The Los Angeles Smog Problem

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The smog of Los Angeles is unique in that it sometimes produces severe and disagreeable eye irritation. In common with the smog in other parts of the country, however, it also imparts a murkiness to the atmosphere. Eye irritation is severe on some twenty occasions during a year, and then in only limited areas and for relatively brief periods of time. Reduced visibility in connection with smog occurs very much more frequently. The peculiar meteorology of the Los Angeles area appears to be decisive in controlling the time and duration of eye-irritating smog. Studies of meteorological influences have revealed an empirical correlation between certain meteorological factors and the time of occurrence of eye irritation from smog. This correlation gives promise of being useful as a means of forecasting such smog. The nature of the substances in smog that cause the eye irritation is not yet known. Work on this problem is currently progressing by the invention of improved ways to collect and identify the particles that compose smog, and by determining, under laboratory conditions, the eye-irritating properties of these substances in various aerosol forms in a specially built "smog chamber."

OF ALL the industrial cities in the United States, why is Los Angeles so peculiarly a victim of smog—that unhappy combination of atmospheric pollutants which produces eye irritation and reduced visibility?

In order to answer this question and to find out what smog is and where it comes from, the Stanford Research Institute is conducting an extensive research on the subject for the Committee on Smoke and Fumes of the Western Oil and Gas Association.

"Smog" is a term made up by combining parts of the two words "smoke" and "fog." Properly applied to the Los Angeles County region, it denotes an abnormal weather condition in which man-made contaminants in the air mingle with haze or fog to produce a dense smoky atmosphere. It results in a sharp reduction in visibility, and causes irritation of the eyes and sometimes of the nose and throat. It is the eye-irritating aspect of smog about which people complain the most bitterly, and the results presented in this paper refer principally to an investigation of the causes of eye irritation. The murkiness of the atmosphere and the poor visibility encountered are not to be discounted and are being actively investigated; the results of this study will be reported in a later paper.

Unpleasant odors are also sometimes associated in public complaints with smoggy weather conditions, but they almost invariably arise from local, easily identifiable sources and are not genuinely connected with the more general and characteristic aspects of smog.

FREQUENCY OF SMOG OCCURRENCE

Smog of the type which irritates the eyes is severe in the Los Angeles basin 10 or 20 times a year, in attacks lasting 4 hours or less and occurring most frequently in the late morning hours of the summer and autumn months. It seldom occurs during stormy or cloudy weather.

Although severe smog is not common, threshold smog conditions (or conditions approaching smog) occur with much greater frequency. During threshold days a certain percentage of people find that their eyes are irritated, and measurements show the number of times they must blink is greater than normal.

On threshold days and severe smog days alike the eye irritation effects are likely to be fairly local. On the worst days recorded at least 85% of the people in the Los Angeles region, depending on location, consciously noticed smog effects (see Table I).

HISTORY OF SMOG DISTURBANCES

There are no written records, prepared by trained observers, concerning the eye-irritating effect of smog in past years. People who have lived in the Los Angeles County area for many years state positively that smog is not new; reports of its presence date as far back as 1912. However, the consensus is that the frequency of smog and the severity of its eye-irritating effects have increased markedly during recent years.

The same period of time has witnessed a remarkable growth in the population and industrialization of Los Angeles County. It seems logical to seek an explanation for the increased frequency and intensity of smog in the increased quantities of man-made contaminants exhausted into the air as a result of this growth.

Other industrialized cities also have their air-pollution problems; those of Pittsburgh and St. Louis are notorious. There have been isolated instances of air contamination sufficient to cause eye irritation in New York, Chicago, Paris, and Rome, but in these cities it is a rare occurrence. Frequent and powerfully eye-irritating smog appears to be peculiar to the Los Angeles area.

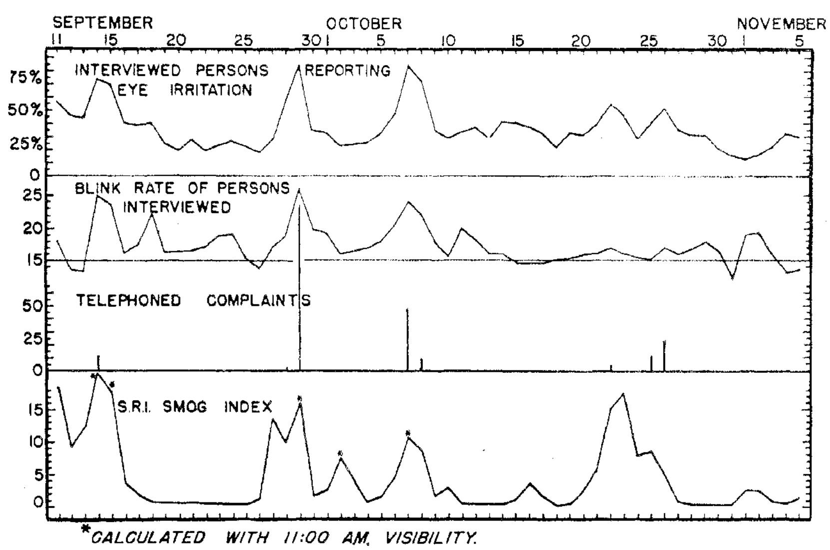

Figure 1. Public Reaction to Smog

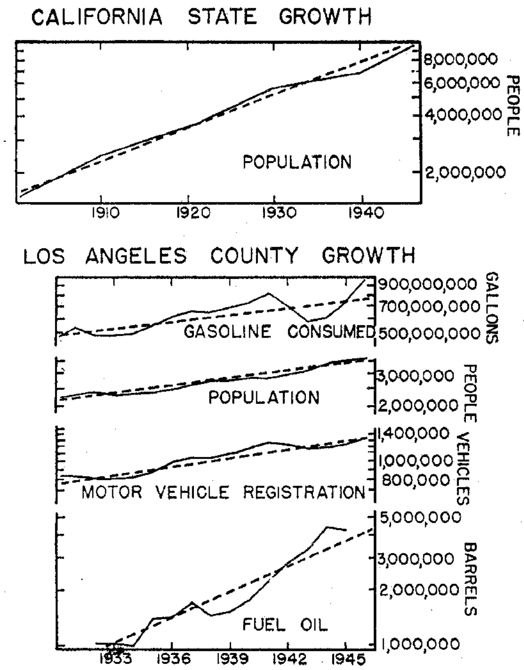

Figure 2. Growth of California and Los Angeles County

PRELIMINARY CONSIDERATIONS

In order to clear the ground for research into the mechanism of the smog and the properties of the contaminants it contains, investigations were made of two preliminary considerations:

The relationship between smog as indicated by human experience and smog as associated with a certain set of meteorological conditions.

The possibility that the climate of Los Angeles County may have undergone some change, resulting from increased population or other causes, exclusive of the increase in man-made contamination of the atmosphere.

Public Reaction to Eye Irritation. Although complaints of smog have been numerous, no very exact correlation of public complaints of smog had been made prior to this investigation. Accordingly, a study of public reaction to smog was conducted for the Stanford Research Institute by the American Research Service, Los Angeles.

Interviewers questioned approximately 15,000 pedestrians in downtown Los Angeles, Pasadena, and Glendale during the morning and afternoon hours.

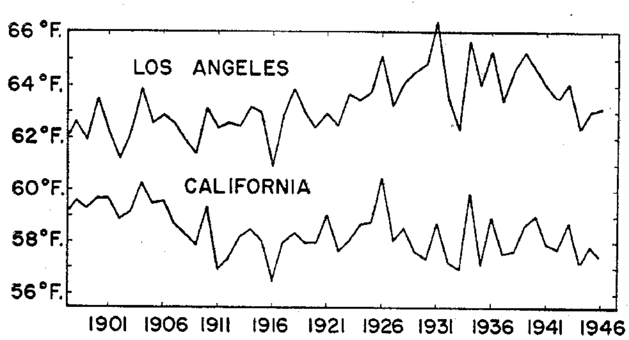

Figure 3. Annual Mean Temperatures

Population figures for the City of Los Angeles for the same period are: 102,479 in 1900; 319,198 in 1910; 576,673 in 1920; 1,238,048 in 1930; and 1,504,277 in 1940. The metropolitan district of Los Angeles had 2,318,526 people in 1930 and 2,904,596 people in 1940

Table I. Number of Persons Reporting Eye Irritation

(September, October, November 1948)

