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Title: A Prototype Wet Packed Bed Scrubber for Controlling Odor Emission From a Confinement Livestock Building

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A prototype cross flow wet bed scrubber was designed and built to study the process of washing particles from the exhaust air of a livestock confinement environment. Livestock production trends have been toward more concentrated, confined production units. A small, but significant number of producers are under pressure to decrease or eliminate the odor emitted from their livestock facilities.

Control of odor from livestock production facilities by a scrubber raises the following questions which this research will resolve:

a. Is effective removal of dust particles possible using wet scrubbing methods?

b. Is removal of odors directly associated with dust removal?

c. What are the design parameters for dust removal

by the wet scrubber, and its technical feasibility for livestock odor control?

The research supports the hypothesis that the scrubber is 95 percent effective for removal of particles 5 microns and larger, with more than 50 percent removal measured at the 2 micron particle size. A decrease in odor intensity was statistically correlated to particle removal. Though the scrubber was designed for particle removal, over the entire period of experimentation, 20 percent of the ammonia in the air was removed by the scrubbing action.

For qualitative comparison of odor intensity, cloth swatches were used to adsorb odorants on their surface. These swatches were then transported to a remote odor panel which conducted the odor comparison. This inexpensive, simple, and fast sampling procedure gave a positive indication that odor of the confinement building exhaust air was reduced by the scrubber.

From this research, design criteria are now available for a prototype scrubber adaptable to current swine production buildings. The physical and operational attributes of the scrubber would allow odor control by removal of particles from the ventilation system of production buildings.

A Prototype Wet Packed Bed Scrubber for Controlling Odor Emission From a Confinement Livestock Building

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I. INTRODUCTION

Recent trends in modern livestock production can be characterized as the following:

a) A decrease in the number of livestock producers.

b) An increase in livestock population.

c) An increase in the average herd or flock size.

d) An increase in numbers of livestock in feeding lots, or environmentally controlled buildings.

These trends have resulted in new management problems for the producer. Among these new problems, the legal and social implications of the release of odors to the surrounding environment are significant. This release of malodorants exceeding reasonable limits has affected the quality of life for neighbors (Willrich and Miner, 1971). Odors are one of the most controversial and difficult air pollutants to control. Though odorous compounds have never exceeded safe air health standards in areas surrounding livestock production facilities, they are regarded as nuisance pollutants and are legally dealt with by the Doctrine of Nuisance (Miner, 1974).

Odor control techniques by livestock producers currently keep the animal separated from the manure, and control the manures' environment. However, these techniques do not prevent malodorants from escaping to the surrounding air and noses of the neighbors.

With confinement techniques, it may be possible to control the transport of malodorants by washing them out of the exhaust air. The concept of gas washing is new to livestock production, but is common in many other industries, such as paper, petroleum, steel and rendering. Gas scrubbing has applications in removal or reduction of noxious chemicals, reduction of odorant concentrations, and recovery of valuable raw materials or products (Calvert, 1977).

Recent evidence indicates that most malodorants from hog production are in particulate form (Hammond, et al., 1977). There are many types of gas scrubbers for removing particles, each with specific characteristics. For the purpose of removing offensive odors from confinement building exhaust air, the use of wet scrubbing is the most suitable process (Schirz, 1977).

The purpose of this research was to investigate particulate removal effectiveness, and odor removal effectiveness from hog confinement exhaust air by a cross-flow, packed-bed, wet scrubber.

A prototype scrubber was designed to monitor effects of changing air speed and packing thickness on the following dependent variables: a. Overall particle removal, and removal of particles in specific size ranges; b. Ammonia removal; c. Odor removal or reduction.

II. REVIEW OF LITERATURE

The sense of smell is unique in that no mechanical or chemical alternative device exists for measuring odor. The basic detector in odor analysis is the human nose. Thus, odor is essentially a subjective phenomenon for which no quantitative standard or comparision exists (Turk and Hyman, 1978).

2.1 Mechanism of Olfaction

When molecules of an odorous compound are inhaled into the nasal passages, the olfactory receptors respond, triggering a signal which is transmitted to the olfactory bulb in the brain through olfactory cells and associated fibers. The brain is able to discriminate between different types of odor; fragrant, sour, burnt, etc., and to record their intensity which is a function of the molecular concentration (Dorling, 1977).

The basic mechanisms of olfaction are still not fully understood, but among the many theories suggested, two have received the most support. The Dyson-Wright vibration theory hypothesizes that molecular vibrations determine the odor quality, with strength determined by odorant volatility and absorbability. The Moncrieff-Amoore stereochemical theory (Amoore et al., 1964) hypothesizes that molecular configuration is complementary to certain receptor sites, i.e. a lock and key concept.

2.2. Characteristics of Odor

Odors are characterized by quality, intensity, and absolute threshold. Quality classification compares an odor with an odor that is familiar, and depends on past experience. Many attempts have been made to produce a list of basic odor classes that would describe the qualities of all other odors. Davies (1965) constructed a table of six classifications, ranging from musky to almond. Odor strength, or intensity, is commonly measured by the quantity of an odor-free medium required to dilute to extinction the odor (Miner, 1974). The detection, or absolute, threshold is the minimum odorant concentration distinguished from an odor-free environment. The recognition threshold is the minimum concentration at which an odorant can be specifically identified, and is never lower than the detection threshold (Turk, 1978). For the air in contact with anaerobically decomposing manure, eighty-two organic compounds have been identified in Table 1.

For thirteen selected compounds in hog house exhaust air, threshold values from several studies are tabulated in Table 2.

TABLE 1. VOLATILE COMPONENTS IDENTIFIED IN THE ATMOSPHERE OF SWINE CONFINEMENT BUILDINGS

Amines

Methylamine
Ethylamine
n-Propylamine
i-Propylamine
Pentylamine
Trimethalamine
Triethylamine

Esters

Methylformate
Methylacetate
i-Propylacetate
i-Butylacetate
Propylacetate
Butylacetate

Fixed Gases

Carbon dioxide
Hydrogen sulphide
Ammonia
Methane

Mercaptans

Methylmercaptan
(Ethylmercaptan,
Allylmercaptan,
Benzylmercaptan,
Crotylmercaptan)

Phenolic subst.

Phenol
p-Cresol
Ethylphenol

N-Heterocycles

Indole
Skatole
Pyridine
3-Aminopyridine

Others

Toluene
Xylene
Alkylbenzenes
Indane
Methylnaphtalene

Sulphides

Diethylsulphide
Dimethylsulphide
Dimethyldisulphide
Dimethyltrisulphide
(Methylsulphide)
(Ethylsulphide)
(Diphenylsulphide)
(Thiophenol)

Aldehydes

Formaldehyde
Acetaldehyde
Propionaldehyde
i-Butyraldehyde
Valeraldehyde
Carponaldehyde
Enanthaldehyde
Caprylaldehyde
Nonylaldehyde
Decylaldehyde
Acroleine
Benzaldehyde

Acids

Acetic acid
Propionic acid
n-Butyric acid
n-Valeric acid
n-Caproic acid
Enanthic acid
Benzoic acid
i-Butyric acid
i-Valeric acid
i-Caproic acid
Caprylic acid
Pelargonic acid

Alcohols

Methanol
Ethanol
n-Propanol
i-Propanol
n-Butanol
i-Butanol
i-Pentanol
2-ethoxy-1-propanol

Keytones

Acetone
Butanone
3-Pentanone
2, 3-Butanedione
3-Hydroxy-2-butanone (acetoin)
2-Octanone
Acetophenone

(Reference-Linn and van de Vyver, 1977)

TABLE 2. THRESHOLD CONCENTRATION VALUES FOR SELECTED COMPOUNDS FOUND IN THE ATMOSPHERE OF SWINE CONFINEMENT BUILDINGS.

SUBSTANCE	CONCENTRATION 10^{-9} g/l
Acetaldehyde	360
Acetic Acid	25
Ammonia	35
n-Butyl acetate	710
Butyl mercaptan	35
Diethylamine	75
Dimethylamine	18
Ethylamine	18
Ethyl mercaptan	25
Isopropylamine	12
Methylamine	12
Methyl mercaptan	20
Triethylamine	100

(Reference: Miner, 1974)

2.3 Odor Intensity Measurement

The technological problems of quantitative odor measurement are formidable (Miner, 1974). Odor is essentially a subjective response to the mixture of chemical compounds present in an atmosphere. This response is not only a function of the chemical makeup, but also that psychological disposition of the observer.

Hyman (1977) presented a tabulation of different investigations in which correlations between odor intensity and odorant concentration were established for thirty-three compounds. The values for the detected concentration of a compound varied greatly from test to test, subject to subject, and large differences occurred between repetitions by the same individual. The variances between tests were random. For several compounds, the difference in detected odorant concentrations had a range of six orders of magnitude.

To minimize discrepencies, it is appropriate to test odor intensities for a specific situation with a statistically significant number of subjects to determine any intensity differences. ASTM (1968) states tha the minimum number of observers for any test is five. Fewer than five observers places too much significance on the response of any single individual. Subjects must also pass a preliminary screening to assure that they are capable of a minimum response to the stimuli presented. This may be done by allowing subjects to smell standard odorant samples of various strengths. Subjects which detect high odor thresholds due to low olfactory sensitivity should not be used for odor intensity testing.

Complex mixtures of odorant compounds invariably occur in agricultural and livestock operations. The perceived odor may not necessarily be a simple summation of all the individual compound contributions. There may be an antagonistic effect, by which one odor will counteract another, or a synergistic effect produced by mutual enhancement (Dorling, 1977).

2.4 Odor Fatigue

Fatigue, or olfactory adaptation, is the decrease in sensitivity to an odorant following a prolonged exposure. The rate and degree of loss, and subsequent recovery, depend on the odorant and its concentration (Steinmetz et al., 1971). This fatigue affects the perceived intensity of the odorant, though the physiological mechanism is not fully known.

Odor fatague interferes with the sensory measurement of odor intensity carried out in testing for intensity. Evidence points out that a person is capable of good sensory evaluation when exposed for intermittent periods in an open environment, such as downwind from a point source, like a hog house. However, a person in an odorous enclosure, who is subject to unrelieved exposure to odor, will become adapted to a point that can invalidate any sensory judgment (Cain and Engen, 1969).

2.5 Measuring by Direct Methods

Because of odor nuisance complaints from livestock production and other sources, it has been necessary to devise methods for the assessment of odor intensity. This assessment determines the legitimacy of complaints, and provides a means whereby the efficiency of any remedial control measures can be monitored.

Direct methods of measuring present to a panel of observers samples of odorous air which have been diluted to different degrees with odor-free air. The dilution attempts to decrease the concentration of odorant to the odor threshold. A range of dilutions is obtained corresponding to a positive response varying from zero to 100%. The direct method provides the means for comparing odor intensity of emissions before and after treatment by control equipment, thus yielding a measure of equipment efficiency. It also enables odorous emission comparisons of similar odor types from different sources, such as the swine odor from different hog production units (Dorling, 1977).

Various methods have been used to prepare and present the diluted samples to the observer, including portable devices for ambient air monitoring (Cooper, 1973). Principle methods currently used are the following:

a) The odor room

Diluted samples are prepared by admitting known volumes of odorous air into a specially constructed room equipped with fans. Fans enable the contaminated air to be exhausted and replenished with clean air between tests. Panel observers enter through an air lock and stay long enough to make an assessment (Leonardos et al., 1969). This method provides the nearest approach to practice, as observers are totally immersed in the odorous air. However, this test is very time consuming and the provision of an odor room is expensive.

b) ASTM syringe method (ASTM, 1968)

Odorous air samples are aspirated into a 100-ml capacity syringe and subsequent dilutions are prepared in other syringes by dilution of aliquots with odor-free air. The panel members inject the samples into a nostril and record their response. Problems with this method include: preparation of the dilute sample may be laborious, as scores of syringes may be required; injecting the samples into the nostril can be aesthetically unacceptable;

further dilution may occur between the syringe and the nasal receptors; and because of the high surface-to-volume ratio of the syringe, considerable losses of odorant can occur by surface adsorption.

c) Dynamic dilution method

Samples of odorous air are mixed at known flow rates with a measured flow rate of odor-free air into a mixing chamber. Panel members make their assessment at each dilution by sniffing the air which is discharged into hoods, face masks, sniffing ports, or spray fountains (Cooper, 1973). Problems arise with locating the apparatus so the odorous air stream can be directly metered into the sniffing apparatus while the device is in an odor-free environment. This may require transport of an air sampling system. A sampling system consists of a 50-liter capacity polyvinyl fluoride plastic bag contained in a rigid, air-tight plastic drum. The bag is evacuated prior to transport to the sampling site where it is connected to the odorous air stream. Filling is accomplished by evacuating the rigid container. The sampling bag is then sealed for transport (Cormack et al., 1974).

d) Scentometer

A device used for intensity measurement in the field, the scentometer is essentially a rectangular plastic box with two air inlets (one for each activated charcoal bed) and four odorous air inlets of various diameters as shown in Figure 1. When the odorous air inlets are opened in different sequences, various air dilution ratios are attained. The observer is able to determine the minimum concentration at which he can detect the odor. The scentometer has received widespread application in animal waste odor evaluation. However, there are several basic limitations to this approach. The scentometer problems include the following: the sensitivity of the observer may be limited due to odor fatigue; complete restoration of the sense of smell does not occur between observations; the charcoal bed may become saturated with odorant; intermittent odors which are common in animal waste present additional difficulties and require the use of the scentometer over a period of time to get significant data (Barnesby-Cheney, 1973).

