RECEIVED
SEP 20 1974
POLLUTION CONTROL BOARD

September 20, 1974

Exhibit 60
R72-18
Grain Handling

Mr. Russell Odell
Pollution Control Board
309 West Washington Street
Chicago, Illinois 60606

Dear Mr. Odell:

Control efficiency for existing elevators within an MPA area in the opinion of Industry Members of the Task Force should be 98% instead of 99%. By allowing 98% to be the guiding criteria an elevator has a control option available, although admittedly small, whereby they can use high efficiency designed cyclones in series to meet the control parameter. There are very few companies which can meet and guarantee this performance but in my opinion this option should be left open to those willing to risk the capital. The cost of cyclones initially is considerably less, and as reported in Midwest Research Institute Report the maintenance cost is about one half of bag collectors. Additionally, there would be little, if any, effect on air quality.

Maintaining the control parameter at 99% almost precludes the use of high efficiency cyclone. As will be shown later, it is our opinion that the lowering by 1% of the control parameter will not allow any mass change from bag houses to cyclones but rather it allows those willing to risk the capital investment, the option of installing equipment which will have a better efficiency during its life, and with a considerable less initial capital, maintenance, and operating cost. Since bag collectors require more horsepower pr cfm, it is a waste of energy to require this when we can accomplish the same objective of lowering the emissions from an elevator by the use of high efficiency cyclones.

Referring to the attachments 1, 2 & 3, it can be seen that the particle size distribution of corn dust is generally larger than 44 micron, the range is from 84 to 99% larger than 44 micron. Attachment (1) is from permit information furnished to the permit section, (2) is correspondence from Ed Campbell and (3) is from testimony submitted at the hearings by Mr. Detweiler.

The attachment on cyclone efficiency is from an article published in Chemical Engineering, January 27, 1969, entitled "Dust Collection Equipment" by Gordon D. Sargent. On page 141 of this article we see cyclone efficiency, refer to the one entitled High-efficiency Cyclones. Cyclones can achieve a high collection efficiency and the record demonstrates this. Dr. Matkovic, in an answer to Mr. Marder, testified as follows:

> ". . . And I think with a single-stage cyclone I can collect about 97 1/2 to 98 per cent of the dust, which you can see just a little bit coming out of the cyclone, which I think should be satisfactory for everybody. . . ."
> (LaSalle, Illinois hearing of July 17, 1974, page 949)

On this question of cost, we can refer to Table VI on page 147 of the attached Chemical Engineering article, and we can readily see that the installed cost and operating cost comparisons of High-efficiency cyclones versus bag collectors. The total annual cost of cyclones bag house ranges from 3.2 to 5.2 times more for bag houses than cyclones.

I cannot see how we can justify saddling industry with the only option of bag houses for control of basically a nuisance problem at these greater costs when 1% less efficiency will allow an elevator a small option at a great savings of both initial cost annual operating cost. Refer to Ed Campbell's letter of July 31, 1974 to Del Haschemeyer titled, "Grain Elevator Emissions," page 3 under expected emissions. By decreasing the 99% to 98%, we increase the emissions from 17.6 lbs. to 35.2 lbs. which is still below the 70 lbs. which he calculated as the maximum allowable under rule 203(a).

I believe all the facts weighed give justification for consideration of lowering the control parameter for MPA's from 99% to 98% and we will still clean up the environment around the elevators.

I am also enclosing a definition of grain as was requested by you. We would appreciate that all these documents be made a part of the grain handling regulations record R 72-18.

Sincerely,

Jerry Detweiler
Mgr. Process & Facility Planning

JD/jm
Attachments

Exhibit 60
R72-18

DEFINITION OF GRAIN

GRAIN: Grain as herein used includes the whole kernel or seed of the corn, soybean, wheat, oats, and any other cereal, bread or oil seed plant; and shall include the normal fines, dust and foreign matter which results from harvesting, handling or conditioning. The grain shall be understood to be unaltered by grinding and/or processing.

TABLE-1 (DUST SIZE CONSIST)

ILLINOIS GRAIN Corp - Creve Coeur - Illinois

	BEES-WINGS		STARCH-WHITE DUST BEING collected AT STALEY Mfg. DECATUR, Ill.		BEANS-DUST	
	RETAINED ON		RETAINED ON		RETAINED ON	
UST SIZE in ICRONS	%	% Cum	%	% Cum.	%	% CUM
150	94.3	94.3			17.7	17.7
0x100	3.8	92.1			12.4	30.1
0x74	0.9	99.0			13.0	43.1
74x33	0.9	99.9			14.6	57.7
+21	0.1	100.0	31	31	16.1	73.8
1-16			28	59	13.8	87.6
16-8			22	81	9.0	96.6
8-6			10	91	3.0	99.6
6-4			3	94	0.4	100.0
4-2			2	96		
2-1			3	99		
-1			1	100		

Total efficiency in my SYSTEM PRIMARY+Secondary cyclones is: 99.1% according to Mr Tom Scott of STALEY Mfg. Co

DUST CHARACTERISTICS !

one LITER OF WATER = 1000 GRAMS

one Liter of Beeswings = 90 GRAMS

one liter of starch-dust = 342 Grams

one liter of Beans-Dust 451 Grams

Jan. 73

Ferrell-Ross Dryer Dust Sample

Micron Size Less Than	% by Weight
105	1.45
150	3.2
335	13.9
1316	9.1
1923	44.5
2345	5.8
3125	11.7
3906	6.6
5469	3.65
	99.9%

PCB 72-215 -Weldon- Corn Dust Sample

Micron Size Less than	Grams	% by Weight
150	2.0	1.1
1000	19.5	11.0
1700	24.5	13.8
2500	18.5	10.5
3/16	112.5	63.6
	177.0	100.0

From Testimony by Dr. Matkrevic

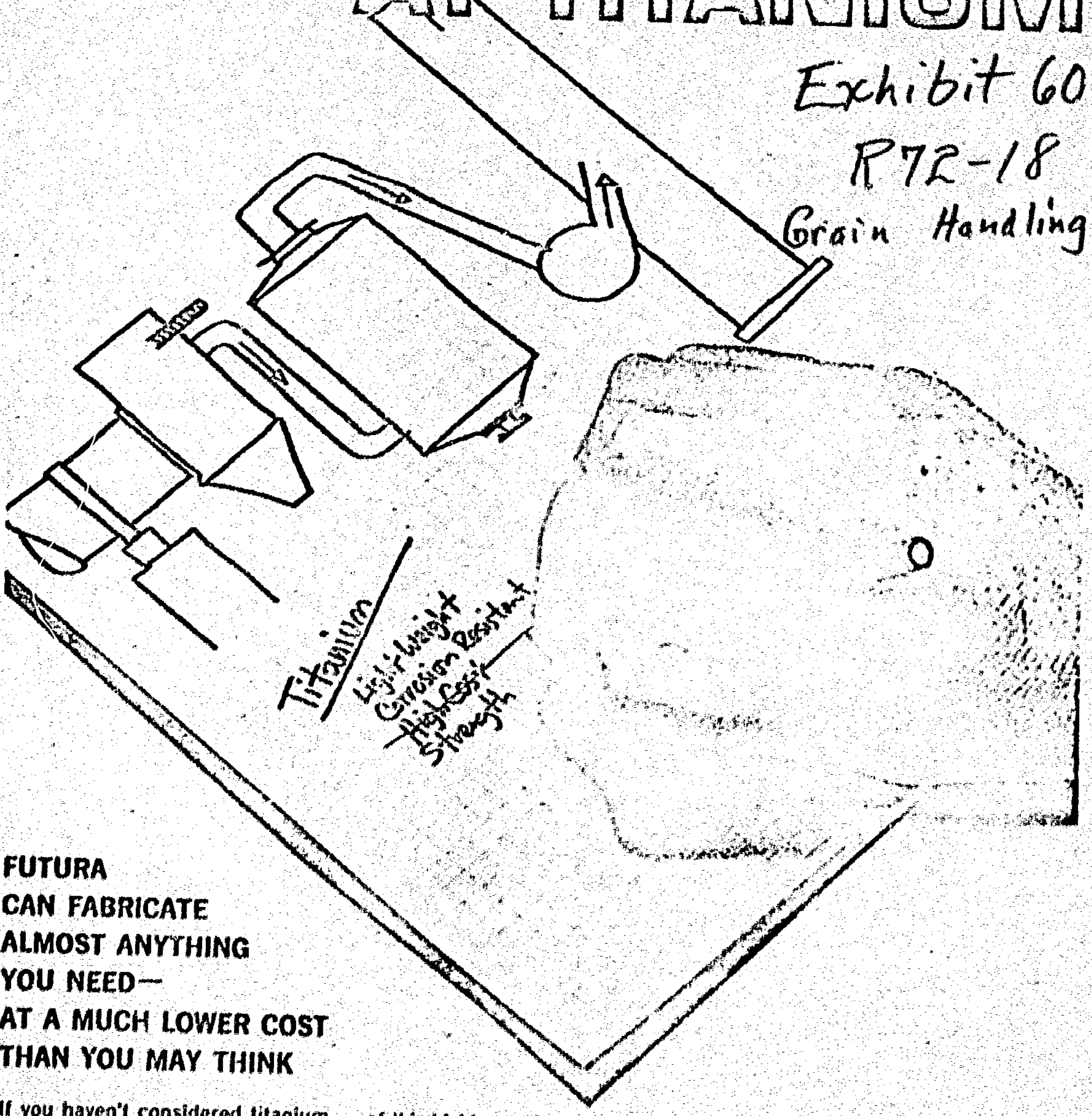
U.S. Sieve Series	Micron Size	AP42	Creve Cour	PCI 1-2B-2	PCI 1-3C1	PCI L-3A2	ITL 26-5-306-7	Shanzer	Dekalb
10	2000	-	-	-	-	-	-	-	5.1
20	841	-	-	-	-	-	7.7	-	33.2
30	595	-	-	-	-	-	-	-	-
40	420	-	-	-	-	-	12.3	-	29.8
50	297	-	-	-	-	-	-	-	-
60	250	-	-	-	-	-	10.	-	18.7
70	210	-	-	-	-	-	-	-	-
80	177	-	-	-	-	-	-	-	7.3
100	149	-	94.3	-	-	-	8	-	2.9
120	125	-	-	81.1	81.1	85.4	-	86.	0.5
140	105	-	-	-	-	-	5.	-	0.5
170	88	-	4.7	0.1	0.1	0.2	-	0.1	1.4
200	74	-	-	-	-	-	7.	-	0.3
230	63	-	-	-	-	-	-	-	-
270	53	-	-	-	-	-	-	-	0.4
325	44	85	-	2.7	2.7	2.6	12.	2.1	-
400	37	-	-	-	-	-	15.	-	-
	<37	<40	1.0	16.1	16.1	11.8	-	-	-
TOTAL %		125	100	100	100	100	77	88.8	100.1

TAKE A NEW LOOK AT TITANIUM

Exhibit 60

R72-18

Grain Handling



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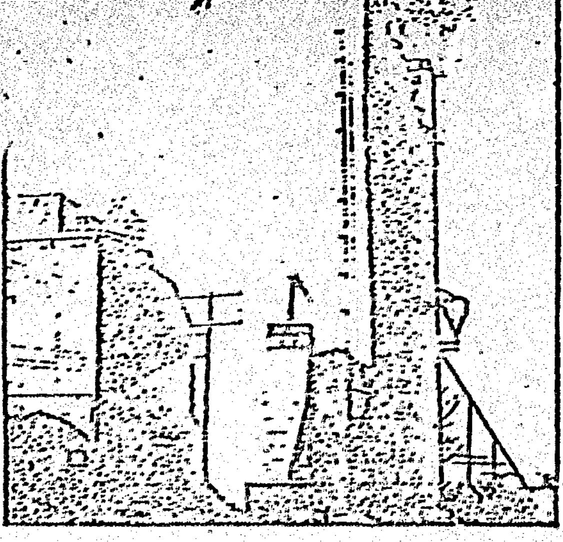


Pollution

Attachment B

Let's Start Getting Smart

Pollution

69%

20 or less

grain elevators in [illegible] also compare emissions from this equipment to existing and proposed air pollution standards.

A typical approach to evaluating an elevator dust problem is to first determine and compare the actual and permissible emissions. If the emission is in excess of that permitted, or if the dust presents a safety hazard or nuisance, then a solution based on evaluating the various dust collection equipment commonly available is required.

A hypothetical example has been selected to demonstrate this approach, with specific data included where possible.

The example selected is for the collection of grain dust generated from elevating 5,000 $\frac{bu}{hr}$ of soybean to a belt conveyor.

