REPORT

ANALYSIS OF HELIOSTAT DESIGN AND COST WITH REDUCED WIND LOADS

December 1986

R. J. Thomas

SERI Technical Monitor: A. Lewandowski

Consultant Agreement No. CA-6-00548-01

For

SOLAR ENERGY RESEARCH INSTITUTE
1617 Cole Boulevard
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1.0 INTRODUCTION

Researchers at Colorado State University (CSU) have recently completed an experimental and analytical study to identify possible strategies for reducing the wind loads on heliostats (Reference: SERI/STR-253-2859, P~~a~~eterka et al, Wind Load Reduction for Heliostats). The study shows that wind loads on heliostats within a field can be reduced significantly, perhaps to below 30% of the load on isolated heliostats, by appropriate design of the field and external fences or berms.

The purpose of this task (Ref. SOW, Appendix A) was to evaluate the potential for cost effectiveness of wind load reduction concepts proposed by CSU, when combined with appropriate reductions in heliostat structural requirements. This was accomplished by analytically determining the effect of reduced wind loads on the heliostat structure and upon the cost of the heliostat.

The design baseline selected for the anlysis is the ARCO/Advanced Thermal Systems (ATS) 150 m^2 glass/metal heliostat recently installed at the Central Receiver Test Facility (CRTF) of Sandia National Laboratories, Albuquerque, New Mexico. A drawing of the heliostat configuration is included as Figure 1.

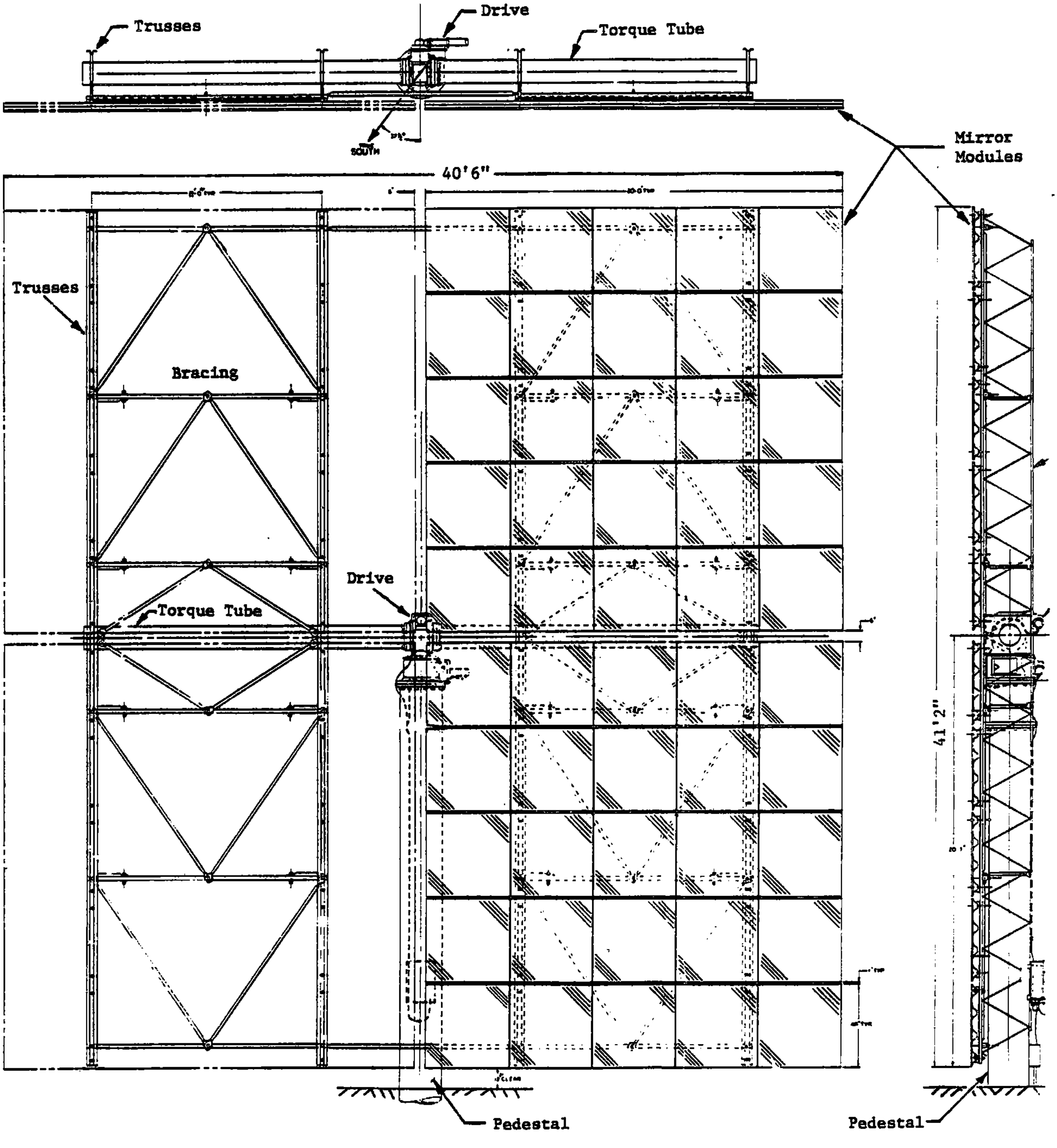


FIGURE 1 - LARGE AREA HELIOSTAT

2.0 STUDY APPROACH

The results of the CSU study for reduction of wind loads on heliostats are summarized on the load reduction curves shown in Figure 2. These curves describe the load reduction as a function of the upwind obstacles interfering with the wind. The load reduction (ordinate) is expressed as a fraction of the force and moment coefficients that would exist on an isolated heliostat. The upwind obstacles interfering with the wind (abscissa) are expressed as the term "generalized blockage", which is the ratio of the wind blockage area due to heliostats, fences, or berms, to the field area containing the blockage.

The primary conclusion of the CSU study and resulting curves is that wind loads on heliostats can be reduced to less than 30% of those imposed on isolated heliostats. These curves were used as a guide in establishing the approach for determining the savings on the heliostat structure. Two points on the load reduction scale were selected for analysis to establish a cost saving trend due to load reduction. The two points selected are:

a) 50% wind load
b) 30% wind load

Implicit in this approach is the assumption that loads in all directions are reduced by the same percentage simultaneously, as is indicated by the curves.

