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Comparison of Alternative Washing Systems for Heliostats

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COMPARISON OF ALTERNATIVE WASHING SYSTEMS FOR HELIOSTATS

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ABSTRACT

Two methods have been proposed for washing heliostat mirrors in a solar central receiver facility. One method involves truck-mounted washing mechanisms continuously traversing the heliostat field, washing mirrors sequentially on a fixed schedule. The other concept involves a washing unit affixed to each heliostat, permitting near-simultaneous washing of all heliostats on demand. The former, "scheduled" washing system has the advantage of lower capital costs, while the latter, "responsive" system has more operational flexibility. Cost-benefit evaluation of the two systems, taking into account the random nature of rainfall patterns and soiling processes, indicates that the scheduled system is preferable.

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Background

Most solar energy conversion technologies require exposure to environmental effects of surfaces whose optical qualities strongly affect system performance. For instance, reduction of the reflectivity of heliostat mirrors due to soiling reduces the net electrical output of solar central receiver facilities. In Reference [1], Eason has shown that **washing the heliostats about 1-2 times per month is cost-effective** based on a simple model of the soiling and washing processes and some preliminary cost and environmental data. His results have been extended to take into account natural cleaning, which introduces a non-trivial question of washing strategy due to the random nature of precipitation patterns [2].

Washing strategy is of concern because two alternative heliostat washing concepts with different degrees of operational flexibility have recently been proposed for solar central receiver facilities. One concept involves truck-mounted washing mechanisms continuously traversing the heliostat field, washing mirrors sequentially on a fixed schedule [3]. The other concept involves a washing unit affixed to each heliostat, permitting near-simultaneous washing of all heliostats on demand [4]. The latter, "responsive" system, has more operational flexibility than the former, "scheduled" system.

Operational flexibility is one of several criteria in the comparison of these systems. Other criteria are cost, washing effectiveness, and operational risks. Comparisons with respect to these criteria are quantified wherever possible. Where the necessary data or models are lacking, the discussion is qualitative.

Cost Estimates

Comparison of the costs of alternative washing systems, even on a relative basis, is subject to considerable uncertainty at present because insufficient information is available to evaluate washing mechanisms (sprayers, brushes, etc.) for these systems. Specifically, the combined effects of washing procedure, mirror characteristics, heliostat design, soil composition and ambient temperature and humidity on short-term and long-term soil adhesion are not well understood, though progress has been made [5]. Another issue with major cost consequences is the environmental impact of proposed cleansing agents. Recovery and recycling of the agent would be costly, but restriction to benign agents would narrow the tolerance on the other factors which affect soil adhesion.

In the absence of a suitable physical model of soil adhesion and removal, a performance standard for comparison of alternative washing mechanisms on a consistent basis has not been established. We therefore do not attempt quantitative comparison of alternative washing mechanisms. However, the washing systems (scheduled vs. responsive) are amenable to quantitative comparison. In making this comparison it is assumed that both systems employ mechanisms which restore mirror reflectivity to its clean value. Cost estimates for the scheduled system are taken from Reference [6], and for the responsive system from Reference [4]. Since these cost estimates are based on mechanisms not subject to explicit performance and environmental standards, they will be called "nominal" cost estimates.

TABLE I

WASHING SYSTEM COST ESTIMATES ($/HELIOSTAT)

Item	Responsive System	Scheduled System	Assumptions
Fixed charge/yr.	$180	$3	FCR = 18%
Cost per wash	$0.22	$2	Levelization factor = 1.86
No. of washes/yr.	x 102	x 34	R = .005/day; no rain
Incremental costs/yr.	$22	$68	Equal as a consequence of Eason's result
Annual value of energy lost via degradation	$22	$68	
Total cost/yr.	$224	$139	Increase over "ideal" plant cost
Balance-of-plant cost/yr.	$2500	$2500	"Ideal" plant
Ratio (%)	9%	6%	

A cost budget for each washing system is given in Table I. The capital cost and incremental cost per wash for the responsive system is taken from Reference [4], and an 18% fixed charge rate is used to convert the capital cost to an annual fixed charge. The capital cost and incremental cost per wash for the scheduled system are averages of estimates of the respective quantities for two alternative system configurations, one with a single truck per crew, spraying a sheeting agent, and the other with two trucks per crew, one for washing and one for rinsing [6]. Selection of a configuration will ultimately depend upon establishment of and testing with respect to a performance standard.

