PARTICULATE AIR POLLUTION
GENERAL

8000 0614

# PARTICULATE EMISSIONS

by W. R. Pierson

## I. Aerosols - General

Suspended in the atmosphere are small particles of diameter up to, say, 0.01 cm (that is, 100 microns of 100 μ). Some of these particles are solid, some are liquid (usually containing dissolved solids), and some contain both a solid phase and a liquid phase. These particles are collectively called "particulates" or "aerosols."

The size distribution of particulates in continental air is usually found to be as in Fig. 1, the right-hand part of which has a slope approximating - 3 on a log-log plot of dn/d log r vs. r.

This is what is called the Junge distribution. A plot of $r^3$ dn/d log r vs. r for an aerosol following the Junge distribution looks like Fig. 2. Since $r^3$ dn/d log r = dV/d log r, what Fig. 2 says is that in a continental aerosol there are generally about equal amounts of particle volume (hence, mass) in each log r interval; for example, the mass between 0.1 and 1 μ is approximately equal to the mass between 1 and 10 μ. This holds true in polluted atmospheres sufficiently far from a single source but is not true in clean marine atmospheres, where large sea-salt particles predominate.

Particulates are involved in several atmospheric phenomena; as shown in Fig. 3, a given effect will generally be dominated by particles of certain sizes rather than by all the particulates in the air sample. For example, visibility reduction has to do mostly with particles in the size range of 0.1 to 1.0 μ.

Gravitational settling velocities depend on particle size as shown in Fig. 4. It is gravitational settling that limits the upper end of the particulate size spectrum (Fig. 1). However, gravitational settling is unimportant for particles smaller than 1 $\mu$. The atmospheric residence time of airborne particulate matter is on the order of days or weeks. Mechanisms for removal of particles are, besides gravitational settling,

1) Inertial impaction onto surface obstacles (trees, buildings, and so forth) (mostly large particles)
2) Growth by coagulation with other particles (mostly small particles)
3) Growth by accretion of material from the vapor phase (including condensation of water vapor to form raindrops) (mostly large particles) (2 and 3 can then be followed by removal by gravitational settling and inertial impaction)
4) Washout by raindrops falling from the clouds above (mostly large particles).

There is, additionally, one major mechanism for particle shrinkage, though not usually complete disappearance; namely, evaporation.

Nucleation of particulates is of two types: 1) heterogeneous nucleation, i.e., buildup onto a tiny already-existing particle, or 2) homogeneous nucleation from the gas phase without benefit of nucleating centers. There are usually plenty of nucleating centers present to allow process 1), so that process 2), which requires a many-fold supersaturation of condensable material in the vapor phase, seldom occurs.

Processes of formation of aerosols include combustion; chemical reactions of gases in the atmosphere (e.g., photochemical smog); condensation from the vapor phase; injection by biological processes (e.g., spores, pollen); spray from the sea surface; dust stirred up by the wind or kicked up by men, animals, and machines; comminution (grinding up material by natural or man-made operations); and many other processes. The first two dominate in considerations of air pollution.

Representative particulate loadings for various situations on the earth's surface are shown below.

Table I. Examples of particulate loadings

| Place | Number/$cm^3$ | $\mu g/m^3$ |
|---|---|---|
| Remote ocean | 200 | 10 |
| Remote rural | 10000 | 35 |
| Settled rural | 35000 | 65 |
| Industrial areas | 200000 | 150 |
| Auto exhaust pipe | $10^8$ | 40000 |

## II. Air Pollution Aerosols

Emissions inventories have produced the following numbers for the amounts of various materials emitted to the atmosphere. (Ref. 5 has most of these numbers.)

Table II. Estimated annual emissions, tons

(Particulate emissions refer to material emitted as particulates, and not particulates formed photochemically, etc.)

| | |
|---|---|
| Global particulates from natural sources | $2{,}400 \times 10^6$ |
| Global particulates from pollution | $100 \times 10^6$ |
| Total U. S. air pollution (1968) | $214 \times 10^6$ |
| Total U. S. particulates from air pollution (1968) | $28 \times 10^6$ |
| Total U. S. gaseous emissions from gasoline-driven vehicles | $81 \times 10^6$ |
| Total U. S. gaseous emissions from diesel vehicles | $1.3 \times 10^6$ |
| Total U. S. particulate emissions from gasoline-driven vehicles | $0.5 \times 10^6$ |
| Total U. S. particulate emissions from diesel vehicles | $0.3 \times 10^6$ |

(The last figure does not include railroads and other non-highway diesel fuel consumption, which is about equal to the consumption by road diesels.) Particulates formed in the atmosphere from gaseous pollutants (that is, sulfates from $SO_2$, nitrates from NO and $NO_2$, particulates formed by atmospheric photochemical reactions of hydrocarbons, etc.) amount to some $200 \times 10^6$ tons worldwide annually, or twice as much as the emissions of particulates qua particulates - so-called "primary" particulates - given in Table II.

## III. Air Pollution by Aerosols from Vehicle Engines

In discussing particulates from motor vehicles we will consider only the primary particulates and ignore the secondary particulates (e.g., photochemical smog) even though the latter are very important. As seen in Table II, the total mass of primary particulates from motor vehicles is a small part of the pollution from venicles or of the aggregate pollution picture nationwide and world wide. But within a restricted locality, the particulate contribution of the automobile can be significant as shown in Table III (from Refs. 4 and 7).

