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THE DETERMINATION AND CONTROL OF INDUSTRIAL DUST

PREFACE

In recent years, the subject of the health of workers in dusty trades has been receiving considerable attention from students of industrial hygiene and others interested in the various phases of this problem. When one realizes that the workmen employed in the dusty trades comprise the largest group exposed to any one industrial hazard, it is quite apparent that the importance of this problem has not been overestimated. Furthermore, it is now well established that exposure to certain kinds of dusts, such as those containing considerable amounts of quartz, has increased the morbidity and mortality rate from respiratory diseases; while metallic dusts, such as lead and its compounds, have been associated with general systemic poisoning of workers.

In view of the fact that certain kinds of dusts have been known to produce definite damage to the workers exposed to them, it is obvious that a knowledge of the properties of a given dust, which determines its capacity to produce injurious effects, is essential. Experience has shown that these properties are the composition of the dust, the quantity suspended in the industrial atmosphere, and its particle size.

In order to study all these factors involved in the industrial dust problem, it is necessary to conduct careful investigations. Such studies in industry serve a three-fold purpose. First, they enable one to evaluate the extent of the hazard; this is accomplished by obtaining occupational dust exposures, which disclose the dust-creating tasks. Second, if clinical studies are also made, dust counts may indicate the permissible amount of dust which may be breathed with impunity. Third, dust determinations are used in an attempt to control the hazard; this is effected by testing the efficiency of such devices which have been developed for this purpose.

The purpose of the present bulletin is to present the methods and instruments used in conducting dust studies in industry, the manner of interpreting the results of such studies, and their practical application to industrial problems, especially those phases dealing with the control of the dust hazard. The material in this bulletin is based largely on the practical experience gained by the authors in engineering studies of the dust problem in numerous industries in the United States. It is their sincere hope that this little volume will serve as a guide to engineers, chemists, and others interested in those studies designed to minimize the hazard associated with the inhalation of certain types of dusts.

J. J. B.
J. M. D.

I. PRELIMINARY STEPS: THE SANITARY AND OCCUPATIONAL SURVEY[1]

In the study of industrial health problems it is necessary to accumulate certain fundamental data which may serve in the interpretation of these problems on a scientific basis. One outstanding example of such studies has been the investigations conducted in connection with the influence of the inhalation of atmospheric dust on the health of workers in industrial environments. In all such investigations there are certain preliminary steps of fundamental importance which must be undertaken in order to serve as a guide in the more detailed studies to follow. Roughly, these preliminary steps may be divided into two parts, (1) the sanitary survey, and (2) the occupational analysis.

THE SANITARY SURVEY

The sanitary survey of the workroom environment may be likened to the inventory of materials and stock which a business establishment usually undergoes annually. The sanitary survey may well be regarded as a listing of the facilities afforded the workers while in the industrial environment. When one realizes that one-third of the worker's day is spent in this environment, one clearly sees the necessity for a study of all those factors which bear on the health of the industrial worker.

In the course of certain studies conducted in munition plants during the last war, Winslow and Greenburg devised an inspection form which proved very useful in their studies of factory workrooms. (1) This form has been utilized in numerous investigations in industrial establishments throughout the United States, and it has been found in nearly all instances that the filling out of this form has proved a valuable guide and starting point in the study of the workroom environment Under items 1 to 4 provision has been made to record general sanitary and hygienic data concerned chiefly with the workrooms. Under numbers 5 to 11 are noted those industrial hazards created more particularly by special processes and materials used in these processes. Item 12 of the inspection card deals mainly with the occupational analysis and will be discussed in more detail in the section of this chapter dealing with this subject.

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[1] Received for publication Aug. 25, 1934.

No.

FIELD INVESTIGATIONS

1. City
Type of building
Size
Establishment
Shop
Date
Location
Crowded
2. Ventilation—Natural
Artificial
Ample
Deflectors

Temperature						Remarks:
Dry						
Wet						
Humidity						

3. Illumination——Natural
Window space
Type of window
Artificial—Type and no.
Shadows or glare
General impression
Maximum distance from window
Ratio to floor space
Condition
General impression
4. General conditions—Refuse cans
Cuspidor service
Sweeping service
Fire protection
Fire escapes
Coat rooms
Washing facilities
Eating facilities
Toilet facilities—Type and no.
Light
Ventilation
Condition
Ample
Male
Female
Drinking water
5. Safety hazards
6. Fumes and gases
7. Dust
8. Specific poisons
9. Exposure to heat or cold
10. Fatigue
11. Excessive noise
12. Employees

Process	Raw material	Finished product	Employee	Day shift				Night shift				Method of payment	Seats and backs	Replaceable by females	Hazards	Rest period	Exercise period
				Skilled		Unskilled		Skilled		Unskilled							
				M	F	M	F	M	F	M	F						
Total												Employees at full production				Color	

Absenteeism and labor turnover.
Remarks:

In practice, the sanitary survey consists in carefully filling out the inspection form and jotting down any additional notes on items which may not be provided for in the survey form. Under certain conditions, such as may exist in a coal mine, or a cement mill, some of the items listed in the card may obviously be omitted. After filling out a survey card for each workroom in the entire plant a detailed analysis of the data contained in the cards is then in order. It is such an analysis that enables one to form a picture of the hygienic conditions in each of the workrooms studied and in the plant as a whole.

One or two illustrations of an analysis of data obtained in a sanitary survey of a plant will suffice to clarify the technic involved in such an analysis. Reference to the survey card shows that under item 1, the size of each workroom is obtained and that under item 12 the workroom population at full production is also recorded. In the example given below a survey of 50 workrooms was completed and the following table illustrates how the data on space allotment was handled:

TABLE 1.—*Distribution of workrooms according to per capita space allotment*

Square feet floor area per capita	Number of rooms in each group	Cubic feet per capita	Number of rooms in each group
Less than 25	3	Less than 250	2
25–50	2	250–500	3
50–100	15	500–1,000	12
100–150	20	1,000–1,500	23
150–200	8	1,500–2,000	7
More than 200	2	More than 2,000	3

According to the Tentative Code of the United States Public Health Service on Workroom Sanitation, 25 square feet of floor area per capita, or 250 cubic feet of air space per capita, may be considered as a fairly ample space allotment. In the light of the above standards the data indicated in table 1 show that 3, or 6 percent, of the rooms did not fulfill the requirement for area allotment and that 4 percent of the rooms did not meet the standard for per capita cubic content. Similar analyses may be carried out for the other items listed in the survey form.

Several years ago, in studying the dust hazard in a modern factory, it was considered best to conduct a sanitary survey of the numerous workrooms in this factory, in order to be able to locate the dusty workrooms and processes, and to plan the dust sampling schedules intelligently. As a result of such a sanitary survey numerous safety hazards were encountered in the various workrooms and in addition a lead and benzol hazard (unknown to the plant officials) were also disclosed.

To recapitulate, the sanitary survey of workrooms in any plant yields definite information concerning the presence and extent of various health hazards and often serves as a guide in establishing which hazards require further study in the form of actual quantitative analyses; such, for example, as the determination of hydrogen sulphide in the spinning room of a rayon silk manufacturing plant using the viscose process. Unquestionably, many problems arise in industry for which there are no simple solutions. Others require considerable expenditure of funds and ingenuity for their complete eradication. On the other hand, a sanitary survey of a factory will often disclose many small problems which require very little expenditure of money and effort for their elimination. The solution of such small problems may eliminate sources of ill health or unpleasantness to the industrial worker, so that the worker and, in the end, the plant management are those to benefit.

OCCUPATIONAL SURVEY

A very important part of any study of workroom environment is the occupational analysis, which permits one to learn of the activities involved and the particular hazards associated with each occupation. Such an analysis also discloses the number of persons in each occupation, which gives one an idea of the importance of each hazard from the viewpoint of the numbers involved. Perhaps a typical example of such an analysis will serve to portray the value of the occupational survey. For the sake of simplicity an analysis of workrooms in which only one major hazard was found to exist is herewith presented, namely, the occupations involved in granite-cutting plants. The table below shows the various occupations followed in 14 typical granite-cutting plants (2).

TABLE 2.—*Analysis by occupation of certain granite-cutting sheds*

Occupation	Number of men	Occupation	Number of men
Granite cutters:		Sawyers	86
Pneumatic-tool workers	565	Engineers	
Surfacing-machine operators	68	Firemen	
Sand-blast operators	4	Draftsmen	
Carvers and letterers	24	Foremen	
Lathe operators and others	41	Blacksmiths	
Tool grinders	20	Carpenters	
Lumpers	164	Night watchmen	
Boxers		Clerks	
Cranemen		Salesmen	
Polishers		Superintendents	
Bed setters		Manufacturers	
Tool carriers			
Machinists		Total	972
Laborers			
Stone washers			

There are several important facts to be derived from a study of the occupations in granite-cutting plants, such as in the analysis presented in the above table. First, the processes involved in granite stone-cutting may be divided roughly into two parts, namely, those occupations dealing with the actual cutting of the stone and the additional labor necessary for the conduct of the former processes. Examination of table 2 shows that under the heading of granite cutters there are five general occupations. Also by far the greatest number of persons are engaged in tasks involving the production of dust. Furthermore, that 565 of the 702 persons creating dust are engaged in work involving the use of the hand pneumatic tool, a device well-known to be productive of enormous quantities of dust. It is at once obvious from such an analysis that considerable time should be devoted to the study of the dust exposure of granite cutters in general and of hand pneumatic-tool workers in particular. The results of such a study are presented in table 3.

Table 3.—*Ranking the various occupations in the granite-cutting industry according to their dust exposure*

Occupation	Number of men exposed	Number of observations	Dust count (in millions of particles per cubic foot)		
			Minimum	Maximum	Average
All pneumatic hand-tool operators	565	56	2.4	201.0	59.2
Surface cutters:					
Inside	58	34	.6	165.7	44.0
Outside	10	10	14.0	102.2	43.9
Carvers and letterers	24	20	11.7	99.8	37.0
Tool grinders	20	14	6.3	62.0	27.1
General plant atmosphere	121	42	2.5	64.0	20.2
Lathe operators	4	4	6.0	25.7	17.9
Polishers	43	16	1.3	26.8	9.0
Sand-blast operators	4	6	1.9	13.4	6.2
Sawyers	10	4	4.0	4.9	4.6
Blacksmiths and others	103	5	.9	8.2	2.5
Office employees	10	4	1.5	2.4	1.9

As a result of a prolonged study of the health of the workers engaged in the various occupations of granite-cutting, it was possible to demonstrate that those persons engaged for many years in tasks associated with a dust exposure of less than 10 million particles per cubic foot of air were not suffering from silicosis or tuberculosis, the diseases most prevalent among these granite cutters. It was also possible to demonstrate that among these granite cutters, the incidence of silicosis and tuberculosis, all other factors being equal, was directly proportional to the degree of dust exposure.

The importance of an occupational analysis from the viewpoint of determining the extent of an occupational hazard is at once obvious. Such an analysis is of still greater importance in the subsequent steps necessary for the elimination of a condition known to be inimical to health. Unless one knows definitely which occupations in a workroom, containing many diverse processes and activities, are associated with unhealthful conditions, it is impossible to map out a constructive and effective program of prevention. We have just seen that in the case of the granite-cutting study the problem resolves itself to keeping the dust content of the workroom air below the level of that associated with those occupations found to be free from silicosis and tuberculosis, even after many years of industrial exposure; namely, those occupations exposed to less than 10 million particles of dust per cubic foot of air. The same technic may be applied to other industrial problems, which on first examination seem more difficult of solution than the case just cited. Perhaps another single illustration will demonstrate the value of the occupational analysis as a guide in the elimination of industrial health hazards.

Studies of industrial morbidity made by the United States Public Health Service indicate that the greatest percentage of lost time in industry is caused by respiratory diseases. One of these studies showed that pneumonia, in all forms, occurred in nearly twice the amount among iron and steel workers as it did among the employees of other industries, during a 3-year period of observation (3). A 5-year inquiry into the causes of high pneumonia sickness rates among iron and steel workers in a representative mill disclosed the fact that the largest number of pneumonia cases occurred in certain departments, such as in the blast furnace and open-hearth steel-making plants. When one realizes, however, that these departments contain anywhere from 60 to 100 different occupations, the task of a preventive program is a hopeless one unless definite information is obtained concerning such important factors as (1) the number of persons in each occupation, (2) the activities associated with each occupation, (3) the health hazards associated with each occupation, and (4) the incidence of penumonia for each occupation. Such data are available from an occupational analysis of each department. For example, in the iron and steel plant under consideration morbidity statistics for the period of 1924–27, showed that 38 cases of pneumonia occurred among the 1,637 bituminous coal miners employed during the same period in the mines operated in connection with this iron and steel plant. An occupational analysis disclosed the fact that there were 69 different occupations in the mines and that 33 of the total of 38 pneumonia cases were associated with only two occupations—those of pick mining and loading of coal. The pneumonia rate per 1,000 men for miners and loaders was shown, by this study, to be 31, whereas the rate for all other mine workers was found to be only 8.5. It is quite obvious, therefore, that of the 69 occupations involved in the mining of coal, one's attention should be concentrated on the activities of coal miners and loaders, in an attempt to determine those factors in the industrial process and environment which contribute to the high pneumonia incidence experienced by those workers.

In practice the making of an occupational analysis has for its basis the filling out of item 12 of the survey form previously mentioned. The data obtained cover such subjects as the manufacturing process, the raw materials entering into the process, and the finished product associated with the occupation of each employee. To obtain such data it is necessary for the investigator to become thoroughly familiar with the activities of each occupation and the processes of the workroom as a whole. One must not take anything for granted in a study of this sort. For example, in a study of the hazards involved in the application of radium paint to watch and clock dials in a certain workroom (4), one of the employees listed was the foreman supervising the work of the radium dial painters. Upon close study it was discovered that this worker, in addition to allotting and supervising the work of each painter, spent 1 hour a day in mixing paint for all the dial painters and once a month blended various radium powders in such a manner that he was exposed to the inhalation of enormous quantities of radioactive dust. This latter brief exposure to radioactive dust was of far more significance from the viewpoint of radium poisoning than his total exposure during his supervisory duties.

The remaining subjects listed under item 12 of the survey form are all of a simple nature, but are often of assistance in presenting a complete picture of the workroom environment, and at times serve to explain certain unusual phenomena. Take for example the subject of labor turn-over. In a certain lead storage battery factory the plant officials pointed to the small number of lead poisoning cases occurring in their plant to show that this disease was not an important problem in their workrooms (5). Investigation of the workroom atmosphere disclosed that in the lead-mixing and pasting rooms of this plant enormous quantities of lead dust were present, quantities sufficient to produce lead poisoning in a comparatively brief period of exposure, as judged by our present knowledge of lead poisoning. Further inquiries revealed the fact that the labor turn-over in these two workrooms was very great, in fact, so great that the men left employment before real serious symptoms of lead poisoning manifested themselves. The presence of a high labor turn-over in times of normal production is often highly suggestive of unhealthful or unpleasant working conditions.

The remaining subjects under the item dealing with employees, need no further comment, since their purpose will be quite obvious to the average investigator. It is often very helpful to obtain a sketch or blueprint of the workroom layout, on which may be noted such important items as the location of ventilating systems, points of sampling, and any other data bearing on the problem under study. These data may then be used in the subsequent steps of an investigation of this type, namely, the recommendations necessary to eradicate certain unhealthful or unpleasant conditions which the study may have disclosed.

II. THE INSTRUMENTS AND METHODS USED IN THE SAMPLING OF ATMOSPHERIC INDUSTRIAL DUSTS

GENERAL CONSIDERATIONS

Atmospheric dust may be definied either on a basis of one of its physical characteristics, such as size, or physiological grounds, depending on the effects produced on the human body by the inhalation of the dust. Drinker and Thomson (6), in their classification of dusts, fumes, and smoke, have defined dusts as "particles or aggregates of particles, 150 to 1 micron in diameter, that are thrown into the air by mechanical agencies * * * Examples are silica, talc, cement, organic dusts such as hard rubber, starch, and cocoa; flocculated fume and smoke products." In the present volume dusts will be interpreted as particles or aggregates of particles suspended in the atmosphere and of a size capable of being inhaled (in industry this size is usually less than 10 microns in diameter), and will be considered in two classes, namely, those which may be capable of producing fibrosis of the lungs or other respiratory conditions, and dusts which may cause systemic poisoning, as typified by certain compounds of lead.

Since our interest in the dust problem has a purely industrial aspect, it is essential that any dust-sampling instrument which one will use should be capable of collecting effectively dust of a size present in the industrial atmosphere. As will be shown later, industrial dusts are mainly from 0.5 to 10 microns in size, so that an instrument capable of collecting these sizes with a fairly high degree of efficiency will meet the present-day requirements. The range in dust concentrations encountered in industries is very great, depending, of course, on the industrial processes, the devices installed for mitigating the dust created, and the efficiency with which such devices function. For these reasons, an ideal instrument should be one capable of sampling with equal efficiency in both high- and low-dust concentrations. This factor calls for the prerequisite of a dust-collecting medium which shall not add dust to any great degree to the dust in the sampled air. Furthermore, the collecting medium must be uniform in dust content, so that one or two control tests on this medium will be sufficient for a series of samples.

Since the dust content of industrial air is ever varying, it is essential that the dust-sampling instrument be capable of collecting air in large quantities at a rapid rate in order to obtain a representative picture of existing conditions. And, finally, the ideal instrument will be one that requires only a simple and fairly rapid method of analysis. Suffice it to say that an instrument designed for use in the field should embody all these principles and in addition be light in weight, portable and compact in construction.

To recapitulate, the final selection of a dust-sampling instrument for industrial use will depend on the collecting efficiency of the device, on its small errors in analysis, on its portability and on the ease with which a sample once obtained may be analyzed.

Many methods have been devised and used for the purpose of determining the quantity of dust in air. Knowles (7) lists some 53 different instruments developed and used for this purpose at one time or another. Because most of these instruments have proved impractical and are no longer in use, no discussion concerning them will be given. The reader is referred to an excellent review of this subject by Dr. Leonard Greenburg (8). However, it may be of some interest to review, briefly, the history of the development and use of some of the dust sampling instruments in vogue today.

HISTORY OF PRESENT DAY DUST SAMPLING INSTRUMENTS

The South African investigators began using the sugar tube method for the sampling of atmospheric dust in 1911 (9), and Lanza and Higgins in their Joplin study also availed themselves of the same technique (10). In fact, no other suitable method was then available. In 1912 the Committee on Standard Methods for the Examination of Air of the American Public Health Association recommended the sugar tube as the standard method for the sampling of atmospheric dust.

This method of dust sampling had several drawbacks, the chief of which were its slow sampling rate (the American Public Health Association Committee sampled 5 cubic feet in 18 minutes) and the fact that the sugar always contained a certain quantity of dust which introduced a variable, and sometimes considerably doutbful, element into the final results.

To overcome the limitations of the sugar-tube method, various investigators attempted to devise other procedures for the sampling and analyisis of atmospheric dust. One of the most fruitful studies was that of Palmer (11), who in 1916 presented his water-spray apparatus for sampling dust. This method was adopted in 1917 by the Committee on Standard Methods of the American Public Health Association and was recommended as the standard technique for the sampling of dust in air. The United States Public Health Service began employing this apparatus in 1918 in its studies of dust in air.

In 1916 the South African investigators, desirous of obtaining a more portable type of instrument and one which would yield results more rapidly, described a new instrument known as the Kotzé konimeter (12). In this instrument a small volume of air, approximately 10 cubic centimeters, is impinged at a high velocity (30 to 80 meters per second) against the surface of a vaseline-coated glass plate, the vaseline serving to retain the particles of dust after they strike the plate. The plate is then removed and placed under the microscope, the adherent dust being counted at a suitable magnification. The United States Bureau of Mines, which had been using the sugar-tube method for dust sampling, began at once to study the performance of this new instrument.

In 1922, the instruments mentioned were the ones in most common use. In addition, however, the United States Bureau of Chemistry (13), in its dust-explosion work, employed an apparatus which consisted essentially of an adapter for holding a Whatman filter paper thimble through which air was drawn by a suction pump, thus sampling the atmospheric dust. By the difference in weight of the paper thimble before and after dust sampling, the weight of the dust was easily determined. Finally, mention should be made of the Anderson and Armspach (14) dust determinator which, in 1922, was in use by the American Society of Heating and Ventilating Engineers. This instrument measured the loss of pressure incident to forcing air through a piece of filter paper; this rate of loss of pressure was then regarded as a measure of the air dustiness.

Very briefly, such was the status of the technique of atmospheric dust sampling in the year 1922, when it became apparent that the various dust-sampling methods did not yield results which could be regarded as absolute or even comparable. In fact, sampling in a given industry, by different methods, usually gave findings which were not of the same order of magnitude. As a result, a conference of interested persons was held at the United States Bureau of Mines Experiment Station, Pittsburgh, Pa., in 1922. It was decided at that time to conduct a laboratory study of dust-sampling instruments.

The study was started in the summer of 1922 at the Pittsburgh Experiment Station. Suspensions of dust (five different powdered substances were used) were set up in an air-tight chamber and simultaneous samplings were carried out at first with the sugar tube, the Palmer apparatus, the konimeter, the filter-paper thimble, and the dust determinator.

During the course of the study a new instrument, the impinger, for the sampling of dust was devised. This new instrument was included in the later stages of the laboratory study of dust-sampling instruments described in the report published as Public Health Bulletin No. 144.

In this instrument the air to be sampled is drawn through a glass tube and impinged at a high velocity on a glass plate which is kept beneath the surface of the water or other suitable fluid in the collecting flask. The dust is momentarily arrested, wetted by the collecting fluid, and in this manner trapped. After a sufficient volume of air has been sampled, a portion of the collecting fluid is removed to a suitable counting chamber or cell for microscopic count to ascertain the number of particles in a manner to be described later. The remaining portion of the sample may be subjected to any desired analysis.

In the comparative study the dust-catching efficiency of the impinger was found to be high. Consequently, its physical principles and characteristics were the object of a special study, and finally a satisfactory and practical form of dust-sampling instrument, based on this principle, was evolved.

The apparatus (essentially in its present form), as described in Public Health Bulletin No. 144, possessed an efficiency of 94 to 97.5 percent when sampling a finely divided silica dust suspension at the rate of 1 cubic foot per minute. The tests used in estimating this efficiency were conducted by an optical method in which a portion of the dusty air being delivered to the collecting device was diluted with measured amounts of dust-free air until a "match" was obtained on comparison with the stream of air emerging from the dust-collecting device. The comparison, or matching, consisted in producing equal Tyndall effects (equal amounts of reflected light) by the two dust streams when they are simultaneously observed in a beam of light.

So far as the quantitative results of the dust-sampling instruments are concerned, the conclusion of the comparative study was as follows:

> Considering the dust caught by the Palmer as unity, the instruments take the following order: On basis of numbers of particles determined—impinger, 5.0; sugar tube, 2.1; and Palmer apparatus, 1.0. On basis of weight of dust determined—impinger, 2.1; thimble, 1.5; sugar tube, 1.6; Palmer apparatus, 1.0.

These results have led to the selection of the impinger as the most efficient apparatus for all-round industrial dust sampling. The instrument has been used in a number of studies in the dusty trades, in the studies of lead tetraethyl, and many other investigations to be mentioned later. Twelve years of field experience with the impinger apparatus have given confirmatory evidence of its value as a dust-sampling device.

DESCRIPTION OF PRESENT-DAY DUST-SAMPLING INSTRUMENTS

Of the various instruments mentioned in the history of the development of dust-sampling devices, two which are at present finding some use in dust determinations were developed since 1922. These are the Owens Jet Dust Counter (15) and Drinker's modification of the electrical precipitator device for dust collection (16). As a result of the comparative study carried out in 1922, the Palmer, and the Anderson and Armspach dust determinator are employed very little for dust sampling at the present writing. The instruments employed in dust studies are practically limited to the following: Impinger, Electrical Precipitator, Owens Jet Dust Counter, Paper Thimble, and Kotzé Konimeter. The text which follows describes the working principle of each of these five instruments, their construction and use, and their advantages and disadvantages.

The Greenburg-Smith impinger

The impinger apparatus (17) consists essentially of two portions: First, a source of sufficient suction to draw the air to be sampled through the sampling device; and, second, the sampling device or impinger itself, which consists of a container and the impinger tube and plate. As a source of suction, an electrically-driven and a compressed-air-driven apparatus have been designed. A hand-driven apparatus developed at the United States Bureau of Mines will also be described.

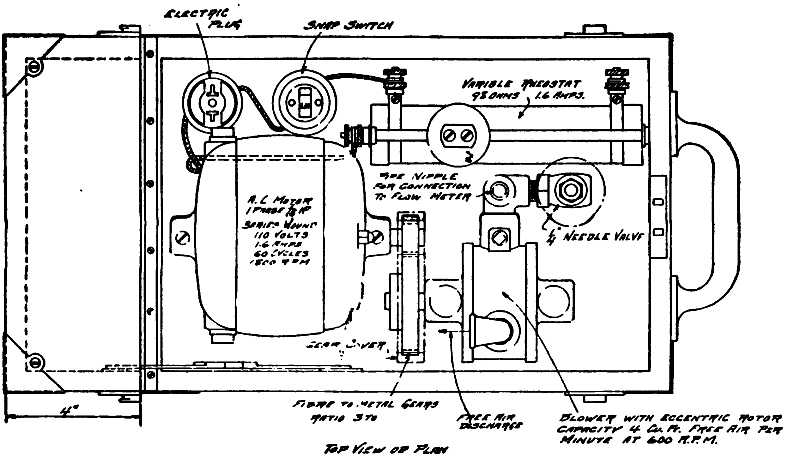

FIGURE 2.—Drawing of electrically driven suction apparatus, top view.

Electric suction apparatus.—The electrically-driven suction apparatus is designed to be used in places where electrical energy is available. A photograph of the apparatus is shown in figure 1, and the mechanical details are presented in figures 2, 3, and 4. The motor is a series-wound, single-phase, 60-cycle, one-fifteenth horsepower, rated at 1.6 amperes, at 110 volts, with a speed of 1,800 revolutions per minute. This motor, being series-wound, operates on either alternating or direct current. The motor is geared to a rotary eccentric positive pressure blower by means of a set of gears having a 1 to 3 ratio. In order to minimize noise, the smaller of

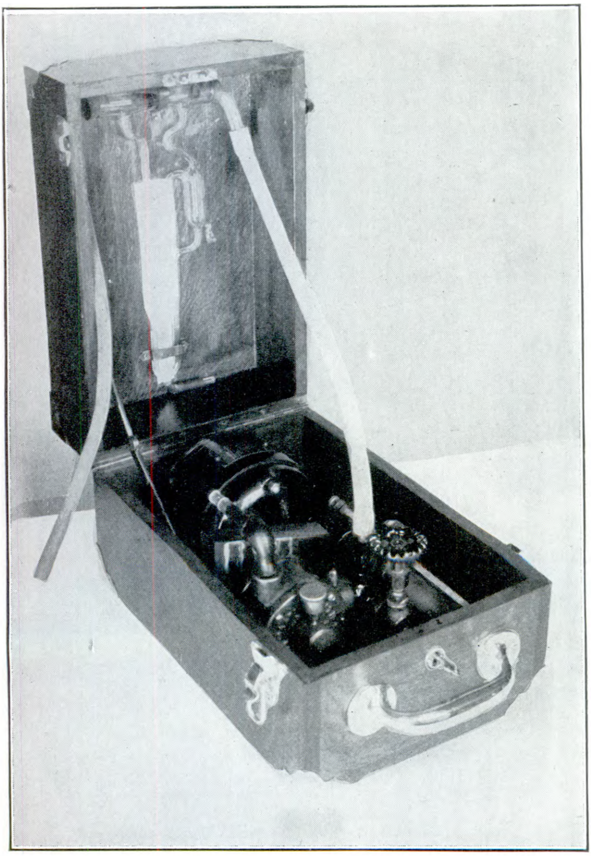

FIGURE 1.—ELECTRICALLY DRIVEN SUCTION APPARATUS FOR IMPINGER.

these gear wheels is made of fiber, the larger being metal. The blower is rated at 4 cubic feet of free air per minute when rotated at a speed of 600 revolutions per minute, and is used as a source of suction rather than as a source of air pressure. Wired in series with the electric motor is a 98-ohm, 1.6-ampere variable sliding rheostat used for speed control of the motor. By employing such a rheostat a voltage of 110 or 220 volts may be used. To the intake or suction side of the blower is attached a ¼-inch malleable-iron elbow fitting provided with two inlets. To one of the inlets a ¼-inch brass needle valve is attached, which serves as a by-pass in regulating the rate of suction. The second inlet of the elbow is connected to a constriction-type glass flowmeter by means of a suitable length of noncollapsible rubber tubing; the flowmeter is fastened on the inside of the lid of the carrying case. The inlet side of the flowmeter is connected to the sampling flask by means of a second piece of noncollapsible rubber tubing. The latter piece of rubber tubing may be of any suitable length. The flowmeter scale is calibrated in a manner to be described later. A vacuum gage may be used instead of a flowmeter as a measuring device for the air flow.

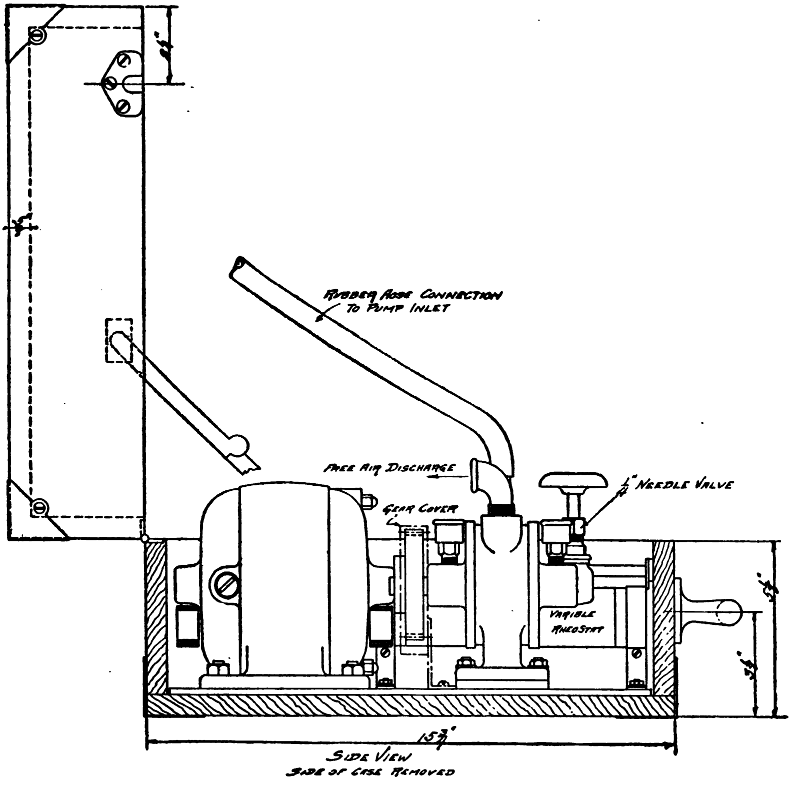

FIGURE 3.—Drawing of electrically driven suction apparatus, side view.

The electric motor, blower, sliding rheostat, electric plug, and switch are all assembled on a metal plate 9 by 14 inches and ⅛ inch in thickness, and this plate is in turn firmly screwed to the base of the carrying case. The carrying case is made of ½-inch quartered oak, the outside dimensions being 10½ by 15½ by 9¼ inches. The weight of the apparatus is 45 pounds.

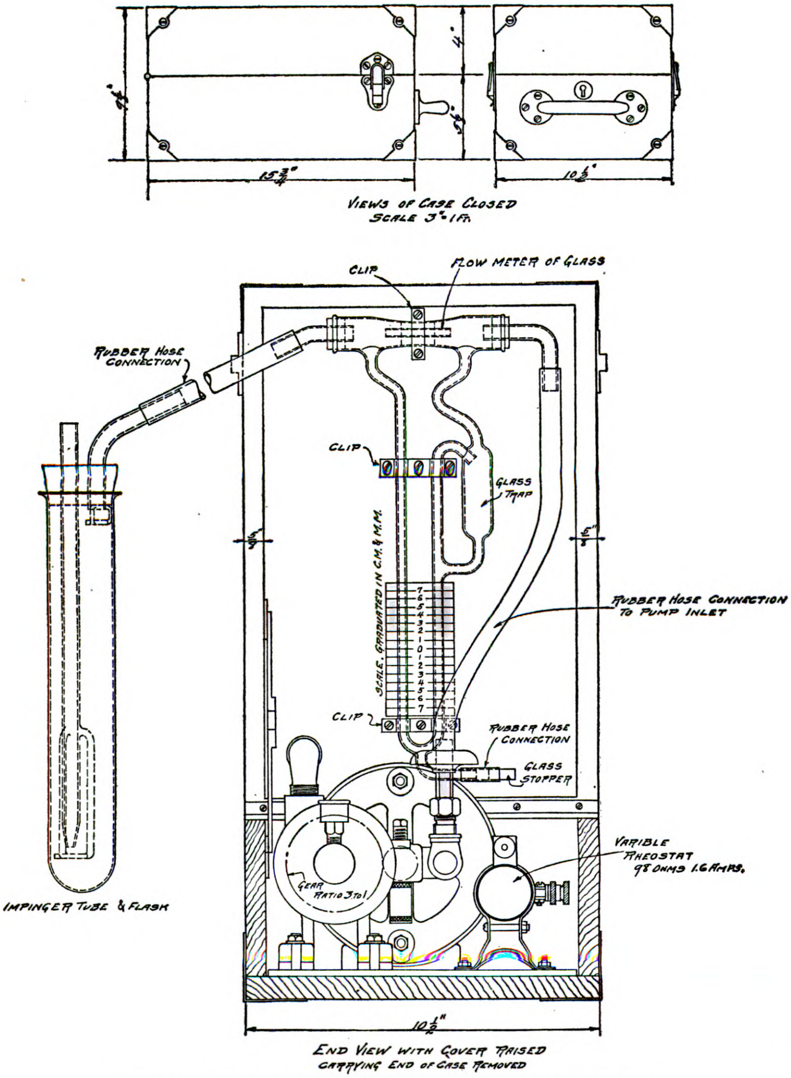

FIGURE 4.—Drawing of electrically driven suction apparatus, end view.

Compressed-air suction apparatus.—In many industrial establishments, mines, and quarries, compressed air is readily available. By means of a very simple device called an ejector, the energy of the compressed air may be converted into suction and then utilized with the impinger tube and flask for the sampling of the dust in air. Hatch has recently described a suction device of this type which has the added feature of a constant flowmeter (18). Details of this instrument are presented in figure 5. This device uses about 50 cubic feet of free air when functioning and a constant rate is obtained with it regardless of the variation in air pressure, so long as this pressure is within the limits of 30 and 75 pounds per square inch. For an indicating device a simple pressure gage, connected to the compressed air supply, is employed.

The constant flow in this meter is due to the fact that the pressure drop across the orifice ($p_1 - p_2$) is greater than the critical pressure, which for air is 0.53 p, (where p_1 is the upstream and p_2 the downstream pressure). Under this condition the flow depends upon p_1 only, and since this remains constant (within the limits of barometric pressure), the rate of air flow has a constant value. With a barometric pressure equal to 30 inches of mercury and the pressure loss through an impinger device equal to 2.9 inches, $p_1 = 27.1$ inches. To meet such a requirement $p_1 - p_2 \geqq 14.5$ inches ($\geqq 0.53\ p$), and p_2 (absolute) must be less than 12.6 inches of mercury, that is, -17.4 inches of mercury gage pressure. A suction in excess of this value is obtained with the aid of a No. 2 Hancock ejector, when the pressure in the air line is between 30 and 75 pounds. The orifice as designed by Hatch and his co-workers was found on testing to yield rates of flow from 28 to 29 liters a minute (about 1 cubic foot per minute) with a maximum variation of 3.5 percent.

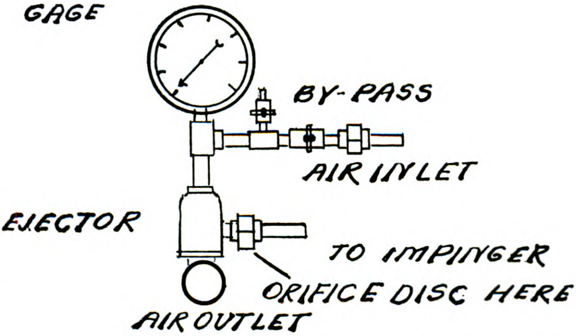

FIGURE 5.—Compressed-air-driven suction apparatus for impinger.

Hand-driven suction apparatus.—Early in the course of the studies at the United States Bureau of Mines Experiment Station at Pittsburgh, the necessity became apparent for a hand-actuated apparatus, to be used in work places lacking electric power or compressed air. Such a device was designed and constructed and is fully described in Public Health Bulletin No. 144. The apparatus in its present form (fig. 6) consists of a tripod of metal tubing supporting a vertical post and a horizontal bar at its apex. The horizontal bar is provided with an ordinary bicycle seat. To the vertical post at a suitable level (adjustable) there is attached a positive pressure blower (used as a source of suction) of the same size and capacity as that used with the electrically-driven type of apparatus. In this case, however, all of the excess metal of the blower has been removed by machining in order to reduce the weight of the apparatus. The blower is geared to a pair of crank handles by a pair of gears having an 8 to 1 ratio. The suction inlet of the blower is attached to the impinger sampling bottle which is supported near the top of the vertical post of the tripod. The steel tubing of which the tripod and its appendages are constructed may be dismantled and the complete apparatus fitted into a canvas case somewhat resembling a gun case. The weight of the complete apparatus is approximately 17 pounds.

A revolution counter attached to the large gear records the number of its revolutions. Calibration of the instrument with a gas meter showed that the volume of air sampled per revolution of the pump varied somewhat with the rate of revolution. The calibration curve presented herewith (fig. 7) is taken from Public Health Bulletin No. 144. The particular pump tested aspirated 1 cubic foot of air per minute when operated at 92 revolutions per minute.

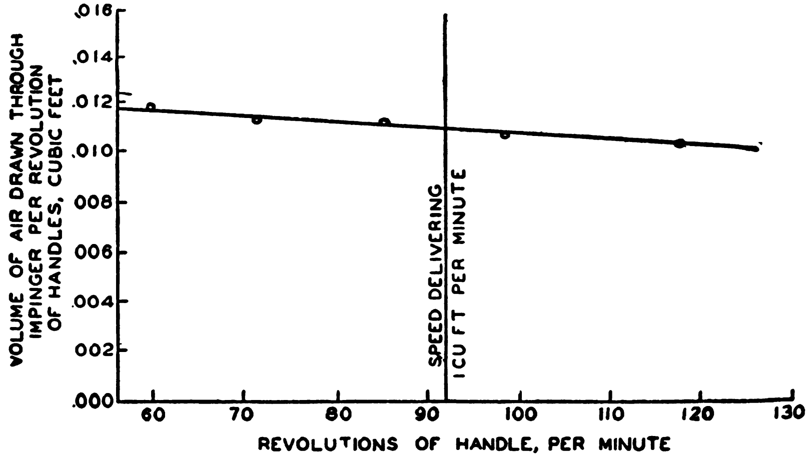

FIGURE 7.—Calibration curve of rotary pump for hand-driven suction apparatus.

When the apparatus is in use the operator turns the crank at the rate of approximately one and one-half revolutions per second, maintained as constantly as possible, for an appropriate length of time. The number of revolutions per minute is determined by dividing the total number of revolutions by the time of sampling. From a curve similar to that shown the volume per revolution is calculated, which is multiplied by the number of revolutions to give the total volume of air sampled.

For general field use, the compressed-air device has been found to be the most satisfactory form of apparatus.

Impinger tube and sampling flask.—The impinger tube in the model of the apparatus described in Public Health Bulletin No. 144

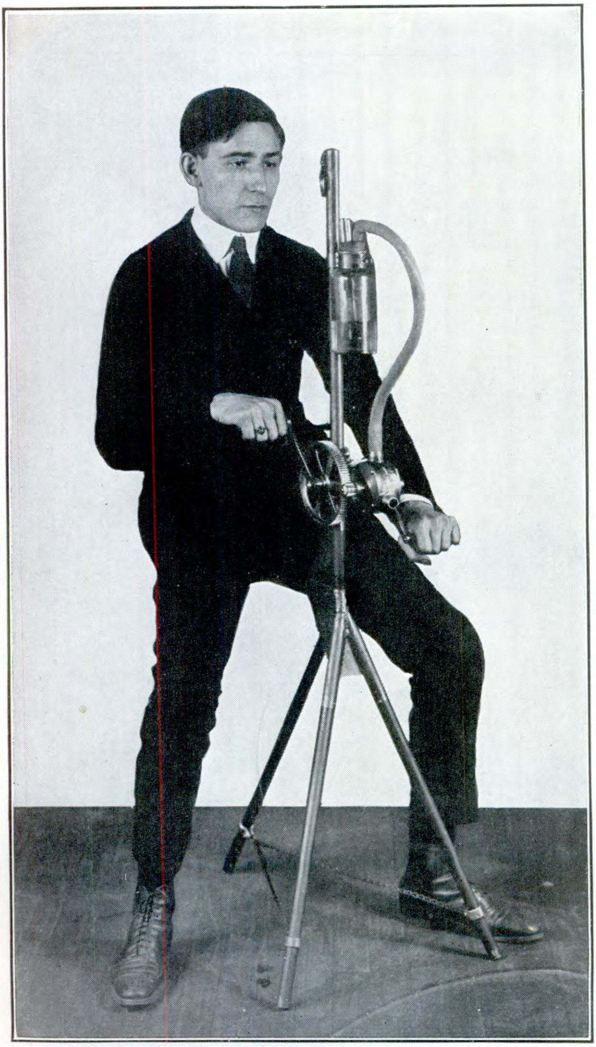

FIGURE 6.—HAND-DRIVEN SUCTION APPARATUS FOR IMPINGER.

(p. 67) consisted of a piece of Pyrex glass tubing, drawn down to a tip with a 2.3-millimeter orifice. To this tube a metal tripod and circular impinging plate were attached by means of a bronze split-sleeve clamp. The distance between the orifice and the upper surface of the plate was kept at 5 millimeters.

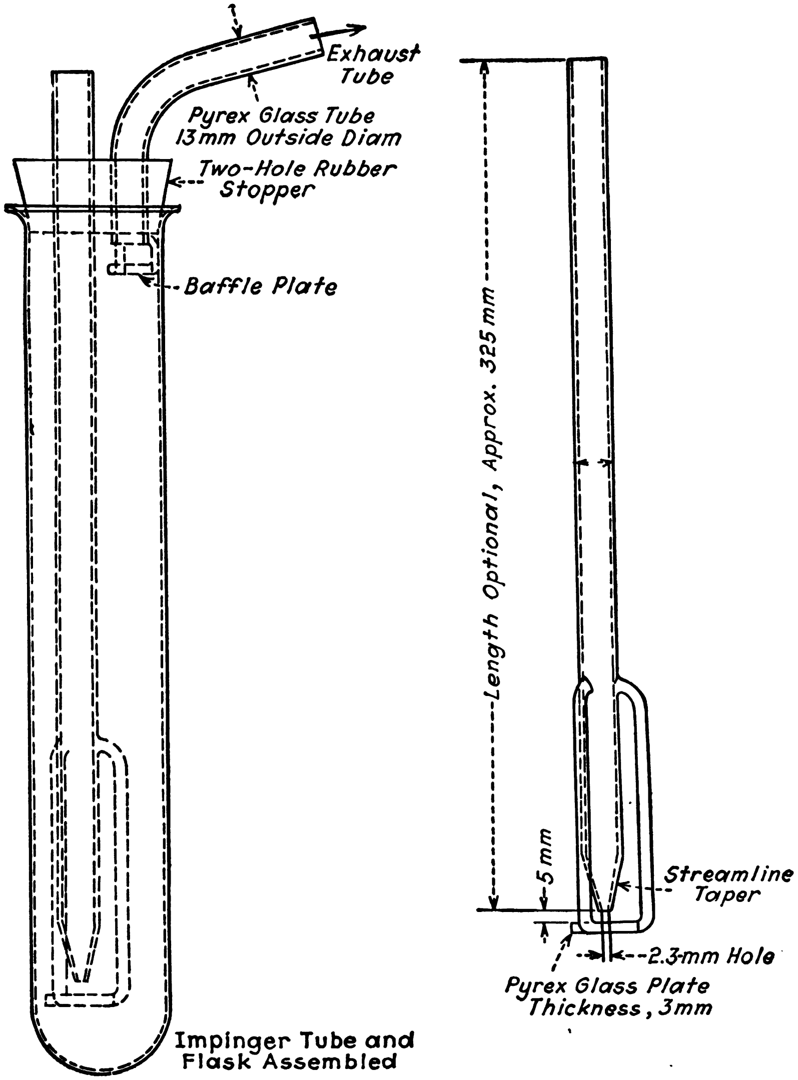

FIGURE 8.—Drawing of impinger tube and flask.

In practice, this impinger tube yielded satisfactory results. Nevertheless, it was felt that it would be preferable to eliminate the use of metal, particularly where acid or alkali was to be used as the collecting fluid. Accordingly, there was designed and constructed the all-glass impinger tube shown in figure 8, with circular glass impinger plate about 2.5 millimeters in diameter, fixed by three supporting rods about 9 centimeters long to the impinger tube at a distance of 5 millimeters from the orifice. The tube was 13 millimeters in outside diameter. Pyrex glass was used throughout. Tubes of this type have been employed without an undue amount of breakage.

A few modifications have been made in the impinger flask. Originally, a round 16-ounce glass bottle fitted with a 2-hole rubber stopper was used. A short time later a 500-cubic centimeter Pyrex glass assay flask (wide-mouth conical Erlenmeyer type) was substituted, which proved to be very satisfactory.

