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The Optical Losses of Solar Mirrors Due to Atmospheric Contamination at Liberal, Kansas and Oologah, Oklahoma

L. S. Dake
M. A. Lind

September 1981

Prepared for
the Solar Energy Research Institute
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The authors wish to express their appreciation to T. Stewart, M. Nordmeyer, D. Chaudiere and K. Mallory for their contributions to the optical evaluations. D. Chaudiere was particularly helpful in devising computer software that greatly facilitated the data analysis. The authors also wish to thank J. Coleman for the SEM work. The generous cooperation of Black & Veatch Engineering Consultants, in particular, M. Bohon, is greatly appreciated. Black & Veatch holds the primary credit for initiating the study, designing and deploying the heliostat simulators, and collecting the samples.

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EXECUTIVE SUMMARY

This joint PNL and Black & Veatch study is an assessment of the effect of outdoor exposure on mirrors located at two sites selected for potential solar cogeneration/repowering facilities: Liberal, Kansas and Oologah, Oklahoma. Mirror coupons were placed on tracking heliostat simulators located in the proposed heliostat fields and were removed periodically. The spectral hemispherical and diffuse reflectances of these coupons were measured. Representative samples were analyzed for the chemical composition of the dust particulates using SEM/EDX. Other samples were washed with a high pressure spray and recharacterized to determine the effects of the residual dust.

Average specular reflectance losses over the entire test period (up to 504 days) were 6 to 12%, with a range of 1 to 30%. Specular reflectance losses varied widely from day to day depending on local weather conditions. The losses due to scattering were 2 to 5 times greater than the losses due to absorptance. The average degradation rate over the first thirty days was an order of magnitude larger than the average degradation rate over the entire sampling period. Specular reflectance loss rates averaged 0.5% per day and greater between periods of natural cleaning. The chemical composition of the dust on the mirrors was characteristic of the indigenous soil, with some samples also showing the presence of sulfur and chlorine, possibly from cooling tower drift.

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INTRODUCTION

Black & Veatch (B&V), in conjuction with the Department of Energy (DOE) and the Public Service Company of Oklahoma (PSO), has been studying the feasibility of solar repowering and cogeneration projects at two sites. These projects involve using a heliostat field and receiver system to generate power in conjunction with existing fossil power generation facilities. Since the reflectivity of the heliostat field plays a vital role in the performance of the collector systems, part of the B&V study involved assessing the effect of outdoor exposure on the reflectivity of heliostat mirrors.

B&V placed mirror coupons on heliostat simulators that were positioned at representative locations in the proposed heliostat fields. Samples were removed periodically and the weather was monitored on a daily basis at the two sites.

Optical characterizations of the weathered samples were performed by the Pacific Northwest Laboratory (PNL) to quantitatively assess the effect of dust accumulation on the reflectivity of the mirrors. PNL also performed an SEM/EDX analysis on selected samples to determine the composition of the dust adhering to the samples.

The data was analyzed to determine the magnitude of the total loss in reflectivity over the entire test period and to estimate the average degradation rates at each site. The relationship between absorption losses and scatter losses was also examined. Correlations were also made between the weather data and changes in the mirror's reflectivity. Some of the samples were cleaned to determine how tenaciously the dust was adhering to the coupons and to determine what fraction of the dust build-up was not easily removable with simple cleaning procedures.

EXPERIMENTAL

SAMPLES AND EQUIPMENT

Mirror coupons placed on heliostat simulators were exposed at Oologah, Oklahoma and Liberal, Kansas (see Figure 1). The mirror coupons were 0.05 m x 0.05 m (2 in. x 2 in.) squares cut from commercially manufactured mirrors. In addition to the standard PPG grey paint backing, the mirrors were coated with Krayton rubber on back and sides. The mirror coupons were mounted on heliostat simulators as shown in Figure 2. To approximate the motion of a tracking heliostat, each simulator assumed four positions during the day. At 6:00 am (approximately sunrise) the simulator table holding the mirror coupons was positioned face up (i.e., mirrors facing up) and tilted toward the southeast. At 10:00 am, the platform rotated to face south. At 2:00 pm, it moved to face the southeast. At 6:00 pm (approximately sunset) the table assumed the face down, stow position. In addition to the heliostat simulators, a fixed position table holding mirror coupons face up was erected approximately 15 m (50 ft) downwind from a cooling tower at the Liberal, Kansas site. Data from the coupons on this table were used to estimate the maximum effect of the cooling towers on a mirror.

SITE CHARACTERIZATIONS

Oologah, Oklahoma[1]

Oologah, Oklahoma is the site of the northeastern station of the PSO. The site is shown schematically in Figure 3. Units 1 and 2 are gas- and oil-fired power plants; while units 3 and 4 are coal-fired power plants. Unit 1 is being considered for repowering. Six cooling towers are associated with the units. "Cooling tower drift" is the vapor, which contains dissolved solids, that cooling towers emit. This vapor may condense on the mirror surfaces and evaporate, leaving the solids deposited on the mirror surface. Prevailing winds are from the south. Therefore, cooling tower drift may be a significant factor in mirror contamination at this site. An active coal pile is located south of the proposed heliostat field. Coal dust in the air may also settle on the mirrors and contribute to mirror contamination.

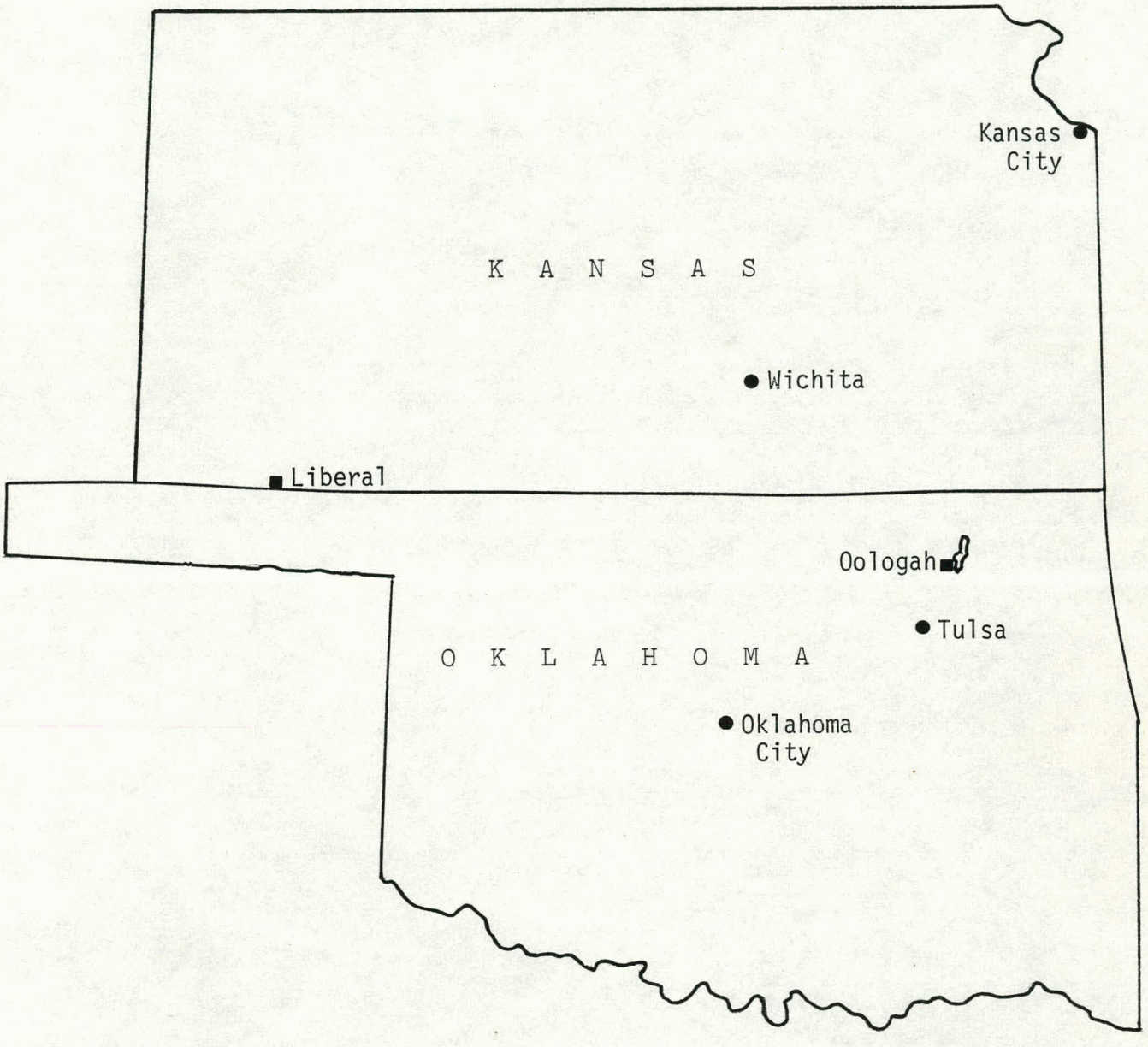


FIGURE 1. Map Showing the Location of the Exposure Test Sites at Oologah, OK and Liberal, KS

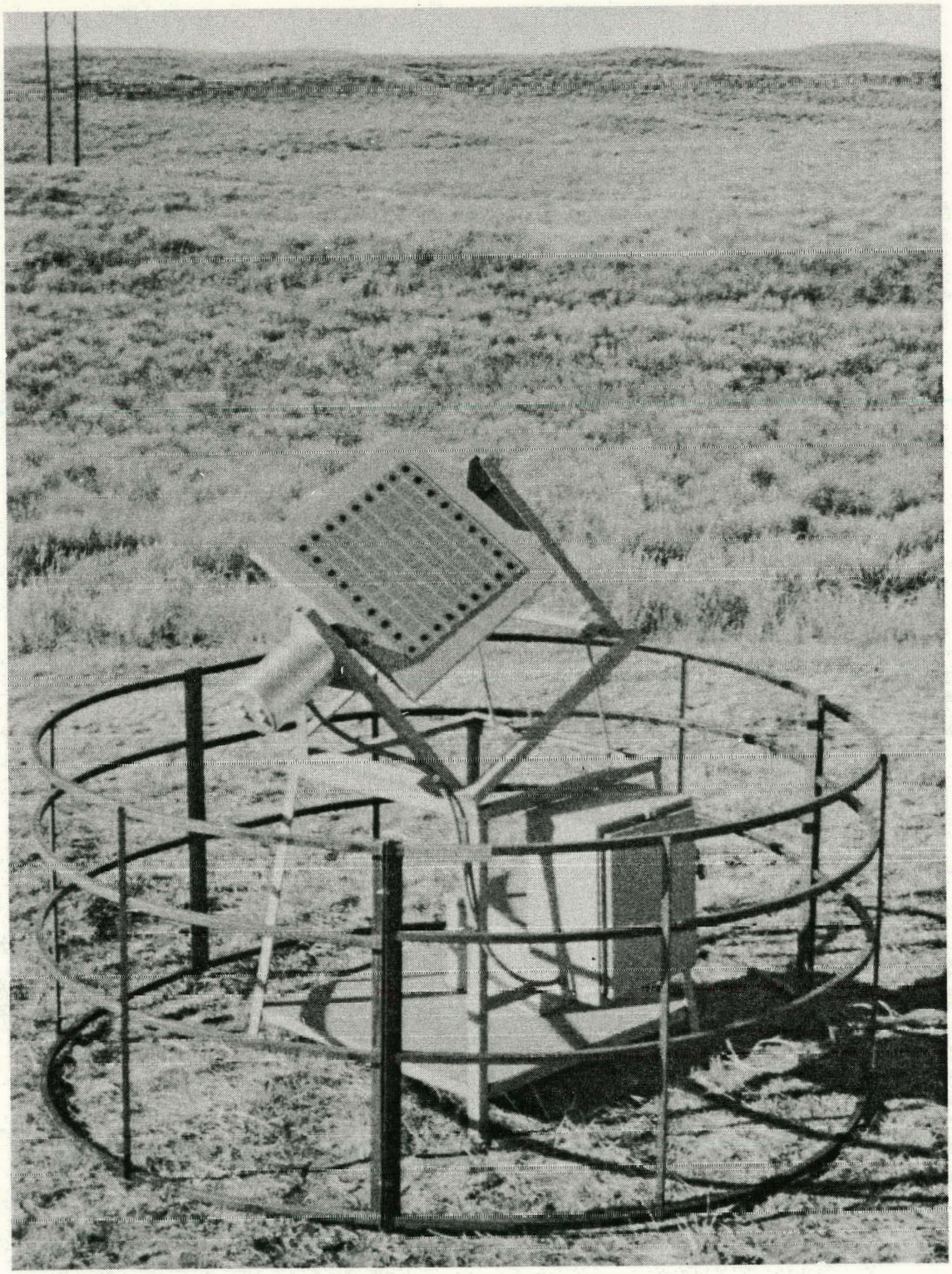


FIGURE 2. Black & Veatch Heliostat Simulators
(photograph courtesy of Black & Veatch)

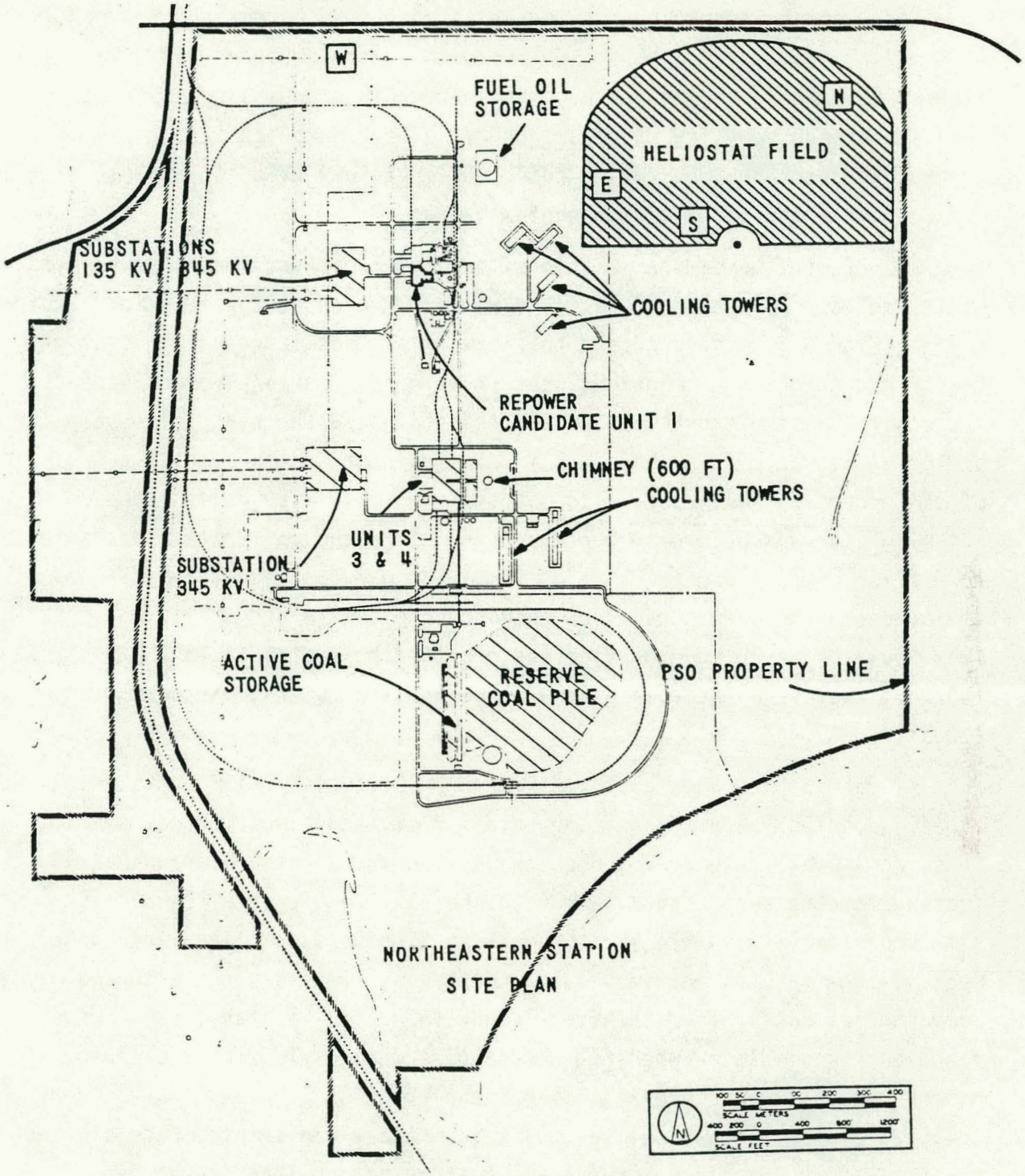


FIGURE 3. Location of Proposed Collector Field and Test Equipment at Oologah, OK (site plan courtesy of Black & Veatch)

The Oologah Reservoir and a gravel access road border the Oologah site on the east, U.S. Highway 169 forms the western border and Oklahoma Highway 88 borders on the north. The surrounding land is grassy prairie land containing very few trees or bushes. The ground is silty clay (0.3-0.9 m deep) on top of limestone. So a variety of dust and pollens may also be a source of mirror contamination.

