Field Measurements of the Benefits of Increased Stack Height

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ABSTRACT

Analysis of a series of 31 field diffusion experiments permitted direct specification of the benefit of increased stack height. In the experiments, two tracers were released simultaneously from two different elevations on a 122 m tower, and were sampled at ground level on a series of arcs concentric about the release point. The ratio of observed concentrations at any sampling distance provides a measure of stack height benefits which is unobscured by differences in meteorology between experiments.

Three combinations of upper/lower release elevations were used: 26 m/2 m, 56 m/26 m and 111 m/56 m. Over the 10 km range of field measurements, ground-level concentration ratios (upper source origin/lower source origin) were larger than similar ratios computed using observed meteorology and a Gaussian plume model. Since a larger ratio implies smaller benefits from increased stack height, the Gaussian model overemphasized the benefits resulting from increased stack height.

In a plume with minimal initial rise, there is a dilution at stack exit which is directly proportional to the wind speed at the top of the stack. At distances relatively far from the source, the benefits in reduced concentration resulting from increasing source height from 26 m to 56 m were found to plateau at approximately the ratio of wind speeds at the 26 and 56 m levels. Benefits accruing as a result of increasing from 56 m to 111 m exceeded the wind speed ratio at all distances. Conversely, benefits for an increase from 2 m to 26 m were lacking at distances beyond about 4 km.

1. Introduction

There is no doubt that the ground-level concentration of a pollutant at near-source distances can be reduced by increasing the height at which the pollutant is released to the atmosphere. However, from a practical standpoint the benefits in lower concentration must be balanced against the increased cost incurred in constructing taller stacks. How tall is tall enough? Modeling can give some guidance. This paper offers guidance based on field measurements. The benefits accruing by virtue of increasing stack height over several specific increments are examined.

Experimental investigation of source height effects has conventionally entailed the release of a tracer or pollutant from one elevation under certain meteorological conditions, and then repeating the release from a different elevation at a time when the meteorology is similar to that existing during the first release. Unfortunately, the free atmosphere is an uncooperative laboratory which never precisely repeats itself, and thus the effects of such a variable as source height can be somewhat obscured by the changes in meteorology between experiments. Further, there remains the problem that "similar" meteorology is relative to our understanding or modeling of atmospheric diffusion. In other words, even if such parameters as vertical temperature gradient, wind speed gradient and wind direction variances are found to be identical on two separate occasions, the observed concentrations of a tracer might well vary significantly because more than the measured parameters are affecting the diffusion.

The simultaneous release from more than one elevation of atmospheric tracers with similar aerodynamic properties would assure identical meteorological conditions during each tracer release (although, of course, most meteorological variables depend on height). A number of field experiments carried out at the U.S. Department of Energy's Hanford Area entailed simultaneous releases at different heights. These experiments, included in the Hanford 67-Series experiments (Nickola, 1977), are the data base for the results to be presented.

2. The Hanford field grid

The Hanford field diffusion grid is located in a semiarid region in the southeast of the state of Washington. Sagebrush 1–2 m in height is interspersed with steppe grasses resulting in a roughness length of ~3 cm. The diffusion grid is located near the center of a basin which is approximately 40 km in diameter. During the 67-Series experiments, 14 concentric sampling arcs were used—the nearest arc at 0.2 km from the source point, and the farthest at 12.8 km. A 122 m tower stands at the center of the field grid. All but the 12.8 km sampling arc are located on a relatively flat area where the extremes in elevation range from 200–230 m MSL.

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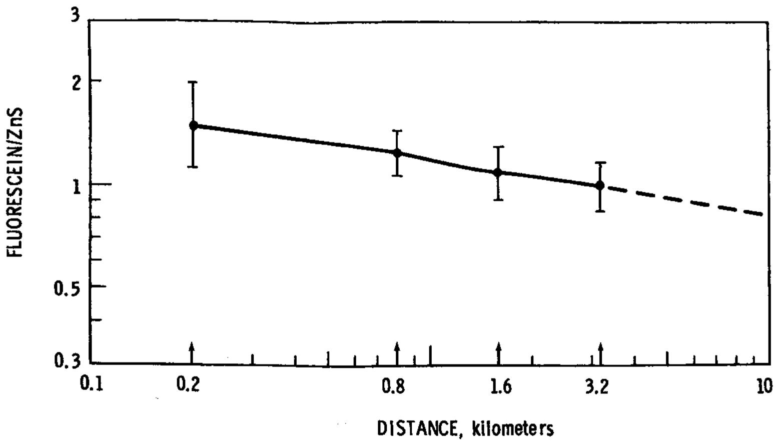

FIG. 1. The observed ratio of fluorescein to zinc sulfide tracers following release from a common source.