The incremental cost per wash is a recurring cost and therefore subject to levelization [7]. The levelization factor and the fixed charge rate are assigned the same values used by Eason to estimate the balance-of-plant cost given at the bottom of Table I. Balance-of-plant cost is defined here as all costs not associated with the washing system.

The incremental cost per year is the product of the incremental cost per wash and the number of washes per year. The washing frequency depends upon cost and environmental factors, as analyzed in detail elsewhere [8]. A schematic argument is presented in Figure 1. In the absence of soiling no washing system would be needed, and the cost of electricity produced by such an "ideal" plant would be determined by the balance-of-plant cost divided by the "clean-mirror power output". Since soiling does occur, the power output is degraded. With less electricity to sell, the cost per unit output increases. This cost increase, denoted in Figure 1 as the power output degradation penalty, may be mitigated by washing, but then the cost of washing must be included. These two cost factors both vary with washing frequency, so their sum, the incremental cost of electricity, is also frequency dependent. To a good approximation, the incremental washing cost is proportional to the washing frequency, while the power output degradation penalty is inversely proportional to washing frequency [1]. The latter dependence is reasonable because it reflects the diminishing returns of successive increases in washing frequency. Under these assumptions, the incremental cost of electricity is least when the incremental washing cost and the power output degradation penalty are equal. The quantitative results, assuming no natural cleaning and a power output degradation rate of 0.5% per day, are given in Table I. (The power output degradation rate is expressed as a percentage of the clean-mirror power output.)

The principal cost component for each washing system is indicated by a box. The responsive system is capital-intensive because thousands of washing mechanisms with associated piping and other equipment must be installed, while incremental costs predominate for the scheduled system, which is labor-intensive. The total cost per year is defined as the revenue required to cover all expenses minus the revenue required if the plant were "ideal", with no soiling and no washing system. It is important to use the ideal plant as a baseline so that proper account is taken of the relative benefits (increased power output) as well as the relative costs of alternative washing systems.

At the bottom of the Table, total washing system costs are expressed as a percentage of balance-of-plant cost. Balance-of-plant cost, taken from Reference [1] for a plant with glass mirrors, is prorated on a per-heliostat basis, consistent with the washing cost estimates. It is converted from 1978 dollars to 1980 dollars based on an assumed 10% annual rate of inflation.

For the set of assumptions incorporated in Table I, the scheduled system is substantially preferable to the responsive system. The sensitivity of this result to changes in the assumptions is the subject of the remainder of this analysis.

Sensitivity to Degradation Rate

The power output degradation rate is the most important parameter because it is known to vary significantly from site to site [5]. Although the