In certain studies it was found desirable to obtain dust samples in the region of the mouth and nose of a worker in order to secure a more representative picture of the air actually breathed. This was done in a very ingenious manner by the Australian workers, Badham, Rayner, and Broose (19) who utilized as the sampling flask a cylinder 12 inches in length, and 2 inches in inside diameter. The cylinder was fastened to the worker by a specially designed strap passing around the chest. We have employed a similar flask made in the form of a tube sealed at the lower end, 300 millimeters in length and 50 millimeters in diameter, provided with the 2-hole rubber stopper (shown in fig. 8). For protection from the impact of large pieces of flying material, as well as for convenient support, the tube was placed inside of a cylindrical leather holster which in turn was made fast to the chest of the worker by means of a pair of straps fastened about the chest and shoulders. Thus, the inlet end of the impinger tube was fixed at a point very close to the nose and mouth of the wearer. As before, the outlet tube from the sampling cylinder is connected to the source of suction by means of a convenient length of noncollapsible rubber tubing. Figure 9 shows this form of impinger sampling cylinder with its leather holster, as used in our studies.

Whether bottle, flask, or cylinder is used, sufficient liquid should be kept in the container during use to cover the impinger plate to a depth of approximately 3 centimeters. In the cylinder type of flask 100 cubic centimeters are sufficient to accomplish this, whereas if the Erlenmeyer type of flask is used, 250 cubic centimeters are required. A baffle plate on the exhaust tube, as shown in figure 8, is sometimes advantageous.

A more compact and convenient impinger flask and nozzle has been recently developed for field use (18). The modifications in the design of the impinger have in no way altered the basic principle on which the instrument operates. Figure 10 shows the latest form of the impinger flask and nozzle.

The modified impinger does away with the glass impinging plate, utilizing the bottom of the flask for this purpose. The suction con-

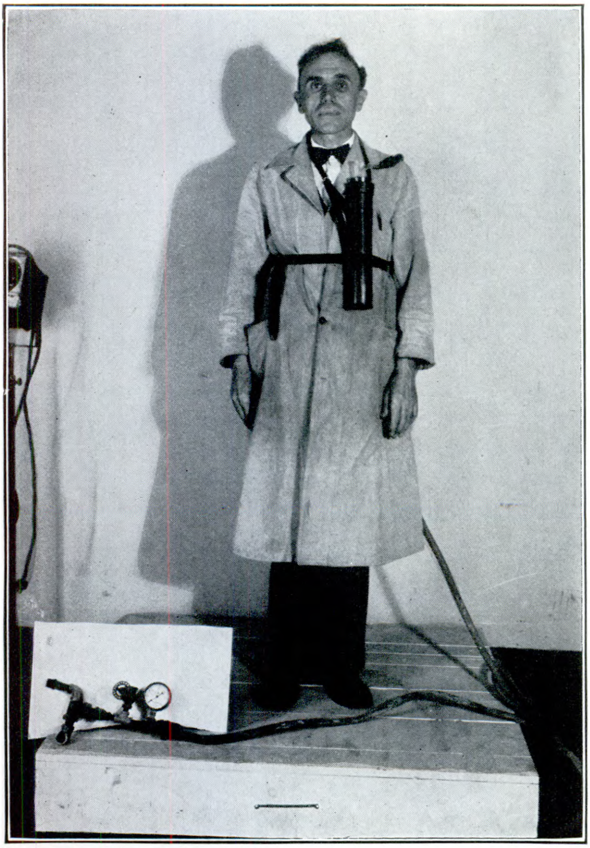

FIGURE 9.—IMPINGER SAMPLING TUBE ATTACHED ABOUT NECK OF WORKER.

nection is combined with the inlet tube, thus simplifying the deviec still further. The essential portions of the device consist of a straight piece of Pyrex glass tubing 15 mm in outside diameter and approximately 275 mm in length. The tube is drawn down in stream-line form at its lower end, to a tip with a 2.3 mm orifice. In sampling this orifice is kept approximately 5 mm from the bottom of the flask, a guide line on the flask indicating this distance. The flask is 50 mm in diameter and 210 mm in height and requires a fluid (water) volume of only 75 cc to give the proper depth of immersion to the nozzle.

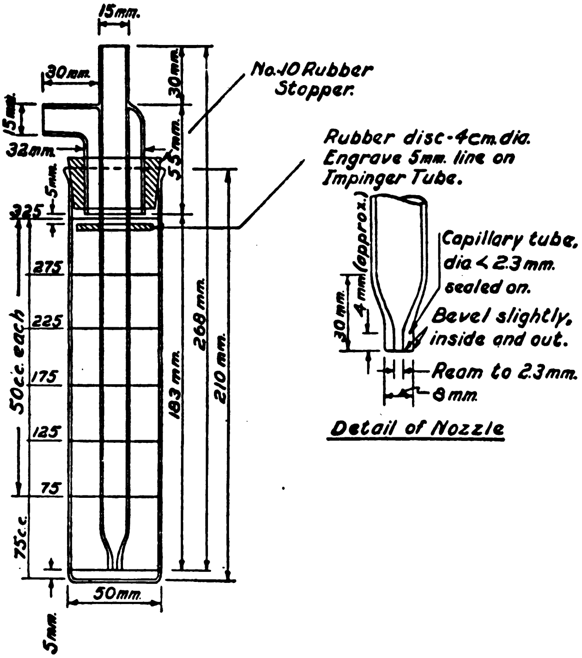

FIGURE 10.—Drawing of modified impinger and detail of nozzle, with construction specifications.

An entrainment trap in the form of a rubber ring prevents the possible loss of the liquid (and dust) with the outgoing air.

Since the impingement distance in this instrument is not fixed, as in the previously described type, it was necessary to determine the limits within which this distance, as well as the angle of impingement from the perpendicular, varied. Studies conducted on these factors by the designers of this instrument showed that as regards the angle of impingement (using silica dust) one can have a maximum displacement of the nozzle without changing the efficiency obtained when the nozzle is in the vertical position. Also, it was found that the impinging distance can be varied from 2 to 12 millimeters without impairing the efficiency against silica dust to any appreciable degree. The data pertaining to the experiments made on this modified device are shown in the following tables, 4, 5, and 6:

TABLE 4.—*Effect of impinging distance on efficiency of impinger*

[Sampling rate=28.3 liters per minute]

Impinging distance (mm)	Percent efficiency				
	Silica	Tobacco smoke		Magnesium oxide	
		Wet	Dry	Medium	Fine
2	+98	88	82	64	55
5	+98	89	81	77	55
7	97	87	80		54
10		84	72		53
12	97			75	
13		81	73		49
15	94				

TABLE 5.—*Effect of varying angle of impingement*

[Impinging distance=5 mm; sampling rate=28.3 liters per minute]

Adjustment of impinger nozzle	Percent efficiency		
	Silica	Wet smoke	Magnesium oxide [1]
Maximum angle from perpendicular	98	[2] 87.77	69
Perpendicular	+98	[2] 89.88	77

[1] Medium size.

[2] At high and low concentrations respectively.

TABLE 6.—*Effect of sampling rate on efficiency of impinger*

[Impinging distance=5 mm]

Sampling rate (liters per minute)	Percent efficiency				
	Silica	Tobacco smoke		Magnesium oxide	
		Wet	Dry	Medium	Fine
15.0		57			15
20.0	91		69		25
23.0		76			
25.0	98		73	72	38
28.3	+98	90	79	77	55
35.0	+98	93	87	84	62
39.0		94			
42.5		94			
45.5		95			

Method of sampling—Calibration of the impinger apparatus.—It is necessary to calibrate the air-measuring device of the impinger apparatus so that one may control the rate and quantity of air sampled. The technique employed for this purpose with the hand-actuated suction apparatus has already been described. With the electrically driven suction device a suitable flowmeter or vacuum gage is commonly used as the measuring device, while the ejector instrument uses a pressure gage as an indicator for the air flow through the impinger. For calibration, the apparatus should be assembled in a manner precisely similar to that employed in field sampling, but with the outlet tube of an accurate five-light, dry, test gas meter attached to the inlet of the impinger apparatus. A calibration curve is then obtained, showing the relationship between rates of air flow, as measured by the gas meter during observed intervals of time, and the readings on the scale of the flow meter or vacuum gage. The scale reading corresponding to 1 cubic foot per minute may then be ascertained. The air-measuring device should be calibrated at frequent intervals and always after any readjustment of the apparatus. In the field, the predetermined reading should be maintained throughout the course of each sampling period by adjustment of the needle valve.

Prior to the taking of dust samples in the field it is important that the suction apparatus be carefully inspected and completely cleaned so as to insure proper functioning while in use. Care should be exercised to insure against leaky connections in the air circuit.

Choice and preparation of sampling fluid.—In spite of the generally contrary belief, many dusts, including even silica, are soluble in water (20). This is to a great extent due to the large surface area exposed to the solvent by small particles of suspended material. A proper sampling fluid should be used in order to avoid solution. As a rule distilled water is used and by conducting the analyses within 24 hours, it is possible to avoid significant dust loss. Preferably, the counting should be done on the day of sampling. In the case of those dusts not easily wetted by water, such as coal dust, a mixture of 25 percent alcohol and 75 percent water yields excellent results. The alcohol increases the wetting power of the solution and at the same time greatly reduces the solubility of mineral dusts in water. Possible action on the rubber stopper of whatever collecting fluid may be chosen should be appropriately controlled.

It is important that the sampling fluid itself be comparatively free from suspended matter. Distilled water should be prepared, if possible, by one of the continuous types of water stills and, after distillation, should be permitted to stand for about 24 hours, the upper part being drawn off for use. If alcohol is employed, it should be redistilled before use.

Preparation of sampling flasks.—Prior to taking samples in the field the desired number of sampling flasks are thoroughly cleaned with hot cleansing solution, rinsed several times in tap water, and finally rinsed with the fluid used as the sampling medium. The stoppers are thoroughly freed from adventitious dust by several washings in tap water and finally in the sampling fluid. The required amount of sampling fluid is placed in each impinger flask, a cleaned solid-rubber stopper is put in place, and a cap of paper is fastened over the top by means of a rubber band. The flasks are now ready for transport to the place where samples are to be taken.

Field technique in sampling.—In taking dust samples the location of the sampling place, the time during which sampling is conducted, and the duration of sampling are all chosen in an effort to obtain the data required by the study in progress. Obviously the requirements of the study under way govern the procedure to be employed.

The two-hole rubber stopper fitted to the impinger tube and exhaust elbow may be transported in a spare flask containing some of the sampling fluid. Such a procedure serves both to protect the impinger tube and to keep it clean and ready for use. The exposed ends of the impinger tube and exhaust elbow should always be protected against accidental contamination.

After the selection of the sampling position, the stopper of one of the impinger flasks is replaced by the two-hole rubber stopper containing the impinger tube and exhaust elbow. The solid stopper is put on the spare bottle, thus protecting the rinse fluid and at the same time preventing contamination of the stopper. This completely equipped impinger is now placed in the leather holster, while the holster in turn is securely strapped about the worker or held by an assistant at the desired sampling point. The holster serves a twofold purpose: First, it serves to protect the glass tube from breakage by flying objects in the work place, and second, it fixes the entrance to the impinger tube very close to the nose and mouth of the worker. The outlet or suction elbow of the sampling flask is connected with the source of suction by means of a suitable length (commonly 25 feet) of noncollapsible rubber tubing.

In certain cases it is not feasible to place the impinger flask about the neck of the worker, nor is it convenient to have an assistant hold the flask near the worker. Under these conditions a length of rubber tubing (about 15 feet) may be connected to the inlet of the impinger apparatus (the impinger tube) and the free end fastened at the desired sampling point. With a sampling rate of 1 cubic foot per minute, dust particles pass through a ⅜-inch tube 15 feet long in less than a second, hardly sufficient time to allow settling to take place.

The duration of the sampling period should be such as to yield a satisfactory suspension of dust for analysis, and is thus dependent on the concentration of dust in the atmosphere. Under the usual industrial conditions, samples of from 10 to 30 cubic feet of air are sufficient to yield enough suspended dust for analysis. Since a sampling rate of 1 cubic foot per minute is maintained, this will require a sampling period of from 10 to 30 minutes. A stop watch is used to measure this period.

After the sample has been taken, the impinger tube is withdrawn. The tube is rinsed both inside and out with some sampling fluid from a fresh bottle, the rinsings being added to the original sample and the sampling flask stoppered and capped for transport to the laboratory. Should the impinger tube be found to be contaminated with adherent dust after rinsing, it should be carefully cleaned or, better still, replaced by an unused tube. Spare tubes should always be carried.

Notes are promptly made of all the pertinent data with reference to each sample.

ALTERNATING CURRENT PRECIPITATOR

Professor Philip Drinker and his colleagues at the Harvard School of Public Health have had a good deal of experience during the past 12 years with electrical precipitators for collecting atmospheric particulate matter. As a result of their work they have found that nonrectified alternating current is superior to rectified current for precipitating dry, poorly conducting suspensions, such as most industrial dusts of hygienic significance. Figures 11 and 12 present the essential parts of such precipitators. The tubes are made of pyrex of a size called for by the particular problem involved. The large tube shown in the drawing is adaptable for dust sampling at 15,000 volts, whereas the smaller tube is used at lower voltages and rates of air flow. A General Electric Co. luminous-tube transformer is used for obtaining high voltages. This transformer unit weighs 32 pounds, operates from a 110-volt, 60-cycle line and furnishes a secondary current of 30 milliamperes at 15,000 volts. By means of a rheostat in the primary circuit, the voltages can be regulated from 8,000 to 15,000. In this apparatus the midpoint of the high voltage winding is grounded to the metal casing of the transformer. Fuses are placed in both the low-tension lines, rather than in the main line, so that these fuses blow in case of a disruptive discharge.

A rather fine wire of gold-plated drill steel is used in the larger size tube for the precipitating or central electrode, whereas it has been found best to use fine platinum, gold, or copper wire in the smaller tubes. The outer electrode is made of either metal netting, of metal foil, or of copper wire wrapped spirally along the tube. Such wrappings must be pulled tight by hand and may be kept in place by electrician's tape. Celluloid foil or filter paper placed inside the tube is used as the collecting medium. The precipitating electrode must be kept well up the tube to insure efficient collection on the celluloid foil or filter paper; this precaution precludes dust from being caught on the glass tube itself.

Since gases of a toxic nature may be produced in the operation of the precipitator, and moreover, since these gases destroy the rubber stoppers and tubing used in the device, it is advisable to insert a chamber containing activated charcoal in the circuit (see sketch) in order to absorb these gases. In view of the destructive action of the gases on the rubber parts of the apparatus it is advisable that the instrument be inspected frequently for damaged parts.

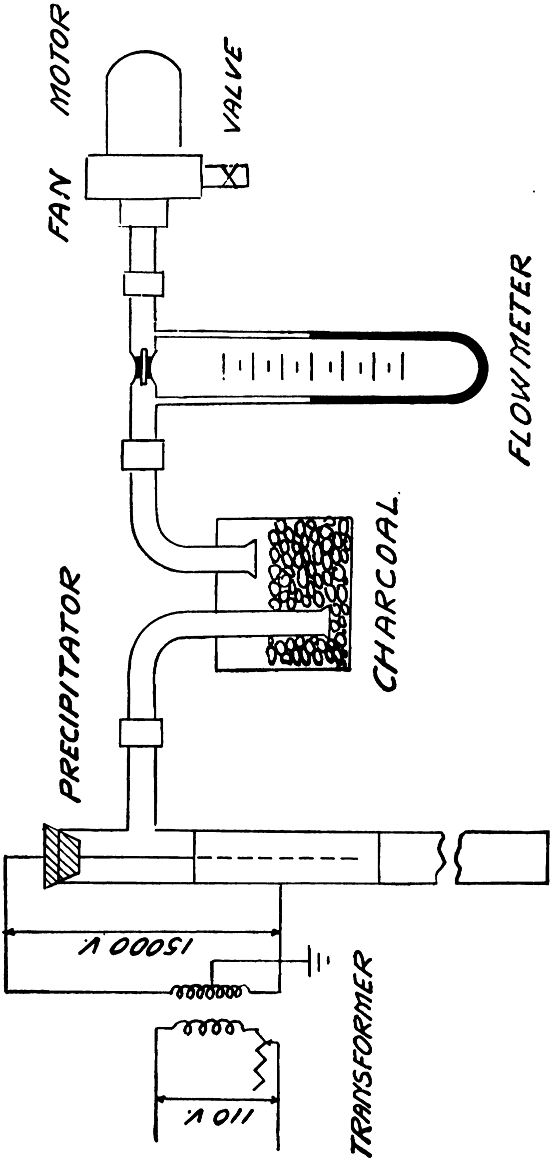

FIGURE 11.—Drawing of electrical precipitator assembly

As a source of suction one can use either a compressed air ejector, with a calibrated glass flowmeter, or a hand-size vacuum cleaner fan employing a small metal orifice meter for measuring the air flow. The resistance to air flow of the precipitator tube is small, so that all the resistance to be overcome is due mainly to the charcoal trap. At a sampling rate of about 50 liters a minute, this resistance has been found to be 10 to 15 cm water gage.

In operation a sufficient volume of air is passed through the precipitating tube to yield a visible deposit of dust. The foil or filter-paper containing the dust deposit is then removed from the tube and placed in a receptacle for transmittal to the laboratory. The practical operating efficiency of the precipitator is nearly 100 percent. If low efficiencies are obtained, they are probably due to either high rates of air flow, low voltages or too great a diameter in the tube, factors which may be easily corrected. The method of analysis and the various advantages and disadvantages of this device will be discussed at the end of this section. A list of equipment for collecting dust samples by the precipitation method is given by Professor Drinker in his article appearing in the Journal of Industrial Hygiene, for December 1932.

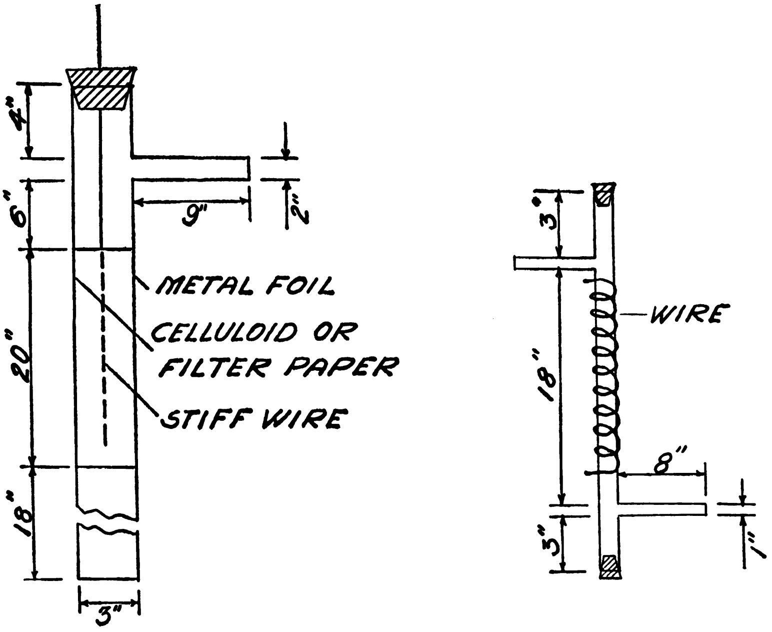

FIGURE 12.—Drawing of two useful sizes of Pyrex precipitator tubes.

PAPER THIMBLE APPARATUS

Paper filters for collecting dust in air have been used for many years by numerous investigators. In 1905, Simon in Germany used a paper thimble for determining dust in blast furnace gases (21). Mariner and Hoskins utilized this principle in studying the extent of smoke pollution in Chicago in 1915 (22). However, it was not until 1922 before definite data were available on the various characteristics of this device when Trostel and Frevert reported the results of their studies of the paper thimble in connection with the development of this instrument for the collection and examination of explosive dusts in air (13).

Description of apparatus

Figure 13 shows the details of the thimble and brass capsule which holds it in place. The thimbles used are single thickness, Whatman

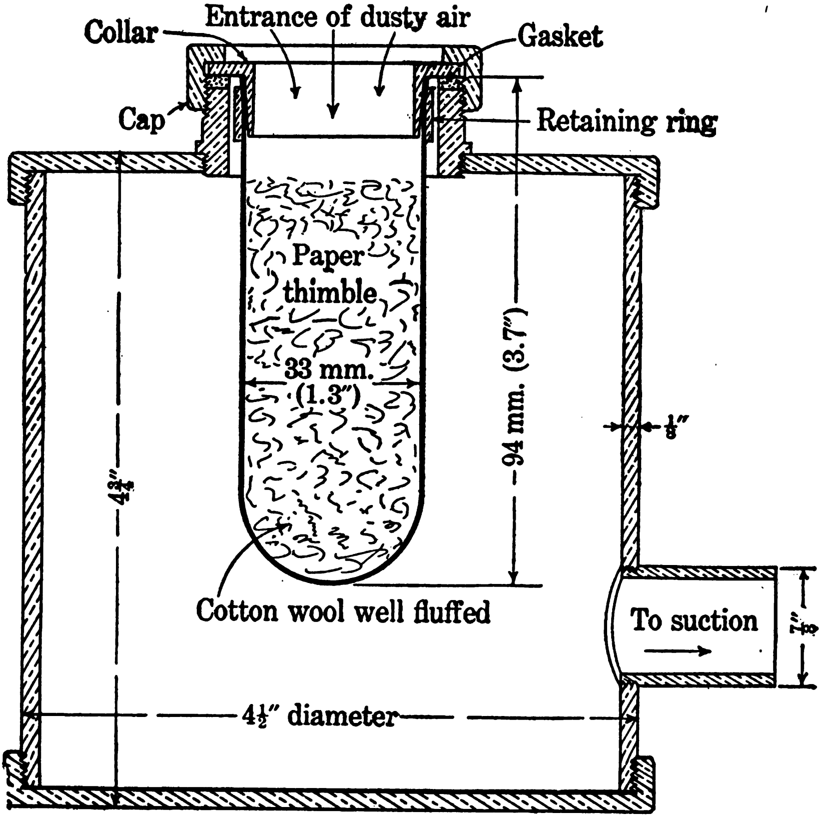

FIGURE 13.—Details of paper thimble and suction capsule.

extraction shells, 33 by 94 mm, with a small amount of cotton wool (weight about 125 mg), well fluffed out, inserted inside the thimbles for the purpose of supporting the dust and to preclude the possibility of clogging the pores of the paper. The suction side of the capsule is connected to either a calibrated foot pump, an electrically driven blower, or an ejector device of the type described with the impinger outfit. In operation the dust-laden air enters the opening of the brass capsule, as indicated in the sketch, passes into the paper thimble, and after depositing the dust escapes into the expansion compartment of the capsule and thence through the suction device;

the latter, be it an ejector, electrically driven blower, or foot pump, is provided with a metering device for measuring the air flow, which is usually maintained at the rate of 2 cubic feet per minute.

Before using a thimble it must be dried to a constant weight. This may be accomplished by one of two ways. First; thimbles can be given a preliminary drying at 90° to 95° C. for 3 to 7 days in an ordinary drying oven, and then just before using they are dried in a vacuum oven for 7 hours at 90° C. and weighed. To obtain a check weight they are exposed overnight to room air and again dried in vacuum for 7 hours. After sampling, the same 7-hour vacuum drying period is employed. Second, the thimbles which have had the preliminary treatment may be dried just before use in an ordinary hot-air oven for two days at 90° to 95° C. This period is sufficient to bring them to constant weight with no check drying being necessary in this instance. After sampling the same 2-day drying period is followed. Two blank thimbles, not used in the collection of dust, are dried, and weighed according to one of the two methods outlined, which enables one to check the constancy of the thimble weights during the drying period.

The thimbles are placed in a special glass weighing container after removal from the oven and are allowed to cool in a dessicator. A counterpoise weighing bottle is placed on the pan of the balance opposite to the one containing the thimble, thus compensating for moisture condensation on the somewhat large surfaces of the bottles. The thimble and bottle are weighed rapidly to the nearest milligram and then the empty bottle is weighed. The difference in weight represents the dry weight of the thimble. After a sample of dust is collected the thimble is placed in the drying oven and brought to constant weight, as described. The increase in weight of the thimble is the dry weight of the collected dust. This weight is divided by the volume of air sampled, yielding a weight per unit volume, such as milligrams per cubic foot, etc.

Efficiency of thimbles

Tests on the filtering efficiency of the paper thimble were conducted by Trostel and Frevert on various dusts of different sizes. These tests showed that the device recovered nearly 100 percent of the dust sampled. Against tobacco smoke of a 0.27 micron size the thimble device was found by optical methods to be 46 percent efficient. Against silica dust of a size from 1 to 2 microns (average industrial size of dust), the optical method showed 100 percent efficiency after 37 seconds of sampling had elapsed. Again, gravimetric tests with very finely divided cornstarch showed this instrument to be practically 100 percent effective in collecting dust.

It might be expected that since paper is highly hygroscopic that the rates of air flow through thimbles would be different in atmospheres of varying humidities. This possibility, if true, would tend to increase the resistance through the thimble, thereby decreasing the rate of air flow and vitiating the volume readings on the metering device. In order to test the effect of humidity on the thimbles, tests were conducted at 25, 50, 75, and 90 percent humidities for a total period of 7 days. The thimbles were first dried to constant weight and the rate of air flow determined. Then the 7-day test on the thimbles was made until their regain in weight was constant, when the rate of air flow was again determined. It was found that the rate of air flow over the range of relative humidities tested was not affected, even at the highly saturated condition of 90 percent.

The application of this device to industrial dust sampling will be discussed more fully in the portion of this section dealing with the various advantages and disadvantages of the instruments covered in this discussion.

THE KONIMETER

The konimeter instrument, which samples dust by impinging air at a high velocity against a sticky glass plate, was developed by Sir R. N. Kotzé for use by the Miners' Phthisis Prevention Committee of South Africa. The type of konimeter most frequently used in this country is the one employing a circular glass plate which is revolved to produce a ring of dust spots near the periphery.

Description of instrument

The circular type of konimeter is depicted in figure 14. It consists essentially of a valveless cylindrical suction pump and a dial of brass; the piston of the pump is actuated by a spring which insures uniform operation. About 10 cc of air are sampled per stroke, the exact amount being determined by calibration of the instrument. This may be accomplished by attaching the suction side of the device to a graduated gas burette containing water and noting the amount of water displaced. The dial chamber contains a circular glass plate, resting on a hard-rubber ring so arranged that the air from the surrounding atmosphere is drawn, upon releasing the piston, through a nozzle 0.0225 inch (0.57 mm) in diameter and is impinged upon the plate, located 0.0197 inch (0.5 mm) from the end of the nozzle. For the purpose of retaining the dust effectively, a thin film of petrolatum is usually smeared on the glass plate. The glass plate is attached to a toothed brass ring, which engages a pinion operated on a rod extending outside the instrument. The glass is revolved to expose fresh surfaces as needed. The instrument is provided with 29 sectors on the ring, each one numbered so as to record each dust spot or sample.

The konimeter is compact, simple to operate, is only 6½ inches long, and weighs but 2.2 pounds.

Method of sampling

Prior to obtaining samples of aerial dust with the konimeter it should be carefully cleaned and prepared for use. The orifice of the nozzle may be cleaned with a horsehair or other suitable material and the volume of the device is determined from time to time in the manner already mentioned. The glass plate is covered thinly with filtered petrolatum, by rubbing evenly over the plate with a clean glass stirring rod containing a quantity of petrolatum about the size of a pinhead. The parts of the instrument are then assembled and the rod operating the pinion which engages the toothed brass ring and glass plate is so moved as to expose sector no. 1 opposite the nozzle. To obtain a sample of dust the piston is pushed inward until it is caught and held in place by a locking pin provided for that purpose. The orifice at the back of the konimeter is held at the sampling point and a sample is procured by pressing the trigger which releases the spring. Air rushes in through the nozzle at a high velocity impinging its dust content in the petrolatum film on the glass plate. To obtain another sample the pinion is turned to bring the next sector into position. The method of examining the dust samples will be treated in the next section which deals with this subject.

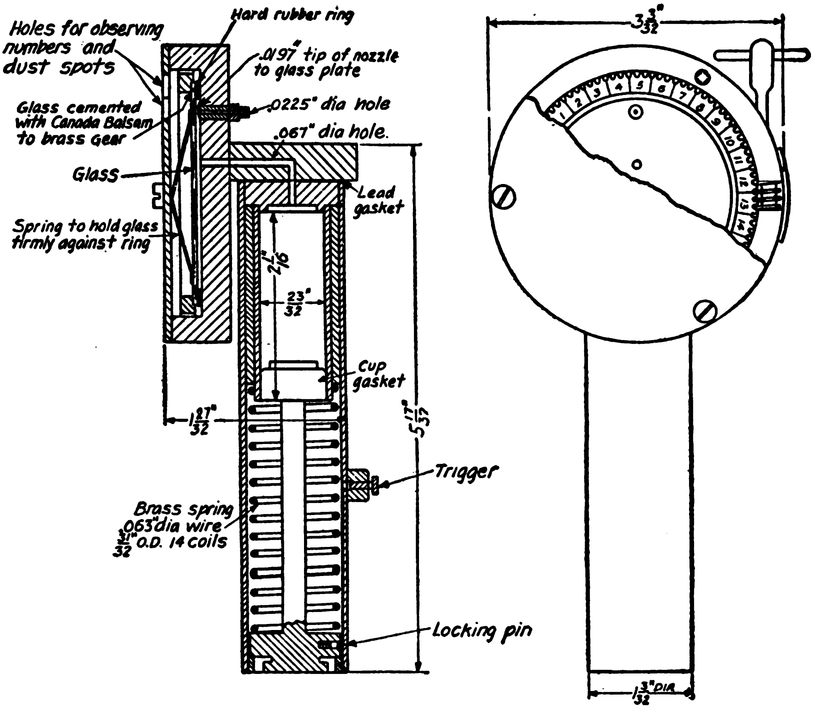

FIGURE 14.—Details of konimeter device.

The efficiency of the konimeter, when sampling in moderately dusty atmospheres, has been found to be about 1.5 times that of the impinger device, both in laboratory tests and in comparative studies conducted in the field under practical operation (23) (24).

OWENS JET DUST COUNTER

Principle of instrument

The jet dust counter was devised by Dr. Owens, of London, England, for the study of atmospheric smoke in connection with the work of the Advisory Committee on Atmospheric Pollution. The principle of this apparatus is very similar to the konimeter. The device depends for its action on the principle that when air containing dust passes through a narrow orifice facing a glass surface a short distance away from the jet, the dust will adhere to the glass. In the Owens instrument this result is achieved by causing a very fine, ribbon-shaped jet of air to strike a microscope cover glass situated about 1 mm from a slot-shaped opening forming the jet. The air, before entering the slot, is passed through a damping chamber, and the velocity in the jet is such that a fall of pressure results, in this way bringing about a condensation of moisture. The air is then deflected and the dust, being unable to turn the corner, strikes the cover glass; the velocity of the air drops, the pressure and temperature rise, causing the water to be evaporated and to leave the dust behind.

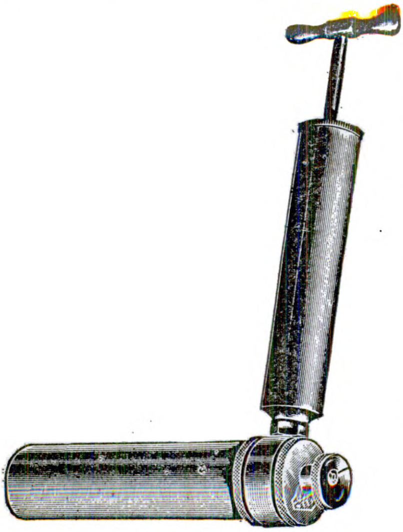

FIGURE 15.—Owens jet dust counter assembled for use.

Description of instrument

Figure 15 shows the instrument in its assembled form while figure 16 depicts the essential portions of the device in more detail. The apparatus shown in figure 16 consists of a brass sleeve B open at the top and bottom and screwed internally for the reception of the part K. This part (K) is perforated by a central hole for admitting the air to a narrow slot formed diametrically across the hole by means of two semicircular metallic plates, held in position by a ring R attached to the plug K.

Into the upper opening of the sleeve B is fitted a screwed plug C, provided with an attachment consisting of a spindle L which penetrates the sleeve formed in the plug C and ends at the outer end in a knurled head J, and at the other end in a carrier plate O. This carrier plate receives the cover glass and has two stops on its edge to aid in centering it. A flat spring P is fixed above the plate O with its ends bent round so as to hold the cover glass firmly against the plate O when the glass is in position. A spiral spring M, located between the plate O and the plug C, keeps the cover glass pressed downward over the slot of the instrument when the plug C is screwed into place. To insert the cover glass on the carrier plate O the plug C with its attachments is held in one hand and the knurled head J withdrawn sufficiently to press the spring P against the plug C, thereby lifting the bent ends of the spring P from the plate O, allowing a cover glass to be inserted. When the knurled head J is released it is drawn back by the spring M, the spring P comes out of contact with the plug C and the bent ends press down on the cover glass, thus holding it tightly in place. When the plug C is screwed into position in the instrument (in the sleeve B), the stops upon plate O make contact with the ring R which forms the cell around the slot. The distance of the cover glass from the slot is thus fixed and the cover glass may be rotated to any position by means of the knurled head J.

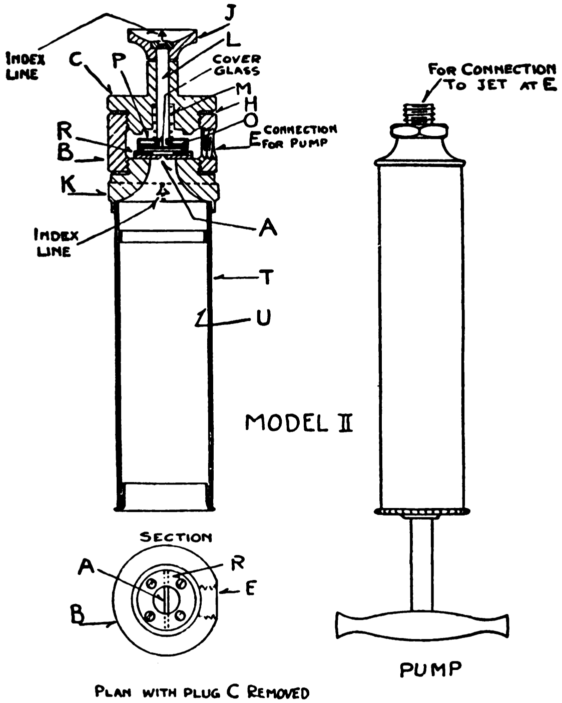

FIGURE 16.—Details of Owens jet dust counter.

The washer H makes an air-tight joint between the plug C and the sleeve B. Inside the sleeve B and surrounding the cover glass is an annular recess which communicates with a connection E for attachment to an air pump of 50 cc capacity. A damping chamber T is furnished, which is detachable from the plug K by unscrewing. This chamber is lined with blotting paper which is wetted prior to using the instrument.

Method of operation

Prior to sampling one should make sure that the slot is clear of any obstruction. It may be cleaned by means of a slip of thin paper pushed through from below. The air pump should be tested for leakage from time to time. This is accomplished by holding a moistened finger over the opening, drawing out the plunger smartly, holding it a few seconds, then letting it go, when it should return to the bottom of the pump. If the plunger does not return it may be necessary to grease it slightly with vaseline or renew the valve.

To obtain a dust record the pump is fixed to the connection E, and before the plug C is removed three or four strokes of the pump are made in order to fill the damping chamber with the air to be tested, leaving the pump plunger pushed in all the way. The blotting paper in the damping chamber should be wetted before sampling is started. The plug C is rapidly removed and a carefully cleaned cover glass is inserted upon the ring R, after which the plug C is quickly replaced and screwed in tightly. The pump plunger is then pulled out smartly so as to draw in 50 cc of air through the jet. If more air is desired the plunger can be operated again after allowing an interval of 15 or 20 seconds to elapse in order to allow the air to absorb moisture from the damping chamber. The plug C is then removed, the cover glass dropped out on the hand, when it is ready for mounting.

The dust record is mounted on thin, tin rings cemented onto a microscope slide. Several such slides are previously prepared for this purpose. This may be done by placing a few drops of the cement, which accompanies the instrument, onto the slide and placing a tin ring onto the glass, squeezing gently down on the ring. The dust record is mounted dry, face down, so that oil immersion may be used in examining the record. To mount the coverslip one merely places three small drops of the cement onto the tin ring and then places the coverslip gently on it, pressing down so as to allow the cement to flow around the ring and complete the seal. Two rings may be placed on one slide if one so desires. When one is finished with an examination of a record, the coverslips, rings, and slides may be salvaged for further use by placing them in a dish of water, thus loosening the coverslip and ring from the glass. After proper cleaning these objects may be used again.

SUMMARY

An attempt has been made to describe the most frequently used instruments employed in dust sampling at the present time, in such a manner that very little difficulty should be experienced in operating the five instruments discussed in this chapter. Illustrations of the instruments, their principle of operation, calibration, and method of sampling have been given in some detail. In the following table (table 7), a summary of some of the characteristics of these instruments is given. It may be seen that all of the devices have a high sampling efficiency. Although each instrument has some disadvantages, experience has shown that there is a specific use for each device. The impinger apparatus, which is the one used most universally, both in this country and abroad, can be employed for sampling in both high and low dust concentrations, and has the added advantage that the samples may be analyzed microscopically, chemically or gravimetrically. In fact, it has also proved useful for sampling fumes and gases, provided certain precautions are exercised (25) (26). The electrical precipitator is not used very frequently for dusts, finding its greatest field in the sampling of smoke and fumes. The paper thimble has been used for the sampling of radioactive dusts very successfully and is constantly employed in sampling organic dusts in connection with dust explosion prevention work. The Owens Jet Dust Counter was primarily developed for the sampling of outdoor dusts and smoke and is still used for this purpose quite universally. It is not practical for the sampling of industrial dusts of high concentration, the dust record being so thick as to make it impossible of enumeration. However, it has been used successfully for obtaining samples of industrial dusts for the purpose of particle-size measurements. This use will be dealt with in more detail in section IV. The konimeter is very useful in obtaining rapid samples in moderate concentrations of aerial dusts. For quantities of 15 to 18 million particles or less per cubic foot of air it is very efficient and should find considerable use in control work and in preliminary studies. For such investigations the Owens and konimeter have the added advantage that they require no power for operation, are very small and compact and do not need a highly skilled observer to obtain samples, although some skill is required in the enumeration of the dust records and in the interpretation of results.

So far this discussion has been limited to the collection of dusts of the type capable of producing fibrosis of the lungs or upper respiratory damage. For the collection of poisonous dusts, such as lead, the impinger or electrical precipitator have been found to be best suited for this purpose. The paper thimble has been used successfully for the collection of radioactive dusts, but on the whole the impinger and precipitator collect such dusts in a manner best suited for the subsequent chemical analysis. In the case of the impinger when used in sampling lead dusts, care should be taken that the sampling flask is of lead-free glass and that the distilled water also contains no traces of this compound. It is customary to run a blank for every 10 samples or so, which takes into account any lead present in the reagents. In sampling for minute traces of poisonous compounds, it is very essential that sufficiently large samples be obtained, enough to contain adequate amounts of the material for the particular method of analysis to be employed. It is apparent that both the impinger and electrical precipitator fulfill this requirement owing to their high air sampling rates.

TABLE 7.—*Summary of characteristics of certain dust-sampling instruments*

Instrument	Characteristics								
	Principle of operation	Efficiency against industrial dusts (percent)	Application	Method of quantification	Skill in quantification	Sampling skill	Volume of sample	Advantages of instrument	Disadvantages of instrument
Impinger	Impingement	98+	General	Count, gravimetric, chemical.	Considerable.	Some	Any amount; rate=1 cubic foot per minute.	1. High sampling efficiency in either low or high dust concentrations. 2. Sample can be quantificated by counting, weighing, or chemical analysis.	1. Requires power for operation.
Electrical precipitator.	Electrical precipitation.	100	do	do	do	Considerable.	Any amount; rate=10 to 50 liters a minute.	1. High sampling efficiency in either low or high dust concentrations. 2. Sample can be quantificated by counting, weighing, or chemical analysis. 3. Large samples obtained rapidly.	1. Requires electric power for operation. 2. Some danger from high voltages.
Paper thimble	Filtration	100	do	Gravimetric, chemical.	Some	Very little	Any amount; rate 1 to 2 cubic feet per minute.	1. High sampling efficiency 2. Samples large volumes rapidly. 3. Laboratory technic requires only drying and weighing for most dusts. 4. Samples may be kept indefinitely without deterioration.	1. Samples cannot be counted. 2. Drying of thimbles is a very slow process.
Owens jet dust counter.	Jet condensation.	99+	Outdoor dust and for particle-size studies.	Count	do	do	50 to 1,000 cc.	1. Light, simple, and quick to operate. 2. High efficiency for atmospheric smoke. 3. No power needed for operation. 4. Laboratory technic requires only a microscope.	1. Dust cannot be weighed or analyzed chemically. 2. Obtains only "grab" samples due to small sampling volume. 3. Impractical in high dust concentrations. 4. Selective action; efficient only for dusts 2 microns or less.

Konimeter	do	99+	For concentrations less than 18 million particles per cubic foot.	do	do	do	10 cc	1. Light, simple, and quick to operate. 2. Efficiency high for moderate concentrations. 3. No power needed for operation. 4. Laboratory technic requires only a microscope.	1. Dust cannot be weighed or analyzed chemically. 2. Obtains only "grab" samples. 3. Not practical in high dust concentrations; limited to 15 or 18 million particles, or less, per cubic foot.

III. THE QUANTIFICATION OF INDUSTRIAL DUSTS

PNEUMOCONIOSES-PRODUCING DUSTS

General considerations

The method of quantification used on the samples of aerial dust collected by the various instruments described in the previous section will be governed largely by the fact that our interest in the dust problem is primarily a hygienic one. In the case of fibrosis-producing dusts it has been found that the particle count offers the best index of the hazardousness of a dusty operation, especially in extensive studies of the problem dealing with the health of workers in dusty trades. Obviously, the method of enumeration which is utilized should be governed by the consideration of the size of the dust which is of hygienic significance. To date, the relative significance of various sizes of dust particles in the production of lung fibrosis has not been satisfactorily established. However, we do know that the inhalation of certain industrial dusts has been found to be associated with definite injury to the pulmonary tissues. Hence, a knowledge of the size frequency of these industrial dusts will in a measure determine the method of enumeration to be employed in order to evaluate the industrial dust hazard.

At present there are several sources of information which cast some light on this subject. One is the work of pathologists, who have determined the size of dust particles recovered from silicotic lung tissue; another source is the work done in connection with the retention of dusts, while additional information is presented by particle-size studies which have been made on industrial dusts.

Moir (27), Watkins-Pitchford (28), and Mavrogordato (29), of South Africa, have shown that most of the dust particles recovered by them from both human and animal silicotic lungs were between 1 and 3 microns in size. Only 13 percent of the particles were found to be less than 0.5 micron. These results are somewhat similar to those obtained by Scheid of Germany (30). Drinker, in comparing the size frequency of the particles measured by Moir with the particles found by him in the sputum of men employed in ore mills, found a very close correspondence (31). Recent experiments by King and Dolan (32) on the metabolism of silica indicate that extremely fine particles of quartz, those less than 3 microns in size, are rapidly dissolved in the mildly alkaline body fluids, and are excreted in the urine. The results of these findings raise two very pertinent questions; namely, (1) to what extent are minute particles of dust retained by the human lungs, and (2) do appreciable percentages of industrial dusts ever fragment into those minute sizes less than 0.5 micron?

The work of Drinker (33) and his associates, and that of Brown (34) on the retention of certain dusts and fumes by man when known amounts were breathed, seem to indicate that the coarser suspensions were retained more effectively than the more finely divided materials. Percentage retention was found to be directly proportional to particulate size and to the density of the dust suspension in the air. Sayers and his colleagues (35), in a study of the health hazards associated with the use of tetraethyl lead gasoline, found that fine particulate matter such as the lead dust from automobile exhaust gas using ethyl gasoline was retained to an average extent of only 15 percent of the amount inhaled. Shaw and Owens, upon measuring the amount of dust in expired air of London inhabitants, found that only 25 percent of the dust was retained (36). The average size of the dust inhaled in their experiments was about 0.5 micron. This work on dust retention seems to indicate that dust particles of a size less than 0.5 micron play but a small role in the problem of industrial dust inhalation, and in a manner furnishes an answer to the question raised earlier in this discussion; namely, the extent to which minute particles of dust are retained by human beings.

The answer to the second question—that is, the ability of the ordinary industrial process to fragment appreciable quantities of dust to a size less than 0.5 micron—is partially answered by a particle-size study of the dusts actually suspended in industrial atmospheres. Such a study made by the authors in the course of their numerous investigations in dusty industries reveals the fact that practically all of the dust particles examined by them (more than 10,000 particles in about 50 samples) are between 1 and 3 microns in size, about 70 percent of the dust particles lying in this range. Only about 20 percent of the particles were found to be less than 1 micron, the average median size being 1.3. Although no two dusts were found to have exactly the same size frequency, differing at times for the same dust created by different operations, it was found that for all practical purposes the dust particles fall into very narrow limits, the majority being between 1 and 3 microns (37).

From the foregoing information it is evident that in order to obtain a representative sample of industrial dust in air, one should employ an instrument capable of arresting with a high degree of efficiency all kinds of dusts, of sizes ranging from 0.5 to 5 microns at both high- and low-dust concentrations. The instruments described in the previous chapter fulfill this requirement. In addition, the method of counting the dust particles in the samples should have small analytical errors and should reveal only those significant particles present in industrial atmospheres. It should not be the aim to count all the dust particles present in the samples (which may be accomplished by either the use of high magnifications, dark-field illumination, or combinations of both), since it is necessary to differentiate between the dust content in normal air and industrial air. As has been just indicated, this difference is sharply marked insofar as the dust particles between 0.5 and 5 microns are concerned; but this difference would be masked and lost should we include in our determination the particles of ultramicroscopic size which are present in vast numbers in all air.

The method of dust counting to be described in the following pages fulfills the requirements set forth in the present discussion with reference to industrial dusts. As a proof of the value of the method of dust counting to be presented, high correlations have been obtained between counts in various industries and the degree of silicosis and tuberculosis among the workers exposed to the dusts investigated (2). It is obvious, therefore, that the technic of dust analysis which is now being used extensively in this country and which is described in the pages to follow, constitutes a valuable index of the hazardousness of dust inhalation.

