SAND77-1919
Unlimited Release

VERTICAL AXIS WIND TURBINE TIE-DOWN DESIGN WITH AN EXAMPLE

Robert C. Reuter, Jr.

Prepared by Sandia Laboratories, Albuquerque, New Mexico 87115 and Livermore, California 94550 for the United States Department of Energy under Contract AT(29-1)-789

Printed December 1977
Reprinted October 1984

Issued by Sandia Laboratories, operated for the United States Energy Research & Development Administration by Sandia Corporation.

VERTICAL AXIS WIND TURBINE TIE-DOWN DESIGN
WITH AN EXAMPLE

Robert C. Reuter, Jr.
Sandia Laboratories
Albuquerque, New Mexico 87115

ABSTRACT

Design of cable tie-down systems for vertical axis wind turbines is discussed and guidelines are furnished. Topics such as the number, size and material of the cables, cable elevation angle, tensioning, and thermoelastic effects are discussed in detail. The tie-down system of the existing Sandia 17 meter VAWT is used throughout as a numerical example.

INTRODUCTION

Vertical axis wind turbines of the curved blade, Darrieus type that have been designed and erected have had, in general, some type of guy cable support at the top of the turbine. The purpose of this report is to discuss the VAWT guying problem and to provide guidelines for efficient tie-down system design. Cantilevered, unguyed designs will not be discussed.

Lateral stability is essential in VAWTs as steady and vibratory overturning loads caused by the action of the wind on the turbine must be resisted. Guy cables directed from ground locations to some point on the turbine tower (usually near the top) provide the necessary stabilization, however, several problems may arise if cable selection is not made carefully. For example, the number of cables must be selected to ease turbine erection, provide uniform polar support and minimize wind blockage. Consequences of non-uniform polar support (an extreme example is two diametrically opposing cables) is obvious. The size and material of the cable is selected to control deflection of the tower, and support initial cable tensions and subsequent tension changes. If the selected cable has a limited tensile capability, for example, large cable sag may result causing 1) higher blade strike probabilities, 2) loss of support capability due to non-linear cable stiffness/sag behavior, and 3) cable vibration frequencies which are incompatible with turbine operating speeds.

Initial tensions in the cables are selected to minimize cable sag, provide adequate tower support and eliminate cable vibrations from turbine operating ranges. Cable vibration frequencies vary as the square root of cable tension, so that initial cable tension selection is tantamount to locating cable natural frequencies. Unintentional cable tension changes from carefully selected initial values may cause excess cable sag and a loss of tower support, and will cause a relocation of natural frequencies. Such tension changes may result from cable relaxation (which practically dispppears with time) and from ambient temperature and insolation changes.

Several problem areas associated with VAWT guy cable design have been mentioned. In what follows, four areas of concern will be discussed in more detail. These areas are initial cable design and selection, statics of guy cable tensioning, cable vibrations, and thermal effects.

CABLE STATICS

Selection of the number of cables to be used in a tie-down system cannot be made entirely on a technical basis. Along with technical guidance the final design must include economic trade-offs between, for example, the number of cables, their size, unit cost and ease of installation. These considerations are beyond the scope of this report. A technical requirement of interest, however, is that there be uniform polar support, or polar symmetry in the tie-down system. Clearly, one or two tie-down cables do not fulfill this requirement. Any tie-down system with 3 or more cables, placed at equally spaced polar intervals, does meet the symmetry requirement. It can be shown that the stiffness of a system will be proportional to $(\frac{n}{2})$ times the single cable stiffness, where n is the number of tie-down cables. Also, for a given overall tie-down stiffness, and for equal cable lengths, $n_iA_iE_i = n_jA_jE_j$, where i and j represent two different tie-down systems. For example, in changing a tie-down design from a 4 cable system ($n_i = 4$) to a 3 cable system ($n_j = 3$) without changing the overall tie-down stiffness, or the cable material, the cross-sectional area of each cable in the 3 cable system must equal $\frac{4}{3}$ times the cross-sectional area of each cable of the 4 cable system; i.e., $A_3 = \frac{4}{3} A_4$. Therefore, for a given tie-down system stiffness, the fewer the number of cables used, the greater will be their individual cross-sectional area. This means their linear weight will be greater and also their sag per unit of tension. The relationship between sag and cable tension will be discussed later.

The next topic to be treated in this section covers the selection of a tie-down cable elevation angle, the angle made between the tie-down cable and the horizontal plane. A vertical tie-down cable provides no stiffness to the top of the tower because horizontal tower loads have no components which the cables can react. A nearly horizontal cable provides no stiffness because of its great length. Somewhere between these extreme angles of 90 degrees and near zero degrees is an optimum value which provides maximum stiffness. The nomenclature illustrated in Fig. 1 is adopted. This figure shows the turbine base (assumed rigid), blade support tower, cable outriggers (also assumed rigid) and four tie-down cables equally spaced in the polar direction. The view in Fig. 1 is normal to a plane containing the tower and two of the cables.

The ith cable changes length according to

$$\Delta C_i = \frac{H}{C}\Delta H_i + \frac{V}{C}\Delta V_i \qquad (1)$$

Assuming that the deflection is confined to the plane of the figure, then

$$
\begin{aligned}
\Delta H_1 &= \delta \quad, & \Delta V_1 &= \epsilon - \ell\beta \\
\Delta H_2 &= -\delta \quad, & \Delta V_2 &= \epsilon + \ell\beta \\
\Delta H_3 &= \Delta H_4 = 0 \quad, & \Delta V_3 &= \Delta V_4 = \epsilon
\end{aligned}
\tag{2}
$$

Equilibrium of forces and moments at the top of the tower requires that

$$
\begin{aligned}
&\frac{H}{C}(P_1 - P_2) + P_H - \bar{A} = 0 \\
&\frac{V}{C}(P_1 + P_2 + P_3 + P_4) - P_T = 0 \\
&M - \frac{V\ell}{C}(P_1 - P_2) = 0
\end{aligned}
\tag{3}
$$

where P_i, $i = 1,4$ are the tensile loads in the cables, P_T is the resulting compressive load in the tower, P_H and M are the horizontal load and moment resistance offered by the tower and $\bar{A}$ is the external load applied in the horizontal plane causing the deflection. Since the cables can support tension only and no bending,

$$P_i = \frac{A_c E_c}{C} \Delta C_i$$

Using (1) and (2), this gives

$$
\begin{aligned}
P_1 &= \frac{A_c E_c}{C} \left[\frac{H}{C}\delta + \frac{V}{C}(\epsilon - \ell\beta)\right] \\
P_2 &= \frac{A_c E_c}{C} \left[-\frac{H}{C}\delta + \frac{V}{C}(\epsilon + \ell\beta)\right] \\
P_3 &= P_4 = \frac{A_c E_c}{C}\left(\frac{V}{C}\right)
\end{aligned}
\tag{4}
$$

Two tower base fixities are considered; they are pinned and clamped. Using elementary beam theory,

$$\left.\begin{aligned} P_H &= \frac{3E_T I_T}{L_T^3}(\delta + \beta L_T) \\ M &= \frac{3E_T I_T}{L_T^2}(\delta + \beta L_T) \end{aligned}\right\} \text{pinned tower base} \qquad (5)$$

$$\left.\begin{aligned} P_H &= \frac{6E_T I_T}{L_T^3}(2\delta + \beta L_T) \\ M &= \frac{2E_T I_T}{L_T^2}(3\delta + 2\beta L_T) \end{aligned}\right\} \text{clamped tower base} \qquad (6)$$

$$\text{and } P_T = \frac{A_T E_T}{L_T}\,\epsilon \qquad (7)$$

Substituting (4), (7) and (5) or (6) into the equilibrium equations (3) yields three equations for determination of the three unknown displacements, δ, ϵ and β. Our present interest is with the horizontal stiffness at the top of the tower, a property clearly dependent upon the geometric and material properties of the tie-down cables. After performing the operations mentioned above the following expressions for a normalized horizontal stiffness at the top of the tower are obtained.

$$\left(\frac{\bar{A}}{\delta}\right)\left(\frac{L_T}{A_c E_c}\right) = \frac{6\left(\frac{L_T}{V}\right)\sin\alpha\left[\cos\alpha + \left(\frac{\ell}{L_T}\right)\sin\alpha\right]^2}{\left[3 + 2\sin^3\alpha\left(\frac{A_c E_c L_T^2}{E_T I_T}\right)\left(\frac{L_T}{V}\right)\left(\frac{\ell}{L_T}\right)^2\right]} \qquad (8)$$

for the pinned tower base, and

$$\left(\frac{\bar{A}}{\delta}\right)\left(\frac{L_T}{A_cE_c}\right) = \frac{2\left\{\frac{3E_TI_T}{A_cE_cL_T^2} + 2\left(\frac{L_T}{V}\right)\sin\alpha\left[\cos^2\alpha + 3\left(\frac{\ell}{L_T}\right)\sin\alpha\left(\cos\alpha + \left(\frac{\ell}{L_T}\right)\sin\alpha\right)\right]\right\}}{\left[2 + \sin^3\alpha\left(\frac{A_cE_cL_T^2}{E_TI_T}\right)\left(\frac{L_T}{V}\right)\left(\frac{\ell}{L_T}\right)^2\right]} \tag{9}$$

for the clamped tower base.

