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The Impact of Natural Cleaning on the Selection of a Washing System for Solar Collectors

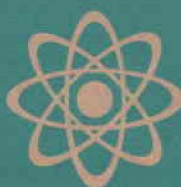
A. Kerstein

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THE IMPACT OF NATURAL CLEANING ON THE SELECTION
OF A WASHING SYSTEM FOR SOLAR COLLECTORS

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ABSTRACT

The desired optical properties (reflectivity, transmissivity, etc.) of solar energy collector surfaces such as mirrors and photovoltaic surfaces are degraded over time by soiling. Cost-benefit evaluation of alternative methods for washing the surfaces or retarding the optical degradation must take into account natural cleaning processes such as precipitation and frost, which impact the scheduling as well as the benefits of washing. A probabilistic method developed to address this question is used to compare truck-mounted versus mirror-mounted washing systems for central receiver plants. The comparison of these systems is shown to be sensitive to the seasonally-varying frequency and effectiveness of natural cleaning processes. The implications of this analysis for such diverse issues as cost/benefit evaluation of soil-retardant mirror coatings and formulation of plant site selection criteria are noted.

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THE IMPACT OF NATURAL CLEANING ON THE SELECTION OF A WASHING SYSTEM FOR SOLAR COLLECTORS

Introduction

Technologies for the conversion of solar to thermal, chemical or electrical energy will generally require exposure to environmental effects of surfaces whose optical qualities are critical to system performance. For example, the reflectivity of mirrors and the transmissivity of protective coverings, lenses and photovoltaic surfaces must be high for cost-effective energy conversion. Environmental exposure of these surfaces will cause both reversible and irreversible degradation of these qualities. In many localities the dominant degradation process will be dirt buildup [1] which is partially or totally removable by washing or by rain, snow, frost or other natural cleaning phenomena [2]. Roughly speaking, washing is beneficial if the cost of washing is less than the value of the additional energy produced due to the improvement in optical quality. By making this tradeoff more precise, various methods for mitigating the effects of soiling may be compared.

Soiling effects may be mitigated by:

- Siting the solar energy facility at a locale which is relatively benign with respect to amount and type of dirt buildup.
- Minimizing dirt buildup through collector design, choice of materials, and operating procedures (such as protective stowage during shutdown).
- Removing accumulated dirt by washing or other procedures.

To illustrate how the relative merits of these alternatives may be affected by natural cleaning, a specific question is considered in detail. Two alternative methods are compared for washing heliostats, which are flat-plate mirrors used to direct sunlight to a tower-mounted central receiver in a solar-thermal-electric plant.

One method utilizes truck-mounted sprayers, with each truck repetitively traversing a portion of the heliostat field, washing heliostats sequentially. The number of heliostats assigned to each truck, and consequently the time interval, I , between successive washes of a given heliostat, are inversely proportional to the number of trucks employed. In the model developed below, I is treated as a continuous parameter which may be selected to minimize the cost of electricity produced by the plant. In situations of practical interest,

optimal values of I may range from a few days to a few weeks [3]. The truck-mounted washing system will be called a scheduled system because once deployed, it affords no flexibility in its utilization. The consequences of possible exceptions to this idealized assumption are discussed elsewhere [4].

The second washing method consists of a sprayer unit mounted on each heliostat, permitting nearly simultaneous washing of all heliostats on demand. We call this a responsive system to emphasize the flexibility, for instance, to delay washing if an effective natural cleaning occurs.

The comparison of these two washing systems is of timely interest because such systems have been proposed for use in solar-thermal-electric central receiver power plants [4].

Assumptions

This analysis is a generalization of the method used by Eason to determine the optimal washing frequency in the absence of natural cleaning [3]. The following baseline assumptions, some of which will later be modified, are adopted:

- In the absence of natural cleaning, the daily reduction, R , in the plant power output due to mirror soiling is constant.
- Every washing or natural cleaning of a mirror restores it to the same optical quality.
- Natural cleaning events constitute a Poisson process in time, with mean time λ between events.

The objective function to be minimized is the cost per unit energy expressed as the ratio $B = C/E$, where C is the total plant cost (including washing costs) per unit time, and E is the energy output per unit time. In the absence of soiling, the objective function becomes $B_0 = C_0/E_0$, where E_0 is the "clean-mirror power output" and C_0 is the plant cost excluding washing costs, since in the absence of soiling no washing system is needed. If soiling occurs, as is the case in practice, the denominator of B becomes $E = E_0 - x$, where the time-dependent quantity x is the power deficit resulting from reduced optical quality. If a washing system is installed and operated, the numerator of B becomes $C = C_0 + C_w + wf$, where w is the incremental cost of each wash (due to labor, consumables, etc.), f is the number of washes per unit time, and C_w is the cost per unit time of amortizing and maintaining the washing system even if it is never used. C_w includes any increase in the cost of other plant subsystems resulting from redesign to accommodate the washing system. Cost per unit time is obtained by amortizing capital costs over appropriate depreciation periods using financial assumptions consistent with those used to estimate balance-of-plant costs [3,4]. All costs are prorated on a per heliostat basis.

