

A STUDY OF METHODS FOR IMPROVING
CYCLONE COLLECTION OF
ALFALFA DUST

by 544

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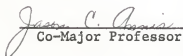
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INTRODUCTION

Man's industrialized society has created countless problems for itself. Among these, air pollution is one of the most complex and serious to be faced. Continuous efforts have been made to reduce the quantity of pollutants discharged to the atmosphere, either by new techniques or by providing adequate legislation to enforce the installation of existing cleaning devices and control of the manufacturing processes that can cause such emissions.

In the area of grain milling the generation of dust in the form of finely ground particulate matter is a direct consequence of the nature of the operation itself. Particularly in alfalfa dehydrating mills, where air conveying is required, the problem becomes more serious.

Chopped alfalfa is dried in a direct-fired rotary drum drier and is pulled with the hot gas stream through the drum by a fan at the outlet end. Customarily, the material is then blown to a primary cooling cyclone collector in which the dried material is separated from the moisture laden gas stream. At this point it is carried again by a new cool air stream, driven by another fan, to the secondary cooling cyclone. Dehydrated alfalfa is then fed to grinding equipment, generally a hammer mill. The resultant meal is a relatively fine material, with a very broad particle size distribution. A blower, downstream from the grinder, delivers the product to the air-meal cyclone separator, where the meal is collected for bagging, bulk

storage or pelleting. This third cyclone, in most operating plants, is the main source of air pollution. The finest material cannot be collected and is carried by the air stream to the atmosphere.

Alfalfa dust can cause allergic reactions in people, and persons living in the vicinity have always complained about the soiling effect of settled alfalfa dust in their homes. For these reasons and because of the high nutrient value of the lost meal [1], many plant operators have installed cleaning devices at the discharge of the air-meal cyclone collector.

Cloth bag filters are occasionally used as cleaning devices in these plants [1]. Unfortunately they are expensive solutions and many operators can't afford to install them. Also, fire hazard is a danger in this case.

There is a lack of knowledge of the basic mechanisms of the drying and milling processes, thereby making it difficult to control the process such that the main source of air pollutants is avoided.

Background Information about Cyclone Collectors

Stern, Caplan and Bush [2:p.71] described a cyclone in general terms as follows:

"Structurally, a cyclone must have an axial gas outlet, a dust discharge and a means for gas inlet which will produce the gas rotation necessary to create the vortex. These three elements may be combined in a number of different ways. Rotation may be produced by tangential gas entrance or by axial gas entrance through a set of

swirl vanes. Separated dust may be removed either axially or tangentially from the periphery. Dust may be removed from the end opposite to the axial gas outlet or from the same end. There may be either one or multiplicity of tangential inlets. The cyclone body may be completely cylindrical, completely conical, or made of both cylinders and cones. The gas outlet may be either cylindrical or conical. Cyclones in common use may be classified as follows:

- (1) Cyclones with tangential inlet and axial dust discharge.
 - (1a) Large-diameter ("conventional") cyclones.
 - (1b) Small-diameter ("high efficiency") cyclones.
- (2) Cyclones with tangential inlet and peripheral dust discharge.
- (3) Cyclones with axial inlet and axial dust discharge.
- (4) Cyclones with axial inlet and peripheral dust discharge."

A "conventional" cyclone similar to the one used in this study is shown in Figure 1, with its respective usual nomenclature. Ideally, one could analyse the mechanism of dust collection by following a single particle during its travel inside this cyclone. As the gas enters the cylindrical casing near the top it is forced, by the external wall to change its direction of flow to a circular path inside the annular space. Each particle carried into the cyclone has associated with it the same velocity component tangential to the circular path followed by the gas. By inertia, this particle tends to continue its straight line movement toward the outer wall of the cyclone. If one prefers to follow a non-inertial reference system

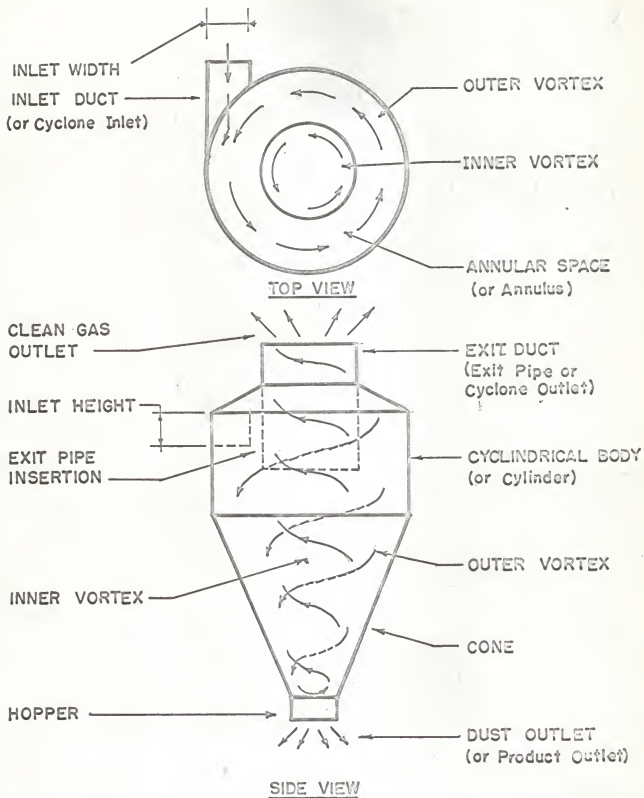


Figure 1. "CONVENTIONAL" CYCLONE DUST COLLECTOR.

centered at a moving point in the gas stream, the particle moves radially due to centrifugal reaction, to the external layers of the gas. This centrifugal reaction (F_1) is proportional to the volume of the particle, i.e.:

$$F_1 \sim D_p^3$$

where:

$$D_p = \text{particle diameter}$$

This force is counteracted by the resistance of the gas to the movement of the particle, and:

$$F_2 \sim D_p^\eta$$

where:

$$F_2 = \text{resisting force}$$

$$\eta < 2$$

The resulting effect is a net force on the particle acting toward the outer wall of the cyclone, and such that larger particles should settle first.

As the gas stream completes one turn inside the annulus, it is deflected downward by the entry stream, producing the outer vortex. This vortex continues to the vicinity of the dust outlet, where it reverses and travels upward with the same direction of rotation. This is the secondary or inner vortex that goes to the gas outlet

and leaves the cyclone. A dust particle that reaches the external wall is "trapped" in the laminar sub-layer existing between the outer vortex and this wall, and is carried toward the hopper.

In a practical case many other phenomena, like the overlapping of gas layers in the same horizontal plane or the reentrainment of particles into the gas stream, can cause the cyclone to behave quite differently.

The following are terms used frequently in describing cyclone performance:

Mass efficiency of a cyclone is the fraction of the total mass of dust entering the cyclone separated during a certain period of time.

Grade efficiency of a cyclone is the mass fraction separated at a certain particle size. Generally, it decreases with the particle size.

Cut size of a cyclone is the size of the particle collected at 50% efficiency, on a mass basis.

Pressure drop across the cyclone is an important characteristic because it often dictates the feasibility of use in a given system. Most "high efficiency" cyclones have high pressure drops.

Objectives

The first objective of this study was to measure the effect of air inlet velocity and alfalfa feeding rate upon the mass efficiency

of a "conventional" cyclone collector.

The second objective was to determine the effect of the addition of small percentages of hot animal fat to the dehydrated alfalfa before grinding upon mass efficiency.

Other objectives were to determine the reasons for changes in mass efficiency, if any occurred, and the effect of the addition of animal fat to dehydrated alfalfa on the grinding energy requirements. Attention was paid to the quality of the modified product.

LITERATURE REVIEW

Since the German patent granted to the Knickerbocker Company of the U.S.A. in 1895 [3], considerable effort has been devoted to improving cyclone collectors. Prandtl (1902), Prockat (1928), and Rosin, Rammler and Intelman (1932) contributed much to the early development of this dust collector which is the most widely used at present [3]. Initial progress was relatively slow, following very closely fluid mechanics theory where explanations of the collection mechanism were always based upon the behavior of the internal gas flow pattern.

Gas Flow Patterns in Cyclones

The first attempts to describe the flow pattern in cyclones assumed the gas performed a simple vortex. The tangential velocity (V_t) at any point was then related to the radius (r) at that point by the equation:

$$V_t = K/r^n \quad \text{where } K = \text{constant} \quad (1)$$

In the application of this equation, Seillan (1929) took $n = -1$, Lissman (1930) decided on $n = 1$, and Rosin, et al., assumed $n = 0$ [2:p.74].

Later, Stairmand (1951) denied such a simple picture of the gas flow, stating that the flow could have the shape of a "Swiss roll",

i.e., there was overlapping of gas streams in the same horizontal plane [2:p.74]. Other workers followed a different procedure by determining the flow pattern experimentally and studying the effect of variations in the cyclone configuration upon the vortex with clean air. Among these should be mentioned Shepherd and Lapple (1939), Ter Linden (1949), and First (1949).

Shepherd and Lapple [2:p.77] [4] used a "conventional" cyclone of glass, 12 inches in diameter, with an 18-inch insertion of the exit pipe. They studied the velocity direction with short rayon streamers and the velocity profiles with directional pitot tubes at two horizontal planes: 3.5 inches above and 3 inches below the bottom of the exit pipe. The widths of the inlet pipe and diameters of the exit pipe were varied, with all other dimensions maintained constant, at several flow rates.

Turbulence pointed out the inadequacy of the streamers for such studies. However, the authors concluded that "no definite radius, marking the limit of the outer spiral could be observed, but a reasonable interpretation of streamer and pitot tube determinations indicated that this radius varied approximately with the size of the exit pipe and was roughly equal to the exit pipe radius". Evidence was found of overlapping gas layers in a same horizontal plane for narrower inlet pipe widths, and for broader inlets n in Eq. (1) becomes 0.5. Some tendency of the gas in the outer vortex to slip into the inner vortex just below the exit duct was also observed

when large exit diameters were used. This study was somewhat incomplete and no three-dimensional flow pattern could be deduced.

Ter Linden [2:p.83], using clean air, studied a single "conventional" cyclone. He determined the tangential, radial and vertical velocities, together with the total and static pressures at six horizontal planes in the cyclone. He observed that the interface between the two vortices had the shape of an inverted cone and a gradual velocity transition, instead of a sharp discontinuity. The tangential velocity dominated across the planes, except very near the vertical axis where the upward vertical component was predominant. In the inner vortex, the tangential component varied as the radius and the radial component was directed toward the wall. This component, plus the small radial component toward the axis in the outer vortex caused an upward flow in the boundary region. Inside the exit pipe the tangential velocity was greater near the walls than near the center. As far as static and total pressure are concerned, he found a great difference across any section of the cyclone, but no discontinuity. One major observation was the fact that the static pressure near the walls was below, but not much different from that at the inlet. In fact, it could be very close to atmospheric pressure, which explains why cyclone collectors are known to operate satisfactorily with holes in the external wall. At the axis, however, the static pressure is quite low, even extending into the hopper. Thus, holes in this part would cause a profound effect on the flow pattern.

First [2:p.87] [4], in 1949, made a more complete clean air study with different structural configurations. His work showed clearly the overlapping of gas streams in the same horizontal plane inside the annulus, previously reported by Stairmand. Inside the cone, below the exit pipe, he confirmed most of the results obtained by Ter Linden. He found no appreciable effect of cyclone size on the flow pattern for geometrically similar units provided the flow conditions were equivalent. In the space around the exit pipe, he observed that the effect of the walls on the flow patterns increased as the annular space was reduced. Reduction of the relative height or width of the entry caused more gas layers inside the annulus, either vertically or horizontally, respectively. Entry vanes or extension of the exit pipe into the cyclone resulted in changes. Reduction of the cone length was accompanied by extra energy losses.

