A LABORATORY STUDY ON THE DRAG FORCE DISTRIBUTION WITHIN MODEL FOREST CANOPIES IN TURBULENT SHEAR FLOW

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Technical Report

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ABSTRACT

The objective of this study was to determine the distribution of the tree drag force within various model forest canopies subjected to various ambient wind conditions. Ultimately this information may be related to diffusion within the forest canopy.

The influence on individual tree drag due to neighboring trees was investigated by arranging the trees in various configurations of columns and rows, the columns being parallel to the ambient wind and the rows being perpendicular. Two tree spacings for the columns and rows were investigated. Furthermore, a large forest canopy field was investigated that covered an area of twenty-one square meters. For this arrangement it was determined that the tree drag field can be classified into two zones - an initial zone and a steady decay zone.

In order to study the influence of the boundary layer development on tree drag, the various arrangements of trees were tested under a thin boundary layer condition and under a thick boundary layer condition.

In the course of this study a strain gage force dynamometer was developed that can reliably measure a drag force as small as 0.1 gram on a model tree.

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1. INTRODUCTION

This laboratory study is one part of a program to study diffusion and flow characteristics in canopy fields under laboratory conditions by the staff in the Fluid Mechanics Program at Colorado State University. The canopy fields considered to date have been those composed of closely spaced plastic strips representing a vegetative field, small cylindrical pegs and small plastic model trees representing a forest. Within the program of study it is intended to relate diffusion characteristics to the drag forces on the elements in the canopy field.

This study investigated the drag forces on the individual elements in a model tree forest. The purpose of this report is to present the methods used and the laboratory information obtained. Subsequent reports will present theoretical developments.

It was not intended to perform a completely exhaustive study of how tree drag varies with the change of certain canopy parameters. Rather, it was intended to obtain at least preliminary knowledge of the influence of the number and spacing of trees and tree submergence in the boundary layer on tree drag. Therefore, the following experiments were performed on both tree spacings of 0.127 m and 0.254 m:

1. Various arrangements of trees in columns and rows were used, ranging from one tree to several.
2. Ambient wind velocities ranged from 0.61 mps to 13.70 mps.
3. The Army Meteorological Wind Tunnel was used for the case where the boundary layer thickness was about three times the

height of the tree, and this was defined as the thick boundary layer condition.

4. The Colorado State University Wind Tunnel was used for the thin boundary layer condition, for which the boundary layer thickness was about 3/4 the height of the tree at the first tree position.

This study was made feasible through the development of a strain gage force dynamometer. This transducer measures accurately the total drag force on an artificial tree regardless of where the resultant of the drag force is applied.

All the experimental work was carried out in the Fluid Dynamics and Diffusion Laboratory, Colorado State University, Fort Collins, Colorado.

2. EXPERIMENTAL EQUIPMENT

2.1 The Model Forest Canopy and Individual Tree Elements

Each artificial tree in the model forest was made of plastic and is ordinarily used for decoration. The dimensions of the trees were about 16 cm in height and 10.8 cm in the largest horizontal direction. Of course, some variation existed from tree to tree. The tree trunk was 0.47 cm in diameter and the distance from the floor to the lower branches was about 3.5 cm (see Figure 2.1).

A 0.0127 m x 0.915 m x 2.440 m plywood plate was used for the foundation of the trees. Holes were drilled in the plate 0.127 m apart in both the longitudinal and lateral directions. The tree trunks were taped to pegs which fitted snugly into the holes. Hence, for the 0.127 m tree spacing, the trees were placed according to the holes on the plate and the 0.254 m tree spacing case was obtained by placing trees in every second hole.

The arrangements of the model tree forest canopies varied quite widely. The trees were arranged in one and three columns parallel to the flows, with from one to several trees in each column. In this report the term "row" refers to the alignment perpendicular to the flow. A sketch of the tree arrangements is placed on each of the figures in Chapter 3. Drag force readings were taken on the following columns:

1. Column A only - trees placed along the centerline of the wind tunnel in the longitudinal direction only.
2. Readings taken on column A with columns B and C in place - columns B and C placed on both sides of column A.

3. Readings taken on column B - columns A and C were still in place.

2.2 The Strain Gage Force Dynamometer

The dynamometer was made of brass and was set on a metal plate as shown in Figure 2.2. This transducer measures accurately the total drag force on an artificial tree regardless of where the resultant of the drag force is applied. The mathematical proof follows.

Figure 2.3 shows a constant resultant force applied at a position, ℓ , on a stiff rod which is inserted into the vertical receptical of the transducer. The force pushes the rod through a horizontal displacement, e . L is a constant, from level A to the bearings at level B . Consider ℓ as a variable, from level B to the resultant position of the force. Two shearing forces, V_1 and V_2 , and two restoring moments, M_1 and M_2 , are exerted on leg 1 and leg 2 respectively. T_{1A} is the tension in leg 1 and T_{2A} the compression in leg 2. W is the total weight of the instrument, considered as a concentrated load at the center.

Consider the free body diagram 1 shown in Figure 2.4:

$$\Sigma F_x = 0 \tag{1}$$

then

$$F = P_1 + P_2 \tag{2}$$

and

$$\Sigma F_y = 0 \tag{3}$$

hence

$$W = T_{2B} - T_{1B} \tag{4}$$

Taking moments about hinge 1 gives:

$$\Sigma M_1 = 0 \tag{5}$$

then

$$T_{2B} = \frac{F\ell}{x} + \frac{W}{2} \tag{6}$$

thus

$$T_{1B} = \frac{F\ell}{x} - \frac{W}{2} . \tag{7}$$

Now consider the free body diagram 2 shown in Figure 2.5:

$$e_1 = e_2 = e \tag{8}$$

from

$$\Sigma M_{A1} = 0 \tag{9}$$

$$M_1 = P_1 L - T_{1B}\, e \tag{10}$$

and

$$\Sigma M_{A2} = 0 \tag{11}$$

$$M_2 = P_2 L + T_{2B}\, e \cdot \tag{12}$$

The total moment is

$$M_1 + M_2 = L\,(P_1 + P_2) + e\,(T_{2B} - T_{1B}) \tag{13}$$

or

$$M_1 + M_2 = LF + eW \tag{14}$$

but ,

$L >> e$ and $F > W$, therefore $LF >> eW$

thus,

$$M_1 + M_2 \cong LF . \tag{15}$$

From Equation (15), the conclusion can be drawn that the total moment depends only on the constant resultant force F and the constant distance L .

The above results were verified experimentally for F ranging from 1 gram to 50 grams and for ℓ ranging from 5 cm to 14 cm. Figure 2.6 is the calibration curve which was obtained by applying the various loads at one position on the stiff rod. The response did not change when the load was shifted to another position on the rod.

Figure 2.7 shows the bridge arrangement of the strain gages and Figure 2.8 shows the dynamometer placed in the model forest.

Instruments used for the study are shown in Figure 2.9. The eight-volt D.C. power supply for the strain gages is shown on the far left and next to it is the circuit which adds M_1 and M_2 electronically. The D.C. Micro Volt-Ammeter, model 425 A type by Hewlett-Packard, is at the far right of Figure 2.9. The strain gages used for this force dynamometer were made by Micro-Measurements Co., type EA-09-125BB-120, which has resistance 120 ± 0.15% ohms and gage factor tolerance ± 0.5.

2.3 The Army Meteorological Wind Tunnel and the Colorado State University Wind Tunnel

The Army Meteorological Wind Tunnel was constructed by Colorado State University for the U.S. Army under Contract DA-36-039-SC-80371. The tunnel features a test section of 27 m length and a nominal cross-sectional area of 1.8 m by 1.8 m with a movable ceiling which can be adjusted for establishing negative and positive longitudinal pressure gradients or a zero pressure gradient. A large contraction ratio of 9:1 in conjunction with a set of four damping screens yields an ambient turbulence level of about 0.1%.

The tunnel can be used for either closed or open loop operation. Test-section air velocities range from about 0 to 37 mps and the ambient temperature of the air can be varied from $0^{o}C$ to $85^{o}C$ at medium speeds. The humidity of the ambient air can be controlled.

The tunnel has a 12.2 m section of the test-section which can be heated or cooled to permit temperature differences between the cold plate and hot air of $65^{o}C$ and the hot plate and cold air of more than $105^{o}C$.

A carriage system is available which permits remote placement of probes. Instrumentation associated with the facility consists of a complete system for sensing, analyzing and recording turbulence statistics and mean value of velocity, temperature and concentration of the tracer (mean values only).

The Colorado State University Wind Tunnel has a test section of 9 m length and a nominal cross-sectional area of 1.8 m by 1.8 m. This tunnel compliments the longer tunnel in that it allows the pursuit of less complex programs in an economical manner. The performance characteristics of the two tunnels are summarized in Table 2.1. Drawings of the wind tunnels are presented in Figures 2.10 and 2.11.

3. RESULTS AND DISCUSSIONS

The model tree forest canopies were subjected to a thin boundary layer condition and to a thick boundary layer condition. Ambient wind velocities of 0.61, 1.52, 3.05, 6.10, 9.15 and 13.70 mps were applied for both conditions of the boundary layer. The flow conditions were thermally neutral, i.e., neither air nor wind-tunnel floor were heated or cooled. Tree spacings of 0.254 m and 0.127 m were studied.

In general, the tree drag force was larger for the thin boundary layer than for the thick boundary layer. The tree drag force was also larger for the 0.254 m tree spacing case than for the 0.127 m tree spacing case.

A three-dimensional flow condition existed for the tree arrangements adopted for this study. The first row of trees created an arrangement of jets and wakes, which persisted for some distance downstream. A wake was formed behind the body of each tree and a jet was formed between the trunks and below the branchy portions of the trees. These jets and wakes showed some degree of influence on the mean value of tree drag force.

The local tree drag vs the longitudinal distance of a tree from the origin are presented in Figures 3.1 to 3.6 for the thin boundary layer condition and in Figures 3.12 to 3.17 for the thick boundary layer for the case of twenty rows of trees and various wind velocities. The local tree drag for similar conditions but for various numbers of rows is summarized in the tables. Figure 3.7 shows the boundary layer development over one column of trees for the thin boundary layer condition and Figure 3.11 shows the boundary layer development over the center column of three columns of trees for the thick boundary layer condition. Figures 3.8 to 3.10 summarize the results for the thin boundary layer condition for a wind velocity of 13.7 mps. The origin was considered to be one tree spacing upstream of the first tree so that the position of the first tree could be plotted on logarithmic graph paper. The reader should note three things, the drag forces of the first row of trees, the reduction of the drag forces from the first row to the second row, and the decay of the drag forces from the third row onward. All the laboratory information is tabulated in Tables 3.1 to 3.12.

Vertical mean velocity profiles were taken behind and between trees, and within and above the canopy at various stations. The transverse mean velocity profiles were also taken at two elevations within the canopy in accord with the above various stations. These are not included in this report.

3.1 Forest Canopy Subjected to a Thin Boundary Layer

The thin boundary layer case was studied in the Colorado State University Wind Tunnel which provided a boundary layer of about eleven centimeters at the first tree position as shown in Figure 3.7. The first tree was located at 1.45 m from the leading edge of the thermal floor test plate on the wind tunnel floor as shown in Figure 2.11. At the tenth tree position, the boundary layer had developed to 29 cm under 6.10 mps ambient wind velocity. The boundary layer development for 1.52 and 13.70 mps ambient wind velocities are also shown in Figure 3.7.

3.1.1 <u>One column of trees</u> - Because of the large number of different test canopy conditions, only one example will be discussed - that for the 13.70 mps ambient wind velocity, considering all the tree rows for 0.127 m and 0.254 m tree spacings (see Figure 3.8).

For all conditions, the drag force on the first tree varied only from 47 grams to 52 grams. The 0.127 m tree spacing had a 9 gram average tree drag force and the 0.254 m tree spacing had a 16 gram average tree drag force. Hence, the average tree drag force for 0.254 m tree spacing was 1.77 times larger than that of 0.127 m tree spacing. The average tree drag forces were calculated without including the forces on the first tree.

For both tree spacing cases, the tree drag force dropped sharply after the first tree. The lowest tree drag occurred at either the second or third tree. Then the drag force varied rather mildly, or even remained constant, on downstream. The lowest tree drag force was at the third tree for the 0.127 m tree spacing and was at the second tree for the 0.254 m tree spacing.

The laboratory data for all the various ambient wind velocites are reproduced in Tables 3.1 and 3.2. Figures 3.1 and 3.4 show the case of twenty rows of trees for all the various ambient wind velocities and Figure 3.8 summarizes the information for all row conditions for an ambient wind velocity of 13.7 mps.

3.1.2 <u>Three columns of trees</u> - As in Article 3.1.1 only one example of the results will be discussed. The example will be the test data for 13.70 mps ambient wind velocity and all the row arrangements (see Figures 3.9 and 3.10).

Once again, the drag force on the first row of trees varied from 47 grams to 52 grams for all row situations. The average tree drag was calculated in the same manner as for the one column of trees case. The 0.127 m tree spacing had a 6.3 gram average tree drag force on column A and a 7.8 gram average drag force on column B. The 0.254 m tree spacing had an average drag force of about twice as large as on the corresponding column in the 0.127 m tree spacing case. They were 13.8 grams and 15.2 grams for column A and column B respectively. Column B consistently had more drag force than column A.

For the 0.254 m tree spacing, the drag force dropped sharply from the first tree to the second tree of column A and column B. The drag force increased at the third row of trees, then decreased slowly farther downstream. For the 0.127 m tree spacing, the drag force dropped sharply to the third row of trees, then increased somewhat for the trees on column B, but dropped slowly and continuously downstream for the trees on column A.

The laboratory data for all the various ambient wind velocities are reproduced in Tables 3.3 to 3.6. Figures 3.2, 3.3, 3.5 and 3.6 show the case of twenty rows of trees for all the various ambient wind velocities and Figures 3.9 and 3.10 summarize the information for all row conditions for an ambient wind velocity of 13.7 mps.

3.2 Forest Canopy Subjected to a Thick Boundary Layer

The model forest subjected to a thick boundary layer was studied in the Army Meteorological Wind Tunnel. The boundary layer thickness at the first tree position was 57 cm thick, which was about three and a half times the height of the trees. The first tree was located at

0.725 m from the leading edge of the thermal floor test plate as shown in Figure 3.11.

The drag force for the thick boundary layer condition was found to be about 14% to 38% lower than that of the thin boundary layer condition for the same ambient wind.

3.2.1 One column of trees - Once again, the condition demonstrated is for 13.70 mps ambient wind velocity and for all row arrangements. Both the 0.127 m and 0.254 m tree spacings will be discussed (see Figure 3.18).

The drag force on the first row of trees for any number of rows was within the range of 32 grams to 37 grams.

The average drag force, not including the forces on the first tree, for the 0.127 m tree spacing was 7 grams and for the 0.254 m tree, spacing was 12 grams. Thus, average drag force for the 0.254 m tree spacing was 1.71 times larger than for the 0.127 m tree spacing, which is the same ratio as that for the thin boundary layer condition.

For the 0.127 m tree spacing, the drag force dropped sharply after the first tree, then increased slightly to the third tree and then kept almost constant to the twentieth row of trees. For the 0.254 m tree spacing, the drag force dropped sharply after the first tree and then stayed almost constant downstream.

Laboratory data for all the various ambient wind velocities are shown in Tables 3.7 and 3.8. Figures 3.12 and 3.15 show the case of twenty rows of trees for the various ambient wind velocities and Figure 3.18 summarizes the information for all row conditions for an ambient wind velocity of 13.7 mps.

3.2.2 Three columns of trees - The example will be the test data for 13.70 mps ambient velocity and for all the row arrangements (see Figures 3.19 and 3.20).

The drag force on the first row of trees varied from 31 grams to 38 grams for all cases.

For the 0.127 m tree spacing, the average drag force was 3.9 grams for trees on column A, and 6.36 grams for trees on column B. The average drag force for the 0.254 m tree spacing was 2.66 times larger than on the 0.127 m tree spacing for readings taken on column A. However, this ratio was equal to 2.04 for readings taken on column B. For the same tree spacing and comparing between the readings taken on columns A and B, the drag force was about 1.63 times larger on column B than on column A for the 0.127 m tree spacing, and was about 1.25 times larger on column B than on column A for the 0.254 m tree spacing.

The drag force dropped mildly after the second row of trees for the 0.254 m tree spacing. For the 0.127 m tree spacing the drag force had another drop at the fifth row for readings taken on column A, however, such a phenomenon did not exist on column B.

The laboratory data for all the various ambient wind velocities are reproduced in Tables 3.9 to 3.12. Figures 3.13, 3.14, 3.16 and 3.17 show the case of twenty rows of trees for various ambient wind velocities and Figures 3.19 and 3.20 summarize the information for all row conditions for an ambient wind velocity of 13.7 mps.

3.2.3 The model forest canopy field - The model forest canopy field covered a 1.83 m x 12.2 m wind tunnel floor area which was covered by 1.27 cm thick plywood. Holes of 0.475 cm diameter were drilled into the plywood at a 0.127 m spacing for both longitudinal and lateral directions. Artificial trees were positioned on the plywood which extended from the leading edge of the thermal floor test plate of the Army Meteorological Wind Tunnel to 12.2 m downstream. Figure 3.21 shows the tree arrangement on the floor of the wind tunnel.

This study was conducted in order to clarify the drag force variation along the longitudinal distance with approximately a two-dimensional flow condition. With the rows of trees extending farther downstream than in previous tests, it was anticipated that the end trend of drag force variation would appear. The following significant information was determined. Two zones of the tree drag phenomena were found as shown in Figure 3.22. These are termed the initial zone and the steady decay zone. The initial zone extended from the first row of trees to the fourth row of trees. In this zone, the drag force decreased steeply from the first row of trees to the second row of trees, then tended to be constant to the fifth row. The steady decay zone started from the fifth row of trees and extended to the end of the canopy field. The steady decay zone is fairly linear on the log-log plot. Figure 3.23 shows the data of the local drag force vs longitudinal distance in dimensionless form for the 6.10, 9.15, and 13.70 mps ambient wind velocities. Figure 3.24 shows a three-dimensional plot of the tree drag force vs longitudinal distance, in dimensionless form, for the 9.15 mps ambient wind velocity.

3.2.4 <u>The influence of tree spacing on the drag force for two trees in line and four trees in line</u> - Figure 3.25 shows the influence of tree spacing on the tree drag force on the downstream tree for two trees placed parallel to the flow direction in a thick boundary layer. Nine tree spacings were tested under three ambient wind velocities. Zero tree spacing means that the measurement was on the first tree alone with the second tree not present.

The figure indicates that the lowest drag force occurred at 0.127 m tree spacing, then it became larger as the trees were separated. The influence of the wake from the first tree on the drag force on the second tree was negligible at about 60 tree heights (or 100 crown diameters) downstream from the first tree for all three ambient velocities.

Figure 3.26 shows the influence of tree spacing on the tree drag force on the first tree for equally spaced four trees in a line parallel to the ambient flow. Drag force measurements were taken on the first tree only. Five tree spacings were tested under three ambient wind velocities. Zero tree spacing means that the measurement was on the first tree alone with the rest of the trees absent. The figure shows that there was very little difference for the tree drag force for all spacings.

3.3 Drag Coefficients of a Single Tree Under Various Ambient Wind Velocities

A single plastic model tree was placed in the free stream region of a wind tunnel air flow. Drag force measurements were made with the strain gage force dynamometer, which was set on a thin flat plate thirty inches above the wind tunnel floor. The boundary layer build-up on the plate was only one-fourth of the tree trunk height at the tree position. The boundary layer thickness was thus, well below the lowest branch of the tree. A uniform wind velocity was thus assured to reach all parts of the tree crown.

Tests were also carried out for the same plastic tree in a thick boundary layer. The ratio of boundary layer thickness to tree height was about three times. The wind velocity profiles were recorded at the tree position with the tree absent. Thus, these two experiments were used to find the drag coefficient of the same model tree in a uniform velocity flow and in a velocity gradient flow.

The drag coefficient C_D and Reynolds number Re are defined as

$$C_D = \frac{f_D}{\frac{1}{2} A \rho \overline{u^2}} \qquad (3.3.1)$$

and

$$Re = \frac{\sqrt{\overline{u^2}}\sqrt{A}}{\nu} \qquad (3.3.2)$$

where

C_D = drag coefficient

f_D = total drag force on the single tree

A = estimated gross silhouette area of the tree crown

ρ = mass density of the fluid acting at the tree crown

ν = kinematic viscosity of the fluid

u = velocity acting at the crown, which varies with distance from the wind tunnel floor for the thick boundary layer condition, but is constant for the uniform velocity.

