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Weather Modification and Smog

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The three essential ingredients in the recipe for the Los Angeles type of smog (*1*) are (i) sources emitting pollution into the air, (ii) atmospheric conditions which deter or prevent rapid transport of these pollutants in the atmosphere, and (iii) solar radiation for the photochemical reactions which transform the relatively innocuous pollutants into substances which cause irritation to the eyes and the respiratory tract and damage to plants. In the Los Angeles area the first ingredient is continually present and constantly increasing. The second ingredient, the lack of dispersal by atmospheric motions, and the third, the intense short-wave radiation, depend on weather conditions, and the conditions in the Los Angeles Basin are predominantly favorable for accumulation, rather than dispersal, of pollutants and for plentiful sunshine for photochemical reactions during much of the year (Fig. 1). The prevalence of the subtropical inversion and the preponderance of light winds or calms make it possible for objectionable concentrations to accumulate in the basin within the course of a single day, and days with low inversion tend to be cloudless and bright.

It is frequently suggested that it might be simpler to attack the problem of eliminating the second ingredient or the third rather than the first, since the first ingredient is so intimately associated with a healthy industrial and economic development.

In the present article, the various proposals for modifying the weather in order to eliminate smog are discussed. The conclusion, unfortunately, is that elimination of smog by weather modification is even more difficult or costly than control at the sources. This applies, of course, only to those proposals which have thus far come to my attention. It is quite conceivable, however unlikely, that someone will come forward with a feasible scheme. My intention in this article (*2*) is not to discourage speculation along these lines, but only to insure that persons who engage in such speculations are aware of the proposals which have been made previously, and the reasons why they are impractical. With this background to guide their thinking, it is hoped that further speculation will not be repetitive and that it will have a better chance of being fruitful.

Meteorological Factors Leading to High Pollution

The conditions which are responsible for the accumulation and lack of dispersion of pollutants emitted into the atmosphere in the Los Angeles area are part of a large-scale pattern associated with dynamic processes involving tremendous quantities of mass and energy. The subtropical inversion which prevails over Los Angeles is characteristic of the entire eastern portion of the Pacific Ocean as well as of the subtropical oceans and the adjoining west coasts of continents throughout the world. The inversion is produced by subsidence of air circulating from the north around a high-pressure center which is present over the eastern North Pacific Ocean most of the time during the warm months and frequently at other times during the year.

The prevalence of light winds and calms over the Los Angeles Basin is likewise associated with the basin's position in relation to the general circulation of the atmosphere. The normal wind in the Los Angeles area may be regarded as a monsoon, or seasonal wind, on which is superposed a diurnal sea-land and valley-mountain wind effect. In summer, the prevailing seasonal surface wind is southwest or west, representing the tendency of the air to flow from the high-pressure area over the ocean to the thermal low over the interior desert. The addition of the effects of diurnal heating and cooling result in moderate winds from the ocean during the day, and calm or light land breezes from the north and east at night.

To illustrate the nature and significance of the inversion, Fig. 2 shows the average variation of temperature with height at Long Beach at 7 A.M. in September. On the average, the inversion layer begins at 475 meters above sea level. Below this level the temperature decreases with height, as is normal in most places and situations in the lower atmosphere. Above 475 meters, however, the temperature increases as one proceeds upward, until the top of the inversion layer is reached, at 1055 meters, at which point the temperature begins to decrease with height once more. It has been found (*3*) that, as one proceeds inland from the coast to the foothills, the height of the inversion above the ground is, on the average, about constant.

To see why the base of the inversion acts as an effective lid on the upward dispersion of pollutants, it must be remembered that, when a parcel of air rises, it cools at a rate of about 1°C per 100 meters of rise. If a parcel of air is given an upward impetus from the ground, it will arrive at any level below the inversion with a temperature only slightly lower than that of the surrounding air and, thus, will be subjected to very little downward force. Consequently, it would have a moderately long period during which it could mix with its surroundings before it sinks. On the other hand, air which rises into the inversion immediately finds itself much cooler than the air surrounding it and is quickly accelerated downward, so that it gets little opportunity to mix its contaminants with the inversion air.

The typical wind regime in the Los

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Angeles Basin during the warm season, which includes most days with severe smog, is illustrated in Figs. 3 and 4. Figure 3 shows streamlines and isotachs (lines of equal speed) at 2:30 P.M. P.S.T. on 21 September 1954, when the sea breeze was near its maximum. Most of the streamlines originated near the west coast of the basin, and the wind speed was greatest there. During the afternoon and early evening the sea breeze died down and was replaced by a land breeze. Figure 4, the map for 2:30 A.M. on 22 September, is fairly representative of the entire period from 8:30 P.M. to 8:30 A.M. At this time the streamlines were generally the reverse of those at 2:30 P.M. The speeds were 2 miles per hour or less over most of the basin. The speeds remained low until the sea breeze replaced the land breeze at about 9:30 the following morning. The daytime hours are thus characterized by light or moderate winds from the ocean, and during the night and early morning hours gentle land breezes or calm conditions prevail. From the standpoint of air movement, the concentrations of pollutants emitted during the night and morning hours build up to high values, and then, with the onset of the sea breeze, the air containing these high concentrations is transported across the basin.

Proposals for meteorological modification are ordinarily aimed at increasing the volume into which the contaminants may spread, either by raising or eliminating the inversion or by causing the air to move more rapidly across the basin. Occasionally methods have been proposed for reducing the solar radiation below the level required for photochemical reactions. In the following sections, each of these types of proposals is discussed in turn.

Penetrating or Dissipating the Inversion

The first idea which suggests itself to one who is aware that the inversion is a prime factor responsible for the high concentration of pollutants is to consider ways of eliminating it or at least "punching a hole" in it. In considering the practicality of this idea, it is important to realize exactly what is meant by the phrase *eliminating the inversion.* It is not at all a matter of removing the air in the inversion layer. If one were to do so, of course, the result would be to have the warmer air above the inversion top immediately in contact with the cool air at the inversion base, and thus have a still more impenetrable ceiling on the upward movement of pollutants.

Elimination of the inversion can mean only one of two things: (i) cooling all of the air from the inversion base upward to a temperature below that at the inversion base, or (ii) warming all of the air below the inversion top to a temperature higher than that at the inversion top. Since there is much less air below the inversion top than there is above the inversion base, it is obvious that the simpler procedure would be to raise the temperature of the air up to the inversion top sufficiently to eliminate the inversion. "Punching a hole" in the inversion can be interpreted intelligently only as eliminating the inversion in the same fashion over a restricted area.