Summarizing his results, First stated [2:p.93]: "At all levels in the cyclone the gas nearest the axis has been in the cyclone the longest time and hence has made the greatest number of revolutions. In the annulus the entering stream displaces towards the center that fluid which has made one or more revolutions, while part of the entering stream flows downward along the outer wall; as a consequence, for the entire height of the cyclone, air near the outer wall has entered most recently, made the fewest number of revolutions and incurred the least energy loss. That portion of the entering stream furthest from the wall possesses the least downward angle of flow.

It tends to complete one more revolutions in the upper section and becomes displaced laterally toward the axis by successive laps of the entering stream. There is again appreciable downward flow of the gas stream close to the outer wall of the exit duct. Gas flowing downward at the exit duct wall has a lower energy content than gas at the cyclone body wall and tends to slip around the bottom of the exit pipe so as to join the rising stream within it. In the conical section, gas at the outer periphery of the descending spiral has a greater downward angle of flow than gas at the inner radius, and thus makes fewer revolutions to reach the same depth in the cone. Gas at lower levels must be displaced toward the axis for downward flow to occur at the cone wall. For this reason gas at the inner radius of the descending spiral is always of less energy than that at the outer radius. Since the gas at the inner radius of the outer spiral is that portion that soonest joins the ascending spiral the result is a radial energy gradient as well as a vertical energy gradient, higher energy gas being, at all times, highest in the cyclone and nearest the body wall."

In addition to this already complex flow pattern, van Tongeren (1935) predicted secondary flows, or eddy flows, along the walls of the cyclone and in the main body of the fluid [2:p.76] [4]. Ivanov, Katsnel'son and Pavlov (1960) [2:p.101] partially confirmed that statement but restricted it to the wall boundary layer. In this stagnant region, gas molecules are no longer subject to centrifugal

reaction and thus tend to react to the pressure gradients, flowing toward the low pressure regions within the boundary layer.

Cyclone Performance

That a relationship exists between the gas flow patterns and the dust collection efficiency of a cyclone is obvious, but no quantitative theory has been shown valid for a wide range of practical cases. With the addition of dust many unpredictable results happen. Due to the difficulty in measuring velocities in dust laden gas streams, no worker has succeeded in checking the flow pattern of a cyclone under loaded conditions. It is well established that a fluid can behave quite differently with suspended solids. Therefore, most of the work in the area of collection efficiency has been based upon experimental results, sampling the dust upstream and downstream of the cyclone.

Many workers [2:p.245] have studied the effect of flow rate upon the pressure drop across a cyclone and found, on the average, that the latter is a function of the square of the flow rate. Any attempt at increasing the mass efficiency by increasing the gas flow rate (and thus the centrifugal force) is accompanied by an increased pressure drop across the cyclone, as mentioned by Stern, et al. [5].

Inlet dust concentration affects both pressure drop and mass efficiency [5]. Increasing dust concentration decreases the pressure drop and increases mass efficiency. The effect upon mass efficiency is explained by the air drag of the larger particles sweeping finer

particles in the same direction. There is increased impaction of large particles against small particles and cushioning of particles on impact at the wall, with consequent reduction in bouncing.

Jackson [2:p.266] (1963) explained the reduced pressure drop as an energy transfer process associated with the movement of the dust particles from the inner high velocity layers of gas to the outer lower velocity layers. As a result, the greater the number of particles moving, the smaller the demand on the pressure potential to overcome the usual velocity gradients. Evidently, this mechanism would cause modifications in the general flow pattern.

Whitby [4], in 1950, summarizing the existing literature, noted the factors affecting cyclone performance as follows:

- "1. Energy loss is the result of internal shear between adjacent strata rotating at different speeds and angles.
2. Energy loss is independent of cyclone size.
3. Energy loss varies approximately as the $3/2$ power of the inlet velocity.
4. Dust separating efficiency varies inversely as the cyclone diameter.
5. Gas flow rate is not a major factor affecting cyclone efficiency.
6. Dust loadings of 20 - 30 grains per cubic foot decreased energy losses by 16%.
7. Decreasing inlet width decreased losses.

8. Decreasing inlet height decreased losses.
9. For a given gas velocity a high narrow inlet will give the least pressure loss and the greatest dust collection efficiency.
10. Extension of the exit duct into the cyclone has little effect on the pressure loss, but may increase the efficiency.
11. Exit duct diameters less than 1/2 the diameter of the cyclone increase pressure losses.
12. Short cones increase the pressure losses and decrease collector efficiency.
13. Entry vanes may decrease pressure losses, but will decrease collector efficiency."

Usually forgotten by many workers in the area, particle size distribution is a very important factor affecting the efficiency of a cyclone collector. Hawksley, Badzioch and Blackett [2:p.250], in 1961, according to an assumed mechanism of collection, stated that the grade efficiency of a cyclone was a function of the free falling velocity of particles (Stoke's Law) and other parameters. They wrote:

$$E = f \left[\frac{v \cdot V_1}{g D} \right] = f \left[\frac{(\sigma - \rho) \cdot d^2 \cdot V_1}{18 D \eta} \right]$$

where

$$v = \frac{(\sigma - \rho)d^2}{18\eta} = \text{free falling velocity of particle}$$

σ = density of particles

ρ = density of gas

d = particle diameter

g = acceleration due to gravity

V_1 = inlet gas velocity

η = viscosity of gas

D = cyclone diameter

From this equation, they could predict the grade efficiency under limited range of conditions. Prediction compared well with experimental results only for similar cyclones.

Conclusions

The complicated picture presented demonstrates the difficulty in composing any general theory to predict the behavior of the cyclone collectors. The large number of variables in the problem, the natural instability of this peculiar form of flow, and the inability to measure velocities in gases with suspended solids have discouraged many investigators. Dimensionless numbers, which are used to solve many complex problems in fluid mechanics and heat transfer, show little promise in this situation.

First [2:p.73], 1949, stated that "published reports of cyclone collectors have been characterized by a considerable lack of agreement..." He also stated, from the results of his work, it was hoped that such information would put cyclone design on a rational basis and help reconcile inconsistencies in the results of other investigators. However, this was not achieved despite his superb efforts in

this area.

Nevertheless, based on the existing literature it is possible to understand and to interpret the effect of the several variables upon the collection mechanism of a functioning cyclone.

In spite of all the work in the area of "cleaning cyclones", there is a considerable lack of information about heavy loaded cyclones, which is the usual situation in the milling industry. It has already been mentioned that the inlet dust concentration plays a major role, both in the efficiency of collection and in the total pressure drop across the cyclone. However, modifications in the flow pattern under heavy loading are unknown, no experimental work having been found for inlet dust loadings above $0.020 \text{ lb}_m/\text{ft}^3$. A typical air-meal cyclone separator could operate at $0.035 \text{ lb}_m/\text{ft}^3$ and more [1].

TEST FACILITIES AND APPARATUS

This research project was carried out at the pilot feed manufacturing facilities of the Department of Grain Science and Industry, at Kansas State University. Modifications in the equipment were made only when imperative to the study.

The great majority of alfalfa dehydrating mills are placed outdoors, because alfalfa is a seasonal product and the equipment operates during the summer only. Using an indoor installation, tests could be made regardless of the weather conditions and were in fact performed during the winter of 1967-68.

The main parts of the test equipment were the experimental apparatus to grind dehydrated alfalfa, the dust discharge sampling system and the liquid animal fat system. Figure 2 represents the general layout of the test facilities inside the building.

Experimental Apparatus to Grind Dehydrated Alfalfa

The grinding apparatus consisted of feeding system, hammer mill, air conveying system, and the cyclone collector.

The dehydrated alfalfa feeding system included a surge bin and a screw conveyor, controlled by a variable speed driver. The screw conveyor was 3 ft. long by 6 in. (internal diameter). The variable speed drive unit was a Variable-V- Planetary model with a 1/2 HP, 3- phase motor which could vary the speed of the auger continuously from 0 to 200 R.P.M. The maximum capacity of this system was greater

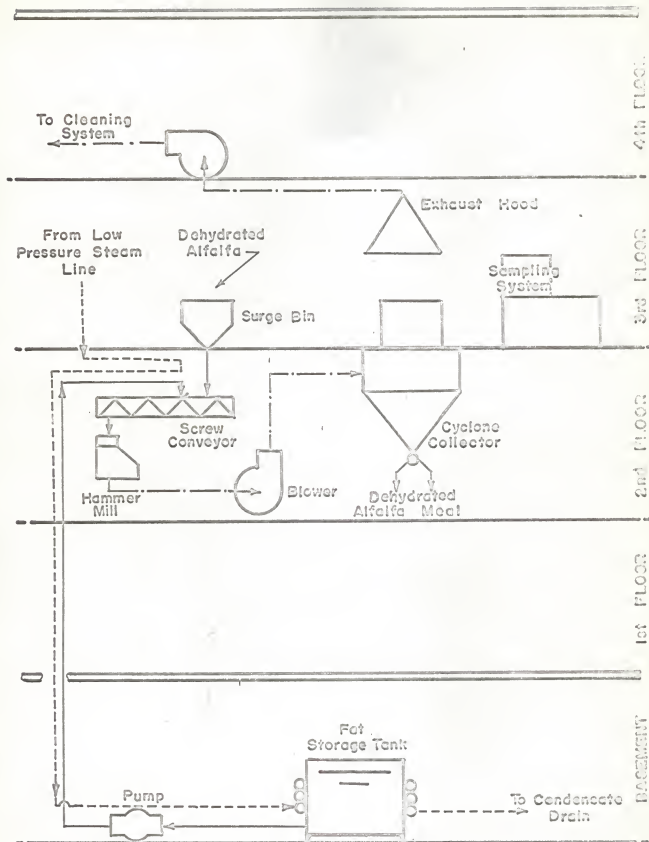


Figure 2. SCHEMATIC LAY-OUT OF TEST FACILITIES INSIDE THE BUILDING.

than the grinding capacity of the hammer mill. The surge bin was fed by hand and was not kept full because flow properties of the dehydrated alfalfa caused plugging of the system during trial runs. Two flash-light bulbs were placed 6 in. apart in small holes along the vertical duct connecting the surge bin to the screw conveyor. The operator used these lights to maintain a constant amount of material above the screw conveyor inlet. Figure 3 shows details of the system.

The hammer mill, see in Figure 4, was a Prater Pulverizer, model GS 5, driven by a 7.5 HP, 3-phase motor. It had four rows of fifteen 5.75 in. x 1.25 in x 0.125 in. hammers each. A 3/32 in. grinding screen (lower 180°) was used and the spacing between hammers and grinding screen was 1/4 in. Normal capacity was estimated at 24 lb_m/min of dehydrated alfalfa, based on a typical air-solids ratio, but the equipment could operate at 36 lb_m/min for one minute.

Ground alfalfa was carried to the cyclone collector by means of an air conveying system. It was composed of a centrifugal fan, with an estimated capacity of 1,000 cfm connected to the cyclone by a 15 ft. duct. The air flow rate could be controlled by a slide valve at the main air intake to the system.

Modifications were made in the duct close to the cyclone to provide a flow measurement section. These included an egg-crate flow straightener and pipe fittings in the duct wall for pitot tube insertion, as shown in Figure 5.