Two approaches to reducing heliostat cost were evaluated and costed separately.

a) The first approach was to relax or reduce the structural loads on the heliostat and determine the reduced structural sizes and accompanying reduced cost.

b) The second approach was to increase the reflective array area in the reduced wind load environment to the point where gear box moments are equal to those experienced by an isolated heliostat with the baseline array size in an unreduced wind environment. The

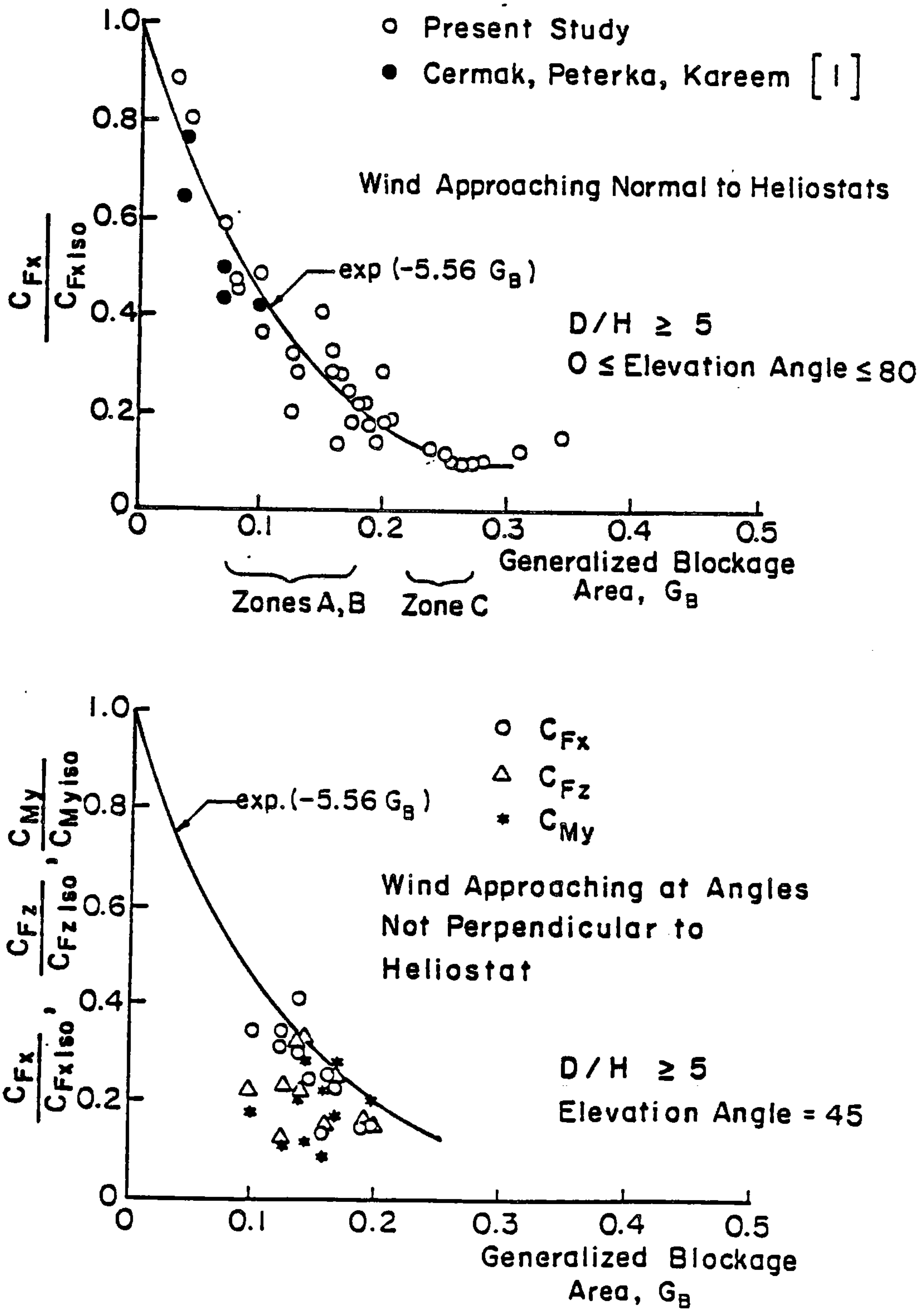


Figure 2 Mean Load Reduction as a Function of Generalized Blockage

increased array size for a reduced wind load of 50% was computed to be approximately a 50' x 50' array. The array size for a reduced wind load of 30% is approximately 60' x 60'. The calculations in which these sizes were derived are given in Appendix C, page C-3.

3.0 STRUCTURAL BASELINE

The baseline heliostat for this analysis is the 150 m^2 ARCO/ATS unit currently installed at the CRTF. It was designed as a modification to the 40' x 40' Photovoltaic Tracker currently in operation at the ARCO Carrisa Plains Photovoltaic Site in California. It is the same as the Carrisa Tracker except for small changes in the rack assembly to accommodate twenty (20) 4' x 20' mirror modules in place of the ten (10) 8' x 20' Carrisa PV panels.

A unique set of design analysis was not developed for the heliostat. Due to its similarity to the tracker in shape, size, stiffness, and weight, the wind load design conditions for the heliostat are assumed to be the same as for the tracker. The wind loads for the tracker were developed by performing scaled wind tunnel tests to obtain forcing functions, then analytically predicting the dynamic response of the structure. The wind environment used for the load predictions is that unique to the Carrisa Plains site.

Using dynamic response loads from site specific winds resulted in considerably higher loads on the heliostat than those estimated by using static wind coefficients. Dynamic response moments at the drive are compared below to static moments computed for 10° angle of attack, 90 mph wind, and coefficients from ASCE paper 3269.

	Static Moment (ft kips)	Dynamic Response Moment (ft kips)
Elevation	126.5	241.6
Cross-elevation	124.4	308.7
Azimuth (30 mph)	20.7	181.5

The majority of the tracker (and heliostat) structural components is critical for the stow condition, in which the array is positioned 3° from horizontal. This includes the panels (mirror modules), trusses, torque tubes, gear drive for elevation and cross elevation loading directions, and the top of the pedestal. The parts designed by the operational condition are the base of the pedestal and the gear drive for the torsional (azimuth) loading direction. The array bracing is designed by seismic loading.

A control setting is used to allow the unit to operate in a normal mode, including vertical, up to a wind velocity of about 25 mph at drive centerline elevation. Velocities in excess of this will cause it to stow into a horizontal position.

The tracker was designed to comply with allowable stresses in accordance with UBC-82, AISC - 8th edition, and AISI-80, whichever governs. Member allowable stresses were increased by 33% for load combinations which included the effects of wind or earthquake.

The current structural design, unmodified, is used in this study as the baseline for a heliostat in an unreduced wind environment (isolated heliostat). The study further assumes that the structural design is optimum for the unreduced wind loading. This assumption is appropriate in that a survey of the major structural elements which would be influenced by load reduction shows that they are within 6% of optimum. This was determined by reviewing the list of unity checks(1) computed for the pedestal, torque tube, truss chord, truss diagonals, and drive. The critical checks ranged from .94 to 1.02.

(1) Unity check is the ratio of actual stress to allowable stress.

4.0 STRUCTURAL MODIFICATIONS

Both approaches to reducing heliostat cost, as identified in Section 2, required structural analysis of the heliostat structural components to determine what modifications are appropriate when wind loads are reduced. This analysis was performed and is included as Appendix B and Appendix C.

The analysis is based on strength considerations only. No analysis was made to evaluate the consequences of reducing stiffness, or increasing the mass moments of inertia of the array. These effects would cause the natural frequency of the heliostat to decrease, which is believed to have the effect of increasing dynamic response loading, which would tend to offset the advantage gained from reducing wind velocities. The increase could result from increased turbulence due to the blockage, and the increasing power spectral density of wind as frequency is reduced, as presented by some sources. An analysis of this type is not considered to be within the scope of this study, nor is all the necessary information readily available to conduct such an analysis. However, it is recommended that such an analysis be accomplished in the course of establishing an operational design.

Modifications to the structure were determined primarily by a method of ratioing to obtain new internal member loads from the loads which design the baseline. Scaling formulas were written which accounted for changes in wind pressure, array area or side dimension, moment arms, etc. Some analyses required separation of gravity loads and dead loads in order to ratio the partial load due to wind.

