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Air Resources
Atmospheric Turbulence and Diffusion Laboratory

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METEOROLOGICAL EFFECTS OF THE COOLING TOWERS
AT THE OAK RIDGE GASEOUS DIFFUSION PLANT

PART I: DESCRIPTION OF SOURCE PARAMETERS AND ANALYSIS
OF PLUME PHOTOGRAPHS AND HYGROTHERMOGRAPH RECORDS.

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Meteorological Effects of the Cooling Towers at the Oak Ridge Gaseous Diffusion Plant

I. Description of Source Parameters and Analysis of Plume Photographs and Hygrothermograph Records.

By

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Abstract

Measurements of source parameters, downwash criteria, visible plume dimensions, and water deposition rate, taken at the Oak Ridge Gaseous Diffusion Plant are presented. In some cases, such as the measurements of the initial droplet size distribution, comparisons are made with similar measurements taken by other groups. The most significant findings are listed in the summary at the end of the report.

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1. Introduction

In the fall of 1972, we were asked by Mr. Ted Shapiro and Dr. George Kidd of the Oak Ridge Gaseous Diffusion Plant (ORGDP) to help develop a program for determining the environmental impact of the cooling towers at that site. These mechanical draft towers, which were built in the 1950's, can dissipate as much heat as a large power plant (on the order of 1800 MW). Chromium is used to treat the cooling water and is sprayed on the surrounding vegetation by the water (drift) that splashes out of the tower. Other groups are studying the effects of the chromium on the vegetation and animals in the vicinity of the tower.

Our study is limited to the following specific atmospheric problems:

a) Measurement of source terms, such as initial plume buoyancy, vertical speed, drift flux, and droplet size distribution.

b) Determination of downwash criteria. Downwash is the mixing of the plume to the ground behind the tower due to aerodynamic effects.

c) Measurement of visible plume length and height and comparison with model predictions.

d) Measurement of drift deposition downwind of the towers and comparison with model predictions.

e) Determination of increases in fog frequency.

f) Determination of whether rainfall in the vicinity of ORGDP has increased due to the operation of these towers for twenty years. Problems, a, b, c, and the measurement section of problem d will be treated in this report. The model of drift deposition and fog frequency and the analysis of rainfall will be described in a future report.

One of the first documented accounts of precipitation caused by cooling towers was given by W. Culkowski (1967) of our laboratory. In this case, light snow was observed on the ground several miles downwind of the ORGDP cooling towers.

Our current measurement program began in December 1972, as we started taking photographs of the plumes on whichever days that it was possible. In March, 1973, we erected a 20 m meteorological tower and two hygrothermograph systems near the cooling towers. We took part in the source and drift measurements made by Pacific Northwest Laboratory (PNL) in April, 1973, and by PNL and Environmental Systems Corporation (ESC) in June, 1973. We hope to use our drift deposition model to verify measurements of chromium concentration and deposition in the air and in vegetation around the ORGDP measured by the Environmental Sciences Division of Oak Ridge National Laboratory (ORNL).

The credit for coordinating this interdisciplinary experiment goes to Dr. George Kidd and Mr. Ted Shapiro. Hopefully this program can grow into a comprehensive program which will really answer, in detail, the question of the environmental impact of mechanical draft cooling towers.

2. Source Characteristics

The source measurements are discussed first because they represent the initial conditions necessary for analyzing whatever happens to the plume in the atmosphere. Since cooling tower plumes are highly buoyant, it is necessary to determine the initial volume and buoyancy fluxes. Since the surface deposition of water drops is of interest, it is also necessary to measure the initial liquid water flux and drop size spectrum. Mike Wolf of PNL attempted to measure these initial fluxes at ORGDP in April, but had severe problems with his liquid water sampler. Fred Shofner of ESC (1973) had better luck in June with his instruments, which had been tested at several other locations. However, ESC measured only one cell on each of the counterflow and crossflow towers. Our measurements, although cruder than ESC's, were made on all operating cells. Furthermore, our system could detect drops with diameters greater than 1000 μm, which could not be detected by the ESC system.

2.1. Physical Size of Cooling Towers

The map in Figure 1 shows the location of ORGDP and the cooling towers and their relation to topographic features. The northernmost tower (K-33) is of the counterflow design and is 21 m high, 283 m long, and 20 m wide. The two sections of this tower each consist of two parallel rows of 11 cells. Each cell is 6.2 m in diameter.

The southernmost tower (K-31) is of the crossflow design and is 17 m high, 117 m long, and 19 m wide. This consists of a single row of 16 cells. Each cell is 6.8 m in diameter. A plan view of these towers and the number assigned to each cell is given in Figure 2.

2.2. Vertical Speed and Volume Flux at Tower Mouth

The most extensive tests were taken on the K-31 crossflow tower, since this design is more common than the counterflow design. We used a small, propellor-type anemometer, bolted to the end of a length of 2" aluminum pipe. Great care was taken, for we were informed by the engineers that if the pipe fell into the fan, a fan blade might shear off.

Only seven of the sixteen cells were operating during most of the experiment week June 25 - June 29. Power usage during this summer was only half of that during the previous winter (Jallouk, 1973). However these cells were each dissipating a load equivalent to the typical load during the winter. Speeds were measured at each tower on two separate days. The fans at each of the cells produced nearly the same speeds as shown in Table 1. The speeds at a radius of 1.8 m, where the bulk of the transport takes place, vary by less than 10%.

Table 1

Average Vertical Air Speed (m/s) at Mouth of K-31 Cooling Tower Cells

Week of June 25 - June 29, 1973.

Cell		1	2	3	4	5	6	7
Vertical Speed (m/sec)	1.8 m radius	14.9	15.4	15.0	16.2	15.8	14.2	15.7
	3.1 m radius	4.9	6.2	2.9	3.6	--	--	--

On the basis of these measurements, it is assumed that the volume flux from each cell is equal, for purposes of calculating total fluxes and plume rise.

A detailed cross-section of vertical speed was takenby us and by ESC, using a different make anemometer, on cell number 6. The results are shown in Figure 3, which indicates that the two measurement systems are in fair agreement. Our maximum speed is about 15% greater than that measured by ESC. Their measured speed may be low due to the interference of their instruments with the updraft. The average vertical speed is about 9 m/sec and the total volume flux from each cell is about 330 m^3/sec. Total volume flux from all cells at the K-31 tower is about 2300 m^3/sec. In the center of the cell, where the fan hub is located, the vertical speed is relatively low and in some places negative. However, this region makes an insignificant contribution to the fluxes of air and water. Most of the flux is from a donut-shaped ring near the outer edge of the cell. Axial symmetry can be assumed.

Measurements were also take on the K-33 tower. During these experiments, only a couple of fans were turned on and a few cells were dissipating heat without the benefit of fans. However, a check of the vertical speed at cell number G-12 indicated that the speed is within 20% of that measured on the K-31 tower and reported in Figure 3. Due to the slightly smaller diameter of the K-33 cells, the volume flux from each cell is only about 250 m^3/sec.

2.3. Temperature and Buoyancy Flux at Tower Mouth

Temperatures were measured with a Taylor indoor-outdoor thermometer taped to the end of a length of 2" aluminum pipe. Because of the water drops in the air, the dry bulb was acting like a wet bulb. But fortunately, during such saturated conditions, the dry bulb temperature is very close to the wet bulb temperature. ESC measurements of the true dry bulb and wet bulb temperatures indicate that they differ by less than a fraction of a degree.

Unlike the distribution of updraft speed, the distribution of temperature is found to be not axisymmetric. The temperature near the east and west edge of each cell was consistently higher than that near the north and south edge of the cell. This lack of symmetry is due to higher water temperatures in the cooling tower fill on the east and west edges.

Table 2 gives the average temperatures measured at each cell during the period June 25 - June 29, 1973.

Table 2

Temperature (°C) at Mouth of K-31 Cooling Tower Cells, along Radius to the West, Week of June 25 - 29, 1973.

Cell		1	2	3	4	5	6	7
Temperature	3.1 m radius	36	38	37	35	36	34	35
(°C)	1.8 m radius	31	32	33	32	31	29	33

It was found that the maximum temperature in any cell was independent of the ambient air temperature, which ranged from 20 to 32°C during this experiment. However, the average temperature over the entire cell mouth increased as ambient air temperature increased, as shown by Table 3.

Table 3

Average Cell Mouth Temperature (Cells 1, 4, and 5) as a Function of Ambient Air Temperature, at K-31 Towers. Week of June 25-29, 1973.

Average Cell Temperature	29°C	31°C	31°C	32°C	33°C
Ambient Air Temperature	22°C	22°C	24°C	29°C	31°C

The measurements at two cells on the K-33 towers indicated that the temperatures of the initial plumes from those towers were nearly the same as the temperatures on the K-31 towers.

The lack of axial symmetry in temperature is illustrated in Figure 4, in which the temperature distributions along the west and south radii of K-31 cell number 2 are shown. This assymetry is due to the fact that the hottest water is beneath the east and west edges of each cell. The average temperature difference between the initial plume and the ambient air for this figure is about 9°C.

For the week of this experiment, the average temperature difference between the plume and the environment was about 6°C, which yields an average dry energy flux from each cell of about two megawatts. The latent energy flux from each cell, assuming that the initial plume is saturated, is about ten megawatts. Thus the total energy flux from each cell is about 12 megawatts. During the week of this experiment, the total energy flux from the K-31 towers can be calculated to be about 100 megawatts. This figure is close to the total energy flux at the K-31 tower of 130 MW measured by ORGDP engineers (Jallouk, 1973) from the inlet and outlet water temperatures and circulating water rate. At the K-33 tower, they measured a total-energy flux of 180 MW. Our measurements at the K-33 tower are not sufficient for comparison.

