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Solar Reflector Soiling Pattern Distributions and Reflectance Measurement Requirements

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PREFACE

The research and development described in this document was conducted within the U.S. Department of Energy's Solar Thermal Technology Program. The goal of this program is to advance the engineering and scientific understanding of solar thermal technology and to establish the technology base from which private industry can develop solar thermal power production options for introduction into the competitive energy market.

Solar thermal technology concentrates the solar flux using tracking mirrors or lenses onto a receiver where the solar energy is absorbed as heat and converted into electricity or incorporated into products as process heat. The two primary solar thermal technologies, central receivers and distributed receivers, employ various point and line-focus optics to concentrate sunlight. Current central receiver systems use fields of heliostats (two-axes tracking mirrors) to focus the sun's radiant energy onto a single, tower-mounted receiver. Point focus concentrators up to 17 meters in diameter track the sun in two axes and use parabolic dish mirrors or Fresnel lenses to focus radiant energy onto a receiver. Troughs and bowls are line-focus tracking reflectors that concentrate sunlight onto receiver tubes along their focal lines. Concentrating collector modules can be used alone or in a multimodule system. The concentrated radiant energy absorbed by the solar thermal receiver is transported to the conversion process by a circulating working fluid. Receiver temperatures range from 100°C in low-temperature troughs to over 1500°C in dish and central receiver systems.

The Solar Thermal Technology Program is directing efforts to advance and improve each system concept through solar thermal materials, components, and subsystems research and development and by testing and evaluation. These efforts are carried out with the technical direction of DOE and its network of field laboratories that works with private industry. Together they have established a comprehensive, goal-directed program to improve performance and provide technically proven options for eventual incorporation into the Nation's energy supply.

To successfully contribute to an adequate energy supply at reasonable cost, solar thermal energy must be economically competitive with a variety of other energy sources. The Solar Thermal Technology Program has developed components and system-level performance targets as quantitative program goals. These targets are used in planning research and development activities, measuring progress, assessing alternative technology options, and developing optimal components. These targets will be pursued vigorously to ensure a successful program.

In support of the objectives of the Solar Thermal Research Program, SERI is conducting research to optimize the performance of the reflecting elements of the concentrating systems under study. This includes the development of new lightweight reflector films and studies of the accumulation and removal of soil layers from optical elements in the field. The latter task is oriented at developing effective methods for minimizing the efficiency losses of large-area heliostats and dishes. An integral part of this research is the determination of the optical properties of the reflecting elements as a function of exposure to terrestrial conditions. Field measurements use light beams of approximately 1 cm in diameter, which is quite small with respect to the total area of a concentrating system. The work reported here addresses the question of how to make optical measurements on systems with different soil distributions and patterns, such that a minimum number of measurements are required to provide any desired confidence level in the measurement. This work was conducted during the summer and part of a school year (1988), and formed the basis of a senior thesis for the author.

SUMMARY

Objective

The objective of this research is to classify natural and laboratory soiling patterns on solar optical materials and to develop a method to determine how many reflectivity measurements of a soiled solar reflector are required to obtain an accurate average reflectance value of the surface. An accurate value will be defined as not having an error of more than ±3% with a 95% confidence level.

Discussion

Samples of silvered glass and silvered polymer mirrors were subjected to natural soiling in two separate locations and to a laboratory soiling procedure, which was set up to simulate natural soiling for accelerated testing. The specular reflectance of these materials was measured with instruments of varying beam size, and these measurements were used with a model of the soil distribution to calculate the number of measurements required to give values within a specific accuracy at a given confidence level.

The distributions of circular and near circular spotting patterns were found to follow a lognormal distribution. Five distinct patterns were observed, measured, and set into categories for measurement strategies. Three of the observed patterns (uniform coverage, dense coverage of spots that are small compared with beam size, and widely distributed spots) can be characterized with 10 measurements to place the reflectance value within 3% of the true value with a 95% confidence level. A fourth pattern, where the spots and their separation and the probe beam all share the same characteristic dimension, is more interesting. It was found that it would take 50 measurements in order to bring the error limits within the 3% range when the spots are very opaque optically. In the more common natural soiling cases, the spots are not often so opaque, and it is estimated that 20 measurements are sufficient to place the average value within the acceptable range. A fifth pattern, where wavefronts of the particles are left in squiggly lines of varying opacity, requires a different treatment. Probably, one could follow the recipe for spots and use 10 measurements for the cases of almost uniform coverage, dense coverage of lines that are small with respect to the beam size, and very widely distributed lines and 20 measurements for the case of line width and line spacing having the approximate dimensions of the beam. A complete analysis of this case was not possible in the time allotted for this study.

Conclusions and Recommendations

The results of this study have practical implications for field measurements using Devices and Services' specular reflectometers with probe beam diameters of 1 cm. Ten random measurements are sufficient to bring the measured value within 3% of the true value with a 95% confidence level for almost all field conditions. In the less common case where the spot sizes and their separations are approximately 1 cm, 20 measurements should suffice to bring the

measured value within the 3% interval. For very opaque spots in the latter case, 50 measurements are required.

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1.0 INTRODUCTION

For current solar receiving systems to be fully efficient, direct sunlight must fall on the reflective surfaces that are used to concentrate the light. However, the reflectivity of the surface is degraded because of soiling by the natural elements and meteorological cycles in the terrestrial environment. The soiling on the mirrors usually consists of various patterns of spotting. Spots are created by moisture and dust particles gathering in droplets on the mirror surface with the moisture eventually evaporating. The moisture comes from several sources: rain striking the surface, dew condensing on the surface, and water used for washing the mirrors to remove dust. In all of these cases, dust particles concentrate in the droplets. As the moisture evaporates, the heavy concentration of dust particles adhere to the mirror surface in the shape of the droplet, thus forming the spots.

The reflectivity of the mirrors is measured using an electro-optical instrument that reflects a light beam off the surface and into a detector. This measurement is then compared to a standard reflectance and the reading is in the form of a percentage (the measured reflectance/standard reflectance).

Observations of concentrators in the field, as well as of test samples with new materials weathered naturally and artificially, indicate that a wide range of soiling patterns form on optical elements. Because the method by which the performance of the material is monitored involves measuring the specular reflectance of the material (through soil layers) and because the beam diameter of the instruments is finite, the question of how many measurements to take on a soiled surface to provide an average value within a chosen confidence interval has arisen. This report describes the soiling patterns observed on various materials exposed in a variety of locations. This report also presents the method to estimate the appropriate number of reflectance measurements needed, based on beam diameter and soil distribution, so the average value will be within ±3% of the true value with a 95% confidence level.

2.0 APPROACH

The problem will be simplified by considering a special case of spotting. The assumption is that the spots are discrete, circular areas of soil with uniform opacity. This simplification makes it possible to model the spot population with a simple probability distribution function. Once the spot size data have been taken from the actual soiled samples, the mathematical distribution can be matched to the data. The two most important variables that will be determined are the average spot size and the number per unit area (density). These two variables provide the means necessary to determine the probability of finding a spot in a given area. With this information, an approximate value for the reflectivity can be calculated for any known density.

The lognormal distribution is the hypothesized distribution because of field observations on soiled optical elements and physical considerations. Droplet formation originates from either dew formation or washing procedures. Droplets of minimum size are formed by nucleation during dew cycles. As these grow, some coalesce in a random fashion to form larger droplets.

There are a large number of droplets at a minimum nucleation size, followed by a gradual decay in frequency as the spot size increases. This is a rudimentary description of a lognormal distribution. As for droplets formed during wash cycles, the frequency distribution trails off more gradually for large sizes than it does for small sizes. Perhaps this has something to do with a minimum droplet size in a water spray bouncing off the surface either under a pressure wash or from falling rain. At any rate, many physical systems can be modeled with this distribution, following the common declaration that, "a superior approach for displaying PSD (particle size distribution) is to use a lognormal probability method" [1].

The lognormal distribution is closely related to the normal (Gaussian) distribution, which is the well-known bell curve. The normal distribution, however, is centered about the origin with its average being zero. In the case of the spot sizes, all of the data must lie on the positive side. This requires a modification of the normal distribution that allows only positive occurrences. The lognormal distribution takes this into account by assuming that the occurrences are a result of multiplicative independent random effects [2].

Consider the probability of occurrence, Y:

$$Y = X_1 X_2 \cdots X_n \ .$$

The random variables $X_1, X_2, \ldots, X_n$ are considered to be independent and identically distributed and can take on only positive values. The distribution of Y is the one of interest. By taking the natural logarithms of both sides, the previous equation becomes

$$\ln Y = \ln X_1 + \ln X_2 + \ldots + \ln X_n \ .$$

The term ln Y is now seen as the sum of the independent and identically distributed random variables $\ln X_1$, $\ln X_2$, ..., $\ln X_n$.

The Central Limit Theorem states that a distribution, in this case ln Y, becomes a normal distribution as The term Y is related to the normal random variable X by

Transformation of the normal distribution function then yields the lognormal distribution function [2],

$$f_Y(y) = \frac{1}{y\sigma_{\ln Y}\sqrt{2\pi}} \exp\left(-\frac{1}{2\sigma^2_{\ln Y}} \ln^2\left(\frac{y}{\theta_Y}\right)\right) \qquad y \geq 0$$

$$= 0 \text{ elsewhere },$$

where θ_Y is the median of Y and the standard deviation of ln Y is

and m_Y is the average of Y.

The density function is the normalized probability curve, where the total area under the curve is unity. The probability of finding an occurrence between any two points is in the area under the curve between those two points. For a normal distribution, the probability of occurrence between ±1 standard deviation is 68.3%, ±2 standard deviations is 95.5%, and ±3 standard deviations is 99.7% (Figure 2-1). In the spotting case, the density function will correspond to the number of spots that are found in a particular size range.

Once the distribution function has been determined, the problem can be simplified by modeling the distribution using the same number of samples and the average spot surface area, which is calculated using the surface mean diameter, x_{NS}

$$\sum_{i=1}^{N}$$

where x_i is a sample spot diameter, n_i is the number of samples of size x_i, and N is the number of different sample sizes [3]. The denominator in this case is equal to the total number of samples. The total area that is covered is calculated by

$$\text{Area}_{\text{Tot}} = \left(\frac{\pi x^2_{NS}}{4}\right) \sum_{i=1}^{N} n_i$$

where in this equation, n_i is the number of samples in range i, and N is the total number of ranges.

