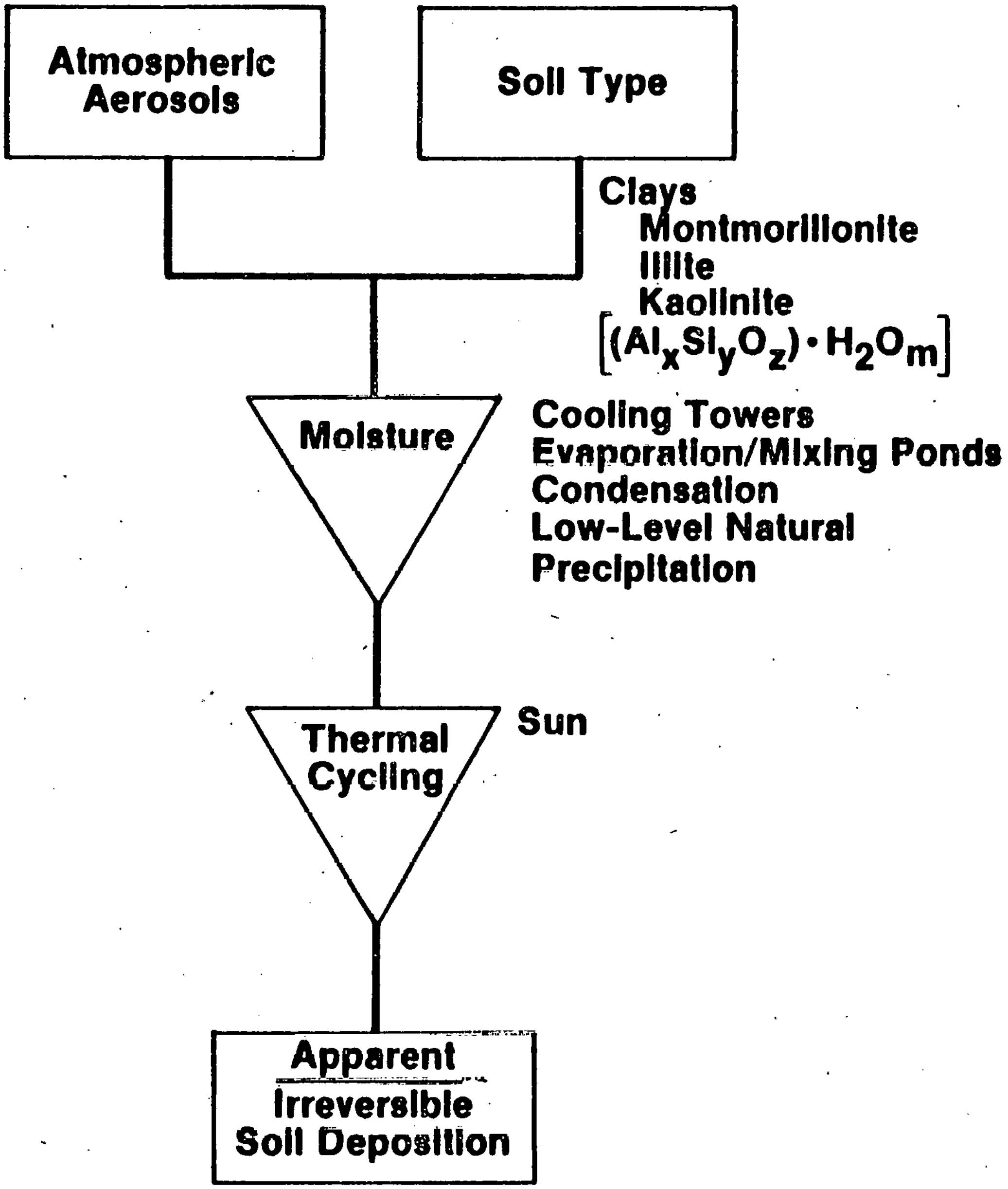


Figure 59. Soiling Mechanism

there was no apparent chemical attack by the soil layer on the glass. These methods could not be used with the FEK-244 and Alzak specimens because of their soft surfaces and the reaction of the reflector material with an acidic medium. Neither of these methods is feasible for field cleaning procedures.

Limited experiments on increased frequency of cleaning on a monthly basis at the worst site, Southern Union Refining Co., indicated the development of this residual layer of soil would be significantly retarded but probably not prevented. Increased frequency of cleaning would most certainly be beneficial in extending the useful life expectancies of the solar reflector materials, but the solution to preventing the residual soil layer is not apparent at this time.

It is theorized that soil types may play a significant role in the soiling mechanism. The results from the nine sites show that the acidic soils have generally the lowest specular reflectance losses, followed by the neutral soils, with the highest losses in specular reflectance being reported at sites with alkaline soils.