2.4. Drift Droplet Size Distributions and Liquid Water Flux

During the experimental period June 25 - June 29, the main thrust of the ESC (1973) effort was the measurement of the drift droplet size distribution and liquid water flux. We also measured the droplet sizes, using a sensitive paper technique described by Engelmann (1962). A sheet of 8 1/2" by 11" Ozalid paper is hand-held over the mouth of a cooling tower cell. The time of exposure is typically two seconds, which is long enough for a sufficient number of drops to strike the paper, but not so long that the paper becomes saturated. The paper is then developed in a chamber containing ammonia fumes. The droplets of certain size ranges are counted later in the office. Measured droplet diameters are related to actual diameters using calibration curves developed by Engelmann (1962).

Our sensitive paper technique can be used only for drops with diameters greater than about 100 μm, since smaller drops cannot be distinguished in the grain of the paper. At the ORGDP cooling towers many drops with diameters are large as 5000 μm (.5 cm) were seen.

Since the mass flux of liquid water is the most important parameter in drift studies, we chose to plot the droplet distribution in Figure 5 as mass flux per unit drop diameter ($\mu g/m^2$sec μm). In order to make all regions of the figure readable, log-log coordinates are used. However, the use of these coordinates eliminates the main advantage of the use of linear coordinates; i.e., that an increment of mass flux equals the increment of area under the curve. The ATDL data for cell 6 and for the average of cells 1 through 8 are plotted on the figure, as are the data obtained by ESC (1973) for cell 6 during the same experimental period. The point for the 275 μm diameter on the ATDL curve is doubtful because these small drops are extremely difficult to see on the sensitive paper. The ESC curve was obtained by assuming that mass flux equals air concentration times the difference between the updraft speed and the drop settling speed.

The ESC and ATDL measurements represent two different regions of the drop spectrum. We find that the drift loss from a cell is about 36 gm/sec for drops with diameters greater than 500 μm, while ESC finds that the drift loss is about 140 gm/sec for drops with diameters less than about 500 μm. The total drift loss is 176 gm/sec. Thus we suggest that the dot-dash line on Figure 5 be adopted as the characteristic drop distribution curve for the ORGDP cooling towers. This curve agrees with the ESC curve at small drop diameters and with the ATDL curve at large drop diameters.

Very little difference in drop distributions were found among the eight operating cells of the K-31 towers. Two tests taken on the K-33 towers suggest that the total drift rate is only about a tenth of that at K-31, and that droplets with diameters, D, greater than about 1500 μm are absent, but that the general shape of the distribution curve is similar to that in Figure 5.

Liquid water fluxes from K-31 and K-33 are listed in Table 4.

Table 4

Liquid Water Fluxes (gm/sec) Measured at the ORGDP Cooling Towers During the Week of June 25-29, 1973.

Tower-Cell	Investigator	Component of Liquid Water Flux(gm/sec)
K-31-1	ATDL	20 (D>500μm)
K-31-2	ATDL	18 (D>500μm)
K-31-3	ATDL	25 (D>500μm)
K-31-4	ATDL	17 (D>500μm)
K-31-5	ATDL	28 (D>500μm)
K-31-6	ATDL	36 (D>500μm)
K-31-6	ESC (1973)	140 (D<500μm)
K-31-7	ATDL	31 (D>500μm)
K-31-8	ATDL	23 (D>500μm)
K-33-G-16	ATDL	6.0 (D>500μm)
K-33-G-18	ATDL	7.0 (D>500μm)
K-33-G-2	ESC (1973)	2.0 (D<500μm)

The sum of liquid water fluxes from the K-31 towers is about 1400 g/sec. Because of the spotty operation of the K-33 towers during this experiment, it is difficult to estimate their total liquid water flux. An upper limit would be 1000 g/sec, based on the flux from cell number G-16 and the power figures given by Jallouk (1973).

These data can also be used to calculate the drift fraction, which is the ratio of the flux of drift from the tower cell to the flux of circulating water in the cell. From data provided by ORGDP for the ESC (1973) report, it is seen that the flux of circulating water in cell 6 of the K-31 tower is 1.8×10^5 gm/sec. In cell G-2 of the K-33 tower this flux is about 3.6×10^5 gm/sec. Thus the drift fractions at K-31 and K-33 are about .1% and .003%, respectively.

The droplet size information reported above is being used as input to a model of drift deposition. These results will be reported in Part II of this series.

3. Downwash Criteria, based on Hygrothermograph Records.

Standard "cotton region" weather shelters were installed on the lawn 15 m to the east and west of the center of the bank of K-31 cooling towers. Continuous records of temperature and relative humidity were taken by hygrothermographs in each shelter at a height of 1.5 m above the ground. Also, continuous records of wind speed and direction at a height of 20 m (approximately the height of the cooling tower) were made from a pole in a field about 100 m south of the K-31 towers.

Two hour averages of all hygrothermograph and wind observations were made by eye for the period 1 April 1973 through 2 July 1973. On many occasions, when the cooling tower plume would downwash to the ground, differences in temperature and relative humidity would occur between the east and west instruments. An example of the data is given in Table 5.

Table 5

Example of Hygrothermograph Records from Instruments in Ground Shelters 15 m East (E) and West (W) of K-31 Cooling Towers.

Date and Time	T_W °C	T_E °C	ΔT °C	RH_W %	RH_E %	ΔRH %	Mixing-ratio m_W gm/gm	m_E	Δm	U m/sec	Wind direct.
4/1/73 10	18.3	20.6	-2.3	49	74	-25	.00676	.01154	-.00478	7.5	240°
12	19.4	21.1	-1.7	43	68	-25	.00628	.01102	-.00774	9.5	240
14	20.0	21.7	-1.7	40	70	-30	.00604	.01183	-.00579	8.5	240
16	19.4	20.6	-1.2	37	62	-25	.00540	.00967	-.00427	9.5	280
18	17.2	17.2	0	40	75	-35	.00512	.00960	-.00448	7.5	270

The data in Table 5 were obtained during relatively high winds following the passage of a cold front. Downwash occurred during this period, as indicated by non-zero values of temperature difference ΔT and relative humidity ΔRH. The air to the lee of the tower is warmer and more humid than the ambient air. In the spring and summer, the shading effect of the plume can counterbalance the warming effect, causing a temperature decrease in the shelter that the plume is shading.

3.1. Relative Occurrence of Downwash

In April, downwash occurs about 40 per cent of the time. During the night (8 p.m. - 6 a.m.) the frequency is 32 per cent and during the day (8 a.m. - 6 p.m.) the frequency is 48 per cent. In May, downwash occurs about 22 percent of the time, with the night-day ratio the same as in April. In June, downwash occurs about 20 per cent of the time. The frequency of downwash is strongly related to wind speed. Since the wind speed decreases during the night, so also does the downwash frequency. Similarly, as the average wind speed decreases from April to June, so also does the downwash frequency.

Since downwash is an aerodynamical phenomenon, it makes a difference whether the wind is blowing parallel or perpendicular to the tower. There were about 60 two hour periods during which the wind direction was within 10° of the tower axis (north-south). For these data, downwash occurs about 15 per cent of the time. In some instances, such as at 10 a.m. on April 9, the wind speed is as high as 10 m/sec and no downwash occurs. The tower presents less of an obstacle to the wind when the wind direction is along the tower. The same conclusions were reached by Reisman (1972) as a result of wind tunnel modelling of cooling tower recirculation.

3.2. Downwash Criteria

The standard criterion for smoke stacks (Briggs, 1969) is that downwash occurs when the ratio of stack updraft, w_o, to wind speed, U, is greater than 1.5. However this criterion is not necessarily true for strongly buoyancy dominated plumes or for plumes that are not emitted by tall stacks. At the ORGDP towers, the Froude number is sufficiently high that the criterion does not have to be corrected for buoyancy effects. The major problem at these towers is that there is no stack; the plumes are emitted effectively from the top of a long rectangular building. The aerodynamic cavity downwind of this building extends to a height of roughly 1.5 x building height, or about 30 m, and to a distance of roughly 3.5 x building height, or about 70 m. If the plume does not escape the cavity, then it is brought to the ground and downwash occurs. Briggs (1973) suggests the downwash criterion that if the product $2(w_o/U - 1.5)\ D$ is less than 1.5 x building height, then downwash occurs. D is the cell diameter, 6.8 m. Thus the theoretical critical wind speed is about 4 m/sec.

It is important to realize that at wind speeds less than 4 m/sec, some downwash effects can be detected by these hygrothermographs, as the bottom of the plume can be mixed to the ground. From the April through June data summary, it is seen that downwash is observed for wind speeds greater than about 3 m/sec. This is in rough agreement with the predictions of Briggs' theory. However, occasionally downwash is observed for wind speeds as low as 1 m/sec. As stated previously, when the wind direction is nearly north or south, along the tower axis, winds as high as 10 m/sec cause no downwash. While the exact criteria at these towers are uncertain, the existence of a downwash problem is certain. Many aspects of the construction of these towers, such as their long, bulky shapes and the lack of an elevated stack, promote downwash.

3.3. Maximum Water Vapor Concentrations

The column labeled Δm in Table 5 is basically the concentration of water vapor in the plume. There is an upper limit to this, set by the air temperature. The dependence of the maximum water vapor concentration on temperature is shown in Table 6.

