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Evaluation of Inverted-Stow Capability for Heliostats

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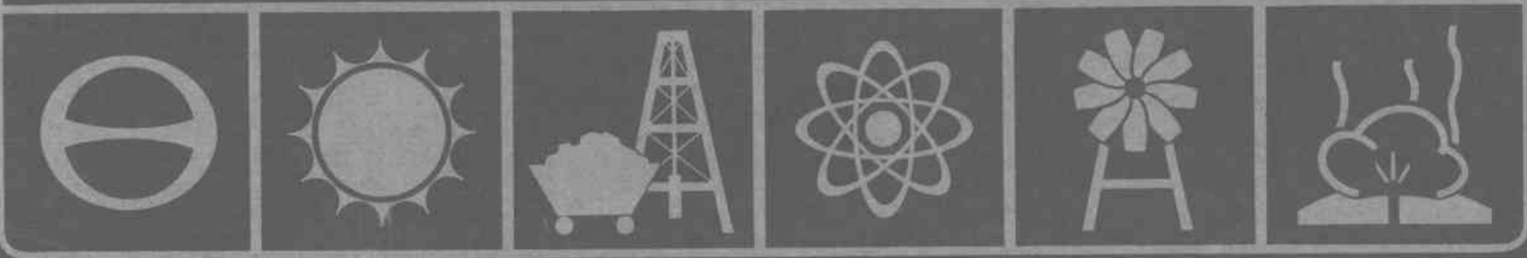

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EVALUATION OF INVERTED-STOW CAPABILITY FOR HELIOSTATS

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ABSTRACT

A previous assessment of the costs and benefits of inverted-stow capability is updated based on recent developments in heliostat design and washing cost estimation. The previously-estimated 12 percent cost advantage of non-inverting heliostats is found to be design-specific. The present analysis identifies circumstances in which non-inverting and inverting designs may be evenly matched on a cost basis. Therefore, a clear preference between non-inverting and inverting designs cannot be established at this time.

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EVALUATION OF INVERTED-STOW CAPABILITY FOR HELIOSTATS

Introduction

When heliostats are not in use, it is desirable to stow them in a manner which protects them from physical damage and dust buildup. Potential causes of physical damage are wind loading, impingement of wind-blown objects, and hail. The rate of dust buildup and ease of cleaning may be influenced by angle of stow, mirror module design, and site-specific factors such as ambient dust composition and weather conditions. Selection of a heliostat stowage strategy therefore involves a tradeoff of the following desired objectives:

- minimization of heliostat cost
- protection from damage
- prevention of soiling
- minimization of other operational costs and risks.

The issue of immediate concern is whether it is cost-effective to provide heliostats in solar central receiver facilities with the capability to stow in an inverted (face down) configuration. Inverted stow is desirable because it minimizes soiling while providing protection from physical damage.

Non-inverting heliostats may be stowed vertically or face up. Face up stow results in the greatest soiling, but it provides better protection from damage than vertical stow during high winds. Therefore, it is probably best to stow non-inverting heliostats vertically except during high winds.

The operational disadvantages of non-inverting heliostats must be weighed against the cost savings associated with the non-inverting design. These savings may result from a variety of design differences between inverting and non-inverting heliostats.

Heliostat Design Comparison

It is assumed that the heliostat mirror structure is supported by a single pedestal, with the drive mechanism atop the pedestal. Although this configuration is generally favored in recent heliostat designs, there may be other viable options, such as a two-pedestal configuration, which might affect the evaluation of inverted-stow capability. It is further assumed that the reflective surface is rectangular in shape (with exceptions to be noted) with an aspect ratio close to unity, and with an area of approximately 50 m^2. For an inverting heliostat, the reflective surface has a vertical slot allowing the mirror structure to clear the pedestal as it is rotated to the face-down orientation. The slot must extend from the bottom edge at least to the point of support of the mirror structure. To maintain design simplicity and balance wind loads, it may be advantageous to extend the slot along the full height of the reflective surface, as in the conceptual design shown in Fig. 1.

Design of the mirror support structure and the drive mechanism may be affected by the slot. The shape of the reflective surface determines the orientations at which individual mirror modules are mounted, and consequently influences support structure design. The mirror and support structure configuration affect the gravity and wind loads on the support structure and drive mechanism.

