Paper No. 98-4030
An ASAE Meeting Presentation

ENGINEERING ASPECTS OF SIMULATING THE EXPOSURE OF FEEDYARD CATTLE TO FUGITIVE PM_{10}

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Summary: Of the many environmental factors and stressors associated with clinical illness in cattle feedyards, fugitive dust is recognized as an important but ill-defined contributor. To date, little research has been conducted to quantify accurately the contribution of fugitive dust to the onset, duration and severity of respiratory disease in feedyard cattle. As a result, the art and science of conducting controlled experiments to quantify such effects are poorly developed. We report preliminary results of an attempt to correlate two independent means of estimating the cumulative exposure of livestock to dust in a semi-enclosed environment. In this experiment, a known quantity of simulated feedyard dust was manufactured from dried, sieved feedyard manure. The dust was delivered via a Venturi device into a leaky tent constructed over two sorting pens at a research feedyard in Bushland, TX. Particle-size distributions of the manufactured dust were determined using a Coulter Counter. High-volume PM_{10} samplers operated inside the tent for the duration of dust delivery. An analytical model of the tent system was derived to predict the average concentration of PM_{10} in the air during the dust event. Model-predicted concentrations based on Coulter Counter analysis were a factor of 28.2 greater than the concentrations measured with EPA-designated Federal Reference Method PM_{10} samplers. The disparity between measured and predicted concentrations appears to be a result, in part, of the use of ultrasonic energy to suspend the dust samples in electrolyte for Coulter Counter analysis.

Keywords: Fugitive dust, feedyards, beef cattle, bovine respiratory disease, PM_{10}

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Introduction

The Southern High Plains (including the Texas Panhandle, western Oklahoma, eastern New Mexico, southwestern Kansas and southeastern Colorado) is the largest cattle-feeding area in the United States. More than 6 million head of cattle per year are fed to slaughter in confinement facilities known as feedyards (SPS, 1997). The average one-time capacity of individual cattle feedyards in the Texas Panhandle is approximately 40,000. Cattle feeding represents the single largest sector of the regional agricultural economy.

Calves are typically brought to the feedyard at a weight of 318 kg (700 lb) and are fed a series of high-concentrate diets for a period of 130-150 days, depending on market conditions. During the feeding period, each animal consumes approximately 9 kg (20 lb) of feed per day and gains approximately 1-2 kg/d of body weight. Fed cattle are sold for slaughter at weights from 455-590 kg (1000-1300 lb).

The most direct measure of the instantaneous profitability of cattle feeding is the so-called "cost of gain" (COG), which has the units of $/kg of weight gain. COG is a measure of how much money is required in the form of feed, veterinary care, pharmaceuticals and other feedyard costs to generate a kilogram of increased body weight. For a given price of feed ingredients (principally grain, which represents 80-90% by dry weight of typical feedyard rations), the COG reflects the average feed efficiency (FE) of the herd, expressed as kg of weight gain per kg of feed consumed. Typical FE values are in the range 0.13 to 0.20. In general, the higher the FE, the lower the COG and the more profitable the feeding enterprise. The generic term encompassing the concepts of COG and FE in livestock production is cattle "performance."

Cattle performance is a complex function of many influences including genetics, hormonal implants, feeding strategies and cattle health, among many others. In particular, poor cattle health may affect the overall profitability of a feedyard in three main ways: (1) Reducing feed intake during periods of high FE, (2) reducing FE by increasing metabolic demands and main-tenance requirements and (3) increasing COG through increased veterinary treatment costs and mortality. As a consequence, cattle health is an important determinant of feedyard profitability.

According to MacVean et al. (1986), bovine respiratory disease complex (BRDC) is "the most economically devastating condition of the cattle industry," accounting for three-fourths of cattle morbidity and two-thirds of all cattle mortality. As such, management strategies that minimize the occurrence and persistence of BRDC may be among the better strategies available to the cattle feeder to improve overall profitability. Other than clinical approaches such as vaccination and diet fortification, such strategies usually involve maintaining an optimum 25-35% (wb) moisture content in the manure pack on the feedyard surface to minimize both dust and odor.

