CHARACTERISTICS OF MIXING AND THE DILUTION OF WASTE STACK GASES IN THE ATMOSPHERE

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A study has been made to determine the general characteristics of mixing and the amount of dilution that waste stack gases would experience when discharged into the atmosphere. It was assumed that such was dependent upon the meteorological conditions. Hence, for the experimental work, a 16 inch stack, 200 ft. high, was erected through which, by means of blowers, the whole discharge of an Army M-1 "smoke" (oil-fog) generator was ejected into the air. The stack was provided with 1-½ inch outlets at each 50 ft. interval (up to 150 ft.) through which came enough smoke to act as tracers for air flow at the various altitudes. These jet pipes extended outward 3 feet from the stack; from each jet and at 200 feet a shielded thermo-couple was suspended and connected to a precision potentiometer in the nearby office building. Recording anemometers were placed at 16 and 60 feet and a recording anemometer and wind vane at 200 feet. This instrumental arrangement provided data on the lapse rate, the wind velocity, the change of wind velocity and the wind direction of the stack top.

To determine the amount of dilution, sulphur dioxide was mixed with the oil-fog (which served as a tracer) and attempts were made to collect field samples of the amount of SO_2 present when the

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oil-fog came to the ground. However, [illegible] the relatively long period of time required to obtain a sample, approximately 20 minutes, and the short duration of oil-fog at any given spot on the ground, this method was promptly discarded. In its place a photoelectric instrument was designed and built. The instrument was based on the principle of exposure of a photoelectric cell to a light of fixed intensity between which was drawn the diluted oil-fog; any change of the light intensity caused by oil-fog droplets would vary the current output of the photoelectric cell. The "photoelectric vapor densitometer" was extremely sensitive, rapid in action, and quite rugged. It was mounted in a truck capable of going over any type of terrain. The air with the diluted oil-fog was drawn continuously through the instrument by suction from the wind shield wiper. The same type of instrument was used to determine the dilution when the oil-fog did not come to the ground except that the suction was produced by an aspirator device which operated when there was wind. The instrument and wires to the indicating meter on the ground were supported by a small barrage balloon.

The smoke generator produced a dense white cloud of condensed oil particles about 0.3 micron in diameter. The droplets were very stable. There terminal velocity of the falling droplets was about 0.2 inches - hour. After passing through the blowers and 10 feet of the stack, the temperature of the oil-fog was near 135° F. No observations were made of its temperature at the top of the stack because there would be only a minor temperature difference between the atmosphere and the oil-fog; essentially, the oil-fog may be considered as "cold" smoke with a negligible [illegible] to its temperature.

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Each day, or more often, the "densitometer" was calibrated by drawing from the stack a known volume of oil-fog, mixing it with known volume of air, and then forcing this mixture through the instrument. Several different concentrations of mixture would be used each time the instrument was calibrated. The instrument would measure concentrations as low as 1/50,000 th of that in the stack.

It was assumed that the oil-fog would follow directly, without appreciable lag, any and all air movements in the area occupied by the oil-fog, that the presence of the oil-fog would not materially affect the air movement in any direction, and, finally, that the dilution of the oil-fog would represent within reasonable limits of accuracy the dilution of gaseous or minute solid particles emitted from a stack under similar meteorological conditions. Our experience leads us to believe that the oil-fog fulfilled these assumptions to a high degree of fidelity.

Character of mixing

The visual train of oil-fog, as the wind flows by the point of emission, has shown three clearly defined types of mixing, these types being dependent on certain meteorological conditions. These three types have been called "looping". "coning" and "fanning", which occur under lapse rates showing unstable, approximately neutral (with wind) and stable conditions, respectively.

"Looping" is defined as the condition which occurs when the oil-fog alternately ascends and descends after leaving the stack. When it comes to the ground, the oil-fog will remain in contact with the ground for a minute or two as it travels with the wind and then ascend only to repeat this same procedure again some

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distance downwind. The oil-fog forms rough vertical columns downwind. "Looping" occurs when the wind velocity is approximately the same at 16, 60 and 200 feet but is not in excess of 20 mph. The lapse rate invariably is superadiabatic; there is no doubt that the vertical currents which produce the ascent and descent of the oil-fog are of thermal origin. The oil-fog demonstrated that the descending currents were of greater time duration than the ascending currents because downwind the profile of the trail showed the vertically rising columns were of smaller dimensions than the spaces between them. The height to which mixing may occur is definitely restricted to that layer in which there is negative stability.