It is relatively simple to compute the amount of energy required to heat the layer below the top of the inversion sufficiently to eliminate the inversion. Assuming that the energy would be injected at the ground, the process of heating

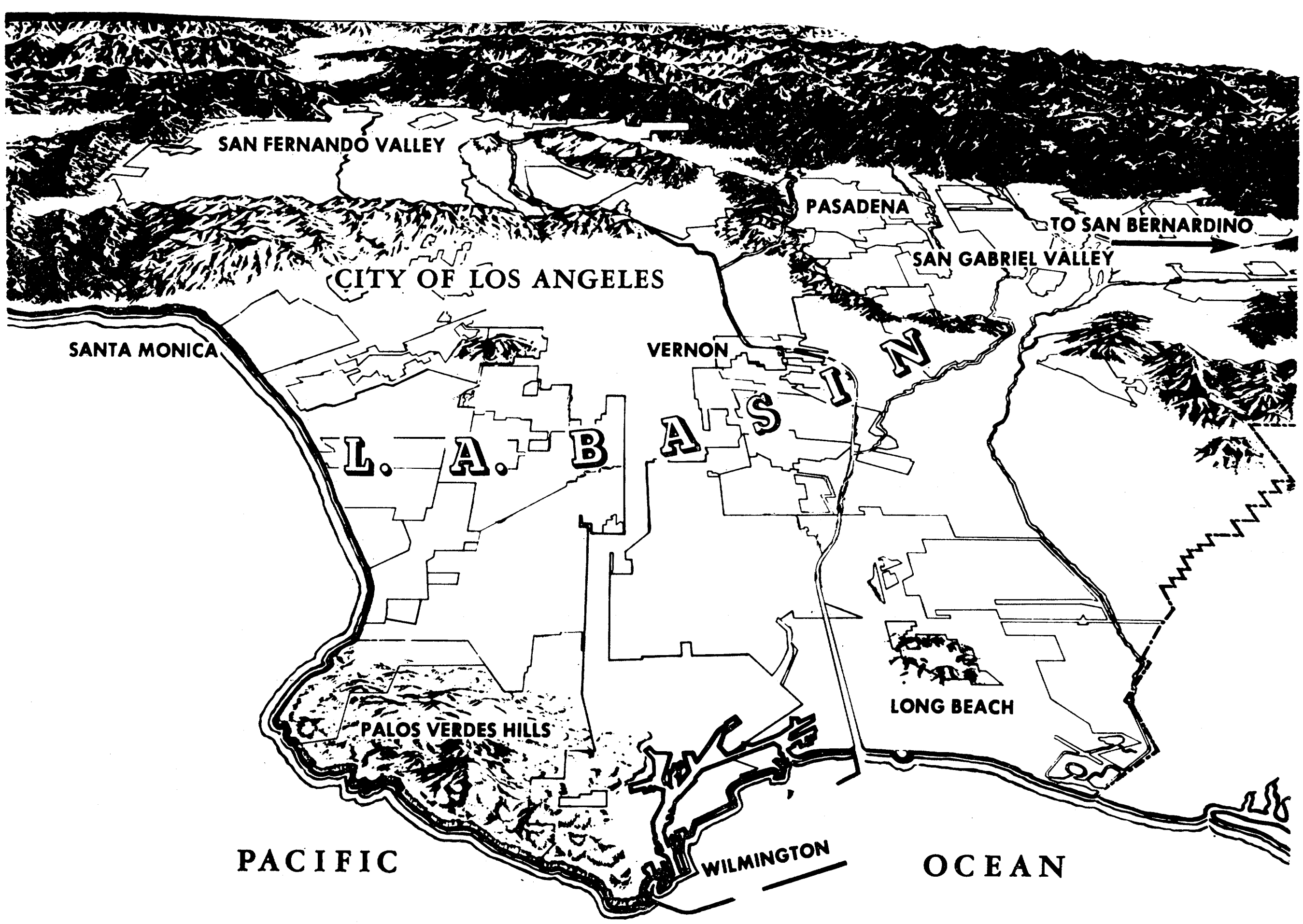

Fig 1. Topography of the Los Angeles Basin. [Watson Photos]

would necessarily establish an adiabatic lapse rate. If we assume that the lapse rate below the base of the inversion is initially adiabatic, and that the rate of temperature increase with height in the inversion is linear, it is easily shown that the energy E required to eliminate the inversion is given by the following equation:

$$E = c_p\rho[\gamma_d(H_T - H_B) + (T_T - T_B)]\frac{H_T + H_B}{2} \qquad (1)$$

where c_p is the specific heat of air at constant pressure, ρ is the average density of the air below the inversion top, γ_d is the dry adiabatic rate of cooling, H_B and H_T are the heights, and T_B and T_T are the temperatures at the base and top of the inversion, respectively. For the average conditions at Long Beach at 7 A.M. in September, we have the following values: H_B, 475 meters; H_T, 1055 meters; T_B, 14.1°C; T_T, 22.4°C.

Inserting these values in Eq. 1, we find that the energy required to eliminate the inversion is 330 calories per square centimeter. The area of the Los Angeles Basin is usually taken to be 4000 square kilometers, so that the amount of energy required to eliminate the inversion over the entire basin is 1.32×10^{16} calories. It would take approximately 1.27 million tons of oil burned with 100-percent efficiency to produce this amount of heat. This would be equivalent to burning the amount of crude oil that is processed by all the refineries in the Los Angeles Basin during 12 days.

The preceding computation is made on the assumption that the air remains in place throughout the heating period. However, actually the process of heating itself would create horizontal motion which would bring new cool air in over the basin and thus tend to restore the inversion or to make it necessary to use more fuel in order to eliminate it. This, indeed, is what happens every day as a result of the sun's radiation. The total energy arriving at the earth's surface from the sun ranges between 500 and 700 calories per square centimeter, per day during the smog season. While part of this energy is utilized to heat the ground, to compensate for long-wave radiation, and in evaporation and transpiration, and part of it is reflected from the ground, a considerable proportion is utilized in raising the temperature of the air.

Ordinarily, the amount of heat going into the air is not sufficient to eliminate the inversion, except in the foothills, where the layer below the inversion top is shallower than it is over the coastal plain. However, the amount of heating which it achieves is sufficient to set up the sea breeze and bring in the cooler air over much of the basin. The incoming cooler air results in a greater intensity of the inversion than would exist if the direct effect of heating were not accompanied by its indirect consequence. The divergence of the air flow in the sea breeze actually results in a lowering of the height of the inversion base from morning to evening near the shore (*4*).