Table 6

Saturation Water Vapor Concentration (gm of water vapor/gm of air) as a Function of Temperature (°C)

Temperature (°C)	0	10	20	30
Saturation Vapor Content $\left(\frac{gm}{gm}\right)$	.0039	.0080	.015	.028

Any excess water vapor in the plume condenses, forming the familiar vapor plume seen at most cooling towers. At constant ambient temperature and relative humidity, the concentration of water vapor in the plume at the hygrothermograph station will be mainly a function of wind speed.

However, wind speed has two opposing effects: a) an increase in wind speed dilutes the plume; b) an increase in wind speed causes more severe downwash. In Figure 6, wind speed is plotted against plume water vapor concentration, Δm, illustrating that the effect of downwash is predominant, since vapor concentration generally increases with wind speed. The correlation coefficient is .68 between U and Δm for the periods in April through June 1973 when downwash occurs. Maximum observed vapor concentration is .005, compared to a vapor concentration at the tower mouth of about .01 to .02.

4. Analysis of Plume Photographs

Photographs of the ORGDP cooling tower plumes were taken by S. Hanna during the period December 1972 through June 1973. The photos were usually taken from the "overlook", about 2 km south of the towers, and the peripheral road, about .5 km north of the towers. Both sites are marked on Figure 1. Because of security restrictions, we could take no photos from inside the fence. Generally, the photos were taken in the afternoon, when the visible plume is the smallest. During the most intensive observation period, from January through March, photos were taken nearly every day. These photos were used to estimate the frequency of downwash and the length and height of the visible plume. During most of this time period, the heat flux from the K-33 towers was obviously greater then that from the K-31 towers.

4.1. Frequency of Downwash, Based on Plume Photos

Downwash was observed on the photos on 65% of the days. This compares to an observed frequency of 48% in the daytime in April, based on the hygrothermograph records. However, it is expected that the frequency estimated from the photos would be higher, since the plume sometimes downwashed in the photos but did not quite reach the level of the weather shelters.

Up until April, the wind observations that were used were from our weather station 10 km east of the towers, since the instruments at ORGDP were not yet installed. We conclude that downwash occurs when the wind speed exceeds about 2.5 m/sec, in fair agreement with the criterion based on the hygrothermograph records. Similarly, on one instance when the wind was from due south at 5 m/sec, parallel to the line of the towers, no downwash was seen.

4.2. Cloud Development

About 10% of the time, the cooling tower plumes were observed to initiate cloud development. On a cold afternoon (-5°C) in January, with nearly calm conditions, a cumulus cloud of depth .5 km was initiated at a height of .5 km above the ground. On another calm day with drizzle from a stratus deck at about 1 km, a cumulus cloud formed at a height of about .5 km. The most frequent cloud development occurred during rainy periods with moderate winds. In these periods, the plume usually formed a stratus deck just beneath the main stratus deck, and the man-made cloud could be seen extending tens of kms to the horizon. It would be interesting to see if rainfall were increased beneath this new cloud.

4.3. Observations and Models of Plume Length and Height

Plume dimensions were estimated from the photos by scaling the plume using a 120 m water tower that was usually visible. Ideally, photos taken at right angles to each other should be used, to better account for distortion caused by oblique angles between the plume direction and the camera direction. We did the best we could with the available information. Usually two major plumes could be seen, one from the K-31 tower and one from the K-33 tower. The plumes from individual cells on each tower merged into a single plume at a distance from the cell of less than about 50 m.

4.3.1. Plume rise. The invisible vapor plume can continue to rise long after the liquid water in the plume evaporates. It is of interest to know the final plume rise, H, in order to calculate the influence of the plume on cloud growth and the dispersion of the water vapor to the ground to form fog. Briggs (1969) suggests formulas for the rise of single plumes from smoke stacks. Hanna (1971, 1972) shows how the basic formulas should be modified for use at cooling towers, where latent heat effects are often important and the plumes from multiple cells combine.

For a single cell at a mechanical draft cooling tower, the first 100 or 200 m of plume rise, Δh, are described by the formula:

$$\Delta h = 1.6\, F^{1/3}\, U^{-1}\, x^{2/3} \qquad (1)$$

where U is wind speed, x is downwind distance and F is the initial buoyancy flux, defined for dry plumes by

$$F = \frac{g}{T_p} w_o R_o^2 (T_p - T_a) \qquad (2)$$

In this expression g, w_o, R_o, T_p, and T_a are the acceleration of gravity, the initial plume vertical speed and radius, and the initial plume and ambient air temperatures, respectively. The plume rise, Δh, refers to the height of the plume centerline above the top of the cooling tower cell. The total sensible heat flux, E, which was calculated to be 2 MW per cell in Section A.3, is related to F by:

$$F\left(\frac{m^4}{sec^3}\right) = E(MW) \frac{g}{\pi c_p \rho T_p} , \qquad (3)$$

where ρ is the air density and c_p is the specific heat of air at constant pressure. Thus, for each cell of the K-31 tower during the week of the intensive cooling tower experiment, the dry buoyancy flux equals about 20 m^4/sec^3.

Usually the visible liquid water plume evaporates about 100 or 200 m from the towers, and the net effect of latent heat effects is nearly zero. However, in order to calculate plume rise for those cold or humid days when the visible plume does not evaporate, it is necessary to add the initial latent heat flux to the sensible heat flux. In this case, the initial buoyancy flux is defined by:

$$F = \frac{g}{T_p} w_o R_o^2 \quad (T_p - T_a) + \frac{L}{c_p} (m_p - m_a) \quad , \qquad (4)$$

where L is the latent heat and m_p and m_a are the initial water vapor mixing ratios in the plume and the ambient air. For the ORGDP cooling towers the latent heat flux is typically four or five times the sensible heat flux.

An additional factor is the combination of plumes from neighboring cells. There are no documented measurements of this effect at cooling towers. The available theories are also inadequate. Yet it is obvious that the individual cell plumes at the ORGDP soon combine with their neighbors. A rough rule outlined by Hanna (1971) is that the buoyancies of the cell plumes should be combined if the calculated plume rise for a single cell is greater than the crosswind distance between the cells. This criterion is usually satisfied at the ORGDP.

The final rise, H, of the plume is given by the formula:

$$H = 2.9\ (F/Us)^{1/3} \qquad (5)$$

where s is the atmospheric stability, $(g/T_a)(\partial T_a/\partial z + .01°C/m)$. For an isothermal atmosphere, $\partial T_a/\partial z$ equals zero and s equals about $3 \times 10^{-4}\ sec^{-2}$. Average wind speed near ORGDP is about 5 m/sec. For these conditions, the final plume rise on a dry day from a single K-31 cell is

$$H = 2.9 \left(20\ \frac{m^4}{sec^3} \Big/ 5\ \frac{m}{sec}\ 3 \times 10^{-4}\ \frac{1}{sec^2} \right)^{1/3} \simeq 75\ m\ .$$

If all the latent heat were released, plume rise would be increased by a factor of $5^{1/3}$ to 130 m. During the intensive experiment, eight cells at the K-31 tower were usually operating. Calculations similar to the above yield the results in Table 7.

Table 7

Calculated Plume Rise from K-31 Cooling Towers at ORGDP, for $U = 5$ m/s and Isothermal Atmosphere.

Source	Plume Rise, H
Sensible heat flux, single cell	75 m
Sensible + latent, single cell	130 m
Sensible, eight cells	150 m
Sensible + latent, eight cells	260 m

Measurements taken during this experiment were not sufficient to test the above calculations. In the next report, on drift deposition and fog frequency, a typical plume rise of 100 m will be assumed.

4.3.2. Visible Plume Height and Length. The dimensions of the visible liquid water plume are strongly dependent on the rate of entrainment of ambient air into the plume as it rises. It is important to know the ratio of the plume volume flux, V, to the initial volume flux, V_o. For plumes which do not downwash, values of V/V_o are given by Hanna (1972):

$$\frac{V}{V_o} = \left(1 + \frac{z}{D}\left(\frac{U}{w_o}\right)^{1/2}\right)^2 \qquad \text{windy} \qquad (6)$$

$$\frac{V}{V_o} = \left(1 + .4\,\frac{z}{D}\right)^2 \qquad \text{calm} \qquad (7)$$

For plumes which downwash, the plume photos permit us to make the very crude assumption:

$$\frac{V}{V_o} = \left(1 + .8 \frac{x}{D}\right)^2 \qquad \text{downwash} \qquad . \quad (8)$$

The visible plume ends when the initial flux of water, $V_o m_o$, becomes less than the flux of water necessary to saturate the plume, $V(m_s - m_a)$. Here the symbols m_o, m_s, and m_a represent, respectively, the initial, saturation, and ambient mixing ratios. Hence, at the end of the visible plume,

$$V_o m_o = V(m_s - m_a) \qquad . \quad (9)$$

The difference $(m_s - m_a)$ is commonly known as the saturation deficit.