The mean square velocity was taken with respect to the vertical distance above the wind tunnel floor and was calculated from:

$$\overline{u^2} = \frac{1}{A} \iint_A u^2 \, dA \qquad (3.3.3)$$

Figure 3.27 shows that the drag coefficient C_D is about 0.74 for the tree in free stream and Reynolds number range $7.4 \cdot 10^3 \leq Re \leq 8 \cdot 10^4$, and for the tree well submerged in the boundary layer the Reynolds number ranging $1.27 \cdot 10^4 \leq Re \leq 7.31 \cdot 10^4$. It is interesting to note that a finite cylinder with L/d equal to 5 has $C_D = 0.72$ for $4 \cdot 10^3 \leq Re \leq 2 \cdot 10^5$, with the finite cylinder subject to uniform velocity perpendicular to the axis.

For the single tree submerged in a thick boundary layer as described in this report, it was found that the ambient velocity at the height of the geometric center of the crown was nearly equal to $\sqrt{\overline{u^2}}$. A table of wind velocities at the geometric center of the tree crown and of $\sqrt{\overline{u^2}}$ from Equation (3.3.3) is furnished below.

Wind Velocity Outside the Boundary Layer (mps)	Velocity at the Geometric Center of the Tree Crown (mps)	$\sqrt{\overline{u^2}}$(mps)
3.05	2.74	2.70
6.10	5.12	5.09
9.15	7.75	7.71
13.70	11.65	11.52
18.30	15.72	15.51

4. CONCLUSIONS

A three-dimensional turbulent boundary layer was formed over the one-column and three-column model tree forests. The irregularity of the shape and density of the trees added some variation in the trend of the tree drag forces. After consideration of the drag forces on the individual trees under various configurations of the canopies, the following conclusions can be drawn:

1. Generally, a model tree spacing of 0.254 m spacing gave a larger drag force per tree than the 0.127 m spacing.
2. The thinner the boundary layer, the larger the drag force.
3. Generally, the drag force per tree was not greatly affected by the number of rows of trees. The drag force on a particular tree depended mostly on the position of that tree from the first row.
4. For three columns of trees, the drag force on the center column was smaller than on the side columns.
5. The drag force on one column of trees only was larger than that on the center column of three columns of trees. However the drag force on the outside column of the three column arrangement, in general, was only slightly smaller than on the one column only arrangement.
6. The drag coefficient for a single tree, as based on Equation (3.3.1) is constant within the Reynolds number range in which this work was performed. Therefore, it can be concluded that

the drag phenomenon was that of form drag, not viscous shear drag.

The study of the 0.254 m tree spacing model forest canopy, which covered a wind-tunnel floor area of 1.83 m x 12.2 m, provided approximately a two-dimensional flow condition. Two zones, namely an initial zone and a steady decay zone, for the individual tree drag force, were found. Each of the zones possess unique characteristics on how the drag forces vary. The initial zone shows a sharp drop in tree drag force from the first row of trees to the second row and then maintains constant tree drag force downstream. The steady decay zone has a tree drag decreasing trend which shows a linear line on a log-log plot. A more dense tree arrangement which furnishes a better two-dimensional flow condition may give a better understanding of the behavior of the tree drag in these two zones.

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6. APPENDIX

6.1 List of Symbols

Symbol

Symbol	
f_D	Local drag force of a tree, kilograms on Figures, grams in Tables
f	The drag force on a tree which is presented at the first row of that column
x	Longitudinal distance along the wind tunnel floor, meters
y	Vertical distance above the wind tunnel floor, meters
L	The tree spacing, meters
U_a	Ambient wind velocity, meters per second.

6.2 List of Tables

Note: The drag forces of the first row of trees, the reduction of the drag forces from the first row to the second row, and the decay of the drag forces from the third row onward are tabulated in Table 3.1 to 3.12 for each case of the one-column and three-column tree arrangements.

THIN BOUNDARY LAYER

THICK BOUNDARY LAYER

TABLE 2.1 PERFORMANCE CHARACTERISTICS OF THE ARMY METEOROLOGICAL AND THE COLORADO STATE UNIVERSITY WIND TUNNELS

Characteristic	Army Meteorological Wind Tunnel	Colorado State University Wind Tunnel
1. Dimensions		
Test-section length	27 m	9.2 m
Test-section area	3.4 m^2	3.4 m^2
Contraction ratio	9.1	9.1
Length of temperature controlled boundary	12 m	3.1 m
2. Wind-tunnel drive		
Total power	200 kw	75 hp
Type of drive	4-blade propeller	16-blade axial fan
Speed control: coarse	Ward-Leonard DC control	single-speed induction motor
Speed control: fine	pitch control	pitch control
3. Temperatures		
Ambient air temperature	5^{o} C to 95^{o} C	not controlled
Temp. of controlled boundary	5^{o} C to 205^{o} C	ambient to 95^{o} C
4. Velocities		
Mean velocities	approx. 0 mps to 37 mps	approx. 1 mps to 27 mps
Boundary layers	up to 50 cm	up to 20 cm
Turbulence level	low (about 0.1 percent)	low (about 0.5 percent)
5. Pressures	adjustable gradients	not controlled
6. Humidity	controlled from approx. 20% to 80% relative humidity under average ambient conditions.	not controlled

For all the following tables:

I: Drag force of the first tree of that column, gram.

II: The reduction ratio of the tree drag between first and second tree.

III: The maximum and minimum of the local tree drag from third tree onward, gram.

TABLE 3.1 THIN BOUNDARY LAYER, 0.127m TREE SPACING, Col. A. only.

Row	1			2			3			5			10			20		
Meter/sec	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III
.61	.18	-	-	.18	1.80	-	.18	2.57	.05	.18	1.50	.05~ .07	.18	1.80	.03 ~ .05	.18	1.80	.05 ~ .05
1.52	.65	-	-	.60	1.71	-	.35	1.75	.22	.50	2.78	.11~ .19	.66	2.64	.10 ~ .10	.65	3.61	.11 ~ .18
3.05	3.30	-	-	3.12	3.67	-	2.15	4.30	.69	2.50	5.30	.30~ .47	2.46	3.28	.39 ~ .44	2.60	5.20	.35 ~ .50
6.10	9.70	-	-	9.70	4.85	-	9.70	9.70	2.00	10.20	6.18	1.40~ 2.00	9.60	3.43	1.65 ~ 1.85	7.50	2.60	1.02 ~ 1.70
9.15	24.50	-	-	22.70	4.55	-	22.50	3.60	3.80	24.40	5.74	3.30~ 4.50	23.50	3.91	3.60 ~ 9.20	23.50	5.53	3.30 ~ 4.40
13.70	52.00	-	-	50.50	4.81	-	49.00	3.22	9.50	50.30	5.03	7.80~10.00	52.00	4.33	8.60 ~ 10.90	47.00	4.95	7.30 ~ 9.00

TABLE 3.2 THIN BOUNDARY LAYER, 0.254m TREE SPACING, Col. A. only.

Row	1			2			3			5			10			20		
Meter/sec	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III
.61	.10	-	-	.10	2.00	-	.10	2.00	.07	.10	2.00	.05~ .06	.10	4.00	.029~ .040	.18	1.06	.07 ~ .08
1.52	1.20	-	-	1.00	10.00	-	.70	7.00	.10	.66	1.32	.35~ .37	.85	3.86	.25 ~ .30	.66	1.88	.21 ~ .26
3.05	4.10	-	-	3.40	4.25	-	2.60	3.25	.82	3.20	3.90	.90~ .98	3.50	3.50	.98 ~ 1.45	2.60	2.82	.83 ~ .90
6.10	11.60	-	-	12.50	3.91	-	11.40	3.80	4.00	11.00	2.29	4.20~ 4.50	11.00	2.50	4.10 ~ 5.30	10.20	3.11	3.20 ~ 3.50
9.15	25.00	-	-	27.40	4.15	-	26.20	4.22	9.00	23.80	2.80	8.40~ 8.40	24.70	3.08	7.60 ~10.00	24.30	3.47	7.00 ~ 8.20
13.70	50.70	-	-	50.30	2.58	-	50.30	2.96	22.50	51.50	3.22	16.80~17.00	50.70	3.57	16.00 ~20.00	52.00	3.42	15.50~19.00

TABLE 3.3 THIN BOUNDARY LAYER, 0.127m TREE SPACING,

Three Columns - Readings taken on Col. A.

Row	1			2			3			5			10			20		
Meter/sec	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III
.61	.10	-	-	.10	2.00	-	.10	2.00	.05	.18	1.80	.05 ~ .07	.10	2.00	.03 ~ .03	.10	4.00	.025 ~ .025
1.52	.66	-	-	.51	2.83	-	.18	1.20	.15	.82	1.34	.10 ~ .15	.65	2.50	.11 ~ .18	.50	5.00	.09 ~ .10
3.05	2.78	-	-	2.62	3.12	-	1.81	2.41	.59	2.71	2.42	.28 ~ .50	2.45	2.88	.33 ~ .50	2.65	4.42	.20 ~ .72
6.10	10.50	-	-	8.80	2.44	-	8.60	2.92	2.30	10.00	2.66	1.20 ~ 1.45	9.00	3.05	.98 ~ 1.12	8.70	3.78	.78 ~ 2.65
9.15	25.10	-	-	22.70	2.98	-	21.40	3.51	5.50	23.60	3.47	2.75 ~ 3.60	21.70	3.34	3.00 ~ 4.50	22.50	4.10	1.71 ~ 5.10
13.70	52.00	-	-	50.30	2.96	-	47.90	3.15	12.50	48.70	3.53	6.20 ~ 9.80	47.00	3.31	8.00 ~ 11.00	45.50	4.13	4.30~10.20

TABLE 3.4 THIN BOUNDARY LAYER, 0.127m TREE SPACING,

Three Columns - Readings taken on Col. B.

Row	1			2			3			5			10			20		
Meter/sec	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III
.61	.18	-	-	.18	1.80	-	.18	3.61	.05	.18	1.50	.04~ .05	.18	1.80	.03 ~ .03	.18	6.00	.025~ .03
1.52	.59	-	-	.51	1.46	-	.26	1.44	.16	.68	3.78	.15~ .22	.75	4.16	.15 ~ .22	.50	4.16	.05~ .10
3.05	2.78	-	-	2.30	3.07	-	2.30	2.53	.66	2.14	3.96	.44~ .58	2.45	5.83	.42 ~ .46	2.65	5.30	.33~ .56
6.10	10.50	-	-	9.50	2.52	-	9.60	2.93	2.95	9.40	4.39	1.82~ 2.30	9.50	5.25	1.51 ~ 1.80	8.70	4.35	1.02~ 2.50
9.15	25.10	-	-	22.70	2.99	-	22.00	3.05	5.70	22.00	4.80	3.45~ 5.00	23.50	4.95	3.25 ~ 4.60	22.50	4.75	2.75~ 5.20
13.70	52.00	-	-	50.30	2.96	-	49.60	3.22	12.60	48.70	5.60	7.00~12.00	48.70	5.41	8.00 ~ 10.50	45.50	4.13	6.00~10.80

TABLE 3.5 THIN BOUNDARY LAYER, 0.254m TREE SPACING,

Three Columns, Readings taken on Col. A.

Row	1			2			3			5			10			20		
Meter/sec	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III
.61	.10	-	-	.10	3.33	-	.10	1.43	.08	.10	3.33	.035 ~ .039	.10	3.33	.03 ~ .05	.18	6.00	.05~ .06
1.52	.66	-	-	.51	5.10	-	.54	2.46	.26	.58	3.22	.20~ .22	.66	3.50	.24 ~ .28	.47	4.70	.17~ .19
3.05	2.62	-	-	2.30	3.07	-	2.46	2.93	1.00	2.46	3.72	.66~ .66	2.78	4.36	.72 ~ .83	3.25	5.00	.44~ .94
6.10	9.80	-	-	10.00	2.78	-	9.80	2.72	4.00	9.80	3.15	3.10~ 3.10	9.50	4.25	2.70 ~ 3.50	10.00	3.23	2.30~ 3.20
9.15	20.40	-	-	24.40	3.13	-	23.60	3.07	9.00	23.60	3.57	6.60~ 7.00	21.70	3.82	5.90 ~ 7.30	23.50	3.62	5.00~ 7.80
13.70	50.30	-	-	50.30	2.68	-	50.30	2.82	24.00	50.30	3.26	15.50~17.00	50.30	3.87	15.50 ~ 19.00	52.00	3.35	11.50~18.20

TABLE 3.6 THIN BOUNDARY LAYER, 0.254m TREE SPACING,

Three Columns - Readings taken on Col. B.

Row	1			2			3			5			10			20		
Meter/sec	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III
.61	.10	-	-	.10	3.33	-	.10	2.00	.07	.08	1.60	.046 ~ .053	.10	2.00	.03 ~ .05	.10	2.00	.07~ .07
1.52	.66	-	-	.48	1.85	-	.57	2.85	.29	.66	2.64	.26~ .29	.35	3.30	.10 ~ .25	.47	4.70	.16~ .25
3.05	2.78	-	-	2.30	2.13	-	2.62	3.12	1.08	2.46	3.28	.96~ .10	2.45	3.47	.50 ~ 1.15	2.62	3.97	.66~ 1.00
6.10	9.20	-	-	9.60	2.26	-	10.02	2.91	4.90	9.70	2.81	3.65~ 4.40	9.00	3.16	1.50 ~ 4.50	9.25	2.58	2.48~ 3.70
9.15	25.10	-	-	22.00	2.62	-	22.70	3.07	10.00	22.00	3.06	9.00~ 9.00	21.00	3.50	5.25 ~ 10.00	22.00	3.14	6.00~ 9.30
13.70	50.30	-	-	50.30	3.58	-	50.30	2.96	23.00	50.30	3.27	20.00~20.30	50.40	3.33	12.90 ~ 21.50	52.00	2.92	13.00~22.00

TABLE 3.7 THICK BOUNDARY LAYER, 0.127m TREE SPACING,

Col. A. only.

Row	1			2			3			5			10			20		
Meter/Sec	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III
.61	.06	-	-	.17	3.40	-	.12	2.40	.05	.10	2.00	.05 ~ .05	.10	2.00	.04 ~ .06	.18	1.20	.041 ~ .082
1.52	.50	-	-	.55	9.20	-	.50	2.94	.15	.42	2.47	.17 ~ .22	.42	4.20	.10 ~ .17	.77	2.20	.10 ~ .18
3.05	1.81	-	-	1.50	6.00	-	2.00	5.72	.41	1.56	5.02	.36 ~ .50	1.81	6.03	.26 ~ .40	2.60	3.38	.30 ~ .48
6.10	7.50	-	-	7.00	6.06	-	7.20	7.20	1.15	5.70	6.70	1.01 ~ 2.00	6.60	6.21	.92 ~ 1.55	6.00	2.40	1.18 ~ 1.45
9.15	18.00	-	-	16.20	6.17	-	15.20	7.16	3.80	14.70	8.05	2.43 ~ 3.60	15.20	6.60	2.40 ~ 4.00	14.20	3.22	3.00 ~ 3.70
13.70	35.70	-	-	35.70	6.26	-	35.70	9.13	7.00	31.20	7.10	5.00 ~ 8.00	32.50	6.50	4.20 ~ 8.40	32.50	3.35	5.80 ~ 8.00

TABLE 3.8 THICK BOUNDARY LAYER, 0.254m TREE SPACING,

Col. A. only.

Row	1			2			3			5			10			20		
Meter/Sec	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III
.61	.18	-	-	.20	1.33	-	.18	1.50	.07	.20	1.82	.042 ~ .05	.12	2.40	.04 ~ .045	.12	1.09	.04 ~ .08
1.52	.35	-	-	.51	1.45	-	.35	1.94	.15	.68	1.79	.12 ~ .15	.35	2.34	.13 ~ .15	.43	1.95	.16 ~ .18
3.05	1.18	-	-	1.51	1.78	-	1.51	2.60	.55	1.32	2.31	.61 ~ .61	1.34	2.63	.54 ~ .64	1.68	2.47	.58 ~ .72
6.10	6.10	-	-	6.40	2.25	-	6.70	2.86	2.45	6.20	2.65	1.95 ~ 2.00	5.80	2.67	2.00 ~ 2.40	6.70	2.68	2.20 ~ 2.60
9.15	14.40	-	-	15.10	2.36	-	15.10	2.48	5.70	14.40	2.53	4.70 ~ 4.70	14.80	2.74	4.80 ~ 5.20	15.10	2.70	4.50 ~ 5.70
13.70	35.00	-	-	35.00	2.32	-	36.70	2.43	15.00	33.40	2.33	10.8 ~ 11.8	33.40	2.74	11.70 ~ 12.50	35.00	2.44	10.80 ~ 12.50

TABLE 3.9 THICK BOUNDARY LAYER, 0,127m TREE SPACING,

Three Columns - Readings taken on Col. A.

Row / Meter/sec	1			2			3			5			10			20		
	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III
.61	.05	-	-	.12	2.40	-	.17	3.40	.05	.15	3.00	.05 ~ .05	.12	2.40	.05 ~ .06	.10	2.00	.04 ~ .046
1.52	.43	-	-	.46	4.60	-	.57	3.35	.10	.50	1.92	.104~ .17	.50	4.16	.13 ~ .13	.35	1.59	.062~ .14
3.05	2.00	-	-	1.67	4.80	-	2.00	4.72	.30	1.65	2.84	.44 ~ .46	1.65	4.12	.25 ~ .35	1.51	2.56	.18 ~ .43
6.10	7.10	-	-	6.50	3.89	-	7.00	4.50	1.05	6.20	3.10	1.42 ~ 1.47	6.50	4.81	.80 ~ 1.35	6.00	2.40	.54 ~ 1.45
9.15	17.00	-	-	15.50	4.13	-	15.20	4.65	2.95	15.00	3.41	3.60 ~ 3.60	14.50	4.92	2.00 ~ 2.50	13.50	2.81	1.20 ~ 3.30
13.70	35.70	-	-	34.00	4.14	-	35.70	5.66	7.00	32.50	3.74	7.50 ~ 7.50	32.50	5.80	4.00 ~ 6.70	31.70	2.86	2.99 ~ 7.00

TABLE 3.10 THICK BOUNDARY LAYER, 0.127m TREE SPACING,

Three Columns - Readings taken on Col. B.

Row / Meter/sec	1			2			3			5			10			20		
	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III
.61	.05	-	-	.12	1.71	-	.10	2.00	.05	.10	2.00	.05 ~ .05	.10	2.00	.06 ~ .064	.10	2.50	.032~ .037
1.52	.35	-	-	.42	1.68	-	.58	2.63	.12	.45	1.80	.12 ~ .17	.50	1.67	.16 ~ .20	.34	4.85	.07 ~ .08
3.05	1.65	-	-	1.67	2.89	-	1.50	2.31	.45	1.50	3.00	.35 ~ .55	1.56	2.21	.34 ~ .42	1.25	2.98	.27 ~ .42
6.10	7.00	-	-	5.60	2.84	-	5.50	2.59	1.80	5.60	3.39	1.25 ~ 1.65	5.60	2.14	1.25 ~ 1.50	5.80	2.90	.94 ~ 1.94
9.15	15.50	-	-	13.20	3.11	-	14.00	2.80	4.00	13.70	2.88	3.00 ~ 3.90	13.60	2.72	2.90 ~ 3.40	14.20	3.30	2.16 ~ 4.10
13.70	35.70	-	-	35.70	3.80	-	35.70	4.46	10.00	31.20	3.46	7.50 ~ 8.00	32.50	3.16	6.20 ~ 7.20	32.50	3.38	5.00 ~ 9.80

TABLE 3.11 THICK BOUNDARY LAYER, 0.254m TREE SPACING,

Three Columns - Readings taken on Col. A.

Row / Meter/sec	1			2			3			5			10			20		
	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III
.61	.07	-	-	.20	1.33	-	.18	1.63	.07	.20	1.82	.04 ~ .05	.11	1.57	.044 ~ .05	.12	2.40	.04 ~ .06
1.52	.51	-	-	.60	6.66	-	.51	1.59	.15	.58	1.52	.12 ~ .17	.35	1.29	.21 ~ .28	.35	2.33	.11 ~ .16
3.05	2.84	-	-	1.84	3.60	-	1.51	2.13	.42	1.84	3.23	.47 ~ .56	1.26	1.25	.56 ~ .92	1.51	1.96	.36 ~ .60
6.10	8.90	-	-	6.70	2.68	-	6.40	2.56	2.15	6.20	2.74	2.00 ~ 2.20	4.50	1.44	2.10 ~ 2.50	6.40	2.26	1.50 ~ 2.40
9.15	18.40	-	-	15.10	2.25	-	15.10	2.65	6.00	15.60	2.52	5.10 ~ 5.40	15.10	2.48	4.80 ~ 5.40	15.10	2.69	3.20 ~ 5.10
13.70	38.40	-	-	33.40	2.21	-	33.40	2.49	15.00	35.00	2.32	10.80 ~12.00	36.70	2.31	11.30 ~ 13.50	35.00	2.21	8.00 ~12.80

TABLE 3.12 THICK BOUNDARY LAYER, 0.254m TREE SPACING,

Three Columns - Readings taken on Col. B.