A numerical example for the stiffness given by Eq. (8) is provided using $\left(\frac{L_T}{V}\right) = 1$, $\left(\frac{E_TI_T}{AEL_T^2}\right) = 6.9 \times 10^{-3}$ and two values of $\left(\frac{\ell}{L_T}\right)$; 0.01 and 0.1. Results are shown in Fig. 2. Here it can be seen that when outrigger lengths are small (1% of the tower length), the maximum stiffness occurs at an elevation angle of about 35°. By increasing outrigger length (to 10% of the tower length) two undesirable effects occur. First, the maximum stiffness has been reduced in value, and second, the peak has shifted to the left suggesting longer cables, greater sag per unit of tension, and greater land usage. Since the optimum elevation angle (that which maximizes stiffness) is relatively shallow already, there is no incentive to provide outriggers in the tie-down system for blade clearance. Allowing the outrigger length, ℓ, to approach zero, Eqs. (8) and (9) become, respectively,

$$\left(\frac{\bar{A}}{\delta}\right)\left(\frac{L_T}{A_cE_c}\right) = 2\left(\frac{L_T}{V}\right)\sin\alpha\cos^2\alpha \tag{10}$$

for a pinned tower base, and

$$\left(\frac{\bar{A}}{\delta}\right)\left(\frac{L_T}{A_cE_c}\right) = \frac{3E_TI_T}{A_cE_cL_T^2} + 2\left(\frac{L_T}{V}\right)\sin\alpha\cos^2\alpha \tag{11}$$

for a clamped tower base. These equations are valid for outrigger lengths equal to about 1% of the tower length, or less. Equation (10) shows that the pinned base tower stiffness is independent of tower properties. Equation (11) shows that the top of a clamped base tower is stiffened additionally by that amount appropriate for a cantilever beam (tower). By differentiating both sides of (10) or (11) and setting the result equal to zero, the optimum elevation angle can be found directly. It is

$$\alpha = \cos^{-1} (2/3)^{\frac{1}{2}} = 35.3^{\circ}$$

and is independent of all tower and cable properties.

In the example above, where numerical values characteristic of the Sandia 17 meter turbine were used, clamping the tower base increases the overall tower/tie-down stiffness only by about 3%. There is no real incentive, therefore, to provide a moment carrying capability at the base of the blade support tower, at least from a tie-down stiffness viewpoint. This is consistent with the intended purpose of using tie-down cables in the first place; they are present to support the tower so that it doesn't have to support itself.

The topics of sizing the cable and selecting initial tension were treated fairly thoroughly in Ref. (1), however, some of the highlights are repeated here for completeness. The sag in a cable stretched to connect two points, as in Fig. 3, is given by

$$\delta_p = \frac{4\delta_c x(S - x)}{C^2 \cos^2 \alpha} \qquad (12)$$

where δ_c is the midpoint sag given by

$$\delta_c = \frac{wC^2}{8T} \cos \alpha \tag{13}$$

Here, T is the chordwise component of cable tension and w is the linear weight of the cable. Results for (12) and (13) are shown in Fig. 4 where numerical values characteristic of the Sandia 17 meter turbine are used. The dashed line shows the sag at a point along the undeflected cable which is closest to the passing blade. Note the rapid growth of sag for small values of tension.

Cable stiffness, or the property characterizing a cable's ability to support the tower, is given by

$$K = \left[\frac{C}{A_c E_c} + \frac{512\,\delta_c^3}{12(1 + b)\; wC^3\; \cos\alpha}\right]^{-1} \tag{14}$$

where $b = \frac{8}{3}\left(\frac{\delta_c}{C}\right)^2$. It is seen that cable stiffness depends upon cable sag (or equivalently, on cable tension) in a nonlinear fashion. Numerical results for cable stiffness of the 17 meter turbine are shown in Fig. 5. When sag is low (tension is high), cable stiffness is high since it is dominated by elastic stretch of the cable. When sag is high (tension is low), cable stiffness is low since it is dominated by cable weight. It is advisable to have enough tension present to keep stiffness high in order to preserve tie-down support, however, it is not sufficient to use Eq. (14), or Fig. 5, to determine what value of δ_c (and therefore T) is necessary to achieve a desired stiffness. The difficulty lies in determining the <u>change</u> in stiffness with change in chord length of a down wind cable when the tower deflects. The down wind cable is of interest because is will develop additional sag and therefore lose part of its initial stiffness and load carrying capability. Equation (14), which gives the instantaneous values of cable stiffness must be integrated to give a relationship between chord length changes and tension changes. This yields Ref. (1)

$$\Delta C = \left[\frac{C\Delta T}{A_c E_c} + \frac{w^2 C^3 \cos^2\alpha}{24(1 + b)} \frac{\Delta T(\Delta T + 2T_i)}{T_i^2(\Delta T + T_i)^2}\right] \qquad (15)$$

The horizontal component of ΔC, ΔC_h, is given by

$$\Delta C_h = \sec\alpha\, \Delta C$$

Tension change, ΔT, is shown in Fig. 6 as a function of both ΔC and ΔC_h, along with the linear cable stiffness, K_s. It is seen that for small values of ΔC, all curves behave linearly and approach K_s. Equation (15) may be used to size the cable as follows. An overall stiffness for the tie-down system/tower is first selected by choosing an acceptable, maximum down wind deflection. For the Sandia 17 meter turbine, this value was one inch in an 80 mph wind, yielding $K_s \simeq 9000$ lb/in. After the geometry of the turbine has been determined, it is necessary to select a cable with a modulus, linear weight and cross-sectional area which, when used in (15) for small values of ΔT, yields a stiffness value of K_s or greater. Another cable property to keep in mind is its ultimate load. This value should be five times the maximum tension (to be determined later) or greater. Initial tension can be selected next by referring to Fig. 6 and selecting a value for T_i which will permit essentially linear behavior of the tie-down system. For the present example, a value of 12,000 lbs. is suggested. Another set of curves of interest are presented in Fig. 7 where final strike point sag is shown as a function of tower deflection. If the selection of initial tension is based on blade clearance, these curves can be useful. For example, if a horizontal tower deflection, ΔC_h, of 2.5 in. is allowed then for a strike point sag to be 1 foot or less, the initial cable tension should be 12,000 lbs. or more. If a deflection ΔC_h, of 3 in. is allowed, then 16,000 lbs. or more of initial cable tension is required to keep the strike point sag 1 foot or less. For the 17 meter turbine, a 12,000 lb. initial cable tension provides a maximum strike point sag of 0.3 feet when the tower deflection is approximately 1 inch, and the response remains nearly linear.

CABLE DYNAMICS

The problem of selecting initial tension for tie-down cables is generally not limited to static considerations only. Natural frequencies of tie-down cables are a strong function of the tension in them which must be adjusted so as not to be excited by prevalent forcing functions. In the case of a two bladed VAWT the fundamental forcing function for lateral cable vibrations is two/rev; i.e., two cycles of the forcing function for one revolution of the turbine. This comes about by virtue of the flatwise aerodynamic loads which act on the turbine blades.

Natural frequencies for taut, heavy cables are given by Ref. (2)

$$\omega_{mc} = \frac{m\pi}{C}\left(\frac{Tg}{w}\right)^{\frac{1}{2}} \tag{16}$$

where m is the mode number (1,2,3,...), T is cable tension, g is the acceleration of gravity, w is the cable linear weight and C is the cable length. For the 17 meter turbine, (16) yields

$$\omega_{mc} = 9.58 \times 10^{-2}\ m(T)^{\frac{1}{2}}\ \text{rad/sec}$$

or

$$f_{mc} = 1.53 \times 10^{-2}\ m(T)^{\frac{1}{2}}\ \text{hz}$$

Variation of the first two modes with cable tension are shown in Fig. 8. Turbine speeds which yield a two/rev forcing frequency equal to the cable frequencies are indicated in the ordinate direction along the right hand side of the figure. It can be seen in the figure that the original, initial tension value of 12,000 lbs. would cause the first cable mode to have a frequency of about 1.65 hz and it would be excited if the turbine were operated at about 50 rpm. This was corroborated experimentally. The initial tension was subsequently elevated to 16,000 lbs. in order to increase the turbine operating range below the first cable mode.

This example illustrates that tie-down cables can be "tuned" successfully in the field for cable vibration control. For higher speed turbines, it may be more desirable to lower the initial cable tension in such a way that the 2/rev frequency of the turbine is midway between the first two cable modes. Whenever tension is reduced, however, care must be taken to insure that too much nonlinear stiffness behavior has not been induced which would cause significant loss in tie-down support capability.

A trade off evaluation between location of cable frequencies and the tensioning guidelines of the previous section is implied.

