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Economic and Technical Review
Report EPS 3-AP-74-2

Air Pollution
Control Directorate

April 1975

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AIR POLLUTION EMISSIONS AND CONTROL TECHNOLOGY

ASPHALT PAVING INDUSTRY

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Combustion Sources Division

Air Pollution Control Directorate

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ABSTRACT

This report examines the present and future contributions to air pollution by the Canadian hot-mix asphalt industry and discusses the equipment and technology available to control these air pollution emissions.

There are 357 reported asphalt plants in Canada and their annual production in 1972 was 14.5 million tons of asphalt. Particulate emissions are the largest air pollutant associated with the industry and amount to more than 60 000 tons per year. Methods for controlling these emissions and costs associated with providing pollution control equipment for the industry are discussed in detail.

RÉSUMÉ

Le présent rapport fait état de la quantité actuelle et prévue de polluants rejetés à l'atmosphère par l'industrie de la préparation à chaud de revêtements bitumineux et traite du matériel et des techniques disponibles pour réduire cette quantité.

Au Canada, cette industrie qui compte officiellement 357 installations du genre, a produit, en 1972, 14.5 millions de tonnes d'asphalte. Elle rejette annuellement plus de 60 000 tonnes de particules, qui constituent le polluant le plus important de cette industrie. Le rapport traite en détail des méthodes antipollution et des coûts d'acquisition de matériel antipollution.

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1 INTRODUCTION

1.1 Scope

This study provides technical information for use in the development of emission guidelines for the Canadian hot-mix asphalt paving industry. The study provides a brief, general description of the industry and examines the manufacturing process and sources of emissions. Methods for controlling emissions from hot-mix asphalt plants and the costs associated with providing pollution control equipment for the industry are discussed in detail.

1.2 Information Sources

Information contained in this report was obtained from a literature survey and from discussions with equipment manufacturers. Production statistics were obtained from Statistics Canada and from the Federal Department of Industry, Trade and Commerce. Discussions were held with major users of hot-mix asphalt, such as the provincial departments of highways, and the Federal Departments of Transport, Public Works and National Defence, to determine their annual usage figures and material specifications. Hot-mix asphalt producers and contractors were contacted either directly or through subcommittees for air pollution control and road builders associations across Canada to obtain information on the size and type of existing plants, plant locations, and the pollution control equipment being used. Finally, discussions were held with Canadian provincial agencies and with the United States National Asphalt Paving Association to obtain information and comments on various aspects of this study.

2 THE HOT-MIX PAVING INDUSTRY

2.1 General

Most highways in Canada are surfaced with hot-mix asphalt which is a combination of aggregates uniformly mixed and coated with asphalt (or asphaltum). The term aggregate is used to describe the solid, load-bearing constituents of hot-mix asphalt such as sand particles and fragments of stone and gravel. A hot-mix asphalt paving plant is used to heat, mix and combine the aggregate and asphalt in the proper proportions to give the desired consistency and strength. After the material is mixed, it is transported to the paving site and spread as a loosely compacted layer with a uniformly smooth surface. While still hot, the material is compacted and densified by heavy, motor-driven rollers to produce a smooth, well-compacted course. Some hot-mix asphalt plants are moved from one job site to another whereas others are set up for efficient operation in a relatively permanent location, usually in a metropolitan area.

Specifications normally require that hot-mix asphalt be laid at ambient temperatures of 50°F or higher. Therefore, the industry is seasonal in nature and in Canada paving operations are usually limited to the period from June until mid-September. The number of reported hot-mix asphalt plants in Canada, compiled from information obtained from provincial departments of highways and provincial road builders associations, is shown in Table 1. Also shown in Table 1 are estimates of the annual production of hot-mix asphalt by provinces during 1972. Although figures for municipal and private use of hot-mix asphalt are not included in the table, the Canadian Road Builders Association has estimated that such usage would only amount to 10-15% of the total Canadian production.

TABLE 1 LOCATION AND CAPACITY OF CANADIAN HOT-MIX ASPHALT PLANTS, 1972

Province	Type of Plant		Production (tons)
	Batch	Continuous	
Alberta	12	4	2 500 000
British Columbia	28	7	1 500 000
Manitoba	5	7	465 000
New Brunswick	14	8	550 000
Newfoundland	9	4	475 000
Nova Scotia	11	4	1 100 000
Ontario	104	21	3 300 000
Prince Edward Island	6	2	260 000
Quebec	80	21	2 800 000
Saskatchewan	4	6	1 570 000
Total	273	84	14 520 000

The production of 14.52 million tons of asphalt in 1972 is only 2% higher than the production in 1970 and, therefore, is considered to be representative of the annual production for the industry. At an average cost of $7.50/ton this production represents annual sales of approximately $108 900 000 for the Canadian hot-mix asphalt industry.

The more modern asphalt plants with automatic aggregate loading systems normally require only two operators whereas older plants without automatic aggregate loading systems require three operators. Depending on the plant size and hauling distance (for both the aggregate and hot-mix asphalt), one plant may employ up to twenty truck drivers and an additional 10 people on the paving crew.

Asphalt plants vary considerably in size and capacity. The average batch plant has a capacity of 3000 lb per batch and is capable of production rates of 100-120 tons of asphalt paving mix per hour. This production rate is limited by the asphalt mixer or pugmill and the rotary dryer. The mixing time for each batch is about one minute for most batching conditions. New asphalt plants have production capacities of 250-350 tons per hour and cost $400 000 to $750 000. The cost of the dust collection portion of the plant is 15-25% of the total plant cost. The average life of a plant is about 15-20 years and it has been found that most contractors write off the equipment cost in 10 years.

The asphalt rotary dryer is the principal emission source of pollution in the hot-mix asphalt operation. The discharge consists of extremely fine particles (under 200 mesh) and the uncontrolled emissions amount to approximately 5% of the total weight throughput (1). Uncontrolled emissions from a plant operating at 150 tons per hour are approximately 7.5 tons per hour. A wide variation of control methods and collection efficiencies are used by Canadian plants and the average reported collection efficiency has been estimated to be 92%. Annual particulate emissions, estimated from the production figures, are approximately 60 000 tons per year.

2.2 Process Description (2)

All conventional hot-mix asphalt plants incorporate the following processes: conveying proportioned quantities of cold aggregate to a dryer; heating and drying the aggregate; screening and classifying the hot aggregate into bins; heating the asphalt; measuring and mixing the aggregate and asphalt in proper proportions; and delivering the hot mixture into trucks which haul it to the paving site.

With regard to the final mixing process, plants are either of the batch or continuous-mix type. Both types of plants have the same pattern of material flow up to the point of measuring the aggregate from the hot bins into the mixer. In the batch type plant, the operator weighs out the correct quantity of aggregate from each hot bin in succession. The total batch of aggregate is then dry-mixed in the pugmill for approximately 20 seconds, and during this time the operator proceeds to accumulate another batch in the weigh hopper. When the dry-mix cycle is complete, hot asphalt is added to the mixer by either metering or weighing the correct amount. The hot asphalt may be sprayed or dumped into the pugmill, and upon completion of the proper mixing cycle the hot-mix asphalt is delivered through a hopper into trucks hauling to the job site. Figure 1 shows a typical batch plant and identifies potential sources of air pollutants.

The continuous mix plant transfers a preblended mixture of the dried and graded aggregate from the gradation unit by means of a bucket elevator to the mixer. Dry mixing in the mixer is not required, as it is in the batch plant. The hot asphalt is sprayed on the aggregate as it falls from the top of the elevator into the mixer. The length of the mixing cycle in a continuous mix plant is governed by an adjustable dam at the discharge end of the pugmill; the hot-mix asphalt flows over the dam into the discharge hoppers. Mixing time can be varied without changing the hourly tonnage output by varying the height of the adjustable dam. In Figure 2 a typical continuous plant is shown with potential sources of pollutants identified.

2.2.1 Drum Mixing Plants. The processes described above apply to conventional plants now in operation. In recent years, the drum mixing plant (Figure 3) or turbulent mass process has been introduced for the production of asphalt concrete. To date, there are three known plants of this type operating in Canada.