Table III. Vehicle particulate emissions and total particulate pollutant emissions in selected urban areas (includes gasoline- and diesel-powered vehicles).

| Urban area | Tons of particulate annually | |
|---|---|---|
| | Total | Motor vehicles |
| Washington, D. C. | 35000 | 5700 |
| New York and North N. J. | 231000 | 33800 |
| Kansas City | 60000 | 5000 |
| Jacksonville, Fla. | 14000 | 600 |
| St. Louis | 147000 | 4700 |
| Los Angeles County | 43000 | 16400 |

In the L. A. area, vehicles contribute an estimated 38% of the total particulates.

An idea of the rate of emissions from an individual vehicle can be obtained from the following (See Refs. 6, 7, 23):

Total particulate from automobile exhaust

≃ 0.35 g/mile or ~ 5 g/gallon of fuel consumed

Total particulate from diesel exhaust ~ 50 g/gallon of fuel consumed

The level of emissions depends on fuel composition, engine design, operating conditions, and other variables.

Gasoline-engine exhaust particulate contains the following (if leaded fuel is used):

Pb (mostly in compounds ) 20 to 40%

Carbon particles and various organic compounds, including raw or partially burned lubricating oil - variable ≈ 40%

Compounds of Ca and Mg ~ 2%

Cl and Br (in Pb compounds mostly) - 15 to 30%

Sulfur (largely as sulfate) - up to a few %

Fe and Fe oxides - a few %

Zn - a few tenths %

Al, Si, Cu - traces

The Pb, Cl, and Br are present by virtue of the tetra-ethyl lead together with the ethylene chloride and bromide added to scavenge the lead. Lead compounds that have been reported include PbClBr, $NH_4Cl(PbClBr)_2$, $(NH_4Cl)_2$ PbClBr, $[Pb_3(PO_4)_2]_3PbClBr$ if phosphorus additives are present, $PbSO_4$, and $PbO \cdot PbSO_4$ (see Refs. 4, 25, 30, 31, 32, 36). The lead halides form by condensation from the vapor phase as the cooling exhaust gas reaches the 350°C range. The Mg,Ca, and Zn are primarily from the lubricating oil, the ferrous material from wear

and rusting, the sulfur from the small amount (ca. 0.035%) present in gasoline. Solid hydrocarbons arise from the same sources as the gaseous ones in general. The carbon particles constitute a combustion aerosol, as would be formed in any flame.

Most of the particles in gasoline-engine exhaust are very small, as shown in Fig. 5. Particles as small as 0.01 μ are present in large numbers. Composition varies with size; for example, Fe is found mostly in the larger particles, while Pb concentrates in the small ones, as would be expected from their respective modes of formation.

Diesel engine exhaust particulate contains carbon particles (~50%), paraffin hydrocarbons (including unburned fuel) (~50%), paraffin acids (~1%), $H_2SO_4$ (~1%), Si(~0.01%), Fe (~ 0.005%), Zn (~0.005%), and traces of Al, Ca, Ni (see Refs. 41, 44); there will be compounds of barium or other elements if smoke suppressants are used. (Refs. 6, 7, 40, 41) The particles tend to be larger than those from gasoline-engine exhaust (see Ref. 6).

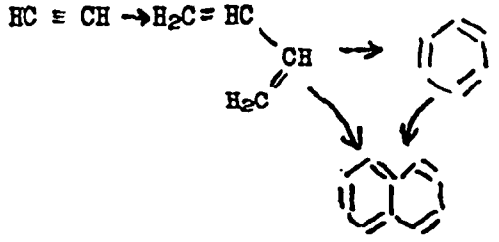
A given particle from a vehicle exhaust is unlikely to be simple in composition but rather will generally be a hodge-podge of inorganic and organic material. Because of their vapor pressures, the organic species can generally be expected to condense from the gas phase, normally onto some already-existing site. The amount of particulate matter experimentally found thus depends on experimental conditions. If the sample is collected hot, organic material will be in the vapor phase and will be missed. If the sample is cooled below ~50°C, water droplets will be collected unless the stream is diluted. Some organic constituents will evaporate after collection.

The unburned fuel comprising much of the diesel particulate has a room-

temperature vapor pressure of the order of $10^{-5}$ mm Hg (e.g., cetane, $C_{16}H_{34}$) and hence could not exist alone in a condensed phase unless the surrounding atmosphere were about 1 ppm diesel fuel by volume (10 ppm by weight); this illustrates the proposition that complex processes must be at work in order that certain species be observed at all.

Common to both gasoline exhausts and diesel exhausts, and indeed to combustion of any fossil fuel, are compounds called polycyclic hydrocarbons or polynuclear aromatic hydrocarbons (PNA). A few of them are shown in Fig. 6. There are a number of related compounds which, though not strictly hydrocarbons, should be considered along with the PNA's; examples are shown in Fig. 7.

PNA's are produced in greatest amount when the engine is run rich. They are present in gasoline to the extent of a few ppm, of which some 0.1 to 0.2% survives the combustion process and is emitted in the exhaust (see Ref. 24). A primary source of PNA's in exhaust, however, is thought to be a buildup from molecular fragments formed by pyrolysis of fuel or lubricating oil in the combustion chamber (see Ref. 8 Ch. 20, Refs. 39, 45):




napthalene

and so forth. About 30 PNA's have been found in automobile exhaust. They amount to some 0.1% of the particulate from a gasoline engine and a similar percentage of the particulate from a diesel engine. (Reference 46)

The vehicle has been estimated to contribute 2 to 40% of the compounds of this class found in urban atmospheres, depending on the city. (The main source of PNA in city air is the burning of coal, particularly in antiquated residential heating units; the strongest doses to individuals come from smoking -- cigarette smoke is full of PNA's.) The reason for concern about PNA's is that many of them, and their methyl derivatives, are carcinogens.