Quantification of impinger samples

Counting in cells.—Earlier in this bulletin it was pointed out that practically all dusts are, to some extent, soluble in water and, hence, counts should be conducted within 24 hours after sampling. Such a practice tends to prevent any undue flocculation as well as solvent action on some of the minute dust particles.

As soon, therefore, as the samples can be transferred to a satisfactory place for counting, the stopper of the flask is removed and carefully washed, the washings being added to the contents of the flask. Next the entire sample may be filtered into a previously cleaned graduated flask through a screen of appropriate fineness (325 mesh) so that only particles smaller than 40 microns in diameter are permitted to pass through. If the dust suspension in the graduated flask is too dense, further dilution is advisable. This dilution may conveniently be such that the number of particles counted in each microscope field is about 50 to 75. The contents of the graduated flask are next thoroughly agitated in order to obtain a uniform suspension, and two portions of about 1 cubic centimeter each are removed with a pipette so as to just fill, without bubbles, two Sedgwick-Rafter counting cells (see fig. 17). The cells have been previously cleaned very carefully in order to remove any adventitious dust, and have been kept protected from dust particles by the cover slip.

In making dust counts an eyepiece micrometer known as a "Whipple disk" is employed. (See fig. 17.) This disk has a large square engraved on it, covering a large part of the field, and this square is divided into 100 medium-sized squares, 1 of these in turn being further subdivided into 25 very small squares. Using an ordinary microscope provided with a suitable eyepiece and objective and fitted with an Abbe condenser, the proper tube length of the microscope is determined by calibration with a stage micrometer, so that the side of the large square of the eyepiece covers 1,000 microns (1 mm). (A 7.5X eyepiece, 16 mm objective, and a tube length of 178 mm has been found to yield this result.) The large square of the eyepiece ruling, therefore, encloses the dust in an area of 1 square millimeter; and since the cell is 1 millimeter deep, all the dust suspended in 1 cubic millimeter of the water is under the ruled field. This examination is accomplished by raising and lowering the lens system so as to focus throughout the entire depth of the cell. As a source of illumination an ordinary small electric microscope lamp may be employed. In order to provide a high degree of visibility for refractile objects it is best to lower the Abbe condenser system below the usual focusing point and to restrict the opening in the iris diaphragm.

The dust is allowed to settle for 20 minutes before counting is done. In general, only particles less than 10 microns in diameter are counted. The inclusion of particles larger than 10 microns in the filtered specimen would make but little change in the total count. The average diameter of a particle for the purpose of this exclusion is judged by inspection. In practice it is necessary to count the dust in only one-quarter of each ruled field, the entire field having been examined for uniformity. Such counts on 5 fields, so dispersed as to be representative, are made on each of the 2 Sedgwick-Rafter cells. These 10 counts are averaged, but this average is not to be taken as the final count until a corresponding control count has been subtracted. In all cases a sampling flask which is handled in the plant, but through which no air has been aspirated, is used as the control for the particular series of samples taken in that plant on that particular day, and counts are made on this control fluid in the same manner as on the fluid through which the air sample has been impinged. The control sample takes into consideration any dust which may be present in the eyepiece micrometer, in the lenses of the microscope, in the Sedgwick-Rafter counting cell, and in the sampling fluid itself. From the average gross count obtained on the impinger sample, the average control count is to be subtracted to give the average net count per ¼-microscopic field.

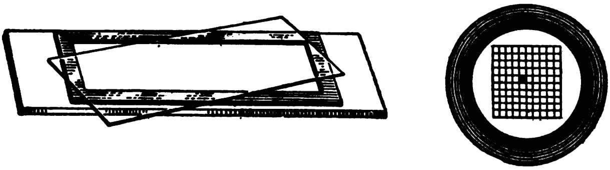

FIGURE 17.—Sedgwick-Rafter counting cell and Whipple ocular micrometer disk.

The average net count per ¼-microscopic field is multiplied by 4 to yield the average count in the total field. Since the Sedgwick-Rafter cell is 1 millimeter deep, this figure represents the number of particles in a cubic millimeter of the diluted sample. This value is multiplied by 1,000 to give the count per cubic centimeter of sample and again by the total number of cubic centimeters of fluid to which the original specimen was diluted. This product is divided by the number of cubic feet of air sampled. In summary, the number of particles per cubic foot of air=average net count per ¼ field times a factor, where the factor=

$$\frac{4\times 1{,}000\times \text{total volume of diluted sample in cubic centimeters}}{\text{Volume of air sampled in cubic feet}}$$

The record should show the sample number, date, sampling location, and volume of air in cubic feet. The steps in counting should be recorded as to date, volume of fluid, volume taken for dilution, calculated total volume at final dilution, average gross count per ¼-microscopic field, average control count, average net count, factor according to above formula, and finally number of particles expressed in millions per cubic foot, together with any additional notes.

Table 8, which follows, shows some typical dust counts obtained with the impinger apparatus in the various industries listed.

TABLE 8.—*Average dust count in certain dusty trades*

Industry	Dust count in millions of particles per cubic foot of air
Slate finishing mills:	
Floormen	1598.0
Loaders	1276.0
Disc-crusher operators	312.8
Talc mining:	
Jack-hammer drillers	2159.8
Muckers	44.8
Talc finishing mills:	
Crushers and cylindermen	14.0
Packers	50.1
Marble carvers	19.1
Marble cutters	32.8
Granite quarrying:	
Leyner drillers	144.4
Jack-hammer drillers	112.1
Plug drillers	36.9
Cement mill, average of all operations	26.0
Granite cutting:	
Hand pneumatic-tool operatives	59.2
Machine pneumatic tool operatives	35.9
Attendant labor	17.0
Anthracite coal mining:	
Miners and miners' helpers	231.5
Attendant labor	31.1
Bituminous coal mining:	
Coal cutters and coal loaders	112.3
Attendant labor	3.9
Silverware manufacturing:	
Dusty processes	5.2
Nondusty processes	1.7
Municipal dust (street cleaners):	
Congested district	4.1
Residential district	1.8
Cotton industry:	
Carding room	8.6
Weaving and spinning room	4.5

Gravimetric analysis of impinger samples.—The weight of the dust sampled by the impinger may be determined in 1 of 2 ways. The microscopic analysis consumes but a very small amount of the sample, at times as little as 2 cc. The remaining portion of the sample may be evaporated to dryness in a platinum or other suitable dish and weighed on an analytical balance. This weight (subtracting the weight of the empty dish) will yield the total weight of the sample and dividing by the number of cubic feet sampled will give the total weight per unit volume, correction being made for the dust contained in the volume of water used in the microscopic analysis. To determine the amount of organic and inorganic matter present in the sample, the dust in the container is ignited in a muffle furnace. The new weight is the inorganic matter present, while subtracting this weight from the total gives the amount of organic matter in the sample.

An alternative method of gravimetric analysis consists of filtering the portion of the sample not used microscopically through an ignited and weighed Gooch crucible, drying the crucible in an oven at 105° C. for 4 hours or more, and weighing again. The crucible may then be ignited in a muffle furnace if it is desired to determine the percentage of organic and inorganic matter. In all analyses, regardless of the method used, control weights are necessary on the distilled water itself for every set of 10 or more samples.

During the conduct of various dust studies both weights and counts have been obtained on the dust samples collected by the impinger apparatus. The following table shows the correlations between counts and weights on the various dusts investigated:

TABLE 9.—*Correlation between particle counts and weights of industrial dusts in air*

Dust	Number samples	Coefficient of correlation	Millions of dust particles equivalent to 1 milligram
Bituminous coal	40	0.847	31
Anthracite coal	80	.771	44
Granite	220	.755	31
Metal grinding and polishing dusts	176	.698	19
Cement	95	.694	15
All dusts	611	.726	35

It may be seen from the results of the above table that high correlations exist between counts and weights. However, it has been the general experience that weight determinations are more time consuming than particle counts and require no less skill in their performance. This is the main reason why the microscopic method of dust quantification has been widely used.

Quantification of electrical precipitator samples

The dust collected on the strip of celluloid foil used as the collecting medium in the electrical precipitator, may be washed into a graduated flask and then examined microscopically in a manner similar to that used for impinger samples. For gravimetric analysis one only needs to place the foil with its adhering dust into a special type of weighing bottle and determining the weight on an analytical balance. This weight subtracted from the weight of the bottle and empty foil yields the total weight of collected dust. Titration methods for soluble dusts may be used in lieu of direct weighing.

Quantification of paper thimble samples

The method of quantificating paper thimble samples and the precautions to be used in the analytical work involved, have already been presented in detail, in that portion of the previous section dealing with this device.

Quantification of konimeter samples

The konimeter samples lend themselves only to the counting process. The glass plate upon which the samples are obtained is adjusted on the microscope stand with the aid of a special holder with a pinion similar to that on the konimeter itself. This device enables one to bring the various dust spots into view much easier than could be attained with the naked eye. The microscope is provided with an ocular and objective and so adjusted to give approximately a 200-diameter magnification. An 8-millimeter objective and a 10X ocular have been found to give this result. A micrometer screen placed in the ocular is so designed as to have two cross lines which outline 9° sectors (fig. 18).

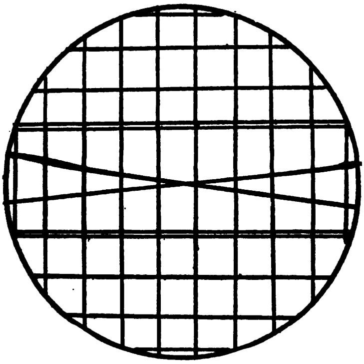

FIGURE 18.—Konimeter ocular micrometer disk.

Before counting a sample a blank determination is run on unused portions of the glass plate, usually on four sectors. This blank number, due to impurities in the petrolatum, is subtracted from the subsequent counts. The petrolatum (vaseline) generally used has a refractive index of 1.48, enabling most dusts in industry to be readily visible.

The dust spots are adjusted under the microscope so that the sectors divide them symmetrically. All of the particles in one sector are then counted; by rotating the eyepiece other portions of the spot are brought into the sector. Counting four such sectors on one spot has been found to give a representative result. Subtracting the blank and then multiplying by 10 (36° have been counted and 10 times the count will give the dust in the entire circle, 360°) will give the dust count in the entire spot. If the instrument samples a volume of 10 cc then it is not necessary to multiply by 10, since the 36° count will give the number of particles per cc as shown in the following computation:

$$\frac{\text{Number of particles in 4–9° sectors, or } 36^\circ \times 10}{10 \text{ cc}} = \text{number particles per cubic centimeter.}$$

Quantification of Owens jet dust counter samples

The Owens record, which consists of a linear deposit of dust, may be located under the microscope with the aid of a 16 mm objective and dark ground illumination (fig. 19). Dark ground illumination may be readily obtained by inserting a suitable stop under the substage condenser. Counts of the particles are generally made using a $\frac{1}{12}$-inch, oil immersion objective. In order to facilitate counting, the eyepiece is provided with a net-ruled micrometer of 1 mm squares (fig. 20). With the aid of this eyepiece micrometer, a count of the number of particles in a strip one square wide is made across the entire record at one or two places, and an average taken. This figure multiplied into a factor, depending on the magnification used, will give the number of dust particles on the record. To determine the factor it is first necessary to ascertain the number of strips in the length of the record; this may be done under low magnification. For example, with a $\frac{2}{3}$-inch objective 50 strips in the length of the record are found; then the $\frac{1}{12}$-inch objective, which is found to magnify 10 times as much as the $\frac{2}{3}$-inch, will have 500 strips. Suppose that 300 particles are found in a strip across the record using a $\frac{1}{12}$-inch objective and that the volume of air sampled was 50 cc: the number of particles per cc will then be:

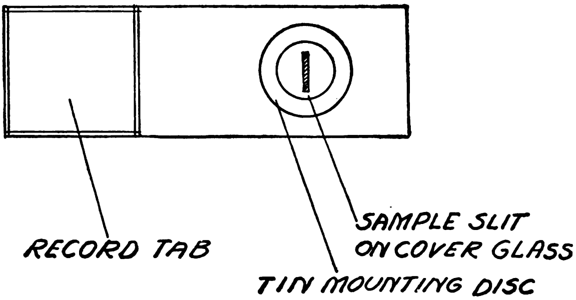

FIGURE 19.—View of Owens record mounted on slide.

$$\frac{300 \times 500}{50} = 3000$$

If S represents the number of strips found in the record, N the number of particles per strip and C the number of cc drawn through the jet in taking the record, then the number of particles per cc of air $= \frac{N \times S}{C}$.

If the same volume of air is used for all the samples and the same eyepiece and objective are employed, then the factor $\frac{S}{C}$ will remain constant. The microscope should be supplied with a mechanical stage to facilitate moving the record across the field.

Another method of enumerating the dust particles in an Owens record has recently been suggested by two Russian scientists, Kagan and Broumstein (38). Their method is a graphic one using distribution triangles, and according to them it is more accurate and takes less time than the method given by Owens, described here. For details of the graphic method the reader is referred to the original article.

QUANTIFICATION OF POISONOUS DUSTS

Of the five instruments described in this book, only the impinger, electrical precipitator, and, in a limited sense, the paper thimble are useful in collecting dusts which may be analyzed by chemical methods. The thimble has been utilized for the collection of radioactive dusts, which permitted the contents to be completely ignited, in place, under such conditions as to avoid any dust loss (4). The resulting ash was then analyzed by fusion, in place (in an 8-inch pyrex test tube), with acid potassium sulfate. It is apparent that the thimble may only be used under conditions in which it is possible to ash the thimble without loss of the material under analysis. The impinger and electrical precipitator have no such restrictions placed on them. In the case of both instruments it is only necessary to collect a sufficiently large enough sample to enable one to determine the dust accurately with the specific method of analysis employed. A sensitive and reliable method of analysis is the other requirement when dealing with dusts to be determined chemically. Blanks on the reagents are run in the usual manner.

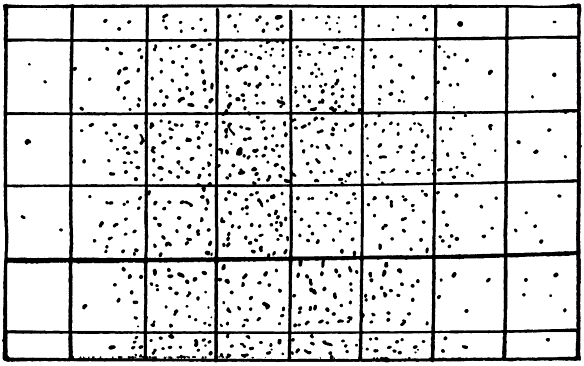

FIGURE 20.—Typical Owens dust record and ruled ocular disk.

Both the impinger and electrical precipitator have been used for the collection of such dusts as lead compounds, zinc compounds, cadmium compounds, etc. Specific methods of analysis are used, depending on the material and the quantity present in the sample. Perhaps a single example will suffice to illustrate the technic involved in the analysis of certain poisonous dusts, namely, the determination of minute amounts of lead collected by the impinger apparatus, using lead-free distilled water as the collecting medium (5) (39). The samples thus obtained are analyzed in a central chemical laboratory using lead-free reagents. The method which is extremely important, follows:

Fifty cubic centimeters of 1:1 nitric acid solution are added to the sample and the mixture is evaporated to dryness on a hot plate. Care should be taken to avoid spattering. The residue is digested with 5 cubic centimeters of 1:1 hydrochloric acid solution. The mixture is evaporated to a volume of about 2 cubic centimeters and diluted to 100 cubic centimeters with distilled water. In cases where the original residue is small the dilution at this point is halved. The solution is neutralized with 25 percent sodium hydroxide till just alkaline to methyl orange (use ½ percent aqueous methyl orange, 4 drops) then (1:2) hydrochloric acid till the faintest pink appears. Cool. Precipitate by passing H_2S gas through the solution for 1 hour. Stand over night. Filter on a 12.5 cm Whatman No. 40 filter paper. Wash with freshly prepared H_2S water to which has been added 0.1 percent of its volume of HCl.

Wash the precipitate off the paper, using hot (1:1) HNO_3, into the beaker in which the sulphide precipitation was made. Wash well with hot water. Wash down the sides of the beaker and the inside and outside of the gassing tube, using hot (1:1) HNO_3 followed by hot water. Remove the gassing tube.

Evaporate the solution to a small volume on a hot plate and transfer to a 100 cc beaker. Add 1 cc of H_2SO_4 (specific gravity 1.84) and evaporate to fumes of H_2SO_4. Cool. Take up in 30 cc of a mixture of 10 cc 95 percent ethyl alcohol (C. P.) and 20 cc of water. Stand over night.

Filter on a 7 cm hard filter paper (Munktell No. 1–F). Wash the beaker and the paper thoroughly, using a solution containing 1 cc H_2SO_4 (specific gravity 1.84), 10 cc ethyl alcohol (C. P.) and 20 cc water. Dissolve the precipitate off the paper into a 600 cc beaker, using 10 cc hot 10 percent ammonium acetate, followed by hot water. It is well to wash the beaker first and decant the solution through the filter. Dilute the filtrate to 300 cc, using cold water, add 2 drops HNO_3 (specific gravity 1.42). Neutralize after adding 4 drops of a solution of methyl red in 50 percent alcohol, by adding 25 percent NaOH to alkalinity, then (1:2) HCl to a faint pink color, then 1 cc of (1:2) HCl is added in excess. Cool. Precipitate by passing H_2S gas through the solution for 1 hour. Stand over night.

Filter as before with extreme thoroughness. Dissolve the sulphides from the paper with hot (1:1) HNO_3, catching the solution and washings in the beaker in which the sulphide precipitation was made. Wash the paper thoroughly with hot water, and wash the sides of the beaker and the inside and outside of the gassing tube with hot (1:1) HNO_3 followed by hot water. Remove the gassing tube. Evaporate the solution to a small volume, 1 to 2 cc, and transfer it to a 150 cc beaker. Dilute to 80 cc with cold water. Neutralize, after adding 4 drops of an aqueous solution of phenolphthalein (½ percent in 1 percent NaOH), using 25 percent NaOH free from iron and aluminum. The solution is made alkaline. An excess of 5 drops of 25 percent NaOH is added. Acidify with 5 percent acetic acid till pink color just disappears, and add 2 cc of 5 percent acetic acid in excess.

Bring to a boil and precipitate as chromate by adding 1 cc of a 1 percent K_2CrO_4 solution. Place on a steam bath 1 hour and stand in a warm place at least 60° C. over night. Filter on a Munktell No. 1–F filter paper. Wash beaker carefully with hot water and the paper very thoroughly with hot water to remove all possible traces of soluble chromate. Dissolve the precipitate from the paper, into a 250 cc volumetric flask containing 100 cc water, using 15 cc cold (1:2) HCl, followed by cold water. Wash the beaker and rod and decant through the paper.

In a 250 cc volumetric flask prepare a standard containing sufficient $K_2Cr_2O_7$ solution to be equivalent to 0.30 milligrams of lead, precipitated as $PbCrO_4$. Add 100 cc water and 15 cc cold (1:2) HCl. To each of the samples and the standard add 2 cc of a 1 percent solution of s. diphenyl carbazide in glacial acetic acid. Dilute to 250 cc and mix thoroughly. Estimate the lead in the samples by comparing the intensity of the pink colors, using a colorimeter.

The following tables present some typical results of lead determinations using the impinger apparatus for the collection of the samples and the method just described for the quantification of these samples. It may be observed that the instrument and method of analysis is capable of yielding results, ranging from the minute amounts of lead found in streets to the greater quantities encountered in a lead storage battery plant.

TABLE 10.—*Lead content of air in a storage battery plant*

	Milligrams of lead per 10 cubic meters of air	
	Occupation	Department
Mixing		120
Oxide reclaim (laborers)		189
Pasting		50
Paddler, scraper, take-off	78	
Sweeper and trucker	75	
Unspecified and other	50	
Put-up, grid, and paste feeder	38	
Inspector	20	
Picklemen	15	
Foreman and clerk	9.3	
Burning		5.7
Unspecified and other	5.7	
Burning inspector	3.8	
Burner, laborer, helper	3.6	
Casting:		
Total (except pitmen)	1.2	1.2
Pitmen	19	
All other departments		2.0
Planté	2.9	
Battery assembly	2.9	
Developing and forming	2.2	
Lead plate	2.2	
Machine and tool shops	2.0	
Boosting	1.9	
Primary battery (dry cell)	1.7	
Separators	1.5	

Table 11.—*Summary of tests for lead dust in the air of nonlead-using industrial establishments*

Industrial establishment	Workshop	Milligrams of lead in 10 cubic meters of air
Underwear factory	Sewing room	0.35
Shirt and overall factory	do	.26
Machine shop (brass)	Lathe room	.24
Bakery	Bake room	.21
Cigar factory	Automatic cigar rolling	.18
Laundry	Calendering room	.17
Fur products manufacturing	Fur-handling room	.15
Dairy	Milk-bottling room	.11
Wooden heel factory	Heel turning	.10
Tapestry manufacturing	Tapestry weaving	.10
Machine shop (steel)	Lathe room	.10
Dry cleaning factory	Pressing room	.09
Mail bag manufacturing	Sewing room	.08
Shoe manufacturing	Cutting room	.08
Baking powder factory	Shipping room	.07
Bakery	Mixing and baking room	.07
Ice-cream plant	Mixing room	.02
Retail grocery	Salesroom	.02
Electric appliance manufacturing	Sheet metal working	.01
Chocolate factory	Mixing chocolate products	.00
Dairy	Pasteurizing room	.00
Waste packing factory	Grading wastepaper	.00
Tire manufacturing plant	Curing room	.00
Clothing factory	Trousers-manufacturing room.	.00
Food packing factory	Olive-packing room	.00
Total samples		25
Average		.10

Table 12.—*Comparing lead dust in the air of automobile repair shops, streets and nonlead-using industries in 14 cities*

Sampling location	Total samples	Average volume of samples (cubic meters)	Milligrams of lead in 10 cubic meters of air[1]	
			Average	Maximum
Automobile repair shops	25	9.4	0.13	1.11
Nonlead-using industries	25	8.0	.10	.35
Streets[2]	28	6.1	.09	.34

[1] The minimum values were zero for each of the 3 sampling locations.

[2] 1 sample taken in the country showed .04 milligram of lead in 10 cubic meters of air.

Table 13.—*Percentage distribution of samples as to lead content (air of automobile repair shops, streets, and nonlead-using industries in 14 cities)*

Lead in milligrams per 10 cubic meters of air	Percentage			Number		
	Street samples	Automobile repair shop samples	Nonlead-using industries samples	Street samples	Automobile repair shop samples	Nonlead-using industries samples
0–0.09	68	64	56	19	16	14
0.1–0.19	18	24	28	5	6	7
0.2–0.29	3	0	12	1	0	3
0.3–0.39	11	4	4	3	1	1
0.4–0.49	0	4	0	4	1	0
0.5 and over	0	4	0	0	[1] 1	0
Total	100	100	100	28	25	25

[1] 1.11 milligrams in 10 cubic meters.

IV. THE DETERMINATION OF THE CHARACTER AND COMPOSITION OF INDUSTRIAL DUSTS

With reference to fibrosis-producing dusts it has bean demonstrated during the past few years that the properties of a dust which determine its capacity to produce pulmonary pathology are the nature of the dust, that is, its mineralogical composition, its particle size, and finally the quantity of dust dispersed in the atmosphere. The instruments and methods used in determining the quantity of dust in the air have already been treated. The present section discusses the other two characteristics of dust which are of importance in industrial hygiene studies.

SIZE OF INDUSTRIAL DUSTS

So far as the size of the dust particles is concerned, it is apparent that in order for any given dust to produce injury to the lungs it must gain access to the parenchyma of the lungs, the site where the harmful effects of the dust take place. It has already been shown that not all of the particles of inhaled dust gain access or are retained by the human lungs. For these reasons it is of some value to determine the size of the dust present in the industrial atmospheres.

It has also been demonstrated in the previous section that particles of a size greater than 10 microns in longest dimension are very seldom found in the lungs. This absence of larger particles has been shown to be partly due to the fact that the number of such particles greater than 10 microns in size present in industrial air is comparatively small when particles in the lower size range are considered. Due to gravity which causes rapid settling of suspensions and due to the protective action of the mucous surfaces of the upper respiratory tract, these larger particles do not penetrate to the terminal portions of the lungs. Hence, it is obvious that attention should only be given to those particles which are less than 10 microns in longest dimension.

Instruments and methods used in determining particle size of dusts

The obvious procedure for the sampling of atmospheric dusts for particle-size studies would be to employ the same instrument utilized in sampling dust for quantification. In the past, however, the Owens jet dust counter has been employed extensively for such investigations, although of late impinger samples have been utilized for this purpose; comparative results between the two instruments will be shown in a later portion of this discussion. The Owens jet dust counter, described in section II, obtains a sample of dust from the air in more or less unaltered condition, since with this device the atmospheric dust is directly projected on a naked cover slip. Moreover, the instrument is small, compact, requires only hand power, and samples are obtained quickly and easily without needing much skill of operation. Once these samples have been obtained and mounted in a manner already described, the dust particles may be measured by the use of a filar ocular micrometer at a magnification of 1,000 diameters (oil immersion objective) (40). The horizontal diameter of at least 200 dust particles in several representative fields are measured for each sample. With this magnification it was found possible to measure particles as small as 0.5 micron in size, while particles smaller than this size are easily distinguished at this magnification and their presence recorded.

Photographic methods have been suggested and used for measuring dust particles, but in order to obtain good photomicrographs it is essential that the dust particles be in one plane, free from Brownian movement, and well dispersed. Since industrial dusts are seldom of a uniform size, it is difficult to fulfill the first requirement. Comparisons have been made between the results obtained with the direct filar measurements and the photographic method on typical industrial dust samples. This comparison demonstrated that the simpler and less expensive filar method yielded practically the same results. Since the filar method fulfills the requirements of this problem it is suggested for use in such studies.

Once a sample has been measured in the manner outlined, the results of such readings may be analyzed in the form shown in the following table. This table presents the size-frequency distribution of various industrial dusts and compares these findings with outdoor dust.

TABLE 14.—*Size–frequency distribution of various industrial dusts as compared to outdoor dust*

[Average frequency in percent]

Kind of dust	Number of samples	Median	Size group in microns											
			0–0.49	0.5–0.99	1–1.49	1.5–1.99	2–2.49	2.5–2.99	3–3.49	3.5–3.99	4–4.49	4.5–4.99	5–5.49	5.5–5.99
Outdoor dust	179	0.5	56.0	41.0	2.5	0.5								
Sandblasting	9	1.4	1.4	19.7	34.7	20.3	12.6	5.2	2.8	1.6	1.1	0.2	0.2	0.2
Granite cutting	4	1.4	2.0	19.0	33.6	24.5	10.4	4.6	3.1	.6	.9	.3	1.0	
Trap-rock milling:														
Crusher house	1	1.4		13.0	39.0	33.0	10.5	2.5	2.0					
Screen house	1	1.3	2.0	31.5	33.0	16.0	10.0	4.5	2.5	.5				
Disc crusher	1	.9	10.0	48.0	31.0	6.0	3.0	1.0	1.0					
Foundry parting compound	2	1.4	.5	22.0	42.0	17.3	9.2	5.0	1.5	2.0	.5			
General foundry air	1	1.2		26.0	48.0	17.0	8.0	1.0						
Talc milling	1	1.5		16.0	32.0	20.0	13.0	7.0	5.0	2.0	2.0	2.0		1.0
Slate milling	1	1.7	1.0	13.0	29.0	17.0	14.0	14.0	6.0	4.0	1.0		1.0	
Marble cutting	1	1.5		12.0	37.0	21.0	10.0	11.0	3.0		1.0	2.0	2.0	1.0
Soapstone	2	2.4	1.2	16.0	19.0	13.0	11.0	6.0	6.5	4.5	5.5	3.3	2.5	11.5
Aluminum dust	1	2.2	3.0	8.0	20.5	14.0	11.5	9.0	6.5	3.0	3.5	4.0	7.0	10.0
Bronze dust	1	1.5	1.0	12.0	33.5	25.0	21.0	6.0	1.5					
Anthracite-coal mining:														
Breaker air	2	1.0	7.0	51.0	26.0	8.0	3.0	3.0	2.0					
Mine air	1	.9	11.0	60.0	17.0	7.0	3.0	1.0	1.0					
Coal drilling	1	1.0	1.0	55.0	34.5	7.5	1.5		.5					
Coal loading	3	.8	11.5	56.3	24.3	5.5	1.5	.7	.2					
Rock drilling	1	1.0	4.0	49.0	25.5	12.5	5.5	1.5	.5	1.5				

An examination of the data in table 14 discloses a striking difference between the size-frequency of outdoor dust and indoor industrial dust. Ninety-seven percent of the outdoor dust particles were found to be of a size less than one micron in diameter, with a median [2] of 0.5. Practically no dust particles larger than 1.5 microns were found to exist in outdoor air. These results on the size-frequency of outdoor dust are similar to those obtained by Owens in London. In contrast with this result it is found that only 3 percent of the industrial dust particles are less than 0.5 micron and but 32 percent less than 1 micron. The average (median) size of these particles was found to be 1.4 microns. It is evident from the results shown in table 14 that the majority (60 percent) of the dust particles present in the industrial atmospheres investigated was found to be between 1 and 3 microns in average diameter with but 7 percent of the particles exceeding 3 microns.

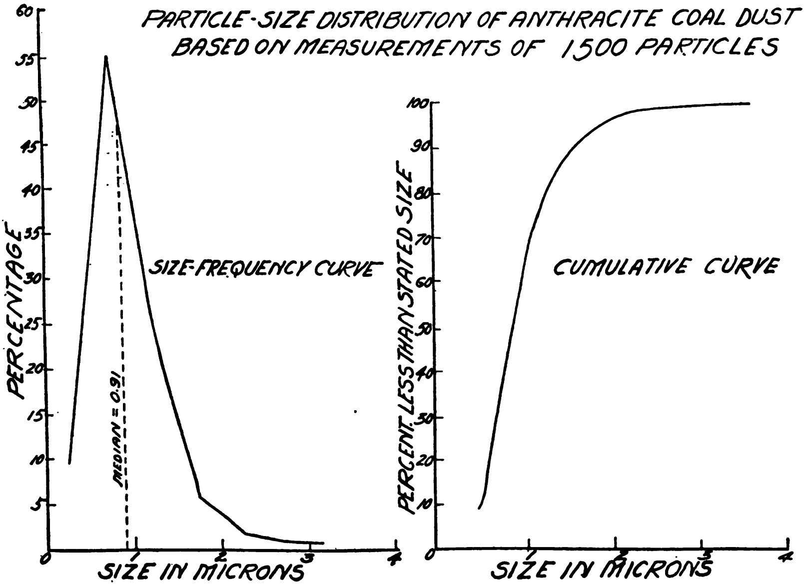

FIGURE 21.—Particle-size distribution of anthracite-coal dust.

Figure 21 shows a typical graphic illustration of the size distribution of industrial dusts, plotted from some of the results in table 14. Figures 22 and 23 are photomicrographs of these dusts, indicating visually the size of the dusts encountered in industry.

It may be said that since the impinger apparatus is used to collect samples for dust counting that the samples obtained with this instrument should also be used for particle-size measurements. This would be a just criticism if the two instruments did not collect the significant

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[2] The median is the center item in an array and may be strictly defined as a point on the abscissal scale of a frequency distribution with 50 percent of the items on either side.

sizes of dust particles with the same degree of efficiency. The Owens' samples lend themselves more readily for particle-size measurements than do impinger samples, since the sample in the form obtained is immediately available for microscopic examination, may be readily photographed and moreover collects the dust directly on a cover slip in practically the form it exists in the atmosphere. In order to determine the sizes of particles obtained by the two instruments comparative studies were made on several samples collected with the Owens and Impinger. The Impinger samples were prepared by placing several drops of the dust suspension in the water on a microscope slide, evaporating the water rapidly on an electric hot plate, and covering the smear of dust with a cover slip. The particles were measured under oil immersion with the filar micrometer method. Table 15 presents the comparative measurements and indicates that a very close relationship exists between the size of dust particles collected by the two instruments. For all practical purposes, therefore, the Owens apparatus may be used in collecting dust samples for praticle-size studies.

TABLE 15.—*Comparison between Impinger and Owens dust measurements*

Size group in microns	Owens		Impinger	
	Number	Percent	Percent	Number
0–0. 49	42	6. 0	6. 0	41
0.5–0.99	387	55. 3	53. 6	375
1–1.49	193	27. 6	29. 0	203
1.5–1.99	48	6. 9	6. 0	42
2–2.49	14	2. 0	3. 7	26
2.5–2.99	10	1. 3	1. 3	9
3–3.49	6	. 9	. 4	4
Total	700	100. 0	100. 0	700

COMPOSITION OF INDUSTRIAL DUSTS

The methods used in determining the composition of certain poisonous dusts, such as lead compounds, have already been discussed in the previous chapter. Concerning the so-called "fibrosis-producing dusts", the work of the past 20 years on the problem of dust inhalation has demonstrated that, in general, the degree of health hazard associated with the inhalation of any dust, all other factors remaining constant, is dependent upon the mineralogical composition of the dust. For example, it is now established that the inhalation of certain types of dust, such as granite dust (2) will in time produce fibrosis of the lungs, frequently associated with tuberculosis. In other cases exposure to dust may result in the production of a far lesser degree of fibrosis without subsequent tuberculosis; this is true of cement dust (41). And finally, there are certain types

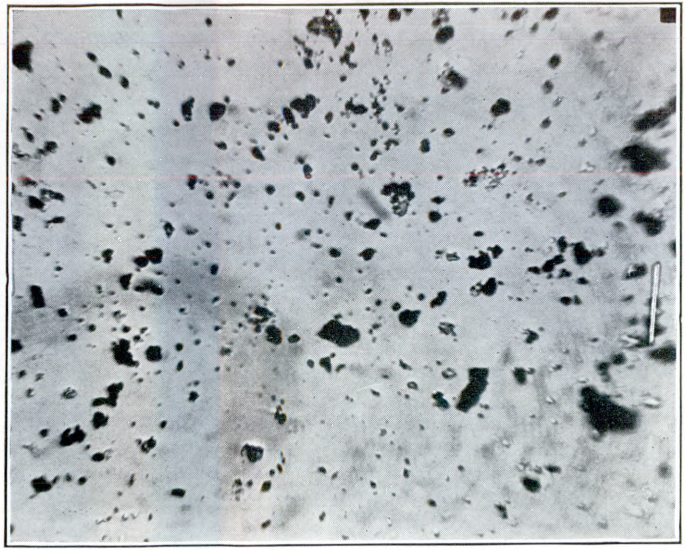


FIGURE 22.—PHOTOMICROGRAPH OF ANTHRACITE-COAL DUST, 1,000×.

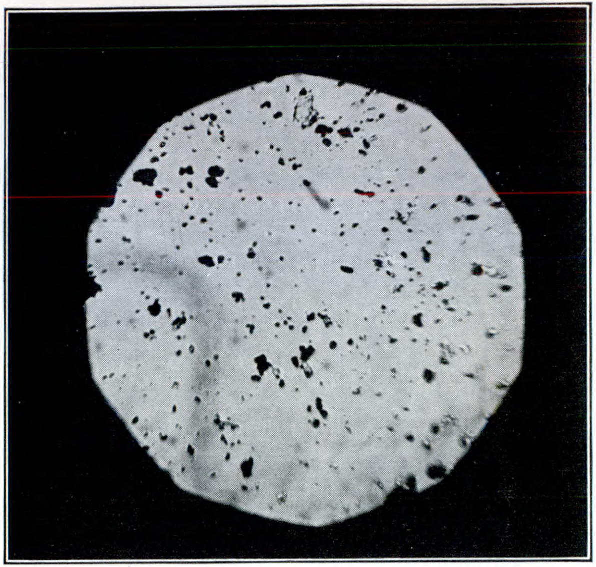


FIGURE 23.—PHOTOMICROGRAPH OF ANTHRACITE-COAL AND SILICA DUST, 1,000×.

of dusts which produce little lung fibrosis, as typified by marble dust (42). In general, it has been found that those dusts which are high in quartz content are the ones which most readily produce a disabling fibrosis of the lungs. Hence, the necessity for knowledge concerning the chemical and mineralogical composition of a dust is obvious.

Concerning the chemical composition of various mineral dusts found in industry the reader is referred to such treatises on this subject as The Analysis of Silicate and Carbonate Rocks, by W. F. Hillebrand (43), and The Commercial Granites of New England, by T. Nelson Dale (44), both of the United States Geological Survey. It has been found, however, that a chemical analysis of a mineral dust will not disclose the various percentages of minerals existing in the dust. For example, a chemical analysis of granite dust will not reveal the percentage of quartz present in the dust, but will only tell the analyst the total silica, combined and uncombined. For this reason there is presented herein a discussion of this very vital subject with reference to one of the important industrial dusts—namely, quartz-containing dusts. Much of the material which follows is taken from an article prepared by Dr. Adolph Knopf, professor of physical geology at Yale University and consultant to the United States Public Health Service (45).

SILICA

Silica is the name given to the chemical compound silicon dioxide (SiO_2). It occurs in nature most commonly in the crystalline form as the mineral quartz. Several other minerals are also composed of silica, for example, tridymite, cristobalite, opal, and chalcedony, but in comparison with quartz they are relatively rare.

A long-established convention has led to the reporting of chemical analyses of rocks and minerals in terms of certain chemical compounds (usually oxides) rather than in terms of chemical elements. During analysis the silicon is isolated in the form of silica, and consequently the chemical analysis of an average granite, for example, is reported as containing 70 percent of silica. About 30 percent, or roughly one-third of this granite, consists of quartz, whereas the other two-thirds of the granite is made up chiefly of minerals that are complex salts of silicon-bearing acids. Such minerals are known as "silicates." The remainder of the silica reported in the chemical analysis of the granite, amounting to 40 percent, is locked up in the silicate minerals, chiefly feldspar and mica.

The distinction between free silica and combined silica

This arbitrary convention of reporting rock and mineral analyses in terms of oxides has necessitated the use of the expressions "free silica" and "combined silica" to distinguish between the silica that makes up quartz (or the few other minerals that are composed of silica alone) and the silica that is combined with other elements in the various silicate minerals. In the granite just cited the 70 percent of total silica is the sum of 30 percent of free silica plus 40 percent of combined silica.

As the relative danger of silicosis to workers in certain dusty trades is determined chiefly by the amount of free silica (as quartz) present in the dust in the form of quartz rather than by the silica that is in chemical combination, it has become necessary to devise a method for determining accurately how much of the dust in a given sample consists of quartz. For example, in the dust arising from cutting a granite whose chemical analysis shows 70 percent of total silica the percentage of free silica will be far less than 70, since only one-third of the granite is made up of quartz. Furthermore, rocks and minerals can show as much as 68 percent of silica, although they contain no free silica (quartz). In short, the total silica reported in customary chemical analysis is no measure of the amount of free silica.

DETERMINATION OF FREE SILICA (QUARTZ) IN ROCKS

In general it is comparatively easy to determine the percentage of quartz in a rock specimen by petrographic methods, because it is easy for a petrographer to distinguish between quartz and other minerals by the use of a polarizing microscope, or petrographic microscope, as it is more commonly called.

Preparation of material

The determination can be made in two ways: By examining a thin section of the rock ground to a thickness of approximately 0.03 mm and mounted in Canada balsam upon a glass slide, or by studying a pulverized fragment of the rock, prepared by crushing the material to a powder whose individual grains are about 0.06 mm in thickness. Portions of the powder are then successively immersed in oils of known refractive indices until a point is reached where in one position of the microscopic stage the boundary between the grains and the liquid disappears. This occurs when a refractive index of the mineral is the same as the index of the liquid in which it is immersed. In this way the refractive index (if the mineral is uniaxial) or refractive indices (if biaxial) can be numerically determined, together with other optical properties. This method of studying powdered rock and mineral fragments is known as the "immersion method."

Criteria for petrographic identification of minerals

The petrographic identification of minerals depends upon the following optical properties:

(1) Color.

(2) Pleochroism, in minerals that show selective absorption of light.
(3) Crystal form.
(4) Cleavage.
(5) Refractive indices and relief.
(6) Birefringence. Numerical value.
(7) Isotropy or anisotropy. Extinction (complete, parallel, or inclined).
(8) Optical character of the mineral.
(9) Optical elongation of principal zones.
(10) Optical orientation of mineral.
(11) Value of optic axial angle.
(12) Twinning.
(13) Inclusions.
(14) Alteration products.

No one of the preceding criteria alone is sufficient to determine a mineral, although one criterion may be enough to distinguish it from some other mineral with which it is associated. Some minerals can be identified by determining three or four optical properties, others require more for conclusive determination.

The methods of determining the optical properties require a familiarity with the difficult principles of optics and a special laboratory training in petrography. The reader who desires further information about the detailed technique of the petrographic identification of minerals is referred to the standard works on optical mineralogy, such as Rosenbusch's Mikroskopische Physiographie der Petrographisch Wichtigen Mineralien, volume 1, part 1, revised by Wülfing; Rock Minerals, by J. P. Iddings; Manual of Petrographic Methods, by A. Johannsen; or Dana's Textbook of Mineralogy, fourth edition, by W. E. Ford. For a comprehensive description of the immersion method of studying minerals, the reader is referred to The Microscopic Determination of the Nonopaque Minerals, by E. S. Larsen.

Quantitative determination

An easy and satisfactory way to determine the percentage of any mineral in a rock section is by the Rosiwal method. This method consists in measuring the linear intercepts of a given mineral along numerous parallel lines. The ratio between the sum of all the intercepts of quartz to the length of the measured traverse gives the percentage of quartz, because, as can be shown mathematically, the linear intercepts are proportional to volumes. The measurement is carried out by the use of a screw micrometer ocular or a mechanical stage. The Rosiwal method can be applied both to rock sections and to rock powders examined by the immersion method.

DETERMINATION OF QUARTZ IN DUSTS

It is comparatively easy for the petrographer to apply the methods described above in making a quantitative determination of quartz in thin sections of rocks or in rock powders, but in dusts where the individual particles are of the order of magnitude of 0.005 mm (5 microns) in diameter petrographic examination of the material must be supplemented by other methods, because the minimum grain size that can be conclusively identified under the petrographic microscope is about 0.010 mm (10 microns) in diameter.

The results of quantitative dust analysis can only be conclusive when several methods are used on the same material, thereby checking one against the other; and the accuracy of the final result depends largely on the skill and experience of the analyst, because each sample to be analyzed presents an individual problem.

The general method that has been found highly satisfactory is a combined chemical and petrographic procedure by which all the constituents other than quartz are eliminated from the material. The accuracy of any method of quantitative estimate is much greater where the estimate is applied to two constituents than where many constituents are present. Therefore, by concentrating the quartz a large factor of error in quantitative determination is eliminated.

If the dust is chiefly composed of quartz, the elimination of foreign constituents is not difficult. If the quartz is in smaller amount than the other constituents, a clean concentration may be more difficult. But a satisfactory quantitative estimate can always be made on a moderately clean quartz concentrate, because the mineral present in marked excess can be much more accurately determined than the other constituents.

For the fine dusts whose individual particles cannot be satisfactorily determined chemical methods are necessary in order to remove the constituents other than quartz. Various methods are used dependent upon the composition of the dust, but the first step in the analysis is to examine a small portion of the material under the petrographic microscope.

Preliminary petrographic examination of the dust

It is a common practice to cite the percentage of silica in the chemical analysis of a dust as a measure of the quartz present. The erroneous nature of this conclusion has been already emphasized. The only value of the chemical analysis to the dust analyst is based upon the fact that the amount of silica locked up in the various silicate minerals in the dust can be calculated from the percentages of bases (K_2O, Na_2O, CaO, etc.) that are shown by the analysis. The percentage of silica that remains after all the bases in the various silicate materials have been satisfied should represent the free silica present.

This method of computation is useless, however, unless the mineral composition of the dust has been determined petrographically. For example, in potassium feldspar, which is a common constituent of all granites, every molecule of potash is combined with 6 molecules of silica. If the only minerals in the dust are quartz and potassium feldspar, obviously the silica left over after the potash in the analysis is computed as feldspar will be an accurate measure of the quartz present. But if, as is often true, the dust is made up of several potassium-bearing minerals, such as potassium feldspar, biotite, and muscovite, it is impossible to compute how much silica is required to satisfy the potash, because neither the relative proportions of the various minerals are known nor are their compositions known. Most rock-forming silicate minerals have wide ranges in their chemical composition.

As the chemical analysis of a dust can only serve as a rough guide to the possible amount of quartz present, it cannot be too strongly emphasized that a careful petrographic examination is an indispensable prerequisite to the quantitative determination of quartz in a dust sample. For although it may be impossible to make an accurate quantitative determination of extremely minute individual grains by petrographic methods, it has proved possible in all the samples so far examined to obtain a clear idea of the general composition of the dust by a petrographic examination. The analytical method best suited to the individual sample can then be selected. For example, if the dust shows under the microscope a large admixture of organic material, a preliminary sample should be ignited and the residue again examined under the microscope in order to decide on the further procedure. If the dust shows a large amount of metallic mineral, free iron may be extracted by a magnet or the sample may be heated with hydrochloric acid to remove the iron oxide and such metallic particles as brass shavings from brass-works dust. Dust from marble works containing chiefly particles of carbonate minerals should be heated with hydrochloric acid to dissolve the carbonate, and the residue should then be examined with the petrographic microscope. The most difficult problem is the separation of quartz in rock or mineral dusts that contain silicate minerals, such as granite, slate, or asbestos dust. The procedure employed to separate the quartz in such material depends upon the fact that cold hydrofluosilicic acid, H_2SiF_6, will in time decompose the silicate minerals but will not attack quartz.

Chemical examination of the dust

After the preliminary petrographic examination the procedure in the chemical separation of quartz is as follows:

Grinding.—In order to facilitate the action of the hydrofluosilicic acid the material is ground to pass a 150-mesh sieve, thus insuring uniformity of size and a large surface for treatment.

