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Cleaning Strategies for Parabolic- Trough Solar-Collector Fields; Guidelines for Decisions

Kenneth D. Bergeron, James M. Freese

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Cleaning Strategies for Parabolic Trough Solar
Collector Fields; Guidelines for Decisions

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ABSTRACT

This report is intended to assist the owner or operator of a parabolic trough solar collector system to decide on a cleaning strategy (equipment, materials, procedures, and schedules). The guidelines are based on information obtained in past research studies, as well as interviews with vendors and users of cleaning and water treatment equipment. The basic procedure recommended utilizes high pressure portable washing equipment. However, since the cleaning problem is so site-specific, no single, detailed approach can be specified. A systematic procedure for evaluating the particular requirements of a site is therefore given. This will allow the solar energy system operator to develop a cleaning strategy which is cost-effective because it is suited to local conditions.

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I. Introduction

Solar energy systems are capital- and materials-intensive compared to fossil energy systems. This fact has dominated most discussions of the relative economics of the two energy alternatives, but an important corollary is often overlooked: despite the large amount of physical equipment, operating and maintenance (O&M) costs of solar energy systems must be kept low for solar to compete in the energy marketplace. The principal O&M cost for concentrating collectors may be for periodic cleaning of reflector surfaces. Thus, it would be difficult to overstate the importance of developing effective, low-cost cleaning procedures.

The issue of cleaning is much more important for concentrating collectors than for nonconcentrators (e.g., flat plates). The reason is simple: soiling has a larger effect on the efficiency of a concentrating collector than on a nonconcentrator. This is illustrated in Figure 1a, which shows several possible paths of a light ray impinging on a typical solar mirror. The most common effect of a dirt particle is not to absorb the light, but to deflect or scatter the ray. For a concentrating collector, even a

Figure 1. Paths of light rays for reflecting (a) and transmitting (b) surfaces. Dashed lines represent scattered light which is not collected. (For simplicity, effects of refraction have been neglected.)

small deflection will cause the ray to miss the receiver and not be collected, so that in the figure, only the undeflected ray 1 is collected. For a flat plate collector

(Figure 1b) on the other hand, most of the scattered light is collected; only the large-angle deflected rays (7) are lost, and these represent a small fraction of the scattered light. An additional problem for second-surface mirrors is that each ray must pass through the soiled surface twice, doubling the effective rate of scattering and absorption.

It is useful to introduce two definitions at this point. The specular reflectance of a surface is the fraction of a collimated beam impinging on a mirror which is reflected as a collimated beam (as with ray 1 in Fig. 1). The hemispherical transmittance is the fraction of a beam which passes through a surface, whether it is deflected or not (e.g., rays 5 and 6). Thus, we can summarize the previous paragraph by saying that flat plate collector performance depends on the hemispherical transmittance of the cover plate, whereas concentrator performance depends on the specular reflectance of the mirror surface (which is more strongly affected by soiling).

Because natural soiling usually has such a small effect on flat plate collector performance, it is often considered cost-effective to forgo active cleaning and to rely on natural processes (e.g., rain) to limit the accumulation of soil on collector surfaces. For concentrators, the opposite is true: the loss of specular reflectance has, in most cases, been found to be great enough to justify the cost of cleaning.

Most high-temperature thermal line-focus collectors utilize a glass receiver tube cover to reduce thermal losses. This surface also requires cleaning and will be discussed separately in Section IV, but the focus of attention in this report will be on mirror surfaces because of the much larger surface areas involved. At the present time, the most common surface material on high-temperature parabolic trough collectors is aluminized acrylic (polymethyl methacrylate) film. Since these surfaces are easily scratched, they pose special problems for cleaning. Other mirror surfaces (polished aluminum, glass) will also be discussed in this report.

There has been a significant amount of research concerning soiling mechanisms for collector materials and the effectiveness of different cleaning procedures on test samples. However, there has been little practical guidance for the designer or operator of full-scale solar collector fields. Although there is some engineering development of

specialized collector cleaning equipment underway, nothing is expected to be available commercially for several years. Thus, the owner of a concentrating collector system needs to have practical, economical cleaning procedures based on the research results, but which make use of commercially available cleaning equipment. The purpose of this report is to provide guidance for devising such a cleaning strategy for parabolic trough collector fields.*

The emphasis will be on near-term solar projects (e.g., those in the Department of Energy's Solar Industrial Process Heat [IPH] Program). Thus, for example, we will not consider improved (abrasion resistant) reflector materials. Similarly, specialized equipment, solar-specific cleaning materials, and untested cleaning techniques will receive little attention, although such developments may be essential for achieving low solar energy costs in the future. As new approaches develop and new information is obtained, many of the recommendations to be made here will be superseded. It is also expected that experience gained in operating full-scale solar projects will provide useful feedback so that optimizing the cleaning strategy for each site will be a continuing process.

The cleaning problem is one of the most site-specific features of solar energy systems. The rate and nature of soiling depends on relative humidity, rainfall, wind, temperature, and the presence of natural or artificial substances in the atmosphere. In addition, cleaning costs can be strongly affected by wage rates and local water quality, both of which vary considerably around the country. For these reasons, a universal, detailed cleaning procedure will not be specified here. Instead, we will recommend a general approach, based on high-pressure water spray, which must be tailored to local conditions. Thus, the most important purpose of this report is to provide guidelines for making decisions about the details of a collector cleaning strategy, on the basis of site-specific field conditions.

Two principal sources of information served as input to the cleaning recommendations. First, a number of research studies have been undertaken which have addressed numerous soiling and cleaning mechanisms in both controlled conditions, and at actual

*The focus of attention in this study has been on parabolic troughs for thermal energy, but the analysis also applies, substantially unchanged, to concentrating photovoltaic systems.

solar project sites. Second, numerous interviews have been conducted with individuals who deal with cleaning problems similar to those of solar collectors (e.g., car wash equipment manufacturers). This provides information of a more practical nature about cost-effective cleaning procedures using off-the-shelf equipment and materials. Section II of this report reviews and summarizes the relevant information from both sources. This serves as motivation for Section III, which is the decision procedure for cleaning strategies. Some specific, practical suggestions concerning cleaning techniques are given in Section IV. Finally, Section V contains a summary and conclusion.

II. Background Information

Research Results

It has long been recognized that significant degradation in solar collector performance can occur as a result of the accumulation of dirt on transparent and reflective surfaces. A number of studies have addressed various aspects of this problem (References 1-11). One of the most important findings, for the purposes of this paper, is the high degree of variability in the nature of the material which adheres to the optical surfaces and in the rate at which it accumulates.

Reference 2 describes an on-site solar materials exposure program which is being conducted for Sandia National Laboratories (SNLA) by McDonnell Douglas Astronautics Company (MDAC). Test racks (see Figure 2) holding 144 samples of different reflective materials have been deployed at ten industrial sites which are candidates for solar energy projects. Each month, mirror samples are retrieved and specular reflectance

Figure 2. Solar material exposure rack at IPH project site is measured. Transparent and selective absorber materials are also analyzed for degradation. The most significant general result from this study is that there is a great deal of variation in the effect of the environment on solar collector materials. At some sites, the specular reflectance is maintained at a high level, while at others, losses in reflectance of over 70% have been observed in less than three months. Typical

results for reflective materials are shown in Figure 3.