Method of Analysis

Since natural cleanings are randomly distributed in time, x is a random variable, as is f for the responsive system. The objective function to be minimized is therefore the time-average of B , which may be approximated under the assumptions $x \ll E_0$ and $C_w + wf \ll C_0$ as

$$\bar{B} = B_0 \left(1 + \frac{C_w + w\bar{f}}{C_0} + \frac{\bar{x}}{E_0} + \text{terms of higher order in small quantities} \right), \quad (1)$$

where overbars denote time averages. Eason has shown that the assumptions are justified in applications of interest [3]. For the scheduled system, $\bar{f} = 1/I$ and \bar{x} is derived in reference [5] as an explicit function of I and the parameters λ and R under the assumptions stated earlier. The result is

$$\bar{x} = \frac{\lambda^2 R}{I} \left\{ \exp(-I/\lambda) - \left(1 - \frac{I}{\lambda}\right) \right\}. \quad (2)$$

Using these expressions for \bar{f} and \bar{x} , minimization of \bar{B} with respect to I is straightforward. Also in reference [5], the optimal decision rule for the responsive system is shown to be of the form, wash whenever $x = M$. The expressions obtained for \bar{f} and \bar{x} are

$$\bar{f} = \left\{ \exp\left(\frac{M}{\lambda R}\right) - 1 \right\} / \lambda \quad (3)$$

$$\bar{x} = R \left(\lambda - \frac{M}{\lambda R \bar{f}} \right). \quad (4)$$

Again, minimization of \bar{B} is straightforward. Thus, for any set of parameter values λ , R , E_0 , C_0 , C_w and w , with the latter two quantities given for the scheduled and responsive systems respectively, \bar{B}_{\min} can be determined for the respective systems and the preferable system identified. By expressing power output in units of E_0 , so that R becomes the power loss per unit time as a fraction of E_0 , the parameter E_0 can be eliminated from the system comparisons.

System Preference in the Absence of Natural Cleaning

Estimates of the parameter values are taken from [4] and from references cited in [4]. (In the sensitivity studies below, parameters are assigned the "nominal" values given in Table I unless specified otherwise.) It is found that the scheduled and responsive systems strongly differ in the nature of the costs incurred by each. The major cost factor for the scheduled system is the incremental cost, mainly because labor and related operating expenses far exceed the capital costs for trucks and associated equipment. On the other hand, capital costs for the responsive system far exceed operating costs

TABLE I
DEFINITIONS OF SYMBOLS AND "NOMINAL" VALUES OF PARAMETERS

Symbol	Definition	"Nominal" Value	
input parameters:			
λ	mean time between natural cleanings	∞	
E_0	clear-mirror power output	arbitrary	
R	daily reduction in power output, as a fraction of E_0	0.005	
C_0	annualized plant cost (excluding washing costs), prorated on a per-heliostat basis, 1980 \$	\$2500	
		<u>scheduled system</u>	<u>responsive system</u>
C_w	annualized washing system capital cost prorated on a per-heliostat basis, 1980 \$	\$3	\$180
w	incremental cost/wash/heliostat, levelized, 1980 \$	\$2	\$0.22
derived quantities:			
\bar{f}	time-averaged washing frequency		
\bar{x}	time-averaged shortfall in power output, as a fraction of E_0		
I	time between successive washes of a given heliostat (scheduled system)		
M	magnitude of power output shortfall such that washing is initiated (responsive system)		
\bar{B}	time-averaged busbar energy cost		
\bar{B}_{min}	minimum value of \bar{B} as a function of I or M respectively		

because thousands of individual washing units are required, while relatively little labor is needed for system operation. All results of the sensitivity analyses to be discussed are displayed on charts which show washing system preference as a function of responsive system fixed charge C_w (along the vertical axis) and scheduled system incremental cost per wash w (along the horizontal axis). For each system, the cost factor which is less important in terms of its contribution to total washing cost is held fixed at the nominal estimate. The nominal estimates of the dominant cost factors are indicated by the point near the upper-left corner of each chart. These nominal estimates are highly tentative. They are based on limited data and on assumptions not yet validated by operating experience. Therefore they should be regarded only as indicative of the ballpark in "cost-space" in which the actual costs will fall. Since the cost impacts of washing are not yet fully known, actual costs for either washing system are likely to exceed the nominal estimates. The actual costs would therefore tend to fall somewhere above and to the right of the indicated point.