The next step is to take reflectivity measurements of the spots. Many measurements are taken to ensure that there are more than enough values to obtain an accurate estimate of the true average reflectance. A test can then be performed to see how many measurements are needed to fall within a certain ±%

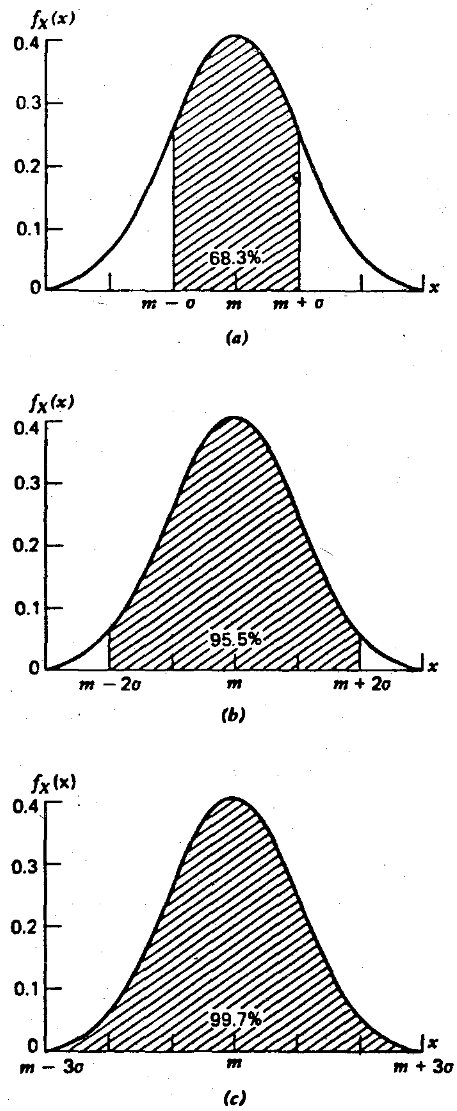

Figure 2-1. Areas under normal density function for ranges of ±1, ±2, and ±3 standard deviations

of the true average. The test that will be used is the t test, which is useful when the number of samples is small (usually <30) [4].

The test results in an interval in which the true average should lie. Different levels of confidence can be used when applying the test. The less confidence required, the smaller the error limits. In other words, the test can be performed so that there is a 95% chance that the true average is within the limits calculated. If the desired confidence was 90%, then the limits would be smaller because you are willing to accept a greater chance that the average is outside the limits. For this study a confidence interval of 95% was selected. With the confidence interval set, the size of the limits depends directly on the number of samples and the sample standard deviation. The t value is based on the number of samples taken. It is chosen by the degrees of freedom of the sample set or simply the number of samples minus 1. The limits for a 95% confidence interval are

$$\bar{x} - t_{0.05} s_{\bar{x}} \leq \bar{x} \leq \bar{x} + t_{0.05} s_{\bar{x}} ,$$

where $\bar{x}$ is the sample mean, $t_{0.05}$ is the value for a 95% confidence interval and can be looked up in standard text [2], and $s_{\bar{x}}$ is the standard error of the mean calculated by

$$s_{\bar{x}} = \frac{s}{\sqrt{N}}$$

where s is the mean standard deviation and is given by

$$s = \left(\frac{\sum_{i=1}^{N} (x - \bar{x})^2}{N - 1} \right)^{1/2}$$

It is easy to see that the number of samples is the dominant factor in determining the size of the interval. This is the way in which the number of measurements needed for a reasonable error limit can be determined. Measurements can be taken until the average value has a possible error of plus or minus any chosen percent. If the sample standard deviation is large, a large number of measurements will be needed to meet the given limits. Conversely, if the sample standard deviation is small, relatively few measurements will be required.

3.0 PROCEDURE

The first step was to determine if the spotting patterns actually followed a lognormal distribution. We made several trips to different stations where solar reflectors are studied and used. The Golden, Colo. site is on SERI property and is used to observe how different reflective surfaces perform in the environment. The other site is in Brighton, Colo., and is a parabolic trough solar heating station that supplies hot water and electrical power to the Adams County Retention Facility. The Brighton site also has a rack where flat solar reflectors are observed for their reactions to various cleaning methods. At these locations, many photographs of the spotting patterns were taken so that the spots could be measured and thus we could determine the distribution the spots follow.

Samples were needed to obtain accurate reflectivity measurements. The samples were small to make transporting them to and from the laboratory easy. To obtain portable reflector samples, mirrors were made by cutting a 4 in. x 4 in. piece of glass and carefully adhering a film of ECP 300 (a silvered acrylic) to it, which currently is the best candidate for use as a lightweight, reflective surface material for solar applications. The glass was used only as an optically flat substrate to support the ECP 300; it was not otherwise used in the experiment.

Six mirrors were made, and they were placed in pairs in three different environments. Four of the mirrors were placed at the outside locations in Golden and Brighton. Both sets were placed in stationary positions at a 45° angle and were exposed 24 hours a day. After two weeks, the reflectivity of the mirrors was checked using the Devices and Services (D&S), Dallas, Tex., instrument, which is a portable device used to check reflectance in the field. After an additional month, the mirrors were brought back to the lab and checked using a laboratory reflectance measuring instrument called the specularometer (for more information on the design of this instrument see Schissel and Neidlinger [5]). Both reflectance measuring instruments have a beam diameter of 10 mm. The two remaining mirrors were dusted using a standard dust (GM Fine, air cleaner test dust) from the Arizona desert and placed for 24 hours in an accelerated weathering tester (QUV). The QUV is commercially available from The Q-Panel Company. This 24-hr test simulates approximately two weeks of actual environmental exposure. The QUV was used because it often results in a close-to-ideal formation of spots. Because these samples were not subjected to elements such as wind, blowing rain, or snow, they can be used as a standard or ideal spotting case.

4.0 RESULTS AND ANALYSIS

4.1 Spot Size Distributions

The mirrors placed in the QUV had by far the most ideal spotting patterns. There was a defined pattern that made measurement extremely easy (Figure 4-1). While being weathered in the QUV, the samples were clipped to an aluminum strut. Where the mirrors were not touching the strut, there was open air behind them. An interesting note is that where the glass rested on the aluminum, the spots were much larger with much more space between them. This phenomenon is easily identifiable in Figure 4-1. Measurements of the spots revealed that the distribution of sizes did appear to follow a lognormal distribution. This was true for both the spots that were in the open air and the spots that were formed above the aluminum. Figure 4-2 shows the measured size distribution along with the predicted size distribution.

Data were also taken from several photographs of reflectors at the Brighton site. The spot sizes were measured using a microscope with a reticle in one eye piece. An area of the photograph was marked off, and then all of the spots inside that area were measured. Each spot was measured and marked so it would not be counted more than once. These spots also followed a lognormal distribution as illustrated in Figure 4-3. One photograph of a recently washed reflector (Figure 4-4) revealed a series of tracks that were formed by water running down the reflector surface. Measurements of these tracking spots showed a double nodal distribution (Figure 4-5). The running water left a large number of very small droplets that were only identifiable when the surface was freshly cleaned.

To test exactly how well the observed data fit the predicted curves, the chi-square goodness-of-fit test was used. The chi-square test compares a hypothesized distribution to the observed distribution. The observed values are compared with the calculated values by a natural least-squares type deviation measure [2]. At a 95% confidence level, all of the spots measured followed the predicted lognormal distribution. However, there were cases where the soiling patterns were not spots at all.

The "spots" that appeared on the parabolic reflectors at the Brighton site were not the circular, well-defined spots expected. On the upper half of the reflector, the soiling pattern consisted of squiggly lines instead of circular, defined spots (Figure 4-6). The soiling pattern on the lower half of the reflector tended to be more uniform with little variation (Figure 4-7). We believe there are two factors that account for the patterns on the parabolic troughs.

The first factor is that the parabolic reflectors are rotated to follow the sun during the day and are stowed in an inverted position at night or during periods of heavy cloud cover. When inverted, rain and snow cannot collect on the mirror surface. The top of the reflector is 4 ft above the ground, and the bottom is only 3 ft off the ground. When the wind is blowing, the low level of the reflector allows dust and other particles to be blown onto the surface. The bottom half is more affected by blowing dust because the concentration of blown dust is greater nearer the ground and, perhaps, because the bottom is on the north side of the collector, it shields the top from the prevailing winds. If this occurs during a dew cycle, or periods of precipitation, many of the particles will remain on the surface. The large size of

