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PHYSICAL PROPERTIES OF CIGARETTE SMOKE

Summary Report, November 1954

for

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DEFENDANT'S EXHIBIT
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PHYSICAL PROPERTIES OF CIGARETTE SMOKE

PART 1: GENERAL DISCUSSION OF RESULTS

This project, initiated in June 1953, has as its primary objective the study of the physical properties of smoke from Old Gold and Kent cigarettes. The properties of the smoke particles of particular interest are size distribution, concentration, physical state, and behavior on filtration. Answers to these questions will not only provide information of general fundamental interest but will also yield data to help in the systematic development of improved smoking products. For instance, particle size distribution and concentration are very important in the development of filter-tip cigarettes. The physical properties of smoke particles are closely related to color and appearance of smoke, its taste, and the degree of its retention by the body. Although there is relatively little information on its physical properties the chemical nature of cigarette smoke has been studied extensively. An investigation of this field appears to be particularly promising for new and useful information.

Over the past year and a half much has been accomplished in answering these basic questions. It is now possible to characterize fairly closely the physical nature of the smoke as it leaves the cigarette. The smoke consists of liquid droplets containing many extremely small solid particles. The droplets are quite stable and are essentially of an oily nature. The smoke itself behaves like a continuous fluid rather than an aggregate of particulates in an enclosed air space, showing a strong tendency to hang together, and to settle rapidly through quiet air.

Microscopic and photomicrographic examinations of the freshly formed smoke show that most of the particles are less than 1 micron in diameter.

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cut down. This seemingly high loss of smoke agrees well with other studies on the loss of aerosols in the lungs. Investigators also demonstrate that retention is reduced markedly as the particles become smaller than 0.5 micron. This points out the importance of having sound fundamental data to understand adequately the behavior of cigarette smoke.

The interesting answers obtained on the subject of the quantity of inhaled smoke retained by the body brought up a problem of immediate practical use, namely, if the size of the smoke particles can be reduced, would the retention be less at the same time. Figure 11 shows that if the smoke particles could be reduced by several tenths of a micron, smoke retention may be cut considerably. Also this smoke should be rather mild and voluminous; this may be accomplished by special selection of tobaccos, addition of inert fillers to control the burning temperature, or chemical extraction. In studies at Duke University sponsored by the Damon Runyon Fund extraction with alcohol has been shown to reduce particle size. Equipment to study the effectiveness of such modification is already available.

The chemical composition of cigarette smoke may vary with the particle size, the moisture content of the tobacco, the number of the puff, and the type of cigarette, ie, plain or filter tip. Information on these variables is of great interest, since the physiological effects of cigarette smoke are due to its chemical composition. The present equipment can readily provide samples for quantitative analysis, and it may be possible to carry out qualitative chemical tests on individual particles by means of chemical microscopy.

In all this work the cigarettes were smoked at standard conditions, but in actual use the smoking conditions may be far from standard. Changing

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the smoking rate and moisture content may change particle size and concentration considerably and there is some evidence that this is the case. Therefore, some study of these variables would make the present data much more complete and inclusive.

A graphic summary of the most important results and of some equipment is shown on the following pages. These results and the techniques used in this program are discussed in detail in the second part of this report.

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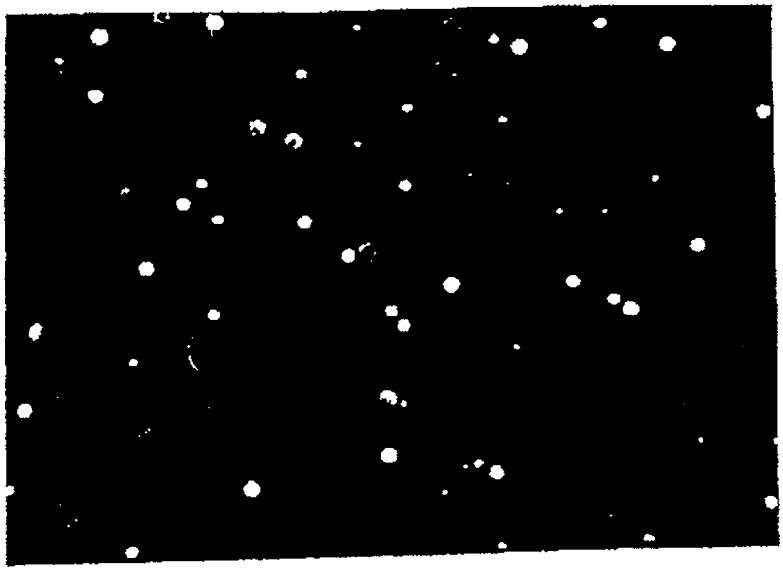


Fig. 1 OLD GOLD PUFF 2 5 μ



Fig. 2 KENT PUFF 2 5 μ

These photomicrographs are taken from smoke samples taken under identical conditions. They show the lower concentration and the somewhat smaller particle size of the Kent smoke.

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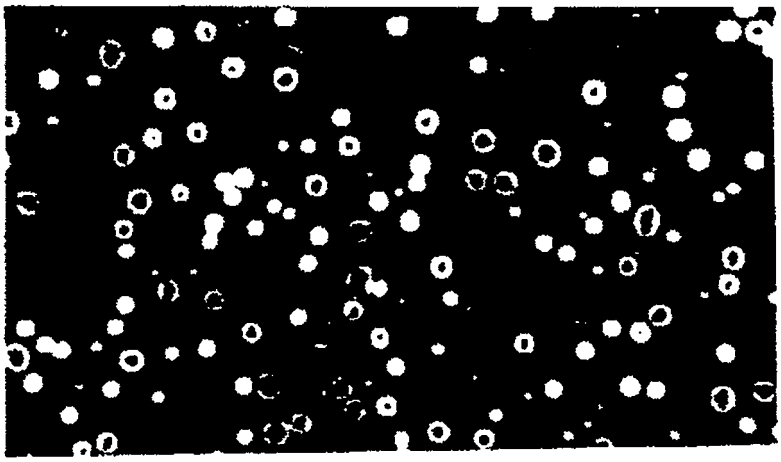