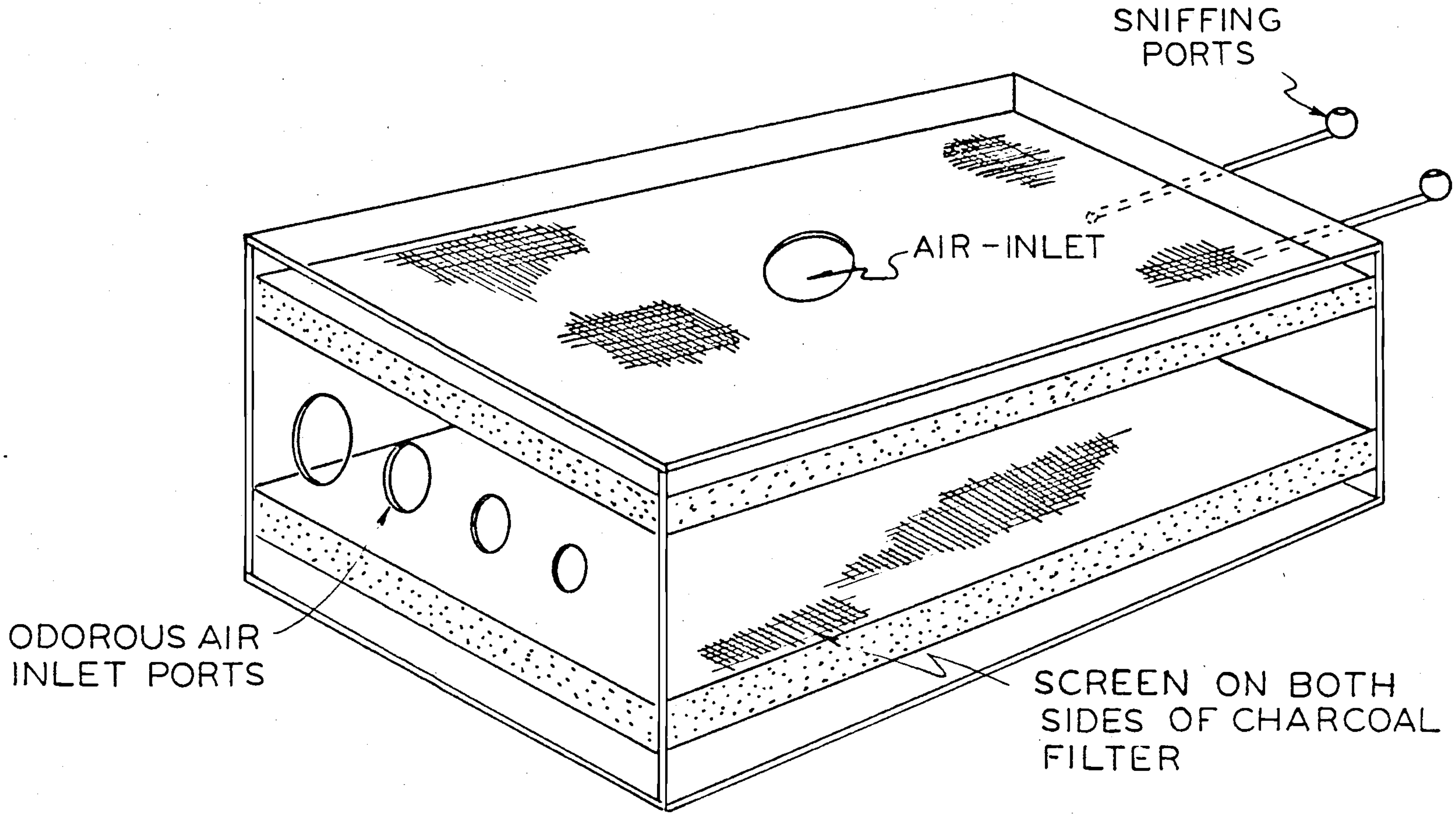


Figure 1. Diagram of the scentometer

e) Liquid Dilution Technique

In the liquid dilution technique, a sample of the odorous material is mixed with odor-free water. Generally, the diluted sample along with some odor-free samples are then offered to a panel of observers. By making a series of dilutions and offering them to the panel for evaluation, a minimum detectable concentration of the material can be determined (Miner, 1974).

2.6 Cloth Absorption of Odor

All surfaces adsorb odorants due to electrical charge imbalances. Cloth surfaces have been documented by Peters and Blackwood (1977) in their ability to adsorb several of the organic compounds found in hog exhaust air. Indole has a powerful harsh odor in large concentrations. Skatole has been called the "odor principle of feces" because of its powerful disagreeable odor which is present even upon great dilution. Both indole and skatole are very tenacious odorants which cling to cloth and persist for long periods. This attribute makes the use of cloth a potential portable device for transporting of odor samples for qualitative comparison.

2.7 Odor Control

Odor control is the application of a treatment that makes odors more acceptable to people. Currently, for livestock confinement production units, treatments for odor control usually reduce odor intensity. The following odor control techniques dealing with the odor sources are utilized (Miner, 1974):

1) Management of the animal/manure interface. Manure coating on the animal increases the surface area and volatile gas emission. The principle goal, therefore, is to remove manure from the animal's confinement area.
2) Management of the waste in the waste system. Controlling pH, moisture, and temperature within specified limits will reduce odor. Keeping a system aerobic will reduce the gaseous anaerobic emissions. Chemicals for deodorizing wastes or masking odors, have also been used with limited success (Miner, 1971).
3) Control of the animal's diet to alter the volatile organic compounds emitted from the feces and urine.

These techniques of managing waste do not prevent the transport of odorants from the odor source to the surrounding environment by the exhaust air.

A reduction in odor intensity is also accomplished by removal of odorous gases, vapors, or aerosols from the exhaust air following odor emission. The concentration reduction during the transport phase of odor emission can be accomplished by gas cleaning.

Before gas cleaning is applied, however, several considerations must be given to its appropriateness (Turk and Hyman, 1978).

1) The chemical and physical composition of the odorous contaminants.
2) The diffuse or sporadic nature of the odor source.
3) The concentration of the compounds in the gas stream.

2.8 Odorant Composition

There are few odorless gases or vapors, exceptions include oxygen, nitrogen, hydrogen, steam, hydrogen peroxide, carbon monoxide, carbon dioxide, methane, and the noble gases. Most odorants encountered are a mixture, and it should not be assumed that the odor of the mixture is that of its major ingredient (Turk and Hyman, 1978).

Although it is often assumed that all odors are gases or vapors, particles can stimulate the sense of smell because of volatility, or because they desorb a volatile odorant. There are theories that some particles directly stimulate the sense of smell. This association of particulates to odors is supported by observations that odor levels of an air stream are reduced by air filtration (Turk and Hyman, 1978). It has also been demonstrated that virtually all the odor from hog confinement exhaust air was eliminated by a .45-micron Millipore filter (Hammond et al., 1977).

2.9 Particulate/Odor Hypothesis

Aerosols, both solid and liquid, may be sufficiently volatile that, upon entering the nasal canal, enough gaseous material vaporizes to be detected by smell. Temperature and length of dispersal time affect the retention of odorous properties to volatile aerosols (Turk and Hyman, 1978).

The surface of an odorless airborne particle may become an odor intensifier if:

a) The sorptive capacity of the particle for the odorant was less than the affinity of the odorant for the nasal receptor.

b) The sorptive capacity of the aerosol for the odorant was large enough to produce an accumulation on the particle surface.

Such an aerosol would concentrate odorants on their surfaces, yet the odorant would be transferred to olfactory receptors when the particle entered the nasal cavity. Therefore, the odorous matter would be present at the receptor sites in concentration higher than in the absence of aerosols. The counter effect could also take place. If the odorant had more affinity for the particle than the olfactory receptor, the particles would impede odor (Turk and Hyman, 1978).

2.10 The Current Theories of Livestock Odor

Of the chemical compounds already identified in swine odor, Hammond et al. (1977) made this observation; if acetic, propionic, butyric, phenylacetic, and 3-phenyl propionic acids, and phenol, p-cresol, and ethyl phenol were placed on a glass slide, typical odor of the swine house was generated.

Interestingly, the odor was much more typical when a fan was blown across the slide than if the odor was smelled directly. This leads one to assume that the principle components of hog odor are known.

The form by which these principle odorants are air-borne is still debated. Research into the contribution of various compounds (Hammond et al., 1974; and Miner et al., 1975), were concerned with compounds dispersed as gases emitted from liquid manure and confinement buildings.

However, Day et al. (1965) and Hammond et al. (1977) have proposed that most of the odorants are dust borne, including a statement by Hammond, "The odors of a swine confinement facility were all dust borne."

2.11 Characterizing the Particulate

The common classification of the major types of air pollutants are the following (Dixon et al., 1976):

a) Noxious gasses—substances such as H_2S or NH_3 that are normally emitted in the vapor state.

b) Liquid entrainment—Liquid particles ten microns and larger that are created by sprays, agitation, or bubbling and picking up by the exhaust air.

c) Mists—Liquid particles usually ten microns or smaller, formed by condensation of molecules from the vapor state.

d) Dusts—solid particles, usually five microns and larger, dispersed in a gas.

The term aerosols, is a broad term which includes particles, mists, dusts, solid and liquid particles.

The size of a particle can be expressed as a physical diameter. This size can be determined by various means, depending on the size-range of interest. Sieves are effective for measuring particles larger than five microns and can determine the physical diameter. The National Air Pollution Control Administration (NAPCA, 1969) has listed other concept categories. Stokes Law will theoretically determine particles with a diameter larger than one micron. This law is based on a spherical particle settling through a fluid, where both the density of the fluid and particle are known. The size, or size grouping, determined from this law is known as Stokes or aerodynamic diameter. Size determination by optical means is based on the fact that the amount of light scattered by each particle is proportional to the size of the particle. By examining a very small volume and adjusting a level detector in an electrical circuit with a photodiode light collector, the number of particles equal to, or greater than the selected size level can be counted in a stream of air (Royco, 1973).

Besides particle size, the distribution of particle sizes are important in this research. The scrubber effectiveness depends on the particle size, and the size distribution of particles in the exhaust air stream will determine the scrubber's overall efficiency.

2.12 Gas Cleaning Equipment

Factors to be considered in the choice of an optimum scrubbing system are (Cheremisinoff, 1975):

1) The process from which the particulate is released.
2) The type of atmosphere in which the particles are entrained.
3) Particulate characteristics.
4) Equipment size and economic limits.

A comparison of particulate size categories, typical particles in that size category, and gas cleaning equipment for various particles sizes are presented in Figure 2 (Royco, 1973). Characteristics for common particulate

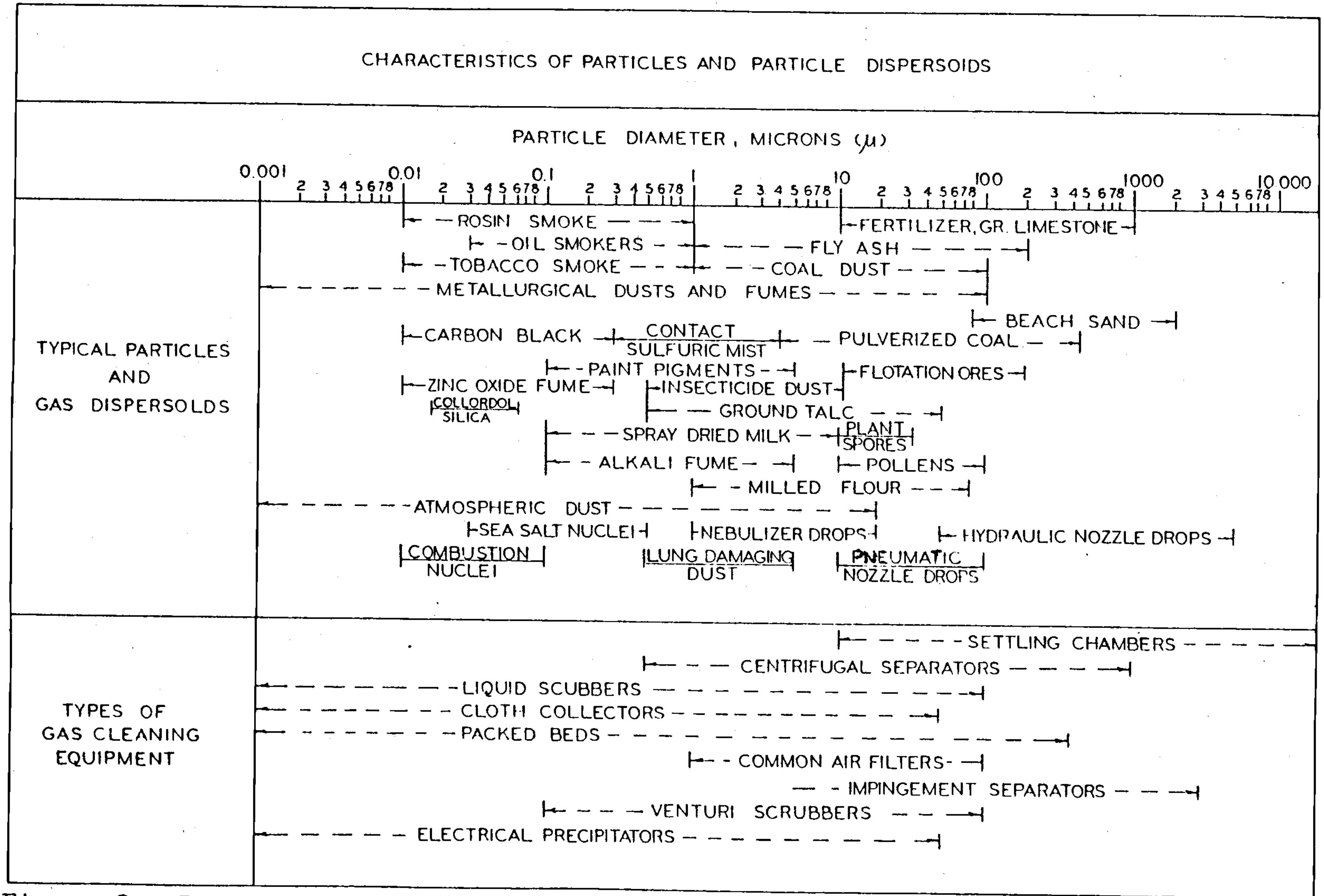


Figure 2. Particle size ranges, with typical particles and appropriate gas cleaning equipment for each range (Reference-Royco, 1973).

control devices are presented in Table 3 (Cheremisinoff, 1975).

2.13 Wet Scrubbing

Adsorption is the phenomena of gas or vapor adhering to a solid surface. This process is applicable in odor control because it is a method of concentrating odorants, the first step in disposal, recovery, or conversion to some less odorous or more valuable product.

Odor adsorption using wet scrubbers has been widely used for odor control by industries which produce gas streams that are toxic, economically recoverable, or highly odorous (Turk and Hyman, 1978). Table 4 contains a list of industries which utilize wet scrubbing in their particulate control systems (Cheremisinoff, 1975).

Mechanisms of wet scrubbing include (Calvert, 1977):

1) Solution of the odorous vapors into the scrubber liquid.
2) Condensation of odorous vapors by cooling action of the liquid.
3) Chemical reaction of odorants with the scrubber liquid to produce an odorless product.
4) Adsorption of odorant on particles suspended in the scrubber liquid.
5) Entrainment of odorous particles into the liquid stream, or onto the scrubber surface, and washed into the liquid stream.

TABLE 3. COMMON AIR SCRUBBERS AND RESPECTIVE PERFORMANCE UNDER VARIOUS APPLICATIONS*

Applications / Type Scrubber	Noxious Gases: High Solubility	Noxious Gases: Low Solubility	Mists under 10μ	Entrained Liquids over 10μ	Fumes under 1μ	Dusts over 5μ: Low Load	Dusts over 5μ: High Load	Dust under 5μ	Cost
Countercurrent Packed	E	E	F	E	NR	E	NR	NR	Med
Co-current Packed	G	F	F	E	NR	E	NR	NR	Med-Low
Cross flow Packed	E	F	F	E	NR	E	NR	NR	Med-Low
Wet Cyclone	F	NR	P	E	NR	G	G	NR	Med
Plate	E	E	F	E	P	E	P	P	Hig
Venturi	F	NR	E	E	E	E	E	E	Hig
Fibrous Packing	NR	NR	P	E	NR	G	NR	NR	Low
Spray Chamber	F	NR	NR	G	NR	F	F	NR	Low
Injector Venturi	F	NR	E	E	G	E	F	E	High
Baffle	NR	NR	F	G	NR	F	P	NR	Low

*Code for Removal Efficiencies

E 95-99%

G 85-95%

F 75-85%

P 50-75%

NR Not Recommended

TABLE 4. INDUSTRIAL APPLICATIONS OF PARTICULATE CONTROL EQUIPMENT.