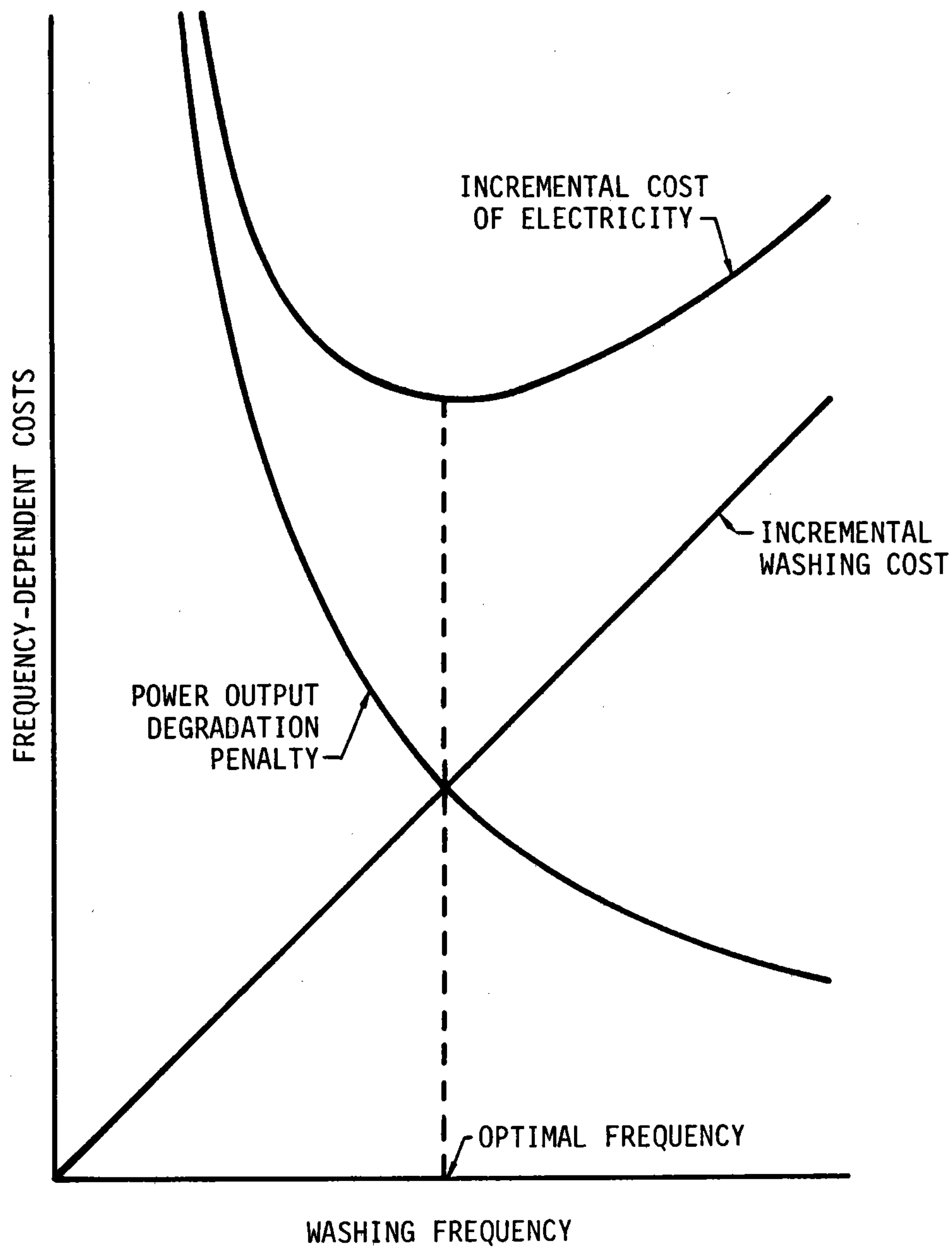

FIGURE 1. Optimization of washing frequency (schematic).

consequences of this variation are discussed elsewhere [8], the discussion is repeated here due to its importance.

The sensitivity of washing system preference to the power output degradation rate, R, is shown in Figure 2 as a function of the dominant cost factors, responsive system fixed charge (along the vertical axis) and scheduled system incremental cost per wash (along the horizontal axis). The less important cost factor for each system is held at its "nominal" estimate. The nominal estimates of the dominant cost factors are indicated by the point near the upper left-hand corner of the Figure. Since actual costs for either washing system are likely to exceed the nominal estimates they would tend to fall somewhere above and to the right of the indicated point.

The curves in Figure 2 divide cost space into regions of preference for each of the two washing systems, assuming no rain. These curves were computed by the method of Reference [2]. The range of assumed values of R is representative of soiling rates of observed at several sites [9]. The solid curve is adopted as the base case. Cost estimates which lie above and to the left of this curve result in a preference for the scheduled washing system, and conversely. If the nominal cost estimates are accurate, then throughout the indicated range of values of R, the scheduled washing system is preferred. Furthermore, the region in cost-space of preference for the schedule system increases significantly as R decreases. This is understandable because as R decreases, the need for washing decreases, so the scheduled system costs decrease as washing occurs less frequently. Responsive system costs are mainly fixed charges, unchanged as washing frequency decreases, so the responsive system is at a relative disadvantage when R is small. No doubt, sites will be identified with R large enough to reverse the preference, but such sites are unlikely to be utilized until the more desirable sites with lower soiling rates have been exploited.