Other than the present study, no controlled, "in-feedyard" studies have been conducted to date to quantify the contribution of fugitive dust to impaired cattle performance resulting from immune suppression or other physiological response. Consequently, the engineering design of such "in-feedyard" studies is in its infancy, requiring not only a good clinical and epidemiological foundation, but also an ability to correlate particular physiological responses to identifiable particle-size fractions within the dust. To close the loop that links human epidemiology, veterinary clinical medicine and aerosol engineering, we must develop confidence that experimental validations of the posited event-exposure-dosage-response pathway are based upon consistent, repeatable and fundamentally sound sampling measurements. We report on the first attempt to correlate EPA-designated PM_{10} sampling data with known exposure levels in a feedyard-scale clinical setting.

Methods and Materials

Test enclosure. A canvas tent (5.2m wide X 3.7m high X 7.3m long) was erected on a 4cm (dia.) PVC superstructure above two adjacent sorting pens at the USDA-ARS/TAES experimental feedyard in Bushland, TX. The tent had zippered, retractable doors at each end to permit cattle access and egress through the gates. Additional zippered ports allowed access to three low-volume, two-stage (impactor) microbial samplers (Graseby-Andersen, Smyrna, GA) mounted on the fences inside the enclosure. Two oscillating fans were mounted on elevated brackets at the SE and NW corners of the tent. High-volume PM_{10} samplers (Wedding and Associates, Ft. Collins, CO) were arranged on the floor of the enclosure (see Figure 1). The low-volume sampler in the southeast corner was mounted approximately 1m below the centerline of the circulating fan; the other two were mounted at the midpoints of the west and east fencelines, respectively.

Manufactured dust. Simulated feedyard dust was manufactured by drying, grinding and sieving (100μ) manure collected from the feedyard surface. Samples of the dust were sent to the Texas A&M Department of Agricultural Engineering in College Station, TX, where particle-size distributions were obtained using the Coulter Counter (Herber, 1988). Coulter Counter analyses of the dust were also performed at the Pantex nuclear-weapons disassembly plant using a different electrolyte solution.

Dust delivery system. Dust was added to a stream of air manually through a Venturi device and was delivered into the tent through 4cm (dia.) PVC conduit strapped to the superstructure of the enclosure. The blower, circulating fans and air samplers were powered by 5.5kW gasoline-fueled electric generators. During the dust treatment, approximately 300g of simulated dust was introduced into the tent environment over a period of 30 minutes as shown in Figure 2.

PM_{10} sampling. Microquartz filters (Whatman QM-A) were dried at 65.6 degrees Celsius for 24 hours, then weighed to 0.0001g using an analytical balance (Mettler-Toledo, Model AG245) and inserted into standard 20.3 cm X 25.4 cm filter cassettes. The three samplers operated simultaneously for thirty (30) minutes, with the dust-delivery system and circulation fans running. No cattle were in the chamber during any of the PM_{10} sampling events. The PM_{10} sampling was conducted first without the addition of manufactured dust (Run #1 - control), then with the addition of 300 g of dust over 30 minutes (Run #2). The filters were removed, re-dried and weighed to determine the net accumulated mass on the filters. The net accumulated mass was then converted to a 30-minute average concentration ($\mu g/m^3$) by dividing by the sampler flow rate and the event duration. The samplers operated at a nominal design flow rate of 40 actual cubic feet per minute (ACFM). Internal calibration of the patented Wedding size-selective inlet was conducted using a differential manometer (Wedding and Weigand, 1987). External calibration (i. e., with respect to an independent reference measurement of flow rate) was not attempted.