The 12.8 km arc is at an elevation 35 m lower than the nearer source arcs.

Several hundred controlled-flow vacuum sources were activated during each experiment. Although samples were collected on a field array of towers during a number of the 67-Series experiments, only ground-level (1.5 m elevation) samples were used in the assessment of the benefits of stack height treated in this paper.

3. Common source experiments

In order to employ a dual tracer technique in source height investigations, it is necessary to establish the compatibility of two tracers. Simultaneous releases of the tracers zinc sulfide FP 2210[1] and fluorescein[2] began at the Hanford Area in 1964. This dual tracer technique (Ludwick, 1966) involves simultaneous collection of the tracers on a common set of filters, and subsequent noninterfering assays for each tracer. The compatibility of the tracers was investigated in the field in several experiments in which the two tracers were released from the same location. The Hanford 67-Series data volume documents four of these common-source experiments and 34 dual-release-height experiments. The dispersal technique employed in the common-source experiments was identical to that used in the dual-level releases.

More than 400 filter samplers were exposed during each of the common-release-point experiments, with more than half the samplers deployed on an array of 20 towers. The release point was at an elevation of 2 m. Sampling was done on arcs at radial distances of 200, 800, 1600 and 3200 m from the source.

Inasmuch as identical masses of fluorescein (FL) and zinc sulfide (ZnS) were released, identical masses collected on filters would have indicated perfect compatibility of tracers. Such was not the case. Fig. 1 shows the ratio of FL to ZnS observed at each sampling arc. Twelve FL/ZnS ratios[3] contribute to each logarithmic mean. Error bars depicting $\pm 1\sigma$ about the mean value are included on the figure. The prime cause of the deviation from perfect agreement between the two tracers is speculated to be due to differences in gravitational and other depletion characteristics of the tracers (i.e., differences in deposition velocity). The tracer assay techniques also leave some margin for error.

Ratios of FL to ZnS observed in the 31 usable dual-release-height experiments were adjusted on the basis of the curve presented in Fig. 1. Any difference in observed concentration was presumed to be due primarily to release height and not to tracer properties. The possibility of biasing conclusions was reduced by the fact that the same tracer was not always released from the upper elevation. (FL was released from the higher elevation on 12 occasions; ZnS on 19 occasions.)

4. Dual-release-height experiments

It was concluded that investigation of source height effects could best be done through crosswind-integrated concentration (CWIC) rather than plume centerline concentration, although ratios formed from either measurement were generally of similar magnitude. Since CWIC at a specific distance from a source is based on a number of measurements (as opposed to a single measurement for the centerline exposure), the CWIC is a more reliable parameter. Furthermore, it is the CWIC summed over a meteorologically long period of time that prescribes the dosage available to receptors at any distance.

The field releases, generally 30 min in duration, were divided into Pasquill-Gifford stability categories on the

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[1] A fluorescent pigment manufactured by the U.S. Radium Corp., Morristown, NJ.

[2] A water soluble uranine dye manufactured by (among others) Allied Chemical Co., San Francisco, CA.

[3] For each of four experiments, these are the ratios of the peak concentrations at ground level (1.5 m), the ground level crosswind-integrated concentrations, and the peak concentrations observed on a tower.

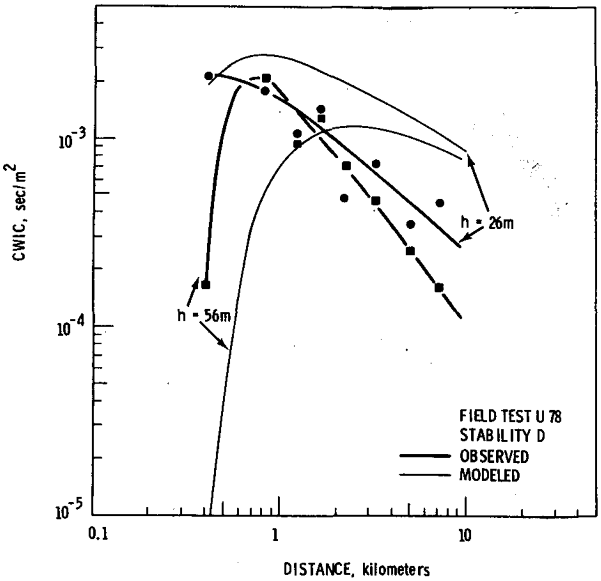

FIG. 2. Normalized CWIC values observed during field test U78. *h* indicates tracer release height.

basis of temperature differences as specified in U.S. Nuclear Regulatory Commision Guide 1.23 (USNRC, 1972). This classification prescribes measurement of a temperature differential (ΔT) between 40 and 10 m for release at or below 40 m. For releases above 40 m, the differential between the release height and 10 m is used. (Ordering of the experiments on the basis of bulk Richardson number showed minimal variation from the ΔT ordering.)