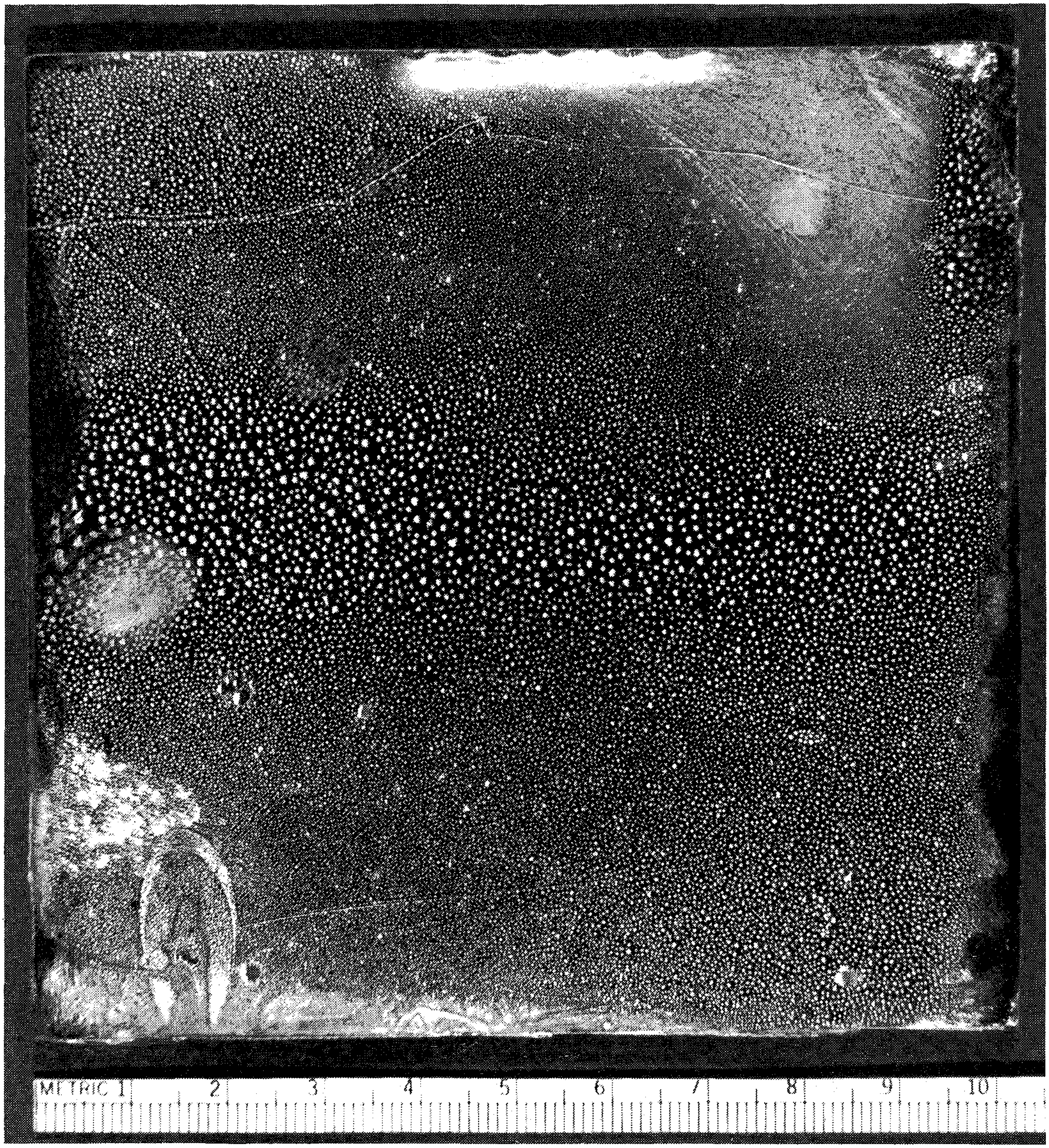

Figure 4-1. QUV sample

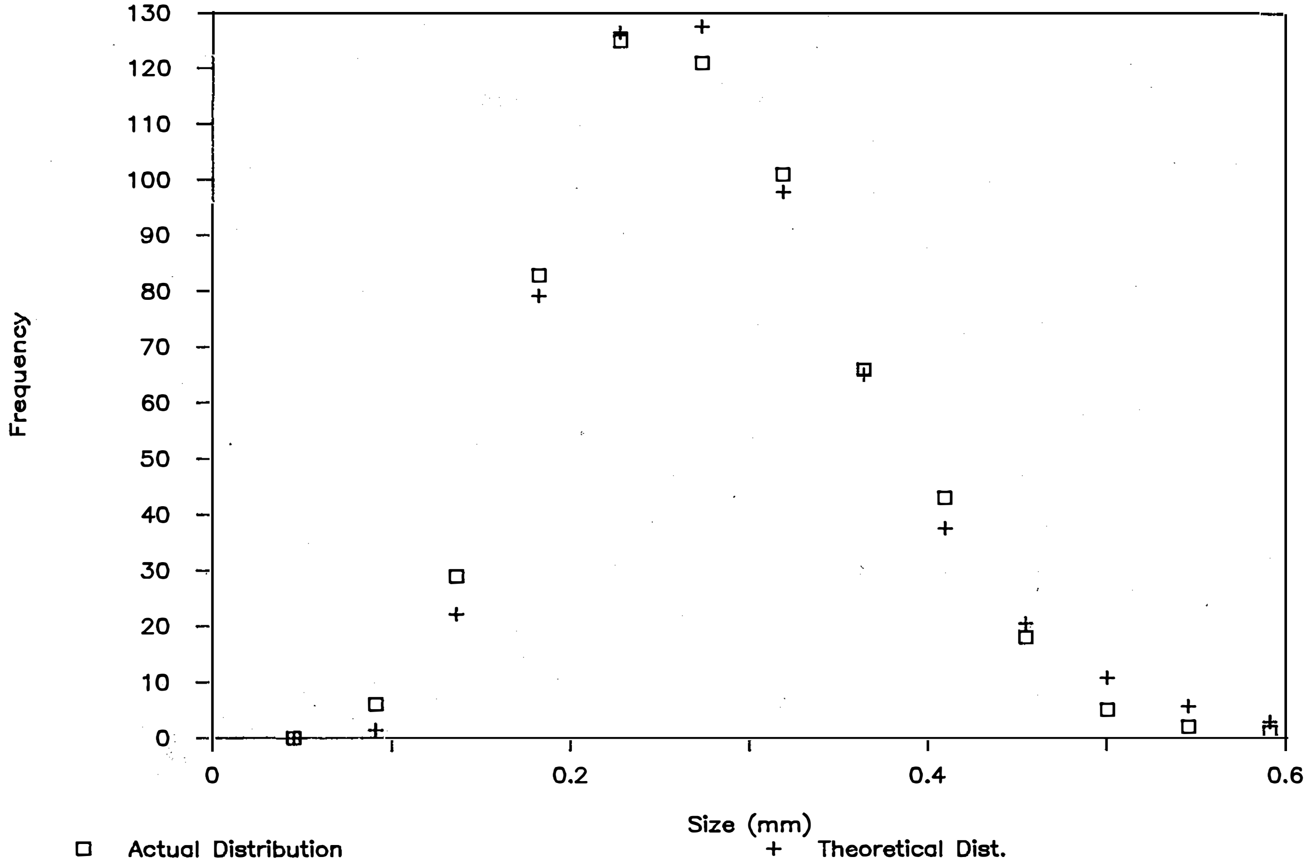

Figure 4-2. Measured spot size distribution of QUV sample and theoretical size distribution

the trough (7 ft wide by 16 ft long, with four troughs placed end-to-end in each row) increases the chances for dust to settle on the surface by causing a wind block that slows the air and dust (Figure 4-8). As the air and dust slow down, the heavier dust particles fall to or near the ground. More of the heavier dust could come in contact with the reflective surface nearest the ground.

Moisture accumulates from rain and dew on the surface. The liquid has a surface tension that will allow a droplet to build up to a certain weight on a tilted surface before running. Once the droplet exceeds the critical size for an incline, the liquid begins to stream down the incline. As it runs, it collides with other stationary droplets that also begin to run because of the increased weight. The result is a snowball effect that causes much of the liquid under the initial droplet to run down the surface. This is the probable cause of the difference between soiling patterns on the upper and lower half of the reflector. As the water and dust flow from the top to the bottom of the trough, the parabolic shape causes the mixture to slow down and settle as it reaches the less severe slope of the lower half. The angle of the trough during operation can range anywhere from 90 deg at the top to 0 deg at

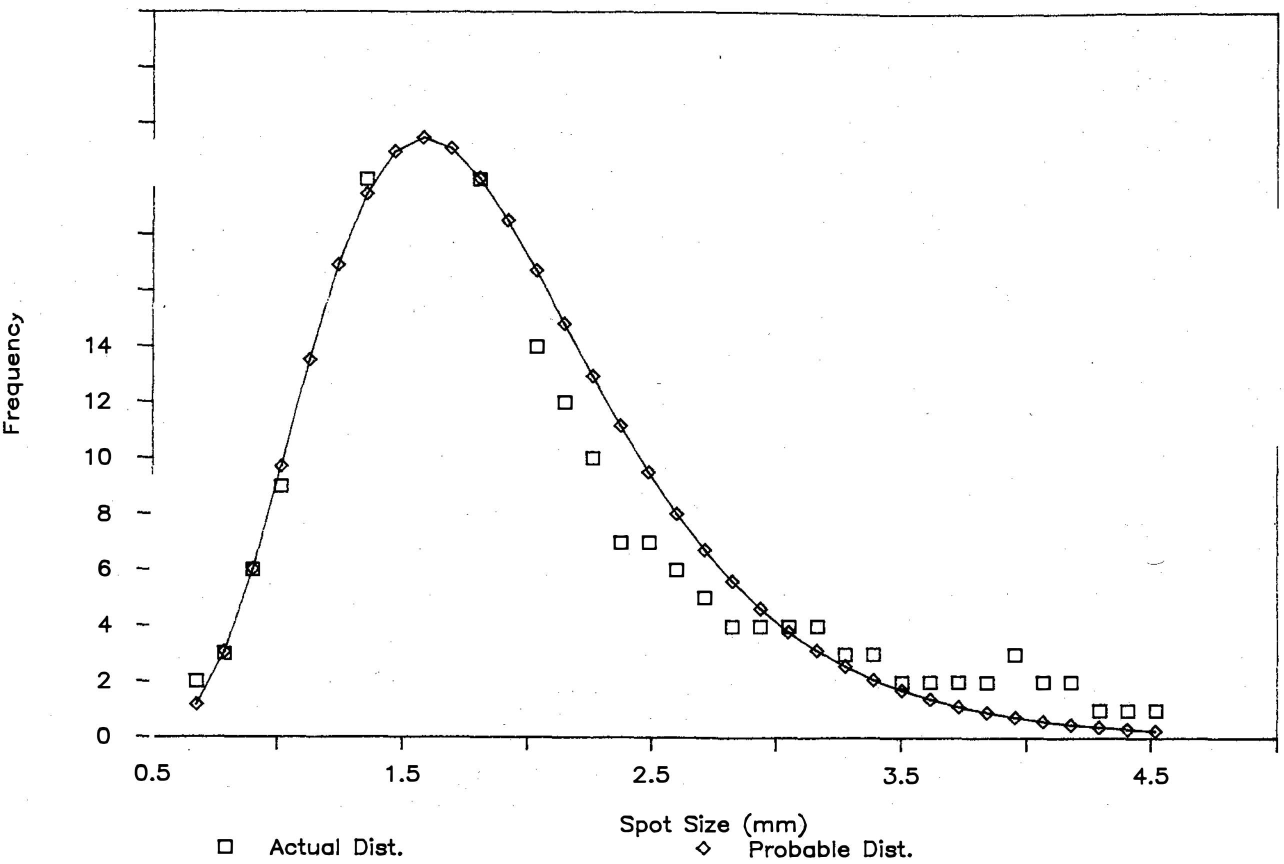

Figure 4-3. Measured spot size distribution of Brighton photograph and theoretical size distribution

the bottom. Much of the combination of liquid and dust collects on the gentler slope where a heavy concentration of dust is deposited. When the water evaporates, all of the dust remains and is dispersed enough that it covers the surface uniformly.