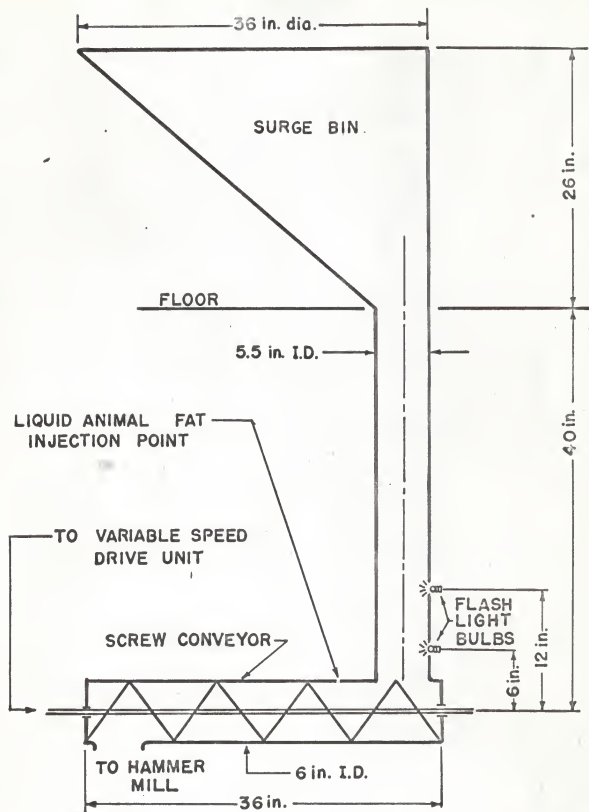


Figure 3. SCHEMATIC OF DEHYDRATED ALFALFA FEEDING SYSTEM.

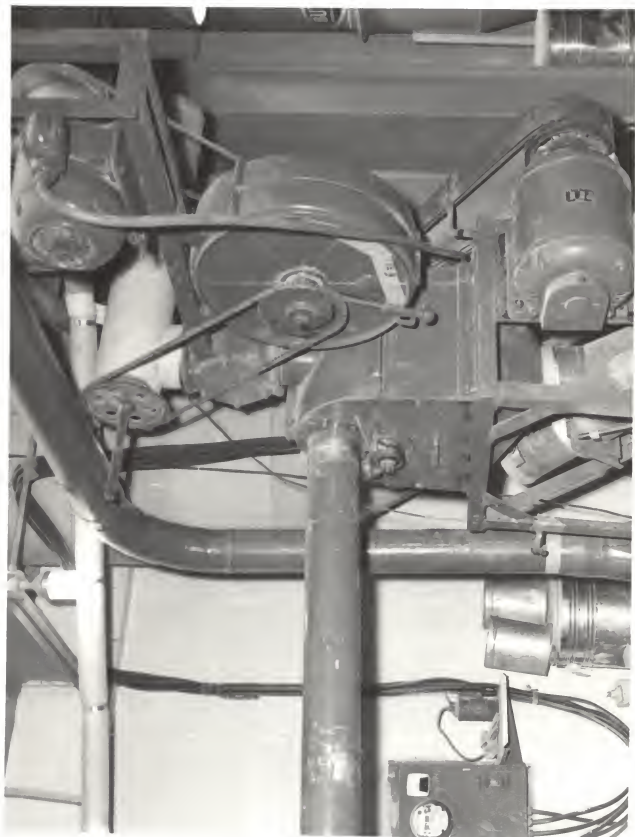


Figure 4. Grinding and feeding equipment.

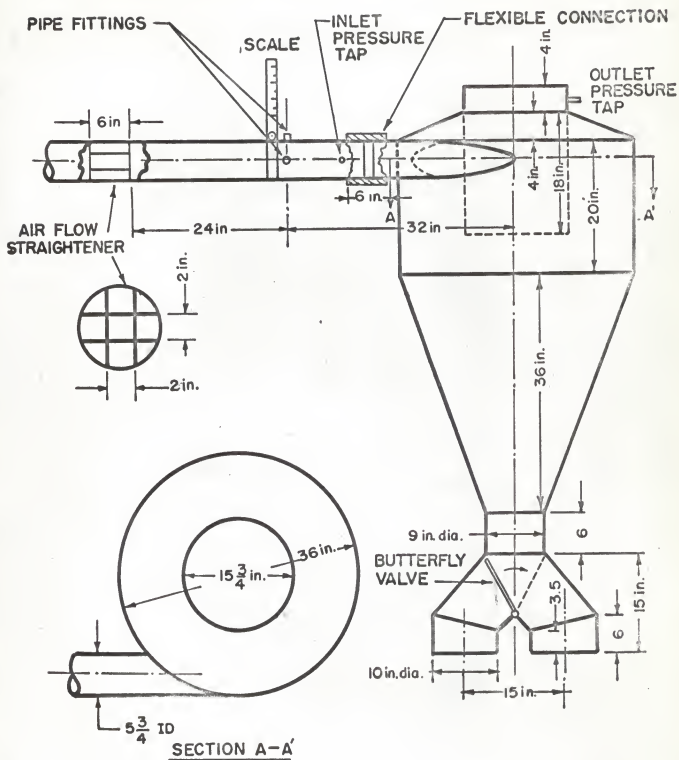


Figure 5. CYCLONE COLLECTOR AND AIR FLOW MEASUREMENT SECTION.

The cyclone collector was a "conventional" Prater Pulverizer air-meal collector having two product outlets controlled by a butterfly valve. A vibration absorbing flexible connection joined the cyclone inlet duct to the air conveying duct. Pressure taps were placed upstream and downstream of the cyclone to measure the pressure drop during test runs. A water U-tube manometer was used for that purpose.

Cyclone Discharge Sampling System

Any air pollution study has to incorporate a good sampling technique. Therefore, a major part of this study comprised the design, installation, and operation of a reliable cyclone discharge sampling system.

The usual method of evaluating dust concentration in a gas stream is to draw a known portion of the gas through a filtering device under carefully controlled conditions and to determine the weight of the particulate matter retained by the filter. This sample has to be representative, i.e., it has to be an unbiased estimator of the true average concentration of dust in the gas stream.

The primary requirement is to design the apparatus so that the gas velocity entering the sampling device is equal to the local velocity of the gas in the duct. The reason for such a criterion, as shown by Badzioch [6] and others, is to avoid sampling errors. When the velocities are different (anisokinetic sampling), the gas streamlines are disturbed and, because of varying inertia, coarse

particles will have a greater tendency than fine ones to continue their straight line trajectories instead of following the streamlines. When the sampling velocity is greater than that of the gas stream, particles will leave the deflected streamlines, passing around the nozzle. At too low sampling velocities, particles will leave the deflected streamlines and enter the nozzle. An illustration of this source of error is shown in Figure 6. Doyle et al. [7], using data collected by Watson [8], stated that for 30 micron particles of unit

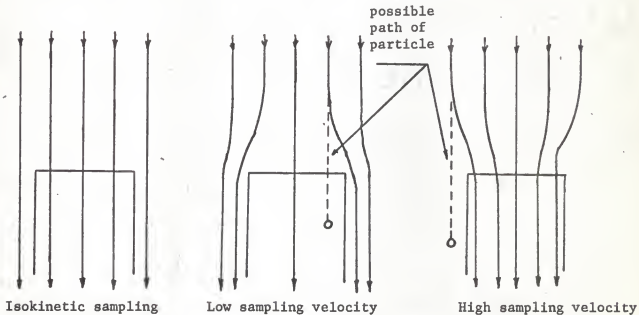


Figure 6. Effect of anisokinetic sampling.

density (equivalent to the maximum alfalfa dust particle size obtained by other researchers [1]), an 8% in mass error could result if the sampling velocity was 20% above or below the gas stream velocity.

As the velocity profile and the dust concentration profile across the duct are not uniform in most cases, it may be necessary to sample at several positions to obtain a weighted average. One alternative is to make the velocity profile uniform, by inserting a screen or a perforated plate upstream of the sampling section, and use a multipoint probe, where each sampling velocity is the same. It is even better to provide both the uniform velocity profile and the uniform dust concentration profile [9]. Then only one probe would be necessary and sampling error would be virtually eliminated.

Rotational flow at the cyclone outlet causes predominantly non-uniform tangential components and, consequently, a highly non-uniform dust concentration profile. Accurate sampling at these conditions is unattainable. Therefore a flow straightening duct extension was added to the exit pipe of the cyclone. In order to avoid an appreciable increase in pressure drop across the cyclone, which would affect the normal behavior of a collector, a low resistance flow straightening section, as recommended by Buffalo Forge Company [10], was installed. A bank of 6-in. x 2-in. diameter pipe sections was inserted inside the duct extension to eliminate rotation. This bank of tubes was followed downstream by a screen of 1/2 in. hardware cloth creating a flat velocity profile. The space between these two

modifications acted as a dust mixing chamber, creating a more uniform dust concentration across the duct before sampling. At the end of the duct, two jigs were located to assure reproducible positioning of the probe. An exhaust hood was installed above the cyclone exit duct to prevent a build up of background dust level. Care was taken to have an exhaust hood entrance velocity nearly equal to the exit velocity of the duct, to avoid any serious disturbance of the velocity profile in the sampling plane. These modifications to the system are shown in Figure 7.

The dust sampling system was based upon a similar system devised by Whitby [11] with some modifications. Its main parts were a five point sampling probe, a previously calibrated venturi meter, a Rockwell LPG (83 test index) volumetric gas meter, a Gast model 0740 vacuum pump, two solenoid valves (JE B3P), three Hoke long-taper needle valves, a 3-in. draft gage, a 10-in. U-tube mercury manometer, and selector switch, as shown in Figure 8. The entire sampling apparatus, except for the probe was mounted on and inside a box as a portable unit. During dust size analysis test runs, the mercury manometer was replaced by a less accurate 30 in. mercury Bourdon vacuum gage. All flow measuring instrumentation was connected by transparent plastic tubing with an internal diameter varying between $3/4$ in. and $3/8$ in., depending on the air flow. Thus, pressure drop between devices could be neglected. In order to insure stable air flow, one of the solenoid valves was always opened, and the needle

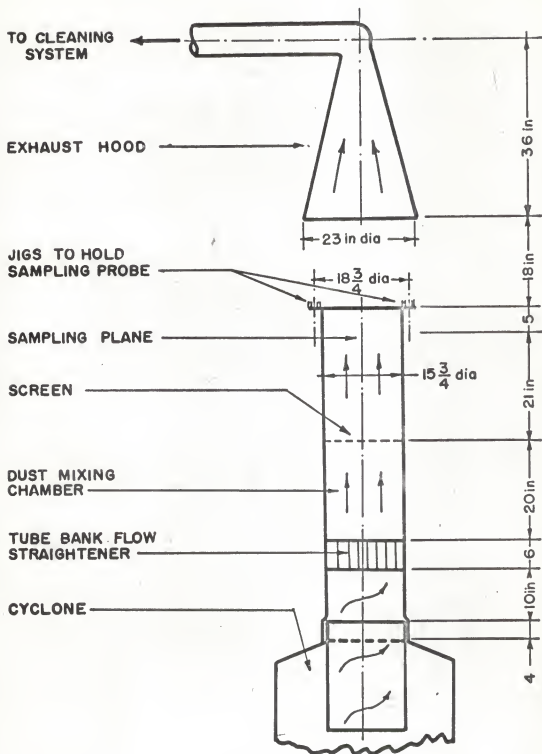


Figure 7. AIR FLOW STRAIGHTENING DUCT EXTENSION AND EXHAUST HOOD.

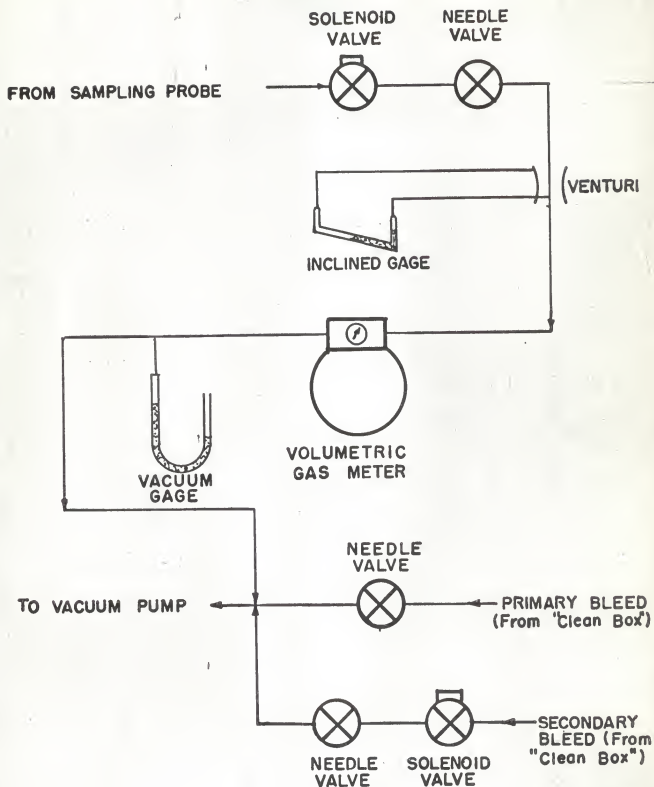


Figure 8. DIAGRAM OF SAMPLING SYSTEM.

adjusted so that the load in the vacuum pump was always constant. Therefore, the sampling period could start after the probe was set up in position with minimum transient effect in the vacuum system. An electrical switch controlled the solenoid valves.