Before considering equipment for control of this emission, the allowable emission must be determined in order to complete Illinois Air Pollution Control Board Form "B" which is required for all air contaminate sources (Fig. I). The process weight rate for this example is:

$$(5{,}000\ \frac{bu}{hr})\ (60\ \frac{lb}{bu}) = 300{,}000\ \frac{lbs}{hr}$$

The allowable emission for this process rate is found in Table I of the "RULES AND REGULATIONS GOVERNING THE CONTROL OF AIR POLLUTION" (Fig. II).

Since there is no value in Figure II for 300,000 $\frac{lbs}{hr}$ the allowable emission is calculated as follows:

$E=55\ P^{.11}-40$ where E=Emission Allowed, $\frac{hr}{lbs}$

P=Process Rate, $\frac{tons}{hr}$

$$E=55(150)^{.11}-40$$

$$E=55(1.735)-40=55.4\ \frac{lb}{hr}$$

The inlet gas rate and inlet loading required to complete Form "B" for this example are assumed to be 5,000 SCFM and 5.0 grains/SCF air based on typical values. For a specific application these values must be determined.

The inlet loading expressed in lbs/hr would be:

$$\left(\frac{5\ grains}{SCF}\right)\left(\frac{1\ lb}{7000\ grains}\right)\left(\frac{5000\ SCF}{min}\right)\left(\frac{60\ min}{hr}\right)=214\ \frac{lbs}{hr}$$

Prior to comparing equipment it's important to consider particle size due to its effect on efficiency. The following data is for grain dust from the boots on three elevating legs.

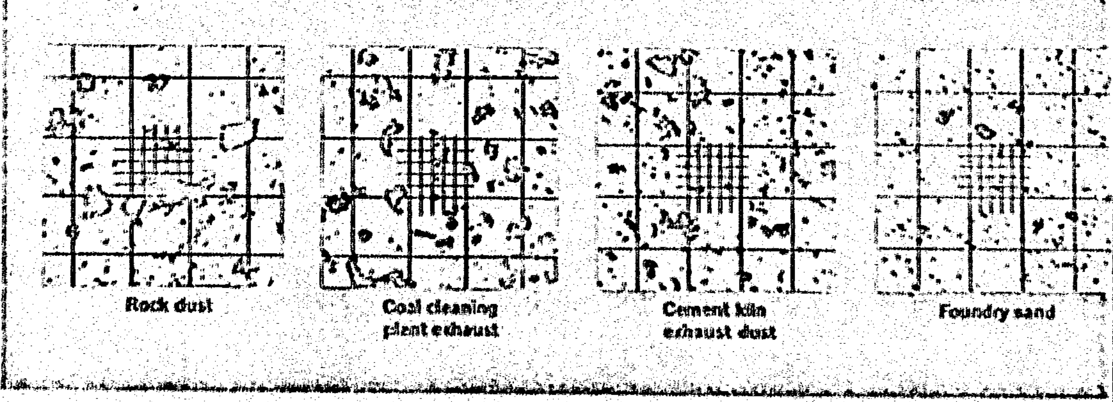
TABLE 1

Grain Dust Particle Size Analysis

Weight %	*Cumulative %*	*Particle Size, Microns, 95% Probability*
31	31	21 and Larger
28	59	16-21
22	81	8-16
10	91	6-8
3	94	4-6
2	96	2-4
3	99	1-2
1	100	<1

[illegible]

Chemical Engineering


Rock dust

Coal cleaning plant exhaust

Cement kiln exhaust dust

Foundry sand

PHOTOMICROGRAPHS of various dusts

Dust Collection Equipment

GORDON D. SARGENT, Nopco Chemical Div., Diamond Shamrock Chemical Co.

In solving a dust collection problem, an engineer must first evaluate his own situation in order to select the most promising types of collectors. This article puts together the available facts and sources that the engineer needs for background information. After making a preliminary equipment selection, suitable vendors can be contacted for help in developing the final answer. An early and complete definition of the problem can reduce the false starts that lead to wasted pilot trials or costly, inadequate installations.

Selecting a dust collector for cleaning a process gas stream can be a challenge. Some engineers may try to find shortcuts, and quick estimates put on both gas flow and collection efficiency may be the entire extent of the collector specification. The result can be an ineffective installation that has to be replaced.

Treating a gas stream, especially to control pollution, may not be a money-maker, but costs can be minimized, not by buying the cheapest collector but by thoroughly engineering the whole system, as is normally done in other process design areas.

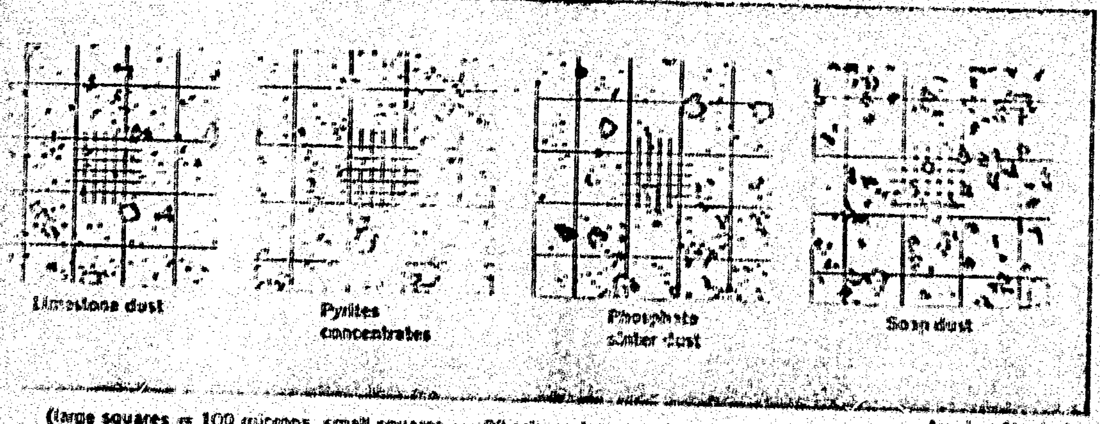
What data are needed? What equipment might be suitable? The usual questions that immediately arise in the choice of a pump or heat exchanger have well-established routes to the answers. By contrast, the extremely heterogeneous nature of particulates in gas streams has led to a wide variety of equipment for which engineering principles are either lacking or not available to the practicing engineer; equipment manufacturers must be relied upon for proprietary designs and for performance guarantees.

Gas-cleaning equipment discussed here will handle dust particle sizes between 0.1 and 100 microns and concentrations from 0.1 to 100 grains/cu.ft. The micron (μ) is the commonly used unit of particle-size measurement and is defined as 1/1,000 mm. or 1/25,400 in.

Dust concentrations are usually given in terms of grains/cu.ft. of gas (7,000 grains = 1 lb.).

Air cleaners for fumes with much smaller particle size and loadings are beyond the scope of this article, as are combustion or catalytic incinerators, gas or odor absorbers or adsorbers, ventilation-air cleaners and mist eliminators.

The need for gas cleaning may be either for process, protection or profit. A collector may be an integral part of a process such as spray-drying or an auxiliary to recover valuable byproduct. The main requirement may be safety, as by reducing toxic or combustible dust. People and property in the plant or neighborhood may need to be protected by a good dust collection system, or the requirement may be to



Limestone dust

Pyrites concentrates

Phosphate sinter dust

Soap dust

(large squares = 100 microns, small squares = 20 microns).

American Standard

Selecting a dust collection system is not as straightforward a procedure as choosing a pump or heat exchanger. Here is a guide to the complexities of the numerous kinds of equipment available, the jobs that they do, and the way to select wisely.

meet air pollution laws and to clean up an unsightly stack plume.

Equipment Applications

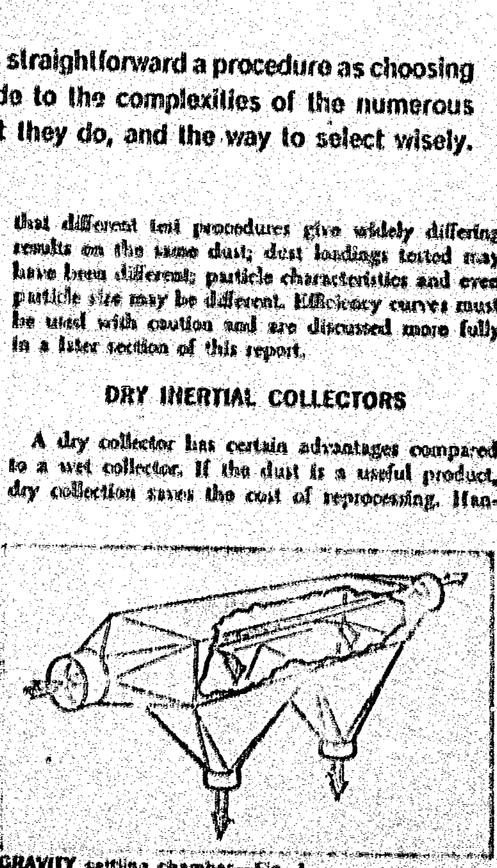
The many different dust collectors available today are summarized in Table I, Equipment Application Table, which simplifies a review of the whole collector field. The table is intended to be used along with descriptions, illustrations, and efficiency curves that follow. Ranges and limits tabulated are typical values but naturally may vary widely for unusual applications. More background is available in the publications listed under "General Equipment" in the references at the end of this article. Suppliers can be found listed in the Environmental Engineering Deskbook (*Chem. Eng.*, Oct. 14, 1968) and should be consulted especially for integrated systems, packaged units and air cleaners.

Performance of the different types of collectors can be roughly compared by means of the curves showing grade or fractional-size efficiency, Fig. 20. The data were obtained by Stairmand[11] on one standard test-dust with characteristics as shown in Table V.

Other performance curves cannot be compared to these for several reasons. Obviously, equipment design may affect efficiency. We must also consider that different test procedures give widely differing results on the same dust; dust loadings tested may have been different; particle characteristics and even particle size may be different. Efficiency curves must be used with caution and are discussed more fully in a later section of this report.

DRY INERTIAL COLLECTORS

A dry collector has certain advantages compared to a wet collector. If the dust is a useful product, dry collection saves the cost of reprocessing. Han-



GRAVITY settling chamber—Fig. 1

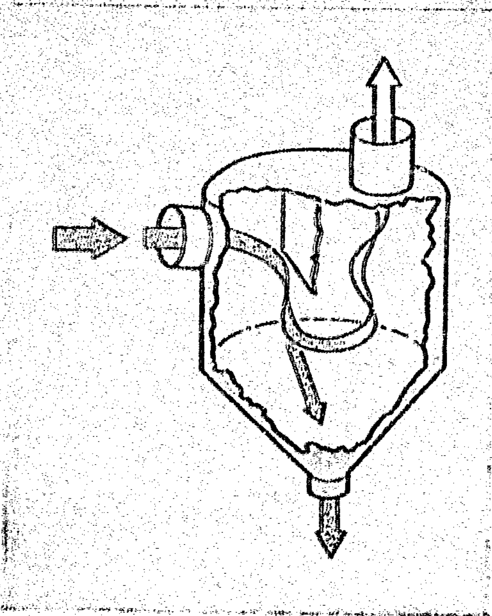
dling the collected material can give rise to additional dust problems. Dry, dusty material has the disadvantage of requiring ventilation and if hygroscopic, caking can be a problem. The cleaned gas will not be cooled or completely free of fines. Without cooling, the temperature limits of equipment will have to be considered. Corrosion will be minimum unless the fumes contain corrosive mists. Equipment generally is bulky.

Inertial or mechanical collectors are best suited for medium or coarse particulates. High dust-loadings can be handled at moderate pressure drops and power consumption. Simple construction of this type of collector results in lower cost and maintenance than other types. Efficiency is not very high; hence, for a really clean effluent, some other type of collecting device must be used in combination with or in place of the inertial collector. The inertial or mechanical collectors depend on particle inertia in a gravity or centrifugal force field.

Gravity Settling Chamber

Principle—Dirty gas is directed through an oversized duct where velocity drops low enough to let large particles settle out by gravity. (Fig. 1.)