INDUSTRIAL PROCESS	PARTICULATE	TYPICAL CONTROL METHOD
Chemical Milling	Mists	Wet collector, baffle or spray type
Dryers	Dust, smoke	Scrubber and/or cyclones
Fish Cannery	Dust, smoke	Cyclones and contact condensor scrubber
Insecticide Manufacturing	Aerosols	Packed Tower Scrubber
Rendering	Mists, Aerosols	Cyclones and packed bed
Deep Fat Frying	Smoke, dust	Incineration and Spray Scrubber
Air-blown asphalt	Aerosols	Scrubbers and/or incineration

Reference-Cheremisinoff, 1975

2.14 Industrial Wet Scrubbers

Particulate scrubbing for industry is normally done with the devices presented in Table 5 (Cheremisinoff, 1975). This table includes information on scrubber types, appropriateness of application, and indicates a relative installed cost factor per cfm of output with respect to other scrubbing techniques.

TABLE 5. OPERATING CHARACTERISTICS FOR SIX COMMON PARTICLE SCRUBBERS.

Type Scrubber \ Characteristics	Effective Removal- Minimum Diameter (micron)	Efficiency % of Total Weight	Livestock Dust Removal		Capitol Cost $/cfm capacity
			Labor Requirements	Technical Management	
Electrostatic Precipitator	.01	50-99	Low	High	.75-2.50
Baghouse	.05	99	High	Low	.75-1.50
Packed-Bed, Wet Type	.1	50-99	Med.	Med.	.25-.50
Gravity Chamber	10.0	35-93	Low	Low	.10-.40
Centrifugal Separator	.5	40-95	Med.	Low	.50-1.50
Venturi	.1	99	Low	High	.50-2.00

(Reference-Cheremisnoff, 1975)

2.15 Previous Application of Scrubbers to Livestock Production

The removal of odorants by gas cleaning equipment has been examined in European countries. Shirz (1977) commented, "There are a great number of methods for purifying industrial exhaust air. In agriculture, however, the only process suitable for removing offensive odors from exhaust air of animal shelters is gas scrubbers."

2.16 Biological Air Washers

A counter-current air washer (See Figure 3) in which activated sludge was introduced to give a biological odor removal bed, was reported to reduce odors from a swine confinement building by 60 to 85%. Van Geelen and van der Hoek (1977) reported that by installing air scrubbers in the swine building's ventilation system, air can be made dust free, and the odor components can be reduced. The quantities of exhaust air at maximum capacity is 1 m^3 air per kg liveweight per hour for swine, 3.6 m^3 per kg per hour liveweight for chickens. The design of the air wash system was 6000 m^3/hr. of air. Fixing the maximum air speed at 1 m/sec (190 ft/min), the cross-sectional area is 1.67 m^2. Air flow of 6 m^3/m^2/min is recommended. The packing height was about 0.5m, the retention time of the air was 0.5 seconds. The packing material used to maximize the contact surface between wash water and exhaust air was

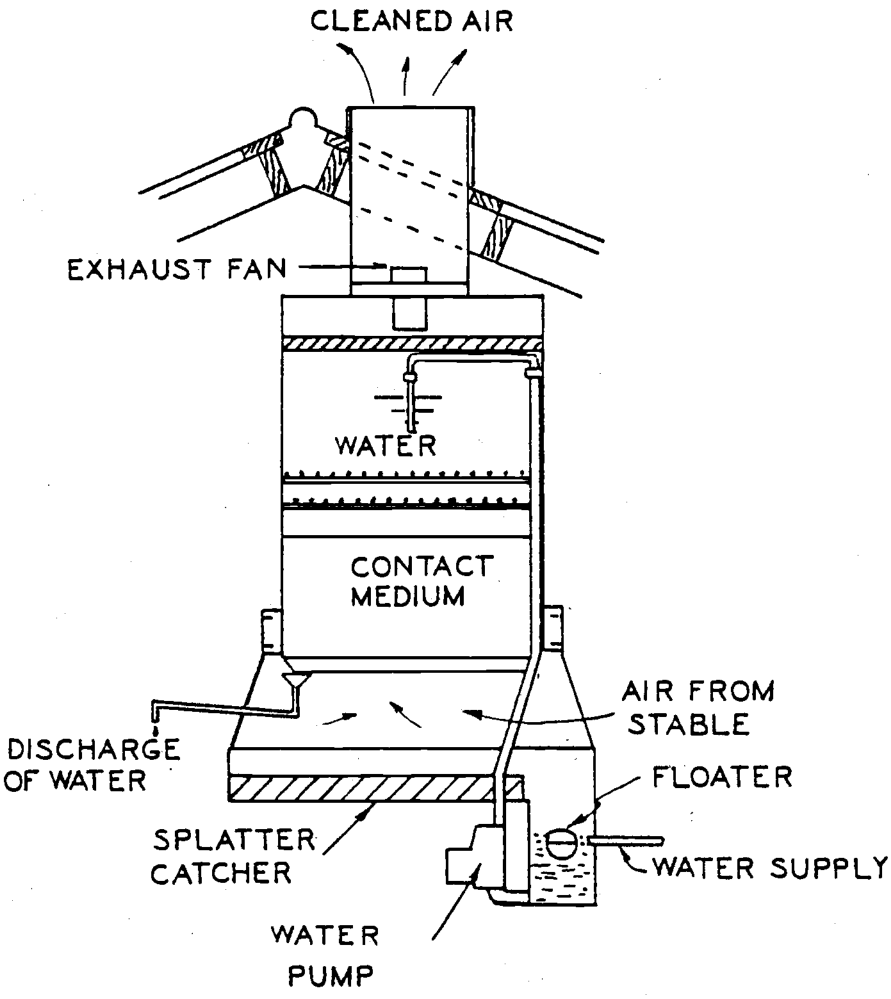


Figure 3. Schematic diagram of counter-current air washer used in van Geelan and van der Hoek 1977 research (van Geelan and van der Hoek, 1977).

5 cm (2 in.) saddles with good results. The counter-current washer used a nozzle to distribute the wash water over the upper surface of the packing material, with water being recirculated by a Jung immersion pump (See Figure 3).

Water consumption has two components; evaporation and discharge. Estimates of water loss daily due to evaporation was 720 liters. One hundred thirty-nine liters of water were discharged daily to prevent accumulation of salts and dry matter.

Schirz (1977) used a similar type of biological counter-current air scrubber in washing odorants from swine building exhaust air. Problems were encountered in the design, including clogged water spray nozzles and liquid level control in the water system. An air flow rate of 7500 m^3/hr which corresponded to the ventilation requirements of one hundred fattening hog spaces. Efficiency of odorant removal varied from 50% to 90%, depending on the degree of biological building up on the packing. Annual cost for odor control ranged from 4.50 DM ($2.00 U.S.) for 50% control to 7.00 DM ($3.11 U.S.) for 90% control per hog space.

III. SCRUBBER DESIGN

After reviewing existing designs for wet air scrubbers, a cross-flow, wet scrubber capable of testing scrubber effectiveness in removal of livestock particulate was designed and built as shown in Figure 4. The scrubber included three subsystems:

a) Packing

b) Water System

c) Air Handling System

3.1 Packing

Packing characteristics for three types of industrial packing are compared in Table 6.

TABLE 6. PACKING CHARACTERISTICS FOR THREE INDUSTRIAL PACKINGS.

Characteristics	Packing Type		
	1.2-cm. Rashing Rings	1.2-cm. Intalox Saddles	1.2-cm. Berl Saddles
Surface Area (m^2/m^3)	122	190	155
% Free Gas Space	64	78	60
Weight (kg/m^3)	800	544	864

(Reference-Peter and Timmerhaus, 1968)

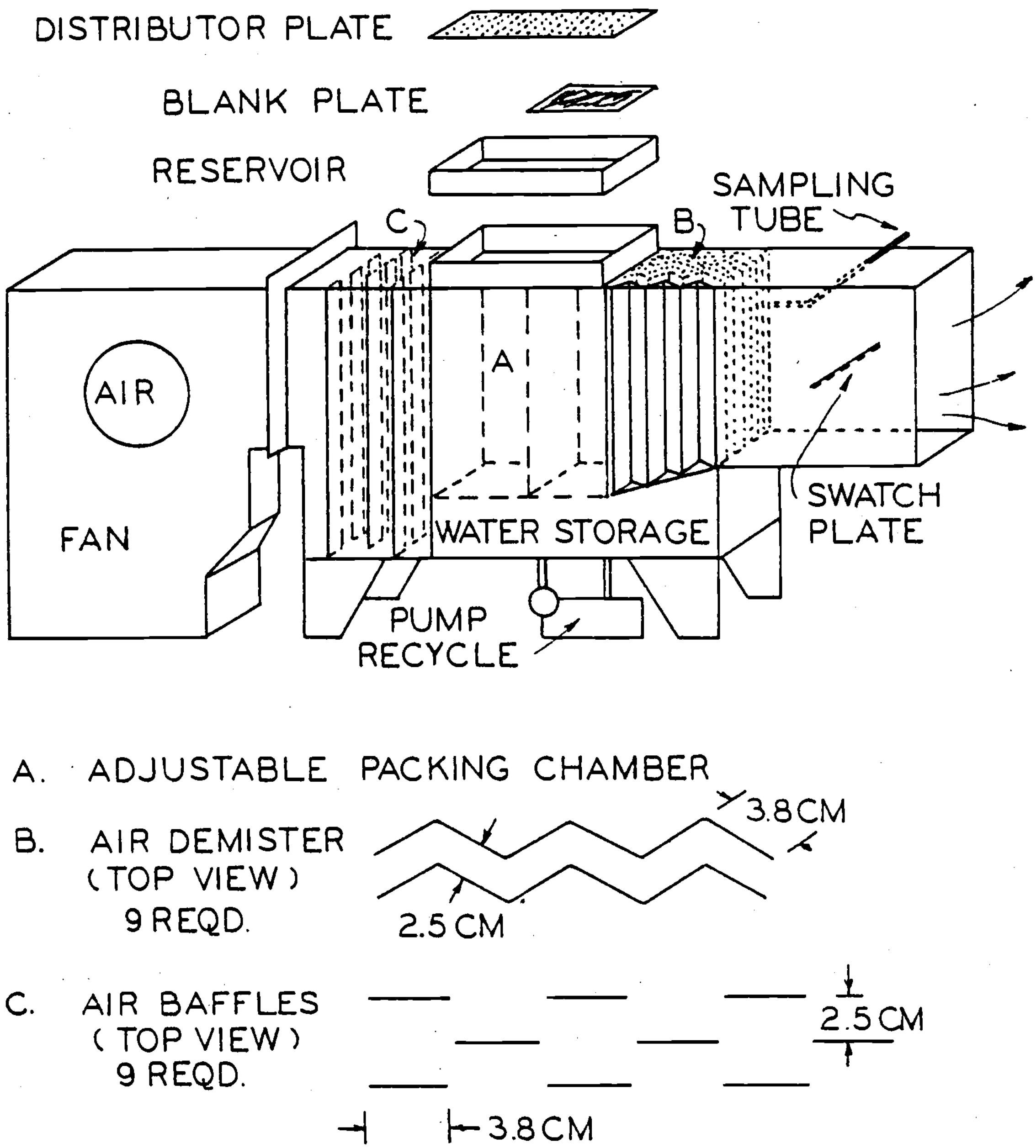


Figure 4. Diagram of cross-flow, packed scrubber used in experimentation.

Stoneware 1.2-cm Rashing Rings were used as the packing media because of known characteristics, a backlog of data from previous application, and availability from the Oregon State University Chemical Engineering Department. The packing bed was adjustable in thickness from 0 to 30.5 cm. The bed was supported and held in place with .6-cm mesh screen. Packing thicknesses chosen for this study were 5.1 cm, 7.6 cm, 15.2 cm, 22.7 cm and 30.5 cm.

3.2 Water System

A 19.5-liter water collection tank fed by gravity to a .63-l/sec, impeller-type, submersible pump. The water was pumped to a reservoir above the packing. For reliable and uniform water flow in the packing, water was distributed by a horizontal, perforated distributor plate (See Figure 4), with 2-mm holes drilled 6.4 mm on center. A 1-cm head of water was maintained in the reservoir by regulating the valves on the pump outlet or the reservoir overlow. The water was only distributed over the thickness of packing being tested. The area of distributor plate over the void packing chamber was blanked off with a sheet-metal section to prevent uncontrolled leakage and maintain uniform water flow through the packing. Water flowed through the packing, returning to the collection tank to be recycled.

3.3 Air Transport System

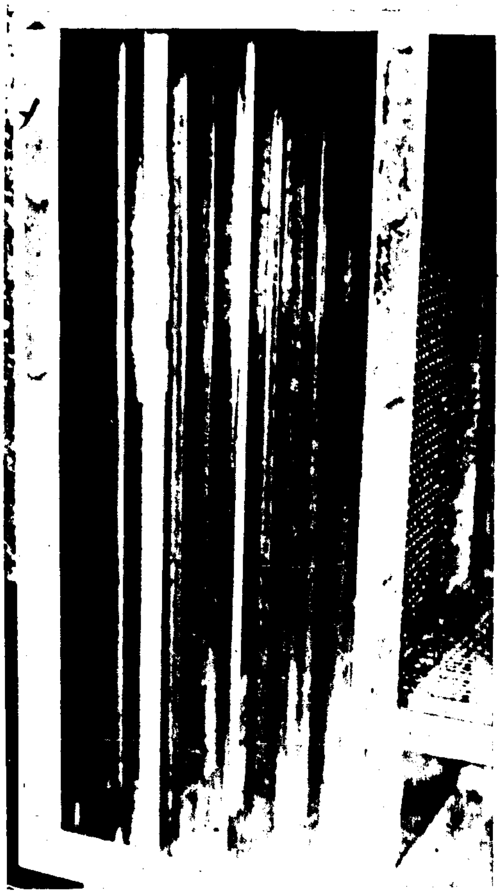
The fan was an Aladdin backward-curve centrifugal, with design capacity of 2000 cfm (944 1/sec) at six inches (15.24 cm) static head and 3300 RPM. Air flows were measured with an Alnor Thermal Anemometer; head losses were measured with a Magnehelic manometer. A baffle mixing section (See Figure 5), 22.8 cm deep with nine, 3.8-cm wide baffles was placed between the fan and the packing chamber. The baffles did the following:

a) Reduce uneveness in air flow from the discharge.

b) Compensate for the change in cross-sectional area between the fan and the packing.

c) Create a uniform forward air velocity at the packing surface.