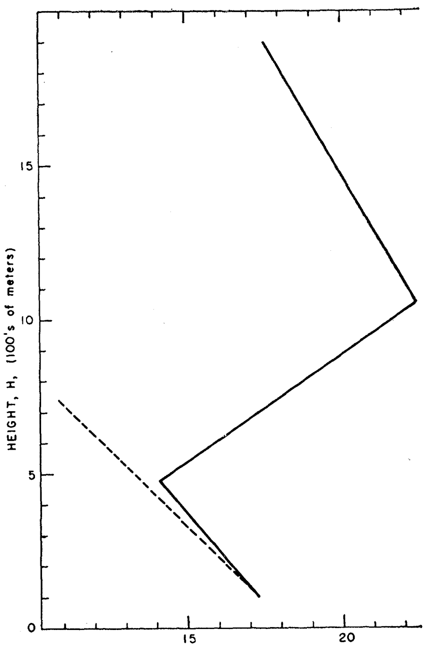

Fig. 2. Average variation of temperature with height at 7 A.M. P.S.T. in September at Long Beach, California.

The tremendous amount of energy required to eliminate the inversion completely leads to the suggestion that the heating be confined to a much smaller area. Since the amount of energy is proportional to the area, it is readily seen that, for instance, a 1-square-kilometer "hole" in the inversion would require 3.3×10^{12} calories, corresponding to burning about 320 tons of oil. It is often suggested that such a hole in the inversion would enable all the pollutants in the basin to pass upward. However, to cause any air to rise through the hole in the inversion, it would be necessary to heat it to the same potential temperature as that which was necessary for the elimination of the inversion. Thus, the amount of energy required would be the same, whether one attempted to get the air to pass through a small hole in the inversion or to eliminate the inversion over the area the air occupied originally.

There would be little advantage in building a stack up to the top of the inversion. Doing so might reduce the amount of radiation lost from the heated column and would surely eliminate the effect of entrainment, but the basic fact remains that all the air which one wishes to have penetrate the inversion must be heated to the potential temperature of the inversion top.

It has been suggested that if all the combustible rubbish in Los Angeles County were burned in a single large incinerator, adequate heat could be engendered to cause the pollutants from it to penetrate the inversion and, incidentally, to carry with them a large amount of entrained air containing other pollutants. It is estimated that about 14,000 tons of combustible refuse is burned in the basin. Allowing for its moisture content, we may reasonably assume a heat of combustion of about 5000 British thermal units per pound for the refuse. Using this value, we find that the total amount of refuse collected per day is adequate to eliminate the inversion over an area of about 10 square kilometers. Obviously, this is too small an area to create much interest from the standpoint of general removal of smoggy air. However, if it were possible to carry out the combustion in such a fashion that the pollutants therefrom penetrate the inversion, this would be one excellent way of eliminating a not inconsiderable source of pollutants, particularly particulates which reduce visibility. To achieve this, it would probably be necessary to erect huge stacks to heights of 2000 feet or more, in order to avoid entrainment and to conserve the high temperatures in the rising gases.

It has been suggested that some of the engineering difficulties in constructing stacks of this height can be avoided by having them take the form of pipes going up the slope of a mountain rather than having them be free-standing. The extra length of pipe in this case would increase the heat loss and decrease the flow rate, making it necessary to use tubes of larger diameter. The relative cost of constructing such a "smoqueduct" up the mountain, versus transporting the unburned rubbish up to incinerators at the top by truck or by conveyer belts, should be investigated if serious consideration is ever given to this scheme. Actually, it presently appears that the methods of disposing of rubbish by cut and fill or by well-designed incinerators equipped with adequate controls on the effluents represent more economical procedures.

In connection with the idea of eliminating the inversion by heating the air over the basin, it should be noted that the result would be to establish temperatures in the vicinity of 100°F over the basin for average inversion conditions, and somewhat higher values on days of low inversion which produce the most severe smog manifestations. Those who prefer these high temperatures to the smoggy conditions which are the unfortunate corollary to the otherwise more salubrious climate the inversion brings