Day and Date		% of All Persons Interviewed Who Complained of Eye Irritation: Los Angeles	Glendale	Pasadena	No. of Blinks per Minute, All Persons: Los Angeles	Glendale	Pasadena
Sat.	Sept. 11	57.2	..	..	17.3	..	..
Sun.	Sept. 12	45.7	..	..	13.4	..	..
Mon.	Sept. 13	43.9	..	..	13.4	..	..
Tues.	Sept. 14	74.7	..	..	25.0	..	..
Wed.	Sept. 15	69.4	..	..	23.3	..	..
Thurs.	Sept. 16	41.3	..	..	16.6	..	..
Fri.	Sept. 17	38.4	..	..	17.3	..	..
Sat.	Sept. 18	40.3	..	..	22.0	..	..
Sun.	Sept. 19	25.4	..	..	16.3	..	..
Mon.	Sept. 20	20.0	..	..	16.9	..	..
Tues.	Sept. 21	27.6	..	..	16.7	..	..
Wed.	Sept. 22	20.3	..	..	17.1	..	..
Thurs.	Sept. 23	24.3	..	..	19.3	..	..
Fri.	Sept. 24	26.4	..	..	18.8	..	..
Sat.	Sept. 25	23.1	..	..	15.5	..	..
Sun.	Sept. 26	18.2	..	..	13.7	..	..
Mon.	Sept. 27	30.0	..	..	17.0	..	..
Tues.	Sept. 28	60.0	..	..	18.6	..	..
Wed.	Sept. 29	85.2	..	..	25.8	..	..
Thurs.	Sept. 30	35.4	..	..	19.6	..	..
Fri.	Oct. 1	32.4	..	..	19.3	..	..
Sat.	Oct. 2	23.1	..	..	16.3	..	..
Sun.	Oct. 3	No interviews made			No interviews made		
Mon.	Oct. 4	26.1	..	..	17.1	..	..
Tues.	Oct. 5	33.1	..	..	18.2	..	..
Wed.	Oct. 6	47.2	..	..	20.4	..	..
Thurs.	Oct. 7	84.1	..	..	23.5	..	..
Fri.	Oct. 8	71.7	..	..	22.0	..	..
Sat.	Oct. 9	33.9	..	..	17.4	..	..
Sun.	Oct. 10	29.4	..	..	15.5	..	..
Mon.	Oct. 11	34.1	..	..	19.0	..	..
Tues.	Oct. 12	36.4	..	..	17.3	..	..
Wed.	Oct. 13	28.4	..	..	15.9	..	..
Thurs.	Oct. 14	41.3	..	..	16.1	..	..
Fri.	Oct. 15	39.9	..	..	14.4	..	..
Sat.	Oct. 16	36.6	47.3	34.6	14.4	18.4	13.3
Sun.	Oct. 17	31.4	18.2	27.6	14.5	15.7	12.7
Mon.	Oct. 18	22.3	14.3	17.3	15.0	14.5	14.2
Tues.	Oct. 19	34.3	15.0	17.4	15.5	15.4	10.9
Wed.	Oct. 20	30.4	20.9	28.8	16.4	17.4	14.4
Thurs.	Oct. 21	38.5	36.4	26.7	16.1	19.2	13.0
Fri.	Oct. 22	54.5	28.8	29.9	17.0	15.5	15.2
Sat.	Oct. 23	46.1	25.5	34.0	16.9	19.8	18.0
Sun.	Oct. 24	28.8	4.3	22.4	15.5	18.6	17.7
Mon.	Oct. 25	40.8	45.8	29.8	15.0	23.8	17.5
Tues.	Oct. 26	50.8	49.0	45.4	17.2	23.4	19.0
Wed.	Oct. 27	35.7	25.5	39.6	16.1	20.9	15.5
Thurs.	Oct. 28	31.8	30.6	21.4	17.4	21.7	15.2
Fri.	Oct. 29	31.2	24.6	32.6	18.2	21.0	16.1
Sat.	Oct. 30	21.0	16.8	14.8	16.5	19.5	19.4
Sun.	Oct. 31	15.7	13.0	19.8	11.4	19.3	23.2
Mon.	Nov. 1	12.7	17.8	19.7	18.7	23.5	19.7
Tues.	Nov. 2	15.6	13.9	31.9	19.2	20.0	17.9
Wed.	Nov. 3	22.8	20.7	46.8	15.4	19.1	17.7
Thurs.	Nov. 4	33.3	26.4	31.8	12.6	19.3	20.0
Fri.	Nov. 5	30.0	14.2	22.4	13.7	19.1	20.4

In addition, an effort was made to find an objective measure of eye irritation. The blink rate per minute was considered as a possible satisfactory standard. The blink rate and the number of persons reporting eye irritation were then plotted and, as may be noted from Figure 1, the average blink rate increases simultaneously with the increase in the number of people reporting eye irritation. The blink rate thus served generally as a check on the presence of real eye irritation.

Another indication of the occurrence of smog is the number of complaints that are telephoned in to the Los Angeles County Air Pollution Control District offices. These are shown graphically in Figure 1, together with the Stanford Research Institute Smog Index, described below.

As a result of the survey, several conclusions were reached:

1. The number of persons complaining of eye irritation varied from 4.3 to 85.2% (Table I), depending upon the conditions at the time.
2. About 3 out of every 4 persons who complained of eye irritation mentioned smog as the cause.
3. The percentage of people noticing eye irritation is approximately the same in the cities of Pasadena, Glendale, and Los Angeles, but maximum eye irritation occurs approximately 1 hour later in Pasadena and Glendale than in Los Angeles.

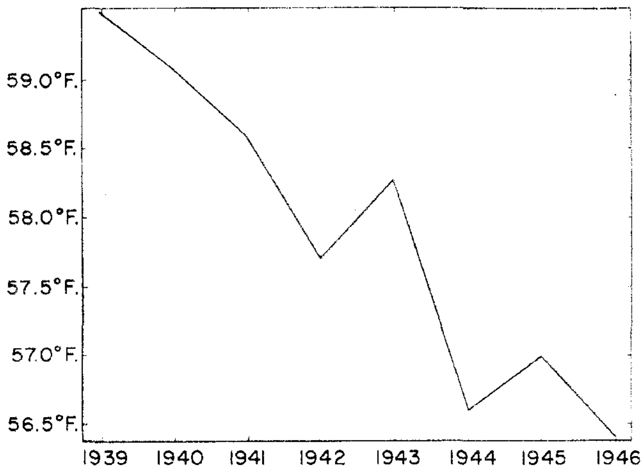

Figure 4. Los Angeles Noon Wet-Bulb Temperatures

During the course of the survey people were asked to give their opinions as to the sources of smog. In Los Angeles 45.4% assigned factories as the cause of smog; 18.2% attributed it to automobile fumes; 14.4% blamed smoke; 19.6% gave a variety of reasons; 8.8% believed that it was due to climatic conditions; and 24.3% said they didn't know (many people mentioned more than one cause).

Has the Climate Changed? The climate of the Los Angeles area was studied to determine whether there had been any change, caused by increased population or any other factor, that might be reflected in the apparent increase in smog.

In the period from 1930 to 1946, the population of Los Angeles County increased at the rate of about 4% per year. The motor vehicle registration and gasoline consumption increased at the same rate. Fuel consumption for heating purposes doubled every 6 years (Figure 2).

Effect of Human Habitation on Climate. There are a number of ways in which increased human habitation may affect climate in a locality (*11*), in addition to the obvious factor of increased contamination of the air. Wind speed may be reduced by greater air friction caused by new buildings; visibility may be reduced by an increase of moisture in the air, due to irrigation; and temperature may be affected, in either direction, by air pollution. The records on each of these factors were studied.

TEMPERATURE. Temperature readings at the Los Angeles Weather Station have been tabulated for the period from 1878 to 1946. In this time, there has been an approximate increase of 1.9° in the mean temperature (Figure 3).

This increase, however, does not seem to have any bearing on smog, except that perhaps it may be a result of it—that is, the density of the covering canopy of smoke and fumes may conserve the heat in the area, producing a so-called "greenhouse effect."

HUMIDITY. When the relative humidity of the air is high (between 85 and 100%), visibility is likely to be lower than during a dry day, assuming a constant wind speed. Data from Long Beach, the University of California at Los Angeles, and Santa Maria show that visibility may drop from between 5 and 10 miles at approximately 55% humidity to less than one mile at 98% humidity (*2*).

However, wet bulb temperatures, charted in Figure 4 for the period 1939 through 1946, show a 3.1° decrease. This, together with the 1.9° F. increase (Figure 3) of the mean temperature, resulted in a decrease in relative humidity. This lessening in relative humidity occurred despite the fact that the amount of water brought into the Los Angeles basin for purposes of irrigation and for human and industrial use has substantially increased.

Because the relative humidity has lessened rather than increased, it can scarcely have contributed to the increase in smog.

WIND SPEED. There is a close correlation between wind speed and visibility; good visibility usually accompanies high wind speeds (*10*). This effect of wind speed as a controlling factor in visibility has been observed in most cities in the United States where surveys have been made; and it is also indicated in the charts that have been made for smog days in Los Angeles.