The mirrors that are stationary and flat possess the expected spotting pattern and are the samples that were used for measuring the spot size distribution previously discussed (Figure 4-9). These mirrors are held at a constant angle of 45 deg and are subjected to all of the precipitation all of the time. Figure 4-10 shows the stationary stand and five different samples. Factors that probably contributed to the formation of the spots were the flat surface and the relatively small size compared with the parabolic troughs. The approximate area of 4 ft^2 and the relatively gentle angle of 45 deg reduce the chances of the water droplets running. The spots present on these mirrors tended to be of uniform opacity with a heavier concentration of dust particles around the perimeter of the spot. As the water droplet is formed, it acquires a bubble shape as seen in the cross-sectional view in Figure 4-11a. The dust particles flow down the side of the droplet into a heavy concentration at its base. When the droplet evaporates, the dust remains as seen in Figure 4-11b.

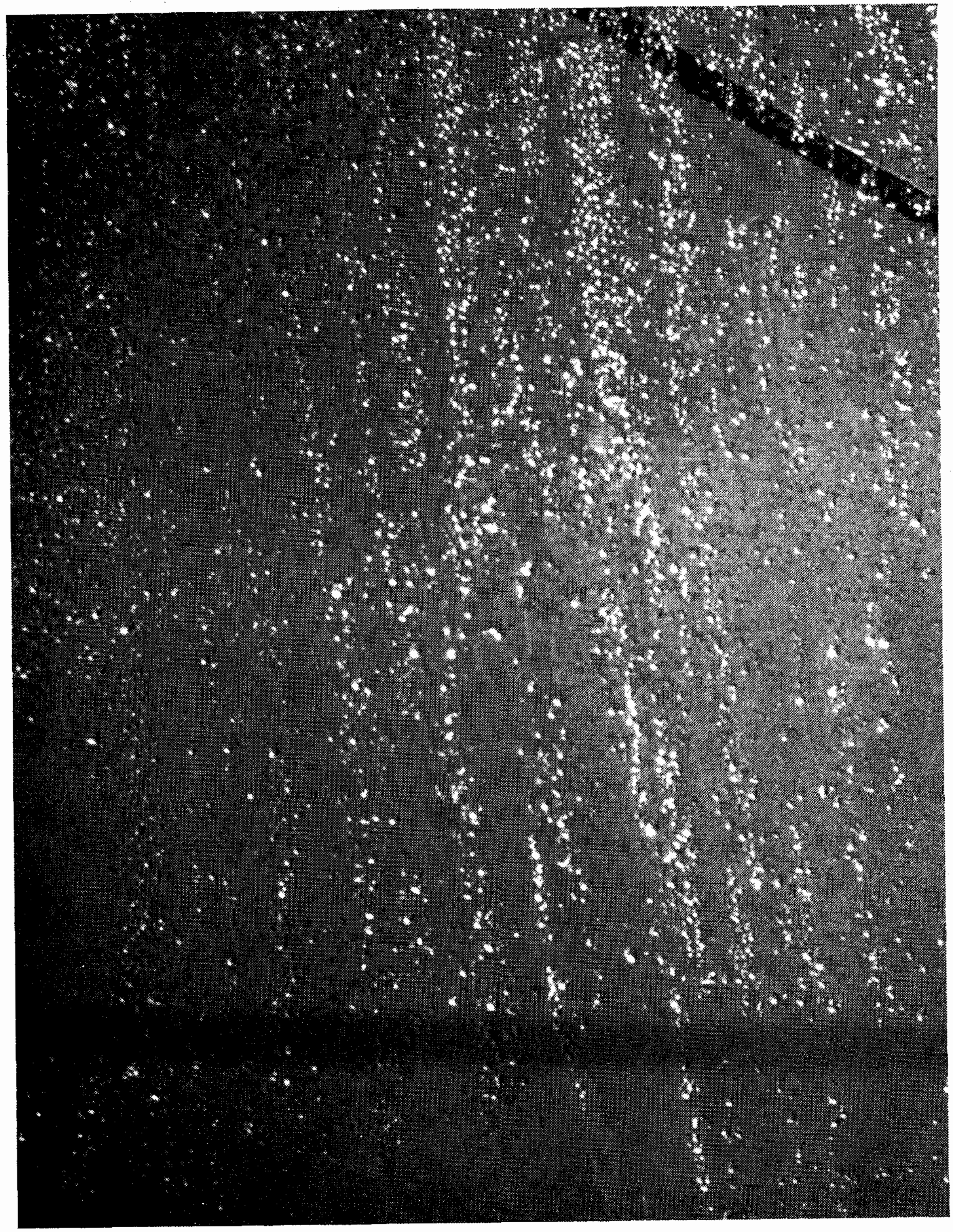

Figure 4-4. **Washed reflector**

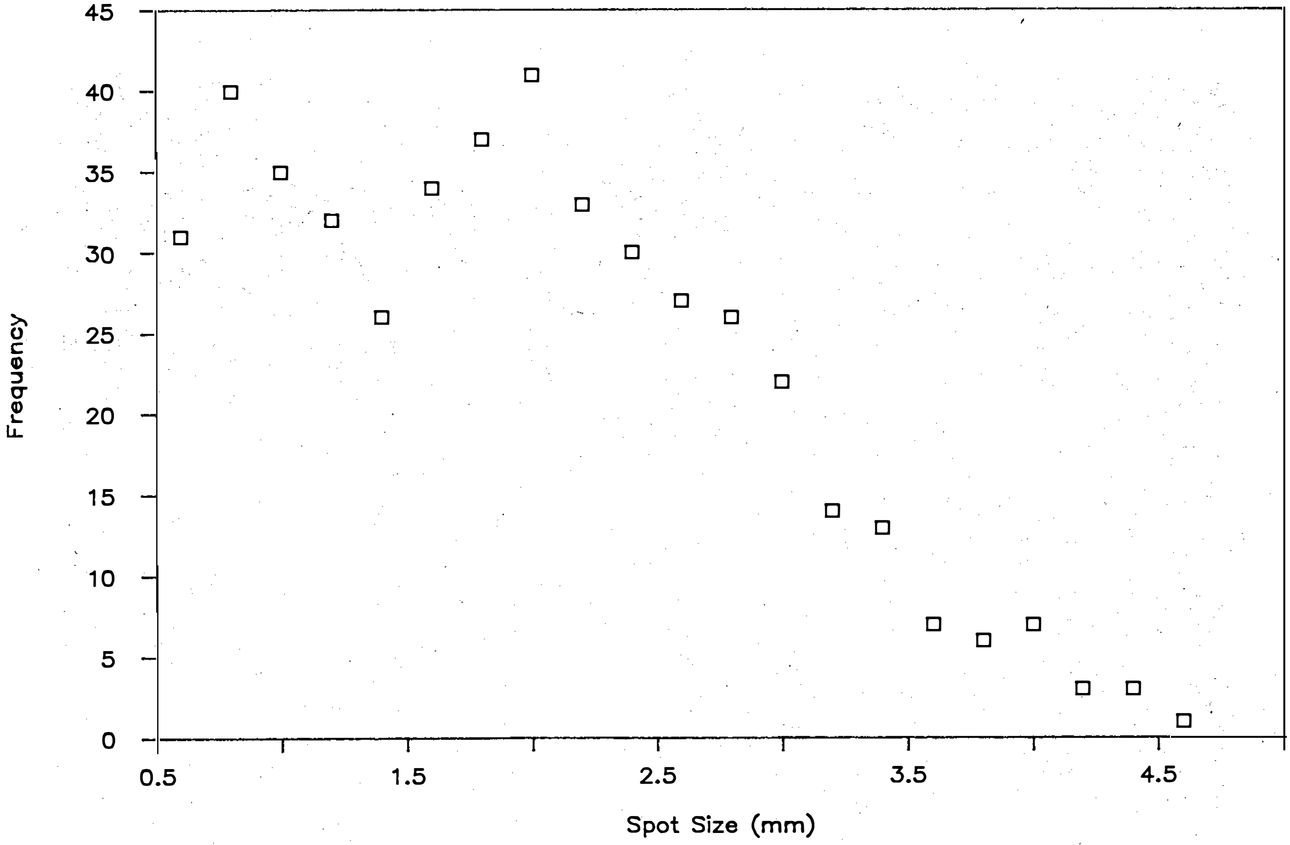

Figure 4-5. Measured spot size distribution of washed reflector

This outer ring occupies a negligible percentage of the spot and, for the purpose of measuring the average reflectance of the field, the spots can be considered to have uniform density.

4.2 Reflectivity Measurements

Reflectivity measurements were made on all of the 4 in. x 4 in. samples that were placed at the various sites, and different patterns resulted in different reflectances. The first case is the simplest, where the soiling pattern is relatively uniform. This situation occurs during periods of little or no precipitation and is also the dominate pattern in areas of low humidity and rainfall such as the Desert Southwest. The two instruments used in this case were the D&S reflectivity instrument and the specularometer. The distribution of reflectances lies within a very narrow range (Figure 4-12). The deviations occur because the pattern is not completely uniform and the various dust particle sizes reflect the light in various directions, which may or may not be within the 25 mrad cone of the detector aperture of the D&S instrument.