Numerous observations on the rate of descent of the oil-fog were made. These gave an average rate of slightly more than 4 feet per second in the summer through the rate varied from zero to more than 7 feet per second. In winter the average was fractionally less than 3 feet per second. Assuming a downward velocity of 4.2 feet per second, segments of the oil-fog trail would first contact the ground 80 feet from the stack with a horizontal wind velocity of one mile per hour, 390 feet from the stack with a 5 m.p.h. wind, 775 feet away with a 10 m.p.h. wind, and 1170 feet distant with a 15 m.p.h. wind. The above distances are computed for smoke which "levels off" 225 feet above the ground. Considering the same downward velocity and a leveling off at 400 feet above the surface, the smoke or waste stack gases would first reach the ground 140 feet, 700, 1380, and 2080 feet from the stack for horizontal wind velocities of 1, 5, 10, and 15 m.p.h, respectively.

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When vertical currents are prominent, the oil-fog not only "loops" within a fairly wide angled cone vertically (interessected by the ground), but also the trail swings through a wide angle horizontally. We have found that when the wind is between 1 and 3, or even 4 mph the arc through which the trail may swing will be close to 360°. The stronger the wind, the narrower the angle through which the smoke will swing and the longer a point downwind will be in or beneath the trail.

"Coning" is defined as the condition which occurs during periods of near neutral stability and wind velocities of 20 mph or more. However, if a well developed inversion had formed, or a pronounced superadiabatic lapse rate was established prior to an increase of velocity, it required a wind of 22 to 25 mph to produce "coning". If the above conditions are satisfied the trail then assumes the shape of a narrow cone the axis of which appears, when viewed on the profile, to be inclined at a small angle toward the ground downwind. This angle is so small that, coupled with the gradual widening of the trail, the first fringes of oil-fog do not reach the ground within 1600 to 2000 feet of a 200 foot stack. The upper boundary of the trail at that distance from the stack was still estimated to be no higher than the stack top.

Not only does the trail widen slowly downwind, but also it swings through a much smaller angle than when "looping" is in progress. For a wind between 22 and 25 mph, this arc was slightly more than 90°, though this value was doubtlessly caused by turbulence set up by a large building just upwind from the stack. Later records show the arc of swing to be in the neighborhood of 30° to 40° with an undisturbed flow.

Segments of the oil-fog trail indicate that the air flow is comprised of eddies whose axes are in a horizontal plane where the upper portion (highest from the ground) has the highest velocity and the lower portion is retarded by friction, This evidence points to mechanical eddies whose character is in striking contrast to those termally produced and maintained.

"Fanning" is defined as the condition that occurs when the trail gradually widens in a horizontal plane and remains in a vertically thin layer. This flow develops when the degree of stability is $+10{:}10^{-6}$/ft. (where the degree of stability, $E = \frac{1}{\theta}\frac{d\theta}{dz}$ and the wind velocity is less than 16 mph). This critical value is represented by an isothermal lapse rate. When this positive stability value is reached, the trail begins to widen in a fairly uniform sheet after the turbulence initiated in the stack has been smoothed out. The uniformity of this sheet isin striking contrast to the lack of uniformity of the trail when "looping" is occurring. The trail, under stable conditions, remains in the layer of air at the altitude into which it was ejected, and it will flow along distance over level ground in this condition before any comes to the ground. The sheet increases in vertical thickness downwind at so slow a rate that rarely does it reach the ground (over level country) within 5 to 10 miles of the stack.

The spread downwind seems intimately related to the degree of positive stability; i,e., the greater the positive stability, the wider the angle of spread. This is especially true when the stability is greater than $+40{:}10^{-6}$/ft. Normally, with an inversion and nearly laminar flow, the wind velocity increased sharply (proceeding upward) and the layers move progressively to the right. Occasionally the profile will reverse, but this is only a temporary condition. Recording wind vanes of high precision were not available at this phase of the research, but the "jets" and character of the main trail showed

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that the lateral spread is definitely related to the vertical rate of change of wind direction within the cloud layer.