The curves in Figure 1 divide cost space into regions of preference for each of the two washing systems, assuming no natural cleaning. For the case of no natural cleaning, B_{min} for each system is determined using the $\lambda \rightarrow \infty$ limit of equations (2)-(4). This procedure yields the result derived by Eason. The range of assumed values of R is representative of soiling rates observed at several sites [4]. The solid curve is adopted as the base case in all the sensitivity studies. Cost estimates which lie above and to the left of this curve result in a preference for the scheduled washing system, while cost estimates which lie below and to the right of this curve result in a preference for the responsive system. If the nominal cost estimates are accurate, then for the base case, and for the two indicated excursions as well, the scheduled washing system is preferred. Furthermore, the region in cost-space of preference for the scheduled system increases significantly as R decreases. This is understandable because as $R \rightarrow 0$ the need for washing decreases, so the scheduled system costs decrease as washing occurs less frequently. Responsive system costs are mainly capital costs, unchanged as washing frequency decreases, so the responsive system is at a relative disadvantage when R is small. No doubt, sites can be identified with R large enough to reverse the preference, but such sites are unlikely to be utilized if sites with lower soiling rates can be exploited.

The Impact of Natural Cleaning

The occurrence of natural cleaning events affects the preference between washing systems in two disparate ways. If cost factors for the two systems were identical, natural cleaning would tip the preference to the responsive system, which provides the freedom to choose the most opportune time to wash based on the pattern of natural cleaning events. On the other hand, the time-averaged effect of natural cleaning is a reduction of the desired washing frequency, an effect which tends to favor the system with lower fixed costs, as shown above. The net outcome of these two competing influences depends in a complex fashion on all the parameters of the problem, but in all cases considered below, the net result is enhanced preference for the scheduled system.

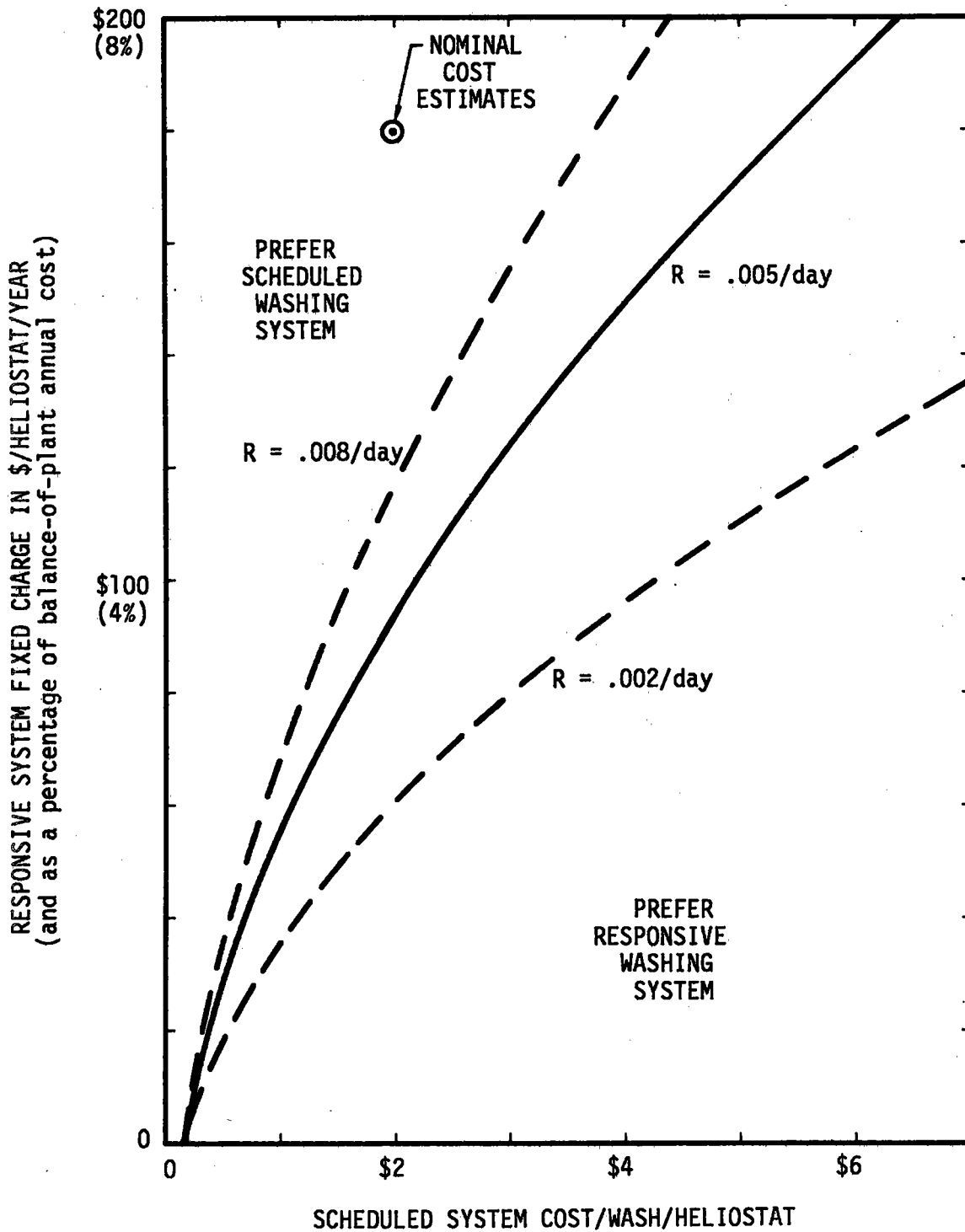


FIGURE 1. Sensitivity of washing system breakeven costs to mean rate of power output degradation = R.