In equation (6), height can be related to downwind distance using equation (1). The following equations are obtained for the height, h', and length, ℓ', of the visible plume from a single cell:

i. Windy, no downwash

$$\text{height } h' = 1.5\, D \left(\frac{w_o}{U}\right)^{1/2} \left[\left(\frac{m_o}{m_s - m_a}\right)^{1/2} - 1\right] \qquad (10)$$

$$\text{length } \ell' = .60 \frac{D^{3/2} U^{3/4} w_o^{3/4}}{F^{1/2}} \left[\left(\frac{m_o}{m_s - m_a}\right)^{1/2} - 1\right]^{3/2} \qquad (11)$$

ii. Calm

$$\text{height } h' = 2.5\, D \left[\left(\frac{m_o}{m_s - m_a}\right)^{1/2} - 1\right] \qquad (12)$$

iii. Windy, much downwash

height $h' \sim .4\ x$ (13)

$$\text{length } \ell' = 1.2\ D \left(\frac{w_o}{U}\right)^{1/2} \left[\left(\frac{m_o}{m_s - m_a}\right)^{1/2} - 1\right] . \qquad (14)$$

The plume photographs were divided according to these three categories and the predictions made using equations (10) through (14) were compared with observations. The results are presented in Figures 7 and 8. The correlation between observed and predicted plume length in Figure 7 is .68. However, the observed length is about four times the predicted length. The plumes from each cell do not act individually, but combine to form a larger plume. The effective diameter of the combined plume from the 16 cells on the K-31 tower is $(16)^{1/2}$, or four times the diameter of a single cell. Thus, if we use the effective diameter, $D_e = 4\ D = 27$ m, in equations (10) and (14), then the magnitude of the predicted and observed visible plume lengths are in good agreement.

Observed and predicted plume heights are plotted in Figure 8, yeilding a correlation coefficient of .48. Again, the magnitudes differ by a factor of three or four, indicating that the plume we are seeing is a combination of the plumes from the many cells. An effective diameter of 27 m should be used in equations (10), (12), and (13).

As another test, the purely empirical formulas

$$\ell' = \frac{a}{U(m_s - m_a)} \qquad (15)$$

$$h' = \frac{b}{U(m_s - m_a)} \qquad (16)$$

were compared with observations. The parameters a and b are dimensional constants, with units $(sec)^{-1}$. From Figure 9, where observed length is plotted as a function of $1/U(m_s-m_a)$,it is seen that the constant a equals about 1.5 $(sec)^{-1}$, and the correlation coefficient is .46. From Figure 10, where observed plume height is plotted as a function of $1/U(m_s-m_a)$, it is seen that the constant b equals about 1.0 $(sec)^{-1}$, and the correlation coefficient is .66. It can be concluded that the empirical formulas (15) and (16) can explain the observed plume lengths and heights as well as the theoretical formulas (10) through (14). Of course the theoretical formulas are better suited to general applications.

5. Observations of Drift Deposition Downwind of the Tower

The sensitive paper technique for measuring drop sizes and water fluxes was described in section 2.4. This technique was used for measuring rain-out or drift deposition, as well as source characteristics. Some measurements were taken on the walkways of the K-31 and K-33 towers, and others were taken on the ground under the plume axis, at distances up to 30 m from the towers.

5.1. Drift Measurements on Tower Walkways

The paper was held face-up, for about 10 seconds, on the walkway abo t 2 m from several of the cells. The larger drops would fall out at these points. Deposition rates and mass median drop sizes are given in Table 7.

Table 7

Liquid Water Deposition Rates 2 m Downwind of Cell

Cell No.	Deposition Rate ($\mu g/cm^2 sec$)	Mass Median Drop Diameter (μm)
K-31 - 3	13	2500
K-31 - 6	27	2500
K-31 - 4	5.7	2000
K-33 - G-16	.71	900
K-33 - G-18	.29	600

It is mainly the largest drops which fall out of the plume at this distance. The deposition flux per unit area at a distance of 2 m from the cells at the K-31 towers is about 3% of the initial flux per unit area of liquid water at the cell mouth reported in Table 4. A meteorologist standing on the walkway would classify the precipitation as "light rain." At the K-33 tower the measured deposition flux near the cells is one or two orders of magnitude less than at the K-31 tower. This would be expected because of the smaller total initial liquid water flux and smaller median droplet size at the K-33 tower.

5.2. Drift Measurements on Ground.

The paper was held face-up, for about 30 seconds at the ground downwind of the K-31 tower. We tried to position ourselves beneath the axis of the plume. Measured deposition rates are given in Table 8.

Table 8

Liquid Water Deposition Rates and Mass Median Drop Sizes at Ground Downwind of K-31 Tower

Distance From Tower	Deposition Rate ($\mu g/cm^2$ sec)	Mass Median Drop Diameter (μm)
7 m	7.1	750
7 m	6.1	750
10 m	7.4	1000
15 m	6.6	1000
15 m	20.7	600
15 m	2.0	750
30 m	2.2	450
30 m	7.7	450

The deposition rates per unit area reported in this table do not seem to depend on distance from the tower. All these measurements are in the aerodynamic cavity to the lee of the towers. Possibly deposition rates in the cavity are uniform due to the great mixing rate in this region.

Drop deposition was also measured by ESC (1973). While their data have not yet been converted to total deposition rates, it is seen that their observed mass median drop sizes are in agreement with ours.

6. Meteorological Tower

In cooperation with ORGDP, a 25 m telephone pole was erected in March, 1973, in the field 100 m south of the K-31 tower. We installed a cup anemometer and a wind vane at the top of the pole, and a temperature difference system with junctions at the top of the pole and at a height of 1 m above the ground. Wind speed, direction, and 20 m - 1 m temperature difference are recorded continuously on strip charts in a shed at the base of the tower. The data have been freely provided to all participants in the experiments.

Wind speed and direction, and dry and wet bulb temperature have been measured for 20 years on top of a nearby building. These data are summarized in a report published by the ATDL (1972). In the ORGDP area, winds are channeled by the ridges into the SW-NE directions. Because of the influence of the large building on which these instruments are mounted, it was decided that a separate tower should be erected to provide data of sufficient accuracy.

7. Summary.

On the basis of data contained in this report, we can make the following generalizations about ORGDP cooling towers.

7.1 Source Characteristics:

a. The average updraft speed, 9 m/sec, does not vary appreciably from cell to cell.

b. Volume flux from each cell of K-31 is 330 m^3/sec.
   Volume flux from each cell of K-33 is 250 m^3/sec.

c. Temperature distributions in each cell are not axi-symmetric.

d. Sensible heat flux from each cell is about 2 MW.

Latent heat flux from each cell is about 10 MW.

Total energy flux from all K-31 cells (June 26, 1973) is about 100 MW.

Total energy flux from all K-33 cells (June 26, 1973) is about 150 MW.

e. Mass median drop size is 1000 μm.

f. Liquid water flux from each K-31 cell is about 150 gm/sec.

Liquid water flux from each K-33 cell is about 6 gm/sec.

Total liquid water flux from all K-31 cells (June 26, 1973) is about 1400 gm/sec.

Total liquid water flux from all K-33 cells (June 26, 1973) is about 1000 gm/sec.

7.2. Downwash Criteria:

a. Downwash occurs about 50-60% of the time during the daytime in fall, winter, and spring.

b. In summer, due to lighter winds, downwash occurs only about 30% of the time during the daytime.

c. Due to lighter winds at night, the downwash frequency is about 50% during fall, winter, and spring nights, and about 20% during summer nights.

d. At wind speeds greater than about 3 or 4 m/sec, downwash is likely to occur.

e. When the wind direction is nearly parallel to the axis of the cooling towers, downwash will not occur even at wind speeds of 5 m/sec.

f. Maximum observed water vapor concentration at the ground near the towers is .005 gm water/gm air.

7.3. Visible Plume.

a. About 10% of the time, the cooling tower plumes were observed to initiate cloud development.

b. Typical final plume rise is about 100 - 200 m.

c. Observed visible plume length and height are in agreement with the predictions of a theoretical model if it is assumed that the plumes from individual cells combine.

7.4. Deposition Rates.

a. Liquid water deposition rates on the tower walkway and on the ground within 30 m of the tower are in the range .2 - 30 $\mu g/cm^2 sec$, averaging about 7 $\mu g/cm^2 sec$.

b. Mass median drop size is about 1000 μm on the walkway, and 450 μm at a distance of 30 m from the tower.

8. Acknowledgements

This experiment was possible only through the close cooperation of many persons and organizations. We especially thank Dr. G. Kidd and Mr. W. Simon of the ORGDP for their assistance. This research was performed under an agreement between the Atomic Energy Commission and the National Oceanic and Atmospheric Administration.