Weighing.—It is then weighed in a platinum crucible. About half a gram makes a convenient amount to work with.

Ignition.—If the preliminary microscopic examination indicates the presence of any organic material, the platinum crucible and its contents are carefully heated to white heat for 30 minutes to burn off the organic matter. It is then cooled. Dusts that are strongly contaminated with oil are digested for 5 minutes with ether, then filtered, and ignited for half an hour to an hour.

Hydrochloric acid treatment

If the preliminary examination shows the presence of carbonate minerals, hydrochloric acid is added to the contents of the platinum crucible and the crucible is gently heated. The contents of the crucible are filtered, washed, and the filter paper and precipitate are ignited in the same platinum crucible, which is then allowed to cool.

Hydrofluosilicic acid treatment

After these operations hydrofluosilicic acid in moderate excess is added to the material in the platinum crucible. If the composition of the dust is such that the ignition and hydrochloric-acid treatment are unnecessary, the hydrofluosilicic acid is added to the substance to be analyzed immediately after the first weighing. The crucible is carefully covered and set away in a place where the temperature is reasonably constant and not above room temperature. Care must be exercised not to raise the temperature during the hydrofluosilicic acid treatment, because hydrofluosilicic acid (H_2SiF_6) decomposes on heating into silicon tetrafluoride (SiF_4) and hydrofluoric acid (HF), which will readily attack the free silica. It is left for a time that ranged in different specimens from 24 to 48 or even 72 hours.

It is then carefully decanted into an ashless filter paper and the crucible is thoroughly washed onto the filter paper. The precipitate is washed until the wash water gives no precipitate in a clear mixture of dilute KCl with 95 percent alcohol. The precipitate is dried, ignited in the platinum crucible, and weighed, and the percentage loss in weight noted.

The hydrofluosilicic acid treatment is repeated until the weight of the residue remains unchanged.

Microscopic examination of residue

A small portion of the residue is then examined under the petrographic microscope. If minerals other than quartz are present, the amount of quartz in the residue can be estimated with a reasonable degree of accuracy. If quartz is the only mineral indicated by the microscopic examination, the percentage of quartz in the sample can be calculated directly from the weight of the residue.

Volatilization of residue with hydrofluoric acid

A check on the microscopic determination of quartz is given by volatilizing the residue with hydrofluoric acid in the platinum crucible. Free silica volatilizes completely with hydrofluoric acid. Combined silica in silicate minerals volatilizes with hydrofluoric acid, but after the treatment a residue remains made up of the bases that were in combination in the silicates. If no residue is left after the hydrofluorization, the material was all quartz.

RATE OF DECOMPOSITION OF QUARTZ ON PROLONGED TREATMENT WITH HYDROFLUOSILICIC ACID

As the rate of decomposition was found to differ considerably in different silicates, a control test was run on pure quartz in order to determine the error introduced into quantitative analyses by prolonged treatment of quartz with H_2SiF_6 at room temperature during analyses of dusts that contain refractory silicates requiring a week or more to decompose.

The following table shows the results of a test on 0.509 gm of pure quartz ground to pass a 150-mesh screen:

TABLE 16.—*Quartz*

[Original weight before treatment with H_2SiF_6=0.509 gm]

Time in days	Loss after treatment (grams)	Percent loss in weight	Rate of loss in weight per day in percent of original weight
5	0.015	2.9	[1] 0.59
7	.024	4.7	[1] .67
10	.037	7.3	[1] .73
12	.049	9.6	[1] .80
14	.057	11.1	[1] .78

[1] Average=0.7 percent per day is rate of loss in original weight.

By using the above factor of error it is possible to compute at the end of an analysis the maximum possible loss in weight of quartz originally present, thus obtaining a maximum figure for quartz.

It is apparent from the preceding discussion that each dust presents individual problems in regard to the purification of the sample to be analyzed, the methods of eliminating the various mineral constituents, etc. Therefore, the best procedure in analyzing a given dust must be selected after the minerals and other constituents making up the dust have been identified; consequently it is impossible to set forth any one technique that will apply to all dusts regardless of their composition.

In the following table a few results are presented on the determination of quartz in industrial dusts:

TABLE 17.—*Percentage of quartz present in various industrial dusts*

	Percentage of quartz
Rock drilling dust (bituminous coal mine)	54.0
Granite cutting dust	35.2
Rock drilling dust (anthracite coal mine)	31.0
Brass foundry dust	19.0
Dust from raw mills in cement plant	6.5
Slate mill dust (Vermont red slate)	3.0
Silverware polishing dust	1.7
Anthracite coal dust	1.5
Bituminous coal dust	1.2
Cement dust	<1.0
Slate mill dust (Vermont green slate)	Trace
Talc mill dust	None
Marble cutting dust	None

V. THE APPLICATION OF DUST DETERMINATIONS TO PRACTICAL PROBLEMS

Dust determinations in industry serve a three-fold purpose. First, they enable one to evaluate the extent of the hazard; this is accomplished by obtaining occupational dust exposures, which disclose the dust-creating tasks. Second, if clinical studies are made, dust counts may indicate the permissible amounts of dust which may be breathed with impunity. Third, dust determinations are used in an attempt to control the dust hazard; this is performed by testing the efficiency of any devices which may have been introduced for the suppression of dust in those processes which have been revealed by investigation to be hazardous.

DETERMINATION OF THE EXTENT OF THE DUST HAZARD

Attention has already been called to the three properties of a dust which determine its capacity to produce injury. Having established the composition and size of a dust the only important item remaining for study is the quantity of dust in the air. Prior to evaluating the quantity of dust in the industrial atmosphere, however, certain preliminary steps, such as those outlined in section I, are essential. For the sake of emphasis these steps are briefly reviewed.

The investigator should first become thoroughly familiar with the industry being studied. This is best accomplished by conducting a sanitary survey and occupational study of each workroom (46). The sanitary survey of workrooms in any plant yields definite information concerning the presence and extent of various health hazards and often serves as a guide in establishing which hazards require further study in the form of actual quantitative analyses. In other words, the sanitary survey may well be regarded as a listing of the facilities afforded the workers while in the industrial environment. The occupational study permits one to learn of the activities involved and the particular hazards associated with each occupation. Such an analysis also shows the number of persons in each occupation, which gives an idea of the importance of each hazard from the viewpoint of the numbers involved. In the case of a dusty industry, the occupational study shows (1) the dusty occupations, (2) the number of persons in each occupation, and (3) the various activities and the time devoted to each activity in any one particular occupation. All this information is essential in the preventive program which should follow, and experience has proved that only by such a systematic and careful study can dust determinations be of any real value in the control of the industrial dust hazard. Perhaps a typical example of such a study may serve to clarify further the methodology involved.

TABLE 18.—*Occupational classification of granite quarriers*

Occupation	Number in each occupation	Occupation	Number in each occupation
Drillers:		Other quarry employees—Continued.	
Leyner	17	Derrick men	24
Plug and jack hammer	37	Muckers	24
Other quarry employees:		Blacksmiths	6
Superintendent	1	Tool boys	2
Foremen	7	Water boys	1
Compressor engineer	1	Machinists	3
Hoisting engineers	12	Air-line repairers	1
Locomotive engineer	1	Pipe fitters	2
Locomotive fireman	1		
Steam-shovel man	1	Total	142
Crane operator	1		

Table 18 shows the various occupations in a granite quarry and the number of workers employed in each occupation, and that drillers are the only persons using pneumatic tools, devices known to produce considerable quantities of dust. In other words, 38 percent of the quarry personnel are shown to be exposed to dust of a potentially dangerous size and quality. The occupational analysis at once indicates that the dust investigation should especially concern itself with drillers in an effort to control the dust exposure of these workers.

The next step in this study involves the determination of the occupational dust exposure. Table 19 shows the results of such a study.

TABLE 19.—*Occupational dust exposure of granite quarriers*

Occupation	Number in each occupation	Dust counts in millions of particles per cubic foot of air		
		Weighted average	Minimum	Maximum
Leyner drillers	17	144.4	5.3	1,085.0
Plug and jack-hammer drillers (quarry hole)	37	112.1	4.1	396.8
Plug drillers (yard)	--------	36.9	5.3	58.0
All other workers	88	5.8	4.1	10.7

It is apparent from the results shown in this table that the drillers are exposed to high dust concentrations, especially the Leyner and jack-hammer drillers working in the quarry hole. From a further analysis of the occupational dust exposure of drillers it is possible to determine which activities are responsible for the dust associated with this occupation. For example, experience has taught us that the various operations comprising the processes of most dusty occupations are usually associated with dissimilar dust exposures. For this reason it is essential to estimate the amount of time spent in each activity in any one occupation and to determine the dust exposure for each activity in that occupation. Table 20 shows the results of such a differential dust study in the case of a Leyner driller.

TABLE 20.—*Summary of dust exposure of Leyner drillers in a granite quarry*

Activity	Average dust exposure in millions of particles per cubic foot of air (*a*)	Number of hours spent in each activity (*b*)	Particle-hours in millions per cubic foot (*a*×*b*)
Drilling	213.4	4	853.6
Changing drills	9.8	1	9.8
Watching drills	8.0	2	16.0
Broaching	6.0	¾	4.5
Blowing off holes	1,085.0	¼	271.3
Total		8	1,155.2

$$\frac{1{,}155.2 \text{ particle-hours in millions per cubic foot}}{8 \text{ hours}} = 144.4 \text{ million particles per cubic foot.}$$

It will be seen from table 20 that a Leyner driller has five different dust exposures. A differential analysis, such as the one presented in table 20, yields several valuable findings. First, it enables one to obtain a true average dust exposure for workers engaged in the occupation of Leyner drilling. (In this case the weighted average is 144.4 as contrasted with 213.4 million particles per cubic foot found during drilling operations only.) Second, it enables one to determine which activity, or activities, contribute the most to the dust hazard. In this instance it is quite evident that the practice of blowing off holes by means of inserting a compressed air line into each hole is attended with an exceedingly great amount of dust; and though it is an activity lasting but 15 minutes of the 8-hour working day, it is one which is responsible for 23 percent of the total dust exposure. It is evident that 23 percent of the Leyner driller's dust exposure may be at once eliminated by the prohibition of this practice. And lastly, such an analysis indicates the necessity for devoting all one's efforts to the removal of dust during the drilling process, since this activity accounts for 74 percent of the total dust exposure, although a Leyner driller spends but one-half of the working day at his drill.

So far we have dealt with an industry in which the workers, as a rule, do not change their occupation. Often one encounters workers who have had several occupations, either in the same industry or in several different kinds of establishments. If the worker has been employed in various occupations in the industry under investigation, it is a simple matter to determine his total dust exposure during his entire trade life in that industry. This is important from the viewpoint of correlating a worker's dust exposure and his clinical condition. A typical example of such a case will suffice to clarify this point.

TABLE 21.—*Total occupational dust exposure of an anthracite coal worker*

Occupation	Number of years in each occupation	Dust concentration in millions of particles per cubic foot	Millions of particle-years per cubic foot
Slate picker	2	380	760
Patcher	2	71	142
Mule driver	3	71	213
Miner's laborer	3	480	1, 440
Miner	15	480	7, 200
Section foreman	5	7	35
Total	30		9, 790

$$\frac{9{,}790 \text{ millions of particle-years per cubic foot}}{30 \text{ years}} = 326 \text{ millions of particles per cubic foot.}$$

In the above table the worker's occupations are arranged in the order of employment, the last one being his present occupation. It is obvious that had one considered this last occupation only the dust exposure for this individual would not have yielded a true state of affairs, nor would it have been possible to correlate this dust exposure with the man's clinical picture. In the above technic correct weight is given to the number of years spent in each occupation and the dust exposure associated with each occupation. Only by such an analysis is it possible to arrive at a fair estimate of a worker's dust exposure and his proper designation. That one is justified in resorting to such an analysis is evidenced by the fact that results obtained with this technic yield excellent correlations with the clinico-roentgenological studies conducted on anthracite coal miners.

APPLICATION OF DUST COUNTS TO CLINICAL STUDIES

Earlier in this chapter it was pointed out that one of the purposes of dust investigations is the determination of the threshold dose for any one particular dust, so that permissible amounts of this dust may be known and efforts to suppress the dust to this limit may be made. Such evaluations are sometimes made possible in studies in which in addition to the occupational dust exposure one also obtains clinical, morbidity, and mortality data on a large group of workers over a period of time. One such study was made in connection with an investigation of the health of granite cutters. Table 3, shown earlier in section I, is repeated at this time to show the occupational dust exposure of a group of these workers.

TABLE 3.—*Ranking the various occupations in the granite-cutting industry according to dust exposure*

Occupation	Number of men exposed	Number of observations	Dust count in millions of particles per cubic foot		
			Minimum	Maximum	Average
All pneumatic hand-tool operators	565	56	2.4	201.0	59.2
Surface cutters:					
Inside	58	34	.6	165.7	44.[illegible]
Outside	10	10	14.0	102.2	43.9
Carvers and letterers	24	20	11.7	99.8	37.0
Tool grinders	20	14	6.3	62.0	27.1
General plant atmosphere	121	42	2.5	64.0	20.2
Lathe operators	4	4	6.0	25.7	17.9
Polishers	43	16	1.3	26.8	9.0
Sand-blast operators	4	6	1.9	13.4	6.2
Sawyers	10	4	4.0	4.9	4.6
Blacksmiths and others	103	5	.9	8.2	2.5
Office employees	10	4	1.5	2.4	1.9

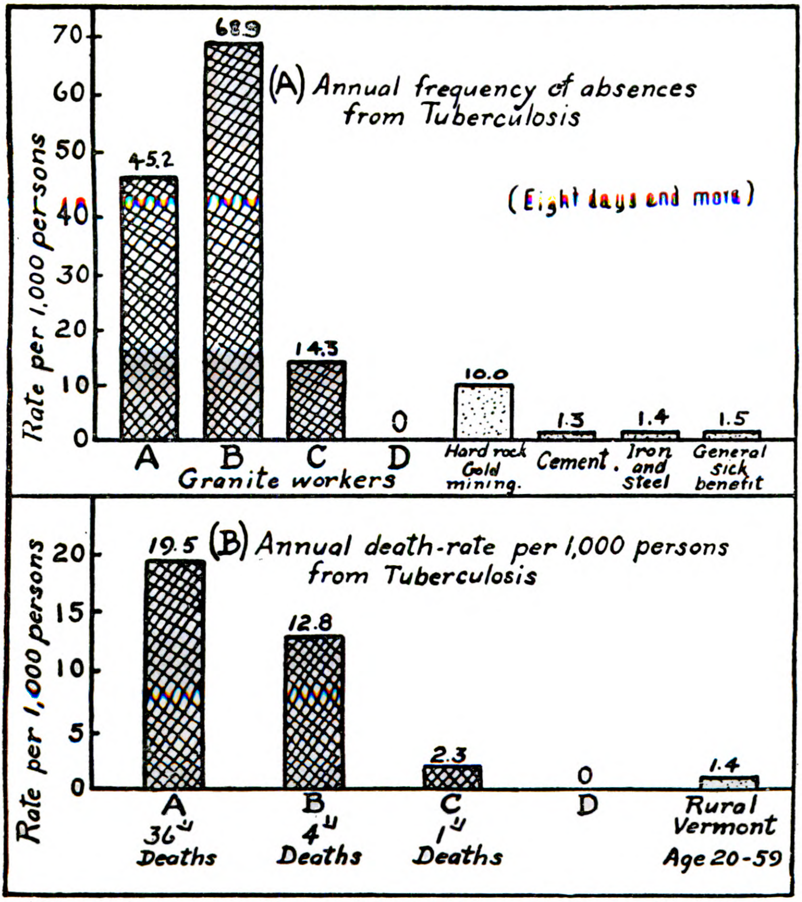
It was found possible to divide these granite cutters into four groups, depending upon the average exposure in terms of the amount of dust in the air, when considering the clinical picture associated with these workers. Figure 24 shows the annual frequency of absences from tuberculosis and the annual death rate from this disease among the men in the four groups.

In group A, which included hand-pneumatic tool operators and in which the exposure averaged about 59 million particles per cubic foot of air, it was found that practically 100 percent developed an established silicosis within 10 years from the time of beginning employment. Also, in this group the highest rate was found for cases diagnosed on physical examination as having active tuberculosis. Furthermore, a definite relation was established between length of service in the industry and the prevalence of tuberculosis. All of the statistical data obtained indicated definitely that hand-pneumatic tool operators in these plants suffered from an occupational hazard.

In group B were included those workers other than hand-pneumatic tool operators who were also exposed to more than the average plant dustiness. Taking the group as a whole, the average dust concentration was nearly 45 million particles per cubic foot of air. This group showed the same reflection of a dust hazard as group A.

In group C, consisting of those occupational groups exposed to the average plant dustiness (about 20 million particles per cubic foot of air), silicosis developed much more slowly than in the groups just discussed and there appeared to be very little excess in the rate for tuberculosis, with no tendency for an increase according to length of service. Analysis of occupational mortality over a period of 25 years, however, indicated that some of the occupations in this group may have been exposed to a real dust hazard.

Group D was made up of those occupations in which the dustiness was less than that of the average plant atmosphere. The average exposure for the group was less than 10 million particles per cubic foot of air. Although a certain amount of silicosis was found even in this group, there was no indication of serious results, even when the workers had been employed for many years.



↲ From beginning of study to working up of report — about three years — among 972 workers: A, 614; B, 104; C, 146; D, 108.

FIGURE 24.—Relationship between tuberculosis morbidity and mortality and dust exposure.

From the results of this study it was found practicable to suggest a tentative standard for the upper limit of allowable dustiness between 10 and 20 million particles per cubic foot of air for workers exposed to dust resulting from granite cutting.

DUST COUNTS AS CRITERIA IN THE CONTROL OF THE DUST HAZARD

The sections which will follow discuss in some detail the various principles and methods involved in the control of industrial dust. Descriptions are presented on the correct design, air-flow requirements, and other pertinent data dealing with the control of dust by wet methods, mechanical enclosure, exhaust ventilation, and personal respiratory protection. One of the important factors in the use of such protective equipment is the proper maintenance of these devices and the testing of their efficiency in an effort to determine whether or not the dust is actually being eliminated by the particular equipment in use. Such efficiency tests resolve themselves in making dust determinations in order to determine the dust content at the breathing level of the worker operating a dust-creating machine equipped with a dust-removal device. A few examples of the practical application of efficiency studies may serve to indicate the value of such criteria in the present problem.

Mention has already been made of the study of the health of granite cutters (2) in which it was possible to demonstrate that those persons engaged for many years in tasks associated with a dust exposure of less than 10 million particles per cubic foot of air were not suffering from silicosis or tuberculosis, the diseases most prevalent among these granite cutters. It was also possible to demonstrate that among these granite cutters the incidence of silicosis and tuberculosis, all other factors being equal, was directly proportional to the degree of dust exposure. The solution of the dust problem in the granite-cutting industry therefore, resolved itself in the removal of the dust at its source, to an amount less than 10 million particles per cubic foot, preferably by exhaust ventilation devices (47). Studies of the efficiency of such dust-removal devices have been made, using the dust determination at the worker's breathing zone as a final criterion. In table 22 a comparison of air dustiness is presented between granite-cutting plants using exhaust ventilation devices and those not equipped with such protection.

Table 22.—*Comparison of atmospheric dust conditions between two groups of granite-cutting plants*

Occupation	Average dust count in millions of particles per cubic foot of air—winter observations		
	Plants without efficient local exhaust system	Plants with efficient local exhaust system	
		Plant X	Plant Y
All pneumatic hand-tool operations	55.2	23.5	9.5
Surface cutting	45.0	15.3	10.6
Tool grinding	30.0	5.9	12.1
Sand blasting	6.9	3.5	5.5
General plant atmosphere	22.6	5.6	8.9

It is apparent from the results presented in table 22 that in plant X the exhaust devices in use with pneumatic tool operations needed attention, since the dust concentrations associated with these operations were slightly higher than the prescribed standard. On the other hand, the ventilation system in plant Y was apparently functioning satisfactorily at the time these studies were conducted.

In studying the degree of exhaust ventilation necessary to keep the dust at the worker's breathing level to an amount less than 10 million particles per cubic foot, the dust determination method again proved very useful. Figure 25 presents the results of a study of the relation between the degree of air velocity at exhaust ducts and the amount of dust inhaled by granite cutters using various pneumatic tools. It is apparent from this figure that by maintaining an exhaust velocity of 1,500 linear feet per minute at the face of the dust-removal hood of the type investigated in the present study, the dust concentration at the worker's breathing zone will be less than 10 million particles per cubic foot.

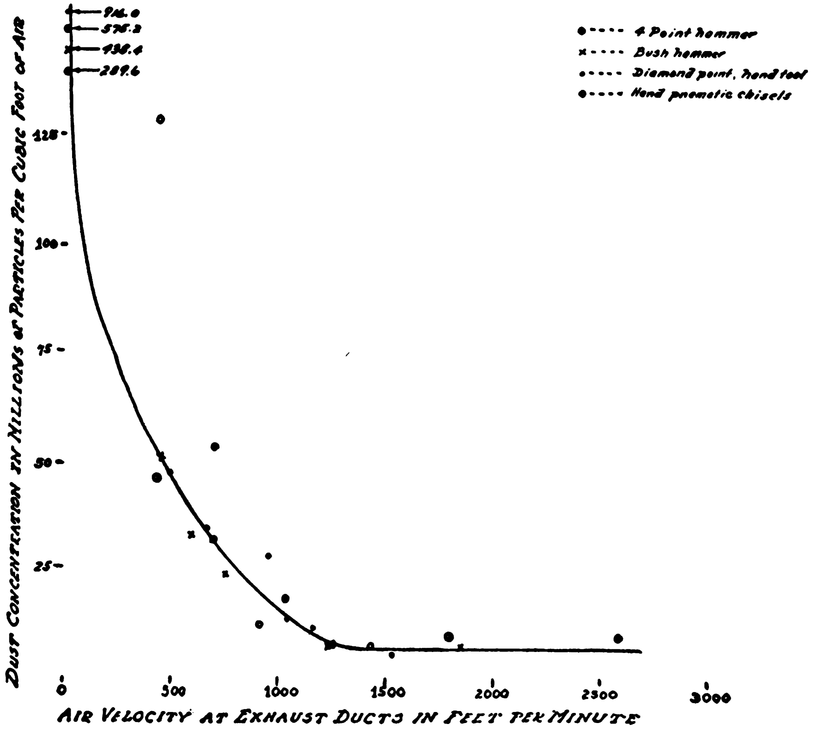


FIGURE 25.—Relationship between the degree of air velocity at exhaust ducts and the amount of dust inhaled by granite cutters using pneumatic tools.

Again, in studying the efficiency of sand-blast helmets used in the protection of men working inside sand-blast rooms, it was found that a relationship existed between the amount of air supplied to the helmet and the concentration of dust inside the helmet during blasting (48). In an attempt to determine the optimum air volume to be supplied to such protective devices, it was necessary to obtain dust samples from inside the helmet while varying the air volume, at the same time maintaining the dust concentration in the sand-blast room (outside the helmet) constant. Figure 26 shows the results of such a study

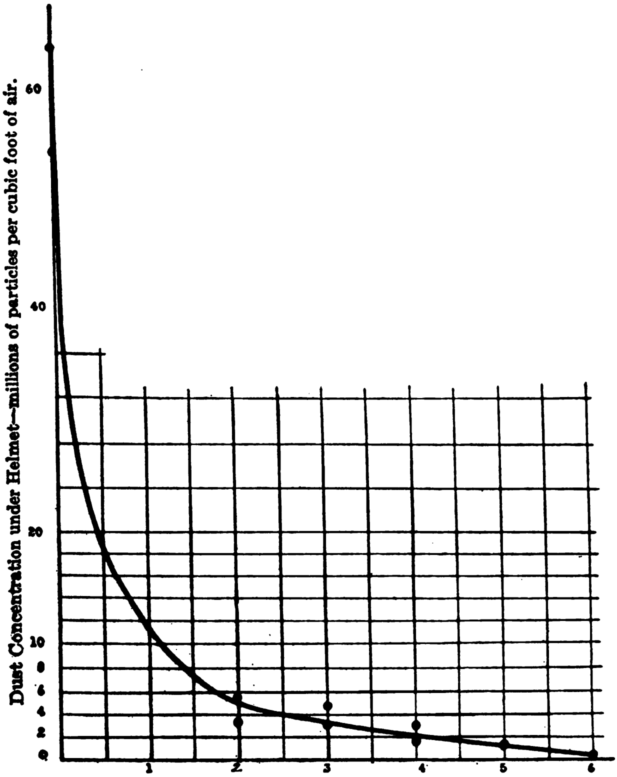


FIGURE 26.—Graph showing relationship between the volume of air supplied to helmets and the number of dust particles in air breathed by workers.

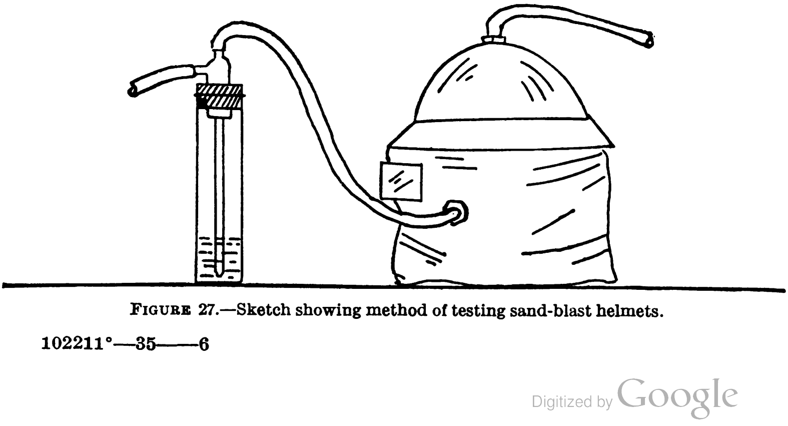


FIGURE 27.—Sketch showing method of testing sand-blast helmets.

and clearly indicates that the positive supply of 6 cubic feet of dust-free air per minute will protect a worker under the operating conditions now in practice in sand-blast rooms. The ultimate criterion of protection, however, is the result of dust determinations of the air within the helmet; that is, the air actually breathed by the worker and not the volume of air supplied. Figures 27 and 28 show the arrangement of the dust sampling devices used in determining the degree of protection afforded a worker by such protective equipment.

It is apparent from the few practical applications shown in this discussion that the dust determination method offers a real criterion for determining the effectiveness of the various dust-control measures which are treated in the sections to follow.

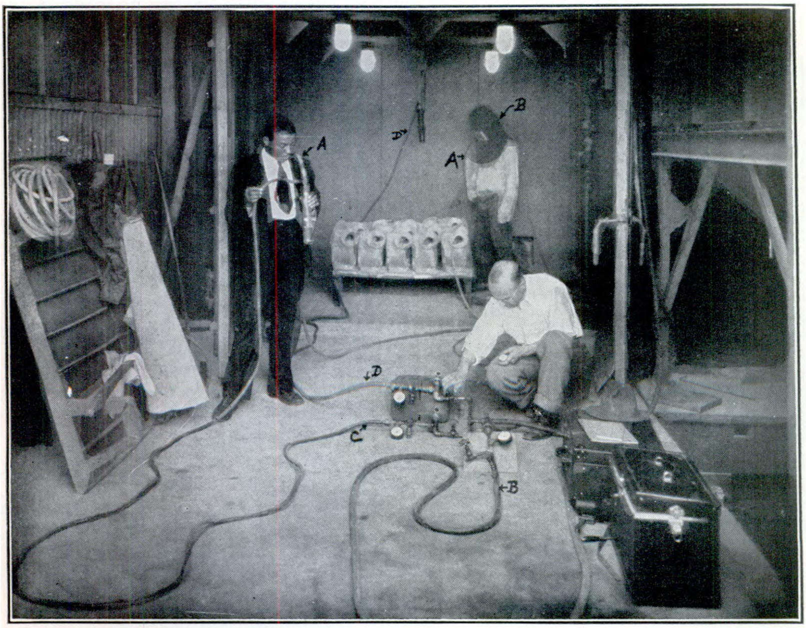


FIGURE 28.—ASSEMBLY OF APPARATUS FOR TESTING THE EFFECTIVENESS OF SAND-BLAST HELMETS.

VI. GENERAL DUST-CONTROL METHODS

The prevention of occupational disease hazards is chiefly an engineering problem. Until recently, very little definite information was available and scarcely any attempt was made to develop control methods. In an age of progress, during which production and mechanization were uppermost considerations in industry, comparatively little thought was given to the health hazards associated with them. The serious consequences of the neglect to provide adequate facilities for prevention have grown, until at the present time, their cost has become a vital concern to industry. There is, moreover, a realization that compensation for the occupational diseases is only a matter of time, and that, as in the case of accidents, a preventive program must be worked out. Just as the cost of insurance under workmen's compensation acts are in a large measure based upon accident experience, so also will the cost of caring for those suffering from the diseases of occupation be determined by their relative frequency. The formation and development of a preventive program at this time is of utmost importance.

It must be realized that the benefits of even the most extensive program of controlling dusts are not always immediately realized. This is particularly true of the fibrosis-producing dusts, whose effects are not evidenced except after a long period of time. Thus, occasional disabilities are likely to occur amongst workers exposed prior to initiating a preventive program. On the other hand, the control of toxic dusts containing lead or cadmium may produce beneficial results in a comparatively short time.

Not all the methods in use for controlling dusts are successful. The choice of any method depends chiefly upon its efficiency in reducing a given hazard and upon its adaptability. A large percentage of reduction in dust concentration achieved by a certain device does not necessarily imply that it is efficient, since the measure of success attained depends upon the ability of the device to reduce concentrations below the threshold or safe limit. A method of control also cannot be said to be completely successful which interferes with the process or which hinders the worker in the performance of his duties.

The chief methods of controlling industrial dust hazards are (1) substitution of nondust-producing or harmless substances, (2) isolation of dusty processes, (3) wetting dust at source, and (4) local exhaust ventilation applied at point of dust generation. All these methods have been used and have achieved considerable success in many instances.

With regard to the first method of controlling dust—namely, substitution of nondust-producing or harmless substances—there is only limited application. In certain cases substances have been replaced by others known to be less harmful, such as in the case of parting compounds applied on foundry molds. Pure silica was formerly widely used; but recently this has given way to other compounds which are noninjurious to health. Considering that the chief dust exposure of foundry molders is from the application of parting compounds (49), the substitution of a nonsilica-containing compound has eliminated a serious occupational disease hazard. Again, in the case of abrasive cleaning, sand has to a large measure given way to metal shot. The improvement obtained by such substitution is clearly shown by the dust counts given in the following data, taken from a report on abrasive cleaning (48):

Dust concentration in sand-blast room using sand abrasive, 969 million particles per cubic foot.

Dust concentration in sand-blast room using metal abrasive, 155 million particles per cubic foot.

The improvement as shown by these figures is remarkable, and it is possible that with the cleaning of castings preliminary to blasting with metal shot, the dust concentration might be further reduced.

The second method of controlling an industrial dust hazard consists of isolating the dusty process. This method possesses many possibilities, but unfortunately is not widely used. The theory underlying isolation is to concentrate the dust sources to one locality or to a single closed space. In this way, a minimum number of employees are exposed to dust. At the present time, many foundries, during shake-out, expose workers who normally are engaged in occupations with low dust concentrations. Thus, molders in a particular foundry may be exposed to a dust concentration of 3 million particles per cubic foot under normal occupational conditions, but when shake-out operations are carried on close by their exposure may be increased to more than 50 million. The same condition exists when annealing flasks containing ground slag are emptied in malleable iron foundries, frequently exposing grinders and tumbling barrel attendants at work close by.

Perhaps the best example of isolation of a dusty process is the abrasive cleaning room. This completely encloses a very hazardous process and exposes only the blaster who is generally equipped with a protective helmet. The room is also exhausted which further assists in reducing the dust concentration. Processes which are isolated require good ventilation. Other examples of isolation are the automatic turntable for abrasive cleaning, tumbling barrels, and batch-mixing rooms that are found in some pottery establishments.

A practice which has lately gained wide use in foundries consists in limiting the shake-out operations to a single night shift when a minimum number of workers are employed. While such methods may be described as isolation, they are not exactly so, since isolation implies that dusty operations shall be carried on in separate quarters with provision for exhaust ventilation.

The third dust control method—namely, wetting at the dust source—is generally employed in rock drilling. Water is sprayed about the hole being drilled, thus preventing the dust generated from getting into the air. Considerable success has been achieved by wetting, which is perhaps the oldest dust-control method known. The following dust counts exhibit the success attained in an actual rock-drilling operation (50).

Dust concentration with water spray 11.2 million particles per cubic foot.
Dust concentration without water spray 614.5 million particles per cubic foot.

While the reduction has been considerable, it is still possible when several drills are working simultaneously on rock high in free silica content, that the concentration of dust produced may become excessive. In view of a more positive method of controlling dust in rock drilling, which will be described later, it is sufficient to point out that wet methods actually reduce the concentration of dust.

That wet methods are not positive methods of control is borne out by a study of wet grinding in a Connecticut ax factory (51), which shows an abnormally high death rate from tuberculosis presumably brought on by dust exposure. The data follow:

Tuberculosis death rate (male), State of Connecticut, 1.7 per 100,000.
Tuberculosis death rate (grinders), ax factory employees, 19.0 per 100,000.

Recently there has been developed a combination of isolation and wet methods for controlling foundry shake-out dusts. This method consists of a large room similar to a sand-blast room in which the fresh castings (generally with cope and drag removed) are placed. Water under high pressure is then directed against these castings by an operator outside the room until the molding sand and cores are washed away. In order to facilitate cleaning, the castings are sometimes placed on a slowly revolving table. The sludge is collected in a suitable hopper and the water drained off and recirculated. Unfortunately, there is a lack of published data relative to the applicability of this type of hydraulic cleaning to all the various forms of castings found in industry, but it is obvious that this method of dust control is far superior to many other methods now in use. While the method at present has only limited use and is in the process of development, there can be no question that the problem of controlling the dust formed at foundry shake-outs, which has always been extremely difficult to attain, will gradually be an accomplished fact.

With regard to the fourth method of controlling dusts, it may be said that of the various mechanical methods devised, none has such wide application as exhaust ventilation. Exhaust systems are designed to utilize the directional forces of air currents at the dust source and to convey the dust captured to a suitable collecting place. An exhaust system may briefly be divided into four distinct parts: (1) The hoods used to capture the dust, (2) the duct system to convey the air flow and dust collected by the hood, (3) the dust-collecting equipment, and (4) the fan and motive power.

Hoods assume a wide variety of shapes depending on the manner of dust production. In some cases they completely enclose the dusty process, as in rock drilling, while in others they utilize the directional effects of a dust producing source, being placed so that the issuing dust is thrown into it. Upon hoods which are correctly designed depends a great deal of the success of exhaust methods in controlling dust sources.

The duct system consists of an outlay of duct work so proportioned that its various branches handle the necessary volume of air required by the hoods. The system conveys the dust collected and hence every part of it must maintain velocities which will transport the largest particles which enter it.

Dust-collecting equipment, where used, is designed to capture and to restrain the dust collected by the hoods. Cyclones and cloth filters are frequently used and, in cases where high efficiencies of separation are obtained, recirculation may be practiced.

The fan and motor serve to maintain the air flows through the hoods and duct system. Their size is dependent upon the volume of air handled and the total resistance of the system. The type of material to be conveyed often determines the type of fan blade and housing which must be used.

In the subsequent sections, the chief applications of exhaust ventilation are described, giving the results of researches in granite cutting and rock drilling and the status of exhaust ventilation with respect to grinding, polishing and buffing wheels, foundry shake-outs, and abrasive cleaning. Because methods of exhaust ventilation vary widely even in identical industries, and because pertinent data pertaining to them are meager, the following sections will be devoted to discussing the underlying principles of this method of control.

VII. DESIGN OF HOODS

No field in industry has received so little attention as the design of exhaust hoods. With the exception of two or three instances where some research work has been done, there is a surprising lack of data pertaining to their requirements and design. Hoods have been constructed and installed without any certainty that they will perform as expected.

The design of local exhaust hoods is complicated chiefly by the fact that the conditions vary tremendously, ranging from possible complete enclosure of the point of dust generation to the need for an exhaust hood operated independently of a moving cutting tool, interfering in the least possible way with the manufacturing process. This is well illustrated by comparing the conditions associated with rock drilling where the point of dust generation may be completely enclosed with those involved in the operation of the hand-pneumatic granite carving tool to which no attachment can be made, which is moved about over the stone at will and which is in the hands of a highly skilled and often temperamental individual.

The function of a hood is to create a velocity at the dust source which will direct the particles into the opening and thence through the duct work to a suitable collecting point. Obviously, therefore, if the velocity characteristics of hoods are available, an approximate idea of the performance of the hood could be gained. For it is from such data that the designing engineer can foretell what to expect of a particular hood with a given flow of air. This procedure would be far better than merely stating that so many "inches of suction" are required; the term is perhaps convenient, but it does not express the reaching-out qualities of a hood which are so important. This chapter, therefore, is concerned with the velocity characteristics of hoods and presents many important principles pertaining to them which have practical application.

ESTIMATION OF VELOCITY-DISTANCE RELATIONSHIP

It is well known that the air velocities in the region in front of an opening under suction change rapidly. To obtain an approximate relation between air speed and distance, consider a small opening under suction surrounded by an imaginary sphere of radius r, figure 29. It is clear that all the air entering the opening must pass through the surface of the sphere, except at the region cutting the opening which may be considered small in comparison. If the amount of air flowing be represented by Q, then the velocity along the surface of the sphere will be given by the equation $V=Q/A$ where A is the surface of the sphere. The value of A is, however, from elementary geometry equal to $4\pi r^2$. Hence,

$$V=\frac{Q}{4\pi r^2}=0.89\frac{Q}{r^2} \qquad (1)$$

The relation indicates, therefore, that the velocity at any point on the surface of the sphere is proportional to the volume flowing and inversely proportional to the square of the distance from the opening.

VELOCITY CONTOURS AND STREAM LINES OF HOODS

If the actual distribution of velocities be ascertained and drawn for a circular opening in a diametrical plane they would be of the shape indicated in figure 30.[3] The curves marked A, B, C, etc., are known as equal velocity curves, that is, every point on the curve represents a constant velocity. The curves 1, 2, 3, etc., drawn so as to be perpendicular at the points of intersection with the velocity contours, are called stream lines, or lines whose tangent at any point indicates the direction of air flow. Obviously, the total flow between two such curves is constant, the convergence of the curves indicating an increased velocity toward the opening.

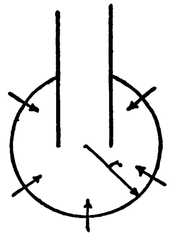


FIGURE 29.—Flow in duct end considered as passing through an imaginary sphere of radius r.

From the symmetry of a circular opening it is easily seen that the velocity conditions shown in figure 30 are the same in any other diametrical plane. Consequently, the rotation of the plane about the axis will generate surfaces of equal velocity and tubular sheets of flow. Thus the velocity and stream-line distributions in a single radial plane of a circular opening represent the velocity conditions existing throughout the sphere of influence of the opening.

The determination of velocity conditions in cases of perfect symmetry, as in the case of the circular opening described, is simple. For rectangular openings, however, the procedure would be intricate and practically impossible of representation in two-dimensional figures. A fair approximation of conditions is, however, deducible if the contours be mapped in two radial planes perpendicular to the sides as shown in figure 31. In the case of square openings the contours in each of the planes are identical.

PRINCIPLE OF SIMILARITY OF VELOCITY CONTOURS

It can be shown for a circular opening that whatever its size or volume of flow, the velocity contours and stream lines are always of

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[3] The method of developing the velocity characteristics of a hood is given in section IX.

the same general form (52). These facts have been experimentally determined and may be extended to all hoods (53); they are covered by the following theorem: *The positions of the velocity contours for any hood when the contours are expressed in terms of the velocity at the hood opening are purely functions of the shape of the hood; the contours are identical for similar hood shapes when such hoods are reduced to the same base of comparison.* For example, if the velocity 4 inches outward along the axis of an 8-inch diameter duct end under suction is 26 percent of the velocity at the plane of the opening, the same value must occur for a 12-inch diameter opening at a distance of 6 inches.

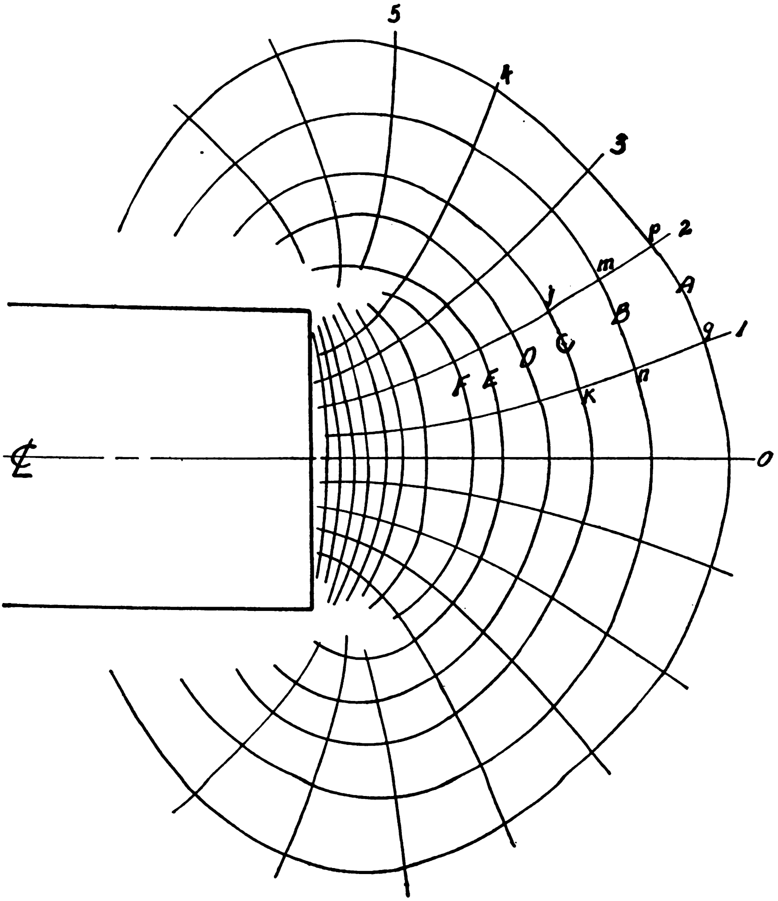

FIGURE 30.—Velocity contours and stream lines for a circular duct end under suction

That the above principle holds for rectangular hoods may appear confusing, since the velocity distributions will vary in every axial plane through a whole quadrant. However, in corresponding planes of two openings the principle does hold (53).

Rectangular hoods are designated as similar if the ratio of their sides is the same. Two rectangular hoods, therefore, will have similar velocity characteristics provided the radial planes are mapped in corresponding units and if the velocities are expressed as percentages of the velocity at the opening.

The principle of similarity offers a powerful tool for research, for large hoods may be tested in model form and their characteristics deduced. It is a basic principle applying to all hoods, reducing them to their simplest terms.

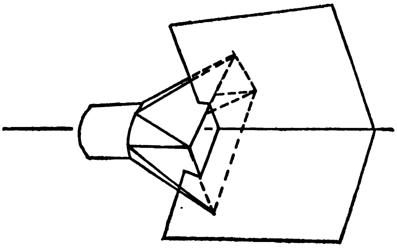

FIGURE 31.—Axial planes in which velocity contours have been determined for rectangular hoods.

VELOCITY CHARACTERISTICS OF COMMON OPENINGS

The velocity contours and stream lines for the usual openings found in practice are shown in figures 32–36. Thus, provided the region of influence for all round openings is mapped in the coordinate units corresponding to figure 32 the velocity contours will all be identical and will be expressed in percent of the average velocity in the plane of the opening. The same is true for the various shaped rectangular hoods where the short side of each is divided into eight units, and the long side in the same units in proportion to its length. An opening, therefore, with a ratio of sides of 3 to 4 will have $\frac{8\times 4}{3}=10\frac{2}{3}$ units on the long side.

An example will illustrate the application of the contour lines of figures 32–36. Suppose it is desired to find the speed and direction of the air movement at a point 4 inches outward and 5 inches upward in the radial plane perpendicular to the short side of a 4- by 8-inch hood handling 640 cubic feet per minute. The ratio of sides is one-half and expressing the coordinates of the point on the basis that there are 8 units of length on the short side the coordinates of the point in question are 8 units outward of the axis and 4 units upward, as shown by the circle in figure 35. The velocity at this

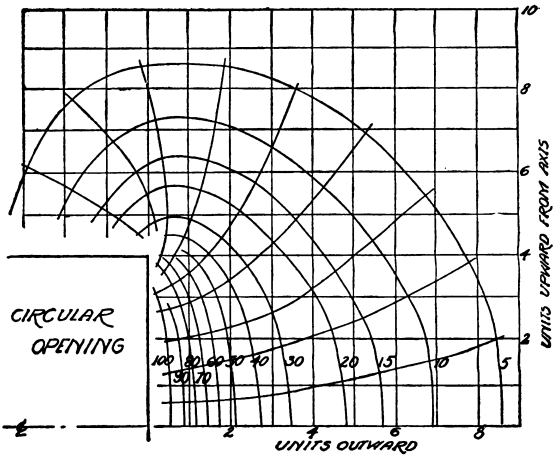

FIGURE 32.—Velocity contours and stream lines in a radial plane of a circular opening. Contours are expressed as percentages of the velocity at the opening.

point is approximately 12½ percent of the velocity at the opening. Hence, the velocity at the opening being $\frac{640\times144}{4\times8}=2{,}880$ feet per minute, the velocity at the point must be $0.125\times2880=360$ feet per minute. These calculations assume that the flow in the region of influence is not grossly impeded by an obstruction. Otherwise the contours are altered and must be redetermined with the obstruction in place. It may be said, however, that if the obstruction is considerably smaller in cross-sectional area than the surface area of the contours passing through it, the velocity distributions as shown in the figures are not substantially altered. The farther the obstruction is removed from an opening the less is the error involved.