Certain members were found to have limitations on how thin they could be fabricated. This effect was accounted for. The truss chord and diagonals are limited by the manufacturing process which involves automatic machinery. The pedestal is limited by the UBC and AISC codes to a minimum diameter-to-thickness ratio to avoid buckling and reduced allowable stress.

The baseline loads and allowable stresses were taken mostly from the detailed stress analysis for the Carrisa tracker performed by Fluor Engineers for ARCO.

Additional assumptions made during the course of analyzing structural modifications due to reduced loads are:

- The heliostat array will remain square in shape.
- Secondary effects on loads due to structural member weight reduction or increase are insignificant.
- Structural member thicknesses can be tailored to the exact requirement for a large project.
- Truss configuration will not be changed except for material thickness and the length of truss.
- The mirror glass is not affected by load changes as it is designed by hail resistance. Module support members will remain unchanged by pressure changes in order to retain stiffness and accuracy.

5.0 COSTING METHOD

The ultimate goal of this study is to determine the cost effectiveness of reducing wind loads on heliostats due to blockage. To accomplish this, it was necessary to establish a baseline cost for the heliostat and for each of its major components. Since cost forecasts vary widely, it was necessary to settle on a value which would be appropriate for this study. A cost of \$150/m^2 was selected, which is consistent with Department of Energy estimates, and is believed to be applicable to large fields or procurement lots, probably 5000 units or more. A small procurement in todays marketplace would cost considerably more than \$150/m^2. A representative budget for partial costs — major components and installation — of the heliostat is as follows:

Mirror Modules	\$45/m^2
Drive	40
Structure	20
Pedestal	12
Electronics & Motors	8
Assembly, Installation, Fee, etc.	25
TOTAL	150

These partial costs were then used to compute Δcosts due to identified changes in components from reduced wind loads. Only the first four items in the above list would be affected.

For the main structural parts, Pedestal, Torque Tube, and Trusses, weight change for each part was computed. Δ costs were then computed from the Δ weight by using a cost per pound of fabricated steel. Cost per pound values were derived from supplier recommendations and somewhat verified by past experience. This method was used for both cost reducing approaches defined in Section 2.

For the pedestal and torque tube, the following considerations were made to adjust thickness and length:

- Fabricated steel of this type will cost 45¢/lb to 60¢/lb in general.

- A value of 50¢/lb was used for tube thickness changes, which also affects the flange weld.
- A value of 40¢/lb was used to change length of tube only.
- A value of 45¢/lb was used if both thickness and length ~~is~~ are changed.

To adjust thickness and length of truss members, the following considerations were used:

- Cost per pound will be from 90¢ to $1.00.
- A value of 95¢/lb was selected for this study.

The mirror modules and bracing were increased in area for the second approach in which the array area was increased but the drive moment held constant. Costing the increase was based on dollars per m^2, assuming that the bending stiffness, and the weight and cost per unit area will remain constant, regardless of array size. Mirror module cost is $40/$m^2$ and bracing is $4.50/$m^2$ for this purpose.

Accurate costing of the drive unit is difficult as considerable disparity exists in the available information. Estimates were solicited from capable suppliers for large production runs. The estimates were higher than can reasonably be budgeted within the $150/$m^2$ heliostat cost. They are also higher than believed to be necessary for large production in which automation and dedicated facilities are employed. After reviewing all the available information, the following values were selected for drive costs for this study:

Baseline	$40/$m^2$
50% capacity	x .67
30% capacity	x .5

A tolerance range on this estimate is approximately +25%, -0%.

The detail costing calculations are included in Appendices B and C.

6.0 RESULTS AND CONCLUSIONS

Both approaches described in Section 2.0, "Relaxation of Structural Requirements" and "Increased Reflective Area", have been assessed to determine the cost saving potential as a function of wind load reduction. The decreases in partial costs were totalled and subtracted from the baseline cost in the first approach, and increases were added to the baseline in the second approach to obtain new heliostat costs. New larger array area was computed in the second approach. Cost saving in dollars per m^2 was then computed. The net result is that, by reducing the wind load acting on a heliostat to 30% of the initial load, as much as 19% cost saving per m^2 can be achieved by reducing the structure and keeping the array area the same size. Likewise, for the same reduction, but by increasing the array size to keep the drive design moment constant, as much as 31% cost saving per m^2 can be achieved. A cost summary of these two approaches is presented in Table 1 and Table 2. A set of curves shows the results graphically in Figure 3.

By investigating the elements of Table 1 and Table 2 closely, it is apparent that the largest contributor to cost savings is by far the drive in both cases. The overall conclusion, given the assumptions of this study, is that if heliostat structural loads are reduced by generalized blockage techniques, substantial savings in cost will be realized.

TABLE 1

COST SUMMARY - RELAXATION OF LOADS, CONSTANT ARRAY SIZE (40' x 40')

	Baseline	50% Load	30% Load
Δ Cost - $			
Mirror Modules	—	—	—
Drive	—	-2000	-3000
Structure			
Torque Tubes	—	- 402	- 549
Trusses	—	- 103	- 103
Bracing	—	—	—
Pedestal	—	- 495	- 495
TOTAL		-3000	-4147
Cost per Helio	$22,290	19,290	18,143
m^2 per Helio	148.6	148.6	148.6
Unit Cost $/$m^2$	150	129.80	122.10
Unit Cost Saving $/$m^2$	—	20.20	27.90

TABLE 2

COST SUMMARY - INCREASED ARRAY, CONSTANT DRIVE MOMENT

	Baseline (40' x 40')	50% Load (50' x 50')	30% Load (60' x 60')
Δ Cost - $			
Mirror Modules	--	3933	8240
Drive	--	--	--
Structure			
Torque Tubes	--	490	1498
Trusses	--	335	1058
Bracing	--	390	817
Pedestal	--	189	378
TOTAL		5337	11991
Cost per Helio	$22,290	27,627	34,281
m^2 per Helio	148.6	236.0	331.7
Unit Cost $/$m^2$	150	117.10	103.30
Unit Cost Saving $/$m^2$	--	32.90	46.70