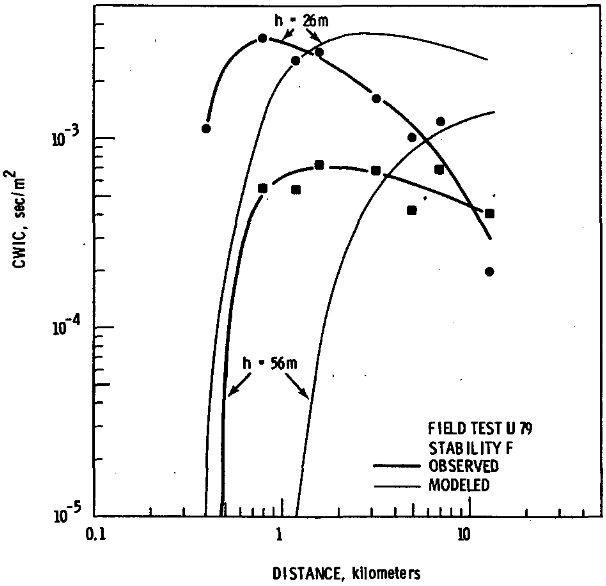

FIG. 3. As in Fig. 2 except during field test U79.

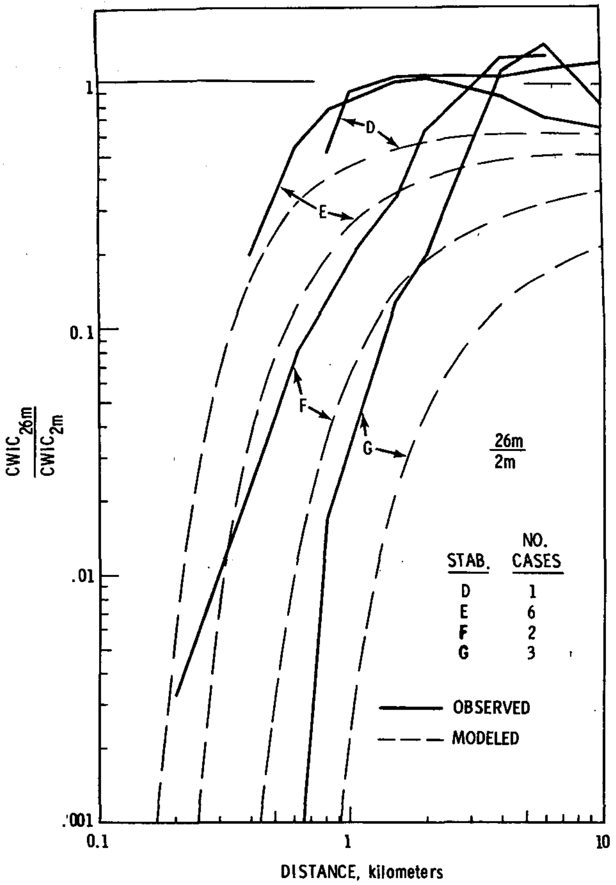

FIG. 4. Ratio of normalized CWIC observed at 26 m to that observed at 2 m. Bold curves are observed values; lighter curves are modeled.

Fig. 2 gives CWIC values observed at ground level during field experiment U78, an experiment carried out during class D stability. The dots represent CWIC's resulting from ZnS released at an elevation of 26 m. The solid squares depic CWIC's resulting from a FL release from 56 m. Heavy smooth curves are sketched through the data points. The data have been normalized to mass rate of tracer emission, but not to wind speed since the intent is to present difference in exposures actually observed with equal releases.

Fig. 3 presents data similar to Fig. 2, but for field test U79 which was completed during class F stability. Note that the observed data reflect the less rapid diffusion of tracer to the surface during the more stable test U79.

Ratios, formed by dividing the observed smoothed CWIC data from the upper level release by similar data from the lower level release, were computed for selected distances. These ratios were then adjusted in accordance with the curve presented in Fig. 1. The summary curves to be presented in Figs. 4–6 are the logarithmic means of the adjusted ratios from the individual experiments.

Precise specification of the accuracy of the observed mean ratios is impossible. However, examination of the observed data points and smoothed curves in Figs. 2 and 3 suggests that it would be very unlikely that an independent second derivation of those curves would change the ratio between curves (at any distance) by as much as a factor of 2. Where more than one experiment contributed to a mean ratio, the uncertainty could be expected to be further reduced.