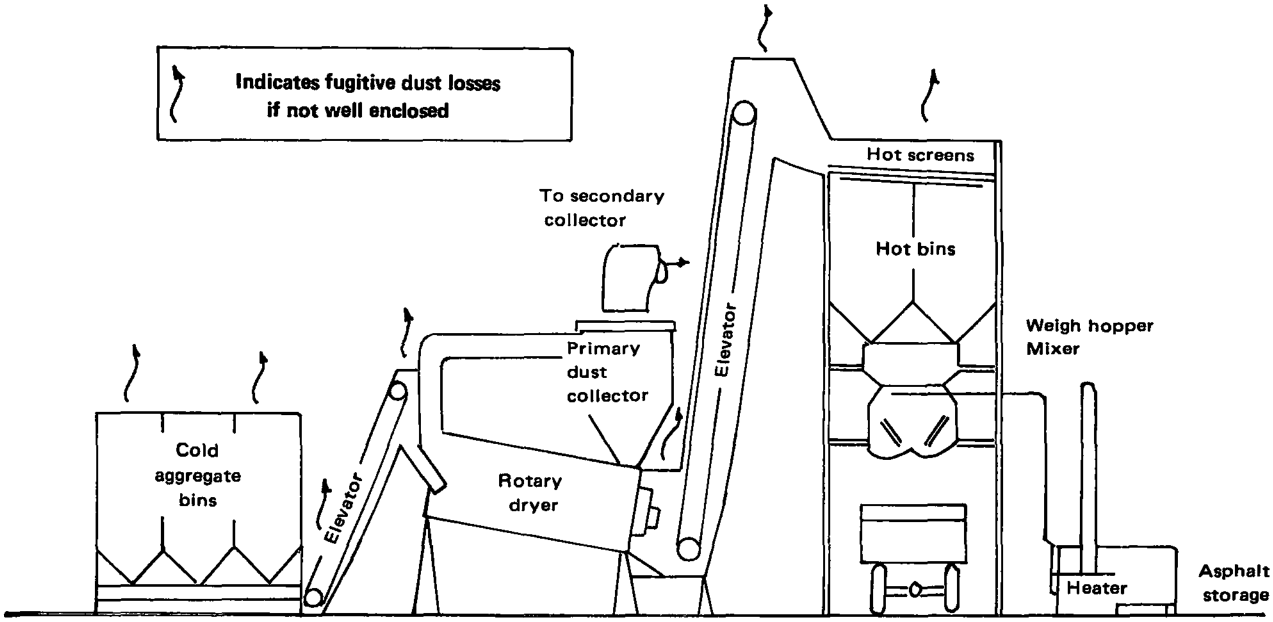

FIGURE 1 TYPICAL ASPHALT BATCH MIX PLANT

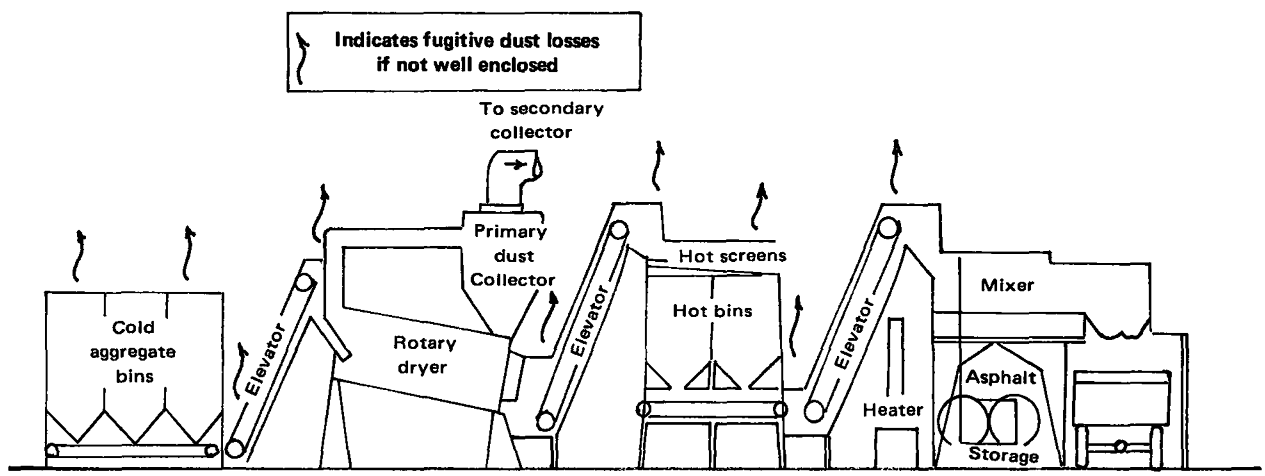

FIGURE 2 TYPICAL ASPHALT CONTINUOUS MIX PLANT

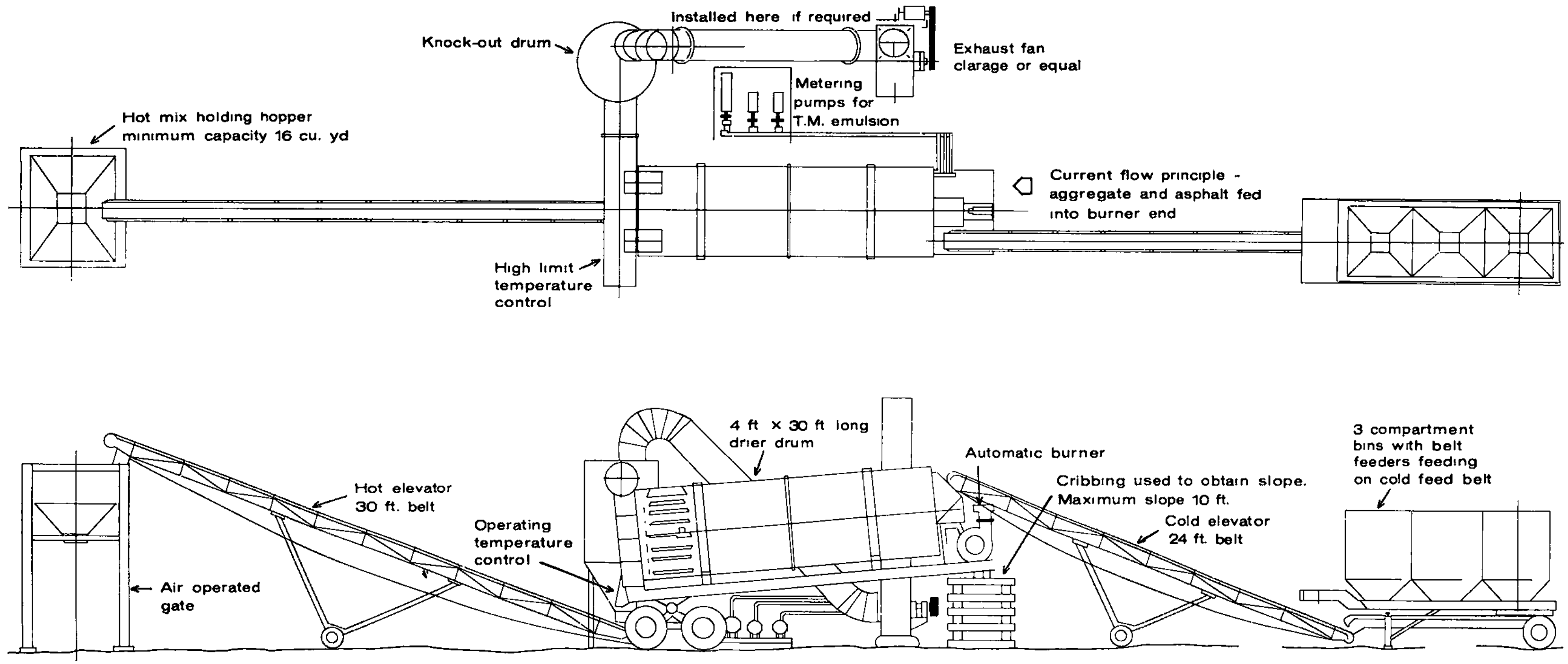

FIGURE 3 DRUM MIXING PLANT

In a conventional hot-mix asphalt process the aggregate is fed to a dryer where the surface moisture is completely removed. It is then transferred from the dryer and mixed with the liquid asphalt in the pugmill or continuous mixer. A drum mixing plant differs from the conventional process in that the asphalt cement and aggregate are heated and mixed in the dryer drum in a single operation.

One advantage of the drum mixing plant is that asphalt production takes fewer operations than with a conventional plant and because the equipment associated with aggregate and asphalt handling is minimal, the capital cost of a new drum mixing plant is roughly 75-85% of the cost of a conventional plant. Moreover, because the aggregate is dried in the dryer simultaneously with the liquid asphalt addition, the amount of dust blown from the dryer to the ambient air is suppressed, and is generally much less than the uncontrolled atmospheric dust emissions from conventional plants.

Some of the disadvantages associated with the drum mixing process relative to asphalt concrete quality and air pollution control are listed below.

(a) The dust particles from the dryer are coated with liquid asphalt and will hinder the operation of a baghouse because of the coating of asphalt on the fabric. It would appear that acceptable control could be accomplished only with a liquid scrubber.

(b) The amount of hydrocarbon emissions and consequently the odor problem is increased over that of a conventional plant.

(c) The aggregate gradation in the raw feed has to be pre-adjusted to meet finished asphalt paving specifications. Conventional plants allow for some segregation of fine material blown from the dryer and thus the overall percentage of minus 200 mesh can be more easily controlled than that produced in a drum mixer.

(d) The residual moisture content of 0.5-2% may present problems in asphalt quality when subjected to freeze - thaw cycles. Some provincial specifications are written to comply with the performance of conventional plants where the dry aggregate is used. The ability of drum mixing plants to meet these specifications is unknown and further testing of the process is required to establish performance in this regard.

2.3 Raw Materials

The two raw materials used in hot-mix asphalt paving plants are asphalt and aggregates. Almost all asphalt used in Canada is a residual product of crude oil distillation. It is produced in a variety of types and grades ranging from hard, brittle solids to low-viscosity liquids. The semisolid form, known as asphalt cement, is the form used in hot-mix asphalt paving plants to mix and coat aggregates.

The most commonly used aggregates are crushed stone and slag, crushed and uncrushed gravel, sand, and mineral filler. Because aggregates normally constitute over 90% by weight of hot-mix asphalt, their properties have an important effect upon the finished product. The control of aggregate properties is as essential as the control of asphalt properties and, for this reason, aggregates are sometimes washed to remove clay, silt, and other extraneous matter.

Aggregates are graded by sieving (or screening) and their principal characteristics are determined by the relative amounts of:

(a) coarse aggregates (those retained on a No. 10 sieve);

(b) fine aggregates (those passing through a No. 10 sieve), and

(c) mineral dust (that passing through a No. 200 sieve).

(A No. 10 sieve has 2.00 mm diameter openings; a No. 200 sieve has 0.074 mm diameter openings.)

Although these are the principal characteristics, specifications normally require a more comprehensive grading. The predominant aggregate mix used by the Canadian hot-mix asphalt paving industry consists of 65% coarse aggregates, 30% fine aggregates, and 5% mineral dust.

Aggregates are produced primarily from naturally occurring materials and because the composition of these materials varies with the geographical area the aggregate composition is a function of location. For example, in British Columbia and Alberta relatively small amounts of mineral dust are found in the aggregate, and mineral dust must be added during the asphalt mixing process. In Nova Scotia and Prince Edward Island, relatively large amounts of mineral dust are found in the aggregate and mineral dust must be removed during the process.

2.4 Plant Equipment

The dryer used to heat and dry the aggregate is the largest source of air contaminant emissions in an asphalt plant. Dryers are usually from 5-9 ft in diameter and from 20-30 ft long. Blended aggregate from the cold aggregate bins is fed, at a continuous rate, to the top end of the sloping dryer at ambient temperature and various moisture content. Heat is supplied by a burner at the lower end of the dryer to maintain a temperature between 290-350 °F. The flow of aggregate is thus counter-current to the flow of hot gases. At the lower end of the dryer, the aggregate is removed via the dry aggregate chute. Total retention time of aggregate in the dryer is about three to four minutes.

Most dryers are equipped with flights, or ledges, parallel to the long axis of the dryer. These flights produce a veil of material in suspension to assist in heat transfer by controlling the flow of aggregate through the drum.

Dryer performance is a result of several interdependent factors each of which is variable and each variation is affected by other factors that are also variable. One manufacturer (3) has found that, all other factors being constant, an increase in production capacity can be effected by the following procedures.

(a) Increasing fuel and air flow. There is no apparent limitation in this procedure although dust carry-out increases and is proportional to the square of the exhaust gas volume.

(b) Increasing the dryer diameter. The production capacity will vary in direct ratio to the drum cross sectional area or to the square of the diameter.

(c) Increasing dryer length. The production capacity will be increased, but at less than a direct ratio.

Heat used to warm and dry the moist aggregate is lost during the process. This heat loss is caused by incomplete combustion; heating up the volume of exhaust gases from ambient temperatures to the stack discharge temperature; and radiation losses through the dryer shell and combustion chamber.

The amount of dryer fuel required per ton of product is primarily a function of the moisture content of the cold aggregate. Aggregates with a moisture content of 3% normally require about 1.5 imp gal of oil (or about 230 standard cubic feet of natural gas) per ton of product; those with a moisture content of 5% require about 2.3 imp gal of oil (or about 360 standard cubic feet of natural gas) per ton of product. Plants in eastern Canada normally burn residual oil; those in western Canada normally burn natural gas, bottled butane, or distillate.

The amount of exhaust gases from the dryers can be determined, approximately, from the following formula:

$$\text{scfm} = 137.5 \times \text{production rate}^{*}$$

where scfm delineates the flow in standard cubic feet per minute (70 °F and a pressure of one atmosphere) and the production rate is expressed in tons per hour (at 5% moisture content and 50% excess air). The volume of exhaust gas required to dry each ton of aggregate increases by more than 10% for each additional percent of moisture removed. Maintaining a production rate with increased moisture means that more exhaust gas may be created from combustion and evaporation of water than the fan can remove. This causes the pressure in the drum to become greater than the outside air. The back pressure thus created causes the familiar puff-back at the burner opening.

Typical exhaust gas temperatures at the exit of the rotary dryer are 250-350 °F. The resultant stack exit temperature is a function of heat loss due to duct length and control equipment. Asphalt application temperatures in the mixer are normally specified and depend on the gradation of the aggregate. The minimum temperature required is 225 °F. To attain this temperature asphalt heaters, either electric, gas- or oil-fired, are used.

3 AIR CONTAMINANT EMISSIONS

3.1 General

Contaminants released to the air during the operation of hot-mix asphalt plants are both gaseous and solid. Gaseous emissions result from combustion of fuel in the dryer burner, the hot asphalt heater and, if electricity is generated on site, from the generator set. There is also some release of odorous vapors from the hot asphalt in the mixer and from the trucks hauling the mix from the plant. Particulate emissions consist of smoke from the dryer burner and hot oil heater (and from the generator, if present), and dust primarily from the dryer exhaust.

* Manufacturers Data - Cedarapids

3.2 Gaseous Emissions

Combustion of fuel in the plant produces combustion products which vary with the type of fuel and efficiency of combustion. From an air pollution control viewpoint, the important combustion products are carbon monoxide, oxides of sulphur, (sulphur dioxide and sulphur trioxide), and oxides of nitrogen (nitrogen oxide and nitrogen dioxide). Emissions of sulphur oxides are essentially fixed by the sulphur content of the fuel; nitrogen oxides are always formed when air is heated by a high temperature flame, and appreciable carbon monoxide emissions occur when the combustion process is poorly controlled.

Offensive odors around a hot-mix asphalt paving plant normally originate from the stack, from the hot-mix trucks beneath the pug mill, and from the asphalt. Odors from the stack may consist of sulphur dioxide or unburned hydrocarbons; odors from the hot-mix trucks are normally caused by the mix coming into contact with kerosene- or fuel oil-coated truck bodies; odors from the asphalt may be hydrogen sulphide and/or combinations of hydrocarbons and sulphur, and may emanate from the asphalt tank, the pug mill, and the hot-mix trucks.

Large quantities of water are generated as steam from the drying of the aggregates in the rotary dryer. At an average moisture content of about 5% of the weight of the raw feed, a typical 250 ton per hour plant will generate approximately 12.5 tons of water per hour or 40 gallons of water per minute. This quantity is variable depending upon location and climatic conditions. However, this rate could result in an objectionable plume opacity or the vaporized water may react with the other gaseous products and cause corrosion of the surrounding property. The steam produced could be condensed in a wet scrubber and, with a suitable settling pond, the water could be used to aid in sustaining operation of the scrubber system.