Factors effecting PNA emissions are the following: High aromaticity in the fuel gives high PNA emissions. High consumption of lubricating oil gives high PNA emissions. The presence or absence of lead anti-knock fluid seems to have little or no effect on PNA emissions if the rest of the gasoline composition is held constant. Avoiding a rich fuel mixture strongly reduces PNA emissions but little is gained by continuing to increase the air-fuel ratio beyond the stoichiometric value and into the lean region. Emissions of PNA's are at their highest during acceleration and deceleration. As a rule, emission controls for PNA's are the same as those for hydrocarbons in general and for CO: air injection thermal reactors on the manifold, catalytic converters, etc. Particulate traps reduce PNA emissions but not to an impressive extent. Much of the PNA produced in the automobile ends up in the crankcase; presumably, then, the control of blowby suppresses PNA emissions.

Fuel factors affecting the mass of emitted gross particulate matter are the following: The presence of Pb gives higher emissions (though Habibi and Jacobs of DuPont claim the opposite), mostly due to an increase in the amount of inorganic material (primarily Pb salts). However, there is some evidence that leaded fuel reduces the emission of carbon and/or carbon compounds during cold start and warmup. An increase in the amount of scavenger (ethylene dichloride, ethylene dibromide) in the anti-knock fluid causes emission of more particulate matter. Fuel additives such as upper cylinder lubricant seem to increase

particulate emissions; detergents may do the same, though this is disputed. Some investigators believe that anything that decreases engine deposits (more scavenger, presence of detergent additive) will increase particulate emissions; this seems possibly true since some 15% of the Pb consumed in running on leaded fuel is retained as deposits in the engine, exhaust system, etc. Another 10% of the Pb consumed seems to be retained in the lubricating oil. Replacement of tetra-ethyl lead with tetramethyl lead has no discernible effect on particulate emissions. High fuel aromaticity gives higher particulate emissions.

The rate of Pb emissions depends strongly on the immediate history of the engine and on engine speed. At low speed with a clean engine, the Pb emitted is only a small fraction (say, 20%) of the amount consumed, and deposits build up. With sustained light-duty service, Pb emissions eventually approach 60% of the Pb consumed. If, after a period of such low-speed driving, the car is suddenly accelerated, the Pb emissions can be as high as 2000% of the amount consumed, owing to the ejection of deposit material, much of it in large (up to 5000 μ diameter) flakes. With protracted running at high speeds the loosening of deposited material will finally subside and the rate of Pb emissions will be just a little less than the rate of Pb consumption in the fuel. If now low-speed driving is resumed, Pb emissions will be very low (say, 10% of that consumed) and will climb slowly to the low-speed value. The emission rate is very erratic, however, since large-particle emissions can be affected by thermal or mechanical shock, changes in gas velocity, etc. There may be another maximum associated with deceleration.

In general, severe engine operating conditions mean that a higher percentage of the Pb consumed is emitted and the particles are bigger. Over the life of

the car, some 75% of the Pb consumed is emitted as particulate. Emissions tend to increase with age.

Emissions of gross particulate matter are highest when the engine is cold. Particles can be expected to be larger at low exhaust gas velocity owing to enhanced opportunity for coagulation and wall loss, and indeed it appears (Ref. 36) that nitrate and sulfate particles are larger at lower road speed. It is presumably true that oil burners are smoke producers. Diesel particulate emissions rise very steeply when the engine load approaches its maximum rating.

Various means of control for gross particulates have been tried. A system of fluted exhaust pipes (for cooling) followed by a mesh-filled box and a cyclone collector (DuPont, Ref. 28) reduced Pb emissions 10-fold. Other systems (Ref. 42) include thermal precipitation in a packed bed or acoustic coagulation in a fluidized bed, or (Ref. 32) a simple trap muffler. The control of blowby gets rid of much of the problem, since the particulate emissions in blowby are in quantities approaching the tailpipe emissions.

Catalysts for the control of gaseous pollutants seem to be very effective in destroying organic particulates. With lead-free fuel, nearly all of the exhaust particulate matter is organic. It is therefore anticipated that the use of catalysts, especially since such use apparently must be accompanied by the use of lead-free fuel, will eliminate the problem of exhaust particulates. Particulate emissions from attrition of the catalyst itself, by chemical attack, exfoliation, pellets wearing against each other, etc., should perhaps be considered, especially in view of the fact that such material is, after all, a catalyst.

## Bibliography


Aerosols -- General

1. C. E. Junge, Air Chemistry and Radioactivity (Academic Press, N.Y., 1963), particularly Chapters 2,4, and 5.

2. C. N. Davies, editor, Aerosol Science (Academic Press, N.Y., 1966).

3. N. A. Fuchs, The Mechanics of Aerosols (Pergamon Press, N.Y., 1964).

Air Pollution Aerosols

4. National Air Pollution Control Administration Publication No. AP-49, Air Quality Criteria for Particulate Matter (U.S.Dept. of Health, Education, and Welfare, 1969).

5. National Air Pollution Control Administration Publication No. AP-73, Nationwide Inventory of Air Pollutant Emissions (U.S. Dept. of Health, Education, and Welfare, 1968).

6. R. L. Duprey, Public Health Service Publication No. 999-AP-42, Compilation of Air Pollutant Emission Factors (U.S. Dept. of Health, Education, and Welfare, 1968).

7. National Air Pollution Control Administration Publication No. AP-51, Control Techniques for Particulate Air Pollutants (U.S. Dept. of Health, Education, and Welfare, 1969).