However, wind speeds in the Los Angeles area for the years 1923 to 1947 show no significant trends (Figure 5). The location of the anemometer used for recording wind velocity at Los Angeles was changed in 1939, and the curve at that time shows a sharp change. Accurate adjustment of the results from the two locations cannot be made.

TOTAL SUNSHINE. Over a 40-year period from 1906 to 1946 records of the Los Angeles Weather Bureau show practically no change in total sunshine (Figure 6).

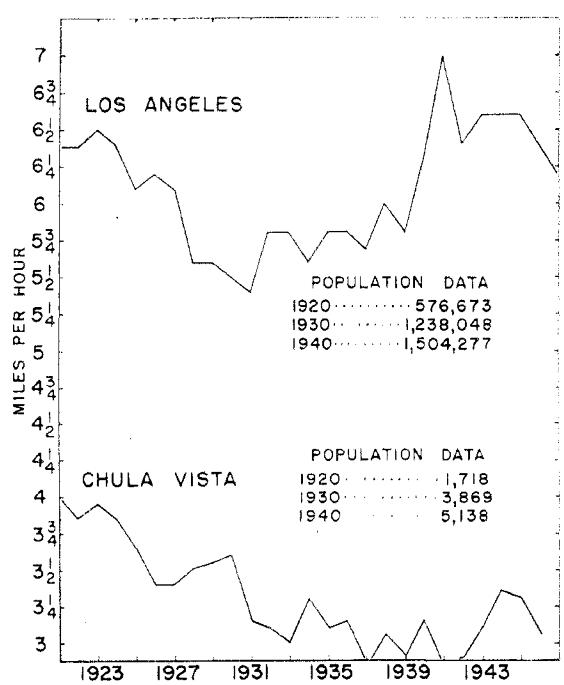

Figure 5. Average Hourly Wind Speed

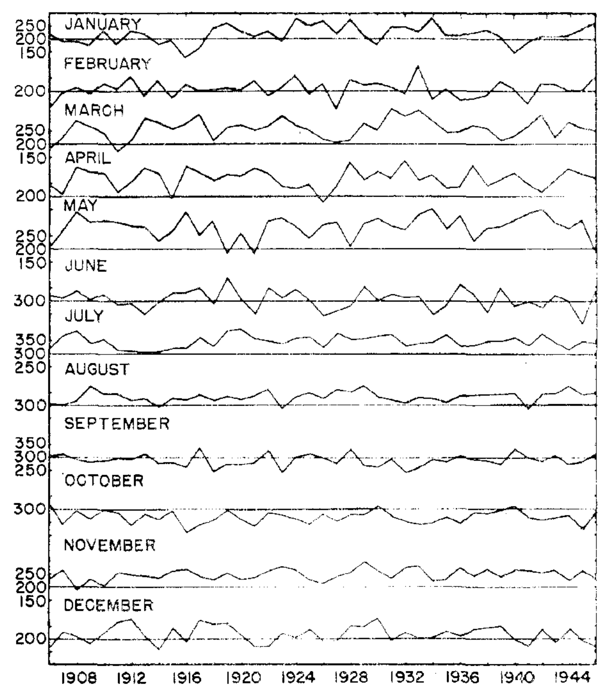

Figure 6. Total Number of Hours of Sunshine by Months at Los Angeles (1906 to 1946)

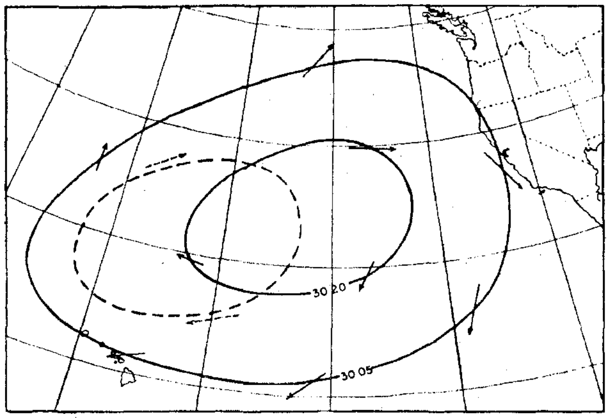

Figure 7. Mean Annual Position of the Pacific High, at the Surface and at 20,000 Feet, Showing Southwest Tilt with Height

On the basis of these data it is clear that there has been no basic change in the Los Angeles area climate in recent years which could account for the frequency of the smogs, exclusive of an increase in man-made contamination of the air.

MECHANISM OF THE SMOG

In dealing with the smog problem, it is essential to understand the peculiarities of the California region in which smog occurs, and the way in which meteorological and topographical factors combine to prevent normal dispersal of polluting substances resulting from human activity.

Los Angeles County is unique in that it is by far the largest industrialized subtropical urban area in the world. The normal waste-disposal problems of such an industrialized region are intensified by its subtropical weather conditions, and further exaggerated by peculiar climatic factors resulting from its unusual topography.

The county is situated in an enormous basin, ringed about with high mountains. Over the entire area extends an inversion layer with a negative temperature gradient.

Inversion Layer and Its Effects. The presence of a semipermanent high pressure area over the North Pacific Ocean is one of the important meteorological factors contributing to the formation of smog.

This high pressure area may be visualized as a giant column of air, elliptical in shape and inclined slightly to the southwest (Figure 7). The air swirls around the axis of the column in a clockwise direction in paths extending from the West Coast of the United States to beyond the Hawaiian Islands (*3*). This high pressure area is called semipermanent because it exists over the mid-Pacific during a large proportion of the summer and fall months. Its position, however, is not always the same with respect to latitude and longitude.

The air paths within this high pressure column at sea level and at levels near the base of the stratosphere are roughly parallel to the earth's surface. At intermediate levels, however, the air paths are inclined to the earth's surface, being lower in the east and higher in the west. Thus they form a layer of air resembling a huge saucer, tilted so that its lower edge is adjacent to the California coast and its upper edge is suspended in mid-Pacific to the north of the Hawaiian Islands.

The air traveling around the southern side of the high pressure area, in a direction away from California and toward the Pacific, is gradually ascending and consequently cooling. But air moving around the northern side toward California is descending, moving progressively downward into levels of increased pressure, and thereby becoming compressed and warmed (Figure 8).

The consequence for the Los Angeles area, because it lies under the eastern end of the column, is that the air arriving over Los Angeles County at levels higher than the surface layer has been subjected to considerable downward motion which has compressed and heated it. The temperature contrast is further exaggerated when the bottom layer of seepage air is cooled from below, in passing over the relatively cold band of water upwelling just off the California coast to replace surface shore waters swept out into the Pacific by the high pressure area winds.

The temperature inversion layer is a result of these phenomena. Normally the temperature of the air decreases directly as the altitude increases, but over the California coast and the Los Angeles area the opposite condition exists. The height of the inversion varies from hour to hour, but during the daytime it may frequently be found at an elevation of approximately 1500 to 3000 feet. According to a typical set of air soundings (Figure 8), air 1500 feet up over the West Coast was warmer than air at 1000 feet. The stratum of heated air is the inversion layer.

The inversion layer may be visualized as a transparent sheet of air extending over the entire Los Angeles area, at a level usually ranging between 1000 and 3000 feet. Sometimes such inversion layers are so sharp and definite a stratification that a balloon, ascending slowly, will rebound momentarily from their under surfaces (*16*).

As a rule, the inversion layer slopes upward in both easterly and westerly directions from the coast (*13*), and rests against the mountains on the east, effectively blocking any eastward outflow of air from the basin. With incoming and outgoing breezes, it simply rises and falls like an enormous deck. Moreover, very little interchange of air takes place between it and the air above or below it. The only exchange of properties in this direction is by means of heat radiation (*20*).

Thus the inversion layer acts as a canopy over the entire Los Angeles basin, preventing contaminated air from escaping vertically, and, by resting against the mountains, preventing it also from escaping toward the east.