Figure 2 shows the impact of occasional natural cleaning, as characterized by a finite value of λ , in comparison to the previous assumption of no such cleaning, i.e., $\lambda = \infty$. Henceforth, $R = .005/\text{day}$ in all cases. For finite λ , there is a region of cost space such that it is preferable not to install any washing system, an option which cannot be preferable in the absence of rain under the constant soiling rate assumption. The space is now divided into three distinct regions of preference for no washing system, scheduled washing system and responsive washing system respectively. The boundaries of these regions meet at the "3-way indifference point," representing values of the cost factors such that B_{\min} is the same for all three options.

In Figure 3, the results for several different values of λ are displayed. The regions of preference for no washing system can be constructed by adding straight lines emanating to the right and upward from the 3-way indifference points, which are indicated by markers along the dashed curve. The dashed curve is the locus of 3-way indifference points as a function of λ . The Figure indicates that the preference for the scheduled over the responsive system increases as the frequency of natural cleaning increases. The extent of the region of preference for no washing system is quite sensitive to λ in the range from several days to several weeks mean time between natural cleanings.

These observations are based on the assumptions that natural cleaning is as effective as washing and that the frequency of natural cleaning is constant throughout the year. These assumptions are likely to be unrealistic for prospective power plant sites. Alternative assumptions are considered below.

Sensitivities to Effectiveness and Seasonal Variability of Natural Cleanings

The locus of 3-way indifference points from Figure 3 is reproduced in Figure 4. The locus is a convenient shorthand representation of the sensitivity of washing system preference to λ . Also shown in Figure 4 is the 3-way indifference locus computed under the assumption that each natural cleaning raises the optical quality of the mirrors to a level such that the power output of the facility is 98% of the output immediately after all mirrors are washed. This level of effectiveness is representative of measurements quoted in [6]. If the mirrors exceed this optical quality when the natural cleaning occurs, then the natural cleaning is assumed to have no effect. These assumptions, though idealized, provide a basis for examining the sensitivity of washing system preference to the effectiveness of natural cleaning. The results were computed using the method of reference [5].

It is important to bear in mind that 98% effective natural cleaning does not mean that 98% of the soil is removed. In the absence of a commonly accepted definition of the effectiveness of natural cleaning, caution is advised in comparing the results of different analyses.

Figure 4 indicates that a reduction in effectiveness of natural cleaning has a qualitatively similar impact as a reduction in the frequency of natural cleaning. In both instances the responsive system improves relative to the scheduled system, and the no-washing option becomes less attractive.