Two studies were done at this site. For the first study, four heliostat simulators (labeled N, S, E and W) were placed at the locations indicated in Figure 3. The proposed heliostat field was large enough that mirrors in different locations might be subject to contamination from different sources. The simulators were positioned so that a representative sampling of locations would be covered. The "E" simulator was located in the portion of the proposed field closest to the cooling towers for Units 1 and 2. The "S" simulator was placed in the area closest to the coal pile and cooling towers for Units 3 and 4. The "N" simulator was positioned in the area of the proposed field furthest from both cooling towers and coal pile. The "W" simulator was placed outside the proposed heliostat field in the area furthest away from the coal pile and cooling towers that was part of the PSO site.

Mirror samples were deployed February 22, 1980. The first samples were collected on February 25, and one sample from each simulator was picked up twice a week thereafter. The testing continued until mid June, 1980. Testing for the second study began October 22, 1980 on the "E" and "S" simulators only, with the first samples pulled October 24 and then once weekly. New samples were deployed on the simulators for the second study. Some samples dating from the first study (deployed February, 1980) were found on the simulator when the new samples were deployed. These old mirror coupons were dispersed among the new coupons. Every fourth week only, an old sample was pulled. Data from these old samples were plotted on the "E" and "S" plots for the first study rather than on the second study plots. First study plots and data are labeled "East" and "South", while second study data and plots are labeled "New East" and "New South".

Liberal, Kansas[2]

Liberal, Kansas is the location of the Cimarron River station, which was under consideration for a solar cogneration project. The proposed collector field associated with this project is located north of cooling towers serving both the Cimarron River Station and the National Helium Corporation, as shown in Figure 4. Prevailing winds are from the south, so there was concern about the potential impact of cooling tower drift on the reflectivity of heliostat mirrors. The surrounding land consists of sandy soil with a light ground cover of grasses, which provides a source of dust and pollen contamination.

Two simulators, labeled "A" and "B" were deployed in the heliostat field in the locations marked in Figure 4. Simulator B was located approximately 150 m (500 ft) north of the cooling towers and was intended to be representative of heliostats exposed to cooling tower drift. Simulator A was located in a remote part of the proposed collector field where it was assumed that the effects of cooling tower drift would be negligible. In addition to the two simulators, a stationary, fixed-angle table holding mirror coupons was located approximately 15 m (50 ft) due north of the cooling towers to assess the maximum effect of cooling tower drift on mirrors. Samples on the cooling tower drift table were labeled "CT".

Samples were deployed on the "A" and "B" simulators on January 15, 1981. Samples were collected weekly beginning January 23. "CT" samples were deployed February 3, 1981, and were picked up once every two weeks beginning February 13.

MEASUREMENTS

The mirror coupons were sent to PNL for optical characterization. Spectral hemispherical and diffuse reflectance measurements were done over the wavelength interval of 300 to 2500 nm using a Beckman 5270 spectrophotometer with a 15 cm (6 in.) integrating sphere. The accuracy of the measurements is believed to be $\pm$0.005 reflectance units. The spectral data was weighted to the NASA AM 1.5 terrestrial solar spectral irradiance distribution (TSSID)[3] using a best fit approximation routine to obtain the solar reflectance. The result of this

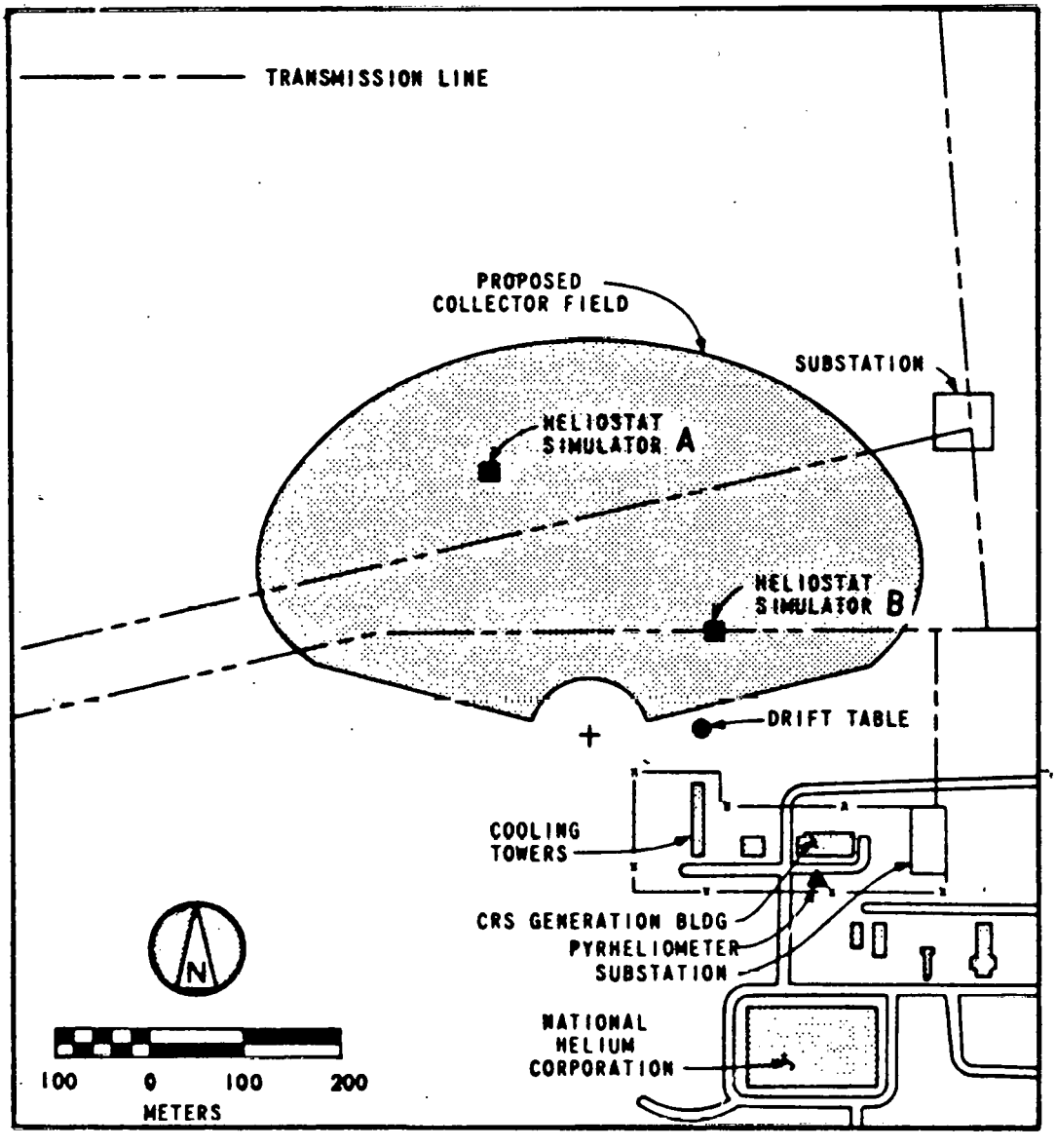


FIGURE 4. Location of Proposed Collector Field and Test Equipment at Liberal, KS (site plan courtesy of Black & Veatch)

calculation is a single number between 0 and 1.000 (called the solar weighted reflectance) that characterizes the entire spectral scan and represents the fraction of solar energy reflected from the mirror.

Changes in reflectance, i.e., the difference (ΔR) between the exposed mirror reflectance (R_f) and clean mirror reflectance (R_i), were plotted. The change in hemispherical reflectance (ΔR_H) indicates the absorptance of the dust layer. The change in diffuse reflectance ($-\Delta R_D$) shows losses due to scattering. The diffuse reflectance measurement collects all radiation scattered greater than a cone angle of seven degrees from the specular direction. The total specualar reflectance loss is equal to the sum of hemispherical and diffuse reflectance losses ($\Delta R_S = \Delta R_H - \Delta R_D$).

Selected samples from the A, B, S and E simulators were analyzed using an SEM, with an energy-dispersive X-ray (EDX) attachment to obtain the chemical composition of the dust.

Some of the A and B samples were cleaned using a commercial high-pressure jet spray of detergent water (from a car wash) followed by a thorough rinsing (using municipal water supply). After air drying, the samples were remeasured (hemispherical and diffuse reflectance), then washed a second time. The second wash consisted of scrubbing with a soft cloth and mild detergent and water solution. The samples were then rinsed thoroughly in DI water, air-dried and remeasured.

DATA ANALYSIS AND RESULTS

OPTICAL DEGRADATION

Changes in reflectance data (ΔR_H, $-\Delta R_D$ and ΔR_S) were plotted for the coupons as a function of exposure time. Diffuse reflectance measurements were not taken for many of the Oologah, OK., "N" and "W" samples, so only ΔR_H was plotted for the "N" and "W" data. The reflectance data for all the simulators is displayed in Figures 5 through 13. Notice that there is often a great amount of variation between successive measurements. These short term variations swamp any readily observable average trends. These plots

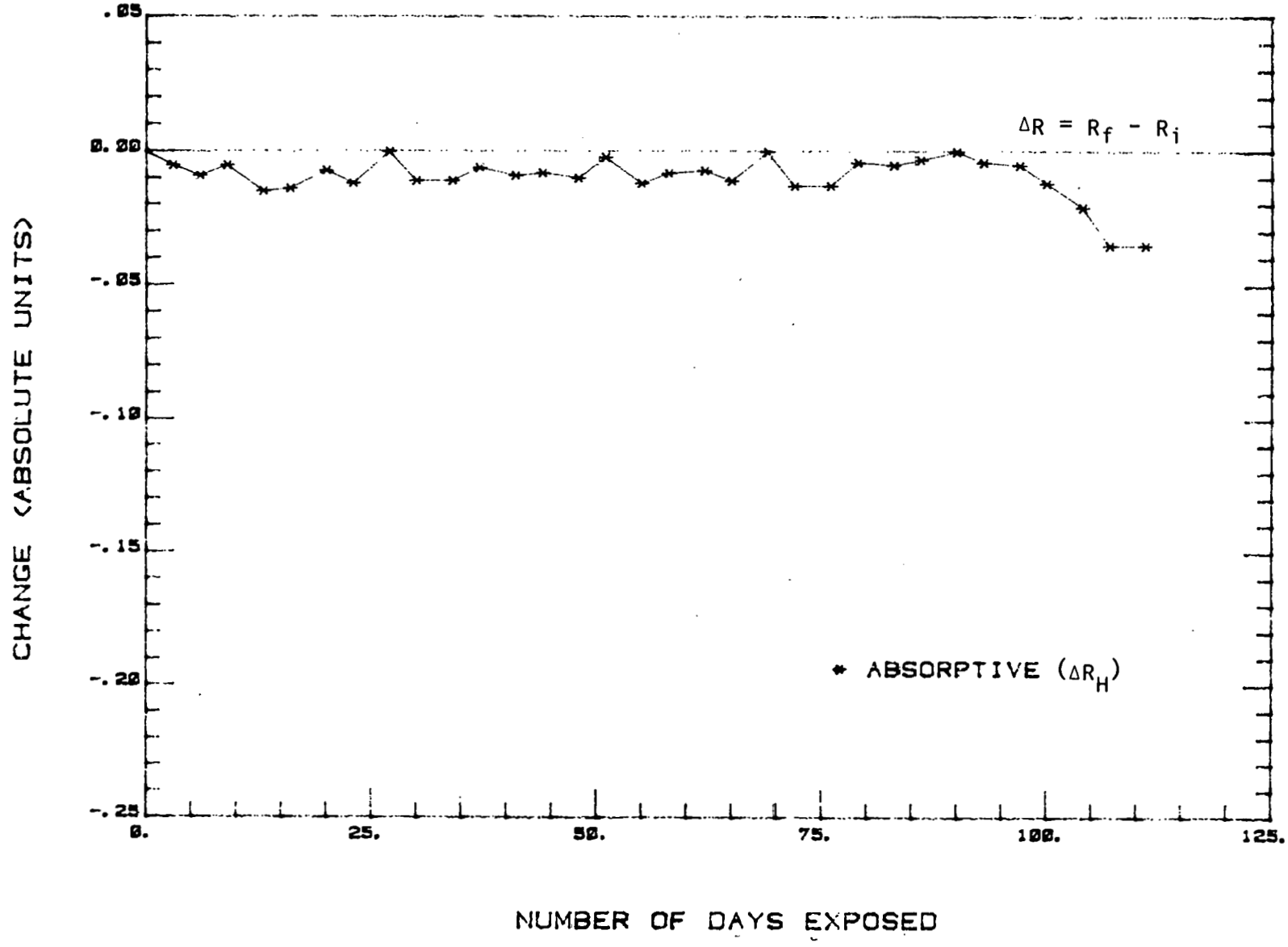


FIGURE 5. Effects of Atmospheric Contamination on the Solar Weighted Hemispherical Reflectance of Float Glass Mirrors Deployed on the North Simulator at Oologah, OK (1980)

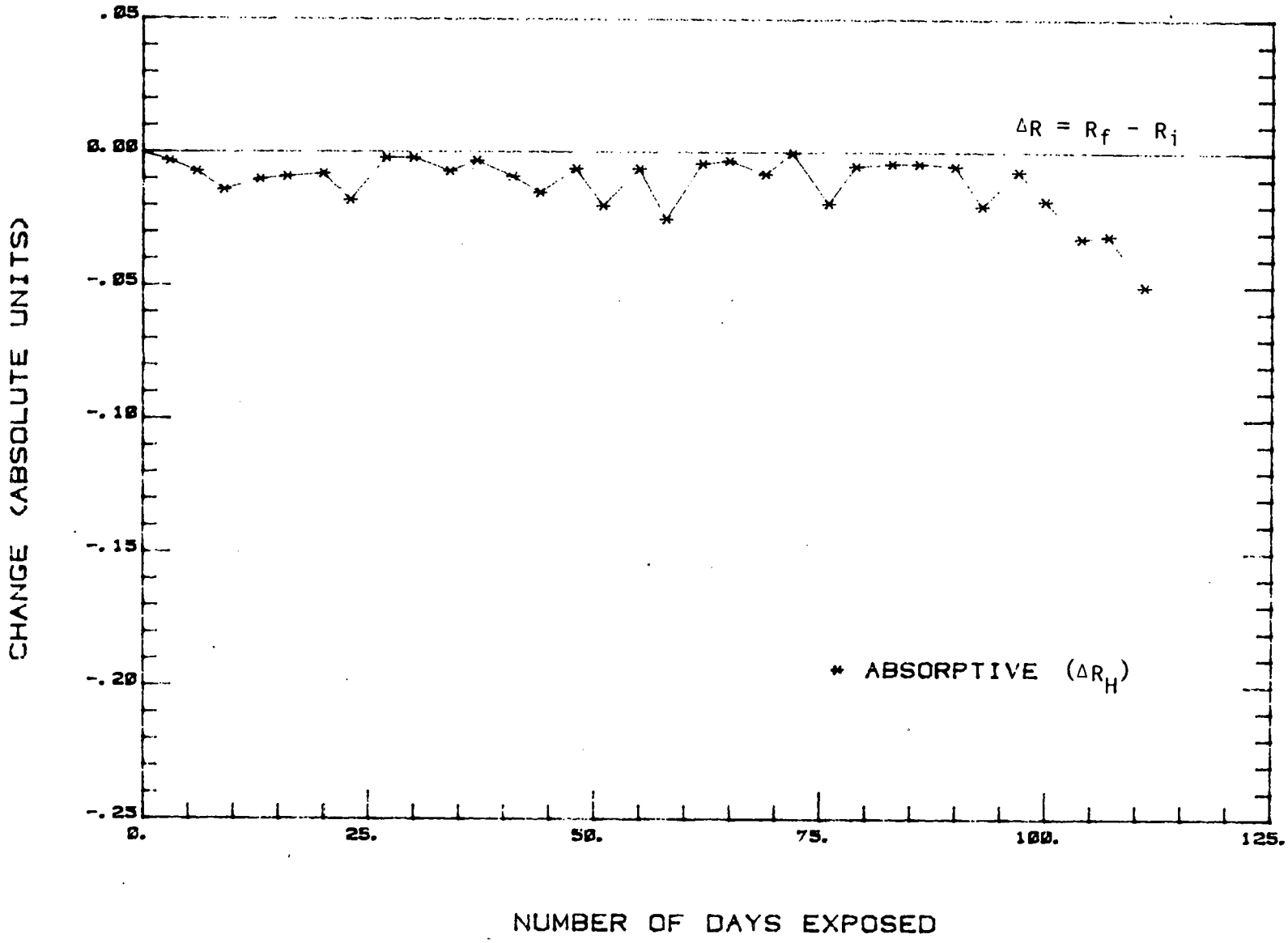


FIGURE 5. Effects of Atmospheric Contamination on the Solar Weighted Hemispherical Reflectance of Float Glass Mirrors Deployed on the West Simulator at Oologah, OK (1980)

