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ENVIRONMENTAL IMPACTS FROM THE OPERATION OF COOLING TOWERS AT SRP

by

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Environmental Impacts from the Operation of Cooling Towers at SRP

Introduction

An assessment has been made of the environmental effects that would occur from the operation of cooling towers at the SRP reactors. A preliminary analysis of these effects was provided in DPST-83-432 (1). In the study reported here, a more realistic numerical model of the cooling tower plume has been used to reassess the environmental impacts. The following effects were considered: (1) the occurrence of fog and ice and their impact on nearby structures, (2) drift and salt deposition from the plume, (3) the length and height of the visible plume, and (4) the possible dose from tritium.

The calculations were made for a circular mechanical-draft cooling tower. This tower design enhances plume rise, thereby significantly decreasing adverse environmental impacts. Design information for a mechanical-draft cooling tower that could be used with the SRP reactors was supplied by the Du Pont Engineering Department. The cooling tower would be 55 ft high and contain a cluster of 12 fans that are 40 ft in diameter. Each fan has 1,103 ft^2 of free area and produces an exit air velocity of 1,525 ft/min. Total air flow through the tower is then approximately 2.02×10^7 cfm. The plume leaving the tower is assumed to be saturated air at 126.4°F (52.4°C). Approximately 10^5 pounds of water are evaporated from the cooling tower every minute. This represents a loss of about 6.6% of the circulating cooling water. Another 3.5% of the cooling water is removed from the tower as blowdown to control the level of dissolved material in the water. Some means of handling the 6,000 gpm of blowdown water at 90°F must be provided. It should be noted that these parameters differ slightly from the values used in the previous model calculations (1).

The model calculations required that a single emission source be specified. Therefore, an equivalent source diameter of 130 ft based on the total free area of the tower was used in the calculations. This assumption neglects the region near the tower exit where plumes from the individual fans merge. The circular tower design minimizes the effect of this region on the final plume. The simplified model should then give an adequate representation of the plume for a circular mechanical-draft cooling tower.

Summary

The one-dimensional cloud growth model developed by Hanna (2, 3) was used in this study. The behavior of the cooling tower plume is predicted by solving a set of equations based on conservation principles and cloud-physics relations. While still limited, this approach allows the vertical variation of significant meteorological parameters to be included in the calculations. This represents an important improvement over the simple analytical model used previously. Details of the model equations and the calculation procedure are given below.

When run with meteorological data from one typical year (1978), the model predicted only one case in which ice would form on nearby stuctures from operation of the cooling tower. Five instances were found where a dense fog could occur at buildings near the cooling tower from impingment of the plume. In a typical year, two naturally occurring days of ice formation and 20 days of fog could be expected. Impact of the cooling tower plume is minimized by locating the tower south or southeast of nearby structures. Ten instances of the formation of dense ground fog approximately one mile downwind of the cooling tower were predicted.

Drift deposition from the cooling tower plume was estimated to be at most 9 inches of water/year near the tower. Water deposition decreases to a negligible value beyond 1000 ft from the tower. Use of river water as a coolant gives insignificant amounts of salt deposition from the drift. The drift deposition was found to be uniformly distributed around the cooling tower.

Calculations using 13 sets of meteorological data representing typical annual conditions at SRP showed that about 30% of the time throughout the year the cooling tower plume would be visible for over one mile. On the average, for the remaining 70% of the time, the cooling tower plume would be less than 1000 ft long and rise 750 ft vertically. Long visible plumes would be present more frequently in the early morning.

Model estimations of the ground level concentration of tritium released into the atmosphere through the cooling tower were essentially identical to values obtained using WIND System codes. Therefore, the WIND System calculations reported previously (1) were accepted as the best estimates of tritium doses that could be obtained. Based on an annual release of 4000 curies of tritium in the form of HTO, the maximum onsite dose was found to be less than 0.10 mRem/yr 250 ft from the tower. Offsite dose from operation of the cooling tower was found to be below 1.0 μRem/year, a negligible value.

Model Description

The Hanna model (2, 3) consists of a set of ordinary differential equations for the conservation of plume momentum, thermal energy, water vapor, cloud water, and hydrometeor water in the vertical direction. Additional equations are included to describe the lateral spread of momentum, moisture, and thermal plumes. That is, the momentum, moisture, and temperature differences between the effluent and the environment are located within separate plumes having coincident centerlines. The equations are solved by numerically integrating from the tower exit up to the point of maximum plume rise. The plumes are assumed to travel downwind of the tower with the prevailing wind. The velocity, temperature, water vapor content, and liquid water content of the cooling tower effluent must be specified to solve the equations. In addition, vertical profiles of ambient temperature, pressure, relative humidity, and wind speed are required in the calculations. Model output yields plume vertical velocity, temperature, water vapor, and liquid water mixing ratios averaged over the plume cross-section. Radii of the three separate effluent plumes are also calculated.

The vertial momentum equation considers the effect of plume buoyancy on the vertical rise. This is, of course, very significant for the hot and moist cooling tower plumes. Parameterizations for the liquid water distribution within the plume and for the precipitation fallout are taken from the model by Simpson and Wiggert (4). This model was developed to describe the growth of cumulus clouds. Equations are given for the conversion between cloud water and hydrometeor water and for precipitation assuming a particular droplet size distribution. The entrainment relations used to calculate plume spread are based on the recommendations by Briggs (5). At wind speeds greater than 1.0 m/s, formulas for a "bent-over" plume are used.

Application of the cloud physics relationships to a cooling tower plume is somewhat uncertain. However, a comparison of the Hanna model to seven other models of similar complexity (6) showed that it gave good results. Visible plume length and height were predicted reasonably well. Values tended to be overpredicted when the relative humidity was greater than 80% and underpredicted at low wind speeds. As a rough approximation, drift water deposition from the plume was equated to precipitation fallout. This neglects evaporation of the droplets during their fall and does not consider horizontal transport after the droplets leave the plume. A more detailed treatment would require specification of the drift droplet size distribution. Use of the cloud model avoids this difficulty and is then a convenient first approximation. Neglect of evaporation will give conservative estimates of drift deposition.

A serious limitation of Hanna's model is the inability to follow the plume beyond its point of maximum rise. Since the equations describing the plume development are written as functions of the vertical dimension, once the plume reaches its maximum height the parameters remain constant. If the plume is still visible at this point, unrealistically long plume lengths are calculated. The plume is assumed to be visible whenever liquid water is present.

Concurrent with this study, a physical model of the same cooling tower system has been tested using the wind tunnel facility at Colorado State University. Preliminary results from the physical model experiments indicate that the cooling tower plume does not downwash. Downwash is movement of an effluent plume toward the ground immediately downwind of the source. This phenomena is caused by a low pressure zone on the lee side of stacks and towers. Downwash can significantly influence ground level concentrations at high wind speeds. Since the physical model results did not show the occurrence of downwash with the cooling tower plume it was not included in the mathematical model.

Leakage from the reactor heat exchangers will result in the presence of tritiated water in the circulating cooling water. This radioactivity will then be released into the atmosphere from the cooling tower. Ground level concentrations and doses from this tritium were calculated assuming a Gaussian distribution about the plume centerline. This model of the tritium cloud corresponds to that used by the SRL WIND System. Therefore, estimates of tritium doses were essentially unchanged from those reported previously (1).

Meteorological Data

Vertical profiles of meteorological variables up to several thousand feet are required for the model calculations. Such data was immediately available from several National Weather Service stations around SRP for 1978. This year has been used in other model validation studies in which the meteorological data needed to be representative of long term average conditions at SRP. This upper air data was combined with observations at the WJBF-TV tower to produce meteorological data appropriate for SRP.

Upper air data from Charleston, SC, Athens, GA, Waycross, GA, and Greensboro, NC taken daily at 8:00 AM EST were used. These data were weighted with an inverse exponential function of the distance from SRP and interpolated to SRP. This weighting makes most use of the Charleston and Athens data. The upper air data were interpolated to 14 elevations between 10 m and 2 km for each day of the year. Ambient temperature, pressure, relative humidity, wind speed, and wind direction were determined. A maximum relative humidity and a minimum temperature usually occur in the early morning each day. Ambient conditions at 8:00 AM are then representative of the worst case conditions for relase of the cooling tower plume. These cases will show the maximum incidence of fog and ice and the maximum visible plume length.

Data for ambient temperature, wind speed, and wind direction were also available from the instruments on the WJBF-TV tower located near SRP. The TV-tower data was taken a 7 elevations between 10 m and 300 m. Fifteen minute average values of this data for 1978 were used. The data was scanned for the time period 6:00 AM to 10:00 AM and the time nearest to 8:00 AM having the fewest missing wind speed measurements selected for use. Whenever it was available, the TV-tower data was used in place of the interpolated upper air data.

Wind speeds between the ground and 60 m were fit to a logarithmic profile. That is, the wind speed u was calculated from

$$u = u_{60} \ln(z/z_o) \ / \ \ln(60/z_o) \qquad (1)$$

where u_{60} is the wind speed at 60 m, z is the elevation in meters, and z_o is a roughness length. In the calculations, z_o was taken to be 3 cm, a value appropriate for an open field. The value chosen for z_o does not significantly affect the calculated velocities.

The data described above is representative of daily worst case conditions for operation of the cooling tower. It was not feasible to run similar calculations for each hour of every day for a one year period. Therefore, to simulate annual average conditions, model calculations were also performed for the 13 atmospheric classes listed in Table 1. This classification was derived from two years (1976 - 1977) of meteorological data obtained at SRP (6). These combinations of wind speed, stability class, temperature, and relative humidity were chosen as representative of annual meteorological conditions at SRP. The listed wind speed is the value measured at 60 m and velocity profiles were calculated using equation (1). The temperature and relative humidity were assumed to be constant with elevation. A pressure profile was generated from the equation

$$p = p_o \exp(- (z + 80) \ g/RT) \qquad (2)$$

where p_o is sea level pressure, z is elevation above the ground in meters, g is the acceleration of gravity, R is the gas constant, and T is the absolute temperature. SRP is taken to be 80 m above sea level in formulating equation (2).

Table 1. ATMOSPHERIC CLASSIFICATIONS

Class	σΘ	σϕ	60 m Wind Speed (mph)		Temp (F)	RH(%)	Stability Class	Frequency (%)
1	21	15	2.2	(1 m/s)	63	79	B	3.6
2	21	15	6.7	(3 m/s)	63	79	B	5.75
3	21	15	11.2	(5 m/s)	63	79	B	4.4
4	21	15	2.2	(1 m/s)	76	48	B	3.6
5	21	15	6.7	(3 m/s)	76	48	B	5.75
6	21	15	11.2	(5 m/s)	76	48	B	4.4
7	12	8.5	4.5	(2 m/s)	76	48	D	11.8
8	12	8.5	11.2	(5 m/s)	76	48	D	7.8
9	12	8.5	15.7	(7 m/s)	76	48	D	6.1
10	6	4.5	4.5	(2 m/s)	63	62	E	12.1
11	6	4.5	11.2	(5 m/s)	63	62	E	12.8
12	3	2	4.5	(2 m/s)	51	83	F	9.4
13	3	2	11.2	(5 m/s)	51	83	F	12.5

Model Results

Fog and Ice Environmental Impacts

Calculations were made to determine the occurrence of ground level fog and ice and the impact of fog and ice on nearby structures from operation of the cooling tower. Ground fog occurs whenever the water vapor concentration at ground level reaches saturation. If the ambient temperature is below freezing, it is assumed that the saturated water vapor will deposit surface ice. An impact on some nearby structure was assumed to occur if air within 100 ft of the ground between 200 and 1000 ft from the cooling tower became saturated. Calculations were made for each day of the year for 1978.

In contrast to results with the previous model (1), the calculations predicted no occurrences of ground level fog or ice near to the cooling tower. This was caused by elimination of the downwash correction to the plume rise. The 11 icing events and 25 fogging events within 1000 ft of the cooling tower predicted by the previous model all occurred when high wind speeds caused significant plume downwash. The empirical downwash correction was based on observations of effluent plumes from stacks and vents.

Application of the correction to the very buoyant cooling tower plume was uncertain but a conservative approach. As noted above, physical modeling studies indicate that the cooling tower plume will not experience significant downwash even at wind speeds of 20 mph. If downwash is included in the current model, ground level fog and ice do occur near the cooling tower. However, the number of cases is reduced to about half of the number found previously.

The model did predict 10 instances where ground fog formed relatively distant from the cooling tower. On the average, this fog began approximately one mile downwind of the tower and persisted for several miles. These events occurred during conditions of low ambient temperature, high relative humidity, and high wind speeds. Environmentally significant impacts could be produced by these fogging cases as visibility is reduced and roadways and other surfaces are wetted in the early morning hours. During the day, as temperatures rise and the relative humidity decreases, these fogs will dissipate. Naturally occurring fog is, of course, also favored under these conditions. Natural fog and rain or ice would act to reduce the significance of these fogging events.

The model also predicted six instances where the cooling tower plume could impact on nearby structures. One of these cases occurred in below freezing temperatures which would lead to the formation of rime ice on the surfaces. These events are listed in Table 2 as a function of compass sector. The compass sector shown is the 45° sector into which the wind was blowing. The frequency with which the cooling tower plume was initially directed into each sector is also given. The plume direction is distributed fairly uniformly around the compass. However, the possibility of the plume impacting on nearby structures can be minimized by locating the cooling tower south to southeast of the buildings. During the winter months, wind direction is from the northwest approximately 25% of the time. Since fog and ice are most likely to occur during the winter, a southeastern location of the cooling tower is most favorable.

In subfreezing weather, the cooling tower fan speed may be reduced to prevent the circulating cooling water from falling below 40°F in temperature. Reduction in the fan speed will reduce plume momentum and therefore may act to increase ice formation near the cooling tower. With reduced plume momentum, downwash may become significant. However, at the same time, the total amount of water being evaporated is greatly reduced. Since, tower operating parameters were not available under these conditions, an assessment of the effect of reduced fan speed on environmental impacts was not attempted.