Comments—Flow may be horizontal or vertical. Dust separation suffers from reentrainment from eddy currents. In the Howard dust chamber, horizontal shelves or trays have been added to shorten the settling path of the particle, improving collection efficiency, but making cleaning much more difficult. The gravity settling chamber is seldom used today, but can be designed for a specific application—ventilation contractors seem to be familiar with them. Space requirement is large and efficiency low, which



BAFFLE CHAMBER uses direction change—Fig. 2

Equipment application table—Table I

Types of Dust Collecting Equipment	Particle Size Microns	Loading Grains/ Cu. Ft.	Collection Efficiency Weight %	Pressure Loss: Gas, In. W.G.	Pressure Loss: Liquid Psi.	Utilities Per 1,000 Cfm.	Gas Velocity, Fpm.	Size Range Limits, 1,000 Cfm.	Space Required, (Relative)
Dry inertial collectors									
Settling chamber	>50	>5	<50	<0.2	—	—	300-600	None	Large
Baffle chamber	>50	>5	<50	0.1-0.5	—	—	1,000-2,000	None	Medium
Skimming chamber	>20	>1	<70	<1	—	—	2,000-4,000	50	Small
Louver	>20	>1	<80	0.5-2	—	—	2,000-4,000	30	Medium
Cyclone	>10	>1	<85	0.5-3	—	—	2,000-4,000	50	Medium
Multiple cyclone	>5	>1	<95	2-6	—	—	2,000-4,000	200	Small
Impingement	>10	>5	<90	1-2	—	—	3,000-6,000	None	Small
Dynamic	>10	>1	<90	Provides head		1-2hp.	—	50	
Wet scrubbers									
Gravity spray	>10	>1	<70	<1	20-100	0.5-2 gpm.	100-200	100	Medium
Centrifugal	>5	>1	<90	2-6	20-100	1-10 gpm.	2,000-4,000	100	Medium
Impingement	>5	>1	<95	2-8	20-100	1-5 gpm.	3,000-6,000	100	Medium
Packed bed	>5	>0.1	<90	1-10	5-50	5-15 gpm.	100-300	50	Medium
Dynamic	>1	>1	<95	Provides head	5-30	1-5 gpm., 3-20 hp.	2,000-4,000	50	Small
Submerged nozzle	>2	>0.1	<90	2-6	None	No pumping	3,000	50	Medium
Jet	0.5-5	>0.1	<90	Provides head	50-100	50-100 gpm.	2,000-20,000	100	Small
Venturi	>0.5	>0.1	<99	10-30	5-30	2-10 gpm.	12,000-42,000	100	Small
Fabric filters	>0.2	>0.1	<99	2-6	—	—	1-20	200	Large
Electrostatic precipitators	<2	>0.1	<99	0.2-1	—	0.1-0.6 kw.	100-600	10-2,000	Large

Note: The terms expressing concentration, or loading, can be defined as light = ½ - 2, moderate = 2 - 5, and heavy = 5+ grains/cu. ft. Particle sizes: fine, 50% in ½ - 7 micron size range; medium, 50% in 7 - 15 micron size range; coarse, 50% over 15 microns.

Data required for equipment selection—Table II

Particulate characteristics

*1. Particle size distribution
*2. Concentration—average and extreme values
3. Particle density (and viscosity)
4. Bulk density
5. Moisture content
6. Electrical resistivity and sonic properties
7. Handling characteristics—erosion, abrasion, frangible, flocculent, adhesive, sticky, linty, bridging
8. Composition
9. Recovery value
10. Flammability or explosive limits
11. Toxicity limits
12. Solubility

Gas characteristics

*1. Flowrate—average and extreme values
2. Pressure
3. Temperature
4. Moisture content, condensable vapors
5. Composition and reactivity
6. Corrosive properties

Effluent

*1. Desired emission of contaminant in clean gas
2. Method of disposal or recovery of collected contaminant

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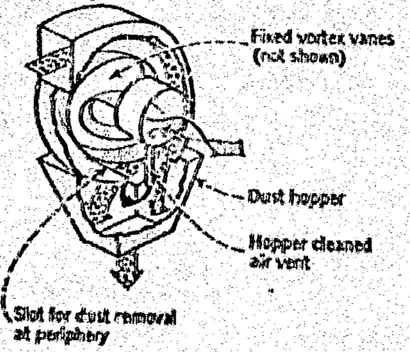
* Required for preliminary equipment selection.

limits this type to precleaning gas to be fed to a more efficient collector. A combination of settling chambers and radiant-cooling connecting ducts is cited in one text[2] as being used in the metal refining industry.

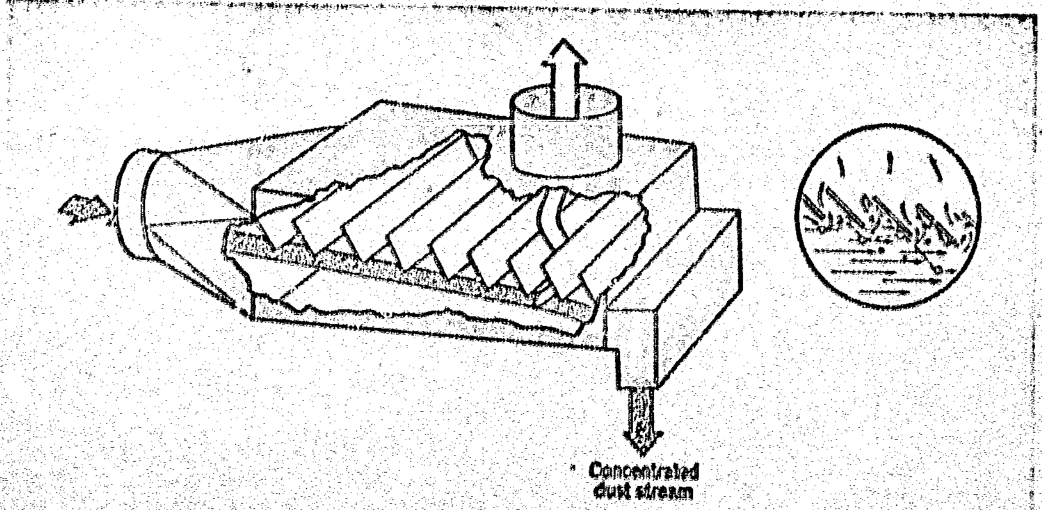


SKIMMING CHAMBER employs scroll—Fig. 3

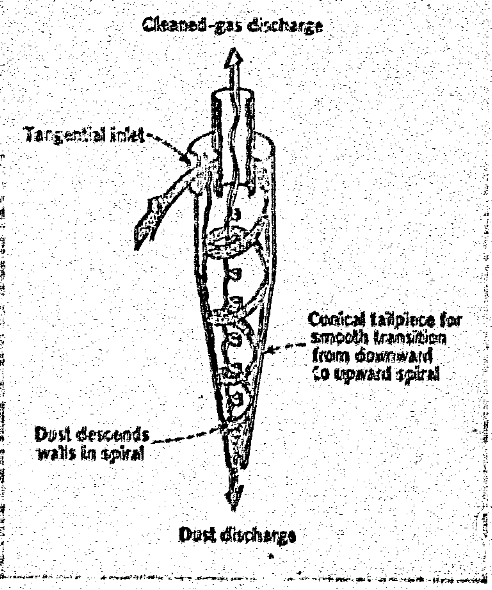
Baffle Chamber

Principle—Settling is aided by using momentum from a direction change. Gas flow is directed downward through a chamber containing a baffle around which the gas is deflected; meanwhile the larger dust particles tend to continue moving downward to be collected in a hopper for later use or removal. (Fig. 2.)

Comments—This collector takes less space than the straight-through settling chamber and has similar efficiency. One chip-trap design[3] (intended to protect downstream fans from very coarse materials) has dimensions given in terms of the inlet duct diameter.



LOUVER TYPE collector, with detail showing method of dust removal—Fig. 4



CYCLONE *removes larger particles—Fig. 5*

Skimming Chamber

Principle—The dirty gas stream enters a scroll tangentially; the dust is carried to the periphery by inertia. Concentrated dusty gas is skimmed by slots and led to a dust hopper or secondary collector. The cleaned gas stream from the hopper is combined with that leaving axially from the skimming chamber. (*Fig. 3.*)

Comments—Dry collectors of medium efficiency such as this one have an exit-gas stream that will probably not satisfy most requirements of dust collecting. A secondary collector may well be required, the skimming chamber being used to reduce the load of coarser particles that are carried into the secondary collector.

Louver-Type Collector

Principle—Gas passes into the wide end of a wedge or cone and must take a sharp bend in order to escape through slots or louvers in the walls. The larger particles are carried by inertia to the narrow end of the chamber where they are purged with a small fraction of the gas stream. (*Fig. 4.*)

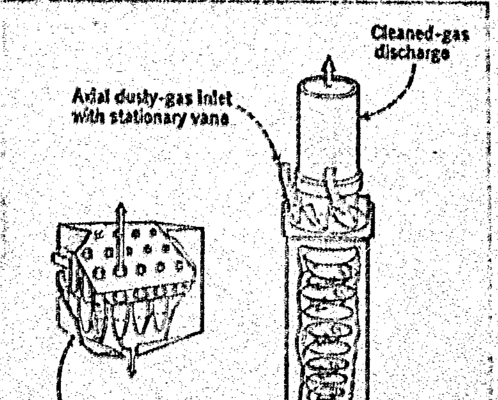
Comments—This collector must be followed by a second collector, such as a high-efficiency cyclone, to separate the dust from the gas. One author (Straux)[14] shows cone-shaped louvered collectors followed by a baffle chamber for coarse dust, followed in turn by a cyclone for fine dust. The gas purged, usually less than 10%, is returned to the inlet of the louvered collector and recycled.

Cyclones

Principle—In the most common arrangement, the gas enters the cyclone tangentially at the top of the cylindrical section and spirals downward into the bottom section, which is usually conical in shape. Dust particles, which have a greater applied centrifugal force than the gas molecules, accumulate at the wall and are carried down, held against the wall by the gas velocity. At the bottom of the cyclone the gas separates from the dust, flows back up in a smaller spiral and exits at the top. Solids are collected in a hopper and removed by a rotary valve, screw conveyor, or other such means. (Fig. 5.)

Comments—Cyclones are one of the most widely used collectors. The unit is low cost, has no moving parts and can be constructed with refractory linings for high temperature, up to 1,800 F. The common arrangement with tangential inlet, and axial outlets for dust and clean gas is shown in the schematic diagram, Fig. 1. Units can be designed for high dust capacity at medium efficiencies and medium pressure drop. High efficiencies are obtained with smaller diameters and higher velocities, which in turn take higher pressure drops. Efficiencies of the high-throughput and high-efficiency cyclones can be compared in *Fig.* 10. Units may be installed in parallel for large gas flows and in series for higher efficiencies (or for both advantages, in combined series-parallel).

Cyclones may have various configurations and still operate on the same basic principle of centrifugal



MULTIPLE CYCLONE (and single element)—*Fig.* 6

separation. Gas entry may be tangential or axial. Gas exit may be axial or axial combined with a pressure-recovery device. Dust exit may be with gas purge or for solids only, with the configuration being axial or peripheral. The skimming chamber, multiple cyclone tubes, and the Uniflow cyclone are variations in the standard design.

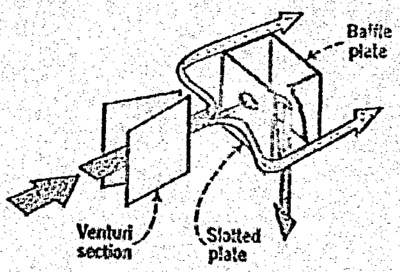
Multiple Cyclone

Principle—Since small-diameter cyclones are more efficient than large ones (centrifugal force for a given tangential velocity varies inversely as the radius of the cyclone), banks of small (10 in. or less) cyclones are arranged in parallel with feed gas from a plenum chamber. (Fig. 6.)

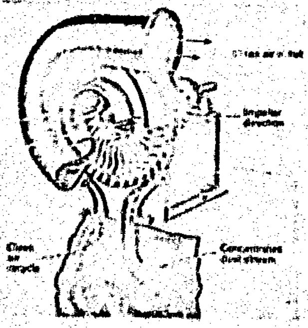
Comments—The major advantage is high efficiency—the disadvantage is plugging of the small tubes. The individual small cyclone does not operate as efficiently in multiple installation as it would by itself. This difference arises from unequal gas or dust distribution to inlets and recirculation of gas from dust hopper back through dust outlets. Consequently, multiple cyclones are best obtained from a manufacturer as a complete unit in order to ensure good design.