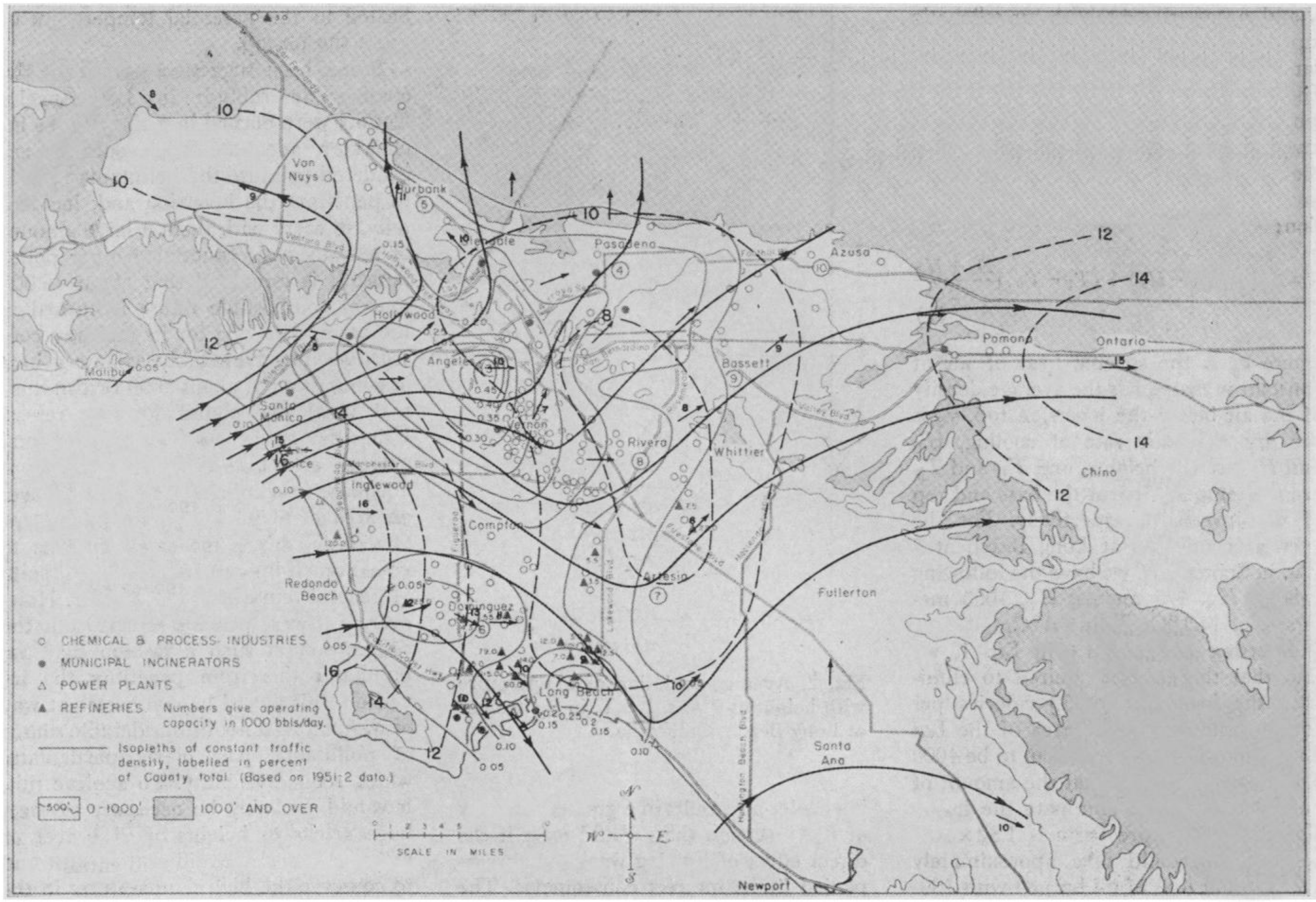

Fig. 3. Streamlines (solid lines) and isotachs (lines of equal speed, dashed lines) for 2:30 P.M. on 21 September 1954. Speeds are given in miles per hour beside station arrows and at ends of isotachs. The principal pollution sources and traffic density are shown in the background.

can achieve the same result with much less effort by moving to desert communities, such as Indio or Thermal.

Blowing the Smog Away

The other general proposal is to move the polluted air out of the basin. Leaving proposals to remove the mountains or dig tunnels through them for later discussion, it is of interest to compute the mass of air which would have to be moved and the energy required to produce the motion.

The average elevation of the inversion base is about 400 meters; over the 4000-square-kilometer area below this level in the basin, there are thus about 1.6×10^{12} cubic meters of air which, under average conditions of temperature and pressure on smoggy days, weighs about 2×10^9 tons. On a day with severe smog, the inversion is lower, but one might expect that, as a minimum, one-tenth of this amount of air, or 200 million tons, is involved.

L. A. Dubridge (*5*) has dramatized the problem by pointing out that this amount of air is twice the weight of all the steel produced in the United States in a year. This amount of steel, corresponding in size to a cube 1000 feet on a side, would be easier to move than the same amount of air "because at least you could load it on freight cars and haul it away."

Moving large masses of air is indeed more difficult than hauling away an equal mass of steel, for, in addition to the problem of getting hold of it, one must displace an equal volume of air (and thus an approximately equal mass) in the place one moves it to, and one must also provide for the energy to move in the air which replaces it. Rather than attempt to solve the complete problem of initiating the motion and providing for the necessary mass exchange, we shall confine our attention to computing the rate of energy expenditure required to keep the air moving over a flat area the size of Los Angeles—that is, the rate at which energy would be dissipated by ground friction. This amount is far below that needed to set up and maintain the motion in actuality, for it makes no allowance for the effect of the confining mountains, the opposing pressure forces which would arise the moment the air begins to move, or the turbulence created by the fans or other propelling apparatus.

If the wind stress is S dynes per square centimeter for a wind velocity v over an area A, the rate of work done in maintaining the wind is SAv. Now, the relationship of frictional stress to wind velocity may be expressed as

$$S = C\rho v^2$$

where ρ is the air density and C is a coefficient depending on the roughness of the surface over which the wind is blowing. Sutton (*6*) gives the following values of C for various surfaces, for v in centimeters per second: Ice, 0.002; close-cropped lawn, 0.005; thick grass up to 10 cm high, 0.016; thick grass up to 50 cm high, 0.032. Unfortunately no estimates are available for the value of C over the complex of surfaces comprising a city such as Los Angeles. It is reasonable to suppose that a value several times that for thick grass should apply.

The power required to keep the air speed constant is thus

$$E = C\rho A v^3$$

Taking A as 4000 square kilometers and ρ as 1.25×10^{-3}, we get $E = 5 \times 10^{10}\ C\ v^3$ ergs per second, or $5\ C\ v^3$ kilowatts. Table 1 gives the values of E for several values of C and v. We see that if the entire Los Angeles area were as smooth as a golf green, it would require about 400,000 kilowatts to maintain a 4.5-mile-per-hour wind, and 3.2 million kilowatts to maintain a wind of 9 miles per hour against friction. For the actual character of the surface, it would seem to be reasonable to assume that the values given in the second column should be minimum, and that the actual values would probably be between those of the second and third columns. Thus the power requirements for maintaining 4.5- and 9-mile-per-hour winds over the Los Angeles Basin are probably more than 2 million and 16 million kilowatts, respectively.

For comparison, the capacity of Hoover Dam is 1.25 million kilowatts. The total capacity of all electric generating plants in California is about 6.5 million kilowatts, and in the United States about 100 million kilowatts. To maintain artificially a 9-mile-per-hour wind over the Los Angeles Basin would require at least 12 Hoover Dams, more than twice the electricity produced in California, or at least one-sixth of all the electricity produced in the United States.

Interpreted in terms of 5000-horsepower engines converting their energy to pure translation of the air with 100-percent efficiency, more than 4000 such engines would probably be required just to overcome surface friction to maintain a 9-mile-per-hour wind. In terms of fuel consumption, this power corresponds to 1000 tons of fuel oil per hour converted with perfect efficiency.

Table 1. Power (E) required to maintain wind speed (v) against friction, for various coefficients of friction (C).

Wind speed, v		Power E (kw) for various coefficients of friction C			
(m/sec)	(mi/hr)	0.01	0.05	0.10	0.50
1	2.2	5×10^4	2.5×10^5	5×10^5	2.5×10^6
2	4.5	4×10^5	2.0×10^6	4×10^6	2.0×10^7
3	6.7	1.4×10^6	6.8×10^6	1.4×10^7	6.8×10^7
4	8.9	3.2×10^6	1.6×10^7	3.2×10^7	1.6×10^8

As stated previously, the problem of actually moving the air is far more complicated, and more requiring of energy, than simply overcoming friction. The fact that the latter process alone would require tremendous expenditures for equipment and fuel should be adequate to discourage proponents of the fan idea.

These computations likewise dispose of the proposal to build a tunnel through the mountains. If the tunnel were 100 feet in diameter, and if the air moved through it with a speed of 100 miles per hour, the amount passing through in a day would be 2.8×10^9 cubic meters, or about 0.2 percent of the air under the inversion when the inversion is at average height. If we consider that natural processes remove at least one-half of the air in the basin almost every day, we see that there is little likelihood that even 50 such tunnels would produce a noticeable effect on smog concentration, without taking into account the tremendous expense of digging such tunnels and the extreme difficulty of producing such velocities in tunnels several miles long.

