CHARA Technical Report

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Thermal Effects on Vacuum Tube Supports

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1. INTRODUCTION

The vacuum tubes relaying light from the six collecting telescopes of the CHARA Array will be supported at heights above local grade of up to 30 feet. These supports consist of galvanized steel pipe attached to concrete footings. This report evaluates the effects of solar irradiation leading to differential expansion/contraction and resulting bending of the pipes which may stress the vacuum connection points between pipes with resulting degradation of the connecting sleeves at pipe joints, and eventual loss of vacuum.

2. ESTIMATE OF THE THERMAL DEFLECTION

2.1. Emissivity of galvanized steel and painted steel

From Wolfe (1965) the total hemispherical emissivity of galvanized steel is 0.07. However, this is most likely for a polished surface, while the CHARA pipes will be relatively rough. Lide (1994) gives an emissivity for steel of 0.35 (clean) and 0.80 (oxidized). For rough, galvanized steel we will adopt a representative value of 0.45, which is unlikely to be incorrect by more than a factor of 2.

From Zissis (1993), paints (almost independent of color) fall in the emissivity range 0.7-0.9. So the emissivity of painted posts will be significantly larger than the emissivity of freshly galvanized posts. The sway will be approximately proportional to emissivity, so this shows without detailed calculation that painted posts will sway up to 2$\times$ more than galvanized posts.

2.2. Effective insolation on the posts

At the altitude of Mt. Wilson, the solar insolation with the sun at zenith is approximately 1 kW/m^2. Maximum insolation on the posts occurs close to zenith distance 30°. From Astrophysical Quantities (Allen) the fractional transmission of the atmosphere to total solar radiant energy with a precipitable water vapor content of 1 cm per unit airmass is no

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less than 0.79 down to zenith distance 60°. Including the geometric projection effect, the effective insolation on a post will be at least 395 W/m^2.

2.3. Estimate conductive heat loss

For this example, consider the larger poles, for which the effects will be greatest: 9 m (30 ft) high, and 30 cm (12 inches) in diameter, with a skin thickness of 3/8 in (0.95 cm). The heat will have to flow an equivalent distance in steel approximately equal to the radius of the post, or 15 cm.

Convert this to a one-dimensional problem by assuming a long sheet of steel. The coefficient of thermal conductivity for steel is 0.107 calories/sec/cm^2/°C.

Changing to common units, the mean insolation on the pole will be 0.0395 W (0.0094 calories per second) per cm^2. For the example case, this corresponds to 0.28 calories per linear cm of vertical height. Initially, assume an emissivity of 0.8, appropriate to typical paints, giving an absorbed insolation of 0.22 calories per linear cm of height.

We use the heat flow equation, requiring that the heat introduced by insolation is equal to the heat conduction to the cool side of the pipe supported by the temperature difference. Since we are computing conduction for only one "half" of the pipe, we reduce the insolation by a factor of 2. This gives a temperature differential of 16°C.

2.4. Estimate radiative heat loss

Thermal radiation from the heated post will tend to reduce the temperature differential. For grey-body emission, the thermal emission from a surface of temperature T will be $\epsilon\sigma T^4$ where $\sigma = 5.67 \times 10^{-12}$ Watt per square centimeter per K^4. For a mean temperature of 270K and a differential of 16K, the differential in radiative power will be 0.0057 Watt per square centimeter. This is only 15% of the insolation, and is negligible, but tends to slightly reduce the temperature differential.

2.5. Estimate convective heat loss

The heat loss due to convection cannot be computed as accurately as the radiative and conductive losses, but an indicative result can be obtained. From Eschbach (1974), for poles described above, the heat loss will be approximately $0.0011(\Delta_T)^{\frac{5}{4}}$ Watts/cm^2. For the assumed insolation, this gives an equilibrium temperature differential of 10°C. Convection, therefore, is about as effective as conduction and may be the dominant heat loss mechanism.

2.6. Estimate of the temperature differential

The conductive and convective heat losses are each approximately proportional to the temperature differential, and combining them in this approximation, the resulting equilibrium temperature differential is approximately 6°C.

2.7. Compute the sway of the post

The displacement of the top of the pipe, in the small angle approximation, will be $S = L^2 \Delta_T C_{TE}/D$, where L is the post height, T is the temperature differential, C_{TE} is the expansion coefficient of the post, and D is the post diameter. For steel, $C_{TE} = 1 \times 10^{-5}$.

For the example of a 9 m high post, $L = 30$ ft, $D = 1$ ft, and the temperature differential is about 6°C. This gives a sway of the pipe of ±0.6 inches, or 1.2 inches diurnal amplitude.

The uncertainties in the insolation, the emissivity, the unaccounted for differential between absorptive and radiative emissivity, and the large uncertainty in convection and wind speed, lead to large uncertainties in this calculation. Maximum thermal sway (maximum is the most relevant information) is likely to be 2× greater than computed here. The sway will be proportional to the emissivity, so for the galvanized finish the sway with the same assumptions would be smaller by about 2×.

3. CONCLUSION AND RECOMMENDATION

Mt. Wilson is characterized, under average conditions, by low winds and clear skies. Under these conditions, the painted post sway due to solar insolation will greatly exceed the sway due to typical winds. Thus the vacuum seal wear will be dominated by thermal effects.

With the galvanized finish, the sway due to solar insolation would be on the same order of typical wind sway, and would not dominate wear. With the galvanized finish, CHARA could expect a seal lifetime of at least 2 years (based on experience at the Navy Prototype Interferometer in Flagstaff). With a painted finish, the lifetime would be shorter — by an uncertain amount.

On the basis of this analysis, it is recommended that all posts taller than 10 ft should be installed with the galvanized finish, which will offer an economical compromise between cost-effectiveness and confidence that thermally induced sway will not be a problem. As the posts age, and the emissivity increases, the sway will increase. At the point where this becomes a problem (if it does), the effected posts should be “re-silvered”. The recommended way to accomplish this is to apply aluminized tape. As demonstrated at many observatories, this provides a long-lived, economical, attractive finish with an emissivity around 0.05, which will be suitable for CHARA. It is possible that a paint can be found which is effectively low emissivity in the critical wavelength region of solar absorption. Such a paint would almost certainly be brilliant white, and might offer a more objectionable appearance in the natural CHARA setting than a reflective finish.

Posts shorter than about 10 ft are much less of a problem, due to the L^2 dependence of the sway effect. The simple model suggests any color paint would be acceptable. However, common sense suggests caution, avoiding very dark colors which would give an even higher effect than calculated.

4. REFERENCES

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