3.3 Particulate Emissions

Stone dust, fly ash, soot, and unburned droplets of fuel oil are the main types of particulate resulting from the operations of hot-mix asphalt paving plants. The predominant particulate emission is stone dust and its major source is the dryer. Other sources of particulate emissions include the screens, open bucket elevators, weigh hoppers, asphalt heaters, storage piles and bins, and traffic dust from the yard. Particulates from the dryer are normally termed "dryer dust"; those from the screen cover, weigh and mix area, and hot material elevator are usually called "fugitive dust".

The solid particles formed during oil or gas combustion are fly ash or soot. Fly ash results from the impurities in fuel oil which create a solid combustion product. Fly ash particle sizes range from 1-100 microns (μ). The amount of fly ash produced is a function of the oil type with residual oils producing a higher proportion of fly ash than distillate oils. Soot consists of unburned carbon particles, resulting from incomplete combustion. The individual particle size of soot is below one micron; however, these particles adhere to one another and agglomerate into much larger particles.

With poor combustion, unburned oil droplets are either emitted from the stack or deposited on the aggregate in the dryer. As they are somewhat sticky other contaminants tend to adhere to them causing larger particles to be formed.

Stone dust ranges in size from 0.1 μ to more than 300μ. The amount of dryer dust depends upon the dryer design and operation, and the aggregate makeup. Studies in the Los Angeles area have shown that, all other factors being the same, the amount of dryer dust increases linearly with the amount of mineral dust in the aggregate. In another similar study it was found that the increase in the amount of dryer dust is proportional to the square of the drum gas velocity index where the drum gas velocity index is defined as the volumetric flow rate of the dryer exhaust gases divided by the cross-sectional area of the dryer (3). (For example, increasing the drum gas velocity index by 50%, from 600 to 900 ft/min, would increase dryer dust by 125%).

In the dryer, the smaller particles are more readily affected by the dryer gases than are the larger ones, as illustrated in Table 2 which provides a comparison of the size distribution of the aggregate and the dryer dust. For example, 5.5% by weight of the cold aggregate will pass through a 200 mesh screen, whereas at a drum gas velocity index between 550 and 650 ft/s, 78% by weight of the dryer dust will pass through a 200 mesh screen. Table 3 shows typical amounts of dryer dust in the minus 200 mesh size range expressed as a percentage of minus 200 mesh cold aggregate entering the dryer, for various drum gas velocity indices (4).

EXAMPLE

Given: 150 tons per hour (TPH) plant
7 ft dryer diameter (38.5 ft^2 cross sectional area)
Flow rate 21 000 acfm
5% minus 200 mesh material content in cold aggregate

$$\text{Velocity Index} = 21\ 000\ \text{ft}^3/\text{min} \times \frac{1}{38.5\ \text{ft}^2} = 545\ \text{ft/min}$$

(Assume 550 ft/min)

Amount of minus 200 mesh material into dryer:

= 150 tons/h x 2000 lb/ton x 0.05
= 15 000 lb/h

Amount of minus 200 mesh material from dryer (Table 3)

= 15 000 x 0.45 = 6750 lb/h

Total dryer dust (Table 2)

= 6750 lb/h x 1/0.78 = 9375 lb/h

This would mean that 2.9% by weight of the cold feed was entrapped by the dryer exhaust gases.

TABLE 2 SIZE DISTRIBUTION COMPARISON OF COLD FEED AND DRYER DUST

Size (μ)	Mesh size	Typical cold feed passing mesh sizes (%)	Typical dryer dust passing mesh sizes for various velocity indices (%)		
			550–650	650–750	750–850
3360	6	56.5	100	100	100
1680	12	43.5	100	100	98.5
840	20	31.5	100	97.5	96
420	40	21.0	96	94	91
149	100	10.0	88	83	78
74	200	5.5	78	72	64
44	325	3.3	68	60	53
20		1.4	51	42	35
10		0.6	35	28	21

TABLE 3 CORRELATION OF MINUS 200 MESH DRYER DUST AND DRUM GAS VELOCITY INDEX

Drum gas velocity index (ft/min)	Dryer dust passing 200 mesh %
550–650	45–55
650–750	60–70
750–850	80–90

Dust collection in asphalt plants is mainly concerned with particulate sizes ranging from 1-100μ. Figure 4 shows that about 5% of the cold aggregate is minus 200 mesh. The dust reaching the primary dust collector is about 70% minus 200 mesh and is the fraction of greatest interest in air pollution control.

In addition to dryer dust, fugitive dust may emanate from the cold feed conveyer, the hot material elevator, the plant tower and reject chutes and bins. It will usually amount to about 10% of the total dust output of a plant (2). Vehicle travel over unpaved roads and dust picked up from aggregate stock piles by the wind may also create dust problems.

As high efficiency collection systems are very dependent upon sizing below 40μ, Figure 4 can be used to size the dust loading from the dryer exhaust and to evaluate collection system performance.

4 CONTROL EQUIPMENT

4.1 General

Collectors for dryer dust have a wide range of efficiencies and corresponding costs. Collection efficiencies in excess of 99% by weight are attainable with some collectors. The actual collector efficiency, however, is dependent on particulate characteristics such as grain size distributions, particle shape, density and abrasiveness. Therefore, an efficiency can be accurately stated only for specific applications and known particle characteristics.

The two general types of particulate control equipment are wet and dry collectors. Each is considered below.

4.2 Expansion Chamber

The simplest and cheapest dry collector is the expansion chamber (or settling chamber) shown in Figure 5. This is the oldest known dust collector and is designed to effect a large decrease in the flow velocity via a large increase in the cross-sectional area. Large particles settle out by the action of gravity. The air velocity must be uniform and low; for best results, the velocity should be 60 ft/min or less. Efforts have been made to improve the efficiency of expansion chambers by the addition of closely spaced, horizontal shelves placed within the chamber to provide more uniform air distribution. This type of chamber has never been widely used because of the difficulty in removing the settled dust from the horizontal plates.

The "skimmer" is basically an expansion chamber with the addition of one or more baffles to change the direction of the gas stream and resulting in increased efficiency. The impinging of dust particles on the baffles further reduces their velocity, causing more and smaller dust particles to be deposited from the gas stream.

While settling chambers and "skimmers" are simple in design and can be manufactured from almost any material, they are rarely used alone because of their large space requirements and relatively low collection efficiency. They rarely achieve an efficiency of dust removal higher than 50% by weight. The smallest particle that can be collected by the normal expansion chamber is about 40μ in diameter. Multiple tray chambers and skimmers can ordinarily collect particles 15 - 20μ in diameter or larger.

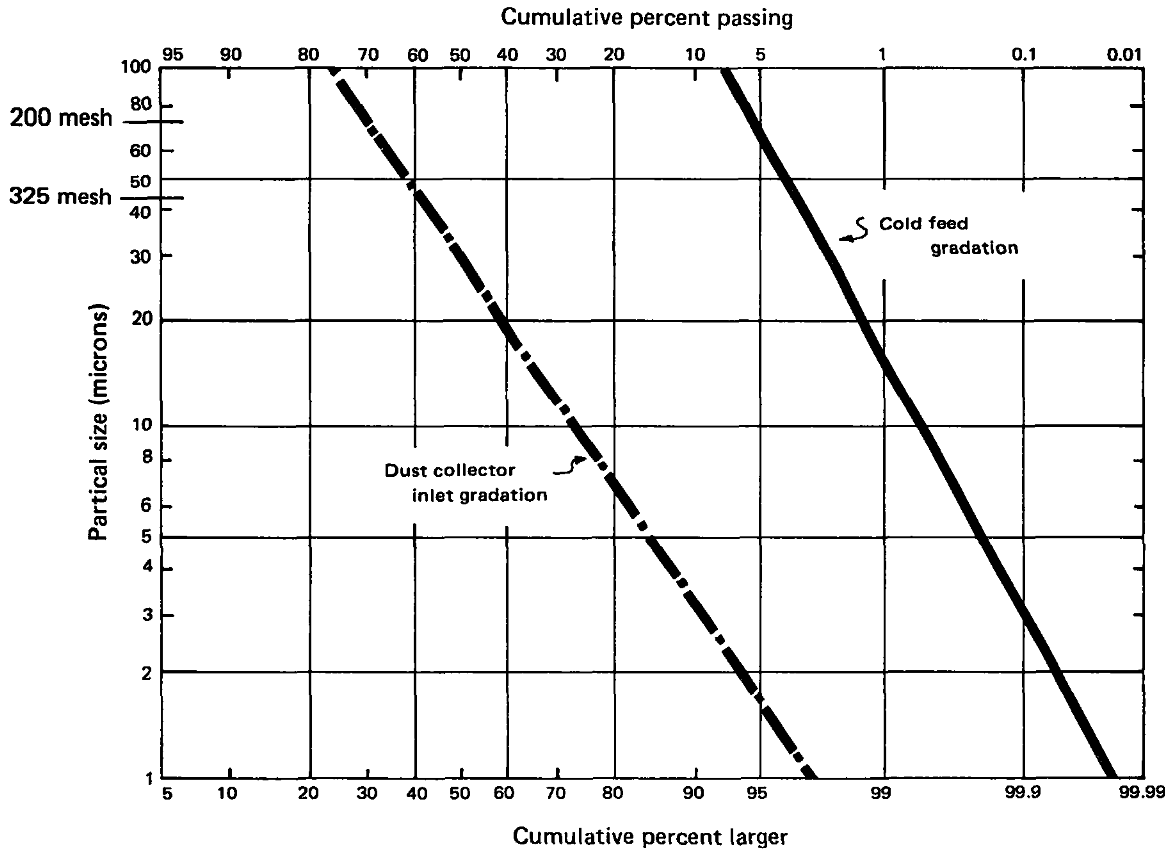

FIGURE 4 TYPICAL COLD FEED GRADATION AND PRIMARY DUST COLLECTOR INLET GRADATION

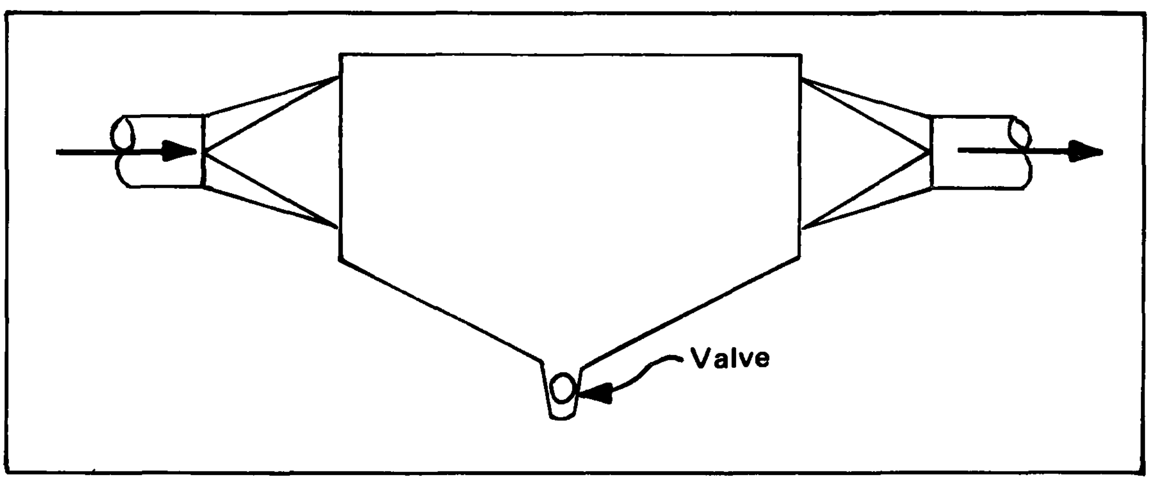

FIGURE 5 EXPANSION CHAMBER

4.3 Cyclone Collectors

Cyclone collectors (or cyclones) operate in the low (50 - 70%) and medium (70 - 80%) overall efficiency ranges, depending on the size of the particulate matter handled and the characteristics of the cyclone. The principle of operation of a cyclone is dust removal via centrifugal force. Dust-laden gases are spun rapidly so that the larger particles are forced to the collector walls and subsequently removed.