In addition to proposals to blow away the smoggy air horizontally, there have been several proposals to achieve the same result by means of fans blowing air vertically. Usually ground-based fans blowing the smoggy air upward have been suggested, but there have also been two or three proposals to blow fresh air

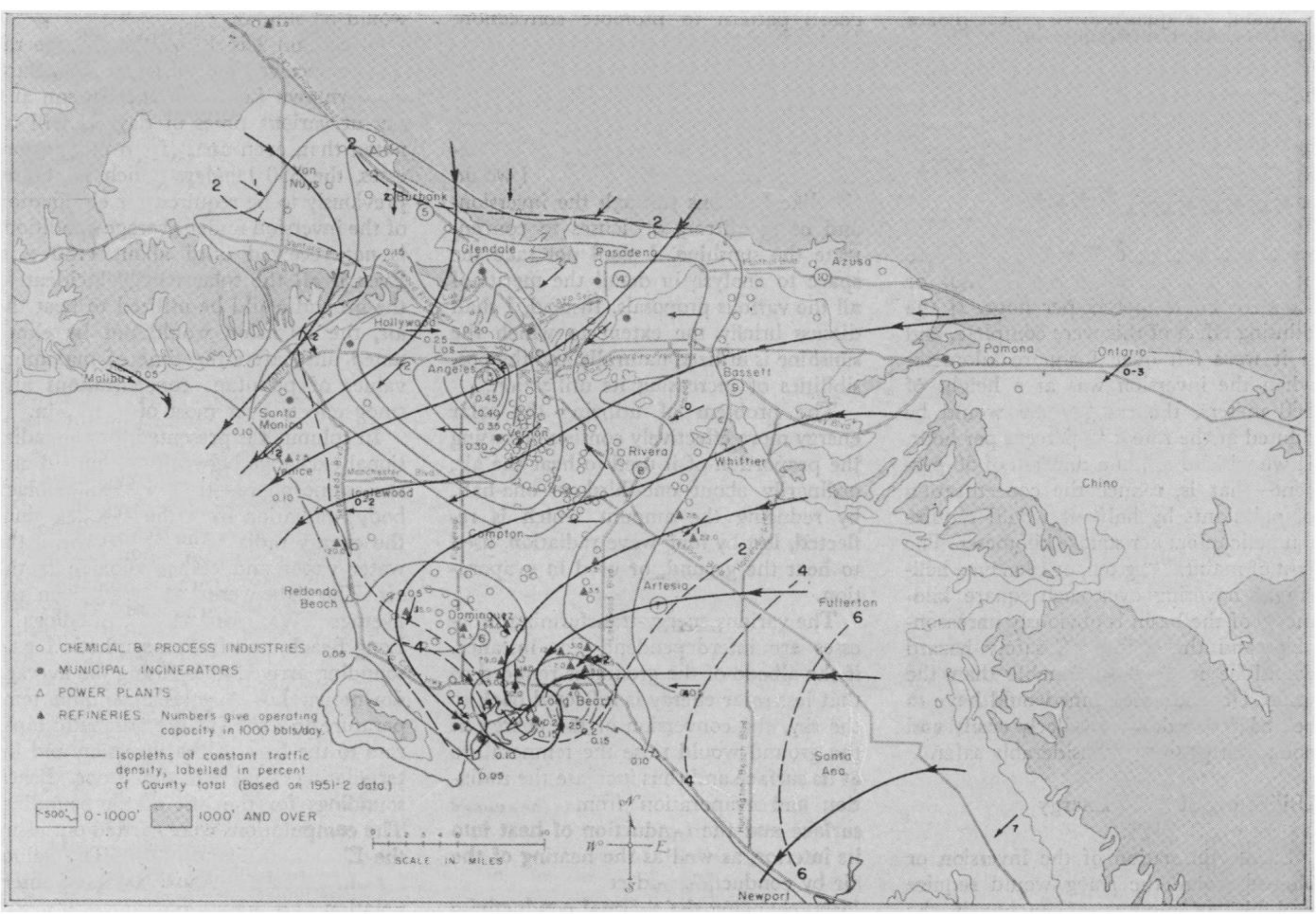

Fig. 4. Streamlines and isotachs for 2:30 A.M. on 22 September 1954 (see Fig. 3 for explanation).

downward from above the inversion base by means of hovering helicopters.

In addition to the problem of the quantity of air to be moved, the difficulty with ground-based fans blowing air upward is that, except for the effect of mixing, the air blown upward would be cooled adiabatically, rapidly becoming colder than its environment and thus subjected to a downward force which would decelerate it and ultimately accelerate it downward so that it would return to the ground. Mixing would, on the one hand, rapidly reduce the velocity of the rising air so that it would not penetrate as far into the inversion, and on the other hand, raise its potential temperature so that its equilibrium position would be somewhat higher and might under some circumstances be in the inversion layer.

The basic idea of having the horizontal fans take the form of hovering helicopters blowing down warmer air from the inversion layer to mix with the polluted air near the ground has the advantage that the mixture will be warmer than the environment at the ground and will rise to some position intermediate between the level of the helicopter and the ground. For the same amount of energy there would be a larger amount of dilution by air from the inversion layer than in the case of horizontal fans blowing upward.

Again, the quantitative aspect makes these proposals unfeasible. For instance, it is estimated that a moderately large helicopter hovering would produce a jet immediately below it of velocity 20 meters per second over an area of about 250 square meters. (This change in momentum corresponds to the hovering of a helicopter weighing 12 tons.) Thus air would be brought downward at the rate of 5000 cubic meters per second, or 1.8×10^7 cubic meters per hour. If the diluting effect of this were complete, and if it were felt over 1 square kilometer when the inversion was at a height of 360 meters, the smoggy air would be diluted at the rate of 5 percent per hour. If we wish to attain a dilution of 50 percent—that is, reduce the concentration of pollutants by half—it would require ten helicopters per square kilometer. The cost of maintaining ten, or even one, helicopter hovering over each square kilometer of the basin is obviously unreasonable, and the noise and safety hazard would be more objectionable than the smog. Ground-based fans would have to be at least as dense, similarly costly and noisy, but probably considerably safer.

Utilization of Solar Energy

Since elimination of the inversion or blowing away the smog would require prohibitive amounts of energy if the energy has to be supplied in the form of fuel or electric power, proponents of eliminating smog by weather modification have looked to the possibility of utilizing natural sources of energy. The approaches most frequently proposed have been (i) more effective conversion of solar energy to eliminate the inversion or cause greater air movements and (ii) triggering some potential instability.