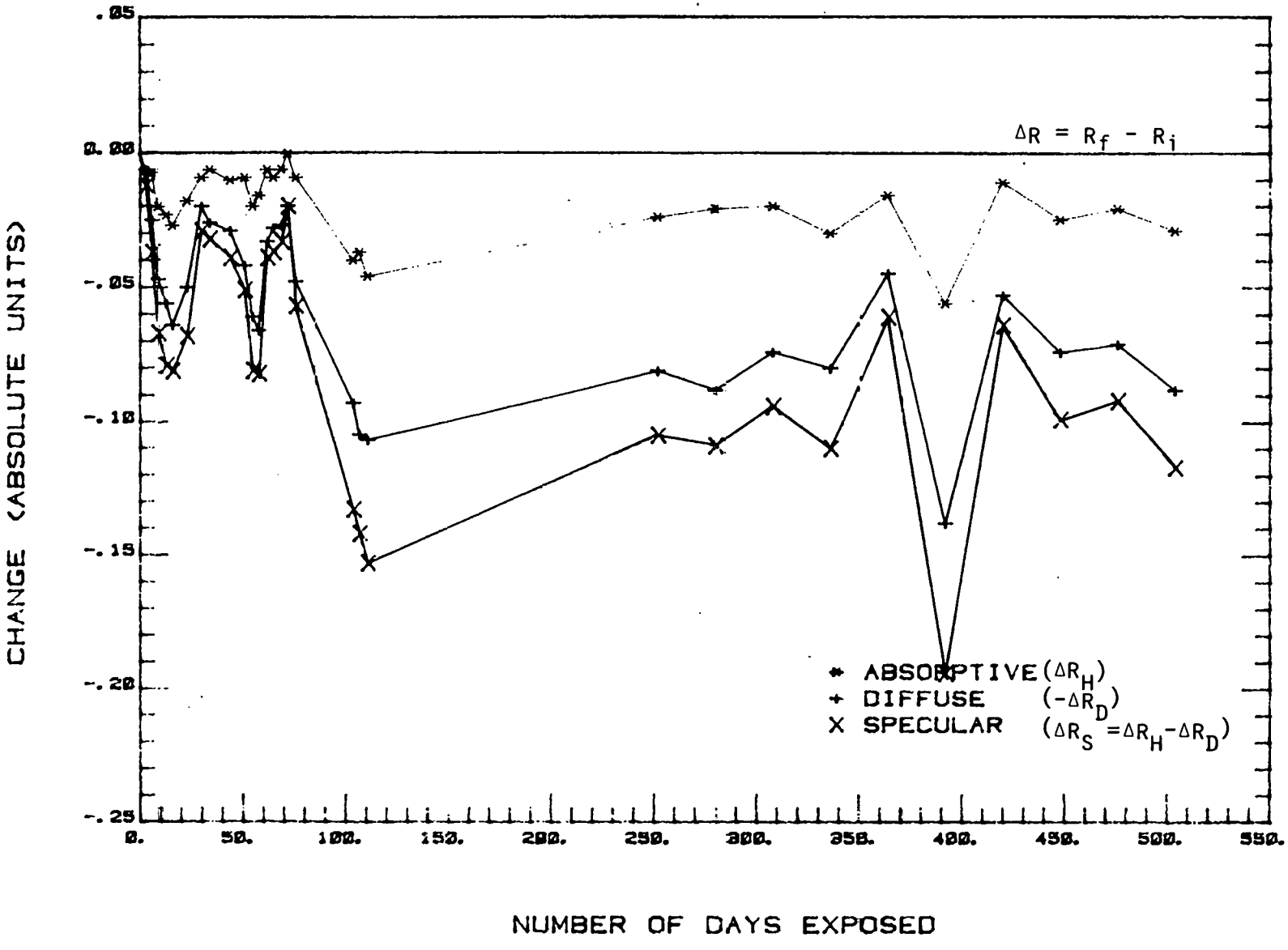


FIGURE 7. Effects of Atmospheric Contamination on the Solar Weighted Optical Properties of Float Glass Mirrors Deployed on the East Simulator at Oologah, OK (1980-1981)

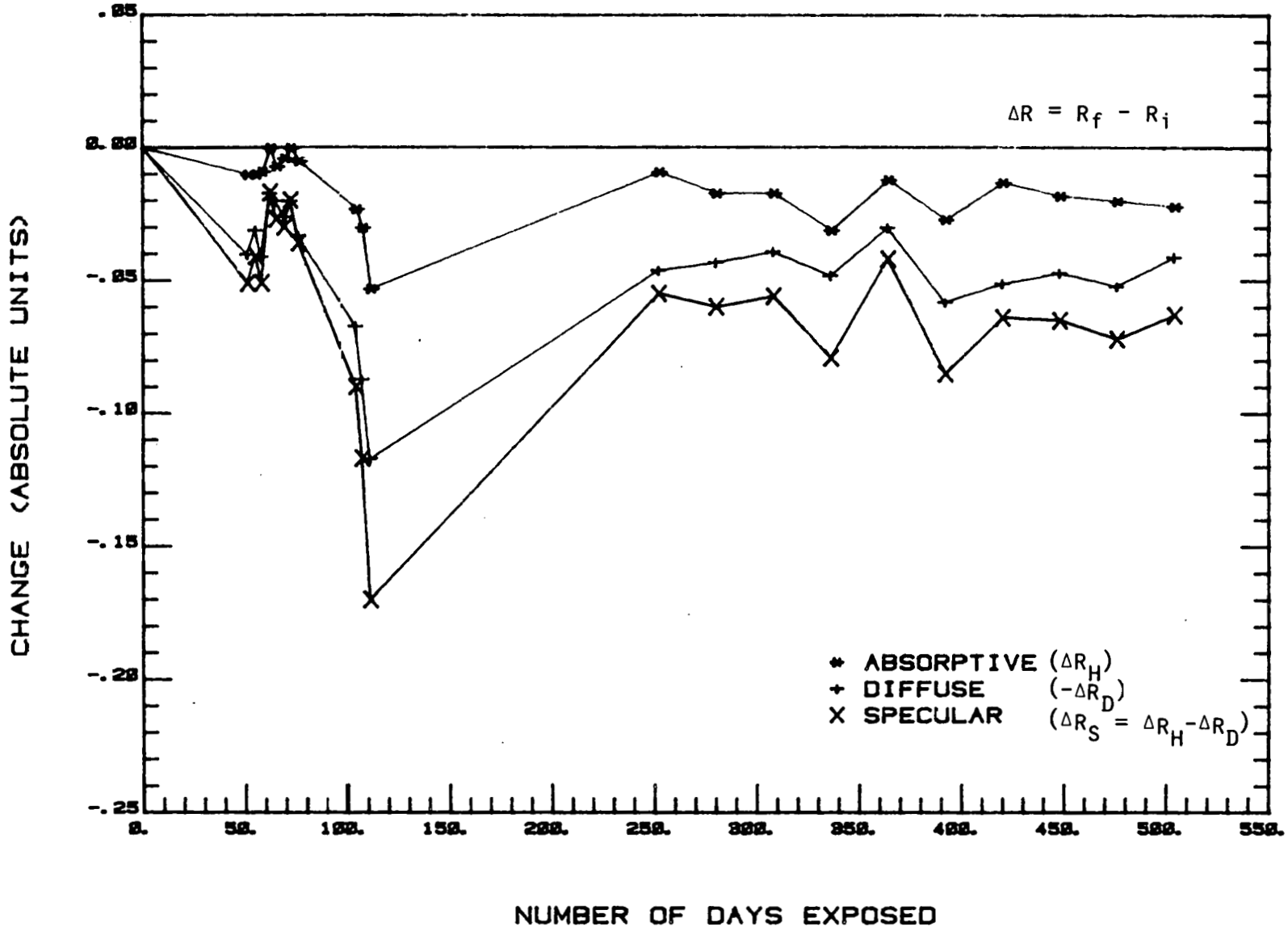


FIGURE 8. Effects of Atmospheric Contamination on the Solar Weighted Optical Properties of Float Glass Mirrors Deployed on the South Simulator at Oologah, OK (1980-1981)

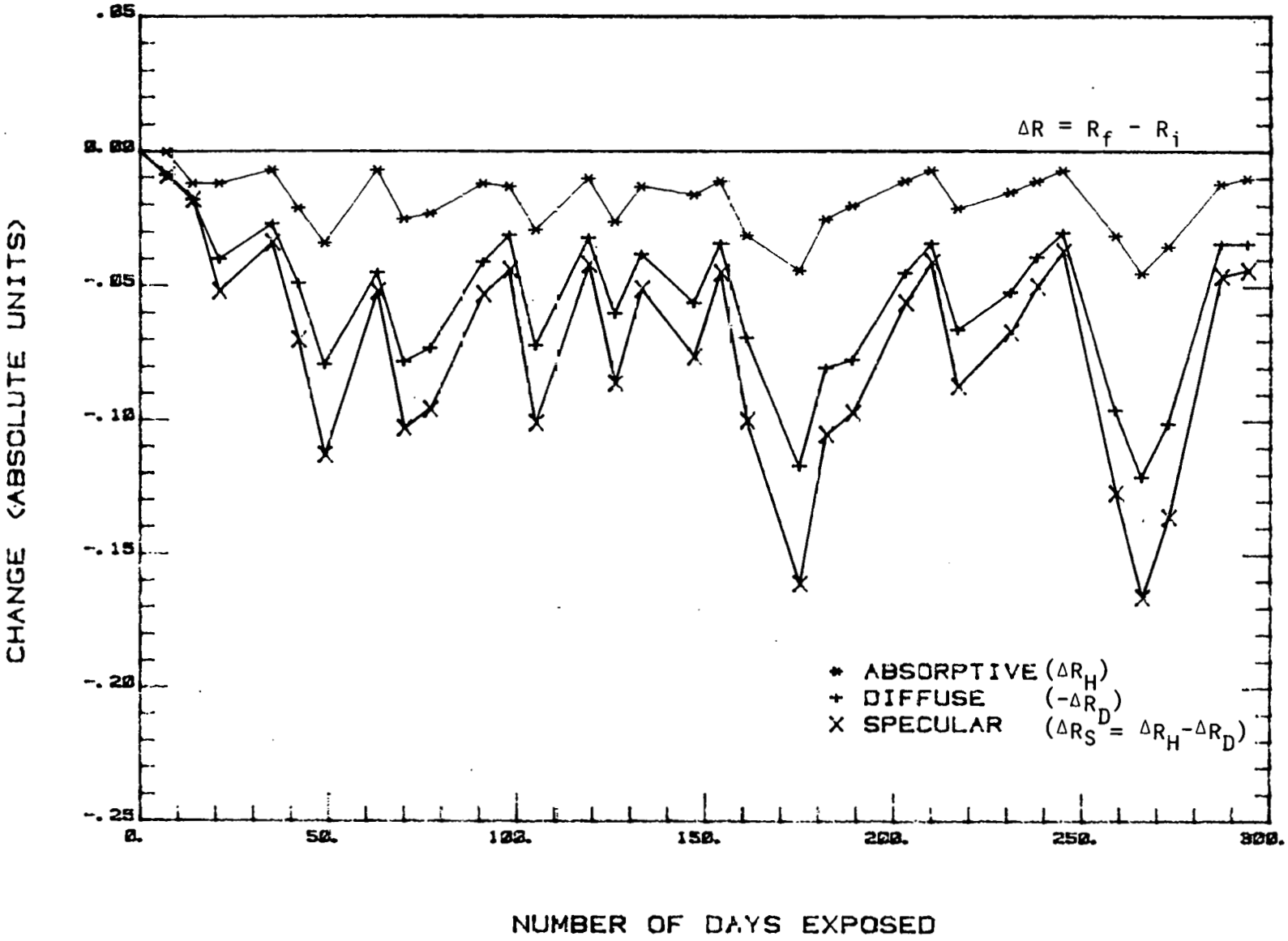


FIGURE 9. Effects of Atmospheric Contamination on the Solar Weighted Optical Properties of Float Glass Mirrors Deployed on the New East Simulator at Oklogah, OK (1980-1981)

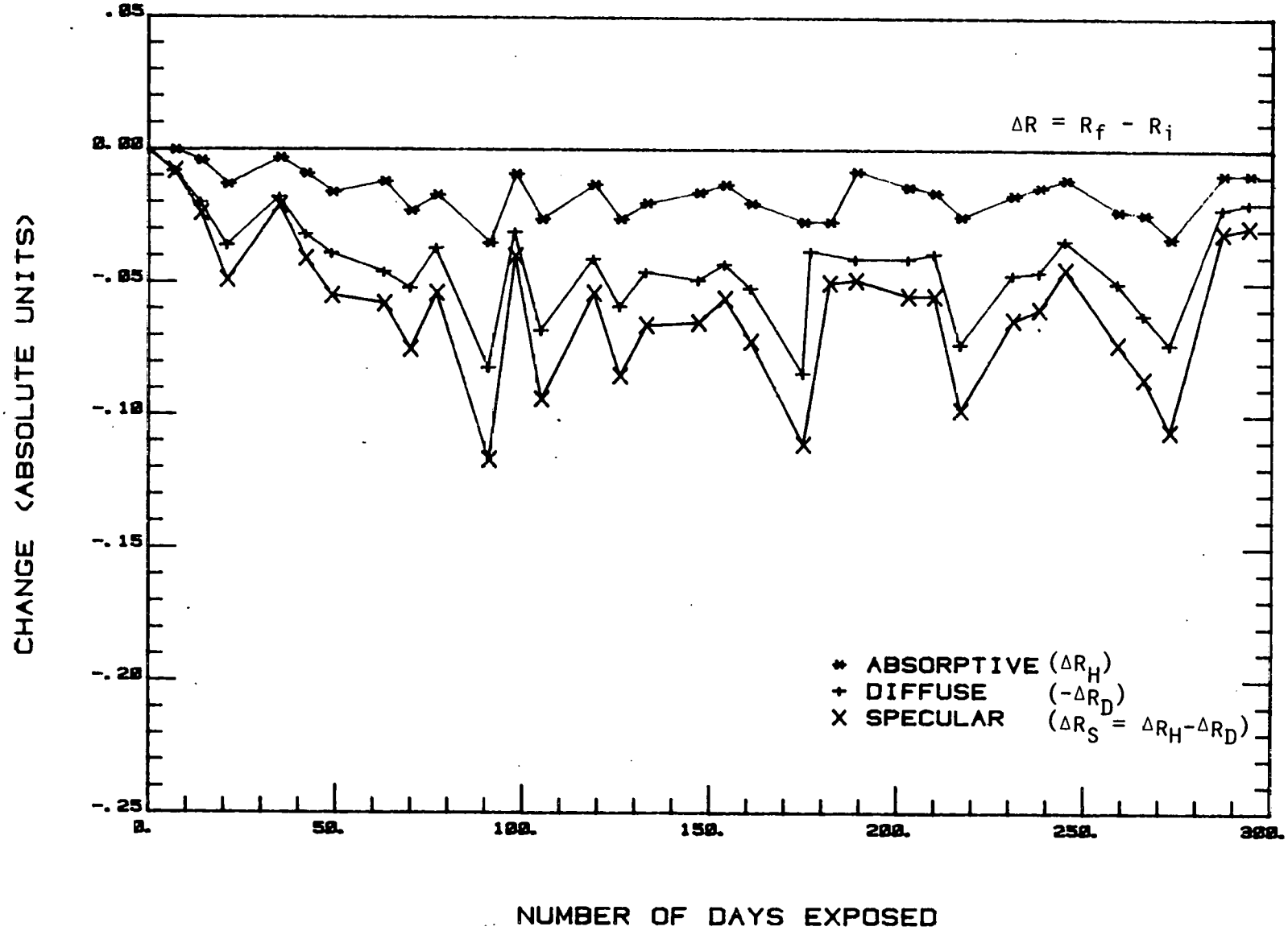


FIGURE 10. Effects of Atmospheric Contamination on the Solar Weighted Optical Properties of Float Glass Mirrors Deployed on the New South Simulator at Oologah, OK (1980-1981)