Horizontal spread occurs with any wind velocity from 1 mph to as fast as the wind blows provided that the stability remains more than the critical value of $+10.10^{-6}$/ft. (10 x 10⁻⁶) At night after the stability has become more than $+30.10^{-5}$ to as much as $+70.10^{-6}$/ft, it was found that a wind increase to 25 mph was unable to reduce the stability below $+20.10^{-6}$/ft. ~~(20 x 10⁻⁶/ft)~~

When "fanning" is in progress, the vertical cross section of the trail is such that the left hand boundary, facing downwind, is ragged, diffuse, and at a slightly lower altitude than the right hand boundary which is rounded and clearly defined.

The change from "fanning" to "looping" begins when there is a change from a stable to an unstable lapse rate. The time required for the trail to change from fanning to looping is a matter of only a few minutes at most because it is necessary to increase the vertical height of the layer of unstable air by only the vertical thickness of the trail. There is a large amount of literature available to show that in the morning the adiabatic or superadiabatic rate, the latter more often and of longer duration than the former, forms first in the lowest layer and progressively builds upward; the "jets" also showed this to be true since the smoke from the lowest "jet" would "loop" while the oil-fog from those jets above would be "fanning". Successively, the oil-fog from the jets above would begin to loop indicating the lapse rate had become unstable to that altitude. Finally, the main body of smoke issuing from the stack top would begin to "loop". The thermocouples showed that the lapse rate was unstable within the layer in which "looping" occurred. Occasionally, before the lapse rate became adiabatic or superadiabatic to the bottom of the main trail.,

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a "thermal" would pierce some distance into the inversion and the compensating down draft would bring a single cloud of oil-fog to the ground. This was the first indication that within the next half hour or less, oil-fog would come to the ground consistently, albeit intermittently. The thermocouples showed repeatedly that at this time the lapse rate was unstable to within 50 ft. of the level of the trail.

As the vertical height of the unstable layer increases, so grows the thickness of the layer through which "looping" functions.

The time of day when the change from stable to unstable conditions occurs has been observed daily for nearly two years. In the period from April to mid-September, the time required after sunrise for an unstable condition to develop to an altitude of 200 feet was from 1 to 1.5 hours for a clear or partly cloudy sky, from 1.5 to 2 hours with low broken clouds or a high thin overcast and from 2 to 3 hours with a low overcast or other conditions obscuring the sun. In winter the corresponding time intervals are about one hour longer.

The change from "looping" to fanning appears to be simpler than the reverse. Positive stability first develops in the layer next to the ground where the air cools most rapidly. As soon as a positive stability of 10.10^{-6}/ft. is reached, no more oil-fog come to the ground. "Looping" continues to occur above 50 feet, but the amplitude of vertical movement is greatly reduced. Cooling progresses in all layers after the maximum for the day is attained, but the higher layers cool less than the lower layers. As time increases there is a tendency toward less instability and, thus, less convection. As positive stability builds upward, the waste stack gases are confined to thinner and thinner layer and "fanning" finally begins. [redacted]

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There is an intermediate stage between "fanning" and "looping" which occurs when the stability is between zero and +10.10^{-6}/ft., with a wind of less than 16 to 20 mph; Under these conditions the oil-fog will come to the ground rarely, more often as the lapse rate approaches the dry rate and less often as the positive stability increases.

Dilution*

During a period of nearly six months a total of more than 40,000 individual samples were taken from clouds of oil-fog which covered dilution over a wide range of stability, wind velocity, and wind direction. About 36,000 readings were made at the ground most of them under "looping conditions; a small number was procured when "coning" was in progress. The remaining 4,000 reading were obtained when the oil-fog trail was "fanning".

The dilution values observed in the field under unstable to neutral stability were compared to the values of the number of observed meteorological elements including the horizontal velocity individually at the three levels, 16, 60 and 200 ft, the vertical velocity gradient, soil minus air temperature (4 ft.) the lapse rate from 4 to 200 ft., and the wind direction at 200 ft.

Unstable Conditions: Visual observations of the oil-fog trail and instrumental measurement of the various meteorlogical elements below the stack top produced the following general conclusions:

1. The dilution of the oil-fog is more rapid in unstable air than in stable air.
2. The vertical currents do not occur in any regular cycle; there is a rough alteration of descending and ascending air currents.

* The dilution figure as used in this paper is the number of volumes of air per unit volume of oil-fog of its concentration in the stack, or a dilution figure of 500 means that the concentration of the oil-fog at a point is 1/500 if that in that stack.