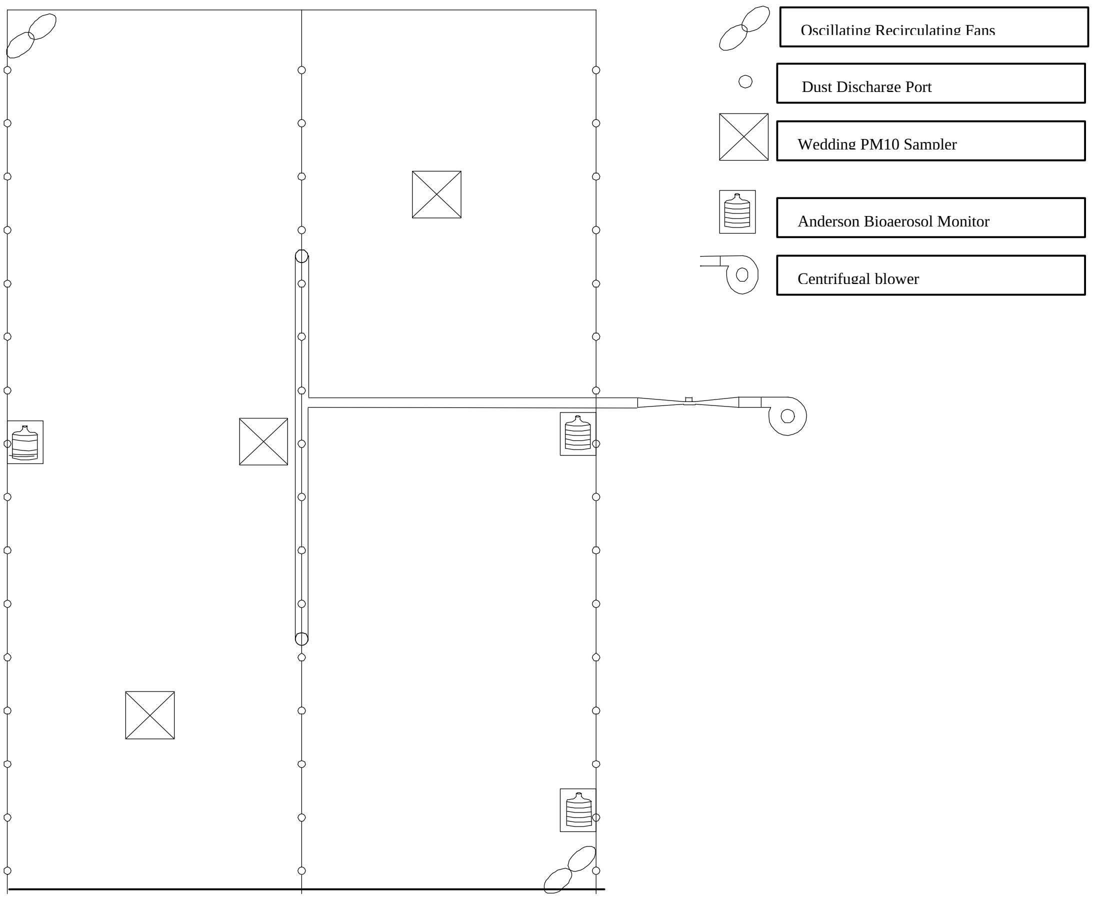

Figure 1. Plan view of the fences and the equipment layout in the dust chamber.

Estimating dust concentrations. The net 30-minute concentration of PM_{10} to which the cattle were exposed was estimated in two ways:

Method 1. Use the results of Coulter Counter particle-size distributions to determine the fraction of added dust having an aerodynamic diameter of 10 micrometers or less; multiply that fraction by the total mass of dust added to the air within the tent; then compute the concentration trajectory C(t) and its 30-minute average value using the analytical model.

Method 2. Use net mass accumulations on the microquartz filters and the volumetric flow rates of the PM_{10} samplers to compute the average concentration of PM_{10} during the 30-minute runs.

Results and Discussion

An analytical equation was derived to calculate the time trajectory of the dust concentration, C(t), in a leaky tent with internal sinks (lungs and samplers). The principal assumptions upon which the analytical model was based were:

1. All of the dust added through the Venturi device was suspended within the tent with 100% efficiency.
2. Dust delivered into the tent was instantly and uniformly mixed throughout the tent volume.
3. The concentration of dust in the air leaking through the corners of the tent was equal to C(t), the mean concentration of dust in the tent.
4. The volume rate of air leakage through the corners of the tent was equal to the volumetric flow rate of air through the dust-delivery system.
5. Internal sinks of dust (microbe samplers and cattle respiratory tracts) were 100% and 70% efficient, respectively, in removing dust particles from respired air (San Diego speaker, 1998).