Table 2. PLUME DIRECTIONAL FREQUENCY

Compass Sector	Frequency of Occurrence	Average Drift Inches/Hour	Number of Plume Impacts Freezing	Nonfreezing
S-SW	0.1456	0.708E-03	0	0
SW-W	0.2390	0.776E-03	0	0
W-NW	0.0962	0.599E-03	0	2
NW-N	0.0742	0.578E-03	0	1
N-NE	0.1016	0.624E-03	0	0
NE-E	0.1429	0.762E-03	0	2
E-SE	0.1264	0.833E-03	1	0
SE-S	0.0742	0.794E-03	0	0

Drift and Salt Deposition

Some of the cooling water is carried out of the tower in the plume as mechanically entrained water droplets. This drift water will carry with it any dissolved solids present in the circulating cooling water. Current designs of mechanical draft cooling towers are able to limit drift losses to approximately 0.05% of the circulating water.

Drift loss from the cooling tower should essentially correspond to the initial hydrometeor water content of the plume in Hanna's model. Hanna initializes the model calculations by assuming both the cloud water and hydrometeor water mixing ratios at the tower exit to be 0.001 g/g. These values are typical of the liquid water content in cumulus clouds. A 0.05% drift loss is equivalent to a mixing ratio of 0.00062 in the exiting plume. Hanna's initial values then correspond very closely to the expected plume liquid water content and so were used for the calculations reported here. Drift deposition was assumed to equal the precipitation rainout calculated from the cloud-model plume.

Maximum drift deposition was determined for early morning conditions for each day of the year in 1978. Averages of these maximum values over the number of occurrences within each compass sector are reported in Table 2. It is seen that the precipitation or drift from the cooling tower plume is distributed fairly uniformly around the compass. The average maximum drift within each sector is always less than 0.001 inches/hour or approximately 9 inches/year additional precipitation from cooling tower drift.

This may be compared to an average natural precipitation in the SRP area of 45.5 inches/year. The evaporation of drift droplets has not been considered in the calculations, the precipitation estimates therefore represent upper bounds on the water deposition. The maximum water drift will occur immediately adjacent to the cooling tower and rapidly decrease with distance from the tower.

The analytical model used previously, predicted a maximum drift deposition of only 0.05 inches of water per year (1). While application of the cloud rainout model to a cooling tower plume may be uncertain, results from the current calculations appear to be much more realistic. The presence of a measurable water spray in the immediate vicinity of the cooling tower is expected.

A more detailed picture of the water deposition pattern was obtained by analyzing each of the 13 cases listed in Table 1. Results of these drift calculations are presented in Figures 1 - 11. For case number 4, the plume did not extend beyond the cooling tower, therefore, no drift deposition was calculated. The model was unable to distinguish between cases 6 and 8 so one curve is presented for both of these classes. The abrupt change in slope in the curves for cases 5 - 9 indicates the point where the liquid water in the plume has completely evaporated and the drift ends.

The maximum drift is found to be less than 0.001 inches/hour in all cases. Figures 1 - 11 plot drift against distance measured from the center of the cooling tower. The maximum drift then occurs immediately adjacent to the 65 ft radius assumed for the cooling tower. Almost all of the drift deposition is seen to occur within 1000 ft of the cooling tower. For all of the cases, the deposition has fallen below 1.0 inch/year 900 ft from the tower. The maximum drift was found to be essentially independent of ambient temperature and relative humidity. At higher relative humidity, the drift did extend further downwind of the tower. The magnitude and the extent of the drift increased with increasing wind speed.

An estimate of the deposition of dissolved materials can be obtained by multiplying their concentration in the circulating cooling water by the water deposition rates. Cooling water would originate from the Savannah River. A summary of the river water composition is reproduced from the first report (1) in Table 3. As shown previously (1), these values will increase by approximately a factor of three in the circulating cooling water. Environmental impacts from the deposition of dissolved salts and minerals would appear to be insignificant. For example, the maximum sodium deposition is estimate to be only 0.5 g/ft^2 - year immediately adjacent to the tower. These estimates should be conservative since droplet evaportion has not been considered. Evaporation will tend to disperse the material over a wider area as the lighter particles are carried further downwind.

Table 3. SAVANNAH RIVER WATER COMPOSITION
Average composition near Clyo, Ga. for the period October 1980 to September 1981.

Silica, ppm[a] (SiO_2)	9.8
Calcium, ppm (Ca)	4.7
Magnesium ppm (Mg)	1.5
Sodium, ppm (Na)	8.9
Potassium, ppm (K)	1.3
Sulfate, ppm (SO_4)	6.3
Chloride, ppm (Cl)	6.7
Fluoride, ppm (F)	0.1
Total Dissolved Solids, ppm	53
Total Hardness as $CaCO_3$, ppm	16.6
Alkalinity as $CaCO_3$, ppm	21
pH, electrometric	7.0
Conductivity, micromhos	82
Turbidity, J.T.U	12
Color, color units	45

[a] ppm equals parts per million by weight

Visible Plume Environmental Impact

A large visible plume will usually be present when the cooling tower is in operation. In the early morning, for a typical year, a visible plume over one mile long was predicted to occur 50% of the time. Some of these events would be obscured by naturally occurring days of fog or rain. As the day progresses, these long plumes will decrease. As indicated above, the Hanna model will give unrealistically long plumes once the point of maximum rise has been reached. Therefore, the results obtained here should be conservative estimates.

Visible plumes predicted for the meteorological conditions listed in Table 1 are shown in Figures 12 -23. The results show plume paths up to one mile downwind of the tower. Wind speeds reported on the plots are the values calculated at the top of the cooling tower using equation (1). The model does not distinguish between class 6 and class 8 in the calculations. For both class 1 and class 12 conditions, the plume was still visible at the point of maximum rise. At this point, the vertical velocity vanishes and the plume is carried horizontally in the prevailing wind. Figures 12 and 22 show an abrupt change in the plume path where this point is reached. Plume lengths may be overestimated in these cases.

As would be expected, long visible plumes are predicted to occur with a low ambient temperature and high relative humidity. Summing the frequency for classes 1, 2, 12, and 13 indicates a long visible plume approximately 30% of the total time during a typical year. The occurrence of long cooling tower plumes is well documented (7, 8). Excluding these four cases the average cooling tower plume was about 1000 ft long and extended vertically for 750 ft.

At high relative humidity and low temperature, a comparison of Figures 12 - 14 shows that an increase in wind speed helps to disperse the plume. At low relative humidity and higher temperatures, the opposite effect is observed. Examination of Figures 15 - 17 and 20 - 21 shows an increase in plume length as the wind speed increases. This apparently reflects the retention of liquid water droplets within the plume to greater downwind distances in high winds. Evaporation of the liquid water extends the visible plume length. This phenomema is not as important as plume dispersion in high relative humidity. The effect of changing the ambient relative humidity with the other varibles fixed may be seen by comparing Figures 14 and 21. The smallest visible plumes are predicted at the lowest relative humidity as shown in Figures 15 - 19.

The model predicted plume was observed to be similar in appearance to those seen in the physical model study. In particular, the plume was found to bend over more sharply than was predicted by the previous model (1). This indicates a more relistic treatment with the one-dimensional numerical model.

Tritium Dose

As noted above, the tritium dose calculation was essentially identical to that reported previously (1). Annual average values were determined using the 13 atmospheric classifications listed in Table 1. The Gaussian plume model used for these calculations yielded different results for each of the 13 classes.

The maximum ground level dose from tritium was found to be less than 0.1 mREM/year at about 250 ft from the edge of the cooling tower. Elimination of plume downwash extended the point of maximum dose from the base of the tower somewhat. The maximum off-site dose was estimated to be less than 1.0 μREM/year. A negligible incremental tritium dose was then predicted to occur from operation of the cooling tower. Details of the calculation and plotted results may be found in the previous report (1).

Conclusions

The mathematical model has shown that the environmental effects likely to occur from operation of mechanical-draft cooling towers at SRP will be minor. Fogging one mile downwind of the tower was predicted to occur on ten occasions per year where there were high wind speeds and high relative humidity. Dense fog or ice could impact structures several hundred feet from the tower approximately six times during a typical year (see Table 2). The probability of building impacts is minimized by locating the cooling tower south or southeast of the buildings. Environmental effects from drift deposition and tritium doses were predicted to be negligible. Large visible plumes would be present 50% of the time in the early morning and approximately 30% of the time overall.

The numerical model used for this study is computationally fast and requires relatively simple input specifications for its operation. It is, therefore, easy to examine many individual situations with this model. However, as discussed above, application of the cloud-physics parameterizations to a cooling tower plume is somewhat uncertain. The one-dimensional treatment using only a vertical coordinate is limited. Nevertheless, the numerical model offers an improvement over the simple analytical model used previously. The results presented in this report should correspond more closely to the environmental effects that would actually occur. Model predicted plumes were very similar in appearance to those observed in the physical modeling study.

A very complete model of cooling tower plumes and drift deposition has recently been prepared by Argonne National Laboratory (9). This model is able to treat mechanical-draft cooling towers by considering each individual fan. The effects of different fan configurations and reduced fan speed during operation in cold weather could be investigated using this model. The Argonne model contains a very detailed description of drift and the associated salt deposition. If a more exact assessment of the environmental effects from cooling tower operation is required for regulatory purposes, it would be desirable to use the Argonne model. This model is extensively documented and validated making it the most acceptable model available for assessing environmental impacts. The computer codes for the Argonne model are currently undergoing independent verification. The model should be available for public use under license from the Electric Power Research Institute after January 1, 1984.

It has been suggested (10 - 12) that the injection of large amounts of heat and moisture into the atmosphere from cooling towers could produce significant meteorological effects. If cooling towers are installed at all SRP reactors, an unusually strong heat source would be created. It has been speculated that large energy centers could alter local precipitation patterns and may trigger severe storms (10, 11). A detailed study of these questions requires the development of a regional scale atmospheric model. Some preliminary two and three dimensional modeling studies of these problems have been made (13, 14). Significant influences were demonstrated with energy releases on the order of 20 - 100 GW. These values are greater than that which would be released at SRP with cooling towers at all of the reactors. The relatively large distances separating the SRP reactors also reduces the energy density from the values assumed in the reported model calculations. Therefore, it does not appear likely that significant meteorological effects would be observed from the operation of cooling towers at SRP. A quantitative estimation of the effects of placing cooling towers at all SRP reactors would require developing a three dimensional atmospheric model for this area.

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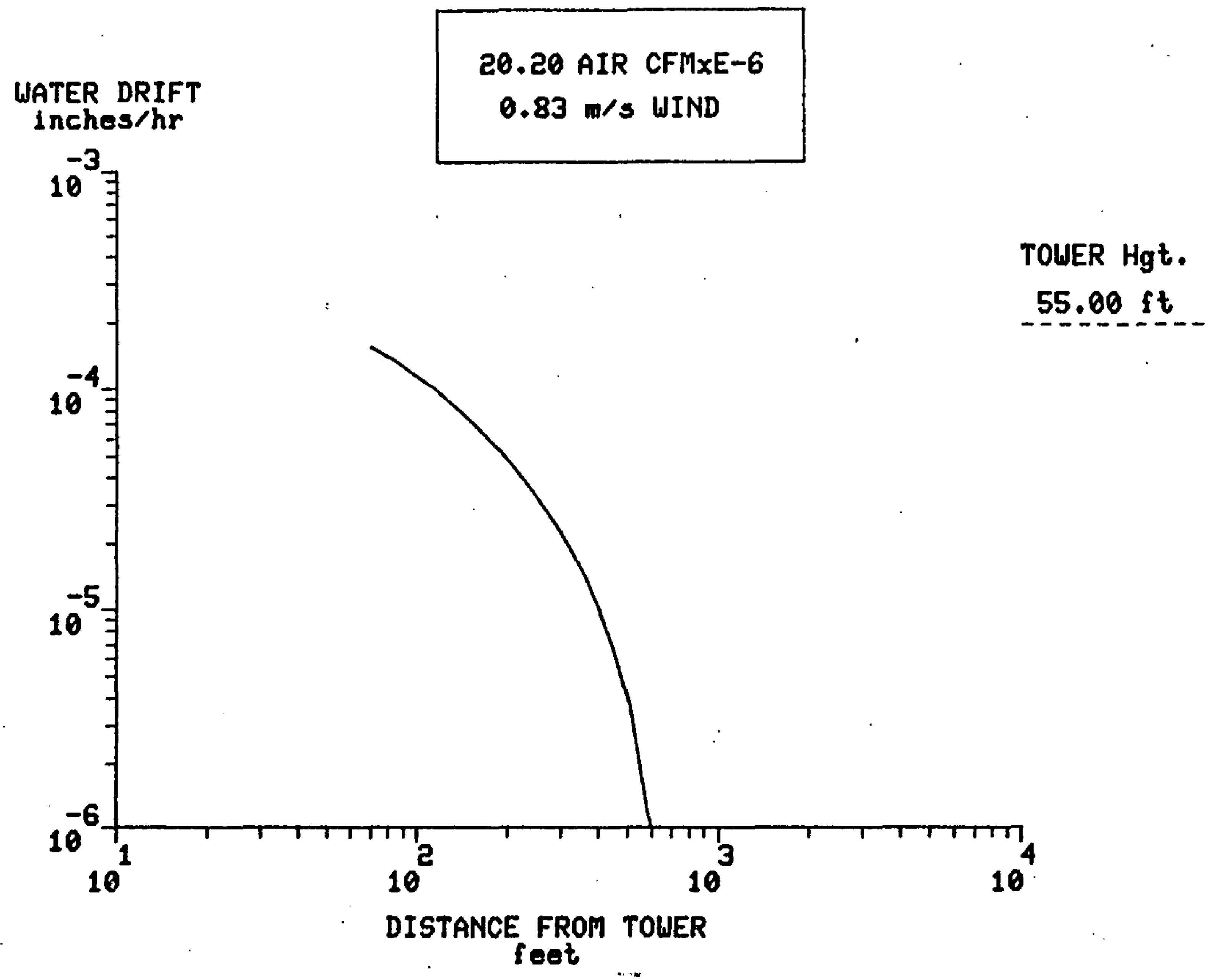

FIGURE 1: Water deposition as a function of distance during Class 1 atmospheric conditions.