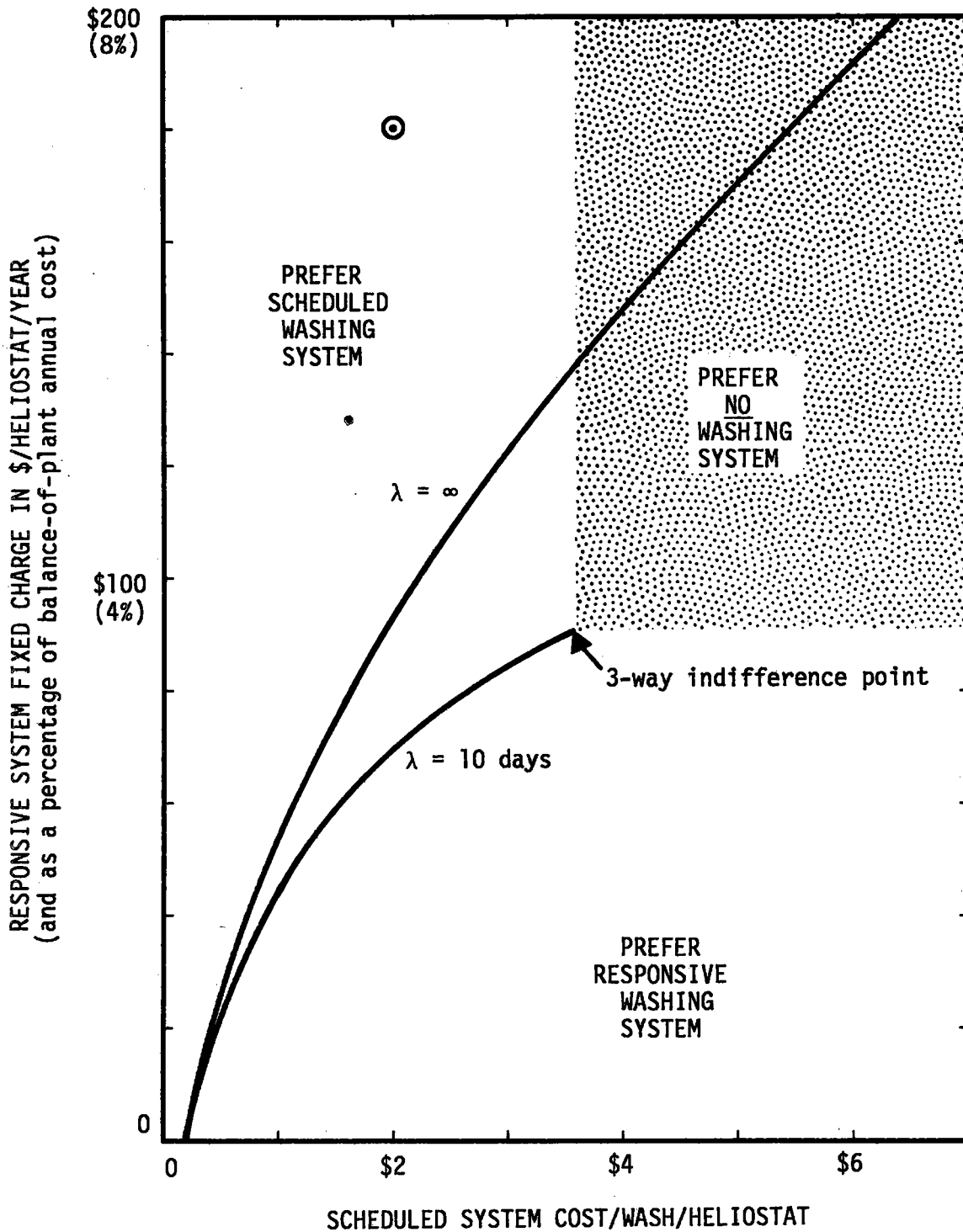


FIGURE 2. Sensitivity of washing system breakeven costs to mean time between natural cleanings = λ ($R = .005/\text{day}$).