The sampling probe, as shown in Figure 9, was basically a large diameter manifold opened at one end. Five Gelman 1109 sample holders were mounted symmetrically such that each represented 1/5 of the total cross sectional area of the exit duct (Figure 10). At the entrance of each holder was a tapered brass sampling tip of 3/16 in. internal diameter. Where the tip entered the holder both tip and holder were modified to a gradual expansion to achieve more uniform filter loading. During the mass efficiency test runs, 31/32 in. diameter discs of M.S.A. 1106-BH glass fibre filter paper were used in the holders. For particle size analysis test runs, 31/32 in. diameter pieces of Milipore type R.A. filters were selected. Both have filtration efficiencies above 99.9% for particles as small as 0.2 micron. They were weighed before and after each sampling test on a Mettler B analytical balance, able to detect 0.05 mg difference if used with exceptional care.

The air inside the pilot plant is normally quite dusty, which required the construction of a "clean box". This chamber was used to provide clean air for the sampling probe during the velocity adjustment periods that preceeded each test, and for the primary and secondary bleed inlets at all times. The "clean box" was 20 in. x 12 in. x 12 in., having a 14-in. by 10-in. opening in one side



Figure 9. Sampling probe

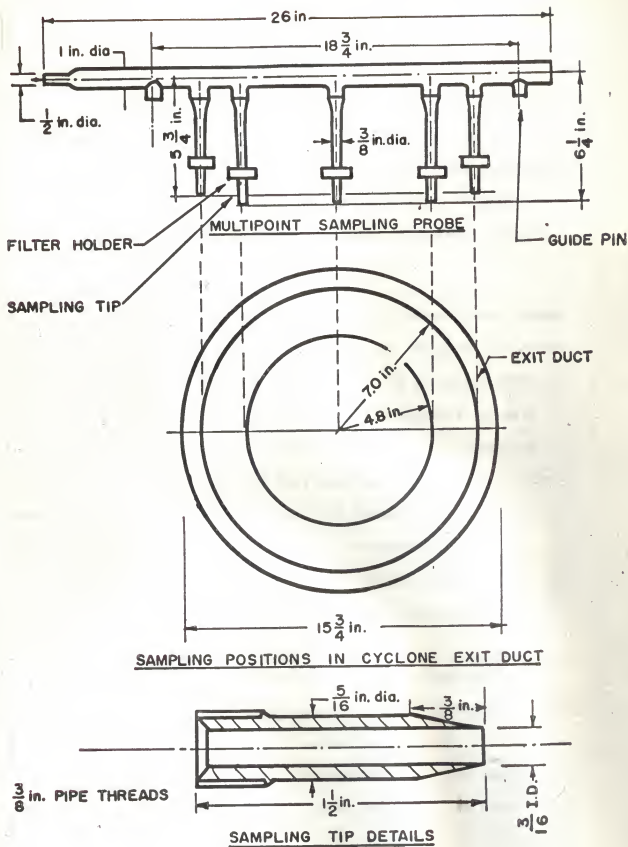


Figure 10. SAMPLING PROBE DETAILS.



Figure 11. Cyclone discharge sampling system

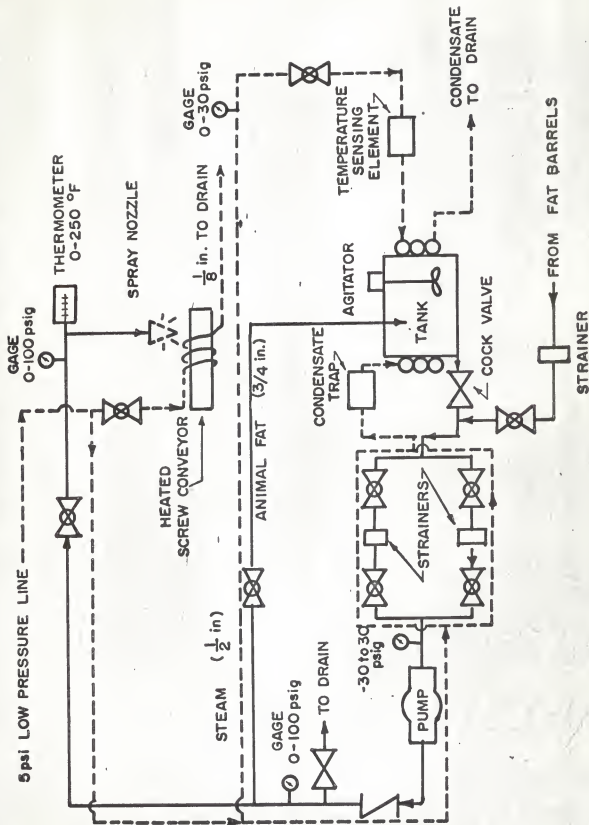


Figure 12. LIQUID ANIMAL FAT SYSTEM.

Figure 13 is a general view of this installation, which was located in the basement.

Five different spray-nozzles of Floodjet model 1/8 K.50, 1/8 K.75, 1/8 K1.5, 1/8 K2.0 and 1/8 K2.5 were used. They could be easily changed and cleaned after each test run. The last section of the line could be rotated for the ease of replacement. The spraying section of the fat system, as well as details of the steam-heated and insulated screw conveyor and the spraying position are presented in Figure 14. The reason for heating the last portion of the alfalfa feeding system was to simulate conditions occurring at the actual alfalfa dehydrating plants, where the dehydrated alfalfa enters the hammer mill at about 110°F, which is above the solidification point of animal fat.

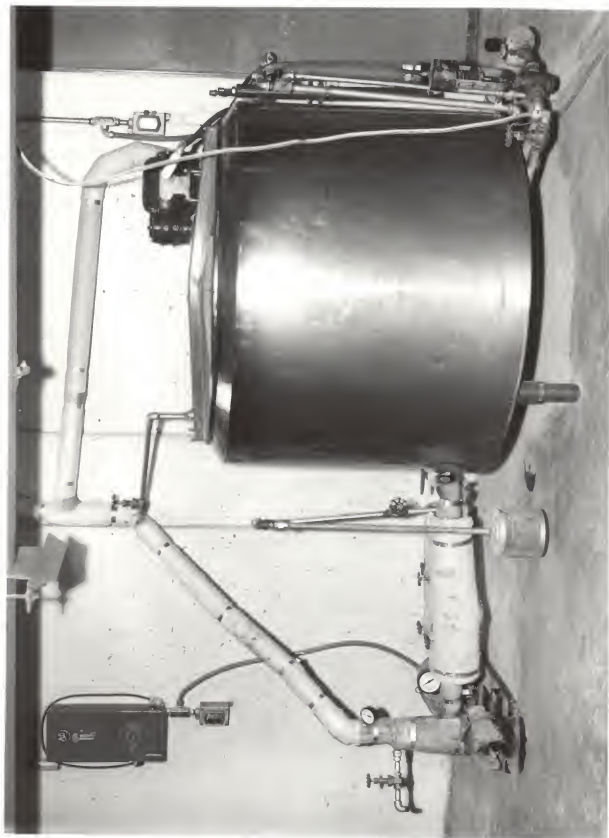


Figure 13. Liquid animal fat system: basement installation



Figure 14. Liquid fat injector and screw conveyor

EXPERIMENTAL PROCEDURES

These experiments were designed to study the mass efficiency of cyclone collection of alfalfa dust:

1. Under various conditions of dust loading, and varying air inlet velocities.
2. After the addition of liquid animal fat to dehydrated alfalfa before grinding.

As a consequence, the first step taken was to establish the number of tests and the range of variables. Due to the absence of information in the area and the relative complexity of the test procedure, the experimental design used only three levels for each variable with two replications. Most of the variable levels were based upon operating conditions in commercial plants [1], so as to attempt to reproduce practical conditions. In order to conserve alfalfa, short test runs of approximately one minute were made. It was hypothesized, and confirmed during tests, that this time interval was sufficient to collect enough dust on the filters, yet avoid any transient effect.

The normal operating conditions of the hammer mill set the medium alfalfa feeding rate at 25 lb_m/min and the other two were selected as 18 and 32 lb_m/min. These corresponded to 105, 80 and 130 r.p.m. of the screw conveyor, respectively, according to preliminary tests. A calibration curve was obtained by collecting the material, without grinding, at the bottom of the hammer mill, but

during trial runs the feeding rate behaved differently, and this calibration had to be discarded. The grinding operation and the air suction of the system may have caused the differences. The high heterogeneity of dehydrated alfalfa was an uncontrollable variable during all tests. However, by setting the variable speed drive at the desired r.p.m., this source of error was minimized.

In keeping with commercial practice, a normal cyclone inlet velocity was selected at 4,000 fpm. Since an absolute minimum velocity of 3,000 fpm is recommended for air conveying with heavy loads [10], 3,500 fpm and 4,500 fpm were the other velocities tested.

Regarding the fat levels, the procedure was to try a geometric progression of ratio two, starting at the minimum allowed by the spraying system. A maximum of 8% was decided upon, because higher percentages of animal fat would produce a meal with problems in materials handling. However, experimental results showed that using nozzle sizes available, levels of less than 2% could not be satisfactorily injected, and levels greater than 4% were judged unnecessary.

Calibrations and Preliminary Checks

Pitot tube traverse studies were made in the flow measurement section of the cyclone inlet to determine the center line coefficients of flow at the three selected levels. The method used was based upon the Standard Test Code for Air Moving Devices, AMCA, Bulletin 210 [10],

with pressure and temperature corrections according to Marangoni [12]. Details, procedure and results are in Appendix A. The center line coefficients were needed to calculate the average inlet velocities from a single measurement.

The sampling velocity was indicated on a draft gage by the pressure drop across a venturi meter. This venturi had been calibrated against a volumetric gas meter prior to its inclusion in the system. A graph was prepared showing the required pressure drop as a function of the desired sampling velocity, the total sampling area, and the vacuum in the system. Calculations and the resulting graph for the five 3/16 in. diameter tips are shown in Appendix B.

Each spray-nozzle was calibrated against the pressure in the line by weighing the liquid animal fat collected during a certain period of time (about one minute). Appendix C presents the final calibration curves.

Preliminary checks were performed on the sampling system to assure equal flow in the five sampling nozzles. The procedure was to sample atmospheric dust in the laboratory for a period of 48 hours. The five sample weights matched within 5%, the limitation of the balance. The velocity profile at the sampling plane was traversed by means of a temperature-compensated hot wire anemometer and a maximum variation established as unlikely to affect isokinetic sampling. Trial test runs were made with the cyclone to check the uniformity of the dust concentration at the sampling plane and to determine the

time required to obtain an optimum sample weight. On the basis of these results, 30 seconds of sampling time was considered adequate to minimize weighing error but yet not have overloading. The dust concentration was found uniform within weighing accuracy.