THERMAL EFFECTS

Another phenomenon occurs which effects initial tensioning of VAWT tie-down cables. Diurnal (and longer) temperature and insolation changes can cause enough differential thermal expansion between the cables and the blade support structure to cause significant cable tension changes. A model suitable for analysis of this problem consists of the turbine blade support tower and four tie-down cables. (Other numbers of cables could, of course, be used.) The tower of this model is an equivalent tower consisting of the upper bearing shaft, the blade support tower, and the turbine base. These are structural components which carry tie-down loads and act in series. Model components are assumed to be one-dimensional with linear behavior.

Total strain in a long, slender structure is the sum of mechanical strain and thermal strain. Therefore, total length changes can be written

$$\Delta L = \eta L \Delta T + \frac{LP}{EA} \tag{17}$$

where η is the thermal expansion coefficient, A and E are cross-sectional area and Young's modulus, L and ΔL are length and length change, P is load and ΔT is the temperature change. Solving (17) for P^* and using subscripts, T and C to denote tower and cable, respectively, yields

*These loads are actually load changes due to temperature changes, length changes, or both. They do not contain initial tie-down loads.

$$P_T = \left(\frac{AE}{L}\right)_T \Delta L - (AE\eta)_T \, \Delta T_T$$

$$P_c = \left(\frac{AE}{C}\right)_c \Delta C - (AE\eta)_c \, \Delta T_c \tag{18}$$

where the tower and cables are allowed different temperature changes. The cable and tower deflections are related by

$$\Delta C = \frac{L}{C} \Delta L \tag{19}$$

Equilibrium requires

$$P_T = -4 \; P_c \; \sin \alpha \tag{20}$$

Substituting (18) into (20) and using (19) gives

$$\Delta L = \frac{\left[(AE\eta\Delta T)_T + 4(AE\eta\Delta T)_c \; \sin\alpha\right]}{\left[\left(\frac{AE}{L}\right)_T + 4\left(\frac{AE}{C}\right)_c \; \sin^2 \alpha\right]} \tag{21}$$

Using (21) and (19) in (18) gives

$$P_T = \frac{4 \; \sin \alpha \left[(AE\eta\Delta T)_c \; \left(\frac{AE}{L}\right)_T - (AE\eta\Delta T)_T \; \left(\frac{AE}{C}\right)_c \; \sin \alpha\right]}{\left[\left(\frac{AE}{L}\right)_T + 4\left(\frac{AE}{C}\right)_c \; \sin^2 \alpha\right]}$$

$$P_c = \frac{\left[(AE\eta\Delta T)_T \; \left(\frac{AE}{C}\right)_c \; \sin \alpha - (AE\eta\Delta T)_c \; \left(\frac{AE}{L}\right)_T\right]}{\left[\left(\frac{AE}{L}\right)_T + 4\left(\frac{AE}{C}\right)_c \; \sin^2 \alpha\right]} \tag{22}$$

Again, using the 17 meter turbine as an example, pertinent parameter and group values are

$$\alpha = 35^{\circ}$$

$$\eta_T = \eta_c = 6.5 \times 10^{-6}/^{\circ}F$$

$$L_T = 74.2 \text{ ft.} = 890.4 \text{ in.}$$

$$L_c = 129.4 \text{ ft.} = 1552.8 \text{ in.}$$

$$\left(\frac{AE}{L}\right)_1 = 2.28 \times 10^7 \text{ lb/in}$$

$$\left(\frac{AE}{L}\right)_2 = 2.73 \times 10^6 \text{ lb/in}$$

$$\left(\frac{AE}{L}\right)_3 = 4.00 \times 10^6 \text{ lb/in}$$

$$\left(\frac{AE}{L}\right)_T = \frac{\left(\frac{AE}{L}\right)_1 \left(\frac{AE}{L}\right)_2 \left(\frac{AE}{L}\right)_3}{\left(\frac{AE}{L}\right)_1 \left(\frac{AE}{L}\right)_2 + \left(\frac{AE}{L}\right)_2 \left(\frac{AE}{L}\right)_3 + \left(\frac{AE}{L}\right)_1 \left(\frac{AE}{L}\right)_3} = 1.51 \times 10^6 \text{ lb/in}$$

$$(AE)_T = 1.35 \times 10^9 \text{ lb}$$

$$(AE\eta)_T = 8780 \text{ lb}/^{\circ}F$$

$$\left(\frac{AE}{L}\right)_c = 9.60 \times 10^3 \text{ lb/in}$$

$$(AE)_c = 1.49 \times 10^7 \text{ lb}$$

$$(AE\eta)_c = 96.8 \text{ lb}/^{\circ}F$$

In general, during daylight hours, the cables were observed and predicted to be at a higher temperature than the tower, Ref. (3). This can be characterized by writing

$$\Delta T_c = k\Delta T_T$$

where $k > 1$ during daylight hours and $k = 1$ otherwise. Numerical results for Eqs. (21) and (22) are presented in Table 1 for various values of k and for (22-b) in Fig. 9. From Ref. (3), values of $k = 1.1$ occur almost daily in Albuquerque (in the absence of clouds), with a maximum value of $k \simeq 1.12$. Another result of Ref. (3) is that the tower temperature is generally above ambient temperature, T_A, during daylight hours. The difference between T_T and T_A varies, but when k reaches its maximum $(T_T - T_A) \simeq 7$ to 10 degrees. Therefore, during daylight hours

$$\Delta T_T = \Delta T_A + 10$$

as a worst case, and

$$\Delta T_T = \Delta T_A$$

otherwise. The ambient temperature change between dawn and the time of maximum solar insolation can easily reach 30°F in Albuquerque. Using $\Delta T_T = 30 + 10 = 40^{\circ}$F and $k = 1.12$, each tie-down cable can lose approximately 3000 lbs. of tension from its initial value at dawn. Approximately 15% of this loss is due to the temperature difference between the tower and cables. This value, however, represents a worst case since it was calculated with the largest predicted value of k and since it was assumed that all cables received the same insolation. On a cloudy day when $k = 1$ and $\Delta T_T = \Delta T_A = 30^{\circ}$, each cable can lose approximately 2000 lbs. of tension from its initial value at dawn.

Equation (22) can be rewritten in the form

$$\Delta P_T = \frac{4 \sin\alpha (AE)_T \ (AE)_C \left[\eta_C k - \eta_T \sin^2\alpha\right] \Delta T_T}{\left[(AE)_T + 4(AE)_C \sin^3\alpha\right]}$$

$$\Delta P_C = \frac{(AE)_T \ (AE)_C \left[\eta_T \sin^2\alpha - \eta_C k\right] \Delta T_T}{\left[(AE)_T + 4(AE)_C \sin^3\alpha\right]} \tag{23}$$

These expressions demonstrate that converting from a steel tower (as on the 17 meter turbine) to an aluminum tower would reduce the magnitude of the thermoelastic problem by virtue of the greater η and the lower E.

SUMMARY

Problems pertinent to the design of an efficient tie-down system have been discussed above. The number of cables must be 3 or greater, but otherwise will probably be guided by cost trade-offs based on size, ease of assembly and availability. Guy wire outriggers were shown to be more of a liability than an asset to a tie-down design. In their absence, the cable elevation angle was shown to be approximately 35°.

Sizing the cable was shown to depend on a predetermined overall tie-down stiffness. Once this value is known, cable size and material, and a minimum value of initial tension can be determined. Cable natural frequencies are also determined, based on initial tension values. If they occur at or near the two per revolution fundamental frequency of a two bladed turbine, then initial cable tension must be adjusted. The final iteration of cable tension determination occurs when thermal effects are considered. Differential thermal expansion between the blade support tower and tie-down cables will, in general, cause a loss of initial cable tension as the ambient temperature rises. Initial cable tensions prior to turbine operation must be adjusted accordingly.

Table 1. Thermoelastic Behavior of Tower and Tie-Down Cables

k	$\Delta C \times 10^{-3}(in/^{o}F)$	$\Delta P_T(lb/^{o}F)$	$\Delta P_C(lb/^{o}F)$
1.0	5.91	147.4	-64.2
1.1	5.93	169.4	-73.8
1.12*	5.93	173.8	-75.8
1.2	5.94	191.4	-83.4
1.3	5.96	213.5	-93.0
1.4	5.97	235.5	-102.6
1.5	5.99	257.5	-112.2

*maximum predicted value for Albuquerque

REFERENCES

1. Reuter, R. C. Jr., "Tie-Down Cable Selection and Initial Tensioning for the Sandia 17-Meter Vertical Axis Wind Turbine," Sandia Report SAND76-0616, Sandia Laboratories, Albuquerque, NM, February 1977.
2. Shears, M., "Static and Dynamic Behavior of Guyed Masts," Structures and Materials Research Department of Civil Engineering, Report No. 68-6, University of California, Berkeley, CA, June 1968.
3. Ortega, A., Internal Memorandum, Sandia Laboratories, May 17, 1977.