The Alnor Thermal Anemometer probe at the packing surface showed an air flow velocity profile with less than 10% difference at the packing surface. Using 15.2 cm of packing, with a 7.2-cm diameter fan pulley, the air speed at the packing facing ranged from 61.5 cm/sec to 65.5 cm/sec. Following passage through the packing, moisture particles entrained in the air were removed by a baffle demister. In the demister, large droplets impinged on the baffle surface as the air made six, 90-degree turns (See Figure 5).



5a. Baffle mixing section of cross-flow packed scrubber

5b. Demistor section of cross-flow packed scrubber

Figure 5. Photographs of cross-flow, packed scrubber construction.

IV. EXPERIMENTAL DESIGN

The primary purpose of this research was to determine the effectiveness of wet scrubbing on controlling the transport of odorants from livestock confinement buildings in the form of particles. Performance of the cross-flow wet scrubber was evaluated by varying packing thickness and fan speed; monitoring the independent variables of particulate removal, ammonia removal, and change in odor intensity.

4.1 Scrubber Operation

For field study, the air scrubber was placed in a vacant swine fattening pen located at the Oregon State Swine Research Center. Pen dimensions were 2.4 x 2.9 m, with a slatted area of 4.2 m^2 over a partially full manure storage pit. The fan inlet was positioned in the corner of the pen, 0.75 m from either wall. The swine building used natural ventilation. In the winter, air enters through a 18-cm opening at the roof edge, and flows by natural convection through a 10-cm space at the roof eave (See Figure 6). The area temperature ranged from 11 C to 22 C, and relative humidity from 48 percent to 89 percent. During the six-week testing period no artificial heating or forced ventilation was provided. The fattening area of the swine building contained three hundred sixty

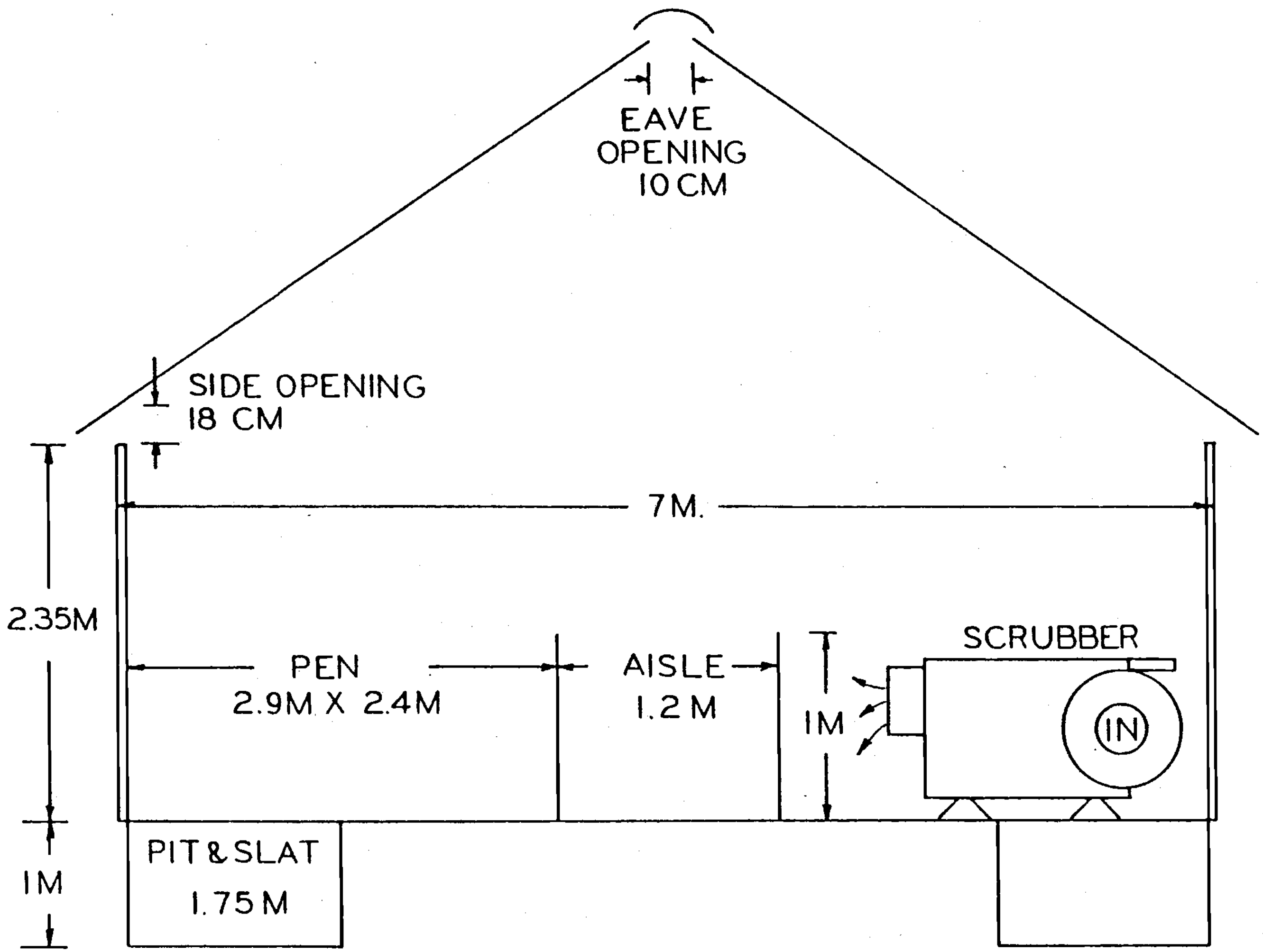


Figure 6. Cross-sectional view of the O.S.U. Swine Research Building including position of scrubber during testing.

hogs between 20 kg and 90 kg. The feed ration was wheat, meatmeal, soybean meal, and alfalfa meal mixture.

The dust concentration is typically a function of several environmental variables (Dixon et al, 1976):

a) The dryness of the floor surface.

b) The building temperature; higher temperatures produce higher dust concentrations.

c) The building relative humidity; humidity is inversely proportional to the dust level.

d) The animal and operator activity level; more dust is generated during the day than evening, at feeding time, and during hog handling by operators.

It was also observed that a high outside wind speed decreased the dust loading of the building air due to an increased natural ventilation flow rate.

The normal air flow within a pen was disrupted by the introduction of the scrubber. Therefore, an equilibrium was produced in the pen by allowing the scrubber to operate thirty minutes before testing was started. Data were collected twice weekly over a six-week period, normally between 3 p.m. and 9 p.m. During this time period, the inlet particulate load normally fluctuated by ±25 percent.

4.2 Experimental Procedure

Three sets of experiments were run to test the effectiveness of the scrubber. The first two were conducted at the O.S.U. Swine Research Center. The first experiment was run with a fan speed of 863 RPM. Packing thicknesses tested were 5.1, 7.6, 15.2, 22.7, and 30.5 cm, with two experiment replications over the entire packing thickness range. The second experiment was run with a fan speed of 1151 RPM, with the same packing thicknesses being tested, and two replications. The third experiment was conducted in the Soil and Water Laboratory located in the Gilmore Hall Annex. Without the heavy dust concentration and particle load fluctuations of the hog confinement environment, the scrubber was tested in the laboratory at the two fan speeds and five packing thicknesses with more uniform results.

4.3 Analysis Equipment and Procedure

For monitoring the effect of the scrubber on the exhaust air from swine production, air samples were taken at the fan inlet and scrubber outlet for comparisons of representative air volumes. Air quality parameters included:

a) Particulate concentration of various size ranges.

b) Ammonia concentration.

c) Odor intensity.

4.3a Particulate Concentration

Particulate concentration and size distribution were measured using a Royco Model 218 Portable Particle Monitor. For particle sizes of .5, 1.0, 2.0, 3.0, 5.0 and 10.0 microns in diameter, the monitor counts the number of particles larger than the indicated size. The sampling tube for the Royco monitor was positioned at the inlet of the fan duct and at the outlet of the demister. The Royco unit pumps 0.01 ft^3 (.028 m^3) metered volume of air in one minute. The principle of light scattering determines the number of particles of a specified diameter or larger (Royco, 1973). Normally, one purge run was conducted when the monitored particle size was changed, two repetitions were run to generate an average number of particles for a specified diameter.

4.3b Ammonia Analysis

Ammonia concentrations were measured by pumping air with a Neptune Dynapump (diaphragm type), at a rate of 3.48 1/minute. Air samples were pumped for five minutes through a diffuser stone into an acid trap, containing 25 ml of .025 normal sulfuric acid at a depth of 5 cm. Air samples were taken through sampling tubes mounted in the inlet and outlet ducts of the scrubber (See Figure 6). Samples were sealed and returned to the Animal Waste Laboratory located in the Gilmore Hall Annex. The procedure used for analysis of the ammonia sample followed the outline of test 132 B, in Standard Methods for the Examination of Water and Waste Water (APHA, 1973). The Nesslerization Method using photometric determination of ammonia nitrogen concentration was measured by the Coleman Model 6/20 Junior II Spectrophotometer. The concentration of ammonia in the acid solution (ppm by volume) is determined from a calibration curve established for the Nesslerization test and the spectrophotometer using standard solutions. This concentration of ammonia in solution could be related to ammonia concentration in the swine environment by the following formula:

$$(\mathrm{Mg}/_{\ell.}\ \text{Nessler Test})(.025\ell.) \times \frac{1}{5.15\ell\ .\mathrm{air}} \times$$

$$\times \frac{28.95\ \mathrm{gr./mole\ air}}{22.4\ell\ \mathrm{./mole\ air}} \times \frac{\mathrm{gr}}{1000\ \mathrm{mg}} \times 1{,}000{,}000 = \mathrm{ppm}\ NH_3\text{-}N.$$

4.3c Odor Intensity Comparison

On site qualitative tests of odor intensity are difficult to conduct due to the following:

a) Difficulty in the logistics of transporting an odor panel with a significant number (greater than five) of members to the odor site for a test requiring repeated ovservations.

b) Odor fatigue of the panel from being immersed in the odorous area.

c) Psychological bias induced by seeing the source.

d) The lack of a completely satisfactory measurement technique for on-site measurement.

To avoid these problems, a method of taking odor samples for comparison by a remote odor panel has been examined.

Dry cotton flannel swatches, 7cmx7cm, were used to qualitatively compare the odor intensity of the scrubber inlet and outlet air using the theory of odor adsorption (See Appendix A). The swatches were prepared by heating 92 degrees C for four hours to remove any volatile adsorbed gases or solids, then placed in a glass desiccator for storage. Four swatches were numbered with a pen, then two were clamped on each mounting plate positioned at a 45 degree angle to the air flow at the inlet and outlet ducts. Following exposure for 30 minutes, the swatches were sealed in individual plastic bags for delivery to the odor panel.

Ten individuals were selected for the odor panel from members of the Agricultural Engineering Department staff. To determine if there was a qualitative difference in odor between the inlet and outlet swatches, a three-swatch grouping was prepared by randomly eliminating either one of the inlet or outlet swatches. The three swatches were placed on a cardboard folder and put before each panel member. The panel member was requested to select the swatch that was different, and to state the detected differences.

V. RESULTS AND DISCUSSION OF RESULTS

The basic function of the cross-flow, wet scrubber is removal of particles from the air. To monitor the scrubber's effectiveness on particulate removal, two independent variables, fan speed and packing bed thickness, were investigated. The dependent variable was percent removal of particles, with effectiveness measured for six different particle-size ranges.

5.1 Fan Characteristics

The Aladdin backward-curve centrifugal fan's performance curve was not applicable to this experiment due to changes in fan speed. The effect of varying the packing thickness on the air flow rate and speed as measured by the Alnor hot wire anemometer, and head loss as measured by a magnehelic meter, is shown in Table 7.

5.2 Removal of Particles by the Cross-Flow, Packed Scrubber

5.2a Particle Removal Data for the Swine Environment

Appendix B displays the collected particle data, as measured by the Royco Model 218 Portable Particle Monitor. The data were collected over a six-week period, and each reading is an average of two measurements. The intake air stream to the scrubber had a particulate load which varied throughout the experiment due to generation factors

TABLE 7. PERFORMANCE OF ALADDIN BACKWARD-CURVE CENTRIFUGAL FAN FOR TWO SPEEDS AND FIVE PACKING THICKNESSES.

	FAN SPEED RPM					
	863			1151		
Packing Thickness (cm)	Head Loss Pascals (IN of H_2O)	Mean Air Speed (M/sec)	Volumetric Flow Rate (1/sec)	Head Loss Pascals (IN of H_2O)	Mean Air Speed (M/sec)	Volumetric Flow Rate (1/sec)
5.1	111.6(.45)	60.7	73.8	136.4(.55)	91.5	111.2
7.6	121.2(.49)	41.5	50.5	143.9(.58)	73.5	89.0
15.2	124.0(.50)	36.7	44.7	153.7(.62)	51.9	63.0
22.7	126.8(.51)	36.1	43.9	158.6(.64)	45.8	55.6
30.2	126.8(.51)	35.1	42.7	158.6(.64)	44.2	53.8

mentioned in Section 4.1. A summary table (Table 8) of the intake particle load throughout the testing period shows the particle size profile, graphically presented in Figure 7.

TABLE 8. SUMMARY TABLE OF THE AVERAGE INTAKE PARTICLE LOAD INTO THE CROSS-FLOW, PACKED SCRUBBER DURING THE TESTING PERIOD AT THE O.S.U. SWINE CENTER.

Particle Size Range	Average #/.01 ft^3 (.00028 m^3)	% of Total	Range
> .5μ	7367	100	9148-4419
> 1.0μ	5667	76.9	6887-3030
> 2.0μ	4140	56.2	6150-2369
> 3.0μ	2390	32.4	3715-1140
> 5.0μ	546	7.4	913-173
>10.0μ	123	1.7	197-33

5.2b Particle Removal Data for a Low, Dust-Level, Uniform Atmosphere

To determine the scrubber characteristics in an atmosphere with more stable dust concentrations, a trial run was conducted in the Soil and Water Laboratory of Gilmore Hall Annex. The test procedures for monitoring particle load was identical to that used at the O.S.U. Swine Research Center.