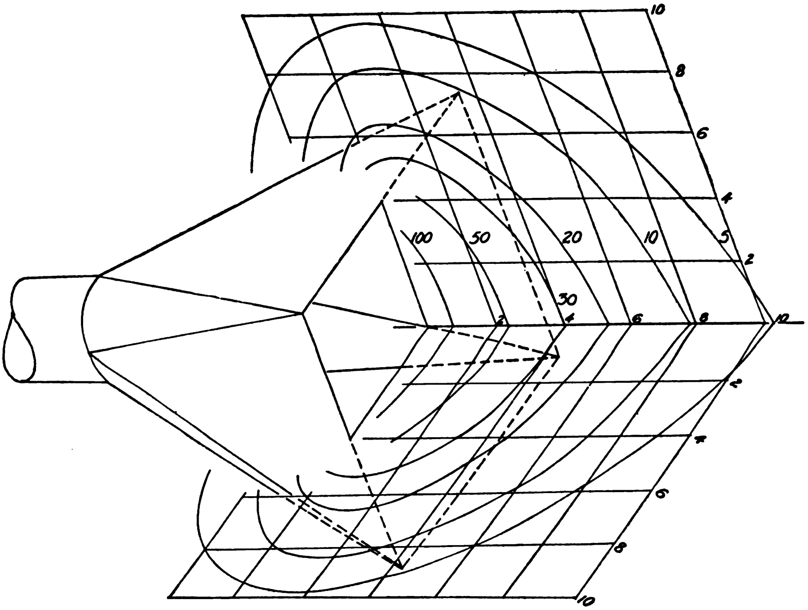

FIGURE 33.—Velocity contours for a square opening. Contours are expressed as percentages of the velocity at the opening.

Effect of shape on the distribution of velocity contours

It may reasonably be supposed that the amount and the degree of flaring of a hood has considerable effect on the distribution of the velocity contours. If, however, it is assumed that the distribution of flow across two openings of the same size and shape are similar, the velocity contours are substantially the same, although the degree of flare in each differs. The main portions of the sphere of influence which are affected lie behind the edge of the opening, the boundary surface of the flared portion being the chief variable. The velocity contour distribution, therefore, may be said to be dependent upon the shape of the opening only, provided the distribution of flow across it does not vary greatly with the degree of flare. As a matter of experiment it has been found that over a very wide range the degree of flare alters the distribution of flow across an opening only slightly (52). Hence a 5- by 10-inch opening with a 12-inch flare to a 3-inch diameter duct gives the same contour distribution forward of an opening as one with an 8-inch flare (say) to a 5-inch diameter duct. In fact, were the opening but the end of a 5- by 10-inch duct, the velocity contour distribution would differ only slightly. Since, as a rule, most hoods are gradually flared in order to reduce entrance losses, it is practical when dealing with contour distributions, to express the overall shape of the hood in terms of the shape or form of its opening—that is, in terms of the side ratio.

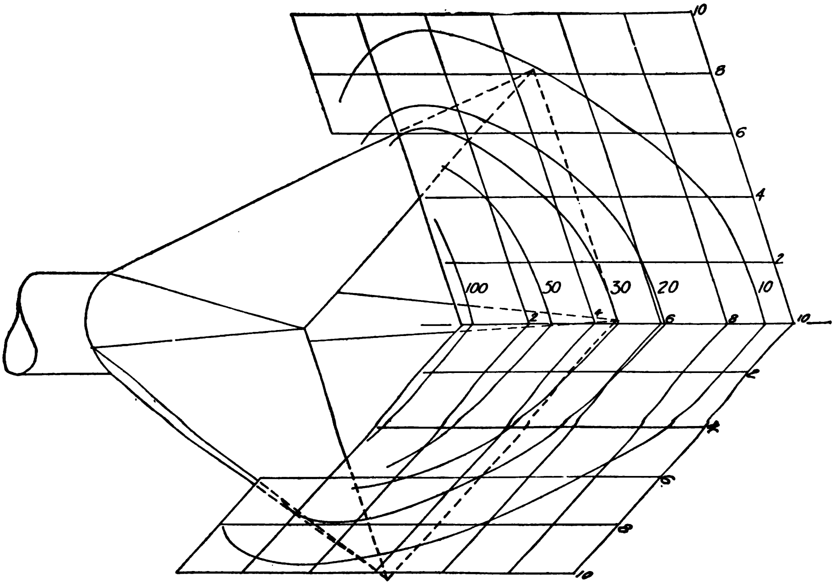

FIGURE 34.—Velocity contours for a rectangular opening whose ratio of sides is 3 to 4. Contours are expressed as percentages of the velocity at the opening.

A matter of considerable importance is the velocity distribution over the hood opening. For the purpose of simplifying calculations, it has been assumed in developing the contours in figures 32–36, that the velocity distribution over the opening is uniform. Such an assumption is not correct, as may be judged from an examination of the figures themselves, which show the 100 percent contour to be somewhat displaced from the opening. In other words, the figures show a higher velocity than the average over the central portions of the opening. The situation is somewhat like the phenomenon occurring when a fluid flows through a pipe which, because of viscosity, gives a higher velocity at the axis than toward the edges. The effect in the case of hoods does not however, arise from similar considera-

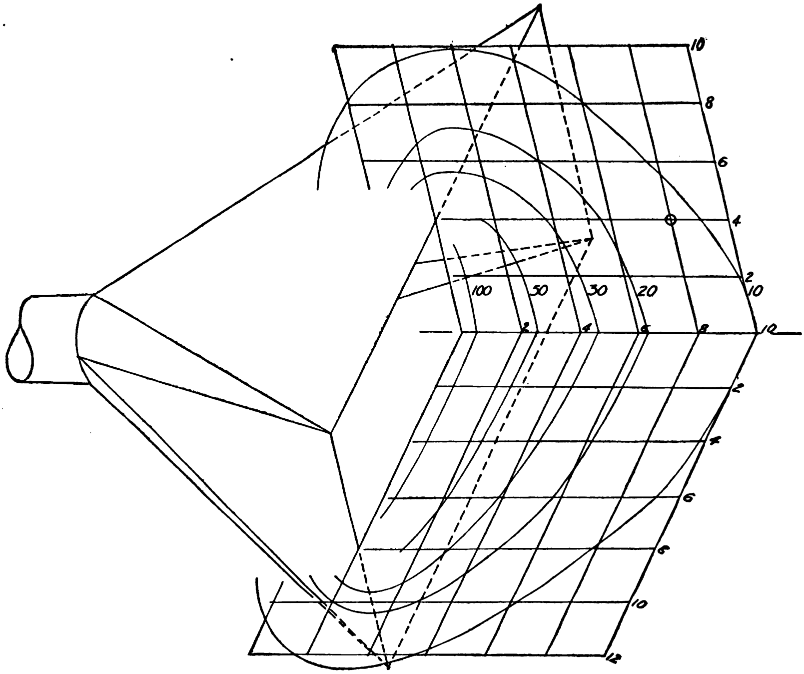

FIGURE 35.—Velocity contours for a rectangular opening whose ratio of sides is 1 to 2. Contours are expressed as percentages of the velocity at the opening.

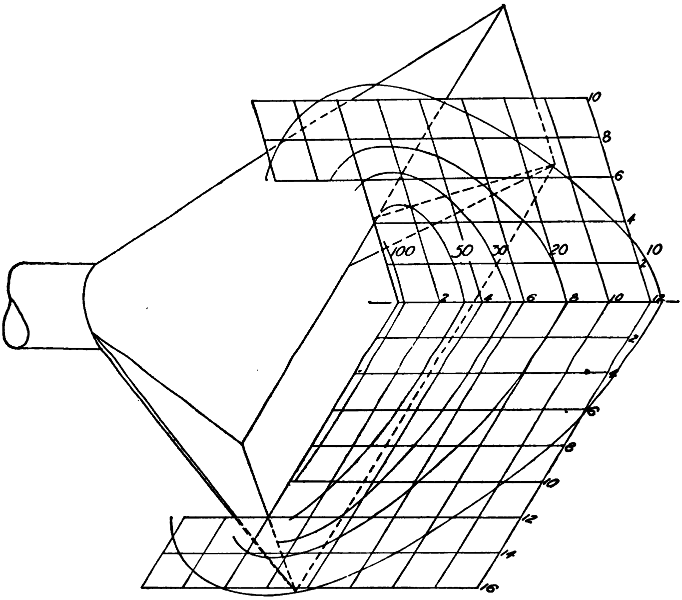

FIGURE 36.—Velocity contours for a rectangular opening whose ratio of sides is 1 to 3. Contours are expressed as percentages of the velocity at the openings.

tions. In hood openings it is necessary to contend with an edge effect. Air entering from behind the hood is forced to turn abruptly into it, thus creating a stationary vortex which restricts the effective area to a value less than the actual. At the corner of a rectangular hood, the effect may be considered as intensified. Experimental data tend to show that the effective area is reduced in proportion to the perimeter of the opening.

The edge effect may be considerably reduced by the use of a flange placed around the edge and lying in the plane of the opening. A flange approximately 5 inches in width is sufficient for hoods up to 3 square feet in area. The flange tends to cut off the flow from the region behind the opening which is frequently useless and is advantageous in two respects: First, it increases the effectiveness of the hood in the forward regions, and second, it reduces the energy consumption of the hood. In figure 37 the velocity contours and stream lines of a flanged circular opening are shown and may be contrasted for the sake of clearness with the characteristics for the same opening in figure 32.

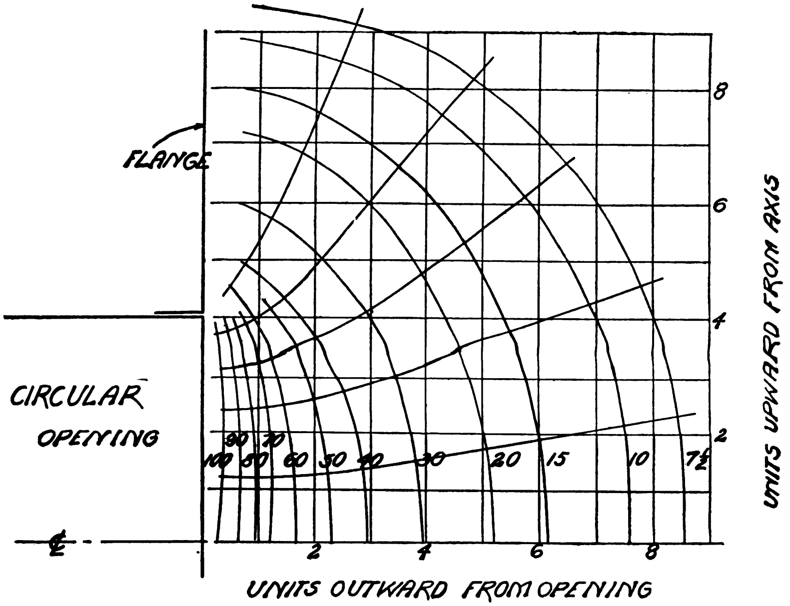

FIGURE 37.—Velocity contours and stream lines in a radial plane of a flanged circular opening. Contours are expressed as percentages of the velocity at the opening.

AXIAL VELOCITIES

The representation of aerodynamic characteristics of exhaust hoods by means of velocity contours offers a fairly simple means of comparing graphically various types of hoods. The determination of contour lines, however, involves considerable time and labor. Moreover, velocity contours do not lend themselves to mathematical analysis.

A simpler and more direct means of comparison of elementary hoods without obstruction to the opening may be had by the analysis of velocities along the projected axis of openings. Since exhaust hoods ordinarily draw dust from the area directly in front, the chief factor governing the efficiencies is the distribution of air flow in this region which may be expressed in terms of the axial-velocity curves. A series of curves for several circular openings are shown in figure 38.

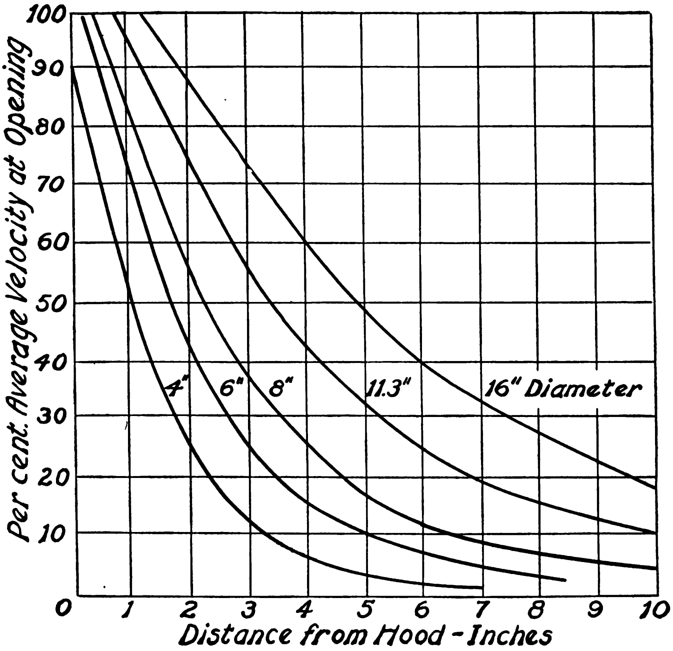

FIGURE 38.—Axial velocity curves for several circular openings

The point velocities are expressed as percentages of the velocity at the opening. As may be seen, the axial-velocity curves are limited in one direction and are almost hyperbolic in shape.

An analysis of the data has shown that the curves may be defined by the equation (52).

$$f(Y) = \frac{m}{x^n} \tag{2}$$

where Y is the point velocity expressed as a percentage of the average velocity at the opening, x the distance from the opening, and m and n are constants. When the function $f(Y)$ has the form

$$f(Y) = \frac{Y}{100 - Y} \tag{2a}$$

a linear relationship results when the equation is written in logarithmic form, thus

$$\log \frac{Y}{100-Y} = \log m - n \log x$$

Hence, the axial velocity curves may be rectified to straight lines by plotting the function $\frac{Y}{100-Y}$ against x on double logarithmic paper and thus the constants m and n may be obtained. The center line velocities for the circular openings above are shown plotted in this manner in figure 39. The data follow the straight lines very closely and are representative of the plotted curves for other openings.

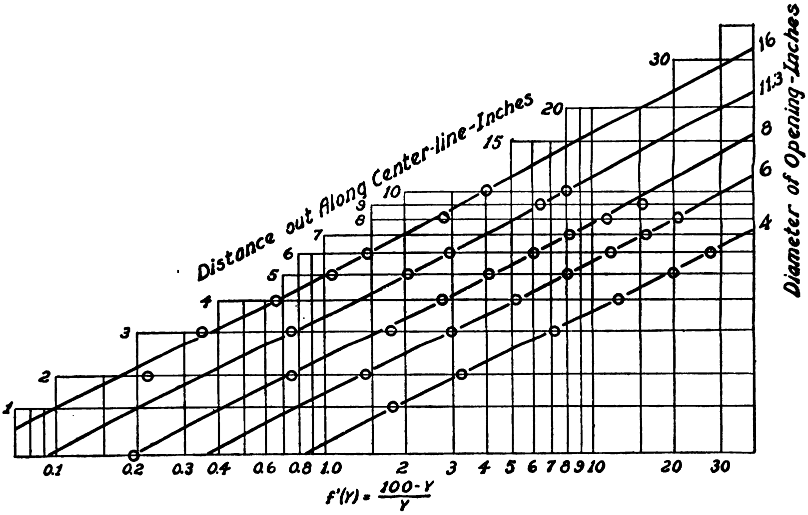

FIGURE 39.—Axial velocity curves for circular openings rectified to straight lines.

It will be observed that the lines are parallel. Square and rectangular openings also give similar lines, thus indicating that the value of n does not change with the size or shape of the opening. Its value obtained from a large number of analyses is -1.91(52).

The value of m has been found to be a function of the area of the opening according to the relation

$$m = bA^k$$

where b and k are constants. Hence, equation (2) becomes

$$f(Y) = \frac{Y}{100-Y} = \frac{bA^k}{x^{1.91}} \tag{3}$$

For round openings the constants b and k have the values 0.0825 and 1.04, respectively. Thus the final equation for round openings takes the form

$$\frac{Y}{100-Y}=0.0825A^{1.04}x^{-1.91} \tag{4}$$

Expressing A in terms of the diameter d, the equation becomes

$$\frac{Y}{100-Y}=0.0645\,d^{2.10}\,x^{-1.91} \tag{4a}$$

d and x being in corresponding units.

For square and rectangular openings, the value of the constant k has been found to be the same as for round openings—namely, 1.04.

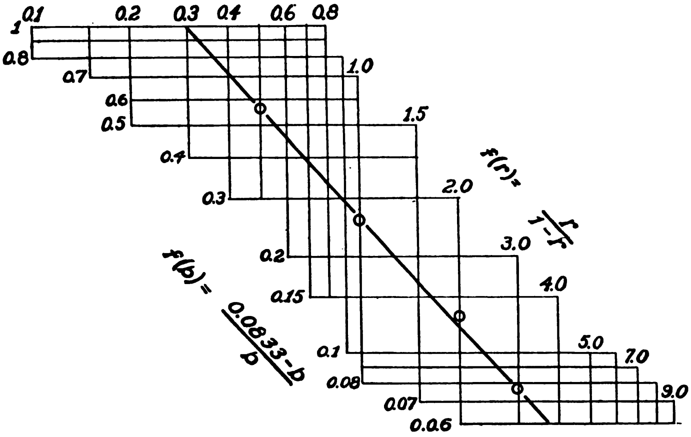

FIGURE 40.—Relation between the constant b in the equation $m=bA^k$ and r, the ratio of sides of rectangular openings.

The value of b, however, varies with the ratio of sides, as indicated in table 23.

TABLE 23.—*Values of b for various side ratios r*

Ratio of sides r	Value of b	Ratio of sides r	Value of b
0.1	0.020	0.6	0.071
.2	.037	.7	.075
.3	.049	.8	.078
.4	.059	.9	.081
.5	.065	1.0	.083

The relationship is definite as may be seen from the plotted values in figure 40 and has the mathematical form

$$\frac{0.0833-b}{b}=0.259\left(\frac{r}{1-r}\right)^{-1.104}$$

Substituting the value of b given in this equation in the general equation (3), we obtain finally for square and rectangular openings

$$\frac{Y}{100-Y}=0.0833\left[\frac{1}{1+0.259\left(\frac{r}{1-r}\right)^{-1.104}}\right]A^{1.04}x^{-1.91} \tag{5}$$

where

x = the distance outward along the axis measured in inches.
A = the area of the opening in square inches.
r = the ratio of sides (less than unity).
Y = the percent velocity at the opening found at the point x.

Thus, the center line velocity curves may be defined completely in terms of the geometric shape and size of the suction openings.

The exponents of A and x in the general equation are close to 1 and 2, respectively. This suggests that the true form of the general equation may be $f(Y)=b'Ax^{-2}$. The following simple formula is suitable for quick and approximate computations for openings usually found in practice:

$$\frac{Y}{100-Y}=\frac{0.1A}{x^2} \tag{6}$$

Equation (6) may also be written so as to give the velocity at a point along the axis directly in terms of the air flow Q, since $Y=V/V_O\times100$ where V_O is the average velocity at the opening and $Q=AV_O$, A being the area of the opening. Thus

$$V=\frac{0.1Q}{x^2+0.1A} \tag{7}$$

It is interesting to note that this equation for values of x^2 which are very large in comparison with $0.1A$ gives the relation

$$V=\frac{0.1Q}{x^2} \tag{8}$$

which is identical to equation (1) deduced from elementary considerations, with the exception of a larger constant in the present instance.

The nomograph of figure 41 has been prepared and gives the value of Y when x and A are known. To use this nomograph a ruler is connected between the values of x and A given, and the value of Y read off at the intersection with the middle scale. The line drawn in the figure connects a value of x of 10 units with an area of 150 square units, giving at the intersection with the middle scale a value of Y equal to 15 percent. In other words, the velocity at a distance of 10 units from an opening 150 units square is 15 percent of the velocity at the opening.

TABLE 24.—*Velocity change along axes of hoods of various sizes with constant air flow of 1,000 cubic feet per minute—determined from formula* (7)

Area of opening	Average velocity at opening (feet per minute)	Distance outward along axis—x				
		6 inches	12 inches	18 inches	24 inches	30 inches
1 square foot	1,000	286	91	43	24.4	15.9
2 square feet	500	222	83	41	23.8	15.5
4 square feet	250	154	72	38	22.8	15.0
6 square feet	167	107	63	35	21.7	14.6
8 square feet	125	95	53	33	20.8	14.2
10 square feet	100	80	50	31	20.0	13.8
20 square feet	50	45	33	23.7	16.7	12.1

Relation between opening area and velocity gradient

In table 24 are given the velocities of various sized openings along the hood axis when the volume of flow is held constant. The data of this table suggest that very little improvement in efficiency can be gained by increasing the open area of the hood, although the average velocity at the opening varies inversely as the area and consequently decreases as the area of the opening increases. However, there are two advantages of a large hood: First, the entrance loss is lowered by reducing the velocities at the opening, and second, the zone of influence is greatly increased in the regions forward of the opening. Relative contours having a value of approximately 14 feet per minute for square openings of various sizes are shown in figure 42. It will be noted that the contour corresponding to the opening 20 square feet in area envelopes a much larger area forward of the opening. The total surface developed by the contour is the same in each case, however, since the total flow, Q, is constant ($Q = VA$).

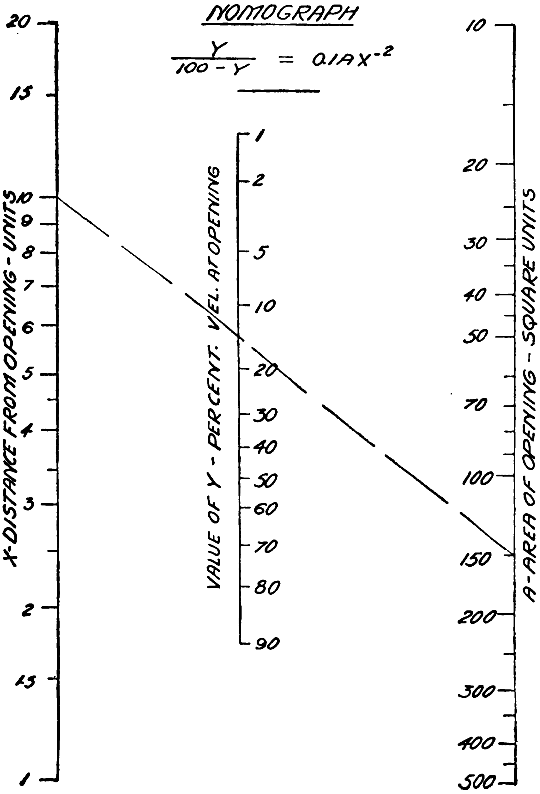

FIGURE 41.—Nomograph for the determination of axial velocities.

The chief disadvantage of a large opening for dust collection lies in the low rate of change of air speed from the point at which the hood is desired to function to its opening. In the collection of dusts, it is highly desirable to have a high rate of change inasmuch as a dust must not only be arrested at its origin but also conveyed into the hood and to a collecting system. On the other hand, large hoods work successfully in the collection of fumes which require low velocities for their control and may therefore be handled with a lower consumption of power. It will be shown later that in practice the zones of influence for most hoods are impeded by obstructions, and that it then becomes necessary to alter the treatment of the problem of velocity distribution. However, the factors to hold in mind in any hood installation are the size of the opening and its location with respect to the region at which it is expected to operate.

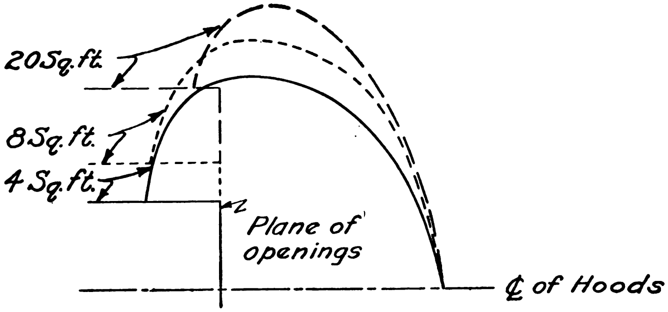

FIGURE 42.—Relative positions of 14 feet per minute velocity contours for a constant rate of air flow of 1,000 cubic feet per minute through openings 4, 8, and 20 square feet in area.

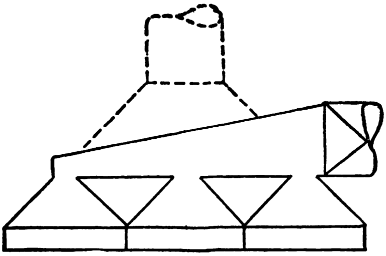

FIGURE 43.—Method of subdividing large hoods.

RELATION BETWEEN SIZE OF HOODS AND CONNECTING DUCTS

The distribution of air flow over the hood opening should be as uniform as possible. This cannot be secured when the ratio of the area of the hood opening to the connecting duct area is large, unless the length of the transition piece is increased to accommodate the change in air speed from section to section. Otherwise, the movement of the air will all be concentrated at the center of the hood opening, and the hood will fail to function properly. Unless there is an even distribution of air flow across the opening, there is little sense in maintaining the full-size hood.

There are many instances where a high ratio between the size of the opening and the connecting duct is necessary, and yet a long flare cannot be used because of lack of space. In such cases, the hood may be designed so that it is divided into several hoods, edge to edge, each of which is independent of the other. A large hood with a side ratio of 1 to 3, for example, may be divided into three square openings connected in the manner indicated in figure 43, thus effecting a considerable saving in headroom over that occupied by a transition piece of the common type.

It is not possible to formulate a definite rule to govern the relationship between the ratio of the areas of the connecting duct and the hood opening and the degree and length of the flare. In modern practice the ratio is generally taken as 1 to 16 at a maximum, and the length of flare as three times the diameter of the connecting duct.

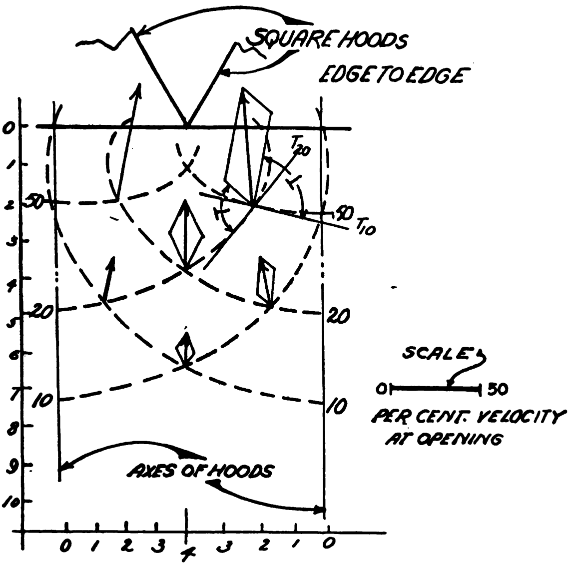

FIGURE 44.—Construction of the velocity contours for a compound hood by vectorial analysis from the contour lines for the separate openings.

DETERMINATION OF VELOCITY CONTOURS FOR COMPOUND HOODS

When hoods are subdivided in the manner indicated above, the velocity distribution is not changed materially from that given by the single large opening. The contour distributions for two square hoods placed edge to edge may be combined vectorially at their intersections as shown in figure 44. From the resultant velocities and directions of the air movement thus obtained, a new set of velocity contours may be drawn. This has been done in figure 45, where the solid lines indicate the contours obtained by the principle of velocity combination and the dotted lines represent the distribution for a single opening whose side ratio is 1 to 2. The proximity of corresponding contour values indicates that the subdivision of a large hood into independent units of smaller dimensions does not alter the original velocity distribution of a hood.

This method of combining square hoods, edge to edge, may be employed in establishing the velocity contours for any side ratio although the method is laborious. It may also be applied to the study of arrangements in which the velocity distribution is not uniform, such as the double hoods recommended for the control of fumes by some State codes. In figure 46 are shown the velocity contours for two square openings, edge to edge, one of which is handling twice as much air as the other. As may be seen, there is considerable distortion although it is not difficult to show that there is a slight reinforcement. Studies of this sort suggest that double hoods do not possess marked advantages over the well-designed single hood.

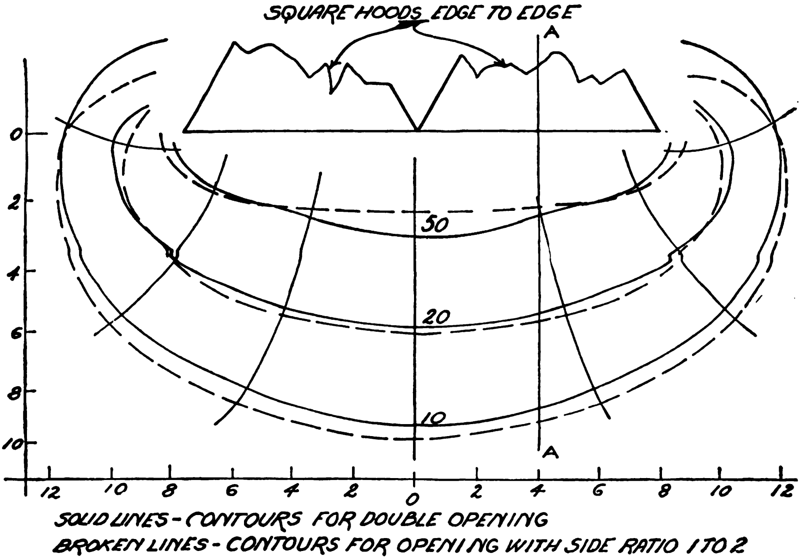

FIGURE 45.—Comparison of velocity distribution for double opening with contours for a single opening of the same shape and size. Contours of double opening calculated as in figure 44.

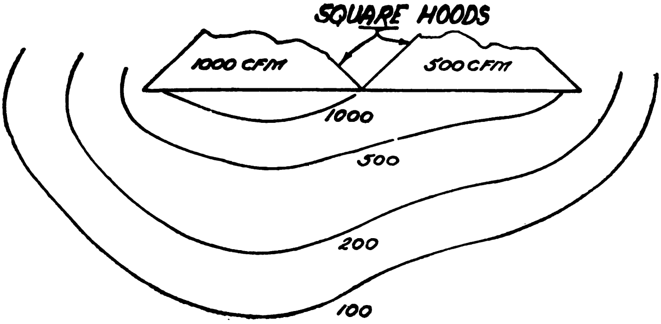

FIGURE 46.—Velocity contours of a double hood having a nonuniform distribution of flow. Contours are expressed in feet per minute (hoods are each 1 square foot in area).

VELOCITY CONTOURS OF HOODS WITH SPECIAL BOUNDARY CONDITIONS

The method of compounding velocity contours can be adapted so that the resultant contours hold for openings with special boundaries (54). Hoods are rarely used without some form of obstruction, being bounded either by extended planes or devices placed close to the plane of the opening. Consequently, if contours for special conditions can be developed from those known for simple openings, considerable information may be gained of much practical value. Four special cases are discussed below which indicate the general procedure for developing contours for any shape of hood under similar conditions. The method, while approximate, nevertheless as indicated above, gives results which are surprisingly accurate.

The procedure in determining boundaries under certain conditions is based on the principle that a solid boundary may be substituted for any free stream surface or for any stream plane of symmetry. In this respect, the problem is analogous to the method of images used in capacitance calculations in electrical theory. In fact, the boundary cases discussed below are distinctly "image" problems.

Case I.—Infinite plane perpendicular to axis of hood at a given distance from the opening.

This condition is obtained in the manner shown in figure 47. The velocity characteristics of two square openings lying along the same axis have been combined in the manner described and the velocity distribution traced. Since no flow can take place across the stream plane of symmetry, this plane may be replaced by a solid boundary. Consequently, the hood drawn in dash lines may be removed without altering the flow into the hood. (The hood and contours removed may, as shown above, be regarded as images.)

The velocity contours are the same for all similarly shaped hoods located above an infinite plane so long as their relative distance above the plane remains the same. In the particular case shown in figure 47, the infinite plane is located at a distance equal to one-fourth the length of one of the hood edges. Thus, for an opening 4 feet square, the distance is 1 foot. At other distances, new contours must be formed.

Case II.—Infinite plane at a given angle to the plane of the hood opening.

This condition is encountered in practice when a hood is placed at an angle to a large surface. An extreme case is given in figure 48 where the edge of a square hood is shown touching a plane at an angle of 45°. The resultant contours are developed from the distributions of two square openings tilted at 90° to each other with corresponding edges touching. As in the previous case, since no flow takes place across the stream plane of symmetry, a solid boundary may be inserted without altering the conditions of flow. The removal of the "image-hood" shown by the broken lines consequently will not change the velocity characteristics of the other. The method may be duplicated for hoods at any angle to a plane (except small angles) and for conditions where the edge of the hood does not touch the plane.

For the case given in figure 48 one may draw conclusions similar to those given for the previous case, namely, that the contours are the same for all square hoods at an angle of 45° to an infinite plane, one of whose edges meets the plane. The length of the hood edge may be used to determine the relative locations of the contours.

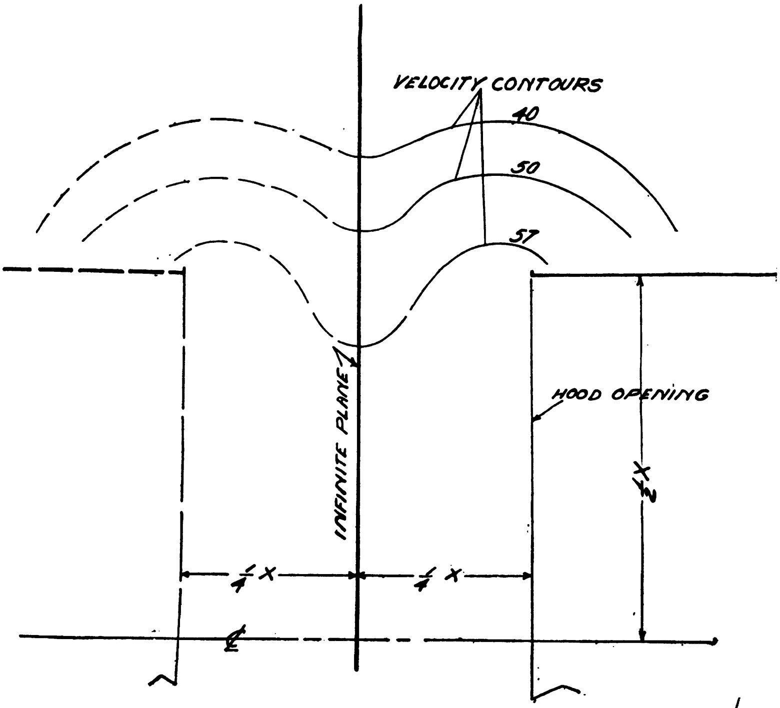

FIGURE 47.—Velocity contours for a square hood located at a distance equal to one-fourth the length of one of the sides above an infinite plane. Contours are expressed as percentages of the velocity at the opening.

Case III.—Infinite plane parallel to the axis of a hood and touching one of its edges.

Since the flow in an upper quadrant of a symmetrical hood is the same as that of the lower, it follows that both halves may be separated by a solid boundary without affecting the contour distribution in either. This implies, for example, that the contours for a square opening drawn in a quadrant plane may represent the velocity distribution of an opening with a ratio of sides equal to one-half with an infinite plane attached to the longer side and parallel to the hood axis.

Hoods included in case III have a very practical application, especially in exhausting fumes from tanks through lateral openings and dust generated by granite-cutting machines (55). Figure 49 shows the velocity distribution obtained in a quadrant plane perpendicular to the long edges of a rectangular opening with a side ratio equal to one-half. However, since we are concerned with the distribution of contours above an infinite plane as shown in the figure, the opening must be regarded as having a side ratio equal to one-fourth.

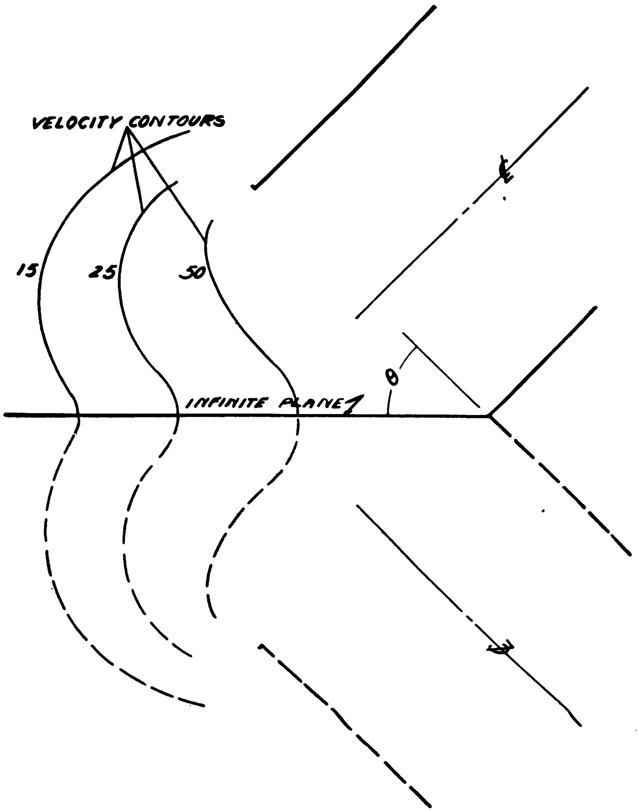

FIGURE 48.—Velocity contours for a square opening at an angle to an infinite plane. Contours are expressed as percentages of the velocity at the opening.

Case IV.—Hood with infinite plane surrounding it and with a plane parallel to its axis.

This case is a combination of the simple-flanged hood and case III and is represented for a circular opening by the region marked "A" in figure 50. This case, however, has only a limited application in industry and need not be discussed in detail.

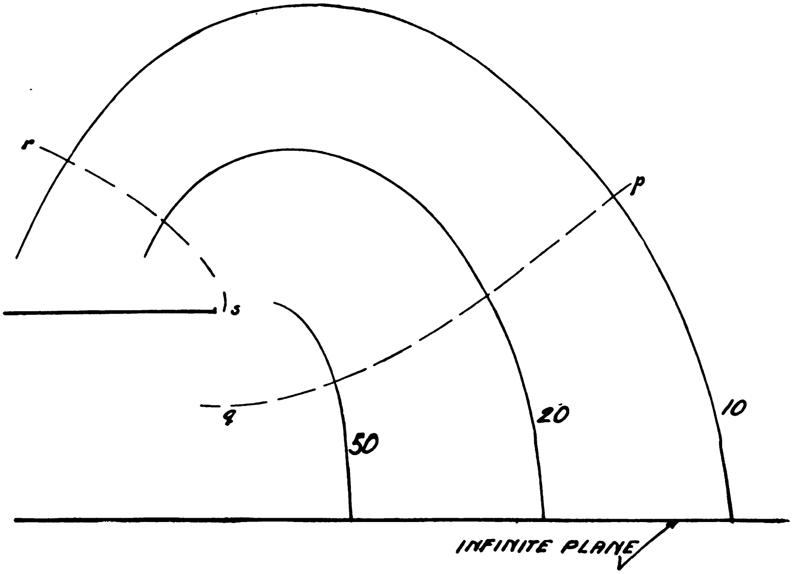

FIGURE 49.—Velocity contours for a hood with a side ratio of 1 to 2 with an infinite plane parallel to the hood axis and touching the longer side. Contours are expressed as percentages of the velocity at the opening.

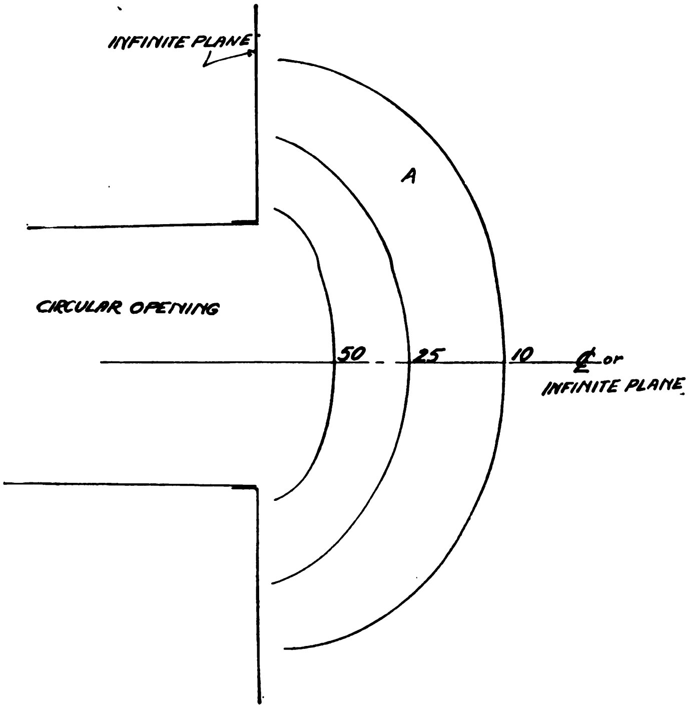

FIGURE 50.—Velocity contours for a circular opening with an infinite plane surrounding it and with an infinite diametrical plane. Contours are expressed as percentages of the velocity at the opening.

SUMMARY OF FACTORS ASSOCIATED WITH THE DESIGN OF LOCAL EXHAUST HOODS

The important factors discussed in the foregoing may be summarized in the following rules of design:

1. Consistent with the required efficiency of dust collection and operation of the machine, the hood should be so shaped and located as to operate with a minimum air velocity requirement. From a study of the characteristics of operation and dust production of the process, the proper location of the hood opening, its shape, and the placing of baffles to interrupt a discharge of the dust should be determined.
2. Locate the hood as closely as possible to the point of dust generation.
3. Choose a hood having a uniform velocity contour over the area of dust production.
4. Choose a hood having a maximum ratio of flow from effective to ineffective areas.

VIII. DESIGN OF LOCAL EXHAUST SYSTEMS

General remarks.—A knowledge of the factors governing the design of exhaust systems is important. Installations for controlling dust have failed in the past, because fundamental principles were not considered in their design. In many plants it was customary to regard exhaust systems as necessary evils, prescribed by "blower laws" and because such systems yielded no visible return, but rather added to the cost of operation and maintenance, no attention was paid to them. Winslow and Greenburg (56) have aptly stated the situation in the following words:

> The engineering journals carry elaborate accounts of the design of ventilating apparatus; but, once installed, we hear nothing about them if they work well; whereas if they fail, the result is usually a sweeping condemnation of the whole practice of fan ventilation, without any serious attempt to discover the exact source of the difficulty.

The following paragraphs are intended to point out the general considerations which enter into the design of exhaust systems. They attempt to illustrate the few simple principles of design which are within the grasp of most engineers and the methods of their application. For the sake of clearness, it will be necessary to begin with a discussion of simple facts and gradually to show how these are utilized in actual problems.

STATIC AND VELOCITY PRESSURES

It is first necessary to begin with the laws governing the movement of air in ducts. These laws are similar to those pertaining to the flow of other fluids and are, in fact, borrowed directly from hydrodynamics. The primary difference between gaseous and liquid flow is that one is a compressible fluid, markedly affected by temperature, while the other is considered practically incompressible with a fairly constant specific volume over a wide range of temperatures. In actual air-flow computations the factor of compressibility is disregarded, and except for temperature corrections, the laws governing the flow of air are identical to those for water.

In a duct system the flow of air is maintained by virtue of a pressure supplied by the fan. This pressure may be positive or negative depending on whether the duct is connected to the exhaust or suction sides of the fan. The total pressure at any point in a duct has two components which are designated as velocity head and static head. The former is the pressure required to produce the velocity, and the latter, a pressure supplied to overcome the frictional resistance of the moving air in the duct.

Since the velocity pressure depends entirely upon the velocity of flow, any change in velocity either from an enlargement or contraction of the duct, causes a corresponding increase or decrease of static head. Theoretically, the static and velocity heads are interchangeable In practice, however, a change of velocity is not exactly compensated by an equivalent change of static head, inasmuch as an enlargement or reduction of a duct is accompanied by certain energy losses.

The movement of air in a duct entails a loss of static pressure. This loss is primarily due to the friction of the fluid to resist motion. A change in the motion as a bending of the air through an elbow or a change in duct size also causes a loss of static pressure through eddy effects set up. The pressure difference between any two points in a duct indicates the losses sustained in moving the air over the distance between them.

RELATION BETWEEN VELOCITY AND VELOCITY HEAD

It is obvious that between velocity and pressure some relation must exist. It is shown in textbooks of physics, that if water emerges from an orifice near the bottom of a tank, that the water velocity at the point of issue can be determined from the following relationship

$$h'_v=\frac{v^2}{2g} \tag{9}$$

where v is the velocity in feet per second, h'_v the height of the water level above the orifice, and g is the constant of gravitation, equal to 32.2.

The relation between the velocity of air flow and velocity head is also given by equation (9). In the case of water, the equation merely expresses the fact that a water column of height equal to h'_v represents a pressure which is proportional to the square of the velocity. The same interpretation applies to air, where now, however, the pressure created by an air column of height h'_v is proportional to the square of the air velocity.

For convenience in air-flow measurements, the term h'_v of the above equation is generally expressed in inches of water. Thus to convert h' in feet of air to h_v in inches of water, we have that

$$h'_v=\frac{\text{density of water}}{\text{density of air}}\times h_v$$

If the density of air is taken as 0.0749 pounds per cubic foot and water as 62.4 pounds per cubic foot at 70° F., then

$$h'_v=\frac{62.4}{0.0749}\times h_v=833h_v$$

If h_v is expressed in inches

$$h'_v = 69.4h_v$$

Thus, the height of an air column at 70° F. equivalent to one inch of water is 69.4 feet.

Substituting in equation (9) we then obtain

$$69.4h_v = \frac{v^2}{64.4}$$

Therefore, if the velocity is expressed in feet per minute

$$V = 4009\sqrt{h_v} \tag{10}$$

EFFECT OF TEMPERATURE

It was mentioned in a previous paragraph that air is affected by termperature changes, contracting in volume when cooled and expanding when heated. If it is assumed that expansion or contraction is proportional to the absolute temperature,[4] T_1 then the following proportion is true

$$\frac{h_1}{h_2} = \frac{T_1}{T_2}$$

or if h_2 is desired, T_1, T_2, and h_1 being known

$$h_2 = \frac{T_2}{T_1}h_1$$

Thus, given the height of air column h_1 corresponding to an absolute temperature T_1, the height of air column for any other temperature is at once determined.