Row / Meter/sec	1			2			3			5			10			20		
	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III
.61	.18	-	-	.20	1.33	-	.20	1.67	.07	.20	1.66	.04 ~ .056	.15	2.14	.038 ~ .070	.15	3.00	.049~ .951
1.52	.68	-	-	.60	1.87	-	.35	1.40	.15	.58	1.52	.12 ~ .17	.47	1.34	.16 ~ .30	.43	2.89	.14~ .18
3.05	2.84	-	-	3.67	4.31	-	1.68	1.98	.76	2.00	1.98	.90 ~ .90	1.68	1.97	.58 ~ 1.00	2.10	3.56	.57~ .75
6.10	9.20	-	-	9.10	2.87	-	7.60	2.28	3.70	7.40	2.02	3.20 ~ 3.20	6.70	2.36	2.48 ~ 3.10	7.60	3.25	2.15~ 3.00
9.15	18.40	-	-	18.40	2.42	-	15.10	1.96	7.70	18.40	2.27	7.40 ~ 7.40	17.60	3.26	5.18 ~ 6.40	17.60	3.52	4.60~ 7.00
13.70	40.00	-	-	40.00	2.25	-	38.40	2.29	16.90	38.40	2.08	16.20 ~17.00	38.40	3.05	12.50 ~ 15.20	38.40	3.05	13.00~16.50

6.3 List of Figures

List of Figures continued

List of Figures continued:

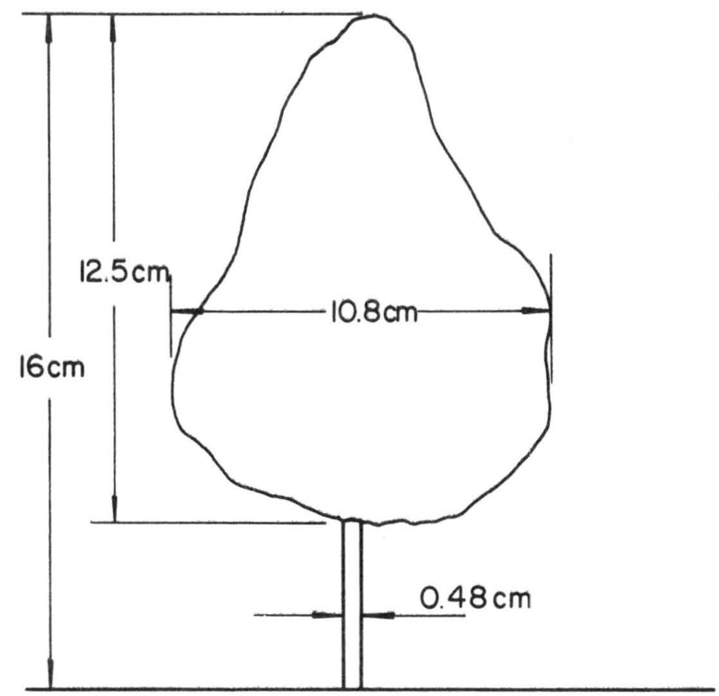


Figure 2.1 The averaged dimensions of a single artificial tree

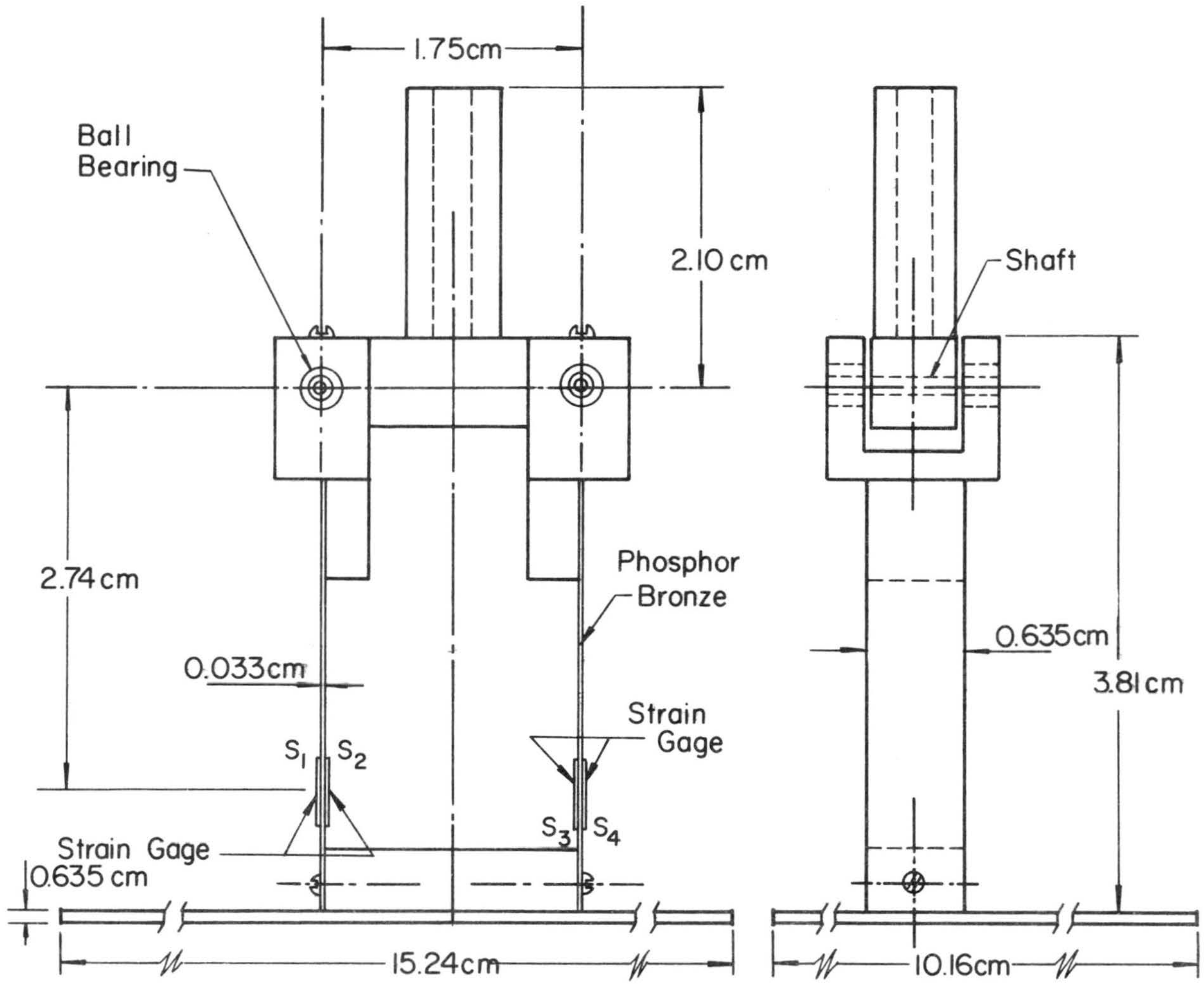


Figure 2.2 The strain-gage force dynamometer

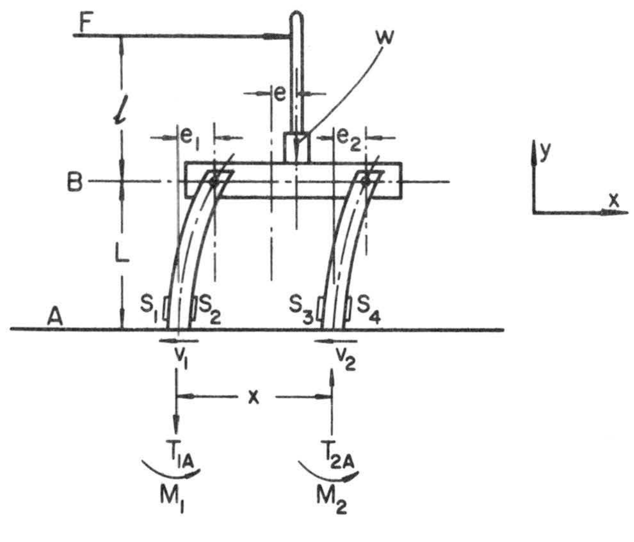


Figure 2.3 The force diagram of the dynamometer

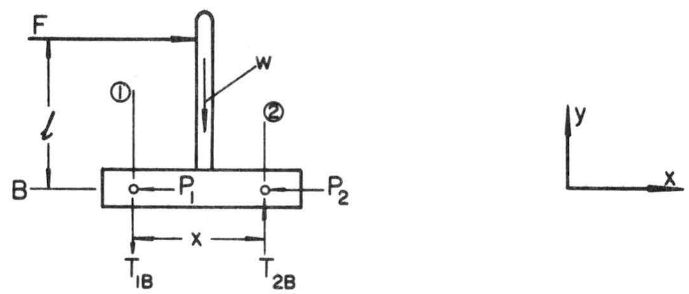


Figure 2.4 Free body diagram 1

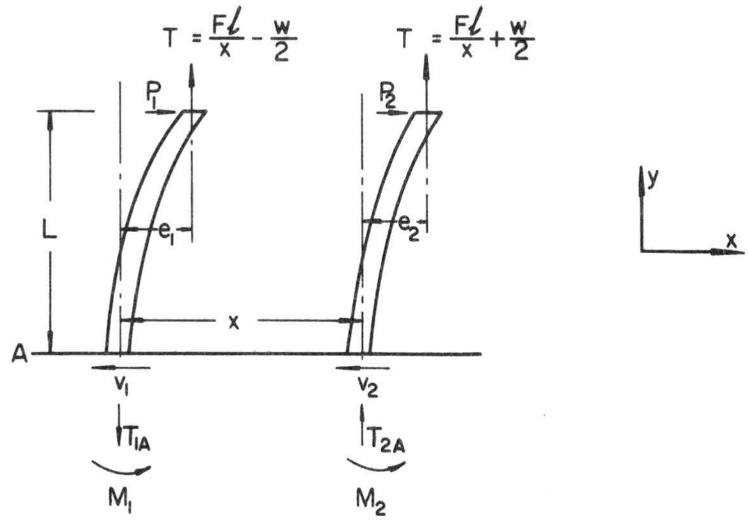


Figure 2.5 Free body diagram 2

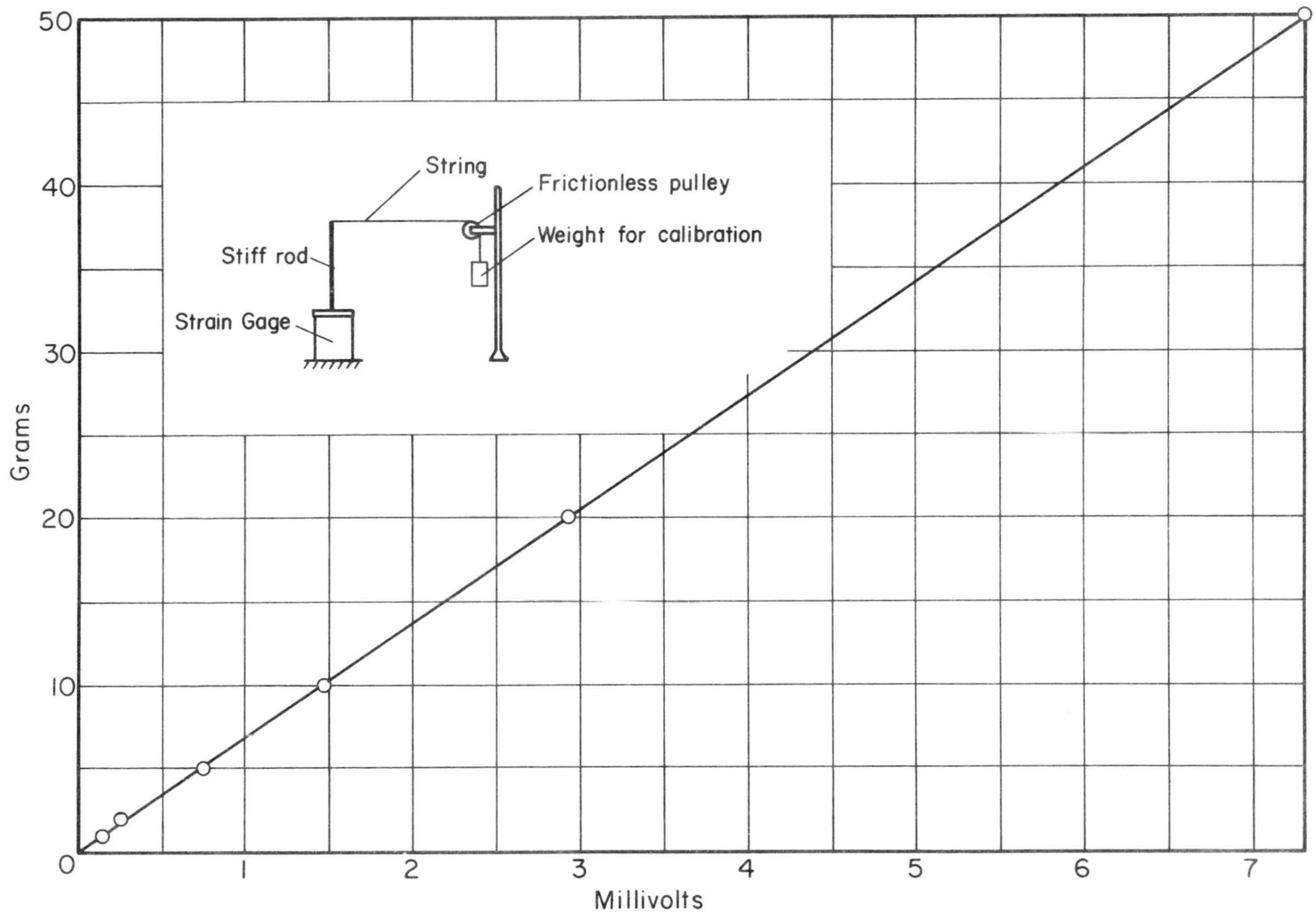


Figure 2.6 Calibration curve for the strain-gage force dynamometer

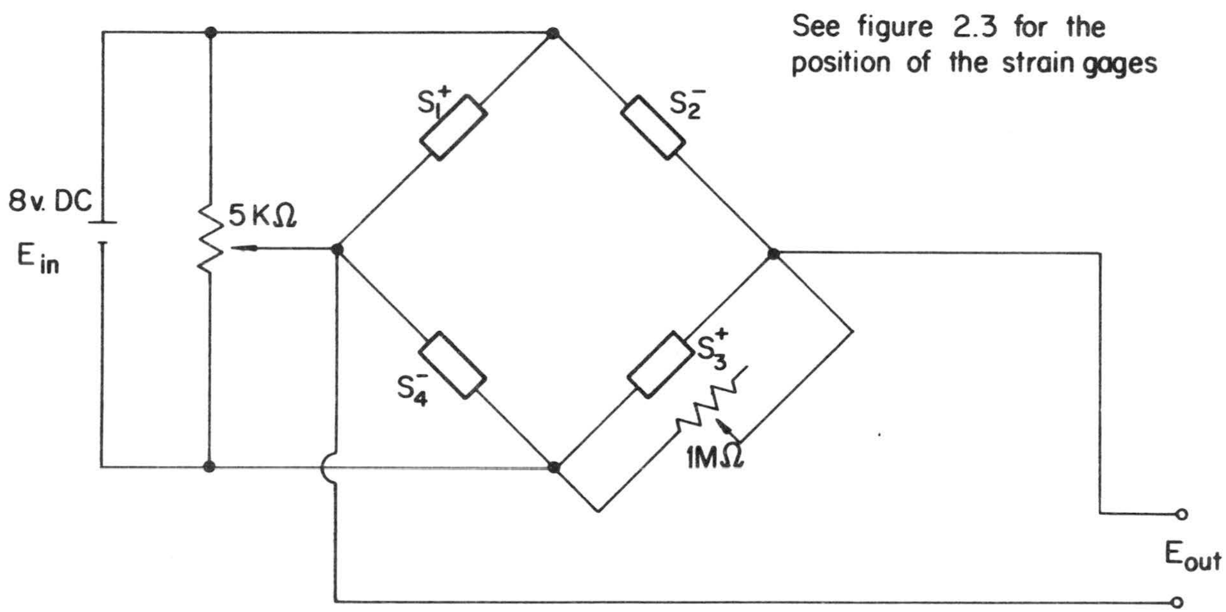


Figure 2.7 Schematic diagram of the electric bridge arrangement for the strain gages on the strain-gage force dynamometer

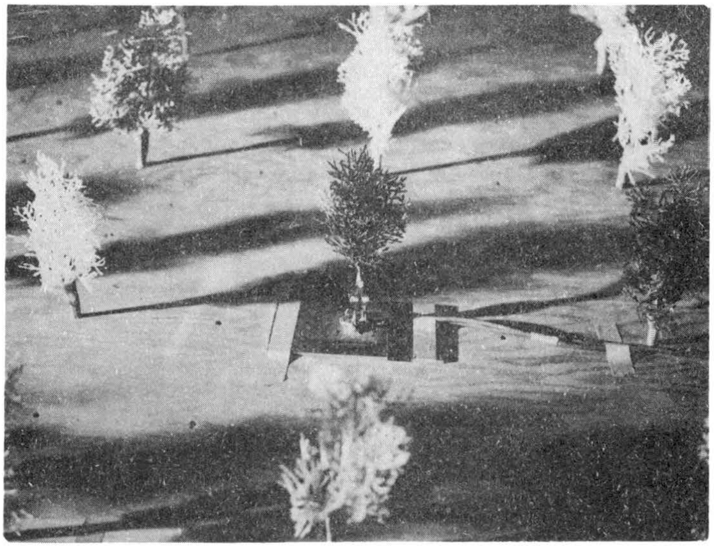


Figure 2.8 The dynamometer arrangement in the model forest

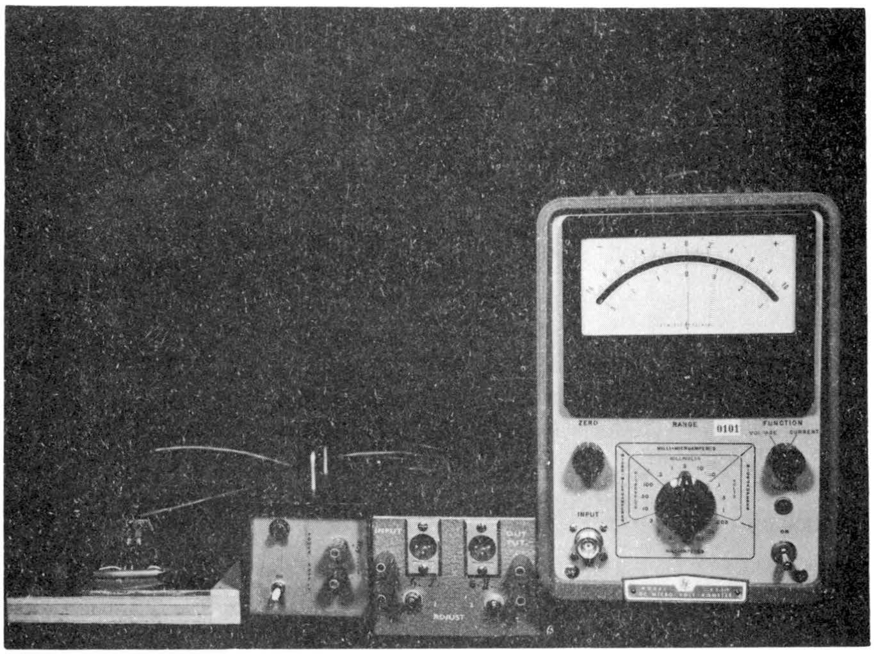
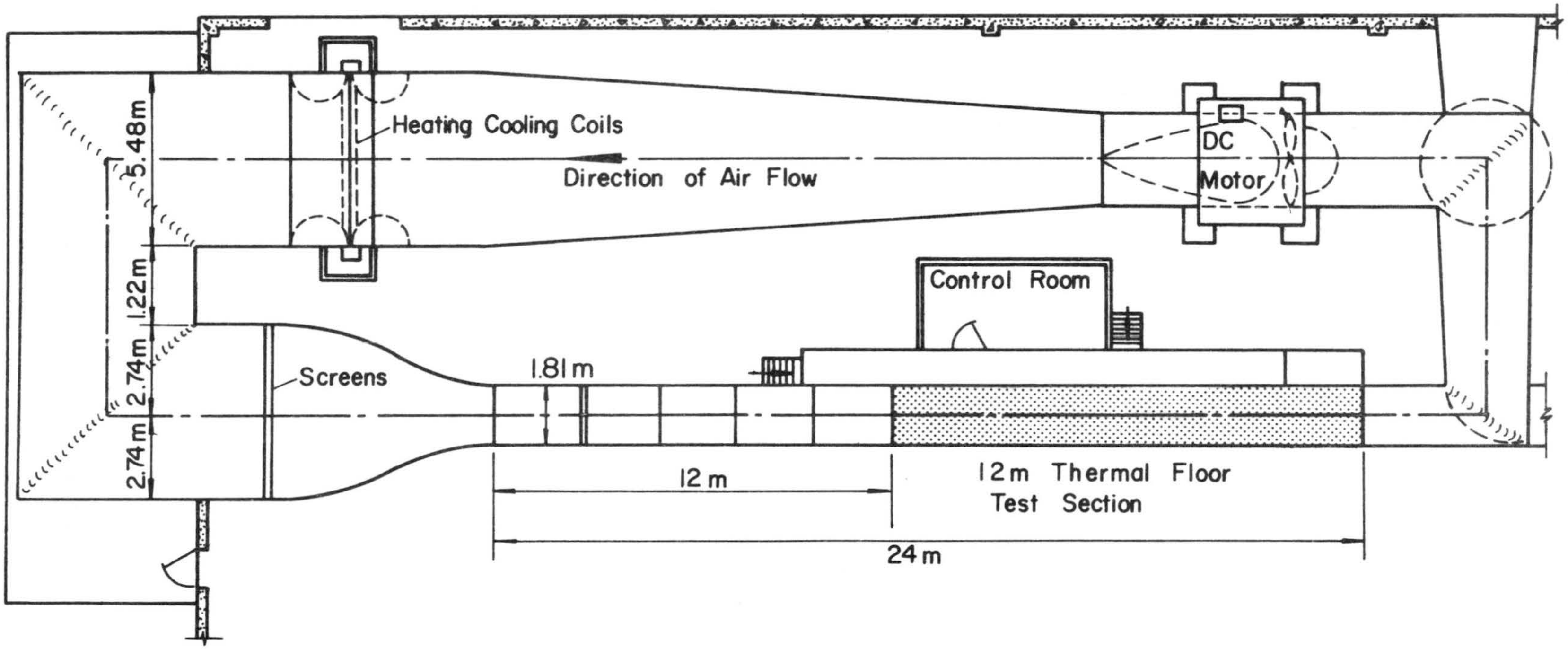