Although not all of the mechanisms are fully understood, there are many possible reasons for the observed variation in the nature and severity of the soiling problem from site to site.⁹ The amount and composition of airborne contaminants is, for

Figure 3. Results from materials exposure test (before washing). Material: FEK-244 aluminized acrylic; Site: Ore-Ida Foods plant, Ontario, Oregon. (Ref. 3)

one thing, highly variable. Arid, desert environments, for example, are characterized by large quantities of wind-borne clay particles which can settle onto mirror surfaces, but which typically do not become cemented down because of the absence of water. On the other hand, in more humid environments, early morning dew can accelerate the contaminant-bonding process, even though there is less airborne particulate material. (One of the severest soiling problems observed to date resulted from a combination of the worst elements of these contrasting situations: a dry desert environment provided high levels of clay dust, and drift from a wet cooling tower provided the moisture for cementing.^{3,12})

Rain and snow introduce another variable. Long, steady rain has been found to be an effective mirror cleaning process.¹⁸ However, if the rainfall is light and the

duration is short, the result can be a significant loss of specular reflectance. One reason may be that the water droplets absorb aerosols and particles suspended in the atmosphere "washing" the air of contaminants and depositing them on mirror surfaces. If the rainfall is not heavy enough, these contaminants are not washed away, and adhere to the surface upon evaporation. In the arid Southwest, particularly, extreme soiling can result when light rain occurs in conjunction with blowing dust.

Like rain, snow can be an effective cleaning mechanism, if it is heavy and wet enough. If the snow builds up to a sufficient depth, the combined effects of soaking and light abrasion at the snow-mirror interface can remove substantial amounts of lightly bonded soil. It has also been observed that early morning frost can improve mirror reflectivity. Presumably, this occurs because water trapped beneath soil particles

Figure 4. Variation of specular reflectance with time of exposure, with significant weather conditions noted (from Reference 14).

expands upon freezing, loosening the dirt from the reflector surface. Figure 4, which is taken from Reference 14, shows the specular reflectance of mirror samples exposed to the natural environment over a period of ten months, illustrating the effects of weather conditions.

Man-made atmospheric contaminants are also important. Diesel exhaust from highways can be a serious problem, as can industrial effluents. Very small quantities of certain substances can play a disproportionately large role if they serve as an adhesive or cement to more abundant materials.

The conclusion is that there can be no detailed prescription for collector cleaning which is optimally cost-effective at all sites. A basic cleaning strategy will be recommended in Section III, but details of the cleaning procedure (e.g., detergent choice, etc.) require decisions based on evaluations of local conditions at the site.

The recommended cleaning strategy is similar to the high-pressure spray wash approach evaluated by MDAC in Reference 1. In this study, three reflector materials were studied: glass, FEK-244 (an aluminized acrylic film manufactured by 3M), and RTV-670 (a silicone elastomer) applied to a polished aluminum sheet. A number of washing techniques and several combinations of materials were evaluated. Conclusions from the study are quoted below:

- o All three surfaces studied adsorb some soil in a nonreversible manner in addition to soil which can be easily rinsed off.
- o Nonreversible adsorption reduced the specular reflectance of glass mirrors by about 2%. Acrylic mirrors were reduced by 5-8%. Silicone surfaces were not measured, but visually they seem to adsorb much more soil and were harder to clean than glass or acrylic.
- o In addition to the nonreversibly adsorbed soil, there was an accumulation of dirt which was rinsed off the mirrors even after being on the surface for some months.
- o Removal of the rinsable soil was accomplished either by a mild detergent rinse followed by a soft water spray or by application of 300 to 1000 psi spray of ordinary tap water containing a sheeting agent.
- o Each rinsing activity restored the reflector to the same specularity; 98% of the original for glass and 92-95% for acrylic. Further soiling and rinsing exercises always regenerate the same 2% specularity loss. No progressive degradation could be observed after 30 soilings and washings.*

*These results are based on experiments involving artificial soiling. Reference 7 reports a gradual decrease in post-cleaning reflectance of samples exposed to natural soiling. See Section 3 for further discussion of this point.

- o The attachment of the soil to the surface was not the result of chemical interaction between soil and substrate, but was simply the result of the intimate molecular contact between the two materials.
- o The glass reflector could be restored to 100% of its original reflectance at any time, either by scrubbing with detergent, or by a spray and rinse with CB 120. Acrylic reflectors could also be cleaned to 100% of their original specularity with CB 120, but scrubbing is not recommended because of the low abrasion resistance of this material.¹⁴

The CB 120 detergent identified in the last item is a proprietary formulation of the McGean Cee Bee Chemical Company, and its mention does not represent endorsement by MDAC or Sandia. The product contains 5% hydrofluoric acid which is diluted to .15% in the wash solution; whether such a small concentration of this corrosive acid will have deleterious effects on the collectors or on the environment has not been determined.

Glass reflector surfaces have the advantage that, as indicated above, contact cleaning methods are allowable. However, the MDAC study indicated that high-pressure spray is nonetheless the preferred cleaning technique, simply because it is faster and more economical. There are several other sources of support for the high-pressure spray approach. For example, the manufacturer of FEK-244 acrylic film recommends a detergent-water wash at 450 psi, and rinse at 750 psi.¹⁵ Another study from Sandia

Figure 5. Pressure wash equipment used in Sandia National Laboratories cleaning study (Reference 7).

National Laboratories reports that the high-pressure approach is relatively effective, but that differences in local water quality may necessitate different choices for wash and rinse water additives.⁷ Figure 5 is a photograph of the high-pressure spray equipment being used on a test rack at Sandia.

Non-Solar Cleaning Applications

The studies discussed above were oriented towards concentrating solar collectors. Additional insights concerning practical and economic aspects of large-scale cleaning problems can also be gained from the experience of other industries. Several well-established cleaning applications which are similar to the trough collector field cleaning problem have been identified. Numerous interviews were conducted with individuals providing manufactured products, cleaning equipment, materials, and services. Such information may be helpful in formulating a cost-effective strategy for washing concentrating collectors, where there is less practical operating experience. Individuals in the following categories were contacted:

- o car wash equipment manufacturers
- o municipal bus companies
- o aircraft manufacturers
- o acrylic film manufacturers
- o "steam" cleaning services (including fleet car and truck cleaners)
- o water treatment services

In the remainder of this section, relevant findings from these interviews will be summarized.

Car Washing--This application has several important similarities to collector cleaning. First, modern acrylic auto finishes are susceptible to scratching, even with light abrasion; trough collectors with acrylic reflector surfaces impose similar constraints on cleaning techniques. Second, visual standards for surface cleanliness of autos are quite demanding, perhaps more so than performance standards for solar collectors. Third, automobile exterior surfaces are curved, and the area involved can be large, especially for fleet car washing operations. Fourth, cost control has a high priority since the business is highly competitive and profit margins are small.

There are also important differences. The soil which builds up on automobiles tends to have more hydrocarbon binding material because of exhaust fumes and petroleum-based road surfaces. Also, it is possible to move the auto into an automated cleaning system while solar collectors are immobile.

Some relevant insights obtained from the survey are:

- o High-pressure spray (500-1200 psi) can clean adequately in most cases, but eventually a "road film" will build up which cannot be removed by any noncontact cleaning method.
- o Softened water is widely recommended. It is said to pay for itself in savings on detergent, and it significantly ameliorates the problems of water spotting and fouling of the spray equipment.
- o There are many environmentally benign detergents available. With softened water, no particular effort to adapt the detergent to local water conditions seems to be necessary.
- o Warm wash water (30°-43°C; 85°F-110°F) is widely recommended. This is not surprising in view of the high level of oily binder in the surface dirt. However, high temperatures are avoided because of potential damage to acrylic surfaces.
- o There are many manufacturers of high-pressure spray washing equipment and hundreds of distributors. It is not difficult or expensive to obtain "customized" cleaning equipment for particular applications.
- o Water spotting can be a problem. Sheeting agents are sometimes used to reduce water spotting. Hand drying with soft cloths or soft paper towels is another approach. Other additives (silicone "wax" added to the rinse water) may be used to reduce water spotting and/or to protect the surface.
- o Cleaning services using high-pressure water spray methods are available in most localities. They are often listed in the Yellow Pages under "Steam Cleaning," even though steam is not necessarily involved. The principal businesses of many of these services are fleet car washing, fleet truck washing, and industrial equipment (e.g., construction equipment) cleaning.