Equipment selection checklist—Table III

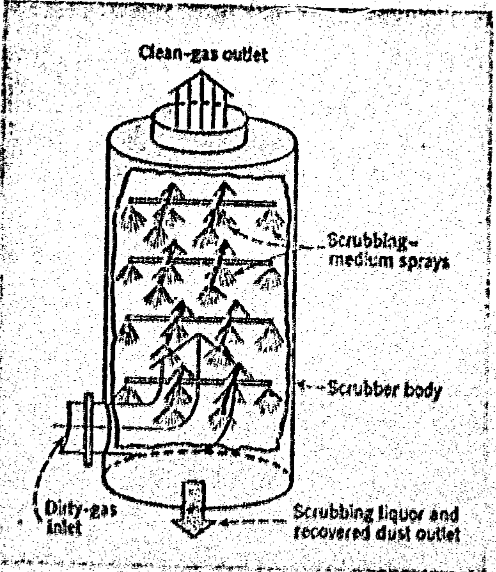
- ***Performance and objectives***
  - *Inlet gas volume*
  - *Efficiency required*
  - *Collected contaminant handling or disposal means*
  - *Operating pressure and allowable pressure drop*
  - *Continuous or intermittent operation—frequency of startups*
  - *Surge loads*
  - *Guarantees*
  - *Acceptance tests*
- ***Dust characteristics***
  - *Particle size and distribution*
  - *Dust quantity per hr.*
  - *Sources*
  - *Handling characteristics—erosion, abrasion, frangible, flocculent, adhesive, sticky, linty, bridging*
  - *Recovery value*
  - *Solubility or slurry characteristics including pH*
  - *Bulk density*
- ***Gas characteristics***
  - *Composition, molecular weight, reactivity*
  - *Conditions of temperature, pressure, moisture*
  - *Soluble or condensable components*
  - *Required outlet temperature*
- ***Mechanical features***
  - *Materials of construction*
  - *Nozzle orientation*
  - *Utility characteristics*
  - *Limitations on space and weight*
  - *Proposed location—indoors or outdoors*
  - *Insulation*



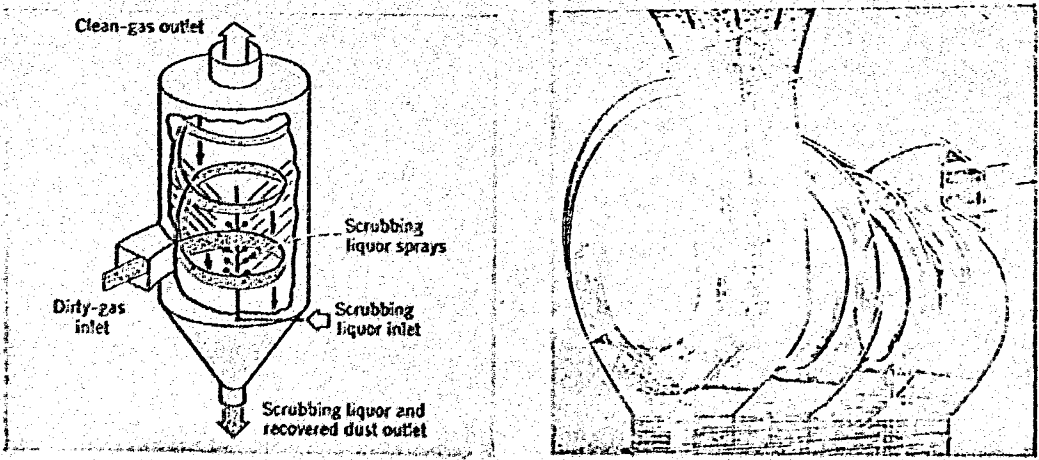
IMPINGEMENT collector (detail of one slot)—Fig. 7



DYNAMIC collector for dust removal—Fig. 8



GRAVITY spray scrubber—Fig. 9

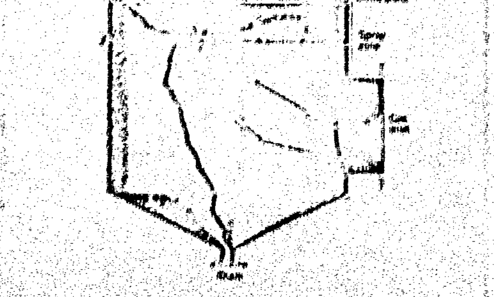


CENTRIFUGAL SCRUBBERS can be had in several versions—Fig. 10a and 10b

Impingement Collectors

Principle–Gas velocity is increased in a venturi and particle momentum carries the particles through slots to a flat plate where they drop to a collector. Dust particles are collected on a surface while the gas stream is diverted around the plate. (Fig. 7.)

Comments–Collection of mist is simplified with this collector, since liquid merely runs down the baffle plate. These devices may require rappers to free dust that builds on surfaces. If the solids are sticky, the surfaces may be continually washed by circulating water; this film, besides cleaning the surface, prevents re-entrainment of particles.



IMPINGEMENT scrubber uses baffle—Fig. 11

Dynamic Collector

Principle–This is a fan with a specially designed impeller and casing that employs centrifugal force to collect particles at the periphery, where they are drawn off in a concentrated stream. (Fig. 8.)

Comments–The unique features of this collector are small space requirement and low pressure drop. The packaged unit by American Air Filter combines exhauster, dust separator and storage hopper. The dynamic precipitator acts as a true fan although at somewhat lower efficiency, 40 to 50% as against 60 to 65% for a fan designed simply for gas service.

WET SCRUBBERS

The wet scrubber recovers product as a slurry or solution that requires further processing either to obtain product or to dispose of as waste.

In a wet scrubber:

- The gas is both cooled and washed.
- Gases may be removed as well as particulates.
- Corrosive gases may be neutralized by proper choice of scrubbing medium.
- The stack effluent usually will be well cleaned but will contain some unwetted fines, mists, and a steam plume.
- The temperature and moisture content of the inlet gas is essentially unlimited.
- Freezing conditions must be considered.
- Hazards of explosive dust-air mixtures are reduced.
- Equipment occupies only a moderate amount of space.

Efficiencies vary with power input and can extend over a wide range depending on the design. Equipment size and initial cost are reasonable, but operating cost is high, especially for high efficiency, which requires large power consumption.

Gravity Spray Scrubber

Principle—Liquid is sprayed into the top of the tower and coarse droplets fall by gravity through a countercurrent flow of the gas being scrubbed. Dust particles are collected mainly by inertial impaction and interception. (Fig. 9.)

Comments—Efficiencies and pressure drops are low, but the scrubber is useful for a heavy loading of coarse particulates, or for absorption accompanied by solids removal. The wet cap used on top of foundry cupolas is a spray and baffle arrangement in which water both cools the baffle and conveys the collected dust. Boiler and process stacks have been scrubbed with sprays installed in the stack, thereby avoiding an additional fan and separate scrubber. Entrainment is controlled by using low gas velocities when designing spray towers, but this results in large equipment. Sprays are selected to give large droplets that must be heavy enough to fall counter to the gas flow, even though they may be further reduced in size by evaporation.

Centrifugal Scrubber

Principle—Liquid is sprayed into the unit and mixed with the rising vortex of gas. By impaction and interception the gas and liquid particles combine and are accelerated to the vessel wall by centrifugal force. There they are collected. The wetted wall also aids collection. (Fig. 10a, b.)

Comments—A variety of types have been developed based on differing of droplet forming and of promoting cyclonic gas action. Vaned baffles (Fig. 10a) direct gas flow and convert velocity pressure to droplet formation energy. Sprays may be installed axially for radially-directed droplets, or circumferentially for tangentially introduced sprays. For higher pressures of 400 psig. or so, droplet size is 50 μ or less, instead of, say, 500 μ.

Impingement Scrubber

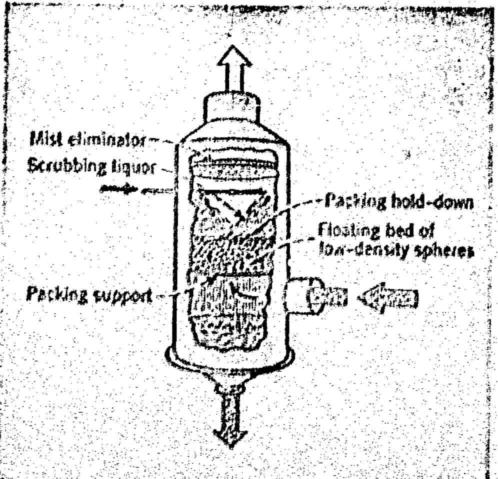
Principle—The gas stream, carrying both dust particles and water droplets from preconditioning sprays, is directed through perforated plates to impinge on baffle plates. Gas velocity acts to atomize water on the perforated plate. Enlarged particles are collected on vaned mist eliminators and are withdrawn along with the solids collected in the liquid overflow from the impingement plate. (Fig. 11.)

Comments—The scrubber is similar to a sieve-plate column and usually has from one to three plates, although there may be more. Extra stages can be added later. Each hole in the "sieve" plate has a baffle or "target" above. Flow is countercurrent. The gas rate in the perforations is high, 75 ft./sec. or more, and is used to provide atomization of the liquid on the plate. Plugging of holes, which may be ¼ in. or less, is not as much of a problem as might be expected, owing to the agitation as well as to the gas preconditioning sprays that wet the underside of the plate. Soluble gases can be effectively removed along with the dust.

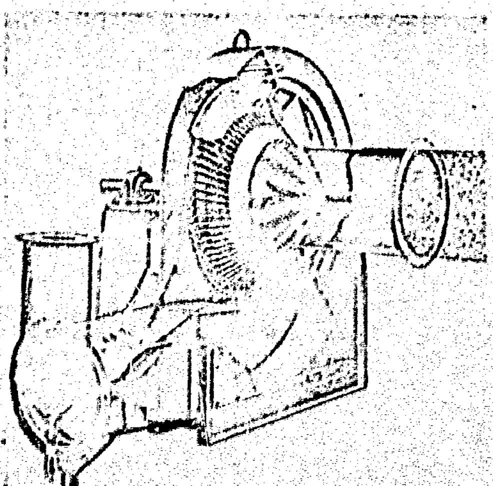
Packed-Bed Scrubber

Principle—Wetted packing provides an impingement surface that prevents reentrainment. The liquor provides a means of washing off dust and conveying it in a slurry or solution. (Fig. 12.)

Comments—Packing may be fixed or it may be a floating bed of low-density spheres. The advantages are: low cost and simplicity, corrosion resistance, and no moving parts. Dust collecting may be secondary to direct-contact cooling and gas absorption.



PACKED-BED scrubber has large surface—Fig. 12

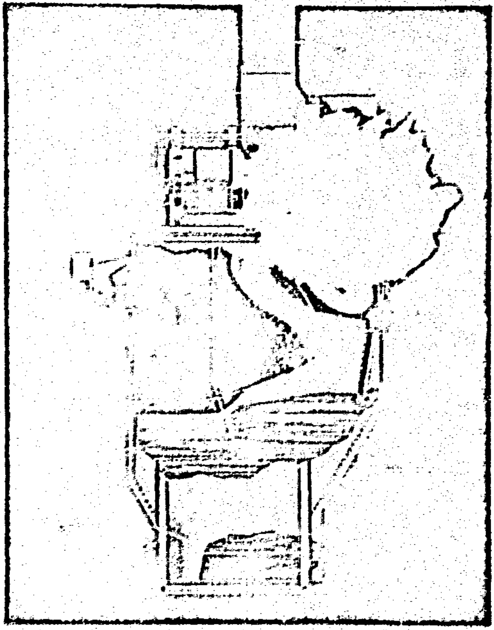


DYNAMIC wet scrubber—Fig. 13

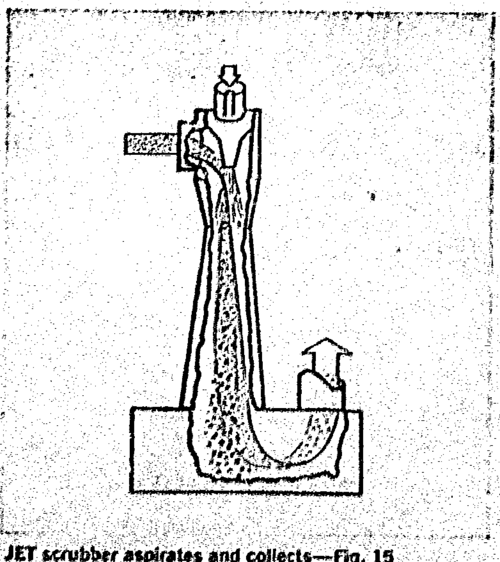
Gases to be removed are below 1% by volume.

The usual countercurrent packed tower has almost no solids-handling capacity, since solids tend to plug the packing and support-plates, which can then be cleaned only by removal. Crossflow scrubbers can handle dust loadings up to 5 grains/cu.ft. by washing the face of the packing with spray nozzles in parallel flow while the body of the packing is irrigated from the top in crossflow.

In a floating bed of plastic spheres, packing movement helps to free the solids.



SUBMERGED NOZZLE type of wet scrubber—Fig. 14



JET scrubber aspirates and collects—Fig. 15

Dynamic Wet Scrubber

Principle—Liquid is sheared mechanically to break the liquid into droplets for collection by inertial impaction between droplets and dust particles. (Fig. 13.)

Comments—In the simplest form of dynamic scrubber, water is sprayed into the suction of a fan, and the wetted impeller and housing holds dust particles from reentrainment. The efficiency is high for fine particles and utilities are 3 to 5 gpm./1,000 cfm. and 2 to 4 hp./1,000 cfm.