The proposals to use solar energy take various forms. Some examples are painting the roofs of buildings in alternate city blocks white and black in a checkerboard pattern to promote convection; paving large areas of the basin with black asphalt for the same purpose and to eliminate the inversion; introducing black carbon dust into the air over the basin at low levels so that the air in contact with it would be heated and would rise like balloons through the inversion; and using mirrors or lenses to concentrate the sunshine. I shall not take the space to analyze in detail the merits of all the various proposals. Instead, I shall discuss briefly the extent to which the sunshine is utilized naturally and the possibilities of increasing its utilization.

The problem of utilizing the solar energy more effectively consists of raising the proportion of it used to heat the air, ordinarily about one-third to one-half, by reducing the amount which is reflected, lost by long-wave radiation, used to heat the ground, or used in evaporation.

The various energy-transforming processes are interdependent. For instance, if the albedo of the ground is reduced so that less solar energy is reflected back to the sky, the conversion of the energy at the ground would raise the temperature at its surface and thus increase the radiation and evaporation from the earth's surface and the conduction of heat into its interior, as well as the heating of the air by conduction and convection. Similarly, changing the thermal conductivity or heat capacity of the ground, or both, or its water content available for evaporation, would affect the surface temperature, and thus the outgoing radiation. Only a part of the energy which it is intended to tap by these modifications would be utilized for reducing the inversion or promoting convection.

As an indication of the possibilities, Table 2 shows an estimate of the average radiational and heat exchange at the ground in September, which is the month of most probable low inversion and smog in Los Angeles. Results for other months would be similar.

Table 2. Estimated average radiation-heat exchange at ground in September.

Hour (P.S.T.)	Accumulated energy (langleys) from sunrise to end of hour				
	Solar radiation	Net long-wave radiation	Conduction to ground and evaporation	Reflected from ground	Used to heat air
7 A.M.	6.2	6.7	2.5	1.2	−4.2
8 A.M.	24.3	13.7	9.5	4.9	−3.8
9 A.M.	58.0	21.1	20.2	11.6	5.1
10 A.M.	105.9	29.1	35.0	21.2	20.6
11 A.M.	164.6	37.5	51.3	32.9	42.9
12 noon	233.1	46.4	69.5	46.6	60.6
1 P.M.	305.2	55.6	89.0	61.0	99.6
2 P.M.	373.7	64.7	108.2	74.7	126.1
3 P.M.	432.2	73.7	125.5	86.4	136.6
4 P.M.	474.9	82.5	139.2	95.0	158.2
5 P.M.	498.3	91.0	147.7	99.6	160.0
6 P.M.	505.1	99.2	150.5	110.0	145.4

In column 2 is shown the average radiation received on a horizontal surface in downtown Los Angeles from sun and sky at various times of day. It will be noted that, even apart from other processes, the 330 langleys which we found previously to be required for elimination of the inversion under average conditions is not received until about 1:30 P.M. Even if all the solar energy incident at the ground could be utilized to heat the air, the inversion would not be eliminated until after the time of maximum values of pollutant concentrations and smog effects over most of the basin.

In column 3 is presented the net radiational exchange between the ground and the atmosphere—that is, the (black body) radiation from the ground minus the energy radiated back to it from the water vapor and carbon dioxide in the air. The data were computed from the average 7 A.M. and 7 P.M. soundings at Long Beach, and from a synthetic 1 P.M. sounding arrived at by using the average downtown Los Angeles maximum temperature to establish the adiabatic lapse rate to the base of the inversion and interpolating between the Long Beach soundings for the rest of the sounding. The computations were carried out using the Elsasser radiation chart. The values for other hours were estimated by interpolation.

It is probable that any modification

designed to increase the atmospheric heating would also, by raising the ground temperature, increase the net outgoing long-wave radiation. Thus the available solar energy would always be reduced by at least the amount in column 3. This would result in elimination of the inversion occurring, at the earliest, at about 2:30 P.M., if all other energy losses were eliminated.

There are no available data on which to base a sound estimate of the average heat conducted into the ground (and buildings) or used in evaporation for the Los Angeles Basin. Homén's measurements for various surfaces in Finland suggest that, while the amount conducted into the soil and that used in evaporation separately vary greatly for rock, sand, meadows, and other surfaces, the total of the two is roughly the same for the various surfaces. This result is reasonable, for, wherever water is available for evaporation, the ground-air interface temperature is kept from rising, and thus the temperature gradient downward into the soil is smaller than it is in the absence of evaporation.

As a crude approximation of the amount of energy consumed by these two processes, the data cited by Sutton from Lettau's evaluation of measurements made by the Sven Hedin expedition were used, with slight adjustment, in column 4 of Table 2. The values are probably slightly high because of the high desert temperatures; a total of about 120 langleys for the 12-hour period might be more reasonable. However, the data obtained by Pasquill for a meadow in England were not significantly lower, and it was decided to use Lettau's data without further modification.

The average reflectivity of the complex of surfaces in the basin is likewise unknown. Measurements summarized in the Smithsonian Meteorological Tables for various kinds of surfaces occurring in the basin (grass, 14 to 33 percent; dry, plowed fields, 20 to 25 percent; sand, 18 percent) suggest that a value of 20 percent might be reasonable, and this value has been used for computing the values given in column 5. Subtracting the values in columns 3, 4, and 5 from those in column 2, we get the amount of energy available to heat the air, column 6.

The occurrence of the cessation of heating of the air between 4 and 5 P.M. appears to be inconsistent with the usual occurrence of the maximum temperature about 2 to 3 hours earlier. The occurrence of the sea breeze, which brings in air which has been over the ocean, may in part account for this discrepancy.

It has already been pointed out that, even if all the energy represented by columns 4 and 5 were utilized in heating the air, the inversion would not be eliminated before 2:30 P.M., considerably after the smog normally is swept away from downtown Los Angeles by the sea breeze. Obviously, a complete elimination of these "losses" is impossible. Only a part of the surface of the basin is subject to being painted black to reduce the reflectivity, or with an insulating material to reduce conduction into the ground. The lawns and gardens, forming part of the attraction of the area to residents and visitors alike, could not be covered with such surfaces without objections even greater than those which the smog has aroused. If, optimistically, one-half the losses were eliminated over one-half the area the air passes over in reaching downtown, the 25 percent saving would be inadequate to eliminate the inversion.

Recognizing that alteration of the entire surface of the basin is impractical, some people have proposed paving selected areas in it, to eliminate the inversion locally and allow the smog to escape through the "holes" thus created. Unless the areas were very large, comprising tens or hundreds of square miles, the air ordinarily would move off them before it was heated enough to eliminate the inversion.