Bus Washing--A representative of a municipal (Albuquerque, NM) bus line was interviewed because the acrylic bus windows are made of the same plastic as the acrylic film on many concentrating collectors. However, unlike solar reflectors, these windows had abrasion-resistant (AR) or super abrasion-resistant (SAR) coatings. The bus wash was an automated system using nylon brushes, softened water, hot detergent wash, and a rinse with sheeting agent. The most important observations were:

- o The AR surface showed some scratching; the SAR surface did not.
- o Water spotting and an accumulation of non-removable deposits were major problems. The next bus wash to be purchased will include a forced air blower to remove residual rinse water. (Water in the Albuquerque area contains 200-300 ppm total dissolved solids.)

Aircraft Windows--This cleaning application was of interest because, unlike bus windows, abrasion-resistant coatings were not used on the acrylic surfaces. The most relevant opinion expressed was that although noncontact cleaning could probably do an adequate job as a regular maintenance activity, it would eventually become necessary to remove built-up film with some form of gentle contact cleaning and/or restoration of acrylic surfaces. Specific procedures recommended will be discussed in Section IV.

III. Guidelines for Collector Cleaning

As with other aspects of solar technology, our understanding of the collector cleaning problem is not yet complete. As more concentrating collector systems are built and operated, we will learn more about cost effective cleaning techniques and equipment. Presumably, the decision-making process will also become simpler and clearer. In the meantime, however, we must operate to some extent on the basis of informed judgement rather than large amounts of operating experience. The decision analysis described below is based on experience and data from many sources, but it also reflects unavoidably the judgements and opinions of the authors.

The basic cleaning procedure recommended for routine mirror cleaning utilizes high-pressure water spray equipment with a hand-held nozzle. Figure 6 shows a trough collector field in Coolidge, Arizona, being cleaned with this type of equipment.

Figure 6. Collector washing at the Coolidge (AZ) solar irrigation project. Separate hoses and wands are used for washing and rinsing. Since the reflector surfaces are aluminum, a mopping step is included between the wash and rinse.

(Receiver tube covers may require different procedures; these will be discussed separately in Section IV.)

Though the type of equipment has been specified, there remain many details of the complete cleaning strategy to be determined. A series of decisions must be made on the basis of information obtained at the solar site. Figure 7 indicates the sequence of decisions required and the basic options available. In this section, each decision will be discussed and guidelines will be presented which will enable the system owner or operator to select the options appropriate to local conditions. As with most real-world problems, it will not always be possible, initially, to determine the best choices with certainty. Thus, the decision procedure should be iterative; a tentative strategy can be initiated, and as more is learned about local conditions, cleaning effectiveness, and economics, the procedure can be adapted or modified. This implies that there is an advantage to maintaining flexibility, especially in the early stages of the field's operation. One of the principal advantages of the portable pressure wash approach (compared to an automatic sprinkler, for example) is that the capital investment is not large and there is a high degree of operational flexibility.

The decision guidelines to be presented below are based on the best information currently available. Two or more options will be suggested at each decision point. The heavy lines in Figure 7 indicate our suggestions for the initial system configuration in the absence of information favoring the other options. This is not necessarily an indication of the most probable final configuration; the intention is rather to minimize capital investments while allowing for future adaptation of the cleaning strategy.

In order for this evolutionary approach to work, it is essential to keep systematic records. For example, it would be helpful to maintain a log with information on labor, water and detergent utilization, measurements of specular reflectance (if available), equipment maintenance costs, changes in system performance after cleaning, significant weather events, etc. Each decision should then be reviewed frequently, as operational experience is gained, in order to insure that a cost-effective cleaning strategy is obtained.

Figure 7. Decision procedure for solar collector washing strategy. Heavy lines indicate preferred initial choice.

Decision 1: One- or Two-Level Cleaning Strategy

It may be desirable to have more than one type of cleaning procedure. A routine, low-cost washing technique might be utilized at fairly short cleaning intervals, which could be supplemented by a more thorough technique one or a few times per year. Certain specific soiling conditions would dictate this approach. Two scenarios for the effectiveness of cleaning are possible; they are illustrated in Figure 8 as hypothetical plots of specular reflectance vs. time with routine cleaning every eighteen days.

In Fig. (8a), each routine cleaning restores the mirror to 98% of its original reflectance, whereas in Fig. (8b), there is an additional 2% reflectance loss with each cleaning. As pointed out in Section II, the MDAC cleaning study¹ indicated that pattern (a) was characteristic of their samples. On the other hand, the non-solar cleaning interviews and Ref. 18 suggested that pattern (b) is also a possibility.

Figure 8. Idealized sequences of mirror soiling and cleaning. The dashed line in (b) corresponds to the build-up of residual film.

If the build-up of a film which is not removable by routine washing continues, a second level cleaning technique may be justified. This is indicated by the arrow in Figure (8b). One possibility, as suggested in Reference 1, is a more aggressive detergent (see Section II), whose more regular use might have undesirable impacts on the solar equipment or the environment. Another approach, as suggested by the car-wash and aircraft window interviewees, is some form of contact cleaning. For glass reflectors, scratching due to contact cleaning should not be a problem if good window washing

techniques are used (e.g., using sponges or nylon brushes and squeegees). Nevertheless, it is likely that high-pressure spray wash will be preferred to contact cleaning procedures for routine washing of glass reflector surfaces simply because it is considerably less time-consuming.

Contact cleaning of acrylic surfaces presents a more serious problem, because care is required to avoid scratching. It may well be that a slight amount of surface scratching must be tolerated as a cost-effective trade-off if a situation such as that depicted in Figure 8b presents itself. Clearly, good judgement and a certain amount of experimentation with techniques will be required. Further information on contact cleaning techniques for acrylic surfaces will be presented in Section IV.

The initial preferred option for this decision is to implement a single-level strategy. That is to say, the decision can be deferred until evidence of the type seen in Figure 8b appears. At that point, the various options for removing the residual film can be evaluated, and economic criteria for when and how often to implement second-level cleaning can be determined by the same methods used to determine first-level cleaning frequency (see below).

Decision 2: Determination of Cleaning Interval

Cleaning the collectors incurs a cost, but by increasing the collector efficiency, it generates a benefit as well. Thus, the determination of the frequency of collector cleaning is an economic decision, and substantially different results will be found to be cost-effective at different locations.

Two quantities enter into the decision of when to clean: the value of the increased energy production and the cost of cleaning. The value of cleaning depends on the difference in specular reflectance before and after cleaning. Let us assume for the moment that each day the reflectance decreases by the same amount. Then the optimum number of days, N_c , between cleanings is shown in Appendix A to be

$$N_c = \left(\frac{2W}{A_o I_o D C} \right)^{1/2} \quad (1)$$

where W is the cost of collector washing per unit aperture area, A_o is the optical component of the collector efficiency, D is the daily loss of specular reflectance,

expressed as a fraction of the restored value, I_0 is the average daily direct solar energy available during collector operation, and C is the value attributed to energy. Suitable units for all quantities in the formula are suggested in Table A1 in the Appendix.