The light curves on Fig. 2 (and on Fig. 3) are CWIC's for class D (and for class F) stability resulting from a Gaussian plume model and the specific wind speeds observed at each release height. The Gaussian equation prescribes that at ground level,

$$\mathrm{CWIC}=\frac{2}{(2\pi)^{\frac{1}{2}}\sigma_z\bar{u}_h}\exp\left(-\frac{h^2}{2\sigma_z^2}\right),$$

where σ_z is the standard deviation of the plume vertical concentration distribution, $\bar{u}_h$ the mean wind speed at source height and h the source height. In this form, total plume reflection without deposition is assumed. *Turner Workbook* (Turner, 1970) values of σ_z were used.

The choices of the NRC stability classification procedure based on vertical temperature profile and of the *Turner Workbook* values of σ_z were rather arbitrary—although both these schemes are rather widely used. It is recognized that there are a number of schemes for specification of stability class and of dispersion parameters. Gifford (1976) presented a review of many of these schemes. Hanna *et al.* (1977) have reported results of a workshop dealing with this subject. It should be noted that the modeled curves presented in Figs. 2 and 3 (and to be presented in Figs. 4–6) are quite dependent on the selected model, method of stability classification and set of sigma curves used. The use of the Gaussian model with stability based on ΔT and with dispersion based on Turner's σ_z values is not intended as an endorsement nor a condemnation, but merely as a plane of reference.

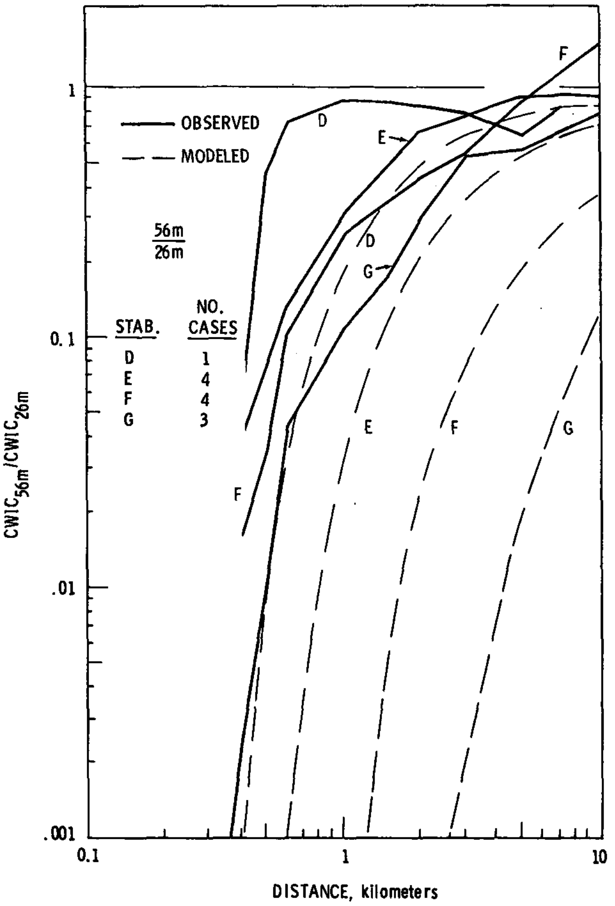

Fig. 5. As in Fig. 4 except for ratio at 56 m to that observed at 26 m.

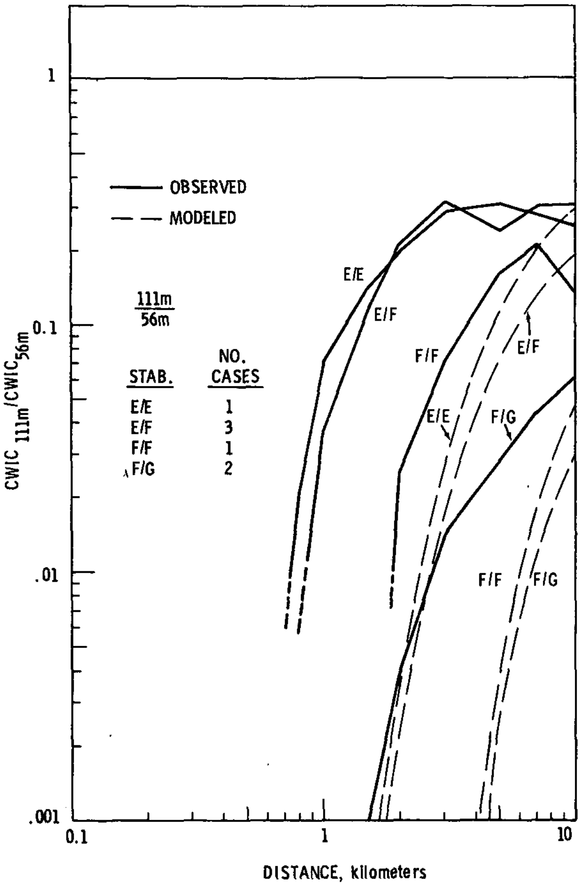

Fig. 6. As in Fig. 4 except for ratio at 111 m to that observed at 56 m.