8. A. C. Stern, editor, Air Pollution, second edition (3 volumes, Academic Press, N.Y., 1968).

Air Pollution by Aerosols from Vehicle Engines

9. R. I. Larsen and V. J. Konopinski, "Sumner Tunnel Air Quality," Archives of Environmental Health 5, 597 (1962).

10. C. J. Conlee, P.A. Kenline, R. L. Cummins, and V. J. Konopinski, "Motor Vehicle Exhaust at Three Selected Sites," ibid. 14, 429 (1967).

11. V.J. Schaeffer, "Auto Exhaust, Pollution and Weather Patterns," Bulletin of the Atomic Scientists, Oct. 1970, p. 31.

12. J. H. Ludwig, D. R. Diggs, H.E. Hesselberg, and J. A. Mags, "Survey of Lead in the Atmosphere of three Urban Communities: A Summary," American Industrial Hygiene Association Journal 26, 270 (1965); The Working Group on Lead Contamination, Public Health Service Publication No. 999-AP-12, "Survey of Lead in the Atmosphere of Three Urban Communities" (U.S. Dept. of Health, Education, and Welfare, 1965).

13. R. I. Larsen, "Air Pollution from Motor Vehicles," Annals of the New York Academy of Sciences 136, 275 (1966).

14. R. E. Waller, B. T. Commins, and P. J. Lawther, "Air Pollution in Road Tunnels," British Journal of Industrial Medicine 18, 250 (1961).

15. J. M. Colucci and C. R. Begeman, "The Automotive Contribution to Air-Borne Polynuclear Aromatic Hydrocarbons in Detroit," Journal of the Air Pollution Control Association 15, 113 (1965).

16. J. M. Colucci and C. R. Begeman, "Carcinogenic Air Pollutants in Relation to Automotive Traffic in New York," APCA Paper No. 68-71, presented at the 61st Annual Meeting of the Air Pollution Control Association, St. Paul, Minnesota, June 1968.

17. J. M. Colucci and C. R. Begeman, "Polynuclear Aromatic Hydrocarbons and Other Pollutants in Los Angeles Air," presented at the Second International Clean Air Congress, Washington, December 1970.

18. R. H. Daines, H. Motto, and D. M. Chilko, "Atmospheric Lead: Its Relationship to Traffic Volume and Proximity to Highways," Environmental Science and Technology 4, 318 (1970).

19. P. R. Atkins, "Lead in a Suburban Environment," Journal of the Air Pollution Control Association 19, 591 (1969).

20. H. W. Georgii and D. Jost, "On the Lead Concentration in an Urban Aerosol," Atmospheric Environment 5, 725 (1971).

Laboratory Measurements on Aerosols from Vehicles

21. C. R. Begeman, "Carcinogenic Aromatic Hydrocarbons in Automobile Effluents," Paper No. 440C presented January 1962 at the SAE Automotive Engineering Congress, published in SAE Technical Progress Series, Vol. 6, "Vehicle Emissions," New York: Society of Automotive Engineers Inc., 1964.

22. D. Hoffmann, E. Theisz, and E. L. Wynder, "Studies on the Carcinogenicity of Gasoline Exhaust," Journal of the Air Pollution Control Association 15, 162 (1965).

23. C. R. Begeman and J. M. Colucci, "Polynuclear Aromatic Hydrocarbon Emissions from Automotive Engines," SAE Paper No. 700469, presented at mid-year meeting, Detroit, May 1970.

24. C. R. Begeman and J. M. Colucci, "Benzo[a]pyrene in Gasoline Partially Persists in Automobile Exhaust," Science 161, 271 (1968).

25. D. A. Hirschler, L. F. Gilbert, R. W. Lamb, and L. M. Niebylski, "Particulate Lead Compounds in Automobile Exhaust Gas," Industrial and Engineering Chemistry 49, 1131 (1957); D. A. Hirschler and L. F. Gilbert, "Nature of Lead in Automobile Exhaust Gas," Archives of Environmental Health 8, 297 (1964).

26. P. K. Mueller, H. L. Helwig, A. E. Alcocer, W. K. Gong, and E. E. Jones, "Concentration of Fine Particles and Lead in Car Exhaust," ASTM Special Publication No. 352, Symposium on Air-Pollution Measurement Methods, presented at the Fourth Pacific Area National ASTM Meeting, Los Angeles, 5 October 1962 (published 1963 by ASTM).

27. K. Habibi, "Characterization of Particulate Lead in Vehicle Exhaust -- Experimental Techniques," Environmental Science and Technology 4, 239 (1970); also the accompanying commentaries by P. K. Mueller and H. C. McKee.

28. K. Habibi, E. S. Jacobs, W. G. Kunz, Jr., and D. L. Pastell, "Characterization and Control of Gaseous and Particulate Exhaust Emissions from Vehicles," presented at the Fifth Technical Meeting of the West Coast Section of the Air Pollution Control Association, San Francisco, October 1970; K. Habibi, "Automotive Particulate Emissions and Their Control," SAE Paper No. 710638, presented at Joint Meeting of SAE Mid-Michigan Section and American Chemical Society Midland Section, Midland, Michigan, October 1970.

29. K. T. Whitby, Generation and Decay of Small Ions (University of Minnesota Particle Laboratory Publication No. 137, July 1969), Section VI.

30. J. S. Ninomiya, W. Bergman, and B. H. Simpson, "Automotive Particulate Emissions," presented at the Second International Clean Air Congress, Washington, December 1970.

31. J. B. Moran and O. J. Manary, U.S. Government Report PB 196783, "Effect of Fuel Additives on the Chemical and Physical Characteristics in Automotive Exhaust," Interim Report from The Dow Chemical Company to the National Air Pollution Control Administration, July 1970.