LIST OF FIGURES

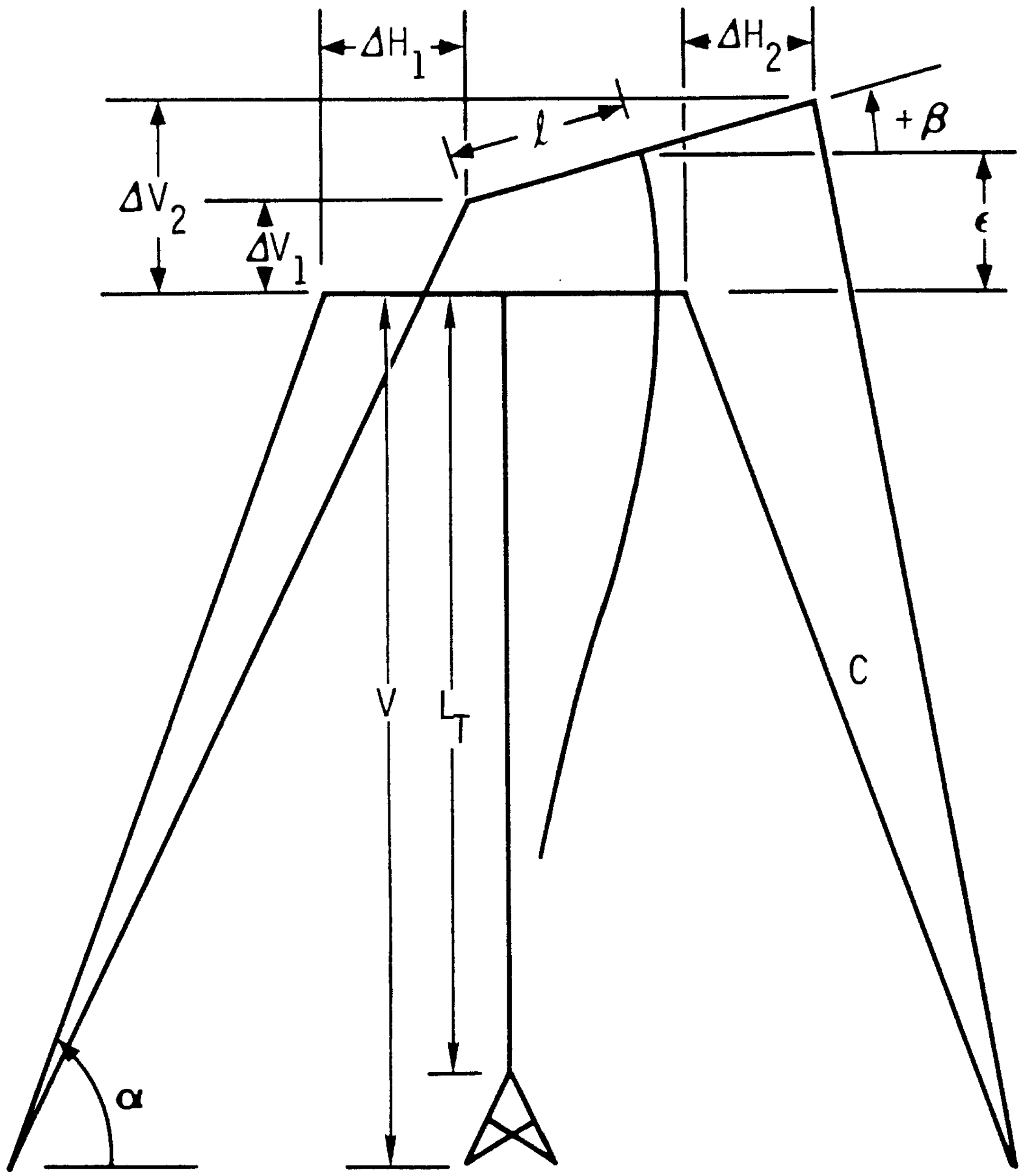


FIGURE 1

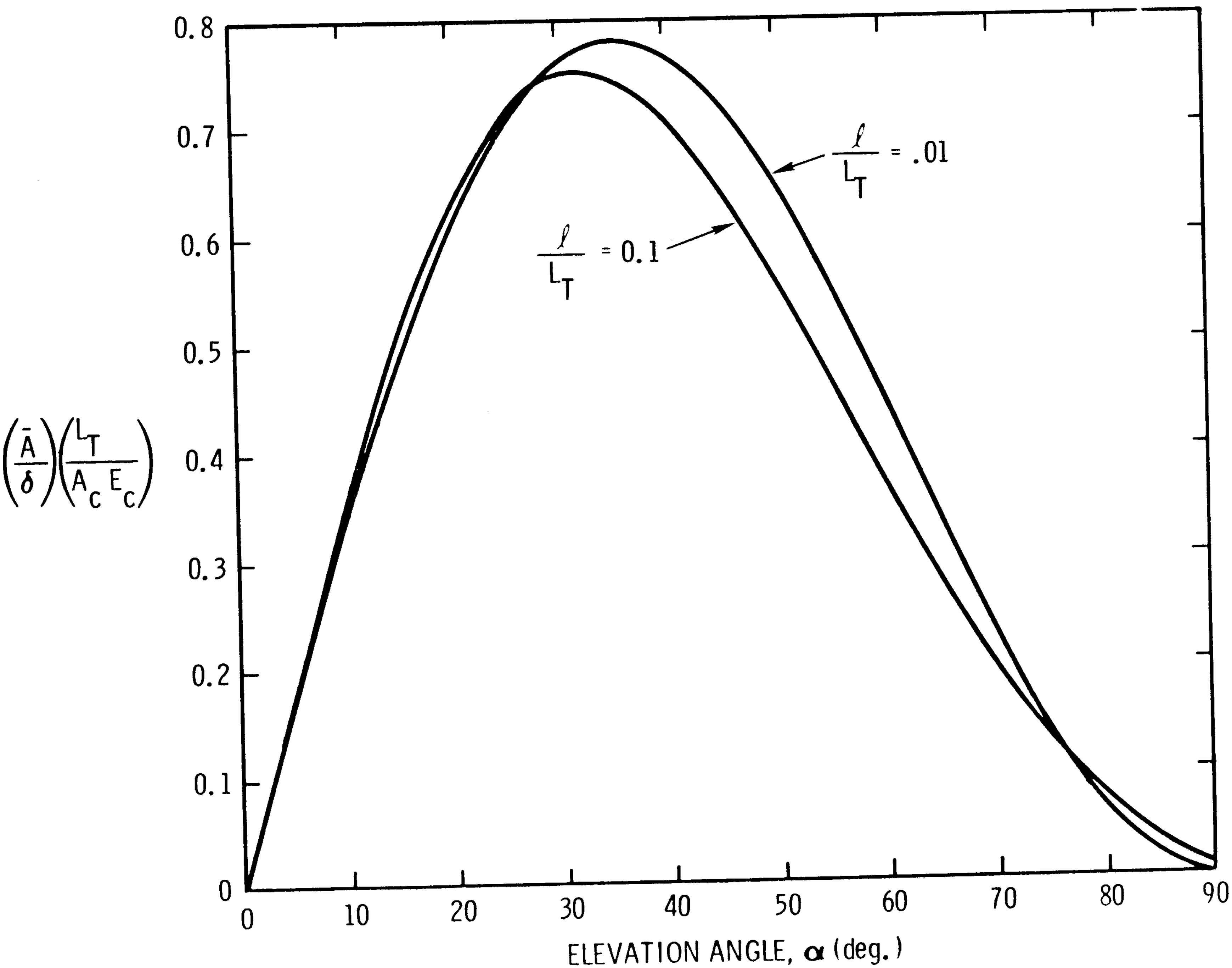
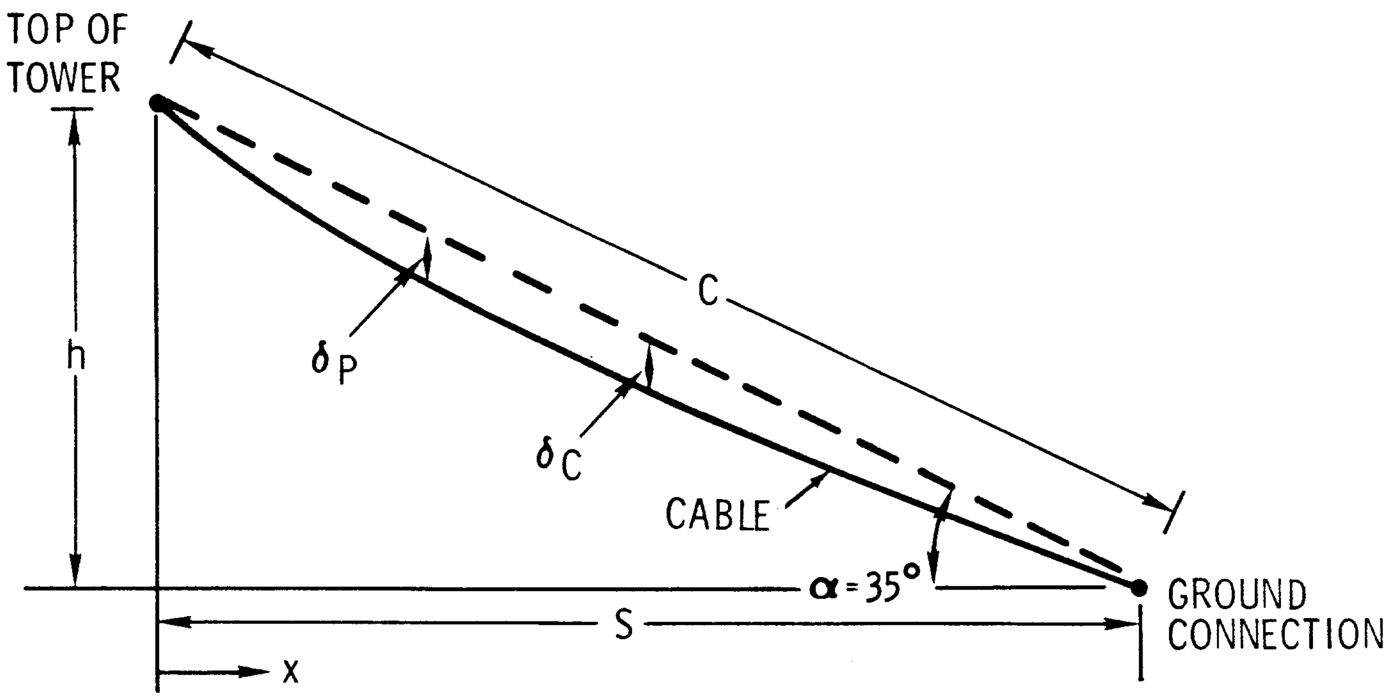