Fig. 3 OLD GOLD PUFF 11 5μ

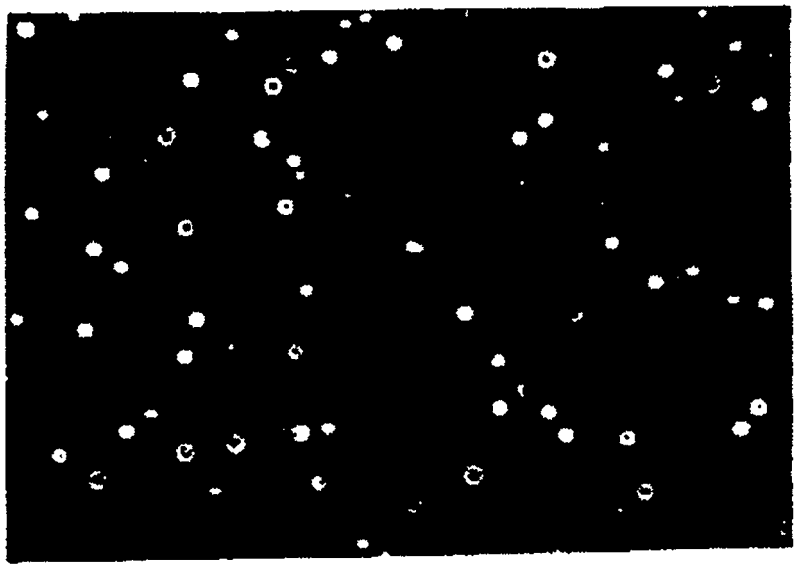
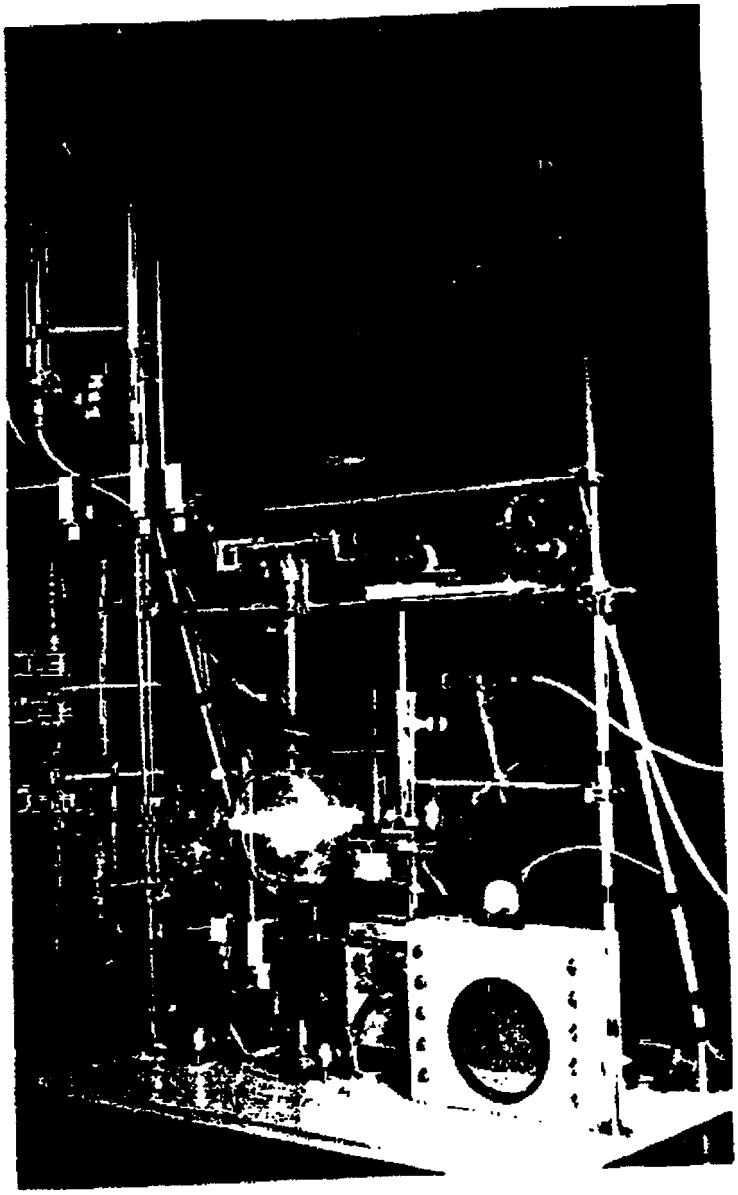


Fig. 4 KENT PUFF 11 5μ

The photomicrographs were taken under the same conditions as the preceding set and show the increase in concentration and particle size as the cigarette is smoked.

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This apparatus combines an automatic cigarette smoker with equipment for accurately diluting the smoke with clean air and then obtaining special samples of smoke particles for detailed study and measurement. The large flask. (lower center), contains diluted smoke. A horizontal beam of light through this flask indicates the approximate smoke concentration. A moving slide sampler is above the flask.

Fig. 5 AUTOMATIC SMOKING MACHINE AND SMOKE-SAMPLING EQUIPMENT

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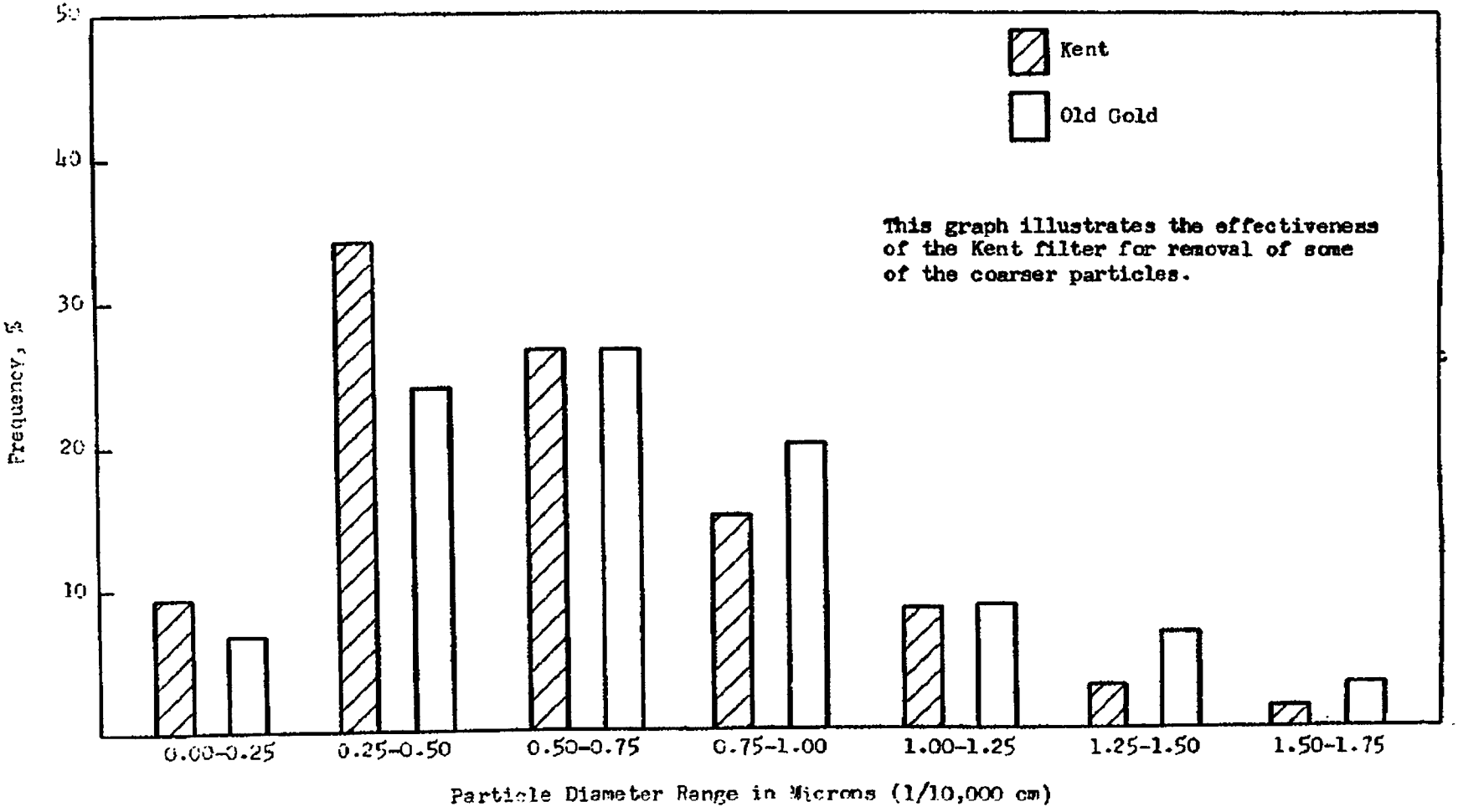