32. G. L. Ter Haar, D. Lenane, J. Hu, and M. Brandt, "Composition, Size, and Control of Automobile Exhaust Particulates," presented at 1971 Technical Session of the Central States Section of The Combustion Institute, Ann Arbor, Michigan, March 1971; same authors, "Composition, Size and Control of Automotive Exhaust Particulates," presented at 64th Annual Meeting of the Air Pollution Control Association, Atlantic City, N. J., June-July 1971.

33. R. E. Sampson and G. S. Springer, "Particulate Formation in Spark Ignition Engine Exhaust," presented at same meeting as preceding reference.

34. G. L. Ter Haar and Ruth E. Stephens,"The Effects of Automobile Exhaust Particulates on Visibility," presented at the 12th Conference on Methods in Air Pollution and Industrial Hygiene Studies, University of Southern California, Los Angeles, April 6-8 1971.

35. J. M. Pierrard and R. A. Crane, "The Effect of Gasoline Compositional Changes on Atmospheric Visibility and Soiling," presented at the 64th Air Pollution Control Association Meeting, Atlantic City, June 1971; same authors, "Auto Exhaust -- lead vs aromatics," Hydrocarbon Processing 50, 142 (1971).

36. R. E. Lee, Jr., R. K. Patterson, W. L. Crider, and J. Wagman, "Concentration and Particle Size Distribution of Particulate Emissions in Automobile Exhaust," Atmospheric Environment 5, 225 (1971).

37. J. Wagman, "Aerosol Composition and Component Size Distributions in Urban Atmospheres," presented at the 11th Conference on Methods in Air Pollution and Industrial Hygiene Studies, Berkeley, California, April 1970.

38. R. H. Herling, W. E. Karches, J. Wagman, O. J. Manary, and J. B. Moran, "A Comparison of Automotive Particle Mass Emissions Measurement Techniques," presented at same meeting as Reference 32.

39. D. Olsen and J. L. Haynes, National Air Pollution Control Administration Publication No. APTD 69-43, Preliminary Air Pollution Survey of Organic Carcinogens (U.S.Dept. of Health, Education, and Welfare, 1969).

40. W. J. Frey and M. Corn, "Diesel Exhaust Particulates," Nature 216, 615 (1967).

41. J. W. Frey and M. Corn, "Physical and Chemical Characteristics of Particulates in Diesel Exhaust," Journal of the American Industrial Hygiene Association 28, 468 (1967).

42. S. K. Sood and R. Karuhn, U.S. Government Report PB 198033, "Development of Particulate Emissions Control Techniques for Spark Emission Engines," Final Report from IIT Research Institute to the Air Pollution Control Office, EPA, February 1971.

43. A. E. Felt and R. V. Kerley, "Engines and Effects of Lead-Free Gasoline," SAE Paper No. 710367, presented at Mississippi Valley Section meeting, October 1970.

44. M. C. Battigelli, T. F. Hatch, R. J. Mannella, and F. Hengstenberg, "Dose Response Relations from Inhalation of Diesel Exhaust," Terminal Report, U.S. Public Health Service, Grant No. OH-00191-02, University of Pittsburgh, 1967.

45. G. M. Badger, "Mode of Formation of Carcinogens in Human Environment," National Cancer Institute Monograph 9, 1 (1962).

46. L. R. Reckner, W. E. Scott, and W. F. Biller,"The Composition and Odor of Diesel Exhaust," Proceedings of the American Petroleum Institue,, Section III, 45, 133 (1965).

47. Carl W. Melton, "Physical and Chemical Characterization of Particulates in Auto Exhaust," paper presented at the 1971 Automotive Air Pollution Research Symposium sponsored by The Coordinating Research Council, Inc., Air Pollution Research Advisory Committee, Chicago, May 1971.