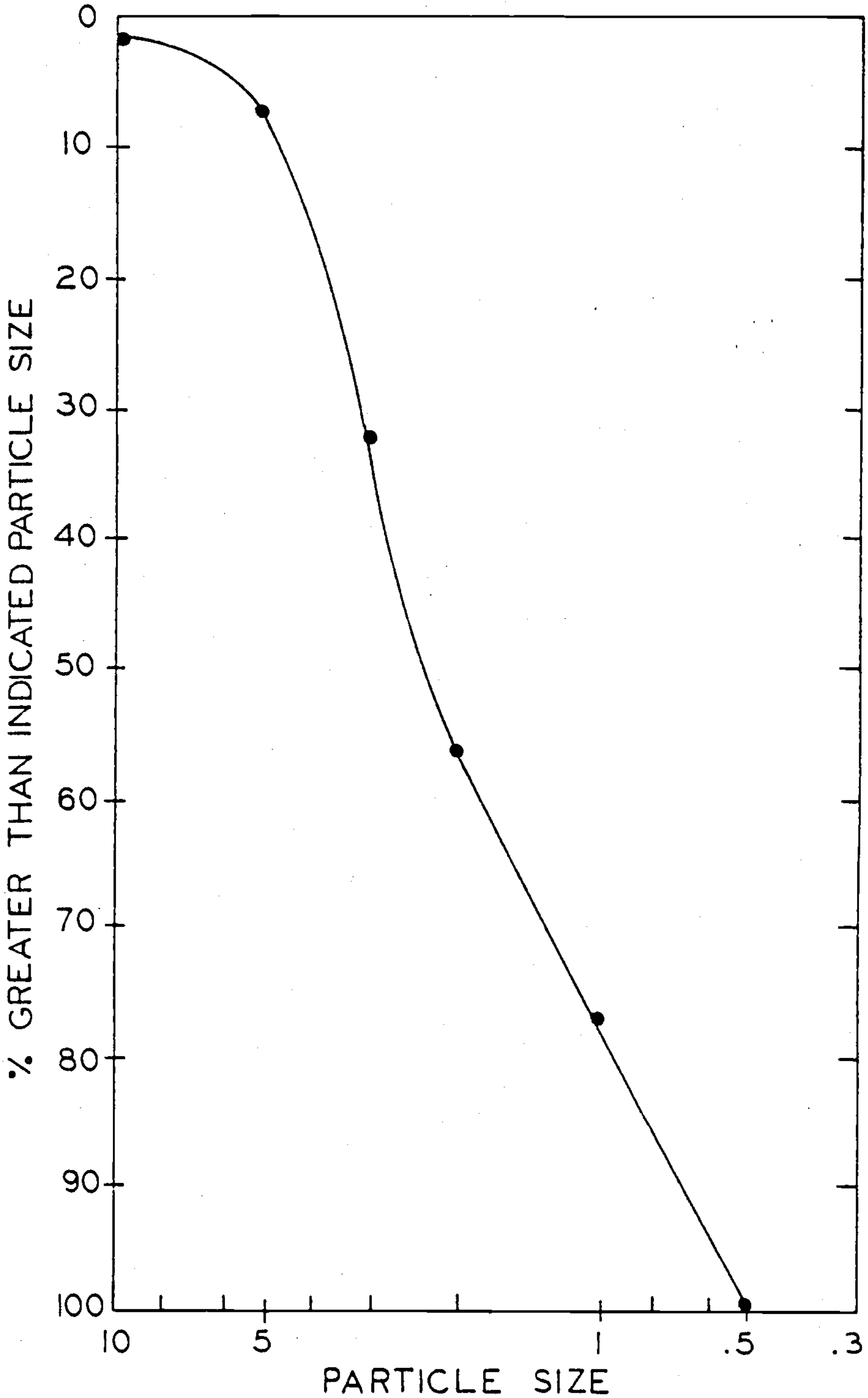


Figure 7. Size profile of the average particle load at the cross-flow, packed scrubber intake during six-week testing period at the O.S.U. Swine Center.

The data are presented in Appendix B. These data, due to the atmosphere's more uniform particle concentration, were examined to determine if the scrubber was acting as a particle generator for the smaller particle sizes.

The results of this test were examined such that the actual number of particles of the input and output stream within a size category (i.e., 0.5 to 1.0) were calculated. This allowed a calculation of the percent removal or addition of particles within this size range. Tables 9 and 10 display the actual values, and percent removal of particles within each size range. It can be seen from this analysis that the scrubber contributed particles in the .5-1.0-micron range for both fan speeds, and there were more 1.0-2.0-micron particles at the outlet than the inlet for the 1151 RPM speed.

These data are graphically presented in Figure 8 with the experimental data from the Swine Research Farm presented in Figure 9.

5.2c Graphical Interpretation of Data

To demonstrate the removal of particles, the following graphs are presented:

1. Percent removal of particles measured at six different diameters for the two different fan speeds averaged over packing thicknesses (Figure 10).

TABLE 9. PARTICLE COUNTS WITHIN SPECIFIED SIZE RANGE FOR INLET AND OUTLET OF SCRUBBER AT 863 RPM

Packing Thickness	Test Location	# Particles in Size Range/.01ft^3 .5-1.0μ	1.0-2.0μ	2.0-3.0μ	3.0-5.0μ	5.0-10.0μ	>10.0μ
5.1	In	280	227	224	312	76	6
	Out	406	221	139	112	0	0
7.6	In	280	227	224	312	76	6
	Out	364	199	108	93	1	0
15.2	In	280	227	224	312	76	6
	Out	375	208	120	88	2	0
22.7	In	308	256	238	298	66	5
	Out	406	200	107	89	0	0
30.5	In	308	256	238	298	66	5
	Out	392	244	86	100	1	0
Average #	In	291	238	230	306	72	6
Average #	Out	388	214	112	97	1	0
% Removal		-33	-10	+56	+69	+99	+100

TABLE 10. PARTICLE COUNTS WITHIN SPECIFIED SIZE RANGE FOR INLET AND OUTLET OF SCRUBBER AT 1151 RPM.

Packing Thickness	Test Location	# Particles in Size Range/.01 ft^3 .5-1.0μ	1.0-2.0μ	2.0-3.0μ	3.0-5.0μ	5.0-10.	μ>10.0μ
5.1	In	289	213	220	301	73	5
	Out	413	259	108	98	1	0
7.6	In	289	213	220	301	73	5
	Out	380	213	100	96	0	0
15.2	In	289	213	220	301	73	5
	Out	378	220	120	80	1	0
22.7	In	312	215	240	285	84	2
	Out	416	212	98	86	0	0
30.5	In	312	215	240	285	84	2
	Out	430	235	97	79	1	0
Average #	In	298	214	228	295	77	4
Average #	Out	401	228	105	88	1	0
% Removal		-35	-6	+54	+70	+99	+100

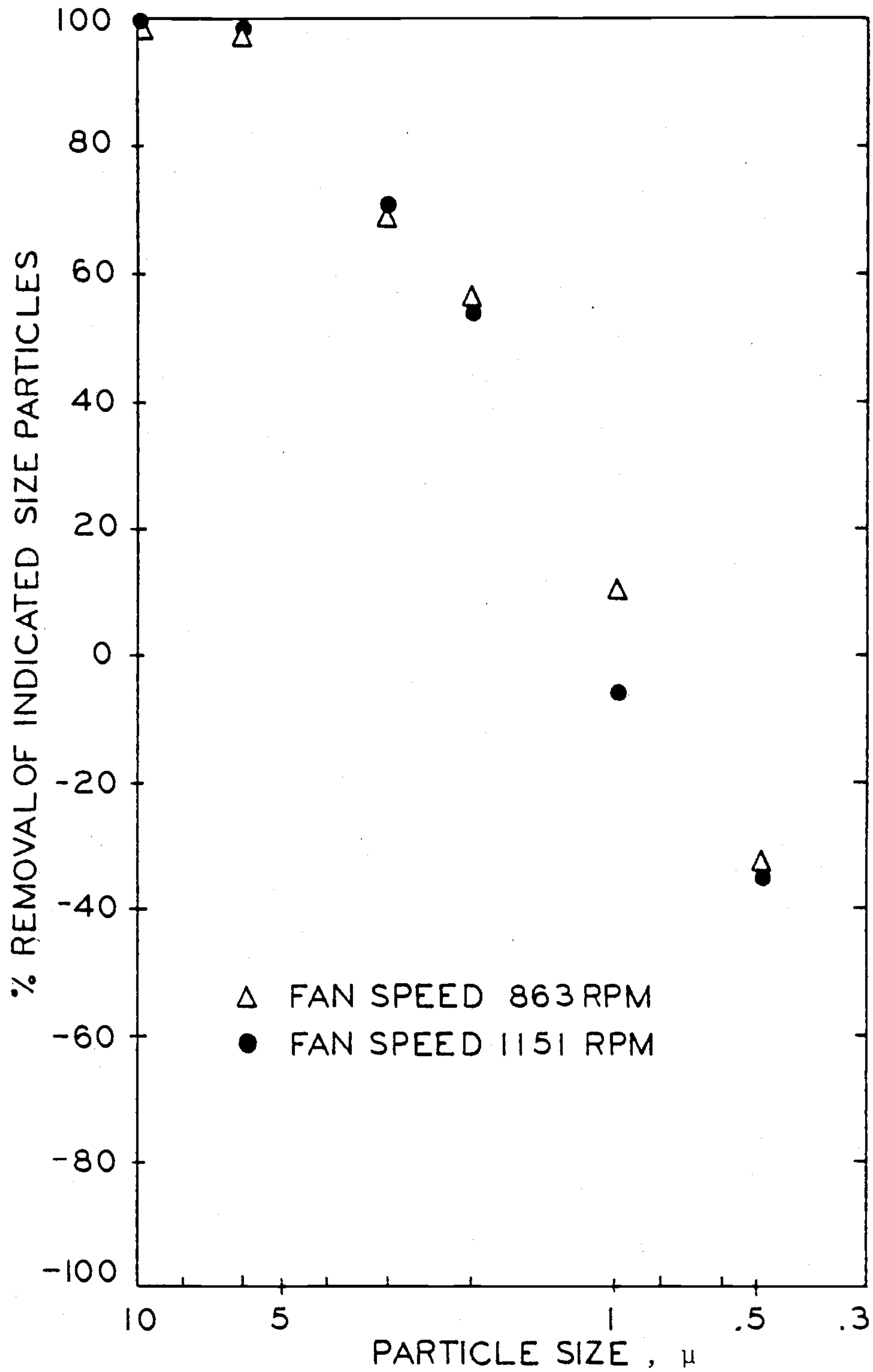


Figure 8. Percent removal of particles by cross-flow, packed scrubber in a uniform, low-dust-level atmosphere.

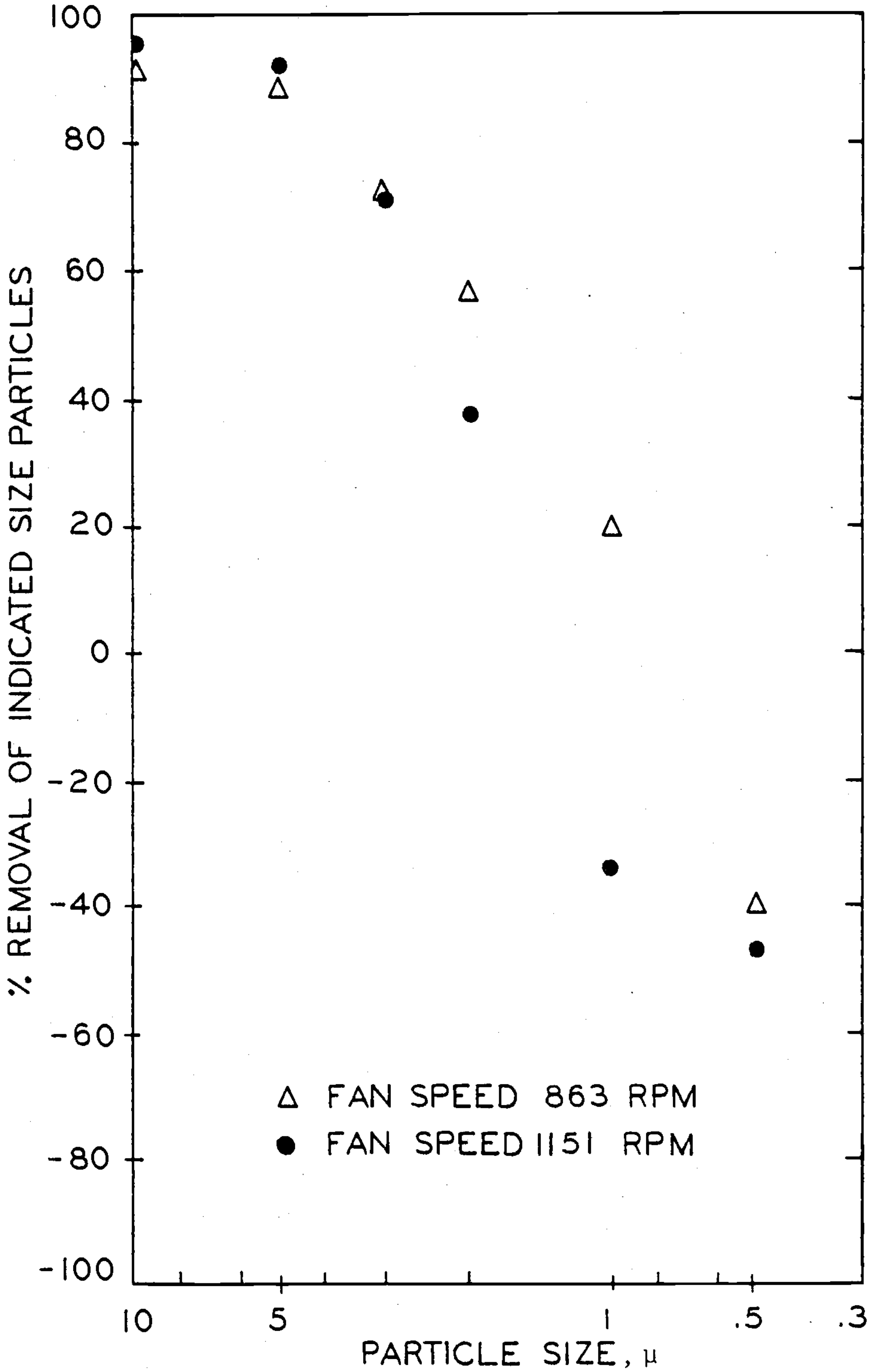


Figure 9. Percent removal of particles by a cross-flow, packed scrubber operating in a swine confinement environment.