Figure 2.9 Instruments



PLAN VIEW

Figure 2.10 The Army Meteorological Wind Tunnel

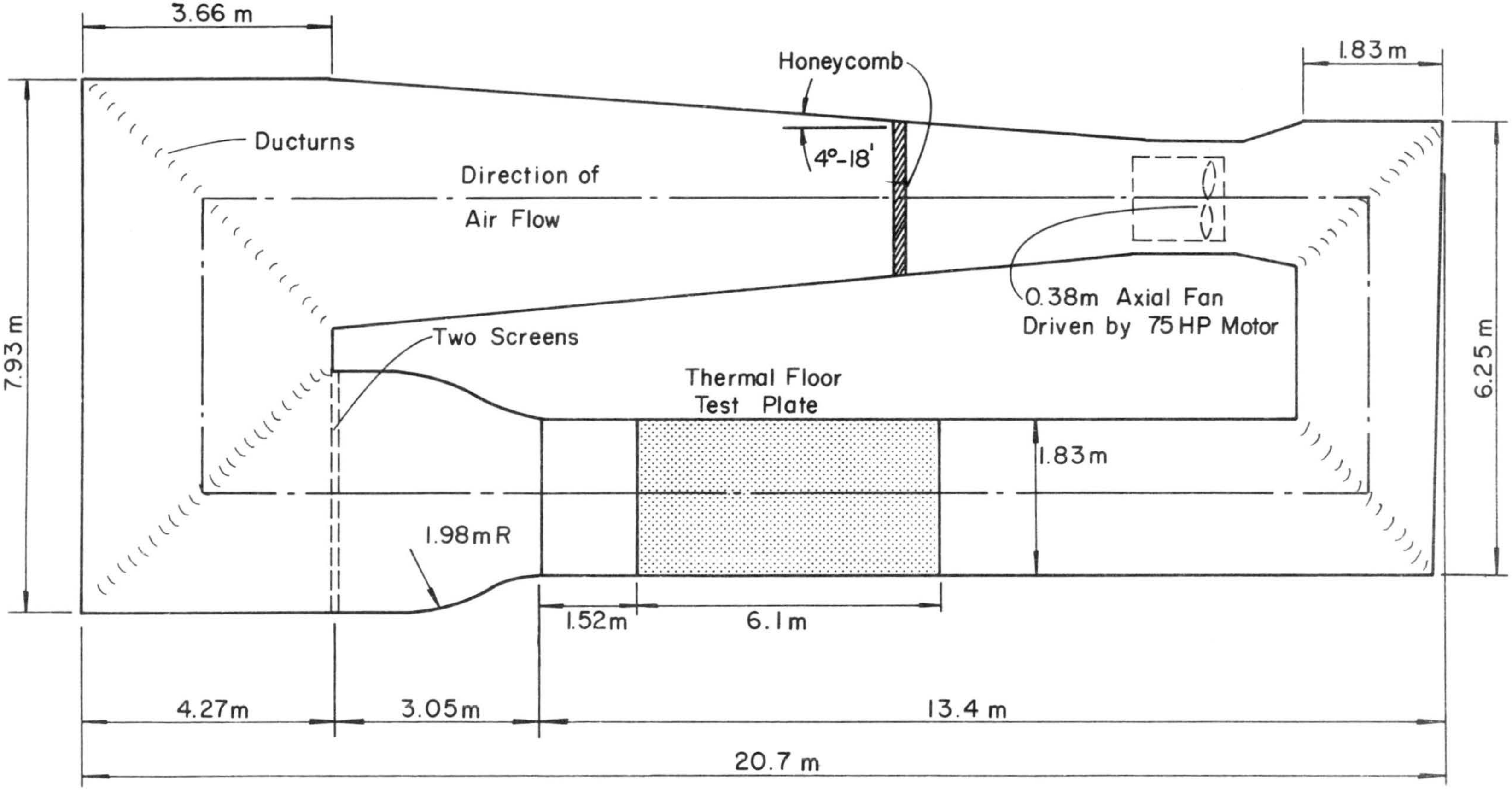


Figure 2.11 The Colorado State University Wind Tunnel

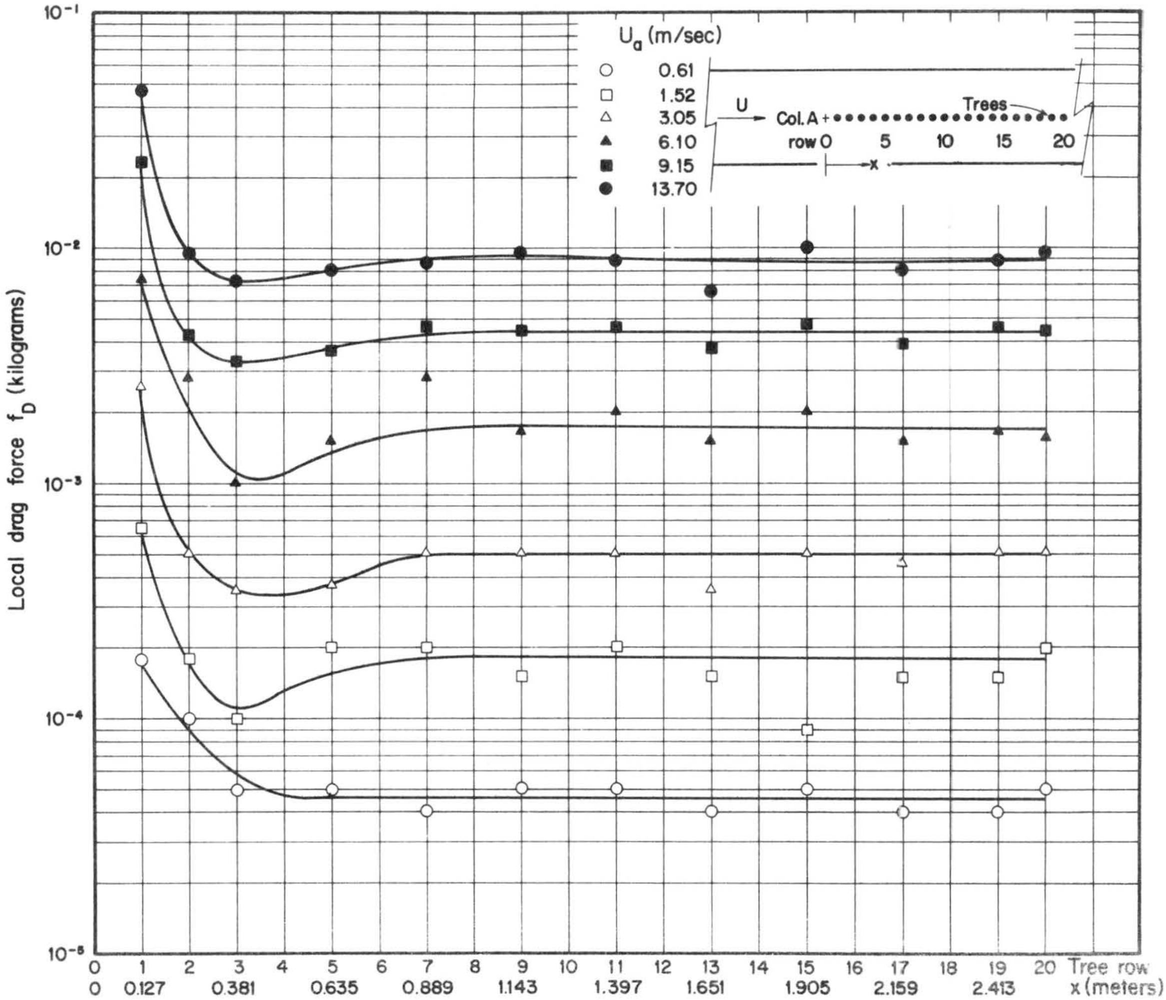


Figure 3.1 One column; twenty rows

Local Drag Force vs Longitudinal Distance, Thin Boundary Layer, 0.127 m Tree Spacing

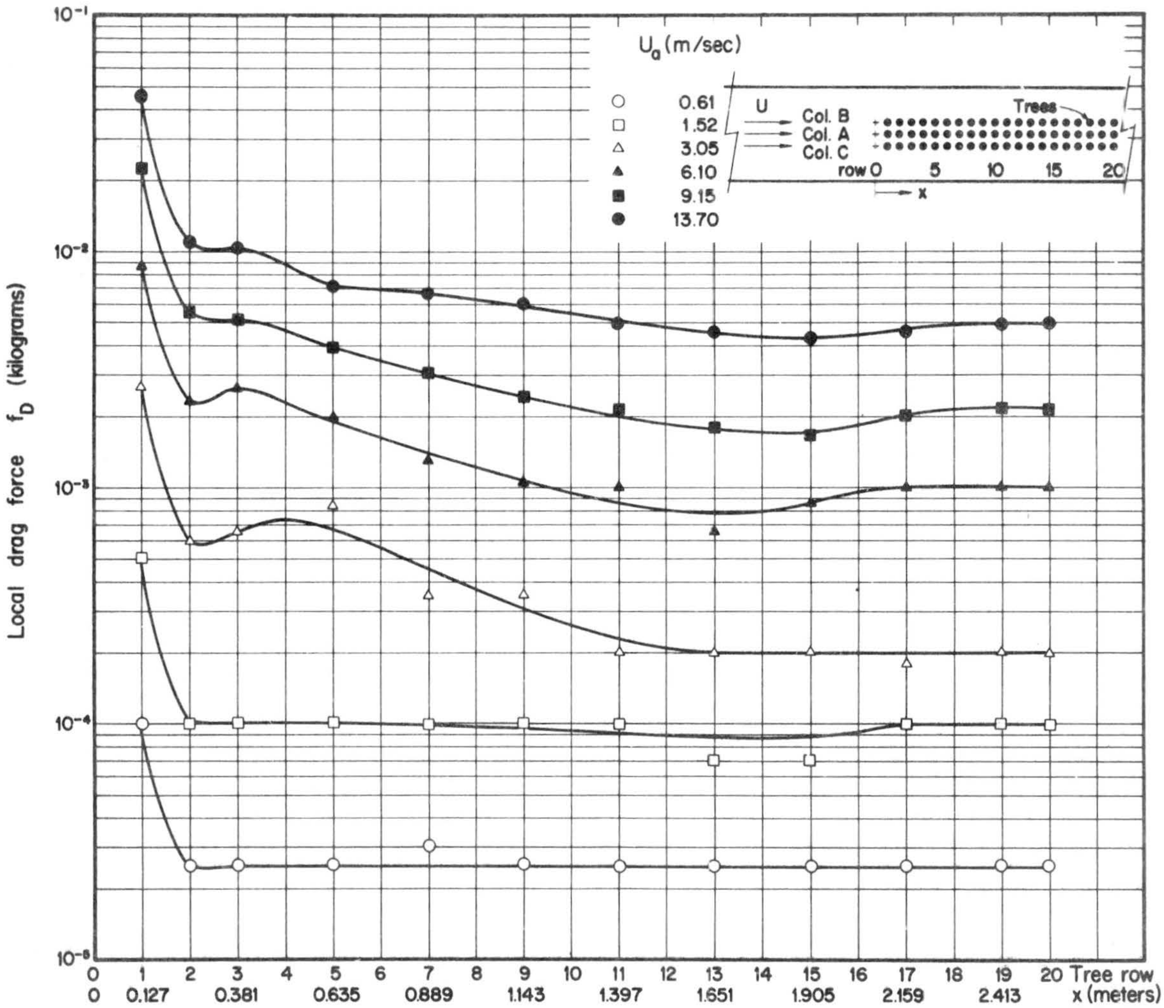


Figure 3.2 Three columns; twenty rows; readings taken on Column A

Local Drag Force vs Longitudinal Distance, Thin Boundary Layer, 0.127 m Tree Spacing

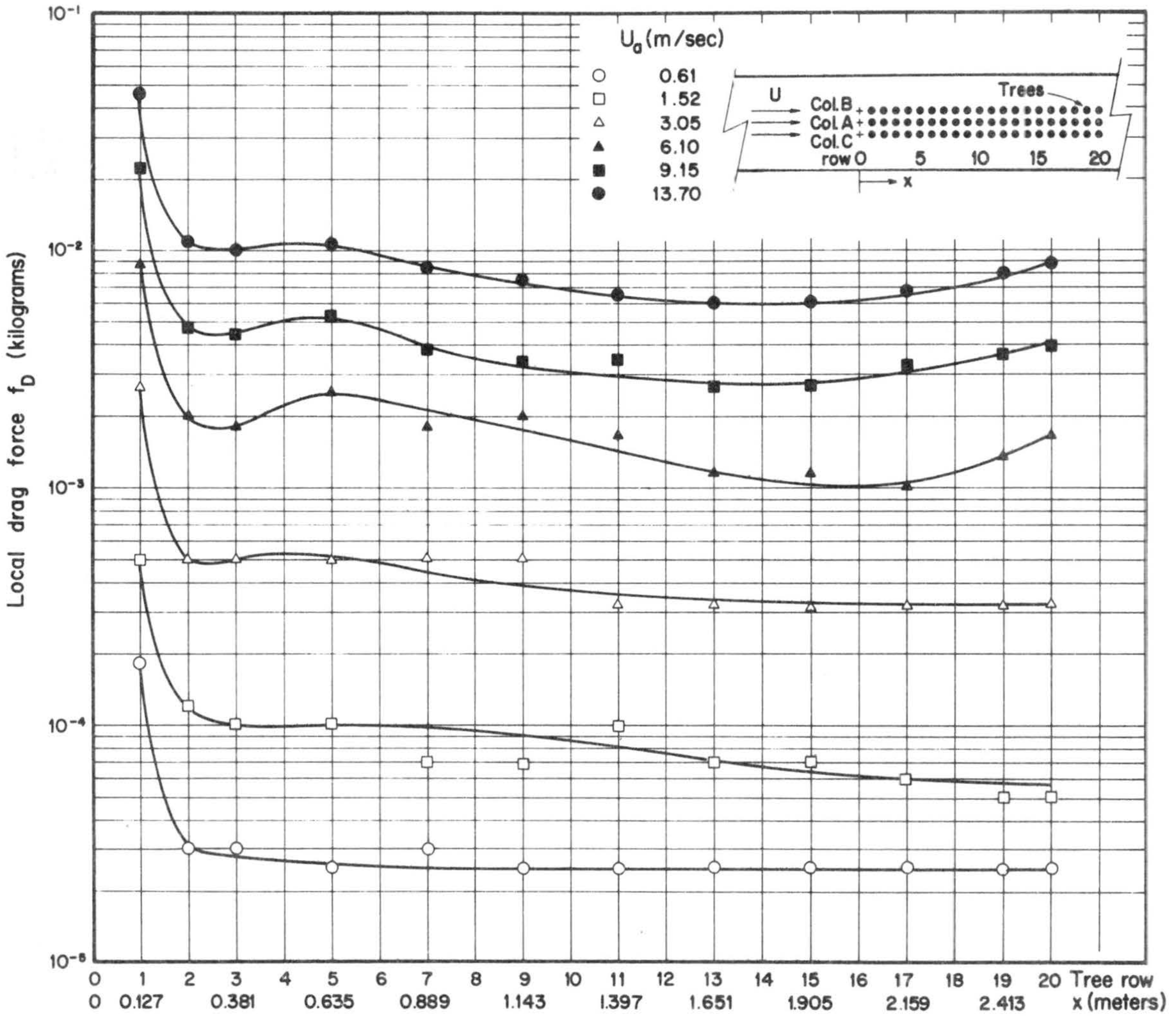


Figure 3.3 Three columns; twenty rows; readings taken on Column B

Local Drag Force vs Longitudinal Distance, Thin Boundary Layer, 0.127 m Tree Spacing

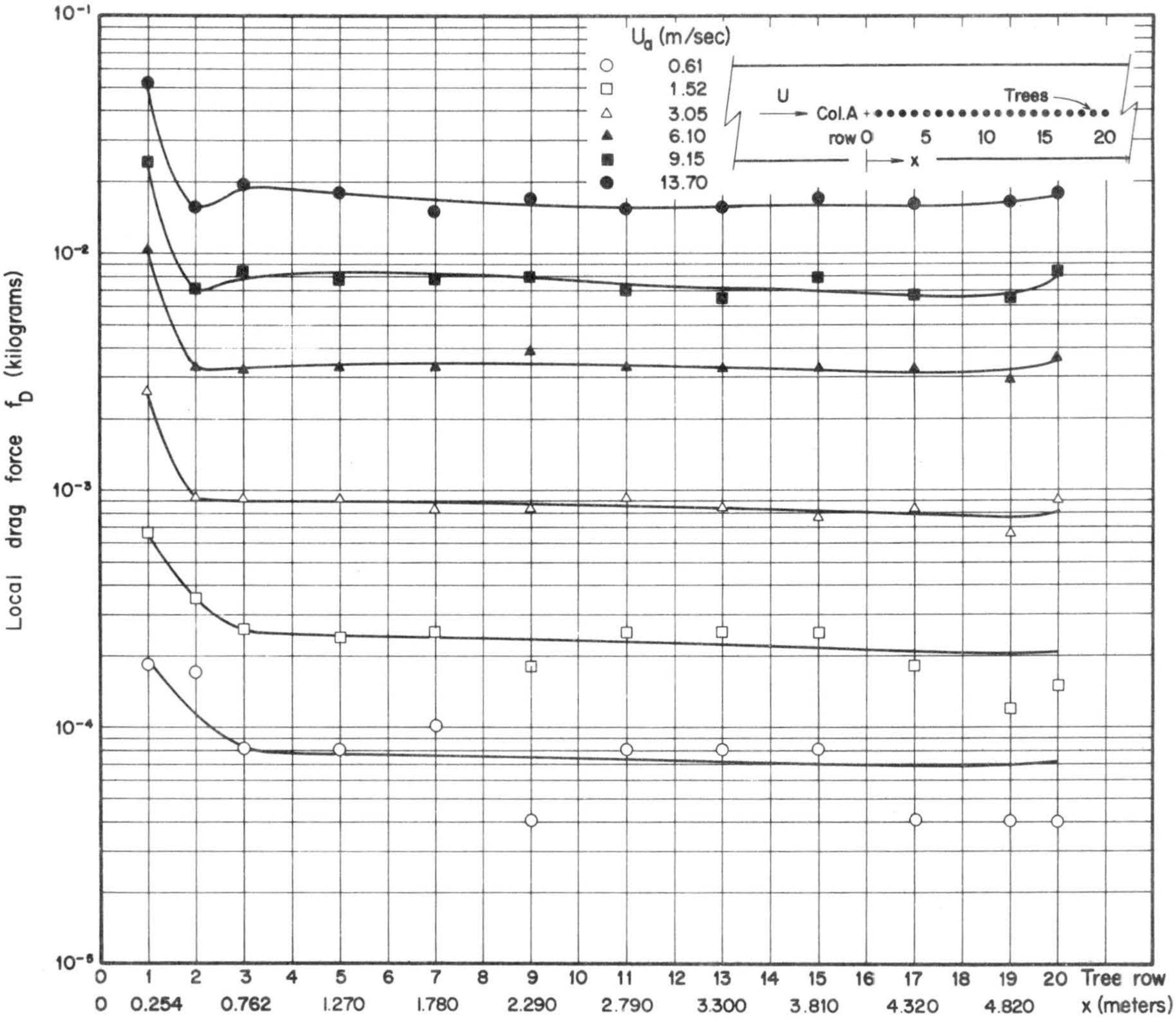


Figure 3.4 One column; twenty rows

Local Drag Force vs Longitudinal Distance, Thin Boundary Layer, 0.254 m Tree Spacing