Fig. 6 AVERAGE SIZE DISTRIBUTION OF KENT AND OLD GOLD CIGARETTE SMOKE PARTICLES

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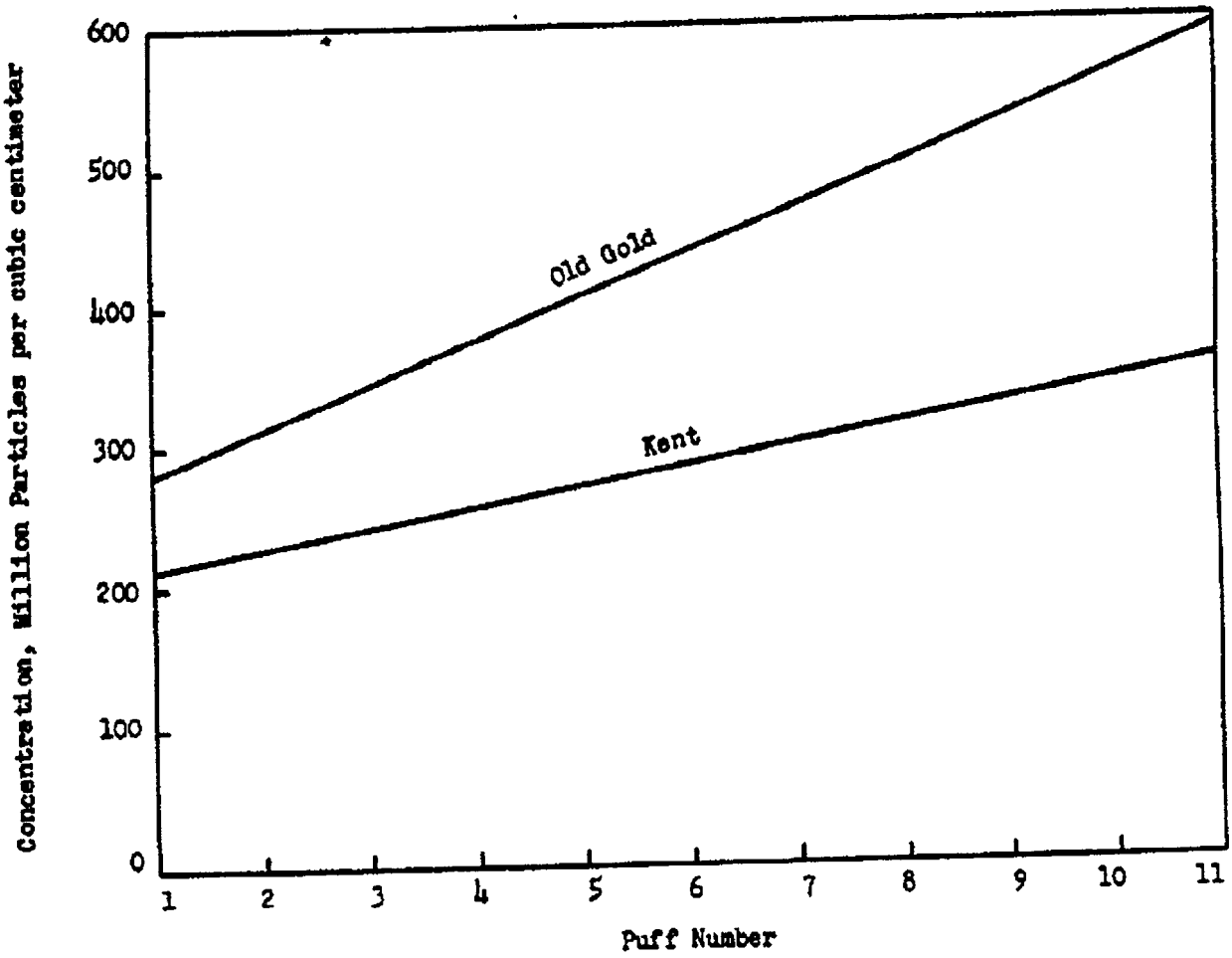


Fig. 7 SMOKE CONCENTRATION DATA

Figure 7 illustrates the main difference between the Kent and Old Gold smoke, namely, the much lower particle concentration of the Kent.. It should be noted that the difference increases as the cigarette is smoked. In other words the tobacco acts as fairly effective filter but loses its effectiveness as the cigarette becomes shorter.

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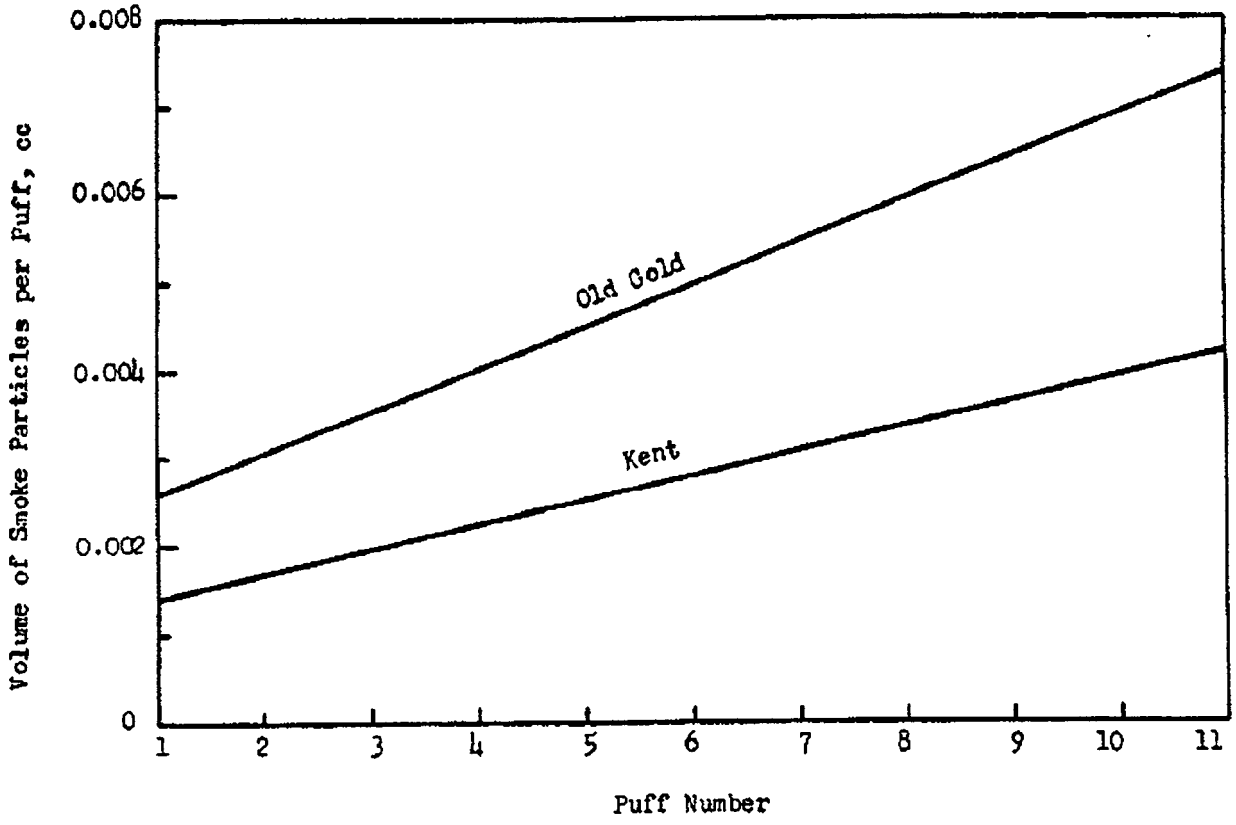