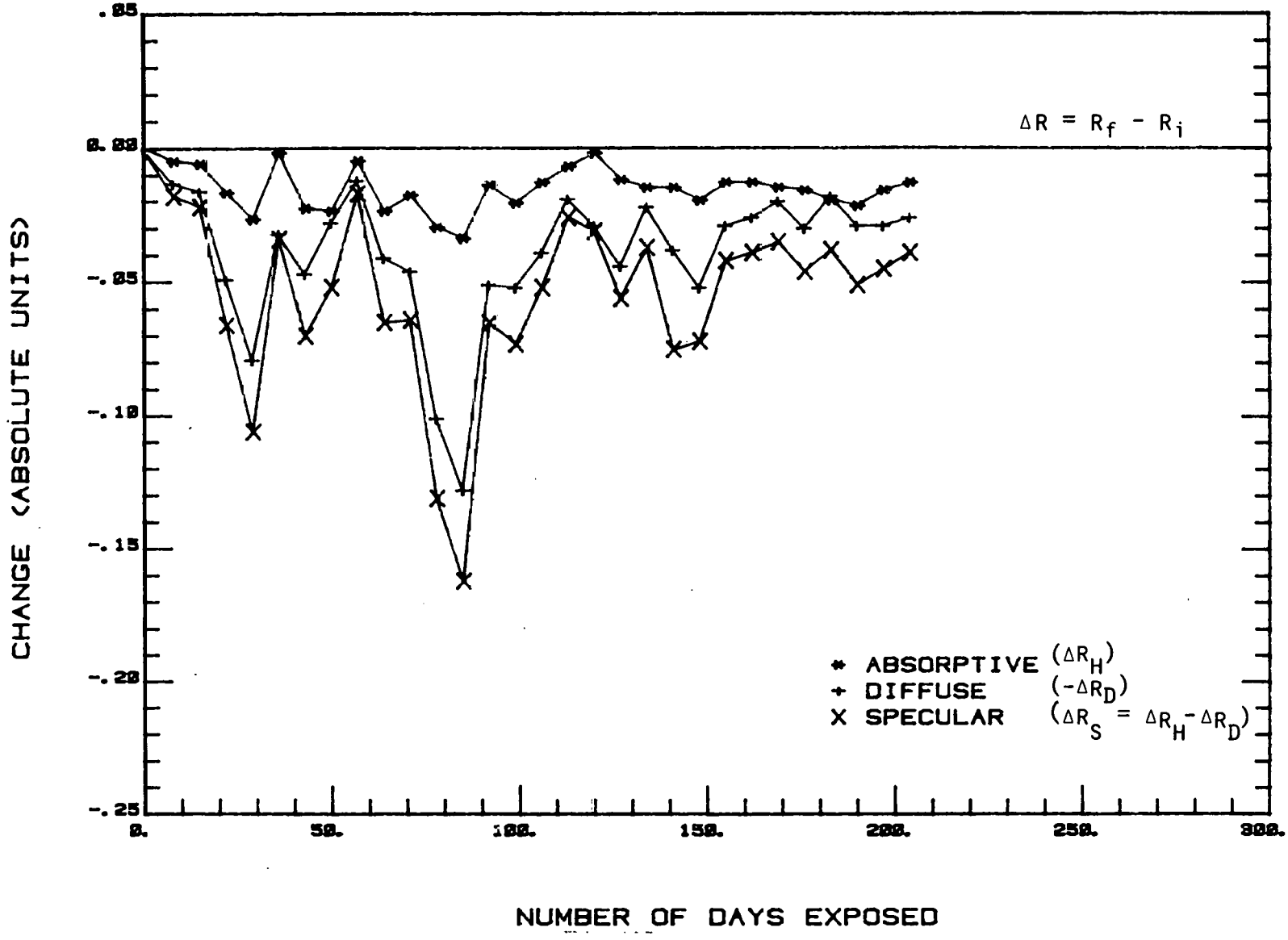


FIGURE 11. Effects of Atmospheric Contamination on the Solar Weighted Optical Properties of Float Glass Mirrors Deployed on the "A" Simulator at Liberal, KS (1981)

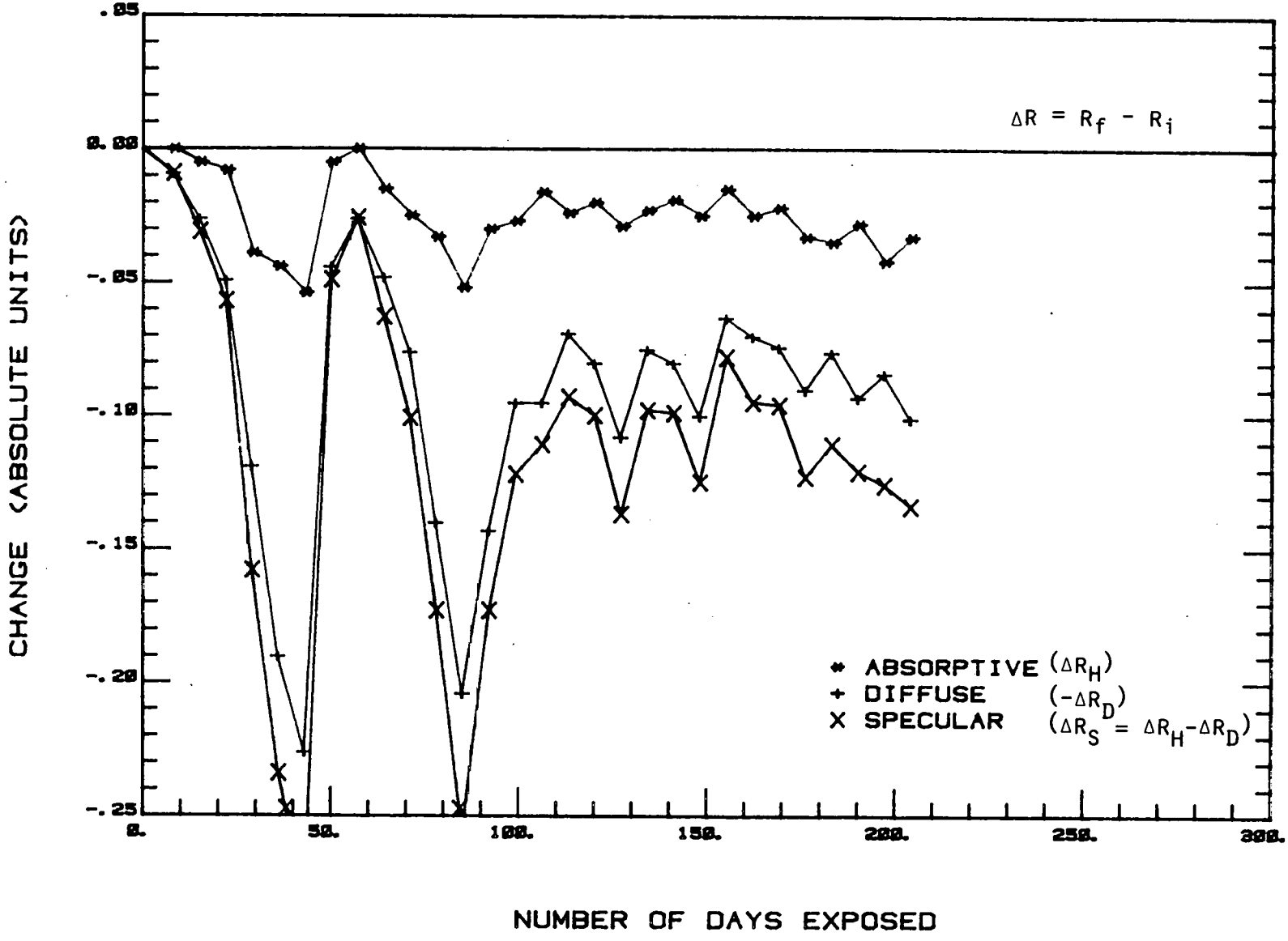


FIGURE 12. Effects of Atmospheric Contamination on the Solar Weighted Optical Properties of Float Glass Mirrors Deployed on the "B" Simulator at Liberal, KS (1981)

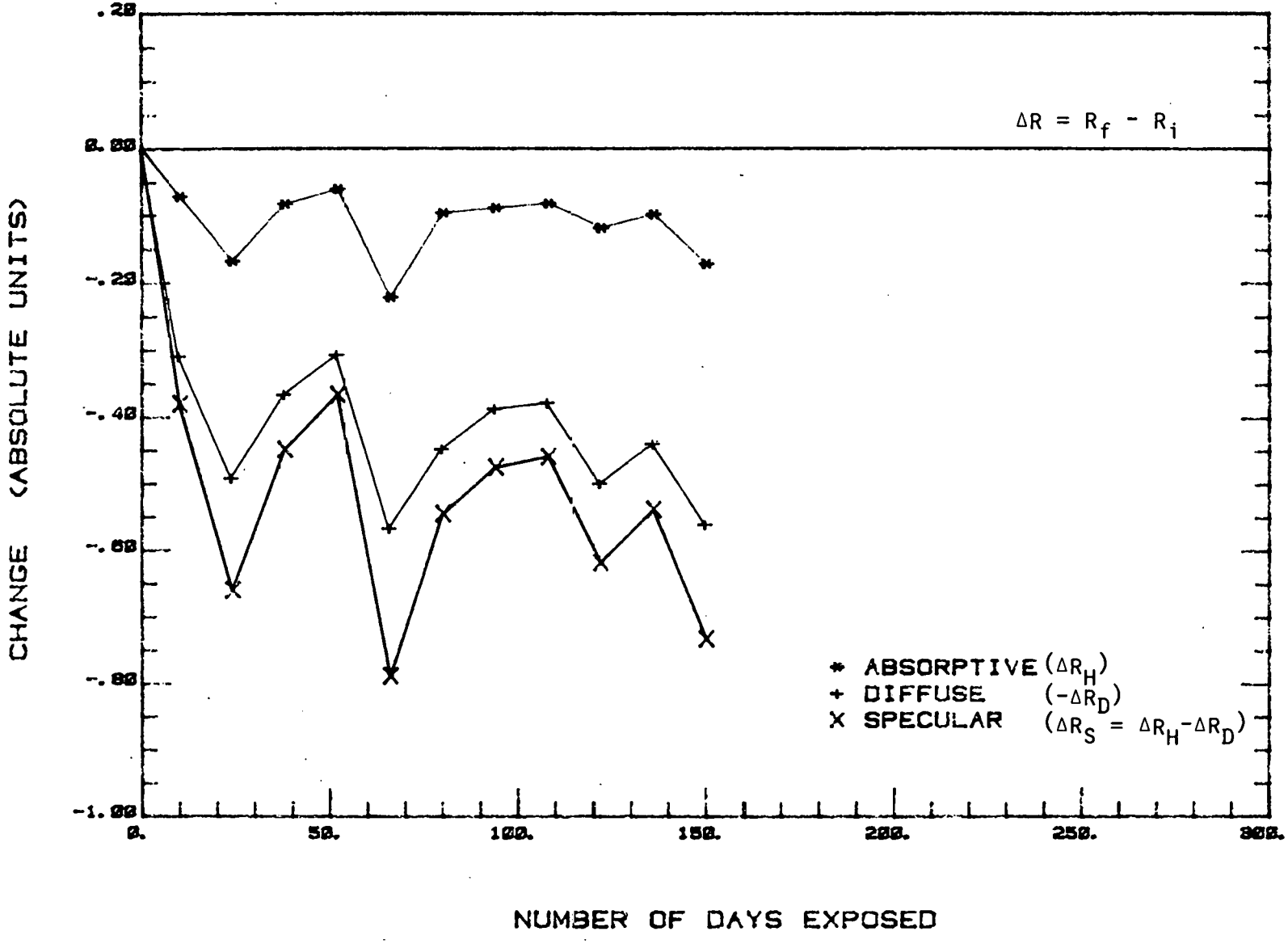


FIGURE 13. Effects of Atmospheric Contamination on the Solar Weighted Optical Properties of Float Glass Mirrors Deployed on the "CT" Drift Table at Liberal, KS (1981)

do show that the major portion of the specular reflectance losses are due to scattering rather than absorption. In general, scattering losses are two to five times as large as the absorptive losses.

In Figure 14, specular reflectance changes (ΔR_S) were plotted as a function of exposure time for the "A" and "B" simulator data. Precipitation data for the Liberal site is shown at the top of the graph. Precipitation is noted as being either light (l), moderate (m) or heavy (h). "Light" indicates that only trace amounts of precipitation were recorded for that day; "moderate" denotes a measurable amount less than 5 mm (0.2 in.) and "heavy" is 5 mm (0.2 in.) or more precipitation. The "A" and "B" simulators malfunctioned occasionally and did not track the sun. When malfunctioning, the simulators remained in a fixed position with the mirror coupons face up.[2] These times are also indicated at the top of the graph in Figure 14.

There does appear to be some correlation between precipitation and cleaning of the samples. But not all of the fluctuations in the graphs can be explained by the precipitation data. Other factors affecting mirror reflectivity include dust storms, cooling tower activity, and high winds.

Several techniques were used to analyze the reflectance data to determine if any meaningful generalizations could be made. The average reflectance loss over the entire test period at each site was calculated. The results are shown in Table 1. For all the simulators, the average absorptive loss (ΔR_H) was only 1 to 2%. The average losses due to scattering (ΔR_D) varied between 5 and 10%. At the Oologah site, the average specular loss (ΔR_S) was approximately 6% for the E and S simulators. At the Liberal site, the average specular loss was approximately 6% for the remote "A" simulator, but was nearly 12% for the "B" simulator. The cooling tower drift table samples (CT) at the Liberal site were much dirtier than samples from the simulators. The relationship between absorptive and scatter losses was about the same as for the "A" and "B" simulator coupons ($\sim$1:4 ratio). But the magnitude of the reflectance losses was much greater for the CT samples; specular reflectance losses averaged 55% over the test period.