A similar case occurs when the spots are extremely small compared with the beam size and they are closely packed together. By using the D&S instrument on the samples weathered in the QUV, this situation can be tested. The reflectivity distribution was roughly the same as with the uniform coverage. The reason is that the spacing between the spot sizes and the size of the

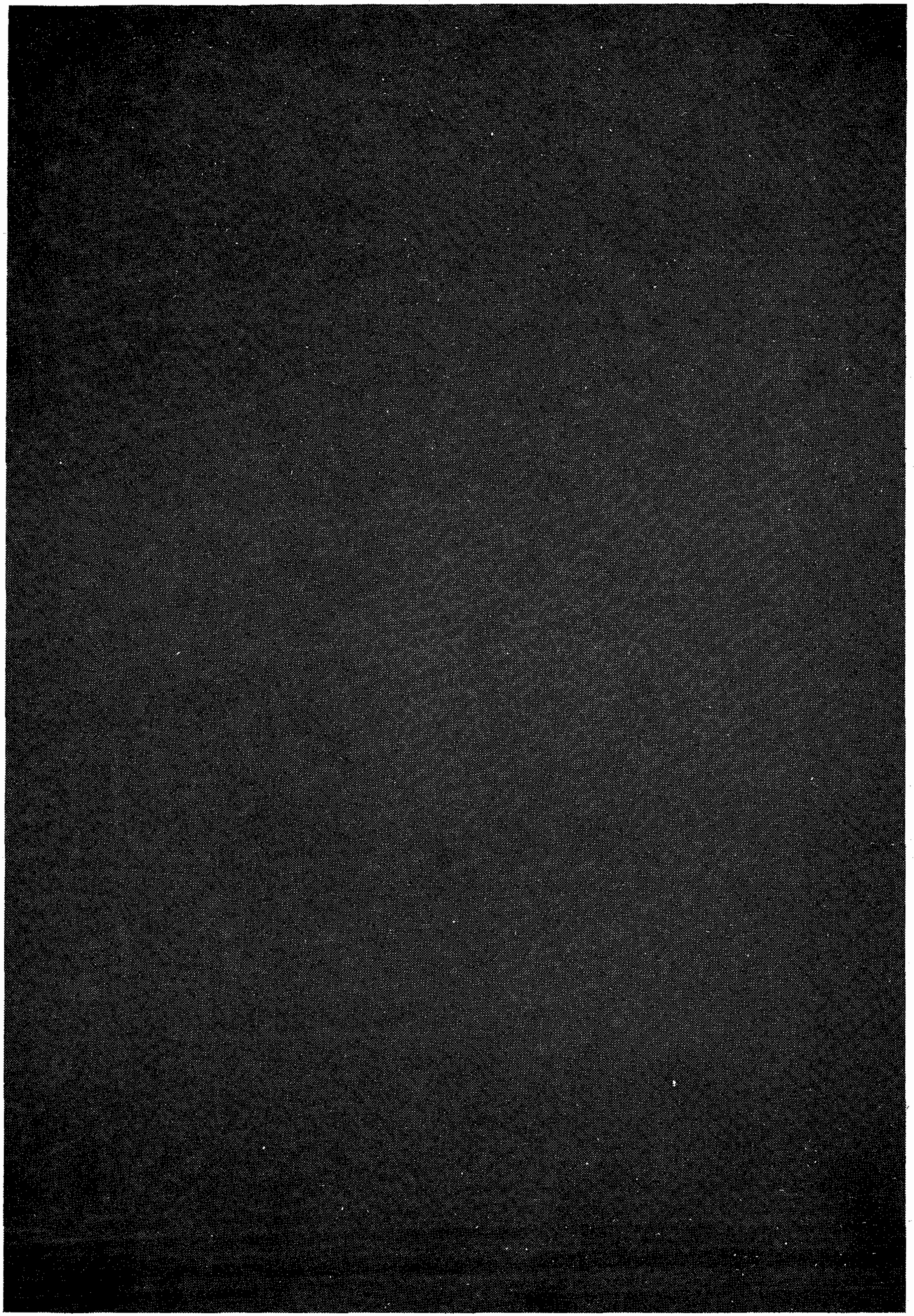

Figure 4-6. Upper half of parabolic trough

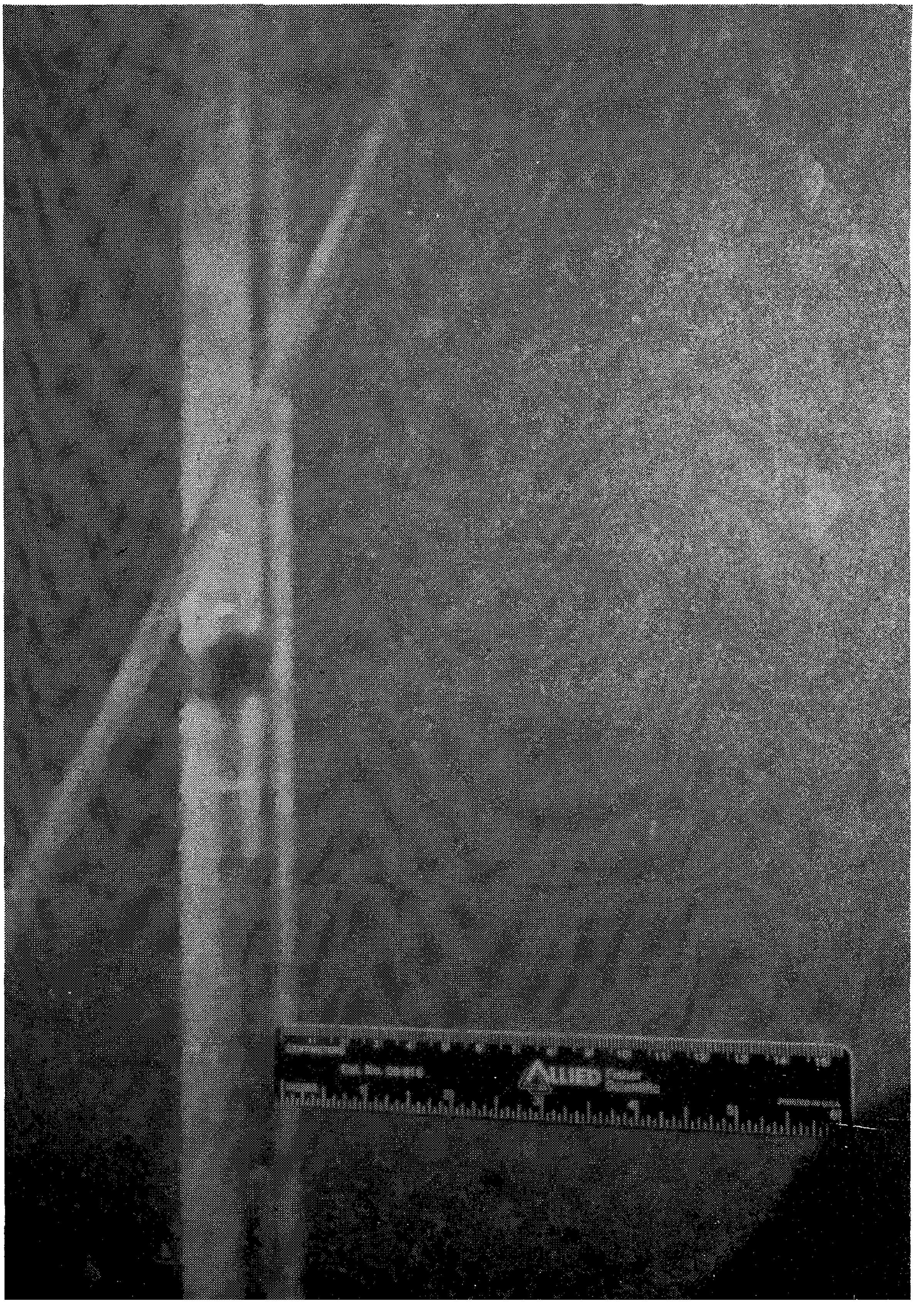

Figure 4-7. Lower half of parabolic trough

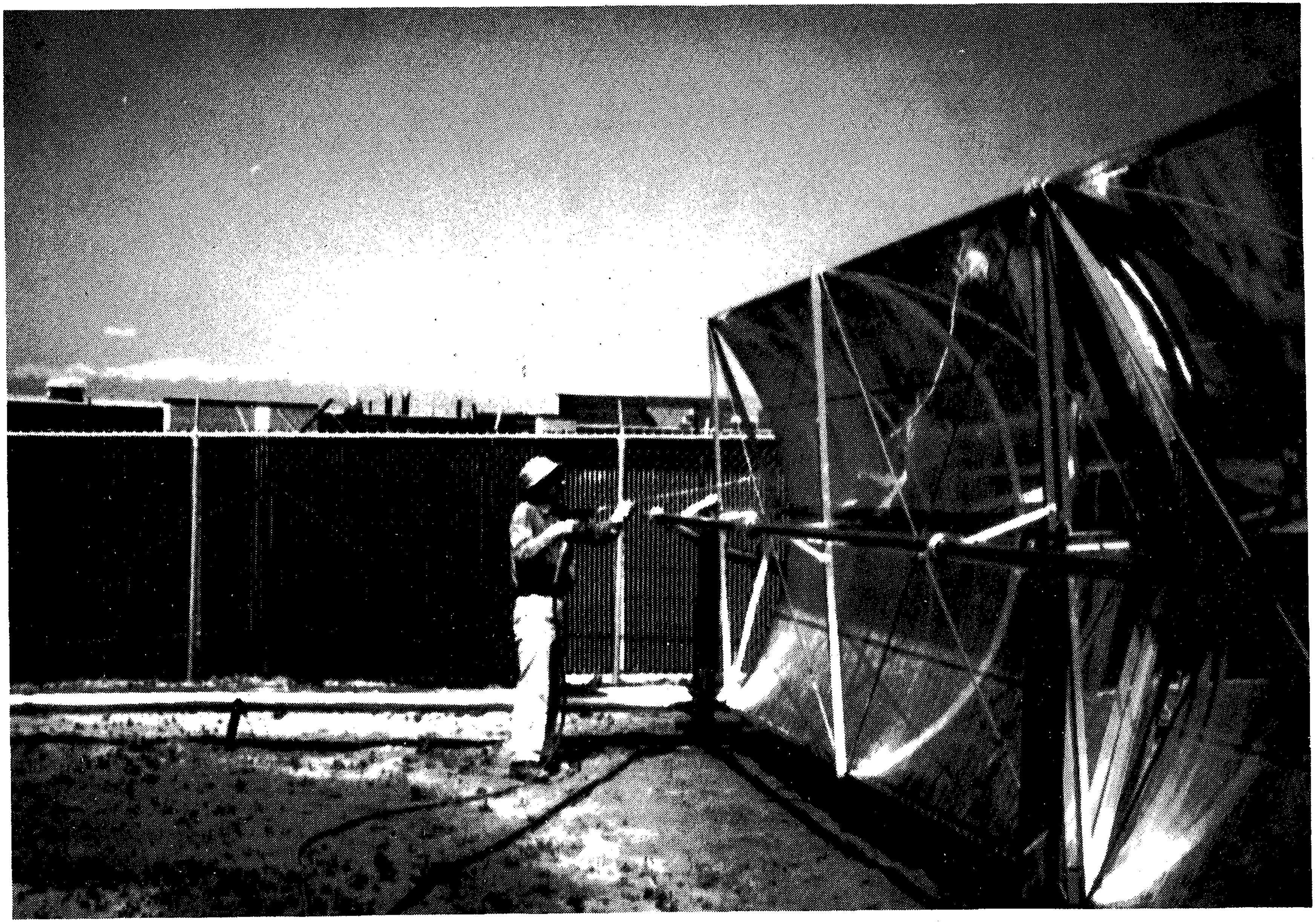

Figure 4-8. Parabolic trough

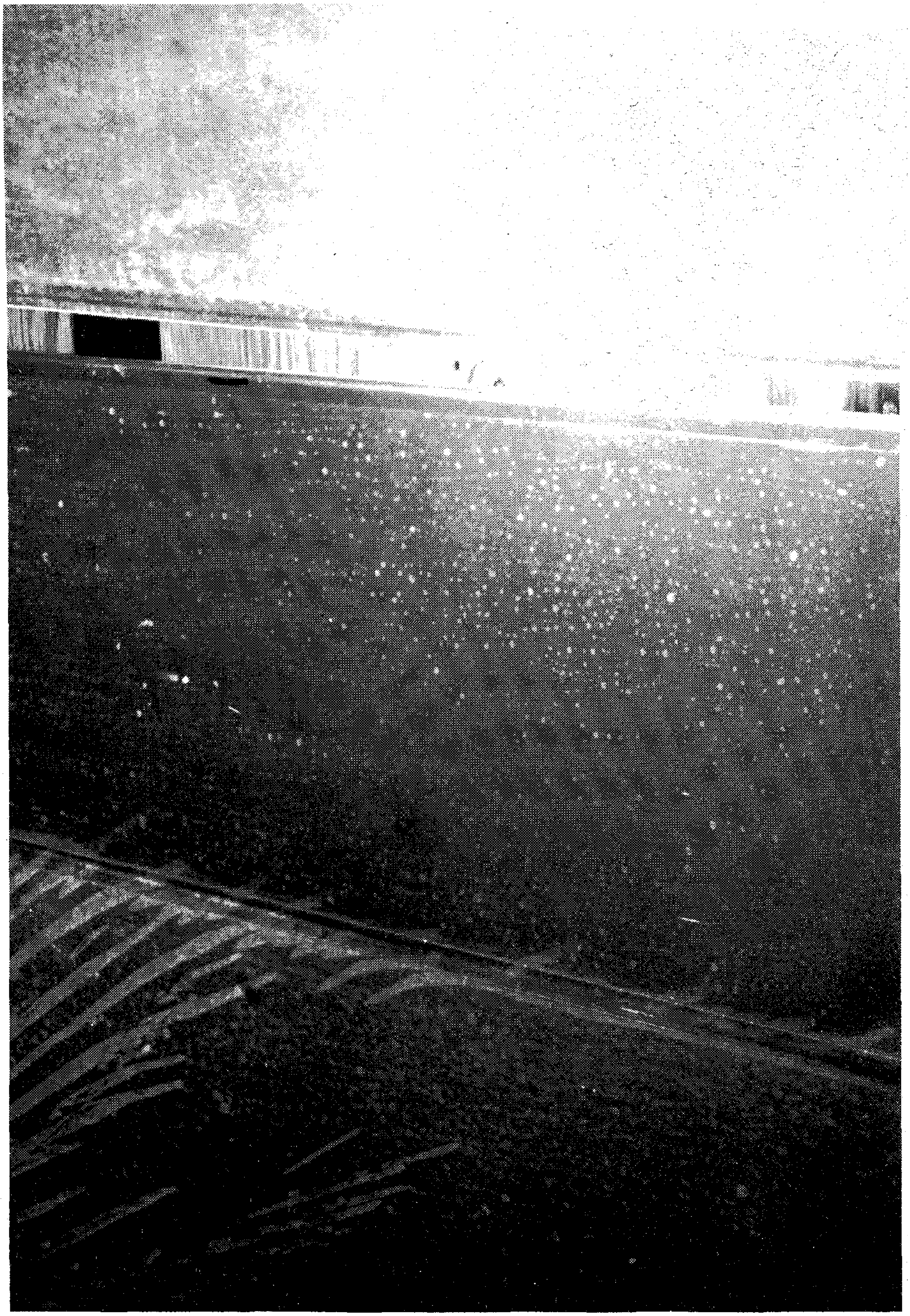