Computations of the time trajectory of C(t) were performed within a Microsoft Excel spreadsheet. The analytical equations for C(t) and its time average were also programmed using a symbolic math processor (MathSoft, 1997) to verify spreadsheet logic.

Analytical expression for C(t). The governing differential equation, forcing functions and initial conditions describing the change in dust concentration in a leaky chamber with multiple internal sinks are

$$V \tfrac{d}{dt}\left[C(t)\right] = m_i(t) - m_o(t) - \sum_j m_r^j(t) \quad \text{[1]}$$

$$m_o(t) = QC(t) \quad \text{[2]}$$

$$m_r(t) = Q_r e_r C(t) \quad \text{[3]}$$

$$C(t=0) = C_o \quad \text{[4]}$$

In Equations [1-4], the variables are defined as follows:

C concentration of a specified fraction of total suspended particulate in air ($\mu g/m^3$)

t	time (min)
Q	volumetric flow rate of air through dust-delivery system (m^3/min)
Q_r	volumetric flow rate of air via respiration of internal sinks (m^3/min)
m_i	mass flow rate of dust into the chamber (µg/min)
m_o	mass flow rate of dust out of the chamber (µg/min)
m_r	mass rate of loss of dust due to internal sinks (µg/min)
V	effective volume of chamber, not including volume occupied by samplers or cattle bodies (m^3)
ε_r	flow-weighted fractional efficiency of removal of dust from respired or sampled air
C_o	initial concentration of dust fraction in air at t=0

For the dust-delivery protocol used in this project, the source function $m_i(t)$ is given by

$$m_i(t) = m_a\left[t_{ok} \leq t \leq t_{1k}\right] \tag{5}$$

$$m_i(t) = 0\left[t_{1k} \leq t \leq t_{0k+1}\right] \tag{6}$$

in which the variables are defined as follows:

m_a	constant mass rate of dust addition (µg/min)
j	index identifying dust-addition intervals of equal duration
t_{0k}	time at which dust-addition interval k begins (min)
t_{1k}	time at which dust-addition interval k ends (min)
t_{ok+1}	time at which dust-addition interval k+1 begins (min)

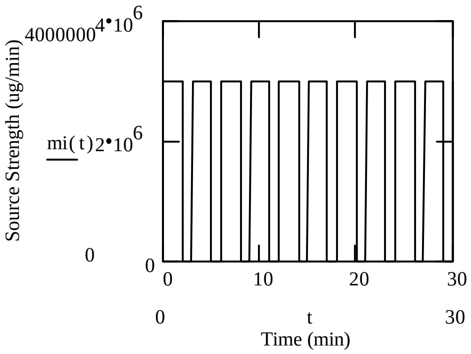

Figure 2. Mathcad™ rendering of the time trajectory of the dust source strength, $m_i(t)$.

We further define a lumped “sink strength” parameter μ (min^{-1}) representing the combined effects of internal sinks (e. g., bovine respiration; air samplers) and dust leakage through the tent lacing:

$$m = \frac{Q+e_r Q_r}{V} \quad \ldots\ldots [7]$$

The physical system represented by Equations [1-4] using the forcing functions [5, 6] is roughly analogous to a capacitive AC circuit with a square-wave AC voltage or current source. As such, an analytical solution can be easily obtained using Laplace transforms on a piecewise time domain. For a test of duration T (min) with n dust-addition intervals of equal duration, the full algebraic form of the solution is extremely cumbersome. However, an equivalent analytical solution may be written recursively for dust-delivery interval j in terms of two piecewise time “subdomains” within interval j. The first time subdomain, $0<\tau<\phi\Delta t$, corresponds to dust delivery as described by Equation [5]; the second, $\phi\Delta t<\tau<\Delta t$, corresponds to the interval described by Equation [6]. For interval j, the recursive solution for the first subdomain accounts for both sources and sinks and is expressed in terms of the final concentration reached during the previous interval, j-1:

$$C_j(t_j) = C_{j-1}(\Delta t_{j-1})e^{-mt_j} + \frac{m_a}{Vm}\left[1 - e^{-mt_j}\right];\left[0 \le t \le f\Delta t\right] \quad \ldots\ldots [8]$$