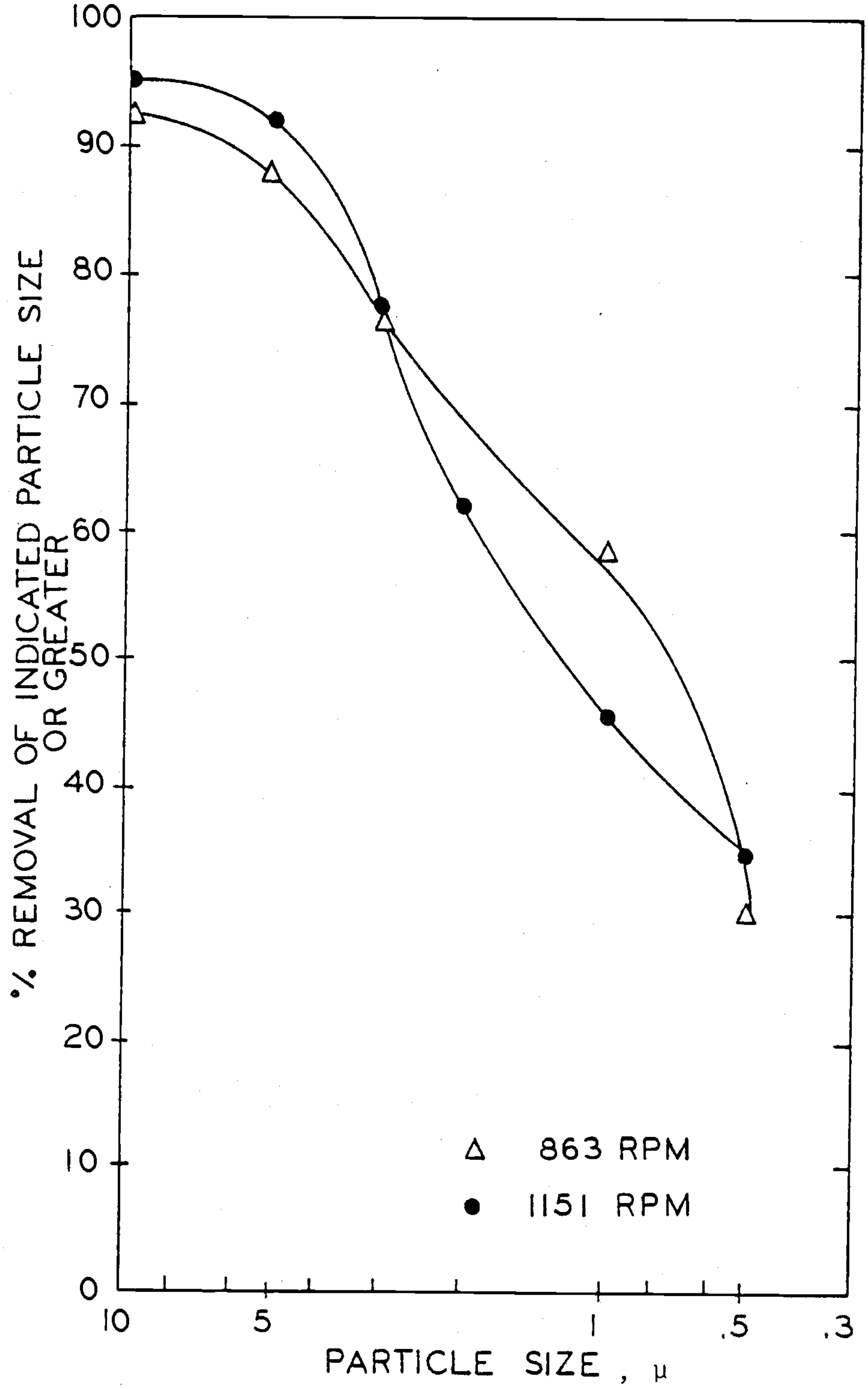


Figure 10. Percent removal of particles at two fan speeds by the cross-flow, packed scrubber.

2. Percent removal of particles measured at six different diameters, for five different packing thicknesses, averaged over the two fan speeds (Figure 11).

These graphs point out the following:

a) The effectiveness of the scrubber is related to particle size. Increased removal efficiencies are reached at increased particle diameters.

b) There is an interaction between the fan speeds and particle size. One fan speed or packing thickness is not best at all sizes, but the ranking varies for particle removal performance as changing particle diameter. Below 3μ, the low fan speed is best, above 3μ, the opposite is shown.

c) The 5.2-cm packing thickness reduces particle concentration the least. The remaining four thicknesses remove particulate with no apparent ranking of performance.

d) For packing thicknesses of 7.6-cm and greater, particle removal efficiencies of 90% or greater were achieved for particles larger than 5μ. This supports the information presented in the scrubber selection guide (Table 3), which states that removal efficiencies by a cross-flow scrubber for 5μ particles is greater than 95%.

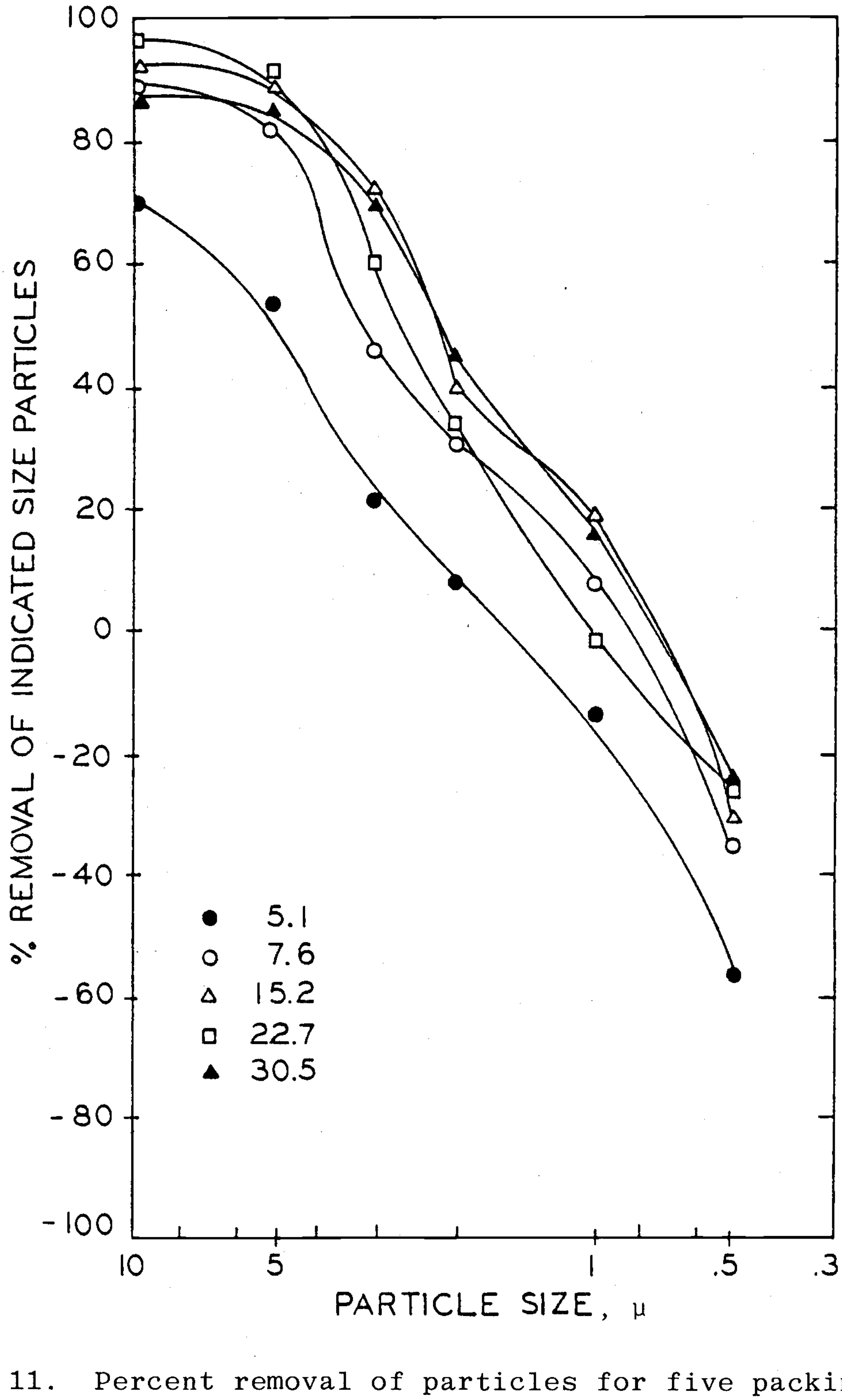


Figure 11. Percent removal of particles for five packing thicknesses by the cross-flow, packed scrubber

5.2d Data Analysis

The method used to determine which results of the experiments were significant was the two-way and three-way analysis of variance (ANOV) with a F-ratio test. The F-ratio test determines whether a statistically significant (95% confidence level) or highly significant difference (99% confidence level) exists with respect to treatments. For each dependent variable an ANOV was performed. From this ANOV, an F value is calculated, and then compared to a tabular value of F. If the calculated value of F was larger than the tabular F value at the 95% level, a significant difference was declared. This signifies that there was a five in one hundred chance that the difference between various treatments are due to random effects.

If the calculated F value is larger than the tabular F value at the 99% level, a highly significant difference was declared. This signifies that a one in one hundred chance exists that the observed difference was due to random effects.

5.2e Particulate Removal ANOV

The measure of scrubber effectiveness is the percent reduction in particulate concentration, the dependent variable. Purpose of ANOV is to determine if the independent variables, fan speed and packing thickness, have an effect on the dependent variable. The computer application of the F test to the two-way ANOV produced the values presented in the significance table (See Table 11).

TABLE 11. SIGNIFICANCE TABLE PRESENTING F VALUES AND SIGNIFICANCE FROM TWO-WAY ANOV OF SCRUBBER PERFORMANCE.

	Particles <5μ		Particles >5μ	
Independent Variable	F Value	Significance*	F Value	Significance*
Fan Speed	.455	N.S.	.005	H.S.
Packing Depth	.323	N.S.	.001	H.S.
Fan Speed/Packing Thickness Interaction	.753	N.S.	.001	H.S.

*N.S. Not significant
S. Significant, 95% confidence
H.S. Highly significant, 99% confidence

This two-way ANOV F test indicates that the results allow statistical significance to be implied only to the results of the > 5 micron particle size.

For particles smaller than 5μ, particle removal efficiency and its low correlation to fan speed and packing thickness is due to a large error. This error was introduced by a fluctuating atmospheric dust load, poorer removal performance of the scrubber at this particle size, and procedural error.

This large error term was more significant than the change in removal efficiency introduced by varying the independent variables.

5.2f Analysis of Five Micron Particle Removal

A three-way ANOV was conducted to determine the removal efficiency of each particle size by all combinations of fan speed and packing thicknesses. For the 5μ and larger particle-size range, percent removal as a function of fan speed and packing thickness is presented in Table 12. A graphical display of this data is presented in Figure 12. This graph shows an interaction between the packing thickness and fan speed, as predicted by the two-way ANOV.

To determine which of these results are significantly different (confidence level of 95%) from each other, a Student, Newman, Kuhls Significance Test (Snedicor, 1967) was performed. This test indicated that the ten values for particulate removal in Table 12 are divided into four subgroups. The values within each subgroup are statistically the same. Therefore, the treatment combinations used to obtain values within a subgroup do not make a significant difference. The results of this test are also presented in Table 12, with subsets indicated by a, b, c, and d.

TABLE 12. PERCENT REMOVAL OF 5μ DIAMETER PARTICLES BY ALL COMBINATIONS OF FAN SPEEDS AND PACKING THICKNESSES.

Fan Speed/ Packing Thickness	863 RPM	1151 RPM
5.1	62.9 (a)	86.3 (b)
7.6	85.8 (b)	92.2 (c)
15.2	96.0 (d)	91.6 (c)
22.7	96.1 (d)	93.8 (c)
30.5	90.2 (c)	95.3 (d)

a, b, c, d - Student Newman Kuhls Statistical Subsets. Values with the same subscript are statistically the same. Different subscripts denote groups different from each other within a 95% confidence level.

5.3 Discussion of the Particle Removal Results

5.3a Past Performance of Wet Type Scrubbers

Previous experimentation with air scrubbers in the livestock industry has shown that wet packed scrubbers are effective in reducing particle concentrations and odors in the exhaust air from swine confinement buildings (van Geelen, and van der Hoek, 1977). The German researcher, Schirz (1977) stated that the wet packed scrubber was the most practical type of scrubber for application to the livestock industry.

Past performance of this type of scrubber (see Table 3), has demonstrated its effectiveness (95%) in removing

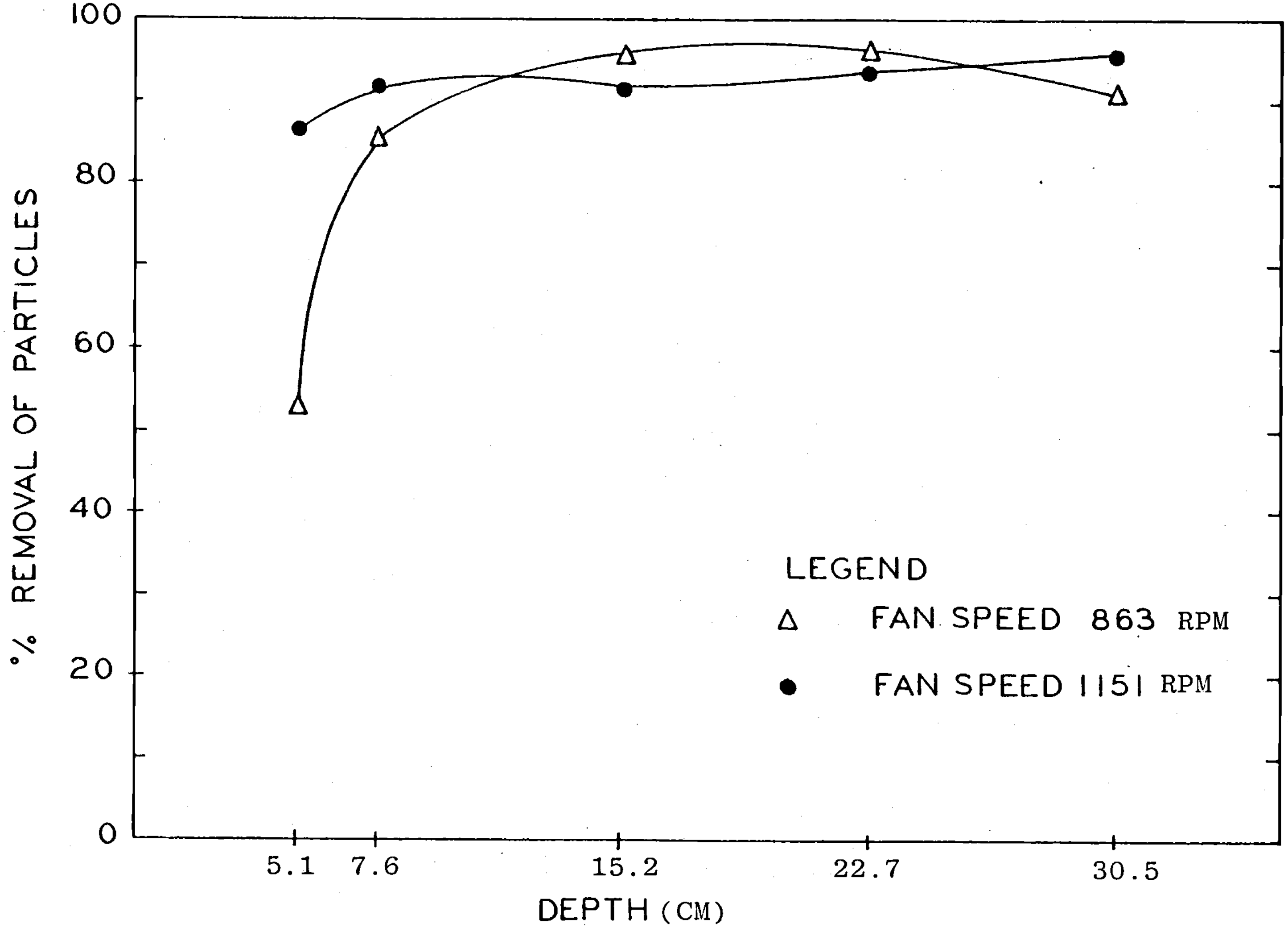


Figure 12. Interaction of fan speed and packing thickness on percent removal of 5μ particles.