Figure 4-9. Close-up of stationary stand showing well-defined, circular spots

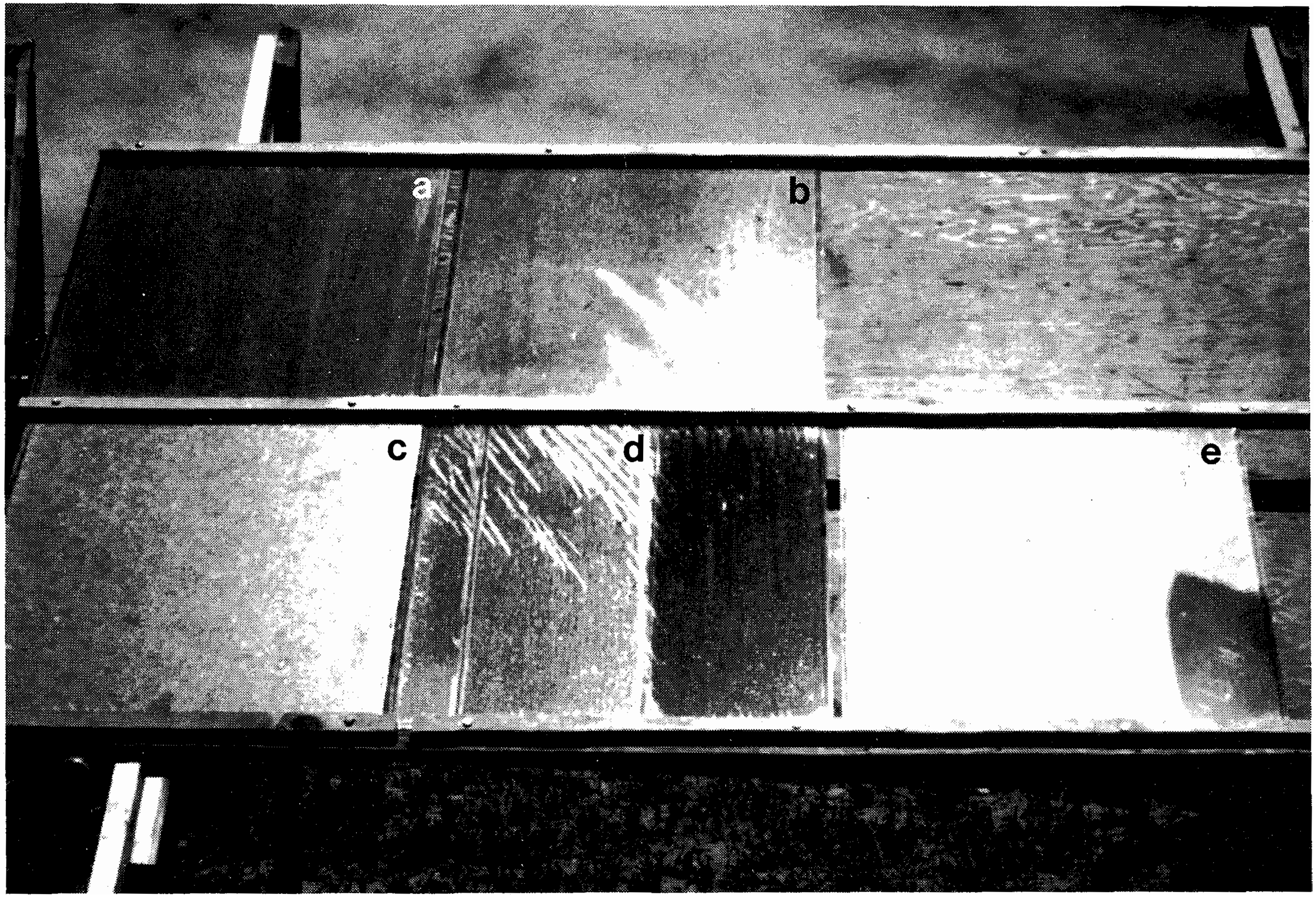

Figure 4-10. Stationary stand (a) ECP 300 washed once per month (noncontact); (b) ECP 300 with hard coating, washed once per month (noncontact); (c) ECP 300 rain washed only; (d) ECP 300 with hard coating, contact washed (lamb's wool applicator); (e) ECP 300, contact washed (lamb's wool applicator).

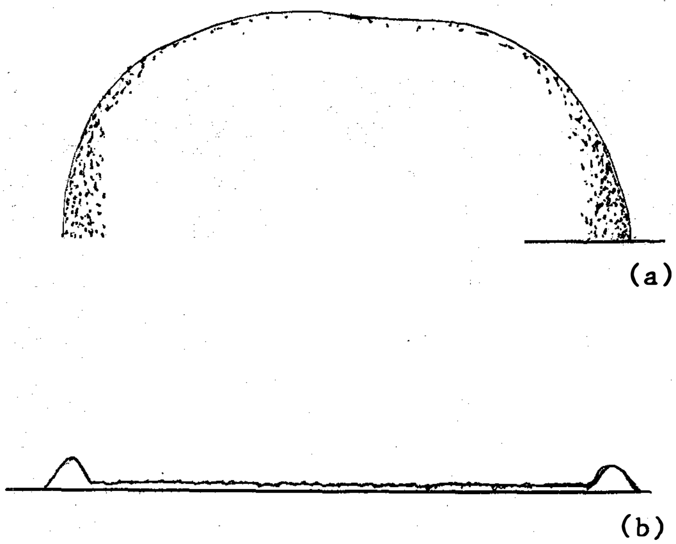

Figure 4-11. A droplet and the corresponding concentration of dust particles (a) and the remaining dust particles after the water has evaporated (b)

spots are relatively constant, and the variation in size and spacing is small compared with the size of the beam.