The recursive solution for the second subdomain has only the sink term and is a simple exponential decay function for which the initial value is calculated using Equation [8] with $\tau_j=\phi\Delta t$:

$$C_j(t_j > f\Delta t) = C_j(f\Delta t)e^{-m(t_j - f\Delta t)};\left[f\Delta t \le t \le \Delta t\right] \quad \ldots\ldots [9]$$

In Equations [8] and [9], φ and Δt are defined as follows:

$$f = \frac{t_{1k}-t_{0k}}{t_{0k+1}-t_{0k}} \quad \ldots\ldots [10]$$

$$\Delta t = T / n \quad \ldots\ldots [11]$$

The analytical solution contained in Equations [8-11] gives a concentration trajectory C(t) similar to the example shown in Figure 2.

Raw PM_{10} sampler data. The PM_{10} sampler data are summarized in Table 1 and Figure 4. Filter weights after each of the two tests (1 – no dust; 2 – dust added) were consistently higher than the pre-test weights, indicating good repeatability. The 30-minute mean concentration (C_{30}) for the no-dust run was 105.9 $\mu g/m^3$. The value of C_{30} for the dust-added run was 1,913.9 $\mu g/m^3$, a net increase of 1,808.0 $\mu g/m^3$.

Calibration of the analytical model. The analytical model of C(t) was calibrated using the results of the Coulter Counter analysis. The particle-size distribution (mean of three replications) of the dust samples showed that PM_{10} accounted for approximately 28% by mass of the total suspended particulate (TSP) in the manufactured dust. That percentage was multiplied by the mass rate of dust (TSP) injection, $m_i(t)$, to produce a new source strength function corresponding to the PM_{10} fraction only. The analytical model was run with the parameter values appropriate for a scenario.