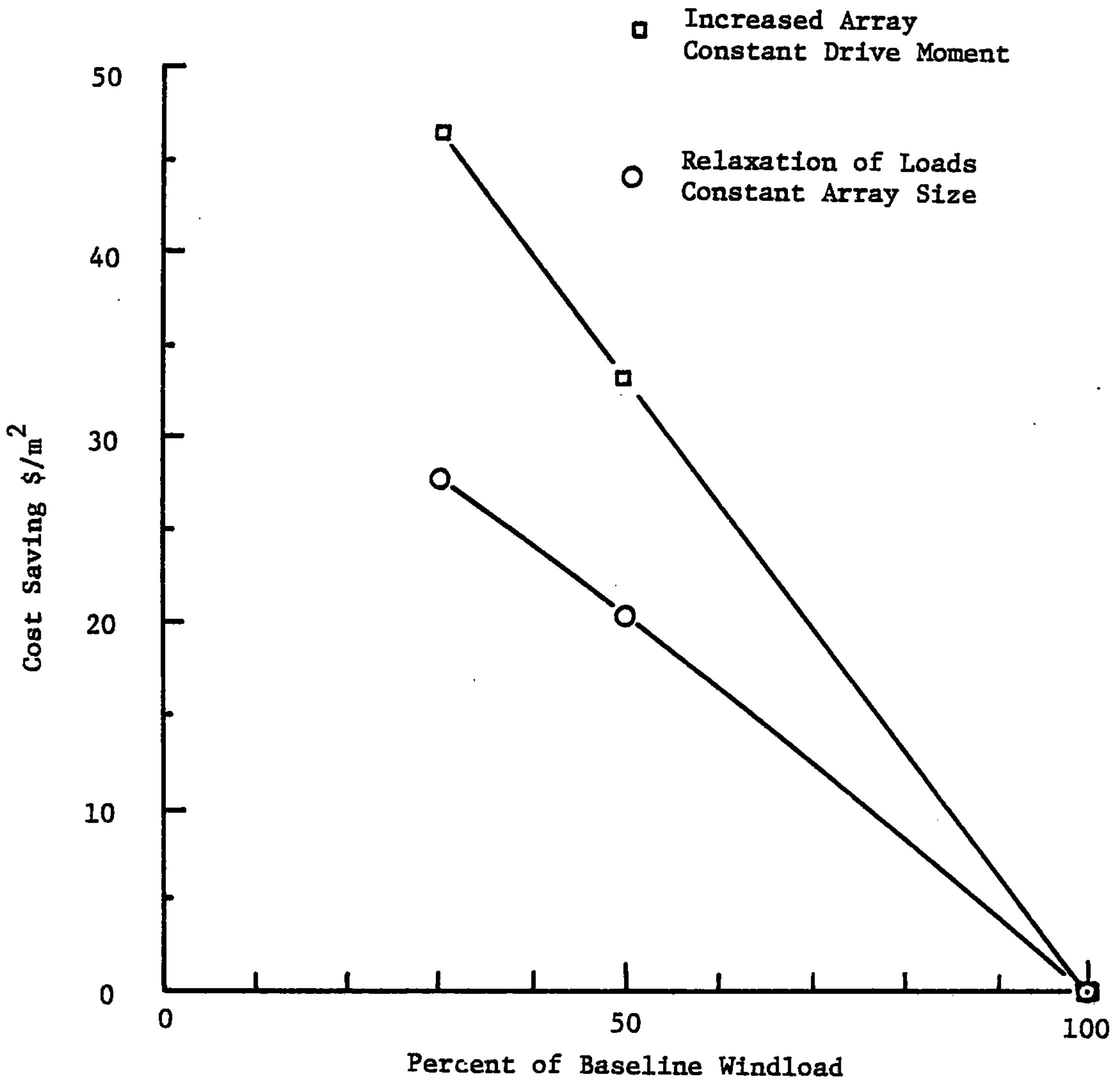


FIGURE 3 - COST SAVING DUE TO WINDLOAD REDUCTION

7.0 RECOMMENDATIONS

The following paragraphs identify a few key recommendations and cautions associated with the use of the information in this study.

(a) The information presented in the previous section, setting forth the cost savings as a function of reduced loads, should be relatively useable in a system study provided an accurate assessment of load reduction is made. However, a gap exists in the completeness of information available from the CSU study to analyze and obtain the actual load reduction of structural components. The needed information is the fluctuating nature of the wind in a sheltered field environment, including frequency content, and subsequently, its effect on the dynamic response of the heliostat. It is recommended that fluctuating wind time histories be extracted from future or past wind tunnel tests and applied to a dynamic response analysis of the heliostat to obtain loads in major structural components. A decision as to a preferred method of implementing an analysis of this type is probably premature and requires some discussion.

(b) If the cost saving method of "increasing the reflective array area" were to be implemented, taller heliostats would result. If fences or berms were employed, they would probably be taller. Increased wind velocities at the slightly higher elevation would not be a large penalty but should be accounted for. Using the .15 power velocity profile, this effect would increase the velocity by about 3.3% for the 50% load case (50' x 50' array), and about 6.1% for the 30% load case (60' x 60' array). Assuming load is proportional to velocity squared, the net result would be that the 50% load case is actually a 53.4% case, and 30% load case is actually a 33.8% case.

If shading and blocking were to remain constant, respacing the field would be required. However, if respaced to give the same shading and blocking, the reflective area per acre of ground would remain constant.

APPENDIX A
Statement of Work
Analysis of Heliostat Design and Cost With Reduced Wind Loads

Background

The DOE Solar Thermal Program continues to strive for low-cost, efficient heliostat systems. Wind loads are the major determinant for the structural design of the heliostat system under both operational and survival conditions. Researchers at Colorado State University (CSU) have recently completed an experimental and analytical study to identify possible strategies for reducing the wind loads for heliostats (Reference: SERI/STR-253-2859, Peterka et. al., Wind Load Reduction for Heliostats). The major conclusions from this study are:

- o Mean wind loads on heliostats within the field can be reduced to below 30% of those on isolated heliostats by appropriate design of field and external fences or berms.
- o A simple design-oriented prediction method (generalized blockage approach) for mean heliostat wind loads in a field was developed.
- o Peak dynamic loads are significantly lower within a field than at the edge for heliostats in operational positions.
- o Limited analysis of dynamic loads has not identified a loading mechanism indicating that on-heliostat spoilers would be beneficial in decreasing mean and dynamic wind loads.
- o The strength of the heliostat should be based on the peak load rather than a mean load multiplied by an assumed gust factor.
- o Full-scale wind loads were not available for comparison with wind-tunnel data.
- o Design forces perpendicular to the mirror plane for an isolated heliostat are controlled by operational winds (50 mph) while design drive moments are controlled by survival winds (90 mph).

Tasks

Using this study as a base, the contractor shall perform the following tasks to evaluate the potential for cost effectiveness of the wind load reduction concepts proposed by CSU when combined with appropriate reductions in heliostat structural requirements.

1. Structural Design Impact.

   This task is to identify the impacts of reduced wind loads on heliostat design and cost. The baseline for the analysis is the state-of-the-art 150 m^2 glass/metal heliostat. Given the potential for reduced wind loads identified in the CSU study, an analysis of the options for improving the cost effectiveness of heliostat systems will be performed.

   - o Initial efforts will be to identify current costs, by component, of the state-of-the-art heliostat. The potential for cost reduction in each of the heliostat components will then be identified assuming a reduced wind load environment.
   - o Alternative approaches to reducing the overall cost will be assessed. Design options to be included, but not necessarily limited to, are the relaxation of structural requirements for the drive mechanism and/or support structure and the increasing of reflective area so that the wind loads are equivilent to those of an isolated heliostat.
   - o Also included in this task will be an identification of the potential impacts (e.g. shading, spacing, etc.) on the overall system of implementing the wind load reduction strategies suggested by CSU.

Milestones/Deliverables

The contractor will provide weekly, verbal progress reports to the SERI Technical Monitor.

A final technical report detailing the contract effort will be submitted 3 weeks prior to the contract end date.