5. Data and discussion

The substance of this paper is presented in Figs. 4, 5 and 6. The bold solid curves in these figures present observed ratios of CWIC resulting from simultaneous tracer releases from two elevations. The diffusion processes leading to these results may be simple or complex, but the curves reflect the result irrespective of the process. They offer guidance based on observation rather than theory and modeling.

Table 1 lists the 67-Series field experiments (with pertinent wind speed and thermal stability data) used in the source height effects investigation. Three com-

TABLE 1. Source height, wind speed and stability for dual releases.

	Upper level release				Lower level release			
Test no.	Height (m)	Wind speed (m s^{-1})	$\left(\frac{\Delta T}{\Delta Z}\right)^*$ [C° (100 m)$^{-1}$]	Stability	Height (m)	Wind speed (m s^{-1})	$\left(\frac{\Delta T}{\Delta Z}\right)^*$ [C° (100 m)$^{-1}$]	Stability
U64	26	5.3	9.9	G	2	1.6	9.9	G
U57	26	4.8	3.4	G	2	1.5	4.8	G
U60	26	4.0	4.2	G	2	1.2	4.2	G
U66	26	3.5	3.9	F	2	1.4	3.9	F
U56	26	4.3	3.7	F	2	1.8	3.7	F
U68	26	4.7	1.5	E	2	2.4	1.5	E
U65	26	5.5	1.5	E	2	3.0	1.5	E
U63	26	6.0	1.2	E	2	3.0	1.2	E
U59	26	3.4	1.1	E	2	1.9	1.1	E
U61	26	8.5	0.2	E	2	5.2	0.2	E
U70	26	7.8	0.0	E	2	4.8	0.0	E
U62	26	8.4	−0.7	D	2	5.4	−0.7	D
U83	56	6.6	8.0	G	26	5.2	8.4	G
U80	56	2.8	6.4	G	26	2.2	7.6	G
U82	56	4.6	5.6	G	26	4.7	7.6	G
U79	56	6.6	3.1	F	26	5.1	3.5	F
U74	56	6.2	2.3	F	26	4.6	2.6	F
U72	56	6.0	2.0	F	26	4.4	2.4	F
U81	56	7.0	1.8	F	26	5.7	1.9	F
U76	56	7.1	1.2	E	26	6.5	1.4	E
U73	56	6.5	1.2	E	26	5.5	1.2	E
U71	56	4.2	0.9	E	26	3.4	1.1	E
U77	56	3.7	0.2	E	26	3.6	0.4	E
U78	56	7.3	−0.54	D	26	6.5	−0.7	D
U88	111	6.4	2.8	F	56	7.6	5.2	G
U86	111	6.2	1.9	F	56	4.9	4.3	G
U92	111	5.4	1.6	F	56	4.7	2.5	F
U90	111	4.1	1.48	E	56	4.3	3.5	F
U89	111	3.6	1.4	E	56	3.0	3.5	F
U91	111	4.1	0.7	E	56	3.8	2.3	F
U85	111	9.7	1.1	E	56	8.2	1.1	E

* For $h=2$ m release, $\Delta Z=40-10$ m; for $h=26$ m, $\Delta Z=40-10$ m; for $h=56$ m, $\Delta Z=56-10$ m; and for $h=111$ m, $\Delta Z=111-10$ m (NRC Regulatory Guide 1.23).

binations of upper/lower release elevations were used: 26 m/2 m, 56 m/26 m and 111 m/56 m. In the 24 releases involved in the 26 m/2 m and 56 m/26 m pairings, stability classification based on NRC Regulatory Guide 1.23 resulted in the same stabilities for upper and lower releases. However, examination of stabilities in Table 1 for the 111 m/56 m pairings reveals a less stable specification for the upper level release in five of the seven pairings. (This fact necessitated the dual-stability labeling on Fig. 6. For instance, the label F/G indicates the 111 m release was into a class F layer, while the simultaneous 56 m release was into a class G layer).