The fact that the curves of Figure 2 have a curvature away from the vertical has significant implications. If responsive and scheduled system costs increase by the same percentage, the preference for the scheduled system is enhanced. The scheduled system absorbs cost increases more gracefully because, as implied in Figure 1, an increase in the slope of the line representing incremental washing cost tends to reduce the optimal washing frequency so as to partially compensate for the rise in the incremental cost of electricity. This reduction in the washing frequency is achieved, for instance, by deploying fewer trucks per heliostat field. Such an adjustment of washing system configuration should be distinguished from operational flexibility, which is considered next.

The Value of Operational Flexibility

In order to properly credit the responsive system for its greater operational flexibility relative to the scheduled system, models of the soiling and natural cleaning processes are required which incorporate the random fluctuations of these processes.

As discussed in Reference [2], the optimal washing strategy under the assumption of constant R and no natural cleaning can be expressed in the form, "wash whenever the power output degrades to a threshold value."

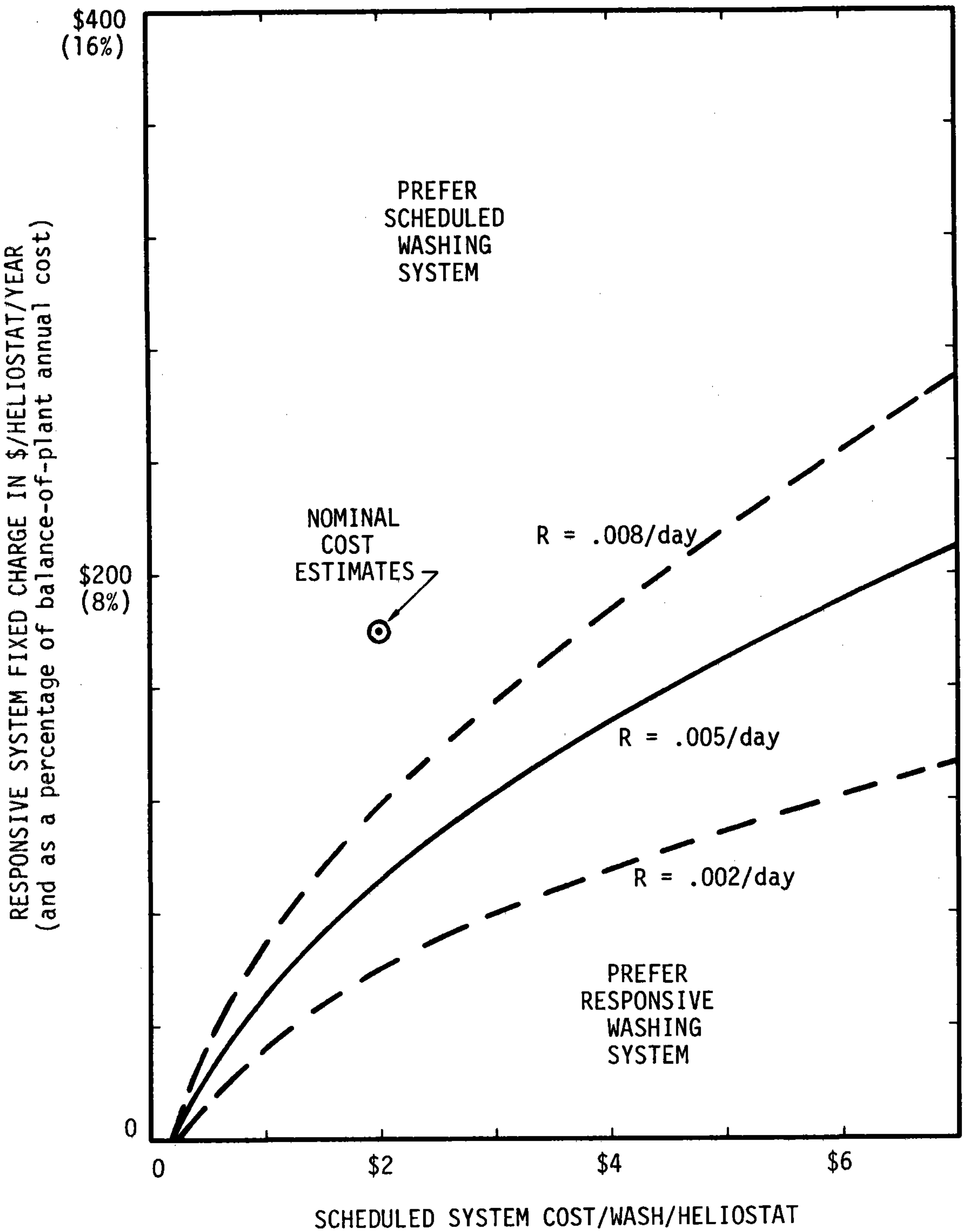

FIGURE 2. Sensitivity of washing system breakeven costs to mean rate of power output degradation = R.