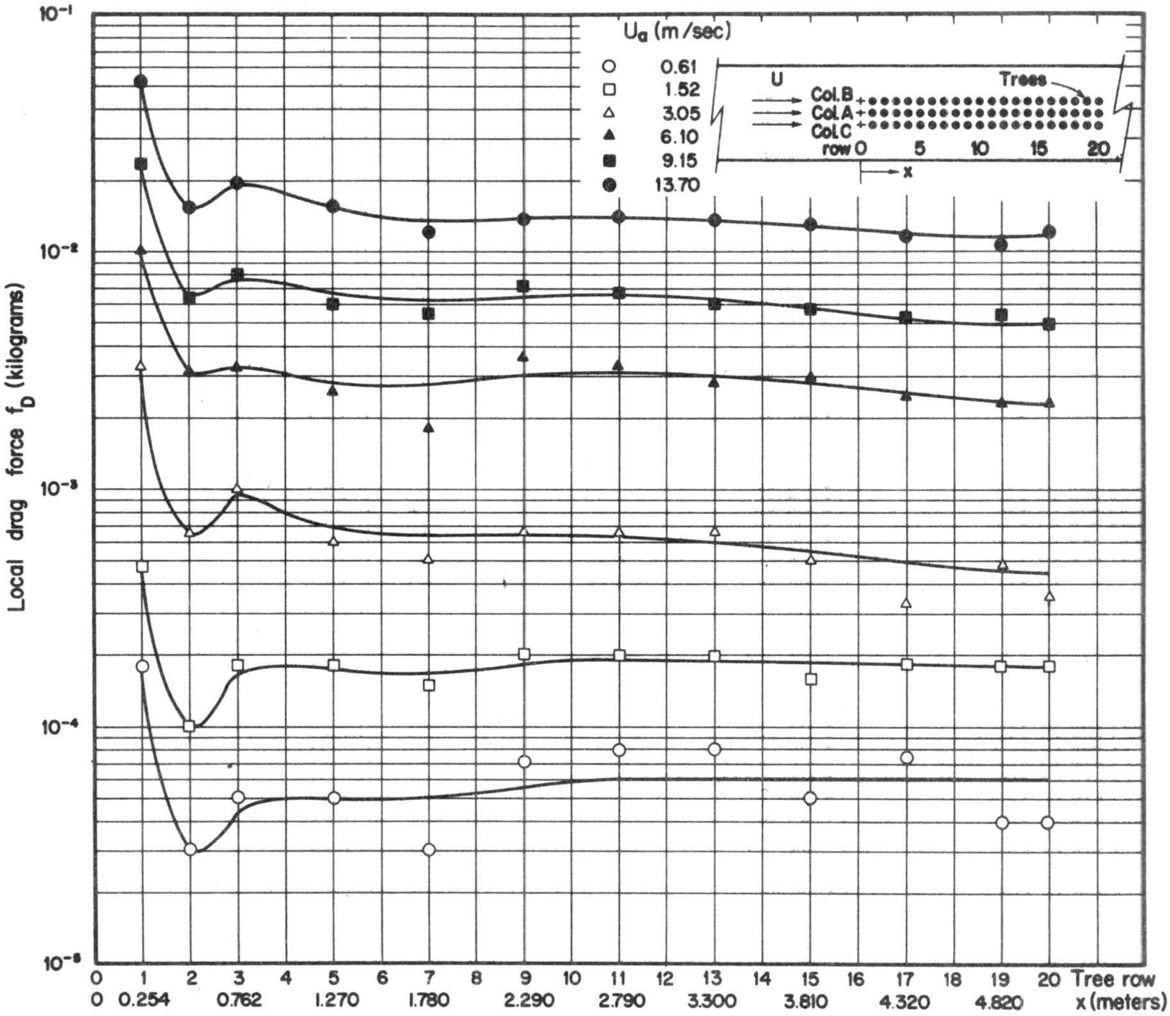


Figure 3.5 Three columns; twenty rows; readings taken on Column A

Local Drag Force vs Longitudinal Distance, Thin Boundary Layer, 0.254 m Tree Spacing

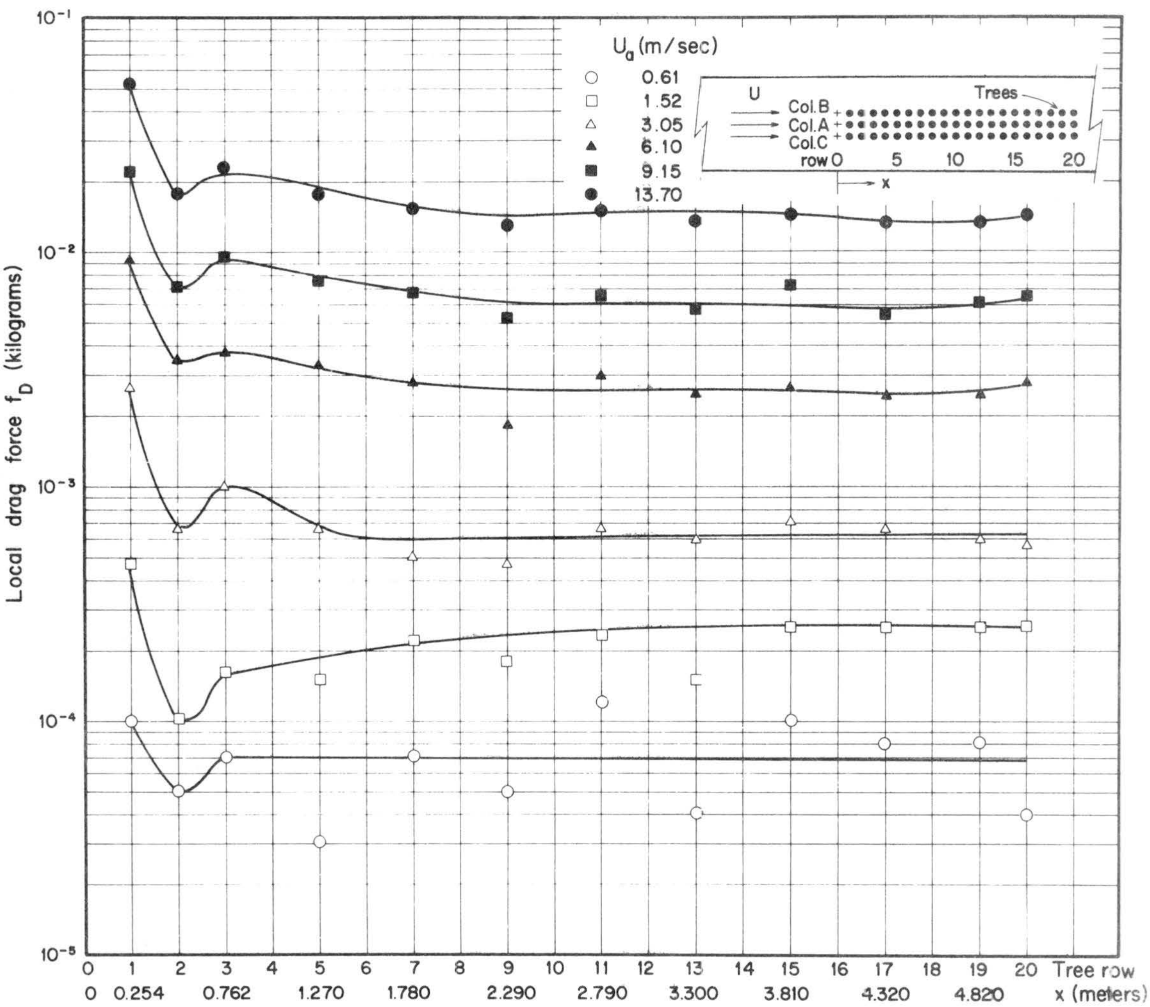


Figure 3.6 Three columns; twenty rows; readings taken on Column B

Local Drag Force vs Longitudinal Distance, Thin Boundary Layer, 0.254 m Tree Spacing

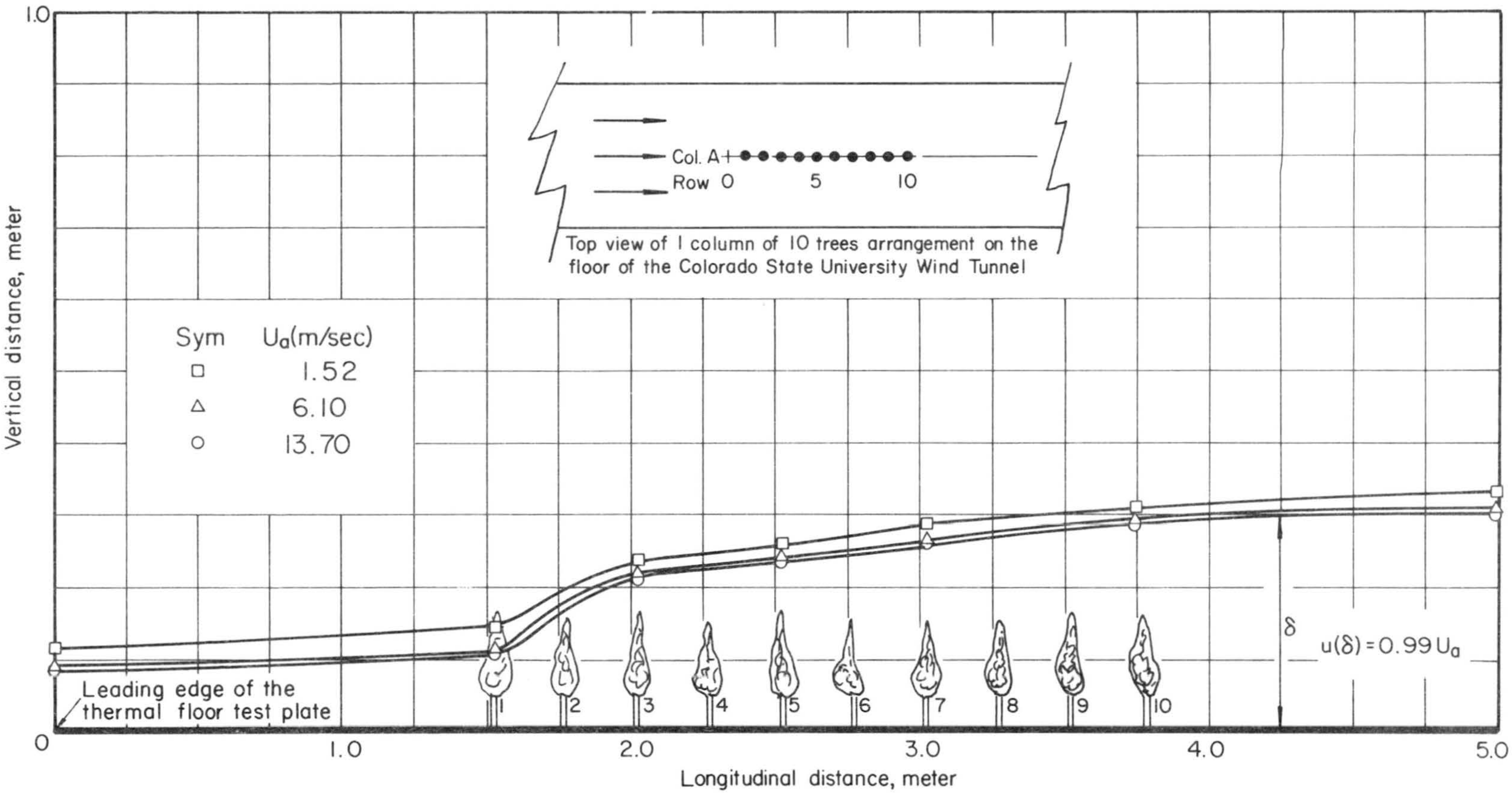


Figure 3.7 Boundary layer development over one column of trees, thin boundary layer, 0.254 m tree spacing

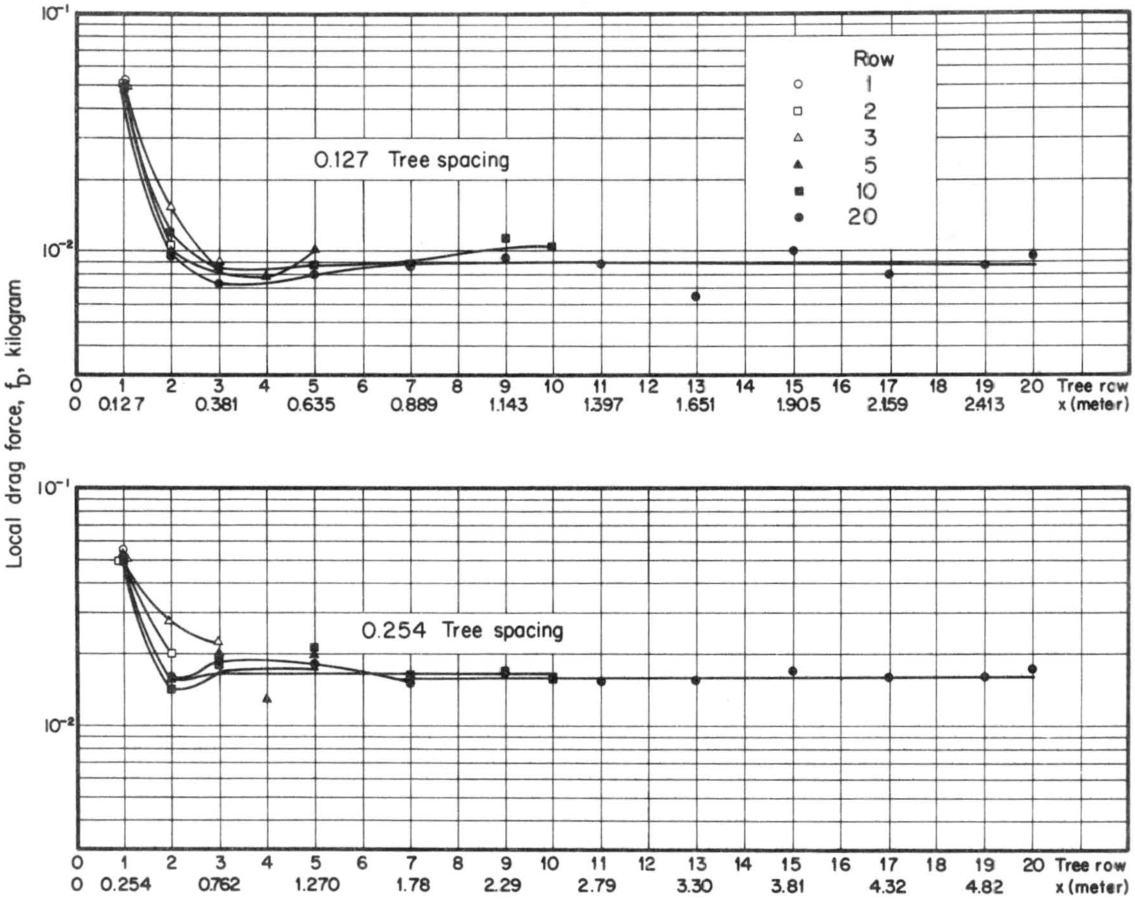


Figure 3.8 Column A only

A Comparison of Local Drag Force vs Longitudinal Distance for 0.127 m and 0.254 Tree Spacings, Thin Boundary Layer, for all Row Arrangements, 13.7 mps Velocity Only

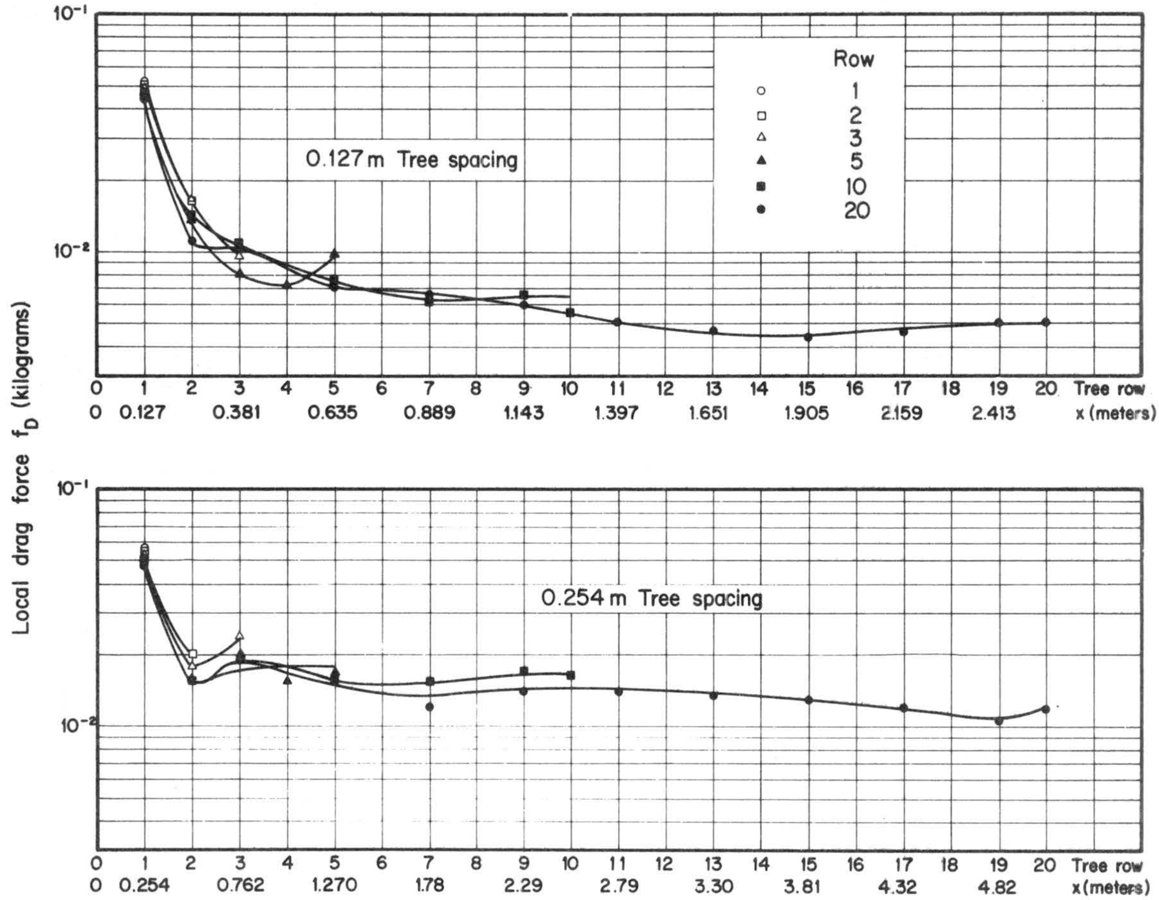


Figure 3.9 Three columns; readings taken on Column A

A Comparison of Local Drag Force vs Longitudinal Distance for 0.127 m and 0.254 Tree Spacings, Thin Boundary Layer, for all Row Arrangements, 13.7 mps Velocity Only