Another unit, the disintegrator, has rotating and stationary bars to break up the water feed stream into fine droplets. This machine seems to be displaced by the venturi today.

Power consumption is very high, 10 to 20 hp./1,000 cfm., efficiency is correspondingly high. Rotor speed is 350 to 750 rpm., and buildup must be avoided to prevent rotor unbalance. Consequently, a precleaner, such as a cyclone or centrifugal scrubber, is needed to hold the inlet dust loading on the disintegrator below 0.5 grains/cu.ft., and the temperature below 125 F. (Other collectors with mechanically driven elements and a pool of scrubbing liquid are included in the following paragraphs on submerged-nozzle scrubbers.)

Submerged-Nozzle Scrubber

Principle—Gas passing through a nozzle or orifice is scrubbed by the liquid and also atomizes the liquid (assisted in some cases by mechanical means) for further collection of dust particles on the droplets. These droplets are removed in a disengagement chamber, aided by baffles. (Fig. 14.)

Comments—This type of collector is taken to include scrubbers that atomize liquid entirely by gas kinetic energy, as well as scrubbers in which the gas merely passes through a mechanically formed spray. High dust-loadings can be handled, especially if the units are designed for continuous sludge removal (by conveyor, screw, etc.). Plugging is prevented by designing to avoid close clearances in the area where dry dust meets the spray. The efficiency curve (Fig. 20) is for a self-induced spray scrubber without mechanical input.

Jet Scrubber

Principle—Water flow is used in a jet ejector, both to aspirate dusty air and to provide droplets for collecting particulates. The conditioned-dust and the water droplets are separated from the gas in a settling chamber (which may be baffled). (Fig. 15.)

Comments—An induced draft of a few inches of water is usual because higher values require very high water rates as well as excessive power. The jet scrubber can be used where it is not economical to add a fan for a dust collection system and where either mist or easily absorbed gas is to be removed from the gas stream.

Venturi Scrubber

Principle—Water is introduced into the throat section and atomized by the high-velocity gas stream. The high relative velocity between the accelerating solid particle and the liquid droplet makes for high efficiency by impingement. Collection is aided by condensation if the gas is saturated in the reduced-pressure section of the venturi, since the solid particles serve as nuclei for condensing in the pressure-regain section. Agglomerated particles built on droplets of 50 μ or more can be collected with high efficiency in a subsequent centrifugal collector. (Fig. 16.)

Comment—High efficiencies require high power input; the venturi scrubber can be designed for large pressure-drops, as much as 80 in. water gage, to collect submicron dusts. Water can be introduced by spraying or by weir overflow. Efficiency is shown in *Fig.* 20, and approaches 100% at 2 μ and 22 in. water gage. The equipment is simple and can be fabricated in a variety of materials for corrosion resistance.

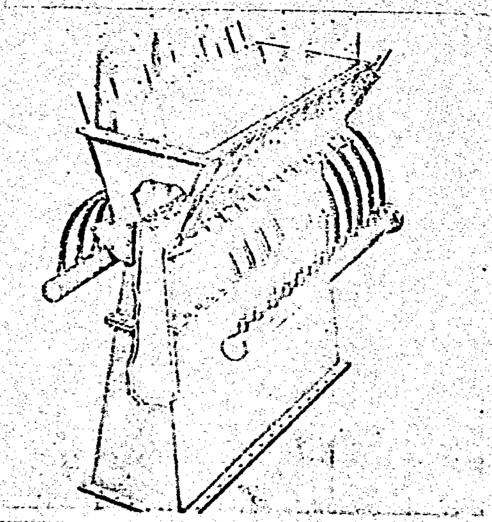
FABRIC FILTERS

Dry collectors have already been compared to wet scrubbers in the previous section on dry inertial collectors. Some functional characteristics of fabric filters are similar to those of inertial collectors: product is collected in usable condition, cleaned gas is uncooled, and secondary dust problems can be created in handling recovered dust. However, the fabric filter can handle much smaller particles at high efficiencies. Temperature is limited by the fabrics. Moisture content is limited because cold spot condensation can cake solids and also cause corrosion.

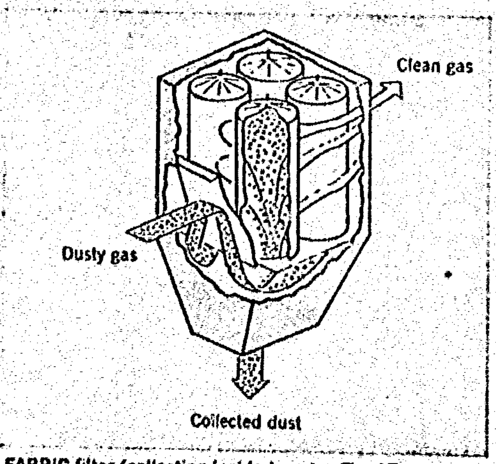
Principle—Filters for industrial gas cleaning are both bag and envelope type, with woven or felted fabric, and made from natural or synthetic fibers. Dirty gas flows through a porous medium and deposits particles in the voids. As the voids fill and a cake builds on the fabric surface, the pressure drop increases to a point where the solids must be removed.

Comments—Filters are used for high efficiency, 99+%, on small particles in the submicron range. Filters will continue to function effectively even when gas properties and process conditions vary. Costs are moderate.

The principal limitation is temperature, with a maximum of 550 F. Cooling a very hot dirty gas may be worthwhile in order to permit using a fabric filter. If the gas is below the dewpoint, heating some 50 to 75 F. above the dewpoint will allow a dry unit. Space required is large but may be acceptable because the recovered material is dry and ready for either use or disposal (unlike wet-scrubber recoveries).



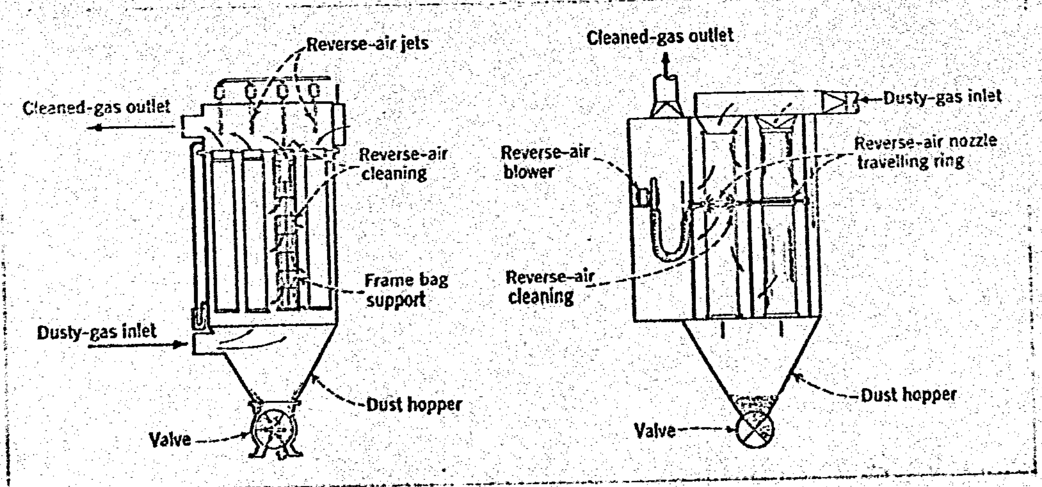
VENTURI SCRUBBER (detail of throat)—Fig. 16



FABRIC filter (collection inside bags)—Fig. 17

Intermittently Cleaned Filters

One type of filter is cleaned intermittently by shutting down the process and using shakers or reverse-air-jets to remove the dust cake. Another type operates continuously by sequentially cleaning one isolated compartment after another. As the compartments comprising the filter are cleaned they are put online again. These filters operate at air-volume/cloth-area ratios of 1.5 to 3 cfm./sq.ft. of filter area, or in terms of velocity, 1.5 to 3 ft./min. Filter media are woven fabrics chosen for thermal, chemical and mechanical endurance.[9] (*Fig.* 17.)



FABRIC FILTERS with reverse air cleaning (dust collected outside and inside bags)—Fig. 18

Continuously Cleaned Filters

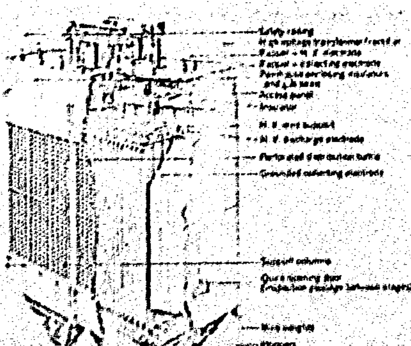
Continuous cleaning of filter media without isolating any part of the equipment is accomplished by a travelling blow-ring or by reverse-air-jets. These cleaning methods are so thorough and leave so little filter cake that woven fabrics cannot be used without loss of efficiency.* Hence felted fabrics are employed.[9] Air flowrates of 15 ft./min. are usual and result in more compact baghouses. This kind of filter permits higher dust-loads, but is more complex, hence has higher first cost and maintenance. (Fig. 18.)

ELECTROSTATIC PRECIPITATORS

The electrostatic precipitator has the advantage of permitting dry collection, and is highly efficient on small particles. A fabric filter might be a first choice, however, unless the process stream is hot or corrosive. If the particulate is coarse, a wet scrubber is lower in cost. But the pressure drop for the filter or scrubber will be higher than for the precipitator, and the scrubber's operating costs are likewise higher. Capital cost of electrostatic precipitators is usually the highest of all collectors, but a complete economic comparison must be made for a true picture.

Principle—The gas between a high-voltage electrode and a grounded (or oppositely charged) electrode, is ionized. Dust particles are charged by the gas ions and migrate to the grounded collecting electrode, where they adhere. Mists run off the collecting surface, often aided by addition of irrigation streams. Solids are most commonly removed by rapping with hammers or vibrators, although removal can be by washing or scraping. Pipe-type precipitators are used for mists or water flushing, and plate-types are used for dry collection and large gas flows. (Fig. 19.)

Comments—Although there is widespread use of electrostatic precipitators and fundamentals are well-developed, piloting a precipitator application is often worthwhile, since particle properties may vary between installations and theoretical efficiency is never attained. Some common applications are the collection of fly ash from pulverized-coal-fired boilers, cement-kiln dust, sulfuric acid mist, catalyst dust in oil refineries, and steel blast-furnace dust. Efficiencies are high, as shown in the curves of Fig. 20. Operating temperatures range from 0 to 700 F, although units have been designed for temperatures of −70 or +1,000 F. Pressure drop is small due to low velocities, but this makes for a large installation.



ELECTROSTATIC precipitator—*Fig.* 19

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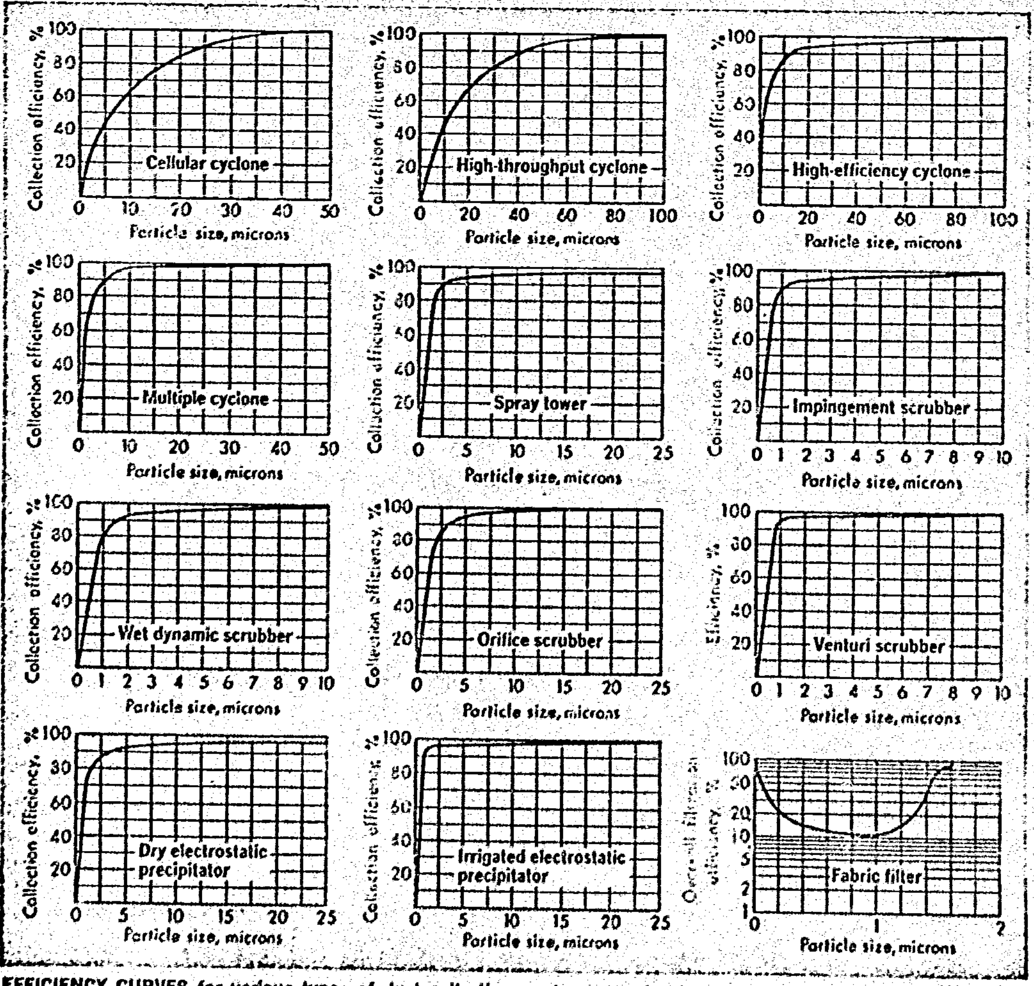
* *Woven filters are porous, and do not filter efficiently until a cake of dust is built up.*