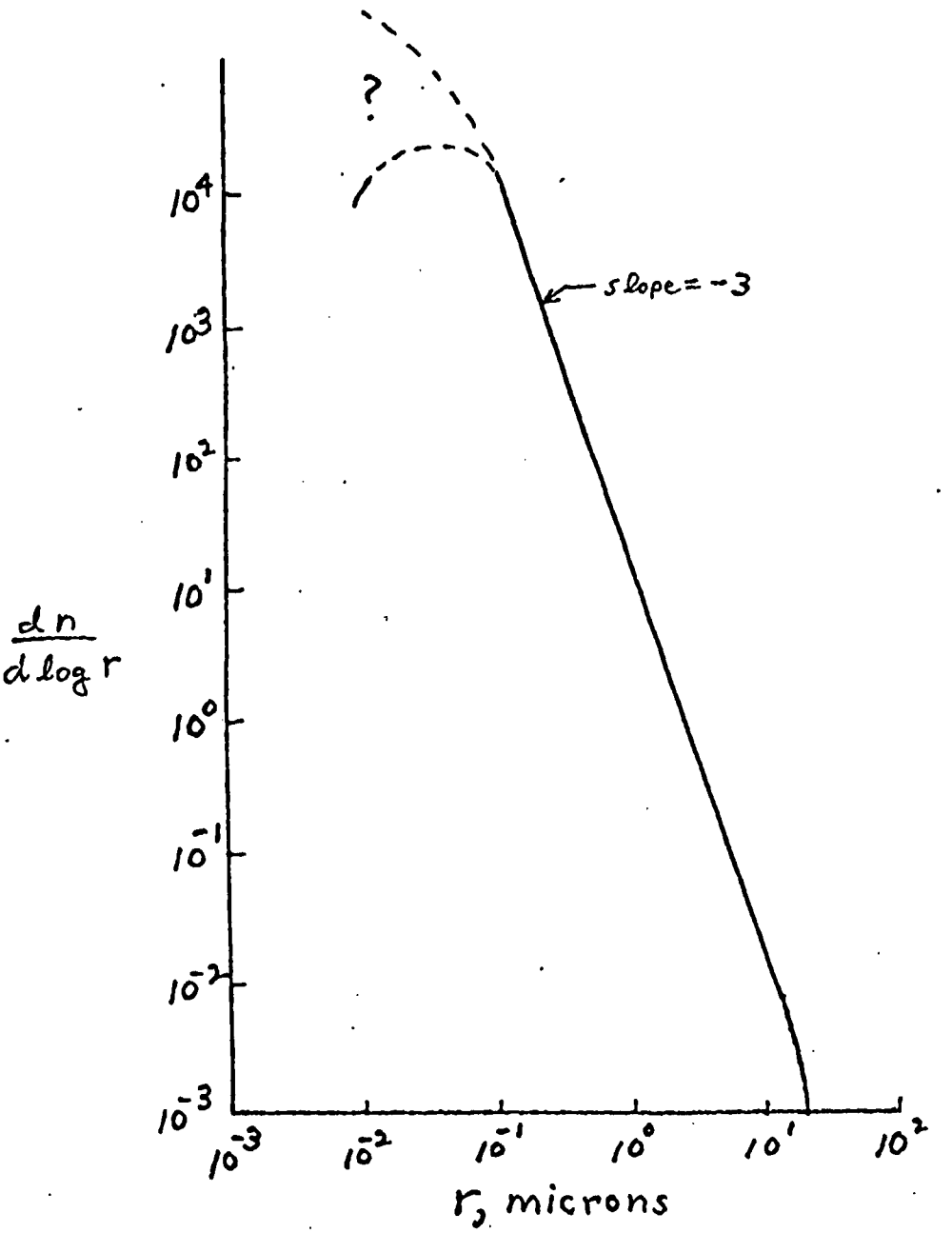



Fig. 1 — The Junge distribution.

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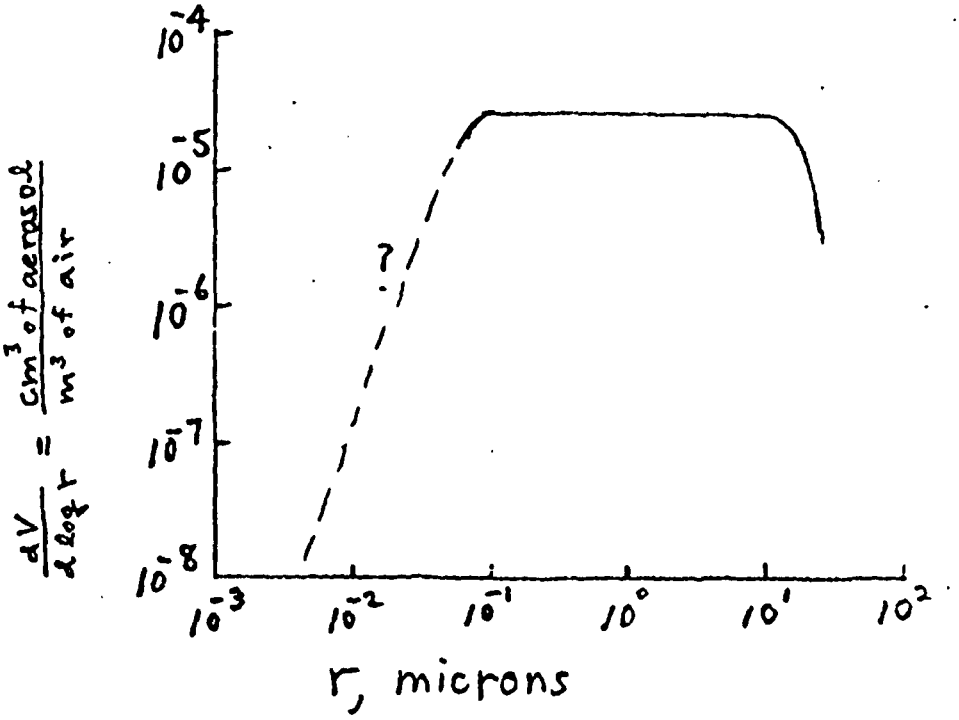