Fig. 8 VOLUME OCCUPIED BY SMOKE PARTICLES

The smoke particles in a puff from a Kent cigarette occupy half the volume of the smoke particles in a puff from an Old Gold

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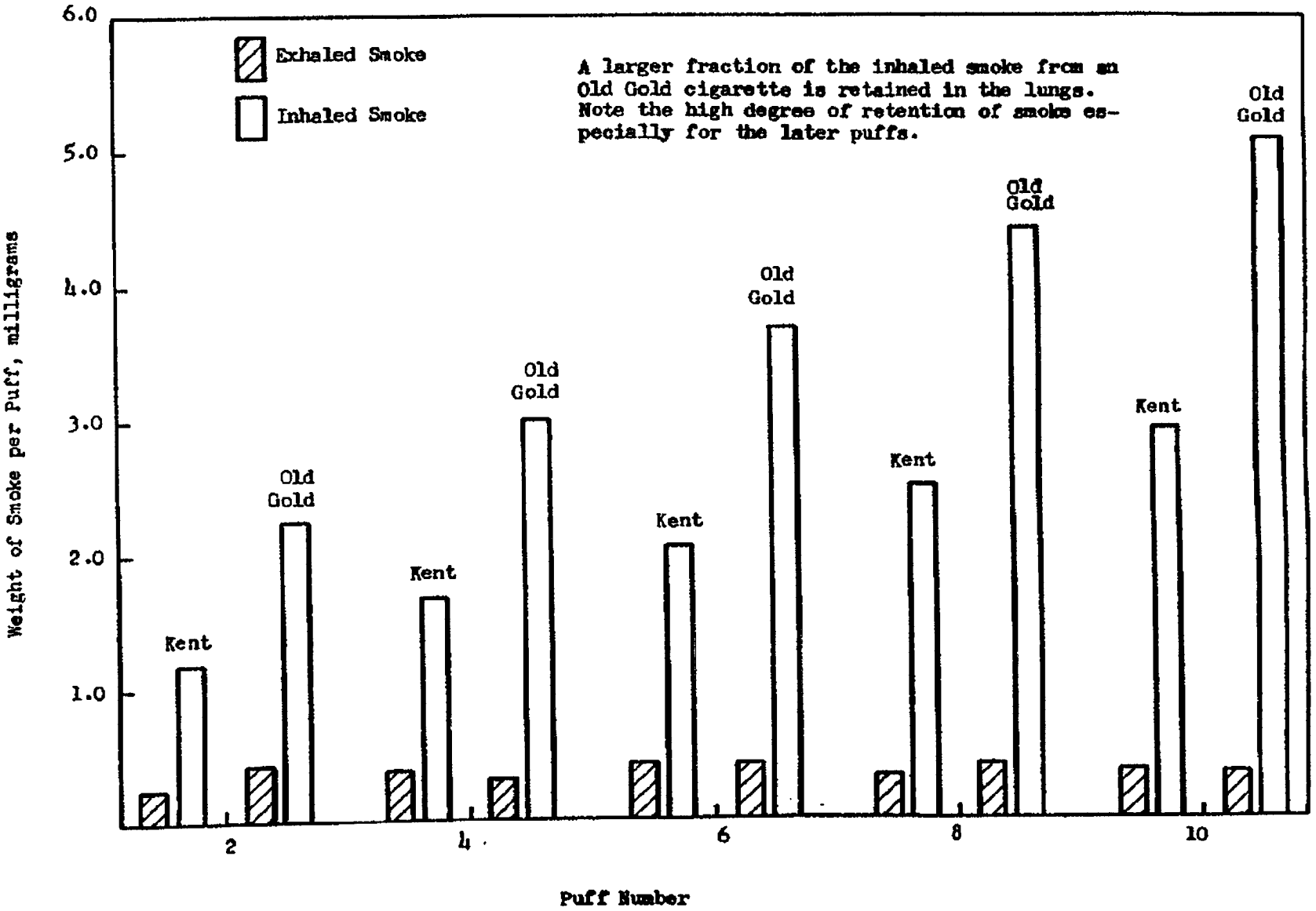