Design of the other heliostat subsystems (mirror modules, pedestal, and electronic controls) may also be affected by inverting capability. Ultimately, optimized designs for inverting and non-inverting heliostats respectively may utilize substantially different design concepts, and may therefore be comparable only in terms of total heliostat cost (or selling price, in the context of a commercial transaction) rather than in terms of subsystem differences. Nevertheless, design-specific comparisons can provide bounds on the cost impact of inverting capability, and therefore may prove useful in the absence of a commercial market providing firm price quotations.

Heliostat Cost Comparison

In 1979, Blackmon, et al. of the McDonnell Douglas Astronautics Company estimated the incremental cost attributable to inverting capability based on a heliostat design concept utilizing jack drives for elevation control.[1] The results of that analysis are shown in Fig. 2, along with an alternative analysis to be discussed shortly. To maintain consistency with the format of the MDAC study, the inverting heliostat is defined to be the baseline design. Cost savings resulting from elimination of inverting capability are defined to be benefits of the non-inverting design. However, the non-inverting heliostat is penalized for additional washing costs because it is soiled more quickly than the inverting heliostat.

In Fig. 2, benefits and penalties of the non-inverting heliostat are expressed as a percentage of inverting heliostat field cost, using the present value method outlined in Ref. 1 to express capital costs and recurring costs on a consistent basis. The zero level on the vertical scale represents indifference to the choice between heliostat designs.

Both the MDAC study and the present analysis, labelled "worst case," assess a 4% washing penalty against the non-inverting heliostat. The basis for this estimate is discussed in the next section.