EFFICIENCY CURVES for various types of dust collecting equipment—Fig. 20

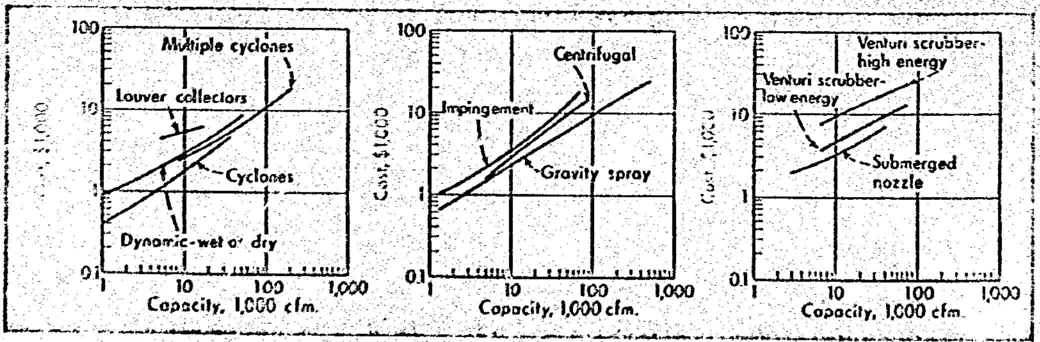
In considering electrostatic precipitation, the most important characteristic of a dust is its electrical conductivity. The dust conductivity must lie between that of a good conductor such as a solid metal and that of a good electrical insulator—and not too near either extreme. The reciprocal of conductivity, electrical resistivity, is used to define this property. For most-effective operation of a precipitator the dust resistivity should be between 10^4 and 10^{10} ohm-cm. Particles with a very low electrical resistivity readily lose their charge on the collecting electrode, only to be reentrained. On the other hand, materials with high electrical resistivity coat and insulate the collecting electrode, thereby reducing potential across the gas stream; this may lead to a spark discharge that reverses ionization and causes reentrainment. Conditioning agents such as moisture, acid mist, and ammonia can be added to the gas to reduce resistivity.

ESTIMATING COLLECTOR SPECIFICATIONS

To make a preliminary selection of a suitable type of gas-cleaning plant, only four basic items are required: dust loading, particle size, gas flow and allowable emission rate. Other factors listed in Table II, Data Required for Equipment Selection, will be important in comparing the collectors that are under consideration.

The required factors can be estimated for an existing process except for particle size. However, for a process in the design stage, both dust size and loading may be difficult to estimate, especially if process experience is not available within the organization or from suppliers or the literature. A broad list of processes and usual collector applications has been compiled by Kane.[7]

If a tentative choice of collector can be made, pilot plant trials may be the simplest approach, oper-



TYPICAL COSTS of various kinds of dust collectors plotted against capacity (costs

ating one or more types of collectors on an existing-process sidestream or in a new-process pilot plant. If pilot apparatus can be chosen and operated, the analysis of particle size distribution of dust can be ignored. The dust loading will be checked in the normal course of efficiency measurement, permitting direct evaluation for simple scaleup. Many suppliers have pilot-model collectors available for rental, often with some refund on purchase of a full-scale unit. Installation and operation of a 1,000 cfm. pilot device may cost from $500 to $5,000 or more, depending on the complexity of installation and the auxiliaries that may be required.

Going a step further, before making a choice, some simple lab work may prove economical in the long run. Laboratory data can be obtained from an existing process by collecting dust samples for particle size determination, either in your plant's lab, or by suppliers or consultants.

A microscopic count (described later) is tedious but requires only equipment usually available. However, collecting accumulated dust from the building corners or duct elbows, instead of sampling properly, can be misleading. The particle size may appear finer or coarser, agglomeration of particulates may change the size, or hygroscopic solids may change characteristics as water is picked up or other contaminants are included.

Lab data on crudely collected samples can be obtained quickly and cheaply but will probably have to be supplemented later by isokinetic sampling (described later), depending on the size of the project and the economic risk that can be tolerated.

It may be feasible to proceed with installation and plan to modify, supplement, or add stages to the collector. For example, a venturi with adjustable pressure drop can be installed, a wet collector can be added after a cyclone, or more stages may be added to some types of centrifugal wet scrubber.

Determining the desired emission depends on one or more factors: air pollution codes, toxicity limits, and economics. Legal requirements of air pollution control in the U.S. are very complex, depending on federal, state and local governments. Laws are concerned with the type and amount of particulate and gaseous emissions and also the appearance of smoke. A dust-control system is subject to future, more limiting legal requirements and should be selected with some thought toward future improvement.

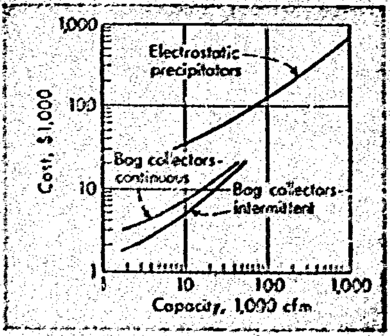
To determine emission requirements of a particular location, government agencies should be contacted. The permit system is used by most control agencies in this country and should be investigated early in the program. Literature on air pollution is helpful as a source of pollution laws. (See "Pollution Laws" in the references at the end of the article.) A digest of state laws[53] (Digest of State Air Pollution Laws) and a bibliography[51] are available from the Government Printing Office. Obtaining the information is simple, but interpretation and compliance may be a problem, which is not within the scope of this article.

Hazard control may be an added initial requirement. Data are available for many dusts and vapors, although new materials may require some lab work. Dust hazards to consider are explosive concentrations with air, flammability, and toxicity to plant or animal life, including radioactive hazards. Vapors in the gas stream must be checked for explosive limits and toxicity. A summary of properties is given in the table "Explosion Characteristics of Various Dusts."[20] It will be noted that concentrations involved in gas cleaning are usually below the minimum explosive concentration. Recommendations for safeguards are contained in the safety codes of the National Fire Protection Association.[23]

A very broad guide to allowable emission may be drawn from the following. Emission limits under an early code permitted 0.85 lb. fly ash per 1,000 lb. of gas corrected to 12% carbon dioxide. This is equal to 0.48 grains/cu.ft. Newer codes limit emission to 0.25 grains/cu.ft. Fine particulate matter of 0.01 to 0.02 grains/cu.ft. is the limit for a power plant emission that is to be invisible. Besides particulate concentration, the particle size and refractive index of the material affects light-scattering ability.

SAMPLING AND ANALYSIS

Sizing a proposed collector or checking the performance of installed equipment may very well re-



are for equipment only)—Fig. 21

Process and safety checklist—Table IV

Dirty gas heat—removal or recovery
Startup preheating equipment
Cleaned gas handling—vent or recycle
Waste treatment and disposal facilities
Storage requirements
Freezeup protection
Auxiliaries required
Controls and measurements required
Utilities—type and capacity available
Layout
  Fan location
  Access—installation, cleaning, maintenance, sampling
Plant location
Future expansions or tightened restrictions
Economics
  Equipment costs
  Operating costs
  Recovered material value
Approvals—insurance and permits
Hazard protection—flammable, explosive, toxic materials
Electrical classification of area
Pollution control—air and water

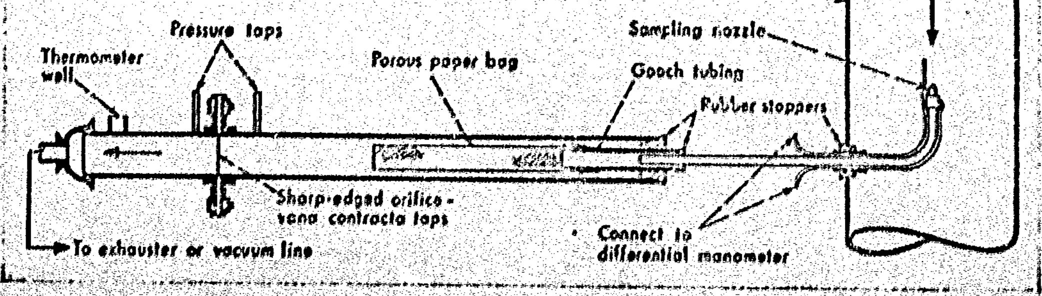
quire sampling and analysis to determine dust loading at inlet and outlet. Or a sample may be needed for particle size determination. There is a variety of techniques which can be used, permitting a choice depending on convenience, cost or accuracy. A summary is presented in "Aerosol Sampling and Analyzing Instruments."[60] As will be seen, test equipment choice depends on the process characteristics, so the investigator must have some idea of the magnitude of the answers he is setting out to find; for example, what rate and time of sampling will yield a significant weight of solids.

The gas flowrate must first be measured. For most process gas streams the pitot tube and inclined manometer are suitable. For obtaining a rough measure of velocity below 10 ft./sec., a vane anemometer may be used. High velocities in small ducts may be measured with an orifice or a venturi meter. Methods are discussed in Perry[9] and the Western Precipitation bulletin WP-50.[44]

There are many means of measuring gas velocity but the standard pitot tube and differential pressure gauge is relatively simple and reliable. The operator must be careful that the section of duct is straight for 6 to 10 duct diameters upstream and 2 to 4 diameters downstream, to ensure uniform flow; also that the dust is easily accessible, and that the pitot tube is pointing directly upstream. The combined pitot-static tube consists of two concentric tubes, one for impact pressure and the outer one for static pressure. The pressure difference, measured by an inclined manometer, is the velocity pressure. The standard type "L" pitot tube is suitable unless dust loading or gas humidity is high enough to cause plugging, in which case, the special type "S" pitot tube is used. Wet- and dry-bulb gas temperatures are taken for use in calculating both gas density and humidity.

Velocity pressures from manometer readings are measured in equal areas in the duct and used to calculate velocities as in Perry.[9]

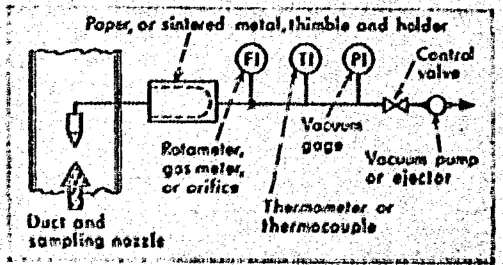
The velocities are averaged, and duct flow is ob-



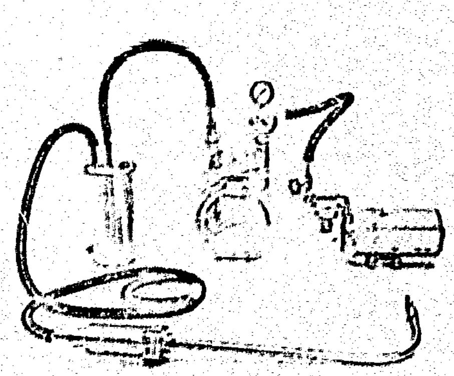
NULL-BALANCE sampling equipment—Fig. 22

tained by multiplying the average velocity and duct cross-sectional area.

To determine the dust loading in a duct, the method of isokinetic sampling is used to withdraw and collect all dust in a measured volume of gas, matching the sampler velocity with that in the main duct and ensuring a representative dust sample. There are two methods of doing this. Duct velocity may be measured and the sampler velocity adjusted to the isokinetic velocity. Or a null-balance probe can be used (Fig. 22) to match static pressures, thereby matching velocities without measuring duct velocity. The former method is described in several references,[22,39,44] and the latter is described by Lapple.[40] See also Ref. 44. The sampling train (Fig. 24) is assembled from a choice of components. Thanks to the growing interest in air pollution, components that once had to be made by the user are now commercially available.