The solid sawtooth function to the left of the shaded region of Figure 3 represents the power output (prorated to a typical heliostat) as a function of time under these assumptions. The assumption of constant R is adequate provided that fluctuations in the daily degradation are small compared the magnitude of degradation which constitutes the threshold. Expressed graphically, the constant degradation assumption is adequate if departures of the actual time-trace of the power output from the sawtooth shape are small compared to the vertical span of the sawtooth.

Maintaining the assumption of no natural cleaning, we consider the consequences of a sudden severe deposition of soil on the mirrors, severe in the sense that the power output is reduced well below the washing threshold. Such a deposition may be caused for instance, by a combination of high winds and light precipitation [5]. Figure 3 schematically illustrates the impact of such an event on the power output time-trace associated with a "typical" heliostat. The vertical drop in power output at the epoch in time labeled severe soiling has different consequences for the scheduled and for the responsive system. Consider first the scheduled system. The heliostat continues to suffer additional degradation at the same rate as previously until the next washing. During the time from the soiling until the next washing, the power output is severely reduced. Thereafter the usual sawtooth time-trace is resumed. On the other hand, the responsive system provides the flexibility to wash all heliostats almost immediately after the soiling event, so the power output rises to E_0 at that epoch and the sawtooth time-trace pattern is immediately resumed.

The shaded region represents the penalty, in the form of lost energy output, attributed to the relative inflexibility of the scheduled system. Since this discussion refers to a typical heliostat (in the statistical sense), the time duration of the reduced power output is equal to one half of the time between successive scheduled washings of the heliostat.

The impact of severe soiling events on the washing system comparison is shown in Figure 4. For the purpose of this comparison, we temporarily define a severe soiling event as one which reduces the power output to zero. The parameter F is the assumed frequnecy of such events, and the F = 0 curve is simply the baseline curve from Figure 2. The dashed curves show that, as expected, the region in cost-space of responsive system preference increases as F increases.

We broaden the definition of F by noting that the penalty associated with severe soiling events is roughly proportional to the severity (in terms of power output loss) as well as the frequency of such events. Therefore, we can sum the severe soiling events in a given year, each event weighted by a severity factor, to obtain an equivalent value for F in that year. For instance, F = 1/yr implies that the total penalty incurred by the scheduled system in one year, due to whatever combination of severe soiling events, is equal to the penalty incurred due to one soiling event which reduces the power output to zero. Applying this definition to soiling data collected at China Lake, California [9], and using the admittedly arbitrary criterion that a severe soiling event is a power output degradation of more than 5% in a single day, gives F = 0.2/yr. As shown in Figure 4, this value of F causes only a