The soil types that are hypothesized to be the most deleterious in the soiling mechanisms are non-swellable clays, which are extremely small in size and are cemented to the reflector surface in an overleaf fashion to create a soil layer seemingly impervious to existing cleaning methods. The primary non-swellable clays are illite and kaolinite and are found in large concentrations in alkaline desert environments.

The Lone Star Brewing and U.S. Steel Chemical sites have other soiling mechanisms, in addition to soil type and moisture entrapment, which caused them to fall somewhat out of the trend. Cooling towers also accelerated results at some sites.

Because of the variety of problems encountered with the three reflector materials in different test environments, no one material can be unilaterally recommended for all environments. From a materials point of view, the single-layer glass mirrors would be recommended for non-corrosive environments that have a significant soiling problem, as the glass surface can be cleaned by a contact cleaning method without damaging the surface. Glass-glass laminated mirrors could potentially circumvent the corrosion problem also. Significantly increased cleaning costs will result from contact cleaning methods.

In environments with less severe soiling problems but corrosive atmospheres, the FEK-244 aluminized acrylic specimen would be preferable because of the initial low cost of the material and the ease of replacing the film periodically when the collector efficiency decreases to a non-useful level. The FEK-244 film has three weaknesses, the long-term impacts of which have not been quantified: (1) the susceptibility of the soft acrylic surface to damage from handling and airborne particulates; (2) the loss of specularity due to cloudiness on most specimens after 1 year of weathering; and (3) the apparent tendency of the soft acrylic film to entrap particulates, thus accelerating the soiling process. The positive aspect of the FEK-244 film is its ability to withstand corrosion as long as the acrylic layer is intact.

The Alzak reflector material could only be recommended for the most benign environment, as it is susceptible to corrosion and probably cannot withstand repeated cleaning by solar field contact methods without sustaining abrasion damage to the surface.

Other conclusions that can be drawn from this study are:

- The Alzak reflector specimens are slightly more susceptible to soil retention than are the second-surface glass and FEK-244 specimens.
- The relative ranking for ease of cleaning of the reflector specimens is: silvered glass > FEK-244 > Alzak.
- The relative ranking for corrosion resistance of the three reflector materials is: FEK-244 > silvered glass > Alzak.
- The black chrome receiver specimens are unaffected by thermal cycling, but they are susceptible to specific environmental pollutant attack. This attack degraded the optical properties of the receiver material.

- The optical properties of the glass cover plate material are unaffected by thermal cycling, but the cyling did cause some specimens to break. The field-exposed specimens showed relatively little change in hemispherical transmittance for the soiled or cleaned specimens. Large losses in specular transmittance for the soiled specimens were reported for some sites, but cleaning restored the specular transmittance values generally to within 90% of the original value.

Questions which arose as a result of this study are:

- How often must the reflector materials be cleaned to maintain the minimally acceptable optical properties? The minimally acceptable optical properties are defined as those which will result in the lowest possible optical efficiency a solar system can tolerate and still be cost effective in terms of the energy produced. The question of the necessity of cleaning the reflector surfaces to the non-exposed condition has not been fully explored. Trade-off studies of cost of energy lost versus cost of cleaning reflectors to the non-exposed optical condition would answer this question.[22]
- Is the process of cleaning going to play a role in accelerating the soiling problem by supplying an additional moisture source and, if so, must the reflector materials be dried following each cleaning procedure?
- Does the residual soil layer on the reflector surfaces reach an equilibrium condition after X years of exposure or does it continue to increase? The Southern Union Refining Co. results would indicate that as long as a moisture source is present, the residual soil layer will continue to increase. This has not been proven, though.

A further conclusion that could be drawn from this study is that all future solar installations, before construction, should be diagnostically evaluated for compatibility with solar optical materials. Parameters that should be evaluated include meteorological data, soil chemistry, plant processes and structures and their impact on resultant air quality, and the effect of nearby industries whose processes could affect the solar structure environment. Insufficient data are available at this time to develop a comprehensive diagnostic plan for new sites, but a considerably better understanding of the impact of "real" environments on solar optical materials does now exist. The effects of environmental impacts, e.g., cooling towers, can be minimized if their impact is considered during the design phase of the solar system and careful consideration is given to the location of the system with respect to many of the identified impacting parameters.

The nine industrial sites used for this study program were selected primarily because of the firms' interest in solar energy for industrial processes. The problems encountered at the sites are, then, typical of problems that will be encountered at future sites. Diagnostic screening processes can eliminate locations having the most severe environments or can provide guidance on selection of materials, but if the basic degradation mechanisms for solar optical materials are not more fully understood and solutions developed, e.g., improved cleaning methods and materials for reflectors, evaluation of the frequency of cleaning, and use of barrier coatings, then solar energy may only be viable in the most pristine environments.