By using the method for describing the distribution by the number of spots and the average surface area (described earlier), this reasoning can be justified. Knowing there were 600 spots measured and that the average spot diameter of the QUV sample (open air behind) was 0.291 mm, the average surface area per spot was 0.0667 mm^2. Consequently, a set of 600 spots, each with a surface area of 0.0667 mm^2, will cover the same area as the original distribution. The area measured was 162.59 mm^2 and 600 × 0.0667 mm^2 = 40.02 mm^2, which is 24.61% of the surface. Because the beam size is 78.54 mm^2, each measurement will contain 19.33 mm^2 (78.54 mm^2 × 24.61%) of spots, or 292.86 spots. With this large amount of spots in each measurement and a standard deviation of 0.03 mm, it can be concluded that there should be little variation in reflectance measurements of the small spots. A rather surprising observation is that although the average surface area of the spots above the aluminum was nearly four times as large at 0.248 mm^2, with much larger spaces between the spots, the area coverage was only 2.26% less at 22.35%. The reflectance differences between the two patterns roughly coincide with the area coverage. The average measurement of the open air area was 64.3% ±3.3%, which is 7.6% less than the aluminum-backed value of 69.6% ±1.4%. The standard deviation, however, was notably better for the aluminum-backed sample.

The next case involves spots that were separated by a large distance compared to their size. This is a variation of the uniform pattern in that a large percentage of the measurements fall within a narrow reflectivity range. If the spots cover a small percentage of the surface, then the reduction in reflectance because of the spots will be negligible, and the case can be treated as though the pattern was a uniform soil distribution (the first case).

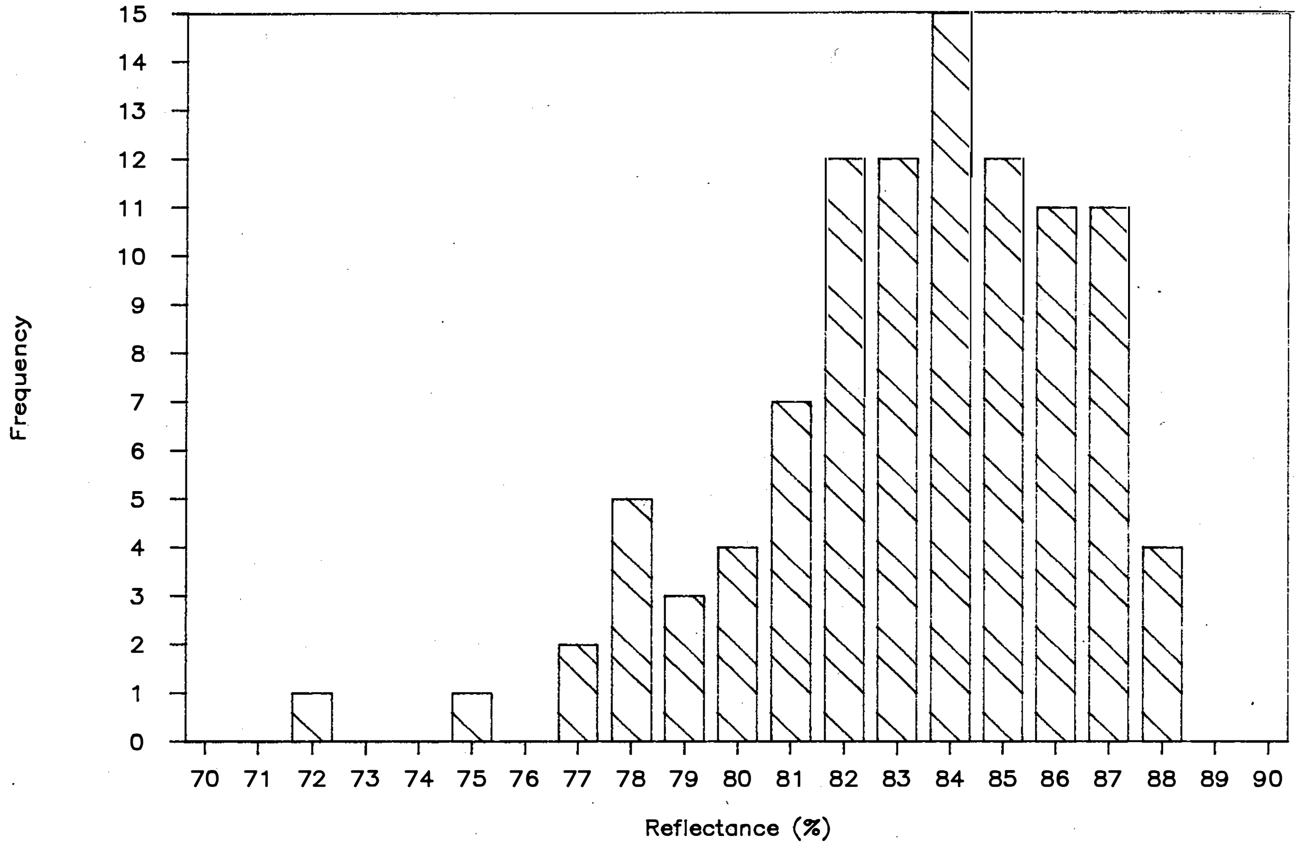

Figure 4-12. Reflectance distribution of uniform soiling pattern

The final case is the most complex and probably the most relevant for areas of harsh weather or large amounts of precipitation. When the spotting pattern has an average spot size that is close to the beam size and the spots are separated by a distance close to the beam diameter, large variations in measurements are probable. This is because the probe may fall completely between spots, completely on a spot, or cover any percentage of a spot. This case was simulated by using the specularometer with a HeNe laser replacing the monochromator and restricting the beam diameter to 1 mm. The laser was needed because the monochromator did not have enough output power for the detector to pick up the restricted beam. Reflectivity measurements were made by moving the beam across the large spots of the QUV sample in small increments. The average reflectivity after 100 measurements was 56.5% ±7.4%, which did have the expected large standard deviation.

This can be modeled crudely but simply by assuming a square area with four equal spots placed in the corners and the side lengths equal to three times the spot diameter (Figure 4-13). If a series of 25 random measurements is taken, the beam will cover various percentages of the spots as previously stated. Assume that the small, solid spots are at the center of each measurement and the dashed circles represent the beam diameter. By monitoring the position of each measurement, we found that 4 fell completely on a spot, 9 fell completely off a spot, and 12 fell partially on a spot. The actual reflectance distribution should and does follow this model (Figure 4-14).

Therefore, the probabilities for measuring each case are

$$P(\text{on}) = \frac{4}{25}$$

$$P(\text{off}) = \frac{9}{25}$$

$$P(\text{partial}) = \frac{12}{25}$$

The actual values have many more intervals in the distribution, but the shape is the same.

The determining factors in the spotting patterns and spot densities are moisture and the harshness of the environment. Moisture allows the dust particles to collect into concentrated "spots," and the environment influences the spotting pattern. During periods of little or no moisture, the reflectors tend to collect a uniform covering of dust. Dew cycles that occur during calm wind conditions appear to create the patterns with small well-defined spots (QUV samples). Light rain would account for the uniform soiling with large spots that are separated by large distances; heavy rain would account for the dense, large spotting pattern. The most extreme case of the squiggly lines would be produced by large amounts of precipitation along with wind and blowing dust.

In this case, the dust is not allowed to pool in circular droplets. The droplets are blown around and mixed together and the squiggly lines are the result.

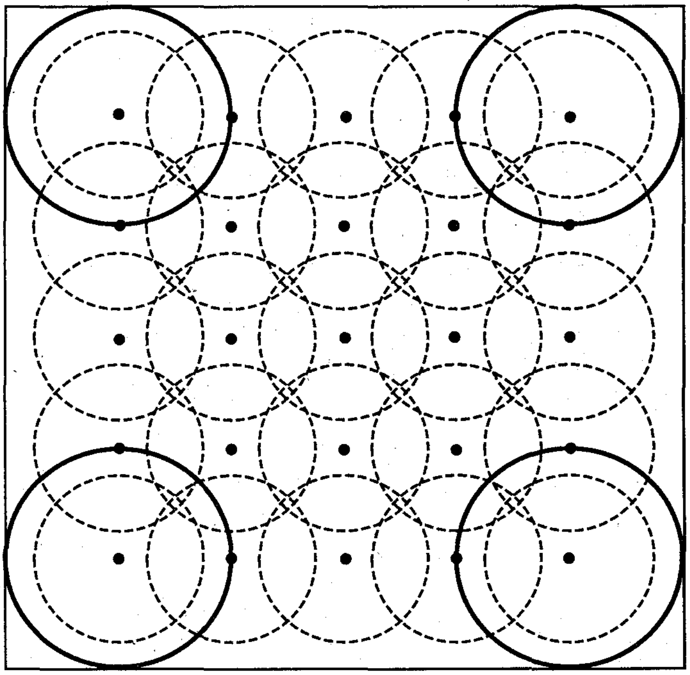

Figure 4-13. Simple model of case where spot size and spot spacing are approximately equal to the beam size