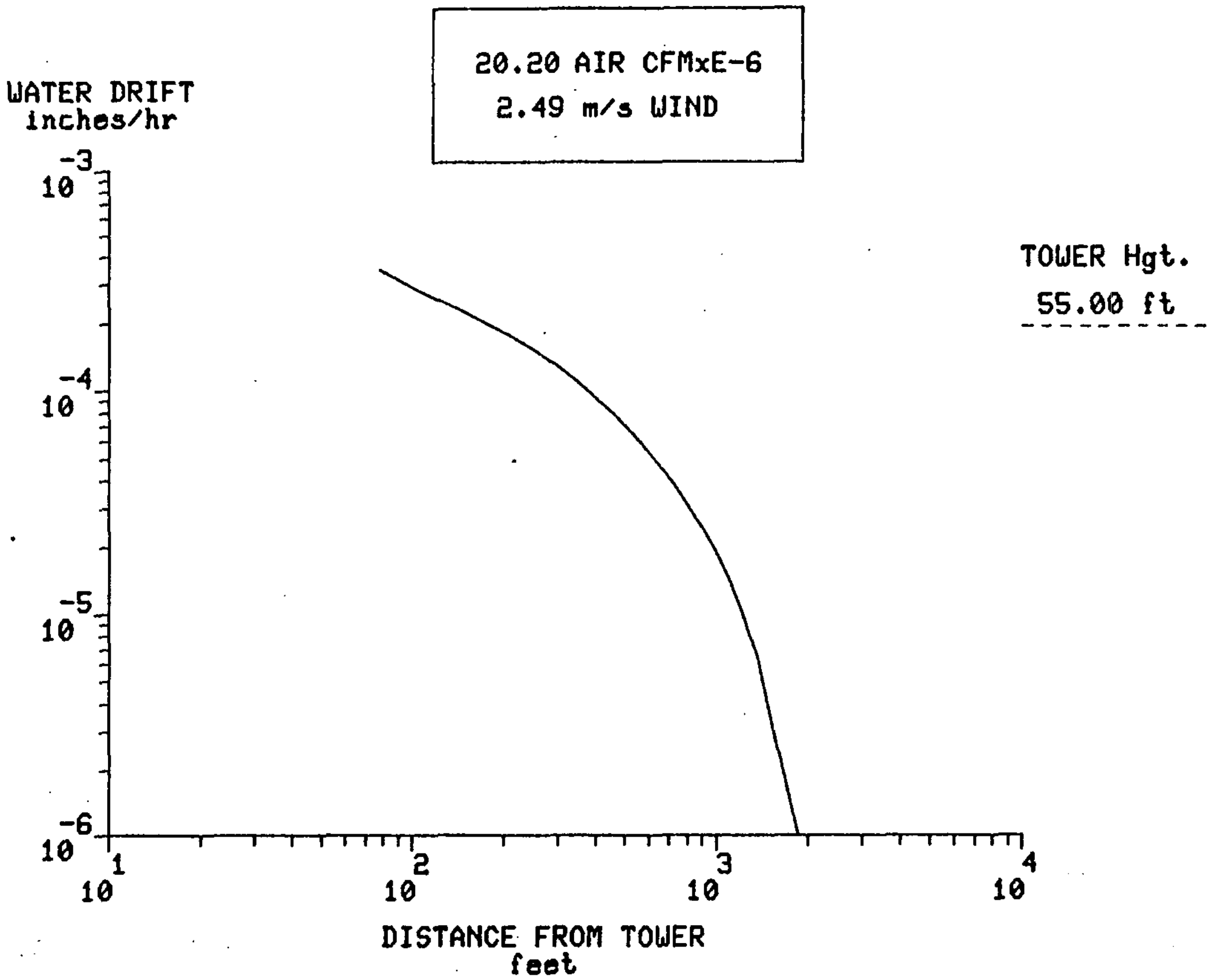

FIGURE 2: Water deposition as a function of distance during Class 2 atmospheric conditions.

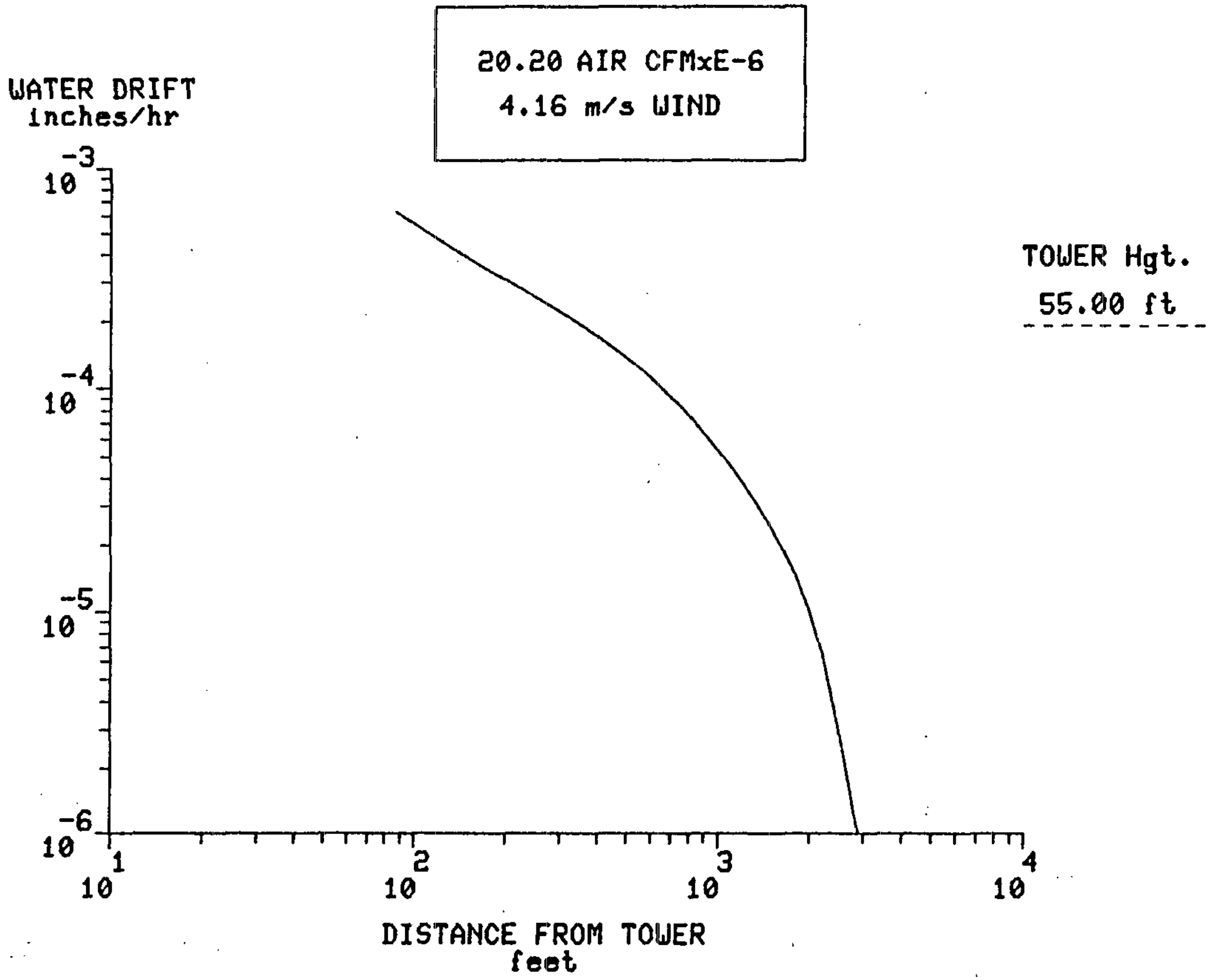

FIGURE 3: Water deposition as a function of distance during Class 3 atmospheric conditions.

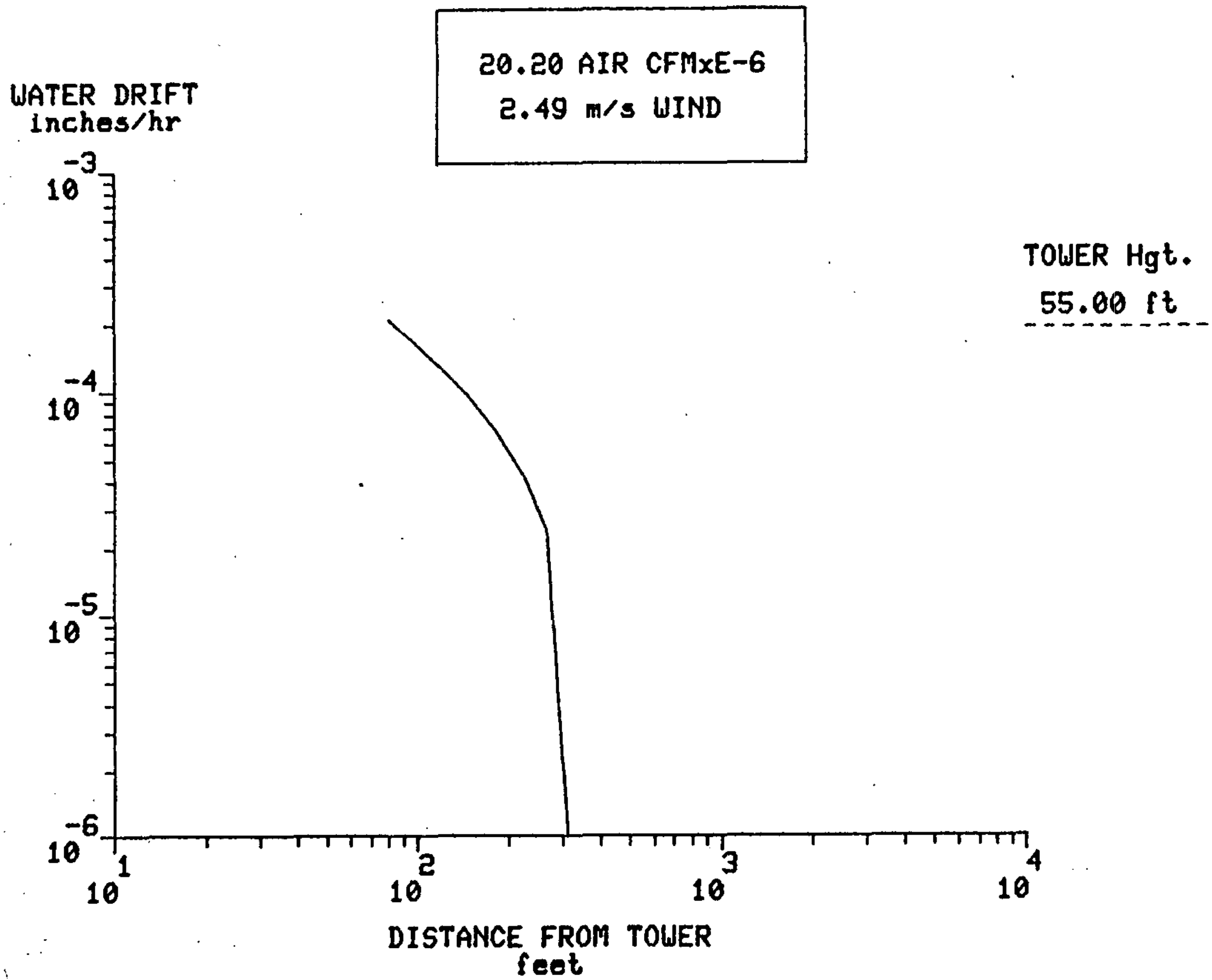

FIGURE 4: Water deposition as a function of distance during Class 5 atmospheric conditions.

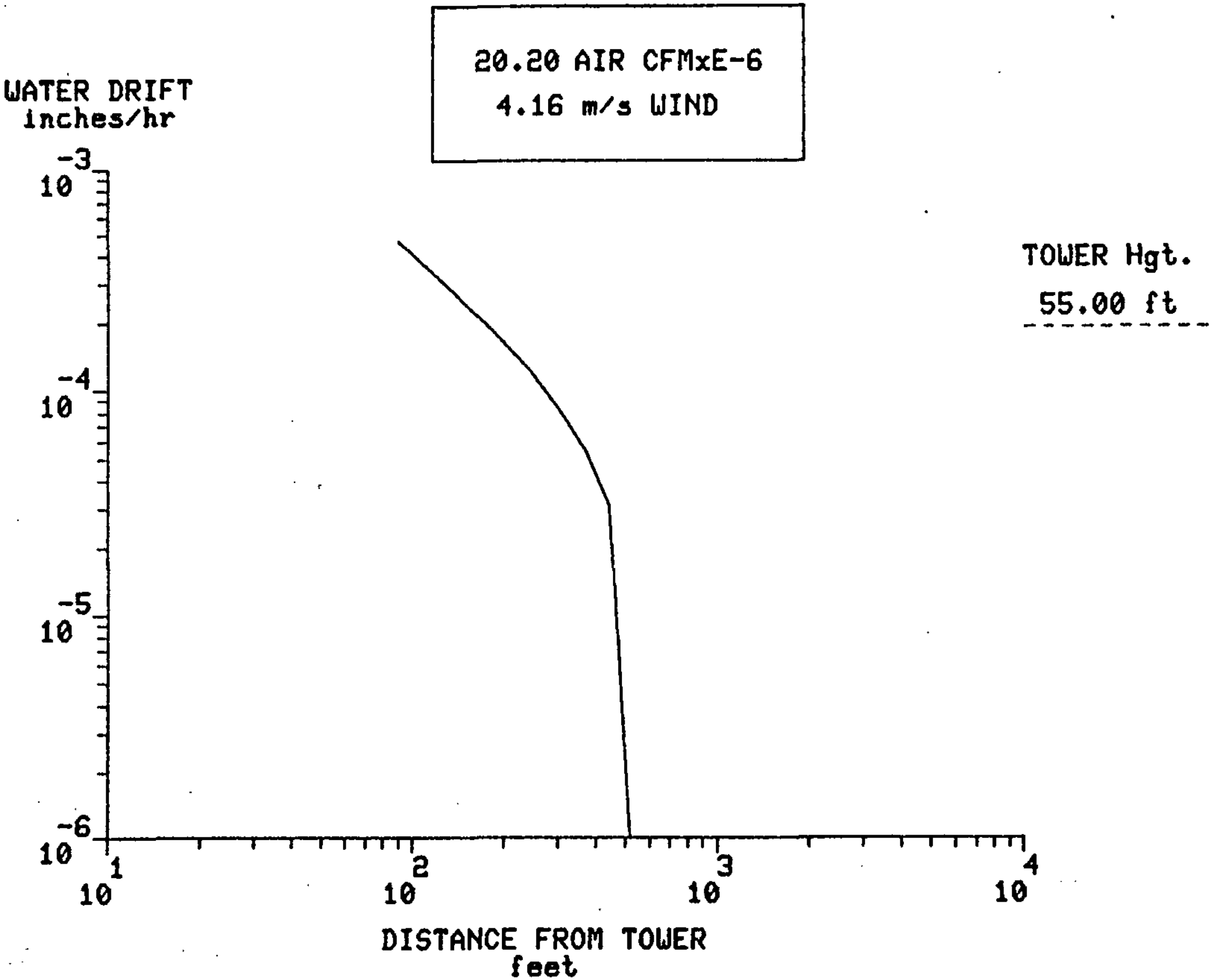

FIGURE 5: Water deposition as a function of distance during Class 6 or Class 8 atmospheric conditions.