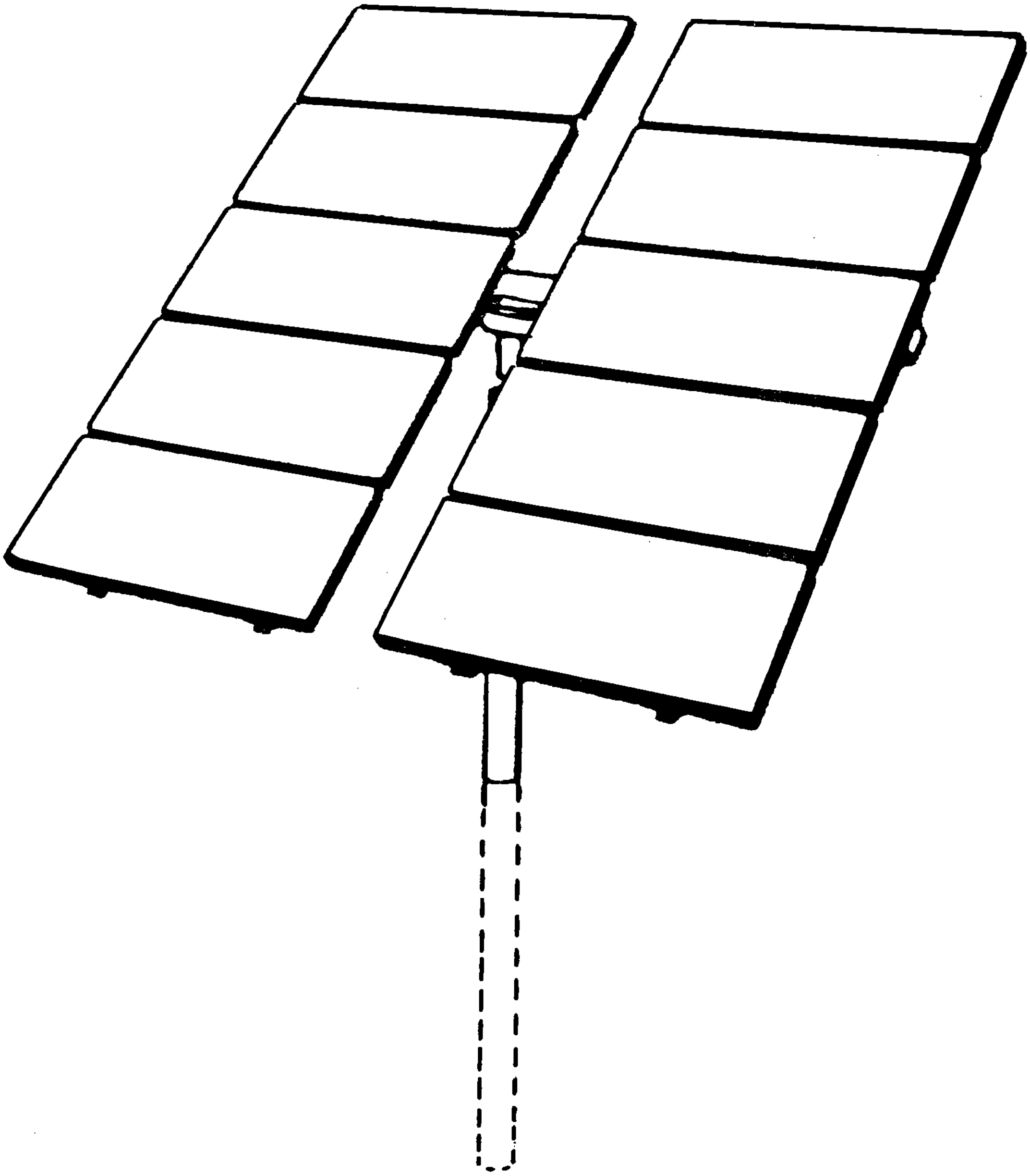

Figure 1. Inverting Heliostat Design Concept with Full Slot

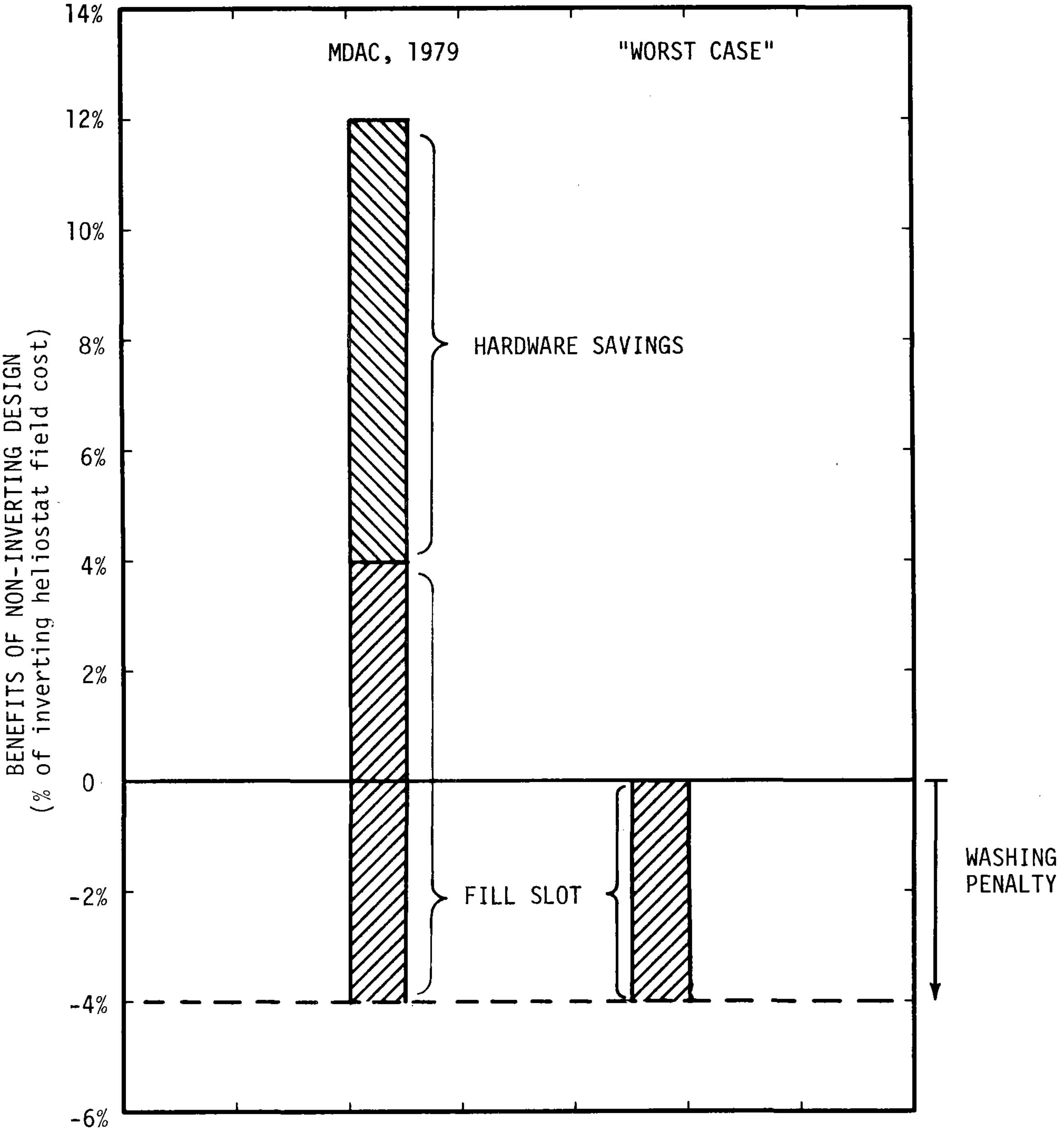

Figure 2. Alternative Evaluations of Non-Inverting Heliostats

The MDAC study identifies two cost advantages of non-inverting heliostats, each contributing approximately an 8% reduction in heliostat field cost, for a total of 16%. Subtraction of the 4% washing penalty yields a net advantage of 12%, as indicated in the Figure. The estimated cost savings are based on the following assumptions (Ref. 1, Table 2-11):

- inverting heliostat reflective surface area = 50 m^2
- inverting heliostat cost = \$66/m^2
- inverting heliostat slot area = 5 m^2
- cost of additional reflector area to fill slot = \$50
- hardware savings from elimination of inverting capability = \$315/heliostat

The first cost advantage identified in the MDAC study results from filling the slot in the reflective surface. It is assumed that the inverting design has a slot spanning the full height of the reflective surface, and that the slot width is 10% of the sum of the widths of the two rectangles comprising the reflective surface. Filling the slot increases the reflective surface area by 10% at a cost of \$50, resulting in an 8% reduction in heliostat cost per unit area. To express the cost savings due to filling the slot as a percentage of heliostat field cost, it is assumed that roughly the same total reflective surface area is required for equivalent performance of fields of inverting and non-inverting heliostats respectively. (Since an inverting field has more heliostats and therefore covers a larger land area, total attenuation and spillage are greater, but the performance impact of these effects is less than 1%. Cost of the additional land required for the inverting field is about 1% of total field cost, and is also omitted from the MDAC analysis.) Under these assumptions, the cost savings are 8% of heliostat field cost, as indicated in Fig. 2.

The second cost advantage results from hardware savings. The \$315 per heliostat hardware savings estimated by MDAC is based on a jack-type drive, with the savings deriving primarily from elimination of the additional jack and motor needed in order to invert. Expressed as a percentage of the cost of the inverting heliostat field, the hardware savings is 8%.