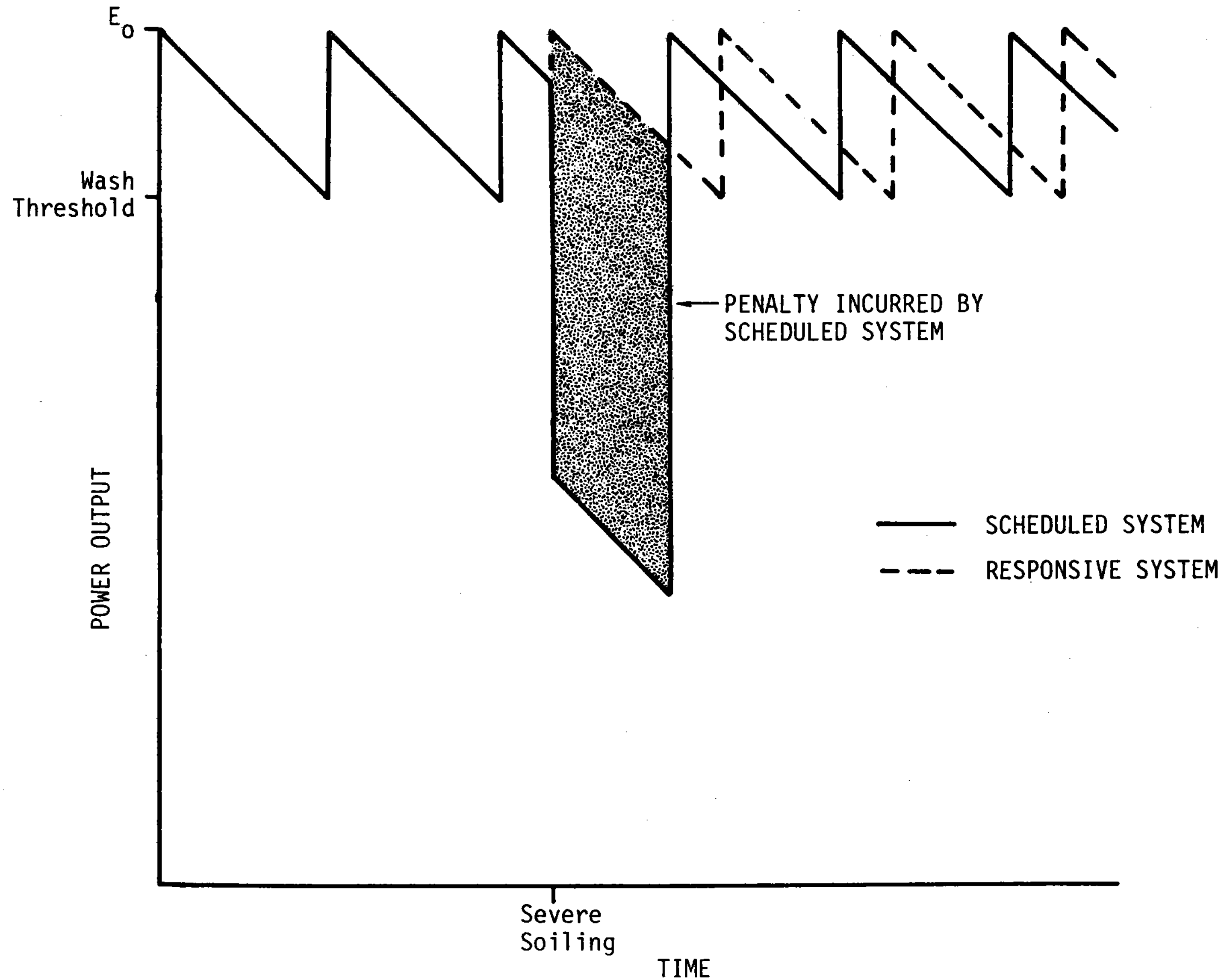

FIGURE 3. Energy loss due to severe soiling (schematic).