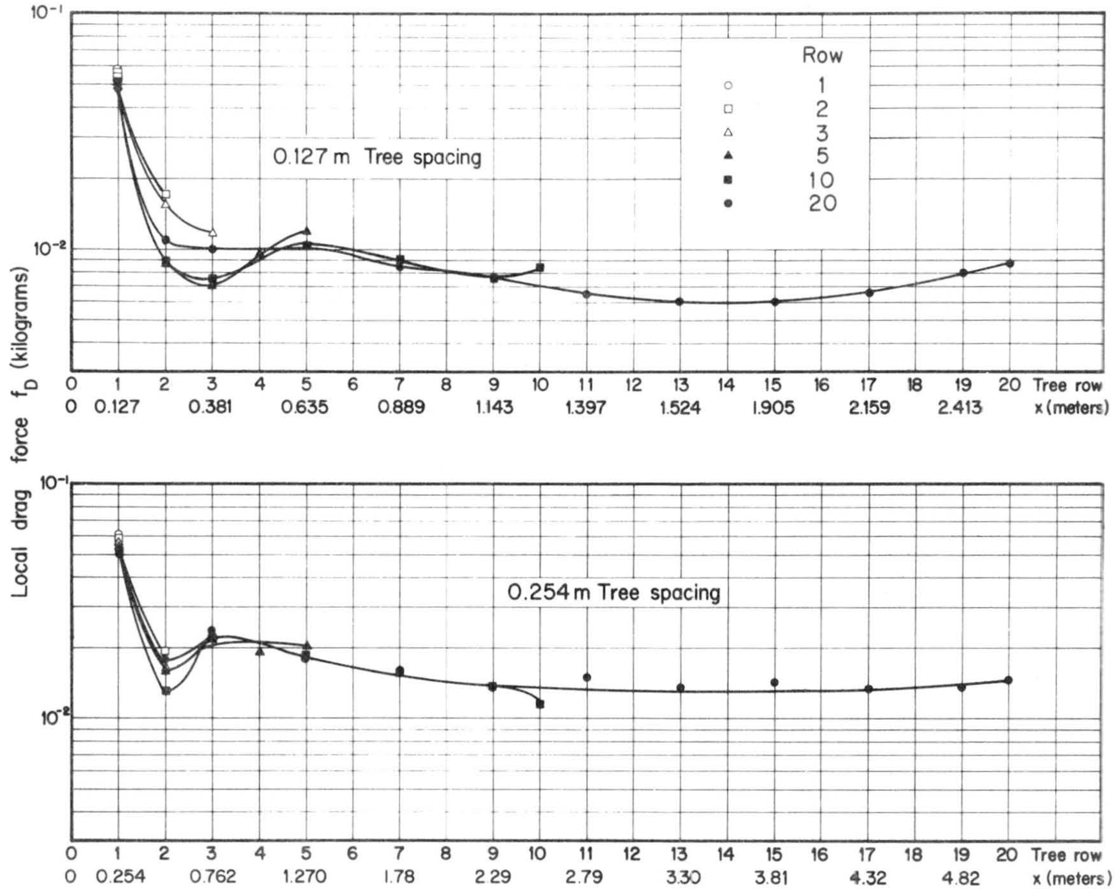


Figure 3.10 Three columns; readings taken on Column B

A Comparison of Local Drag Force vs Longitudinal Distance for 0.127 m and 0.254 Tree Spacings, Thin Boundary Layer, for all Row Arrangements, 13.7 mps Velocity Only

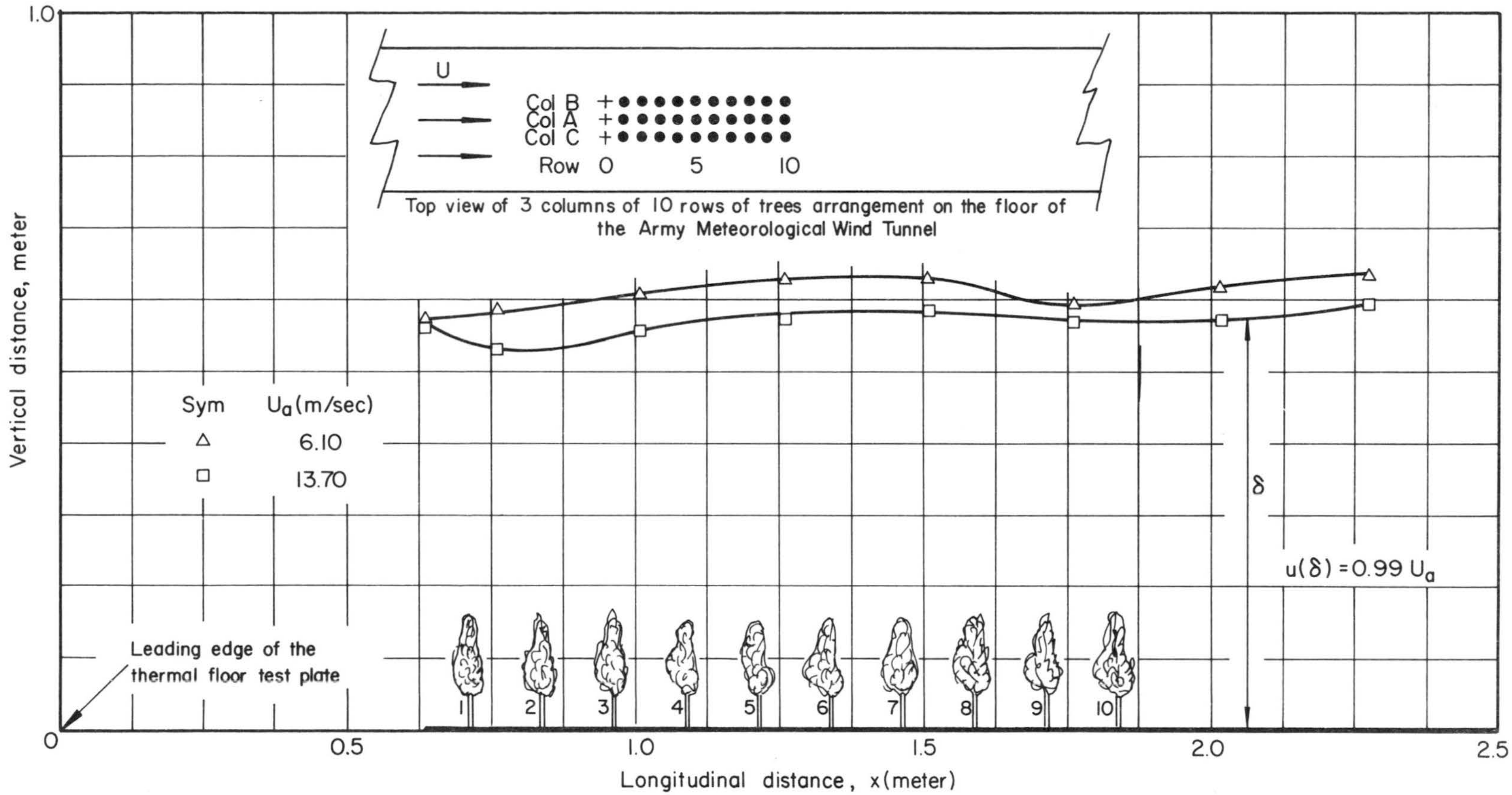


Figure 3.11 Three columns; boundary layer development over the center column of trees, thick boundary layer, 0.127 m tree spacing

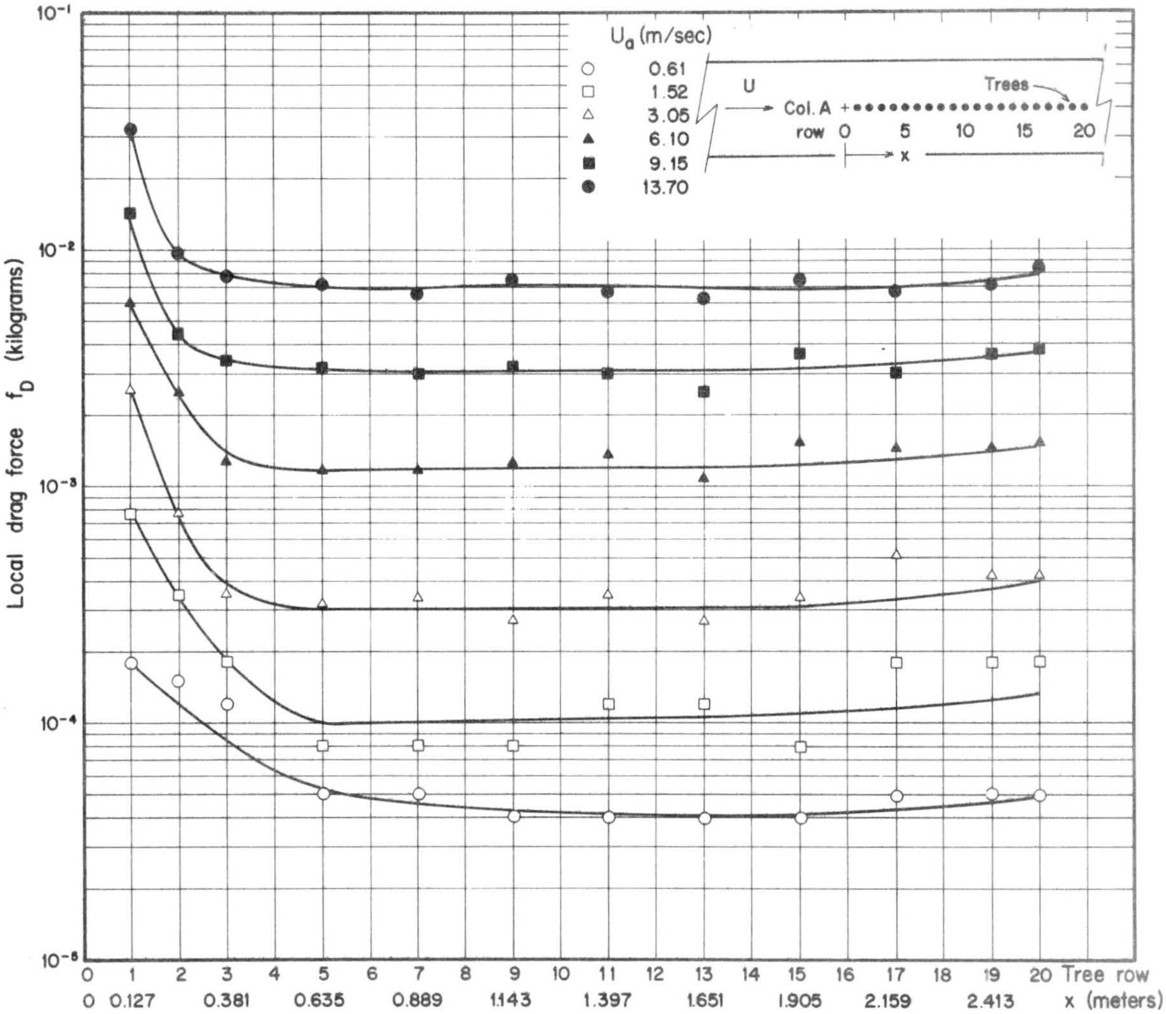


Figure 3.12 One column; twenty rows

Local Drag Force vs Longitudinal Distance, Thick Boundary Layer, 0.127 m Tree Spacing

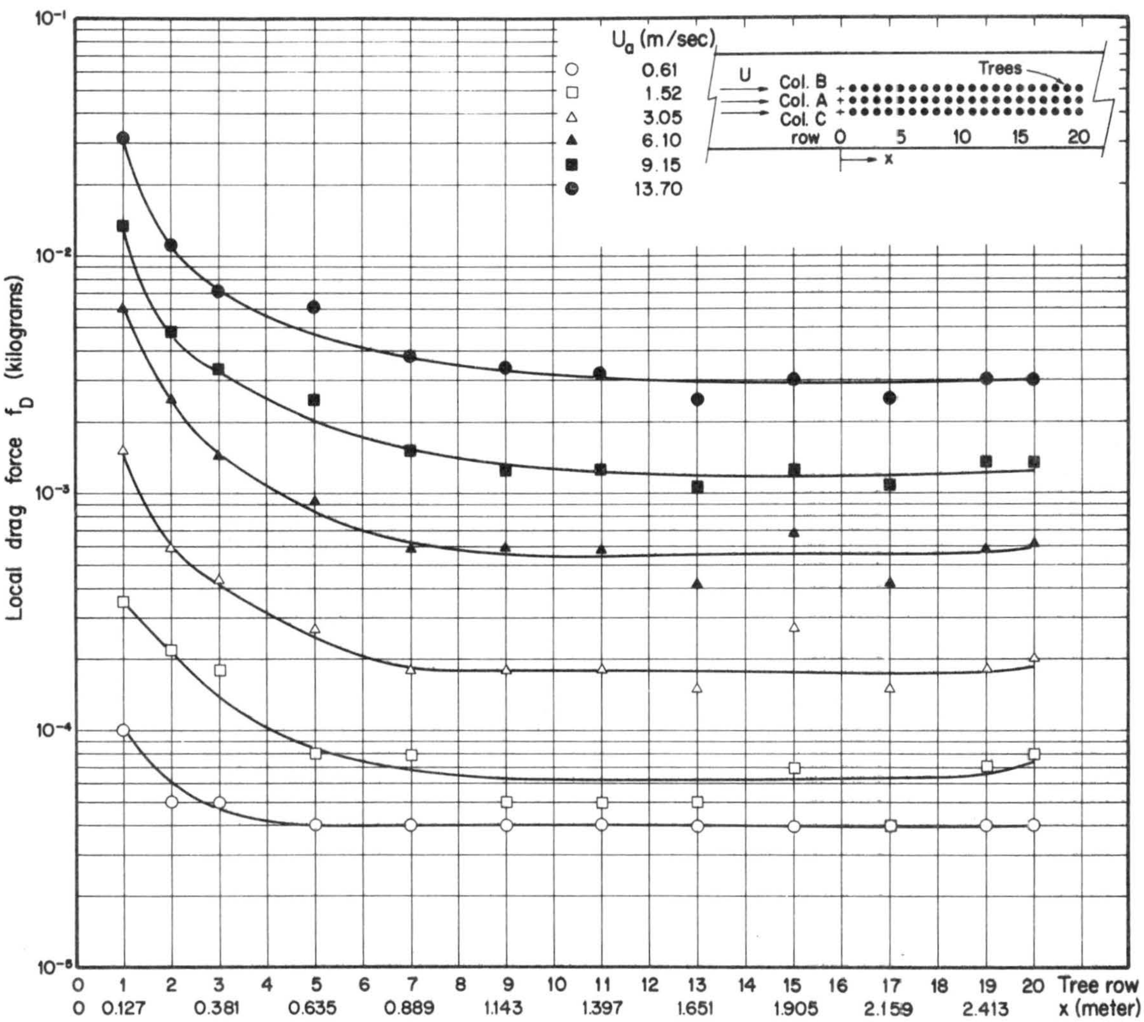


Figure 3.13 Three columns; twenty rows; readings taken on Column A

Local Drag Force vs Longitudinal Distance, Thick Boundary Layer, 0.127 m Tree Spacing

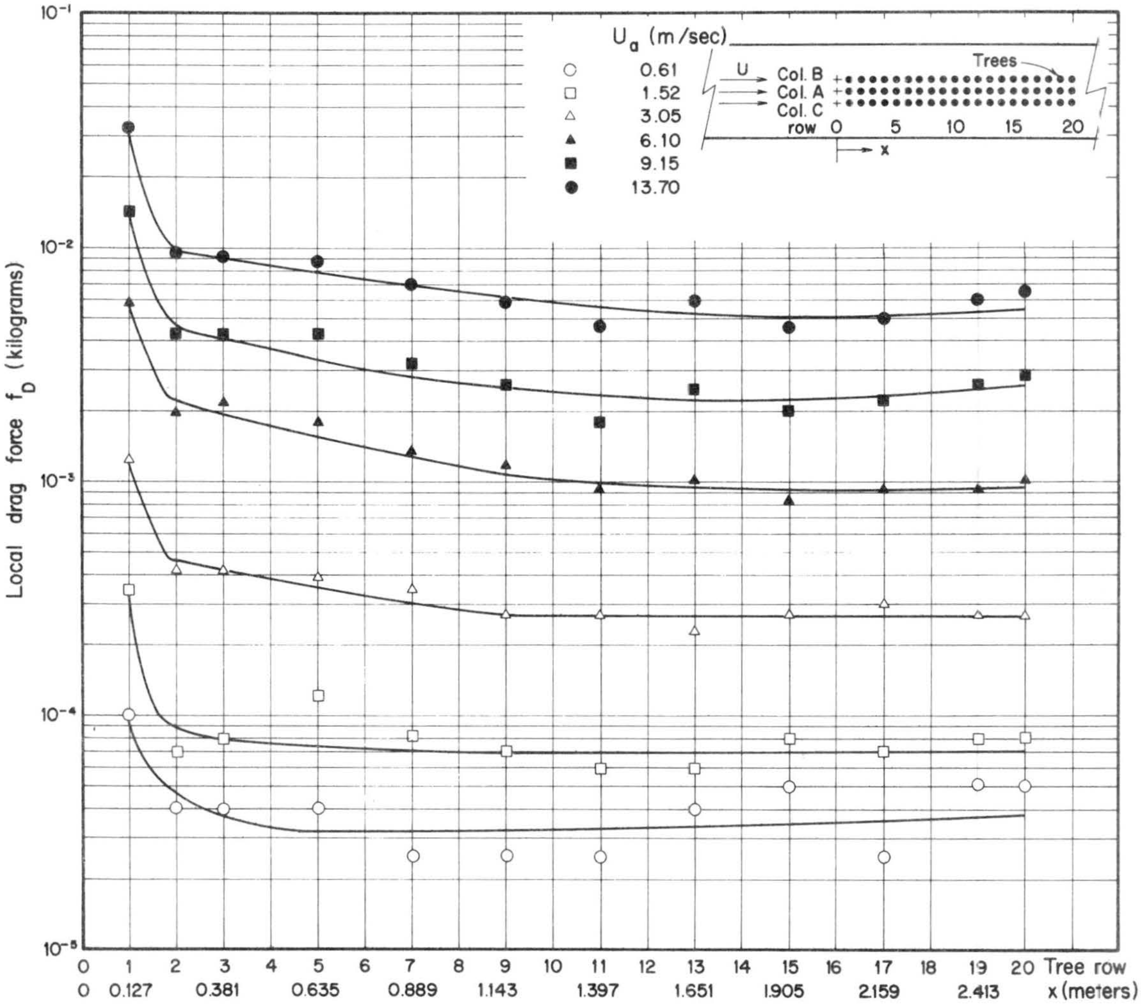


Figure 3.14 Three columns; twenty rows; readings taken on Column B

Local Drag Force vs Longitudinal Distance, Thick Boundary Layer, 0.127 m Tree Spacing

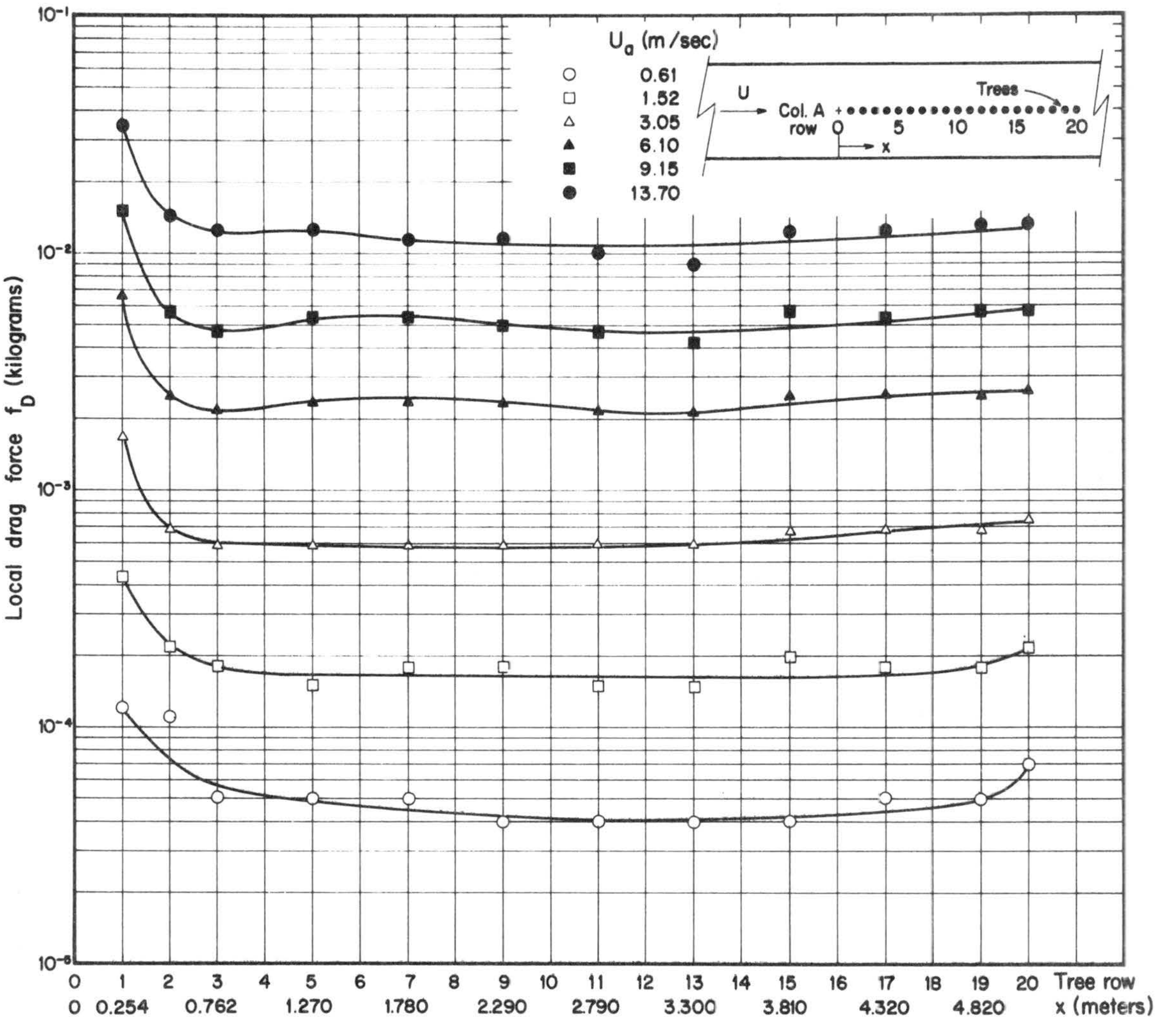


Figure 3.15 One column; twenty rows

Local Drag Force vs Longitudinal Distance, Thick Boundary Layer, 0.254 m Tree Spacing