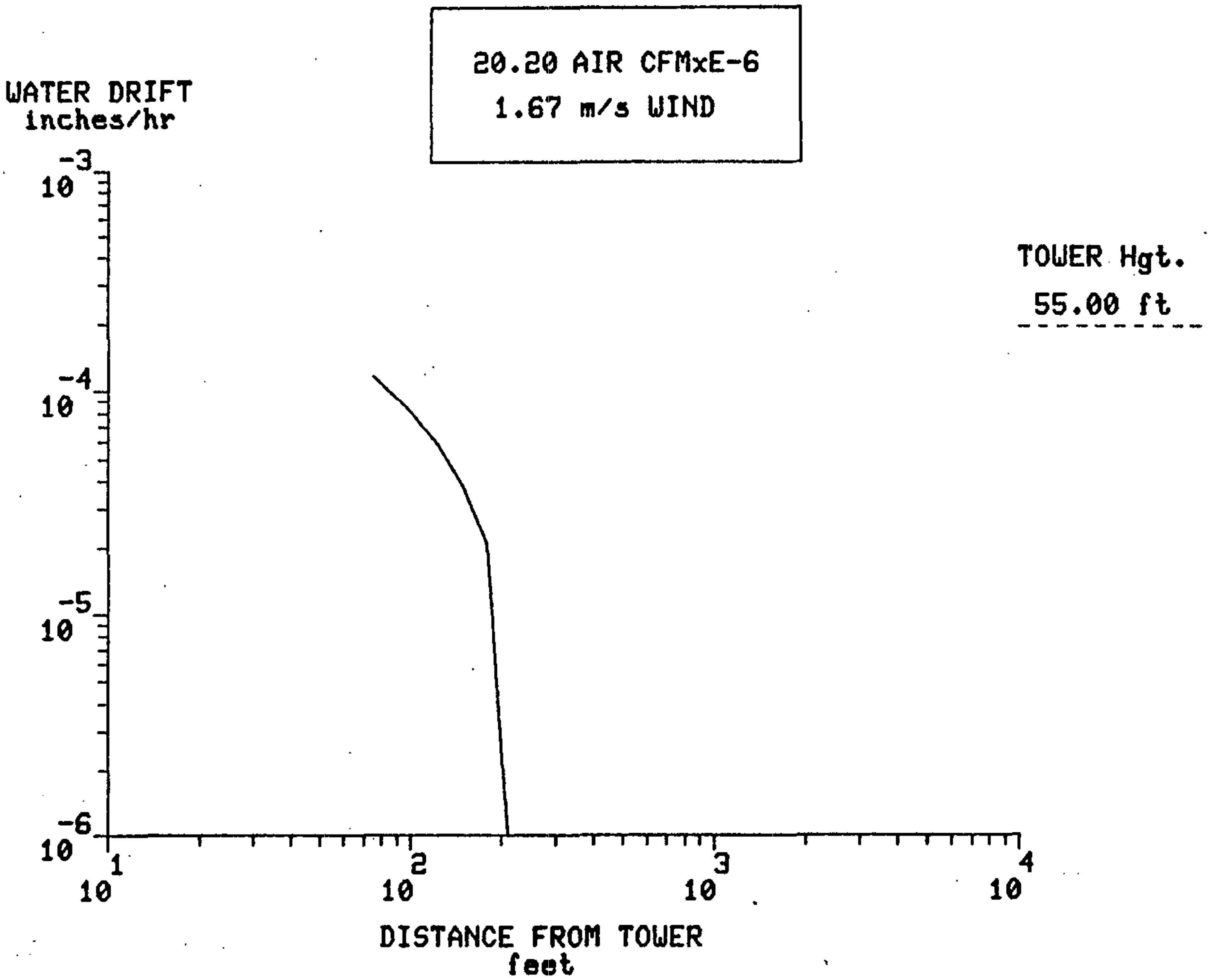

FIGURE 6: Water deposition as a function of distance during Class 7 atmospheric conditions.

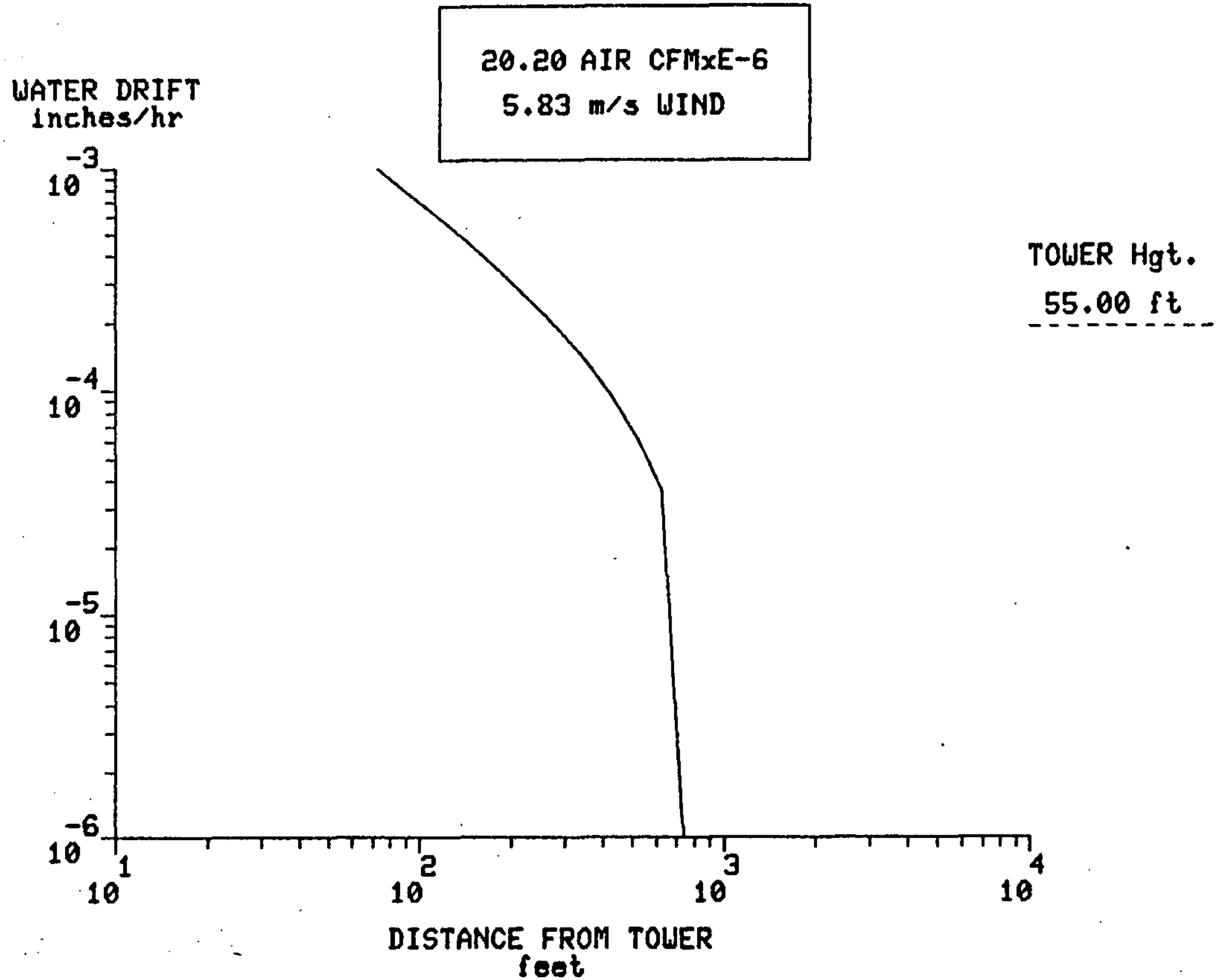

FIGURE 7: Water deposition as a function of distance during Class 9 atmospheric conditions

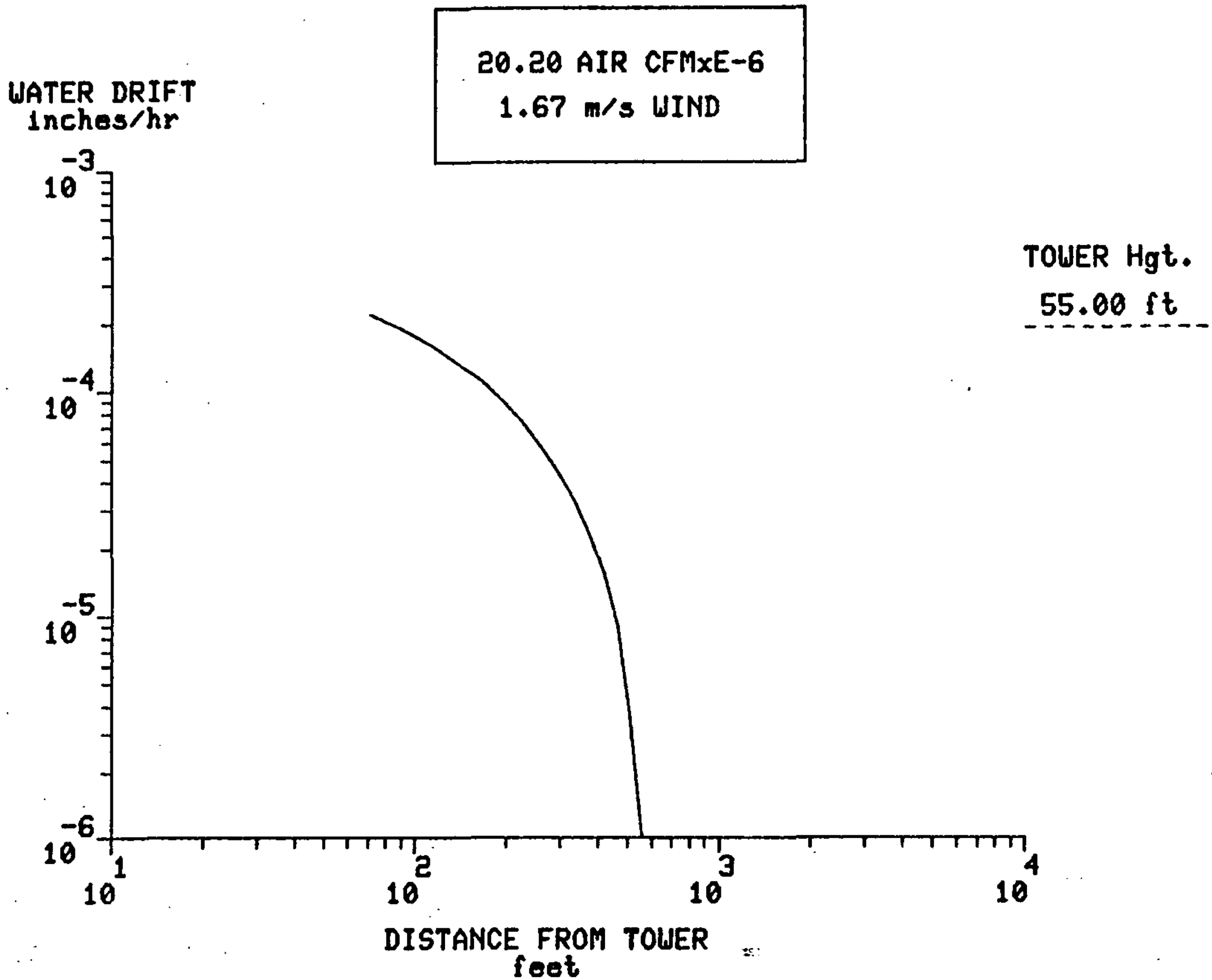

FIGURE 8: Water deposition as a function of distance during Class 10 atmospheric conditions.