APPENDIX B

STRUCTURAL AND COST CALCULATIONS

UTILIZING

LOAD RELAXATION ON HELIOSTAT,

KEEPING REFLECTIVE ARRAY AREA CONSTANT

BY RJT DATE 12-10-86 SUBJECT Cost Summary SHEET NO. OF
CHKD. BY DATE Relaxation of Loads JOB NO.
Constant Array Size

	Baseline	50% Load	30% Load
Δ Cost - $			
Mirror Modules	–	–	–
Drive	–	- 2000	- 3000
Structure			
Torque Tubes	–	- 402	- 549
Trusses	–	- 103	- 103
Bracing	–	–	–
Pedestal	–	- 495	- 495
Total		- 3000	- 4147
Cost per Helio	$ 22,290	19,290	18,143
m^2 per Helio	148.6	148.6	148.6
Unit Cost $/$m^2$	150	129.80	122.10
Unit Cost Saving $/$m^2$	–	20.20	27.90

BY RJT DATE 11-28-86 SUBJECT Pedestal SHEET NO. ____ OF ____

CHKD. BY ____ DATE ____ JOB NO. ____

<u>Current Design</u> 24" OD X .375 wall $F_y = 36$ ksi

U.C. = 1 (optimum)

$M_{max} = 429$ ft K @ base Fluor Anal pg 24

$M_{grav.mom.} = 8$ ft K

P = 11 k Dead load — LAH Helio.

<u>50% wind load</u> $M_{max} = .5\ (429-8)+8 = 218.5$ ftK

try $t = .1875$

$$S = \frac{\pi}{64}\left(\overline{24}^4 - \overline{23.625}^4\right) \div 12 = 82.9\ in^3$$

$$A = \frac{\pi}{4}\left(\overline{24}^2 - \overline{23.625}^2\right) = 14.0\ in^2$$

$$f_a = \frac{11}{14} = .79 \text{ ksi}$$

$$f_b = \frac{218.5\ (12)}{82.9} = 31.6 \text{ ksi.}$$

$F_a = 19.8$ ksi Fluor Anal

$F_b = .66(1.33)(36) = 31.6$ ksi

$$\frac{.79}{19.8} + \frac{31.6}{31.6} = .04 + 1.0 = 1.04 > 1.0$$

Inadequate

BY RJT DATE 11-28-86 SUBJECT Pedestal SHEET NO. OF

CHKD. BY DATE JOB NO.

Check D/t

$$\frac{D}{t} = \frac{24}{.1875} = 128$$

$$\frac{3300}{F_y} = \frac{3300}{36} = 91.7 < 128$$ not good

Required $t = \frac{D}{91.7} = \frac{24}{91.7} = .26$ in

<u>30% Wind Load</u>

Required $t = .26$ in ($\frac{D}{t}$ reqmt)

BY RJT **DATE** 11-28-86 **SUBJECT** Pedestal **SHEET NO.** ___ **OF** ___

CHKD. BY ___ **DATE** ___ **JOB NO.** ___

<u>Weight saved - Pipe</u> 24" O.D.

<u>100% load</u> $t = .375''$ $ID = 23.25''$

$$wt = \frac{\pi}{4}\left(\overline{24}^2 - \overline{23.25}^2\right)(34.5' \times 12)(.283\ \text{lbs/in}^3)$$

$$= 3261\ \text{lbs}$$

<u>50% load</u> $t = .26$ $ID = 23.48''$

$$wt = \frac{\pi}{4}\left(\overline{24}^2 - \overline{23.48}^2\right)(34.5' \times 12)(.283\ \text{lbs/in}^3)$$

$$= 2272\ \text{lbs}$$

$$wt\ saved = 3261 - 2272 = 989\ \text{lbs}$$

<u>30% load</u> $t = .26$ $ID = 23.48''$

$$wt\ saved = 989\ \text{lbs.}$$

BY RJT DATE 11-28-86 SUBJECT Pedestal SHEET NO. ____ OF ____
CHKD. BY ____ DATE ____ JOB NO. ____

Cost Saved

Assume 30¢/lb for matl. + 20¢/lb for fab.+misc

Total cost saved = 50¢/lb

(Includes effect of some saving on connection
flange + bolts)

50% load. $ saved = (989 lbs)($.50/lb)

= $494.50 per helio

30% load $ saved = $494.50 per helio

BY RJT DATE 11-26-86 SUBJECT Torque Tube SHEET NO. OF

CHKD. BY DATE JOB NO.

Torque Tube moment = 172.42 ft k   Fluor Anal, pg 20

This includes dead load, which must be subtracted to determine wind induced load.

Dead Load Moment

	Wt	l	D.L. Moment
Mirror modules	2450 lbs	9.63 ft	23,594 ft lbs
Torque Tube	1063.4	7.63	8,114
Outer Truss	231.4	15.13	3,501
Inner Truss	231.4	4.13	956
Bracing	273.5	9.63	2,634
			38,799

Wind induced load = 172.42 - 38.80 = 133.62 ft.k

50% Load = (.5)(133.62) + 38.8 = 105.6 ft k

30% Load = (.3)(133.62) + 38.8 = 78.9 ft k

BY RJT DATE 11-26-86 SUBJECT Torque Tube SHEET NO. OF
CHKD. BY DATE JOB NO.

Current design 12.75" OD × 0.50 wall 42 ksi stl.

U.C. = 1.0 (ie, optimum size for current load

$S = 56.7 \text{ in}^3$

Required Section Modulus

50% load $S_{reqd} = \frac{105.6}{172.42}(56.7) = 34.7 \text{ in}^3$

30% load $S_{reqd} = \frac{78.9}{172.42}(56.7) = 25.9 \text{ in}^3$

Required wall thickness

I.D. $D_i^4 = D_o^4 - \frac{64 D_o}{2\pi} S = (12.75)^4 - \frac{64(12.75)}{2\pi} S$

$= 26{,}427 - 129.9 S$

50% load, $D_i^4 = 26{,}427 - 129.9(34.7) = 21{,}920 \text{ in}^4$

$D_i = 12.17$ $t = .29''$

30% load, $D_i^4 = 26{,}427 - 129.9(25.9) = 23{,}063$

$D_i = 12.32$ $t = .215''$

Check $D/t = \frac{12.75}{.215} = 59.3 < \frac{3300}{42} = 78.6$ o.k.

BY RJT DATE 11-26-86 SUBJECT Torque Tube SHEET NO. OF

CHKD. BY DATE JOB NO.

Weight of tube saved

$L = 180'' = 15'$

50% load $A = \frac{\pi}{4}(\overline{12.17}^2 - \overline{11.75}^2) = 7.89 \text{ in}^2$

Wt saved $= 7.89 \times 180 \times .283 = 402$ lbs ea

30% load $A = \frac{\pi}{4}(\overline{12.32}^2 - \overline{11.75}^2) = 10.78 \text{ in}^2$

Wt saved $= 10.78 \times 180 \times .283 = 549$ lbs ea

Cost saved

Assume 30¢/lb for matl and 20¢/lb for fabric. + misc.

Total Costs saved = 50¢/lb

50% load \$ saved = (2 × 402 lbs)(\$.5/lb)

= \$402 per heliostat

30% load \$ saved = (2 × 549 lbs)(\$.5/lb)

= \$549 per heliostat

Note: This includes effect of some saving on flange + bolts.

BY RJT DATE 11-28-86 SUBJECT Truss chord SHEET NO. OF

CHKD. BY DATE JOB NO.

Assume bottom Chord is critical

Truss design moment = 53.3 ft k   Existing design

Thickness = .086 in., F_y = 55 ksi   Fluor Anal.
Area = .653 in^2 Pg 6

The design moment includes dead load which must be subtracted to determine wind induced load.