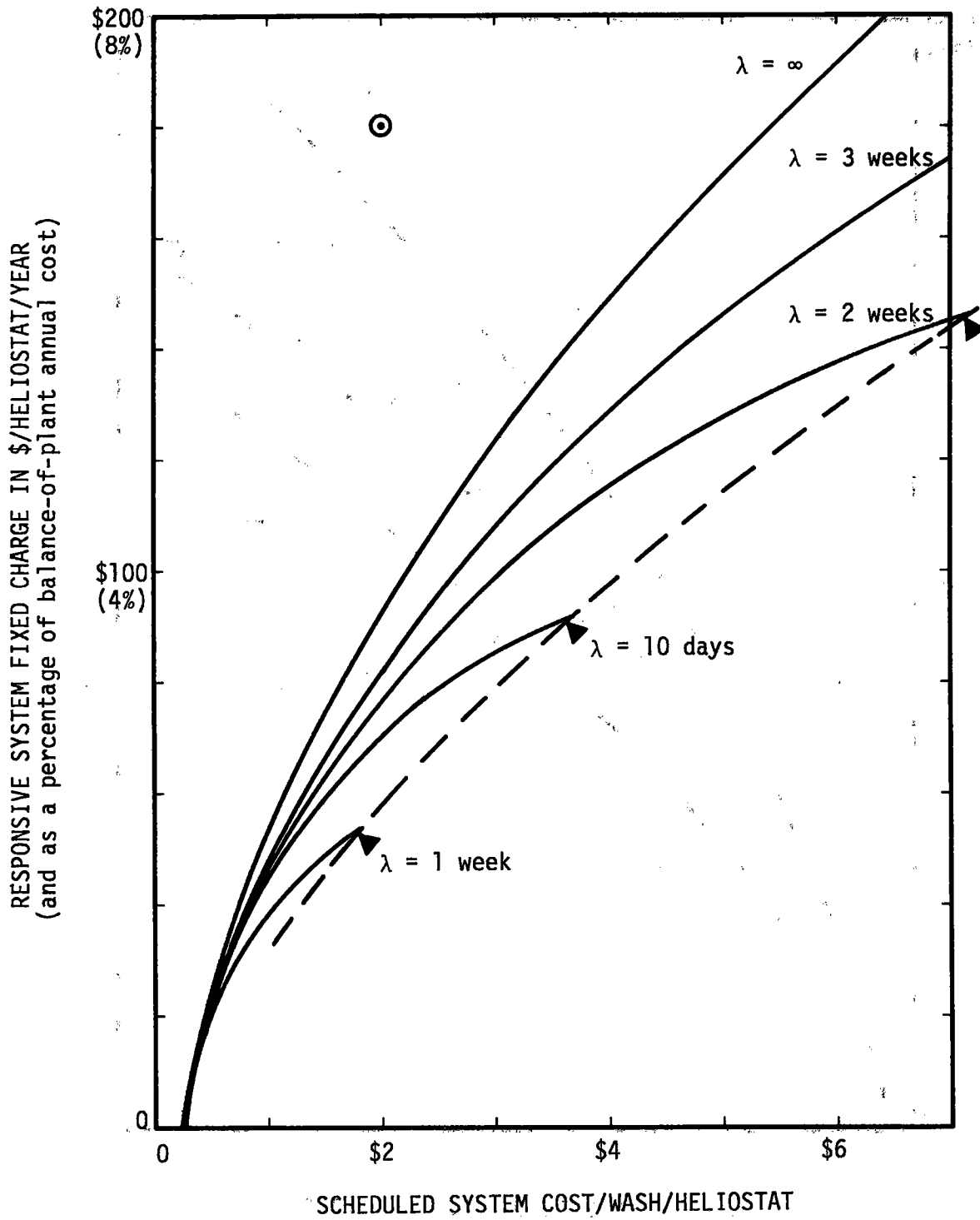


FIGURE 3. Additional sensitivities to λ , including the locus of 3-way indifference points (dashed).

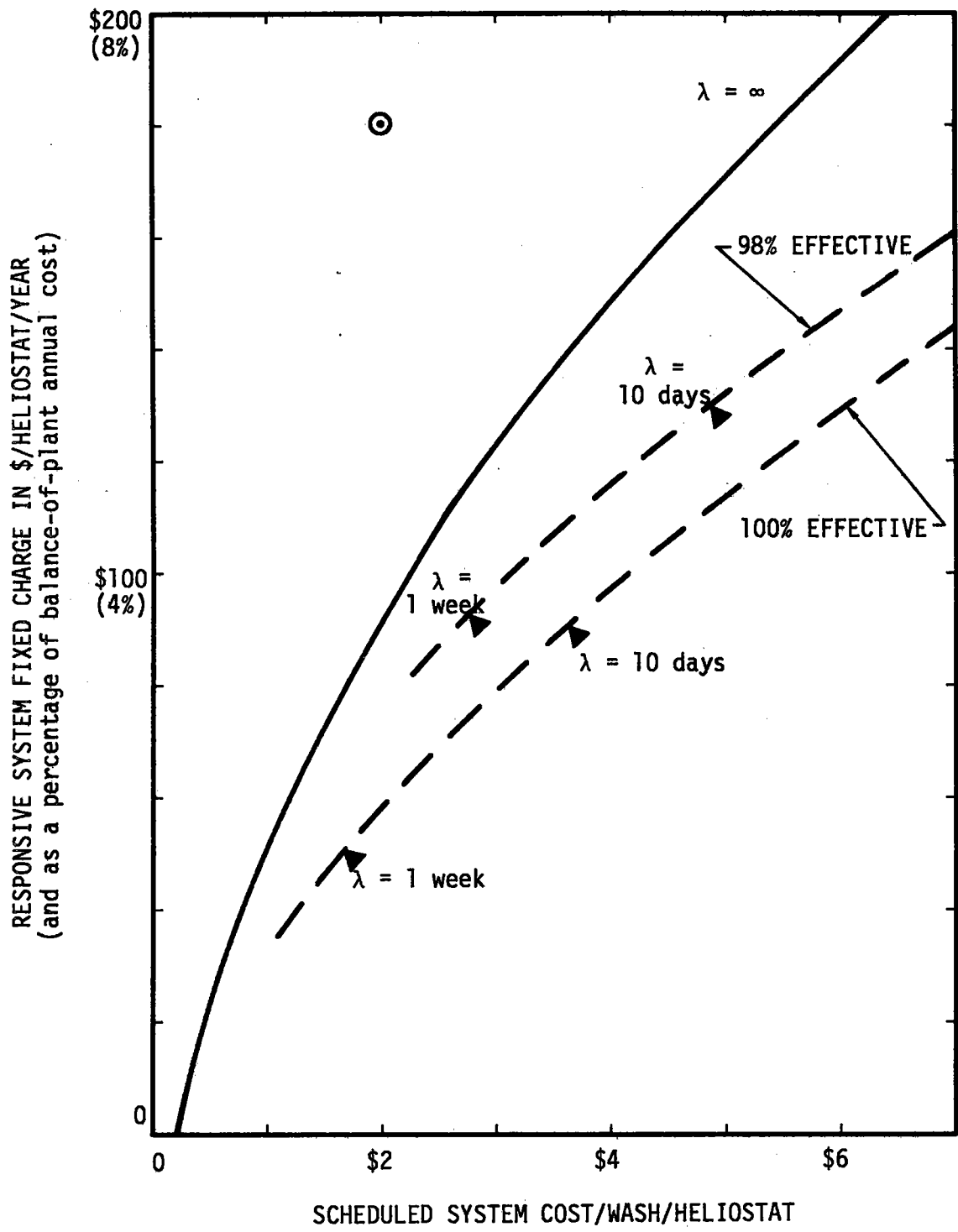


FIGURE 4. Sensitivity of the 3-way indifference locus to the effectiveness of natural cleaning (as a % of clean-mirror power output).