A typical cyclone is illustrated in Figure 6. Dust-laden gas tangentially enters the annular space between the cyclone body and the outlet tube, and begins to traverse a helical path (shown by the solid flow line) called the "main vortex". Near the bottom of the cone, the axial direction of the helix reverses, as shown by the dotted line, and forms the "vortex core". The tangential velocity is greatest at a radial distance from the centerline of 0.4 to 0.8 the radius of the gas outlet tube. The diameter of the vortex core is usually 0.2 to 0.4 times the diameter of the gas outlet. The tangential direction of flow is the same in both the main vortex and the vortex core, so that centrifugal separating forces are exerted on the particles in both sections of flow. The eddy flow in the top of the cyclone is troublesome because the direction of flow is such that dust-laden air is carried down the outside walls of the gas outlet to the opening, and some dust is lost into the outlet at this point.

Several, general statements can be made concerning cyclone collectors:

(a) For a given volume of gas, decreasing the diameter of a correctly sized cyclone will increase the collection efficiency and require an increased pressure drop across the unit.

(b) Large particles are more efficiently collected than are small particles of the same density.

(c) The greater the number of correctly sized cyclones used for a given gas flow rate, the lower the power cost to obtain the same collection efficiency (for a given particle size distribution). Conversely, for the same power cost as a single collector (for a given particle size distribution), a multiple cyclone arrangement will have a collection efficiency that increases with the number of individual cyclones used.

(d) Efficiency increases with an increase in dust loading and gas inlet velocity.

"High efficiency" or "small diameter" cyclones are generally considered to be those nine inches or less in diameter. Typical efficiency ranges for various particle sizes are shown in Table 4.

Typical fractional efficiency curves for a cyclone are shown in Figures 7 and 8. Figure 7 illustrates the rather dramatic variation in cyclone efficiency with particle size. Figure 8 illustrates variation of efficiency with inlet velocity and cyclone diameter.

The advantages of a multiple cyclone collector arrangement were mentioned above. Multiple cyclones are normally operated in parallel. Care must be taken to ensure that equal gas and particulate loadings exist among the tubes. Two such arrangements are shown in Figures 9 and 10. An overall collection efficiency of 90 to 95% may be obtained with particles greater than 10μ using the arrangement shown in Figure 10.