0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
$\left(\frac{\bar{A}}{\delta}\right)\left(\frac{L_T}{A_c E_c}\right)$
$\frac{\ell}{L_T}$ = .01
$\frac{\ell}{L_T}$ = 0.1
0
10
20
30
40
50
60
70
80
90
ELEVATION ANGLE, α (deg.)

FIGURE 2



TOP OF TOWER
C
h
δ_P
δ_C
CABLE
$\alpha = 35°$
GROUND CONNECTION
S
x

FIGURE 3

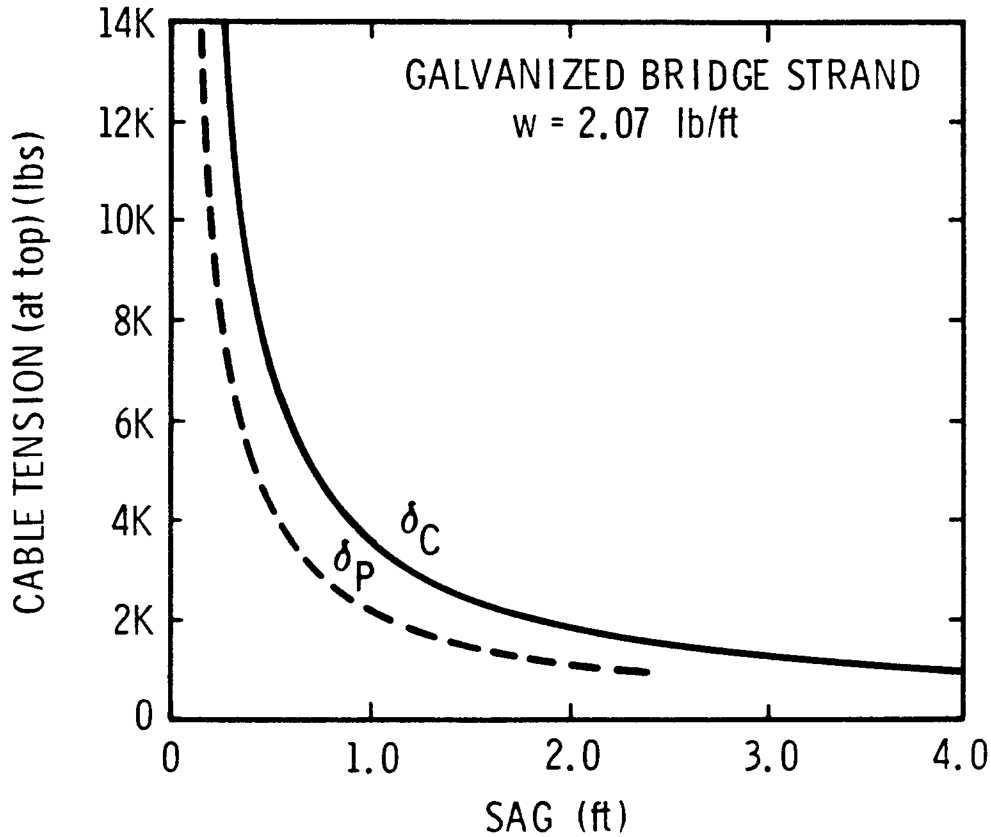

GALVANIZED BRIDGE STRAND
w = 2.07 lb/ft
CABLE TENSION (at top) (lbs)
14K
12K
10K
8K
6K
4K
2K
0
0
1.0
2.0
3.0
4.0
SAG (ft)
δC
δP

FIGURE 4

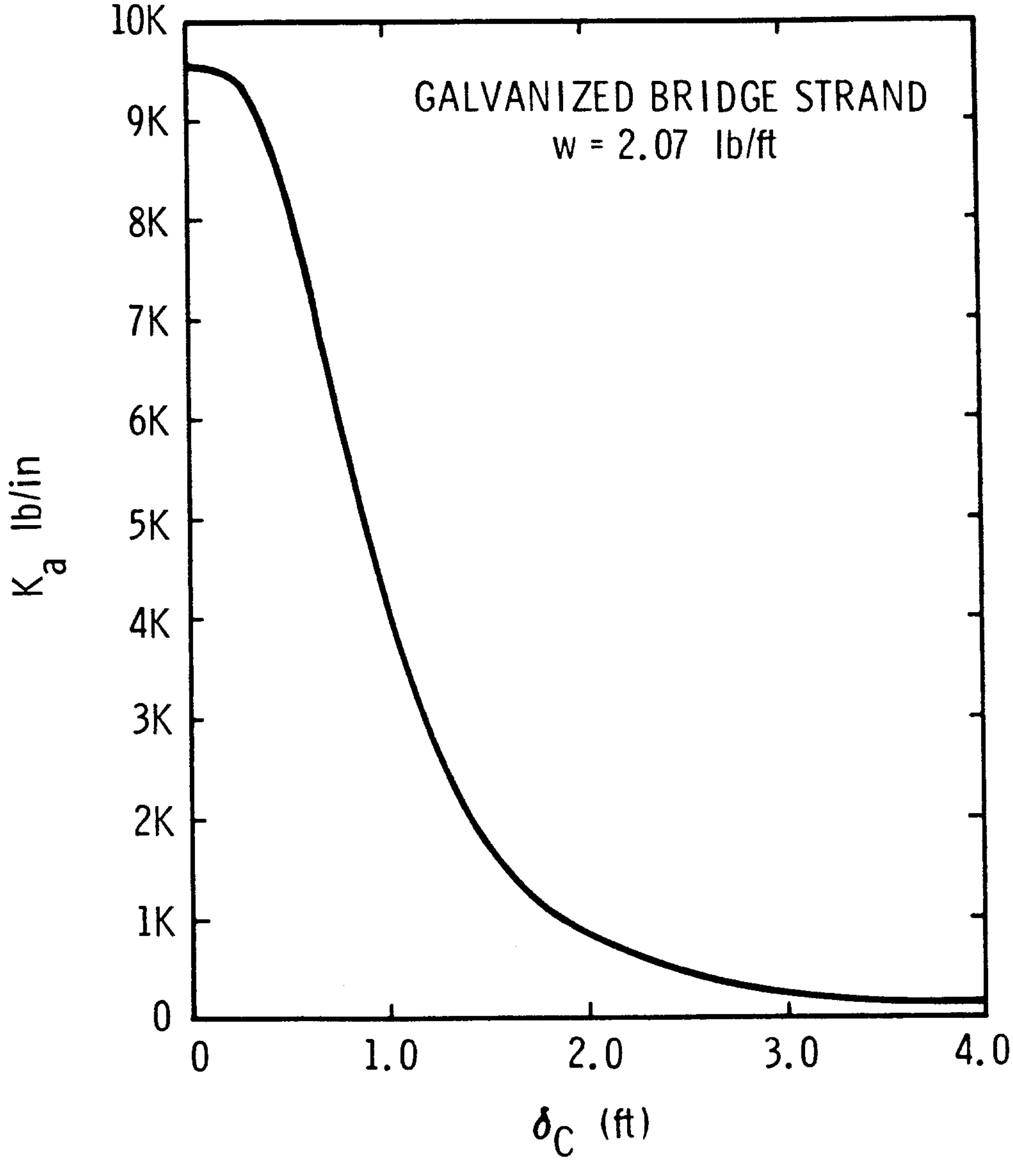
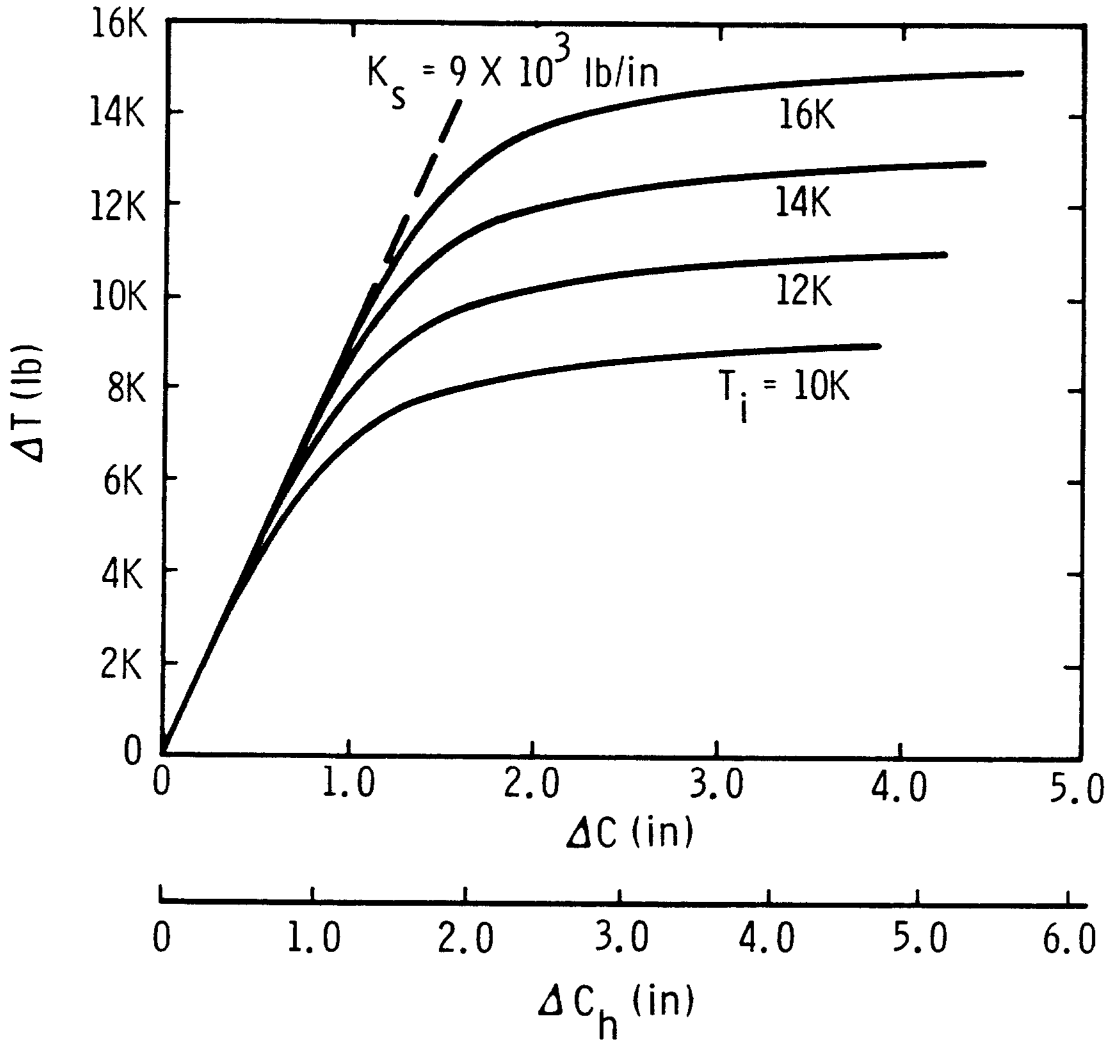