Incorporation of seasonal variations into the analysis requires reformulation of the objective function, equation (1). Assume that seasonal variations may be characterized by $3N$ quantities $\{\lambda_j, R_j, a_j\} j=1, \dots, N$ where λ_j and R_j are the mean time between natural cleanings and the rate of power output reduction respectively during the j^{th} season. a_j is the

duration of the j^{th} season, normalized so that $\sum_{j=1}^N a_j = 1$. Washing strategy

is assumed to vary from season to season, so that the strategy is characterized by N quantities $\{I_j\} j=1, \dots, N$ for the scheduled system, or $\{M_j\} j=1, \dots, N$ for the responsive system. The mean washing frequency \bar{F} and the mean power deficit \bar{x} during the j^{th} season, denoted \bar{F}_j and \bar{x}_j , are computed as previously, now in terms of the parameters λ_j, R_j , and I_j or M_j , as appropriate.

The overall time-averaged quantities $\bar{F} = \sum_{j=1}^N a_j \bar{F}_j$ and $\bar{x} = \sum_{j=1}^N a_j \bar{x}_j$ are

substituted into equation (1) and \bar{B} is minimized with respect to the N strategy parameters. Because \bar{B} is linear in \bar{F} and \bar{x} , and therefore in all the quantities $\{\bar{F}_j, \bar{x}_j\} j=1, \dots, N$, the minimization problem separates into N problems, each formally identical to the problem considered earlier. In other words, to the level of approximation represented by equation (1), the optimal washing strategy during a given season is independent of parameters governing other seasons. This is not the case if higher order terms are retained in (1), in which case the minimization problem becomes more complicated though still tractable. The quantitative impact of these additional terms has been estimated and found to be negligible.

For the following sensitivity analysis, two distinct seasons are assumed, a dry season ($\lambda_1 = \infty$) and a wet season (λ_2 finite), the latter of 4 to 6 months duration. This gives $\frac{1}{3} < a_2 < \frac{1}{2}$. In addition, the quantities \bar{x}_j are weighted by a factor representing the seasonal variation in E_0 due to seasonal changes in insolation. Disregarding cloud cover, the variation in solar inclination will cause the winter power output to be about 70% of the power output averaged over the remainder of the year, based on data in [7]. Since winter is the wet season in much of the southwest U.S. (the most favorable locale for solar facilities), percentages in the range 50% - 70% are assumed, to account for additional reductions in winter power output due to increased cloud cover. In all sensitivities, $R = .005/\text{day}$ during both seasons.

For the idealized case $\bar{x}_2 = 0$ ("perfect" natural cleaning), the envelope of the preference boundaries obtained as the parameters defined above are varied over the indicated ranges is the lower shaded region in Figure 5. If instead we compute \bar{x}_2 by the usual method, assuming $\lambda_2 = 7-10$ days and natural cleaning effectiveness = 97%-98%, and varying the other parameters as before, we obtain the upper shaded region of the Figure, labelled "realistic"