A natural haze composed of oceanic salt, dust particles, and plant pollen combines with man-made pollution and collects at the base of the inversion layer. Owing to the isolating action of the layer, it is possible for the smoke and fumes of several days to build up and remain trapped in the Los Angeles area. Any con-

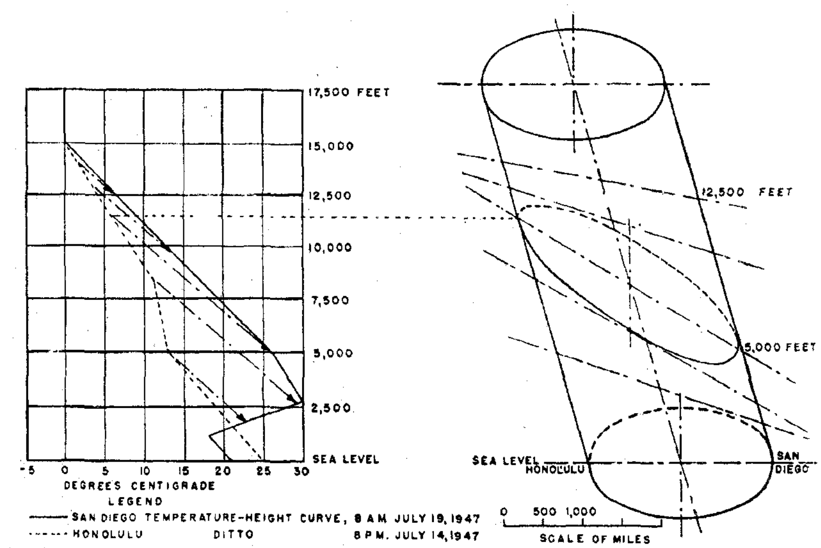

Figure 8. Temperature-Height Curve for San Diego and Honolulu

taminants in the air tend to concentrate at the top of the air layer just below the inversion base, reaching their greatest density within the lower portion of the inversion layer (*7, 9, 14, 20*).

At times, when the air becomes stagnant and the base of the inversion is forced to ground level by movements in the upper atmosphere, the combined natural haze and man-made pollution are sufficiently dense to obstruct visibility seriously; and severe irritation of the eyes results from the concentrated contamination.

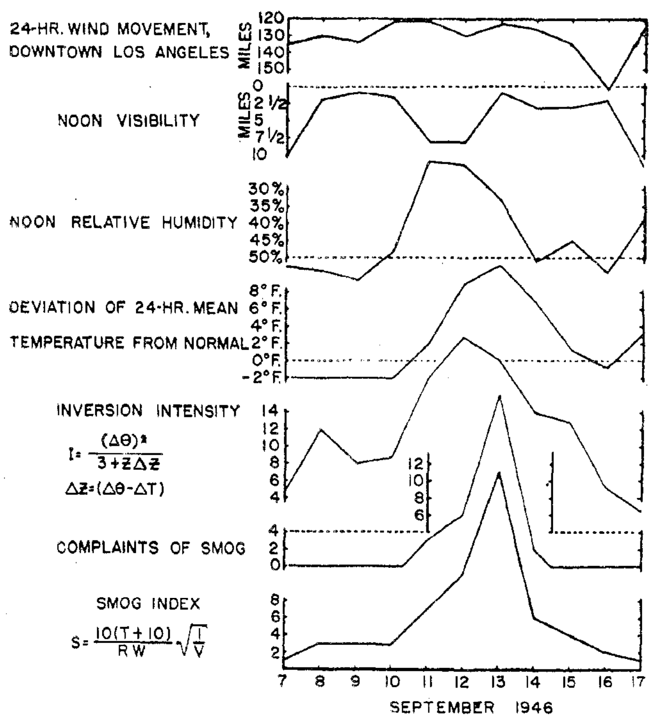

Figure 9. Chart for Calculating Smog Index

Wind Currents and Mountain Effects. The influence of mountain barriers on wind and other climatic factors is exerted in other ways in addition to combining with the inversion layer to prevent the escape of contaminated air from the area. The high and extensive mountain ranges partially surrounding the region prevent the passage of strong winds into or out of the area.

Moreover, as the land surface of the Los Angeles basin is not smooth, the local wind pattern is strikingly irregular. Surface wind direction at any given point may not be at all indicative of wind direction only a few blocks away. Very often flags atop neighboring buildings in Los Angeles blow in different directions. Such a situation makes it extremely difficult to backtrack to the source of contaminated air.

The effects of the Foehn (or Santa Ana winds) from the east are often popularly confused with smog effects. Smoggy days are usually days of high temperature, but even higher temperatures may result from the Foehn because no body of air can pass from the high plateau regions lying to the east of the Los Angeles basin down into the valley without being heated to at least 20° F. (*4*). The Foehn winds are characteristic of mountainous regions, notably the Alps and the Rockies. In the Rockies they are called "chinooks," and they are all dry winds with a strong downward component of motion (*17*). Moreover, the Santa Ana winds are usually of high velocity, and they pick up and carry large quantities of dust. Visibility may be greatly reduced during a Santa Ana, but in the true sense of the word there is no smog present.

PREDICTION OF SMOGGY DAYS

From the outset of this investigation, the desirability of developing some method of predicting smoggy weather with reasonable accuracy was evident. Such a forecasting technique would permit control of the amount of contaminating substances discharged into the air when smog is imminent, thus mitigating the severity of its irritating aspects.

A promising method of predicting the occurrence of smog has been evolved, necessarily based upon past weather conditions. It is now undergoing trial and refinement, and there is good reason to believe that it will prove a reliable method for predicting smoggy weather.

S.R.I. Smog Index. The first step in developing a method of forecasting was to work out a mathematical correlation between smog and the meteorological conditions associated with it. This effort resulted in the Stanford Research Institute smog index—a formula that tells with a high degree of certainty whether eye-irritating smog is, or is not, present in some part of the Los Angeles basin at the moment for which the index is calculated.

Smoggy days were arbitrarily defined as those on which a minimum of four complaints were received by the Los Angeles County Air Pollution Control District. When fewer complaints per day than this are received, they are usually traceable to local irritants, and are not related to the general smog problem.

The smog index was worked out originally by using a chart on which five separate aspects of meteorological conditions for each day during the period from July 1945 to July 1947 were plotted against the number of complaints noted for each day of the same period (Figure 9):

1. Wind movements for 24 hours
2. Noon visibility in miles
3. Relative humidity at noon
4. Difference between the day's 24-hour mean temperature and the normal mean temperature
5. Height, thickness, and magnitude of the temperature inversion

The chart indicated that those days on which severe smog occurs were strikingly similar with respect to certain meteorological conditions.

1. A strong, low inversion must be present. Until the day preceding the smog, the inversion base is often as high as 1000 feet, and seldom as low as 500 feet. But on the day before the smog occurs, the inversion base drops sharply; and on the smog day, it drops still farther, generally to 500 feet or less above mean sea level, or until its base and accompanying pollution touch the ground.
2. The low inversion must be accompanied by several days of stagnant air. The chart indicated that a bad smog day is usually preceded by 1, 2, or 3 days when the average daily wind movement is less than the normal 125 miles.
3. The temperature must be above normal for the time at which the smog occurs. The dry-bulb air temperature usually increases steadily for 2 or 3 days to a maximum noontime temperature on the smog day between 75° F. in winter and 89° F. in summer.

On the basis of such qualitative data, it proved possible to devise an empirical equation which, in turn, yielded a numerical value called the "S.R.I. smog index." The data for the 2-year period were examined, and a smog index was calculated for each day. Agreement is marked between days on which the smog index number is large (indicating smog conditions) and days on which more than the minimum of four complaints were received by the Los Angeles County Air Pollution Control District. Figure 9 shows this relation over a period of 11 days.

An example of the correlation of the smog index and smoggy weather can be seen in the records for Black Friday, September 13, 1946, in Figure 9, and also in the records for the period of September 11 to November 5, 1948, in Figure 1. In Figure 1 there is good correspondence between the days on which eye irritation was reported to interviewers on the streets, a high blink