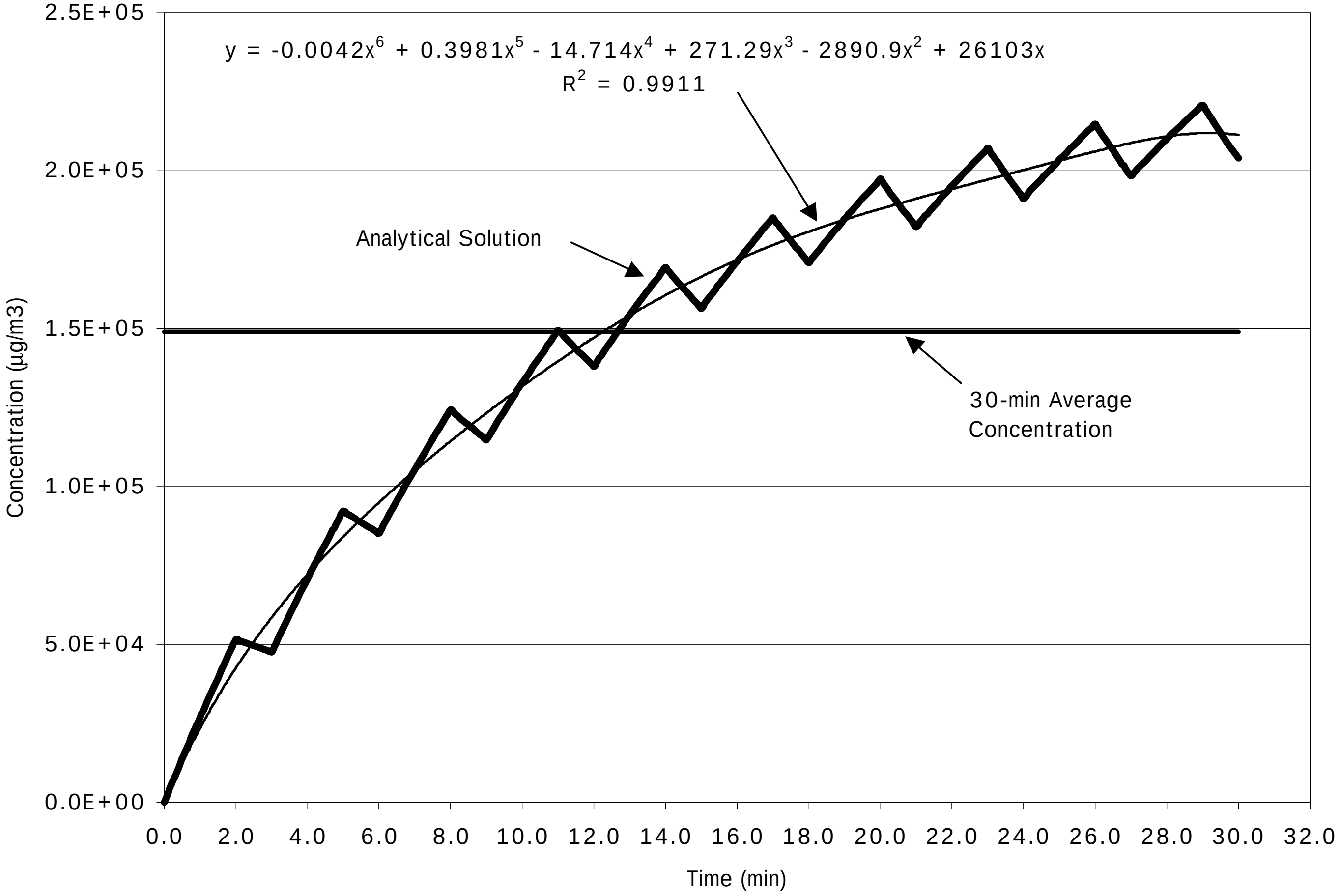

Figure 3. Sample time-trajectory of C(t) using (a) the exact analytical solution and (b) a best-fit polynomial of degree 6. Also shown is the 30-minute average concentration, C_{30}, computed numerically from C(t) using the trapezoidal rule.

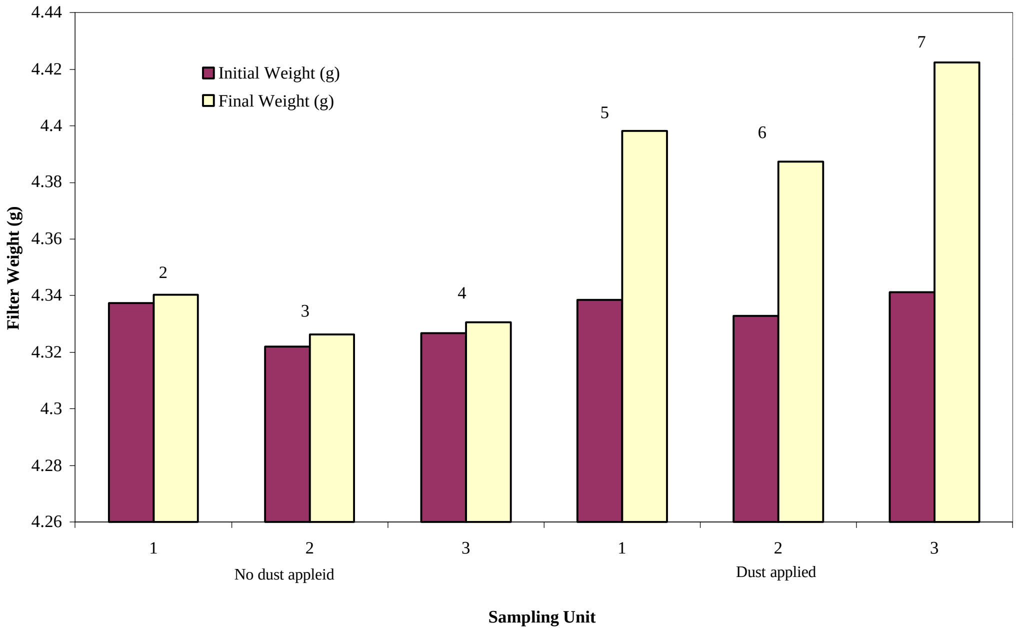

Figure 4. PM_{10} filter weights before and after the 30-minute sampling intervals for the no-dust and dust-added treatments.