The MDAC estimates of the cost advantages of the non-inverting heliostat are based on the assumptions that jack-type drives are used and that the inverting design has a slot extending the full height of the mirror face. As an alternative, we adopt assumptions which are "worst case" in the sense that they are relatively unfavorable to the non-inverting heliostat. First, we eliminate the hardware savings resulting from drive redesign, because the cost of drive mechanisms not involving jacks is likely to be roughly the same for inverting as for non-inverting heliostats. (We deliberately avoid comparing costs for different drive mechanism design concepts. Although there may be significant cost differences between design concepts, they cannot be reliably identified based on experience to date.) Furthermore, we reduce the cost advantage attributed to filling the slot from 8% to 4% because it may be feasible and cost-effective to fill the upper half of the slot on the inverting heliostat. Thus, the total benefit of non-inverting design is estimated to be 4% under the worst case assumptions, counterbalancing the 4% washing penalty. This result indicates the possibility that inverting and noninverting designs manufactured commercially may prove to be evenly matched on a cost basis. If this were the case, the estimate of the washing penalty would play an important role in design selection.

Soiling and Washing

As in Ref. 1, we estimate the average daily reflectance loss due to soiling under benign weather conditions (i.e., conditions not requiring horizontal stow) for non-inverting and inverting heliostats respectively. The reflectance loss for non-inverting heliostats is then incremented to account for additional soiling during severe weather (i.e., conditions such that face up stow is necessary). For the worst-case analysis, the following assumptions unfavorable to the non-inverting heliostat are adopted:

- the inverting heliostat suffers no abnormal degradation during severe weather
- natural cleaning effects such as rain are neglected.

A recent publication provides reflectance loss data under benign weather conditions as a function of mirror orientation and exposure schedule (continuous vs. daytime-only)[2]. Assuming a 45° daytime orientation and nighttime orientations of 180° for inverting and 90° for non-inverting heliostats, the daily loss as a fraction of clean-mirror reflectance is 0.0027 for inverting and 0.0038 for non-inverting heliostats. These estimates are represented in Fig. 3 by the point labelled "benign weather only." The data cited in Ref. 1 indicates a fractional daily loss of 0.0015 for both inverting and non-inverting heliostats, but as demonstrated shortly, either set of estimates leads to the same conclusion.