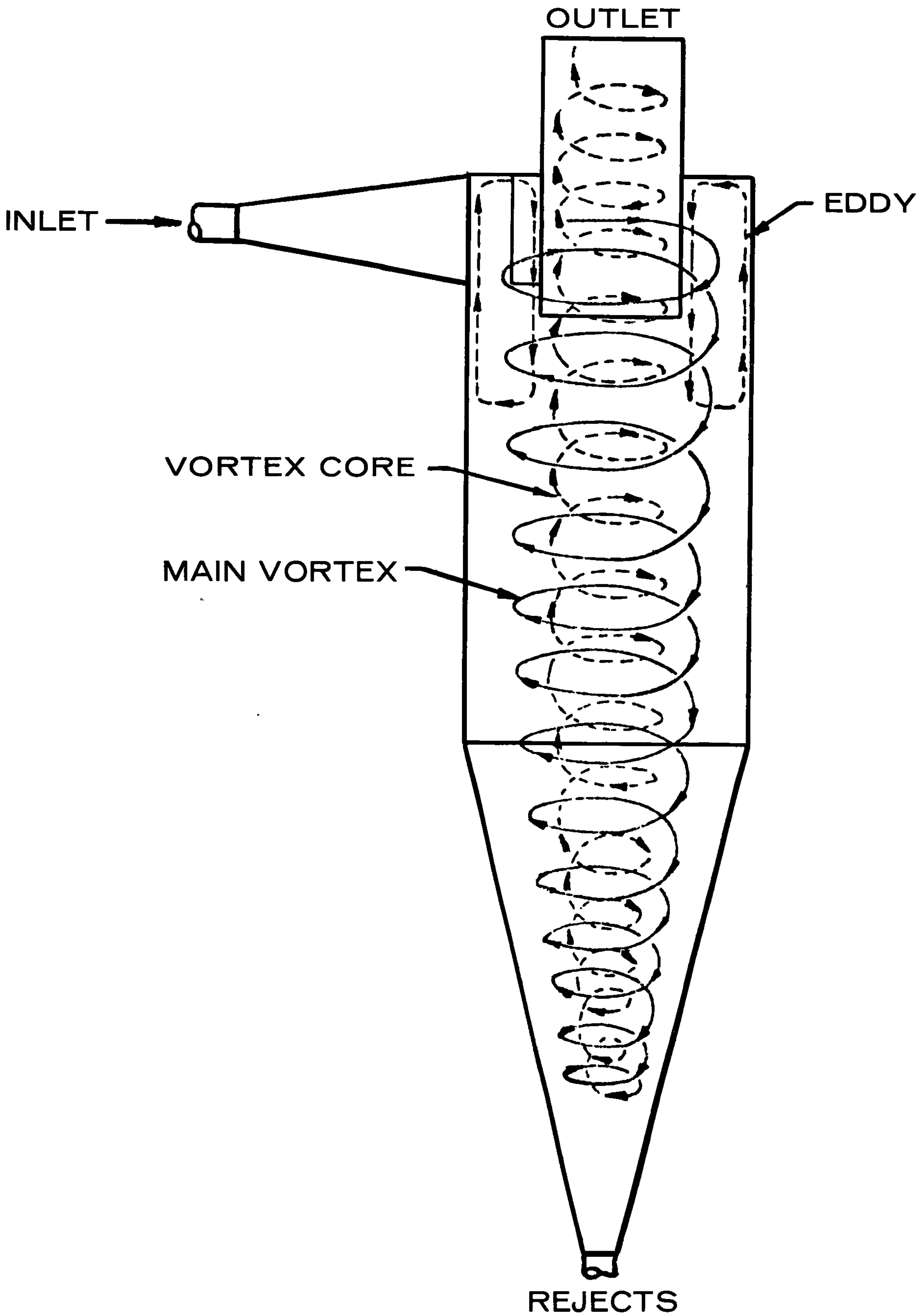

FIGURE 6 TYPICAL CYCLONE

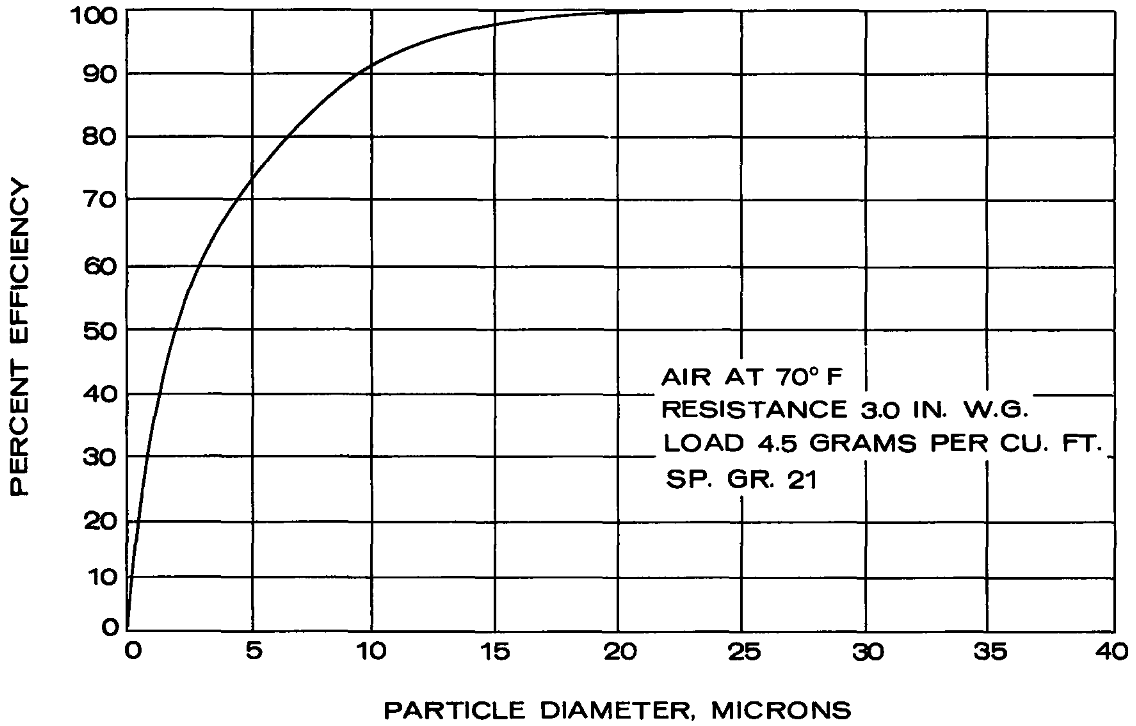

FIGURE 7 GENERAL VARIATION OF CYCLONE EFFICIENCY WITH PARTICLE SIZE

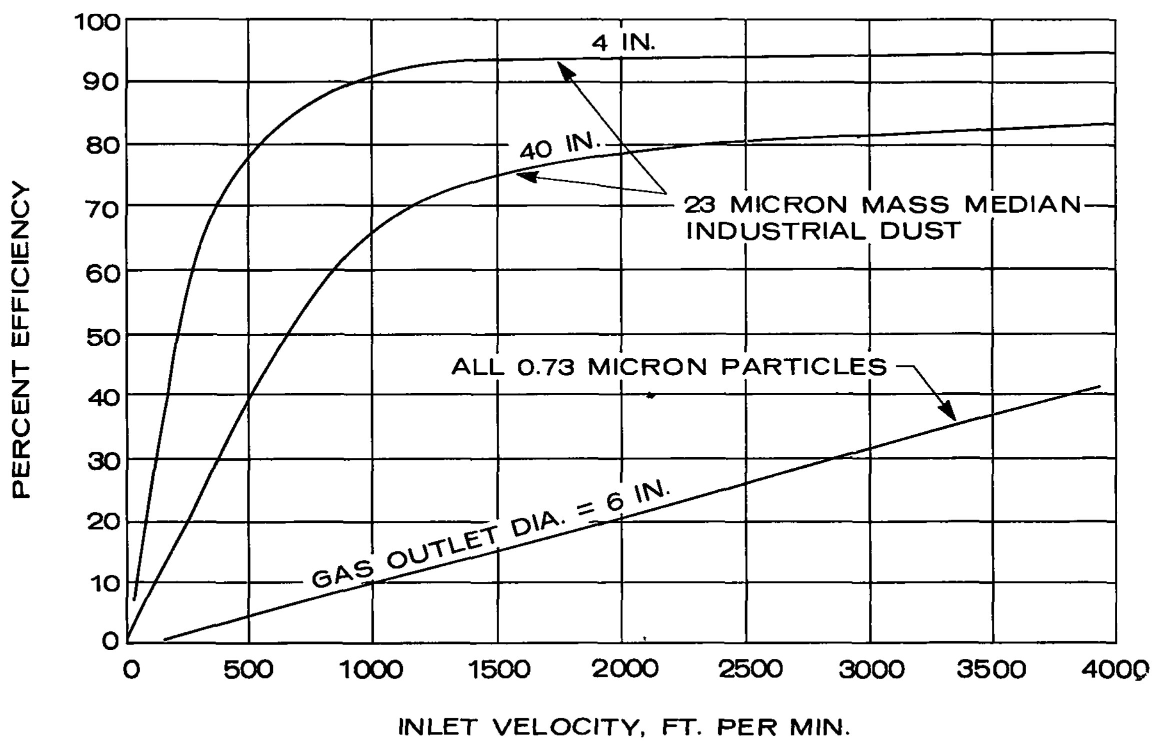

FIGURE 8 GENERAL VARIATION OF CYCLONE EFFICIENCY WITH INLET VELOCITY AND CYCLONE DIAMETER

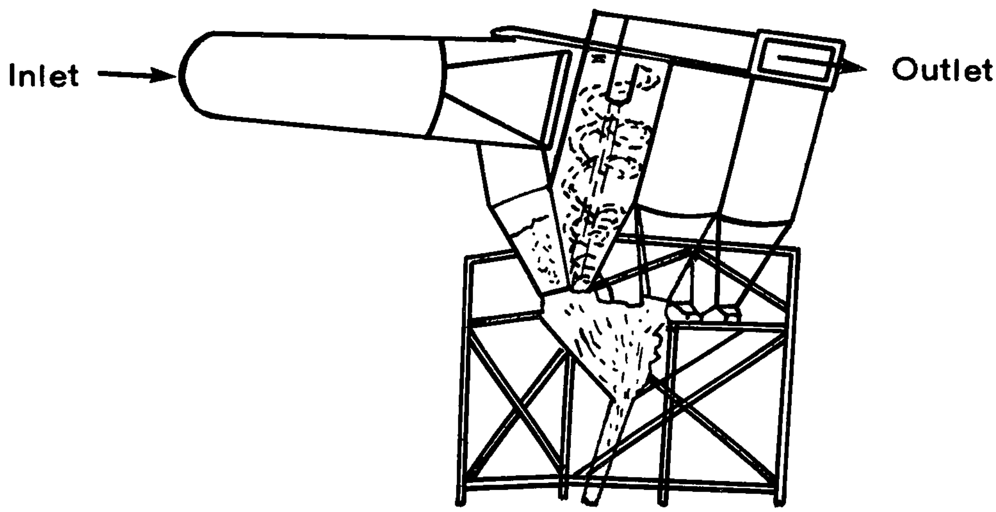

FIGURE 9 GROUP OF SIX MEDIUM CYCLONES

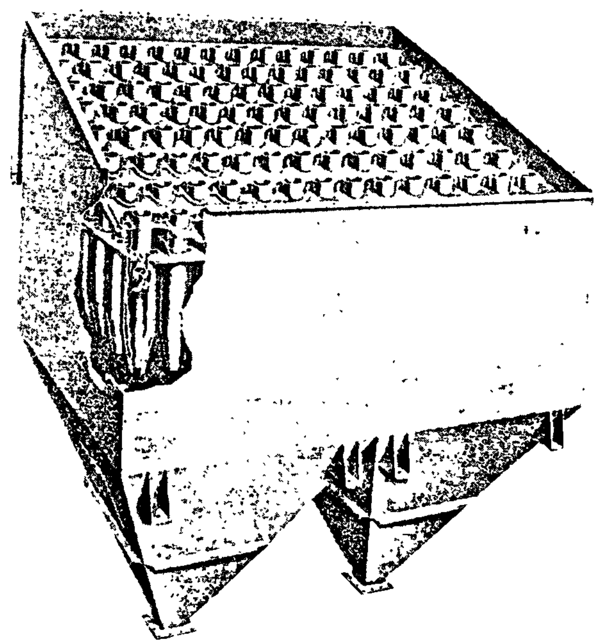

FIGURE 10 TYPICAL BANK OF SMALL DIAMETER CYCLONES

TABLE 4 TYPICAL EFFICIENCY RANGES FOR CYCLONE COLLECTORS

Size range (μ)	Efficiency (%) Conventional cyclone	High efficiency cyclone
5	....	50 - 80
5 - 20	50 - 80	80 - 95
15 - 20	80 - 95	95 - 99
40	95 - 99	95 - 99

As indicated above, cyclone pressure loss depends upon a number of variables. For most applications the pressure loss will be from less than one to about eight inches water gauge.

Because of their simplicity of design, cyclones are the most trouble-free particulate collectors available. In addition to erosion and corrosion, plugging of the dust outlet or cake buildup on the walls are the two most common operating problems encountered. The corrosion problem can be minimized by proper design. Depending on the cause of the problem, cake buildup on the walls of a cyclone can be minimized by several methods including the elimination of condensation through insulation, increasing inlet velocity, electropolishing of inner walls, and removal of precleaners (if any) to allow scouring of walls by coarse material. With multitube units a major operating problem is often caused by leaking gaskets at the tube-header joints.

Because cyclones have a large diameter, buildup of layers of particulates does not appreciably affect pressure loss; consequently flow variations in the system due to changes in operating resistance are minimal.

The main use of cyclone collectors in hot-mix asphalt plants has been as primary collectors.

4.4 Baghouse Collectors

The application of a baghouse or the modern fabric dust collector is comparatively new to asphalt plant air systems. It is one of the most reliable of the high efficiency devices available for the collection of dry particulate matter. Many types of fabric filters are available together with many cleaning methods.

The performance of fabric filters (or baghouses) depends on the properties of the gas stream to be filtered, the properties of the fabric used for the bags, and the modes of operation used for filtration and for bag cleaning. Generally speaking, the efficiency of collection is not affected to any great extent by small variations in the air to cloth ratio (6), particulate size, shape or distribution of aggregates. Emission levels from baghouses are about the same for a wide variety of aggregate feedstocks.

Baghouses are inherently high efficiency devices as long as the fabric used permits a good dust cake buildup and prevents dust particles from blowing straight through. Discounting the above conditions and also the start-up and shut-down periods inherent to the industry, efficiencies obtained are often greater than 99.9%.

There are two basic design procedures that apply to present fabric filters: primary filtration by the filter material; and primary filtration by a cake of particles built up on the front of a filter. Filters in which the fibres act as the primary removal mechanism are often referred to as "fibrous" or "felts". They are usually made from many small strands of fine fibres having an average diameter of about 10μ.

For cake filtration, woven cloth in which the material is smooth and plain with relatively large holes between the threads is usually used. The cloth acts as a support for particulate cake build-up and effective filtration is obtained only when the gaps between the threads are covered with caked particulate.

Particle collection during filtration occurs as a result of one or more of the following mechanisms: inertial impaction, interception, and diffusion. These mechanisms can occur singularly or in combination. The extent to which a mechanism prevails is determined by the structure of the fabric and the size of the dust particles. Recent tests (5) have shown that:

(a) the efficiency of collection by the diffusion mechanism decreases with increasing particle size;
(b) at about 0.9μ both impingement and diffusional efficiencies are lowest; and
(c) the efficiency of collection by the impaction mechanism tends to increase with particle size.

The combination of the above phenomena accounts for the dip at approximately 0.9μ in the efficiency curve shown in Figure 11.

The above results apply only before particles accumulate on the fabric. After sufficient operating time, usually about 10 min for typical units, a deposition of the particulates forms on and within the fabric fibres to account for the increase in filtration efficiency. The importance of this formation on filtration efficiency can best be shown by Table 5.

As the filtration process proceeds, the mass of the dust or filter cake increases so that the resistance of the fluid medium to flow (filter drag) also increases. This necessitates the designing of equipment to permit periodic removal of accumulated solid material. Despite the effectiveness of cleaning, a residual dust layer will be present on the filter fabric at all times after its initial exposure. The collection efficiency of baghouses depends on the cleaning mechanism or cleaning cycles used.

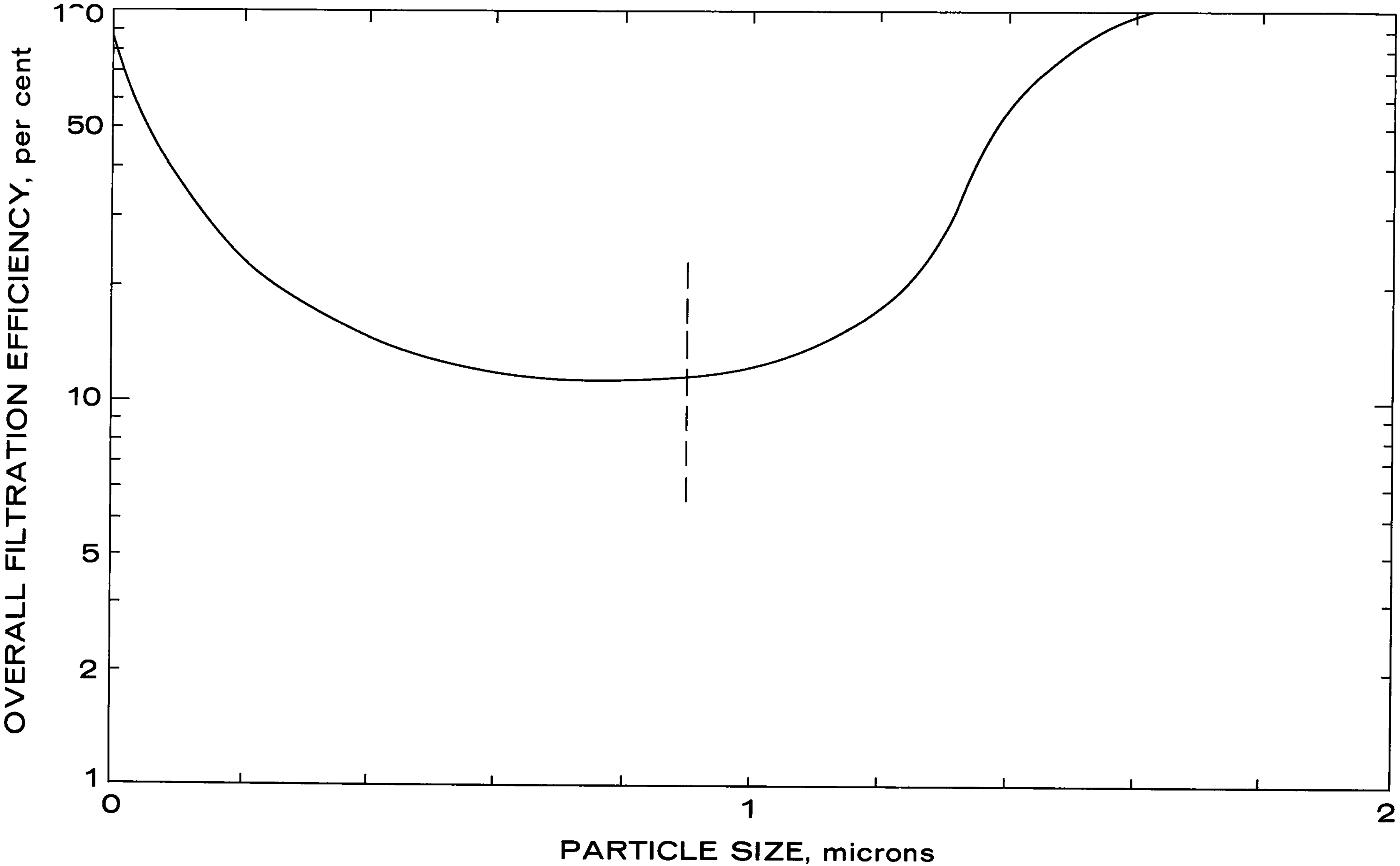

FIGURE 11 GRADE EFFICIENCY CURVE FOR FIBRE FILTER BEFORE PARTICLE ACCUMULATION

TABLE 5 EFFECT OF DEPOSITED DUST ON FILTRATION EFFICIENCY (6)

Fabric	Aerosol Efficiency % New clean cloth	After dust deposition	After cleaning by blowback
Lightweight plain cloth (synthetic fibre)	2	65	13
Heavy raised-surface cloth (synthetic fibre)	24	75	66
Heavy raised-surface cloth (natural fibre)	39	82	69

4.4.1 ***Cleaning Mechanisms.*** Two of the most common cleaning mechanisms used for baghouses on asphalt installations are the shake mechanism and the reverse air pulse. Bags are most commonly shaken from the upper fastening by various combinations of horizontal and vertical motions. The bags may all be fastened to a common framewall which moves horizontally through a common linkage. The cleaning cycle is actuated by a pressure switch and timer and the entire cycle may take from 30 seconds to a few minutes.

In the reverse air pulse system, a low pressure reversal of the air flow is usually enough to loosen the cake. This is accomplished by a damper and by-pass arrangement with either the primary fan exhaust gas or a secondary compressed air system providing the air reversal to complete the cleaning cycle. To minimize flexural wear of the fabric the bags are supported by a metal grid, mesh or rings, and are usually kept under light tension. Total time for the entire cleaning cycle is considerably less than that for the shake mechanism.

Effective cleaning is accomplished by the removal of the desired amount of deposit from the fabric quickly and uniformly without:

(a) removing too much of the residual deposit which greatly improves the collection efficiency of woven fabrics at the start of subsequent filtering cycles;

(b) damaging the cloth or using too much power, either of which can be a substantial part of the operating cost; and

(c) excessively dispersing the removed dust particles, leading to reentrainment.