Fig. 2 - The Junge distribution

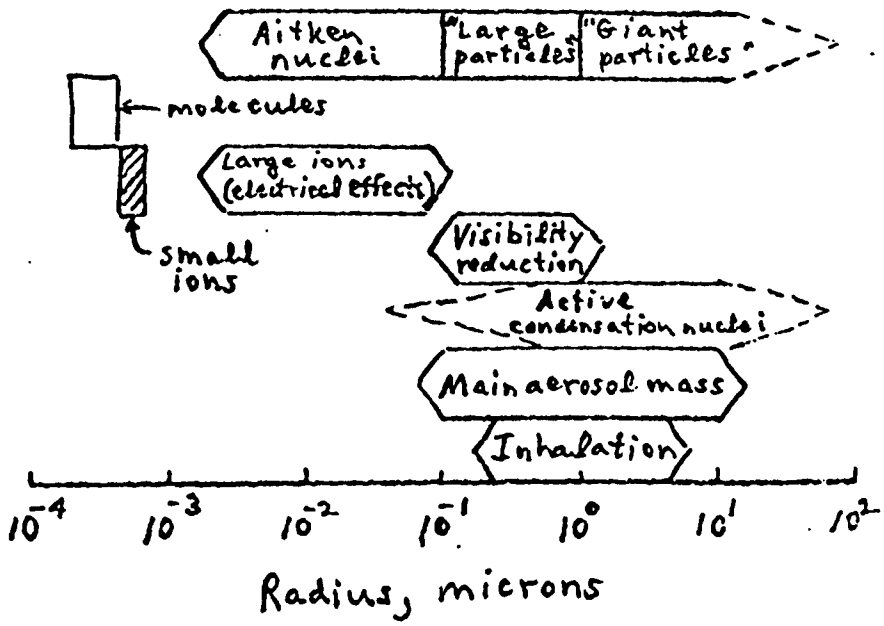


Fig. 3 — Particle size ranges associated with various effects

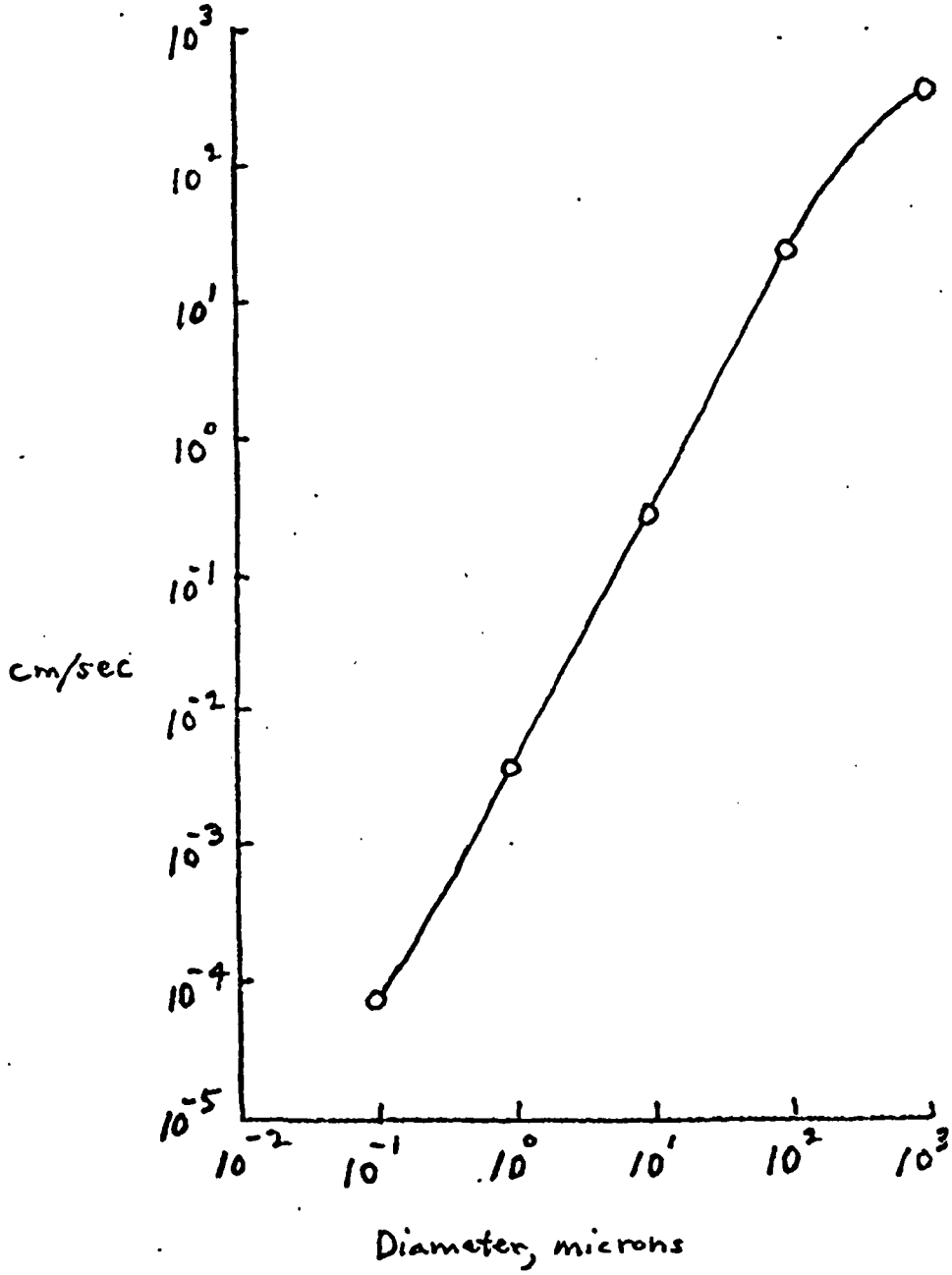


Fig. 4 – Settling velocity for unit-density spheres in air at 0°C and 760 mm Hg

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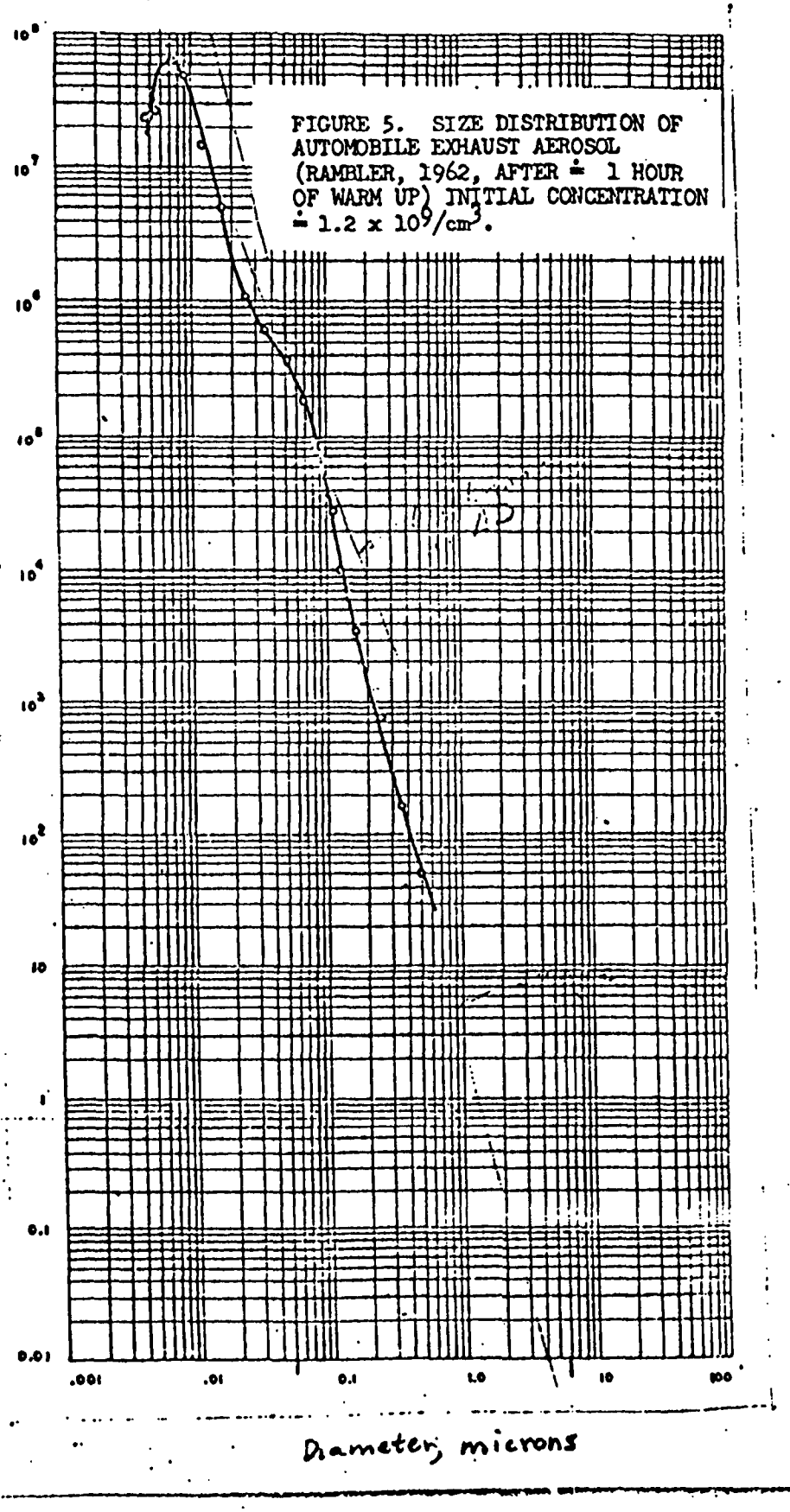
from Whitby et al., "Generation and Decay of Small Ions," July 1969

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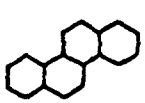
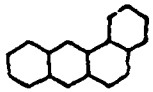
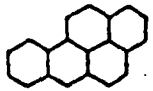


Chrysene



Benz(a)anthracene
(1, 2-benzanthracene)

Benzo(e)pyrene
(1, 2-benzopyrene)



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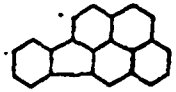
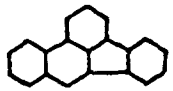
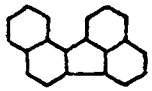


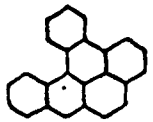
Indeno(1, 2, 3-cd)pyrene
(o-phenylenepyrene)