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3. The length of time at which the oil-fog will remain in contact with the ground varies considerably. The cloud may strike the ground and travel along for several minutes and then ascend; or it may come near the ground and then ascend after a few seconds; or, it may ascend from the stack, travel a few hundred yards and then suddenly descend to the ground.
   Of these patterns there are an infinite number of variations. However, it was found that a cloud at the ground usually passed a given spot in less than two minutes. Owing to convection currents of great intensity and eddies whose axes could be in any plane, the flow pattern of the oil-fog was of a random and irregular nature. This made representative smoke samples difficult to collect and resulted in a low degree of statistical correlation between the amount of dilution and the various meteorological elements.
4. In unstable air the upward currents appeared to be smaller than the compensating downward currents.
5. When the wind velocity is less than 10 mph, the horizontal arc through which the smoke swings is large. Thus a given point within the arc of swing will be exposed to the oil-fog but a small fraction of the time.

Between 5 percent and 10 percent of the sampled clouds or segments of the trail that reached the ground was subjected to statistical analysis. Simple and partial correlation co-efficients with a portion of a report is as follows:

Variable	Correlation Simple	Correlation Partial
Y1 VS X1	-0.1477*	-0.1562*
Y1 VS X2	-0.5095*	-0.4562*
Y1 VS X3	-0.0592	-0.0051
Y1 VS X4	-0.0370	-0.0262
Y1 Vs X5	-0.2767*	-0.0073
Y2 VS X1	-0.2048	-0.1814*
Y2 VS X2	-0.2298	-0.1020
Y2 VS X3	-0.0251 [redacted]	-0.0897
Y2 VS X4	-0.0738	-0.0444
Y2 VS X5	-0.2708	-0.1076*

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Where

Y1 - Lea st dilution

X1 - Stability

X2 - Wind Vel. at 60 ft.
X3 - Wind Vel, at 200 ft.
X4 - Soil-air temp. F°
X5 - Distance from stack, ft.
Y2 - Average dilution

Of these coefficiants only those marded(*) are of any statistical signifigance; however, in view of the large number of observations the degree of correlation is very low. Such also led to the general conclusion that the fraction of observed variation in dilution attributable to the observed conditions were not usable high.

In addition, the data were subjected to a scatter diagram analysis to see if there were any tendencies, or lack of such that might be useful.

Scattergrams were made of:

1. Least dilution observed vs distance os smaple point from the stack.
2. Least dilution observed vs. 60 ft. wind velocity.
3; " " " " groups of wind velocity at 200 ft.
4. " " " " " " " " at 200 ft.-60 ft.
5. " " " " " " " " at 200 ft.-sfc.
6. " " " " stability by groups of wind velocity at 200 ft.

7. Average dilution vs distance from stack.

8. Average dilution vs distance from the stack by various quadrants.

9. Average dilution vs wind velocity at 200 ft.

Using all of the data available, we have found no significant help from numbers 2,4,5, and 8; of some help wer 3 and 9. and of greater value were land 7. The best relationships were found with number 6, especially when used with the table of least dilution vs distance from the stack.

There is some possibility that we have not observed the least dilution that could occur, but from the large number of clouds investe-gated, the probability of still lower dilutions is quiet small exeept in the 6-8 mph range where a smaller dilution is likely.

When the least dilution of all clouds is plotted as the ordinate and the stability as the obscissa, for each wind group 0 -2, 3-5, 6-8, 9-11, 12-15, 16-20, 21-25, and more than 25 mph, the absolute least observed dilution is observed with a wind between 3 and 5 mph which is a velocity about equal to the average vertical velocity of the down drafts.

The absolute least dilution which occurred at various wind velocities and the lapse rate at that dilution value are given below:

Table I

Wind Velocity	0-2	3-5	6-8	9-11	12-15	16-20	21-25	25
T 200'-T4' °F	- 2.5°	-4.0°	-5.0°	-5.7°	-3.5°	-4.5°	-2.0°	-3.0°
Least Dil Obs	270	210	480	300	450	1050	1400	1250 (?)

Table II shows the frequency distribution of the number of separate clouds with dilutions less than 600;1 and less than 1000;1. Note that nearly 75% of the lowest dilutions occurred when the wind velocity was less than 6 mph.

Table II

MPH	Max 600 Dils No. of Clouds	1000 Dils No. of Clouds
0-2	19	32
3-5	15	48
6-8	5	31
9-11	5	17
12-15	2	9
16-20	0	0
21-25	0	0
[illegible]	0	0

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We have made little attempt at computing the average dilution of the cloud segments because normally the dilution ranges from infinity to a minimum value and back to infinity in an irregular manner along a longitudinal section. We do find that the average dilutions are approximately 2000 at 450 ft., 4000 at 900 ft., and more than 10,000 beyond 1700 ft.