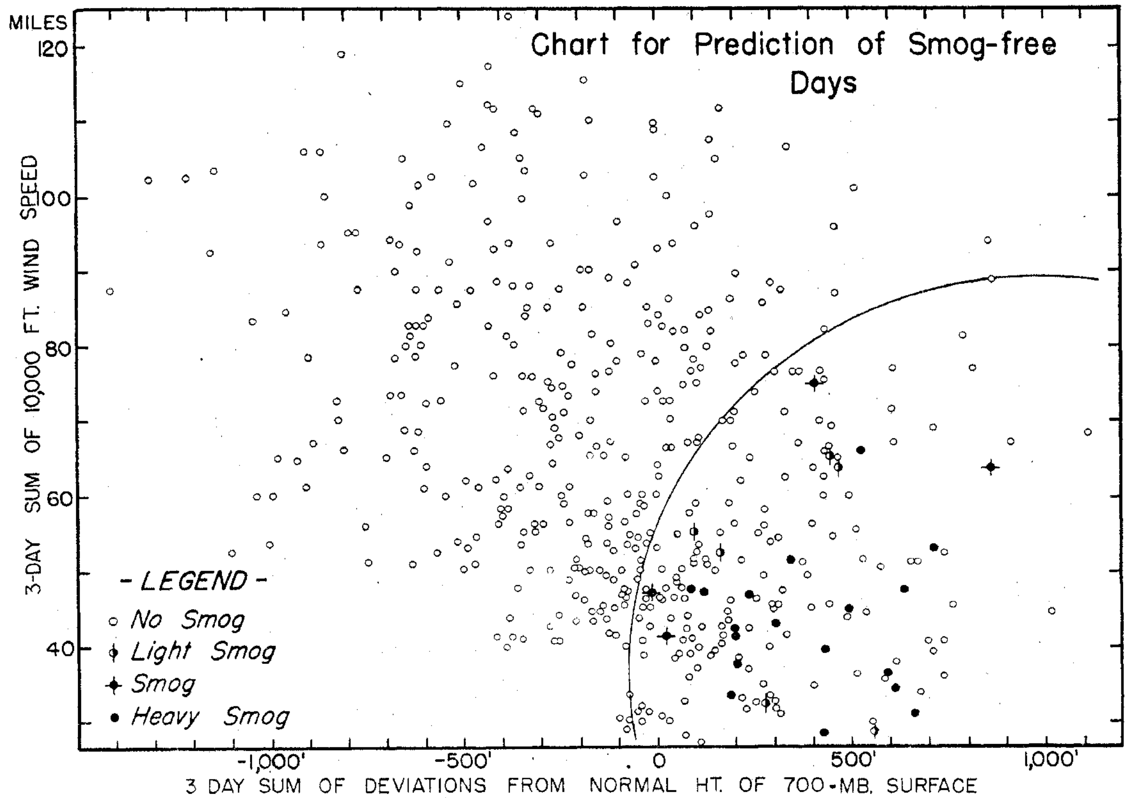

Figure 10. Scatter Diagram Chart

rate among the persons interviewed, a large number of telephone complaints received by the county, and those days on which the Stanford Research Institute smog index (which was calculated solely from meteorological data) attained high values.

Forecasting Smog and Smog-Free Days. The success of the smog index in correlating the presence of smog with weather characteristics gave rise to a method of forecasting smog by correlation with upper air pressures and surface air movements, and by a supplementary correlation with surface wind velocities and sunshine.

Correlation of Smog with Upper Air Pressures and Surface Air Movements. From what had gone before, it was plain that smog is several days in the making. A "scatter diagram" chart was prepared that plotted the position of all days during a certain period (whether they were smoggy, preceded smog, or seemed to have no relation to smog) with respect to the upper air pressure and the surface air movement of that particular day (Figure 10).

Upper air pressure measurements instead of surface pressure measurements were used as a parameter in place of the height of the inversion layer, because small, highly localized influences tending to obscure general relationships are absent from the upper air, and significant changes are slower and more uniform.

Usually the air pressure is about 700 millibars (or 516 mm. of mercury) at the 10,000-foot level, although the average height of the 700-millibar level varies from month to month, as shown in Figure 11. On smoggy days, the 700-millibar air pressure level tends to be higher than normal.

Three days' accumulated deviation from the normal 700-millibar level was plotted on the abscissa of Figure 10. The 3 days' accumulated wind movement was plotted on the ordinate.

Thus if the inversion layer were low for three successive days, the accumulated millibar level would be considerably higher than normal and, as a consequence, the corresponding point on the abscissa would fall on the right-hand side of the chart. If the air were stagnant for three successive days, its total motion would be small, and its corresponding point would fall near the foot of the ordinate.

Study of the chart showed that days characterized by a combined high millibar level value and a low wind movement value fall well within a definite area on the chart. An arc was drawn to enclose that area.

It was found that all days known to be smoggy fall within the arc. Furthermore, all days either 24 or 48 hours before a smog day lie on or within the arc. More than 70% of the days that preceded smog by 72 hours lie within the arc. Days falling outside the arc were shown to be smog-free; and smog did not follow them for at least 2 days, and usually not for 3 or more days.

It follows that if a day falls within the arc, there is a 50-50 chance that smog will occur within the next 2 or 3 days. There is a considerably higher probability that smog will not follow, within 72 hours, days outside the arc.

The steps used in calculating the values used in such a chart as just described are as follows:

1. From the Weather Bureau Office, find out the height of the 700-millibar level for Santa Maria and San Diego for each of the previous 3 days. These are obtained by the Weather Bureau by means of radiosonde observations, and will be reported for the day requested at times designated as 0400Z and 1600Z. The 0400Z observation is taken at 8:00 P.M., P.S.T., the previous day. The 1600Z observation is taken at 8:00 A.M., P.S.T., of the day reported.
2. Obtain from the Weather Bureau the wind velocities at 10,000 feet at San Diego and Santa Maria at the times corresponding to those in Step 1.
3. Average, for each observation time, the height of the 700-millibar surface between the two stations. Then take an average of these averages for 0400Z of the given date (day previous) and for 1600Z of the day previous.
4. Find out, from the curve shown in Figure 11, the normal height of the 700-millibar surface, the usual surface height for the day in question.

5. From the final average obtained in Step 3, subtract the normal height obtained in Step 4. This gives one day's deviation from the normal 700-millibar level.
6. This identical procedure must be followed for the 2 days previous to the day that has just been calculated. Then add all three values together. This determines the point along the abscissa in the prediction graph at which the day falls.
7. Average the 10,000-foot wind speed for the two stations in the same fashion as the millibar heights were averaged.
8. Add this average to the final averages of wind speed for the two previous days. This locates the value along the ordinate of the graph.
9. With the final values yielded from Steps 6 and 8, plot a point on the graph. If the point falls outside the arc, there is a very high probability that there will be no smog on the day just calculated or on the two following days.

EYE IRRITANTS IN SMOG

Unquestionably the most disagreeable aspect of smog is eye irritation. In a public opinion poll made in 1948 by Field & Peacock Associates, of Los Angeles, 52% of county residents questioned said they were affected by smog; nearly 40% complained of eye smarting; 29% said they objected most to the physical discomforts of smog; whereas only 10% objected to the reduced visibility.

The cause of eye irritation is extremely difficult to determine under field conditions, because of the brevity and infrequency of smog attacks. Severe smog occurs in the Los Angeles basin only about 10 to 20 times a year, and seldom lasts longer than 4 hours.

In order to make possible controlled testing of the eye-irritating properties of various substances on human beings, a smog chamber was constructed. The smog chamber is a galvanized metal room, large enough to permit a human being to be seated comfortably, and so designed that irritants may be introduced at various concentrations (Figure 12).

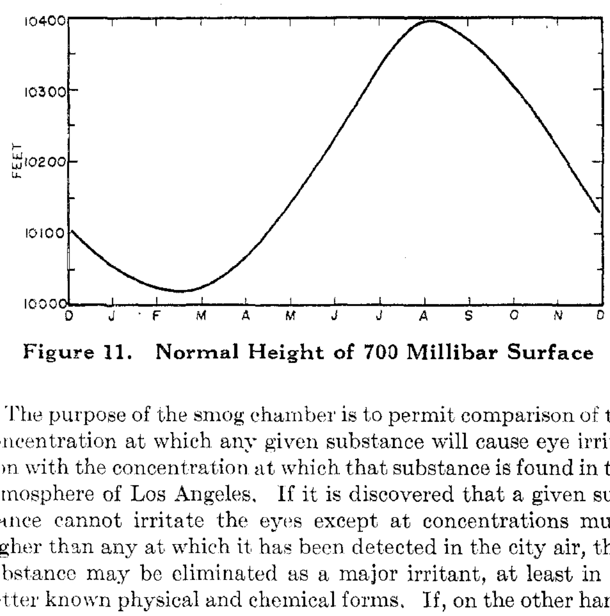

Figure 11. Normal Height of 700 Millibar Surface

The purpose of the smog chamber is to permit comparison of the concentration at which any given substance will cause eye irritation with the concentration at which that substance is found in the atmosphere of Los Angeles. If it is discovered that a given substance cannot irritate the eyes except at concentrations much higher than any at which it has been detected in the city air, that substance may be eliminated as a major irritant, at least in its better known physical and chemical forms. If, on the other hand, it does irritate the eyes at concentrations found in the atmosphere, presumably it may be responsible for some of the irritating aspects of smog. It is recognized that there is a large variation in the sensitivity of individuals, and only a very large number of tests on different individuals will serve to give accurate results on threshold sensitivity. These tests were for screening purposes, and only large differences were sought.

Testing Procedures. The smog chamber was accurately calibrated, and two types of tests, dynamic and static, were made.

Dynamic Tests were those in which the irritant under investigation was mixed with air and blown, in the form of vapor, smoke, dust, or fog, through the sealed chamber at a constant rate.
Static Tests were those in which the contaminants were added to the chamber atmosphere and allowed to mix thoroughly for from 5 to 60 minutes before the observer entered. Static tests were used primarily where it was desirable to have longer test periods to determine the possible absorption of gases in liquid or solid aerosols, after they had been permitted to mix in the air.