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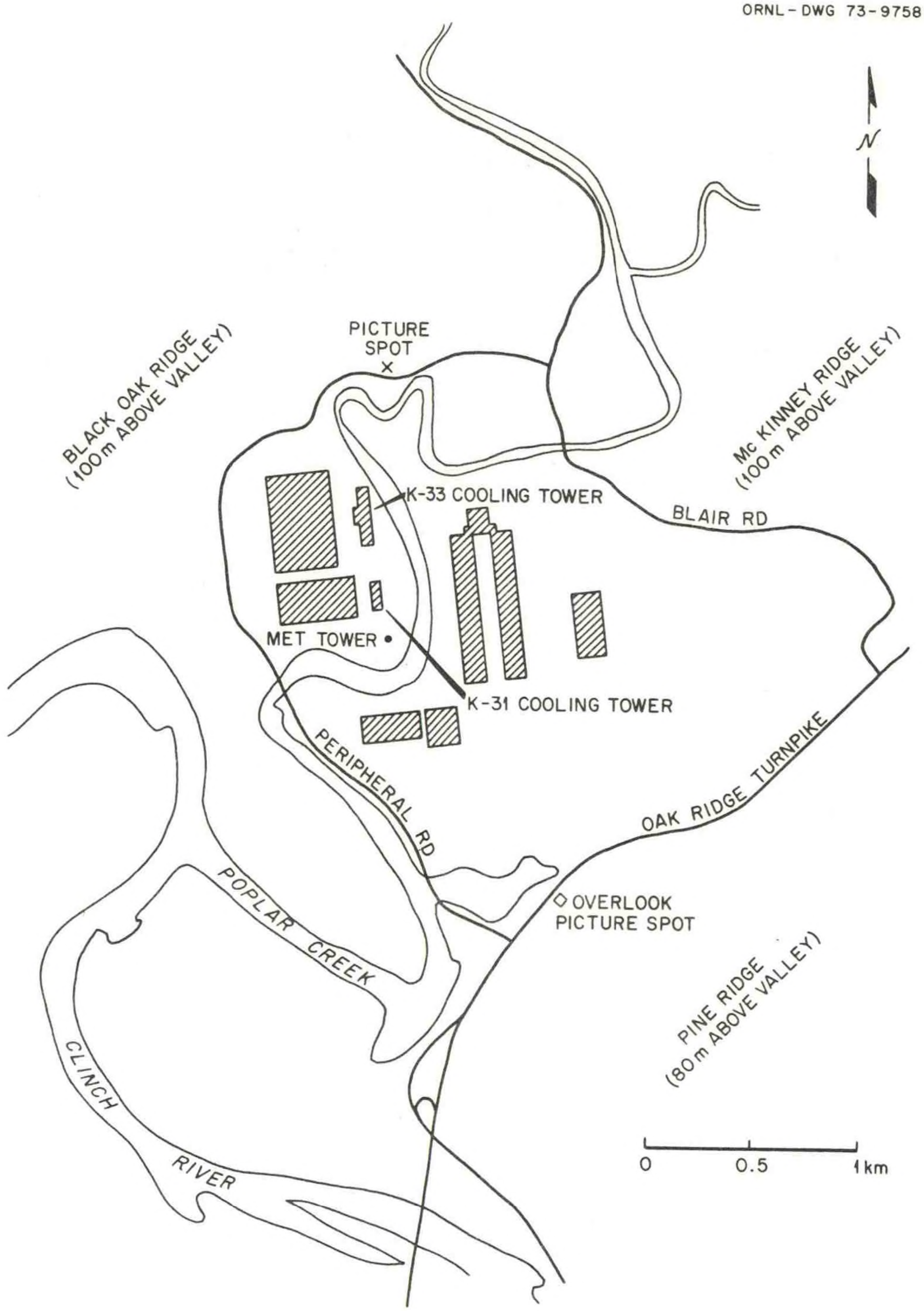

Figure 1. Map of area around ORGDP cooling towers.

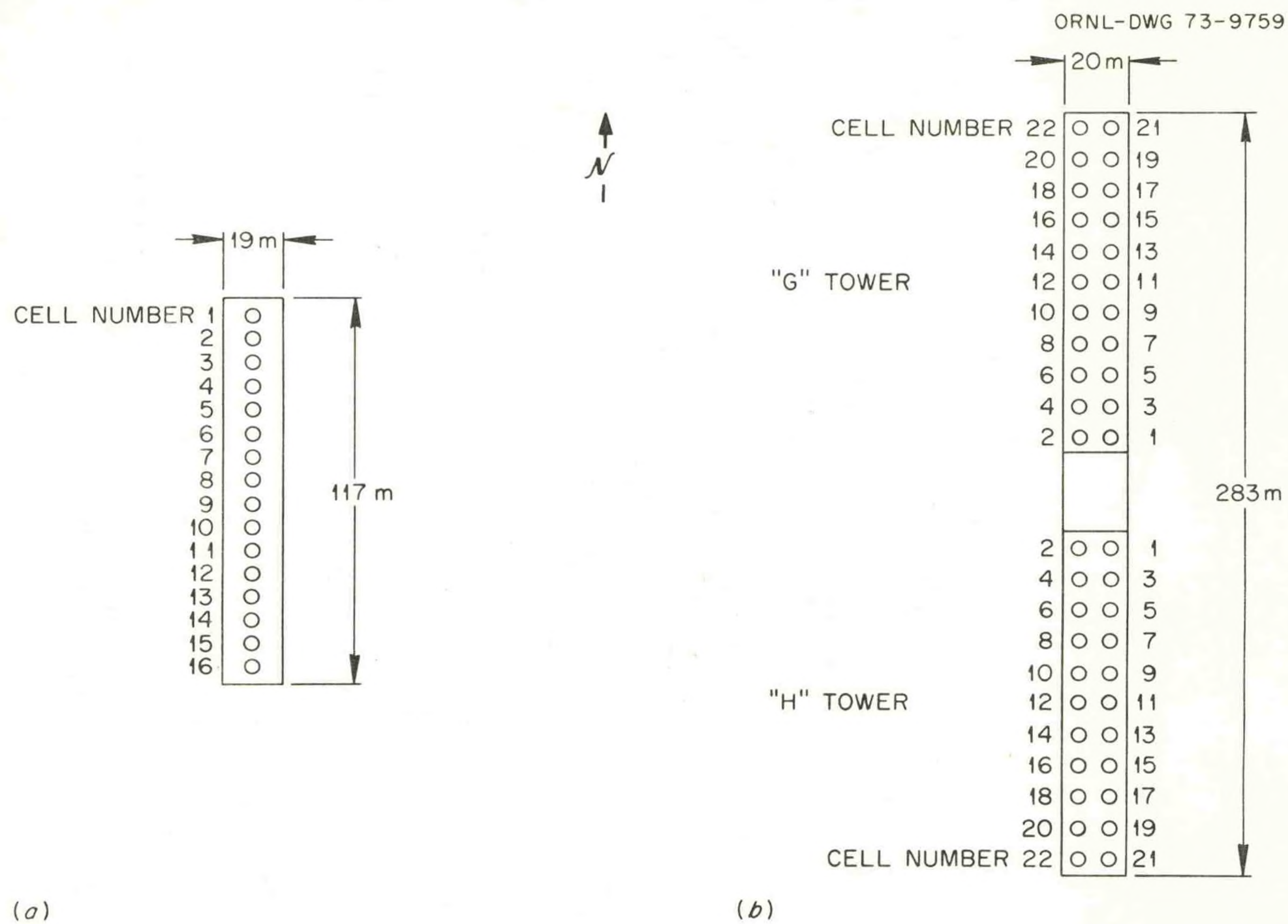

Figure 2. Top view of ORGDP cooling towers.

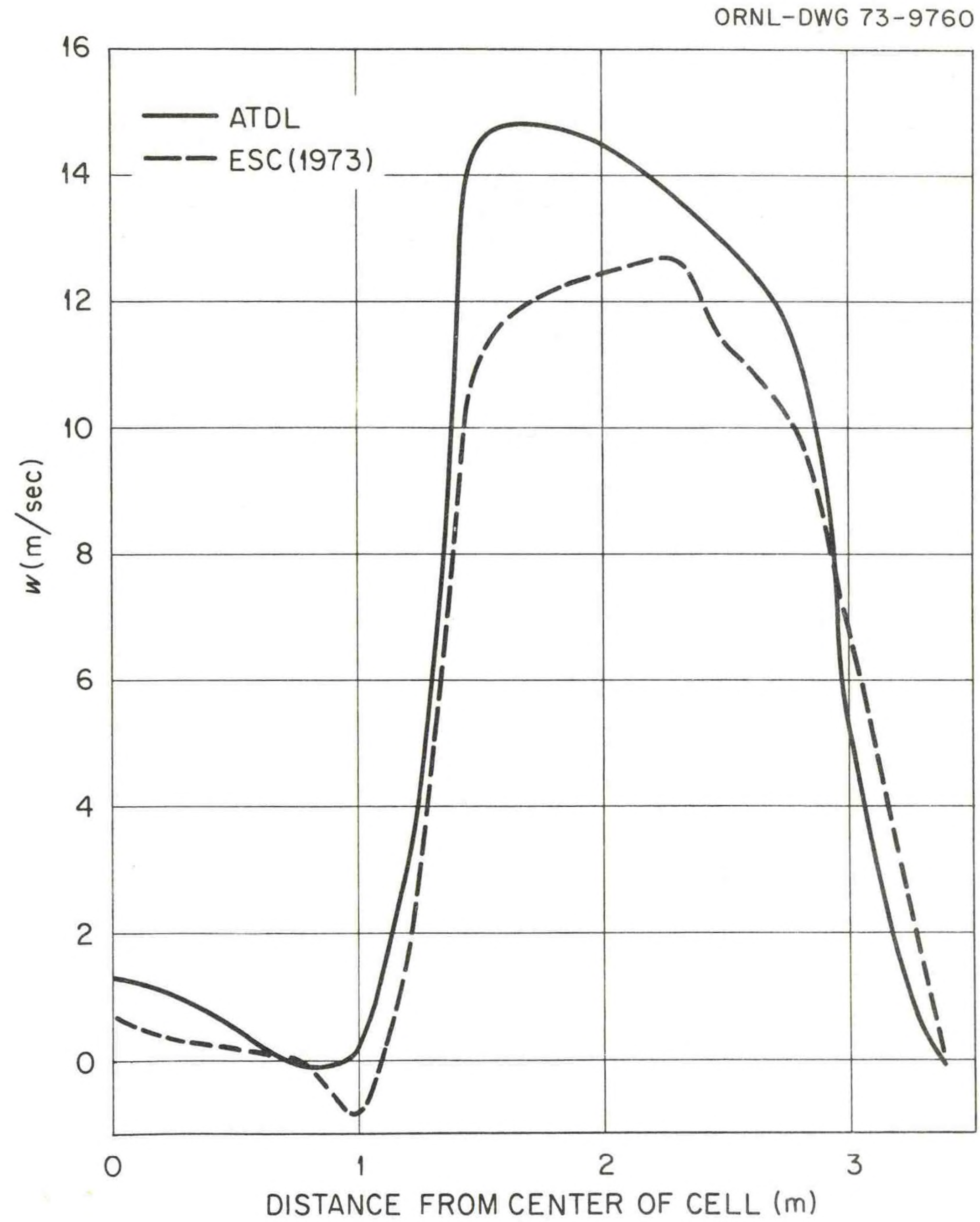

Figure 3. Average updraft speed measured at the mouth of the number 6 cell of the K-31 cooling tower during the period June 25 - June 29, 1973.