DUST SAMPLING equipment diagram—Fig. 23



DUST SAMPLING apparatus assembly—Fig. 24

Equipment is connected as shown in the schematic arrangement, Fig. 23, with a sharp-edged nozzle, usually ¼ in. or more in diameter of opening, pointing upstream. Dusty gas is withdrawn at a rate fixed in such a manner that the velocity at the face of the probe is within 10% of the velocity in the duct near the probe.

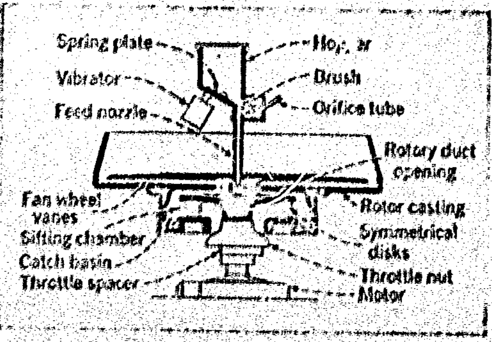
The gas is drawn through the sampling train by a vacuum pump—or an ejector operating on air, steam or water—and capable of maintaining a flow of ½ to 2 cfm. as resistance increases in the filter owing to dust buildup.

The gas sample stream must be metered by some suitable instrument, such as a rotameter, orifice and manometer, or gas meter. The rate of sampling is controlled by a valve for variations in temperature, vacuum or density.

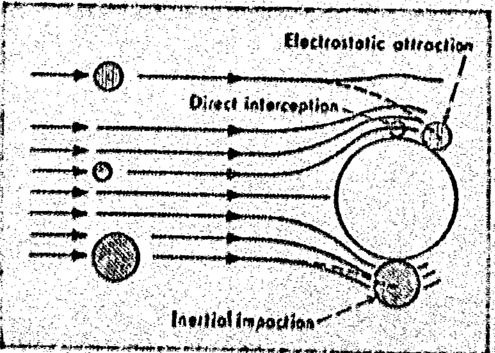
The dusty gas picked up by the sample probe is filtered in a preweighed paper or sintered-metal thimble. The filters or separating devices used are usually at least 99% efficient. The probe is traversed like the pitot tube and held at the same locations with the sampling flow set to equal duct velocity at that location.

A simplified dust sampling may be made on the exit of a wet scrubber if it is felt that all particles are less than a 5μ and sampling need not be isokinetic. Also on a wet scrubber outlet the temperature of the gas up to the filter must be kept above the dewpoint by heating with an electric resistance-heater. Placing the filter in the probe assembly (where it is heated by stackgas) avoids condensation, loss of sample, or plugging in the tube between probe and remote filter.

The sample collector is not limited to paper filters



BAHCO CLASSIFIER, cross-sectional diagram—Fig. 25



MECHANISMS of particle collection—Fig. 26

and in fact, other types may be more suitable. A description of a variety of such devices is given in Stern II p. 497[13] and Western Precipitation bulletin WP-50.[44] The filter medium can be chosen from papers, fabrics, porous alundum, or cellulose ester membranes, thereby permitting selection for special conditions—high temperatures, extremely small particles, low ash content media, or transparency of media with oil or water treatment after sample collection.

Small-diameter cyclones can be used to collect samples if the dust is coarse, or if total dust measurement is not important. One manufacturer (Duster) uses the cyclone efficiency for simple scaleup (assuming no efficiency is lost in gas distribution) to the multiple cyclone needed for the commercial-sized collector.

Another common sampling device, the impinger, consists of a flat surface with sample stream directed through a jet to impinge on the plate, usually submerged. Solid particles down to 1μ are determined after evaporation.

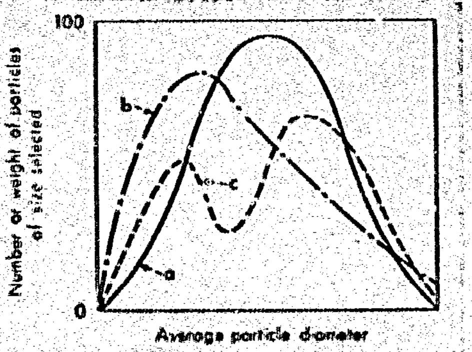
The total gas volume is the product of the rate of sampling and the duration of sampling time. The sample weight is obtained, by difference, after drying and weighing. Dividing the sample weight (in grains) by the gas volume (in standard, or actual, cubic feet) gives the dust loading of the gas stream.*

Efficiency of a collector is the difference between inlet and outlet loading, divided by the inlet loading. The ASME procedure for calculating efficiency permits using the weight of dust caught instead of either inlet or outlet dust.

A particle-size analysis should be run on the sample collected. Some idea of particle size is a prerequisite to selecting a dust collector. There are many approaches depending on the situation. Adequate facilities may already be available within the organization, or it may be worthwhile to obtain analytical equipment for the current study, if future gas-cleaning problems will justify the effort and equipment. On the other hand, the process being studied may be a duplication of an existing plant with much background experience to draw upon.

If answers are needed with a minimum of cost and time, it may be advantageous to call in outside analytical services that can provide the analysis for less than $100 per sample. Many of the dust collection equipment manufacturers—if one can be chosen at this point—can provide the service.

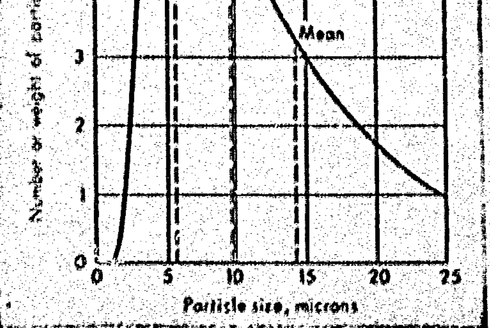
A summary of size analysis techniques and devices appeared in CHEMICAL ENGINEERING recently.[41] Methods of particle-size analysis are varied to suit the nature of the particulate or the needs of the analyst or the method of sample collection; a complete picture of test methods and devices is beyond the scope of this article. However, it might be well to give some specific examples of the commonly used



TYPICAL particle-size distributions, (a) normal; (b) skewed; (c) double peaked probability—Fig. 27

methods that are applied in dust collector work.

The Bahco Micro-Particle Classifier is a combination air centrifuge-elutriator, and is an ASME standard for particle-sizing.[34] A weighed sample of 10 to 20 g. is charged into the hopper, Fig. 25, and introduced through a feed mechanism into a spiral of air having suitable tangential and radial velocities. A portion of the sample is carried by centrifugal force against the air flow and toward the periphery of the spiral. The remainder of the sample—the smaller, lighter particles—is carried with air flow toward the center. The air is pumped through the unit, by means of an integral fan impeller, at a rate controlled by adjusting the air inlet orifice. The residue is weighed after removal of a light fraction,



SKEWED particle-size distribution of typical dust—Fig. 28

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* Sometimes, loading is reported in g./cu.m. (1 grain/cu.ft. = 2.3 g/cu.m.).

Calculation of collector efficiency—Table V

Particle Size Distribution, Microns	Particle Size Midpoint of Range, Microns	Fraction of Total Dust in Range, %		Cyclone Efficiency at Midpoint, %*		Percent Dust Collected	Dust Emitted, %†		Electrostatic Precipitator Efficiency at Midpoint, %		Dust Collected,%
<2½	1¼	12	×	33.5	=	4.0	50.3	×	77.0	=	38.7
2½-5	3¾	8	×	64.5	=	5.2	17.6	×	90.5	=	16.0
5-7½	6¼	6	×	76.7	=	4.6	8.8	×	94.0	=	8.3
7½-10	8¾	4	×	84.2	=	3.4	3.8	×	95.0	=	3.6
10-15	12½	8	×	89.3	=	7.1	5.7	×	95.5	=	5.4
15-20	17½	7	×	92.0	=	6.4	3.8	×	96.0	=	3.7
20-30	25	10	×	94.3	=	9.4	3.8	×	96.5	=	3.7
30-40	35	10	×	96.0	=	9.6	2.5	×	96.8	=	2.4
40-60	50	15	×	97.3	=	14.6	2.5	×	97.7	=	2.4
60-75	67½	10	×	98.5	=	9.9	0.6	×	98.7	=	0.6
75-104	89½	7	×	99.1	=	6.9	0.6	×	99.2	=	0.6
104-150	127	3	×	100.0	=	3.0	—		—		—
						84.1%					85.4%

Data are those of Stairmand (Ref. 12).

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*Efficiencies as read from an enlarged curve.

†Calculating emitted dust from collected:

Percent of 1¼ micron dust emitted = $\frac{12 - 4.0}{100 - 84.1} = 50.3\%$

Calculating combined efficiency:

Cyclone fraction emitted = 1.000 − 0.841 = 0.159

Precipitator fraction emitted = 1.00 − 0.854 = 0.146

Combined fraction emitted = 0.159 × 0.146 = 0.0232

Combined fraction collected = 1 − 0.0232 = 0.977

Combined percent collected = 97.7%

and the light-cut weight is determined by difference. The process is repeated to obtain nine fractions. Each orifice setting must be calibrated on a dust of known size distribution and the terminal-velocity values assigned. The development of standardization techniques are discussed by Crandall.[35]

Other useful methods include electronic counting by the Coulter counter in which a suspension is put through an aperture, essentially one particle at a time, with electronic recording of each particle by size.

The cascade impactor projects particles through a jet onto a plate where large particles are collected, the fines going on to the next stage.

Elutriation is applied in the Roller analyzer on the principle of the settling chamber described under collectors, using an airstream to remove a fines fraction, depending on velocity. These methods and others are reviewed in Perry[5] as well as others.[18, 41, 43]

A sieve shaker can provide several particle size ranges down to 50μ particles (43μ equals 325 mesh). About 100 g. of sample are needed. There are some limitations: thin, flat flakes may give artificially large weight fractions of the larger particles, needle-like crystals may conversely appear in the analysis as smaller sizes, some materials finer than 150μ may flocculate, and other materials may be degraded.

The sieve analysis should be supplemented by a microscopic examination to check particle shape. In the particle sizes between 0.2 and 100μ the optical microscope can be used without sieves. The method is laborious but can be simplified by using photomicrographs or by projecting the image of the particles on a screen. Theoretical and practical aspects are covered in detail in the literature.[43]

An important property needed for selecting an electrostatic precipitator is the electrical resistivity of the dust to be handled. The measurement can be omitted if a precipitator is commonly used for the dust or if the equipment designer is otherwise familiar with it.

Several methods for particle resistivity measurement are discussed in White,[29] and resistivities of some representative dusts and fumes are given. A standard method along with apparatus construction details is given in the ASME Power Test Code 28,[31] and in the API manual, Electrostatic Precipitators.[30]

MECHANISMS

Mechanisms governing the collection of particulate matter have been studied singly and combined but do not serve as a means of classifying collectors, since there may be more than one mechanism at work. Operation of a collector is considered to proceed in three phases: (1) depositing of particles on a collecting surface, (2) retaining solids on the surface, and (3) removal. Parameters describing the mechanisms

Over-all cost of gas cleaning—Table VI

Collector Type	Efficiency on Standard Dust, %	Average Pressure Drop, In w.g.	Installed Cost, $	Power Cost, $/yr.	Water Required, Gal/1,000 Cu. Ft.	Water Cost $/Yr.	Maintenance, $/Yr.	Total Annual Cost, $/Yr.	Total Annual Cost ¢/(Yr.)(Cfm.)
Dry									
1. Louver collector	58.6	1.7	34,500	1,560	——	——	300	5,310	8.9
2. Medium efficiency cyclone	65.3	3.7	25,000	3,380	——	——	200	6,080	10.1
3. High efficiency cyclone	84.2	4.9	48,500	4,520	——	——	200	9,570	16.0
4. Multiple cyclone	93.8	4.3	52,500	3,960	——	——	200	9,410	15.7
5. Electrostatic Precipitator	99.0	0.9	233,000	2,000	——	——	1,300	26,600	44.4
6. Fabric filter, shaker*	99.7	2.5	165,000	3,740	——	——	10,000	30,240	50.4
7. Fabric filter, envelope*	99.8	2.0	152,000	3,380	——	——	9,500	28,080	47.0
8. Fabric filter, reverse jet	99.9	3.0	231,000	7,920	——	——	19,000	50,020	83.6
Wet									
9. Submerged Nozzle	93.6	6.1	66,700	5,640	0.7	1,010	700	14,020	23.3
10. Spray Chamber	94.5	1.4	139,000	4,760	21.7	31,250	1,000	50,910	84.8
11. Impingement Scrubber	97.9	6.1	82,200	5,800	3.6	5,190	1,000	20,210	33.7
12. Wet Dynamic Scrubber	98.5	——	136,000	45,400	6.0	8,640	700	68,340	141
13. Low Energy venturi	99.7	20.0	107,000	18,820	8.4	12,100	1,000	42,620	71.2
14. High Energy venturi	99.9	31.5	117,000	29,740	8.4	12,100	1,000	54,540	91.0

Notes:
The installed cost includes equipment, auxiliaries, such as fans, pumps, and motors (but not including solids disposal equipment), site preparation and installation. Installation charges are 100% of all equipment except electrostatic precipitators and dynamic scrubbers which are 50%.
Prices are adjusted to 1968 with a Marshall and Stevens Index of 273. The British pound is taken at $2.80 U.S.
The cost of power is taken at $0.01 per kwh. Efficiencies of fans and motors are assumed 60%. Water cost is $0.05 per 1,000 gal. and reported usage converted from Imperial (assumed) to U.S. gallons. (Data are from Stairmand, Ref. 11.)