Equation (10) may be written

$$V = K\sqrt{h_v}$$

where K is a constant varying with temperature. This constant, following the method outlined in this and the preceding paragraph has been calculated in table 25.

Table 25.—*Values of air density, height of air column, and K in formula, $V = K\sqrt{h_v}$ for various air temperatures*

Temperature	Density of air (pounds per cubic foot)	Column of air equal to 1 inch H_2O (feet)	Value of K in $V = K\sqrt{h_v}$	Temperature	Density of air (pounds per cubic foot)	Column of air equal to 1 inch H_2O (feet)	Value of K in $V = K\sqrt{h_v}$
32° F.	0.0807	64.40	3863	70° F.	0.0749	69.39	4009
40° F.	.0784	65.44	3894	80° F.	.0735	70.69	4048
50° F.	.0779	66.74	3935	90° F.	.0722	71.99	4084
60° F.	.0763	68.09	3971	100° F.	.0709	73.29	4123

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[4] Absolute temperature is the temperature at absolute zero, plus the observed temperature; that is $459.6+t$, where t is the observed temperature degrees F.

Problem: Calculate the height of air column and the air density at 94° F., given the corresponding data at 70°.

Solution:

$$\frac{h}{69.39}=\frac{459.6+94}{459.6+70}$$

$$h=72.5$$

To calculate the density, we have, since h is inversely proportional to the density D:

$$\frac{D}{0.0749}=\frac{459.6+70}{459.6+94}$$

$$\mathrm{D}=0.0717$$

EQUATION OF FLOW

The volume of air flow may be directly obtained in terms of the cross sectional area of the duct. If Q represents the volume of air flowing in cubic feet per minute at an average velocity equal to V and a is the area of the duct in square feet

$$Q=aV=4009a\sqrt{h_v} \qquad (11)$$

If the diameter of the duct is expressed in inches, $a=0.0055\mathrm{d}^2$ and

$$Q=22.9\ d^2\sqrt{h_v} \qquad (12)$$

In the case of a duct of varying sections of areas equal to a, a', a'', etc., with constant flow,

$$Q=aV=a'V'=a''V''=\text{etc.} \qquad (13)$$

where the V's correspond to the velocities in the various sections. If the velocity is known in one section, it can then be determined for any section provided that the areas of both sections are known. Thus, if V, a and a' are known, the velocity in the latter section is simply

$$V'=\frac{a}{a'}V \text{ or } V'=\frac{d^2}{d'^2}V$$

where d and d' are corresponding diameters in inches or feet. When d is expressed in inches, the corresponding areas in either square inches or square feet may be obtained from table 26.

TABLE 26.—*Areas of circles in square feet and square inches, diameters in inches*

Duct diameter	Duct area		Duct diameter	Duct area	
	Square inches	Square feet		Square inches	Square feet
1 inch	0.785	0.0055	11 inches	95.03	0.660
2 inches	3.14	.0218	11.5 inches	103.86	.721
2.5 inches	4.91	.0341	12 inches	113.09	.785
3 inches	7.07	.0491	12.5 inches	122.71	.852
3.5 inches	7.62	.0668	13 inches	132.73	.922
4 inches	12.57	.0873	13.5 inches	143.13	.994
4.5 inches	15.90	.110	14 inches	153.93	1.069
5 inches	19.64	.136	14.5 inches	165.13	1.147
5.5 inches	23.76	.165	15 inches	176.71	1.227
6 inches	28.27	.196	15.5 inches	188.69	1.310
6.5 inches	33.18	.230	16 inches	201.06	1.396
7 inches	38.48	.267	16.5 inches	213.82	1.485
7.5 inches	44.18	.307	17 inches	226.98	1.576
8 inches	50.27	.349	17.5 inches	240.52	1.670
8.5 inches	56.75	.394	18 inches	254.46	1.767
9 inches	63.52	.442	18.5 inches	268.80	1.867
9.5 inches	70.88	.492	19 inches	283.52	1.969
10 inches	78.54	.545	19.5 inches	298.64	2.074
10.5 inches	89.59	.601	20 inches	314.16	2.182

TRANSPORT VELOCITIES

The design of an exhaust system depends upon the magnitude of the air velocities required for transporting the dust collected by the hood, and upon an estimation of the losses incurred by fluid friction and eddy effects. If the velocities chosen are too low, there is danger of clogging the system with settled dust, while if too high, the friction losses may be so prohibitive as to bring the cost of operation to an unreasonable figure. Great care should therefore be exercised in the choice of velocities to be maintained.

TABLE 27.—*Air speeds in ducts necessary to convey various materials*

Material	Air velocities (feet per minute)
Grain dust	2,000
Wood chips and shavings	3,000
Saw dust	2,000
Jute dust	2,000
Rubber dust	2,000
Lint	1,500
Metal dust (grindings)	2,200
Lead dusts	5,000
Brass turnings (fine)	4,000
Fine coal	4,000

Values of transport velocities are meager. Data for some dusts which have been found practical are given in table 27, but whether they are the most economical cannot be stated. No data regarding the size of the particles or their characteristics are available, and in all probability the figures represent the velocities in accord with existing practice. When, however, the maximum size and density of a particle to be conveyed is known, the following formulas for horizontal and vertical transport are useful (57). For horizontal ducts

$$V=6{,}000\frac{s}{s+1}\delta^{0.398} \tag{14}$$

and for vertical ducts

$$V=13{,}300\frac{s}{s+1}\delta^{0.570} \tag{14a}$$

where V is the air velocity in feet per minute, s is the specific gravity of the particles and δ is the diameter in inches of the largest particle

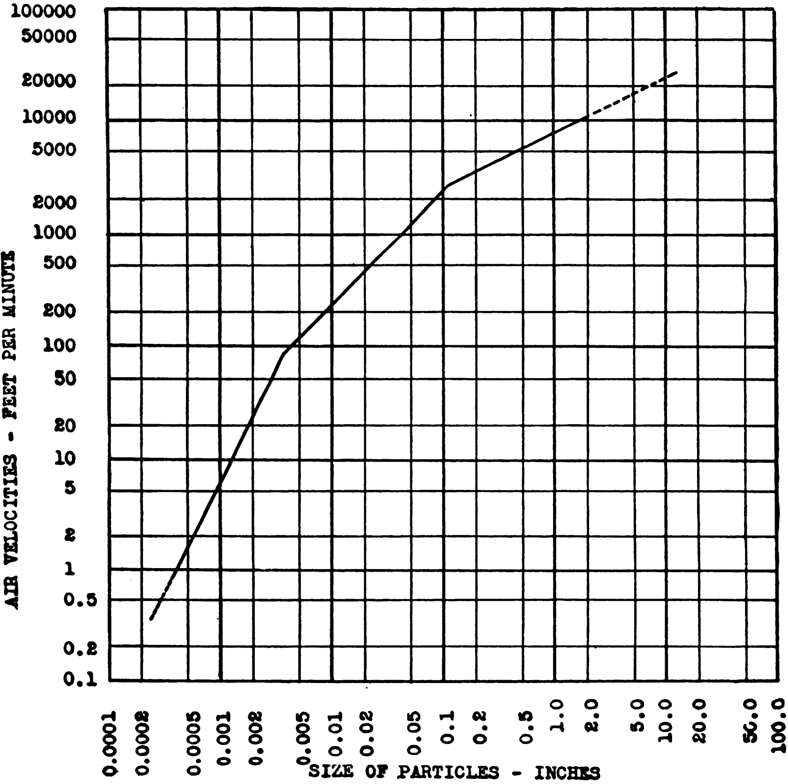

FIGURE 51.—Air velocities required to lift particles of quartz (specific gravity 2.65).

to be conveyed. The velocities determined by the above equations are minimum and should be increased approximately 10 percent to take care of settling which is likely to occur at elbows or enlargements.

For fine particles of dust—that is, those which obey Stokes' law—little is known of the velocities required to convey them. The curve of figure 51 taken from data given by Martin (58) gives the velocities which must be exceeded in transporting particles of quartz ($s=2.65$)

from 10 microns (in the range of Stokes' law) to 10 inches in diameter. The values in the extreme ranges are extrapolated.

Determination of duct diameter

When the volume of air required by a hood to control dust at a given source is known, and when the velocity of transport has been fixed, the size of duct required is at once determined from the equation of flow (equation (12))

$$Q=aV=22.9\ d^2V$$

where d is the diameter of the duct expressed in inches. From this relationship, we obtain

$$d=0.209\sqrt{\frac{Q}{V}} \qquad (15)$$

the size of duct required to maintain a velocity of V feet per minute when a volume of Q cubic feet per minute of air flows.

ENERGY LOSSES IN A DUCT SYSTEM

The calculations involved in the design of an exhaust system depend upon the energy losses incurred at the hood, and various portions of the system, the latter including the losses due to fluid resistance, elbows, transitions (enlargements or reductions of the duct) and collecting devices. For each duct of the system, the losses must be carefully estimated in order that a fan which will maintain the air flows required may be chosen.

It is well known that when water flows in a pipe, the pressure diminishes in the direction of the opening. This loss of "head" indicates a loss of energy. The same is true for air flowing in a duct. There is a decrease in static head toward the opening (that is, if the flow is toward the opening) and this decrease is due to loss in friction. The nature of these losses are discussed in the following paragraphs.

Hood entrance losses

The entrance losses depend almost entirely upon the structure of the hood. It has been found[5] that flared hoods without serious obstruction close to the opening have losses equal to about 50 percent of the velocity head in the connecting duct. In the case of plain duct ends, however, without any flaring, the losses are greatly increased due to the excessive spin of the incoming air from regions behind the edge of the opening. The losses for duct ends must therefore be taken as equal to the velocity head.

Loss in straight ducts

The movement of a fluid in a duct gives rise to friction effects. These losses are made up by the static head so that in a duct of given

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[5] Unpublished data: J. M. D.

length and uniform diameter, the loss is represented by the difference of static pressure between the ends of the section. In the chart of

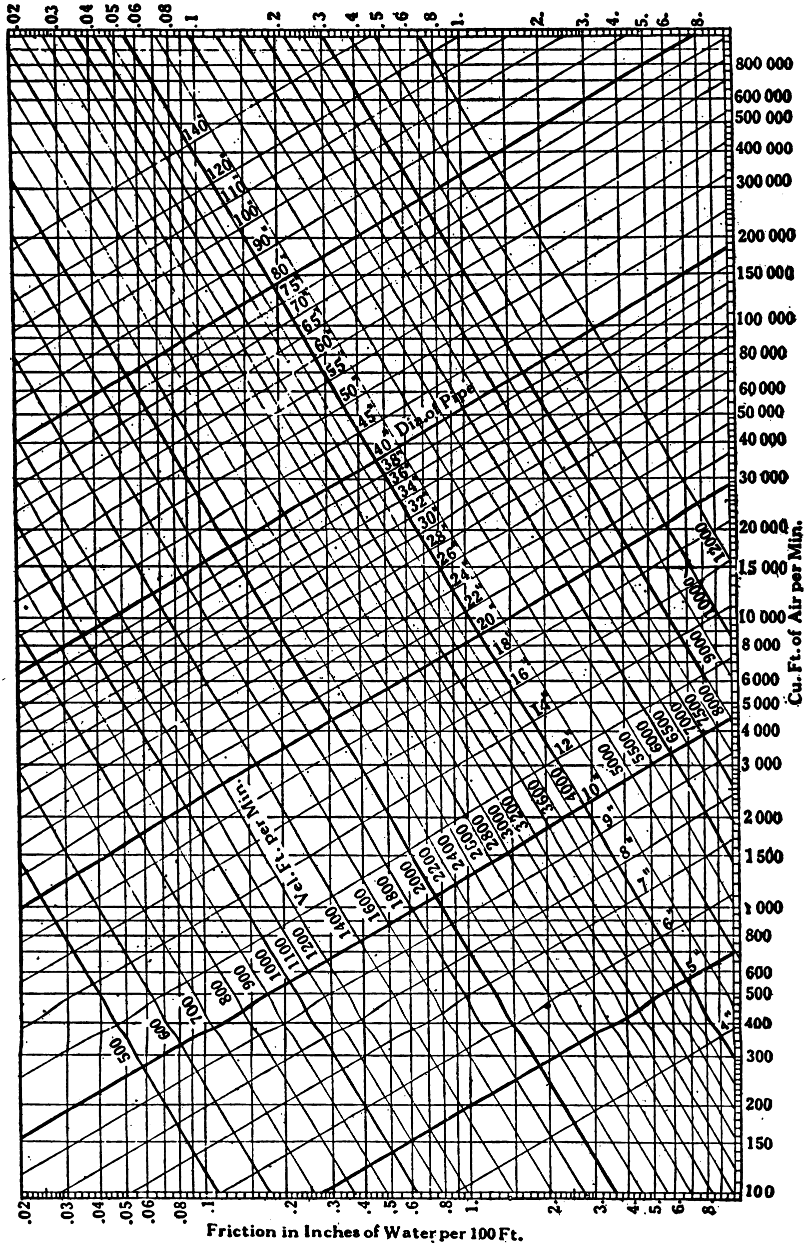

FIGURE 52.—Friction loss in air ducts.

figure 52, the friction losses per 100 feet of duct may be obtained when the duct diameter and either the air velocity or volume of flow are known.

The losses given in the above figure are for sleeve-fitted ducts and naturally include the losses at the connections due to eddy effects. An accurate formula for lengths of duct of less than 10 feet is given by Lees' equation (58) based on conditions at 70° F.[6]

$$h'_f=6.0\frac{V^2}{d}\left(0.0009+\frac{0.036}{(Vd)^{0.35}}\right)\times 10^{-6} \tag{16}$$

where h'_f represents the loss per foot of duct.

Example: Air is flowing in a smooth 6-inch diameter duct at a rate of 4,500 feet per minute. Calculate by Lees' formula the loss in 8 feet of duct and compare with the result obtained from the chart.

Solution:

$$(Vd)^{0.35}=(4{,}500\times 6)^{0.55}$$

$$0.35\ (\log 4{,}500+\log 6)=0.35\ (3.6532+0.7782)$$

$$=1.5510$$

$$\text{antilog } 1.5510=35.57$$

Hence, per foot of length, we have

$$h'_f=\frac{6.0}{6}\times 4{,}500\times 4{,}500\times\left(0.0009+\frac{0.036}{35.57}\right)\times 10^{-6}$$

$$=0.04''\ H_2O$$

For a length of 8 feet, therefore, the loss is

$$8\times 0.04=0.32''\ H_2O$$

From the chart the resistance is found to be 6.3″ per 100 feet, or 0.50″ H_2O for a length of 8 feet.

Loss at elbows

The loss of head at elbows may be expressed in terms of the velocity head. The following data, taken from A. S. H. V. E. Guide (59) may be used in determining the loss for elbows of various center line radii.

TABLE 28.—*Loss of head due to bends*

Radii in percent of duct diameter	Loss in per-cent of velocity head
50	75
100	26
150	18
200	14

---

[6] Formula has been converted from C. G. S. units to foot, pound, second units.

Loss due to sudden transition

The loss due to sudden enlargement or contraction in a duct may be computed from St. Venant's formula (60)

$$h_e = 0.064\left(\frac{V_1 - V_2}{1{,}000}\right)^2 \tag{17}$$

where V_1 is the velocity in the smaller duct and V_2 that in the larger. Values of the loss h_e in inches of water for various differences $V_1 - V_2$ are given in figure 53.

When the enlargement or contraction is gradual, the losses are greatly reduced and may be taken as approximately 10 percent of the loss obtained by the above equation.

HORSEPOWER REQUIRED

The work done by a fan is equivalent to raising the weight of the air handled per minute to a height equal to the resistance against which it must be delivered, expressed in feet of air. If, therefore, the resistance is expressed in inches of water, it must be multiplied by 69.4 which represents the equivalent of 1 inch of water expressed in feet of air at 70° F. For other temperatures the equivalent may be obtained from table 25. If h represents the total resistance against which the air must flow in inches of water and D represents the density of the air, the work done W is

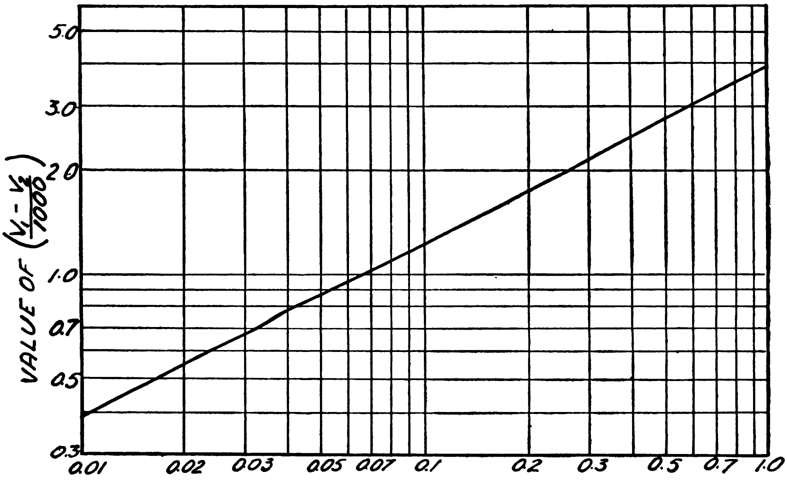

FIGURE 53.—Loss of head at enlargements in ducts.

$$W = QDzh$$

where z is the height of a column of air equal to 1 inch of water. At 70°, $D=0.075$ and $z=69.4$, hence $W=0.52\ Qh$. The horsepower is immediately determined by dividing by 33,000

$$\text{Horsepower}=0.000158\ Qh \qquad (18)$$

DUCT COMPUTATIONS

When the volume of air flow and the sizes of the ducts have been determined, and when the general plan of layout has been drawn, it then becomes necessary to calculate the losses or the total resistance against which the fan must work. Without such information, there can be no assurance that a fan will supply an adequate air flow or any method of determining the horsepower that the fan will require.

The total resistance, as has been pointed out in the previous paragraphs, consists of the losses incurred at entrance, elbows and transitions, and those due to fluid friction in straight ducts. The resistance of collectors (see sec. X), if they form part of the system, are also additive. The total losses, therefore, expressed in inches of water (sometimes ounces per square inch) are for the whole system from the point of air entrance furthest removed from the fan to the point of discharge. In rating a fan it is then only necessary to state the volume of air it must handle and the total resistance against which it must deliver. The horsepower required may be calculated by the method outlined above. It is possible, however, to obtain the horsepower and speed required for a given type of fan from the manufacturers' catalogs.

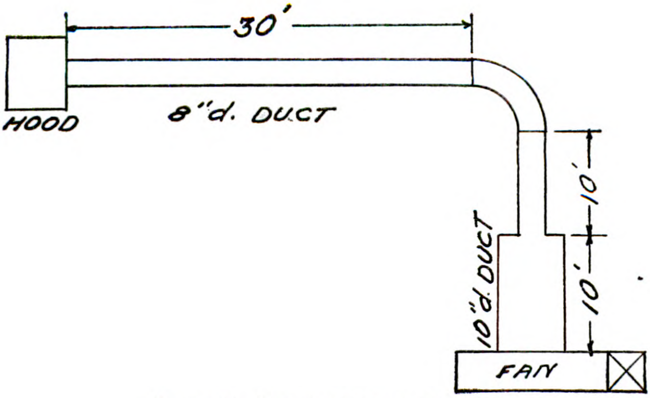

FIGURE 54.—Layout of simple duct system.

APPLICATION OF LOSS DATA

The following problem demonstrates the application of the above data and formulæ:

Given a single duct connected to an exhaust fan as shown in figure 54, determine the resistance which the fan must overcome when 1,000 cubic feet per minute of air is handled by the fan. Take the loss at entrance as 50 percent of the velocity head.

The solution may be arranged as follows:

The cross-sectional area of the 8-inch diameter duct in square feet is from table 26, 0.349, hence the velocity in the duct must be $V=1{,}000/0.349=2{,}865$ feet per minute (equation (13)). For the 10-inch diameter duct, the cross-sectional area is 0.785 square feet, giving a velocity of 1,274 feet per minute. The velocity head is, therefore, substituting for V in equation $h_v=V^2/4009^2=2865\times 2865/4009\times 4009=0.51$ inch H_2O. We are now in position to compute the losses in the duct system as follows:

1. The loss at entrance is $0.50\times 0.51=0.26$ inch H_2O.
2. The loss in an 8-inch diameter duct with an air velocity equal to 2,865 feet per minute obtained from figure 52 is found to be 2.1 inches H_2O per 100 feet of duct, approximately. For a length of 40 feet, therefore, the duct friction loss is $0.4\times 2.1=0.84$ inch H_2O.
3. The loss at the elbow with radius of curvature equal to the duct diameter is given in table 28 and is 26 percent of the velocity head—$0.26\times 0.51=0.13$ inch H_2O.
4. The loss at the enlargement can be obtained from the curve of figure 53 where $(V_1-V_2)^2/1{,}000=2{,}865-1{,}274/1{,}000=1.59$.

   Hence, the loss at enlargement is 0.16 inch H_2O.
5. Finally, we must estimate the loss in 10 feet of 10-inch diameter duct having a velocity of air flow of 1,274 feet per minute. This is found to be approximately 0.33 inch H_2O per 100 feet of duct, or 0.033 inch H_2O for a length of 10 feet.
6. The resistance which the fan must overcome is the sum of the losses in the duct system from the point of entrance to the point where the duct connects the fan, or 0.26 inch H_2O, loss at entrance; 0.84 inch H_2O, loss in 40 feet of 8-inch diameter duct; 0.13 inch H_2O, loss at elbow; 0.16-inch H_2O loss at enlargement; 0.03 inch H_2O, loss in 10 feet of 10-inch diameter duct; total, 1.42 inches H_2O loss in the whole system and resistance which fan must overcome in handling 1,000 cubic feet of air.

Loss computations in a branch system

In a multiple branch system the ducts must be proportioned to handle adequately the air flows required for each hood. The problem is, however, slightly complicated when the velocities are fixed in order that the materials collected by the hoods may be transported. While it is possible to have velocities greater than the lower limit required, it is not good practice to exceed them by a very large amount in view of the increased losses which are incurred. The following problem illustrates the procedure involved for a fixed lay-out.

Given a duct lay-out as shown in figure 55 with air flows at each hood indicated. Calculate the sizes of the ducts and the horsepower required, assuming that a velocity of not less than 3,600 feet per minute must be maintained in each duct and that the entrance losses are equal to one-half of the velocity head in the respective ducts. Assume a collector loss beyond the fan of 2 inches H_2O.

Following the general procedure given in the previous problem, and beginning with the hood *A*, we may arrange the computations as follows:

Step 1.—Since the duct velocities are fixed at 3,600 feet per minute, we have that the area of the duct *AB* is

$$\text{Area } AB = Q_A/V = 300/3{,}600 = 0.084 \text{ square feet}$$

From table 26, the duct which approximates this area has a diameter of 4 inches. The velocity head is from equation (10). $h_v = 3{,}600 \times 3{,}600/4{,}009 \times 4{,}009 = 0.81$ inch H_2O. This value of the velocity head applies to all parts of the system.

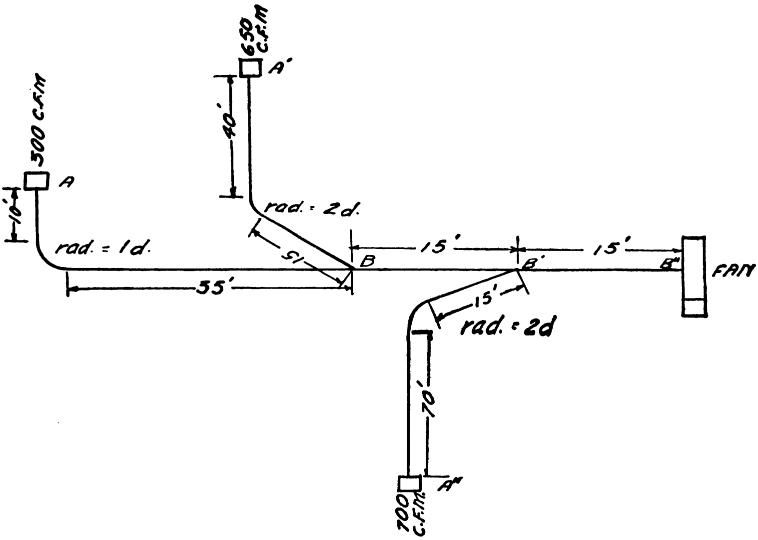

FIGURE 55.—Layout of branch system.

Considering now the losses in the duct *AB*, we have—

1. Loss at entrance $= 0.50 \times 0.81 = 0.41$ inch H_2O.

2. Loss in 4-inch diameter duct at air velocity of 3,600 feet per minute is 6.8 inches H_2O (figure 52), per 100 feet, or $0.45 \times 6.8 = 3.1$ inches H_2O for 45 feet.

3. The elbow loss is, from table 28, 0.26 $h_v = 0.26 \times 0.81 = 0.21$ inch H_2O.

4. The total resistance in the duct *AB* for a flow of 300 cubic feet per minute is, therefore, the sum of the losses $0.41 + 3.1 + 0.21 = 3.7$ inches H_2O.

This value represents the static at *B* and hence the resistance of the branch *A'B* must also be equal to the losses calculated in the branch *AB*. Otherwise the static head at *B* will have two values, which is impossible.

Step 2.—The area of the duct *A'B* is found as in the previous step. Area $A'B = Q_{A'}/3{,}600 = 650/3{,}600 = 0.18$ square foot which corresponds to a duct diameter of approximately 5.5 inches. The losses may now be computed as before.

1. The entrance loss at *A'* is $0.50 \times 0.81 = 0.41$ inch H_2O.
2. The friction loss in a 5.5-inch diameter duct with an air velocity of 3,600 feet per minute is found to be 4.5 inches H_2O per 100 feet of duct, or $0.55 \times 4.5 = 2.5$ inches H_2O for a length of 55 feet.
3. The elbow loss for a bend equal to 200 percent of the duct diameter is $0.14\ h_v$ or $0.14 \times 0.81 = 0.11$ inch H_2O.
4. The total resistance *A'* to *B* is, therefore,

$$0.41 + 2.5 + 0.11 = 2.8 \text{ inches } H_2O.$$

The resistance of the branch *A'B* is seen to be less than the resistance of the branch *AB*. Since the fan must maintain the same static at the point *B* for both branches, it is obvious that if the larger value is to be kept, the air flow in the branch *A'B* will be increased. The alternative is to cut down the diameter of *A'B* so that the resistance is equal to the branch *AB*, or to increase the diameter of *AB*. The latter, however, is not desirable since it tends to cut down the air velocity which is fixed at a lower limit of 3,600 feet per minute. In the present case, although the resistance is less than in *AB*, the increase in flow in *A'B* can be shown to be only slightly greater than the 650 cubic feet required by the hood. The approximation to the actual amount of air handled at *A'* with a static of 3.7 inches H_2O at *B* can be made as follows: Assume that the branch *A'B* handled 700 cubic feet per minute. The air velocity in the 5.5-inch diameter duct will then be $700/0.18 = 3{,}890$ feet per minute, which corresponds to a velocity head of 0.94 inch H_2O.

Proceeding as above in determining the various losses, we find loss at entrance=0.47 inch H_2O; friction loss=2.92 inches; elbow loss=0.13 inch; total loss $A'B$=3.52 inches, which corresponds closely to the loss in the duct *AB*. Thus a volume of air flow corresponding to a static head at *B* is approximately 700 cubic feet per minute. More accurately the flow is found to be 710 cubic feet per minute, but for practical calculations 700 cubic feet per minute is sufficiently accurate.

Step 3.—At the point *B*, there must be a transition to a duct which will accommodate a flow of $300 + 700 = 1{,}000$ cubic feet per minute at a velocity of 3,600 feet per minute. The area of the new duct will be, therefore, 1,000/3,600=0.278 square foot, or a duct which is 7¼ inches in diameter. The loss in friction in such a duct is 3.5 inches H_2O per 100 feet or 0.15×3.5=0.53 inch H_2O for a length of 15 feet.

The loss at enlargement is, of course, nil by St. Venant's equation. Due to the angle at which the flow from *A′B* enters, the loss is usually taken as 10 percent of the velocity head, or 0.08 inch H_2O.

The total loss *BB′* is consequently 0.53+0.08=0.61 inch H_2O. This must be added to the value of the static at *B* and hence gives the static to be maintained at *B′*; that is 3.7+0.61=4.31 inches H_2O.

Step 4.—As in the case of the branch *A′B*, the losses sustained in the duct *A″B′* must equal the static calculated at *B′*, or 4.31 inches H_2O. The procedure is identical to the preceding steps.

The duct area is 700/3,600=0.19 square foot which corresponds to a duct diameter of 6 inches. The loss calculations are then:

1. The entrance loss=0.81×0.50=0.41 inch H_2O.
2. The loss due to duct resistance for a 6-inch diameter duct with air velocity of 3,600 feet per minute is found to be 4.5 inches H_2O per 100 feet of duct or 0.85×4.5=3.6 inches for a duct 85 feet in length.
3. The elbow loss=0.14×0.81=0.11 inches H_2O.
4. Hence the total loss in *A″B′* is 0.41+3.6+0.11=4.1 inches H_2O. Since this is practically equal to the static calculated at the point B′, no corrections need be applied.

Step 5.—There remains now to calculate the loss from *B′* to *B″* and the static at the point *B″* which will indicate the total resistance of the system and the suction which the fan must maintain in order that the air flows and velocities in the various parts. Since we must have an enlargement at *B′*, we may at once calculate the area of the duct *B′B″* to accommodate an air velocity of 3,600 feet per minute. The total volume of flow in this duct is obviously the sum of the flows of the various branches, or 1,700 cubic feet per minute. Hence area *B′B″*=1,700/3,600=0.47 square feet, equivalent to a duct diameter of 9.5 inches (approximately). The losses in *B′B″* are—

1. The duct resistance loss which is found from figure 52 to be 2.7 inches per 100 feet or 0.15×2.7=0.41 inch H_2O for a length of 15 feet.
2. The loss at transition is again taken, because of the branch duct *A″B′*, as 10 percent of the velocity head, or 0.08 inch H_2O.
3. The resistance *B′B″* is, therefore, 0.41+0.08=0.49 inch H_2O. The total resistance to the point *B″* is the sum of the resistance to *B′* plus the loss in *B′B″* or 4.1+0.49=4.59 inches H_2O. This is also the static at *B″* and the suction which the fan must maintain to handle the air flows and velocities in the system.

Since the fan must also overcome a collector resistance of 2 inches H_2O, the total resistance of the system including the collector is 4.59 inches+2.0 inches or 6.59 inches H_2O. The horsepower required by the fan is, therefore, from equation (18), 0.000158×1700×6.59=1.77 horsepower.

We may recapitulate in the following table:

TABLE 29.—*Summary of results, branch system*

Duct	Volume airflow	Diameter	Resistance
	Cubic feet per minute	*Inches*	*Inches* H_2O
AB	300	4	3.7
A'B	700	5½	3.7
BB'	1,000	7¼	0.61
A''B'	700	6	4.1
B'B''	1,700	9½	0.49

NOTE.—Total resistance which fan must deliver against, 6.59 inches H_2O. Horsepower required by fan, 1.77.

Enlargements at branch connections

The above problem illustrates the need of rather extended computations in proportioning a system. It is also quite clear that the sizes of ducts must be carefully determined if proper velocities and air flows are to be maintained in the system. In the calculations given, no allowance was made for future connection or disturbances in air flow which might occur in case one duct or more was cut out of use. Under such circumstances the system should be layed out with all probable connections to be made, and the duct sizes computed on this basis, remembering at all times that velocities in the ducts should with one or more hoods out never get below the limiting transport velocities.

It is necessary to point out that some States require that when a branch duct enters a main, the area of the main duct shall be increased from 10 to 25 percent of the combined areas of both. This rule must be followed, although it is actually not required in a well-designed system. Excess enlargements naturally call for larger air volumes through the hoods in order that adequate velocities may exist.

GENERAL RULES FOR CONSTRUCTING EXHAUST SYSTEMS

The following general rules should be observed in the construction of an exhaust system:

1. The main trunks and branch pipes should be straight, strongly supported, and with the dead ends capped to permit inspection and cleaning when necessary. All branch pipes should join the main at an acute angle, the junction being at the side or top and never at the bottom of the main.

2. Clean-out ports having suitable covers should be placed in the main and branch pipes so that every part of the system can be easily reached in case the system clogs.

3. Elbows should be made at least two gages heavier than straight pipe of the same diameter to enable them to withstand the additional wear caused by changing the direction of flow. They should preferably have a throat radius of at least 1½ times the diameter of the pipe.

4. Every pipe should be kept open and unobstructed throughout its entire length, and no fixed screen should be placed in it.

5. The passing of pipes through fire walls should be avoided whereever possible.

6. All permanent circular joints should be lap-jointed, riveted, and soldered, and all longitudinal joints either grooved and locked or riveted and soldered. Every change in pipe size should be made with an eccentric taper flat on the bottom, the taper to be at least 5 inches long for each inch change in diameter.

IX. EXHAUST VENTILATION IN PRACTICE

The methods of dust prevention vary widely even when identical operations are involved. Each plant in controlling its dust hazards generally applies such methods as it finds best fitted to its particular lay-out. Economic and mechanical factors are also important considerations which result in a diversity of type and construction of preventive equipment. Thus, with few exceptions, information with regard to the performance of various equipment is confusing and renders a comprehensive treatment of preventive methods difficult to accomplish. At the same time, it must be stressed that extensive efficiency data are lacking. This lack may be partially attributed to the reasons stated above, but it especially is due to the fact that methods of testing control equipment as described in section V have not been generally used. The present section, therefore, attempts only to supply information regarding the control of dust in operations which are widely used and for which some data are available.

EXHAUST VENTILATION IN THE GRANITE INDUSTRY

The introduction of pneumatic cutting tools has done much to increase the severity of dust exposure in the industries using them. This has been the case in the granite industry where hand pneumatic tools and pneumatic surfacing machines contribute the maximum dust concentrations.

Reference to table 3 shows that the pneumatic tools create the maximum amount of dust.

Pneumatic hand tools in the granite industry are used for practically all detail work. The tools employed vary in size depending on the type of work done. They are guided by hand over the stone surface and usually demand close attention of the operator whose breathing level ranges from 6 to 15 inches above the tool. Under such conditions it is difficult to control dust without causing some interference in the work performed.

The surfacing machine is used only for bringing the rough stone to a plane surface. The tools used in this machine are larger than the hand pneumatic type. They are graded in size so as to bring the stone surface to any degree of smoothness. The tools are driven by a large pneumatic hammer attached to a horizontal beam which swings about a vertical column which may be raised or lowered to accommodate stones of various sizes. The machine is heavily built and secured.

In operation the hammer and tool of the surfacing machine are guided over the stone by an operator. The amount of dust generated varies with the type of hammer and tool employed; the concentration being a maximum for a four-point tool, decreasing with the fineness of cut.

It is obvious from the foregoing discussion that the control of dust generated by the hand pneumatic tool and surfacing machines must be flexible. In the former, because the worker must cut on stones in vertical and angular positions, it is extremely difficult to secure adequate control at all times. The general method used consists of connecting a flexible hose to the exhaust system and placing the hood in a position offering the least encumbrance to the worker. As may be judged, however, the success of the method depends upon the care with which the worker places the hood; if it is too far from the work being done, it clearly cannot function properly. With surfacing machines, on the other hand, the hoods were formerly placed on the stone and because of the inconvenience incurred, frequently were not moved although the tool would be operating at a considerable distance from them. The exhaust system consequently failed to function efficiently because it was not properly utilized.

The manner of testing pneumatic cutting tools has been indicated in section V. The results obtained by Bloomfield (47) in comparing the dust concentrations in plants with and without local exhaust systems have shown that, for ordinary operations, effective control of the dust generated can be achieved when the exhaust velocities at the hood were kept above 1,500 feet per minute.

The basic fundamentals of hood design presented in part VII are useful in assisting the engineer to estimate a priori the probable performance of an exhaust system. This has been done to a certain extent in the case of granite cutting. Thus, Hatch, Drinker, and Choate (55) applying the methods given in the above chapter were enabled to deduce the fact that, regardless of hood shape, approximately 200 feet per minute are required about the surfacing tool in order to reduce the dust concentration at the worker's breathing level to an estimated safe limit of 10 million particles per cubic foot. The same investigators analyzed the characteristics of a large variety of hoods connected near the pneumatic surfacing tool until one was devised which adequately controlled the dust generated with a minimum amount of hindrance to the work and with low cost of operation. The hood finally designed by these investigators is shown in figure 56. It comprises a rectangular opening with a semicircular barrier to limit the scattering of particles. With the tool in position within this barrier, a minimum flow of about 320 cubic feet of air per minute is required to keep the dust concentration below 10 million particles per cubic foot under normal conditions of operation. The hood is mounted on a carriage holding the cutting tool and connected by means of a flexible duct to an exhaust system. In this way, the hood constantly embraces the cutting tool as it moves over the stone surface.

It is interesting to point out that the study of various hoods used in granite cutting made by Hatch et al., shows that a velocity at the opening which will control the dust generated is approximately 1,500 feet per minute, or the amount specified by Bloomfield in his study above referred to.

CONTROL OF DUST IN ROCK DRILLING

In order to cope with the dust produced in rock drilling, particularly in foundation and tunnel work, special dust traps have been devised.

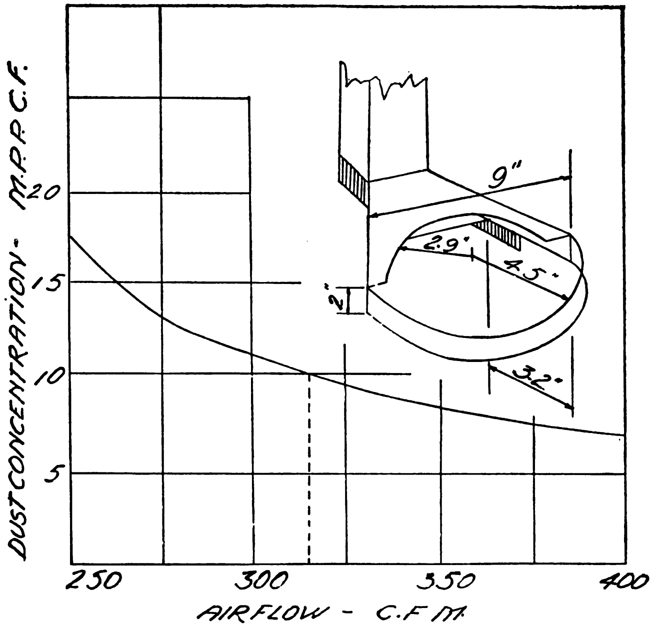

FIGURE 56.—Characteristics of hood used for granite-surfacing machine.

In form these traps are similar to the Hay (61) trap with the exception that, whereas the latter utilizes the suction formed by an ejector connected to the drill exhaust, the new devices are connected to powerful exhaust fans.

The essential requirements of a dust trap have been described by Hatch and his coworkers in a series of articles pertaining to the control of dust in rock drilling (62, 63, and 50). Figure 57 shows the type of trap investigated by the above workers in connection with downward drilling operations in foundation work. The drill is inserted in a hole at the top and the exhaust is applied at the 2-inch connection indicated. About 60 cubic feet of air per minute are required to maintain a low dust concentration, the air passing along the uneven surface of the rock and through the drill hole, thus making an air trap. The dust collected passes through the exhaust ducts to a separator and bag filter of high efficiency. In actual operation, a convenient pipe-exhaust system is installed with a number of manifolds for trap connections.

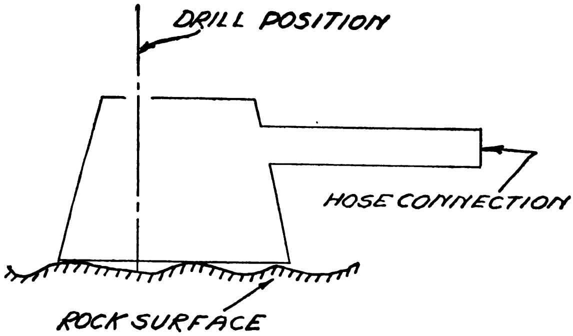

FIGURE 57.—Kelley trap for rock drilling.

The air flow of 60 cubic feet per minute necessary represents a static suction at the trap of only 0.8 inch of water. However, there is considerable loss of pressure in the hose connecting the trap with the exhaust manifold. The suction required at the manifolds for hoses of various lengths have been determined and are presented in the table below.

TABLE 30.—*Static suction at manifold required for various lengths of 2-inch flexible hose with air flow of 60 cubic feet per minute*

Length of hose	Static suction required at manifold (inches H_2O)	Length of hose	Static suction required at manifold (inches H_2O)
25 feet	3.5	75 feet	10.5
50 feet	7.0	100 feet	14.0

In any design, therefore, it is necessary to provide adequate suction at the manifold to take care of the longest length of hose to be used. It is further important to allocate the manifolds at the most advantageous points to take care of the progress of drilling operations.

For vertical or horizontal drilling, Hatch has described special adapters for placing the trap in any position (50), (fig. 58). Under such circumstances air flows of the order of 200 cubic feet per minute have been recommended to keep the dust concentration below 10 million particles per cubic foot.

The proper disposal of collected dust is also important. This is particularly true in tunneling and consequently provision must be made to collect the dust efficiently in order to render the tunnel air safe to breathe. It is further necessary that any collecting device used should be easily moved and compact.

In collecting the dust conveyed by the exhaust system, a collector was employed which consisted of two stages (63)—a preliminary sedimentation chamber and cloth screen filters. In the former, the dust was blown into a bell-shaped entrance where part of the dust was thrown out by inertial force. The air then passed through a baffle arrangement at low velocity causing further separation and thence to the cloth screens. The filtering was conducted at a rate of 3 cubic feet per square foot of filter surface. The total filter area was 1,000 square feet and the complete collector unit was capable of handling the dust from a maximum of 60 drills. The amount of dust varied from 1.5 to 4 tons per day, giving an overall collecting efficiency of 99.7 percent.

The use of the trap was shown by Hatch and his associates to increase the speed of drilling from 11 to 21 percent, while the cost of operation was estimated at $2.21 per day or 1.05 percent of the cost of removing a cubic yard of stone (63). In view of the increased rate at which drilling can be done with a trap for only a slightly greater cost per cubic yard removed, it may be seen that not only are hygienic conditions improved, but the speed of drilling has been increased at only a slight additional cost.

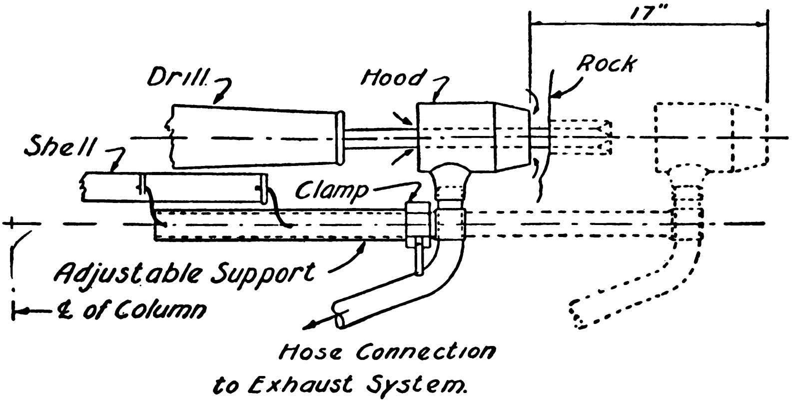

FIGURE 58.—Modified Kelley trap for drilling vertical rock face.

CONTROL OF DUST FROM GRINDING, POLISHING, AND BUFFING WHEELS

Exhaust systems for grinding, polishing, and buffing wheels vary widely in design. In the case of grinding, the hoods used serve not only to provide a means for capturing the dust, but also act to protect the worker in case the wheel bursts. For the prevention of accidents due to the bursting of high-speed grinding wheels a special code covering the requirements of hood construction has been written (64). With regard to polishing and buffing wheels, which must be adapted to handling intricate parts, the hoods used assume a wide variety of shapes.

The chief difficulty to be overcome in grinding wheels is the outward sweep of air, a fan action, due to the revolving wheel. This effect is very marked with high speed and rough wheels, and is so strong that in many instances it is sufficient to counteract the normal inward flow of air. The same effect exists with polishing and buffing wheels, but to a less marked degree.

Practically all industrial States have codes regulating the construction and duct connections for grinding, polishing, and buffing wheels. They also regulate the air required for wheels of various sizes in terms of static suction in the connecting duct. These codes, however, possess no uniformity as may be seen from citations taken from the existing codes for Wisconsin and New York, as follows:

The Wisconsin code requires that—

> On all grinding, buffing, and polishing wheels, the suction at the connection to the hood must be sufficient to displace a column of water in a U-tube, 5 inches.

The New York code reads:

> Sufficient static suction shall be maintained in every branch pipe within 1 foot of the hood to produce a difference of level of at least 2 inches of water between the two sides of a U-shaped tube.

The requirements designated by State codes must be followed. Typical size connections for grinding and buffing wheels required in many States are given in table 31.