The range of stabilities (D–G) observed during the 31 field experiments reflects the fact that all the experiments were carried out during night hours. No unstable data are present. Despite this restriction to stable atmospheres, the distribution of the 31 sets of data into three pairings of release height and four stability classifications for each pairing leaves relatively few experimental cases for input to each of the relationships depicted in Figs. 4–6. (The number of cases input to each curve is indicated on these figures.) Yet the curves stratify reasonably well into the order one would intuitively expect. The benefits from a taller stack increase with increasingly stable stratification.

Before proceeding with a more detailed examination of Figs. 4–6, it should be pointed out that irrespective of the model used or of the subsequent diffusion process postulated, the initial dilution of a release to the atmosphere is directly proportional to the wind speed at the release point. Thus, if releases are made from two elevations with a wind speed differential, but are presumed to diffuse in identical fashion, the limiting ratio of CWIC's (at distances far removed from the sources) is the inverse of the ratio of the initial wind speeds. At least in a modeled situation, the reduction of ground-level CWIC due to an increase in release height can be considered a result of two causes: 1) the increased diffusion between source height and ground level and 2) the initial dilution due to generally higher wind speeds at higher elevations (to be referred to as the "wind speed benefit").

The dashed curves in Figs. 4–6 are ratios resulting from the Gaussian model. The wind speeds used in developing these curves are the specific speeds observed during the field experiments. Since wind speeds (and hence modeled CWIC ratios) were not identical from experiment to experiment, an averaged modeled ratio is presented. This graphed average is the logarithmic mean of the ratios from the contributing experiments. At great distances these curves become asymptotic to the mean ratio of wind speeds observed at the lower and upper elevations—the "wind speed benefit."

Although detailed discussion of Figs. 4–6 is rather superfluous, a few comments are in order. An interpretive example may also prove helpful.

We first postulate a release from an elevation of 26 m into an atmosphere of class E stability. If the release were from 56 m instead, what would be the reduction in CWIC at 1 km from the source? The solid curve (observed) labeled E on Fig. 5 suggests the 56 m release height would result in a reduction of the CWIC at 1 km to about 30% of that resulting from the 26 m release. The dashed curve (modeled) implies a reduction to about 3%, a much different reduction than the observed data show. In fact, the observed ratios are much larger (and hence the increased stack benefits are smaller) than are the modeled ratios on all the paired release heights of Figs. 4, 5 and 6.

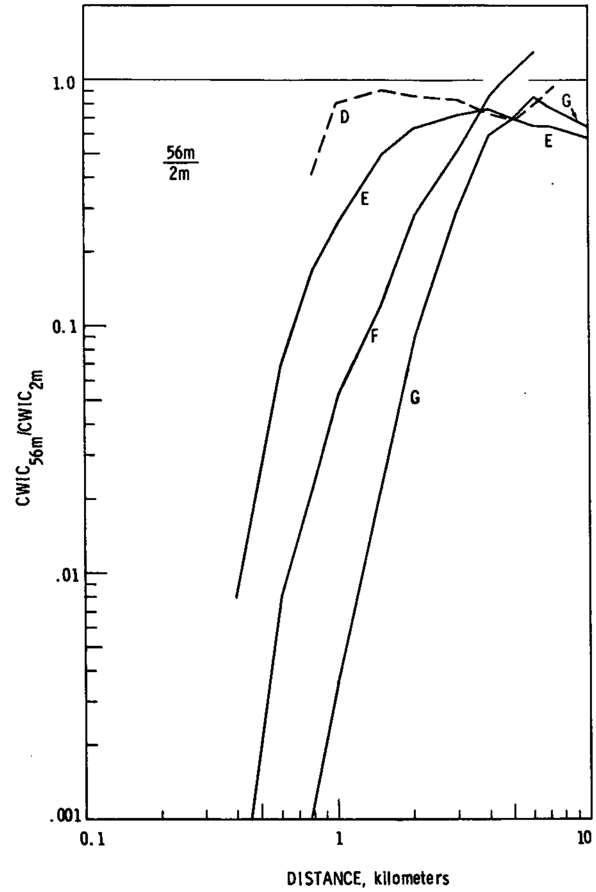

Fig. 7. Ratio of normalized CWIC at 56 m to that at 2 m deduced from observed ratios.