Stable conditions: When the oil-fog remained aloft the pattern of mixing was entirely different from that under an unstable or neutral lapse rate. Under light and moderate wind velocities and with a ground inversion, the smoke remained at approximately the stack height, or slightly higher and the trail took on the shape of a gradually widening ribbon that continued for great distances downwind. Owing to the characteristics of the "fanning" trail we find that :

1. The dilution is much less per unit distance downwind than during "looping"or "coning" conditions.

2. The amount of dilution should then be dependent on the degree of positive stability.

3. The dilution appears to be unaffected by the wind velocity at the stack top. However, the less the wind velocity, the steeper the inversion that can occur. The critical wind velocity which would prevent an inversion from forming was from 16 to 20 mph, but with an existing nocturnal inversion, a 22 to 25 mph wind was necessary to reduce the stability to $+10.10^{-6}$/ft/

4. The dilution within the trail is much more uniform than when the trail is "looping".

Correlation coefficients for selected clouds from a total of 164 sets of readings from the trail aloft with simultaneous meteorological data have been computed. The results with a part of the report flooows;

Variables	Coefficient (Correlation)r.
Y vs X1	-0.1157
Y vs X2	0.0240
Y vs X3	0;03717
Y vs $(X3)^2$	0.6828

Where X1 is the stability
X2 is wind velocity, mph
X3 is stack distance, feet
Y is least dilution

There is a well established correlation between the least observed dilution in the cloud and the square of the distance from the stack to the point of observation. No significant correlations were found between the least dilution and the wind velocity of stability. It was therefore concluded that of the independent variables studied, only the stack distance influenced the least dilution measurably. The relationship is expressed by the equation $Y = a + b (X_3)^2 = 1500 + 0.0001 (X_3)^2$ with a standard error estimate of 1547.

The above is in reference to the least dilution that may be momentarily encountered within the trail downwind at a distnace great engouh so that the turbulence set up in the oil-fog in the stack has been smoothed out. This distance was estimated to be between 500 and 1000 ft. All the observations made under stable conditions were from 2500 to 7300 ft. from the stack.

When the least dilution is plotted against (1) stability, (2) wind velocity, and (3) distance from the stack it was found that at a constant distance the dilution decreased with increasing stability till a value of about $+ 40.10^{-6}$/ft, was attained and thenthe dilution increased. See table below.

Table II Distance from stack-2800ft.

Stability 10-5/ft.	-4	+16	+39	+50	+70
Least Dilution	1200	800	380	550	1300

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When the least dilutions are plotted against distance regardless of stability and wind velocity, the absolute least dilution follows closely the equation below over the distance range of 3,000' to 7,300' from the stack.

$$Ya = a + b x$$

Where a = 400, b = 0.47, Ya = absolute least dilution and X = distance from the stack -3,000 ft.

From 159 individual clouds investigated the average least dilution over the above distance range increased at the rate of 1 per ft. and follows the equation:

$$Ye = a + b x$$

Where a = 2400, b = 1,0, Ye = average least dilution, and X = stack distance -3000 ft.

There appears to be no definite relation between wind velocity and dilution except as the velocity affects the stability.

Using the average, of the mean dilutions of the individual clouds, or average of each 40 successive readings if the cloud yielded more than that number of reading, and plotting these dilutions against stack distance only, the dilution increases with distance according to

$$\log Ym = \frac{\log X - 1}{0.7}$$

Where Ym = average dilution and X = stack distance ft.

The average dilution at various stack distances is given below in tabular form and is extrapolated for distances less than 3000 ft.

Table III

Stack Distance	1000'	2000'	3000'	4000'	5000'	6000'	7000'
Average Dil.	700	1900	3500	5400	7500	9700	21600

Figs. I and 2 show the seasonal variation in the frequency distribution of dilution factors 500:1 and 1000:1. The salient features are as follows:

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1. There is a large diurnal variation in the occurance of the various factors.

2. There is a low frequency rate of factors 1000;1 (and 500;1) after sunset and before sunrise.

3. A regular variation occurs in the duration of the "factor free" period which changes as the lenght of daylight hours increase or decrease.

4. The occurance of factors 1000:1 or 500:1 during hours of darkness reaches a maximum in the rainy winter season.

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