GALVANIZED BRIDGE STRAND
w = 2.07 lb/ft
10K
9K
8K
7K
6K
5K
4K
3K
2K
1K
0
K_a lb/in
0
1.0
2.0
3.0
4.0
δ_C (ft)

FIGURE 5



16K
14K
12K
10K
8K
6K
4K
2K
0
ΔT (lb)
K_s = 9 X 10^3 lb/in
16K
14K
12K
T_i = 10K
0
1.0
2.0
3.0
4.0
5.0
ΔC (in)
0
1.0
2.0
3.0
4.0
5.0
6.0
ΔC_h (in)

FIGURE 6

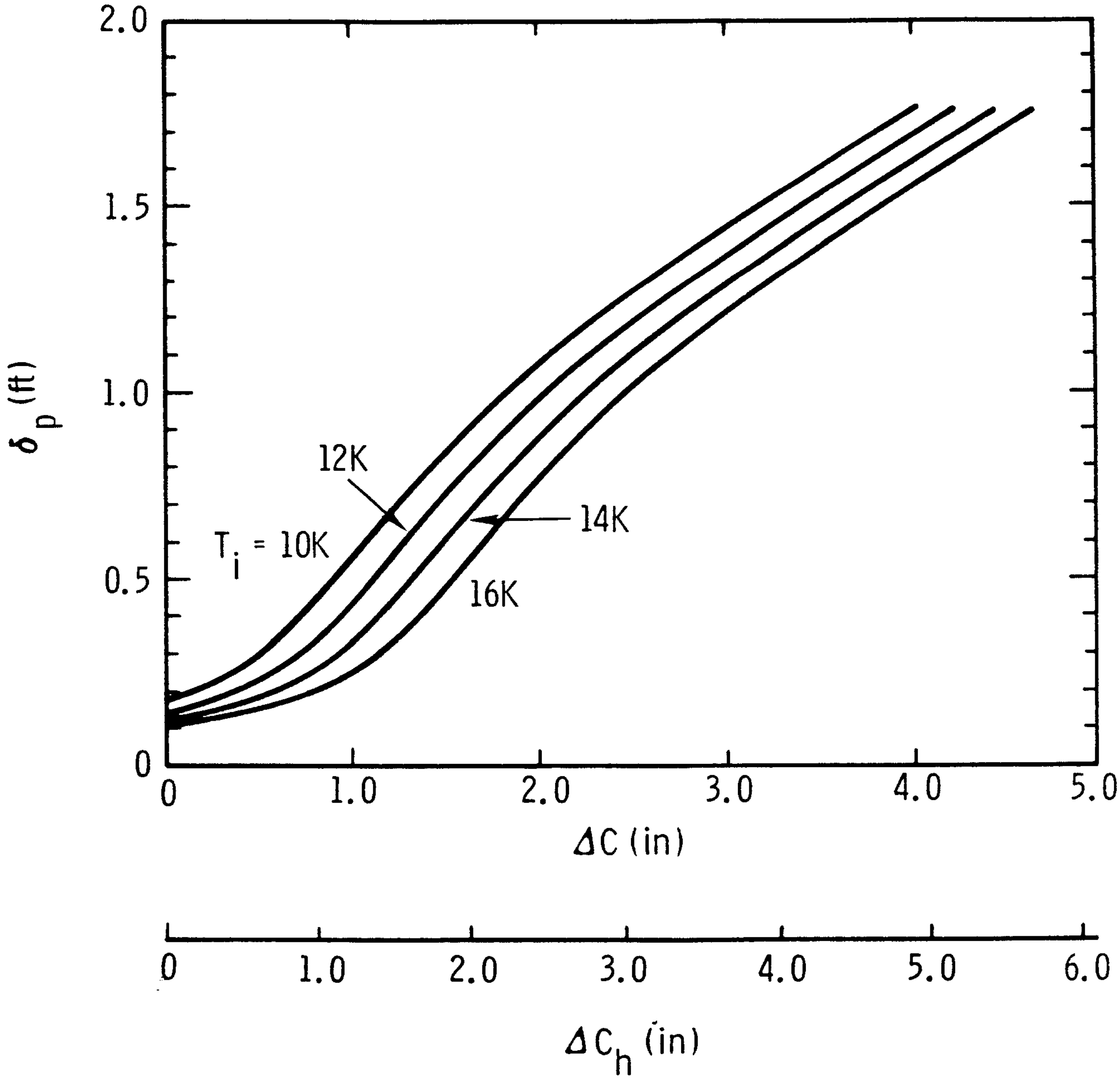
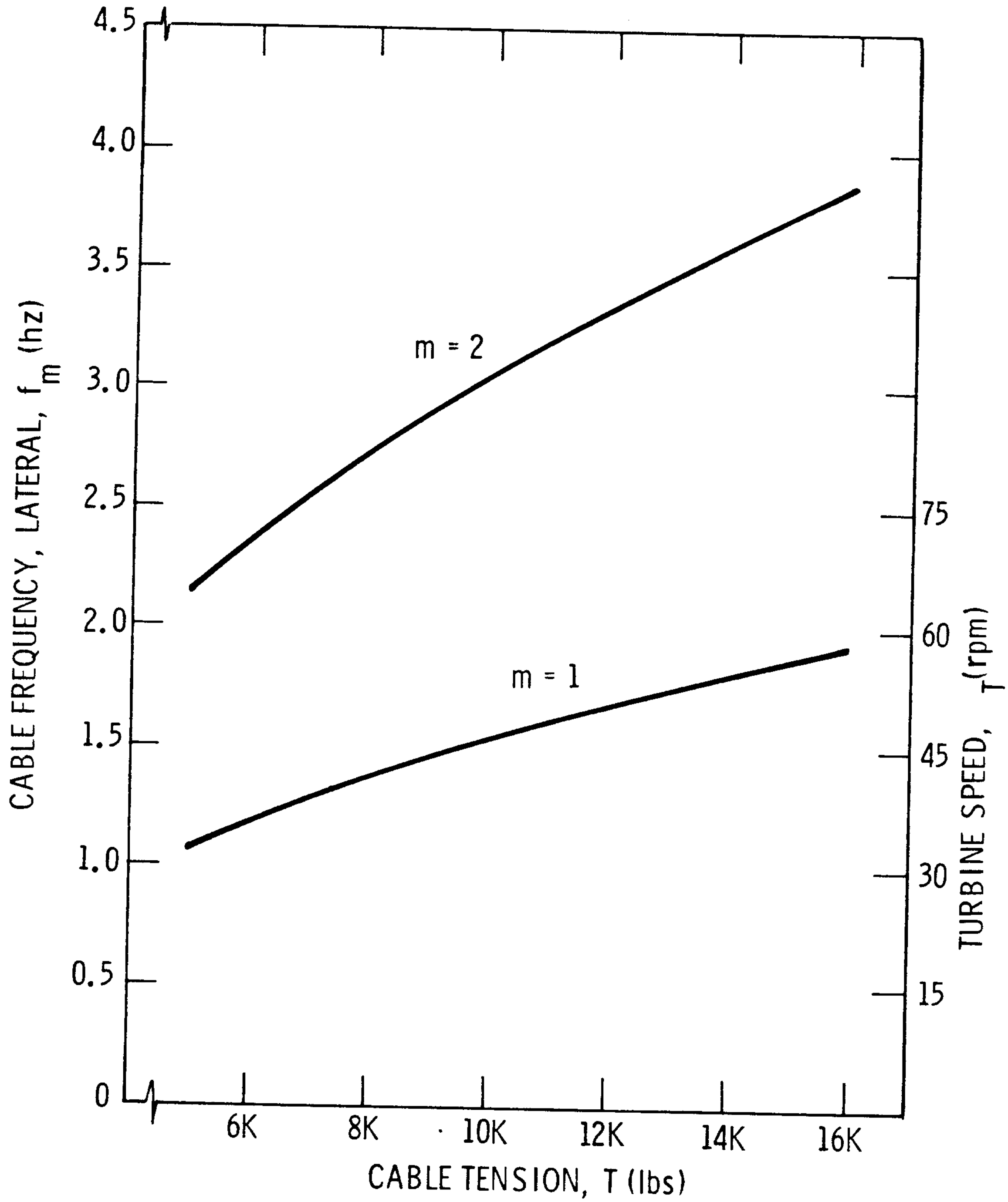