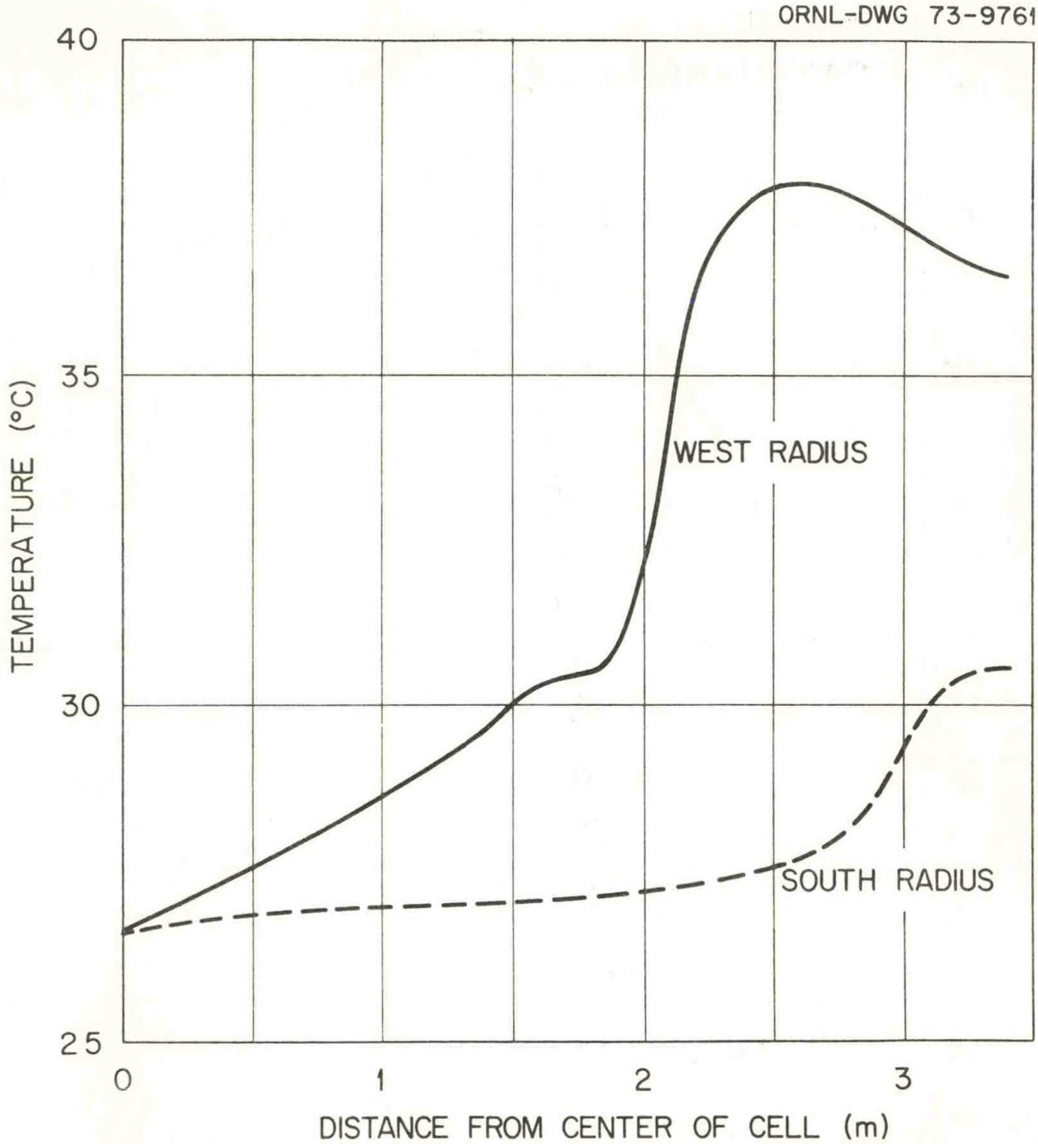

Figure 4. Temperature distribution along west and south radii of K-31 cell number 2 at 10 a.m., 27 June 1973. Ambient temperature 22°C, relative humidity 83%, calm winds.

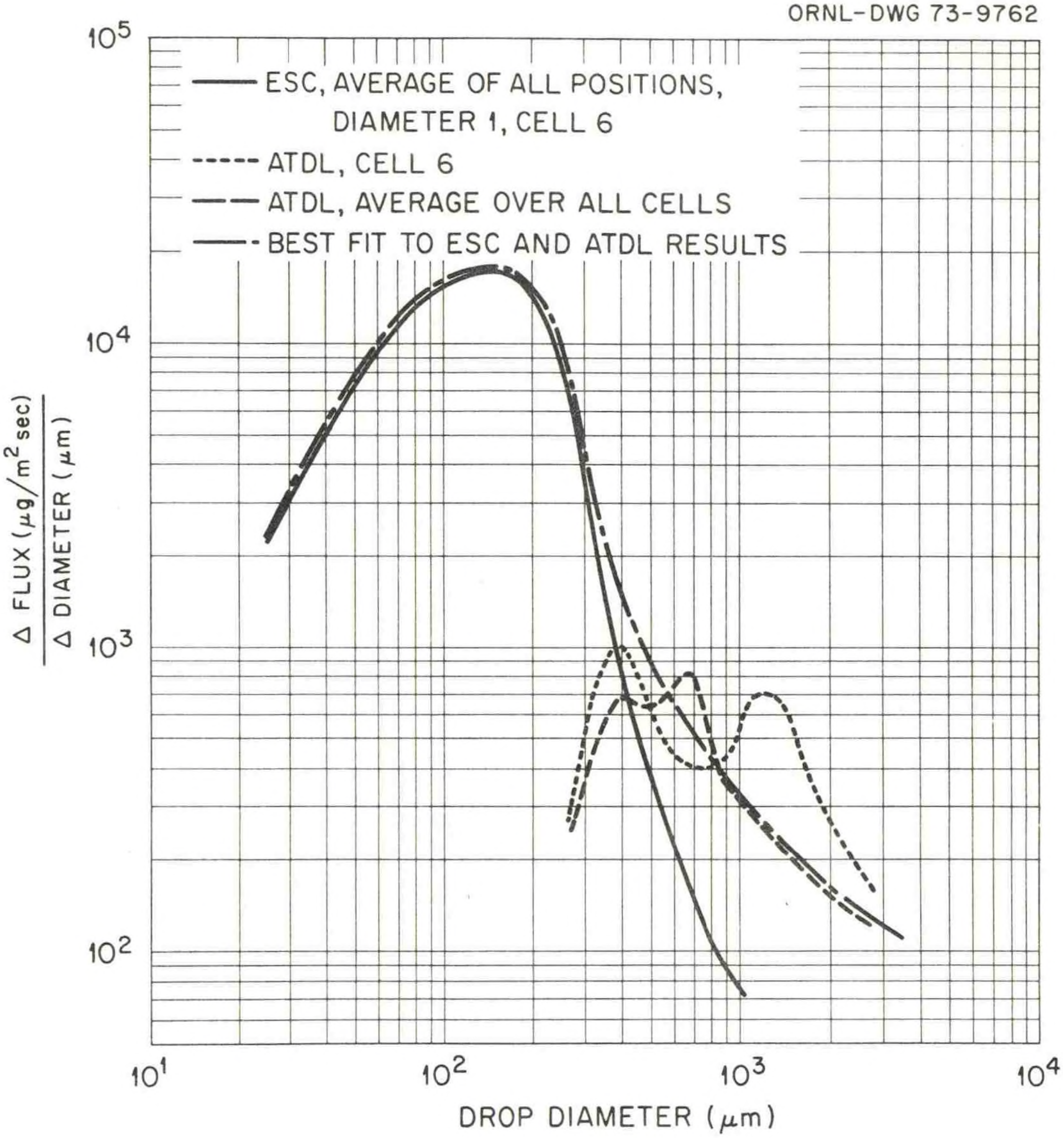

Figure 5. Liquid water flux per unit drop diameter, K-31 towers. Week of 25-29 June 1973.