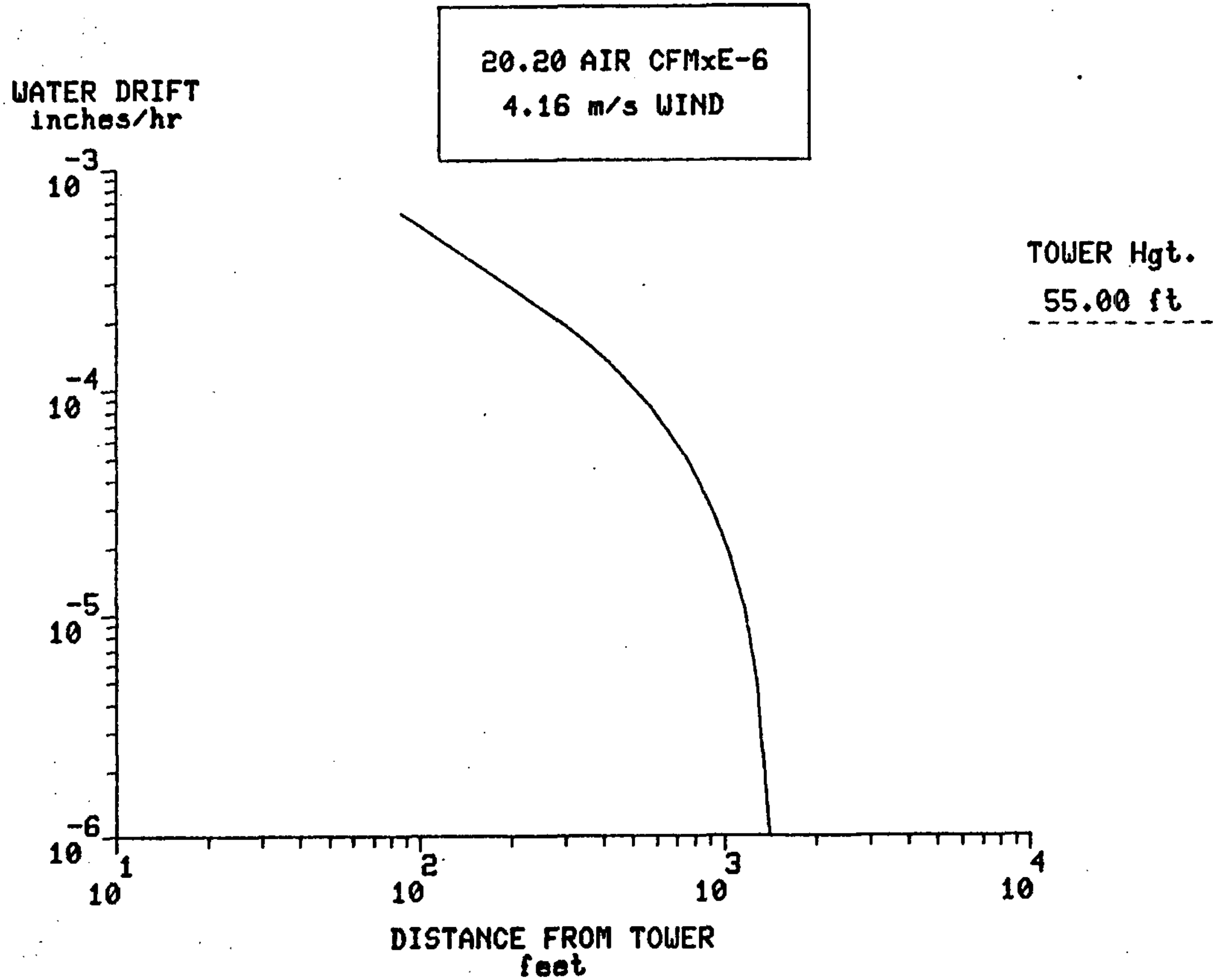

FIGURE 9: Water deposition as a function of distance during Class 11 atmospheric conditions.

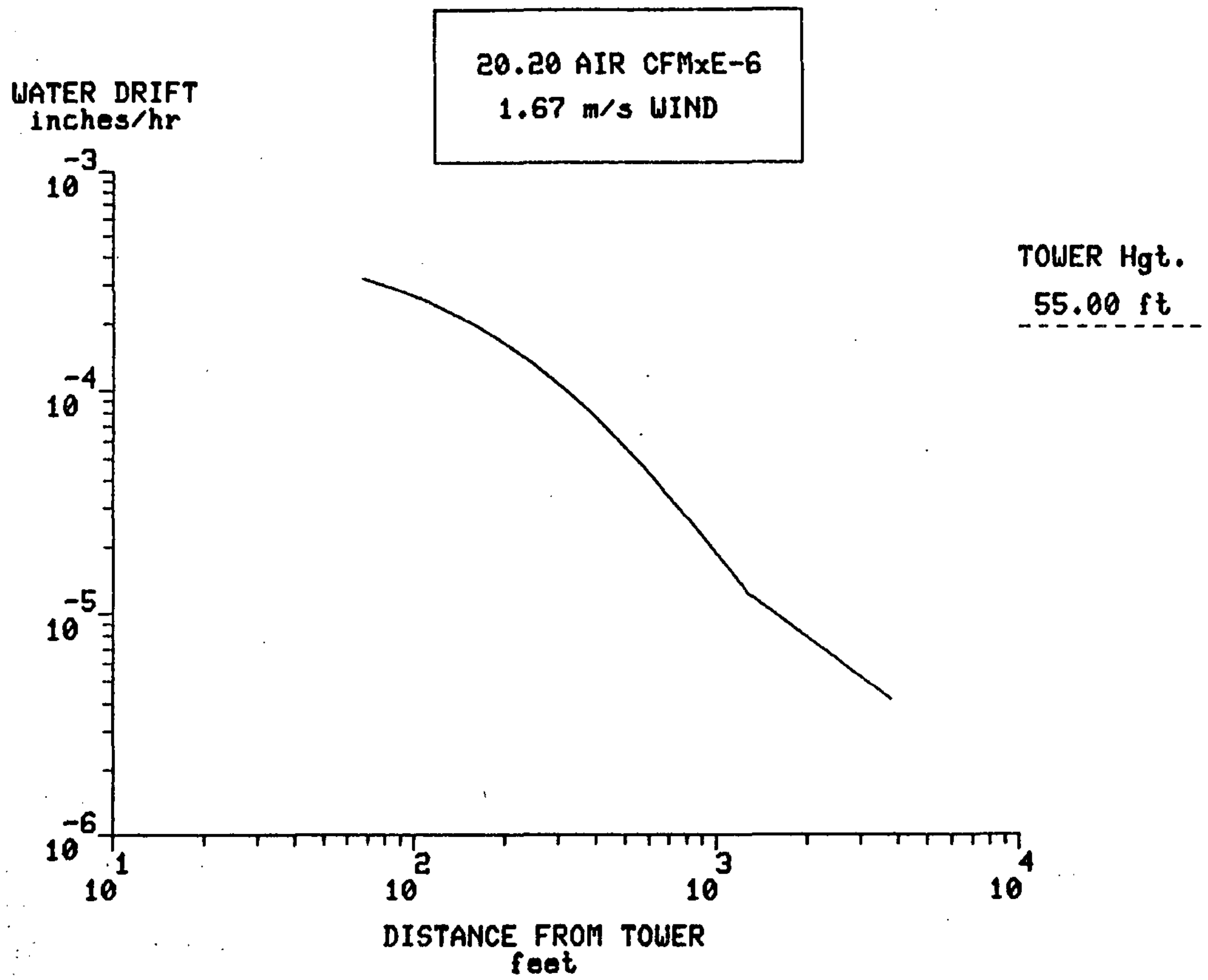

FIGURE 10: Water deposition as a function of distance during Class 12 atmospheric conditions.

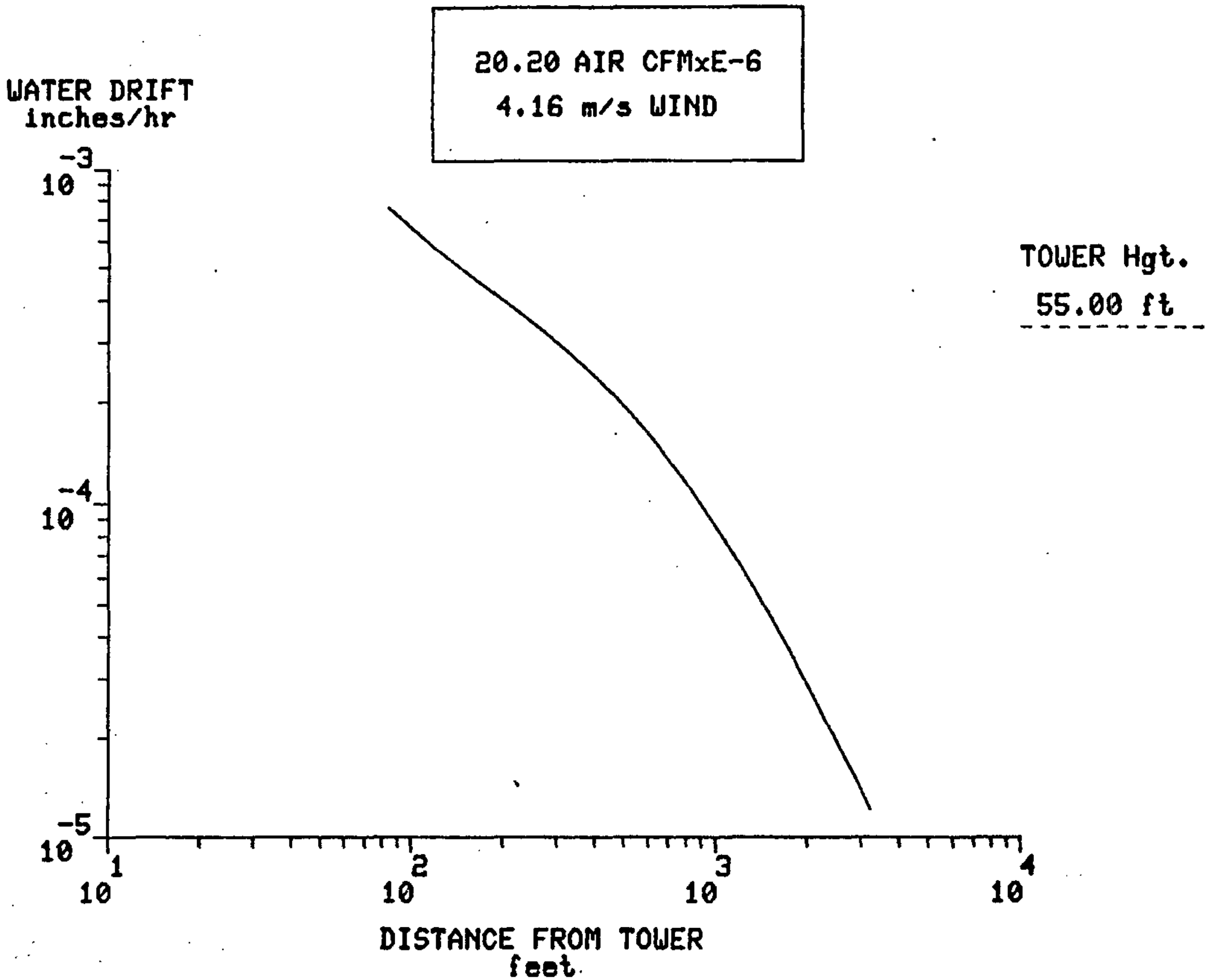

FIGURE 11: Water deposition as a function of distance during Class 13 atmospheric conditions.

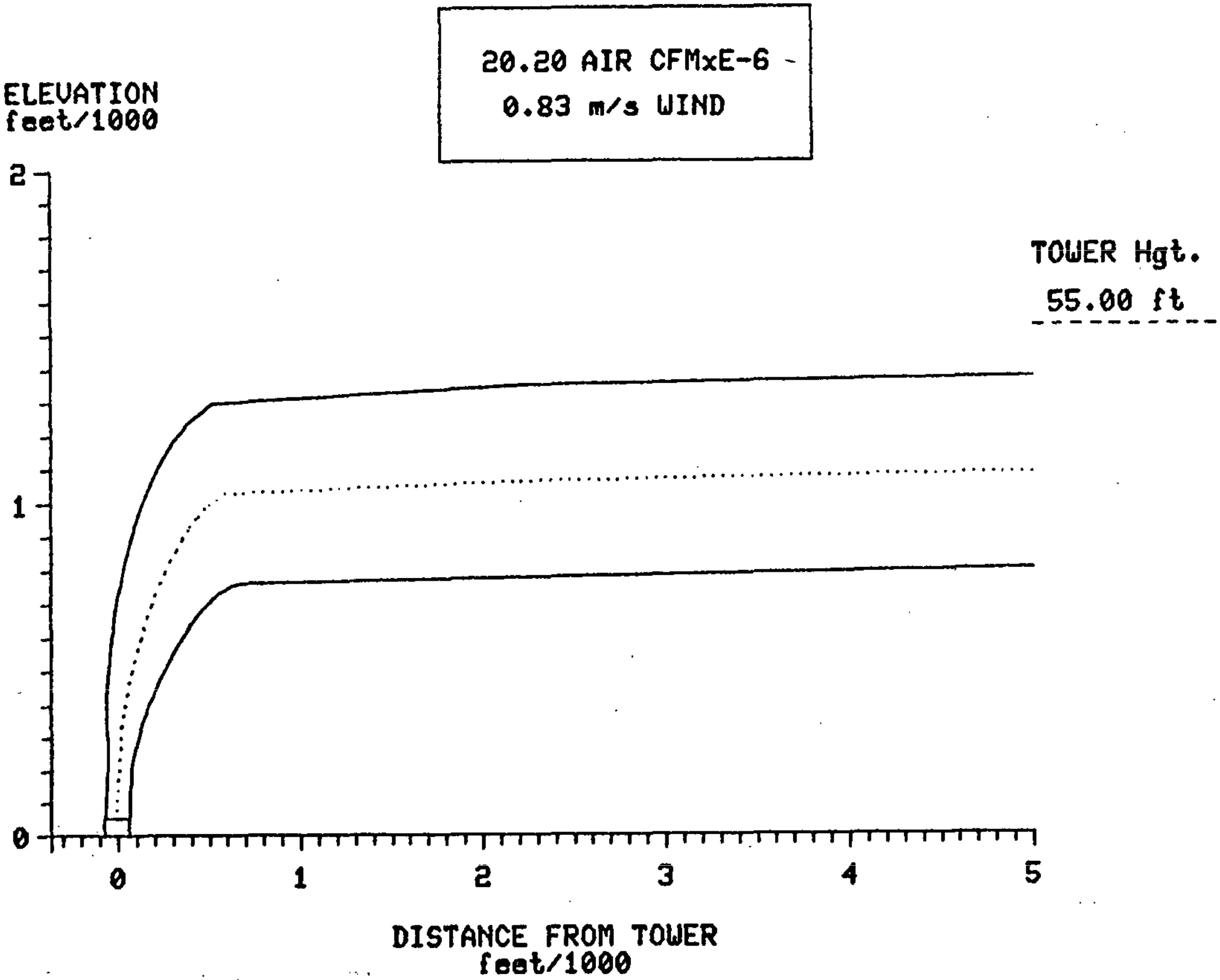

FIGURE 12: Visible plume during Class 1 atmospheric conditions.