In order to determine the relationship between the nominal concentration of a substance (or the concentration to be expected from the amount introduced into the air of the chamber) and the analytical concentration (or the concentration measured by chemical or physical analyses of a sample of air drawn from the chamber), the analytical concentration of formaldehyde in the chamber was compared with the nominal concentration obtained in both the static and dynamic methods.

For dynamic testing, the two concentrations were within 5% of each other and, therefore, were considered the same. For the static method, the analytical concentration was from 30 to 40% lower than the nominal concentration, apparently owing to the surface effects of the chamber.

As all static tests to date have been primarily exploratory, no specific correction factor for the nominal concentration of other substances has been determined; but it has been assumed that all nominal concentrations corresponding to sensory responses are roughly one third too high. For the purpose of this investigation, this difference is considered to be on the safe side for, when the nominal concentration of any agent is within the critical range, the actual effective concentration will be well within it.

Results of Smog Chamber Work. A number of substances known to be present in the Los Angeles atmosphere (Table II and Figure 13) during smog periods have been introduced into the the smog chamber, both singly and in combination, and at various concentrations. Their effects upon human observers have been carefully noted.

Among the substances which have been tested to date are formaldehyde, sulfur trioxide, sulfur dioxide, acrolein, oxides of nitrogen, hydrogen persulfide, and elemental sulfur.

To determine whether any two or more of these substances might have a synergistic or cooperative effect different from that obtained from each of them singly, tests were also made with combinations of formaldehyde and sulfur dioxide, formaldehyde and sulfur trioxide, formaldehyde and acrolein, formaldehyde and carbon black aerosol, acrolein and carbon black aerosol, formaldehyde aerosol, and mixtures of aldehydes.

By correlating air conditions in the smog chamber during tests with air conditions existing in Los Angeles during smog, many of the suspected irritants apparently have been eliminated as causes of lachrymation, at least in the physical form in which they were used in the tests. There is reason to suspect, however, that some of these substances may exist in the atmosphere in other forms, such as aerosols, and as such may cause eye irritation. Study of these possibilities is in progress.

The tests produced one unexpected result: the identification of elemental sulfur (sulfur the element as distinguished from sulfur in compounds) as an agent capable of causing general eye smarting, eye watering, and other unpleasant results, similar to those experienced in smog. It is not likely, however, that sulfur is the only material producing such effects, and aldehydes have not, as yet, been definitely eliminated from consideration.

Investigation of the effects of elemental sulfur and of other possible contributory irritants is continuing. Results to date are summarized below.

Formaldehyde. Twenty-one tests have been completed. The threshold concentration (or concentration required to cause discernible eye irritation) was found to be between 5 and 10 p.p.m. This corresponds rather well with previously published information which lists 10 p.p.m. as a safe working concentration (*18*). Because formaldehyde during smog at no time has been found to exceed 0.5 p.p.m., or less than $^1/_{25}$ that required to cause irritation, it would appear that formaldehyde is not likely to be the primary cause of eye irritation.

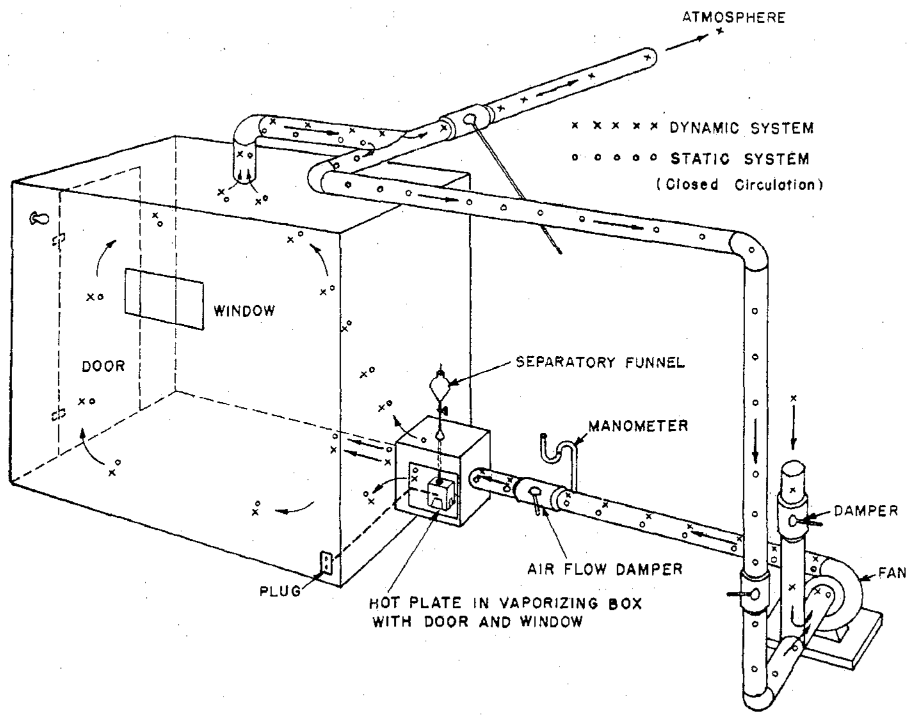

Figure 12. Diagrammatic Sketch of Smog Chamber

Inside smog chamber are a chair and a table. On table are clock, thermometer, and humidity gage

25 p.p.m. As the total sulfur oxides actually present in Los Angeles air range between 0.0 and 0.4 p.p.m., sulfur trioxide was dismissed as an irritant which alone could cause the eye-irritating effects in Los Angeles smog.

SULFUR TRIOXIDE AND FORMALDEHYDE. Exploratory tests were made to determine if a synergistic effect might be obtained from this combination. Sensory responses were the same as those for formaldehyde alone.

MIXTURES OF ALDEHYDES. Formaldehyde, acetaldehyde, crotonaldehyde, and propionaldehyde were mixed in equal proportions. Only enough tests have been made to warrant saying that, although a slight synergistic effect appears to exist, the effect is not powerful enough to differ significantly from formaldehyde alone.

CARBON BLACK AND FORMALDEHYDE. Tests indicated no synergistic effect with formaldehyde and carbon black obtained from the incomplete combustion of hydrocarbon oils.

FORMALDEHYDE IN SEA WATER. Formaldehyde in sea water solution was introduced into the chamber as spray.

At relative humidities below 70%, the sensory responses were the same as those obtained when formaldehyde was added to the chamber as a vapor.

At relative humidities above 70%, however, there was a distinct lessening of the irritant effect of formaldehyde, and the lachrymation concentration threshold was raised to above 10 p.p.m., or 50 times as much as is ever present in Los Angeles smog.

SULFUR DIOXIDE. In concentrations up to 20 p.p.m., no lachrymation or even slight eye irritation appeared.

SULFUR DIOXIDE AND FORMALDEHYDE. To determine whether formaldehyde–sulfur dioxide has a synergistic effect in producing eye irritation, formaldehyde concentrations ranging from 1 to 10 p.p.m. were tested in the presence of 0.5 to 5 p.p.m. of sulfur dioxide.

No synergistic effect was apparent. Sensory reactions of observers were about the same as for formaldehyde alone. Indeed, if the presence of sulfur dioxide produced any change at all, it seemed to decrease the sensitivity of observers to the formaldehyde.

ACROLEIN. The completion of a series of tests shows the threshold eye-irritative concentration for the average person to be within a range of 0.5 to 1.5 p.p.m. Acrolein is the only aldehyde thus far tested which causes lachrymation within the concentration range of the total of all the aldehydes as found to exist in smog (a range between 0.0 and 0.5 p.p.m.).

It was also apparent that people tend to become more sensitive on prolonged exposure. It is therefore possible that a person may be sensitive to a concentration considerably lower than 0.5 p.p.m., if he is exposed for a sufficiently long time.

The question arises as to whether acrolein is present in the Los Angeles smog. The methods of analysis so far used for formaldehyde in the streets unfortunately do not distinguish between acrolein and formaldehyde.

Small amounts of acrolein, however, are known to be produced by varnish manufacturing operations and other operations involving the heating of natural fats and oils. Recent unpublished work has shown, perhaps for the first time, that automobile ex-

On the other hand, these results are not quite in agreement with the results of work recently completed at the University of Southern California by Roth and Swenson (*15*) for the Los Angeles County Air Pollution Control District, which indicate that a significant number of persons are 20 to 40 times as sensitive to formaldehyde as others. Nine people out of 48 in an age group from 50 to 85 reported detectable eye irritation at a concentration of 0.25 p.p.m. of formaldehyde in the air. This would indicate that aldehydes cannot be ruled out completely as one of the sources of eye irritation. However, the proportion of hypersensitive individuals is not as high (19%) as the 85%, or sometimes higher, of the population reporting eye irritation during severe smog.