Reference 1 estimates that the impact of severe weather on non-inverting heliostats would be equivalent to an increase in the fractional daily loss in the range 0.0005-0.002. This range is adopted in the present analysis, and is represented by the vertical segment in Fig. 3. (The fractional daily loss for the inverting heliostat is assumed to suffer no severe-weather increment.) A range rather than a point estimate is used due to the paucity of data on the soiling rate during severe weather, and in particular on the correlation of such effects with the high wind conditions which would necessitate horizontal stow. It should not be inferred that this is the only significant source of uncertainty in this analysis. Explicit characterization of other uncertainties would simply reinforce the conclusion reached below.

In Ref. 1, the cost of washing is estimated to be \$0.77 or \$1.32 per wash per heliostat, depending upon washing system design and operating procedures. The average of these two values is used in the present analysis. Multiplying by an assumed levelization factor of 1.86, the levelized cost/wash/heliostat is \$2. Eason[3] has solved for the dependence of the busbar electricity cost on washing cost, washing frequency, and soiling rate. Using Eason's method, the washing frequency which minimizes the busbar electricity cost for a generating facility with 18,000 heliostats is computed as a function of soiling rate. (An 18% fixed charge rate is assumed for capital

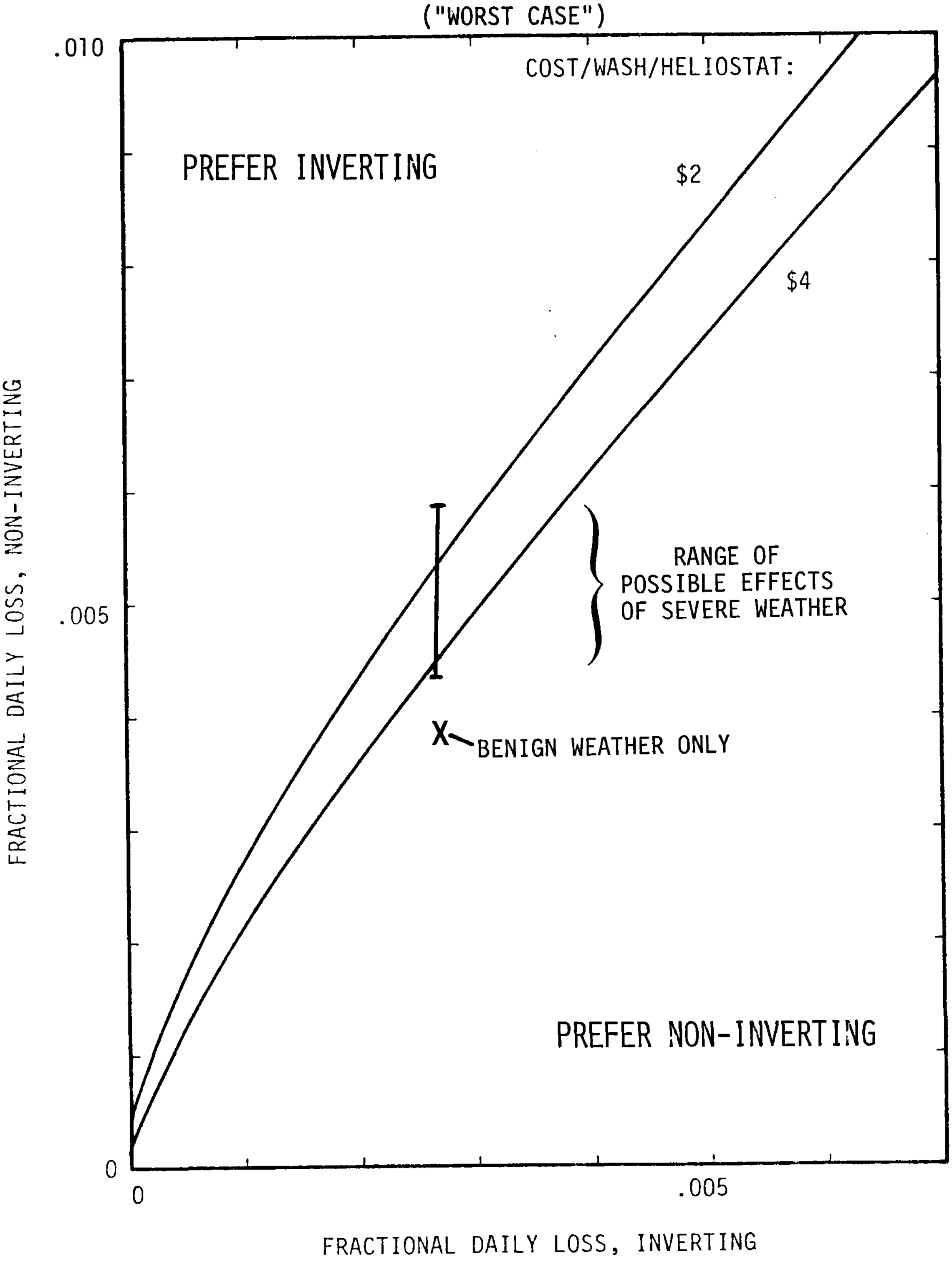

Figure 3. Impact of Soiling and Washing on Design Preference

expenditures.) Performing Eason's calculations for inverting and non-inverting heliostats respectively, the preference is determined by a comparison of busbar electricity costs in each case. In Fig. 3, the curve labelled "$2" is the boundary between regions of preference for inverting and non-inverting heliostats. To illustrate the sensitivity to washing cost, the boundary is also shown assuming $4/wash/heliostat.

As expected, the region of preference for the inverting heliostat increases as the washing cost increases. More important, however, is the observation that the vertical segment representing the range of estimated soiling rates straddles the two preference regions. This observation continues to be valid if the soiling rates are higher or lower than the estimates given here, provided that the inverting and non-inverting soiling rates are roughly proportional (i.e., the vertical segment is translated upward and to the right, or downward and to the left). For instance, if the MDAC estimates of benign-weather daily reflectance loss are used instead of the estimates based on Ref. 2, the conclusion is unchanged. The same conclusion is implied by recent measurements at the Central Receiver Test Facility in Albuquerque, NM, where soiling rates much lower than those quoted here have been observed for both vertical and inverted stow.