2.0
1.5
1.0
0.5
0
δ_p (ft)
12K
T_i = 10K
14K
16K
0
1.0
2.0
3.0
4.0
5.0
ΔC (in)
0
1.0
2.0
3.0
4.0
5.0
6.0
ΔC_h (in)

FIGURE 7



4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
CABLE FREQUENCY, LATERAL, f_m (hz)
m = 2
m = 1
75
60
45
30
15
TURBINE SPEED, T (rpm)
6K
8K
10K
12K
14K
16K
CABLE TENSION, T (lbs)

FIGURE 8

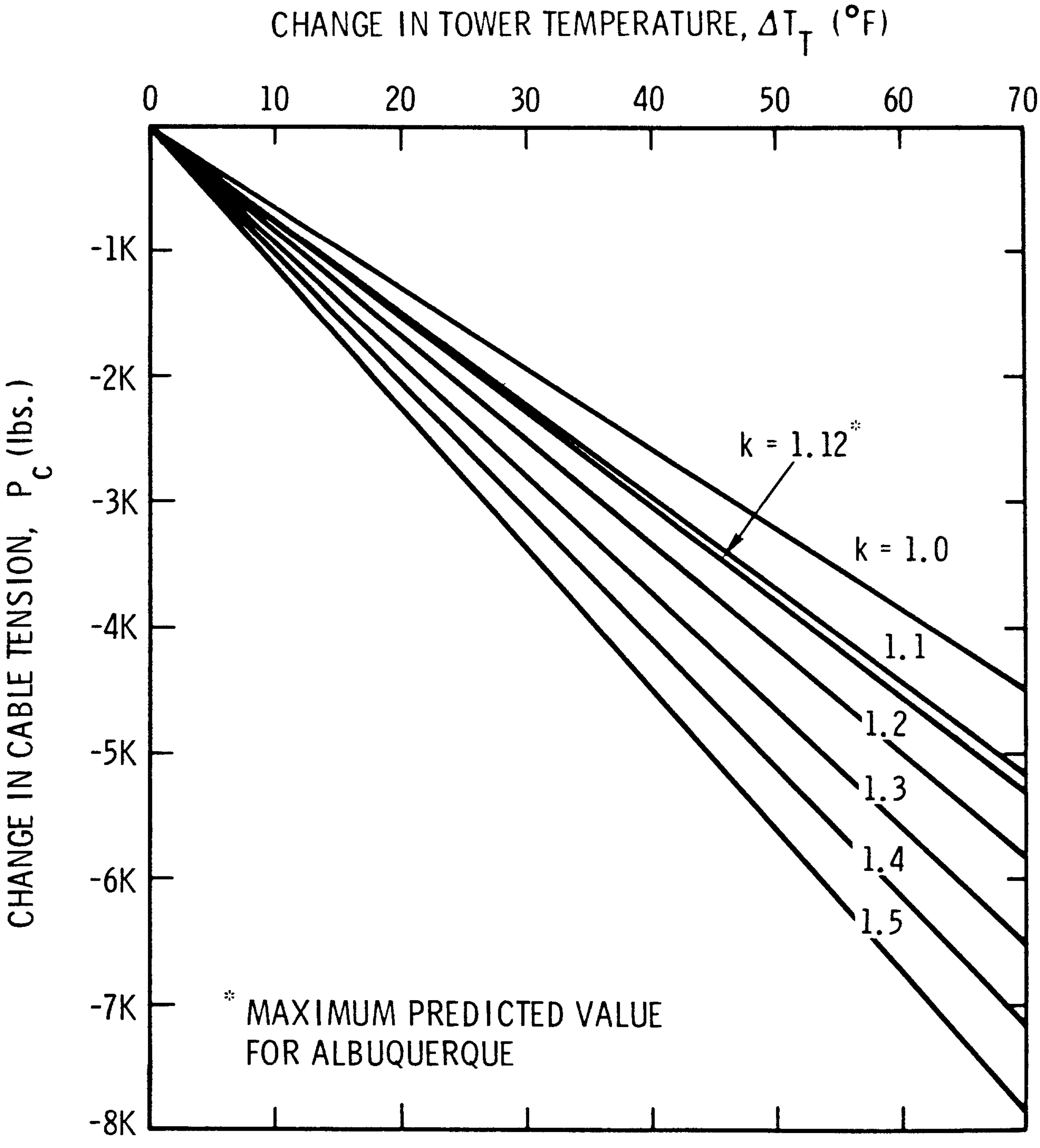

CHANGE IN TOWER TEMPERATURE, ΔT_T (°F)
0
10
20
30
40
50
60
70
CHANGE IN CABLE TENSION, P_c (lbs.)
-1K
-2K
-3K
-4K
-5K
-6K
-7K
-8K
k = 1.12*
k = 1.0
1.1
1.2
1.3
1.4
1.5
* MAXIMUM PREDICTED VALUE
FOR ALBUQUERQUE

FIGURE 9

DISTRIBUTION:
TID-4500-R66, UC-60 (283)

R. J. Templin
Low Speed Aerodynamics Section
NRC-National Aeronautical Establishment
Ottawa 7, Ontario, Canada K1A0R6

A. Robb
Memorial Univ. of Newfoundland
Faculty of Eng. & Applied Sciences
St. Johns, Newfoundland
Canada A1C5S7

H. Sevier
Rocket and Space Division
Bristol Aerospace Ltd.
P.O. Box 874
Winnipeg, Manitoba
R3C 2S4 Canada

V. A. L. Chasteau
Department of Mech. Engineering
The University of Auckland
Private Bag
Auckland, New Zealand

Jet Propulsion Lab
4800 Oak Grove Drive
Pasadena, CA 91103
Attn: G. Herrera

National Aeronautics and Space Adm.
Langley Research Center
Hampton, VA 23665
Attn: R. Muraca, MS317

National Aeronautics and Space Adm. (2)
Lewis Research Center
2100 Brookpark Road
Cleveland, OH 44135
Attn: J. Savino, MS500-201
R. L. Thomas

U.S. Department of Energy (3)
600 E Street NW
Washington, DC 20545
Attn: L. Divone

University of New Mexico (2)
Albuquerque, NM 87106
Attn: K. T. Feldman, Energy Center
V. Skoglund, ME Department

University of Hawaii
Wind Engineering Research Digest
Spalding Hall 357
Honolulu, HI 96822
Attn: A. N. L. Chin

Colorado State University
Dept. of Civil Engineering
Fort Collins, CO 80523
Attn: R. N. Meroney

Illinois Institute of Technology
Dept. of Electrical Engineering
Chicago, IL 60616
Attn: A. G. Vacroux