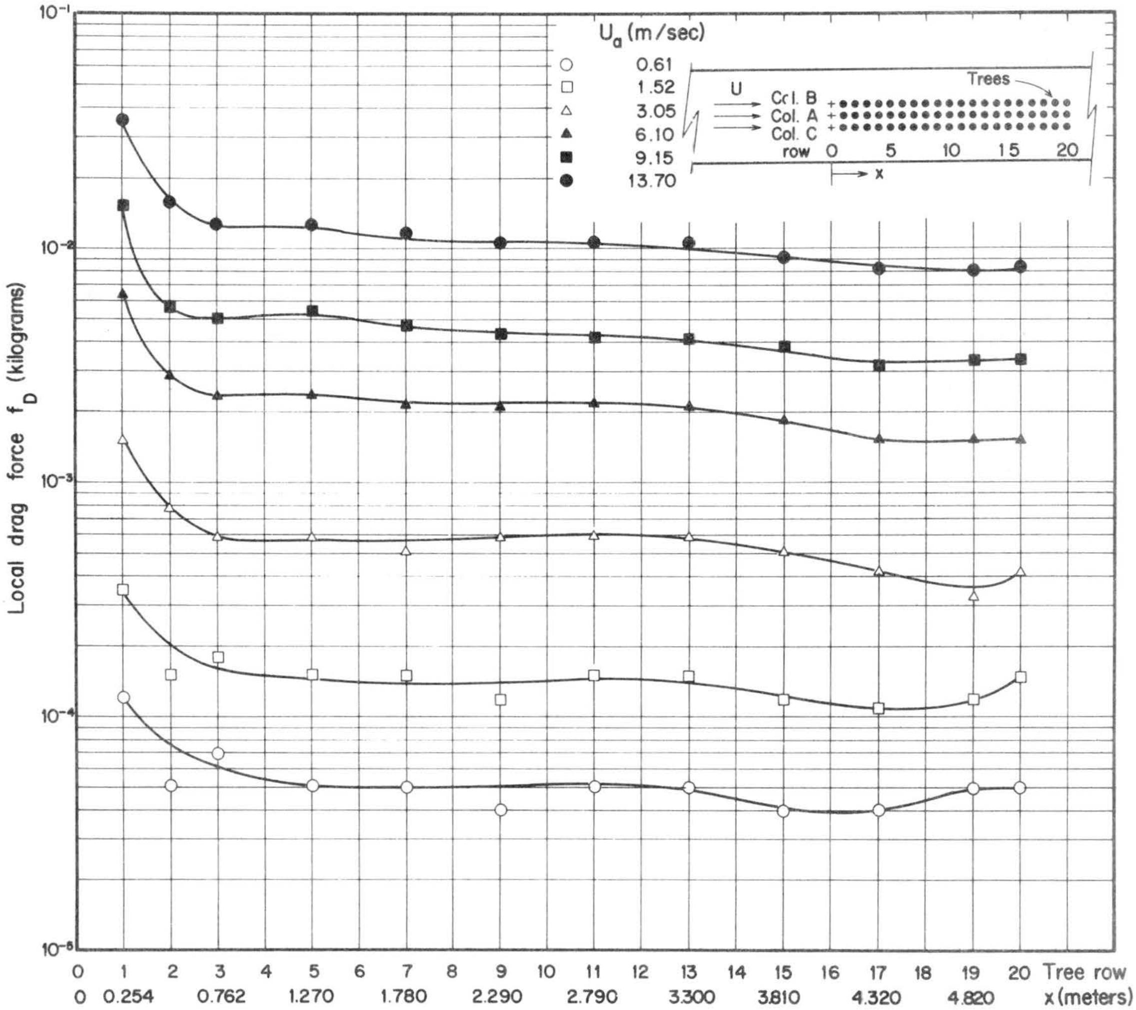


Figure 3.16 Three columns; twenty rows; readings taken on Column A

Local Drag Force vs Longitudinal Distance, Thick Boundary Layer, 0.254 m Tree Spacing

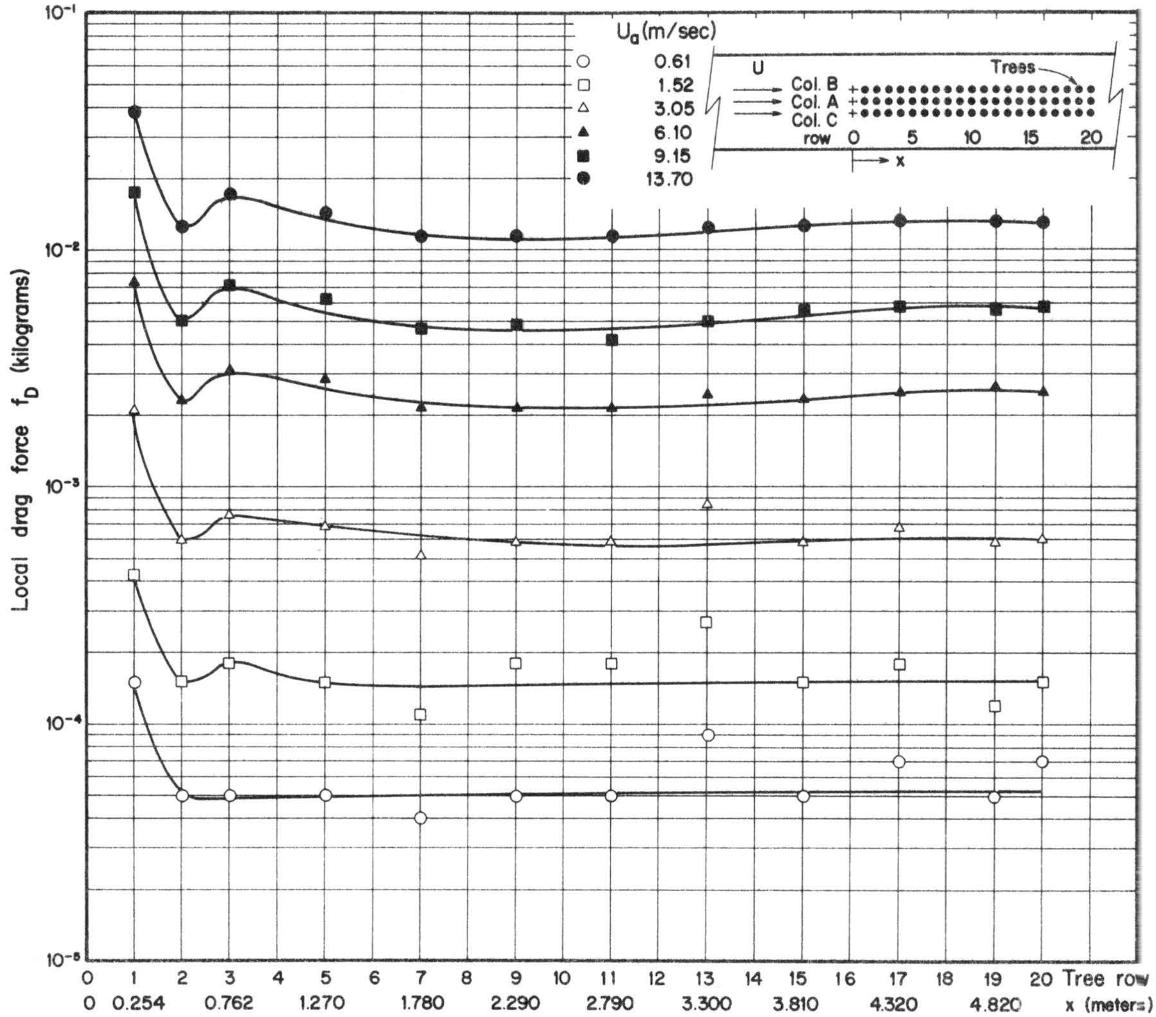


Figure 3.17 Three columns; twenty rows; readings taken on Column B

Local Drag Force vs Longitudinal Distance, Thick Boundary Layer, 0.254 m Tree Spacing

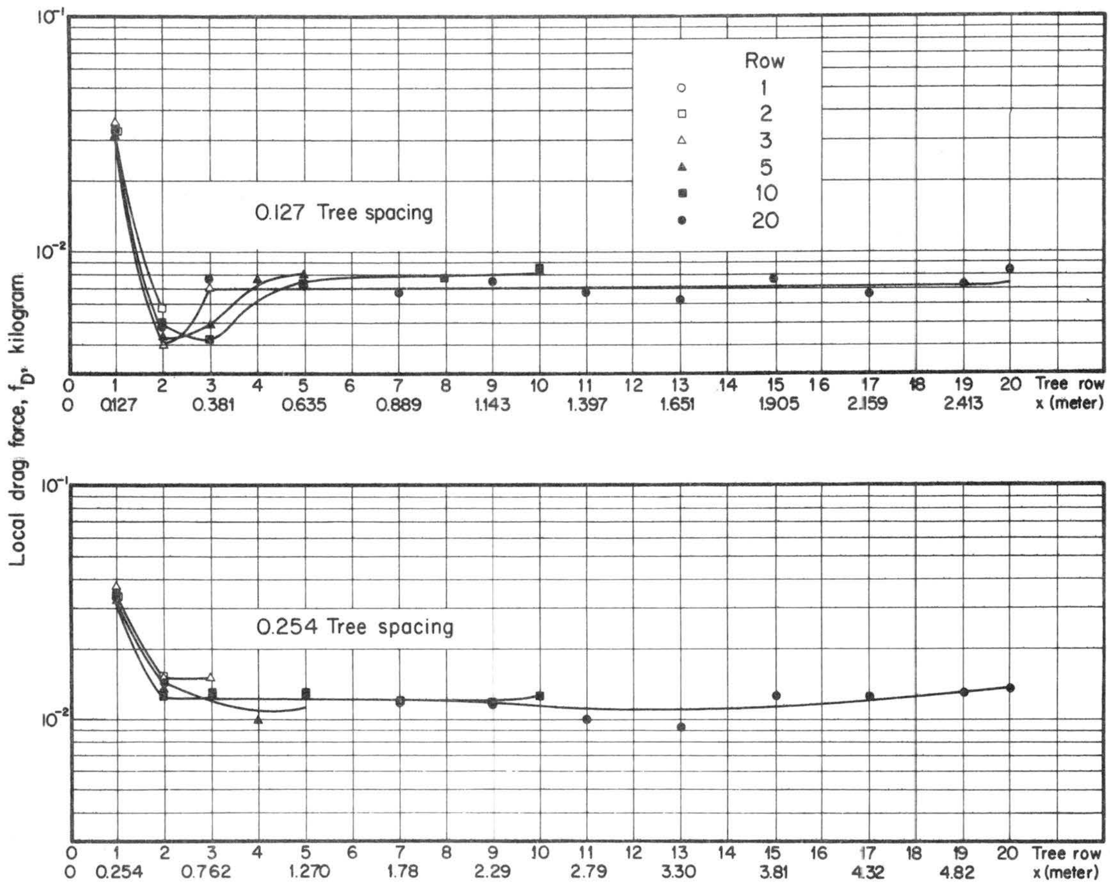


Figure 3.18 Column A only

A Comparison of Local Drag Force vs Longitudinal Distance for 0.127 m and 0.254 m Tree Spacings, Thick Boundary Layer, for all Row Arrangements, 13.70 mps Velocity Only

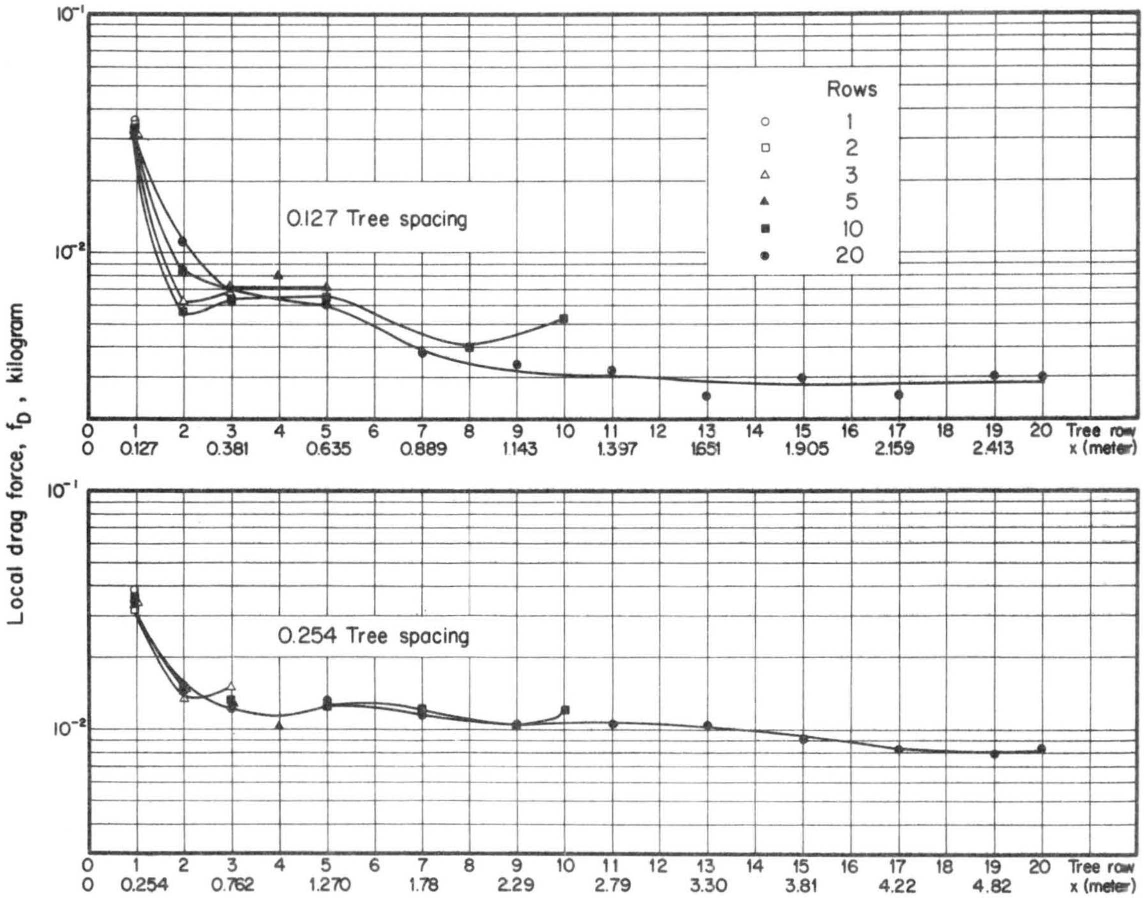


Figure 3.19 Three columns; readings taken on Column A

A Comparison of Local Drag Force vs Longitudinal Distance for 0.127 m and 0.254 m Tree Spacings, Thick Boundary Layer, for all Row Arrangements, 13.70 mps Velocity Only

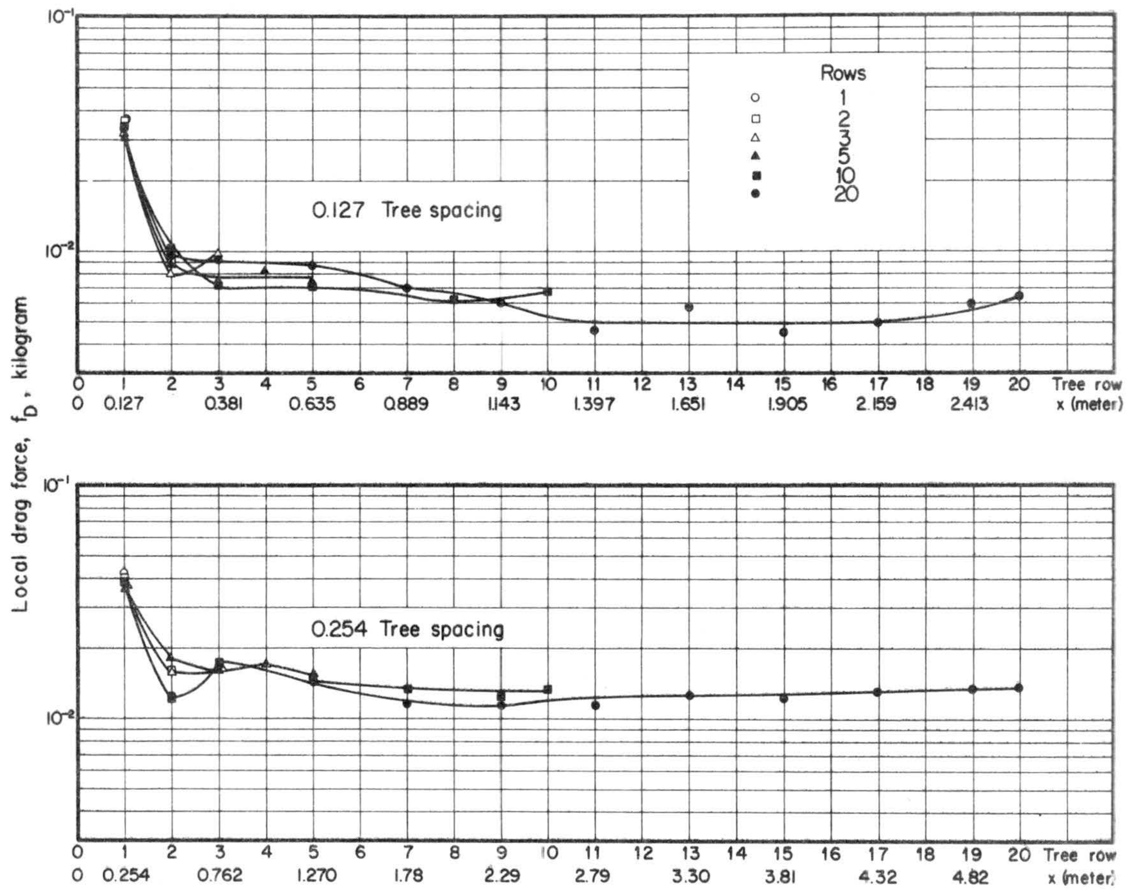


Figure 3.20 Three columns; readings taken on Column B

A Comparison of Local Drag Force vs Longitudinal Distance for 0.127 m and 0.254 m Tree Spacings, Thick Boundary Layer, for all Row Arrangements, 13.70 mps Velocity Only

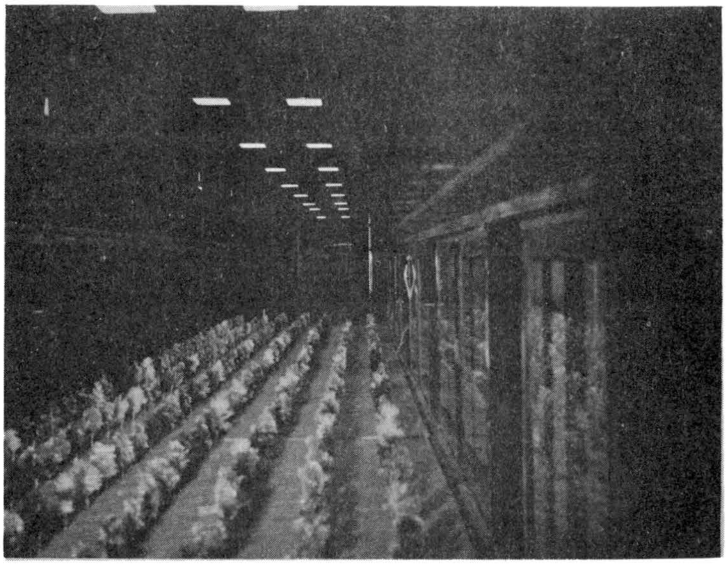


Figure 3.21 The arrangement of artificial trees in the model forest, 0.254 m tree spacing