Another possibility discussed in the Appendix is that the most cost-effective approach may be not to wash the collectors at all.* This would occur if the reflectance did not continue to decrease indefinitely, but reached a plateau value after a period of time (N_p days). It is shown in the Appendix that if $N_c > N_p$, the collectors should not be washed. If $N_c < N_p$, they should be washed every N_c days.

Since most of the parameters involved in this formula are not known with any accuracy, and since the model of constant daily reflectance loss is an idealization at best (see Figures 3 and 4), there is some question how to use this result. Below, practical suggestions for estimating each of the parameters will be given.

Optical Collector Efficiency, A_0 --Most commercially available trough collectors have been tested by Sandia or other qualified testing laboratories. Performance results are usually given as plots of peak efficiency vs. $\Delta T/I$, where ΔT is the difference between the heat transfer fluid temperature and the ambient air temperature, and I_0 is the insolation per unit area. The intercept (at $\Delta T = 0$) is the clean collector optical efficiency, A_0 .

Available Insolation, I_0 --This is the net direct solar energy incident in the plane of the collector aperture while the system is in operation. Systems which have shadow-band pyranometers attached to the tracking collector measure this quantity directly. If such direct measurements are not available, I_0 can be estimated from the graphs given in Reference 18 which contain day by day plots of I_0 for Typical Meteorological Year (TMY) weather data at numerous different locations around the country. Results for both north-south and east-west collector row orientations are given (See Figure 9 for an example). However, to account for periods when the sun is shining but

*Steady rainfall can be an effective cleaning mechanism, but it is necessary to rotate the collectors out of the stow position to benefit from the rain. This should only be done when there is no chance of potentially damaging hail or wind.

the collector is not operating, these results should be reduced by multiplication by some reasonable service factor, e.g., 0.9.

Figure 9. Direct insolation in the plane of the collector aperture for a N-S collector field. Based on TMY weather data for Albuquerque, New Mexico.¹⁹

Other ways of estimating I_0 might also be used, such as computer manipulation of total horizontal or direct normal insolation data, but it is important to realize that the direct normal insolation must be multiplied by the cosine of the angle between the sun's rays and the normal to the plane of the collector aperture.

For a north-south field, the seasonal variation of this cosine effect can augment the variation in total insolation so that I_0 in December is typically 1/2 to 1/4 its value in June (as in Figure 9). This implies the collectors should be washed 1.5 to 2.0 times as often in June as in December, all other things being equal.

Energy Value, C--Washing collectors is in many respects an energy conservation activity, and as in any decision concerning conservation, a value must be attributed to the energy saved. One approach might be to set it equal to the cost of replacing the marginal unit of energy with the back-up fuel. For example, fuel oil at \$1.10 per

gallon, and which is converted to heat at 85% efficiency, would set a value of \$10/MBtu (assuming 1.3×10^5 Btu per gallon). Other decision makers might wish to make the solar energy system cost be the yardstick of energy value (this approach was followed in References 5 and 8).

Cost of Washing, W--Washing costs can be divided into fixed and variable costs.

Fixed costs include the capital equipment costs, which are not affected by the frequency of washing. W is the additional cost each time the field is cleaned, per unit area of collector aperture, so it involves only the variable costs. As time passes, each system operator should obtain accurate information on W, but initially it will be necessary to estimate. An example of such an estimate is shown in Table I, which is taken from Reference 1. The value of W in this case would be 2.53×10^{-3} \$/ft², since the 0.53×10^{-3} \$/ft² for capital costs are fixed and should not be included in the sum. It should be noted that the costs in Table I are for a very large collector field with very efficient procedures hypothesized. Whether costs as low as this can be achieved for small fields is uncertain. In contrast, the experimental solar irrigation facility in Coolidge, Arizona, is being cleaned for approximately 2.2×10^{-2} \$/ft² by a service which must transport deionized water 50 miles to the site.

Daily Reflectance Loss, D--This parameter may be the most difficult to evaluate.

The ideal situation would be for periodic measurements of collector reflectance to be made (e.g., every few days). The value of D could then be obtained by plotting reflectance vs. time and choosing the best straight line fit to the data. If the reflectance reaches a plateau value, the parameter N_p must also be estimated (see Figure 11 for an example of this procedure).

It may sometimes be difficult to decide on the best straight line fit, but the important thing is to match the data for the time period less than the cleaning interval. The instrument required for such on-site measurements is a portable specular reflectometer.¹⁷ Although fairly simple to operate, it may be considered too expensive (several thousand dollars) to be justified for a small field. An alternative approach

Table I

Unit Cost Summary Using Detergent Wash With Subsequent Rinse Cleaning Procedure
(From Reference 1)

Parameters

1. Total surface area to be cleaned is 400,000 square feet.
2. A wash cycle of 0.5 min, a rinse cycle of 0.5 min, and a 0.5 min transit time for each reflector is used.
3. The cleaning solution is 3% detergent in softened water, and the rinse cycle employs softened water.
4. Fuel consumption for the truck and spray apparatus is 12 gal/hr diesel at 56¢/gal.
5. 0.5 hr per truck reload is assumed.
6. The equipment depreciates to zero value over 30 years.
7. A labor cost of \$15/hr is assumed.
8. One operator is required.

Unit Cost Summary

Item	Unit Cost Per Cleaning (\$/ft ²)	Percent of Cost
<u>Materials</u>		
Water (at 300 psi)	1.0×10^{-4}	3.3
Detergent	9.4×10^{-4}	30.7
Fuel	4.3×10^{-4}	14.1
Labor	9.6×10^{-4}	31.3
Equipment	1.0×10^{-4}	3.3
Capital Expenditure	5.3×10^{-4}	17.3
	3.06×10^{-3}	100.0

would then be to use data such as that collected in Reference 3 from on-site materials exposure tests.*

Consider a numerical example. (We use engineering units, but Table A1 indicates how SI units could be used.) Suppose one of the methods suggested above indicates that a slope of $d = 0.0015 \text{ day}^{-1}$ is a reasonable fit. With $W = 0.005 \text{ \$/ft}^2$, $I_0 = 1.4 \times 10^{-3} \text{ MBtu/ft}^2 - \text{day}$, $A_0 = 0.6$, $C = 10 \text{ \$/MBtu}$, we find $N_c = 28 \text{ days}$. If the reflectance has not reached a plateau value within this period the collector should be cleaned every 28 days.

Since there is considerable uncertainty in the parameters affecting the optimum cleaning frequency, it is not necessary to adhere strictly to the result obtained from Eq. (1). For example, it is reasonable to increase the interval to the next larger integral number of weeks to permit more convenient scheduling. (Note that it is better to use an interval which is somewhat too long than one too short. This is a consequence of the fact that the value curve analyzed in Eq. (A.10) is steeper to the left of the optimum interval than it is to the right.)

It may also be possible to follow a strategy of cleaning when necessary, rather than adhering to a rigid schedule. In the previous example, the reflectance will have nominally dropped 4.2% in 28 days. Thus, a reasonable unscheduled cleaning strategy for the same location would be to wash the collectors whenever the reflectance drops below 96% of its original value. This method would, of course, require periodic measurements with a portable specular reflectometer.

Decision 3: Automated or Manually Operated Equipment

As Table I indicates, labor costs represent a large fraction of total cleaning costs. If a high frequency of cleaning is required, the possibility of a more capital

*A certain amount of manipulation of the data in Ref. 3 is necessary, however, since the reflector samples were in fixed positions throughout the test, while the collector itself is in the stow position more than half the time. One way to generate reflectance data which would be more representative of the collector would be the following: obtain the "daytime" reflectance by averaging reflectance of the soiled sample from the 45° south and the horizontal facing up orientations. The "nighttime" reflectance is then the value from the samples facing down. The effective collector reflectance is obtained by averaging the daytime and nighttime reflectances, weighted by the number of hours of daylight and dark during the elapsed period.

intensive, automated wash system suggests itself. At the present time, however, no practical automated systems have been developed to commercial readiness. Therefore, the question is moot for the near term, and the labor intensive approach is the only viable choice.