5 micron and larger particles from an atmosphere with a low dust load. The application of this scrubber to a swine confinement unit would be considered such a situation. The characteristic chart (Table 3) also shows that all wet packed scrubbers are not recommended for removal of particles less than 5 microns in diameter. This recommendation is due to low removal efficiencies (less than 50%) for this range. If high removal efficiencies are required for this particle size range, other air washers, such as a venturi, are prescribed.

5.3b Performance of Experimental Scrubber in the Swine Confinement Environment

The statistical analysis of the scrubber performance at the O.S.U. Swine Research Center indicates the following:

a) The scrubber was effective in removing dust particles, and the size of the particles is statistically correlated with removal efficiency.

b) The overall removal efficiencies of particles by the scrubber for all fan speeds and packing thicknesses are shown in Table 13.

c) For particles smaller than 5 microns in diameter, there is no statistically significant correlation between particle removal and fan speed or packing thickness. A statistically significant relationship (99% confidence) does exist, however, for

TABLE 13. REMOVAL EFFICIENCY OF SIX PARTICLE SIZE RANGES BY CROSS-FLOW SCRUBBERS.

Particle Size and Larger	Removal Efficiency %	Range %
> .5μ	32.5	23-38
> 1.0μ	51	43-59
> 2.0μ	65	54-72
> 3.0μ	77	61-82
> 5.0μ	90	76-96
>10.0μ	93.5	85-98

removal of particles larger than 5-μ diameter in size. Therefore, the 5-μ information should be used in recommendations of the scrubber design for application to the livestock industry. The 5-μ data were further analyzed using the Student Newman Kuhls (SNK) method, in which the combination of fan speed and packing thicknesses were statistically divided into four subgroups. The percent removal values within these subgroups are statistically equivalent (95% confidence level). These subgroups are listed in Table 14 with the best choice within each subgroup for a scrubber design indicated. This best choice would be the minimum packing thickness, which has the lowest head loss and the lowest restriction to air flow.

TABLE 14. STUDENT NEWMAN KUHLS SUBGROUPS FOR REMOVAL EFFICIENCY OF 5-MICRON DIAMETER PARTICLES AND LARGER BY THE CROSS-FLOW, PACKED SCRUBBER

Subgroup (a)	Removal Efficiency (%)	Fan Speed (b)	Packing Thickness (cm)
A	62.9	L	5.1 (c)
B	85.8	L	7.6
B	86.3	H	5.1 (c)
C	90.2	L	30.5
C	91.6	H	15.2
C	92.2	H	7.6 (c)
C	93.8	H	22.7
D	95.3	H	30.5
D	96.0	L	15.2 (c)
D	96.1	L	22.7

b. Fan Speeds L = 863 RPM H = 1151 RPM
c. Best choice within each SNK subgroup, criteria being minimum packing and lowest head loss.
a. Subgroups are indicated under the heading of "set." Each letter indicates group within which the values are statistically the same. The groups are different from each other at a 95% confidence level.

5.3c Particle Removal Characteristics in a Low Dust Level Environment

When the scrubber was examined in an environment which did not have large fluctuations in the number of particles, comparisons of the actual removal of specific sized particles could be made (see Table 15).

TABLE 15. PERCENT REMOVAL OR ADDITION OF PARTICLES WITHIN SPECIFIC PARTICLE SIZE RANGES BY THE CROSS-FLOW, PACKED SCRUBBER (a)

Particle Size Range	Fan Speed 863 RPM	Fan Speed 1151 RPM
0.5-1.0μ	+33 (b)	+35 (b)
1.0-2.0μ	-10	+ 6 (b)
2.0-3.0μ	-56	-54
3.0-5.0μ	-69	-70
5.0-10.0μ	-99	-99
>10.0μ	-100	-100

a. Averaged across packing thicknesses
b. Addition of particles above the intake number

The fact that there was an addition of particles is probably due to liquid entrainment; air moving through the packing and picking up water droplets as liquid cascades down the packing. Taking this particle addition into account, the actual performance of the scrubber is better at removing particles than the raw data indicates. The removal of odorous particles, and the addition of non-odorous water would have a positive impact on the odor intensity of the air. The data however, would not indicate a significant decrease in particle concentration at the small particle size.

5.4 Ammonia Removal by the Cross-Flow, Packed Scrubber

The effect of the cross-flow, packed scrubber on ammonia removal from the exhaust air was monitored, although the scrubber unit was designed for particle removal and not gas removal. The effect of the scrubber was calculated for the two fan speeds and five packing thicknesses by measuring scrubber inlet and outlet ammonia concentrations.

5.4a Ammonia Removal Data

The ammonia removal data, as measured by the Nesslerization method (see 4.3b), is displayed in Table 16. These data were collected over a six-week period, and each reading is an average of two measurements taken concurrently. The percentage removal of ammonia, averaged across replications, is presented in Table 17.

TABLE 17. PERCENT REMOVAL OF AMMONIA BY THE CROSS-FLOW PACKED SCRUBBER FOR VARIOUS COMBINATIONS OF FAN SPEED AND PACKING THICKNESS

	Fan Speed, RPM	
Packing Thickness (cm)	863	1151
5.1	16.3	24.0
7.6	20.7	38.0
15.2	7.7	24.6
22.7	11.6	23.3
30.5	22.7	21.4
Overall Average	15.7	26.3

TABLE 16. MEASURED AMMONIA CONCENTRATION (ppm by weight) AT THE INLET AND OUTLET OF CROSS-FLOW AIR SCRUBBER AT TWO FAN SPEEDS AND FIVE PACKING THICKNESSES

Fan Speed	Run Number	Test Location	Ammonia Concentration in Atmosphere (ppm by wt) Packing Thickness (cm)				
			5.1	7.6	15.2	2.7	30.5
863 RPM	1	In	2.44	2.14	1.28	1.61	1.61
		Out	1.95	1.37	1.24	1.56	1.15
	2	In	2.53	2.21	1.17	1.47	2.65
		Out	2.21	1.77	1.03	1.17	2.21
1151 RPM	1	In	1.78	1.78	1.87	1.88	1.84
		Out	1.31	1.56	1.49	1.54	1.47
	2	In	0.44	0.44	0.78	0.78	0.53
		Out	0.32	0.16	0.55	0.55	0.41

5.4b Analysis of Ammonia Removal Data

A two-way ANOV with an F test was applied to the ammonia removal data, with the results presented in a significance table (Table 18).

TABLE 18. SIGNIFICANCE TABLE FOR AMMONIA REMOVAL BY EXPERIMENTAL CROSS-FLOW, PACKED SCRUBBER.

Independent Variable	F Value	Significance*
Fan Speed	.107	N.S.
Packing Depth	.666	N.S.
Fan Speed/Packing Depth Interaction	.851	N.S.

*N.S. = Not significant
S. = Significant (>95% confidence level)
H.S. = Highly Significant (>99% confidence level)

This two-way ANOV F test indicates that no significant relationships may be implied between the independent variables, fan speed and packing thickness, and ammonia removal. This inability to make any implications is due to a large error term. This error term was generated by:

a) Fluctuating ammonia concentration in the confinement building exhaust air.

b) Equipment design.

c) Lack of precision by measuring equipment and procedure.

5.5 Discussion of Ammonia Removal Results

Though there is no statistical correlation between ammonia removal and either fan speed or packing thickness, the scrubber did remove a portion of the ammonia. Overall average removal rate during the entire six-week test was 21%. This amount of reduction is greater than expected when the thickness of packing is considered, and that the scrubber's operation was not designed for gas removal.

5.6 Odor Removal by the Cross-Flow, Packed Scrubber

The effect of the cross-flow, packed scrubber on odor removal was monitored using the cloth-swatch-adsorption technique described in Section 4.3c. The comparison of cloth swatches subjected to the inlet and outlet gas streams of the scrubber was made by an odor panel conducted at the Agricultural Engineering Department of O.S.U.

5.6a Odor Removal Data

The data were collected over the six-week testing period, with the odor swatches being exposed for thirty minutes while the particulate and ammonia tests were being conducted. The data are presented in Table 19, and represent the average of two readings for each.

TABLE 19. PERCENT OF ODOR PANEL GIVING ANTICIPATED RESPONSE FOR CLOTH SWATCH TEST MONITORING ODOR REDUCTION BY CROSS-FLOW, PACKED SCRUBBER*

	Fan Speed RPM	
Packing Depth (cm)	863	1151
5.1	75.0	70.7
7.6	94.4	77.0
15.2	89.8	77.0
22.7	77.8	94.4
30.5	83.0	81.9
Overall Average	83.8	80.2

*Correct response means picking one different sample from three, and indicating if it is stronger or weaker than the two remaining swatches.

5.6 b Analysis of Odor Removal Data

A two-way ANOV with an F test was applied to the odor removal, with the results presented in a significance table (Table 20).

This two-way ANOV F test indicates that no significant relationship may be implied between independent variables, fan speed and packing thickness, and odor removal. However, there was a highly significant (99% confidence level) relationship between odor removal and particle

TABLE 20. SIGNIFICANCE TABLE FOR ODOR REMOVAL BY CROSS-FLOW, PACKED SCRUBBER.

Independent Variable	F Value	Significance*
Fan Speed	.166	N.S.
Packing Depth	.298	N.S.
Fan Speed/Packing Depth Interaction	.435	N.S.
Particle Removal	.001	H.S.

*N.S. = Not significant
H.S. = Highly significant (99% confidence level)

removal by the scrubber. This relationship was examined by the Null Hypothesis Test (Snedecor, 1967). In this test, the proportion of the odor panel giving the correct response to the swatch test is compared to the proportion of people who would give the correct response by chance, which for our sample is 1/6. The correct response means the selection of the single sample which is different from the remaining two, and identifying this sample's test location as the inlet or outlet of the scrubber.

The test statistic is Zc, calculated as follows:

$$Zc = [(\hat{p}-p) - 1/2N] \; / \; \sqrt{pq/N}$$

where: $\hat{p}$ is the observed proportion of odor panel giving the correct response

$$p = 1/6$$

$$q = 1-p$$

$Z_{.99} = 1.895$. Therefore Zc calculated for an odor trial is greater than this figure, there is a highly significant (99% confidence level) relation between detected odor removal and the air treatment.

The results of the Null Hypothesis Test, shown in Table 21, support the two-way ANOV results. There is a highly significant detectable odor reduction for all combinations of fan speed and packing thickness, though there is no detectable relationship between detected odor intensity and changes in these two independent variables.

5.7 Discussion of Odor Removal Results

Though there is no statistical correlation between odor removal, as measured by the cloth swatch absorption technique, and either fan speed or packing thickness, the removal rate of odor by the scrubber was highly significant. The technique of using cloth swatches to transport odor samples was satisfactory in providing a qualitative comparison of the scrubber effectiveness. The comparison of odor intensity by current techniques has had questionable success in the past, as discussed in Section 2.5. The technique of using cotton flannel swatches as odor absorption sites provide an inexpensive, simple, and statistically significant method for comparing odor intensity. The problem of odor fatigue by the odor panel was observed in members of the panel during sampling. This

TABLE 21. RESULTS OF NULL HYPOTHESIS TEST RELATING THE PROPORTION OF CORRECT RESPONSES (p) TO THE ODOR SWATCH TEST TO CHANGE IN FAN SPEED AND PACKING THICKNESS OF CROSS-FLOW, PACKED SCRUBBER.

Fan Speed	Packing Thickness	P	Zc*
863	5.2	15/19	6.977
	7.6	18/19	8.823
	15.2	17/19	8.208
	22.7	15/19	6.977
	30.2	15/18	7.273
1151	5.2	12/19	5.640
	7.6	13/17	6.291
	15.2	13/17	6.291
	22.7	15/17	8.243
	30.2	14/17	6.942

*$Z_{.99} = 1.845$. If Zc is $\geq Z_{.99}$, there is a highly significant (99% confidence level) relation between detected odor removal and the air treatment. All tests indicate a highly significant relation.

technique may have application to other research in the future.

5.8 Possible Scrubber Applications and Practical Design

The cross-flow, packed scrubber for the livestock industry has proven particle, ammonia, and odor removal performance throughout this preliminary study.

For the swine producers across the country, a small, but significant number are under pressure to decrease or eliminate the odor emitted from their production operation. Air scrubbers do offer a potential method of reducing and controlling odor at the discharge of ventilation systems. At this time, there is no alternative device available to livestock producers with similar capabilities. Mechanical filters have been tried (Wilson and Ely, 1969), but were found to be impractical due to excessive maintenance requirements.

The concept of air scrubbing has been used in the Netherlands and in Germany, though the basic type of scrubber (counter-current flow) was different than the cross-flow. The results from the German study led the researcher to comment that air scrubbing with a packed type of scrubber was the only practical method for the livestock industry.

For the swine industry, a prototype unit of the air washer could be produced to attach to existing fan units, provided that the fan has a sufficient head. Another approach could be production of a fan, packing, and demister unit which would fit existing hog farrowing, nursery, gestation, or finishing confinement building designs. This unit, to be successful for the wide range of climatic zones in which concentrated hog production occurs in the

U.S., should have the following design features:

1. The water reservoir should be located within the confinement unit, rather than outside where there may be freezing problems.
2. The water reservoir should have a water addition and removal system with a constant water bleed off during scrubber operation. This feature will prevent dirt buildups, replenish water lost to evaporation and air entrainment, and keep the scrubber liquid fresh so water entrained in the exhaust air will be odorless. One last reason for a constant bleed off is to prevent nitrate buildup. This problem occurred in the Netherlands study, and the recycled water had a sufficiently high nitrate concentration to kill hogs (van Geelean and van der Hoek, 1977).
3. The packing should be removable or able to be bypassed so the fan can operate free air during low odor emission periods or high ventilation requirements. The elimination of the head loss due to the packing will greatly increase the fan's ventilation ability.
4. The unit can, and should be simple. Access doors should be provided for cleaning of the water reservoir and packing bed. If application is for an environment in which there may be large

foreign objects introduced into the exhaust air i.e. feather, straw), a loose weave mechanical filter should be used at the air inlet to prevent fouling of the packing.

5. From the data generated for removal of five micron particles, a packing bed thickness of 15.2 cm (6 in.) appears to perform well at an air speed through the packing of .612 m/sec (120.4 ft/min). For a packing bed with a packing bed surface of .19 m^2 (2 ft^2) at the bed inlet, this would allow a ventilation rate of 6.82 m^3/sec (14448 cfm). As an estimate of ventilation requirements for various types of swine confinement units, see Table 22.