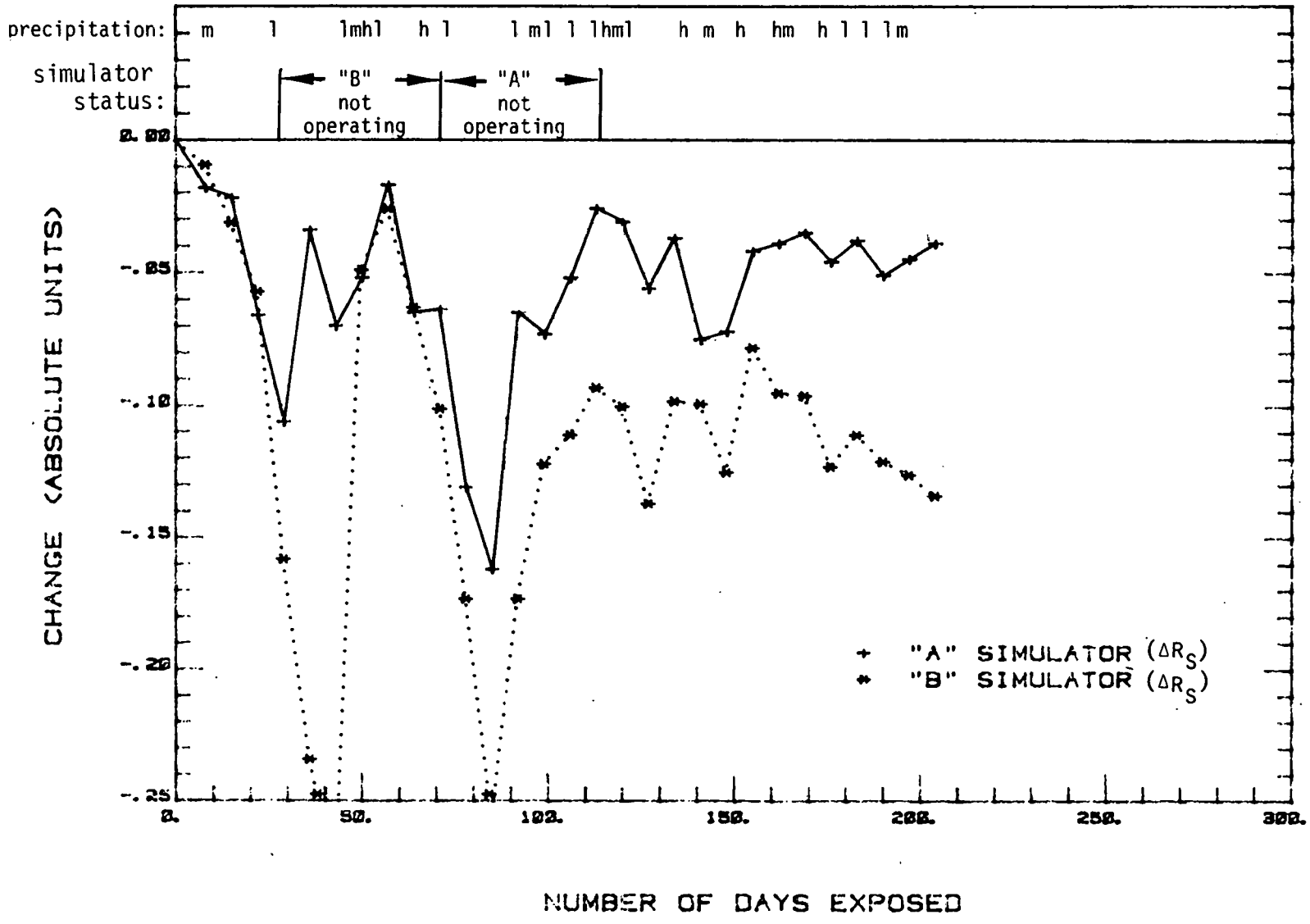


FIGURE 14. Solar Weighted Specular Reflectance Graphs, Simulator Operation Status, and Precipitation Data for the "A" and "B" Simulators

TABLE 1. Average Solar Weighted Reflectance Losses (Absolute Units)

Oologah, Oklahoma 1980-1981 (504 days)

	Absorptive ΔR_H	Scatter $-\Delta R_D$	Specular ΔR_S
"E" Simulator	$-.02 \pm .01$	$-.06 \pm .03$	$-.08 \pm .04$
"S" Simulator	$-.02 \pm .01$	$-.05 \pm .02$	$-.06 \pm .03$

Liberal, Kansas 1981 (204 days)

	Absorptive ΔR_H	Scatter $-\Delta R_D$	Specular ΔR_S
"A" Simulator	$-.02 \pm .01$	$-.04 \pm .03$	$-.06 \pm .03$
"B" Simulator	$-.03 \pm .01$	$-.09 \pm .05$	$-.12 \pm .06$
"CT" Drift Table	$-.11 \pm .05$	$-.43 \pm .09$	$-.55 \pm .14$

A linear regression analysis was done on the specular reflectance loss curves to find an average daily degradation rate. Linear regression was done over the entire curve; over the first 30 days only; and over the curve past the first 30 days. The 30 day cut-off was chosen arbitrarily. The linear regression line was constrained to pass through the origin for the 30 day segments. The lines generated by the linear regression analysis are shown superimposed on the specular reflectance loss curves in Figures 15 through 21. The resulting values for the average rate of change of specular reflectance ($\overline{\Delta R_S/day}$) are summarized in Table 2. In all cases, the specular reflectance degradation rate was markedly greater during the first thirty day period than it was over the remaining days. In fact, the degradation rate over the curves past the first 30 days was close to zero. In some cases the lines generated by linear regression analyses had positive slope, indicating that the mirror reflectances improved with increased exposure times. This phenomena was due to repeated natural cleaning events during the test period under consideration.

Short term specular reflectance degradation rates were also calculated to determine the average daily degradation during periods of continuous soil

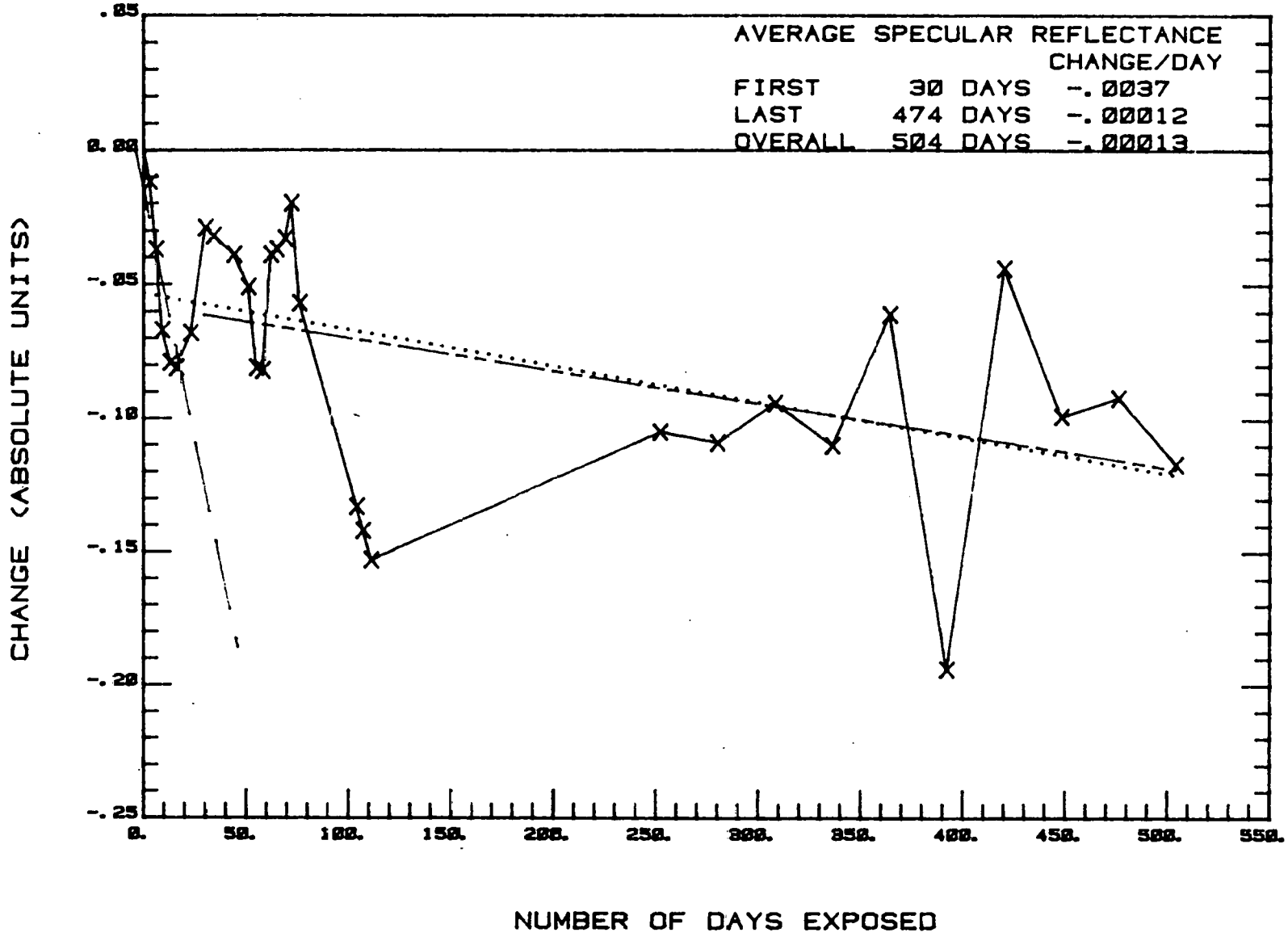


FIGURE 15. Results of Linear Regression Analysis on the Solar Weighted Specular Reflectance Data for the East Simulator Located at Oologah, OK

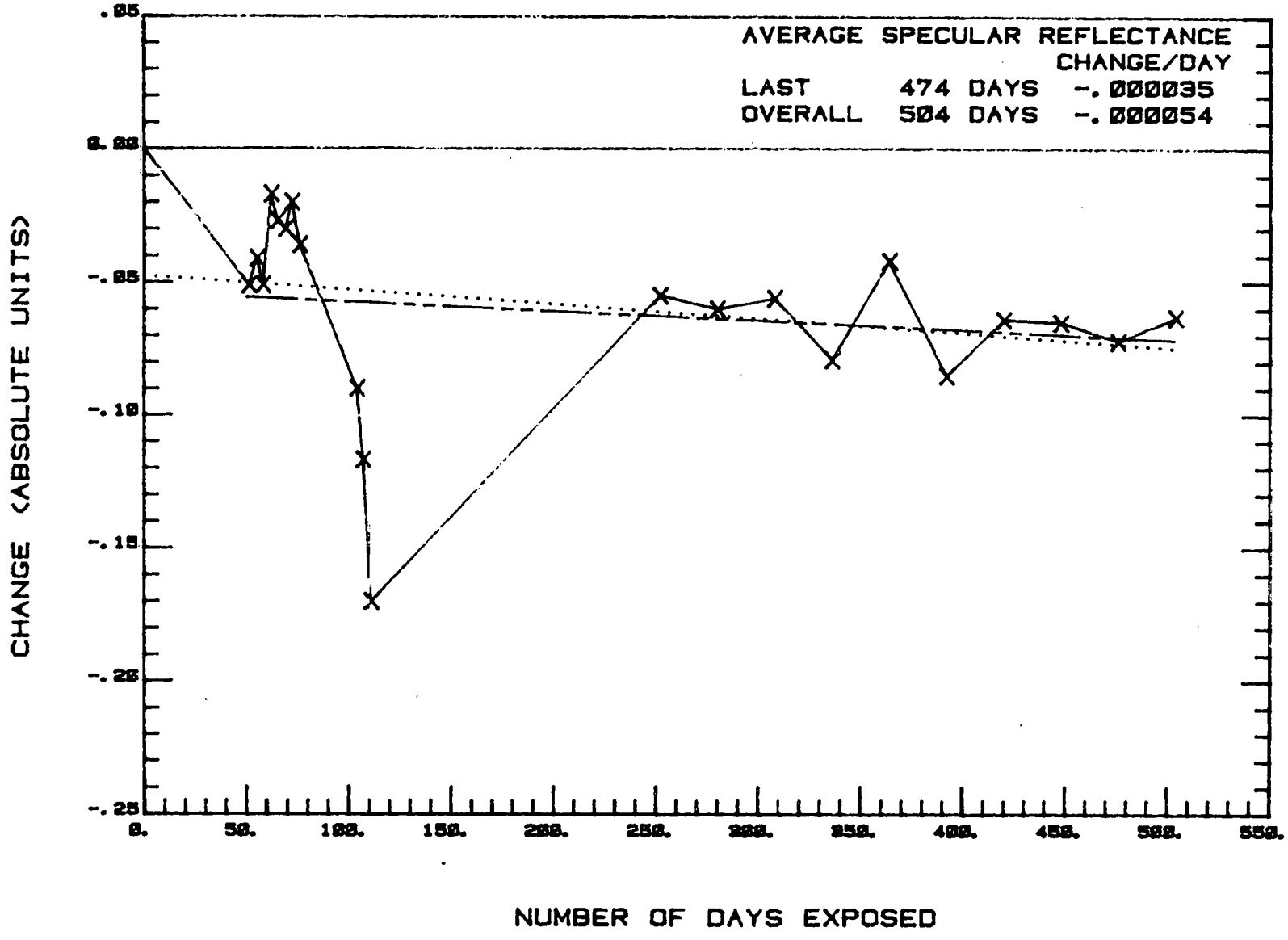


FIGURE 16. Results of Linear Regression Analysis on the Solar Weighted Specular Reflectance Data for the South Simulator Located at Oologah, OK

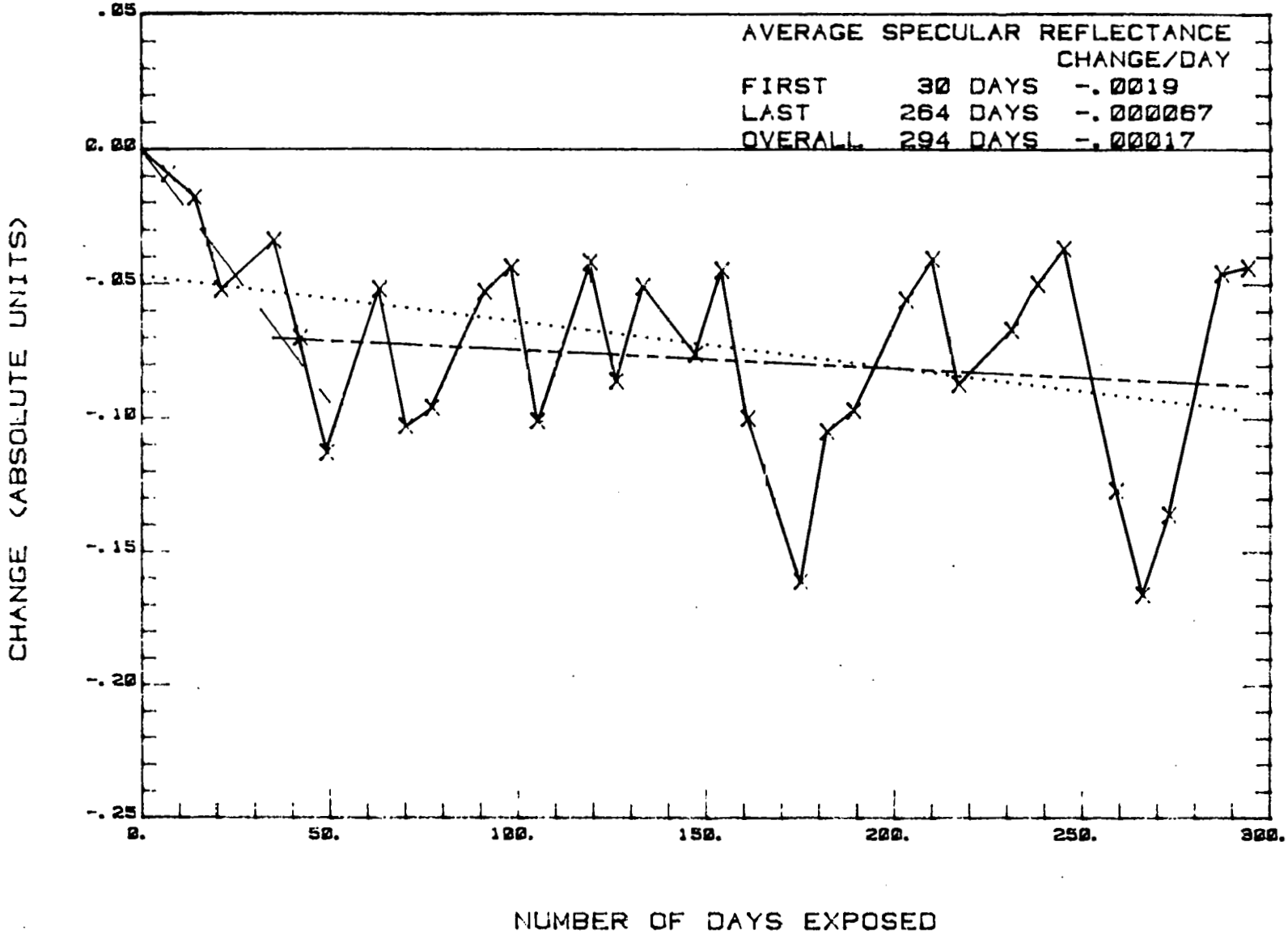


FIGURE 17. Results of Linear Regression Analysis on the Solar Weighted Specular Reflectance Data for the New East Simulator Located at Oologah, OK