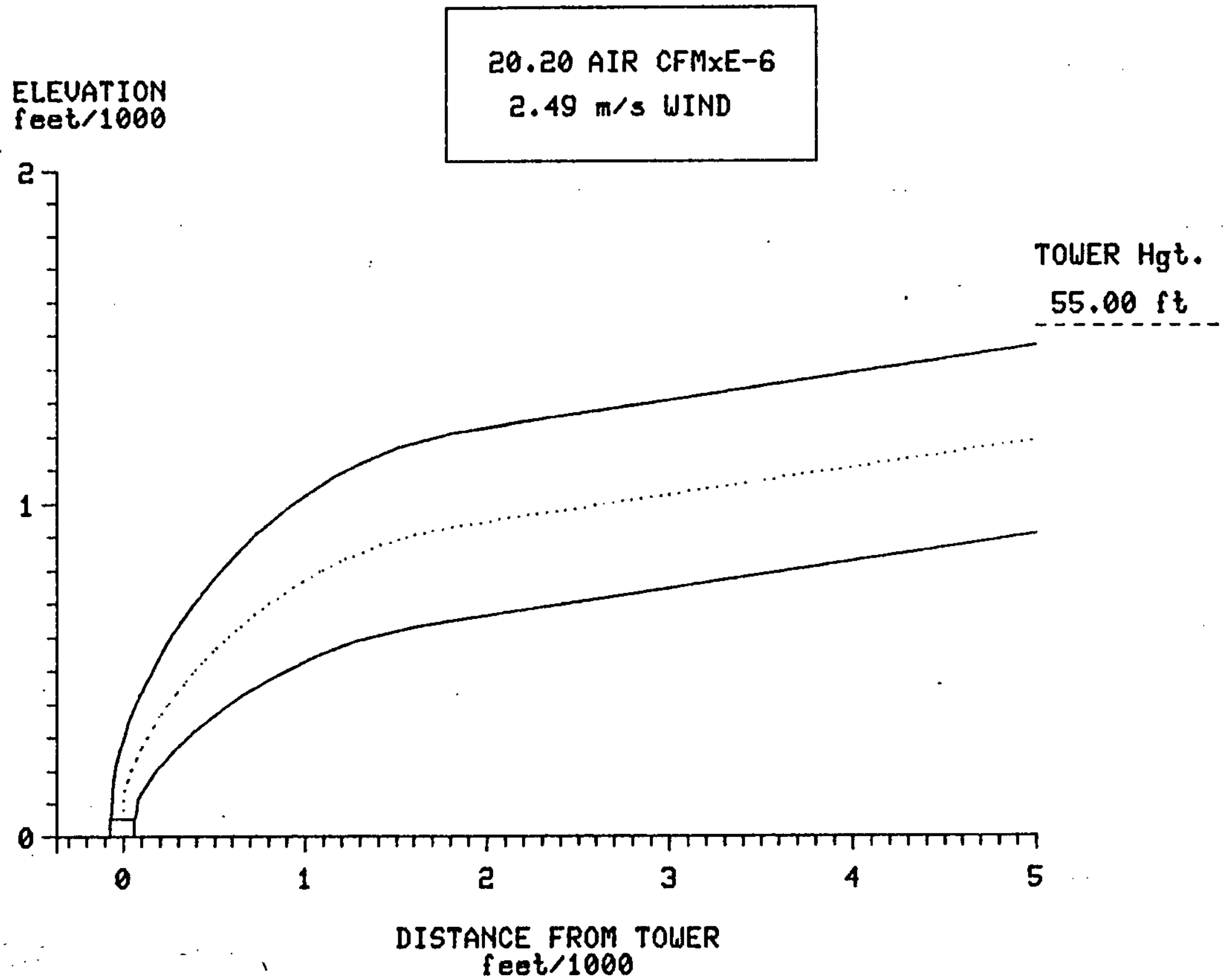

FIGURE 13: Visible plume during Class 2 atmospheric conditions.

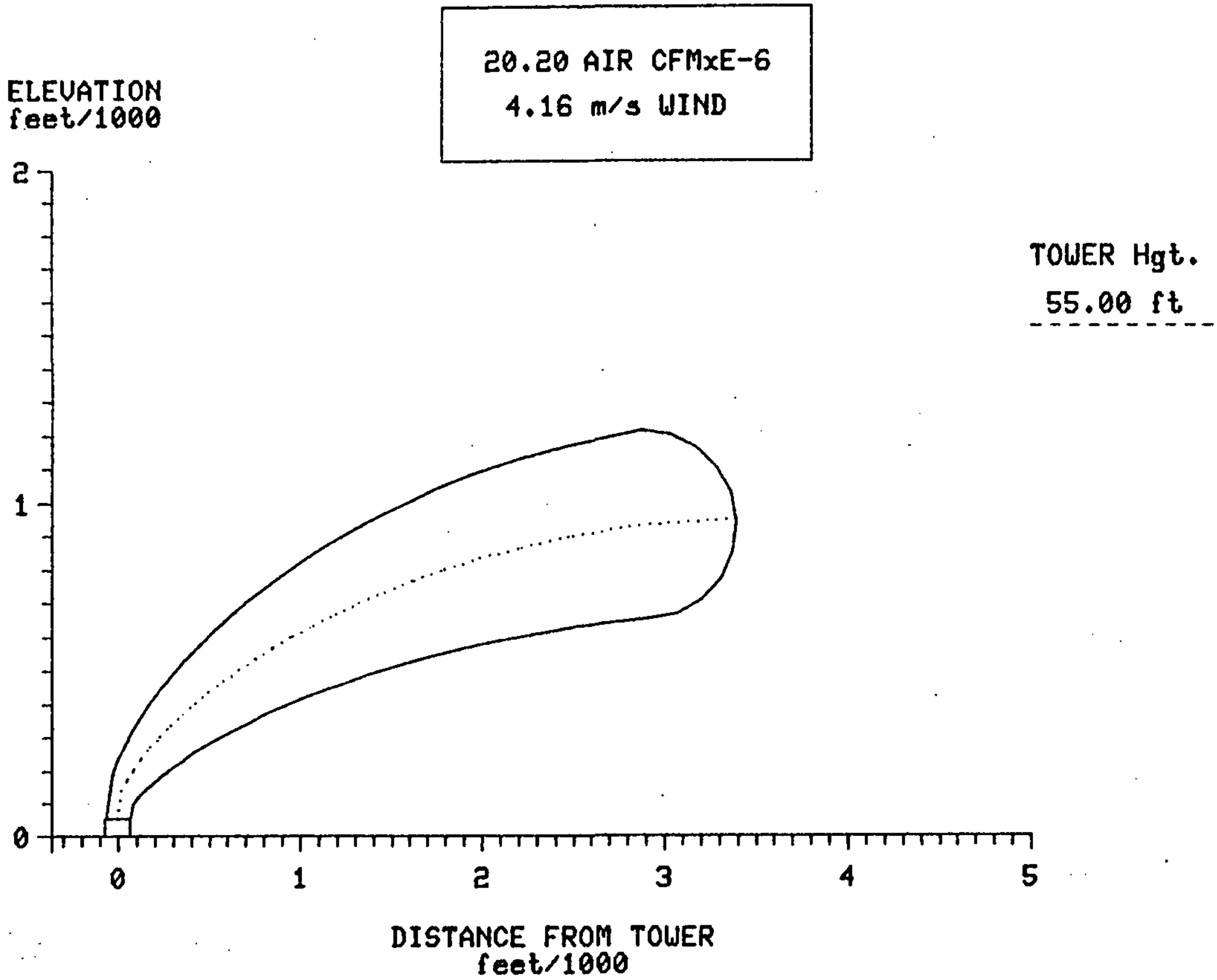

FIGURE 14: Visible plume during Class 3 atmospheric conditions.

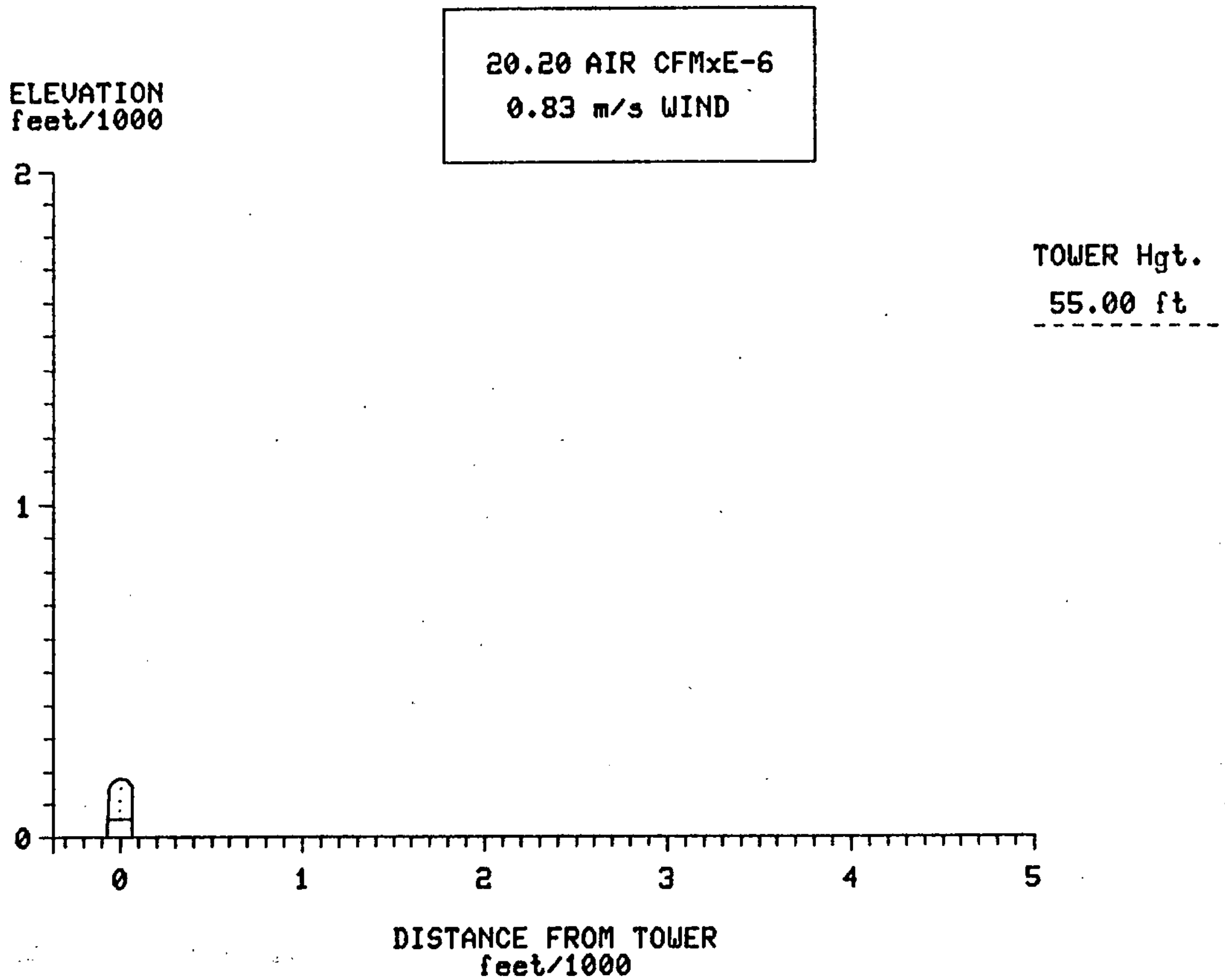

FIGURE 15: Visible plume during Class 4 atmospheric conditions.

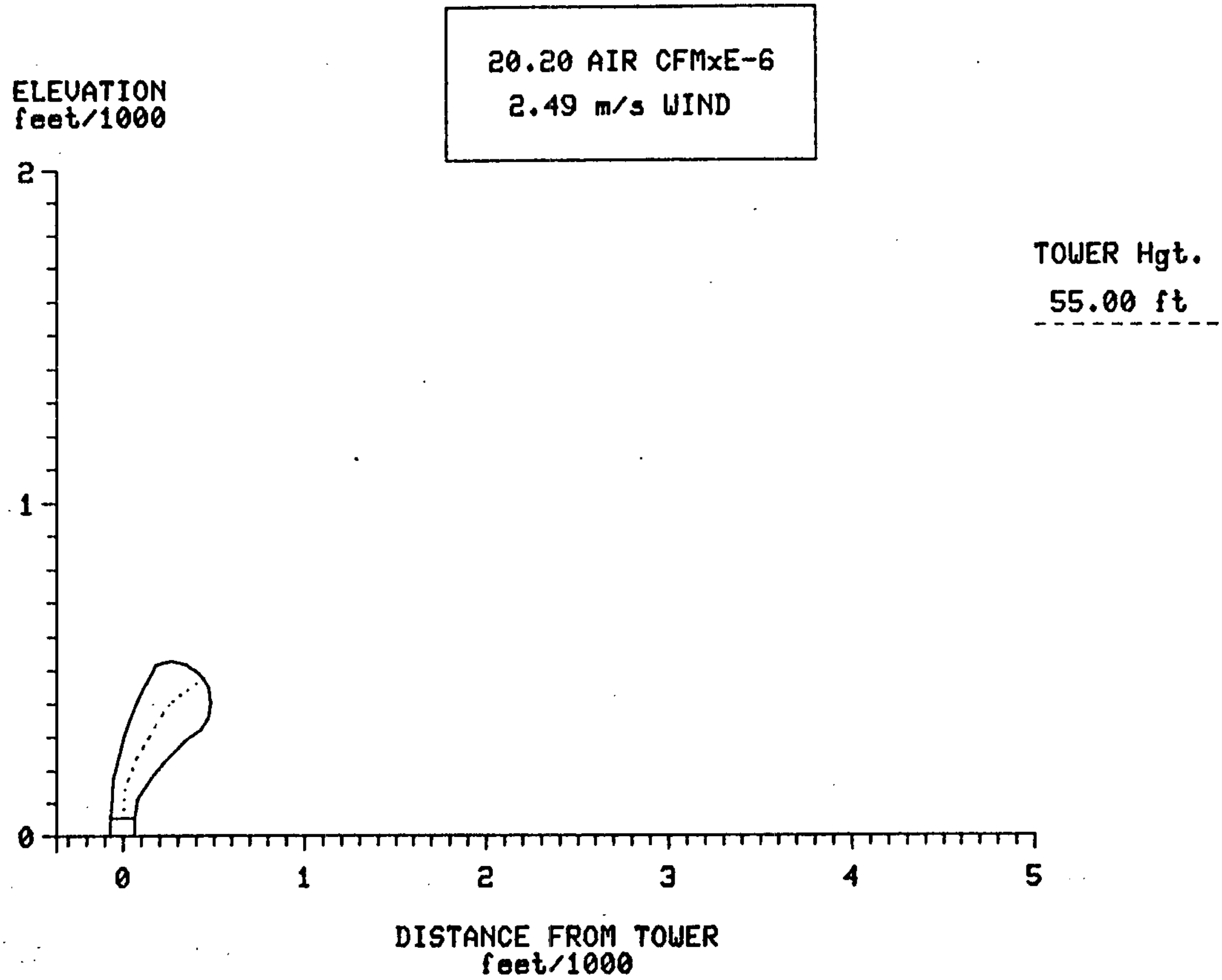

FIGURE 16: Visible plume during Class 5 atmospheric conditions.