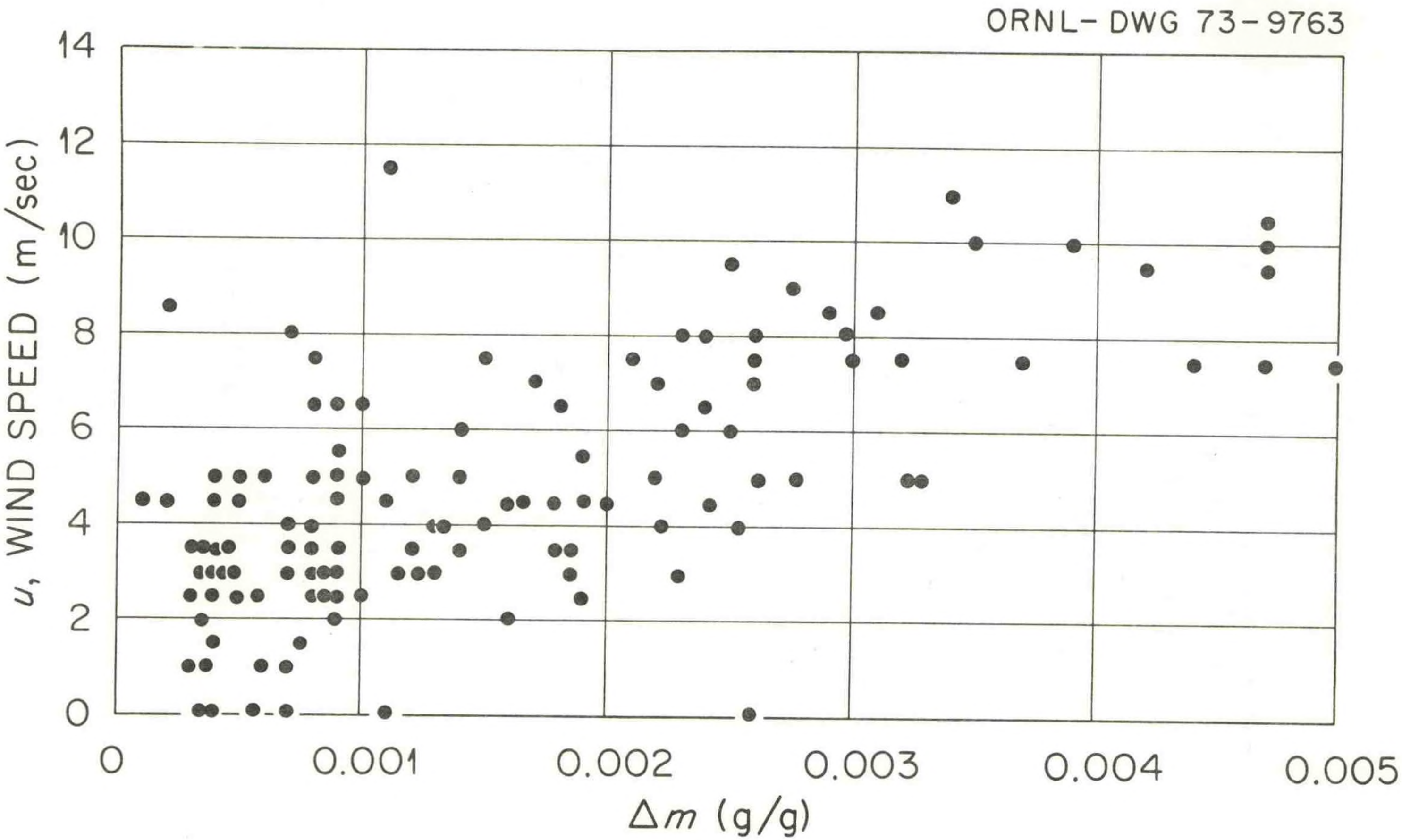

Figure 6. Two hour averages of wind speed U as a function of water vapor concentration Δm at the downwind hygrothermograph, at K-21 towers, for April, 1973

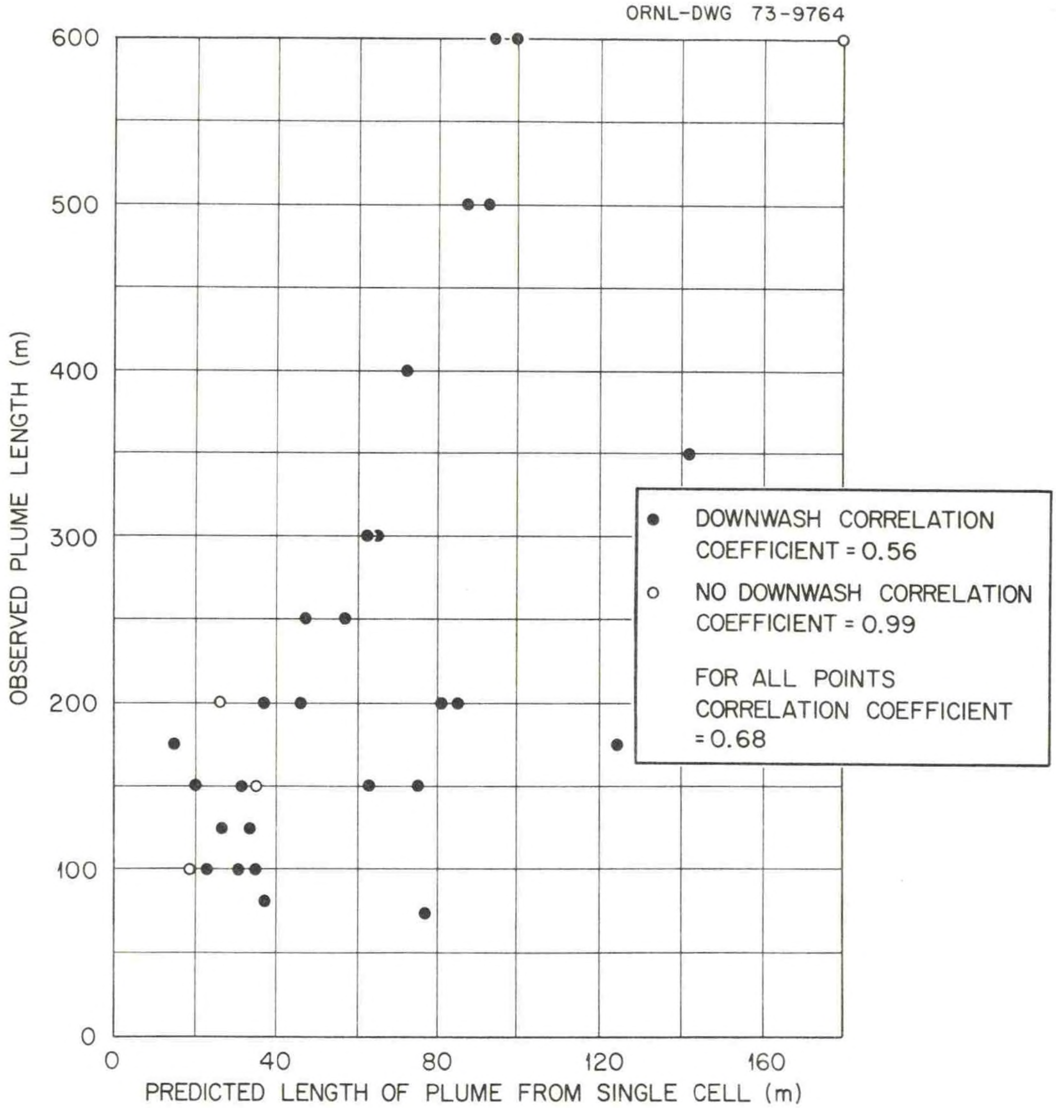

Figure 7. Observed visible plume length as a function of predicted plume length.