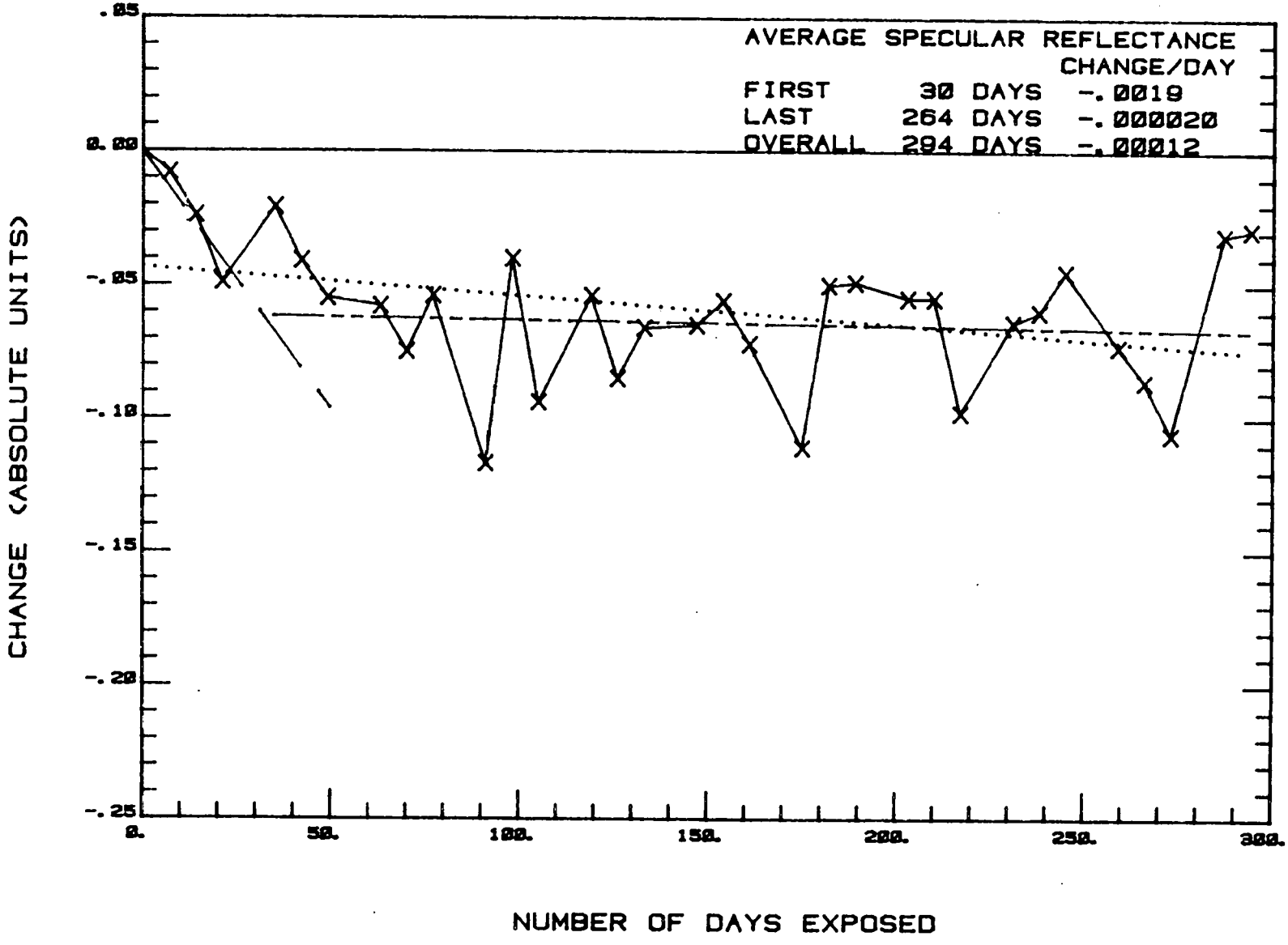


FIGURE 18. Results of Linear Regression Analysis on the Solar Weighted Specular Reflectance Data for the New South Simulator Located at Oologah, OK

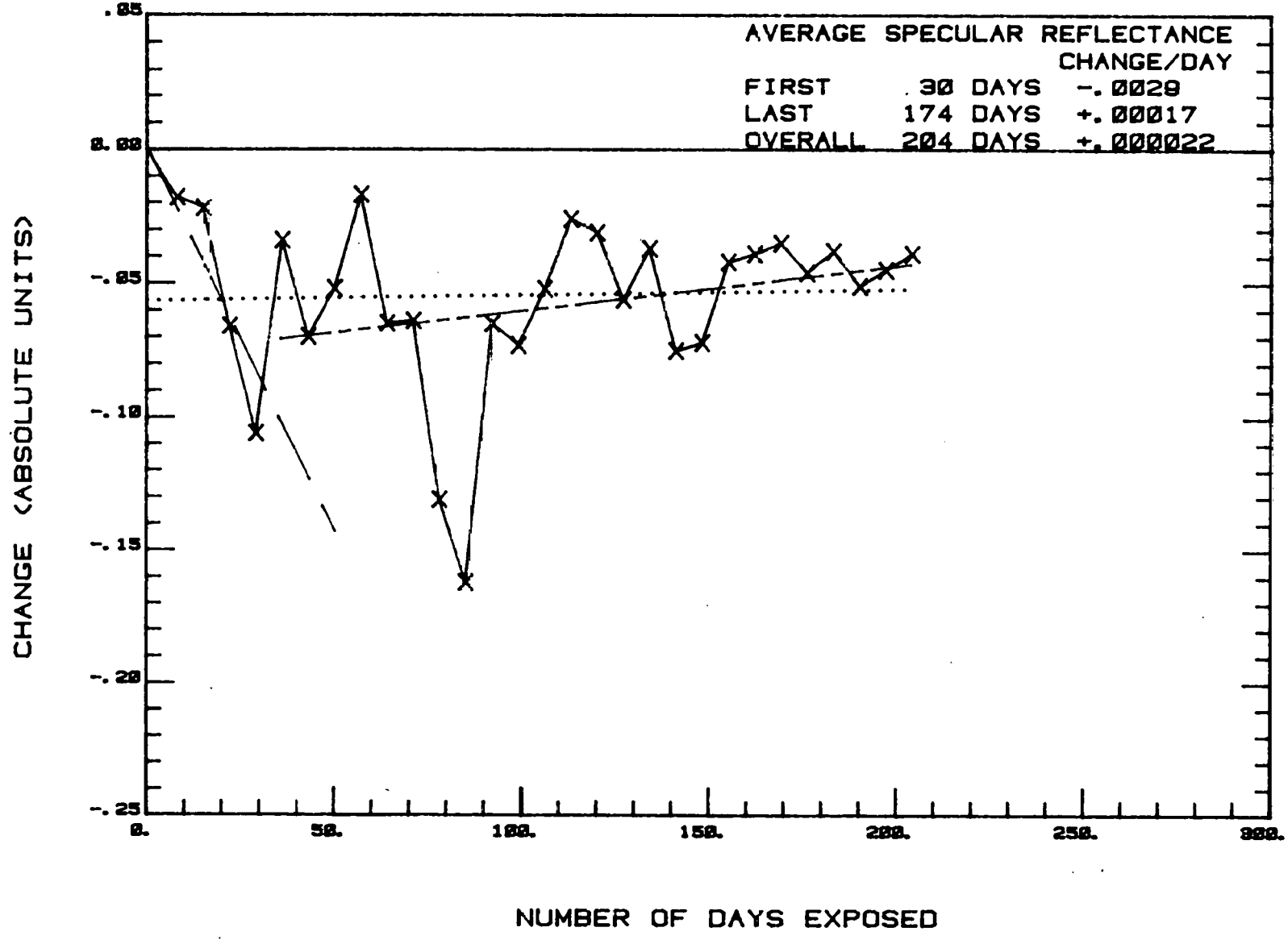


FIGURE 19. Results of Linear Regression Analysis on the Solar Weighted Specular Reflectance Data for the "A" Simulator Located at Liberal, KS

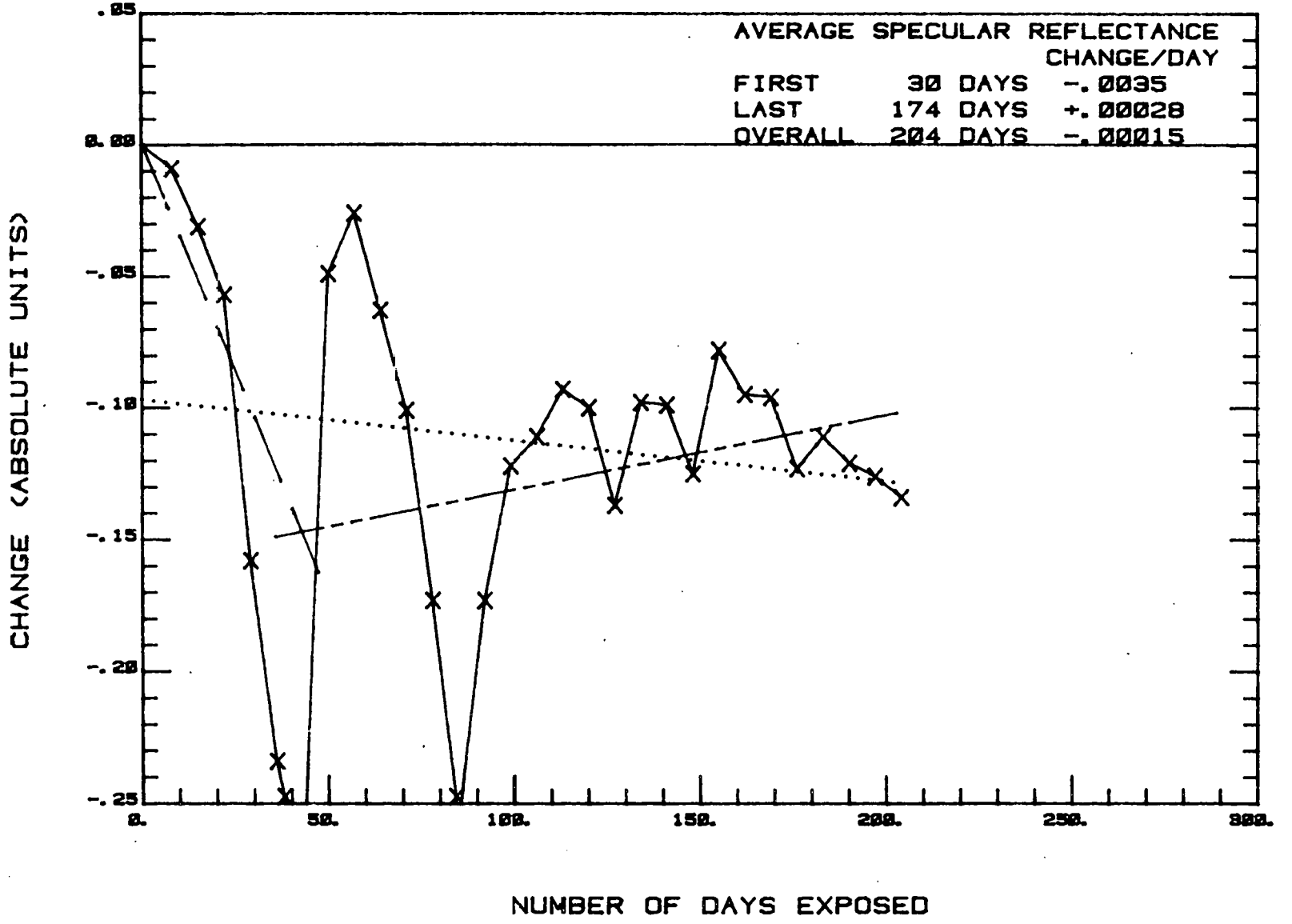


FIGURE 20. Results of Linear Regression Analysis on the Solar Weighted Specular Reflectance Data for the "B" Simulator Located at Liberal, KS

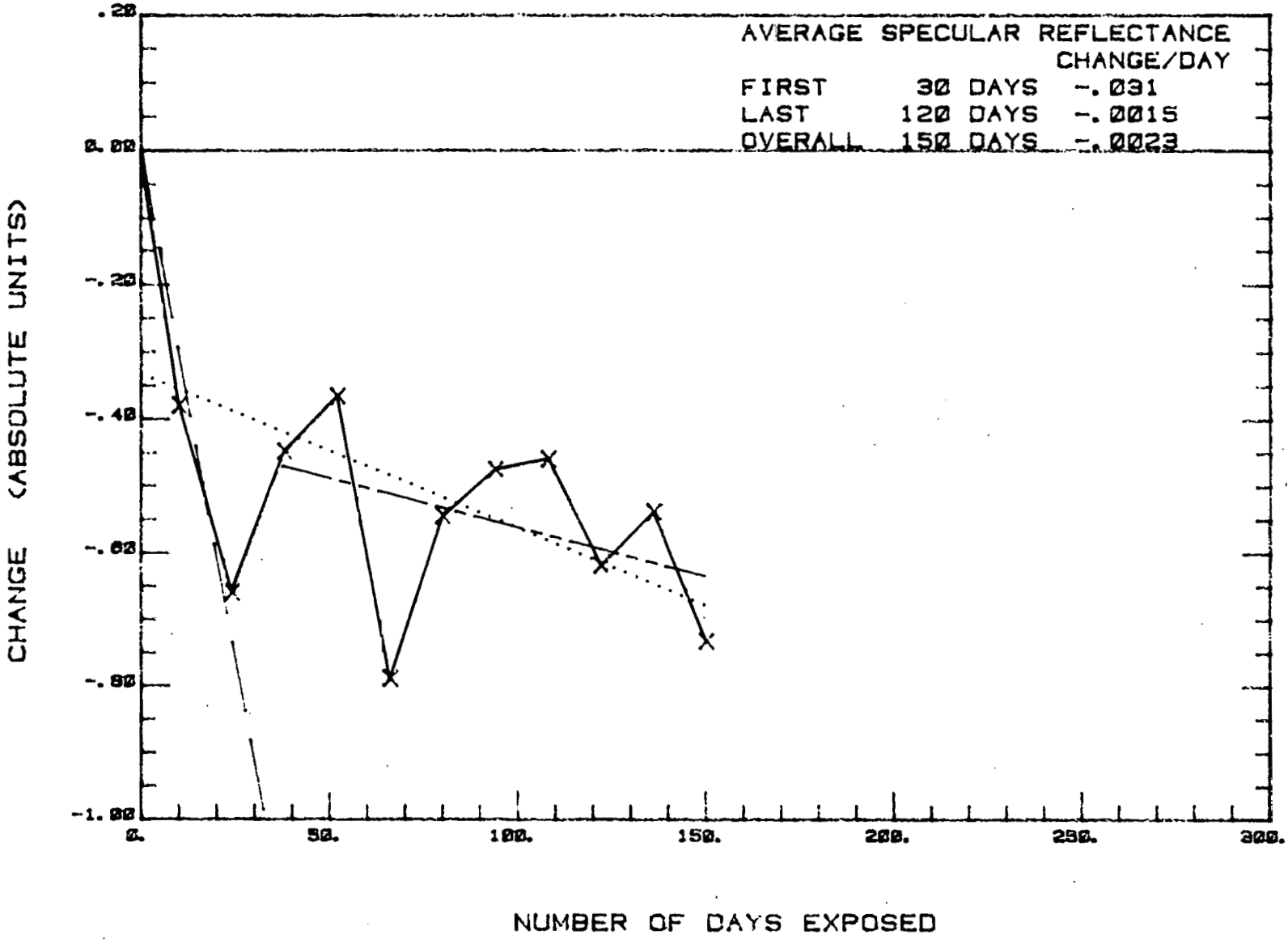


FIGURE 21. Results of Linear Regression Analysis on the Solar Weighted Specular Reflectance Data for the "CT" Drift Table Located at Liberal, KS

TABLE 2. Solar Weighted Specular Reflectance Changes/Day (Absolute Units)

Simulator	Linear Regression Analysis Slope = ΔR_S/Day			Average Decreasing Slope (< -.002) Slope = ΔR_S/Day
	Overall	1st 30 Days	Remaining Days	
A	+.00002	-.003	+.0002	-.006 ± .002
B	-.0002	-.004	+.0003	-.007 ± .004
CT	-.002	-.03	-.002	-.02 ± .01
E	-.0001	-.004	-.0001	-.006 ± .003
S	-.00005	--	-.00004	-.007 ± .004
NE	-.0002	-.002	-.00007	-.006 ± .002
NS	-.0001	-.002	-.00002	-.004 ± .002

build-up. These short term decreasing slope averages more closely approximate the effect of continuous soiling on mirror reflectivity, while the other rates reported here show the net effect of both soiling and natural cleaning events. The average decreasing slope values were obtained by calculating the average value of the negative slopes in the specular reflectance loss curves. Only slope values <-.002 were considered in this calculation, since it was assumed that a slope greater than -.002 indicated that natural cleaning and/or a combination of natural cleaning and soiling was occurring. Results are shown in Table 2. For all the simulators, specular reflectance losses averaged about 0.6% a day when soiling was occurring.