Table II. Concentration Range of Known Substances in Los Angeles Atmosphere

Dust count, number of particles per cc. of air (by use of Smith-Greenburg impinger)	50–1000
Aldehydes, calculated as p.p.m. by volume of formaldehyde	0–0.5
Oxides of sulfur, calculated as p.p.m. by volume of SO_2	0–0.4
Oxides of nitrogen, calculated as p.p.m. by volume of NO_2	0–0.1
Halogen content, calculated as p.p.m. by weight of chlorine in dry air	0.15–0.3

	Low (Dec.)	High (April)	Average
Total dust fall in Los Angeles County for 1946, in tons per sq. mile per month	21.2	38.5	27.7

Some weather conditions were investigated in connection with the eye-irritating effects of formaldehyde. For example, during severe smog, the temperature is sometimes above 80° F., and the relative himidity below 39%. Formaldehyde was tested under parallel conditions of temperature and humidity. Results showed a slight increase in irritation, but not sufficient to warrant further consideration of atmospheric conditions as a factor in eye-irritating effect of formaldehyde.

SULFUR TRIOXIDE. Sulfur trioxide, introduced into the chamber by vaporizing sulfuric acid, gave no lachrymation effects at

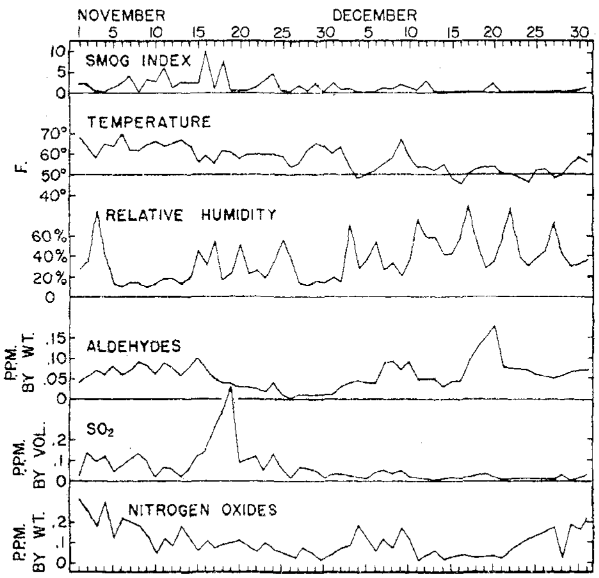

Figure 13. Analysis of Los Angeles Atmosphere

Figueroa St. and Wilshire Blvd.

haust sometimes contains acrolein in quantities as high as 3 p.p.m. It has also been shown (*8, 12, 19*) that aldehydes are produced in heavy concentrations by motor vehicles, but acrolein was not positively identified. It seems likely, therefore, that acrolein may play a supporting role in eye irritation; but it is not believed to be the chief offender.

ACROLEIN AND CARBON BLACK. Tests indicated that no synergistic effects exist. However, the masking of the acrolein odor is apparent.

ACROLEIN AND FORMALDEHYDE. Equal parts of the two irritants were tested, but there is no indication of any synergistic effects.

OXIDES OF NITROGEN. NO_2, N_2O_4, and N_2O_3, formed by the action of arsenic trioxide on concentrated nitric acid, were tested up to concentrations of 10 p.p.m. No lachrymatory responses were obtained; therefore they were eliminated as compounds which alone could cause eye irritation.

HYDROGEN PERSULFIDE. This gas proved highly irritating at concentrations as low as 0.2 p.p.m., although it did not produce the same effect as smog (its aftereffects were nausea and headache). Its significance to the problem is that it may be one of the contributing factors to the eye-irritating effect of sulfur.

The chemical formula of hydrogen persulfide is usually given H_2S_n, where n may be any number from 2 to 8. It is sometimes associated with crude sulfur (*1*). Under some conditions it is formed by the reduction of sulfur dioxide, and it is known to be formed during the fermentation of sewage by certain types of bacteria (*6*). There have been reports of eye irritation from Los Angeles sewers as far back as 15 years ago, and the occurrence of hydrogen sulfide, a decomposition product of persulfides, in the Los Angeles sewer system is well known.

ELEMENTAL SULFUR. Three methods have been used for the dispersal of elemental sulfur in the atmosphere of the smog chamber:

Mixture of flowers of sulfur (rapidly condensed sulfur) in dust form with air entering the chamber. Relatively large quantities of flowers of sulfur were required to result in even slight irritation.

Vaporization of the sulfur, followed by sudden cooling in an air blast. This produced irritated eyes at approximately 2.6 p.p.m.

Vaporization of finely divided sulfur, suspended in water, then suddenly cooled and diluted. To date, 33 tests have been made using trace quantities of elemental sulfur suspended as a finely divided solid by this method in the atmosphere of the smog chamber. Definite eye and nose sensations, usually described as a feeling of dryness and feverishness, occur at concentrations as low as 0.2 p.p.m.

It is clear that finely divided sulfur, if present in certain forms, can be a strong eye irritant. People who have experienced the Los Angeles smog, and who have also been subjected to sulfur in the smog chamber, have commented on the similarity of the sensations produced.

The intensity of these sensations varies to some extent from one individual to another. In most cases, irritation of the eyes increases with lengthy exposure. In one case, exposure for 1 hour to a concentration of 10 to 15 p.p.m. resulted in continued severe eye smarting for 2 hours after exposure.

Discovery that elemental sulfur can be an effective eye irritant was surprising because, although people who constantly work in the presence of large quantities of sulfur sometimes do suffer from smarting of the eyes, it is not the common experience.

Table III summarizes the results to date. The concentrations indicated in Table III are not threshold concentrations, but are the concentrations which were tested and proved to be irritating. It appears that the most potent form of sulfur is fine liquid droplets. This is a form in which the sulfur exists suspended in the air when it is produced by means of vaporization and sudden chilling. These droplets may remain in liquid form for as long as 5 to 7 days without crystallizing, provided they are in a size range below 10 microns. Tests for sulfur in the atmosphere in Los Angeles have shown that it is occasionally present in concentrations ranging from 0.0 to 0.8 p.p.m. Tests on many days when eye smarting was severe failed to show the presence of elemental sulfur, and it is therefore tentatively concluded that other materials are responsible for much of the eye-irritating effect.

Thus far tests on the city streets of Los Angeles have failed to show the presence of irritant materials in concentrations in their normally conceived gaseous or vaporized forms sufficiently high to be responsible for the widespread eye irritation.

From this can be concluded either that the material responsible

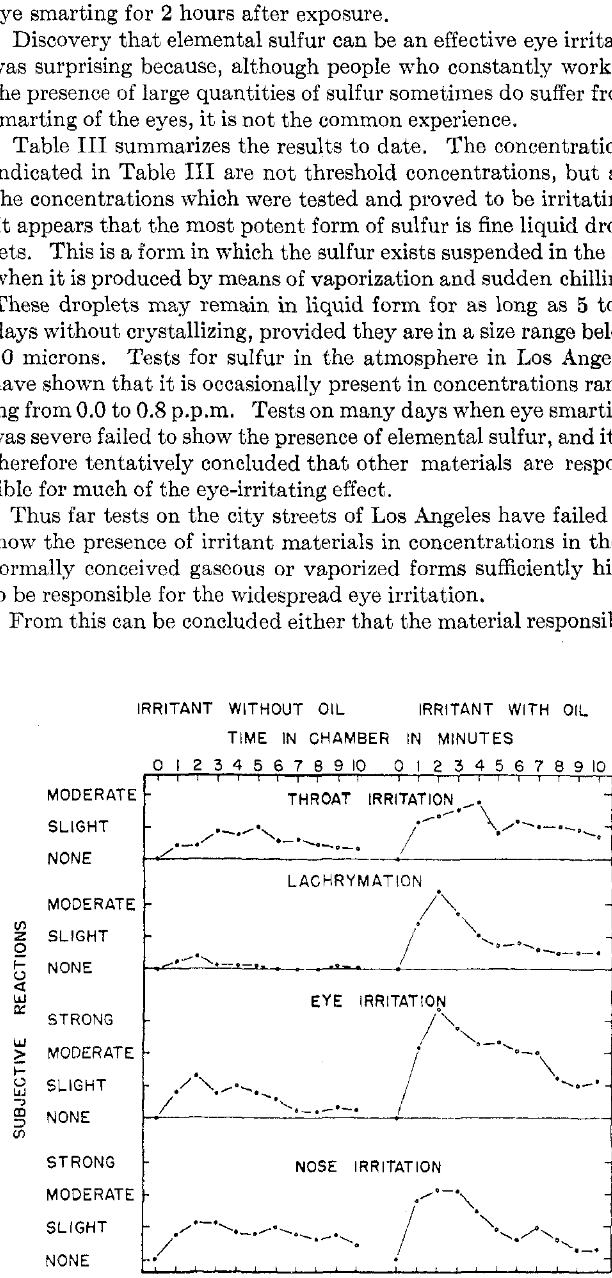

Figure 14. Enhancement of Irritant Effects by Mineral Oil

Irritants used with and without mineral oil:
Tincture of capsicum (10%) in alcohol + water
2% and 4% formaldehyde in water + alcohol
2% and 4% formaldehyde in ether + chloroform
4% formaldehyde in alcohol + alcohol
Acrolein 0.5% + chloroform
Mean relative humidity 38.7%