TABLE 1. MEASURED AND MODEL-PREDICTED VALUES OF THE 30-MINUTE MEAN CONCENTRATION (C_{30}) OF PM_{10} IN A SCENARIO WITH NO CATTLE IN THE ENCLOSURE.

Measured Data

A. PM_{10} Samplers; no cattle; no dust added

	Pre (g)	**Post (g)**	**Mass (g)**
Filter 2	4.3374	4.3402	0.0028
Filter 3	4.3221	4.3263	0.0042
Filter 4	4.3267	4.3305	0.0038
Avg. mass of dust collected (g) =			0.0036
Avg. 30-min conc., C_{30} (µg/acm) =			105.9322

B. PM_{10} Samplers; dust added; no cattle

	Pre (g)	**Post (g)**	**Mass (g)**
Filter 5	4.3385	4.3981	0.0596
Filter 6	4.3329	4.3874	0.0545
Filter 7	4.3413	4.4223	0.0810
Avg. mass of dust collected (g) =			0.0650
Avg. 30-min conc., C_{30} (µg/acm) =			1913.646

Model Prediction

No cattle; PM_{10} Samplers

Avg. 30-min concentration
predicted from model (µg/acm) = 54001

Comparison

Percent error between predicted and measured dust concentrations

% error = 2721.891

with three internal sinks (PM_{10} samplers) and no cattle within the enclosure. Parameter values used in the analytical model are given in Table 2.

TABLE 2. PARAMETER VALUES USED IN THE ANALYTICAL MODEL FOR TWO MODELING SCENARIOS.

Parameter	Units	Scenario	
		PM_{10} samplers; no cattle	Cattle; no PM_{10} samplers
n		10	10
T	min	30	30
ϕ		0.6667	0.6667
V	m^3	139.1	131.7
Q	m^3/min	2.5	2.5
Q_r	m^3/min	3.4	0.5
ε_r		1.0	0.8
C_o	$\mu g/m^3$	105.9	105.9
m_a	$\mu g/min$	1.03×10^6	1.03×10^6

As shown in Table 1 above, the C_{30} value predicted by the analytical model (54,001 $\mu g/m^3$) for the no-cattle scenario was greater than the C_{30} value measured by the PM_{10} samplers (1,913.6 $\mu g/m^3$) by a factor of 28.2. A cursory look at the theoretical basis of the model suggests that any number of the assumptions may be weak. In particular, the assumption of complete and instantaneous mixing seems to be the model's Achilles' Heel, and it surely contributes to the error. In addition, the PM_{10} samplers may not account for all of the PM_{10} in the chamber. With the limited data at hand, there is no way to quantify these kinds of errors.

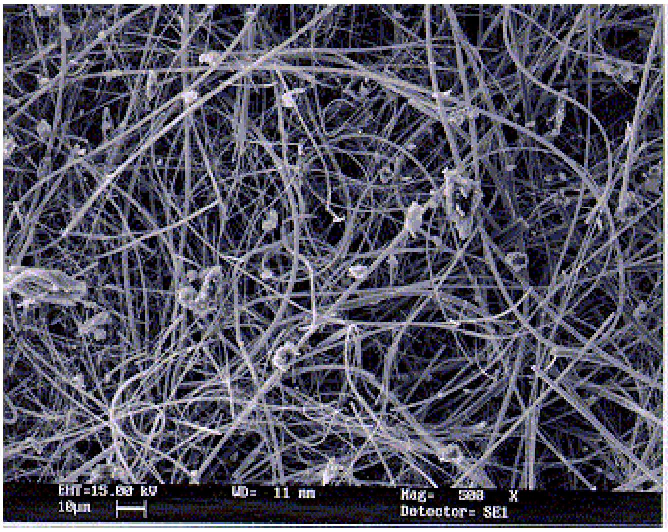

Figure 4. Scanning electron microscopy image of the manufactured dust.