WASHING EFFECTS

Five mirror coupons apiece from the "A" and "B" simulators were selected for the washing study. Samples were measured before washing to determine the reflectance losses (ΔR_H, $-\Delta R_D$ and ΔR_S) due to outdoor exposure. Samples were then washed twice--once using a non-contact method (high pressure detergent and water wash) and then using a contact method (soft cloth and mild detergent scrub). Samples were remeasured after each washing to determine changes in reflectance due to cleaning. The results of this study are shown in bar graph form in Figures 22 and 23. The reflectance losses due to outdoor exposure are shown, as well as residual reflectance losses

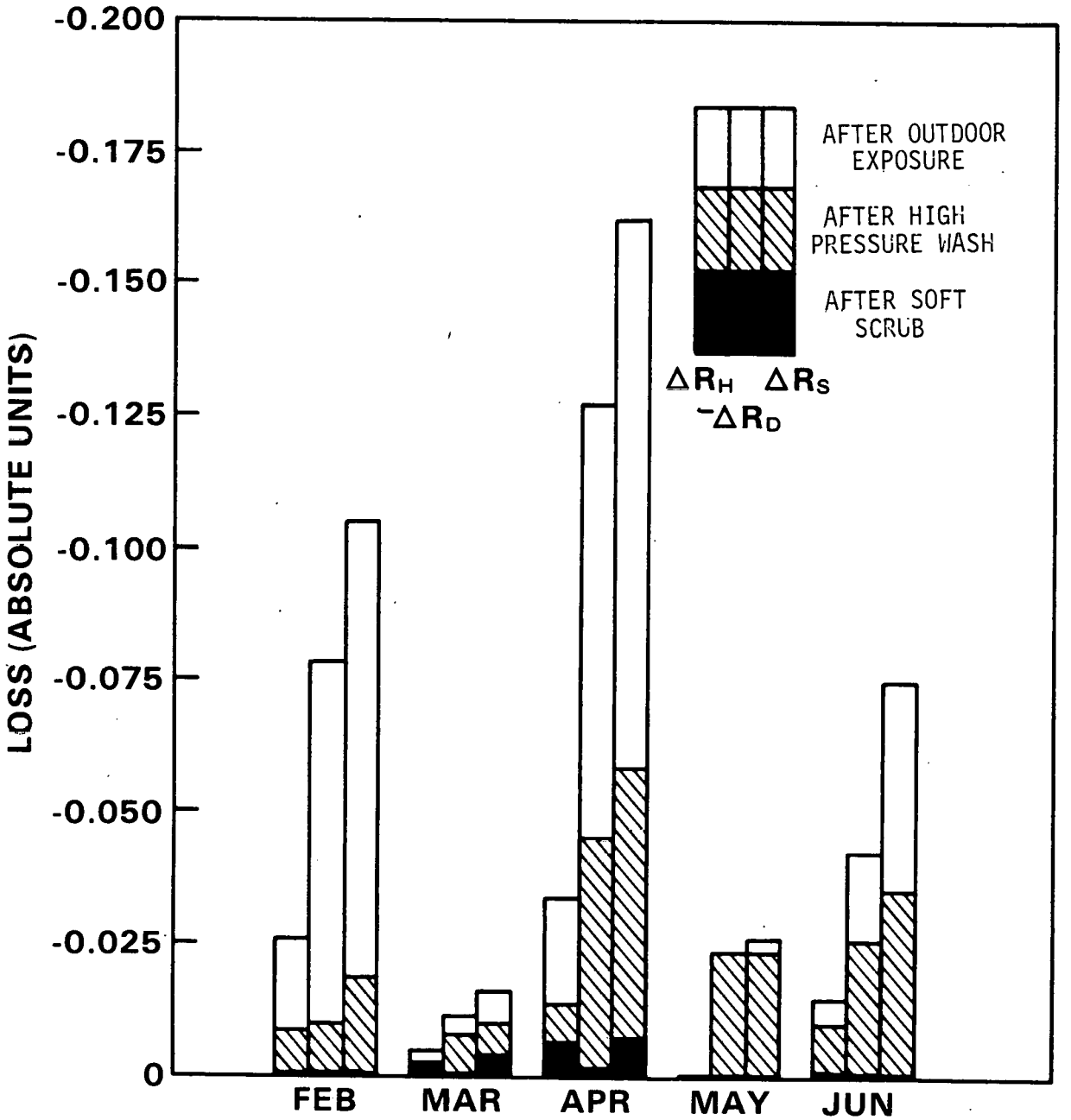


FIGURE 22. Effects of Cleaning on Specular Reflectance Losses for Weathered Soda Lime Silicate Glass Mirrors Deployed on the "A" Simulator Located at Liberal, KS (1981)

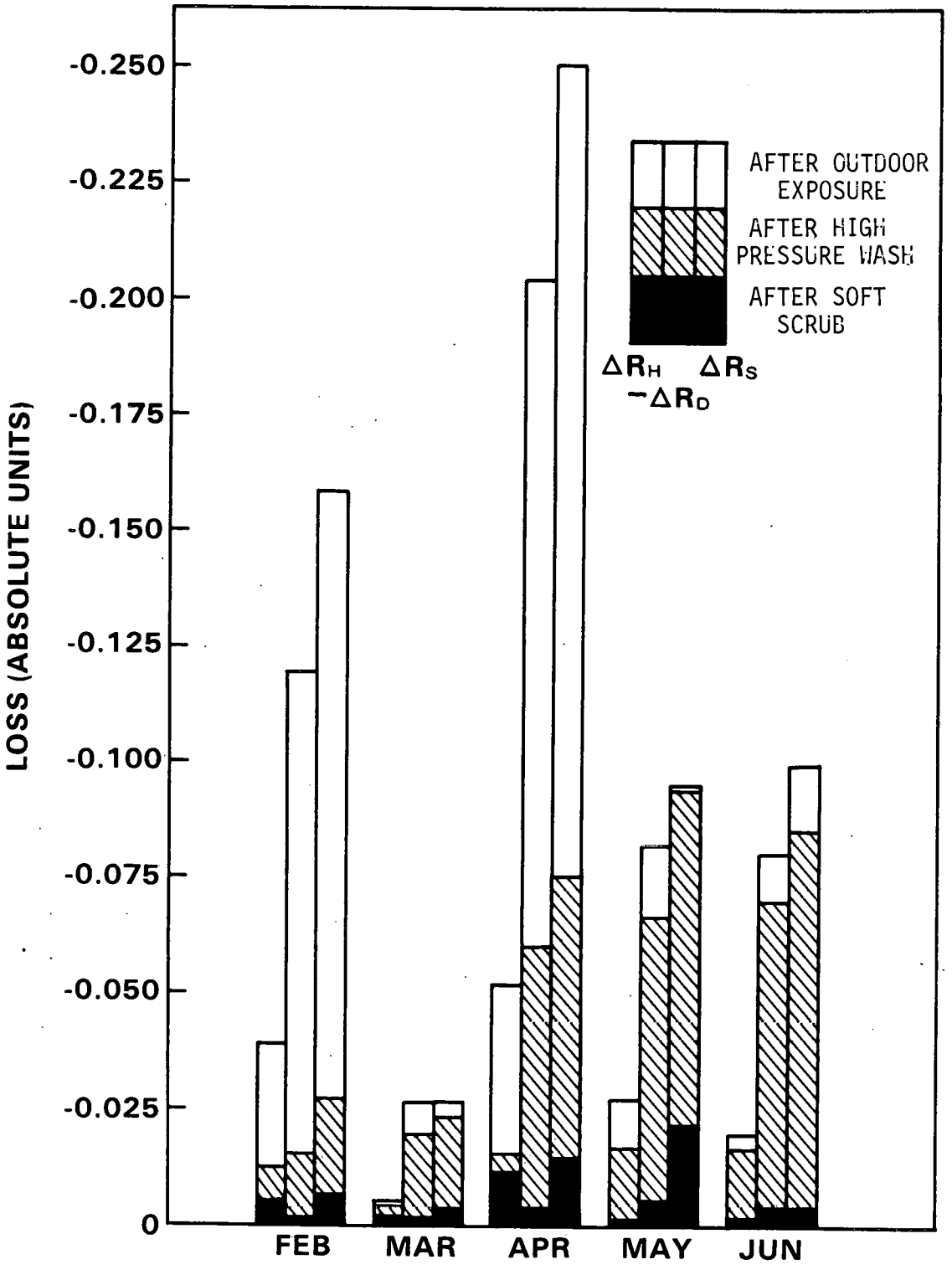


FIGURE 23. Effects of Cleaning on Specular Reflectance Losses for Weathered Soda Lime Silicate Glass Mirrors Deployed on the "B" Simulator Located at Liberal, KS (1981)

after each wash. The graphs indicate that the non-contact cleaning method was only partially effective in cleaning the samples. Losses of up to 10% were still evident after this wash. The second wash, using the soft scrub, was much more effective , restoring mirror reflectance values to within a few percent of their original values.

The "A" samples were not as dirty as the "B" samples after outdoor exposure, and, in general, were cleaner after washing than the "B" samples. It is difficult, on the basis of this study, to determine whether or not any of the dirt build-up was permanent. Some of the sample reflectances are restored to very near the original value after the soft scrub, and some are not. Exposure time does not seem to be a factor, as might be expected if a permanent dust build-up was occurring. In general, the dust was fairly easily and completely removed by using a soft scrub wash method. Permanenet build up, if it exists, is small, at least on the time scale of these tests. No permanent damage to the mirror glass superstrate or reflective layer was observed visually.

COMPOSITION OF DUST

The SEM/EDX analysis proved useful in determining the average size and composition of the particles adhering to the surface of the mirror coupons.

Samples from the "E" and "S" simulators at the Oologah, Oklahoma site were analyzed. The "E" simulator was closest to the cooling towers, while the "S" simulator was closest to the coal pile. The average size of the particles on both samples was in the 5 to 20 μ range (see Figures 24 and 25). On both samples, EDX analysis showed the presence of elements characteristic of the glass substrate and the indigenous soil. In addition, the "E" sample also contained sulfur and chlorine, while the "S" sample did not. EDX analysis cannot detect elements with atomic number less than 11 (sodium) so the presence of coal on the sample could not be determined from this analysis. However, no black particles that would be expected from coal dust were detected visually or with the SEM on either the "E" or "S" sample. Therefore, it is reasonable to assume that the sulfur and chlorine detected on the "E" sample was due to cooling tower drift.

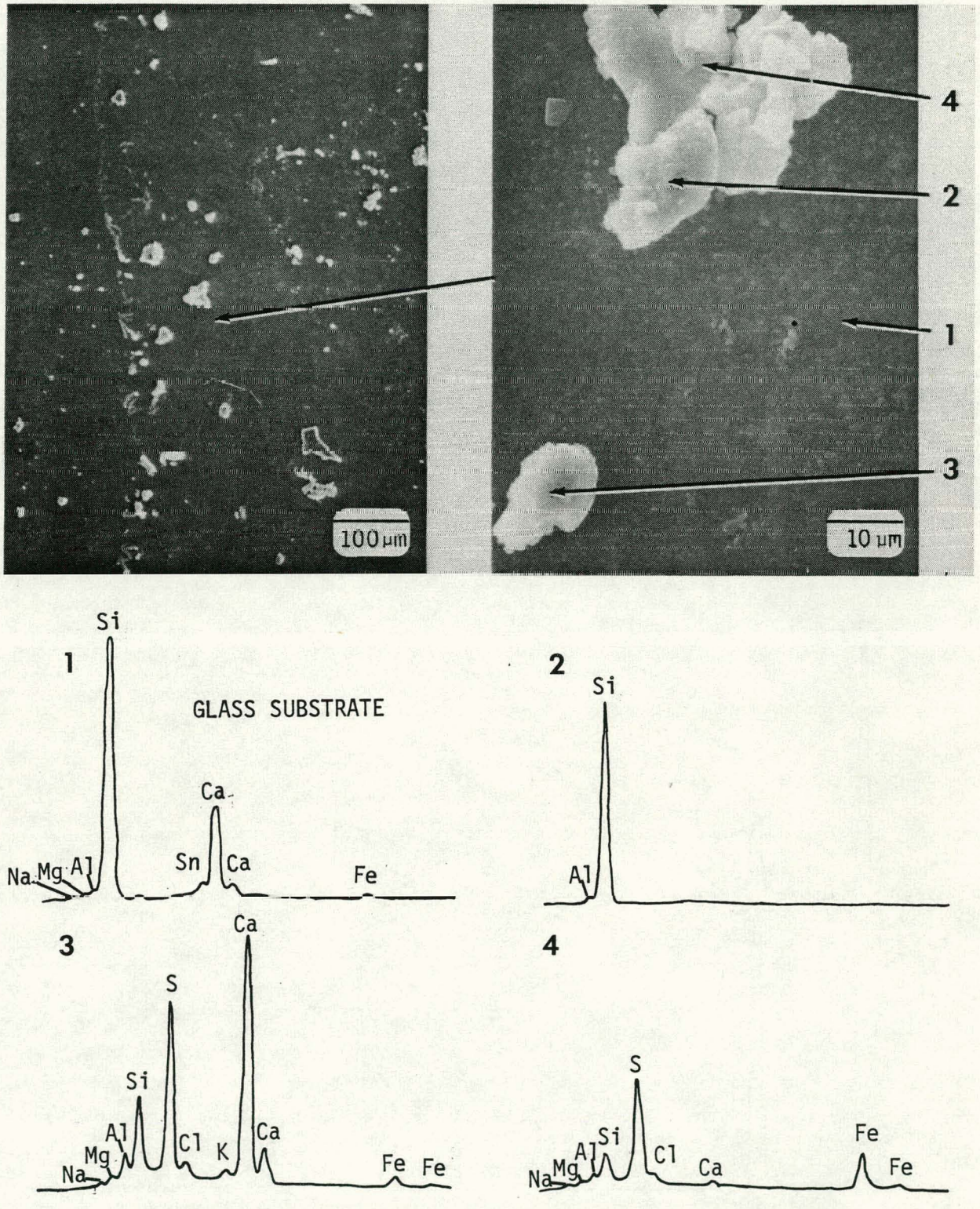


FIGURE 24. SEM and EDX Analysis of Dust on a Mirror Coupon from the East Simulator