Mass Efficiency Test Run Procedure

For mass efficiency tests, where no animal fat was added, two operators were required. Operator X was mainly in charge of the dust sampling equipment and related tasks. Operator Y took care of the grinding equipment and the dehydrated alfalfa feeding. Before each sequence of tests a sufficient quantity of fiber glass filters had been numbered and weighed. These were separated into groups of five, and kept in a dust proof container. These containers were placed in an analytical laboratory adjacent to the pilot plant. Bags of dehydrated alfalfa were weighed and labeled.

During these runs, the operational sequence was as follows:

1. Operator X: prepared raw data sheet (example in Appendix D).
Operator Y: started the main system fan and exhaust hood fan.
2. Operator X: recorded the duct temperature and placed the pitot tube in the centerline position. Operator Y: read the inclined manometer attached to the pitot tube and informed operator X.
3. Operator X: adjusted the slide valve until desired test conditions of flow were obtained, and took the pitot tube

out of the duct. Operator Y: helped establish flow adjustment by informing X of the manometer readings.

4. Operator X: measured and recorded exit duct velocity with the hot wire anemometer and the pressure drop across the cyclone; then went to the laboratory to insert filters in the sampling probe and recorded their respective numbers on the data sheet. Operator Y: disconnected and stored the anemometer inside its case.
5. Operator X: connected the probe to the sampling system, placed it inside the "clean box", and started both the "clean box" blower and the sampling vacuum pump, with the selector switch on a "bleed" position. Operator Y: turned on the feeding system and adjusted the speed of the screw conveyor according to test requirements.
6. Operator X: adjusted sampling velocity by turning the selector switch to a "sample" position and simultaneously adjusting the sample valve and primary bleed valve; returned to a "bleed" position and adjusted the secondary bleed valve until the mercury manometer indicated the same system vacuum at both conditions. Operator Y: started the hammer mill and turned on the lights inside the feeding duct.
7. Operator X: recorded gas meter reading, and told operator Y to start feeding. Operator Y: timed the starting point and began feeding dehydrated alfalfa maintaining a feed rate such

that only the upper light in the duct was visible.

8. Operator X: made sure everything was functioning well for at least 5 seconds, took probe out of the "clean box", placed it carefully in the sampling position, switched to "sample" position on the selector switch as stopwatch was started, and watched the vacuum gage and the venturi draft gage to be able to correct even very small deviations.
9. Operator X: sampled cyclone exit gas for at least 20 seconds, stopped timing while switching to a "bleed" position, and removed the sampling probe carefully, holding it in one hand as sampling time and the final gas meter reading were recorded. Operator Y: timed the end of the feeding.
10. Operator X: took the probe to the laboratory. Operator Y: turned off the lights in the duct, the feeding system and the hammer mill.
11. Operator X: opened the filter holders and placed loaded filters in one dust-proof glass container, for later weighing. Operator Y: recorded feeding time and amount fed on the raw data sheet.
12. Operator X: followed the same procedure, starting at 1 for next run. Operator Y: followed the same procedure, starting at 2 for next run.

The barometric pressure was also recorded for each group of test runs. At the end of the day, loaded filters were individually weighed and their weights recorded. Filters were always handled with tweezers

rather than fingers.

During the tests where small percentages of fat were added at the screw conveyor, a third operator became necessary to take care of the liquid animal fat system. Before each sequence of test runs started, the temperature of the fat in the holding tank was checked with a bimetallic thermometer. The animal fat in the tank was maintained at 130°F. The sequence of operations was practically the same for operators X and Y. Operator Z, based on the same numbers used above, followed this schedule:

- 1-4. Selected appropriate nozzle according to test requirements and installed in its proper location at the spraying terminal. Opened the valve in the steam line which heated the steam traced screw conveyor.
5. Turned on the agitator in the fat tank, closed valve at nozzle, turned on the pump and adjusted the pressure to 15 psig above the selected nozzle pressure.
6. With the spraying terminal out of the fat injection point at the screw conveyor, the control valve was opened to see if the nozzle was spraying properly (used a can under the nozzle). The valve was shut off and nozzle allowed to drain.
7. Returned the spraying terminal to the screw conveyor injection point, told operator Y to start feeding alfalfa and opened the fat valve as soon as operator Y

started feeding.

8. Maintained desired pressure at the spray-nozzle throughout the test period by watching the pressure gage in the line and making minor adjustments on the valve.
9. Shut off the animal fat control valve and quickly turned the spraying terminal away from spraying position, collecting excess fat in the container.
10. Shut off the pump and the agitator, and disconnected nozzle.
11. Recorded operating pressure used at nozzle during the test run and cleaned the nozzle with ether.
12. Followed the same procedure, starting in 1-4.

One difference between these runs and the preceding ones was that the filters were weighed in groups of five. As the percentage of fat increased, less dust was collected on the filters and this procedure reduced the weighing error.

Particle Size Analysis Procedure

The general procedure during size analysis sampling runs was approximately the same as during mass efficiency tests. Membrane instead of fiberglass filters were used, and the sampling time was reduced so as to have an estimated maximum of 0.5 mg on each filter, thus avoiding irreversible agglomeration of particles and density streaming during particle size analysis.

During the particle size analysis, the size distribution of

alfalfa dust was determined by MSA-Whitby sedimentation method [13], using acetone as the sedimentation liquid, and 70% acetone - 30% Skellysolve "S" as the feeding liquid. Alfalfa-bearing filters were dissolved in acetone and centrifuged at 3500 RPM for at least 20 minutes, the time required to settle all particles larger than 0.2 micron. Trial tests were made using Whitby [13] recommendations for alfalfa dust: benzene as the sedimentation liquid and 50% benzene - 50% Skellysolve "S" as the feeding liquid. The re-dispersion was less satisfactory than with acetone. These trial tests also showed some lint on the filters so, as the number of particles above 20 microns was negligible, all samples were filtered through a 20 micron micro-mesh sieve after dissolving the filters in acetone. A sample size analysis data sheet is shown in Appendix E.

Grinding Energy Consumption Test Procedure

These tests followed the previous mass efficiency test run procedure, except the sampling technique was not used. Operator X timed the duration of tests, and controlled the butterfly valve at the product outlet of the cyclone. The energy consumed was indicated by the number of turns of a watt-hour meter during the test period. The advantages of using forced air through a hammer mill when grinding are slight [14]. Thus three replications at each fat level were performed, with essentially zero forced air velocity through the grinder. The feeding rate was approximately 25 lb_m/min. Results were evaluated on the material collected rather than on the feeding rates. These

data permitted the energy required to grind dehydrated alfalfa to be calculated and expressed as kilowatt-hours per short ton of product ground.

-

RESULTS AND DISCUSSION

The main purpose of this study was to obtain valid information concerning the effect of air inlet velocity, alfalfa feeding rate and addition of small percentages of animal fat to dehydrated alfalfa before grinding, upon the performance of cyclone collectors.

Mass efficiency (E) is the most usual way to express the performance of any dust collector. However, mass penetration (P_t) can also be used. This parameter is defined as:

$P_t = 1 - E$, or $P_t = 100\% - E$, where E is expressed by a decimal number, or a percentage, respectively.

Mass efficiency is justified better when the objective of the dust collection device is to separate valuable material from the gas stream. Mass penetration is more meaningful when dust escaping the collector constitutes the most important aspect of the problem. An air pollution study falls in the last category. Therefore, mass penetration of the cyclone collector was the variable studied here.

Runs were discarded in the first part of the experimental work due to irregularities, like the opening of a collecting bag under the cyclone, the interruption of the feeding operation while sampling, or the plugging of a nozzle during the run. Also in the particle size analysis, the presence of lint or the dropping of a filter after air sampling were taken as reasons to eliminate these tests from the final computations. In this study however, no run or test was discarded

as a consequence of its results.

Whenever required, statistical analyses were performed according to methods, nomenclature and tables selected by Fryer [15]. The 5% probability level was the minimum criterion for statistical significance, unless otherwise stated.

Mass Efficiency Studies

A complete summary of results obtained during this portion of the experimental work is listed in tables F-1 (no addition of animal fat) and F-2 (animal fat added before grinding), Appendix F.

For tests with no addition of fat, due to the relatively wide distribution of alfalfa feeding rates within each level, the selected statistical treatment was the analysis of covariance, shown in Table 1. From the F tests, it can be concluded that inlet velocity and alfalfa feeding rate had highly significant effects on penetration of the cyclone collector.

The statistical interaction of inlet velocity and alfalfa feeding rate on penetration was also highly significant, which shows that inlet velocity and alfalfa feeding rate were not independent variables, with relation to mass penetration of the cyclone collector. Based on this observation inlet mass concentration (solids to air ratio) seemed a more important variable affecting the performance of the cyclone.

Figure 15 represents the effect of inlet mass concentration upon cyclone penetration. The regression equation, obtained as shown in Appendix G, was:

Table 1

Analysis of covariance for the effect of inlet velocity and feeding rate on penetration

Source of Variation	D.F.	Σx^2	Σxy	Σy^2	$\Sigma x - (\Sigma xy)^2 / \Sigma x^2$	D.F.	Mean Square	Calculated F ratio	Tabulated F (0.1% level)
Inlet Velocity	2	11.3233	-0.522016	0.027237					
Feeding Rate	2	488.4133	-3.193433	0.018331					
I.V. x F.R.	4	22.6633	-0.604360	0.031022					
Error	9	11.7850	0.782859	0.058439					
Total:	17	534.1850	-3.536950	0.135029	0.006435	8	0.0008044		
"Inlet Vel. + Error"		23.1083	0.260843	0.085676	0.083605				
Adjusted Inlet Vel. SS					$SS = 0.083605 - 0.006435 = 0.077170$	2	0.033585	F(2,8) = 41.7***	18.49
"Feed. Rate + Error"		500.1983	-2.410574	0.076760	0.065143				
Adjusted Feed. Rate SS					$SS = 0.065143 - 0.006435 = 0.058708$	2	0.029354	F(2,8) = 36.5***	18.49
"I.V. x F.R. + Error"		34.4483	0.178499	0.089461	0.088536				
Adjusted I.V. x F.R. SS					$SS = 0.088536 - 0.006435 = 0.082101$	4	0.020525	F(4,8) = 25.2***	14.39

* = significant at the 5% probability level

** = significant at the 1% probability level

*** = significant at the 0.1% probability level

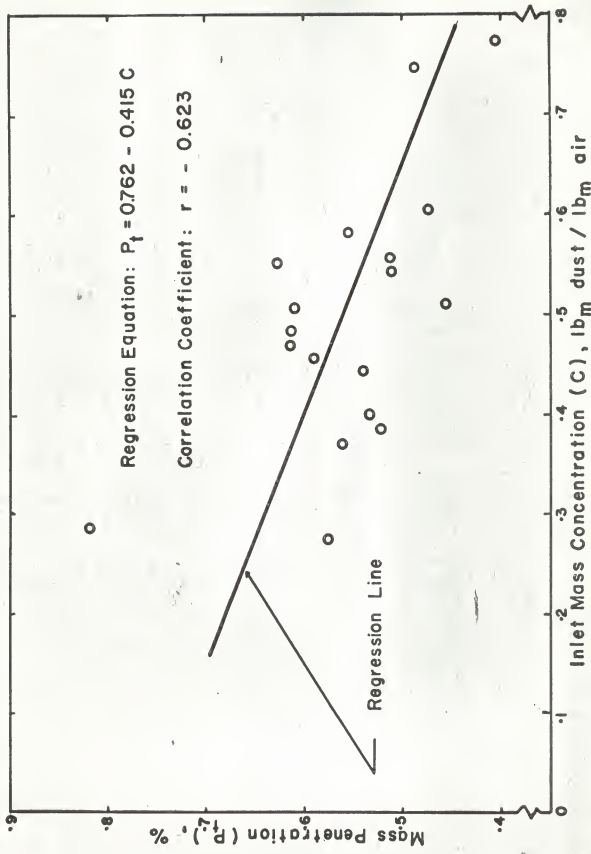


Figure 15. Effect of inlet mass concentration upon mass penetration.

$$P_t = 0.762 - 0.415 C,$$

where

P_t = mass penetration, in %

C = inlet mass concentration, in lb_m of dust/ lb_m of air

A test of hypothesis on the slope (β) of this regression line rejected (with 95% confidence) the hypothesis that $\beta \geq 0$. The conclusion was that $\beta < 0$, i.e., penetration decreases as concentration increases. This result was similar to observations made by Stern et al. [5]. The correlation coefficient was -0.623 , thus only 39% of the variation in penetration can be explained by variation in mass concentration. Some of the remaining variation may have been due to the natural heterogeneity of dehydrated alfalfa.