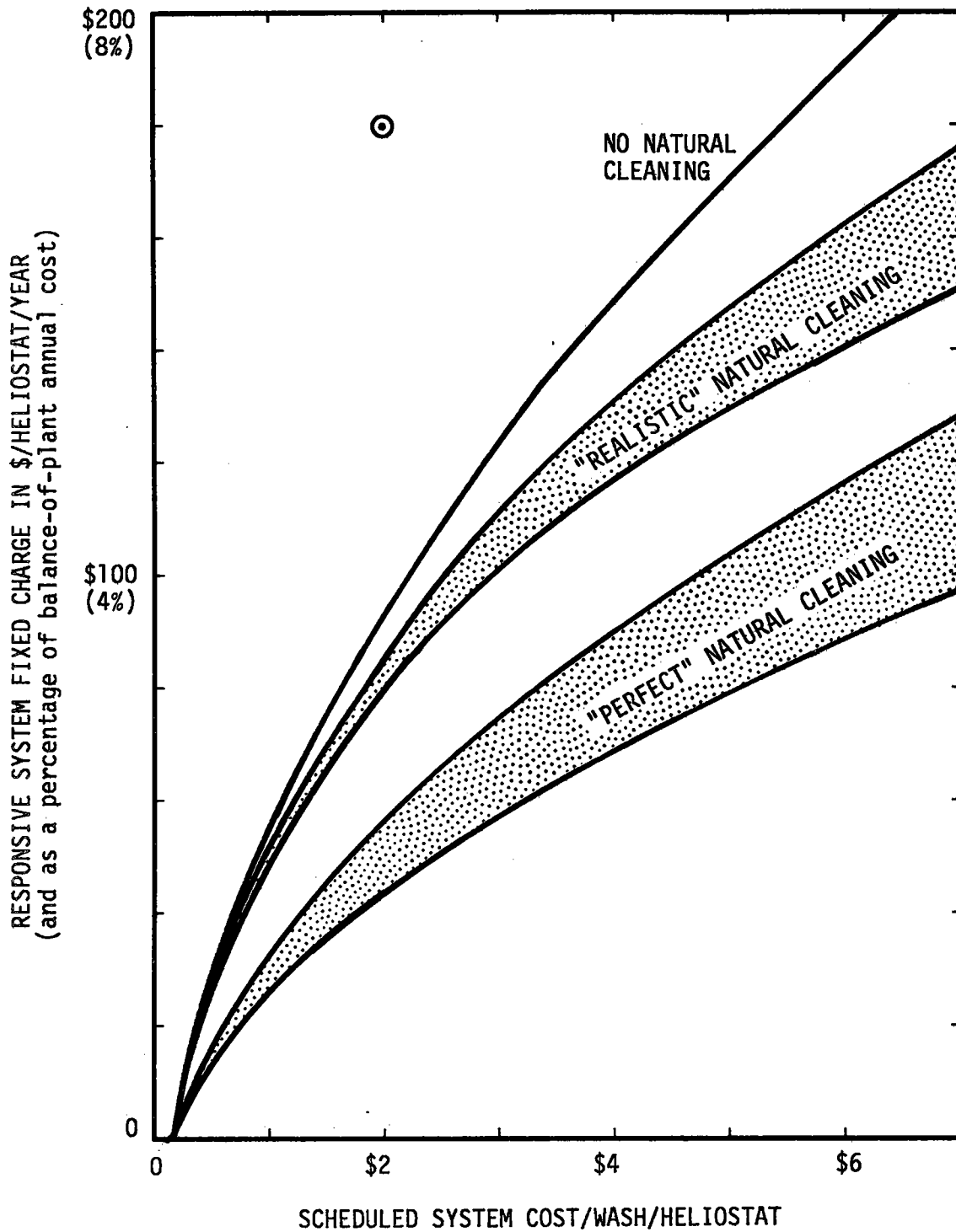


FIGURE 5. Sensitivity of washing system breakeven costs to seasonality.

natural cleaning. The assumed ranges for λ_2 and for effectiveness are based on data taken in Albuquerque, NM and China Lake, CA [6].

The most important feature of Figure 5 is the absence of regions in which the no-washing option is preferred. Such regions do in fact exist, but they begin far above and to the right of the portion of cost-space shown in the Figure. This is a consequence of the large energy deficit incurred during the dry season in the absence of washing. More generally, for a given overall annual frequency of natural cleanings, the viability of the no-washing option decreases as the seasonal variation of the precipitation pattern increases.

We next observe that the "perfect" natural cleaning assumption is more favorable to the scheduled system than is the "realistic" natural cleaning assumption. This is consistent with the previous observation that any assumption which tends to reduce washing will favor the scheduled system.

Finally, we observe that the separation and the widths of the shaded regions are all roughly equal, indicating that accurate characterization of the natural cleaning process is as important as inclusion of seasonal variability in washing system tradeoffs. Failure to incorporate all these factors could result in a regret as large as 2% of total plant costs in a decision involving two closely matched alternatives. For the given nominal cost estimates, the alternatives in this case are not closely matched; the scheduled system is consistently and substantially preferable. However, closely matched alternatives are likely to arise as other tradeoffs, some mentioned in the introduction, are addressed.

Future Applications

This analysis illustrates the application of the mathematical results of reference [5] to design and operational tradeoffs for solar energy facilities. A variety of issues can be addressed using the same approach. For instance, a soil-retardant mirror coating or a protected-stow configuration may reduce R but increase capital costs. The net benefit will depend on the seasonally varying quantities R , λ , and natural cleaning effectiveness.

Not addressed thus far due to insufficient data is the comparison of washing systems which differ in effectiveness. As such data is eventually gathered it can be easily incorporated into the present framework.

As the above considerations indicate, design and operational tradeoffs for solar energy facilities are interwoven. Furthermore, the environmental factors are site-dependent, so plant design decisions will in general be site-specific. Therefore, an environmental data collection program may be needed prior to finalization of the plant design at a given site.

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