Research and development of automatic wash systems for solar collectors is being pursued, so it may be possible to consider this option more seriously in the future. However, preliminary feasibility studies by Sandia (Livermore) indicate that the capital cost of the equipment must be quite low to compete with the high pressure portable spray approach.⁵

Decision 4: Commercial Cleaning Service

Professional high-pressure spray wash services are available in most parts of the country. These operations often specialize in cleaning fleets of automobiles or trucks, construction equipment, oil field equipment, etc. The equipment is typically truck-mounted though it may be cost-effective to install permanent water treatment equipment at the site. Figure 6 shows the Coolidge, Arizona, Solar Irrigation Project being cleaned by such a service.

The advantages of using a service are obvious, but one disadvantage might be a reduced concern on the part of cleaning personnel for damage to the reflector surface. The relative economics of in-house vs. contracted cleaning will also be an important consideration. Cost estimates of in-house cleaning can be prepared using a procedure similar to that indicated in Table I, and these can be compared with bids obtained from local cleaning services.

Decisions 5-9: Water Treatment and Additives

The remaining five decisions depend on the effectiveness of the materials used for cleaning (water, detergent, additives). A certain amount of experimentation and judgment will be needed. A useful approach would be to clean small sections of the collectors or small samples of reflector materials which have the same level of built-up soil, and evaluate cleaning effectiveness visually. A hazy residue or significant water spotting should be cause for concern. However, absolute spotlessness is not necessary--

standards should be based on cost-effectiveness, not esthetics. The important thing is that any residue remaining should wash off in the next cleaning. Otherwise, a steady build-up of nonremovable soil, as described under Decision 1, may occur.

Not every option should necessarily be tried. The simplest and least expensive should be evaluated first, and if these are not satisfactory, the other options should be pursued. Since labor is the most important component of the cost, it will often be cost-effective to invest in capital equipment or pay more for additives if it reduces washing time. A detailed accounting of the cost per wash such as that shown in Table I should guide these decisions.

Decision 5: Wash Water Treatment

In most cases, it will be cost-effective to soften wash water. Softening water removes calcium and magnesium ions from the water, replacing them with sodium. This has two beneficial effects. First, detergents will be more effective at lower concentrations and will leave less of a film. Second, mineral deposits in the cleaning equipment will be reduced. In many cases, softening water will pay for itself in savings on detergent.

The question of whether deionized or otherwise purified water should be used for washing depends on whether it is used for the rinse. There is probably no need for purified wash water, but if the rinse water is purified (see Decision 8), then it might be desirable to use purified water for washing also, simply because it simplifies the equipment and its operation.

Decision 6: Hot or Cold Wash Water

Most commercial high-pressure spray cleaning equipment has the capability to heat water. Whether hot water is used for washing depends on the trade-off between the added cost of heating and the increased cleaning effectiveness which results. It would be particularly important if hot water reduced cleaning time, because the cost of heating the water is quite small compared with labor costs: for example, if the water temperature is raised from 50°F to 110°F, and the energy to do so is valued at \$10/MBtu, then the cost of heating wash water is .005 \$/gal. Suppose the wash unit is operating

for 1/3 the total cleaning time (man-hours). Then, with a 3 gpm washer and a \$15/hr labor cost, the cost of heating water is only 2% of the cost of labor. If hot rinse water is also used, the percentage rises to 4%. Thus, if hot water reduces cleaning time by more than this percentage, it is cost-effective. A good strategy would therefore be to procure high-pressure spray equipment with the capability to heat wash water but to base the decision whether to use hot water on actual cleaning experience in the field.

Very high temperature water should be avoided because of personnel hazard and because of increased susceptibility of the mirror surface to damage or delamination. Most car washes heat wash water to a temperature between 85° and 110°F. (Acrylic films should be safe at temperatures up to 150°F.)¹⁵

Decision 7: Detergent Selection

Under some circumstances, adequate cleaning can be achieved with no detergent. In this case, there is no separate rinse cycle, and the decision on deionized vs. softened wash water will be influenced by the spotting properties of the water. (See Decisions 8 and 9.) If a separate rinse is not needed, labor costs should be reduced significantly. Thus, one approach might be to have a two-level cleaning strategy (see Decision 1) with the first level of routine cleaning requiring no detergent, and the second, less frequent procedure using a detergent and rinse. As always, such decisions will depend on experimentation and judgement at the site.

In the more likely case that a detergent-free wash is not adequate, there is still the question of what detergent to use. A wide variety of commercial products are available which are compatible with high-pressure spray equipment. The collector field operator should make contact with one or more reputable, established distributors of industrial cleaning materials. In many cases, the spray equipment supplier will have suitable products. The larger distributors will be able to recommend a detergent from a selection of four or five available, or if the year-round demand is large enough, they can tailor a product to the particular application. There is generally no charge for this type of service. Assurances should be obtained from the manufacturer or the distributor that the detergent is safe to use, will not damage collector materials,

and is biodegradable and otherwise environmentally acceptable.

Decision 8: Rinse Water Treatment

Water spotting can be an important problem for collector washing. Spotting is controlled in many car washes by wiping the surface dry. This approach is too labor intensive to be practical for routine collector cleaning, so other solutions must be found.

The most serious problem occurs if the spots do not wash away with the next cleaning. The result is a steady build-up of nonremovable deposits which will result in permanent degradation of collector performance. This is often the result of hard water which leaves deposits of calcium (Ca) and magnesium (Mg) salts, which dissolve very slowly. With enough residence time, these deposits could eventually be soaked off, but this is often impractical. Therefore, it is important to remove the Ca and Mg ("hardness") ions from the rinse water. A level below 5 parts per million total hardness is desirable.

Simple water softening, i.e., replacing the Ca and Mg with Na, will solve most of the problem, and the added cost is very low. Sodium salts dissolve much more quickly, and the level of water spotting should not increase with each washing. It should be kept in mind, however, that since we are only replacing one ion with another, the concentration of total dissolved solids (TDS) is unchanged. In areas with low TDS levels, a soft water rinse with a sheeting agent may give adequate results (see Decision 9).

When TDS concentrations are higher, some form of additional water purification may be desirable to minimize water spots and residual film on the surface. There are two basic approaches: deionization and reverse osmosis. Deionized (DI) water typically has had all but 0.5 to 2 parts per million (ppm) of ionic materials removed by ion exchange. It has several disadvantages compared with reverse osmosis, however. First, DI water is relatively corrosive to metal. Tanks and piping must be fiberglass and plastic, and pumps must be made of stainless steel or other corrosion-resistant material. Secondly, high operating costs (principally for recharging the beds) result in costs around 10¢ per gallon. Third, nonionic materials are not removed and can contribute a significant residue.

Reverse osmosis (RO) requires a larger initial investment than deionization, but the operating costs are extremely low (less than 0.5¢ per gallon). The water is not as free of ions (around 5 ppm), but it is probably as pure as necessary for our purposes. If the untreated water is hard, it will probably be desirable to soften it first before processing through reverse osmosis. An additional benefit of RO water is that special precautions against corrosion of metal surfaces are not required. A third option is to add deionization following the RO treatment, obtaining some of the advantages of each approach.