Fig. 9 WEIGHT OF EXHALED AND INHALED SMOKE

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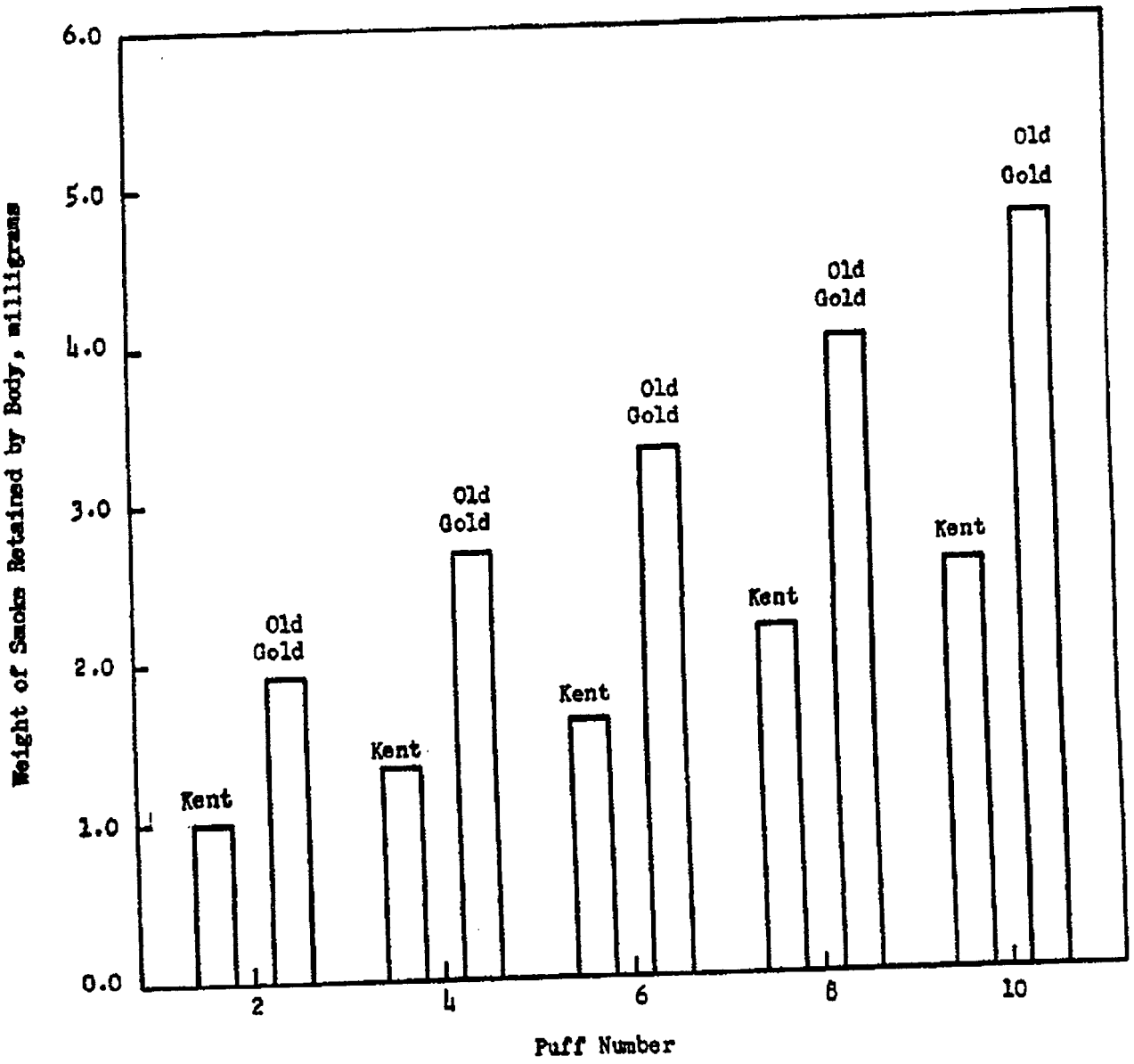


Fig. 10 WEIGHT OF SMOKE RETAINED AFTER INHALING

Figure 10 illustrates the difference between Kent and Old Gold cigarettes. The weight of smoke lost to the body from a Kent is very much lower, largely because the smoke in a puff from a Kent weighs less.

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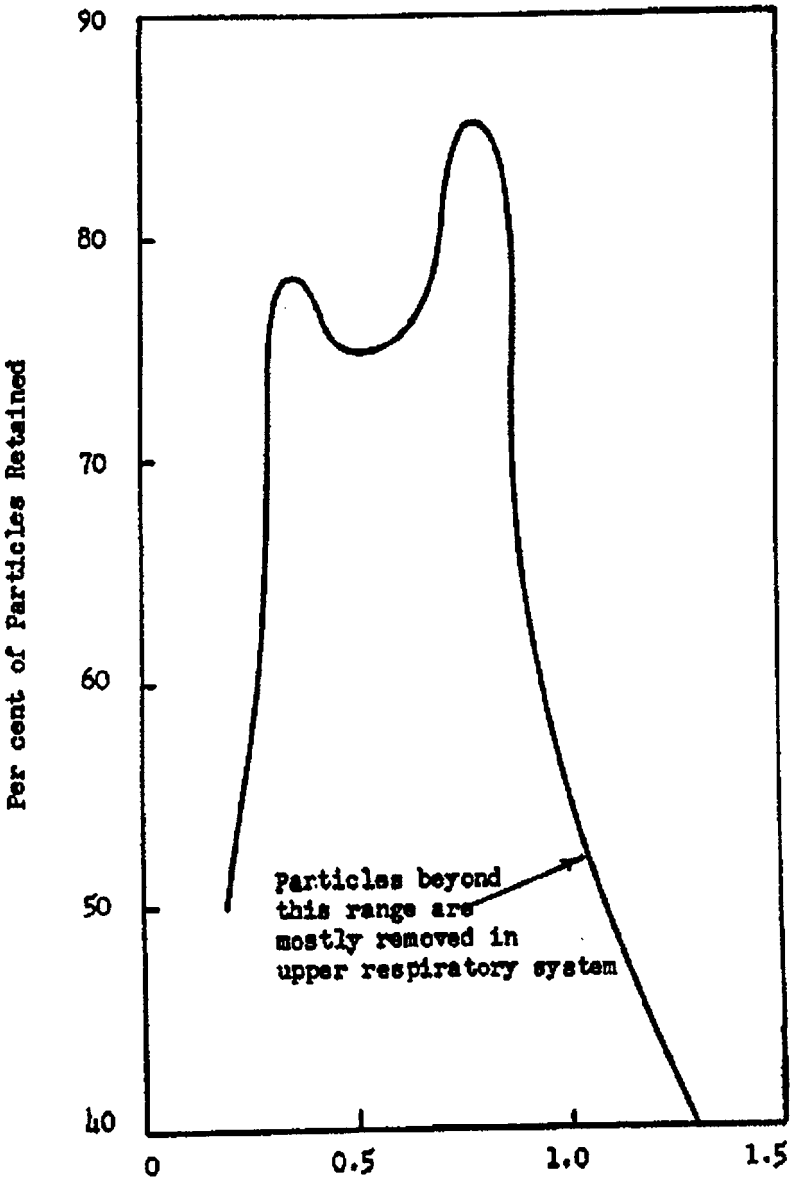


Fig.11 RETENTION OF PARTICLES BY LOWER LUNGS

Note: This curve is for material of unit density. For cigarette smoke the curve should be shifted slightly to the left.