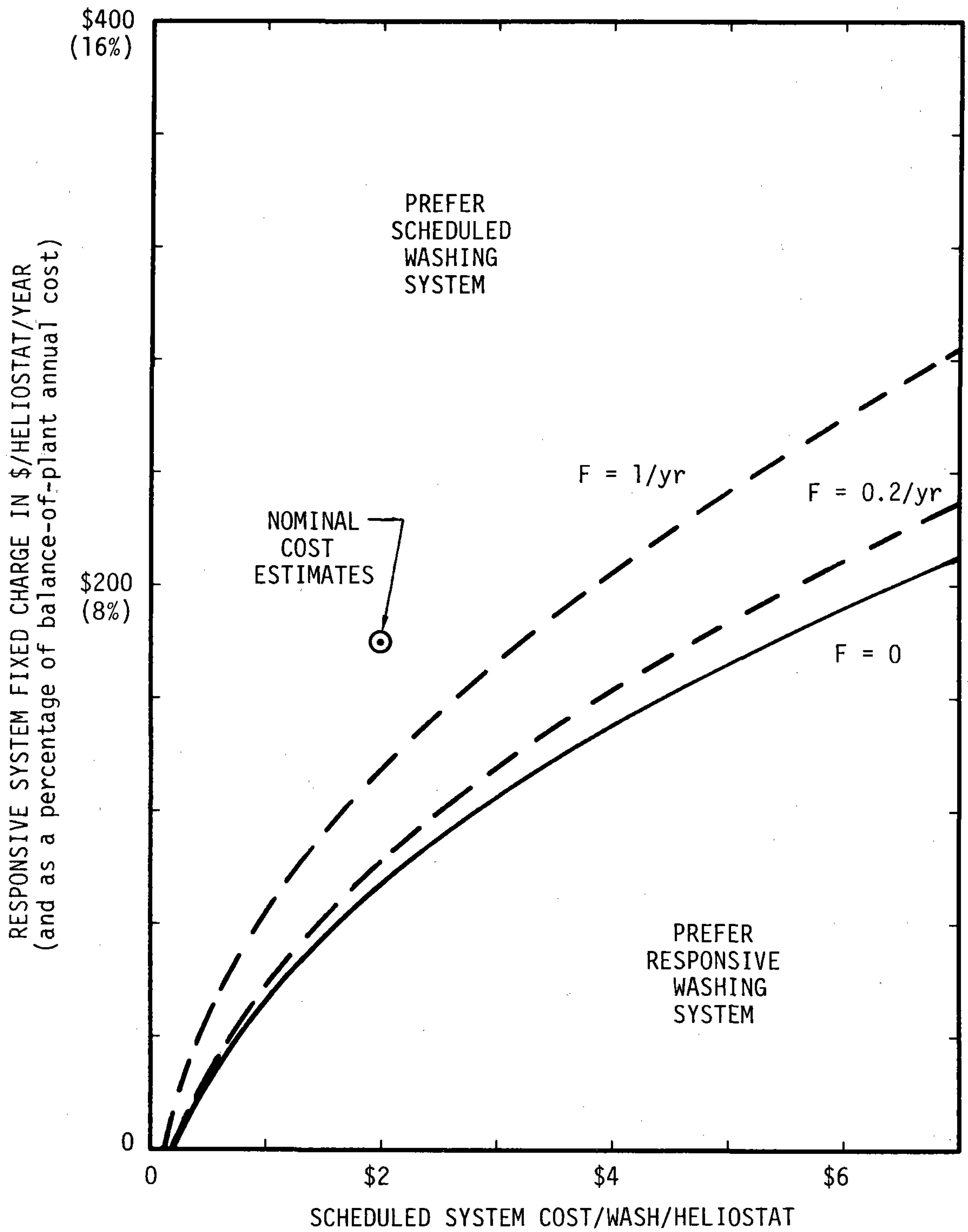

FIGURE 4. Sensitivity of Washing System Breakeven Costs to Frequency of Severe Soiling Events = F (R = .005/day).

slight shift in washing system preference. The effect of an F value five times as large is also shown. The effect is greater, but the point in cost-space representing the nominal cost estimates is still in the region of preference for the scheduled system.

The analysis of an individual severe soiling event in isolation (as in Figure 3) without considering the time-sequence of successive soiling events is a valid approximation to the extent that such events are infrequent relative to the frequency of washing. Determination of the impact of natural cleaning events, however, requires a more detailed mathematical analysis [2].

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

In Reference [8], the sensitivity of washing system preference to the frequency and effectiveness of natural cleaning, and to the seasonal variation of these parameters, is examined. More frequent or more effective natural cleaning in all cases results in greater preference for the scheduled system. Thus, the high capital cost of the responsive system negates the advantage of flexibility of response to the fluctuating character of natural cleaning events. Natural cleaning and severe soiling phenomena thus have opposite impacts.

Operational flexibility is the major identified advantage of the responsive system. Its potential benefits have been examined above. As indicated in Figures 2 and 4, neither a high value of R nor a high value of F is likely in itself to change the washing system preference based on the nominal cost estimates. Therefore, a reversal of preference would require high values of R and F, or a large increase in the estimated cost of the scheduled system with little increase in the responsive system cost estimates. With respect to the possibility of a plant site with high values of R and F, a further mitigating factor comes into play because scheduled systems may have some operational flexibility. The assumptions that the scheduled system has no flexibility and that the responsive system has complete flexibility overly penalize the scheduled system. Since scheduled system capital costs are low, it may be advantageous at sites with relatively frequent severe soiling to provide a surge capability in the form of extra trucks and standby washing crews (who perform other functions during normal operation). Alternative means of manpower augmentation include overtime work, adding an extra shift of workers on call, or hiring of temporary staff as needed, all well-established practices. We do not attempt a quantitative evaluation of such a surge capability, but we note its tendency to dilute the advantage of responsive system flexibility.