TABLE 31.—*Size of connections for grinding and buffing wheels*

Diameter of wheels	Maximum grinding surface	Minimum diameter of branch pipes
	Square inches	*Inches*
Grinding:		
6-inch or less, not over 1 inch thick	19	3
7- to 9-inch, inclusive, not over 1½ inches thick	43	3½
10- to 16-inch, inclusive, not over 2 inches thick	101	4
17- to 19-inch, inclusive, not over 3 inches thick	180	4½
20- to 24 inch, inclusive, not over 4 inches thick	302	5
25- to 30-inch, inclusive, not over 5 inches thick	472	6
Buffing:		
6-inch or less, not over 1 inch thick	19	3½
7- to 12-inch, inclusive, not over 1½ inches thick	57	4
13- to 16-inch, inclusive, not over 2 inches thick	101	4½
17- to-20-inch, inclusive, not over 3 inches thick	189	5
21- to 27-inch, inclusive, not over 4 inches thick	338	6
27- to 33-inch, inclusive, not over 5 inches thick	518	7

Table 32 shows the amount of air handled by grinding wheel hoods with connections of various sizes. The effect of suction is clearly indicated. Thus, a duct connection 3 inches in diameter with 2-inch static suction handles only 0.63 the amount of air as when supplied with 5-inch suction. In other words, the volume is proportional to the ratio of the square roots of the static suction $\left(\sqrt{\frac{2}{5}}=0.63\right)$. At the same time, the increased static implies a higher velocity and a subsequently greater resistance in the duct connection. With 2-inch suction on a 3-inch diameter connection, the air velocity is 4,012 feet per minute while with 5-inch suction it is 6,354 feet per minute; if the resistance is assumed to vary as the square of the velocity, the resistance in the case of the higher velocity is approximately 2½ times that at the lower. Obviously, good design would call for a larger duct connection in the latter instance in order to offset the increased losses. On the other hand, since a 5-inch suction must be maintained in accordance with some State codes, the volume is increased with a larger duct connection and any gain thus obtained is nullified. For example, a suction of 5 inches in a 3-inch diameter duct connection is equivalent to 197 cubic feet per minute; in a 4-inch diameter duct, the volume of flow would be equivalent to a suction of 2½ inches. It is clear, therefore, that the ventilation performance of hoods (at least for the purpose of efficient design) should be based on the air volumes handled and not upon a rigid suction standard. These volumes, of course, should be established by experiment as the most effective for controlling the dust generated. These in turn should take into account the quality, size and speed of the wheel used, the type of hood with which it is fitted and the character of the work done.

TABLE 32.—*Cubic feet of air handled per minute through average grinding wheel hoods*

[Based on restriction coefficient of 0.71]

Diameter of connecting duct	Suction at throat—inches water gage						
	1	1½	2	2½	3	4	5
2 inches	62	76	88	98	107	124	139
2½ inches	97	119	146	153	168	195	216
3 inches	139	171	197	221	242	278	312
3½ inches	190	232	269	300	329	380	424
4 inches	248	304	351	392	430	497	554
4½ inches	314	384	444	496	542	627	705
5 inches	388	475	550	615	675	775	878
6 inches	558	683	789	881	968	1,117	1,250

At the present time, little data are available with regard to the amount of dust generated with and without ventilation. In table 33 are given a number of results taken from a recent Russian publication.[7] No data regarding the speed of the wheels are available; however, the effect of ventilation is clearly in evidence.

In passing, it is interesting to note that although codes regulating the design and construction of grinding wheel hoods are perhaps the oldest specific legislation relating to the control of industrial dust in this country, no basic data pertaining to their actual requirements have ever been obtained.

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[7] Awerjanoff, A. G., and Gurwitsch, B. I.: The Ventilation of Industrial Establishments, vol. V, no. 6. The Ventilation Equipment of Industrial Plants and its Effective Operation. (Works of the Leningrad Institute of the Government and Protection of Labor.)

Table 33.—*Dust collecting efficiencies of grinding and polishing wheels*

Type of wheel	Type of work done	Dust formed	Air flow (cubic feet per minute)	Dust concentration without ventilation (mg/m³)	Dust concentration with ventilation (mg/m³)
Emery, 8-inch diameter (approximate).	Surgical tool finishing.	Emery and metal.	270	21.4	5.55
Do	Tool finishing	do	270	5.7	0.8
Do	do	do	220	19.5	2.5
Do	do	do	220	21.5	3.9
Emery, 27-inch diameter (polishing)	Mirror grinding	Emery and glass.	670	178.2	5.3

FOUNDRY SHAKE-OUT EXHAUSTS

One of the serious occupational disease hazards encountered in industry is the dust arising from foundry shake-outs. Few installations have been generally successful. The problem in this case is to have available means for eliminating the dust during shake-out of molds containing fresh castings. The usual process employed is to knock the flasks containing the mold and castings with sledge hammers to pry them loose. In some instances, this is done in places known as shake-out dumps, but more often it is done wherever the casting happens to be. Large castings containing considerable hard

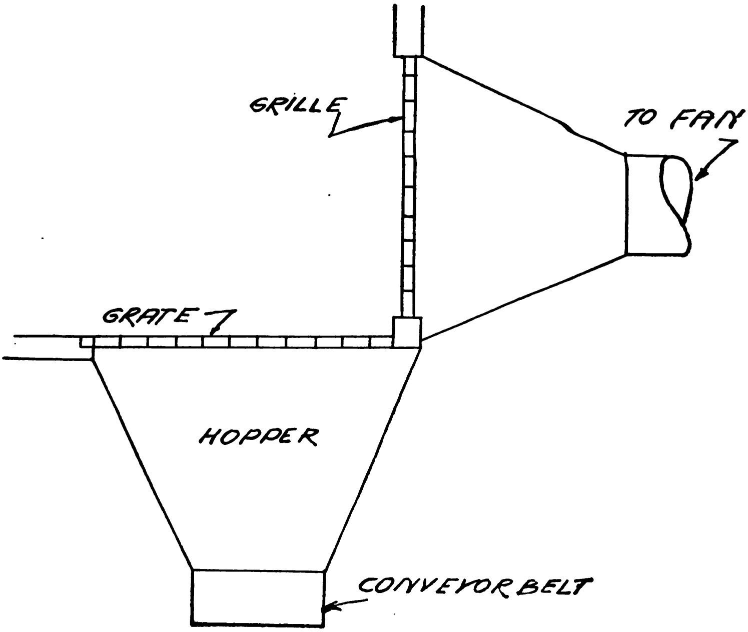

Figure 59.—Lateral exhaust at foundry shakeout.

core work, present serious difficulties and frequently cannot be brought under the control of an exhaust system. The worker is in such close contact with the dusty atmosphere as to cause serious exposure. In addition, this type of work is not generally isolated, and gives rise to a very general exposure which may involve all workers employed in the foundry.

Two systems of exhaust have been employed to cope with the problem. These may be roughly described as the lateral and the combined lateral and down-draft system. In the first type of system, air is drawn through a grill near which the castings are placed (fig. 59). The bulk of the molding sand passes into a hopper which is generally equipped with a conveyor, but as may be expected, considerable sand as well as dust enters the ventilating ducts which seriously burdens the collecting devices and cause considerable wear on all parts. The method is, however, desirable where small castings are to be shaken out and when no large accumulation of molding sand is permitted. The second method, shown in figure 60 consists of a similar grating and hopper for placing the casting but utilizes downward as well as lateral exhaust.

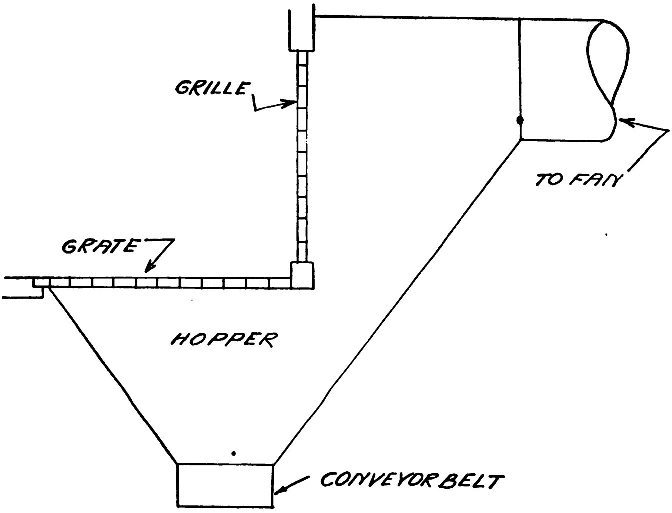

FIGURE 60. Combined lateral and downward exhaust at foundry shakeout.

There are no set air flows which have been determined for either type of control. A determination made of one type of lateral exhaust 5 by 7 feet in area which came flush with the edge of the grating had a velocity of approximately 350 feet per minute in the plane of its opening. This was in a brass foundry where the castings were small. The control, however, was excellent.

A fault of all such large exhaust systems, particularly in foundry practice, is the exposure of the workers to detrimental drafts. This is particularly true in winter when the men are first subjected to the heat from their castings which cause sweating and then are subjected to a cold air movement at the shake-out. As a rule, foundries are seldom heated in winter, and this consideration is one of extreme importance. On the other hand, the advantages are beneficial; an exhausted shake-out tends to localize a dangerous operation and at the same time gives protection to all those exposed to the dust which is generated.

Another difficulty which is common to the grate system of shake-outs is the rapid accumulation of molding sand. Hard cores and chunks often fail to pass through the grating or the rate of dumping exceeds the capacity of the hopper and conveyor to remove the sand. This is a strong argument against the use of a downward-draft system in many foundries which is not easily overcome.

It is extremely doubtful that any method of local exhaust ventilation can be used for castings of extremely large size. The core work frequently encountered in such castings is so closely bound with rods that it is necessary to resort to jack hammers to remove them. Moreover, the difficulties of removing the castings and placing them on the grate are prohibitive. In such cases other methods must be used for the protection of the worker.

DUST CONTROL FOR ABRASIVE CLEANING EQUIPMENT [8]

Abrasive blasting equipment may be roughly divided into four types—namely, rooms, barrels, tables, and cabinets. These four different types of equipment may be classified more simply by stating that rooms are used for the cleaning of large castings, whereas the other three types of apparatus are used to handle material of small size in large quantities.

Blast cleaning rooms

Blast cleaning rooms, are as a rule, constructed of heavy metal plate and the most commonly used size is 10 by 10 by 8 feet. In the more modern type of rooms air is allowed to enter through the ceiling and is exhausted through metal ducts on the sides of the room at the floor level. The material to be cleaned is brought into the room, either on a revolving table or by cars or monorail. When the doors of the workroom are closed, the operator in order to protect himself from the impact of the abrasive and also to prevent inhalation of excessive dust, places a respirator or cloth over his nose and mouth and some form of a canvas helmet over his head. In some cases, positive-air pressure helmets are used. These are provided with a

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[8] Unpublished data J. J. B.

supply of fresh air obtained outside the blast cleaning room and delivered under pressure to the helmet. It is also necessary for the worker to wear heavy gloves to protect his hands from the impact of the abrasive, and at times he wears canvas leggings and shoes provided with metal toe caps as protection for his legs and feet. With the blast hose in hand, he directs the abrasive stream against the surface of the work, the hose being of sufficient length to allow him freedom of movement so that he may direct the blast against any part of the work.

To provide the abrasive jet a pressure tank, known as the "hose machine", is used. This, or a similar piece of apparatus, is the fundamental unit of all room blast cleaning equipment. In this machine the compressed air and the abrasive are combined and discharged together from a single nozzle or a group of nozzles in the form of the abrasive blast.

After the abrasive has once served its purpose it is returned through a proper separator to the hose machine for re-use. This abrasive handling is accomplished by one of several systems, depending on the type of installation. With the mechanical lift system, the abrasive falls through openings in the floor to a hopper below, where it is picked up by a spiral conveyor and carried to the boot of a belt-and-bucket elevator, which in turn raises it to the separator. The separators are a combination of screens and air exhaust, by means of which the heavier particles are separated and the lighter material is drawn off by suction. The clean, sharp abrasive for re-use is delivered to a storage bin, from which the hose machine is automatically refilled. The rejected material and refuse is accumulated in a separate bin provided with a spout for unloadings.

In some installations it is necessary to have a solid room floor, in which case the operator at intervals, shovels the used abrasive into a hopper from which it is raised by a belt-and-bucket elevator to an overhead separator. This system is known as the "semimanual" type.

Where it is practicable and desirable to locate the hose machine in a bin beneath the room no abrasive handling system is necessary since the spent abrasive is allowed to fall by gravity through a hopper to the hose machine below it. This type is known as the "gravity system."

In the pneumatic lift system, the abrasive, after passing through the floor perforations, falls into the air current of a pneumatic lift, which raises it by suction to the separator.

Practically all blast cleaning rooms now in use have provisions for ventilation. In some of the more modern installations, the exhaust air, after passing through dust arrestors where it is cleaned, is delivered back into the workroom in order to save its heat content and to provide ventilation.

The correct amount of ventilation required in abrasive cleaning rooms has not been determined. Older types utilize from 2 to 5 air changes per minute, while the more recent types use from 8 to 12 and sometimes as high as 20 air changes per minute. From a number of observations made in recent types of abrasive cleaning rooms it appears that air movements at the breathing level bear no relationship to the dust concentrations found. For example, a high dust count of 251 million particles per cubic foot was obtained with a velocity of 74 feet per minute at the breathing level, whereas a velocity of 75 feet per minute was associated with 171 million particles per cubic foot, and a velocity of 77 feet per minute with a dust count of 48.8 million particles. In all these cases metallic grit was used as the abrasive. The variation in counts with practically the same air movements in the abrasive cleaning rooms may be ascribed to differences in nozzle pressure, to the cleanliness of the castings, and to the rate at which the work is being done.

The above results may be contrasted with a velocity of 68 feet per minute in an abrasive cleaning room using sand, and yielding a high dust count of 620 million particles per cubic foot. From such data, it would naturally appear that when more than eight air changes per minute are provided, the abrasive used plays an important part in the dust concentration to be expected, and is apparently much more important than the amount of ventilation provided.

The low value of 48.8 million particles per cubic foot cited in a previous paragraph, was found for an abrasive room of modern construction with 12 air changes per minute. It is clear, therefore, that in spite of the best equipment available, it is essential that other methods (personal respiratory protection devices) be used to prevent exposure of the blaster to rather high dust concentrations.

The conduct of work in abrasive cleaning rooms may contribute a considerable quota of dust to the general amosphere of the plant in which the room is situated. Naturally the dust introduced by this means may have an important bearing on the health of workers not specifically engaged in abrasive blasting occupations. The need for maintaining abrasive rooms in good condition is evinced from an analysis of data which show that with average equipment, workers in the general air of a plant in which abrasive cleaning is done may be exposed to concentrations which may run as high as 20 million particles per cubic foot during blasting, while when no blasting is done, the average concentration is normally below 4 million particles. The modern type of abrasive cleaning room is, on the other hand, so constructed that unless it is poorly maintained no dust can possibly escape. Obviously, dust-tight and well-maintained abrasive cleaning rooms are methods of eliminating a considerable portion of the dust which is found in many plants.

Blast cleaning barrels

Blast cleaning barrels are often confused with the "tumbling mill" or barrel as a method of cleaning. The principles on which these methods depend are entirely different. In the "tumbling barrel" cleaning is accomplished by the abrasion of the objects to be cleaned against each other or against a given abrasive which is dumped into the barrel, whereas in the blast cleaning barrel the cleaning is accomplished by the abrasive blast, the rotation of the barrel serving merely to bring the metal objects under the abrasive blast streams. Various types of blast cleaning barrels are in use. In general, a blast cleaning barrel consists of a drum made of heavy sheet plate, mounted as a rule on trunnions and capable of rotating. A rather common type now in use consists of a properly fashioned, movable series of plates driven by a chain drive, and so arranged that the work is constantly carried on this endless belt.

There are various types of blast cleaning barrels, all of them differing in the method of abrasive handling and reclamation. The three most common abrasive handling methods in blast cleaning barrel installations are the suction, pressure, and gravity types.

Some blast cleaning barrels are provided with a complete outer housing which encloses the barrel while in operation. During loading the door of such a housing is opened, the barrel door is then opened and the material to be cleaned is placed in the barrel. Both doors are then closed and the air jets set into operation. Such a housing may be, and often is, provided with exhaust ventilation. In many cases the barrel is not provided with a complete outer housing.

As a rule the use of abrasive blast cleaning barrels constitutes a small portion of the chain of processes in the course of the manufacture of certain articles. For this reason barrels are usually located in one portion of the plant or foundry where the material to be blasted is made. In other words, barrels are not generally segregated from other dusty processes. Thus, it is necessary to bear in mind that adjoining processes may possibly contribute a certain amount of dust to the atmosphere in which the attendant works.

The advantage of housing is clearly demonstrated in the following data obtained from a series of dust counts made on various equipment in use:

	Million particles per cubic foot
Barrel using metal abrasive and housed	6. 2
Barrel using sand abrasive and housed	2. 2
Barrel using metal abrasive and not housed	24. 6
Barrel using sand abrasive and not housed	38. 0

The discrepancy in counts for metal and sand abrasives in barrels which are housed is due to design factors in the equipment studied. However, it is evident from the data presented that unhoused barrels are productive of rather high concentrations of dust.

In the handling of fresh castings, especially while loading the barrels, considerable dust is evolved. The dust, thus formed may be reduced somewhat by the use of chain-hoist loading skips and a certain degree of care on the part of the barrel attendant. During the unloading operation, similar care should be exercised so as to prevent the dissemination of dust from the abrasive admixed with the castings. The most important source of atmospheric pollution however, in connection with blast cleaning barrels is that dust which emerges from the openings in the barrel structure. Such openings are provided to a small extent by poor design and to a greater extent by poor maintenance of equipment.

Blast cleaning rotary tables

For certain types of work, it has been found efficacious to use the rotating blast cleaning table method. These tables are of a heavy metal, substantial type of construction; are circular in shape and of an average diameter of 6 or 7 feet, mounted usually about 3 feet above the floor level and rotating at a speed of 1.5 revolutions per minute. The table is divided into two halves by means of a series of flexible, split rubber curtains. One side of the table is completely enclosed, and is provided with three or more traveling nozzles for directing the abrasive onto the work lying on the surface of the table below. At the other half of the table is stationed a worker, whose function is to remove the finished objects, to replenish the supply of work to be done, and to turn over the objects on the table so that the under surface may be blasted. The abrasive is, as a rule, delivered against the objects at an air pressure of 60 or more pounds to the square inch. With such tables the abrasive reclamation is accomplished by either suction, gravity, or pressure methods.

With reference to abrasive cleaning tables, the remarks made in connection with abrasive cleaning rooms apply to a large extent. Well constructed and maintained tables permit little dust to escape. For example, a poorly maintained table, using metal abrasive, gave dust counts of approximately 42 million particles per cubic foot of air in the general air close by, whereas another table of good construction, using sand, gave dust concentrations below 3 million particles. These results so clearly emphasize the importance of proper care and construction of abrasive cleaning equipment that they should be carefully noted.

Blast cleaning cabinets

For special kinds of work, where it is necessary to clean small objects using air pressures of 60 pounds or more, the blast cleaning cabinet finds much use. Blast cleaning cabinets are of steel plate construction usually approximately 5 by 3 and 7 feet in height. They are, as a rule, provided with a single nozzle through which the abrasive material is forced by means of air pressure. In the front of the cabinet, there is usually provided a window of heavy plate glass, through which the operator may view the work in progress. Also in front of the cabinet there are hand holes through which the worker places his hands and arms in order to manipulate the work. The material to be cleaned is placed inside the cabinet through a hinged door, located at the front or side of the cabinet. The operator then turns on the abrasive jet by means of a foot treadle. The worker exposes all surfaces of the object to be cleaned to the action of the jet and removes the piece on completion of this task. As a rule, most cabinets of this type are provided with an exhaust system for the removal of the fine dust created in the blasting process. The abrasive reclamation employed with cabinets is either of the suction or pressure type.

It is possible to conduct abrasive cleaning in properly designed and well-maintained cabinets with a low dust exposure. It is necessary, however, to point out the important part played in dust control by proper operation of equipment. In many cabinet installations, the hand holes are provided with gauntlets and a separate opening is furnished by which work may be introduced and removed. Such an installation would be considered excellent from the point of view of preventing the pollution of the atmosphere by dust. On the other hand, where gauntlets or curtains are not provided for the restriction of the hand hole openings, it becomes possible for dust to be deflected from the inside of the cabinet through these holes, and contaminate the workroom air. Hand holes, therefore, should be as small in size as compatible with the tasks to be performed, and suitable exhaust ventilation (5–10 air changes per minute) should be provided, in order to minimize the possibility of dust being forced outward through the hand holes.

Automatic blast cleaning equipment

In the blast cleaning of certain large objects ordinarily conducted in rooms, it has been found convenient and desirable to conduct the cleaning operations without the intervention of a worker for the manipulation of the object to be cleaned. Usually this is accomplished by what is known as automatic blast cleaning equipment. The work is placed on a belt conveyor by a "loader", the work passing through the blasting chamber or room where it is cleaned by the abrasive stream. The material emerges in the cleaned state on the endless belt at the exit side of the room where it is removed by a worker.

Automatic abrasive cleaning equipment obviously provides an excellent means for cleaning certain articles too large to be handled by table or barrel equipment. Here again, however, the importance of proper design and upkeep of this type of equipment must be stressed in order to prevent excessive dust exposure of the operators. Housings should be of sufficient length and baffled so as to prevent the egress of dust. Thus, it has been found that old automatic equipment without proper care may expose the operator to concentrations of approximately 90 million particles per cubic foot of air, while newer types of equipment reduce the dust concentration to about 5 million particles.

Tumbling barrels

Tumbling barrels are frequently the source of high dust concentrations. As a general rule, State codes provide that such apparatus shall be exhausted and that a stated suction shall be maintained at the duct connection. Most of the modern equipment is now so constructed that there is little opportunity for the dust to escape. Thus in comparing the new with the old type barrels, the former gave rise to a dust concentration in the general plant air of 2.7 million particles per cubic foot, while the latter averaged 34 million particles. As may be expected, however, the care given the equipment is an important factor in its performance.

HOUSEKEEPING

Good housekeeping is an important aid in reducing dust concentrations. The dust collected on floors, benches, rafters, etc., should be removed at frequent intervals. Either wet sweeping or vacuum cleaning should be used. Good housekeeping not only serves to remove sources which contribute to the general dustiness of a plant, but also adds an important psychological factor. A clean workplace not only tends to keep clean, but frequently compels some method of control to be applied to those sources which are dustiest.

AIR VELOCITY REQUIREMENTS FOR HOODS

The required air velocity at a dust source is determined by the characteristics of dust production and operation of the process. The friction on the surfaces of the particles created by the moving air must be sufficient to overcome the force with which the particles are thrown off. This force is a function of the size, shape, and weight of the particles and their speed of travel. Heavy particles require a higher air velocity than light ones, and the air speed increases with the velocity of the dust particles.

In many instances, the machine throws off the dust in a well-defined direction. This fact should be utilized in shaping and locating the hood, since it has an important bearing on the strength of the air stream required. It is well illustrated in the application of exhaust hoods to high-speed grinding wheels.

The use of partial or complete enclosure of the point of dust generation offers an effective means of reducing the air velocity requirement. The speed of travel of the dust particles may be reduced and their direction changed by the proper location of baffles or housing. This phase of hood design is limited chiefly to processes that do not require close attention of the operator or delicate manipulation. The trap for use with rock-drills is an example of complete enclosure and the application of partial enclosure is illustrated by the hood used on granite surfacing machines. Many examples of partial and complete enclosure are found in the woodworking industry.

The characteristics of operation of the dusty process must be carefully studied and every possible step taken to reduce the air velocity required to capture the dust. In general no other phase of hood design will give as great a saving in operating cost as reduction in the required air speed.

RATE OF AIRFLOW REQUIRED

The air velocity at a given point in the zone of influence of a suction opening is a function of the rate of airflow through the opening, but also of the direction and distance from the opening, and the shape and size of the exhaust hood. Hence, the rate of airflow through the hood, necessary to produce the required air velocity at the point of dust generation, depends upon the size, shape, and location of the hood, as well as the characteristics of dust production. It follows, therefore, that some knowledge of the aerodynamic characteristics of suction openings is necessary to the proper choice of hoods if economic design is to be obtained. The airflow characteristics discussed in section VII are important in this connection.

The rapidly decreasing center-line velocity curves presented in figure 38 show clearly the need for locating the hood as closely as possible to the point of dust generation. This is a general rule, and is applicable to all conditions. It is important to note, however, that the rate of decrease of velocity with distance from the hood decreases with an increase in area of the opening. Moreover, the contour lines become more flattened as indicated in figure 42. These facts point to the desirability of using as large an opening as possible which has the further advantage of reducing the power consumption by lowering the entrance pressure loss.

The area of dust production must also be considered in choosing the size of the hood opening. For a concentrated point of dust generation, a flat velocity contour is not as necessary as for more extensive areas of dust generation. In all cases, the object is to obtain a uniform air velocity over the region of dust production, and the lowest possible flow from areas of no dustiness, the so-called ineffective areas. In other words, the ratio of effective to ineffective flow should be made as high as possible. Since the distribution of flow in the zone of influence of suction openings is intimately associated with the size and shape of the opening, great care must be exercised in choosing a hood to give a high ratio of distribution in effective to ineffective areas. In this connection, the use of flanged openings is often advantageous. The use of flanged exhaust hoods on hand pneumatic granite carving tools (55), in place of unflanged openings, demonstrates the saving in power consumption possible. For this process an air velocity of 200 feet per minute at the tool is required. Operating conditions demand that the hood be at least 5 inches from the tool. At this distance, the required air velocity is obtained by a flow of 300 cubic feet per minute through a rectangular opening 3 by 6 inches in dimension. The addition of a 3-inch flange around the opening reduces the rate of air flow to 200 cubic feet per minute, a saving of 33⅓ percent. Since the pressure loss at entrance is also reduced, the power consumption is lowered by more than a third. Wherever conditions permit their use, the installation of flanges is recommended.

X. DUST COLLECTION AND DISPOSAL

INTRODUCTION

As a general rule, the material collected and transported by an exhaust system yields no economic return. Nevertheless, its proper disposal is an item of considerable importance for three reasons: (1) To prevent reentrance of dust-laden air into a building thus contaminating working places, (2) to avoid public nuisances, and (3) to conserve, especially in winter, warm indoor air for recirculation.

The methods in use for the collection and disposal of dusts are by direct discharge to the atmosphere through suitable ports or stacks, by separators or cyclones, by cloth filters or screens, and by electrical precipitation. Of these methods the first three are most commonly used. Electrical precipitation is usually employed where the material to be collected has some value, such as the recovery of potash dust in a cement plant. It is also used in the abatement of nuisances caused by large power plants burning powdered coal, the ash of which must be discharged through the stack. Because of their limited use as collectors of dusts found in most industries, no further description of them will here be given.

Direct elimination of dust to atmosphere

Unless the dust-laden air collected by the exhaust system can be eliminated through a stack of considerable height, it is undesirable to exhaust directly to the atmosphere. In some States, codes prevent direct discharge. Such methods, if practiced, may with strong contrary winds cause the dust to be swept back into the plant or to adjoining buildings and cause a general nuisance.

Disposal through stacks, if sufficiently tall, has been found adequate and is resorted to in many establishments. The success achieved by this method is due to the dilution attained by the scattering of particles over a wide area.

Cyclone separators

A cyclone consists of two concentric cylinders, the outer fitted to a conical hopper and connected tangentially to the exhaust duct of the fan (fig. 61). The inner cylinder fits partially into the hopper and discharges upward to the atmosphere. The air forced tangentially between the cylinder is caused to rotate at a high speed and forces the dust particles toward the outer shell by centrifugal action. The dust reaching the outer cylinder continues to spin and to drop gradually into the hopper, the clean air passing through the opening provided by the inner cylinder.

Because of their simplicity and freedom from care, cyclones are very widely used. Unfortunately, however, many cyclones have been installed without due attention to their capacities. As a result they frequently do not function effectively and are discarded.

The efficiency of a cyclone depends upon its size and the volume of air handled. Whiton (65) has obtained a number of interesting curves relative to the collection efficiencies and resistances of various cyclones using precipitated fly ash as a dust. These curves are shown in figure 62 and as will be noticed, low resistance indicates a comparatively low collection efficiency. Whiton has also shown that dust concentration does not materially affect percentage recovery.

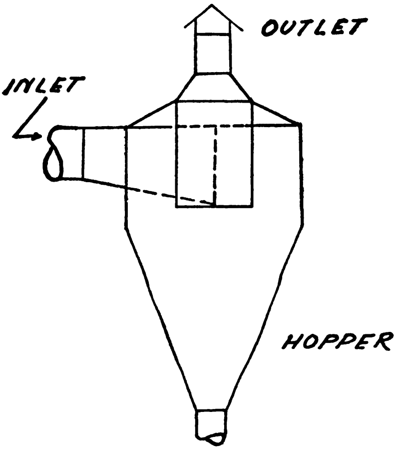

FIGURE 61.—Section through cyclone.

It will be noticed in figure 62 that the smaller the cyclone the more efficient a separator it becomes. In recent years, this fact has been used in the design of small cyclones connected in parallel. These multicyclones have the advantage of being flexible. They can be operated at their maximum efficiencies regardless of varying air flows since units are easily added or shut off as required.

Various manufacturers have designed special cyclones which have relatively high efficiencies. In choosing a cyclone, for a particular operation, therefore, efficiency and cost of operation should receive careful consideration.

When the air velocity in the fan discharge duct is known, the following equation is useful in computing the resistance loss through the cyclone:

$$h_c=0.013\left(\frac{V}{1,000}\right)^2 \qquad (19)$$

where V is the velocity in feet per minute in the fan discharge duct and h_c is the pressure drop through the cyclone in inches of water. The above formula is an average which applies to the common cyclones in use. Whenever possible, it is best to secure the manufacturers' figures for various flows.

Frequently the air exhausted from a cyclone is recirculated without further cleaning. This is possible under certain conditions, but for toxic dusts or such dusts with small particle-size, for which the efficiency of a cyclone is low, the air leaving it should be carefully analyzed by methods described in chapters 2 and 3 before recirculation.

CLOTH FILTERS

Cloth filters are used where the product collected is valuable, or where clean air is desired for recirculation. The materials used for filtering mediums vary considerably. High efficiencies are claimed for both muslin and wool. Each manufacturer of filter equipment recommends that which is best adapted for the collection of a particular product. It is, however, important to remember that cloth filters do not withstand temperatures over 200° F. and are easily acted upon by caustic and acid substances. Wet materials also are not easily collected without overloading the system and it should be held in mind that if filter units are subjected to places where the air temperature is low, the warm air collected may be chilled to the dew-point and cause the filter to become wetted.

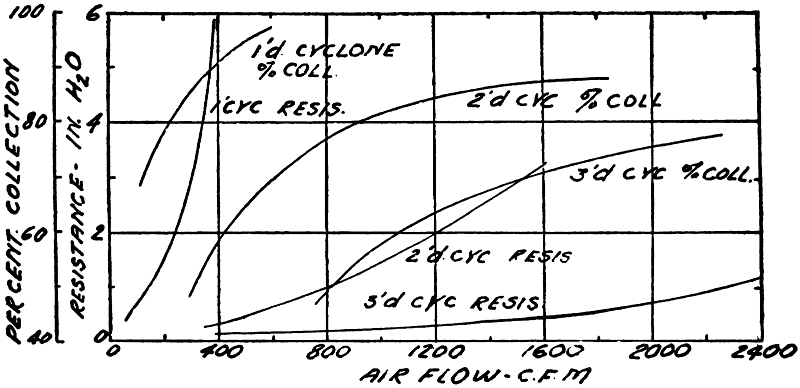

FIGURE 62.—Cyclone characteristics.

A filter unit consists of a closed compartment with either cloth screens or bags so placed that the dust-laden air must pass through them. Filters may be operated either on the positive or negative side of a fan. Cloth screens whether under suction or pressure must be housed while bags need only be housed when placed under suction. Bag filters operated under positive pressure, such as are used for zinc oxide and flour dust collection must be well collared at the duct connection in order to reduce leakages and to support the weight of the bag and the dust collected upon it. Bag filters of this type are suspended vertically, ranging in size from 4 to 40 inches in diameter and from 5 to 20 feet in length.

Because the process of filtration gradually increases the resistance of the system due to the accumulation of material on the filter surface, it is necessary to shake or tap the units at definite intervals. This is accomplished mechanically by clock arrangement, or by hand. Terry (66) has recommended the use of a manometer device whereby filters may automatically be shaken when the limiting resistance set by the manufacturer is reached. Large filter bags of the type described above are mounted in batteries in special buildings and are shaken down manually by tapping with long sticks.

In order to prevent overloading, a cyclone or separator is used to eliminate the coarser and heavier dusts. Some filters operating under negative pressure are so constructed as to produce a cycloning effect before the dust laden air enters the filter. Preliminary separators reduce the load on the filter surface.

The dust collected by filter units is removed from the hoppers periodically or continuously by means of screw conveyors.

The amount of filtering surface necessary varies with the type of material collected and the type of filter surface used. Wool has a very low resistance while some muslins, depending on their weave, may offer considerable obstruction to the flow. Table 34 gives the resistance of some cloths in common use.

TABLE 34.—*Resistance of various filter materials to the flow of air*

Material	Resistance to flow of 1 cubic foot of air per minute per square foot of filter surface (inches water gage)	Material	Resistance to flow of 1 cubic foot of air per minute per square foot of filter surface (inches water gage)
Cotton muslin	0.004–0.011	Vacuum cleaner cloth	0.019–0.060
Wool cloth	.005– .008	Wool pollen filter	.010
Cotton cloth, napped	.012– .020	Felt cloth	.004– .006

A high concentration of dust naturally requires more filter surface in order to keep the resistance of the system low and to avoid frequent shaking of the units. Similarly, materials which pack easily require large surfaces. The usual filter rates employed in practice range from one-half to 10 cubic feet per square foot per minute. Higher rates can be used where filters are shaken at frequent intervals and where the dust is not cohesive in character.

Typical time-resistance curves for flyash are shown in figure 63 for a wool filter operated under suction. The filtration rate for each curve is fixed at 10 cubic feet per minute per square foot of filter surface. The effect of various dust concentrations is clearly indicated.

Under ordinary conditions found in practice, fans operate at constant speed. Hence an increase in filter resistance is compensated by a decrease in the volume of air flow. The curves shown in figure

64 illustrate the relation between resistance and filtration rate in a typical installation due to a dropping fan characteristic. It is obvious, therefore, that filter cloths should be rapped or shaken before the velocities in the various ducts are reduced to a point where they no longer can convey the dust particles. (See sec. VIII.)

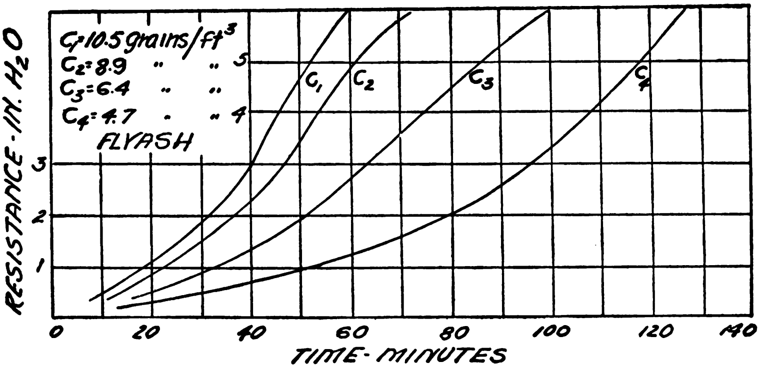

FIGURE 63.—Resistance of woolen filter to various concentrations of fly-ash (rate of air flow 10 cubic feet per square foot per minute).

The curves of figure 65 serve to illustrate the relation between resistance and filtration rates at various times. The curves are produced from data obtained from an experimental unit using a constant rate of feed (425 grains flyash per minute).[9] Thus, when the rate of air flow is 10 cubic feet per minute per square foot of filter surface, the dust concentration is approximately 5.4 grains per cubic foot. At intervals of 5, 10, 15, 20, and 25 minutes, therefore, the corresponding resistances are 0.9, 1.45, 2.15, 2.85, and 3.55 inches of water gage, respectively. These values, it must be remembered, apply only to the conditions under which the curves were determined. Obviously, dusts other than flyash of the type used in obtaining the above figures would give different results. Much preliminary experimentation is necessary in handling materials whose filtering properties are unknown. The rate of resistance build-up, as has been stated, determines in a large measure the type of fan necessary to meet the requirements of the system.

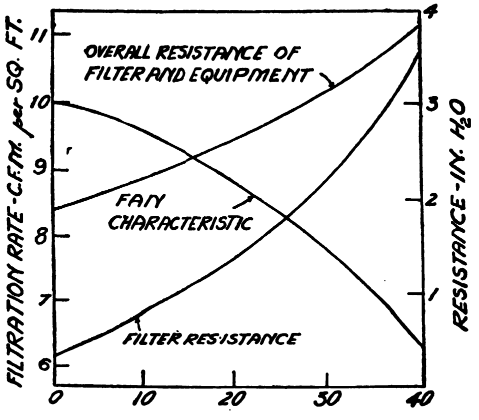

FIGURE 64.—Effect of fan characteristic on filtration rate.

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[9] Unpublished data J. M. D.

Filters, when not overloaded, are very efficient, and it is possible to recirculate the filtered air. In this way, the winter heat losses in a building normally due to exhausting air outdoors may be lowered, frequently to a point where the operation costs may balance those due to heat losses. Here again, however, it is necessary to check upon the efficiency of filtration by means of dust counts.

MAINTENANCE OF DUST COLLECTING SYSTEMS

Dust collecting systems should be inspected at definite intervals. Abrasive materials cause considerable wear in elbows and ducts connected to the collector and these should be repaired as soon as detected.

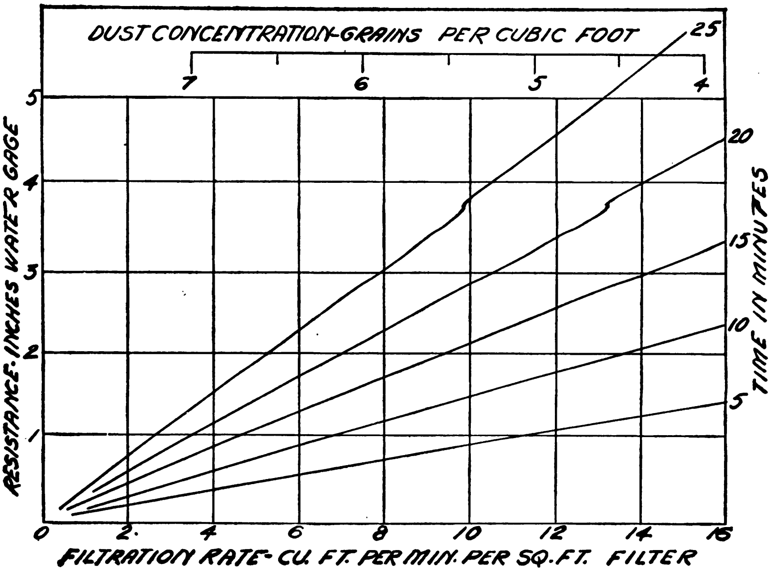

FIGURE 65.—Linear relationship between filter resistance and filtration rate at various time intervals.

Cloth filters often become wetted and mold with non-use, or else break with continued shaking. Tears in the filter medium should be repaired as soon as possible in order to prevent the air from bypassing other units connected to it, or as in the case of some systems, overloading the unimpaired filters. Compartments containing filters should also be inspected for leaks.

Due to the vortex formed in cyclones the cone-shaped hoppers are continually under negative pressure. Consequently, if they are opened, the dust collected in them will be drawn upward and either pass through the exhaust or else circulate continuously, thus reducing the efficiency of the system. It is therefore important to avoid leakages. The usual method of collection for some types of single units is to connect the cyclone hopper with a duct leading to an air-tight compartment. In such a device the suction will be low and will not interfere with the removal of the dust collected while the cyclone is in operation.

When hot substances are conveyed to a filter collector there is danger of setting it on fire. As a method of avoiding such an occurrence, a preliminary coarse screen should be used. Otherwise, it is necessary to remember in case of fire to first shut off the fan or blast gate. The use of a sprinkler system in the filter compartment in plants where potential fire hazards caused by hot substances exist, is good practice.

XI. MEASUREMENT OF AIR FLOW

In Part V it was pointed out that the efficiency of dust control is best measured with dust counts. The methods of air-flow measurement, on the other hand, assist the engineer in checking upon the exhaust system from the aerodynamic viewpoint. It assists him in gaging the velocities which may be required for the transport of certain substances and it gives him a powerful method in estimating the mechanical efficiency of a system. In the present section, it will be shown how the air velocities and volumes necessary to effect control may be measured. Not all the methods for measuring air flow are included but only those which are most widely used and are therefore most practical.

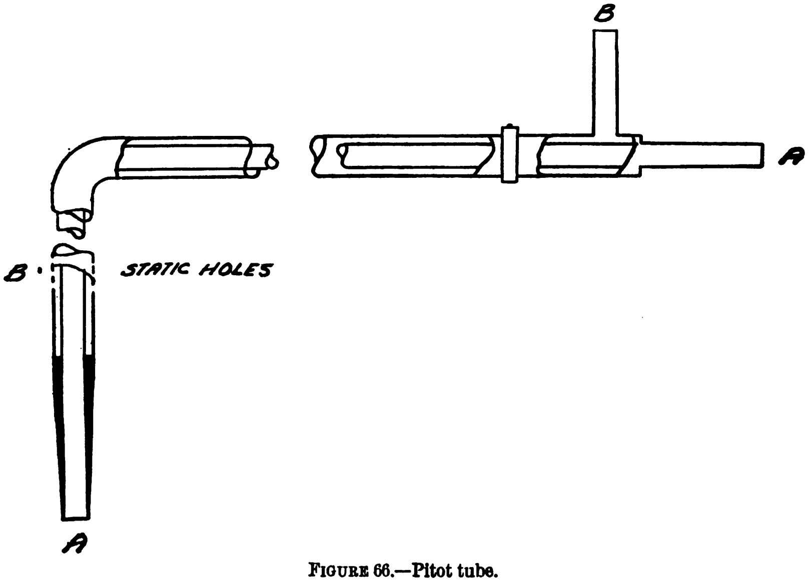

FIGURE 66.—Pitot tube.

THE STANDARD PITOT TUBE

Air velocity is measured by means of a pitot tube shown schematically in figure 66. This instrument consists of two independent concentric tubes bent into an L. In use, the tube is inserted into a duct and directed along the axis so that it points upstream. The two terminals *A′* and B′ are connected to a suitable gage and the deflection observed is a measure of the speed with which the air is moving.

The theory of measurement of this simple device is briefly as follows: The point A measures the total pressure within the duct which consists of a dynamic or impulsive pressure and a static pressure (sec. VIII). The former is accurately measured only when the tube is pointed upstream, but the latter is a pressure which at a given point is the same regardless of direction. If therefore, the total pressure be denoted by H, the velocity pressure by h_v and the static pressure by h_s, then the pressure measured at A is $\mathrm{H}=h_v \pm h_s$ depending on whether the duct is under positive or negative pressure.

Obviously, since the velocity pressure can only be measured in a direction upstream, it cannot possibly exert any effect at B where the holes are perpendicular to the flow. Hence, at B only the static pressure h_s can have any influence. Since also, the two concentric tubes are independent and are connected by means of a U-tube containing fluid, it follows that the deflection observed is equal to $h_v \pm h_s \mp h_s$ or simply h_v, the velocity pressure. By using equation (10), h_v may be directly converted in terms of velocity.

$$V=4009\sqrt{h_v} \tag{10}$$

Information regarding the design of pitot tubes has been given by Ower, (67), who has shown that the static holes should be at least 10 diameters removed from the dynamic opening. Ower has also shown the effect of yawing and turning of the tube in making measurements.

When the volume of air flow is desired from the pitot reading, a correction factor must be applied to obtain the average velocity of flow. The movement of air in a duct is not uniform, but is highest at the axis. The average velocity is generally taken as 0.8 the axial velocity measured by the pitot. Consequently, multiplying through the right hand side of equation (12) by this factor, we obtain

$$Q=18.3d^2\sqrt{h_v} \tag{20}$$

where d, of course, is expressed in inches.

For simplifying calculations, the nomograph given in figure 67 has been prepared. To find Q, it is merely necessary to lay the ruler on the value of d and connect it to the observed pitot reading h_v. The point where the line drawn between the values of d and h_v taken and the intersection of the Q-line indicates the volume of air flowing. The line drawn in the figure connects the point representing a diameter of 5 inches with the observed pitot reading of 1.4 inches. The intersection with Q shows that a volume of 540 cubic feet per minute flows in the duct. Actual computation by equation (20) above gives a value of 539.8 cubic feet per minute.

Simple pitot

In event a pitot tube cannot be secured, the velocity head may be measured by drilling a small hole in the duct, say three-sixteenths inch in diameter, and inserting into it an L-shaped one-eighth inch copper tubing, figure 68, the outer end of which may be connected to a manometer. This gives the total pressure. The tube may then be removed and a nipple with a rubber bushing almost flush with one end placed in the hole as shown in *B* of the figure. If no leaks occur at the bushing the pressure recorded by the manometer will be the static head. The absolute difference observed between the readings thus taken is the velocity head.

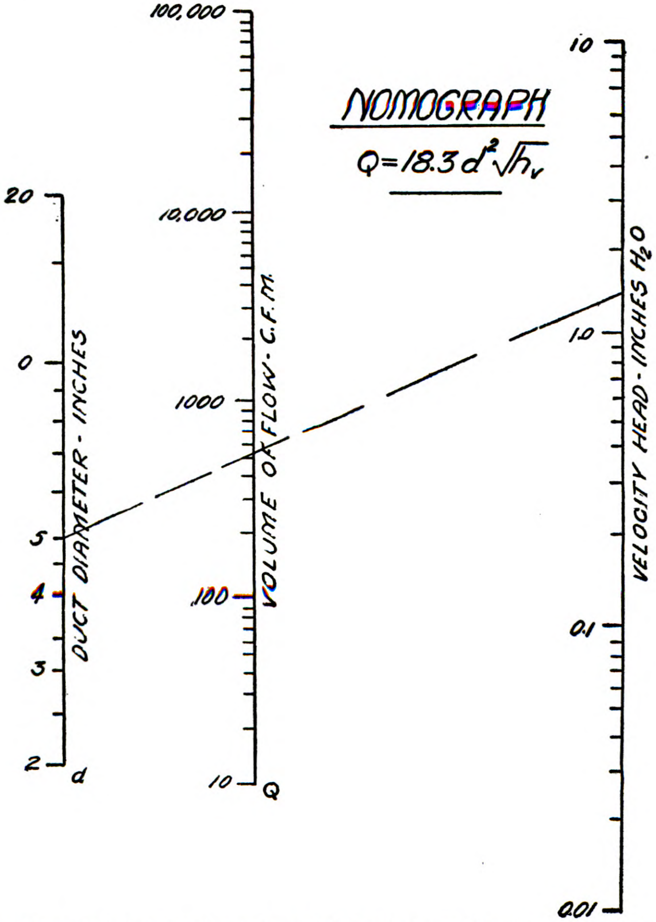

FIGURE 67.—Nomograph for computing volume of air flow in terms of duct diameter and pitot reading.