There is another explanation, however, that may be responsible for part of the disparity between the measured and modeled values of C_{30}. The model prediction is predicated upon an accurate determination of the PM_{10}/TSP ratio from the Coulter Counter in order to generate an accurate source term $m_i(t)$. Sample preparation involves mixing the dust sample with a lithium chloride (LiCl) electrolyte solution and using ultrasonic energy to ensure complete suspension of the particles in solution. It is conceivable that the ultrasonic energy disaggregated the larger particles into PM_{10}. Figure 5 is a scanning electron microscope (SEM) image of the dust, generated by the SEM laboratory at the Pantex nuclear weapons assembly plant northeast of Amarillo. According to the laboratory director (Coleman, 1997), the shape and shading of the particles in the SEM image suggest that the particles are of organic origin and that many of the larger particles are composed of smaller particles that have been cemented together. The disaggregation of particles during sample preparation for Coulter Counter is a venerable criticism of the technique (Buch et al., 1998), but it has not been specifically quantified for the manufactured dust used in this study.

An incorrect value for the particle density is another potential source of error in the modeling effort. We converted equivalent spherical diameter (ESD; an output from the Coulter Counter analysis) to aerodynamic equivalent diameter (AED) by multiplying ESD by the square root of the particle density (McFarland et al., 1978). Because only a particle-size distribution expressed as a function of AED is useful in this context, estimation of the PM_{10}/TSP ratio from the distribution is highly sensitive to errors in particle density. Sweeten et al. (1998) reported a particle density of 1.71 g/cm^3 for ambient feedyard dust, which may have included both organic and mineral components. The apparent particle density of the organic dust used in this study was 1.2 g/cm3. However, that particle density was derived from bulk density measurements (ρ_b=0.829 +/- 0.003 g/cm^3) and an *assumed* porosity of 0.30. If the actual porosity of the dust had been as high as 0.45, the actual particle density of the dust would have been closer to 1.51 g/cm^3. In that case, the PM_{10}/TSP ratio from the Coulter Counter analyses would have been 22.5% instead of 28.2%, and the predicted value of C30 for the test run would have been reduced by 20% to 43,086 $\mu g/m^3$.

None of the possible sources of error is, by itself, sufficient to explain the massive discrepancy between measured and predicted values of C_{30}. It is likely that the discrepancy arose as a combined result of several errors. Those errors need to be investigated and quantified with further research.

Use of the analytical model to predict animal exposure. The final task in this study was to use the analytical model to predict the C_{30} to which the calves were exposed during scenario 2 above. If the error in model-predicted concentrations is ascribed entirely to a bias resulting from the Coulter Counter analysis or some other predictable error, one simple way to correct for the bias is to scale the model predictions by that error ratio for subsequent predictions. Using that ultra-simplified approach, we generated a corrected value of C_{30} by dividing the model prediction by 28.2. Using the input parameters in Table 2 for the cattle/no-samplers experiment, the corrected C_{30} for the cattle exposure was 2041.4 $\mu g/m^3$. Such a correction factor implies, of course, that the true PM_{10}/TSP ratio was on the order of 1%, which is undoubtedly too low. We therefore conclude that the appropriate scaling factor to account for ultrasonic disaggregation lies somewhere between unity and 28.2, with the remainder of the error to be ascribed to faulty assumptions and error in the measurement of particle density. The correct value of the scaling factor needs to be determined experimentally, perhaps by running the Coulter Counter analysis on a carefully sieved sample *without* the use of ultrasound.

Conclusions

This preliminary study showed that an analytical model of a leaky enclosure with internal sinks can be used in conjunction with particle-size distributions from the Coulter Counter to estimate the mean PM_{10} concentration to which cattle are exposed in a controlled, semi-enclosed clinical experiment. Model predictions exceeded measured values by a factor of 28.2, which we attribute in part to the pulverizing action of ultrasound on the dust samples being prepared for the Coulter Counter. Error in the measurement of the particle density may also have contributed to the gross overprediction. Further research is needed to determine the appropriate scaling factor to account for the bias introduced by the ultrasound, which tends inevitably to overestimate the fraction of fine particulate in a sample. In addition, another set of experiments needs to be run on the basis of TSP rather than PM_{10} in order to distinguish between the errors contributed by the ultrasound and those contributed by faulty assumptions or poor sampling technique.

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