4.4.2 ***Baghouse Types.*** Baghouses are generally referred to by their construction as either compartmented or uncompartmented. The compartmented bag collector (Figure 12) is used with either reverse air flow or shaker type bag cleaning. This type of collector is divided into several compartments,

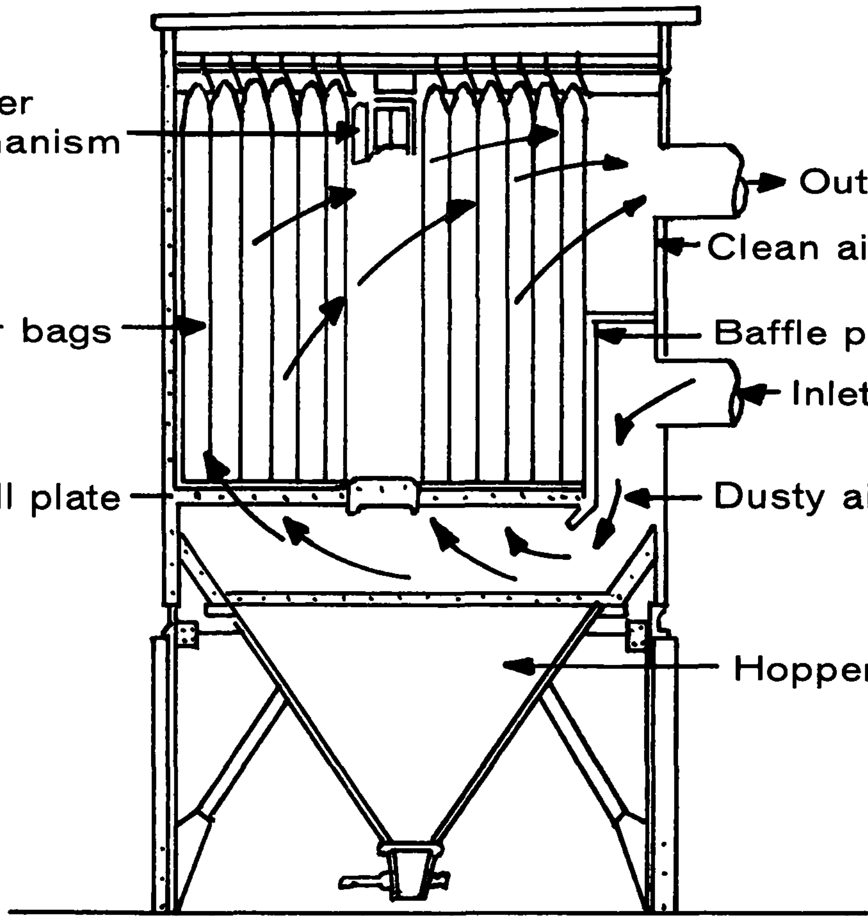

FIGURE 12 SINGLE COMPARTMENT BAGHOUSE FILTER

each with its own damper and bag cleaning system. One compartment at a time can be taken out of service to release the dust from the bags into the bottom hopper. The dust-laden air enters the collector and passes through the inside of the bags where the dust is filtered out of the system. The bags are self-supporting because the air is cleaned while flowing from the inside out. The bags are usually constructed of woven materials. The air to cloth ratio or air velocity must be kept low for this type of collector. It is usually between 2 and 3 cfm of air per square foot of cloth surface.

The uncompartmented bag collector (Figure 13) employs the use of compressed air to sharply reverse the flow through the bags to apply a shock to the dust cake. This permits the use of high air to cloth ratios or air flow rates of 5 to 6 cfm per square foot of cloth surface. In operation, the dirty air enters the hopper, rises upward around the outside of the bags and passes through the fabric from the outside surface of the bag. The clean gas passes upward through the inside of the bag, and out an open end to an air exhaust manifold. This type of collector requires wire cages or some type of support inside the bags to prevent them from collapsing. The cleaning of the bags is done in small groups and does not affect the dryer air volume. A very sturdy fabric must be used because of the high level of energy used in cleaning the bags, and because the cloth is repeatedly moving on and off the bag cages during cleaning.

The high humidity in the asphalt plant stack gases, resulting from both the moisture content of the aggregate and the combustion of the fuel, requires the use of insulation on the baghouse structure to keep the moisture-laden air above the dew point and prevent condensation within the collector. This dew-point control is particularly important for the efficient cleaning of the dust cake formed on the fabric, and to prevent the adverse effects of SO_2 in the stack gases from causing acid attack on the fabrics. With termperatures in the range of 200-250 °F for stack gases issuing from plants with dry collection systems, it is advisable to employ fuels containing less than 2.0% sulphur by weight to prevent the acid dew point of H_2SO_4 from being reached.

4.4.3 Baghouse Fabrics. Of the many fabrics that can be employed in baghouses, the two that have been found most suitable for use in the asphalt industry are glass and Nomex type nylon. Glass can be woven into filament yarns or bulky fill yarns which are finished or treated with a lubricant such as silicone to prevent fibres from breaking through self-abrasion during flexing. This type of material is satisfactory for continuous operation at temperatures up to 500 °F. "Nomex" can be woven, all spun or felted and it can withstand temperatures up to 400 °F.

Good quality fabric, proper cleaning, and the proper attachment of the filter to the gas manifolds will result in bag life in the order of 10^4 to 10^7 flexing cycles. A Chicago plant operating for three years with a baghouse and processing about 350,000 tons of asphalt, has found it necessary to replace only 80 bags out of the original 400 during the three years of operation (6). From examination of numerous bag ruptures it has been concluded that the majority of bag failures occur either along the sewn seams or through abrasion on the wire cage. Through better bag design and improved attachment methods it should be possible to extend the life of a bag to about five years.

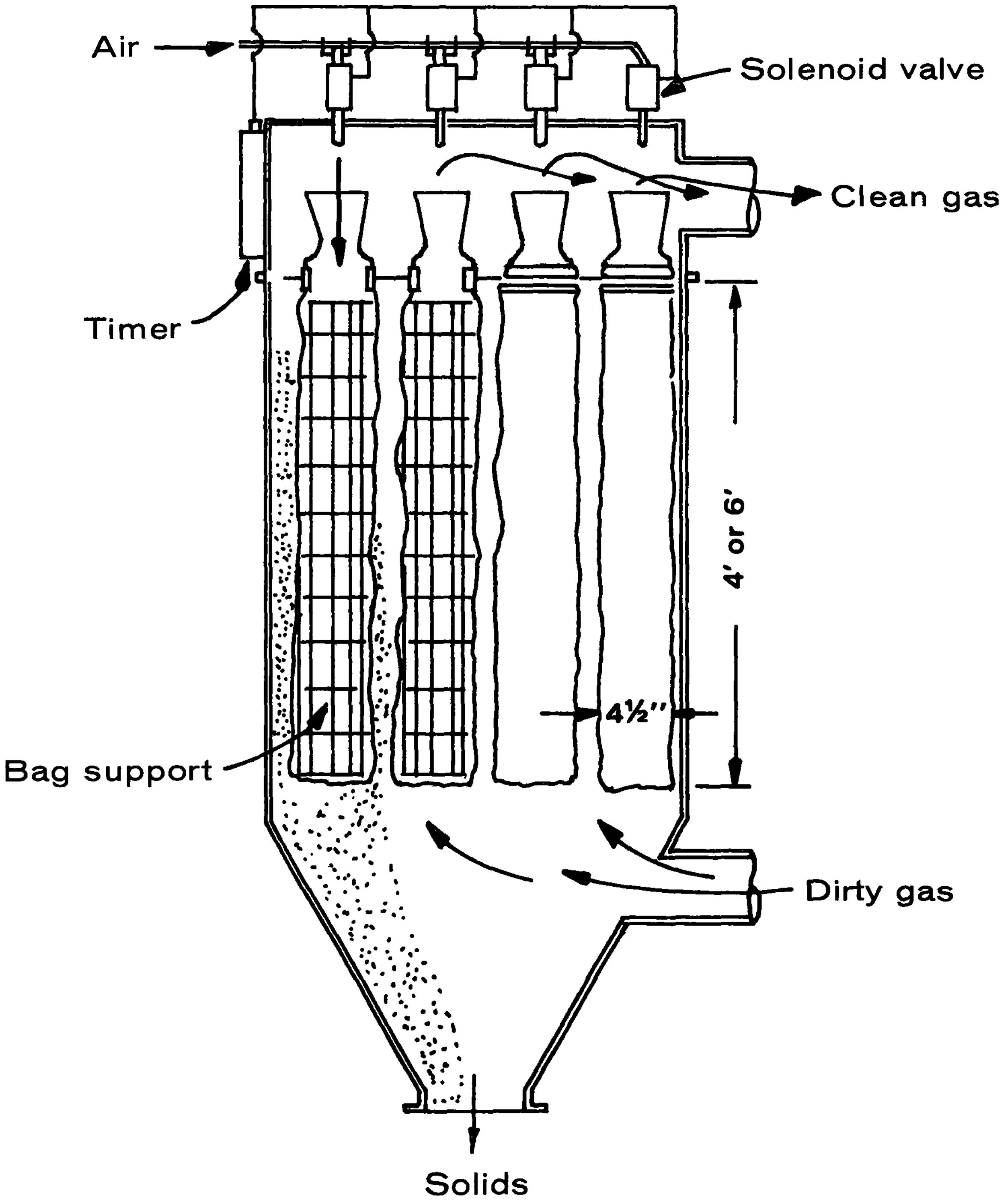

FIGURE 13 UNCOMPARTMENTED BAGHOUSE FILTER

The power costs for operation of a baghouse are a partial function of the cleaning frequency. The majority of installations operate under an air resistance of approximately 5-6 in. of water column. Some newer installations have reported operations as low as 4 in., but it is probably desirable to operate at 5-6 in. of water to prolong bag life by using less frequent cleaning.

4.5 Wet Collectors or Scrubbers

Wet collectors or scrubbers are devices in which the prime means of collection is a liquid, introduced into the collector for contact with the aerosol. The liquid employed in scrubbers for asphalt plants is water. Methods of effecting contact between scrubbing water and carrier gas include spraying the liquid into open chambers, or chambers containing various forms of baffles, grilles or packing; flowing the liquid into these structures over weirs; bubbling the gas through tanks or troughs of water; and utilizing gas flow to create droplets from liquid introduced at a location of high gas velocity. The water can frequently be recirculated to the scrubber after the collected contaminant is partially or completely removed. In general, as long as the interior elements of the scrubber remain clean, pressure drop does not increase with time but usually becomes larger as gas flow rate increases. Collection efficiency varies directly with gas flow rate, provided that the water keeps pace with gas flow and that carry-out of liquid with the effluent gas is effectively prevented.

The contact power concept states, generally, that the increase in efficiency of a wet collector is proportional to the increase in power providing contact between the liquid and the aerosol. Technology is now being directed toward developments to obtain maximum contact between the two phases at reduced energy input.

Wet collectors are usually classified on the basis of the most important particulate separation mechanism designed into the devices. This approach is not necessarily well defined because multiple effects occur and basic design types tend to overlap. The classification of wet scrubbers is sometimes done on the basis of the energy required to overcome the static resistance of the units. In general, wet scrubbers can be classified as follows:

Centrifugal or Cyclonic	–	low energy
Orifice	–	medium energy
Venturi	–	high energy

Those most commonly used in asphalt plants are the centrifugal and the orifice types.

4.5.1 Centrifugal Scrubbers. Centrifugal type scrubbers (Figure 14) are in wide use in the asphalt paving industry and generally give satisifactory results without serious maintenance problems. They may have single or multiple spray chambers into which the dust-laden gas stream is introduced tangentially. There may be as few as five or as many as sixty spray nozzles in each chamber.