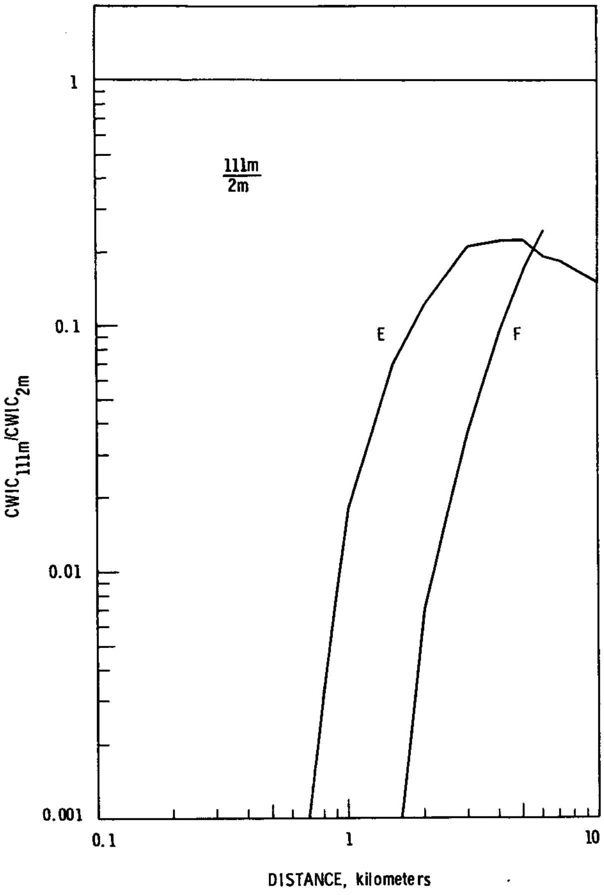

Fig. 8. As in Fig. 7 except for ratio at 111 m to that at 2 m deduced from observed ratios.

On Figs. 4 and 5, observed ratios are greater than 1.0 at several points. Although this result is likely due to uncertainties in the measurement/assessment process, at least one other possibility can be postulated. Since the plume released from a lower elevation interacted with the surface sooner than the upper plume, greater depletion of the lower plume particulates might have resulted in a boost of the ratio to a value greater than 1.0 at relatively large distances.

The limiting wind speed benefit resulting from the observed wind speed differential between the two levels, prescribes ratios that average roughly 0.75–0.90. At greater distances, the observed CWIC ratios from the 56 m/26 m pairings of Fig. 5 generally plateau at about this value. The ratios for the 26 m/2 m pairings of Fig. 4 tend to plateau nearer a ratio of unity, implying an absence of any wind speed benefit. Conversely, the observed 111 m/56 m pairings of Fig. 6 plateau at ratios considerably below 0.75–0.90, im-

TABLE 2. Ratio of maximum CWIC values irrespective of distance.

Stability category	Release heights (m)	Number of cases	Ratio of max CWIC's Log mean	± Standard error
D	56/26	1	1.00	—
E	56/26	4	0.60	0.45 -0.79
F	56/26	4	0.33	0.24 -0.44
G	56/26	2	0.22	0.11 -0.44
E/E	111/56	1	0.27	—
E/F	111/56	3	0.33	0.24 -0.47
F/F	111/56	1	0.23	—
F/G	111/56	2	0.032	0.006-0.16

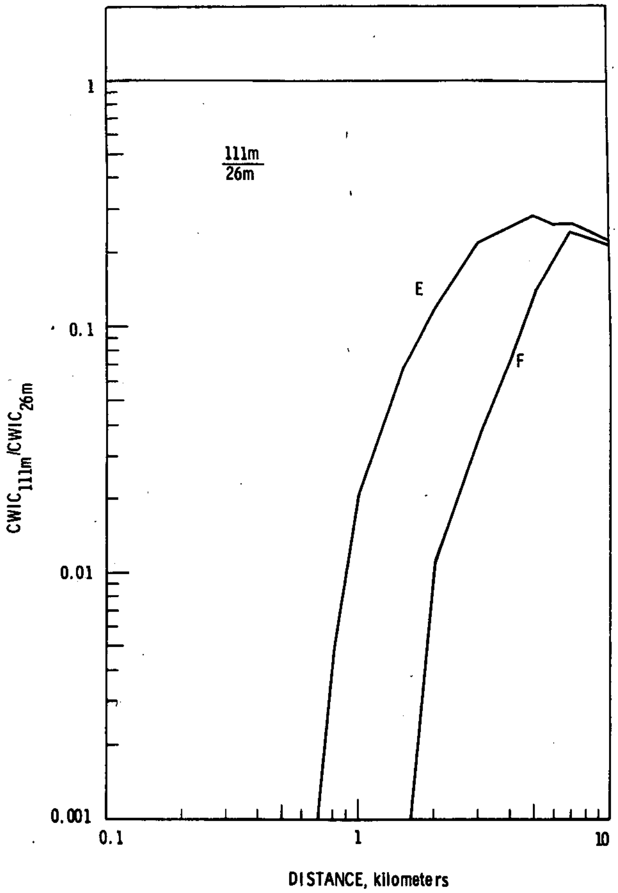

FIG. 9. As in Fig. 7 except for ratio at 111 m to that at 26 m deduced from observed ratios.

plying a limiting benefit greater than that derived solely from source height wind speed.