A variant of this proposal has as its purpose the use of solar energy to cause greater horizontal movement of the air. If the sea breeze starts earlier or is stronger, for instance, the smog will not reach as high concentrations and will move out more quickly. To accomplish this, it has been proposed that the large canyons extending upward into the mountains be cleared of brush and paved with a nonreflecting and nonconducting substance. Clearing the brush and paving would reduce the frictional resistance to flow and at the same time increase the temperature, causing the up-slope winds to begin sooner and flow faster.

Again, quantitative considerations show that this effect at best would be a minor one. For every 1 meter per second that the sea breeze is increased on the average up to the inversion base, and for a 0.5-kilometer wide canyon, the total increase in air transport would be 10^9 cubic meters per hour, or less than 1/1000 of the air over the basin per hour. As in the case of the proposal regarding tunnels, it would require hundreds of such canyons, or, equivalently, hundreds of square miles of mountain slope to be cleared and paved to produce any considerable effect.

Triggering Potential Instability

We have seen that methods of adding energy or making better use of the natural energy input give little promise of ameliorating effects. The question arises, is there any possibility of releasing energy already in the system to produce the desired change? The answer, so far as the thermal stratification is concerned, is that the situation is extremely stable: there is no available potential energy. The large and extensive inversion is analogous to a cork raft on water, which bobs back into position no matter what the disturbance.

The wind distribution during smoggy periods, like the thermal distribution, contains no potential instability. Even at the time of maximum sea breeze, the wind shear through the inversion is very small, and during most hours the winds are light both below and above it. Thus there is no shearing instability to offset the thermal stability. With the warm layer above the cold, and with little or no kinetic energy available for redistribution, the possibilities are absolutely nil.

However, as has been pointed out by D. Van Ornum in proposals to the Air Pollution Foundation, there exists in the moisture distribution a possibility of altering this situation. The air above the inversion is so dry that, by evaporating water into it until it is saturated, it would be cooled to a potential temperature below that of the air below the base of the inversion. Van Ornum suggested that a string of fog nozzles be established along the mountains at, say, the 2000-foot contour. By saturating the air at this level, a downward flow of air would be induced which at night would increase the land breeze, and in the daytime offset the sea breeze, producing a continuous flow of air from land to sea. There are many interesting aspects of Van Ornum's proposal on which to speculate, such as the wind speeds which might be achieved during the day. For instance, it might turn out that the effect would be just sufficient to invert the normal regime, producing fairly rapid flow during the night and practically stagnation during the day. However, the economics of the proposal again make unnecessary the consideration of details.

The amount of water required may be estimated in various ways. Van Ornum's own estimates have varied from 6000 to 11,500 acre feet per day, which correspond to from 5 to 10 times the total water consumed by Los Angeles in a day. Obviously, even apart from the cost, such a large amount of water cannot be diverted to this purpose in a region of dire water scarcity. The possibility of using sea water has been mentioned. The problem of pumping this quantity of water from the sea to elevations of 2000 feet is not insuperable, though doubtless costly, but the problem of designing fog nozzles which would operate with sea water without corroding or clogging appears to be difficult indeed, and the effect of introducing into the air about 4×10^8 kilograms of salt per day might prove as objectionable as the pollution which we are attempting to remove. The visibility would be greatly reduced, and the corrosive action of the air-borne salt would be great.

In addition to the problems involved in water supply, the cost of equipment and power would be tremendous. The height at which the fog nozzles would have to be mounted would depend on the drop size they are capable of producing. The smaller the drops, the less the height required in order to insure complete evaporation, but the more power required to break up the drops and the more nozzles required to produce the same volume of discharge. Even if towers only 100 feet high are required, the cost of constructing several per mile along the 2000-foot contour surrounding the basin, plus the cost of the spray nozzles, the water distribution lines, the pumping stations, and the electric power installations, could surely pay for the installation of equipment for controlling all the sources of pollution in the basin.

There have been other proposals to use water spray to wash and cool the smoggy air, in order to produce a film of clean cool air at the ground, say in the lowest 20 feet where most people are. On the one hand, the difficulties of scrubbing the pollutants, particularly the gaseous ones, even from air with higher concentrations of pollutants, suggest that the cleansing action of the spray would be partial at best. On the other hand, to the extent that the drops are large enough to reach the ground, carrying pollutants with them, the water is not evaporated to cool the air. Sufficient evaporation would be required to offset the solar heating at the ground, and it would have to occur uniformly over the entire area, or else convection would mix the "cleaned" air with polluted air above. Thus the water requirement would be even greater in this case than in Van Ornum's proposal.

Reducing the Insolation

As an alternative to the reduction or elimination of the reagents which participate in the photochemical reactions to form smog, it has been proposed that attempts be made to reduce the sunlight that causes the reactions. The concentration of oxidant, and presumably of other smog effects, appears to be directly related to the intensity of the shorter-wave solar radiation received at the ground. Leighton has studied this relationship (*7*). If the photochemically active portion of the sunlight were reduced sufficiently, the smog effects should be reduced below the noxious or nuisance thresholds.

A reduction of this type could be achieved by introducing an aerosol consisting of small droplets, which would scatter the sunlight, returning much of it back to the sky. The intensity of scattering depends on the drop size and the wavelength. For a given wavelength, there is a particular size of drop which maximizes the amount of scattering per mass of liquid suspended in the form of droplets. Short-wave sunlight is scattered most intensely by a given mass of oil of refractive index 1.5 if it is dispersed in drops with diameter in the range of 0.4 to 0.5 micron. Langmuir has suggested that smoke generators of the type which produce uniform drops of the required size be located along the western coast of the basin and operated for 5 or 6 hours from the time of the beginning of the sea breeze (9 A.M.). Assuming an average sea-breeze speed of 6 miles per hour, and about 15 miles of coast line, the area covered would be about 100 square miles, per hour. Langmuir has computed that about 10 gallons of Diol per square mile, or 1000 gallons (4 tons) per hour would reduce the intensity of sunlight 50 percent. My own computation indicates that the requirement is about 10 times this amount, but in either case the consumption of oil (24 tons per day, or 240 tons per day) would not be prohibitive if it were to produce the desired effect and no others.

The question whether a 50-percent (say) reduction of the insolation would necessarily eliminate the undesirable smog effects is a moot one. There have been days when fog and stratus clouds limited the total radiation for the day below this fraction, and yet severe eye irritation was experienced in some parts of the basin. The peak values of oxidant on these days were generally lower than on clear days, but this is not the only instance of lack of perfect correspondence between oxidant concentration and other smog effects. To settle the question, it might be worth experimenting with smoke screens, were it clear that this solution would be otherwise feasible and acceptable.