For tests with addition of animal fat, the total number of runs per each fat level was reduced to six, as a consequence of the results obtained above. The modified experimental design included: two replications at the highest inlet velocity level and the lowest alfalfa feeding rate level (low inlet dust concentration); two replications at the medium inlet velocity level and medium alfalfa feeding rate level (medium inlet dust concentration); and two replications at the lowest inlet velocity level and the highest feeding rate level (high inlet dust concentration). Two animal fat levels, 2 and 4 percent, were tried. The range of spray-nozzles used limited the minimum fat level at 2 percent. Based on the reduction in mass penetration obtained at the 4 percent level, no tests at higher levels were deemed necessary.

A plotting of mass penetration versus level of fat addition is in Figure 16. This graph shows that addition of fat had a pronounced effect on penetration. The addition of 2 and 4 percent levels produced 30-fold and 180-fold reductions in mass penetration, respectively. A regression analysis was performed (calculations in Appendix G). The regression equation obtained was:

$$P_t = \exp (-0.590 - 2.030 F + 0.181 F^2),$$

where:

P_t = mass penetration, in %

F = percent of animal fat added to dehydrated alfalfa

The multiple linear regression coefficient between the natural logarithm of penetration and the independent variables (F and F^2) was 0.9795. This means that 96% of the variation in the natural logarithm of penetration can be explained by these variables.

A considerable reduction in pressure drop across the cyclone was observed during mass efficiency tests, as compared to its pressure drop before the feeding and grinding operation was begun. Table 2 summarizes results obtained. These agree with similar experiments [5].

It may be noted that during the mass efficiency tests there probably was some suction of air into the cyclone through the collecting bags at the product discharge. The deviations between inlet and outlet air flows appear to confirm this. The same phenomenon was observed by Ter Linden [2:p.85].

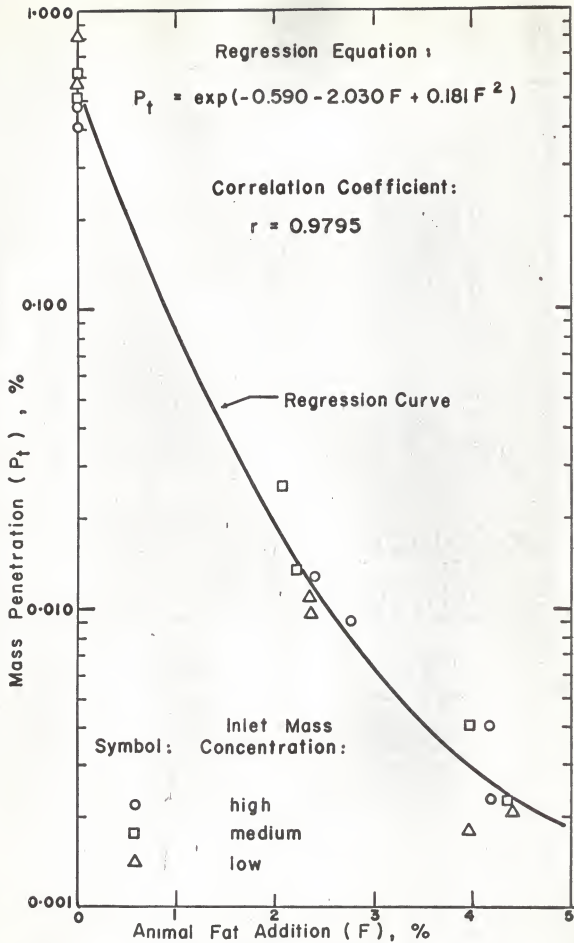


Figure 16. Effect of percent animal fat added upon mass penetration.

Table 2

Average pressure drop across the cyclone, inches of water

	Inlet air velocity level:		
	<u>High</u>	<u>Medium</u>	<u>Low</u>
Clean cyclone	2.60	2.03	1.80
Loaded cyclone	1.88*	1.22**	0.93***
Average reduction	28%	40%	48%

* = low inlet mass concentration level

** = medium inlet mass concentration level

*** = high inlet mass concentration level

Particle Size Analyses

Sixteen different MSA-Whitby sedimentation analyses were made to study the particle size distributions of cyclone outlet dust. By plotting the results on log-probability paper, the mass mean diameters were obtained and listed in Table 3.

By analysis of variance (Appendix G), a significant difference among the mass mean diameters for the three inlet dust concentration levels was found. Particle size distributions, averaged for concentration levels are shown in Figure 17. The mass mean diameter decreased with increased mass concentration, i.e., with an increase in the mass efficiency of the cyclone. This fact was an indication of how the collection mechanism behaved under different inlet mass concentrations. With an increase in mass concentration, the grade efficiency of the cyclone at the coarse end of the particle size

Table 3
 Mass Mean Diameters from Alfalfa Dust Particle Size Analyses

Sample Conditions	Test No.	Mass Mean Diameter (μ)
Low inlet mass concentration and no animal fat added	5	4.9
	8	5.0
	20	4.4
	21	4.4
Medium inlet mass concentra- tion and no animal fat added	1	4.4
	2	4.8
	19	4.6
	26	4.4
High inlet mass concentra- tion and no animal fat added	14	4.1
	15	4.1
	17	4.3
	18	4.4
Medium inlet mass concentra- tion and 2% animal fat added	22	5.7
	23	5.8
	24	5.6
	25	4.8

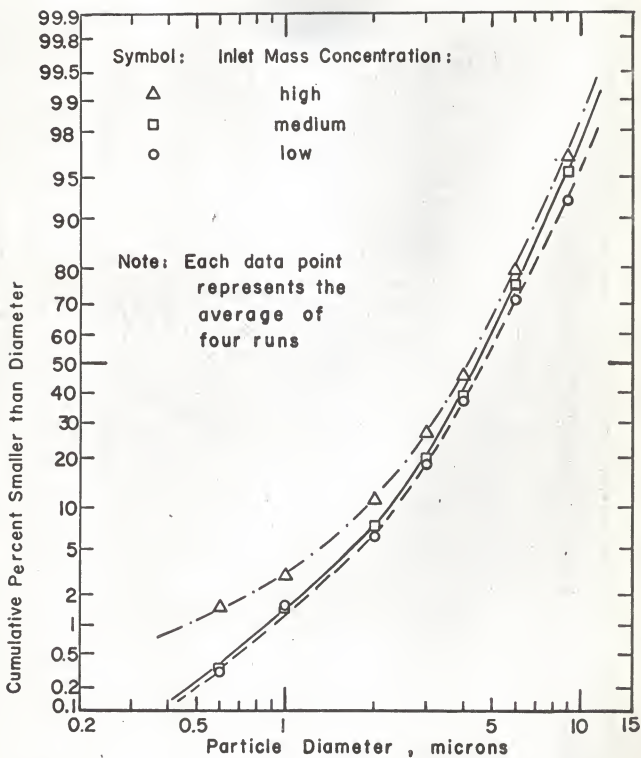


Figure 17-Averaged particle size distributions: no fat added.

distribution was improved.

By comparison of the two population means (Appendix G), it was also found that the mass mean diameters of the particle size distributions "without fat" were smaller than the mass mean diameters of the particle size distributions "with fat". This fact and the higher mass efficiency values obtained during test runs with animal fat added to dehydrated alfalfa, showed that the finest particles either agglomerated because of the presence of fat or fewer fine particles formed during grinding due to reduced shattering. Figure 18 has the two averaged particle size distributions.

Grinding Energy Consumption

A slight increase in energy requirements to grind dehydrated alfalfa was observed as the percentage of liquid animal fat added increased. These results are summarized in Table 4.

Table 4

Grinding energy requirements at different fat levels.

<u>Run No.</u>	<u>Fat %</u>	<u>KWhr/short ton</u>
1	0	9.6
2	0	10.2
3	0	9.6
4	2.10	12.0
5	1.87	11.9
6	1.98	10.5
7	4.87	11.7
8	4.80	12.8
9	4.51	13.1

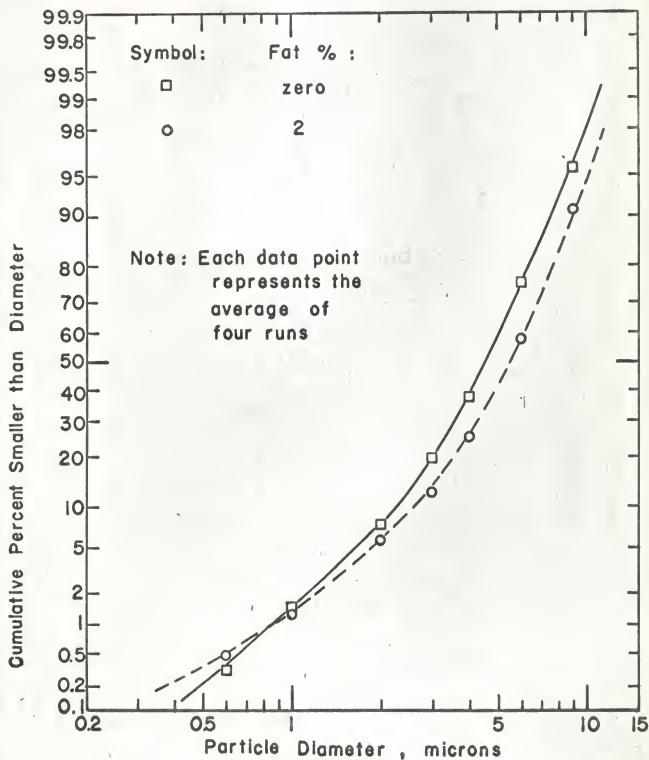


Figure 18 · Effect of addition of fat upon averaged particle size distributions.

SUMMARY AND CONCLUSIONS

The research reported in this thesis was designed to study methods of improving the cyclone collection of alfalfa dust. Essentially, two methods were tested. The first one was to measure the effect of different air inlet velocities and different alfalfa feeding rates upon the mass efficiency of a "conventional" cyclone. The second method was to determine how mass efficiency was affected by the addition of liquid animal fat to the dehydrated alfalfa before grinding. Also, particle size distributions, grinding energy requirements and cyclone pressure drops were measured to further understanding of the problem.

The mass efficiency studies and pressure drop observations were performed at three air inlet velocities (3500, 4000 and 4500 fpm), three alfalfa feeding rates (18, 25 and 32 lb_m/min), and three animal fat levels (0, 2 and 4 percent). The grinding energy requirement study included tests at the three fat levels. The particle size analyses were made using only two fat levels 0 and 2 percent.

Summarizing these results:

1. The mass penetration of the cyclone decreased slightly as the inlet mass concentration increased.
2. The mass penetration of the cyclone decreased sharply when liquid animal fat was added to dehydrated alfalfa before grinding. The addition of 2 and 4 percent levels of animal fat produced 30-fold and 180-fold reductions in mass pene-

tration, respectively.

3. The pressure drop across the cyclone increased with the increased air inlet velocities, but decreased with increased inlet mass concentrations.
4. The mass efficiency of the cyclone on the coarse particles improved with an increase in mass concentration.
5. Either agglomeration or reduced production of fine particles of alfalfa dust caused the significant improvement in the mass efficiency of the cyclone collector when liquid animal fat was added to the dehydrated alfalfa before grinding.
6. Grinding energy requirements were slightly increased by the addition of animal fat.