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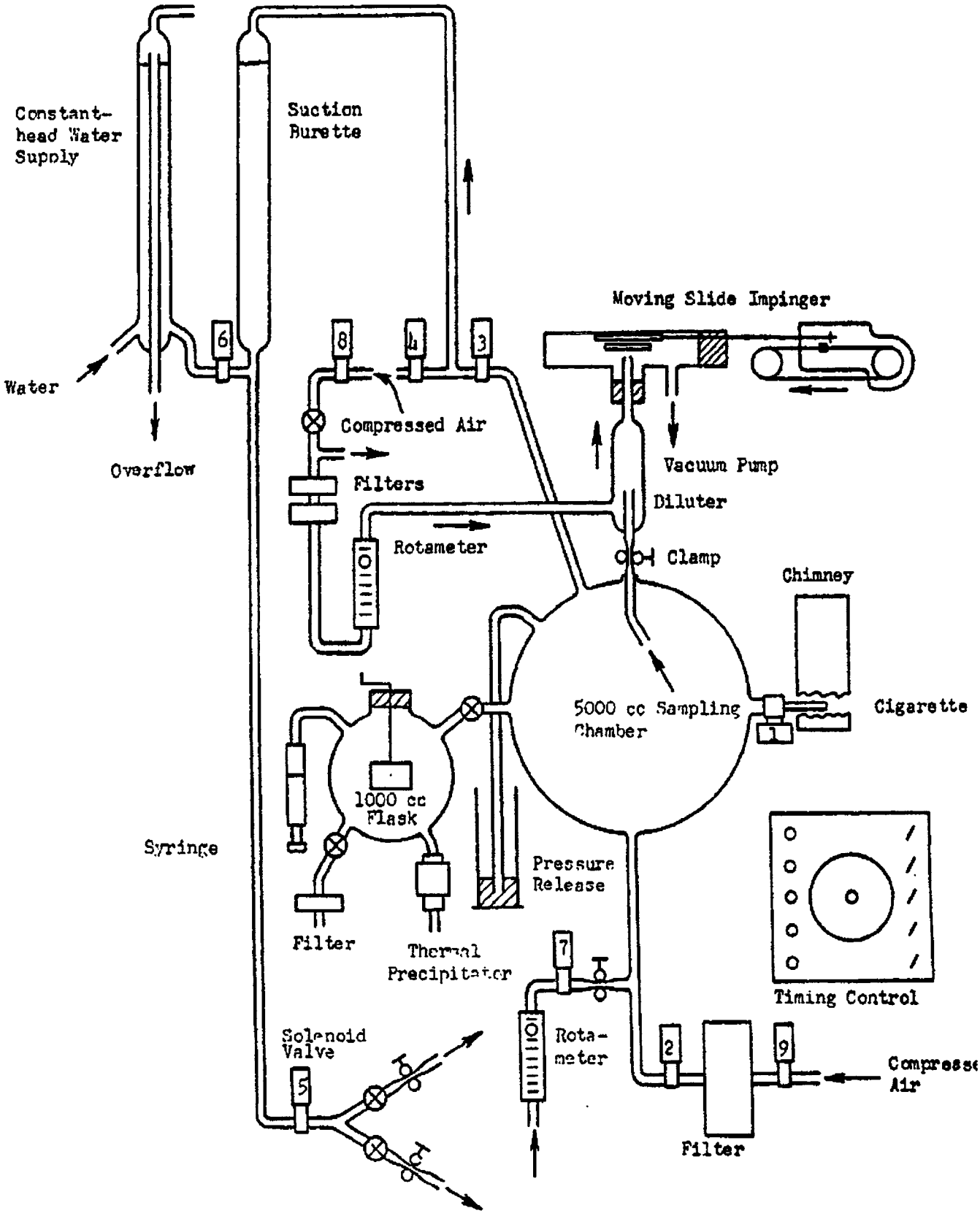


Fig. 12 [illegible] SMOKING MACHINE

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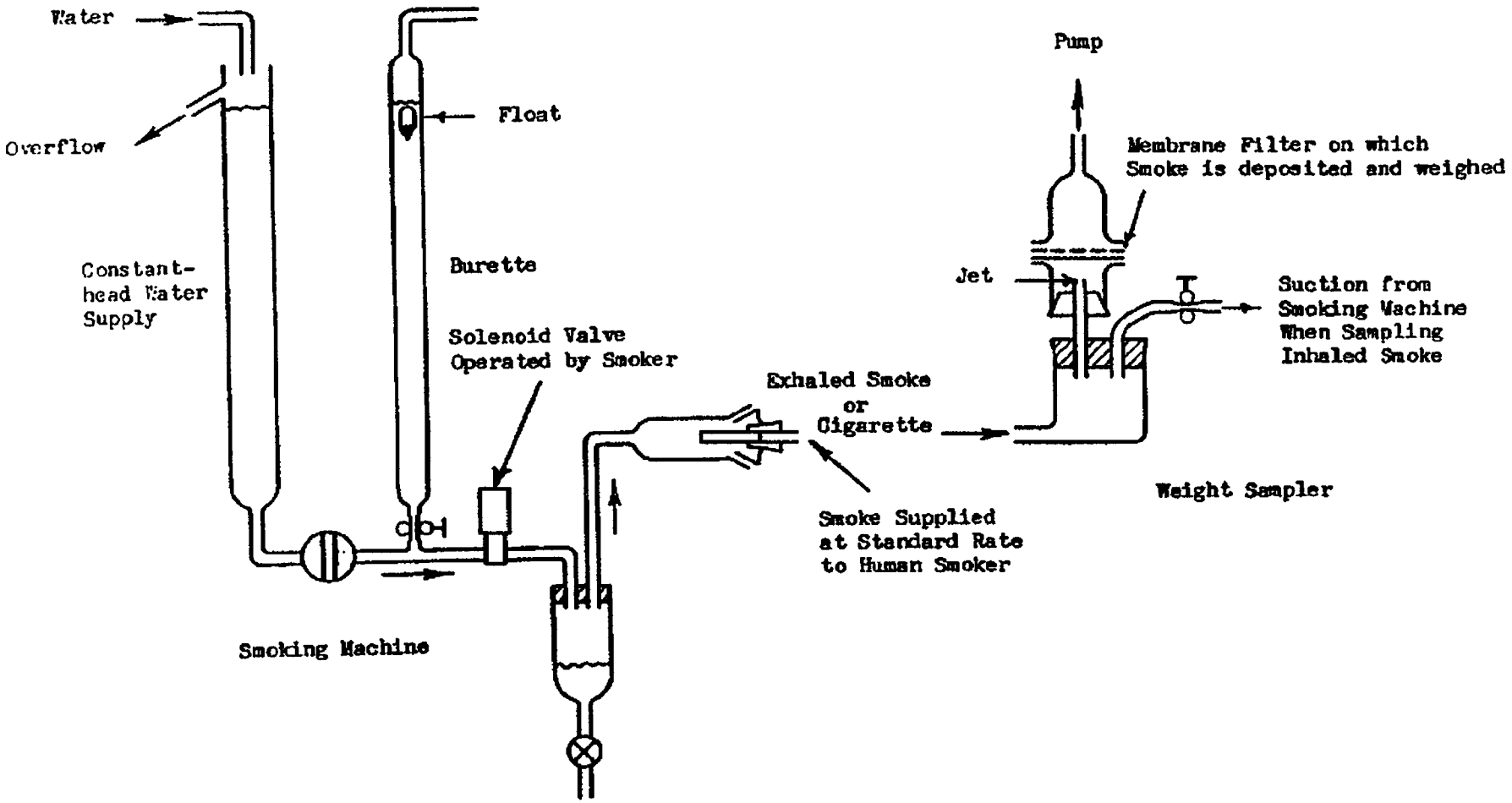


Fig. 13 EQUIPMENT FOR OBTAINING WEIGHT SAMPLES OF EXHALED SMOKE

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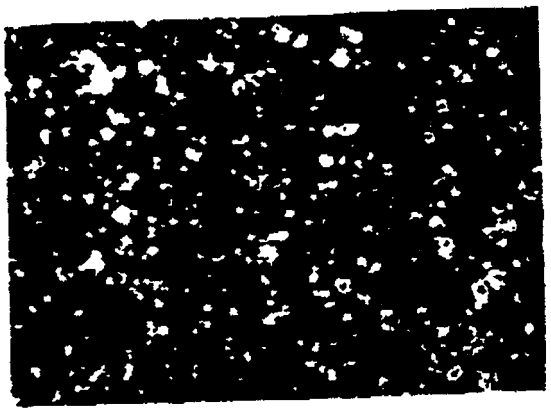