One advantage to starting out with unpurified softened water, even if it is suspected that purification will be needed, is that it will allow the volume of water required per wash to be estimated. The size and cost of an RO system depends on the monthly water requirement so this information will help insure that capital is invested wisely (see Section IV).

Decision 9: Rinse Water Additives

The most commonly recommended additive for rinse water is a sheeting agent (sometimes called wetting agent, rinsing agent, or drying agent). By reducing the surface tension of the water, a sheeting agent reduces the tendency of the water to form droplets on the surface and keeps the deposition of evaporative residue to a minimum. It also hastens drying, which can be important in dusty environments. The MDAC study reported good results when a rinse containing soft tap water and a sheeting agent was used.¹ However, foaming of the rinse water can be a serious problem with pressure wash equipment.⁷ Since the effectiveness of sheeting agents is strongly dependent on equipment and water quality, some care must be taken in choosing a suitable product. The vendors of the pressure wash equipment and chemical suppliers should be consulted about which sheeting agents, if any, would work for the particular conditions of the site.

Other additives to the rinse water are sometimes discussed. These include protective coatings and "soil releasing" agents. At the present time, there is not sufficient information about the availability and effectiveness of such materials to make recommendations. It is hoped that progress in this area will be made as the demand for effective collector cleaning materials grows.

IV. Cleaning Equipment and Techniques

The previous section should serve to define the basic outlines of a cleaning strategy. However, there are many details to be filled in. The purpose of this section is to provide practical information on a variety of subjects related to cleaning equipment and techniques. It is hoped that information based on experiences at other projects and information from the existing cleaning industry may help clarify the choices available.

Cleaning Equipment

There are hundreds of distributors and manufacturers of portable pressure wash equipment. Many companies routinely design "custom" equipment for particular applications. For collector field cleaning, it will probably be desirable to deal with a firm which has the engineering capability to tailor equipment for specific needs. However, this does not imply a great deal of expensive engineering development. What is needed is a combination of standard components which are packaged together on a vehicle suitable for the application.

As we have emphasized in Section III, the choice of cleaning procedures will be influenced by experience gained in the field. This presents some planning problems for equipment selection because the optimum equipment configuration is not known in advance. A partial solution to this problem may be to initiate a cleaning program with leased equipment until sufficient experience has been acquired to make decisions about purchased equipment. In addition, when equipment is purchased, the possibility of future modifications should be discussed with the vendor.

The basic portable equipment required will include a pump with a heater and mixing apparatus, hoses, hose reels, spray wands, possibly a water storage tank, and a vehicle to provide portability. The company which sells the equipment should be able to provide detailed cost and performance information about the many options available. In the following, we will make a number of suggestions which should help the user define his requirements to the vendor.

The choice of method for delivering water to the portable apparatus will govern many aspects of equipment selection. The simplest method is to locate one or more hose bibbs around the field and provide a low-pressure ("input") hose to the portable unit. We will refer to this as the input hose approach. With this system, the portable wash unit would probably be located outside each row of collectors, and the high-pressure output hose and wand would be carried into the collector field by the worker. After one row of collectors is washed, the output hose is reeled in, and the pressure wash unit is moved the short distance to the next row. A careful arrangement of hose reels will be required (e.g., the input hose reel should be oriented at a right angle to the output hose reel). The hose reels can be manually operated or automatic. If line voltage is used to operate the pump, the electric outlets could be at the same locations as the hose bibbs, and the extension could be rolled up on the same reel as the input hose. (Obviously, adequate safety precautions must be taken, and all applicable codes must be followed.)

If no detergent is used, the system requires only a single output hose. Since it will be quite long (several hundred feet possibly), consideration should be taken of the pressure drop and (when hot water is used) the temperature drop between the pump and the wand. A fan-type spray nozzle has been found to give more uniform cleaning than a concentrated jet.

With a two-step (wash-rinse) process, it should be possible to follow the wash step with the rinse after only a minute or two so that the detergent solution will not dry on the surface. With a one-person operation, a double hose (one for water, one for detergent) could be used with mixing at the nozzle controlled by the operator. Another method is for the detergent to be carried in a dispenser on the wand.

With two workers, each can have a separate output hose and wand, one for washing and one for rinsing. This practice has been followed at the Coolidge Solar Irrigation Project. Either one or two pumps can be used. Rinse water should bypass the heater if possible (to conserve fuel). One of the two workers should be able to wipe the receiver tube cover clean after the wash step (receiver tube covers will be discussed in more detail later).

The equipment needed when the input hose approach is used may be relatively light and could be mounted on a handcart. If rolling surfaces are rough, oversize balloon tires may be required.

In most cases, however, a handcart will be impractical because of the weight of the equipment (typically over 500 lbs) and/or because storage facilities may be some distance from the site. The simplest arrangement would then be to use a small trailer hauled by a pickup truck. Custom power wash equipment suppliers routinely design trailer-mounted systems so the cost should be reasonable. A skid mounted system operated from the bed of a pickup is another possibility.

If it is impractical or undesirable to supply input water with pipes and hoses, a water tank is required. This increases the weight considerably. If a high degree of portability is desired, a truck-mounted system can be used. A portable electric generator and a water tank would allow the cleaning apparatus to be completely independent of the field. This approach may be cost-effective for remote sites (e.g., the Coolidge facility). To save costs, the equipment could also be mounted on a large trailer instead of a truck. For systems which have very good vehicle access between collector rows, it may then be desirable to drive the truck down the rows so that very long hoses are not needed. However, procedures which raise dust during collector washing should be avoided.

The pressure wash unit should be capable of generating pressures up to 800 psi at 3 to 5 gpm. It should be possible to heat the water and control the temperature to as low as 120°F. If both detergent and sheeting agents are used, two mixing units are required, though it is acceptable to mix the sheeting agent with both the rinse water and the wash water.

Water Treatment

Water softening units are self-contained, simple, and inexpensive. The only constraint would be adequate flow rate--15 gpm should suffice.

When water purification is needed, some economic analysis is required to decide between deionization (DI) and reverse osmosis (RO). The DI unit itself is relatively

inexpensive, but it must be chemically recharged periodically depending on the quantity and quality of water used. Thus, DI water has a high operating cost per gallon. Since capital costs are not high, the system is usually sized to supply the maximum anticipated flow rate needed (e.g., 15 gpm).

RO equipment is much higher in capital cost and is flow-limited. A storage tank is therefore usually supplied with the system so that the filtration system can operate continually at a low rate of flow. The tank should be large enough to supply all the water needed for one cleaning while the RO flow rate should be large enough to refill the tank during the shortest anticipated interval between cleanings. (The short interval will usually occur in the summer - See Eq. (1).) We estimate that 0.12 gallons per square foot of collector aperture will be more than sufficient for both washing and rinsing.

Once the RO and DI systems have been sized, based on anticipated cleaning frequencies, vendor cost quotations should be obtained. These should include both capital and operating costs and will allow the user to choose the system with the lowest annual cost.

The suppliers of the water treatment equipment should be consulted on the design of the piping system. Adequate storage tanks (in the case of reverse osmosis systems) and freeze protection should be provided. Highly purified water (e.g., 1/2 ppm deionized) requires plastic piping, fiberglass tanks, and special pumping equipment to prevent corrosion of metal parts. Purifying water more than necessary should therefore be avoided. Water at 5 ppm total dissolved solids from a reverse osmosis unit will probably be entirely adequate (especially if a softener is used to preprocess the water). If the water treatment equipment does not have an indicator of delivered water quality (e.g., an indicator light), a total dissolved solids (TDS) meter should be procured.