Dead load moment

	Wt	ℓ	D.L. Moment
Mirror Modules	612.5 lbs (1/8×20×245)	10.4 ft	6,370 ft lbs
Truss	120	9.9	1,188
Bracing	137	10.0	1,370
	869.5		8,928

Wind induced load = 53.3 − 8.9 = 44.4 ft k

50% load = (.5)(44.4) + 8.9 = 31.1 ft k

30% load = (.3)(44.4) + 8.9 = 22.2 ft k

BY RJT DATE 11-28-86 SUBJECT Truss Chord SHEET NO. ____ OF ____

CHKD. BY ____ DATE ____ JOB NO. ____

Chord load

50% $P = \frac{M}{d} = \frac{31.1(12)}{28.42} = 13.1$ k

30% $P = \frac{22.2(12)}{28.42} = 9.4$ k

$F_a = 23.48$ ksi Fluor Anal corrected for weak axis buckling

$P_{allow} = 1.33 F_a A$

Required thickness

50% $A_{reqd} = \frac{P_{allow}}{1.33 F_a} = \frac{13.1}{1.33(23.48)} = .42$ in^2

$t = \frac{.42}{.653}(.086) = .055$ in.

30% $A_{reqd} = \frac{9.4}{1.33(23.48)} = .30$ in^2

$t = \frac{.3}{.653}(.086) = .040$ in.

BY RJT DATE 11-28-86 SUBJECT Truss diagonals SHEET NO. ____ OF ____

CHKD. BY ____ DATE ____ JOB NO. ____

Design Compression load = 5.78 k Existing design

$d = 1.05$, $t = .09$, $F_y = 55$ ksi, $A = .271\ in^2$

Fluor Anal. pg 2

Wind induced load = Design load - dead loa

$= 5.78\ k - .87\ k = 4.91\ k$

50% load $= .5(4.91) + .87 = 3.3\ k$

30% load $= .3(4.91) + .87 = 2.3\ k$

$F_a = 16.66$ ksi

Required thickness

50% $A_{reqd} = \frac{3.3}{1.33(16.66)} = .15\ in^2$, $t = \frac{.15}{.271}(.09) = .05$ i

30% $A_{reqd} = \frac{2.3}{1.33(16.66)} = .10\ in^2$ $t = \frac{.10}{.271}(.09) = .033$ i

Minimum gauge is .078

BY RJT DATE 12-4-86 SUBJECT Truss SHEET NO. ____ OF ____
CHKD. BY ____ DATE ____ JOB NO. ____

Weights

Top chord = $b\, t_c L_{TC} \rho$

$= (8)(.283)(12)\, t_c L_{TC}$ t_c (in), L_{TC} (ft)

$= 27.168\, t_c L_{TC}$ lbs

Bot chord $= 27.168\, t_c L_{BC}$

Diagonal $= \frac{31.3''}{15''} (\pi\, .922\, t_D)\rho\, 12 L_D$

$= 20.526\, t_D L_D$ lbs

Total Wt $= 27.168\, t_c (L_{TC} + L_{BC}) + 20.526\, t_D L_D$
per truss

Baseline Wt = 258.5 lbs per truss

Cost

Δ Cost based on 95¢/lb per Butler Mfg. Co.

BY RJT DATE 12-4-86 SUBJECT Truss SHEET NO. OF

CHKD. BY DATE JOB NO.

Config	t_{chord}	$t_{diag.}$	L_{TC}	L_{BC}	L_D
30%	.078(.040)	.078(.033)	41'	38'	40'
50%	.078(.055)	.078(.050)	41'	38'	40'
Baseline-100%	.086	.090	41'	38'	40'
50x50	.098	.081	51'	48'	50'
60x60 (6-Truss)	.081	.078(.055)	61'	58'	60'

Config	Weight (lbs)		Δ wt	Δ Cost
	each	Total		
30%	231.4	925.6	−108.4	$\$-103.^{00}$
50%	231.4	925.6	−108.4	$-103.^{00}$
Baseline-100%	258.5	1034	0	0
50x50	346.7	1386.8	+ 352.8	$335.^{20}$
60x60 (6-Truss)	357.9	2147.4	+1113.4	1057.70

BY RJT DATE 12-2-86 SUBJECT Mirror Modules SHEET NO. OF

CHKD. BY DATE JOB NO.

Glass will remain unchanged for all mirror modules, as it is designed by hail resistance.

Support members can be reduced from .028 to .020 minimum gauge for 50% or 30% combined pressure and dynamic loading

50% load + 30% load

Wt saved = 80 x .008 x 9.2 x 239 x .283 = 398.2 lbs

$ saved = ($.35)(398.2) = $139.40/helio

Note: The stiffness and accuracy of the mirror module will be degraded by reducing the gauge. Therefore leave the support member stiffness (gauge) as is.

APPENDIX C

STRUCTURAL AND COST CALCULATIONS

UTILIZING

INCREASED REFLECTIVE ARRAY AREA

KEEPING DRIVE MOMENT CONSTANT

BY RJT DATE 12-9-86 SUBJECT Cost Summary Increased Array SHEET NO. OF
CHKD. BY DATE JOB NO.

	Baseline (40'x40')	50% Load (50'x50')	30% Load (60'x60')
Δ Cost - $			
Mirror Modules	-	3933	8240
Drive	-	-	-
Structure			
Torque Tubes	-	490	1498
Trusses	-	335	1058
Bracing	-	390	817
Pedestal	-	189	378
Total	-	5,337	11,991
Cost per Helio	$ 22,290	27,627	34,281
m^2 per Helio	148.6	236.0	331.7
Unit Cost $/$m^2$	150	117.10	103.30
Unit Cost Saving $/$m^2$	-	32.90	46.70

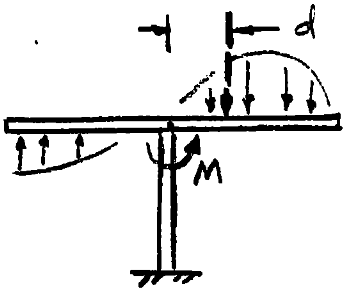
BY RJT DATE 12-1-86 SUBJECT Increased Array Size SHEET NO. ____ OF ____

CHKD. BY ____ DATE ____ JOB NO. ____

Size of array:

a) for reduced wind (+ dynamic response) loads of 50% and 30%

b) keeping drive moment constant



A = Array area
p = pressure (wind + dyn. response)
L = Length (+ width) of array.

$$M = d \int p \, dA = f(d, p, A)$$
$$= f(p, L^3)$$

50% load - same drive moment

$$\left(\frac{L_2}{L_1}\right)^3 = \left(\frac{M_2}{M_1}\right)\left(\frac{p_1}{p_2}\right) = (1)\left(\frac{1}{.5}\right) = 2$$

$$L_2 = (2)^{\frac{1}{3}} L_1 = 1.26 \; L_1 = 1.26(40') \approx 50'$$

30% load - same drive moment

$$\left(\frac{L_2}{L_1}\right)^3 = (1)\left(\frac{1}{.3}\right) = 3\tfrac{1}{3}$$

$$L_2 = (3\tfrac{1}{3})^{\frac{1}{3}} \; L_1 = 1.494 \; L_1 = 1.494(40') \approx 60'$$

BY RJT DATE 12-3-86 SUBJECT Pedestal SHEET NO. OF

CHKD. BY DATE JOB NO.