Washing Effectiveness

Although quantitative comparison of the effectiveness of different washing mechanisms is not possible given the present state of knowledge, several qualitative observations can be made. Whatever washing mechanism is selected for the responsive system, cost of the mechanism must be held to a minimum since thousands of these units must be deployed (one for each heliostat). On the other hand, the duration of each wash is a less critical factor since operating costs are small relative to capital costs. These observations are reversed for the scheduled system. Since operating costs, primarily labor, predominate, the main imperative is to minimize the duration of each wash. The washing mechanisms are few in number and constitute a relatively minor expense, so costly mechanisms are more readily tolerated. This cost-tolerance provides a wider range of options for washing mechanism design than may be feasible for the responsive system, although the responsive system may compensate through longer wash duration. Although the net advantage cannot be definitively ascertained, the limited extant information on the phenomenon of soil adhesion provides some clues.

Experience in the car-washing industry [10] as well as study of the physical and chemical processes of soil adhesion [5] indicates that washing methods such as spraying which do not involve brushing, wiping, or similar physical contact tend to leave a residue of strongly adhering film which gradually builds up and is removable only by a physical contact method or by strong chemical agents. If further experimentation confirms this observation, several possible remedies may be considered. One possible remedy would be to use brushes or wipers rather than sprayers as the washing mechanism. This remedy would further accentuate the preference for the scheduled system because a brush or wiper mechanism would be more costly than a sprayer with respect to both purchase and upkeep. An alternative remedy would be provision of a backup washing system employing a physical contact washing mechanism, to be used less frequently than the main washing system.

To be cost effective, a backup system must have low capital costs, though relatively high incremental costs would be tolerable due to the infrequency of application. These are precisely the requirements which favor a truck-mounted over a heliostat-mounted backup system. Furthermore, a truck-mounted backup system would tend to be more economical and effective in conjunction with a truck-mounted rather than a heliostat-mounted main system; economical because the main and backup truck-mounted systems might utilize equipment such as truck bodies in common, and effective because a heliostat-mounted washing system might obstruct the backup washing mechanism.

Use of a strong chemical agent for the backup washing would require an environmentally acceptable method of collection and disposal after use. A truck-mounted system may be equipped for collection by attachment of a drip pan to the truck body, perhaps incorporating a means for immediate recycling of the chemical agent. Methods of collection and disposal for a heliostat-mounted system would be much more costly, requiring a drip pan for each heliostat and a large amount of piping and/or recycling equipment.

Thus, the likely remedies for the residue problem all tend to reinforce the preference for the scheduled system.

Operational Risks

Having selected a washing system based on the best available information, the plant operator faces several types of risk. First, operating expenses may rise faster than expected, a particular concern with respect to the scheduled system with its high operating (primarily labor) costs. Second, maintenance and repair requirements may exceed expectations, a particular concern with respect to the capital-intensive responsive system. Third, unforeseen long-term mirror degradation processes may require modification of the washing method. Such modification is likely to be less costly for the scheduled than for the responsive system. Finally, there is a possibility that is beneficial rather that detrimental. Future development of an improved washing mechanism may motivate the plant operator to modify or replace washing equipment, provided the capital expense is acceptable. Again, the scheduled system is more readily amenable to such modification.

These observations indicate that operational risk factors tend to reinforce the preference for the scheduled system.

Summary and Recommendation

A number of features of the scheduled and responsive washing systems have been compared. The principal advantages of the scheduled system are

- Less sensitive to an increase in costs.
- Can afford a more costly washing mechanism.
- Less sensitive to operational risks.
- Cheaper to upgrade or modify.

The principal advantages of the responsive system are:

- Hedge against sudden soiling events.
- Can afford longer duration of wash.
- Less sensitive to labor-related issues.

Although the data supporting some of these observations is sparse, the overall trend supports the conclusion that the scheduled system is preferable for washing heliostats.

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