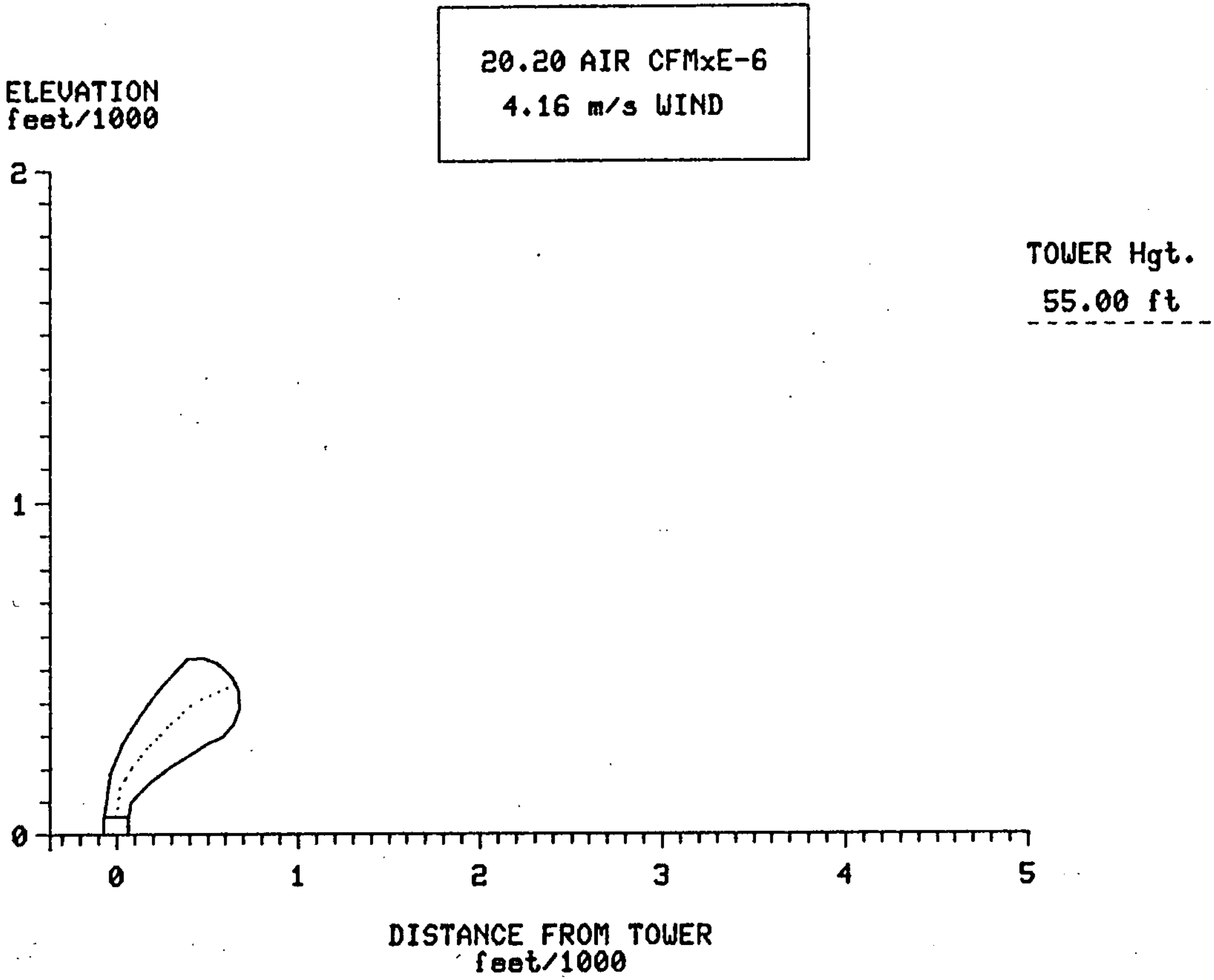

FIGURE 17: Visible plume during Class 6 or Class 8 atmospheric conditions.

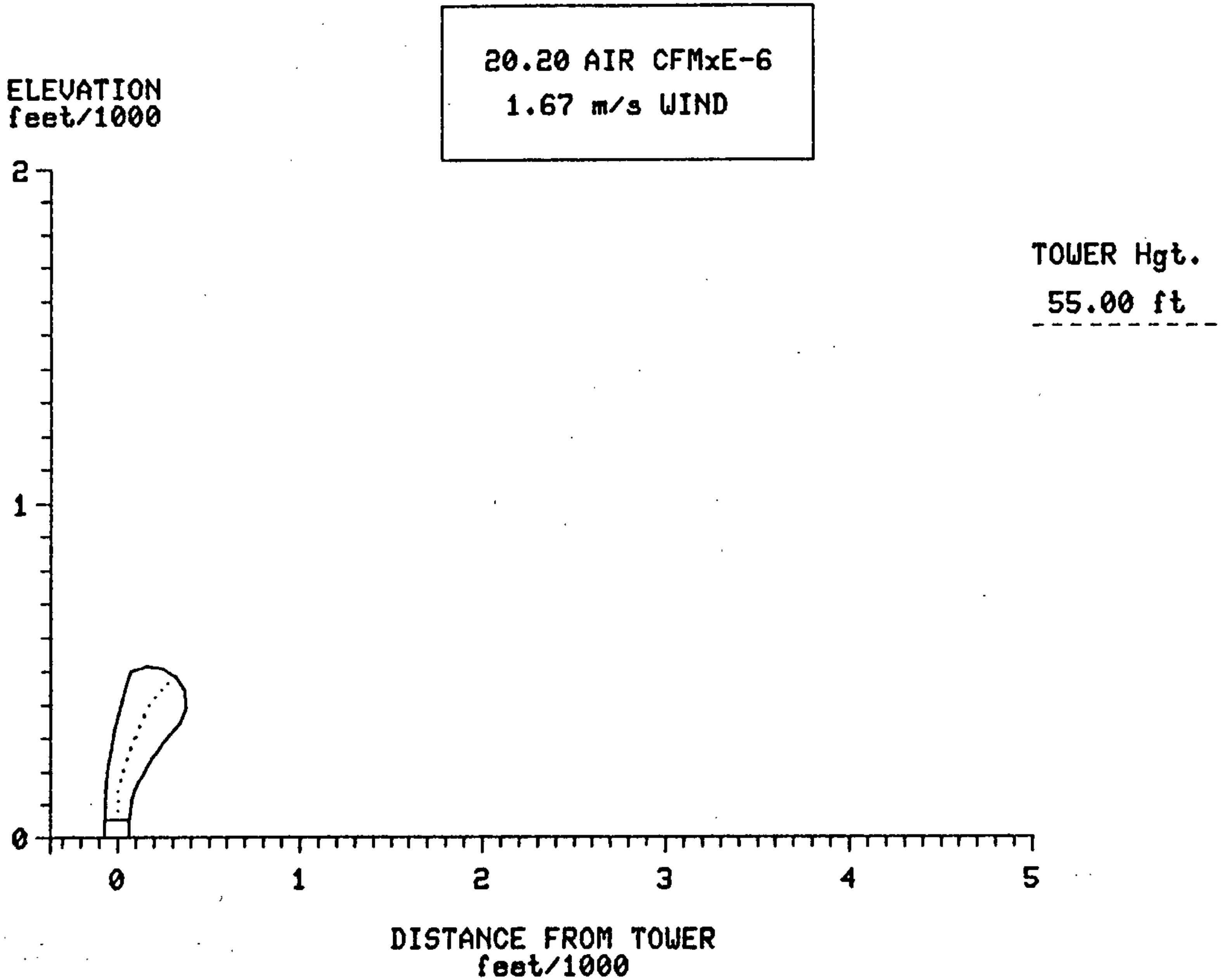

FIGURE 18: Visible plume during Class 7 atmospheric conditions.

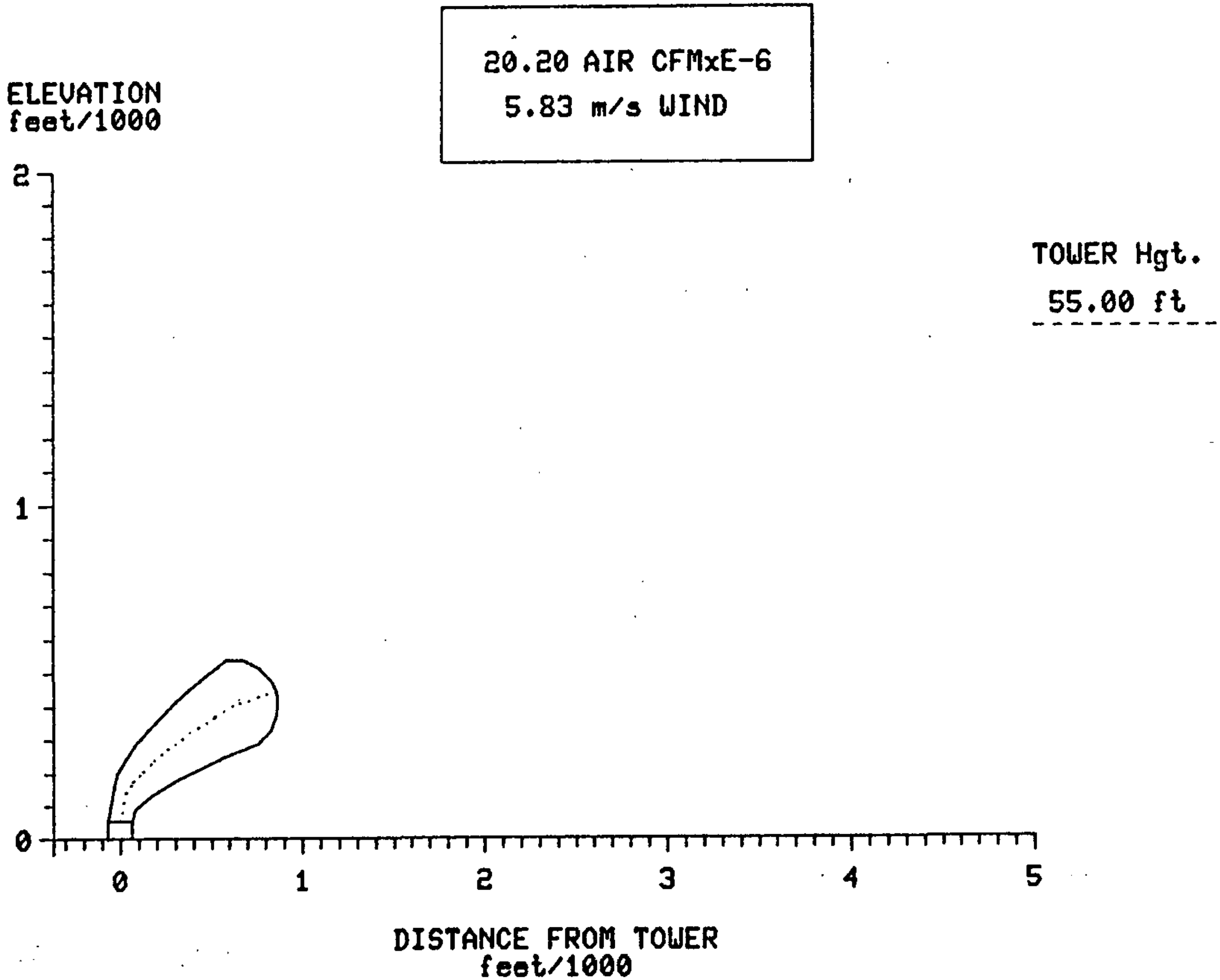

FIGURE 19: Visible plume during Class 9 atmospheric conditions.