Assumptions

Pedestal is critical in vertical position

Original array ℄ is 21' above grade $(+\widetilde{1.5}', \text{c.p.})$

Critical moment is 2' below grade

Orig design — moment = 429 ftK (incl. 8 ftK grav. mo

— $t = .375$, U.C. = 1.0

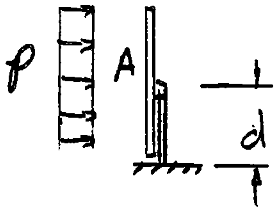
F_a = 19.8 ksi Fluor Anal

$F_b = .66(1.33)(36) = 31.6$ ksi

Wt = 11 K on ped, 8.5 K array (40'x40'), Grav. Mom. will be preserved. = 8 ftK

To Ratio Base Moment

$$M = p\,A\,d$$



$$\frac{M_2}{M_1} = \left(\frac{p_2}{p_1}\right)\left(\frac{A_2}{A_1}\right)\left(\frac{d_2}{d_1}\right)$$ wind

BY RJT DATE 12-3-86 SUBJECT Pedestal SHEET NO. ____ OF ____
CHKD. BY ____ DATE ____ JOB NO. ____

50'x50' 50% load

$$\frac{M_2}{M_1} = (.5)\left(\frac{50^2}{40^2}\right)\left(\frac{26+1.5+2.0}{21+1.5+2.0}\right) = .94$$

$$M_{ped} = .94\,(429-8) + 8 = 404 \text{ ft k}$$

$$P_{ped} = DL = (11-8.5) + 8.5\left(\frac{50^2}{40^2}\right) = 15.8 \text{ k}$$

for 24" x .375 wall, $S = 161.9 \text{ in}^3$, $A = 27.83 \text{ in}^2$

$$f_a = \frac{15.8}{27.83} = .57 \text{ ksi}$$

$$f_b = \frac{404\,(12)}{161.9} = 30 \text{ ksi}$$

$$\frac{.57}{19.8} + \frac{30}{31.6} = .03 + .95 = .98 < 1.0$$

Depth of embedment remains same

Pedestal length = 34.5' + 5.0' = 39.5'

Δ cost = (40¢/lb)(5')(94.5 lbs/ft) = \$189.00/helio.

BY RJT DATE 12-3-86 SUBJECT Pedestal SHEET NO. OF

CHKD. BY DATE JOB NO.

60' x 60' 30% load

$$\frac{M_2}{M_1} = (.3)\left(\frac{60^2}{40^2}\right)\left(\frac{31 + 1.5 + 2.0}{21 + 1.5 + 2.0}\right) = .95$$

$$M_{ped} = .95(429 - 8) + 8 = 408 \text{ ft k}$$

$$P_{ped} = DL = (11 - 8.5) + 8.5\left(\frac{60^2}{40^2}\right) = 21.6 \text{ k}$$

for 24" x .375 wall, $S = 161.9 \text{ in}^3$, $A = 27.83 \text{ in}^2$

$$f_a = \frac{21.6}{27.83} = .78 \text{ ksi}$$

$$f_b = \frac{408(12)}{161.9} = 30.2 \text{ ksi}$$

$$\frac{.78}{19.8} + \frac{30.2}{31.6} = .04 + .96 = 1.0 \leq 1.0$$

Depth of embedment remains same

Pedestal length = 34.5' + 10.0' = 44.5'

Δ cost = (40¢/lb)(10')(94.5 lbs/ft) = \$378.00/helio.

BY RJT DATE 12-3-86 SUBJECT Torque Tube SHEET NO. OF

CHKD. BY DATE JOB NO.

Assumptions

Moment due to wind (incl. dyn.) will be unchanged due to the larger array. (verified in truss anal.)

Moment due to Dead Load will increase due to larger array

Orig. design: $M = 133.6$ ftk wind

$= 38.8$ ftk D.L.

$t = .5$, u.c. = 1.0

$S = 56.7 \text{ in}^3$

New size - for increased dead load

50'x50' array

$$D.L. = \frac{A_2}{A_1}\frac{d_2}{d_1} M_{40} = \left(\frac{50^3}{40^3}\right)(38.8) = 75.8 \text{ ftk}$$

Total moment $= 133.6 + 75.8 = 209.4$ ftk

$$S_{reqd} = \frac{209.4}{172.4}(56.7) = 68.9 \text{ in}^3$$

$$D_i^4 = 26{,}427 - 129.9(68.9) = 17{,}477$$

$D_i = 11.50$ in $\qquad t = .625$ in

BY RJT DATE 12-3-86 SUBJECT Torque Tube SHEET NO. ____ OF ____

CHKD. BY ____ DATE ____ JOB NO. ____

<u>60'x60' array</u>

$DL = \left(\frac{60^3}{40^3}\right)(38.8) = 131$ ft k

Total moment = 133.6 + 131 = 264.6 ft k

$S_{reqd} = \frac{264.6}{172.4}(56.7) = 87.0 \text{ in}^3$

$D_i^4 = 26{,}427 - 129.9(87.0) = 15{,}126$

$D_i = 11.1$ in $\qquad t = .83$ in

BY RJT DATE 12-3-86 SUBJECT Torque Tube SHEET NO. OF

CHKD. BY DATE JOB NO.

Added Weight of tube

Wt of orig tube = 986 lbs 181", t=.5"

50'x50' array

$l = 227"$ $t = .625"$

Wt of tube $= (80.9 \text{ lbs/ft})\left(\frac{227"}{12}\right) = 1530$ lbs

Δwt = 1530 − 986 = 544 lbs ea

60 x 60' array

$l = 301.5"$ $t = .83"$

Wt of tube $= (105.5 \text{ lbs/ft})\left(\frac{301.5}{12}\right) = 2650$ lbs

Δwt = 2650 − 986 = 1664 lbs ea

Added Cost

Assume 45¢/lb for matl. + fab. (increased thickness and increased length)

50'x50' array

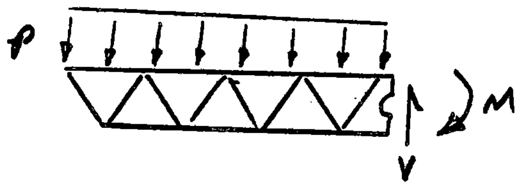
Δ cost = (2×544)($.45/lb) = $489.60 per helio

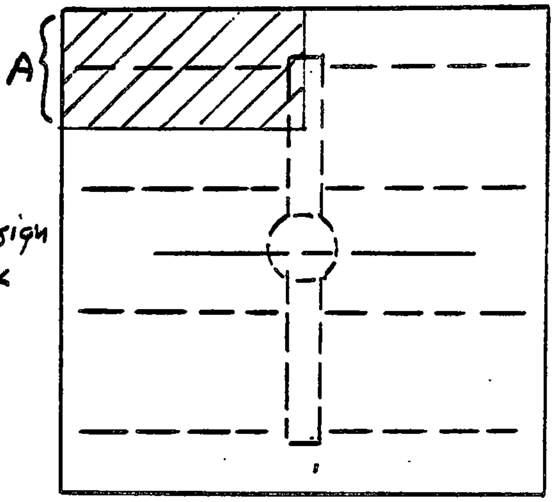
60x60 array

Δ cost = (2×1664)($.45/lb) = $1497.60 per helio

BY RJT DATE 12-1-86 SUBJECT Truss - Increased array SHEET NO. OF

CHKD. BY DATE Diagonals JOB NO.