TABLE 22. NUMBER OF HOGS MAINTAINED AT RECOMMENDED VENTILATION RATES BY A FAN WITH AIR-FLOW OF 6.82 m^3/sec (14448 cfm)*

	Recommended Ventilation Rates (m^3/sec)		# Hogs Maintained	
Hog Type	Winter (Max)	Summer	Winter	Summer
Sow & Litter	.038	.099	181	69
Growing pigs				
a. 40-100 lb	.0099	.0023	722	301
b. 100-150 lb	.0094	.033	578	201
c. 150-200 lb	.016	.047	413	144
Sow				
250-300 lb.	.019	.085	361	80

*Air flow of .612 m/sec (120.4 ft/sec) and fan opening of .19 m^2 (2.0 ft^2).

VI. CONCLUSIONS

As a particle scrubber, the cross-flow, packed scrubber, designed for the removal of particles from a livestock confinement building and tested at the O.S.U. Swine Research Center, demonstrated the following capabilities:

a. For particles greater than 1.0μ in size, averaged across all experiment trials, over 50% removal was achieved.

b. For particles greater than 3.0μ in size, over 75% removal was achieved.

c. For particles greater than 5.0μ in size, over 90% removal was achieved.

d. For particles smaller than 5.0μ in size, no statistical correlation exists between particle removal and fan speed or packing thickness.

e. For particles larger than 5.0μ in size, a highly significant correlation (greater than 99% confidence level) relates particle removal to fan speed and packing thickness.

f. For removal of ammonia, the ability of the particle scrubber is greater than expected. The overall removal rate, averaged over all combinations of fan speed and packing thickness, was 21%, with the range being 7.7% to 38.0%.

g. For removal of ammonia there is no statistical relationship between removal and fan speed or packing thickness.

h. For odor removal there is a high correlation between removal of particles and a detected qualitative difference in odor intensity of samples by an odor panel.

i. For odor removal there is no correlation between the response of the odor panel and scrubber fan speed or packing thickness.

j. For odor removal there is no correlation between the response of the odor panel and the percent removal of particles in any single size range. Though there has been no research on which particle sizes are specifically associated with odor, the documented removal of particles larger than 1.0μ indicate that there may be a correlation within this range.

k. For detecting qualitative changes in odor intensity the method of using cotton flannel cloth swatches for odor absorption sites, exposing these swatches to an odorous gas stream, transporting the swatches to a remote location, and conducting an odor panel at this remote location has been satisfactory. Considering the problems associated with odor panels working at the source of the odorant, this method is more practical and the results are statistically supported.

Experimentation in the low-dust-load, uniform atmosphere of the laboratory demonstrated the following scrubber characteristics:

a. For particles of 0.5μ and 1.0μ, the scrubber is a particle generator, with more particles being emitted from the scrubber than enter within this size range.

b. The scrubber is actually performing more efficiently than indicated by the monitoring of particle counts due to this generation of particles which would be odor-free water.

This scrubber has potential as a practical device for removing odor at the discharge of a ventilation system. The demonstrated particulate removal and the relation of this removal to a decrease in odor indicates performance that is required by many livestock producers.

VII. FUTURE WORK RECOMMENDATIONS

There has not been a study of the cross-flow, packed scrubber operating over sustained period of time. The work would give information on the quality of the scrubber water, and the rates of water addition and bleed off required to control odor, dirt buildup in the system, and scrubber water nitrate levels. This work may also include venting this scrubbed air outside the building with another vent of unscrubbed air close by. This would allow observers to directly compare the scrubber effectiveness.

The sustained period trial would allow bacteria to grow on the packing and scrubber, and test this biological effect on scrubber performance. Head loss, odor removal, particulate removal, and ammonia removal effectiveness should be monitored.

Additives to the scrubbing liquid may be examined. The addition of a surfactant, acid, base, bacteracide or other chemical may enhance the scrubber's effectiveness, though posing other questions of water disposal, corrosion, and odor quality.

The use of packings other than a chemical industry type should be examined. The use of nylon mesh, glass chips, plastic rings, and other inert objects with large surface area may be effective, lighter and cheaper than ceramic rings.

This need for future work should not distract from the fact that the scrubber does reduce odor and particle concentration in its current status.

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APPENDICES

APPENDIX A

Evaluation of Using Cloth Swatches as a Technique to Compare Odor Intensities

An experiment was conducted at the Oregon State University Poultry and Swine Research Centers on February 7 and February 8, 1978 to evaluate the use of cloth swatches as a technique to compare odor intensities. Exposure time, type of cloth, and condition of cloth surface were variables altered during the testing program.

INTRODUCTION

The human nose is the most sensitive and reliable odor detection device. To determine a statistically valid comparison of odor intensities or odor quality between different gases or liquids, an odor panel consisting of several volunteers is used. Difficulties are often encountered when conducting comparisons of two gaseous streams due to:

a) Logistics of getting the odor panel to the source.

b) Time required to organize the odor panel for repeated tests.

c) Partial or total desensitizing of the olfactory system due to contamination before the odor tests are conducted.

These problems contribute to typically poor results when correlating odor changes to a change in a gas concentration.

RESULTS

The responses of the odor panel members to the cloth swatches after various exposure periods in the two animal environments are recorded Tables A-1 and A-2.

TABLE A-1. ODOR PANEL RESULTS FOR PRELIMINARY CLOTH SWATCH ODOR ABSORPTION TEST CONDUCTED AT O.S.U. POULTRY CENTER ON FEBRUARY 7, 1978.*

Fabric	Surface Condition	Exposure (Min.)	# of Panel Responding	Type of Response
Cotton	Wet	5	6	Smelled of wet cotton
	Wet	10	6	Smelled of wet cotton
	Wet	15	6	Wet cotton dominant, but could smell other odors
	Wet	30	6	Detected chicken odor
Cotton	Dry	5	6	No odor
	Dry	10	6	No odor
	Dry	15	5	No odor
	Dry	15	1	Slight chicken odor
	Dry	30	1	No odor
	Dry	30	5	Chicken odor detected
Wool	Wet	5	6	Wet wool smell dominant
	Wet	10	6	Wet wool smell dominant
	Wet	15	6	Wet wool smell dominant
	Wet	30	6	Wet wool smell dominant
Wool	Dry	5	6	Dry wool smell
	Dry	10	4	Dry wool smell
	Dry	10	2	Detected slight chicken odor
	Dry	15	6	Detected chicken odor
	Dry	30	6	Detected strong chicken odor

*Six members on panel

TABLE A-2. ODOR PANEL RESULTS FOR PRELIMINARY CLOTH SWATCH ODOR ABSORPTION TEST CONDUCTED AT O.S.U. SWINE RESEARCH CENTER ON FEBRUARY 8, 1978.**

Fabric	Surface Condition	Exposure (Min.)	# of Panel Responding	Type of Response
Cotton	Wet	5	4	Detect slight hog odor
	Wet	5	1	Smell wet cotton
	Wet	10	5	Detect hog odor
	Wet	15	5	Strong hog odor
	Wet	30	5	Very strong hog odor
Cotton	Dry	5	2	Slight hog odor
	Dry	5	3	No odor
	Dry	10	4	Slight hog odor
	Dry	10	1	No odor
	Dry	15	5	Detect hog odor
	Dry	30	5	Strong hog odor
Wool	Wet	5	5	Wet wool smell
	Wet	10	5	Wet wool smell
	Wet	15	5	Wet wool smell
	Wet	30	5	Wet wool smell
Wool	Dry	5	5	Hog odor
	Dry	10	5	Hog odor
	Dry	15	5	Strong hog odor
	Dry	30	5	Very strong hog odor

**Five members on odor panel

DISCUSSION OF RESULTS

Both the type of fiber (cotton and wool) and the moisture content (wet and dry) are important variables in these tests.

In dry state, wool was found to have a stronger odor intensity than the cotton when exposed to similar conditions for identical time periods. Dry wool has a characteristic odor which tended to mask low level odors. When wet, the odor of the wool masked or significantly altered the absorbed odor such that odors were not identifiable, even after thirty minutes of exposure.

In dry state, cotton has virtually no odor, odors were detectable even after ten to fifteen minute exposures. The overall odor absorbancy of dry cotton was not as great as dry wool. Odors from long exposure periods were more characteristic of the source than wool, due to wool's odor contribution. When wet, cotton does have a characteristic odor, though not as intense as wool. The results show that wet cotton flannel was consistently picked as having more detectable odor than the similarly exposed dry cotton.

The odor intensity of the hog house was greater than that of the chicken house according to this technique. The odor panel was consistently able to identify the swatch with the longest exposure time from the swatches exposed at the swine center.

RECOMMENDATIONS

On the basis of this test, the cloth swatches exposure to air flow, and odor panel analysis can be successfully used in the evaluation of air scrubber effectiveness for odor reduction from swine and poultry confinement building exhaust air. Dry cotton, 7cmx7cm swatches, exposed for thirty minutes, and transported in plastic bags will be classified by a nine-person odor panel. The results will be used to establish a correlation between the removal of dust particles and the reduction of odor in the air.

TABLE B-1. PARTICLE DATA TAKEN AT THE O.S.U. SWINE RESEARCH CENTER OVER A SIX-WEEK PERIOD AT FAN SPEED 863 RPM.

Packing Thickness (cm)	Run Number	Test Location	# Particles larger than indicated diameter/0.01 ft^3					
			.5μ	1.0μ	2.0μ	3.0μ	5.0μ	10.0μ
5.1	1	In	58923*	6887	4900	2464	726	188
		Out	47560*	4421	1998	1386	260	57
	2	In	5422	4426	3981	2114	173	33
		Out	5212	2190	1836	566	54	3
7.6	1	In	48682*	8601*	3239	2114	384	197
		Out	40291*	5037*	1645	845	45	12
	2	In	5422	4426	3981	1843	173	33
		Out	3358	1069	772	276	16	1
15.2	1	In	9148	5717	3687	1843	913	153
		Out	6724	2321	1112	235	49	13
	2	In	7031	5146	4377	3121	533	114
		Out	4593	1761	907	307	15	1
22.7	1	In	9148	5717	3687	1843	913	153
		Out	6212	2936	931	498	36	5
	2	In	7031	5146	4377	3121	533	114
		Out	2979	1622	925	367	16	0
30.2	1	In	8751	5112	3891	2212	348	132
		Out	6312	1732	1261	503	43	21
	2	In	7031	5146	4337	3121	533	114
		Out	3694	1323	851	455	44	3

* Data points removed from statistical analysis due to procedure error.

TABLE B-2. PARTICLE DATA TAKEN AT THE O.S.U. SWINE RESEARCH CENTER OVER A SIX WEEK PERIOD AT FAN SPEED 1151 RPM.

Packing Thickness (cm)	Run Number	Test Location	# Particles larger than indicated diameter/0.01 ft^3 .5μ	1.0μ	2.0μ	3.0μ	5.0μ	10.0μ
5.1	1	In	7200	4576	4038	2087	490	87
		Out	5554	2887	2210	427	62	9
	2	In	4419	3030	2369	1140	347	54
		Out	2664	1491	1018	612	48	6
7.6	1	In	7200	5146	4038	2087	490	87
		Out	4628	2197	1038	351	15	4
	2	In	4419	3030	2369	1140	347	54
		Out	2720	1639	1053	431	43	5
15.2	1	In	7200	5146	4038	2087	490	87
		Out	4195	2283	1574	332	31	3
	2	In	4419	3030	2369	1140	347	54
		Out	2846	1578	739	191	31	2
22.7	1	In	8056	6731	6150	3715	932	159
		Out	6843	4061	2199	819	35	1
	2	In	8909	6447	4764	3039	601	111
		Out	5058	3932	2414	583	43	4
30.2	1	In	8056	6731	6150	3715	932	159
		Out	5973	2931	1400	432	23	3
	2	In	8909	6447	4764	3039	601	111
		Out	5632	3746	2313	522	39	4

TABLE B-3. PARTICLE DATA FOR THE CONTROL EXPERIMENT OF THE CROSS-FLOW SCRUBBER AT FAN SPEED OF 863 RPM.

Packing Thickness (cm)	Test Location	# Particles larger than indicated size/0.01 ft^3					
		.5μ	1.0μ	2.0μ	3.0μ	5.0μ	10.0μ
5.1	In	1125	845	618	394	82	6
	Out	878	472	251	112	0	0
7.6	In	1125	845	618	394	82	6
	Out	765	401	202	94	1	0
15.2	In	1125	845	618	394	82	6
	Out	793	418	210	90	2	0
22.7	In	1171	863	607	369	71	5
	Out	802	396	196	89	0	0
30.2	In	1171	863	607	369	71	5
	Out	823	431	187	101	1	0

TABLE B-4. PARTICLE DATA FOR THE CONTROL EXPERIMENT OF THE CROSS-FLOW SCRUBBER AT FAN SPEED OF 1151 RPM.

Packing Thickness (cm)	Test Location	# Particles larger than indicated size/0.01 ft^3					
		.5μ	1.0μ	2.0μ	3.0μ	5.0μ	10.0μ
5.1	In	1101	812	599	379	78	5
	Out	879	466	207	99	1	0
7.5	In	1101	812	599	379	78	5
	Out	789	409	196	96	0	0
15.2	In	1101	812	599	379	78	5
	Out	799	421	201	81	1	0
22.7	In	1138	826	611	371	86	2
	Out	812	396	184	86	0	0
30.2	In	1138	826	611	371	86	2
	Out	842	412	177	80	1	0

VITAE

Louis A. Licht, son of Robert and Theodora Licht; grew up on his parents family farm in Lowden, Iowa. This German community, with its emphasis on work, education, and religion, was the beginning of interests in music, sciences, the outdoors, and agriculture.

Education has been pursued in many institutions: Trinity Lutheran Parochial School, Lowden High School, Iowa State University, University of Wisconsin, George Washington University, the Belorussian Agricultural Academy, and Oregon State University. These schools have contributed to an education with formal degrees or certificates in Chemical Engineering, Russian Language, Soviet Agriculture, and now, a Masters degree in Agricultural Engineering.

Though formal education varied greatly, work and travel experiences have also added a perspective. Starting early in life doing hog and cattle chores, work experience now includes: two years as a part-time carpenter; one and a half years as a chemical engineer with E. I. du Pont de NeMours and Co.; six months as a staff aide to the Dean of Students at I.S.U.; six months as a singing waiter for Holiday Inns of America; two years as a production foreman for Proctor and Gamble Paper Product Division; six months as an urban planning consultant with Dedeurwaerder Associates; and fifteen months as a Research

Assistant for the Agricultural Engineering Department at Oregon State University. Travel experiences included three months of backpacking around Europe, seven months traveling coast to coast in the U. S., and three and a half months in the Soviet Union and Scandanavia.

The most significant single event to date was being selected as a delegate to the Young Agricultural Specialist Exchange Program, between the U. S. and the U. S. S. R. Fourteen young people, representing twelve states and nine agricultural fields, completed an intensive Russian language course in Washington, D. C., and spent three months in the Soviet Union, learning of their agricultural technology and techniques. The opportunity of speaking to groups, the press, and college classes has followed this overseas encounter with the Soviets.

Future professional plans include working for CH2M Hill Engineers, Planners, and Economists in Corvallis, Oregon, looking at opportunities in the field of animal waste management. In addition, involvement with ASAE Professional Committees, and possibly attainment of a Doctor of Philosophy in a related Agricultural waste field.