In operation, the contaminated air stream enters the lower section of the unit where centrifugal motion is imparted and initial wetting is used to remove the large dust particles from the gas stream. The gas stream then passes through directional vanes and one or more washing stages causing impingement and inertial separation. Both the gaseous and particulate-carrying water particles form a film of sludge on the walls which flows down to a sump at the bottom of the scrubber and is removed

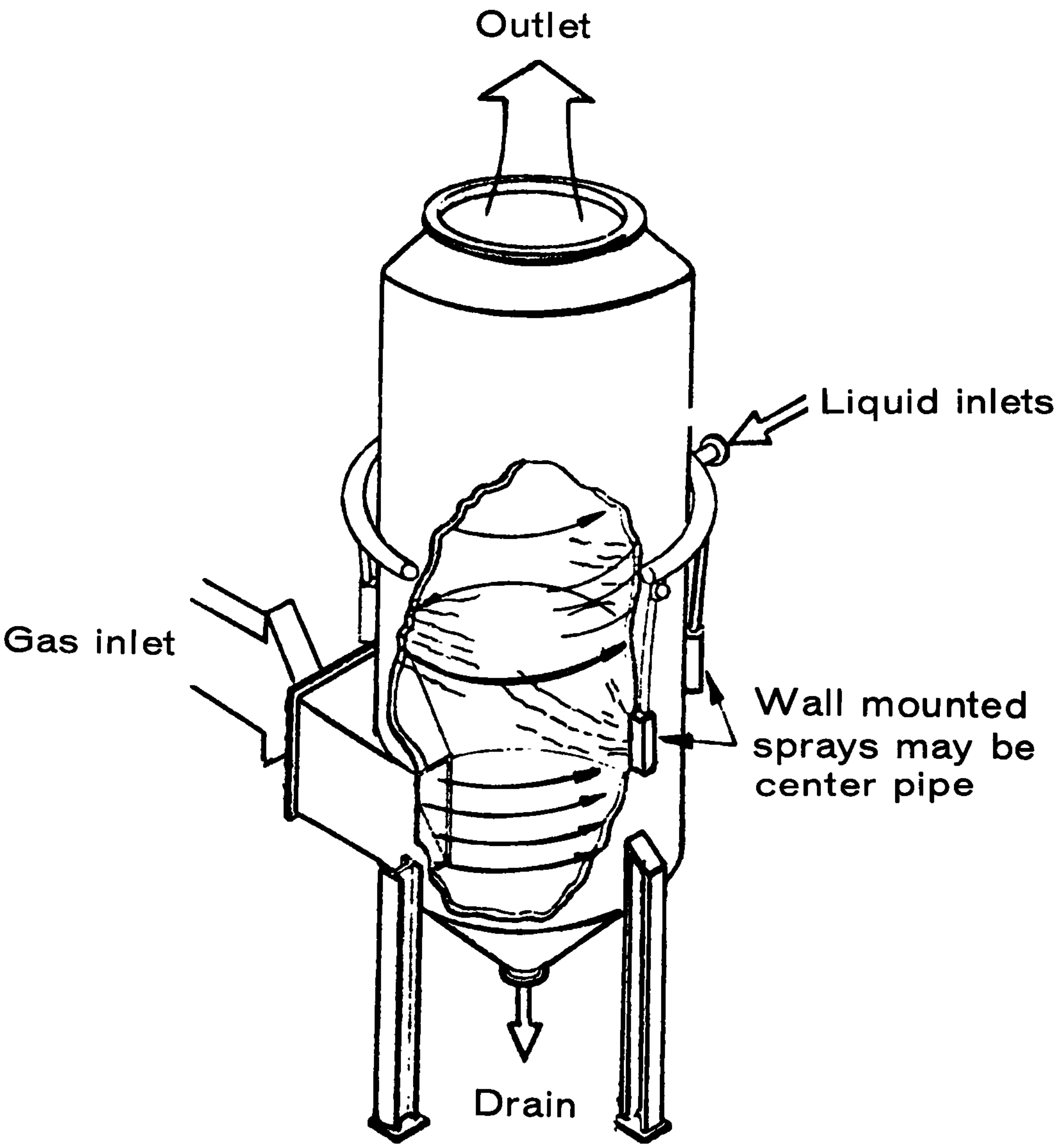

FIGURE 14 CENTRIFUGAL SCRUBBER

either continuously or at frequent intervals. The water requirements for cyclonic scrubbers range from 2-10 gal per thousand cubic feet of gas. The pressure drop usually ranges from 1-3 in. of water and an efficiency in excess of 95% may be obtained for particle sizes of 5μ or greater.

4.5.2 Orifice Scrubbers. In orifice-type scrubbers (Figure 15), particle-liquid contact is obtained through the effects of the carrier gas velocity and, therefore, performance depends on the flow rate of the gas. Both efficiency and pressure drop vary with carrier gas flow rate, with the normal pressure drop ranging from 2-6 in. of water.

Orifice scrubbers are representative of a design in which the scrubbing liquid is fragmented and partitioned at the expense of kinetic energy of the gas stream. Usually the gas stream is made to impinge upon a surface of scrubbing liquids and is then passed through various constrictions to increase its velocity and to promote liquid-particle entrainment.

Collection efficiencies up to 95% for particulates 2μ or larger in size are obtained with a pressure drop of 3-6 in. of water. The advantage of this type of equipment is that the construction does not involve fine clearances or small orifices that may readily become plugged.

4.5.3 Venturi Scrubbers. The venturi scrubber (Figure 16) consists of a venturi type construction through which the carrier gas passes at a linear velocity of 12 000-42 000 ft/min. Water is introduced normal to the direction of gas flow at or near the constriction of the venturi, at the rate of 3-10 gal per thousand cubic feet. High gas velocities atomize the scrubbing liquid introduced at the venturi throat and the turbulence created leads to increasing high collection efficiencies for submicron particles as the energy input is increased.

A pressure drop of 10-20 in. of water will provide efficiences of about 97% for aggregate particles 1μ in size. Pressure drops of up to 40 in. of water yield efficiencies of 99+% for particles in the submicron range. Figure 17 illustrates the general relationship of particle size and pressure drop to performance for a particular scrubber unit.

5 CONTROL METHODS

5.1 General

Most control equipment for asphalt plants will perform close to expected efficiency levels if properly installed and maintained. Because the operation of all control equipment used in asphalt plants is a function of pressure drop, proper fan power is critical. Many field problems associated with poor performance can be traced to inadequate fan sizing or operation. Undersizing manifests itself by puff-back, a condition occurring when all the gases cannot exhaust through the pressure drop of the system. This puff-back is evidenced by spasmodic clouds of dust issuing from the burner opening and any other open seams on the rotary kiln. This situation can be rectified only by a substantial cutback in kiln capacity or an increase in fan capacity through either an increase in fan rpm or fan diameter accompanied by an increase in fan motive power.

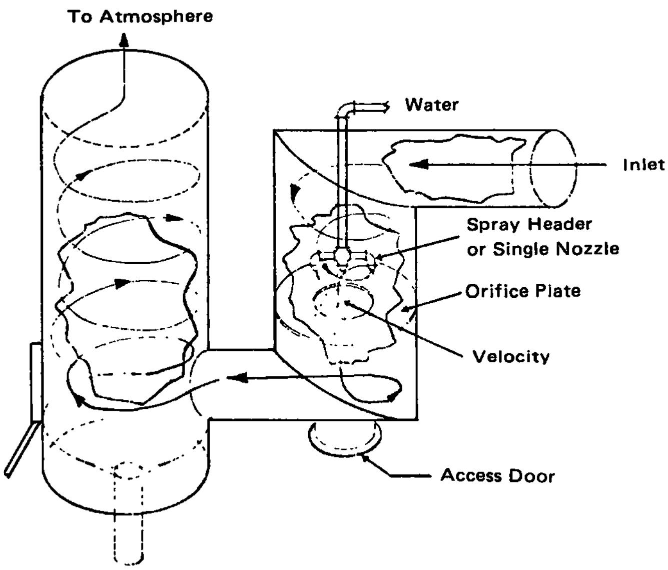

FIGURE 15 ORIFICE SCRUBBER

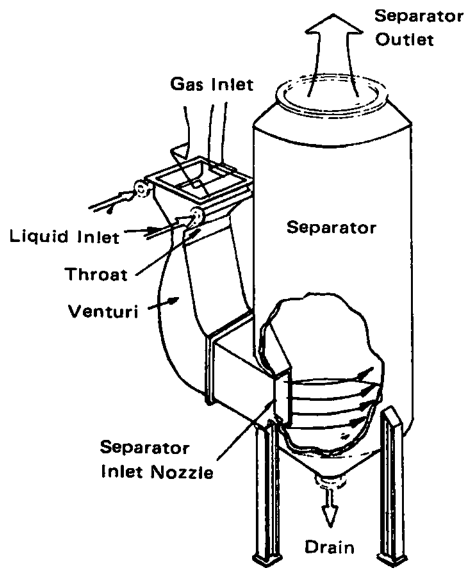

FIGURE 16 VENTURI SCRUBBER

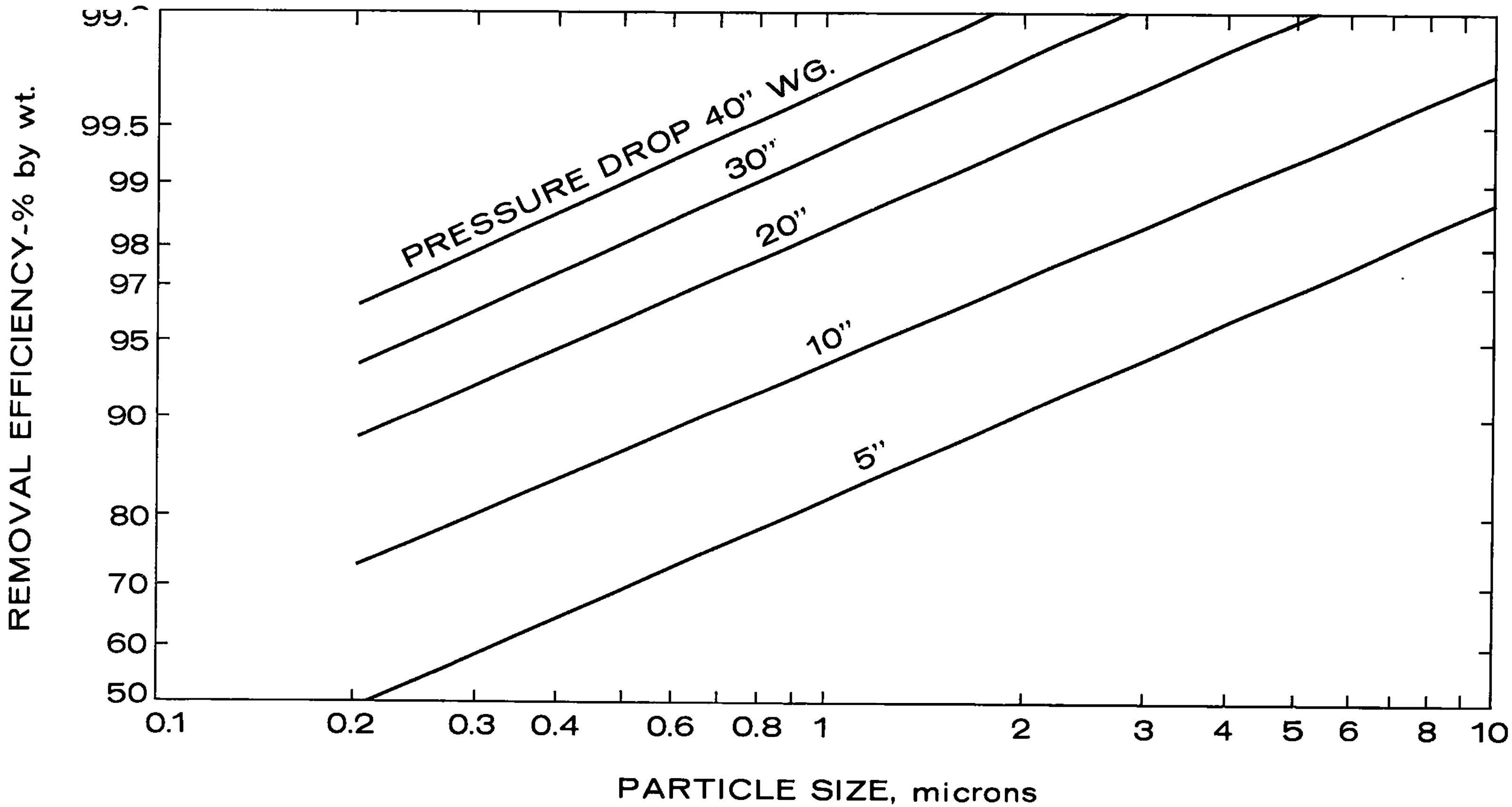

FIGURE 17 VENTURI SCRUBBER EFFICIENCY

For asphalt plants using a wet collector system, two of the main problems that jeopardize system performance are corrosion and inadequate water supply. Corrosion is a function of both the materials of construction and the sulphur content of the fuel being burned. By altering the material of construction and/or the sulphur content of the fuel, corrosion can be significantly reduced. Pumps and other liquid-handling equipment should be made of corrosion/abrasion resistant materials such as stainless steel or plastic. The sulphur in the fuel being burned is oxidized to SO_2 and SO_3. Water added via the scrubber combines with these oxides of sulphur to produce a dilute sulphuric acid which when coupled with high temperatures, sometimes in excess of 200 °F, and the abrasive qualities of the water/particulate slurry, is highly corrosive. Restricting the sulphur content of the fuel to below 1% sulphur by weight will significantly reduce both the corrosiveness of this liquid and the SO_2 emissions from the stack.