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Appendix A
GLOSSARY OF MATERIALS

1. Alzak Specimens

The Alzak reflector specimens were fabricated by bonding 0.032-inch-thick Alzak sheet to a 0.125-inch-thick sheet of aluminum with Mac Bond SB1786 adhesive. The Alzak is produced by Alcoa Aluminum Co. by using high-purity base aluminum, which is rolled to the required thickness and electropolished to remove all surface contaminants. The mill-rolling process gives the Alzak directionality with respect to optical measurements. A transparent anodic oxyd coating 1×10^{-3} inch thick is plated on the surface. The Mac Bond adhesive is produced by Mac Tac Division of Morgan Adhesives Company.

2. Second-Surface-Silvered Glass Specimens

The single-layer glass specimens were prepared by Binswanger Corp. using 0.125-inch-thick PPG Co. low-iron float glass with silver, copper, and alkyd melamine paint layers, in that order. The specimens were randomly divided into three equal lots, and an additional protective backing was used on each 1/3 lot. The three backings are:

A. Imron - an air-dried polyurethane enamel available from E. I. duPont de Nemours & Co.
B. Epoxy - a two-layer epoxy system composed of Bostik-Finch 463-12-8 primer and Bostik-Finch epoxy topcoat, gloss, 443-3.
C. Macol 4302 adhesive-backed vinyl, available from Morgan Adhesive Company.

3. FEK-244 Specimens

The FEK-244 aluminized acrylic specimens were prepared by bonding the FEK-244 film onto 0.125-inch aluminum back-up. The FEK-244 film is composed of a top acrylic layer over aluminum sheet, and has a composite thickness of

0.004 inch. The film was bonded onto the aluminum by a "wet" technique, i.e. the film was cut to size, dipped into a soap/water solution (Joy detergent), and placed onto the back-up. The excess water/soap solution was displaced using a smooth roller. The FEK-244 film was supplied by 3-M Company.

4. Black Chrome Receiver Specimens

The following description of the sample preparation for the black chrome specimens was provided by Dr. R. B. Pettit, SNLA. Dr. Pettit also provided the specimens used in the test.

All black chrome samples were electroplated onto mild steel substrates that were coated with 0.001 in. of sulfamate nickel. The composition of the black chrome bath was carefully controlled to produce thermally stable coatings by reducing the trivalent chromium concentration. The approximate bath composition was:

CrO_3=: 333 g/l
Addition Agent: 26-27 vol %
Iron: 8.7 g/l
Cr^{+3}: 8.5 g/l

All black chrome plating was carried out at 188 mA/cm^2 (175 A/ft^2) for 5.5 6 minutes. Because the emittance values of as-deposited stable coatings are high, all coatings were aged for 24 hrs. at 350°C in air to reduce the emittance. Average properties of the panels supplied to MDAC, both before and after the thermal aging, are listed in Table 1A. Note that the average 300°C emittance, ε(300°C), decreased from 0.36 as plated to 0.27 after the aging. However, the solar absorptance, α_s, decreased less than 0.007 absorptance units.

Table 1A: Optical Properties of Electrodeposited Black Chrome Coatings Before and After Thermal Aging

	As-Deposited	After 24 hr. at 350°C
α_s	0.974	0.967
ε(300°C)	0.36	0.27

5. Glass Cover Plate

These specimens were prepared from PPG Company low-iron float glass.

McGean Cee-Bee DATA SHEET

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GENERAL DESCRIPTION

Clear, liquid concentrate for cleaning desert soil from solar energy mirrors.

ADVANTAGES

1. Highly effective on accumulated desert soil at low concentrations.
2. Requires no agitation.
3. Drains rapidly from surface requiring minimum rinse water.
4. Made with biodegradable surfactants.

INTENDED USE

OPERATION: Thoroughly wet mirror surface by non-atomizing spray application of a 4 to 8 ounce/gal. water solution of CEE-BEE C-120. Allow surface to drain for 30 to 90 seconds. Spray rinse with distilled or deionized water. Do not allow surface to dry before rinsing. It may be desirable to use Cee-Bee C-121 Rinse Aid in the rinse water.

PROPERTIES

Clear straw colored liquid with acidic odor. No flash point.
Contains corrosive acids.
All surfactants contained in product are biodegradable.

PRECAUTIONS

Avoid all skin or eye contact. Use face shield, apron, gloves and boots. Avoid splashing nearby personnel during spray rinse. In case of accidental contact, flush with large volumes of water immediately and seek medical attention. Injury may not be immediately apparent. DO NOT TAKE INTERNALLY. Avoid breathing vapors from the concentrate.

Store at 30°F to 110°F. Pour carefully into water to avoid splashing.

Use in plastic or stainless steel equipment.

HBH/bg
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