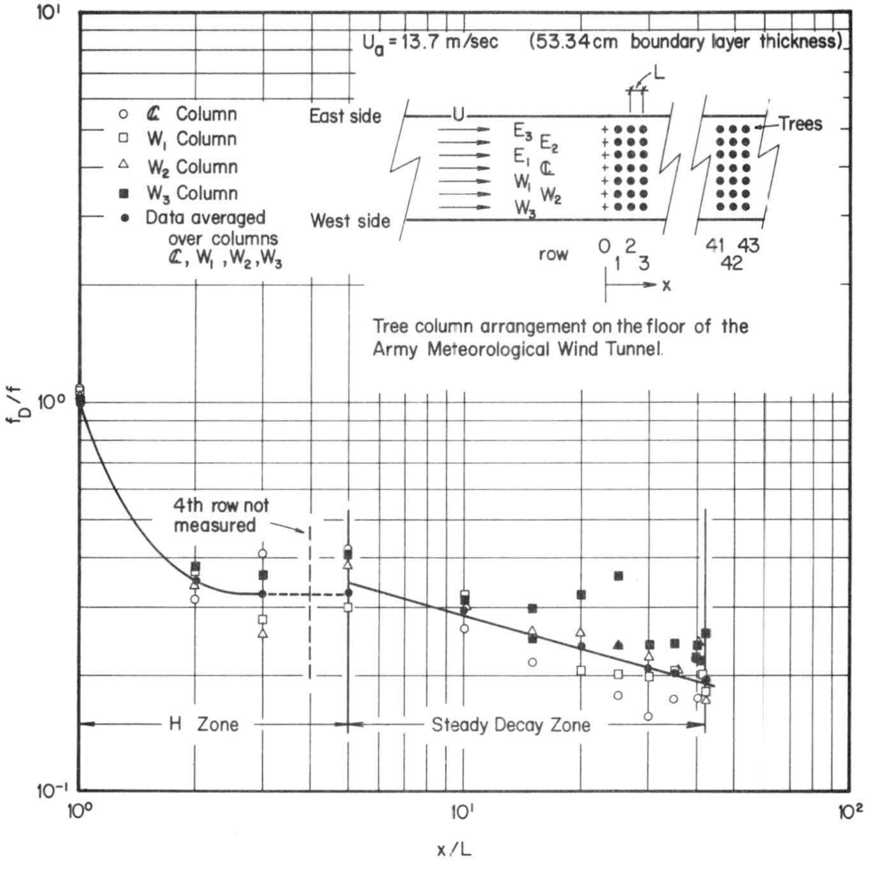


Figure 3.22 f_d/f vs x/L in the model forest canopy field, 0.254 m tree spacing, thick boundary layer

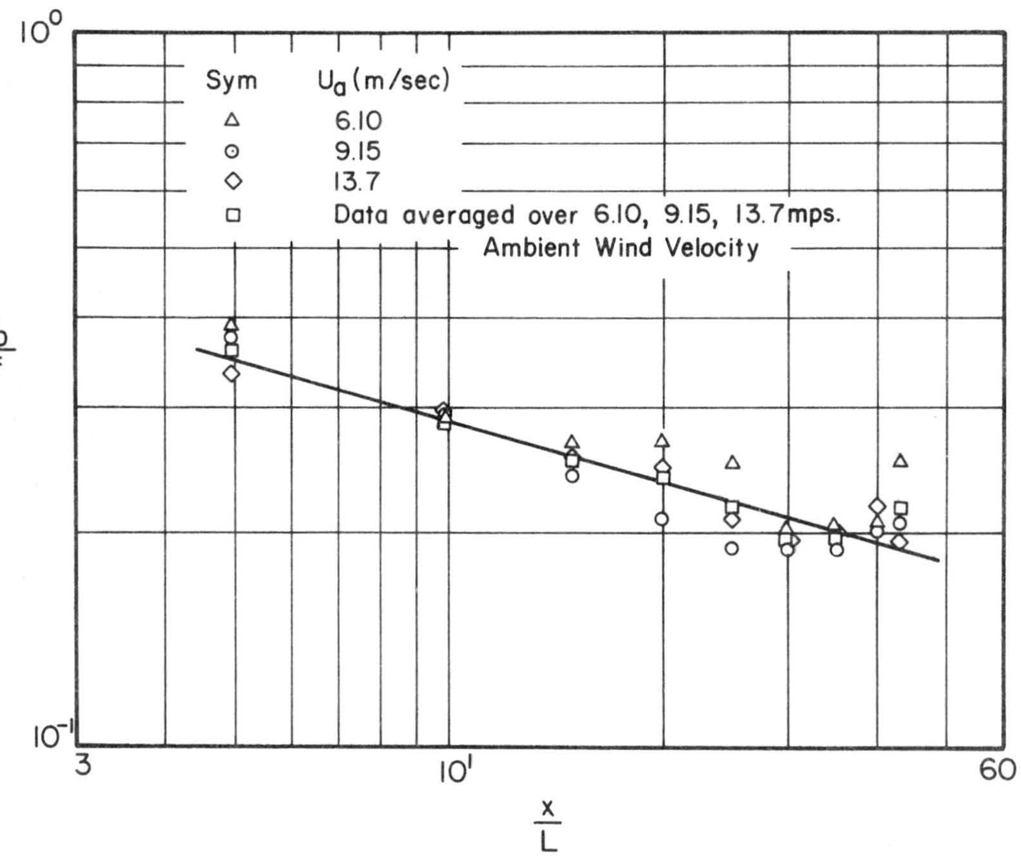


Figure 3.23 f_D/f vs x/L in the steady decay zone of the model forest canopy field, 0.254 m tree spacing, thick boundary layer

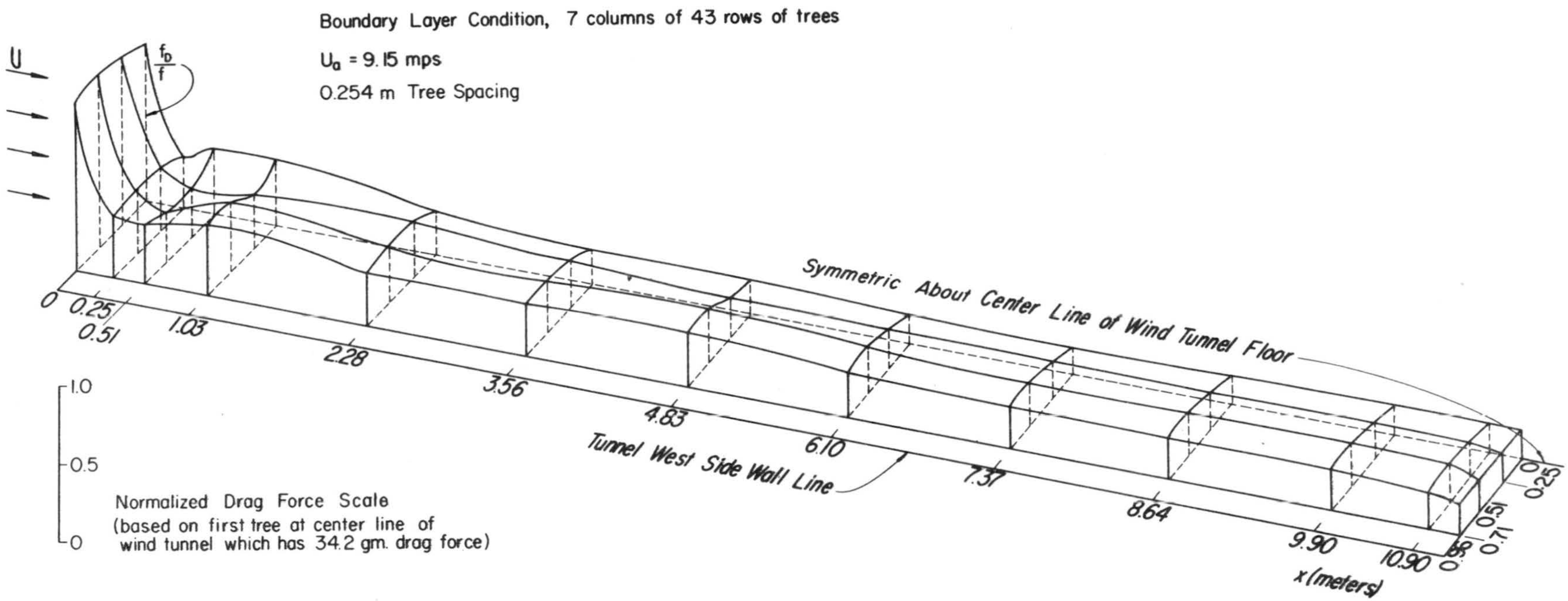


Figure 3.24 A three dimensional plot of the distribution of tree drag force in the model forest under 9.15 mps ambient wind velocity, in dimensionless form, thick boundary layer

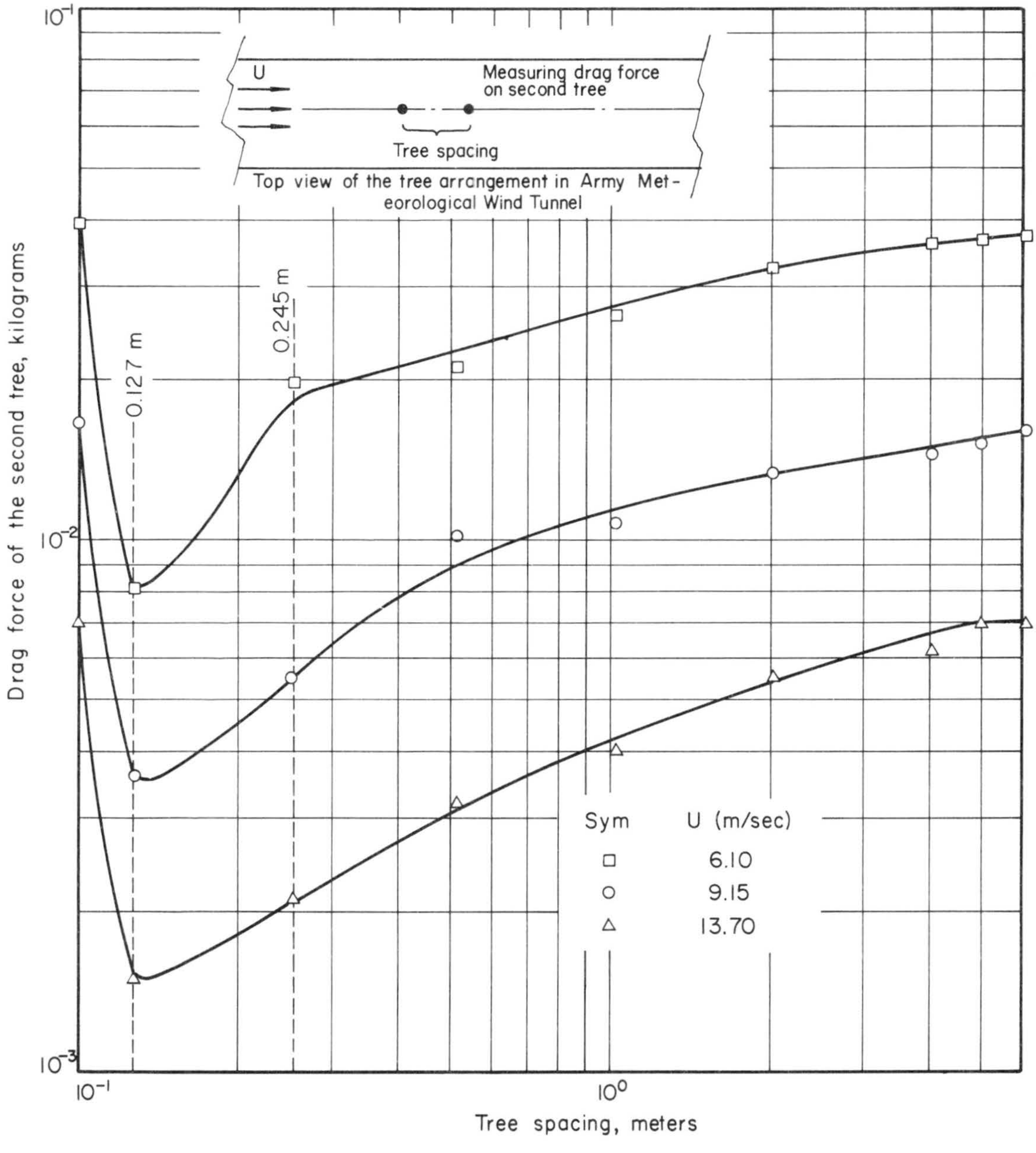


Figure 3.25 The effect of tree spacing on the drag force of the second tree, with two trees in line, thick boundary layer

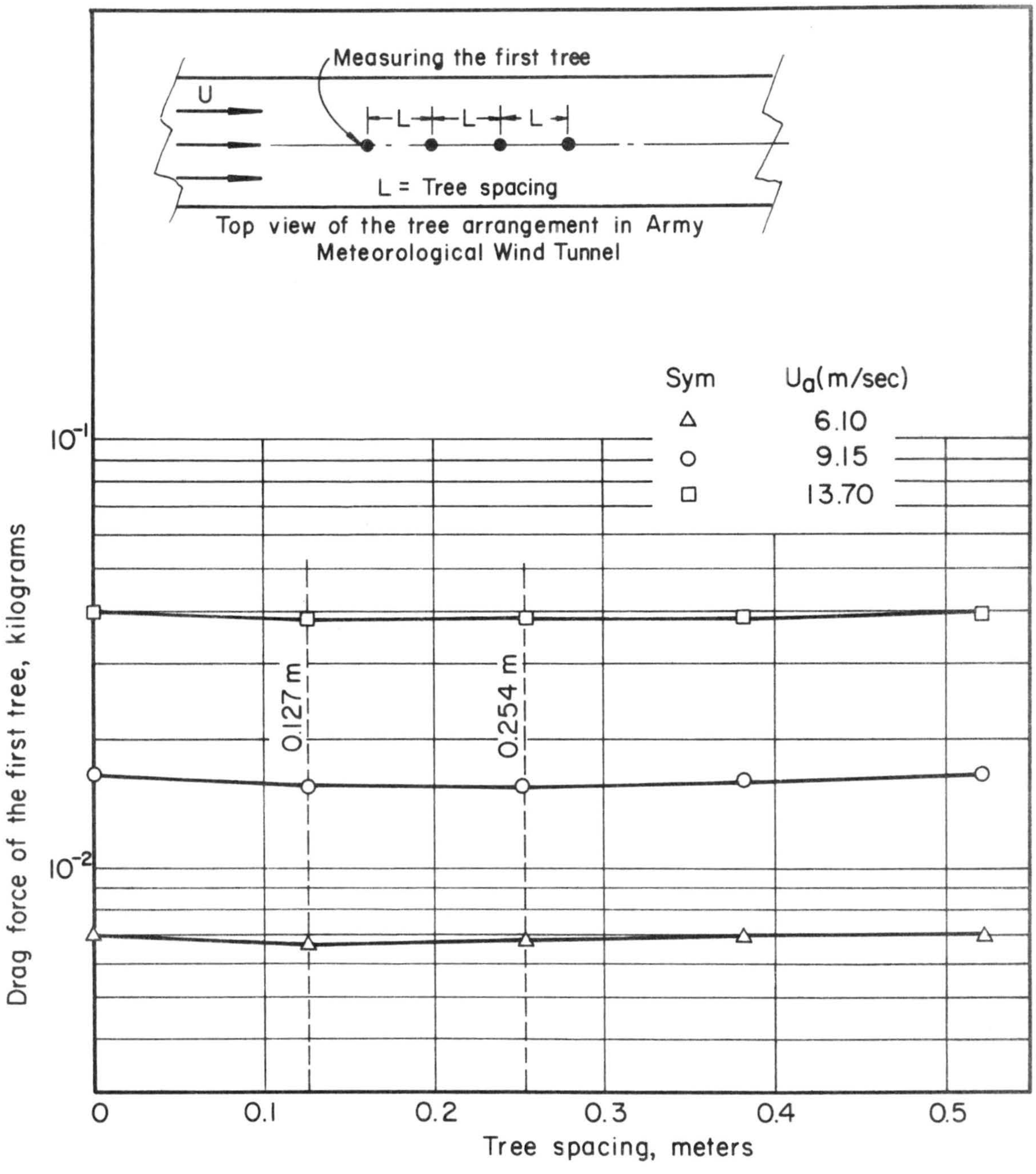


Figure 3.26 The effect of tree spacing on the drag force of the first tree, with four trees in line, thick boundary layer

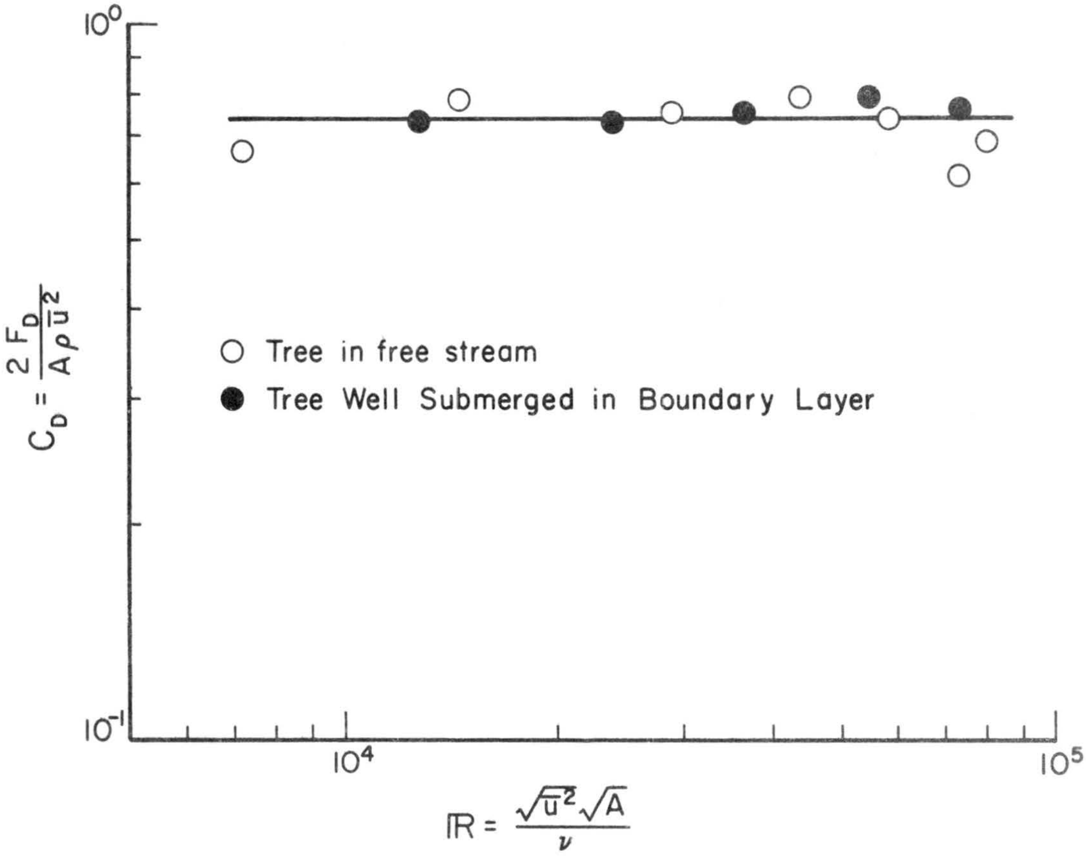


Figure 3.27 C_D vs Re for a single tree in free stream and under thick boundary layer conditions

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The objective of this study was to determine distribution of the tree drag force within various model forest canopies subjected to various ambient wind conditions. Ultimately this information may be related to diffusion within the forest canopy.

The influence on individual tree drag due to neighboring trees was investigated by arranging the trees in various configurations of columns and rows, the columns being parallel to the ambient wind and the rows being perpendicular. Two tree spacings for the columns and rows were investigated. Furthermore, a large forest canopy field was investigated that covered an area of twenty-one square meters. For this arrangement it was determined that the tree drag field can be classified into two zones - an initial zone and a steady decay zone.

In order to study the influence of the boundary layer development on tree drag, the various arrangements of trees were tested under a thin boundary layer condition and under a thick boundary layer condition.

In the course of this study a strain gage force dynamometer was developed that can reliably measure a drag force as small as 0.1 gram on a model tree.

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14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
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