Table III. Smog Chamber Tests with Elemental Sulfur

No. of Observers[a]	Nominal Sulfur Concn., P.P.M.	Method of Introduction	System	Eye Response
2	10–20	Powdered sulfur	Static	None
1	10–20	Powdered sulfur	Static	Irritation
7	Over 10	Evaporation	Static	Lachrymation
1	9.0	Evaporation	Static	Lachrymation
1	8.0	Evaporation	Static	Irritation
2	7.0	Evaporation	Static	Irritation
5	6.0	Evaporation	Static	Irritation
1	6.0	Evaporation	Static	Lachrymation
1	5.0	Evaporation	Static	Irritation
2	4.0	Evaporation	Static	Irritation
1	2.6	Evaporation	Static	Irritation
1	5.0	Vapor-water suspension	Dynamic	Lachrymation
2	2.5	Vapor-water suspension	Dynamic	Lachrymation
1	1.0	Vapor-water suspension	Dynamic	Irritation
1	0.4	Vapor-water suspension	Dynamic	Irritation
3	0.2	Vapor-water suspension	Dynamic	Irritation
1[b]	0.1	Vapor-water suspension	Dynamic	Lachrymation
33 Total				

[a] Number of observers tested at the nominal concentration listed to demonstrate presence or absence of sensation.
[b] Has been a hypersensitive observer in all tests.

for the irritating effect has escaped collection and identification, or that certain combinations or forms of materials exist that have powerful synergistic actions with materials already known. Qualitative tests for oxidizing agents and reducing agents in the atmosphere, polarographic analysis of solutions from scrubbed air, and infrared and ultraviolet spectroscopic analysis have failed qualitatively to show the presence of possible irritant materials other than those already identified. With this in mind, preliminary work has been started and interesting results have been obtained on the possible effects of fine aerosols in enhancing the irritating effects of materials already known to be present.

The recent work by Dautrebande and others (*5*) has shown that fine particles of uniform size and carrying an electric charge can have many hitherto unsuspected physiological effects. In addition, these fine particles exert a marked agglomerating effect on larger particles. As a class of materials, mineral oils appeared to be among the most potent as agglomerating agents.

Recent work at the Stanford Research Institute on the possible synergistic effects of fine oil droplets has shown that they exert a powerful action and enhance the irritant effect of other materials. These results are presented, not because they are conclusive as to the cause of eye irritation in Los Angeles, but because they indicate a new avenue of approach to the possible effect of materials already known to be present.

Figure 14 shows the composite results of a series of experiments conducted in the smog chamber. In all comparative experiments the irritant concentration was the same and the only difference was the presence or absence of a mineral oil. These preliminary results indicate that many of the materials previously examined must be re-examined from the standpoint of their possible existence in aerosol form and association with substances that enhance their irritating effect. This work is now in progress. It is hoped that the results will provide an answer to the question "What is smog?"

SUMMARY

The results of the work described in this paper show the following:

Of the two disagreeable aspects of the Los Angeles smog—reduced visibility and eye irritation—it is the latter about which the population complains most bitterly.

The records do not show that the Los Angeles climate has changed in recent years, although the average visibility is now not as good as prior to 1944, which was about the time that the eye-irritating effect became most evident.

Weather conditions control the time of occurrence of eye-irritating smog in Los Angeles.

A numerical smog index has been developed that may be calculated solely from meteorological data. It has proved to be a reliable indicator of the presence of eye irritation in Los Angeles.

A method of forecasting smog has been devised.

The eye irritation in Los Angeles does not appear to be the result of the presence of any of the known air pollutants in their normally thought-of gaseous, solid, or vaporized forms. Preliminary evidence indicates that the irritant effects of these air pollutants can be greatly enhanced by the synergistic effects of other simple materials such as mineral oils, and this observation has opened a new avenue of approach to the possible causes of eye irritation in Los Angeles.

NOMENCLATURE

For calculation of S.R.I. smog index, S

$$S = \frac{10\,(t_D + 10)}{RW}\sqrt{\frac{I}{V}}$$

where

t_D = degrees Fahrenheit deviation of 24-hour mean temperature from mean temperature for that particular day of year
R = relative humidity at noon
W = total 24-hour wind movement in miles
V = noon visibility in miles
I = inversion intensity from the equation:

$$I = \frac{(\Delta\Theta)^2}{3 + Z\,\Delta Z}$$

$\Delta\Theta$ = change in potential temperature in degrees K. through inversion layer where potential temperature is defined by Poisson's equation

$$\Theta = T\left(\frac{100}{P}\right)^{\frac{R_d}{C_{pd}}}$$

R_d = gas constant for dry air = 287 kilojoules per ton (metric) per degree C.
C_{pd} = specific heat at constant pressure for dry air = 1004 kilojoules per ton (metric) per degree C.
T = temperature in degrees Kelvin
P = pressure in centibars
Z = height of inversion base, in hectometers
ΔZ = thickness of inversion layer, in hectometers

ACKNOWLEDGMENT

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Industrial Dusts and Fumes in the Los Angeles Area

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Meteorological and topographical conditions in the Los Angeles basin cause the retention of dusts and fumes, frequently for several days. Eye irritation and limited visibility are characteristic of the resultant smog. Studies of the aerosols in this area have been undertaken by government and private laboratories. Methods and equipment used by the Los Angeles County Air Pollution Control District in identification of industrial contaminants are described. The roles of sulfuric acid mist and metallurgical dusts in smog formation are discussed.

IN THE Los Angeles basin the term smog is applied to the complex blue haze of air pollution which limits visibility and on 53 days of 1948 caused reports of eye, nose, and throat irritation. Natural gas is used for domestic heating, and natural and refinery gas and fuel oils are the principal fuels of industry. There is no appreciable use of coal.

Smoke, in the common usage of the word, is a minor source of nuisance although it is produced in burning combustible rubbish and in the improper firing of fuel oil. Many of these sources of smoke have been eliminated during the past year and current studies indicate that dust and fumes are the predominant aerosols.

METEOROLOGICAL ASPECTS

Temperature inversion and the local wind patterns aggravate the air contamination (*1*). The persistent temperature inversion limits the vertical distribution of the pollution by turbulence, and advection of the local winds distributes it beneath the inversion layer. Marked inversions are most prevalent in the summer months but sometimes occur in winter especially when a high pressure area develops over the Great Basin. There was an annual average of 262 days of temperature inversion in the Los Angeles area in the 3-year period, 1943 to 1945 (*9*). Figure 1 illustrates a characteristic period of inversion from August 16 to 19, 1948. This was a time of protracted low visibility and eye irritation.

The average wind velocity in the Los Angeles basin is 5 miles per hour in summer and 7 miles per hour in winter. Figures 2 to 4 are composite maps based on a study (*10*) made for the Los Angeles Air Pollution Control District in 1947 by the University of California at Los Angeles, which illustrate the diurnal changes of surface winds throughout the year. Figure 2 shows the location of the principal industrial areas and the direction of the sea breeze from 9:00 A.M. to noon in summer. The sea breeze pattern from noon to midnight in summer and from noon to 4:00 P.M. in winter is similar (Figure 3), although afternoon wind velocities are lower in the summer season. At night, in both summer and winter, a land breeze of 1 to 3 miles per hour moves down from the mountains toward the coast (Figure 4). This régime sets in at midnight in summer and continues until about 7:00 A.M., and begins around 7:00 P.M. in winter and continues until 10:00 A.M.

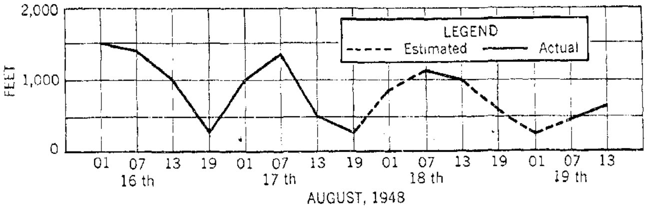

Figure 1. Variation in Base Temperature Inversion at U. S. Weather Bureau Station, Federal Building, Los Angeles, Calif.

The sea wind reaches its highest velocity in mid-afternoon in both winter and summer as a true westerly (Figure 3). As it moves eastward from the coast it follows topographically lower elevations until the stream splits,