[4] The proportionality of inverting and non-inverting soiling rates is also indicated by mirror reflectance measurements at ten industrial process heat sites selected for solar retrofit using troughs.[5] (The test procedures in the latter two studies do not provide direct estimates of the quantities shown in Fig. 3, but they do provide estimates of the inverting vs. non-inverting soiling ratio.)

Summarizing these observations from another viewpoint, the non-inverting washing penalty is equal to 4% ± 2%, with the uncertainty resulting from the range of possible effects of severe weather. Under the assumptions of the worst-case analysis, this penalty counterbalances the 4% benefit from filling the slot.

Operational Factors

In situations for which the assumptions of the worst-case analysis are valid, considerations other than cost will strongly influence heliostat design preference. Specifically, there are several operational risk considerations, all of which tend to favor the inverting heliostat. Two of these considerations are vulnerability to hail damage and eye hazards during face-up or vertical daytime stowage. These risks are examined in Ref. 1 and are found to be minor. An operational risk which is potentially significant though difficult to quantify is the possibility that vertically-stowed heliostats may be subject to damage due to failure to stow horizontally when a high wind condition develops. The risk may be greatest during periods of reduced operator alertness or control system readiness, particularly at night. The magnitude of the risk, the tolerability of the risk, and the cost-effectiveness of measures intended to reduce the risk are all highly dependent upon the operating practices and management policies of the owner of the facility. An upper bound on the impact may be estimated by assuming that face up stow is always required. Assuming therefore that non-inverting heliostats are stowed face-up at night, the data of Ref. 2 indicate an increase in fractional daily reflectance loss of 0.0015. The impact on heliostat design preference is shown in Fig. 4. Expressed another way, the face up stow requirement results in a 6% ± 2% washing penalty against the non-inverting heliostat.

Summary

If vertical stow is deemed acceptable with no costly modification of facility design or operating procedures, then the above analysis indicates that the non-inverting heliostat is preferable if it is at least 4% less costly per unit mirror area than the inverting heliostat. If horizontal stow is required, then the non-inverting heliostat must be at least 6% less costly per unit mirror area to be preferred.