These results indicated that adding small percentages of animal fat to the dehydrated alfalfa before grinding would be extremely effective in controlling the air pollution problem from alfalfa dehydrating mills at a very reasonable cost. When compared to cloth bag filters the proposed solution is less expensive and easier to operate. The addition of animal fat helps to preserve the carotene content in the product during subsequent storage [1]. Although the grinding energy requirements were slightly increased, the lubricant effect of the animal fat might save part of this energy during pelleting [16].

Additional research in this area could study different spraying locations, such as downstream from the hammer mill or immediately after the rotary drum drier. Spraying-chambers and multipoint spraying

terminals might constitute a refinement of this technique. A more detailed study designed to find exactly what happens in the hammer mill when fat is added would be useful.

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APPENDICES

Appendix A

CENTERLINE COEFFICIENTS STUDY

Two 10-point traverses, one in the vertical plane and another in the horizontal plane, were repeated at several different conditions of flow, using a 1/32-in. internal diameter pitot tube. Readings were made on a Dwyer inclined gage (2.00 in. water range, 0.01 in. divisions), using oil of specific gravity 0.826. After the two profiles were finished, the centerline value was also recorded. This sequence was repeated for each different flow situation.

All values were then corrected for barometric pressure and temperature of the air in the duct. As these ten positions represented the centers of equal area zones, the actual centerline velocity divided by the arithmetic mean of the twenty measured velocities was equal to the centerline coefficient. By interpolation, the following results were obtained:

<u>actual centerline velocity (fpm)</u>	<u>centerline coefficient</u>
3,500	0.94
4,000	0.95
4,500	0.96

Appendix B

VENTURI CALIBRATION FOR THE SAMPLING SYSTEM

The venturi calibration against a volumetric gas meter indicated that:

$$Q = 0.250 \sqrt{\Delta p / \rho_c} \quad (B.1)$$

where:

$$Q = \text{air flow, ft}^3/\text{min}$$

$$\Delta p = \text{pressure drop across the venturi, in. of water}$$

$$\rho_c = \text{air density, corrected for actual pressure, lb}_m/\text{ft}^3$$

The average conditions inside the pilot plant were assumed to be:

$$p = \text{barometric pressure} = 29.0 \text{ in. of mercury}$$

$$T = \text{air temperature} = 72 \text{ }^\circ\text{F}$$

$$\phi = \text{relative humidity} = 50\%$$

As a consequence, the uncorrected air density (ρ) was taken as $0.0711 \text{ lb}_m/\text{ft}^3$, and equation B.1 became:

$$Q = \rho AV \left[\frac{p}{p - \Delta p_v} \right] = 0.250 \sqrt{(\Delta p / \rho) \times \left[\frac{p}{p - \Delta p_v} \right]} \quad (B.2)$$

where:

$$A = \text{total sampling area} = 0.0009587 \text{ ft}^2$$

$$V = \text{sampling velocity, fpm}$$

$$\Delta p_v = \text{vacuum in the system, in. of mercury}$$

Finally, from equation B.2:

$$\Delta p = (0.000030316 / (29.0 - \Delta p_v)) \times V^2$$

Figure B-1 represents curves of $\Delta p \times V$, as a function of Δp_v .

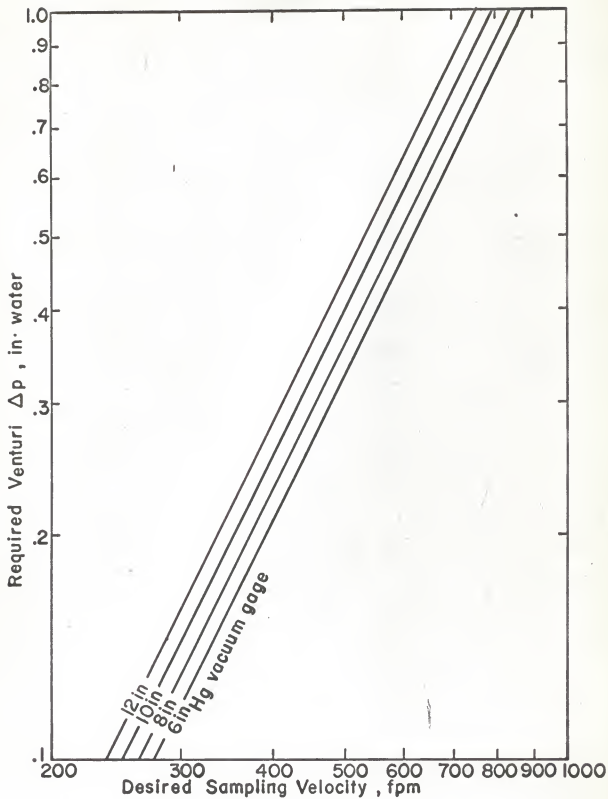


Figure B-1 • Venturi calibration curves for the sampling system.

Appendix C

SPRAY-NOZZLE CALIBRATION CURVES

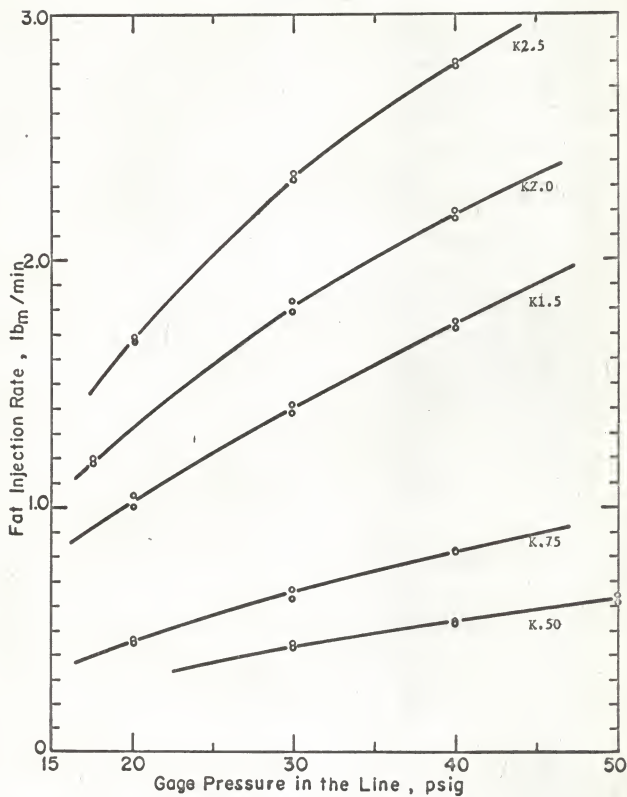


Figure C-1 · Spray-nozzle calibration curves ·

Appendix D

Example: RAW DATA SHEETProject No: 5005 Test No: 20 Date: 2-1-68Design Conditions: 4500 ft/min/ medium feeding level / no fatAir Flow

Atmospheric Pressure: 29.10 in Hg Inlet Head: 1.37 in H₂O
 Inlet Temperature: 72 F Outlet Velocity: 620 fpm
 Cyclone Pressure Drop: 1.8/2.4 in H₂O

Sampling System

Vacuum Gage: 10.0 in Hg Inlet Head: .61 in H₂O
 Sampling Time: 21.8 seconds

Position on the sampling probe	Filter No.	Weight (grams)		
		Clean	Dirty	Dust
1 (near end)	16	.02790	.03130	.00340
2	17	.02785	.03125	.00340
3	18	.02860	.03185	.00325
4	19	.02865	.03210	.00345
5 (far end)	20	.02880	.03220	.00340
	Total	.14180	.15870	.01690

Gas Meter Readings: Start Stop Indicated Volume
655.716 cuft 656.056 cuft 0.340 cuft

Alfalfa Feeding Rate

22 1/2 lbm in 52 seconds

Power Consumption

----- watthr in ----- seconds for -----lbm

Fat Feeding Rate

Nozzle No: ----- Pressure: ----- lbf/sqin Temperature: -----F

Observations:

Screw conveyor at 105 RPM

Appendix E

Example: MSA-Whitby Centrifugal Sedimentation Size Analysis of
Alfalfa Dust, 75 F

Sample No. 2#2 Run 19 Date of Analysis 3/2/68

Sample Description 2nd nozzle; no fat; 4000 fpm; 26.5 lbm/min

Operator Lima Tube size 0.5 mm Actual Room Temp. 74

$K_g = 8.88 \times 10^4$; $\rho_p = 1.45$; Sedimentation liquid: 100% acetone; Feeding liquid: 70% acetone, 30% Skellysolve "S". (3/6/65 Correction Factors Used: 1, 3, 23 sec.)

Particle Diam. -microns	RPM	Time min: sec	Read	%>Diam.	%<Diam.
100		9			
70		18			
50		36			
40		56			
30		1:39			
25		2:22			
20		3:42			
15		6:35	0.1	0.7	99.3
9	600	19	0.7	5.2	94.8
6	600	44	3.5	26.1	73.9
4	1200	29	8.4	62.6	37.4
3	1200	40	10.8	80.6	19.4
2	1800	1:15	12.4	92.6	7.4
1		4:34	13.3	99.1	0.9
0.6		10:29	13.4	99.9	0.1
0.3		47:56	13.4	99.9 +	0.1 -

Appendix F

CALCULATION FORMULAE AND DATA FOR MASS EFFICIENCY RESULTS

Calculations were based upon data recorded on raw data sheets like the example in Appendix D.

Average cyclone inlet air velocity was obtained by multiplying the correspondent centerline coefficient (Appendix A) by the centerline velocity corrected for barometric pressure and duct temperature, according to Marangoni's correction factors [12].

Inlet air flow was the product of inlet air velocity and the internal cross sectional area of the inlet duct (0.1805 ft²).

Inlet mass concentration was alfalfa feeding rate divided by the product of inlet air flow and air density (assuming an average relative humidity of 45%).

Outlet air flow was the product of outlet air velocity (from direct reading with the hot wire anemometer) and the internal cross sectional area of the exit duct (1.355 sq.ft.)

Sampling velocity was the indicated air volume sampled and corrected for the actual pressure at the gas meter, divided by the product of total sampling area and sampling time or:

$$V = 62.6 \times 10^3 \frac{v_s}{t_s} \left[\frac{p - \Delta p_v}{p} \right]$$

where:

$$v_s = \text{indicated volume, uncorrected, ft}^3$$

p = barometric pressure, in. of mercury

Δp_v = vacuum in gas meter, in. of mercury

t_s = sampling time, sec.

Dust loss was calculated by:

$$D.L. = 8.48 \times 10^4 (m_s/t_s) \times (V_o/V_s) \quad (F.1)$$

where:

D.L. = dust loss, gm/min

m_s = total mass of dust collected on samples, gm

t_s = sampling time, sec

V_o = outlet air velocity, fpm

V_s = sampling velocity, fpm

Although exceptional care was taken to sample isokinetically, the ratio (V_o/V_s) had to be included in equation F.1 to correct for slight deviations occurred (below 5%). Where V_o and V_s were not equal, a very small error in m_s would exist due to anisokinetic sampling. Since it is difficult to evaluate, it was neglected.

For the tests where animal fat was added, injection rates were obtained from calibration curves in Figure C-1.

Percentage fat was computed by dividing the fat injection rate by the alfalfa feeding rate.

Mass penetration (P_t) was:

$$P_t = \frac{(D.L.)_c}{A.F.R.} \times 100\%$$

where:

$(D.L.)_c$ = corrected dust loss, lb_m/min

A.F.R. = alfalfa feeding rate, lb_m/min

Tables F-1 and F-2 summarize results.