Fig. 14 DUST COLLECTED FROM 1500 cc OF AIR 10μ

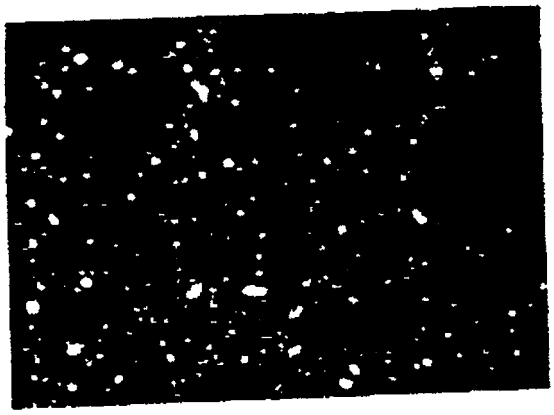


Fig. 15 DUST COLLECTED FROM 1500 cc OF AIR 10μ
FILTERED THROUGH AN OLD GOLD



Fig. 16 DUST COLLECTED FROM 1500 cc OF AIR 10μ
FILTERED THROUGH A KENT WITH A FEW ASBESTOS
FIBERS FROM THE FILTER

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Fig. 17 FIBERS FROM A KENT FILTER THAT HAS NOT BEEN USED 5 μ



Fig. 18 A FIBER COATED WITH SMOKE SUBSTANCE FROM A KENT FILTER USED FOR ONE PUFF 5 μ

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ARMOUR RESEARCH FOUNDATION OF ILLINOIS INSTITUTE OF TECHNOLOGY

PART 2: TECHNICAL DISCUSSION

This part of the report gives some of the technical details of the research on the physical properties of cigarette smoke. First, an adaptation of the standard smoking machine was built that placed special emphasis on handling the smoke so that it is not altered after it leaves the cigarette, and techniques were devised to sample and analyze this smoke. The second phase involved the routine application of the equipment and techniques to many Old Gold and Kent cigarettes to obtain firm data on the size and concentration of the smoke particles. This information was then used in a study of exhaled smoke to investigate the retention of the smoke by the lungs.

The various aspects of this project will be discussed in the following sequence: equipment, analytical procedures, and discussion of results.

I. EQUIPMENT

A. Smoking Machine

An automatic smoking machine was built, as pictured in Fig. 5 and sketched in Fig. 12, based on the standard conditions of a 35-cc puff in 2 sec at 1-min intervals. Other requirements were that the smoke should not be altered after it leaves the cigarette and that it should be possible to sample the smoke from every puff. To meet the first condition, the smoke is immediately diluted by the volume of air in the 5000-cc flask to prevent agglomeration. A quick blast of air breaks up the smoke that enters the flask in the form of a solid stream that does not mix with the surrounding air. In order to sample every puff, the machine has to be fully automatic. This is accomplished with a 1-rpm motor that actuates a series of microswitches through a set of notched metal disks, shown at the lower right of Fig. 5. The switches operate the solenoid valves that control the flow system in the machine.

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Sufficient suction to pull 35 cc of air through the cigarette is applied when water is allowed to run out of the suction burette by opening Valve 5 (Fig. 12). At the same time Valve 1 opens for 2 sec; this is a special valve that gives a direct passage for the smoke. There is a 20-sec interval for sampling after a puff, and then the large flask is purged of smoke with compressed air entering through Valve 9 and 2 and is exhausted through the pressure release tube, which also serves as a manometer to indicate the resistance of the cigarette.

To supply standard amounts of smoke to human smokers for the study of exhaled smoke the manually operated machine. Fig. 13, is used. When the solenoid valve is switched on, 35 cc of water run out of the burette and displace a 35 cc of air through the cigarette from the air space following the solenoid valve. The burning end of the cigarette is held in the shroud by the smoker just before a puff is due. The smoker then receives the smoke and inhales.

B. Moving Slide Impinger

A number of samplers were tested to collect the smoke for analysis. Of these, a moving slide impinger proved to be most successful for routine determinations of concentration and size distribution. Weight samples of the smoke were conveniently collected by combining a membrane filter with an impinger. The other samplers tested were a thermal precipitator, an electrostatic precipitator, and a settling chamber.

A moving slide impinger, shown in the upper right of Fig. 5 and 12, consists of a microscope slide that can be pulled at constant speed past a jet at right angles to the slide. The jet directs the smoke onto the slide at close to sonic velocity. The smoke particles impinge on the slide, since

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their inertia is too high to follow the sudden change in direction of the gas flow. If a stationary slide were used, the particles would pile up too fast and overlap. Even in this case the smoke has to be diluted a second time after leaving the 5000-cc flask by a factor of 15 to prevent agglomeration. The diluter for this purpose surmounts the flask, as seen in Fig. 5 and 12.

C. Weight Sampler

In order to collect all the smoke in a puff and weigh it, the sampler shown at the right of Fig. 13 has proven to be very convenient. Exhaled smoke is simply blown into it while suction is applied to the filter. For samples of inhaled smoke the cigarette is attached to the mouthpiece, and suction is applied to the chamber with the smoking machine. Then the sampling procedure is started. The smoke passes through the jet at a fairly high velocity; most of it impinges on a membrane filter; and the rest is intercepted by the filter, which can then be weighed. A membrane filter (Schleicher and Schuell) is a nonfibrous smooth-surfaced filter with uniform tubular holes. This arrangement was used because of its simplicity and availability. The smoke could also be collected in a small cup facing the jet.

D. Thermal Precipitator

The thermal precipitator is reputedly 100% efficient for particles below 5 microns. It collects aerosol particles by thermal repulsion from a hot wire that faces a cold microscope cover slip which serves as the collector. This instrument requires a good deal of skill and time to operate, but it is useful to check the efficiency of the impinger. The instrument can be seen at the lower left of Fig. 5 and 12 connected to a 1000-cc flask, which in turn is connected to the 5000-cc flask. The smaller flask serves to dilute a 30-cc or so smoke sample pulled from the 5000-cc chamber with the syringe.

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The smoke is mixed with the paddle; then an aspirator connected to the thermal precipitator draws aerosol through it at 6 cc/min for about 3 min.

E. Electrostatic Precipitator

Electrostatic precipitators are also nearly 100% efficient. With this instrument all the smoke particles are collected on the walls of a tube connected to a high voltage source. A central wire in the tube serves as the second electrode and repels the particles onto the wall. The tube is large enough to accommodate a puff of smoke with sufficient dilution to prevent overlapping of the particles on the wall; about 4000 cm^2 of wall area are necessary. The tube, in this case glass covered with aluminum foil on the outside, is filled evenly with smoke, and then the electricity is turned on to approximately 10,000 v. The particles are collected on very small pieces of glass resting on the wall. These pieces are coated with silicone to prevent spreading of the smoke particles. However, they are coated only on the side away from the tube wall; otherwise no particles are collected.

F. Aerosol Settling Chamber

A settling chamber was set up to study the gravity settling of the smoke particles. For this purpose a glass cylinder filled with smoke is submerged in distilled water to keep the smoke at a constant temperature. The cylinder is illuminated with a strong light beam to follow the scattering of light from the particles as an indication of the settling process.