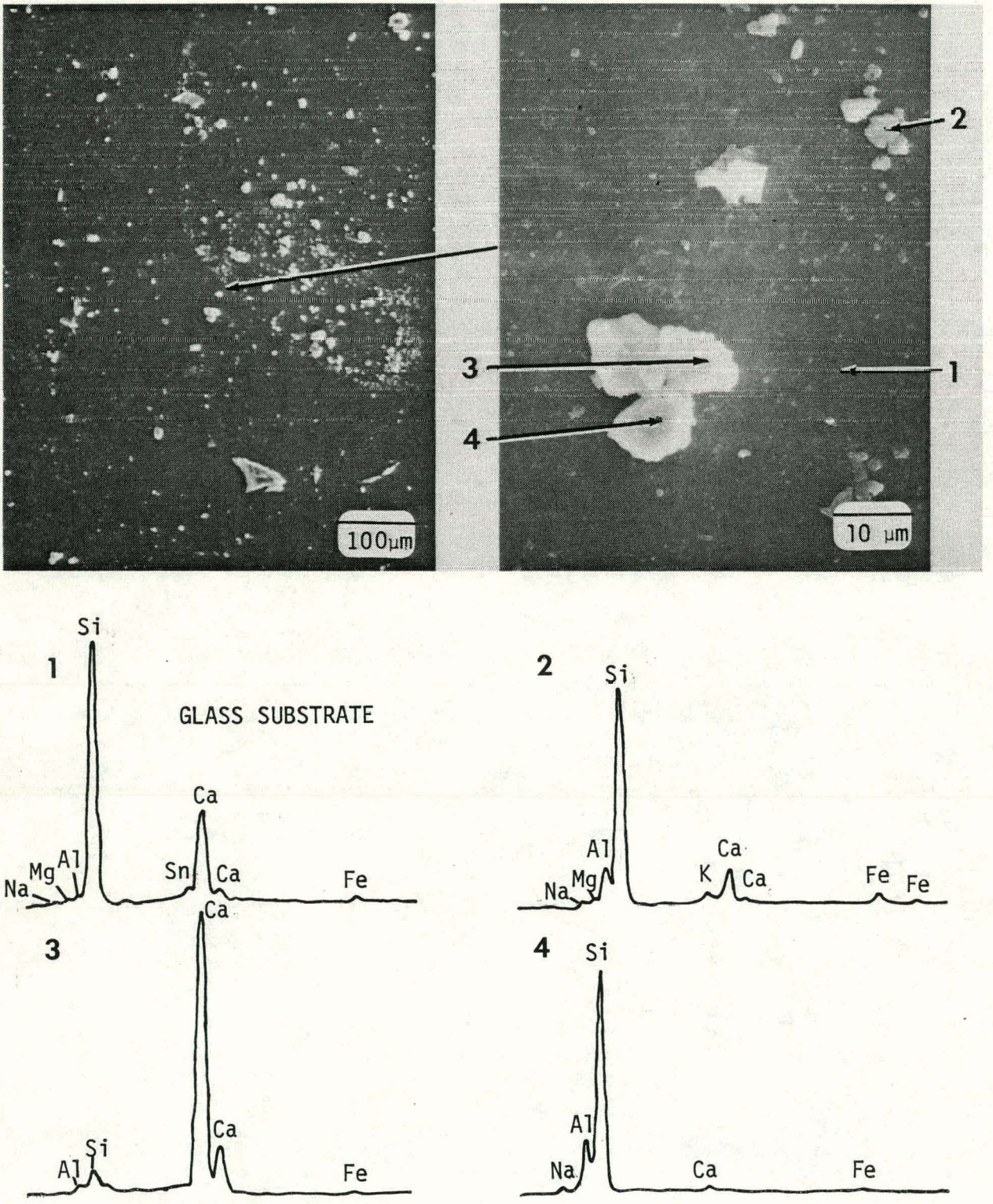


FIGURE 25. SEM and EDX Analysis of Dust on a Mirror Coupon from the South Simulator

One mirror coupon from simulator A and one from simulator B was analyzed. From the Liberal, Kansas site, recall that simulator A was located in a section of the proposed heliostat field quite remote form the cooling towers. Simulator B was located much closer to the cooling towers. As can be seen in Figures 26 and 27, the average size of the adhering particles was different for the two locations. The average size of particles on the "A" sample was in the 1 to 5 μm in size while the particles on the "B" sample were in the 5 to 20 μm size range. Composition of the particles varied on the two samples as well. EDX analysis of both samples showed elemental composition characteristic of glass and the surrounding soil in the heliostat field. Sample "B" also showed the presence of sulfur, and small amounts of chlorine and titanium. These elements may have originated in cooling tower drift.

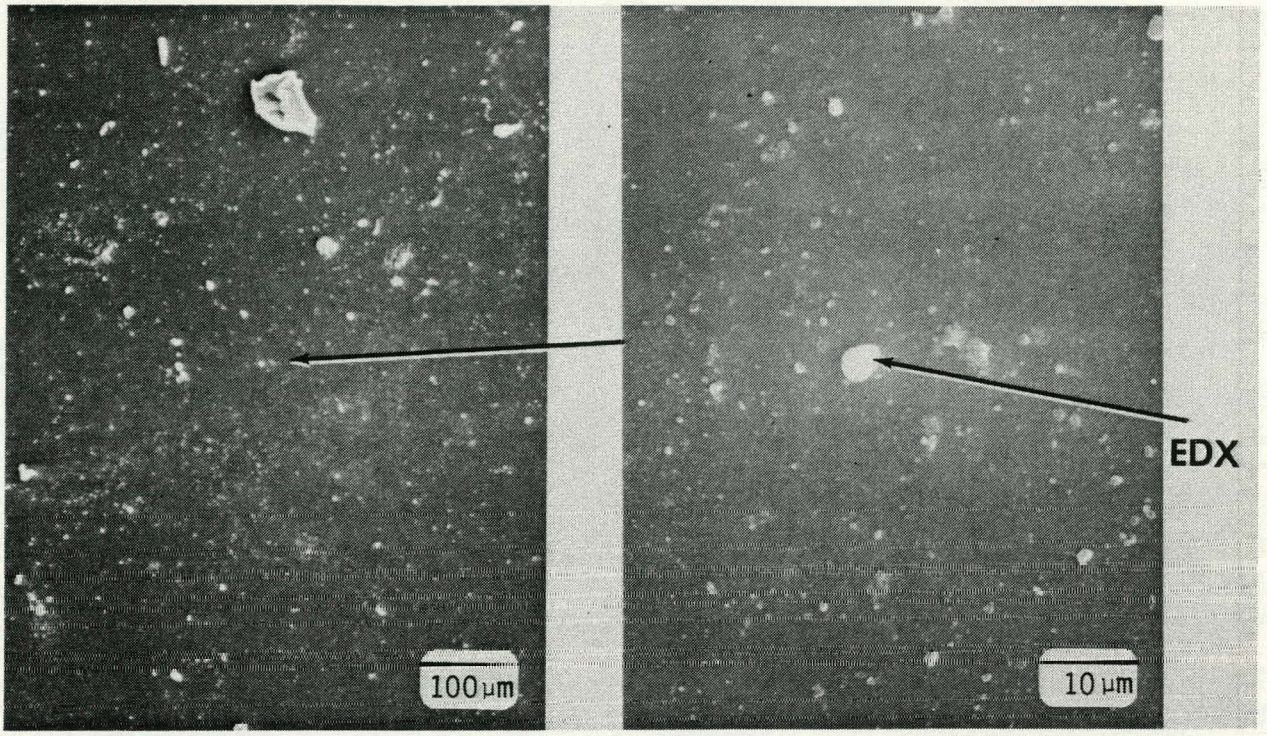
CONCLUSIONS

Some generalizations can be made about the effect of outdoor exposure on mirror samples at Oologah, Oklahoma and Liberal, Kansas. The average loss in specular reflectance over the test periods of six months to a year was 6-12%, with a range of 1-30%. Scattering losses are two to five times greater than absorptive losses.

There was a great amount of day to day variation in the reflectance of the mirrors presumably due to weather conditions. The average daily losses were only a few hundredths of a percent a day over the entire test period. The greatest rate of reflectance deterioration seems to occur in the first 30 days of outdoor exposure. For this initial 30 day period, reflectance losses averaged 0.2-0.4% per day. After the first thirty days, average reflectance losses were close to zero (although a great amount of day to day variation was evident). During periods when little or no natural cleaning took place, average reflectance losses were 0.5% a day or more. The presence of cooling towers may affect the reflectance of some mirrors in the proposed heliostat filed. In particular, at the Liberal site, the mirrors closest to the cooling towers had reflectance losses twice as large as those for mirrors located furthest from the cooling towers.

SEM analysis shows that the dust build-up consisted of particles averaging 1-20 μ in size. EDX analysis revealed the presence of sulfur and chlorine on some of the samples, in addition to elements characteristic of the surrounding soil. The sulfur and chlorine may have originated in cooling tower drift.

The washing study showed that the dirt is fairly easily and often completely removed by using a contact cleaning method. The non-contact cleaning method was not nearly as effective as the contact method. Neither the glass superstrate or the reflective layer appeared to be permanently damaged after one year of exposure time.



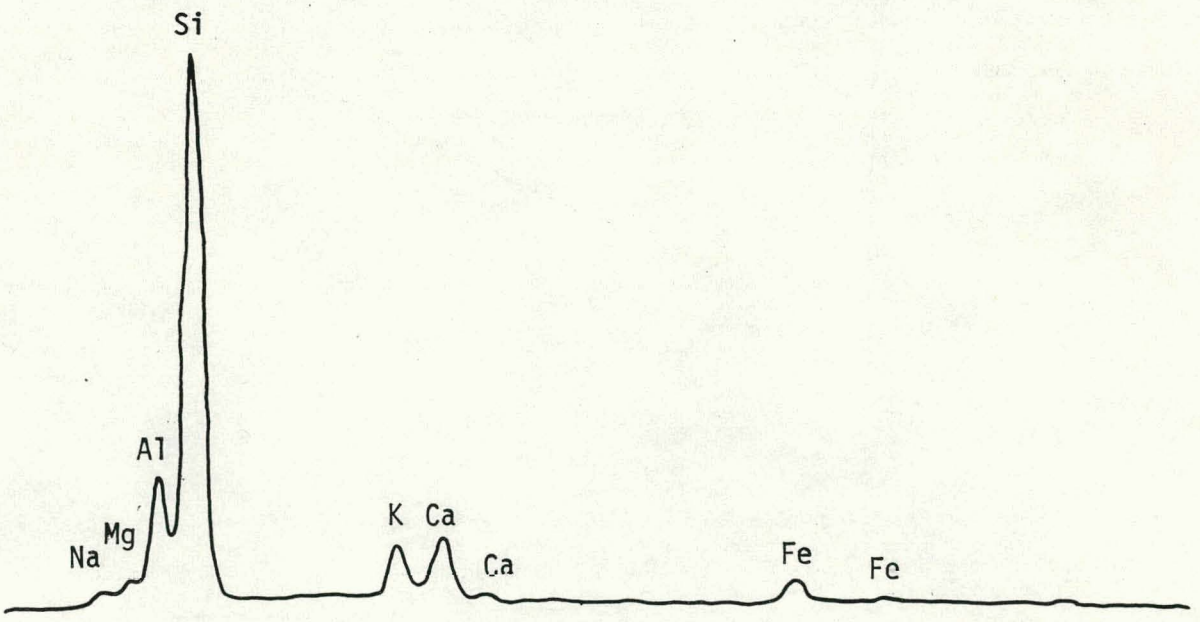
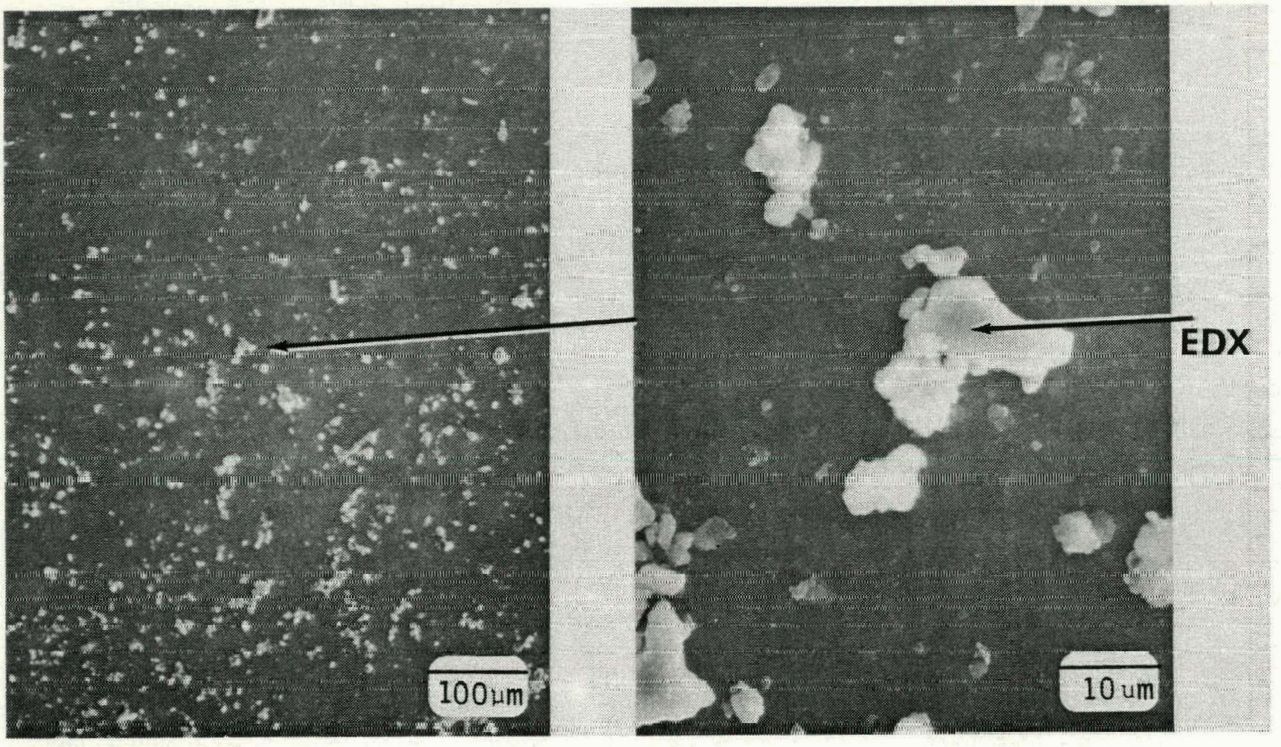


FIGURE 26. SEM and EDX Analysis of Dust on a Mirror Coupon from the "A" Simulator



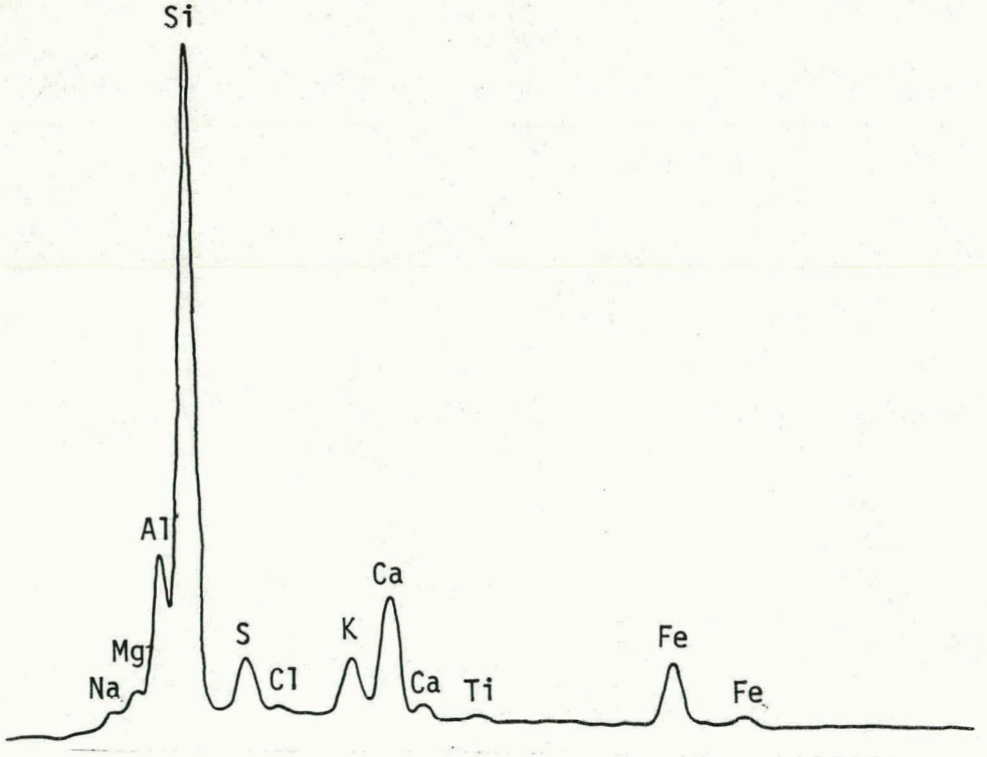


FIGURE 27. SEM and EDX Analysis of Dust on a Mirror Coupon from the "B" Simulator

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3. H.W. Brandhorst, Jr., et al. 1977. "Terrestrial Photovoltaic Measurement Procedures." NASA TM 73702. ERDA/NASA/1022-77116, NASA Lewis Research Center, Cleveland, OH.

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