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Aluminum Tube Specification for CHARA Beam Transport

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1. INTRODUCTION

The CHARA optical train must transmit light to the central laboratories without significant degradation of wavefront quality. For this purpose, vacuum tubes will be provided for turbulence-free beam propagation.

Possible materials for the beam tubes include steel and aluminum, as well as less obvious possibilities such as PVC and fiberglass. Each of these was investigated.

Aluminum tube was selected, and this report reviews the mechanical and other considerations that went into the tube specification.

2. GENERAL REQUIREMENTS

The nominal beam diameter is 125 mm (approximately 5 inches) at the telescope, expanding slightly with distance. The notional tube diameter is 8 inches outside, assuming walls of about 0.25 inch. This allows ample margin for alignment, sag, and some drift of adjustment.

The concept for tube installation required end-supporting tube sections of at least 25-foot and preferably 30-foot length. Increasing length allows increased separation between tube support posts and a reduced support post count. Table 1 gives a calculation of the required pipe length for the full 7-telescope Array with 30-foot sections. The OPLE-POP runs bridge the distance from the M10 turning mirrors at the west end of the OPLE building to the larger POP tubes. Table 1 assumes that the tube support points are at 30-foot intervals. If these are adjusted slightly to allow for local terrain, the tube requirement would be increased.

Damage in operation is possible but unlikely. The pipe is available as a stock item in the LA area, though welding of shorter pieces will be required to obtain 30-foot lengths. The suggestion of two sections as spare is conservative — it would be possible to forego spares. The allocation described in Table 1 will leave about 96 feet of partial pieces, which could be returned as scrap.

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TABLE 1. Pipe sections needed, assuming 30-foot lengths, and no welding of pieces to recover material.

Run	Length (ft)	Number of 30′ sections
S1-OPLE	640	22
S2-OPLE	530	18
S3-OPLE	70	3
E1-OPLE	648	22
E2-OPLE	438	15
W1-OPLE	460	16
W2-OPLE	118	4
OPLE-POP	120	4
Spares		2
Total	3024	106

3. PVC TUBE

PVC pipe is convenient for low vacuum use in laboratory settings. It is available at low cost (typically \$0.50/lb for UV-stabilized pipe) and in appropriate size. The elastic modulus is modest, and sag of an end-supported tube is excessive. Some PVC compositions are damaged by UV exposure, though they can be protected with appropriate paint. PVC becomes brittle at low temperature. This factor is difficult to quantify, and implies a rather indeterminate risk. The CTE is large.

4. FIBERGLASS TUBE

Fiberglass is available in suitable size, and with adequate rigidity for end suppport. Preliminary inquiry indicated that the cost would be high, in the vicinity of \$20/foot.

5. STEEL TUBE

Steel has the advantage that it is readily available with a wide variety of wall thicknesses.

Steel tube and pipe are usually fabricated by rolling and welding steel sheet. Consequently, the cross-section may normally be slightly out of round, and surface irregularities may be expected at the weld seam. Steel is subject to rust. It may be protected with appropriate paint, perhaps implying a maintenance problem. The strength is ample, but the weight is high. Typical prices are in the vicinity of \$7 per foot.

6. ALUMINUM TUBE

Aluminum tube is extruded through a die, and consequently has high dimensional uniformity. Alumimum does not have a corrosion issue. The common alloy, 6061 T6, is readily available in 3000-foot quantity with a 2–3 week delivery time. This alloy has a guaranteed tensile strength of 33,000 PSI and a yield strength of 28,000 PSI. In quantity orders, the tube is available in essentially any section length, subject to delivery concerns. CHARA received quotes as follows: for 8-inch diameter 3/16 inch wall, $9.79 per foot; and for 8-inch diameter 1/4 inch wall, $12.83 per foot.

The stronger 2024 alloy, used for example in aircraft, has a price about 4 times higher and a delivery time approaching 1 year.

7. JOINTS

Slip-fit O-ring or gasket joints are available for fiberglass and PVC tube. They are designed for a pressurized pipe, and the function for an evacuated pipe is uncertain. They are available weather proofed, but the significance of this in a mountain freeze/thaw environment is not clear.

Steel O-ring joints are available for commercial steel pipe vacuum systems, and stainless steel bellows are available to accomodate expansion. These are quite expensive.

Aluminum tube has been used successfully at NPOI and IOTA, with clamped neoprene band seals serving as vacuum connections and also to accommodate differential expansion. NPOI, with a total length of about 700 feet and a proportional number of joints, reports that the system pumps down to 0.01 torr in a few hours, and remains below 0.1 torr for days at a time (White, 1998).

8. RECOMMENDATION FOR MATERIAL

Aluminum is the clear favorite. The somewhat lower initial material cost of steel is outweighed by the weight and handling issues, by the irregular surface, and by corrosion and maintenance concerns.