With respect to feasibility, the location of the smoke generators along the coast presupposes that air reaching all points in the basin with intense smog has entered across the west coast the same morning. Trajectory studies (*8*) have shown that, frequently, air arriving at sampling stations at times of peak concentrations of contaminants crossed the coast the previous afternoon and stagnated over the basin throughout the night. Furthermore, on some days in late fall, when some of the worst smog sieges occur, the winds are easterly during the day as well as at night. Thus, to handle all types of smog situations, the smoke generators would have to be dispersed widely, and the appropriate ones would have to be operated continuously for as much as 24 hours previous to times when conditions are expected to be favorable for smog.

Finally, the question of the acceptability to the community of this type of solution must be considered. Sunshine is one of the assets of the Los Angeles climate. Sacrifice of one-half of this asset, over and above the 10-percent reduction produced by the smog itself, will appear to most citizens as a last resort, to be taken only if it proves impossible to eliminate smog by control of the sources of the pollutants. Similarly, the severe reduction of visibility would meet with great objections. A blanket of white oil smoke would be no more attractive than the yellow-brown pall of smog to people who cherish the view of mountains and sea, and of "Catalina Island on a clear day." Langmuir states, "I have been in London during heavy fogs when the light intensity at noon was much less than it usually is at midnight, yet there was not the unpleasant irritation that exists in Los Angeles smog." But one would hope for a cure which would not so nearly resemble the ailment.

There have also been suggestions that the reaction might be inhibited by dispersal of some additional chemical agent into the air. No specific chemical has been proposed for this purpose, but at least one private organization has expressed willingness to accept a contract to explore the possibility. As in the case of other proposals, the advocates of this vague notion have succeeded in getting newspaper publicity which put pressure on the public agencies to divert funds from the direct attempts to control the sources of pollutants. Even though the Los Angeles County Air Pollution Control District has successfully (and in my estimation wisely) resisted these pressures, it has not been without cost in terms of time required to study each such proposal.

Conclusion

Unfortunately, most proponents of schemes to abate the smog by meteorological modification consider that they have done their share in coming forward with the general ideas, and that it becomes the duty of the county Air Pollution Control District or the private Air Pollution Foundation to work out details and conduct all necessary computations and experimental tests to demonstrate whether or not they are feasible and workable. When it is suggested that the proponents should carry out some feasibility computations on their own to see whether their ideas deserve serious consideration, they frequently reply with the charge that the "vested interests" have "negative attitudes" in their attack on the problem.

Such negative attitudes as exist in this matter are based on familiarity with the situation and repeated computations of the type given here. Having examined many proposals, one is naturally reluctant to spend time on detailed study of another variant.

Only a completely new and unique approach to weather modification could have any hope of success in eliminating or ameliorating smog. Until such a unique approach has been demonstrated to be effective, it is reasonable for the agencies concerned with the solution of the problem to devote their undivided efforts to the detection and control of the sources of the pollutants responsible for the obnoxious and deleterious effects of smog.

References and Notes

1. *Smog,* originally a contraction of *smoke and fog,* has come to mean, generally, obnoxious concentrations of air pollution, and in Los Angeles specifically, the eye-irritating, plant-damaging, and visibility-reducing mixture which develops in the daytime on days of low inversion and light winds.
2. Much of the background work for this article was carried out while I was senior meteorologist at the Air Pollution Foundation, Los Angeles, Calif.
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R. Chambers, Pioneer in the Study of Living Cells

In the death of Robert Chambers in his 76th year, the scientific world has lost one of its most illustrious names. Biologists everywhere will be saddened, but many will call to mind his remarkable contributions to the study of living cells. Chambers was best known for his fundamental and enduring work on the biophysics of protoplasm. Many special problems and characteristics of plant and animal cells were resolved and made understandable by the use of microinstruments which he devised, improved, and logically exploited. To scholars of cellular physiology, his work on the structure of living membranes, capillary physiology, mesonephros function, fertilization problems in marine eggs, and adhesiveness of cancer cells in tissue culture remains classical. His astonishing development of the micromanipulator, along with the essential glass needles, micropipettes, electrodes, and microgages, stands as a landmark in the progress of science.

A contemporary and close friend of men like T. H. Morgan, E. B. Wilson, E. G. Conklin, and G. H. Parker, Chambers was nevertheless a *modern* man. It is to his credit that more than half of the program for the forthcoming International Congress for Cell Biology, in Scotland, is, almost prophetically, directly related to cellular studies in which he was at one time or another actively engaged. He furnished basic ideas for others to follow. His superlative services to biology and to science are, unfortunately, not so well known.

Born in Erzurum, Turkey, of Canadian missionary parents, he grew up in a deeply religious household and in the exciting atmosphere of Armenian-Turkish disputes. He is credited with having, as a boy, single-handedly interrupted a village massacre, preventing further bloodshed.

The prime quality of Chambers throughout his long life was his warm, human sympathy for his family, his students, and his host of friends in many lands. At his home, he and Mrs. Chambers entertained prince and pauper. No one was turned away. In a characteristic way he named his first cottage on the shores of Buzzards Bay "Bobtucket." His hospitality knew no bounds. His long associations with New York University, where he was research professor of biology, and with the Marine Biological Laboratory of Woods Hole, of which he was a trustee, enriched both institutions immeasurably.

This is not the place to review fully his education and early life at Robert College, Istanbul, or his later education at Queens University in Canada and at the University of Munich, where he became Richard Hertwig's favorite (and most famous) student. He belonged to one of the oldest German student corps, but he told me he never actually fought a duel! His numerous honors, positions, and accomplishments will be listed in the archives of many societies to which he belonged. Mention must, however, be made of his having been president of the American Society of Zoologists, the Harvey Society of New York, and the former Union of American Biological Sciences. In the latter group his efforts led directly to the formation and establishment of the present American Institute of Biological Sciences. He was a founder of the Society of General Physiologists. With Josef Spek, he founded and edited the journal *Protoplasma.* He was an active member of the committee of scientists that persuaded the United States Congress to set up the National Science Foundation. As senior scientific adviser to the New York World's Fair, his laboratory provided free motion pictures of living cells that attracted the largest number of public visitors of any educational exhibit. It is noteworthy that he was the chief spirit in the renaissance of the New York Academy of Sciences that led to its present prestige and fame.

Chambers loved adventure, he loved his family, but above all he loved the eternal search for scientific truth. To him, religion and science were indivisibly one. While it it true that he also knew personal tragedy and felt the slings and arrows of outrageous fortune and the discouragements of seeking almost parsimonious research-grant support, it is nevertheless true that his life was a deeply happy one. Indeed, the monuments to his career are the basic facts he discovered, the achievements of his students, the flourishing of the societies, journals, and ideals which he literally built with his own brilliant intellect, and the profound respect and admiration of his world-wide circle of friends and fellow-scientists.

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