The piping layout (e.g., number and location of hose bibbs) should be based on providing convenient enough access that the cleaning operation is as efficient as possible. For a small field (e.g., 10,000 ft²), two hose bibbs on opposite sides of the field should be adequate. For a larger field, one hose bibb every 150 feet on

each of the two sides perpendicular to the troughs will allow a 75-foot input hose to be used.

Operational Information

Time of Day--It is desirable to schedule cleaning when the solar energy system could not otherwise be operating. This could be during cloudy weather or at night. For practical reasons, it may be convenient to schedule cleaning during the first hour after sunrise for several days in a row. There would be adequate light for cleaning but not enough to operate the solar energy system. Furthermore, the receiver tube should be cool in the morning, so that breakage of glass receiver tube covers due to thermal shock should not be a problem. Also, dew on reflector surfaces may help loosen the soil.

Subfreezing Temperatures--It is recommended that washing not be attempted when the ambient temperatures are below freezing. This is based on the assumption that eventually a period of above-freezing temperatures will occur, and the energy which is lost by waiting until then would not be worth the difficulties and costs that would result from subfreezing washing. (Note that Eq. (1) indicates that the cleaning interval increases during the winter months because the insolation level, I_0 , is reduced.)

Damage to Collectors--Glass receiver tube covers are susceptible to breakage, and care must be taken not to inadvertently hit them with the spray wand. A padded sleeve on the wand may help prevent breakage of this sort. Another potential mechanism for breakage is thermal shock due to cool water hitting a hot receiver tube cover. Cleaning should not be attempted until the system has cooled sufficiently.

At very high-pressure settings, the water spray can peel back acrylic film from the substrate. Washing at glancing angles near the edges of the film sheets should be avoided, and the pressure should not be set too high (600 psi or less should be sufficient).

Personnel Hazards--The system should not be washed during operation or when high temperature fluid is flowing in the system, because steam or hot oil leaks can pose a personnel hazard. If the sun is shining, the collectors should face away from the sun during washing, if possible, to avoid the hazards of concentrated sunlight. Very hot

or very high-pressure spray can cause personnel injury. Workers should be well briefed on safe operating procedures for the pressure wash equipment. They should also be safe from electrical shock if long extension cords are used to power the pump. Finally, in cold weather, protective (e.g., waterproof) clothing should be considered.

Cleaning Techniques--The vendor of the pressure wash equipment should provide information on effective washing techniques, but as experience is gained, new and more efficient procedures should be developed by experimentation at the site. A few suggestions based on experience at solar energy sites may be helpful:

(1) When there is a well-defined wind direction, start cleaning on the upwind side of the field, and move downwind so that cleaned collectors will not be soiled by overspray.

(2) Avoid allowing the detergent mixture to dry on the reflector surface, as it can be difficult to remove afterwards. In dry climates, this may mean that only one or two minutes can pass between wash and rinse.

(3) Avoid getting water in shadow band trackers (windows in such devices should be cleaned by hand).

(4) Avoid spraying water into unsealed ends of receiver tube covers.

(5) Avoid cleaning during periods of high wind which might result in immediate resoiling of the surfaces.

Contact Cleaning

As discussed in the section on two-level cleaning strategies, the need may occasionally arise to clean reflector surfaces with contact cleaning methods. For glass reflectors, this should not result in damage to the surface if standard glass cleaning techniques are used. However, it is important to remove loose grit by spray washing before any mops, brushes, or squeegees are applied. Aluminum reflector surfaces are somewhat more susceptible to scratching, but careful washing by swabbing with soft cloth mops has been successful at a number of sites with polished aluminum reflectors.

Acrylic films pose special problems for contact cleaning because of their susceptibility to scratching. It is not possible to give foolproof instructions for

cleaning acrylic surfaces by contact methods without scratching. However, a slight amount of surface abrasion may be preferable to an accumulation of soil which is not removable by any other method. A light level of visible scratches may have a very small effect on specular reflectance. Ideally, contact cleaning methods should be developed by trial and error on small areas using a reflectometer to assess loss in specular reflectance due to abrasion. The following procedure, recommended for acrylic aircraft enclosures, may be a useful starting point:

Acrylic materials and components should be cleaned by washing them with plenty of soap and water, using the bare hand to feel and dislodge any caked dirt or mud. A soft cloth, sponge, or chamois may be used but only as a means of carrying water to the plastic. It should be dried with a clean, damp chamois. Rubbing a dirty surface with a dry cloth will scratch the material. Rubbing also builds up an electrostatic charge in the acrylic so it attracts dust particles from the air. Wiping with a damp chamois will remove both charge and dust and is therefore recommended. Oil and grease should be removed by cleaning and polishing using a material conforming to MIL-C-18767A.¹⁶

Receiver Tube Cover Cleaning

There are several differences in the nature of the cleaning problem for glass receiver tube covers compared with reflector surfaces.

- o There is much less surface area to clean.
- o Performance depends on hemispherical transmittance rather than specular reflectance, and is therefore less affected by dirt and scratches.
- o Careful contact cleaning is always acceptable because the receiver tube covers are invariably made of glass.

Receiver tube covers can be cleaned quite simply and quickly with wet cloths (see Figure 10). The time required is much less than for reflector washing (at Coolidge, it takes one man two hours to clean the tubes for 23,000 ft² of collectors).

The optimum cleaning frequency can be obtained from the same formula as for reflector washing (Eq. (1)). Now, however, W refers to the cost of cleaning the receiver tube covers, per unit area of the collector aperture, and D would be the average daily loss in hemispherical transmittance. We can use Eq. (1) to determine the ratio of cleaning intervals for reflectors (N_r) and receiver tube covers (N_t):

$$\frac{N_t}{N_r} = \left(\frac{\beta}{a} \right)^{1/2} \quad (2)$$

Figure 10. Receiver tube cover cleaning at Coolidge.

where $\alpha = D_t/D_r$ (D_r is the daily loss in specular reflectance, D_t is the daily loss in hemispherical transmittance) and β is the ratio of the variable cleaning costs, w_t/w_r .

Measurements of hemispherical transmittance of receiver tube covers are difficult in the field. Perhaps the most practical approach would be to postulate that the loss of hemispherical transmittance is approximately proportional to the loss of specular reflectance of the mirrors. For example, data from Reference 14 suggests a value of $\alpha = 0.2$. Thus, if we assume $\beta = .17$ (again based on Coolidge data), we obtain $N_t = 0.92 N_r$. This would suggest that the tubes should be cleaned each time the collectors are cleaned.

V. Conclusion

In preparing this report, we have followed two guiding principles. First, the people who are in the best position to determine the particular needs and requirements for cleaning a field of solar collectors are the owners and/or operators of the system. Consequently, some effort will be required on their part to obtain the site-specific information and to acquire the operating experience needed to make rational decisions about cleaning equipment and procedures. This is the only practical way to keep cleaning costs at an acceptable level because it results in a cleaning strategy which is adapted to the site.

The second guiding principle is that the equipment, materials, and expertise of existing industry should be utilized to the greatest possible extent. This principle is also oriented towards controlling cleaning costs, because, at present, off-the-shelf equipment and tested materials and procedures should be more cost-effective than approaches which require substantial engineering development. In particular, two types of suppliers should be consulted: a water treatment service and a pressure wash equipment supplier capable of designing custom equipment.

The goal of this report has been to provide some insight into how to obtain the required site-specific information and how to make use of commercial suppliers. We have identified numerous concrete decisions which each system operator must make and indicated the major trade-offs which must be considered at each point. Since the number of different combinations of decisions is large, and the information bearing on the decisions is often uncertain, the initial system definition task may seem somewhat formidable.