*Maintenance charges include bag changes, once per year for envelope-type and twice for shaker and reverse-jet filters.

of deposition or collection have been described by Lunde and Lapple,[19] (a table of parameters is reproduced in Perry, p. 20-65[9]) and are generally described below as a means of understanding operating principles of collectors.

Gravity Settling—The weight of particles may be enough to permit settling from a moving gas stream, where the dust is more than 50μ, in a gravity settling chamber or a baffle chamber.

Centrifugal Separation—Particles in a vortex gas flow are separated by centrifugal force and are directed to the outer wall, as in a cyclone or centrifugal scrubber.

Direct Interception—A fluid streamline curving around an obstacle such as a filter element or water droplet may carry a particle within contacting distance of the obstacle, and the collision will arrest the particle on the element or droplet. See Fig. 26, Mechanisms of Particle Collection.

Inertial Impaction—The inertia of the particle causes it to continue in its path rather than follow the streamline curving around the obstacle, thus permitting contact of the particle with the obstacle.

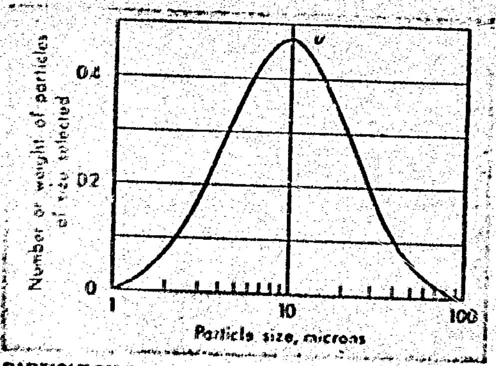
Diffusional Deposition—For particles smaller than 0.1μ at low velocities, molecular impacts of Brownian movement deflect the path of the particle, increasing chances of collision with filter elements or water droplets.

Electrostatic Precipitation—A collector body or a particle, or both, may have a static charge that will introduce a force to affect the movement of the particle.

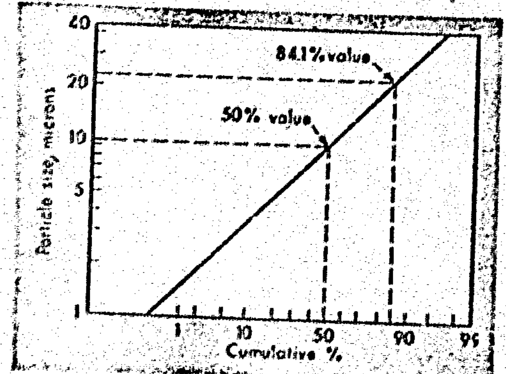
SAMPLE PROBLEM

Over-all collection efficiency can be calculated by using a collector efficiency curve in combination with the particle size distribution curve, provided that the method of particle size measurement is the same for both curves. Calculations are shown in Table V for a high-efficiency cyclone followed by an electrostatic precipitator. Data are from Stairmand.[11] The test dust used compares to a typical fly ash and is given in Table VI, Standard Test Dust Characteristics. The efficiency curves used are those shown in Fig. 20.

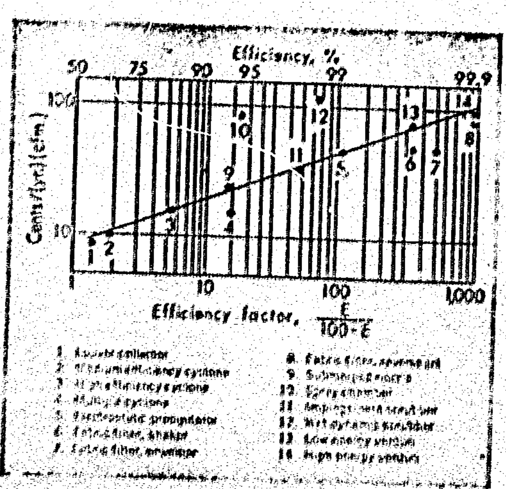
From the collector efficiency curve choose several efficiencies and the corresponding ranges of particle sizes. From the size distribution curve (or table, in this case) obtain the percentage of dust within the



PARTICLE-SIZE distribution of Fig. 28, plotted with logarithmic abscissa (particle size)—Fig. 29



LOG-PROBABILITY curve for particle-size distribution of above figure—Fig. 29



OVER-ALL COST of gas cleaning (Stairmand[14])—Fig. 30

size increment. For example, 12% of the total dust is less than 2½ μ, and the midpoint of the range is 1¼μ. The cyclone efficiency is 33.5% at 1¼μ.

The cyclone has a collection efficiency of 84.1% and emits 15.9% of the inlet dust. The electrostatic precipitator collects 85.4% of the cyclone emission. The combined efficiency is 97.7%.

EQUIPMENT COSTS

Costs shown on Fig. 21 are manufacturers' prices for dust collectors only. System costs must be developed for the individual case, adding the cost of freight, foundations, supports, erection, and auxiliary equipment. Collector costs may be adjusted for special materials of construction. The cost basis year is 1968. (Marshall and Stevens Index = 273).

For any one type of collector, price may vary widely depending on the required duty. The costs presented are for "typical" applications suitable for a preliminary comparison. Where costs of systems are of the same order of magnitude, it is probably worthwhile to obtain quotations for each dust collector.

Over-All Cost of Gas Cleaning

In an economic comparison between different collectors for a particular application, the efficiencies are likely to be different. The higher cost for better collection can be compared with the cheaper installation, as was compared in Table V. Costs above those shown tend toward an uneconomical equipment choice, while those below tend toward being a good buy.

The original data for this figure were presented by Stairmand[13] and are adjusted to current U.S. costs in Table VI. Stairmand developed the operating costs of the various collector systems cleaning 60,000 cfm. gas at 68 F. with an inlet dust-loading of 5 grains/cu.ft. of the standard test dust given in Table V, with 30% less than 10 μ particle size.

It is interesting to note the high-cost units are the spray chamber (with a high water-rate) and the dynamic scrubber (with a high power-rate). Also, the electrostatic precipitator may have a high first cost but efficiency is high and power costs are reasonable.

CHOOSING A COLLECTOR

Let us look at the selection of a collector from meager preliminary information. Take as an example a process in which organic chemicals are spray-dried and collected by a cyclone, the dusty gas then going to a spray tower. It is desirable to replace the existing inefficient wet collector to meet air pollution abatement requirements and to recover product.

Material-balance calculations of product recovery efficiency can be used to determine dust-loading and water evaporated in the dryer. Microscopic counts of dust samples collected downstream from the cyclone give particle size. A manometer can be be used to measure pressures and, with the fan curves, the gas flow is determined.

State air pollution laws fix the emission based on stack height and distance from the property line.

A summary of data looks like this:

Dust loading to collector	50 to 200 lb./hr.
Particle size—Product A	50% < 30 μ
Product B	50% < 20 μ
Product C	50% < 5 μ
Gas flow at inlet conditions	20,000 cfm.
Gas temperature	250 F.
Gas humidity	3,000 lb./hr.
Dust emission allowable from collector	20 lb./hr.

Converting the dust loading to grains/cu. ft.:

$$\frac{200 \text{ lb.}}{\text{hr.}} \times 7{,}000 \frac{\text{gr.}}{\text{lb.}} \times \frac{1}{20{,}000} \frac{\text{min.}}{\text{cu.ft}} \times \frac{1}{60} \frac{\text{hr.}}{\text{min.}} = 1.17 \text{ gr./cu.ft.}$$

The requirement is to emit no more than 20 lb./hr. from a maximum of 200 lb./hr., or 10% emission. Collection efficiency is then 90% for a dust loading of a little more than 1 grain/cu.ft. of particulate with a mean particle diameter of 5 μ.

From the note on Table I, we find that the loading is "light" and the particle size "fine." From the table in Ref. 7, Industrial Collector Applications, Lines 4 and 39 favor high-efficiency centrifugals, wet collectors and fabric filters.

Cyclones are unsuitable, which is evident since we are collecting dust that already has passed a cyclone. Electrostatic precipitators are not likely since the gas-handling capacity is somewhat small for good operating efficiencies, and also the electrical resistivity of an organic dust will probably be too high. Multiple high-efficiency cyclones are small in diameter and subject to plugging with sticky organics. Fabric filters are excellent collectors for fine materials, especially when we would like to recover usable product, but we should keep the sticking problem in mind. Wet scrubbers will give a clean stack but with a wet plume; the recovered product will be degraded in value, since it will have to be dried again. Product value is 2¢/lb. dry and 1¢/lb. wet.

Referring to Table I, Equipment Application, we can choose centrifugal, impingement and venturi scrubbers. Other equipment types are excluded because, let us assume, they are unsuited for scrubbing with dust slurries. Recovered dust will have to be recycled to build up concentration for economical recovery.

We will compare each selection by picking the operating values of pressure losses and liquid rate at midrange. Efficiency is read from the curves of Fig. 20.

Example of collector selection—Table VII

	Wet Scrubbers			Continuous Fabric Filter
	Centrifugal	Impingement	Venturi	
1. Efficiency	94	97	99.6	>99.9
2. Pressure loss—liquid, psi.	60	60	15	——
3. Liquid rate, gpm.	100	60	100	——
4. Pressure loss—gas, in. w. g.	4	5	20	4
5. Power required—gas, hp.	74	79	158	74
6. Power required—liquid, hp.	7	4	2	——
7. Power cost, $/yr.	4,800	5,000	9,600	4,400
8. Equipment cost, $/yr.	1,000	1,200	2,000	2,200
9. Total cost, $/yr.	5,800	6,200	11,600	6,600
10. Recovered product value, $/yr.	15,000	15,500	15,900	32,000
11. "Return" (line 10 —line 9), $/yr.	9,200	9,300	4,300	25,400
12. Over-all cost from Table VI by interpolation $/yr.	3,500	5,000	9,300	15,200
13. Return (line 10—line 12), $/yr.	11,500	10,500	6,600	16,800

Notes

System pressure without collector = 10 in. w.g.

$$\text{Fan hp.} = \frac{\text{cfm.} \times \text{p.}}{6{,}356 \times 60\% \text{ Eff.}} = 5.2 \times \text{p.}$$

$$\text{Pump hp.} = \frac{\text{gpm.} \times \text{sg.} \times 2.31 \text{ psi.}}{3{,}960 \times 50\% \text{ Eff.}} = 0.0012 \times \text{gpm.} \times \text{psi.}$$

Electric cost =

$$\text{hp.} \times 8{,}000 \frac{\text{hr.}}{\text{yr.}} \times 0.746 \frac{\text{kwh.}}{\text{hp. hr.}} \times 0.01 \frac{\$}{\text{kwh.}} = 60 \times \text{hp.}$$

Installed cost = 200% × equipment cost from Fig. 2 × 10% depreciation/yr.

The results of comparing the selected collectors are shown in Table VII. It must be emphasized that this is a preliminary choice only. Added costs such as tanks, bag replacements, larger fans and maintenance costs, have been ignored. The happy factor of a tax credit for pollution-control equipment is also omitted. For the sake of simplicity, the gas-handling requirement is at actual conditions rather than at standard conditions.

An alternative method for quick comparison is the use of Table VI to obtain the over-all cost of gas cleaning as shown on Line 12, Table VII. The two costs for each collector are different, especially in the case of the bag collector, but looking at the recalculated "return" leads to the same conclusions. The fabric filter is probably a good selection if product will not cake on the bags or if product cross-contamination does not require changing bags. A low pressure-drop wet scrubber, such as the centrifugal or impingement type, is a second choice. The high pressure-drop venturi is an excellent guarantee of meeting pollution codes, but is costly. ■

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