The de facto pairings of 26 m/2 m, 56 m/26 m and 111 m/56 m permit the computation of ratios for other pairings when common stability classes are involved. Ratios for these deduced pairings—based on the observed ratios—are presented in Figs. 7–9. Since the Fig. 7–9 curves are only indirectly based on field measurements, they are presented with less confidence than the curves of Figs. 4–6.

Figs. 4–9 present ratios of concentration as a function of distance. Since, during a dual-release-height experiment, maximum CWIC's are not encountered at the same distance, the Fig. 4–9 ratios do not indicate the ratios of maximum observed concentrations.

Such ratios are obtainable from the field measurements. For example, Fig. 3 shows that the maximum CWIC from the 56 m release (7×10^{-4} s m^{-2} at a distance of 1.6 km) is about one-quarter of the maximum CWIC from the 26 m release (3×10^{-3} s m^{-2} at 0.8 km). Table 2 lists the logarithmic means and standard error ranges of the maximum ground-level CWIC values by stability category and by release height pairings. (No data are presented for ground level releases since the maximum CWIC would be at the source.) With the exception of the single stability E/E case with the 111 m/56 m pairing, the trend of the data is as might be anticipated. Benefits increase with increasing stability and the benefit of increasing stack height from 56 m to 111 m exceed the benefits derived from increasing from 26 m to 56 m. Note that under the most stable observed conditions, an increase in release height from 26 m to 56 m reduced absolute maximum CWIC to 22% of the 26 m value. Similarly, a release height increase from 56 m to 111 m under very stable conditions was accompanied by a reduction of the absolute maximum CWIC to 3% of the value observed with the lower level release.

The distance to maximum CWIC can also be gleaned from the graphics exemplified by Figs. 2 and 3. Distance to maximum CWIC for the three elevated release

TABLE 3. Distance to maximum CWIC

	Release height								
	26 m			56 m			111 m		
Stability category	Number of cases	Mean (m)	Standard error (m)	Number of cases	Mean (m)	Standard error (m)	Number of cases	Mean (m)	Standard error (m)
D	1	400	—	1	720	—	0	—	—
E	3	1100	230	4	1900	250	4	3800	1500
F	4	1000	390	8	2900	1900	3	10 300	4200
G	2	1200	350	4	2100	870	0	—	—

heights is given in Table 3. The data do not stratify quite as nicely as did the associated CWIC (max) ratios, but do display in general the expected increase in distance with increasing stability. These observed distances are generally smaller than those Turner graphically presented for plume maximum ground level concentration distances. However, Turner's (1970, p. 29) graphics deal with plume centerline exposure, and are based on data generated over smoother terrain than the Hanford terrain ($z_0 \approx 1$ cm vs $z_0 \approx 3$ cm).

The effects of increased source height presented here are net effects observed for the particulate tracers zinc sulfide and fluorescein over relatively flat terrain. An effort was made to eliminate differences in observed concentrations due to differences in the aerodynamic properties of these specific particulates. Strictly speaking, the ratios apply only to a tracer with properties similar to the two used. For instance, such processes as deposition, gravitational settling or chemical transformations during transport may have uniquely influenced the results presented. However, the tracers employed are relatively small particulates and appear to be chemically stable in the mode they were employed. More detail on the physical characteristics of these tracers is given in the Hanford 67-Series data volume.

6. Conclusions

Figs. 4–9 present field-measurement ratios of normalized crosswind-integrated concentration resulting from simultaneous release of tracers from two elevations. To a distance of 10 km, these ratios are higher (implying lower benefits from increased stack height) than are ratios based on a Gaussian plume model with atmospheric stabilities as prescribed in NRC Regulatory Guide 1.23.

At distances relatively far from the source, the benefits in reduced concentration resulting from increasing source height from 26 m to 56 m plateau at approximately the ratio of wind speeds at the 26 and 56 m levels. Benefits accruing as a result of increasing from 56 m to 111 m exceed the source height wind speed ratio at all distances. Conversely, benefits for an increase from 2 m to 26 m are lacking at distances beyond ~4 km.

Under very stable conditions, the observed value of the ground-level maximum CWIC (irrespective of distance from source) was reduced by a factor of about 5 by increasing source height from 26 m to 56 m, and was reduced by a factor of more than 30 by increasing source height from 56 m to 111 m.

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