9. MECHANICAL DESIGN

From preliminary study it is clear that aluminum tube with wall thickness of about 1/4 inch and length of about 20 feet will be suitable. The choice of exact section lengths and wall thicknesses follows.

The self-weight sag of an end-supported tube can be found from the formula for the deflection of a beam,

$$\delta = \frac{5Wl^3}{384EI} \quad , \tag{1}$$

where W is the total weight, l is the length, E is the elastic modulus (taken here as 10×10^6 P.S.I.), and I is the moment of inertia. For a tube of outer diameter d_o and inner diameter d_i, the moment is

$$I = \frac{\pi(d_o^4 - d_i^4)}{64} \quad . \tag{2}$$

Table 2 shows estimates of sag values for several cases.

TABLE 2. Tube sag under self-weight.

Length	3/16-inch wall	1/4-inch wall
20 ft	0.05 inch	0.06 inch
25	0.13	0.14
30	0.28	0.28

Interestingly, the sag is almost independent of wall thickness, but of course depends strongly on length.

Table 3 gives the computed sag for an additional loading of 7 pounds/foot, as in the case of a significant (2 inch deep) ice coating. These deflections are quite moderate and unlikely to be of operational concern.

TABLE 3. Tube sag under self-weight plus 2-inch ice layer.

Length	3/16-inch wall	1/4-inch wall
20 ft	0.13 inch	20.11 inch
25	0.31	0.27
30	0.64	0.56

The ultimate loading of these tubes is of interest in view of possible misfortunes, such as unauthorized visitors climbing on the tubes or tree limbs falling on them.

The maximum stress in a circular beam is

$$\sigma = \frac{M}{I} r \quad , \tag{3}$$

where M is the bending moment, which for a simple beam is $M = Wl/8$, and r is the radius of the beam. Setting the maximum stress to the yield stress for aluminum tube, 28,000 psi, and solving for the maximum load gives

$$W = \frac{8\sigma I}{rl} \quad . \tag{4}$$

Table 4 gives the maximum load for each tube size computed from classical beam stresses. Since the tube is not subject to end loading, the column instability associated with a slim member is not relevant.

Evacuation of the tube will result in compression of the tube wall. This may be estimated from the projection of the atmospheric force on one quadrant of the pipe, or 60 pounds/inch, which will be supported by the pipe wall. For a 1/4-inch wall, the compressive force will be 240 psi.

The evacuation of the tube will induce shear stresses only if the tube deviates from a circular symmetric cross section. An upper limit to the related stress can be estimated for the case of 1/4-inch wall tube, by supposing a tube eccentricity amounting to 1/4 inch difference in principle axes. Consider a 1-inch length of tube. Atmospheric pressure on the elliptical tube

TABLE 4. Maximum load.

Length	3/16-inch wall	1/4-inch wall
20 ft	5200 lb	6800 lb
25	6600	8530
30	5500	7100

will produce a compressive force from each side on the transverse axis 3.7 pounds greater than that on the longitudinal axis, generating a moment of 14.7 inch-pounds on the wall of the tube. The stress generated in the tube wall can be estimated from Equation 3, with $r = 0.125$ inch, $I = 0.004$ square inch, and $M = 14.7$ inch-pounds. The resulting stress is 460 PSI. This is comparable to the self-weight stress, and negligible compared to the yield stress.

10. FIELD TESTS

Based on the numbers above, it was determined that a 30-foot span should give acceptable static characteristics. To allay remaining concerns about dynamic characteristics, a section of 8″ tube with 1/4″ wall was acquired in 32-foot length (by welding together two shorter sections). This pipe was suspended on supports with a 30-foot separation. A number of tests with loading confirmed the calculations for static deflection. It was established that vibrations of the unloaded pipe damped quickly. The heavily loaded pipe (resonance of a few Hz) damped very slowly.

Finally, a series of potentially destructive tests were conducted to obtain an idea of the tube response to impact. The likely impacts were assumed to be falling snow or tree limbs.

An 80-pound sand bag was dropped on the unloaded tube from a height of about 15 feet. The tube deflected about 6 inches and returned to the original position. A timber of similar weight was dropped from the same height. The deflection was somewhat greater, and after several impacts, the tube center was depressed about 0.1 inch. This may have been due to inelastic deformation, or may have been due to shifting of the end supports. There was no visible damage to the tube surface at the impact point, in spite of the fact that the timber had relatively sharp edges.

11. DECISION

Based on the foregoing analyses and tests, the adopted tube length is 30 feet. The free span between support points will be about 29 feet.

In retrospect, this study was quite satisfactory. Due to the high cost of support piers, the change from the initial, nominal 20-foot length to the 30-foot length will save the project approximately $250K.

12. REFERENCES

White, N.M. 1998, private communication.