II. ANALYTICAL PROCEDURES

A. Microscopy

All the smoke samples, except for the light-scattering and weight samples, have to be analyzed with a microscope. Both electron and optical microscopy have been investigated. The former has not shown too much promise

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for routine work. Difficulties are encountered in preparing a proper mount because of the volatility of the smoke under a high vacuum and because of its chemical composition. Both factors make it difficult to prepare replicas.

Of the optical microscope methods, dark-field illumination gave the best results. Bright-field illumination could not be used directly because of the very low contrast of the smoke particles mounted in air and the lack of a proper mounting medium. Coating the slides with a dye that would be dissolved by the smoke was not feasible because the dye crystals could not be produced small enough without elaborate equipment. Coating the particles with iodine crystals from iodine fumes gave good contrast, but the iodine also made all the submicroscopic rough spots on the glass visible.

Phase microscopy gave negative results in a few initial tests, possibly owing to the lack of a suitable mounting medium. Since the dark-field method gave good results, no further work was done in this field, and no definite statement can be made on the usefulness of phase microscopy.

A Spencer 0.85 N.A. bispherical, oiled, dark-field condenser with a Zeiss Neofluar 0.75 N.A. 40x objective proved to be the best optical combination. The resolving power of the equipment is such that a Leitz Periplan 25x eyepiece is justified for the photomicrographic work. The antireflection coating for reducing glare on the objective may account for its superior performance. Glare is a problem since the condenser design specifies a liquid mounting medium. To compensate for the air space between the cover slip and microscope slide in which the particles are located, the eyepiece distance had to be increased from 160 to 175mm. Kodak Super XX film is used for photomicrography with 1/2- to 3-min exposures.

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The microscope slides have to be of the proper thickness and of the highest quality. They must be cleaned thoroughly and coated with silicone to keep the spreading of the particles to a minimum.

B. Weight Sampling

The analytical procedure for weighing samples of cigarette smoke is rather simple. The filters are allowed to condition in the room atmosphere and are weighed just before and after sampling. The passage of air alone through the filter does not change its weight. The coarse type of membrane filter collects all of the smoke effectively.

III. DISCUSSION OF RESULTS

One of the first objectives of this research is to establish the particle size distribution and concentration of the smoke from Old Gold and Kent cigarettes. This was accomplished with the moving slide impinger. Then, information on the amount of smoke retained after inhaling into the lungs appeared to be highly desirable. To assemble the latter information, weight sampling of the smoke proved to be the most direct method, as every second exhaled breath could be sampled. An over-all summary of the results appears in Table 1.

Table 1

SUMMARY OF RESULTS

Cigarette	Average Particle Size, Microns	Average Concentration, Particles/cc	Average Weight of Smoke per Puff, mg	Average Weight of Smoke Retained after Inhaling into the Lungs, mg
Old Gold	0.6	440 million	3.8	3.3
Kent	0.5	280 million	2.1	1.6

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The particle size and concentration data are shown in more detail in Fig. 6, 7, and 8. Figure 6 shows the range in particle size and points out that Kent smoke consists of somewhat smaller particles. Figure 7 demonstrates that the salient difference between the two cigarettes is the very much lower number of particles in the Kent smoke. The photographs, Fig. 1-4, illustrate the differences between the two cigarettes. Figure 8 gives the volume of the smoke particles in a puff. These data can be converted to weight of smoke per puff to compare with the weight samples from the membrane filters. Figure 9 shows the latter data which parallel the concentration data. The weight of smoke per puff from the size distribution data is calculated to be higher; however, this would be expected because the particles are bound to spread from a true spherical shape on the slide. The spreading factor appears to be close to 1.2. The difficulty in establishing this factor precisely is the lack of data on the density of the cigarette smoke in question.

The results from the study on exhaled smoke show that from 70% to 90% by weight of the smoke is lost when it is inhaled into the lungs. This is based on the premise that all the smoke not retained by the lungs will be expelled in the first exhalation after a puff. Experimental work has shown that smoke is exhaled in subsequent breaths, but results to date show this amount to be negligible. If the smoke is taken into the mouth only, up to 20% by weight may be retained. The particles exhaled from the lungs are smaller than the original. These particle size data were obtained with the moving slide impinger; the smoke was exhaled into the 5000-cc flask of the smoking machine.

Figure 9 demonstrates the high retention of smoke in the lower respiratory system, while Fig. 10 compares the weight of smoke retained from

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Kent and Old Gold cigarettes. These graphs show that the retention of Kent smoke is about 10% less than that of Old Golds. This may be due to the smaller size of the Kent particles. Since there is much less smoke in a puff from a Kent, the weight picked up by the body is much lower than that from an Old Gold. It should be remembered that these results are from one male and one female smoker. But the results seem to be applicable in general, since they are in good agreement with what is known about the retention of aerosols by the lungs. Figure 11, which clearly illustrates the importance of particle size in the study of cigarette smoke, is a part of a report by W. B. Harris (A.M.A. Arch. Indus. Hyg. 8, 445, 1953).

In the section on equipment some auxiliary sampling instruments were discussed. The thermal precipitator was used to carry out concentration and size measurements at the same time an impinger sample was taken. A successful procedure has been worked out for this work after some modification of the precipitator. The heat from the hot wire of the thermal precipitator has no noticeable effect on the particles. Both instruments seem to give the same results but a larger number of tests need to be made for a precise comparison.

The electrostatic precipitator has a desirable feature in that the smoke can be sampled without going through a valve, a second diluter, and a high velocity jet. On the other hand, it is not a practical instrument for routine work in this case. After considerable effort the sampling technique was worked out. Again general agreement was found with the impinger sampler. Lack of time precluded any detailed comparison, though.

The aerosol settling chamber gave some quantitative results when smoke had settled from 5 to 30 min. That is, the light beam exhibited colored

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bands indicating the presence of predominant particle sizes at various levels in the settling cylinder. However, the size data showed the presence of fairly large particles indicating that agglomeration was taking place. Diluting the smoke sufficiently to prevent this makes visual studies difficult and, furthermore, with the smaller particles the operation of the settling chamber becomes very sensitive to minute temperature fluctuations.

In the course of this investigation a number of short-range studies were carried out; one study concerned the filtration of atmospheric dust by unlit cigarettes. On a particle count basis both Kent and Old Gold cigarettes removed about 50% of the dust. However, on a weight basis the Kent is very much more effective as shown in Fig. 14, 15, and 16 which demonstrate the filtration of the larger dust particles that make up most of the weight. Figure 17 shows a few asbestos fibers pulled from the filter by the air stream. When the extinguished cigarette is tested after one puff, hardly any asbestos fibers are found.

Some work was done to follow what happens to the smoke particles caught by the Kent filter. A filter was carefully opened above a microscope slide so many of the fibers would settle on it. Examination showed tha individual smoke particles are rather loosely attached to the fibers, which are considerably smaller in diameter than the particles. When enough particles are on a fiber, they coalesce and coat the fiber. Figures 17 and 18 show the asbestos fibers before and after the first puff of smoke.

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