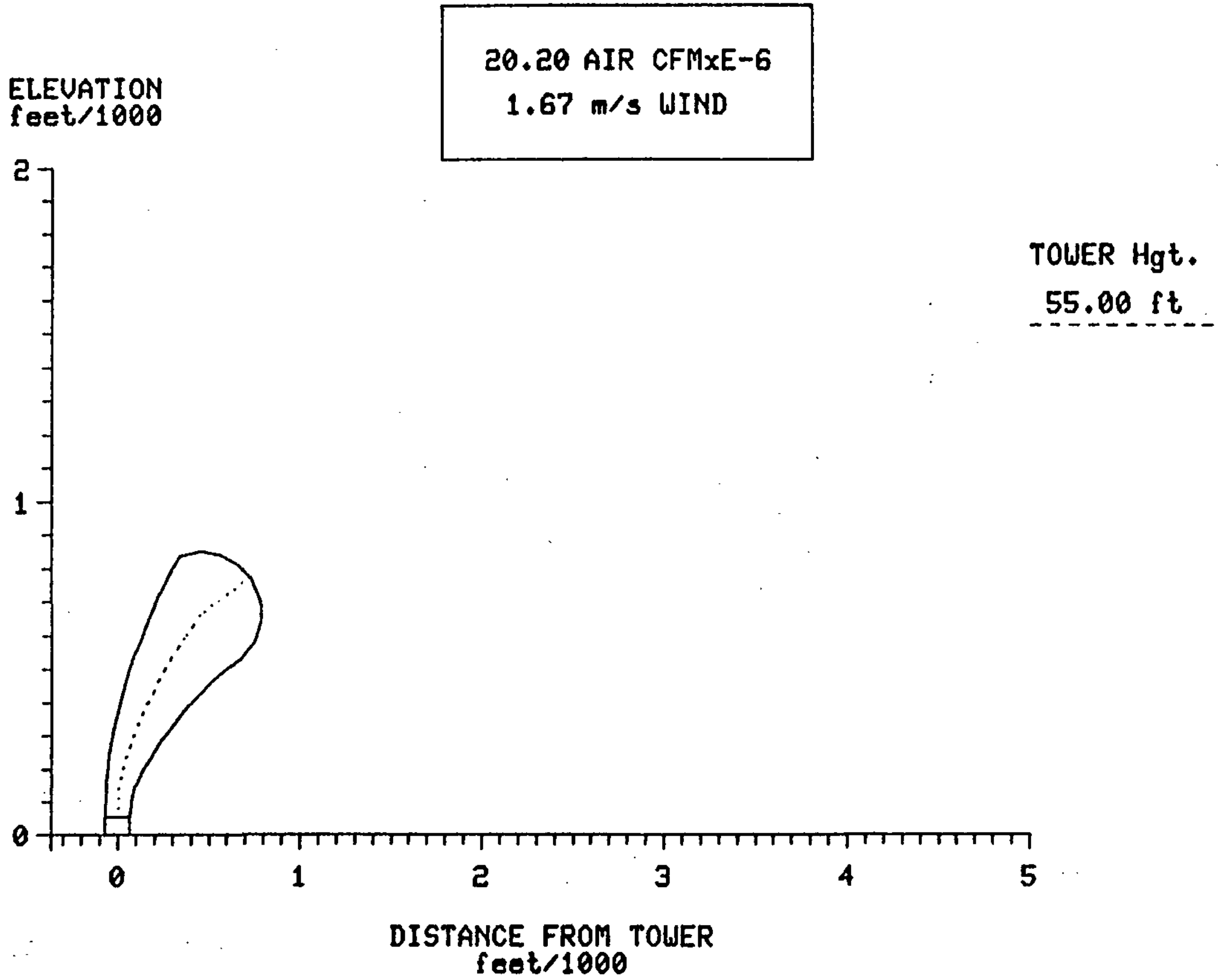

FIGURE 20: Visible plume during Class 10 atmospheric conditions.

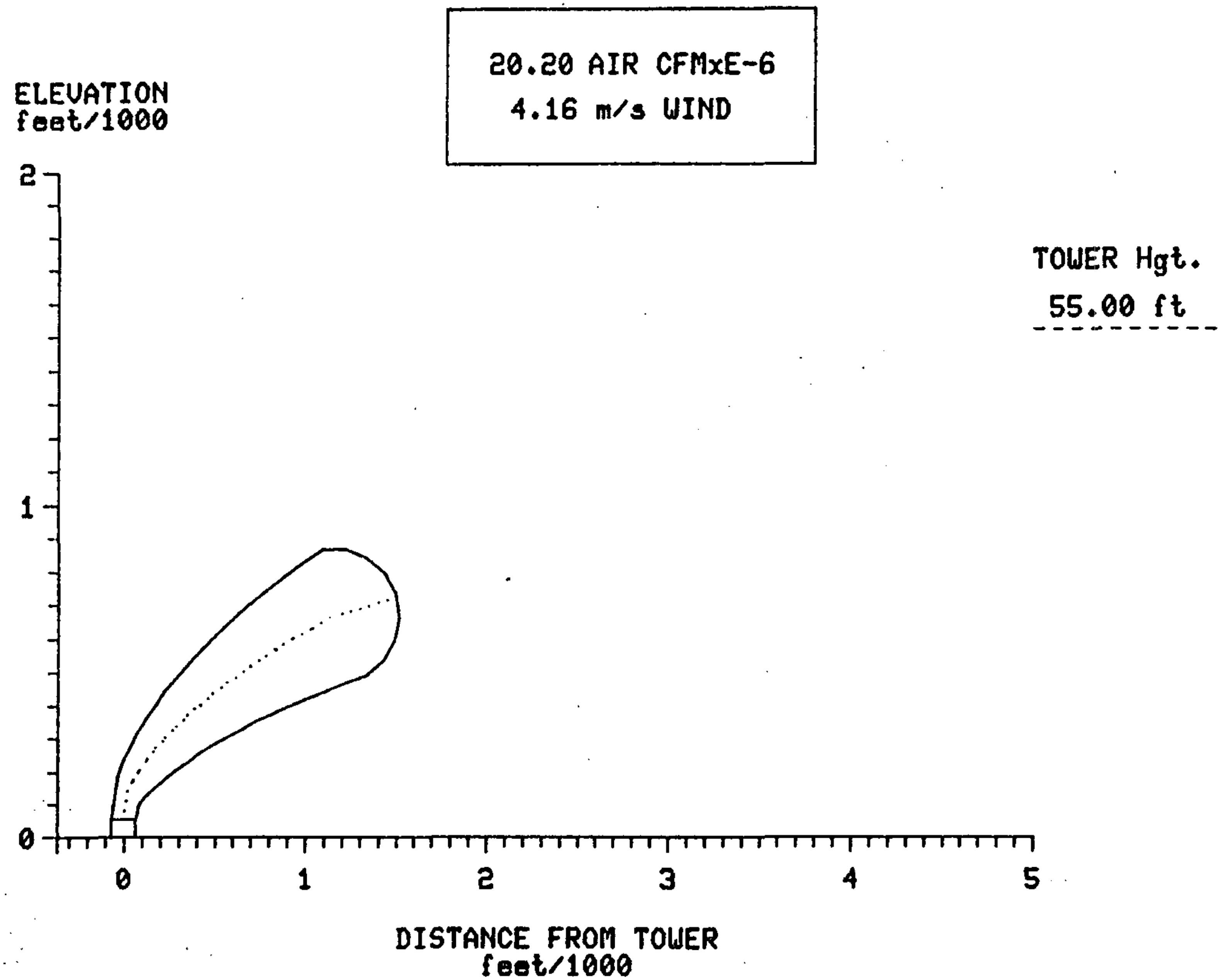

FIGURE 21: Visible plume during Class 11 atmospheric conditions.

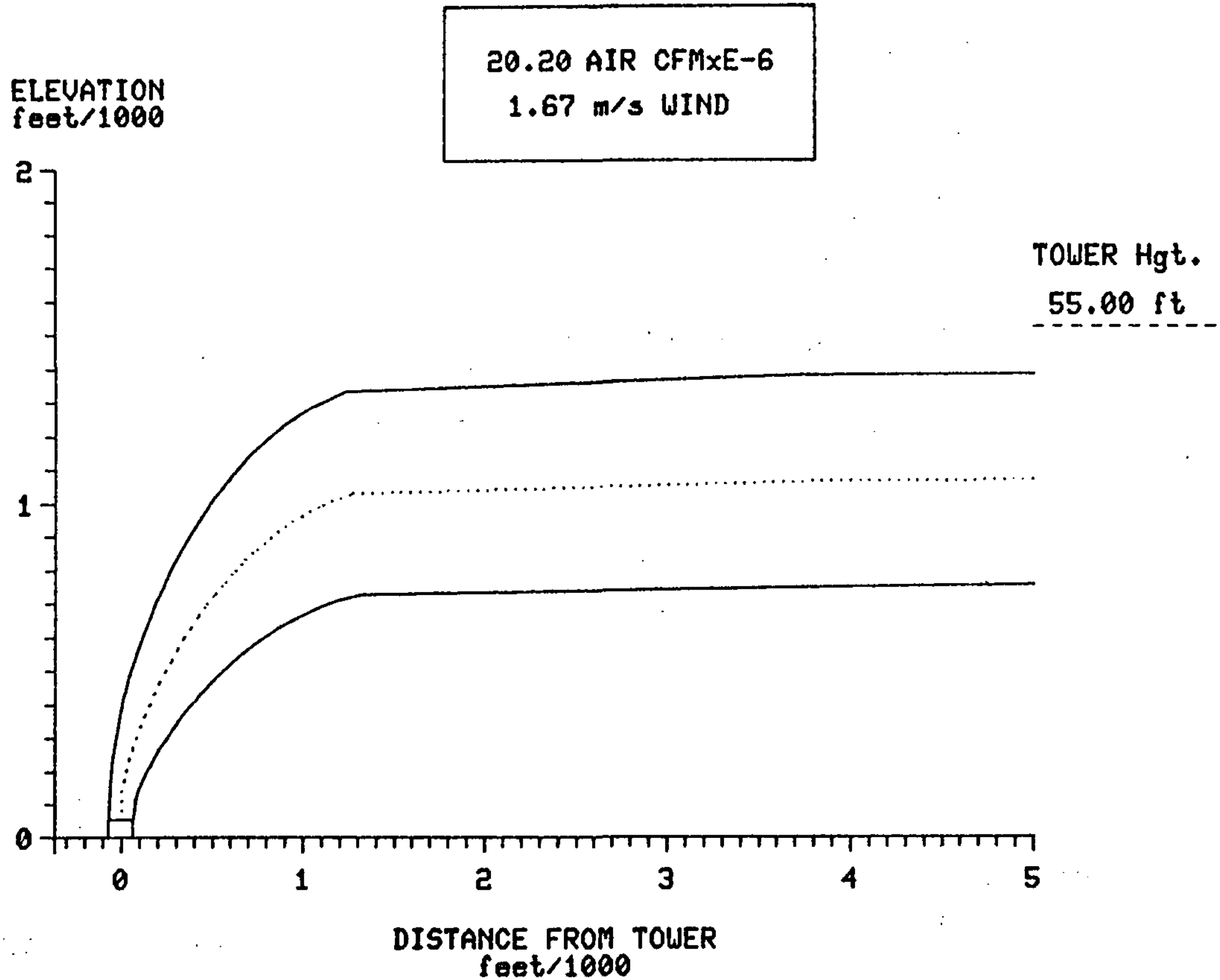

FIGURE 22: Visible plume during Class 12 atmospheric conditions.

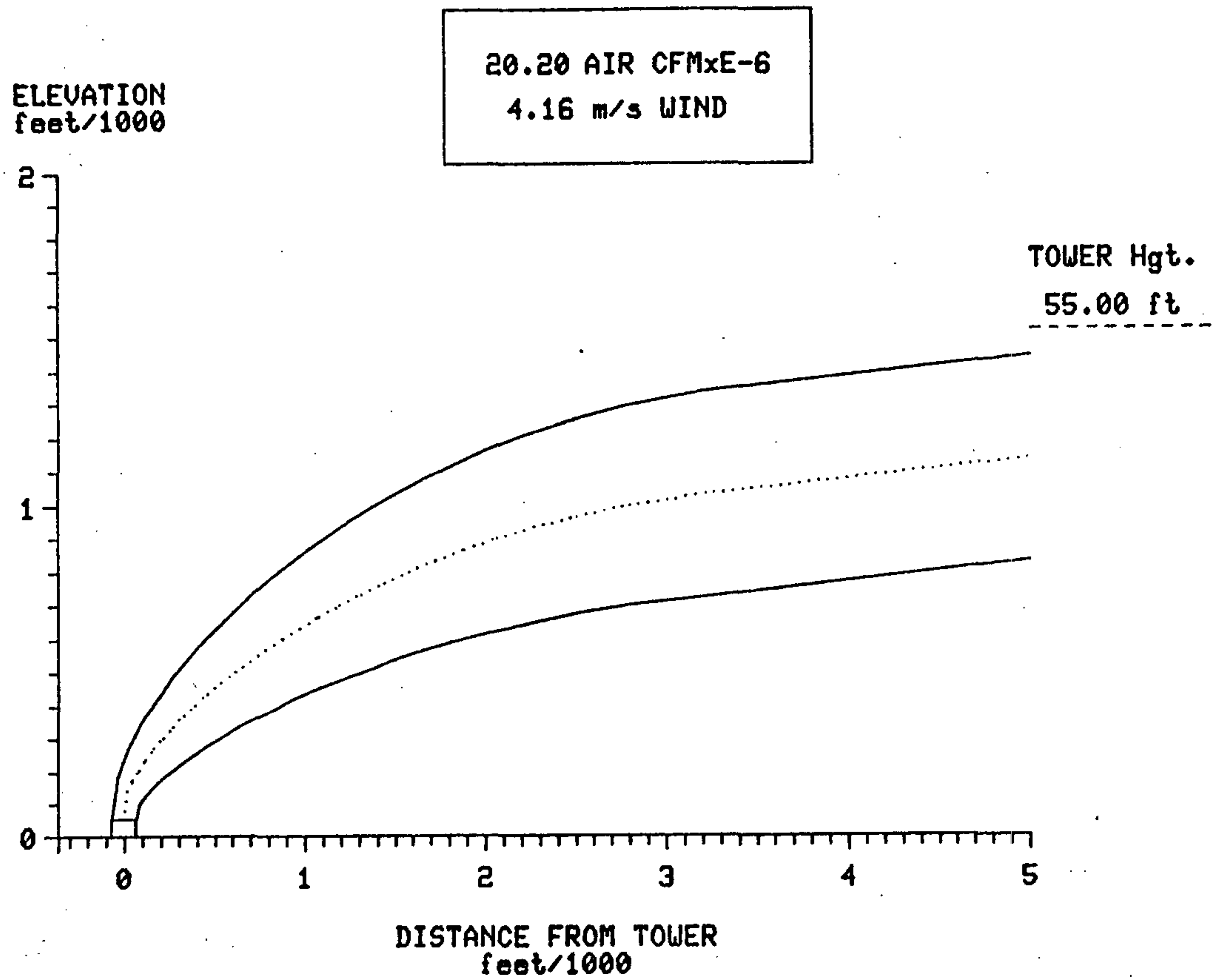

FIGURE 23: Visible plume during Class 13 atmospheric conditions.