New Mexico State University
P.O. Box 3450
Las Cruces, NM 88003
Attn: M. M. Sluyter

Oklahoma State University
Stillwater, OK 74074
Attn: W. L. Hughes, EE Department

Oregon State University (2)
Corvallis, OR 97331
Attn: R. Wilson, ME Department
R. W. Thresher, ME Department

Texas Tech University (2)
P.O. Box 4289
Lubbock, TX 79409
Attn: K. C. Mehta, CE Department
J. Strickland, ME Department

Tulane University
Dept. of Mechanical Engineering
New Orleans, LA 70018
Attn: R. G. Watts

Wichita State University
Aero Engineering Department
Wichita, KS 67208
Attn: M. Snyder

U.S. Department of Energy (2)
Nevada Operations Office
P.O. Box 14100
Las Vegas, NV 89114
Attn: R. Ray, Operations
H. Mueller, ARL

Los Alamos Scientific Lab (7)
P.O. Box 1663
Los Alamos, NM 87544
Attn: R. R. Brownlee, J-9
J. R. Bartlit, QU-26
J. D. Balcomb, Q-DO-T
R. G. Wagner, P-5
J. Nachamkin, T-DO-TEC
S. W. Depp, E-DO
H. Deinken, ADWP-1

U.S. Department of Energy (3)
Albuquerque Operations Office
P.O. Box 5400
Albuquerque, NM 87115
Attn: D. K. Nowlin
D. C. Graves
D. W. King

R. Camarero
Faculty of Applied Science
University of Sherbrooke
Sherbrooke, Quebec
Canada J1K 2R1

American Wind Energy Association
21243 Grand River
Detroit, MI 48219

South Dakota School of Mines & Tech.
Dept. of Mechanical Engineering
Rapid City, SD 57701
Attn: E. E. Anderson

Iowa State University
Climatology and Meterology
312 Curtiss Hall
Ames, IA 50010
Attn: E. S. Takle

Aeroenvironment, Inc.
660 South Arroyo Parkway
Pasadena, CA 91105
Attn: P. B. S. Lissaman

Northwestern University
Dept. of Civil Engineering
Evanston, IL 60201
Attn: R. A. Parmelee

Helion
P.O. Box 4301
Sylmar, CA 91342
Attn: J. Park

Aerophysics Company
3500 Connecticut Avenue NW
Washington, DC 20008
Attn: W. F. Foshag

MIT
Aero/Astro Department
Cambridge, MA 02138
Attn: W. L. Harris

University of Oklahoma
Aero Engineering Department
Norman, OK 73069
Attn: K. Bergey

J. Fischer
F. L. Smidth & Company A/S
Vigerslevalle 77
2500 Valby
Denmark

U.S. Department of Energy
Division of Military Application
Safety and Facilities A-364
Washington, DC 20545
Attn: H. M. Busey

P. Bailey
P.O. Box 3
Kodiak, AK 99615

Arizona State University
Solar Energy Collection
University Library
Tempe, AZ 85281
Attn: M. E. Beecher

Lockheed-California Co.
Box 551-63A1
Burbank, CA 91520
Attn: U. A. Coty

University of California (4)
Lawrence Livermore Laboratory
P.O. Box 808, L-340
Livermore, CA 94550
Attn: D. W. Dorn
D. Hardy
J. Nucholls
J. Emmett

General Electric Co.
Valley Forge Space Center
King of Prussia, PA 19406
Attn: J. A. Garate

Michigan State University
Division of Engineering Research
East Lansing, MI 48824
Attn: O. Krauss

A. H. Stodhart
Electrical Research Associates
Cleeve Road
Surrey, England

West Texas State University
Department of Physics
P.O. Box 248
Canyon, TX 79016
Attn: V. Nelson

Amarillo College
Amarillo, TX 79105
Attn: E. Gilmore

Southwest Research Institute
P.O. Box 28501
San Antonio, TX 78228
Attn: R. K. Swanson

U.S. Department of Agriculture
Agriculture Research Center
Building 303
Beltsville, MD 20705
Attn: L. Lliljdahl

University of Alaska
Geophysical Institute
Fairbanks, AK 99701
Attn: T. Wentink, Jr.

Bonneville Power Administration
1002 NE Holloday
Portland, OR 97208
Attn: E. J. Warchol

Kaman Aerospace Corporation
Old Windsor Road
Bloomfield, CT 06002
Attn: W. Batesole

Stanford University
Stanford Electronics Laboratories
Radioscience Laboratory
Stanford, CA 94305
Attn: A. V. da Rosa

Dr. O. Ljungstrom
Salgstigen 12, S-181 62
Lidingo 3
Sweden

H. Dorner
Institut fur Flugzengbau der
Universitat Stuttgart
7000 Stuttgart 80, Pfaffenwaldring 31
Germany

Dr. A. Fritzsche
Manager, Mechanical Design and Systems
Dornier System GmbII
Postfach 1360
7990 Friedrichshafen
Germany

Maxwell Laboratories, Inc.
9244 Balboa Avenue
San Diego, CA 92123
Attn: A. Kolb

Mission Research Corporation
P.O. Box 1209
La Jolla, CA 92038
Attn: V. van Lint

Director
Naval Research Laboratory
Washington, DC 20390
Attn: T. Coffey, Code 7700

Commander
Naval Surface Weapons Center
Dahlgren, VA 22448
Attn: M. F. Rose

Commander
Naval Air Systems Command
Headquarters
Washington, DC 21360
Attn: R. Wasneski

Physics International Company
2700 Merced Street
San Leandro, CA 94577
Attn: J. Martinez

R&D Associates
P.O. Box 9695
Marina del Rey, CA 90291
Attn: R. LeLevier

Science Applications, Inc.
P.O. Box 2351
La Jolla, CA 92038
Attn: J. R. Beyster

Science Applications, Inc.
1257 Tasman Drive
Sunnyvale, CA 94086
Attn: R. Miller

Simulation Physics, Inc.
41 "B" Street
Burlington, MA 01803
Attn: R. Little

ARACOR
P.O. Box 1439
Los Altos, CA 94022
Attn: R. Armistead

Pulsar Associates, Inc.
7911 Herschel Avenue
La Jolla, CA 92037
Attn: C. Jones

JAYCOR, Inc.
205 S Whiting Street
Suite 500
Alexandria, VA 22304
Attn: R. Sullivan

S. M. Lanbert, Manager
Energy Economics and Forecasting
Planning and Economics
Shell Oil Company
P.O. Box 2463
Houston, TX 77001

Mr. Robert B. Allen
General Manager
Dynergy Corp.
P.O. Box 428
1269 Union Avenue
Laconia, NH 03246

Tim P. Romero
P.O. Box 2806
Las Vegas, NM 87701

Sam Hanson
DOE/DSE
1800 G Street NW
Washington, DC 20550

W. W. Garth, IV
Tyler & Reynolds & Craig
One Boston Place
Boston, MA

Edward Chesbro
Londonderry, VT 05148

James D. Foch, Jr.
Department of Aerospace
Engineering Sciences
University of Colorado
Boulder, CO 80309

Dale T. Stjernholm, P.E.
Mechanical Design Engineer
Morey/Stjernholm & Associates
1050 Magnolia St.
Colorado Springs, CO 80907

Paul N. Vosburgh
Alcoa Allied Products
Alcoa Center, PA 15069

Dr. B. F. Blackwell
Department of Mechanical Eng.
Louisiana Tech. University
Ruston, LA 71270

Fred Thompson
Atari, Inc.
155 Moffett Park Drive
Sunnyvale, CA 94086

Arthur G. Craig
Alcoa Mill Products
Alcoa Center, PA 15069

J. B. Draft
Nederlands Energy Research
Foundation (E.C.N.)
Physics Department
Westerduinweg 3 Petten (nh)
The Netherlands

1000 G. A. Fowler
1260 K. Touryan
1280 T. B. Lane
1281 J. H. Biffle
1281 R. Rodeman
1284 R. T. Othmer
1300 D. B. Shuster
1320 M. L. Kramm
1324 E. C. Rightley
1324 L. V. Feltz
1330 R. C. Maydew
1332 P. C. Klimas
1333 S. McAlees, Jr.
1333 R. E. Sheldahl
3161 J. E. Mitchell (50)
3161 P. Wilson
5000 A. Narath
5333 R. E. Akins
5333 J. W. Reed
5431 D. W. Lobitz
5700 J. H. Scott
5710 G. E. Brandvold
5711 J. F. Banas
5715 R. H. Braasch
5715 E. G. Kadlec
5715 C. E. Longfellow
5715 R. C. Reuter (100)
5715 W. N. Sullivan
5715 M. H. Worstell
5740 V. L. Dugan
5742 S. G. Varnado
8000 T. B. Cook, Jr.
8010 A. N. Blackwell
8100 L. Gutierrez
8121 L. I. Weingarten
8266 E. A. Aas
3141 C. A. Pepmueller (Actg.) (5)
3151 W. L. Garner (3)
For DOE/TIC (Unlimited Release)

Reprinted January 1980
Reprinted October 1984