SPECIAL PITOT FOR MEASURING POINT VELOCITIES

One of the difficulties of the ordinary pitot is the fact that the total and static pressures are not measured at identical points. Consequently in regions where the air movement changes rapidly as at an opening under suction, the ordinary pitot cannot be used. For such conditions, a tube of the type shown in figure 69 may be used. This tube consists of a thin brass cylinder approximately one-eighth inch in diameter with two independent compartments closed at one end. Two small holes 0.02 inch in diameter are drilled at its mid-section and a pointer is fastened near the open end in the direction of the hole. For measurement of duct velocities the tube is inserted diametrically through the duct with the pointer directed along the axis. The readings so taken are a measure of the velocity head. They are much larger than those obtained for an ordinary pitot, ranging from about 1.6 to 1.75 times as great depending upon the velocity measured.

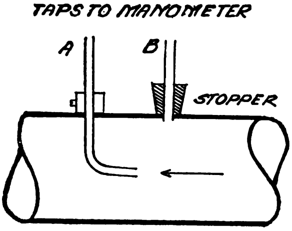

FIGURE 68.—Simple pitot for approximate measurement of air flow.

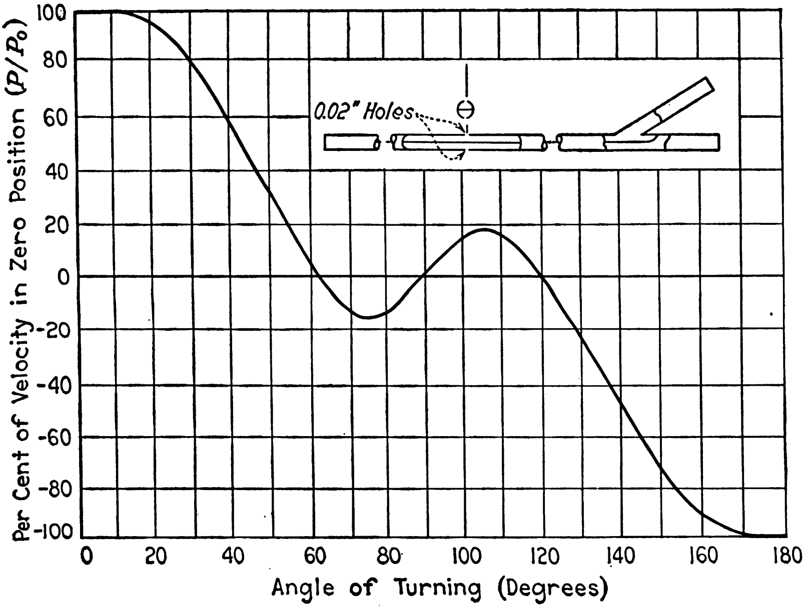

FIGURE 69.—Special pitot for measuring point velocities.

For measuring velocities near a hood, the tube requires a special mounting. The tube is turned at the point where the velocity is desired until a maximum reading is obtained on a manometer. If a calibration with an ordinary pitot has been made, this reading may be converted directly and the velocity determined by equation (10). The tube is very sensitive to the direction of flow and can be used as an indicator within ± 15° of arc as may be seen from the characteristic shown in the figure 69. Because of the comparative smallness of the device and the fact that it does not obstruct the flow of air, the instrument is capable of giving accurate readings at a point.

Determination of velocity contours

The special tube described in the above paragraph may be used in determining velocity contours (52). The tube requires a special mounting which may be moved vertically and horizontally and fixed at definite points with respect to the axis of the hood. The coordinates at which readings are made is indicated in figure 70 (*A*).

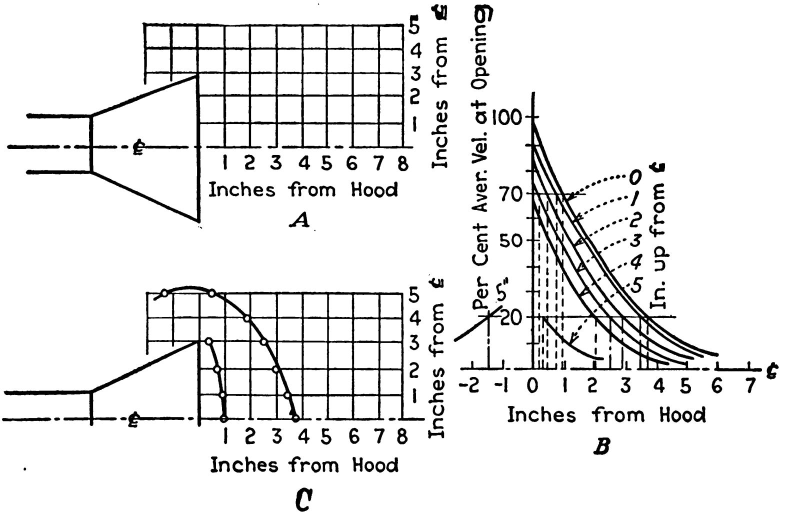

FIGURE 70.—Method of developing velocity contours.

Readings are taken with the tube horizontally outward from the opening at each level above the centerline. The data so obtained are then plotted as shown in *B* of the figure, the ordinates representing the percentage of velocity at the opening and the abscissae the distance from the opening. From these curves the velocity contours may be determined. For example, to determine the contours of velocities equivalent to 20 and 70 percent of the average velocity at the face of the opening, the values of the abscissae corresponding to the intercepts are obtained for the various velocity curves, as in *B* and plotted as in *C* of Figure 70.

THE ANEMOMETER

The vane anemometer is a direct reading instrument. When it is set in an air current, the vanes turn and actuate a calibrated tachometer. A stop watch must be used in connection with this instrument, since the reading of the tachometer dial merely indicates the linear feet of air travel.

Anemometers require calibration at frequent intervals. They are not reliable at low air velocities, although special forms (67) have been developed which are very sensitive. Vane anemometers cannot be used in duct work, but are useful in making quick velocity traverses over large hood openings.

AIR VELOCITY MEASUREMENTS BY MEANS OF THE KATA THERMOMETER

The kata thermometer was originally devised for the measurement of body comfort (68). It is, however, highly sensitive to air movements and can be used for velocity determinations. The instrument is essentially a thermometer with a large bulb filled with red-colored alcohol and two graduation lines on the stem marked 95 and 100, figure 71. When used to measure velocities in air below 95° F., the thermometer is inserted in warm water (about 180° F.) and the fluid allowed to rise half way up the safety bulb at the top. The large bulb is then quickly dried and held at the point where the air velocity is to be measured. The time, in seconds, taken for the alcohol to drop between the markings is observed; the average of 2 or 3 such readings is considered sufficient to insure accuracy.

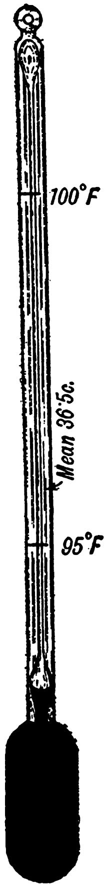

FIGURE 71.—Kata thermometer.

The time θ is then divided into the factor F marked near the top of the kata by the manufacturer, that is, $H=F/\theta$, where H is called the cooling or warming power. For temperatures below 95°, H is positive.

When the temperature is above 100° F., the kata thermometer is immersed in cold water and the time for the liquid to rise from 95 to 100 is noted, first taking care of course that the bulb is carefully dried. H is then obtained in the same manner as previously, with the exception that it is now regarded as negative.

Yaglou and Dokoff (69) were unable to develop reliable formulae for determining velocities with the kata thermometer which would hold over a wide range of air conditions. The kata is inaccurate when used between 85° and 110° F., because these temperatures are near its cooling range and air movements have little effect. The above investigators therefore have prepared a chart (fig. 72) from which the air velocities can be determined. In order to determine velocity, follow the curve corresponding to the given dry bulb temperature to the value of H (equal to F/θ), and read off the velocity vertically on the horizontal scale. The following problem illustrates the use of the chart:

Problem.—The time taken by the liquid in a red kata thermometer to fall from the 100 to the 95 markings on the stem is 53 seconds. The air temperature while taking the reading is 66° F., and the factor engraved on the stem is 477. Calculate the air velocity.

Solution.—The cooling power H is, following the procedure outlined above, $477/53=9$. If now the temperature curve corresponding to 66° is followed until it intersects the H-line corresponding to 9, we find that the velocity read off on the abscissae is approximately 340 feet per minute.

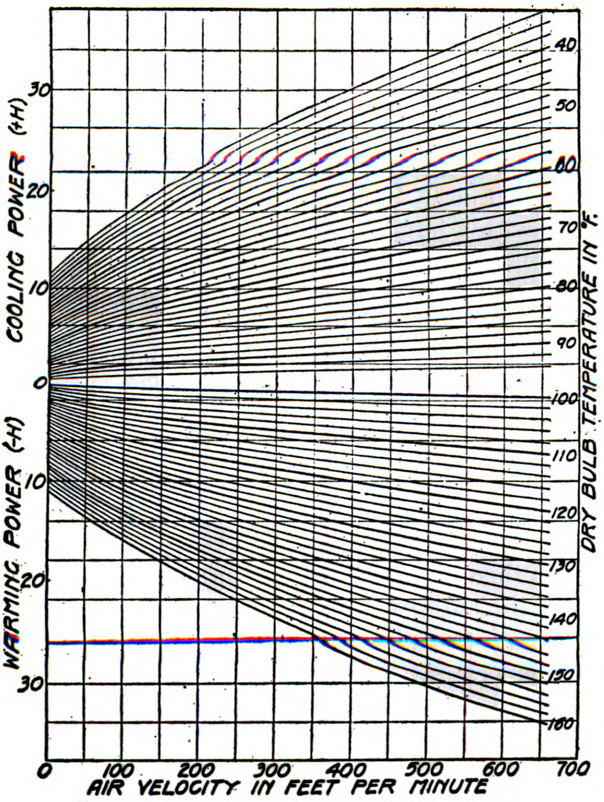

FIGURE 72.—Dry kata chart for computing air velocities.

The principle of the instrument is based on temperature difference and air motion. Except in the temperature range above noted, the kata is very accurate; for obtaining readings from 85° to 110° F., a special high temperature kata (blue kata) has been developed.

Kata thermometers are very sensitive to radiant energy sources. To avoid personal errors the observer should hold the kata at some distance from himself while making observations.

DETERMINATION OF AIR FLOW BY MEASUREMENT OF STATIC AT HOOD

For simple and approximate computation of air flow, the static pressure at the throat of a hood or opening obtained as described for a duct above can be used. The formula for determining the air volume is then

$$Q=4009af\sqrt{h_t} \tag{21}$$

where f is a factor called a restriction coefficient and h_t the static at the throat. This factor varies considerably (59) from 0.63 for obstructed or small openings to as high as 0.94 for shaped openings. A good value for most hoods encountered in practice is 0.71 although values of 0.85 are not too high.

If it is assumed that the static h_t at the throat is proportional to the velocity head h_v, an assumption which is closely in accord with experiment, then f can be obtained from the formula (59)

$$f=\sqrt{\frac{h_v}{h_t}} \tag{22}$$

VENTURI AND ORIFICE MEASUREMENTS

The venturi meter

For continuous measurement of large volumes of air flow, the venturi meter shown in figure 73 is useful. The meter consists of a converging and diverging duct connected by a narrow collar. The usual dimensions followed are given in the figure. The converging tube is coned to one-third of a pipe diameter in a total distance of 2½ pipe diameters. The diverging tube has a length of 7½ duct diameters in order to minimize the losses due to a reduction in air velocity and at the same time to prevent eddying.

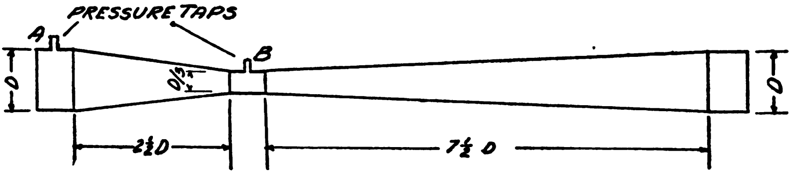

FIGURE 73.—Venturi meter.

The principle of the device is based on the fact that, neglecting losses, the velocity head and the static heads at A and B are mutually convertible. In other words, the total head H is preserved. Thus, we have

$$H=h_{s_A}+h_{v_A}=h_{s_B}+h_{v_B}$$

A manometer connected to A and B will, therefore, register the difference $h_{s_A}-h_{s_B}$. Hence

$$h_{s_A}-h_{s_B}=h_{v_B}-h_{v_A} \tag{23}$$

But $h_{v_A}=\left(\frac{V_A}{4009}\right)^2$ and $h_{v_B}=\left(\frac{V_B}{4009}\right)^2$ by equation (10). Also by the equation of flow, $V_A\,A_A=V_B\,A_B$ where A_A and A_B are the duct areas at A and B, respectively, so that $V_B=\frac{A_A}{A_B}\,V_A$. Substituting in equation (22) and calling $h_{s_A}-h_{s_B}=h$

$$h=\left(\frac{V_A\,A_A}{4009\,A_B}\right)^2-\left(\frac{V_A}{4009}\right)^2=\left(\frac{V_A}{4009}\right)^2\left(\frac{A_A^2}{A^2_{B4}}-1\right)$$
$$=\left(\frac{V_A}{4009}\right)^2\left(\frac{d^4_A}{d_B^4}-1\right)$$

where d_A is the duct diameter at A and d_B the diameter at B. Hence

$$V_A=\frac{4009\sqrt{h}}{\left[\frac{d_A^4}{d_B^4}-1\right]^{\frac{1}{2}}} \tag{24}$$

The volume of air handled is, therefore

$$Q=V_A\,A_A=\frac{4009\;A_A\sqrt{h}}{\left[\frac{d_A^4}{d_B^4}-1\right]^{\frac{1}{2}}}$$

Thus Q is determined in terms of the manometer difference observed and known constants of the instrument. Some loss, however, does take place between A and B; a more accurate relationship is

$$Q=\frac{3889\;A_B\sqrt{h}}{\left[d_A^4/d_B^4-1\right]^{\frac{1}{2}}} \tag{25}$$

where a factor 0.97 has been multiplied into the right side of the equation to compensate for the loss of head due to velocity change.

Orifices

Sharp-edged and bell-shaped orifices are often used for measuring air flows. Orifice measurements depend on a principle similar to the venturi (58). The pressure difference between the upstream and downstream sides of the orifice are observed and a formula identical to equation (24) above is used. Because, however, energy losses are large when an orifice is used, the multiplying factor is approximately 0.60, which is much smaller than the value used for the venturi.

Orifice measurements are not generally used in dust-collecting systems because they act as obstructions and as a result frequently give inaccurate readings.

MANOMETERS

Water manometers

Water manometers are used in connection with pitot tubes and static readings. The simplest form consists of a vertical U-tube partially filled with water, figure 74. When the tube is connected to a pressure source, the water column will be displaced to an amount sufficient to balance the force acting upon it. Thus, the distance between the water levels indicates the amount of pressure exerted by the fluid. When one end of the U-tube is connected to a nipple flush with the inner surface of a duct, the pressure indicated by the difference in water levels is the static head. When both ends are connected to a pitot, the displacement indicates the velocity head. A displacement of 1 inch of water corresponds to a column of air equal to 69.4 feet, or to 0.58 ounces (0.036 pounds) per square inch.

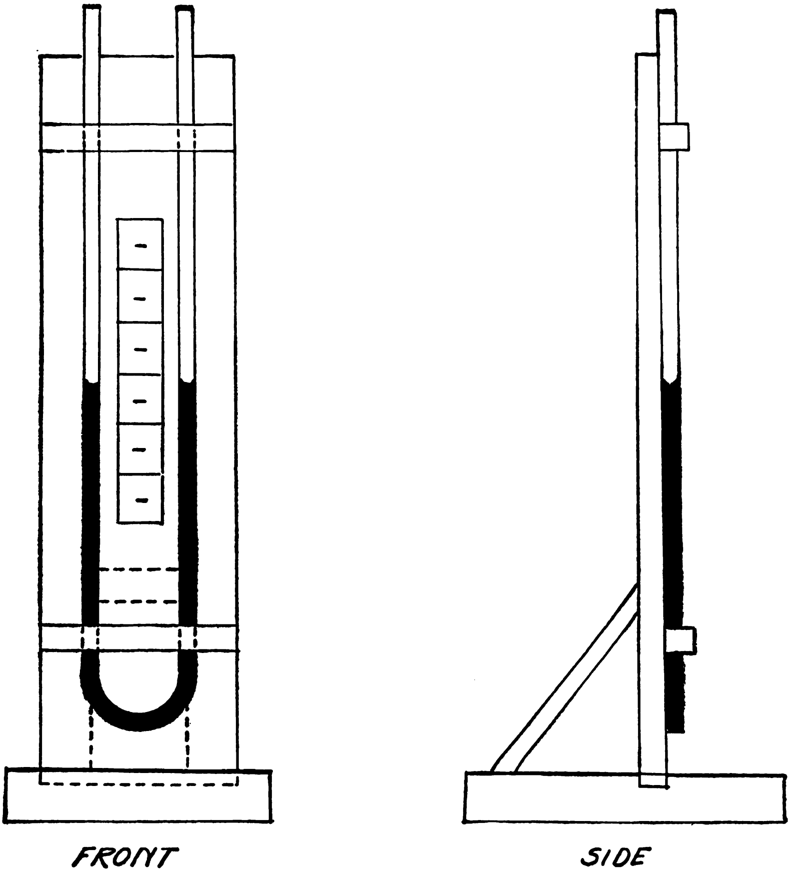

FIGURE 74.—Vertical manometer.

To increase the sensitivity, the U-tube may be inclined. A manometer which is mounted on a right-angled wedge-shaped block with a rise of 1 inch for every 10 inches of tube length (figure 75) has a sensitivity ten times as great as a vertical manometer. In other words, a displacement of 10 inches in a sloping U-tube corresponds to a displacement of 1 inch in a vertical manometer. U-tubes may also be sloped to give sensitivities twenty times as great as vertical tubes, but such sensitivities do not guarantee accurate readings.

In use, a sloping manometer should always be carefully leveled. A three-point mounting should be provided with at least one point adjustable for leveling purposes.

The Wahlen gage

This instrument is extremely sensitive and is used for the measurement of velocities ranging from 100 to 4,000 feet per minute (70). The gage is shown schematically in figure 76 and consists of two large bulbs filled with colored alcohol connected by an inverted U-tube containing kerosene. The bulb *B* is so connected to the U-tube that it can be moved in a vertical direction by means of a vernier calipers mounted to a framework. A stopcock is provided near the bottom of the stem connection the of bulb *B* so that when pressures are applied to the bulbs the liquids will not be violently disturbed. When ready to use an initial reading is taken with both bulbs open to the atmosphere by bringing the meniscus at *D* to the hairline. Connections are then made and the stopcock opened slightly to ascertain the direction in which the liquids move, and the calipers turned until the meniscus at *D* is again on the hairline. The difference between this reading and initial reading of the vernier is the actual displacement in terms of the heavier liquid. The reading may be converted to inches of water by multiplying the difference by the specific gravity of the alcohol. Being a null method, the Wahlen gage has a distinct advantage over other forms of manometers. Accurate readings, however, depend upon a knowledge of the specific gravities of the alcohol over the range of temperatures the instrument is to be used and upon maintaining the instrument level at all times. Zero readings should be taken frequently during experiments since the meniscus at *D* tends to vary somewhat.

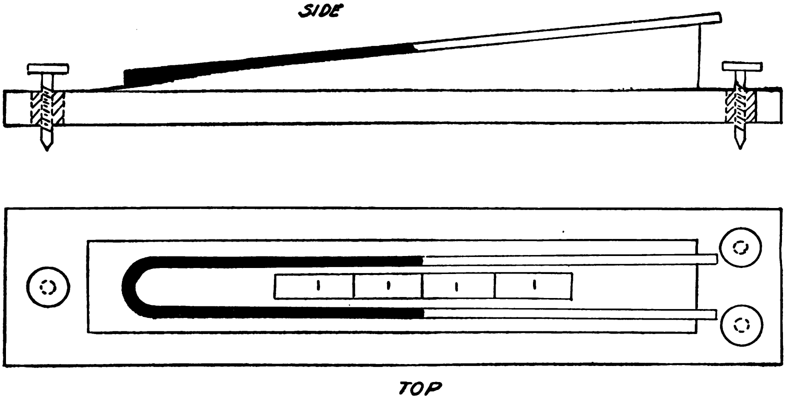

FIGURE 75.—Sloping manometer.

The factors contributing to the sensitivity of the instrument are easily derived by observing the deflections of the liquids when the pressure applied at *A* is greater than that at *B*. Obviously, the liquid columns to the left of the axis of symmetry must balance those on the right. If p_A and p_B represent the pressures at *A* and *B*, respectively, and if s_1 denotes the specific gravity of the alcohol and s_2 that of the kerosene, then the deflection in the *D*-tube, d_3, is determined by equating the net pressures to the left with those on the right, thusly

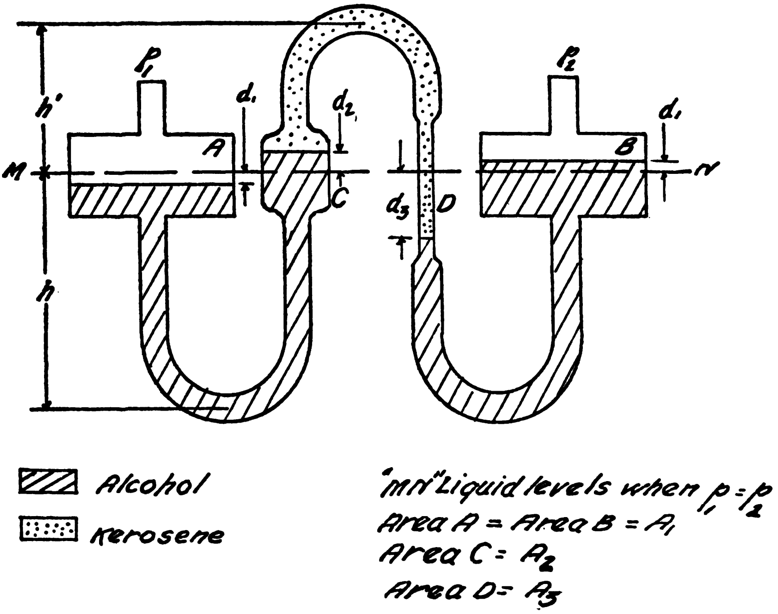

FIGURE 76.—Wahlen gage.

$$p_1+(h-d_1)s_1-(h+d_2)s_1-(h'-d_2)s_2+(h'+d_3)s_2=p_2+(h+d_1)s_1-(h-d_3)s_1$$

If we write $b=s_1-s_2$ and $p=(p_1-p_2)$ for convenience and collect terms

$$d_3=\frac{p-2d_1\,s_1-d_2\,b}{b}$$

But $A_1d_1=A_2d_2=A_3d_3=$ a constant, so that substituting for d_1 and d_2

$$d_3=\frac{p}{b\left\{1+\frac{A_3}{A_2}\right\}-2s_1\frac{A_3}{A_1}} \tag{26}$$

From this relationship, we note that the sensitivity of the gage depends chiefly on a low specific gravity difference between the liquids, *b*, and on the ratio of the areas of the large bulbs to the area of the D-tube. The enlargement at *C*, which acts as a reservoir for the kerosene, does not materially affect the sensitivity.

The liquids used in the Wahlen gage should be allowed to stand in the presence of each other in a stoppered bottle for some time. This permits the liquids to reach a stable condition and reduce the variation of the meniscus at *D* due to the solubility of kerosene in alcohol.

COMPARISON OF DEVICES FOR MEASURING AIR FLOW

In table 35 are given the principle characteristics of the devices used for the measurement of air flow. It will be seen from the arrangement presented that both the standard pitot and special pitot have accuracies dependent on the sensitivity of the manometer used. The pitot is the most practical device which has been developed for measuring air velocities in ducts and requires only moderate skill in use. The anemometer, while being the simplest device to use, has limited application to air-flow measurements and frequently gives erroneous readings.

TABLE 35.—*Comparison of devices used in the measurement of air flow*

Device	Method of use	Range of air velocities or volumes which can be measured	Calculations based on—	Accuracy obtainable	Skill required
Pitot tube	Used for measuring velocity head in ducts. Is pointed against direction of air flow.	200 feet per minute. Upper limit not determined.	Formula $V=4009\sqrt{h}$, (feet per minute).	Depends on sensitivity of the manometer used.	Some. Location of tube is important.
Special pitot	Used for measuring point velocities and velocity of air in ducts. Requires special mounting.	100 feet per minute. Upper limit not determined.	Formula or curve. Device requires calibration against a standard pitot.	do	Considerable. The device is sensitive to direction of flow and requires careful mounting.
Anemometer	A vane instrument actuating a tachometer arrangement.	200 to 5,000	Requires stop watch timing. Device is direct reading, giving linear feet of air travel.	Requires a correction curve for high and low air velocities.	No skill required.
Kata thermometer	Bulb must be dried, and time of fluid fall or rise between 2 markings and air temperature are correlated with velocity.	15 to 500	Requires a chart	With careful use, the device is very accurate.	Radiant energy sources must be avoided.
Venturi	Fixed convergent and divergent tubes forming part of the duct system.	Can be built to handle any volume of air flow.	Formula. $Q=\dfrac{21.2\,d^2_A\sqrt{h}}{\left[\dfrac{d^4_A}{d^4_B}-1\right]^{1/2}}$ d_A=diameter of main (inches). d_B=diameter of throat (inches).	Device is very accurate for volume determinations (0.5 —5 percent error).	No skill required. Manometer scale can be made to read volumes directly.
Orifice	Orifice plate is fixed between two flanges in duct system.	Can be made to handle any volume of air flow.	Formula. $Q=\dfrac{13.4\,d^2_A\sqrt{h}}{\left[\dfrac{d^4_A}{d^4_B}-1\right]^{1/2}}$ d_A=diameter of main (inches). d_B=diameter of orifice (inches).	Device is very accurate when carefully calibrated.	Do.

The kata thermometer is perhaps one of the most sensitive instruments developed for measuring low air velocities. It gives average readings depending on the period of time required by the liquid to pass between the markings on its stem. The device, however, cannot be conveniently used for duct work and must be kept free from radiation effects.

The venturi and orifice are widely used for measurement of air volumes. Since they form a part of the duct system, they give continuous readings. Their characteristics have been determined and are well known, so that when they have been carefully constructed, no extensive calibration is required.

XII. PERSONAL RESPIRATORY PROTECTION

In some dusty occupations the methods of controlling dust have not been developed. In fact, industrial operations, such as removing the cores from very large foundry castings, sand-blasting, handling of used storage battery plates, paint chipping, and cadmium oxide manufacture appear to offer no practical means of adequately controlling the dust generated. In such cases, it is therefore necessary to furnish the worker with personal respiratory protection devices in order to prevent his exposure to the harmful effects of the dusts present. These devices consist of various types of respirators, masks, and helmets.

It is important first of all to hold in mind the limited use of personal protection devices. Because a worker cannot with comfort wear a mask or helmet continuously, such devices must be employed intermittently. As a consequence, their use is generally extended to those operations where all other methods have failed or supplementary to them, as in storage battery repair where the exposure to small amounts of lead breathed is known to be detrimental to health. Respirators and helmets are in a sense the last resort in dust protection.

TYPES OF RESPIRATORY PROTECTION APPARATUS FOR INDUSTRIAL DUST

Respiratory protection devices may be divided into two general groups: (1) Respirators or facepieces using filters, and (2) masks or helmets using positive pressure.

The first group consists of many types, the simplest being perhaps a cheesecloth packing covering the nose and mouth and tied to the back of the neck. Other forms vary from what is generally called a pig-snout type to those consisting of facepieces connected to large filter surfaces strapped about the waist. The pig-snout respirator consists of a metal body, usually aluminum, with a rubber-lined edge, shaped to fit the contour of the face. It covers the nose and mouth and is strapped tightly to the back of the neck. A small cylindrical disk-like filter and a flutter valve form the essential parts of the device. The valve is so arranged that it closes on inspiration forcing the air to pass through the filter piece. On expiration, the flutter valve opens, thus affording the expired air an easy exit. The so-called Folger or Burrell filter is essentially a mask covering the whole face. It is made of a pliable composition with goggles and is comfortably but tightly strapped to the face to prevent leakage. The mask is connected with a corrugated flexible tube to a felt filter strapped to the waist. In this way, a large surface is provided for reducing the breathing resistance.

The filter mediums used in respirators of the first group consist of paper, paper fiber, sponge, wool cloth, and felt. Manufacturers of various respirators provide the type of material believed best suited to their designs. Respirators are so constructed that the filter medium may be easily replaced. In use, because of the small surface given for filtration, the medium must be changed frequently; otherwise the resistance builds up, and breathing becomes difficult. The flat Folger or Burrell type, which has been described, has a longer period of usefulness than the ordinary pig-snout respirator and is capable of being cleaned. It is one of the most efficient of the types so far employed in industry for retaining very fine suspensoids (71)

EFFICIENCIES OF FILTER MEDIUMS USED IN RESPIRATORS

Respirators may be tested by several different methods, of which two are most commonly used. The first consists of testing the filtering medium independently of the respirator while the second consists of tests made with the facepiece imbedded in clay or some similar pliable substance.

APPARATUS FOR DETERMINING EFFICIENCIES OF FILTER MEDIUMS

The usual methods of determining efficiencies are based upon methods described in section V, that is, by use of the impinger or electrical precipitator. A considerable number of published tests, however, are based upon the now obsolete Palmer apparatus (11) whose efficiency in terms of the present impinger is approximately 20 percent (8).

A method which is frequently used with tobacco smoke and dust suspensions is the so-called "tyndall" meter. This consists of an arrangement (72), whereby the suspension to be estimated is passed through a beam of light. The absorption and reflection of the beam on the particles of dust weakens it almost in direct proportion to the concentration of particles present. The readings may be observed with a photometer or photo-electric cell arrangement. In actual tests, the suspension from a dust chamber which is to be used in testing the respirator is passed through the beam chamber and a reading obtained. A second reading is obtained with the filtered air in the same manner and the efficiency determined by the usual relation 100 minus tyndall reading of filtered air divided by the tyndall reading of the original suspension. As a laboratory procedure the method is simple and convenient.

The procedure in testing respirators consists in setting up a dust or tobacco smoke cloud in a dust chamber and passing it at a fixed rate through a definite area of filter medium. The arrangement used for holding the filter is also provided with a means of determining the resistance which is important in estimating the life of the respirator filter.

Results of filter tests

Results of tests of various filter media have been published chiefly by the United States Bureau of Mines (71) and by the Harvard School of Public Health (73). The data obtained from these research laboratories are given in tables 36, 37, and 38. It will be seen that in practically every case the efficiencies are low for sponge filters and high for wool cloths. The efficiencies of industrial respirators against tobacco smoke range from 3 to 33 percent. The Folger flat type filter is most efficient, 97 percent. Against silica dust, the efficiencies are slightly higher. In the case of the Bureau of Mines tests the efficiencies ranged from 9 to 70 percent and in the experiments of Barreto, Drinker, Finn, and Thomson (73) ranging from 49 to 97 percent. The higher efficiencies in the latter experiments are probably due to the larger size of dust particles used. In filtering lead mist the efficiencies given in table 38 are much higher than those for silica, the sponge respirator giving an efficiency of 84 percent. This increase is undoubtedly due to the fact that lead mist is large in size and tends to settle rapidly. Barreto and his associates have also demonstrated that respirators do not favor any particular size range below ten microns, as may be seen in figure 77. The finer particles appear to be filtered with practically the same efficiencies as the larger.

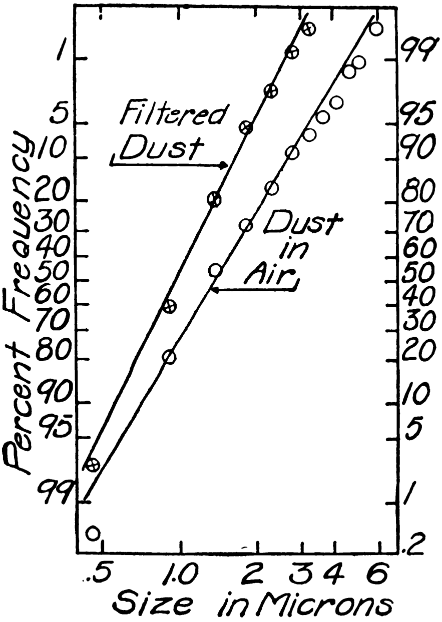

FIGURE 77.—Size frequencies of dust particles in respirator tests (ordinates on probability scale, abscissa on logarithmic scale).

With regard to resistance, it is to be noted that tobacco smoke does not increase the resistance of the filters. Silica dust, on the other hand, increases the resistance to air flow, but some materials have clogging properties more marked than others. Dense paper filters and closely woven muslin clog rapidly, while loose textures clog slowly.

TABLE 36.—*Filtering efficiencies and resistances of masks and respirators when new*[1]

Type of mask	I. Effective filtering area	II. Air flow	III. Resistance	Tyndall efficiency against	
				IV. Tobacco smoke	V. Silica
	Sq. cm	*Liters per minute*	*Mm H_2O*	*Percent*	*Percent*
Burrell	840	85	7.6	82	>97
		70	5.8	85	-------
		50	3.8	88	>97
Experimental cotton	1,290	85	2.7	22	69
		70	1.9	25	-------
		50	1.1	31	71
Pig snout no. 1:					
Sponge:					
Wet	(?)	85	37	41	97
		50	18	15	92
Dry	(?)	85	23	31	89
		50	13	15	72
Pig snout no. 2:					
Sponge:					
Wet	(?)	85	5.8	10	76
		50	3.0	7	64
Dry	(?)	85	5.3	3	67
		50	2.5	3	49
Pig snout no. 3:					
Pad:					
Wet	20	85	56	44	>97
		50	28	39	96
Dry	20	85	30	53	97
		50	18	39	92
Pig snout no. 4:					
2 papers	45	85	6.9	5	86
		50	3.0	5	62
4 papers	45	85	10.2	7	97
		50	4.7	13	88
6 papers	45	85	9.7	8	94
		50	4.6	14	89

[1] Taken from data of Barreto, Drinker, Finn, and Thomson (73). Silica tests on pig snouts are approximate since it was impossible to prevent plugging and rapid increase in efficiency.

TABLE 37.—*Efficiencies of industrial dust respirators filtering silica dust, determined with Tyndall apparatus*

[Rate of air flow, 32 liters per minute]

Respirator	Resistance to flow of air at 85 liters per minute		Number of tests	Initial efficiency		Highest efficiency after clogging	Time to reach highest efficiency	
	Before test	After test (maximum)		Maximum	Minimum		Minutes	Seconds
	Inches of water	*Inches of water*		*Percent*	*Percent*	*Percent*		
Sponge[1]	0.7	1.1	1	9	-------	30	2	0
Do.[2]	.8	1.6	1	22	-------	55	4	0
Do.[2]	.6	.9	2	17	8	28	3	15
Do.[2]	.8	.9	2	23	9	30	2	30
Paper	.5	10.2	4	63	30	100	0	50
Do	.25	5.2	1	45	-------	100	1	30
Felt	1.3	2.8	2	70	70	100	1	20
Do	1.5	2.2	1	37	-------	100	3	0
Do	1.1	-------	1	63	-------	100	3	15
Silk gauze and cheesecloth	.4	6.1	2	20	10	100	3	30
Cotton flannel	.6	6.0	2	61	54	100	5	0
Absorbent cotton	.2	.8	1	50	-------	100	3	0
Cheesecloth[3]	.3	.6	1	23	-------	23	-------	-------

[1] Sponge dry.

[2] Sponge wet.

[3] Filtering efficiency is taken from tests of cheesecloth held in flange exposing 100 square centimeters and tested at rate of 10 liters per minute. There was no increase in filtering efficiency during two minutes.

Table 38.—*Efficiencies of respirators filtering lead in paint mist from spray gun. Rate of air flow, 32 liters a minute. Time of testing, 31¼ minutes giving 1 cubic meter of filtered air. Area of filter medium, 100 cm ²*

Type of filter	Filter material	Resistance to air flow at 85 liters per minute, inches of water		Average amount of lead in air milligrams per cubic meter	Filtering efficiency of respirator per cent	Remarks
		Start	End			
Pig snout	Sponge	0.3	0.3	395	84	Sponge was wet before test.
Do	Cotton paper	1.0	2.5	558	98.7	1-ply paper in filter.
Do	do	1.0	1.6	397	97.3	Do.
Do	do	1.1	2.0	417	98.3	Do.
Do	do	.15	.5	359	96	Do.
Do	do	.2	.6	374	96	Do.
Do	do	.5	.9	353	98.3	2 plies paper in filter.
Do	Gauzy tissue paper	.5	.8	498	92	4 plies paper in filter.
Do	Cotton flannel	.2	.4	458	95	2 plies cotton flannel in filter.
Clock	Silk gauze and cheesecloth.	.05	-------	450	74	1-ply silk, 3 plies cheesecloth.
Do	Cotton wool	.2	.2	351	94	Cotton between cheesecloth, 100 square centimeters of filter was exposed.
Pig snout	Gauzy tissue paper	3.5	4.4	524	99.7	Cartridge with charcoal and 2 filters each of 10 plies.
Do	Cotton wool	3.6	3.9	76.1	99.7	The Army type gas mask canister contains 2 cotton filters, 1 of toweling, and 600 cubic centimeters charcoal.
Do	do	3.6	3.9	71.3	98.8	Do.
Do	do	3.4	3.6	75.3	99.6	Do.
Do	do	3.4	3.5	50.6	99.3	Do.
Do	do	3.6	3.8	65.7	99.7	Do.

With regard to the resistance of filters the following quotation taken from a Bureau of Mines publication (71) gives several important conclusions based on a large number of tests:

> The resistance of the filters to the flow of air through them is a highly important factor in the design of dust respirators, because respirators having a resistance greater than 4 inches of water when the rate of air flow is 85 liters per minute are impractical. They will not be worn, even for short periods, because they necessitate too much exertion in breathing. Respirators with resistances of 2 to 4 inches may be worn, but after about half an hour the wearer must rest or exert himself less. The resistance of filters in dust respirators intended for continuous working use should not exceed 2 inches of water, and preferably should be less than 1 inch. These limitations on the resistance of filters restrict filtering efficiencies, so in a practicable respirator it is necessary to strike a balance between the filter resistance and the filtering efficiency that may be obtained.
>
> The area of respirator filters should be made as large as is practicable, because the increased area reduces the rate of air flow per unit of area and thereby tends to increase the filtering efficiency and decreases the resistance.

POSITIVE PRESSURE MASKS OR HELMETS

The second group of respiratory protection apparatus consists of masks or helmets with fresh air supply. In these types, compressed air from a dust-free source is supplied to the worker. Positive pressure masks as a rule are constructed of light metal, shaped to the contour of the face by special cushions, and supplied with a small valve to permit the vitiated air to escape. The air is bled into the mask near the top and diverted across the goggles to prevent fogging and sensations produced by air jets. It is necessary in using positive pressure masks to fasten the air supply hose to the worker so as not to induce a drag on the mask.

Various types of positive pressure masks are available. Some have been designed with light pumps and motors with cloth filters which may be strapped about the waist. In this way the worker need only carry about with him an electric extension cord. Such devices are especially adapted for operations requiring freedom of movement, which cannot be attained with a stiff heavy compressed air hose.

Positive pressure helmets are made of rubber, leather, or canvas. They fit over the head and rest on the shoulders of the worker. They are provided with large protected windows which may be replaced. Sufficient air is supplied to these helmets to keep a constant flow of air leaking outward at the shoulder contacts, thus preventing any dust from entering.

Positive pressure helmets are used almost entirely in abrasive cleaning rooms and serve a twofold purpose: (1) To furnish the worker with a clean supply of fresh air, and (2) to protect his head and neck from the force of rebounding sand or metal particles.

EFFICIENCIES OF POSITIVE PRESSURE DEVICES

Bloomfield and Greenburg have investigated the air requirements of helmets used in sand-blasting under normal working conditions (48). Their studies were planned with the purpose of obtaining samples of air from inside a helmet, when: (1) The quantity of air supplied to the helmet was varied while the dust concentration in the room was maintained at as constant a level as possible, and (2) the dust concentration in the room was varied while the quantity of air supplied to the helmet was kept constant, this quantity being the optimum as determined in (1) above.

The studies were conducted in an abrasive blasting room in which fairly clean castings were blasted with sand at a pressure of ranging from 55 to 60 pounds. A modern room, equipped with down-draft ventilation, was used. An ordinary cloth-covered, fiber helmet was employed connected in the manner shown in figure 27, section V. This helmet was provided with a rectangular double screen about 4 by 2 inches in size, located at a point directly in front of the worker's eyes. The outer screen was a coarse mesh while the inner one was of a 32-mesh size. The dust concentrations were determined with the impinger apparatus.

The general air of the blast cleaning room (the air in the room, but outside the helmet), was sampled at a time corresponding with the midpoint of a pair of helmet samples by means of a second impinger flask suspended in the blasting zone. (See fig. 28 for assembly details.) The operator was instructed to conduct blasting in a uniform manner so that operating conditions throughout the experiments would be as constant as possible.

In the first series of samples, the helmet was tested with the double screens in place, while in a second series, a glass eyeshield was used. Table 39 shows the results of the two series of tests.

TABLE 39.—*Dust concentration*[1] *beneath helmet with air supply of different volumes*

[Millions of particles per cubic foot]

	Dust in room air	Volume of air supply (c. f. m.)[2]					
		0	2	3	4	5	6
With double eye screen	503	--------	9.7	8.4	2.1	1.8	6.0
Glass eye shield	665	59	4.4	4.0	2.2	1.15	.35

[1] Each average based on 2 samples.

[2] Dust in air supply 0.3 million.

Bloomfield and Greenburg have assumed the inconsistencies of the first series as being due to the fact that the dust deflected from the casting at a considerable velocity gained access to the helmet through the screens. It is clear from the table, however, under the test conditions of the second series, that when 6 cubic feet of air per minute are supplied to the helmet, the worker breathes an atmosphere containing but 0.3 million particles per cubic foot of air. In other words under such conditions, practically no blasting-room dust filters into the helmet. This represents ideal protection for the worker.

In order to determine whether 6 cubic feet of air was sufficient under all conditions of work, another series of samples were taken keeping a constant flow of air of 6 cubic feet per minute through the helmet while the dust concentration in the room was varied by changing the amount of room ventilation.

With 4,000 million particles per cubic foot in the general air, there were 3.1 million particles within the helmet; with 3,000 there was 1.0 within the helmet; with 1,000 there was 0.5. In other words, the dust concentration of the air beneath the helmet during blasting remains low when the air in the room contains as much as 1,000 million particles per cubic foot and more. It is only when the dust concentration in the room reaches the enormously high figure of 4,000 million particles per cubic foot, that the air beneath the helmet was found to contain as much as 3.1 million particles per cubic foot. Such conditions in practice are rare and in fact impossible to work under because of obscured visibility.

It may therefore be concluded that a positive air supply of 6 cubic feet of dust-free air per minute will protect a worker under the operating conditions now in practice in abrasive cleaning rooms if the worker is supplied with a helmet similar to that described above. The final criterion, however, is the result of dust determinations of the air within the helmet, that is, the air actually breathed by the worker, and not the volume of air supplied.

EFFICIENCY STANDARDS IN TESTING PERSONAL PROTECTION APPARATUS

It is necessary to point out that tests of personal protection apparatus should always be carried out against the dust to which these devices are to be used in practice under the most severe conditions which are likely to be encountered.[10] Furthermore, in connection with ratings given in percent, great care should be exercised that correct interpretations be made. For example, a device which is 90 percent efficient, does not necessarily mean that it is sufficient protection against dusts with high quartz content when the concentration is of the order of between 50 and 100 million particles per cubic foot. Under such circumstances, with continued exposure, the worker is likely to breathe dangerous amounts of dust. Ratings, should therefore, be obtained with regard to the quantity of dust which actually passes the respirator or helmet under the conditions employed.

MAINTENANCE OF RESPIRATORY PROTECTIVE DEVICES

Devices used to protect the worker should always be maintained in good order. Frequently, in many industries they are not properly cared for or maintained in good condition, with a result that they no longer function efficiently. It is important that periodic checks be made of all respiratory protective devices, observing any physical defects which they may have, and to retest them whenever any doubt arises as to their effectiveness.

A necessary precaution in connection with positive pressure masks and helmets is to make certain that the air supply is always from a clean or filtered source.

CHOOSING RESPIRATORY PROTECTIVE DEVICES

The choice of respiratory protective devices depends upon a number of factors. As has been pointed out, their efficiencies must be rated in terms of the dust actually passing the respirator or helmet under the conditions against which they will be used; there are, however, other considerations, equally important, which in a large measure are determined by the type of operation under which they must be employed. These factors are—

1. *Lightness.*—Respiratory protection apparatus should be light and durable. Heavy devices are cumbersome and the worker is prone to avoid using them.

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[10] In connection with standard routine tests of respirators, see schedule 21, U. S. Bureau of Mines.

2. *Fit.*—The fit of a respirator or mask is important. They should in every case be fitted to the wearer. Otherwise leaks will interfere with the effective use of the device.

3. *Visibility.*—Masks or helmets should attempt to give clear and easy visibility to the worker. The air supply should attempt to keep the glass from fogging. Glasses should be easily replaced in case of breakage or pitting and should fit well.

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