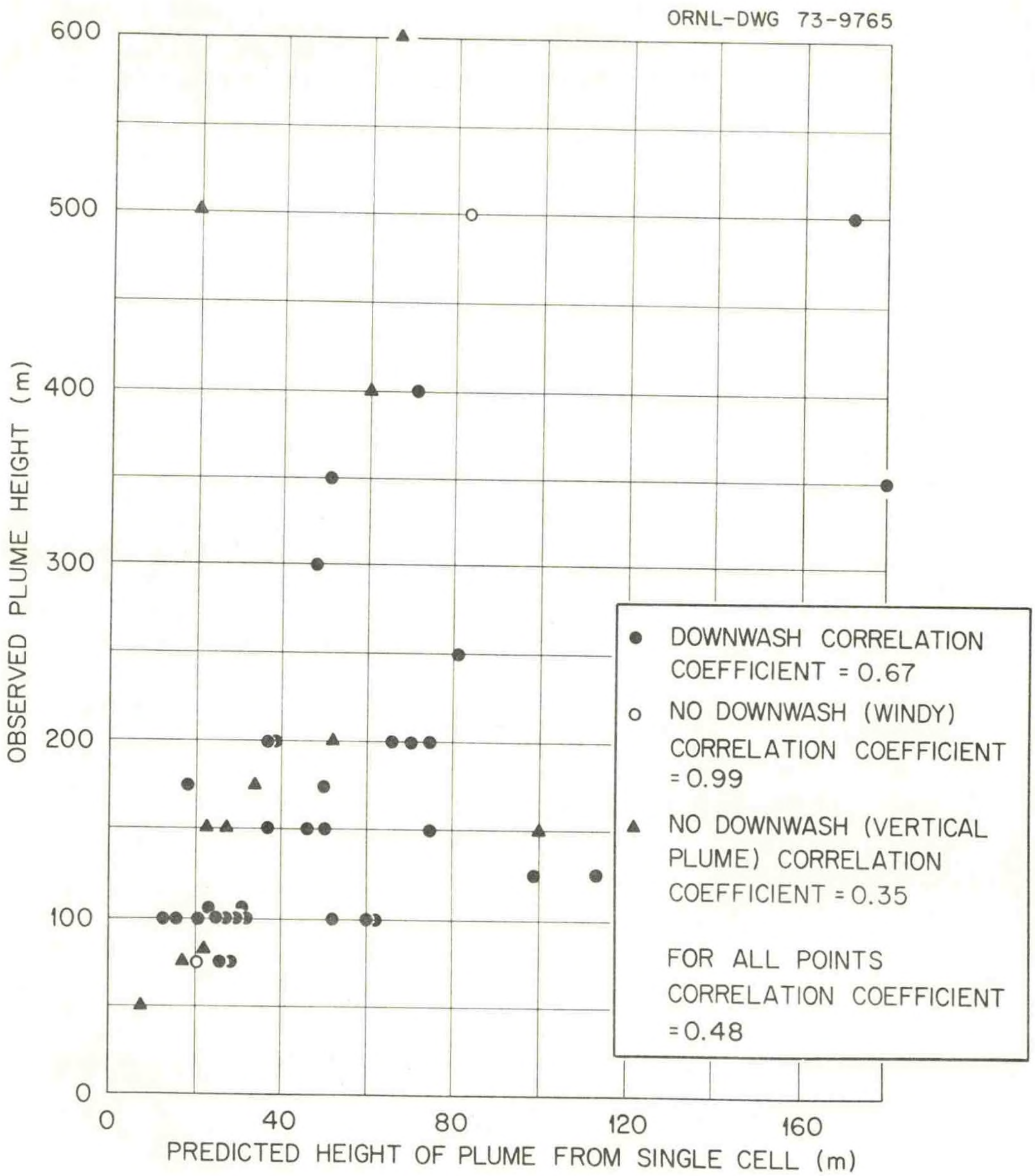

Figure 8. Observed visible plume height as a function of predicted plume height.

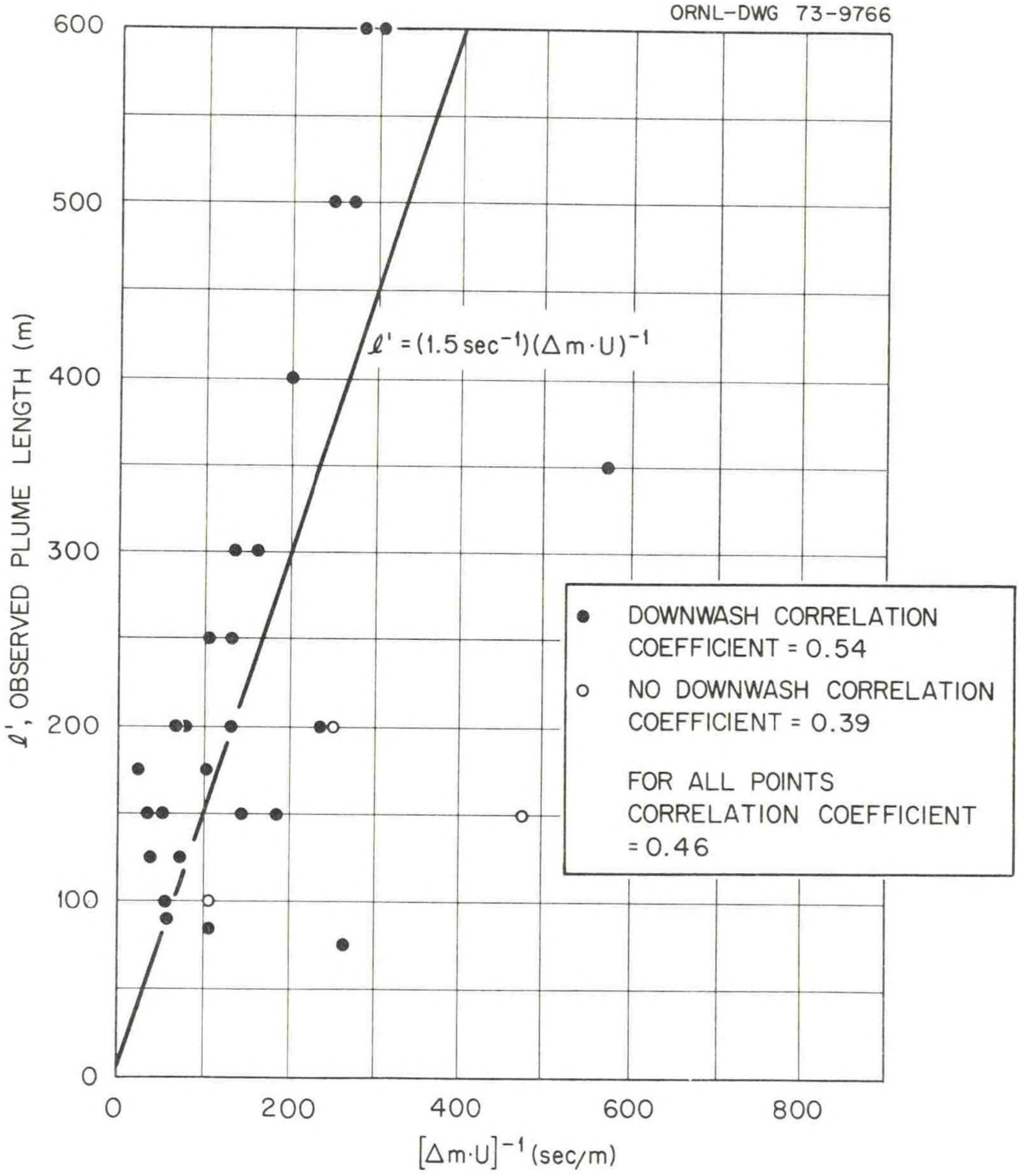

Figure 9. Observed visible plume height as a function of $[\Delta m.U]^{-1}$.

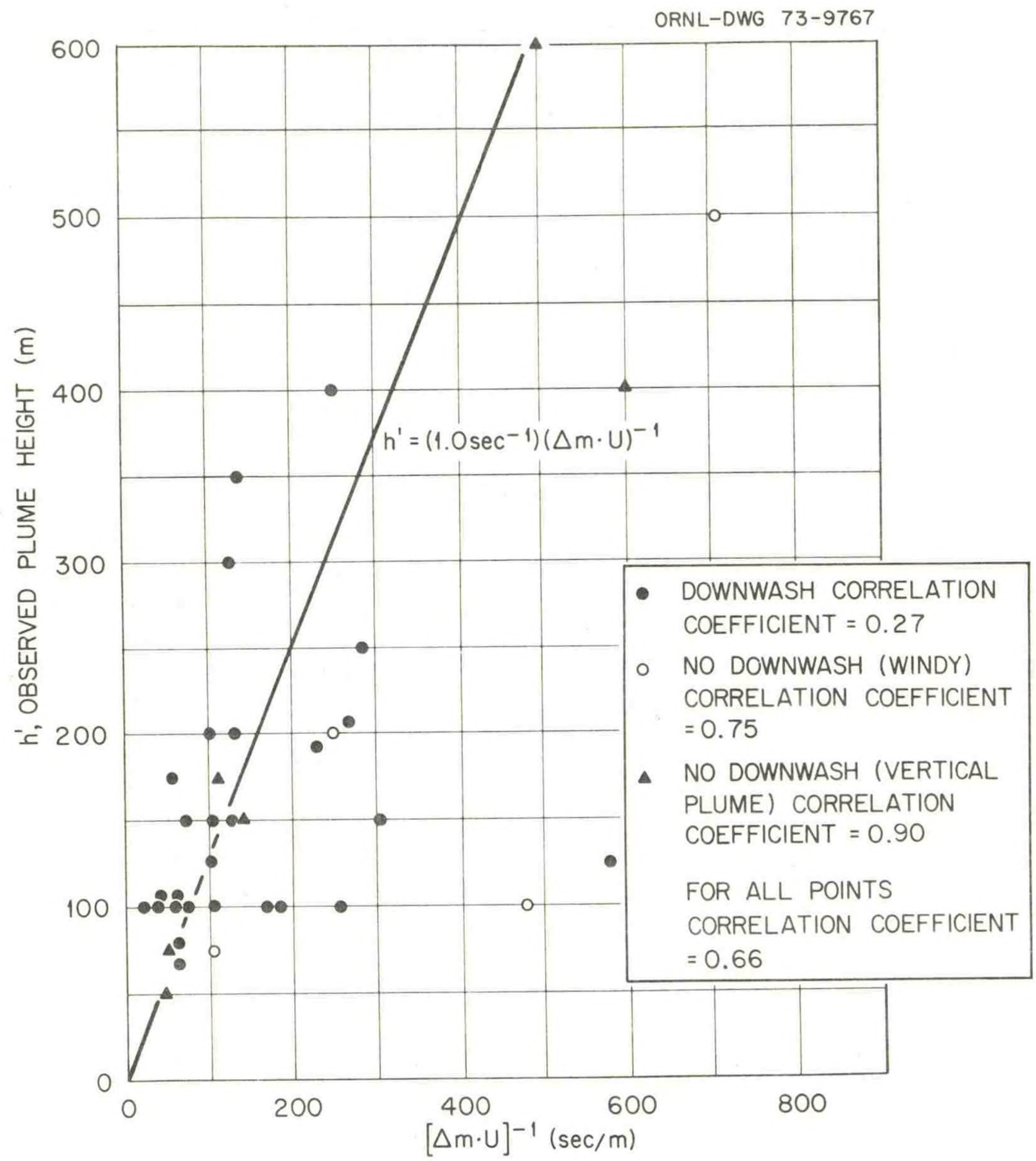

Figure 10. Observed visible plume height as a function of $[\Delta mU]^{-1}$.