Shear Force on truss

Orig design $= 5.78^k$

$V = p A$

$\frac{V_2}{V_1} = \left(\frac{p_2}{p_1}\right)\left(\frac{A_2}{A_1}\right)$ press. + dyn.

Moment about Cross elevation axis.

50' x 50' Array

$\frac{V_2}{V_1} = (.5)\left(\frac{50 \times 50}{40 \times 40}\right) = .78$

$V_2 = .78\ V_1 = .78\ (4.91) = 3.83\ k$ pressure + dyn.

Increased Dead Load $= \frac{A_2}{A_1}(.87k) = \frac{(50)^2}{(40)^2}(.87) = 1.36\ k$

Total Shear $= 3.83 + 1.36 = 5.19\ k$

Diagonal thickness required $= \frac{5.19}{5.78}(.090) = .081$ in

60' x 60' Array

$\frac{V_2}{V_1} = (.3)\left(\frac{60^2}{40^2}\right) = .675$

$V_2 = .675\ (4.91) = 3.31\ K$ pressure + dyn.

$D.L. = \left(\frac{60^2}{40^2}\right)(.87) = 1.96\ k$

Total Shear $= 3.31 + 1.96 = 5.27\ K$

Diagonal thickness required $= \frac{5.27}{5.78}(.09) = .082$ in

BY RJT DATE 12-2-86 SUBJECT Truss- Increased Array SHEET NO. OF
CHKD. BY DATE JOB NO.
Diagonals

If 6-truss system is used for the 60'x60' array

Shear 60'x60'

$$\frac{V_2}{V_1} = (.3)\left(\frac{60}{40}\right) = .45$$

$V_2 = .45\,(4.91\text{ k}) = 2.21\text{ k}$ press + dyn.

$\text{D.L.} = \left(\frac{60}{40}\right)(.87) = 1.3\text{ k.}$

Total Shear = $2.21 + 1.3 = 3.51$ K

Diagonal thickness required = $\frac{3.51}{5.78}(.090) = .055$ in

Minimum gauge = .078"

BY ____ DATE 12-2-86 SUBJECT Truss-Increased Array SHEET NO. ____ OF ____
CHKD. BY ____ DATE ____ Chord JOB NO. ____

Moment on truss

Orig design, 53.3 ft k wind

$M = \rho A d$

$\frac{M_2}{M_1} = \left(\frac{\rho_2}{\rho_1}\right)\left(\frac{A_2}{A_1}\right)\left(\frac{d_2}{d_1}\right)$

50'x50' array

$\frac{M_2}{M_1} = (.5)\left(\frac{50^3}{40^3}\right) = .98 \approx 1.0$

$M_2 = 1.0\ M_1 = 1.0\ (44.4) = 44.4$ ftk (press + dyn)

$D.L.^* = \frac{A_2}{A_1}\ \frac{d_2}{d_1}\ (8.9) = \left(\frac{50^3}{40^3}\right)(8.9) = 17.4$ ft k

Total Moment $= 44.4 + 17.4 = 61.8$ ftk

60'x60' array

$\frac{M_2}{M_1} = (.3)\left(\frac{60^3}{40^3}\right) = 1.0$

$M_2 = 1.0\ M_1 = 1.0(44.4) = 44.4$ ftk press + dyn

$D.L. = \left(\frac{60^3}{40^3}\right)(8.9) = 30.0$ ft k

Total Moment $= 44.4 + 30.0 = 74.4$ ftk

* D.L. = 8.9 ftk for 40'x40' array, ref pg ___

BY RJT DATE 12-2-86 SUBJECT Truss-Increased Array SHEET NO. OF
CHKD. BY DATE JOB NO.
Chord

If a 6-truss system is used for the 60'x60' array

$$\frac{M_2}{M_1} = (.3)\left(\frac{60^2}{40^2}\right) = .675$$

$M_2 = .675(44.4) = 30.0$ ft k press + dyn

$$D.L. = \left(\frac{60^2}{40^2}\right)(8.9) = 20.0$$

Total Moment = 30 + 20 = 50 ft k

BY RJT DATE 12-2-86 SUBJECT Truss-Increased Array SHEET NO. ____ OF ____
CHKD. BY ____ DATE ____ JOB NO. ____
Chord

Required Thickness

Ratio from $t = .086$ for 40' array

$F_a = 23.48$ ksi is appropriate allowable for increased thickness

50'x50' array

$$t = \left(\frac{60.9}{53.3}\right)(.086) = .098 \text{ in.}$$

60' X 60' array 4-truss system

$$t = \left(\frac{74.4}{53.3}\right)(.086) = .120 \text{ in}$$

60' X 60' array 6-truss system

$$t = \left(\frac{50}{53.3}\right)(.086) = .081 \text{ in} \quad \text{(use this)}$$

BY RJT DATE 12-4-86 SUBJECT Truss SHEET NO. ___ OF ___

CHKD. BY ___ DATE ___ JOB NO. ___

Config	t_{chord}	$t_{diag.}$	L_{TC}	L_{BC}	L_D
30%	.078(.040)	.078(.033)	41'	38'	40'
50%	.078(.055)	.078(.050)	41'	38'	40'
Baseline-100%	.086	.090	41'	38'	40'
50x50	.098	.081	51'	48'	50'
60x60 (6-Truss)	.081	.078(.055)	61'	58'	60'

Config	Weight (lbs)		Δ wt	Δ Cost
	each	Total		
30%	231.4	925.6	-108.4	-$103.00
50%	231.4	925.6	-108.4	-103.00
Baseline-100%	258.5	1034	0	0
50x50	346.7	1386.8	+ 352.8	335.20
60x60 (6-Truss)	357.9	2147.4	+1113.4	1057.70

BY RJT DATE 12-2-86 SUBJECT Mirror Modules SHEET NO. OF

CHKD. BY DATE Increased Array JOB NO.

<u>Glass</u> - Remain unchanged - Hail design

<u>Support members</u>

The support members can be reduced in size for strength as they will be subjected to lower loads. However, stiffness should be maintained.

The 50'x50' m/m will lose stiffness with increased length. However, it will be assumed that the support stiffness per unit area can remain the same.

The 60'x60' m/m will probably be a 6-truss system, so the stiffness will be preserved without increasing support member gauge.

BY RJT DATE 12-8-86 SUBJECT Bracing Cost For Scaling Up Array Size SHEET NO. OF

CHKD. BY DATE JOB NO.

Per quadrant - Baseline estimate

Part	Length	Cost/in*	Qty	Cost
Mtg Beam	134	.15	3	$60.30
Cross Brace	120.3	.10	4	48.12
Cross Brace-Short	76.4	.10	2	15.28
Wing Tie	116	.10	½	5.80
Stabilizer	31.3	.10	4	12.52
Brkts				10.00
				152.02

Assume 10% to assemble into rack

Cost = $1.1 \times 4 \times \$152 \div 150\ m^2 = \$4.46/m^2$

Use $4.50/m² for area differential when scaling up array size

* Approx. cost for typical parts in medium production.