From 6-10 gal of water per thousand cubic feet of stack gas is required for effective operation of wet scrubbers. The performance of wet scrubbers can be related to the quantities of fines (-200 mesh) in the aggregate feed as shown in Figure 18.

The performance of wet collectors depends upon the water pressure delivered to spray nozzles. For other than high energy venturi scrubbers, most control equipment requires water pressure in the range of 75 to 100 psig.

Recent tests (6) performed by the United States Environmental Protection Agency on both baghouse equipped and venturi scrubber equipped asphalt plants show that these devices are able to control outlet grain loading concentrations to less than 0.06 grains/dscf of exhaust gas. Well maintained installations fitted with suction-type, cyclic-cleaned baghouses controlled particulates to 0.02 gr/dscf whereas those fitted with high energy venturi scrubbers controlled particulate to 0.03 gr/dscf.

5.2 Availability of Control Equipment

All of the control equipment discussed in this report is readily available in Canada. Correspondence with manufacturers indicates that, even with a rapid increase in demand, the maximum lead time required for purchase of control equipment is no more than six months.

5.3 Performance and Costs

The performance and cost of equipment used to control emissions from asphalt plants are summarized in Table 6. To provide a better understanding of the application of control technology the following example, based on 1974 data, has been included to illustrate one method for estimating the performance and cost of emission control equipment. This example, which may not be applicable under all circumstances, is based on a continuous plant with a capacity of 100 tons per hour which is equivalent to a 3000 lb batch plant. Estimates for larger or smaller production rates are approximately linear.

EXAMPLE

Operation:	600 h/yr
Production rate:	100 TPH

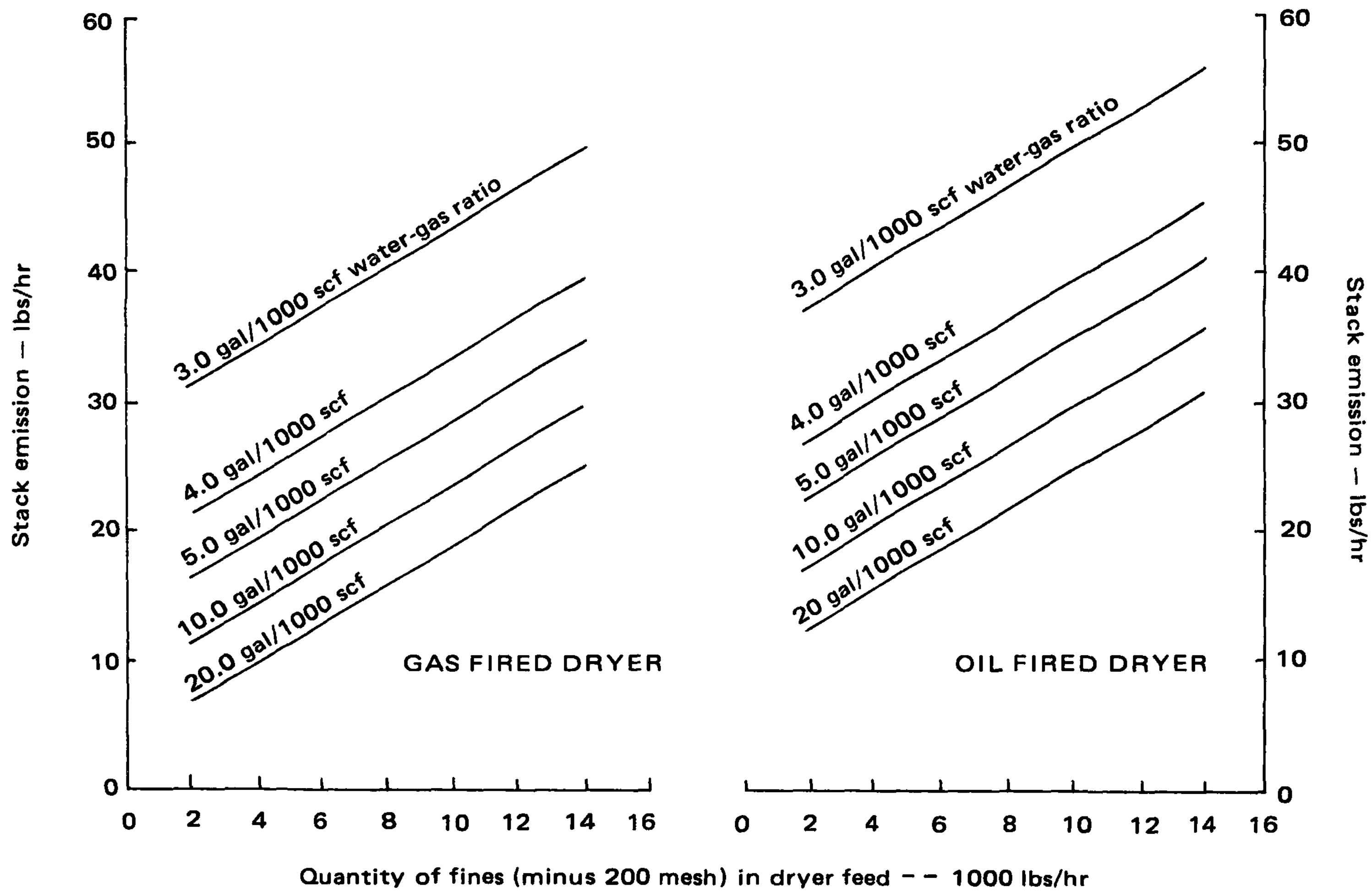

FIGURE 18 EXAMPLES OF EMISSION PREDICTION CURVES FOR MULTIPLE CENTRIFUGAL SCRUBBERS SERVING ASPHALT PLANTS

TABLE 6 PERFORMANCE AND COST OF ASPHALT PLANT CONTROL EQUIPMENT

	Collector type	Performance	Cost in dollars[1] per cubic foot of exhaust gas	Pressure drop	
				Air (in H_2O)	Water (psi)
1	Settling chambers	40% above 50μ	0.07 - 0.10	0.1 - 0.5	-
2	Large cyclones	95% above 20μ 90% above 10μ	0.12 - 0.15	0.5 - 3.0	-
3	High efficiency cyclones	95% above 10μ	0.17 - 0.25	1.0 - 4.0	-
4	Multi tube cyclones	95% above 7μ	0.30 - 0.60	2.0 - 6.0	-
5	Centrifugal scrubbers	[2]>90% above 5μ	0.15 - 0.25	1.0 - 3.0	70 - 100
6	Orifice scrubbers	[2]>95% above 2μ 99.5% above 1μ	0.20 - 0.30	3.0 - 6.0	50 - 70
7	Venturi scrubbers	[2]>98% below 1μ	.80 - 1.20	20.0 - 40.0	20 - 40
8	Baghouses	99.9% above .5μ	2.50 - 4.00	3.0 - 7.5	-

[1]June 1974 estimated cost

[2]Dependent upon contact energy

Dryer diameter:	6 ft (28.27 ft^2 cross section)
Cold feed contains:	5% minus 200 mesh
Stack temperature:	250 °F
Control equipment:	36-in. dry collector
Effluent flow rate:	13 750 scfm (Section 2.4)
Actual flow rate:	18 420 acfm (using gas laws)
High pressure venturi:	40-in. H_2O drop

PERFORMANCE EVALUATION (in accordance with Section 3.3)

(1) Velocity index: 18 420 acfm/28.27 ft^2 = 650 fpm

(2) Minus 200 mesh to dryer = 100 TPH x 2000 lb/ton x 0.05 = 10 000 lb/h

(3) Velocity index 650 ⟶ 55% dust removed from dryer (Table 3)

(4) 10 000 x 0.55 = 5500 lb/h minus 200 mesh from dryer
5500 lb/h represents 78% of total dryer emissions (Table 2)

(5) Total dryer emissions = 5500/0.78 = 7051 lb/h

(6) The 7051 lb/h emitted from the dryer to the inlet of the 36-in. dry cyclone contains the following weight fractions based on the typical gradation shown in Figure 4:

Size range (μ)	% by Weight	Actual (lb/h)
<1	3	211.5
1-2	3	211.5
2-3	3	211.5
3-4	4	282
4-5	4	282
5-10	8	564.1
10-15	5	352.6
15-20	12	846.1
20-25	8	564.1
>25	50	3525.5

(7) Material passing cyclone based on typical efficiencies shown in Figure 7:

Size range (μ)	Amount (lb/h)	Efficiency (%)	lb/h Passing
<1	211.5	15	179.8
1-2	211.5	40	127
2-3	211.5	55	95.2
3-4	282	65	98.7
4-5	282	70	84.6
5-10	564.1	82	101.5

10-15	352.6	92	28.2
15-20	846.1	96	33.9
20-25	564.1	99	5.7
>25	3525.1	100	0
		Total	754.6

(8) High pressure (40-in. H_2O) venturi scrubber efficiency from Figure 17
= 99.5% above 1 μ and 98.5% less than 1 μ

Material Passing:

(a) Smaller than 1 μ	= [179.8 x (1-0.985)]	= 2.69 lb/h
(b) Larger than 1 μ	= [574.8 x (1-0.995)]	= 2.87 lb/h
	Total Material Passing	5.56 lb/h

(9) With a fabric filter installed on this asphalt plant the operational performance would be greater than 99.9% for particulate sizes in this range. The 754.6 lb/h being emitted from the cyclone would be reduced to 0.75 lb/h.

ECONOMICS OF WET SCRUBBING SYSTEM

(a) *Installation Costs*

Venturi scrubber 18 420 cfm x \$1.15/cfm	\$21 183
Shipping and taxes	5 000
Installation (varies)	6 000
Water supply, piping, and sump	5 000
Total installed cost	\$37 183

Water pumping $= \dfrac{185 \text{ gal} \times 20 \text{ lb} \times 2.31 \text{ ft}}{3960 \times 0.75} = 3$ hp

Fan operating $= \dfrac{18420 \text{ cfm} \times 40}{6356 \times 0.65} = 180$ hp

Total (Say) 185 hp

Increase in power due to wet scrubbing:

= 185 hp x 0.745 kW/hp = 138 kW

Total power used for 600 operating hours/yr

= 600 x 138 = 82 800/kWh

Power costs = 82 800 x \$0.010/kWh = \$828

Cost Summary

Venturi cost (Amortized 10 years at 12%)	=	$ 6 400
Maintenance (10% of installed costs)	=	3 700
Operating (Power Costs)	=	828
Total increase in annual costs		$10 928

Cost per ton = $10 928/(100 TPH x 600h) = $0.18/ton

ECONOMICS OF BAGHOUSE SYSTEM

Baghouse: 18 420 cfm x $4.00/cfm	=	$73 680
Erection	=	7 500
Taxes (12% FST plus 8% PST)	=	15 443
Shipping	=	1 000
Total installed costs		$97 632

$$\text{Power required} \quad \frac{18\ 420 \text{ cfm} \times 7 \text{ in.}}{6356 \times 0.65} = 31 \text{ hp}$$

Annual power costs = 31 hp x 0.745kW/hp x $0.010/kWh x 600 h/yr = $139

Cost Summary

Baghouse costs (Amortized 10 years at 12%)	=	$16 807
Annual Maintenance	=	7 500
Operation	=	139
Total increase in annual costs		$24 446

Cost per ton = $24 446/(100 TPH x 600h) = $0.407

In operational areas that are devoid of minus 200 mesh material in the naturally occurring aggregate, the installation with the baghouse can capture and recycle the fine material. This fine material, used as mineral filler, will amount to approximately $6.00 per ton and will partially offset the operational cost of control equipment.

In the above example, with a 100 TPH installation, approximately one tone of fine material could be recycled per hour. This would decrease the cost per ton for control equipment as follows:

Total increase in annual costs:	$24 446
Gain due to fine recycling:	3 600
Net cost	$20 846

Cost per ton = $20 846/(100 TPH x 600h) = $0.35/ton

The unit control equipment costs specified in the above example include the cost of fans and pumps with electrical drives. It is assumed that the required power is available at the plant site. If this is not the case, motive power could be provided by a diesel drive system. A 250 hp diesel engine complete with starter would cost about $10 000. This investment would then have to be included in the above cost estimates to obtain a more representative figure for the increased cost on a cost/ton basis.

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