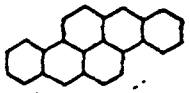
Benz(e)acephenanthrylene
(3, 4-benzofluoranthene)



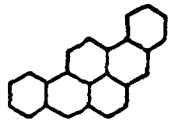
Benzo(j)fluoranthene
(10, 11-benzofluoranthene)



Dibenzo(e, l)pyrene
(1, 2, 3, 4-dibenzopyrene)



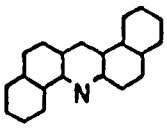
Dibenzo(a, h)pyrene
(3, 4, 8, 9-dibenzopyrene)



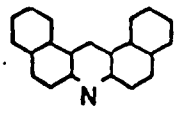
Dibenzo(a, i)pyrene
(3, 4, 9, 10-dibenzopyrene)

FIGURE 6

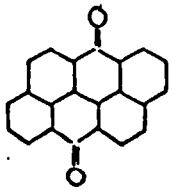
Carcinogenic Polynuclear Aromatic Hydrocarbons
Identified in Urban Air



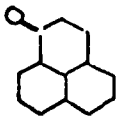
Dibenz(a, h)acridine
(1, 2, 5, 6-dibenzacridine)



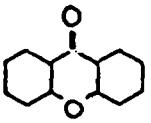
Dibenz(a, i)acridine
(1, 2, 7, 8-dibenzacridine)



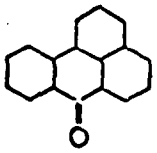
I
Anthanthrone



II
Phenalene-8-one



III
Xanthene-9-one



IV
7H-benz(de)anthracen-7-one

FIGURE 7

Aza-Heterocyclics and Polynuclear Carbonyl Compounds Identified in Urban Air