However, there are two points which should moderate some of the pressure on the initial decision-making process. First, not all the decisions are crucial; in many cases there will be little difference in cost-effectiveness between two options. In these cases, the penalty for making a "wrong" decision would not be high. Second, the determination of a cleaning strategy is expected to be an evolutionary process. As experience is gained, various modifications and adaptations of the equipment, materials, and techniques should be tried until a system well suited to the particular conditions

of the site is obtained. We expect this evolutionary process to take at least a year, but we do not see it as requiring excessive investments of time or money since each step in the evolutionary sequence should result in effective cleaning at reasonable costs.

It is true that capital investments would be minimized if it were known in advance exactly what equipment and facilities are needed, so that upgrades and modifications would be unnecessary. However, over the long run, the operating costs will dominate capital costs so it is worthwhile to pay for this adaptability in order to reduce the cost per washing. The principal focus of attention in this cost control effort will probably be to increase the efficiency of labor.

As more experience is gained at different projects around the country, we expect the decision-making process to be simplified. Ineffective products and techniques will be eliminated from consideration, and choices will be narrowed to a smaller selection of tested strategies. With more fields in operation, new products, equipment, and services may become available which are oriented specifically to concentrating collector cleaning. Moreover, "rules-of-thumb" will be developed which will make the decision process described in this report more systematic and straightforward.

The economic viability of solar energy for industrial process heat depends largely on how two challenges are met. The first is to reduce capital costs of the solar energy system while maintaining a high level of performance. The second, which has received far less attention, is to keep operating costs low while maintaining performance. As more concentrating solar energy systems are installed and operated at industrial sites, the insights gained by the system operators concerning low-cost cleaning will play an important role in this process.

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Appendix A: Calculation of Optimum Cleaning Frequency*

It is customary to express the efficiency of solar collectors in the form

$$\eta = A - B\Delta T/\mathcal{I} \quad (\text{A.1})$$

where ΔT is the temperature difference (in °F) between the heat transfer fluid and the ambient air, and $\mathcal{I}$ is the incident insolation per unit area of the collector aperture.[†] The two parameters A and B are characteristic of the particular collector. Only A, which we will call the optical collector efficiency, depends on the specular reflectance, R.

The key step in determining the optimum cleaning frequency is to assume a reasonable model for the dependence of reflectance with time. Since there is a great deal of random variation in the specular reflectance of mirrors exposed to the natural environment, (e.g., see Figure 4), it is often difficult to deduce a smooth curve representing the average value (i.e., expected value) as a function of time. One approach is to assume a constant loss in reflectance per day.

$$R(t) = R_0 (1 - tD) \quad (\text{A.2})$$

where R is the specular reflectance, R_0 is its initial value, t is the time in days, and D is the reflectance loss per day, expressed as a fraction of the original reflectance. This model was used, for example, in Reference 5.

However, it is often observed that, eventually, the level of mirror soiling reaches a saturation point, so that the reflectance after long periods of exposure tends to vary randomly around a constant or plateau value. In Reference 8, a two-parameter curve fit was employed to make a smooth transition to the plateau value. Unfortunately, this model is difficult to use without the assistance of a computer.

The model we will use for calculating optimal cleaning frequencies includes the plateau effect, but is computationally much simpler:

*This analysis differs from that of Ref. 6 in two ways. First, the energy is valued by its replacement value, C, not by the original cost of the solar energy system. Second, the nonoptical loss terms involving B and C in Eq. A.5 were not considered in Ref. 6.

[†]Units for all quantities appearing in these formulas will be discussed at the end of this Appendix.

$$R(t) = R_0(1 - tD), \quad t < N_p \quad (A.3a)$$

$$R(t) = R_0(1 - N_p D), \quad t \geq N_p \quad (A.3b)$$

This model is thus the same as that of Eq. (2) until $t = N_p$, at which time the reflectance loss ceases abruptly. The sharp change in slope may seem unrealistic, but the random variation of the actual reflectance is so large that this simple model can give as accurate results as a model which uses a smoother curve. Figure 11 shows how a hypothetical set of reflectance measurements might be analyzed to determine the two parameters D and N_p which characterizes the model.

Figure 11. Hypothetical data for reflectance vs. time, showing how the two parameters for Eq. A.3 might be chosen.

Let N_c be the cleaning interval in days. We begin by ignoring the effect of the reflectance plateau, so that Eq. (A.3a) applies. The dependence of the collector efficiency, η , on R should enter in only through the optical term A , and the effect should be linear. Thus, we can define A_0 as the "clean reflector" optical efficiency, and write

$$A = A_0 R / R_0 = A_0(1 - tD) \quad (A.4)$$

Now, in addition to energy losses from the collector, there are also energy losses from the rest of the system (piping, etc.). These should not depend on $\mathcal{J}$, so the efficiency of the system can be written

$$\eta_s = A_o(1 - tD) - \frac{B\Delta T}{\mathcal{J}} - \frac{F}{\mathcal{J}} \quad (\text{A.5})$$

or,

$$\eta_s = \eta_{so} - A_o tD \quad (\text{A.6})$$

where F is a constant and η_{so} is the system efficiency when the collectors are clean.

We first consider the case when $N_p = \infty$, i.e., in the absence of the plateau effect. Since N_c is the cleaning interval in days, the energy collected between washings is

$$\mathcal{E} = \int_0^{N_c} 24 \eta_s(t) \mathcal{J}(t) dt \quad (\text{A.7})$$

The factor 24 enters in order to account for the measurement of t in days rather than hours. $\mathcal{J}(t)$ is the insolation incident on a unit area of collector area. (Note that $\mathcal{J}(t)$ is zero when the system is not operating, even if the sun is shining.) If we define E_o as the daily energy collected per unit area by a clean system, and I_o as the daily energy incident per unit area (while the system is operating), then we can perform the integral in (A.7) and write the collected energy in two parts

$$\mathcal{E} = E_o N_c - \frac{I_o A_o D N_c^2}{2} \quad (\text{A.8})$$

If energy is valued at C dollars per unit, and it costs W dollars per unit area to wash the collector field and restore the reflectivity to R_o , then the net value per day over the N_c day period is

$$V = \frac{C\mathcal{E}}{N_c} - \frac{W}{N_c} \quad (\text{A.9})$$

The optimal cleaning interval is obtained by maximizing V with respect to N_c :

$$0 = \frac{dV}{dN_c} = \frac{d}{dN_c} \left\{ CE_o - \frac{CI_o A_o D N_c}{2} - \frac{W}{N_c} \right\} \quad (\text{A.10})$$

This is satisfied when

$$N_c = \left(\frac{2W}{A_o I_o D C} \right)^{1/2} \quad (\text{A.11})$$

which is Eq. (1).

When N_p is finite, but greater than N_c , the same calculation applies unchanged. However, when $N_p < N_c$, it can be shown that the value with no washing is always greater than the value with washing. Thus, the prescription for determining a cleaning frequency is the following:

- 1) Find the best fit to the reflectance data with the two straight lines specified in Eq. (A.3).
- 2) Calculate N_c from (A.11).
- 3) If $N_p > N_c$, wash at intervals of approximately N_c .
- 4) If $N_c > N_p$, do not wash at all (rely on natural cleaning).

Any consistent set of units can be used in these formulas. Table A.1 suggests two possibilities (A_o is dimensionless).

Unit System	N	W	A_o	I_o	D	C
Engineering	day	$\frac{\$}{ft^2}$	-	$\frac{MBtu}{day}$	day ⁻¹	$\frac{\$}{MBtu}$
SI (modified)	day	$\frac{\$}{m^2}$	-	$\frac{KWH}{m^2-day}$	day ⁻¹	$\frac{\$}{KWH}$

Table A.1 Units for Cleaning Formulas

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