Table F-1
 Summary of results of mass efficiency tests: inlet velocity x alfalfa feeding rate

Run No.	Alfalfa Feeding Rate (lbm/min)	Inlet Air Velocity (fpm)	Inlet Air Flow (cfm)	Inlet Mass (lbm alfalfa/lbm air)	Outlet Air Velocity (fpm)	Outlet Air Flow (cfm)	Outlet Air Concentration (lbm alfalfa/lbm air)	Sampling Velocity (fpm)	Dust Loss (gm/min)	Mass Penetration (%)
14	25.0**	4030**	727	.484	560	760	760	571	69.4	.612
16	30.0***	4030**	727	.581	560	760	760	571	75.4	.555
17	28.4***	4030**	727	.551	560	760	760	548	80.9	.628
18	16.2*	4580***	827	.275	620	840	840	632	42.2	.576
19	16.9*	4580***	827	.288	620	840	840	612	62.8	.819
20	26.0**	4580***	827	.442	620	840	840	640	63.7	.540
21	26.8**	4580***	827	.456	620	840	840	636	71.8	.590
22	29.8***	4580***	827	.507	620	840	840	631	82.5	.610
23	30.0***	4580***	827	.510	620	840	840	636	61.9	.455
24	17.9*	3490*	629	.400	510	691	691	510	43.3	.534
25	20.3*	3450*	622	.469	510	691	691	508	56.4	.612
26	24.7**	3450*	622	.557	510	691	691	502	57.6	.512
27	26.8**	3450*	622	.604	510	691	691	517	57.7	.474
28	33.2***	3450*	622	.748	510	691	691	521	73.5	.488
29	34.3***	3450*	622	.773	510	691	691	528	63.2	.406
32	27.8**	3990**	719	.542	560	760	760	588	64.4	.511
33	18.9*	3980**	718	.370	560	760	760	560	48.0	.561
34	19.7*	3980**	718	.385	560	760	760	568	46.7	.522

* low level

** medium level

*** high level

Table F-2
Summary of results of mass efficiency tests: addition of animal fat

Run No.	Alfalfa Feeding Rate (lbm/min)	Fat Injection Rate (lbm/min)	% Fat	Inlet Air Velocity (fpm)	Inlet Air Flow (cfm)	Inlet Mass		Outlet Air Velocity (fpm)	Outlet Air Flow (cfm)	Sampling Velocity (fpm)	Dust Loss (gm/min)	Mass Penetration (%)
						Concentration (lbm alfalfa/lbm air)	Concentration (lbm air)					
37	24.0**	0.50	2.08	4000**	722	.467		560	760	560	2.73	.0260
39	17.9*	0.43	2.40	4600***	830	.303		620	840	651	1.04	.0130
40	15.8*	0.44	2.78	4600***	830	.267		620	840	637	0.66	.0092
41	24.4**	0.54	2.21	4020**	726	.472		560	760	559	1.50	.0135
42	28.7***	0.68	2.37	3490*	630	.640		510	691	513	1.25	.0096
43	27.6***	0.65	2.35	3490*	630	.615		510	691	520	1.40	.0110
44	16.5*	0.69	4.18	4600***	830	.279		620	840	627	0.31	.0041
46	16.5*	0.69	4.18	4600***	830	.279		620	840	638	0.17	.0023
47	25.8**	1.02	3.95	4020**	726	.499		560	760	573	0.61	.0052
48	23.4**	1.02	4.35	4020**	726	.453		560	760	575	0.24	.0023
49	31.1***	1.37	4.40	3490*	630	.693		510	691	510	0.30	.0021
50	34.6***	1.37	3.96	3490*	630	.771		510	691	515	0.28	.0018

* low level

** medium level

*** high level

Appendix G

STATISTICAL ANALYSIS SAMPLE CALCULATIONS

Effect of mass concentration on penetration

Assuming that X is concentration, and Y is penetration, it was calculated that:

$$\begin{array}{lll} \Sigma X_1 = 8.942 & \bar{X} = 0.4968 & \Sigma x_1^2 = 0.303197 \\ \Sigma Y_1 = 10.005 & \bar{Y} = 0.5558 & \Sigma x_1 y_1 = -0.125787 \\ n = 18 & & \Sigma y_1^2 = 0.135180 \end{array}$$

$$b \text{ (estimated slope)} = -0.125787 / 0.303197 = -0.415$$

The regression line is:

$$\hat{Y} = 0.5558 - 0.415 (X - 0.4968), \text{ or}$$

$$\hat{Y} = 0.762 - 0.415 X$$

Based on this equation:

$$\Sigma (Y_1 - \hat{Y})^2 = 0.08296$$

$$\sqrt{\Sigma (Y_1 - \hat{Y})^2} = 0.2880$$

The regression coefficient is:

$$r = -0.125787 / \sqrt{0.303197 \times 0.135180} = -0.623$$

$$r^2 = 0.389$$

Test of the slope of penetration on mass concentration regression line (β)

Null hypothesis: $\beta \geq 0$

$\alpha = 5\%$

Alternative: $\beta < 0$

$n = 18$

Test statistic: $t = (b - \beta) / S_b$

Rejection region is $t < t_0$ (16 DF; 95%), or $t < -1.75$

$$S_b = S_{y \cdot x} / \Sigma x^2$$

$$S_{y \cdot x} = \sqrt{\Sigma(Y_i - \bar{Y})^2 / (n-2)}$$

$$t = (-0.415) (0.5506) (4) / 9.2880 = -3.18$$

Conclusion: reject $\beta \geq 0$, with 95% confidence

Regression of fat injection rate on penetration

Calculations were performed by means of a computer program, which transformed the dependent variable from penetration (Y) to the natural logarithm of penetration (Z), before doing calculations for a multiple linear regression analysis as recommended by Fryer [15]. In this analysis, fat percentage (X) and fat percentage to the second power (W) were the independent variables. Also calculated was the multiple linear correlation coefficient between the dependent variable Z and the two independent variables (X, W), defined by Fryer [15] as:

$$R_{z \cdot xw} = \sqrt{(r_{zx}^2 + r_{zw}^2 - 2r_{xw} r_{zx} r_{zw}) / (1 - r_{xw}^2)}$$

where

$$r_{xw} = \Sigma_{xw} / \sqrt{\Sigma_x^2 \cdot \Sigma_w^2}$$

$$r_{zx} = B \sqrt{\Sigma_x^2 / \Sigma_z^2} + C \times r_{xw} \sqrt{\Sigma_w^2 / \Sigma_z^2}$$

$$r_{zw} = C \sqrt{\Sigma_w^2 / \Sigma_z^2} + B \times r_{xw} \sqrt{\Sigma_x^2 / \Sigma_z^2}$$

$$B = (\Sigma_{xz} \cdot \Sigma_w^2 - \Sigma_{xw} \cdot \Sigma_{wz}) / (\Sigma_x^2 \cdot \Sigma_w^2 - \Sigma_{xw} \cdot \Sigma_{xw})$$

$$C = (\Sigma_x^2 \cdot \Sigma_{wz} - \Sigma_{xz} \cdot \Sigma_{xw}) / (\Sigma_x^2 \cdot \Sigma_w^2 - \Sigma_{xw} \cdot \Sigma_{xw})$$

From the computations, $R_{z \cdot xw} = 0.9795$

and $R_{z \cdot xw}^2 = 0.9594$

Test of the relative importance of X and W in the multiple regression study

According to Fryer [14], the "success" achieved by using X alone with Z is measured by:

$$F_1 = F(1, n-2) = (n-2) r_{zx}^2 / (1-r_{zx}^2)$$

The significance of the additional reduction of Σ_z^2 achieved by using W and X is measured by:

$$F_2 = F(1, n-3) = (n-3) (R_{z \cdot xw}^2 - r_{zx}^2) / (1 - R_{z \cdot xw}^2)$$

In this analysis, n = sample size = 18

The computer program gave $F_1 = 377.9277$ and $F_2 = 29.1251$, both significant for $\alpha = 0.1\%$.

For this analysis, Z was assumed to be normally distributed in respect to X and W .

Analysis of variance for inlet mass concentration and mass mean diameter

Letting X_{11} , X_{12} and X_{13} represent the mass mean diameters of the outlet dust at low, medium and high inlet mass concentrations, respectively:

$$(\Sigma X_1)^2/4 = 87.4225$$

$$(\Sigma X_2)^2/4 = 82.81$$

$$(\Sigma X_3)^2/4 = 71.4025$$

$$\Sigma X^2/12 = 241.2033$$

Between concentration SS = 0.43167

Within concentration SS = 0.48500

Total SS = 0.08333

Analysis of Variance:

Source of Variation	DF	SS	MS	F
Between Concentrations	2	0.43167	0.21583	$F(2,9)=4.00^*$
Within Concentrations	9	0.485	0.05388	
Total	11	0.91667		

* = significant at the 90% confidence level

Test of mean diameter differences with and without fat

1) Assuming mean diameters X, "without fat", and Y, "with fat", both normally distributed, a test was performed first for the equality of variances. Both variables have $n = 4$ (3DF).

$$S_x^2 = 0.0367 \quad \text{and} \quad S_y^2 = 0.209167$$

$$F(3,3) = 0.209167 / 0.0367 = 5.70$$

At $\alpha = 5\%$ and $F_0(3,3) = 9.28$ the hypothesis that the variances are equal cannot be rejected, so they were assumed equal.

2) Null hypothesis: $\mu_y \leq \mu_x$ $\alpha = 5\%$

Alternative: $\mu_y > \mu_x$

The test statistic is:

$$t(6 \text{ DF}) = \frac{(\bar{X} - \bar{Y}) - (\mu_x - \mu_y)}{S_{(x-y)}} = \frac{0.925}{\sqrt{0.06148}} = 3.72$$

The rejection region was $t > t_0$ or $t > 1.94$, and the hypothesis was rejected. Conclusion: $\mu_y > \mu_x$.

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A STUDY OF METHODS FOR IMPROVING
CYCLONE COLLECTION OF
ALFALFA DUST

by

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AN ABSTRACT OF A THESIS

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ABSTRACT

This study was concerned with methods for improving cyclone collection of alfalfa dust, as an aid in solving the air pollution problem from alfalfa dehydrating mills. The first phase was a study of the effect of various air inlet velocities and alfalfa feeding rates upon the mass penetration of a cyclone collector. The second phase was a study of how the mass penetration was affected by adding liquid animal fat to the dehydrated alfalfa before grinding. Particle size analyses of outcoming alfalfa dust in the effluent gas were made to identify reasons for changes in mass penetration. Grinding energy requirements and cyclone pressure drop measurements were made to further understanding of changes observed.

In order to translate these results effectively to commercial practice, a large size experimental hammer mill was used to grind dehydrated alfalfa. A cyclone discharge dust sampling system, including an air flow straightening duct extension added to the cyclone outlet, was used to measure the efficiency of the cyclone collector. Spray-nozzles injected liquid animal fat into the screw-conveyor that delivered the dehydrated alfalfa to the hammer mill.

Three different air inlet velocities (3500, 4000 and 4500 fpm), three alfalfa feeding rates (18, 25 and 32 lb_m/min) and two fat levels (2 and 4 percent) represented the selected design. Most of the levels were based on operating conditions in commercial plants. One minute test runs provided sufficient time to collect samples, yet avoided any transient effects.

The mass efficiency studies showed that:

1. The mass efficiency of the cyclone increased as the inlet mass concentration increased.
2. The addition of 2 and 4 percent levels of animal fat produced 30-fold and 180-fold reductions in mass penetration, respectively.

Particle size analyses indicated:

1. Increased inlet mass concentration improved the mass efficiency of the cyclone, especially on the coarse particles, of outcoming alfalfa dust.
2. Either agglomeration or reduced production of fine particles of alfalfa dust caused the significant improvement in mass efficiency when animal fat was added to the dehydrated alfalfa.

Increased air inlet velocity increased cyclone pressure drop, but increased inlet mass concentration for a given air inlet velocity reduced the pressure drop. Grinding energy requirements were slightly increased by the addition of animal fat.

The observed results indicated that the addition of liquid animal fat to the dehydrated alfalfa before grinding provides an effective control of one source of air pollution from alfalfa dehydrating mills.