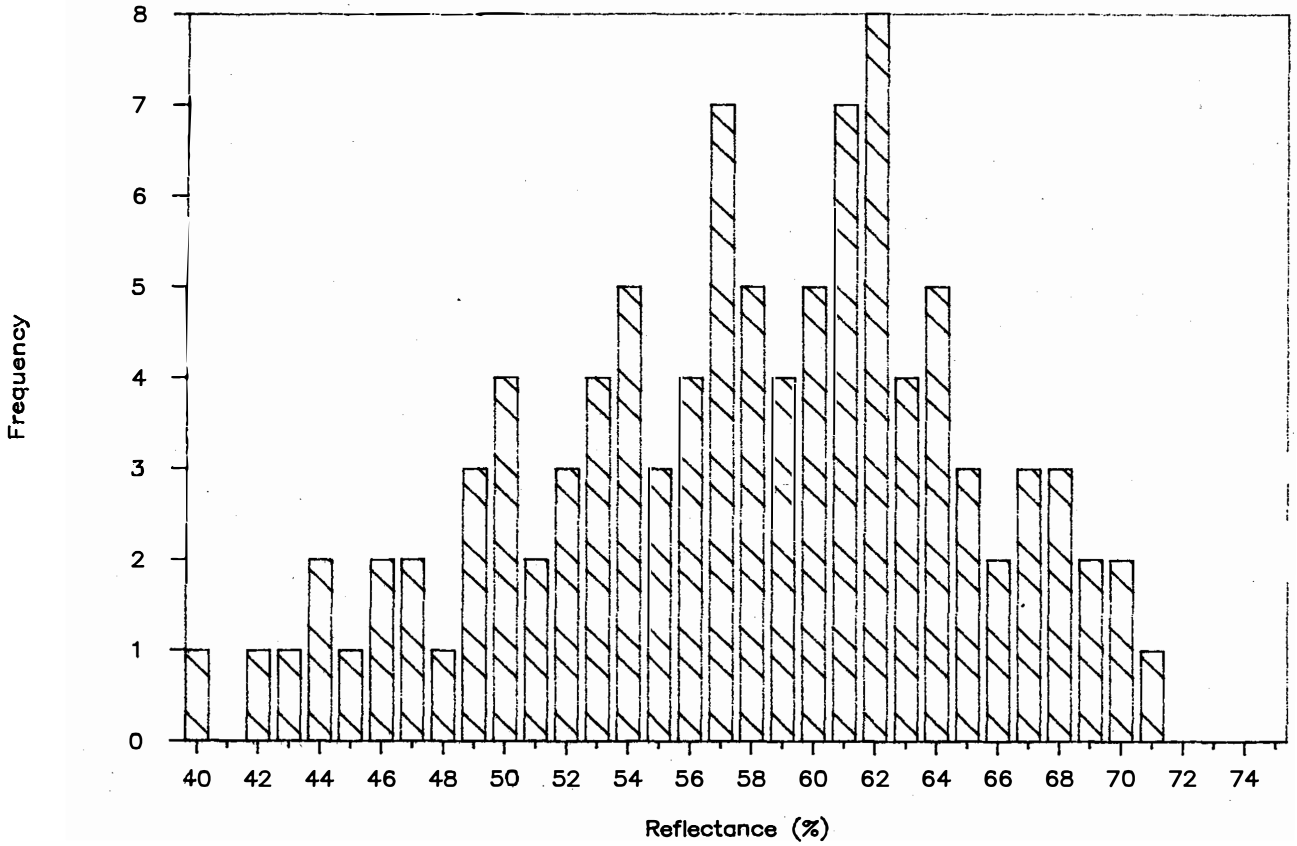

Figure 4-14. Reflectance distribution of soiling pattern where the spot size and spot spacing are near the beam size

5.0 CONCLUSIONS

As stated earlier, the objective for this project was to determine the number of reflectivity measurements needed to obtain the actual reflectance of the solar collector field. The original expectation was that there would be one dominant spotting pattern, and all of the measurements could be based on that pattern. It turns out that there are two major patterns that require a different number of measurements to achieve the actual surface reflectance. Many measurements were taken of each of the patterns described above, and the error of each series of measurements depends on the number of measurements taken and the variance of the measurements. As described earlier, the t test was used to determine the percent error in the average of the reflectances measured. The proposed number of measurements will result in an error of no greater than ±3%.

Of the four patterns described earlier, three were similar enough to be considered one case. These patterns are the uniform coverage, small spot, and few spot cases. Random groups of various numbers of measurements were tested, and all three cases required the same number of measurements to be acceptable. For a group of 10 measurements, the average error was ±1.63%. This is well within the proposed acceptable limit. For the individual groups of 10, the worst error was 2.08% and the best was 0.49%. There was a large variation in errors when groups of five measurements were tested, with the errors ranging from 0.96% up to 7.80%. Groups above 10 did not result in a significant reduction in the errors calculated. Therefore, for these cases, the optimum number of measurements needed to obtain the actual reflectance is 10.

For the case where the spots are close together and near the size of the probe, more measurements are needed to meet the error limit. We assumed that the QUV samples were a worst-case because the spots are opaque compared with what is seen on actual reflectors. Groups of 10 measurements resulted in a large error of 7.38%, and there was apparently an exponential decay in the error when the number of measurements was increased (Figure 5-1). With 20 measurements the error averaged 4.79%, which is considerably above the acceptable range. However, considering this is a worst case, 20 measurements should be enough to be within the maximum error for any naturally occurring spotting pattern.

The model of the squiggly line pattern is a one-dimensional case of the pattern size approximating the beam size. Treatment of this problem is beyond the scope of this work. The reflectivity measurements should coincide to some degree, and I am certain that the two reflectivity distributions would be comparable. The squiggly lines were observed during February, not long after a particularly wet and heavy snow fall. The upper part of the same parabolic troughs were not covered with the squiggly lines when checked again in May, which was during a period of dry, warm weather. This reaffirms the hypothesis that the harsher the climate, the worse the spotting problem becomes.

The project determined how many measurements are needed to obtain a meaningful value for the reflectance of commonly observed soiling patterns. There may be other patterns that could require a different number of measurements to meet any required error limit. The error limit established for this project was completely arbitrary and the t test can be used to meet any desired error range.

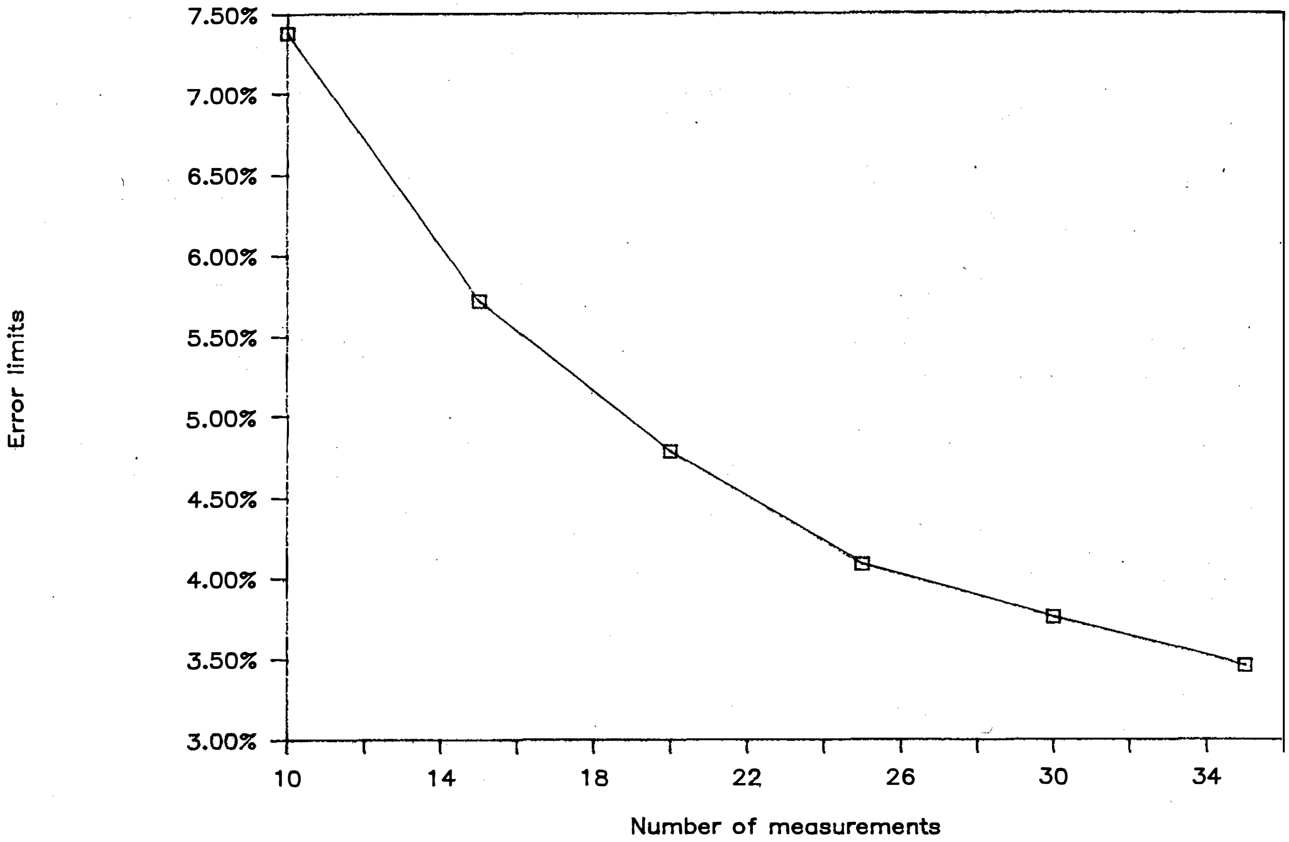

Figure 5-1. Error limits versus number of measurements

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Short-term specular reflectance losses from optical surfaces used in the collection or concentration of solar energy results in significant reduction of these systems' output. Losses range from 0.1% to 1.0% per day, approaching asymptotes of 25% to 60% for periods greater than one year, depending on site and season. To appropriately assess the value of a particular location for the production of power, consideration of the rates of soiling and strategies to minimize losses resulting from soiling must be considered. Strategies for measuring the optical performance of reflector materials to a specified degree of accuracy have been developed, according to the types of soiling patterns observed. It was found that most soiling occurs with the accumulation of particulates in spots of different sizes, and the spot sizes follow a lognormal distribution. For most practical situations, it was determined that 10 measurements with a 1-cm-diameter beam are enough to place the average value within 3% of the true value, with a confidence level of 95%.

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