The assumptions of the worst-case analysis lead to the estimate that a non-inverting heliostat will be 4% less costly per unit mirror area than an inverting heliostat, indicating an approximate breakeven or possibly a slight preference for the inverting design. Since this estimate is a lower bound on the cost differential between designs, the non-inverting heliostat may ultimately prove to be substantially preferable. However, a general statement of preference is not possible at this time. It is conceivable that both inverting and non-inverting designs will ultimately capture substantial shares of the commercial market for heliostats. The choice in individual instances may be influenced by site-specific environmental factors, operating procedures, management philosophy and the economic and regulatory environment as well as cost comparison of alternatives.

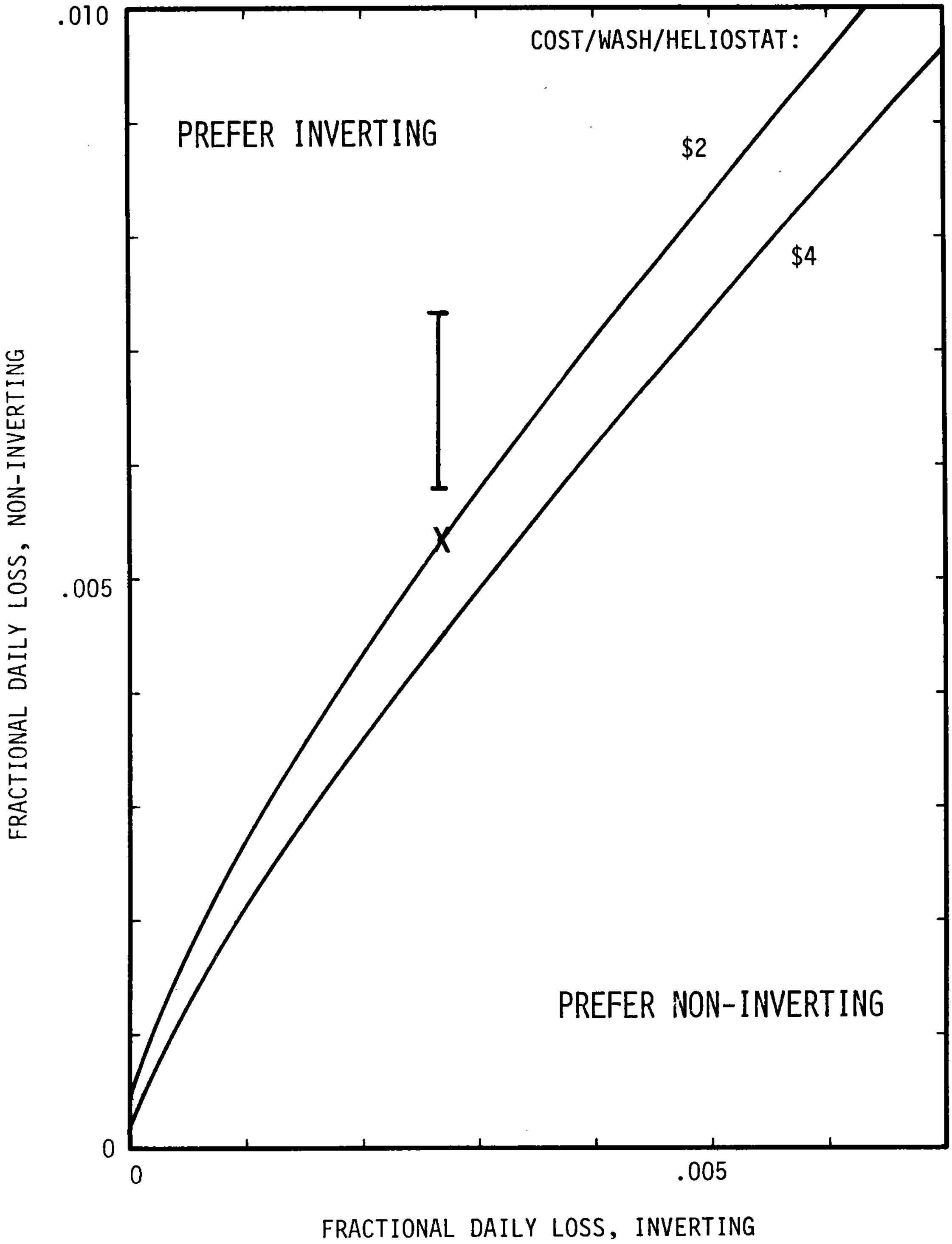

Figure 4. Design Preference Assuming Face Up Stow of Non-Inverting Heliostats

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