A New Strawman Methodology to Predict Combustible Dust Entrainment from Layers

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Abstract

Approximately a year ago, Fire Protection Research Foundation (an affiliate of the National Fire Protection Association) initiated a research project to develop an improved dust explosion hazard assessment methodology. The objective of this project is to establish the technical basis for quantitative criteria for determining that a compartment is a dust explosion hazard that can be incorporated into NFPA 654 and other relevant safety codes and standards. For the purpose of this study, a dust explosion hazardous condition is defined as that which creates a hazard for individuals and property which are not intimate with the initiating event. The first phase of the Project is nearing completion. This paper will discuss the work in progress, significant findings to date, and the anticipated future activities.

I. Background:

In order to prevent devastating secondary dust explosions, plant operators establish combustible dust safety plans, which include housekeeping policies and cleaning frequencies to ensure dust deposit thicknesses will not exceed a maximum threshold value specified in appropriate standards and regulations. The developers and the users of combustible dust standards and regulations are grappling with the conflicting requirements for the maximum allowable “safe” layer threshold thickness specified in different standards. For example, the current (2006) edition of NFPA 654 implies a threshold layer depth of 1/32 inch while NFPA 664 uses a layer depth of 1/8 inch. NFPA 654 permits adjusting the layer depth criterion for variations in dust bulk density while NFPA 664 does not.

The problem is further complicated with the prevailing user perception that existing housekeeping requirements are too conservative, and too impractical. On the other hand, it can be shown, with a simple thermodynamic calculation, that even the 1/32 inch thick dust layer distributed uniformly over the entire floor can be capable of producing tens of psi pressure rise in a typical plant, provided that the all the dust in the deposit is lifted into an explosible dust cloud.

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In an experimental study of grain conveyor galleries, Tamanini (1983) demonstrated that 1/1250 inch thick dust layer on the gallery floor is sufficient to support flame propagation in small scale gallery, and 1/100 inch thick dust layer on the gallery floor is sufficient to support flame propagation in the large scale gallery. Tamanini (1983) states “it is conceivable that propagation would occur at even lower fuel loadings, but no tests were performed to better define marginal conditions.” Furthermore, Tamanini’s results are expected to under-represent the hazard because, cornstarch used as the combustible dust was not dried and contained approximately 10% moisture, with an unusually high Minimum Explosible Concentration (MEC) for cornstarch.

With the recent National Emphasis Program (NEP), OSHA has emerged as a key stakeholder of the combustible dust problems, and has begun to enforce the current edition of NFPA 654 as a standard for assessing compliance with the General Duty Clause of the OSH Act of 1970.

Recently, the Committee responsible for NFPA 654 came up with two new consensus criteria for determining that a compartment is a dust explosion hazard: one aimed at 95% personnel survivability, and the other for room/building collapse prevention. As described in Rodgers and Ural (2010), the criteria are based on maximum allowable airborne combustible dust mass. Both formulas rely on an empirical entrainment fraction, η_D, representing the fraction of dust accumulations that can become airborne during an accident. After much discussion, the Committee selected a value of $\eta_D = 0.25$ which offers the same level of protection NFPA 654-2006 does for typical occupancies, pending the outcome of this Research Foundation sponsored project.

II. The Fire Protection Research Foundation Project:

The scope of the first phase of the project is limited to a study of those combustible dusts covered under the scopes of NFPA safety standards including agricultural and food processing, combustible metals, wood processing and wood-working, and others. However, since these standards cover dusts exhibiting a wide spectrum of properties, the project results could be extrapolated to most other dusts. The project tasks include:

1) Literature review: An international literature review will be carried out on relevant research and dust explosion incidents focused on those factors which impact the dust hazard assessment, such as dispersibility (entrainability), layer thickness and entrainment characteristics of dust particles, facility geometry and deposition characteristics, etc.
2) Development of a proposed strawman dust explosion hazard assessment method based on those parameters which, if validated, would be suitable for incorporation in NFPA Standards and Codes.
3) Validation plan: A detailed plan for full scale and field testing to validate the assessment method proposed in Task 2 will be developed which include an estimate of implementation costs based on a defined number of dust types. The validation will be carried out in a future Phase of this project.
4) Recommendations on future research required (or potential test methods to be developed) to extend the applicability of the assessment method to other types of combustible dusts.

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The research program is being conducted under the auspices of the Fire Protection Research Foundation and managed by its Executive Director, Kathleen Almand. The Fire Protection Research Foundation is the research affiliate of the National Fire Protection Association. Its role is to provide data to inform the development of national fire safety standards. The Foundation serves as a bridge between the needs of NFPA Technical Committees and the research community through a facilitation and peer review process which will be used for this project. The project is being overseen by a Project Technical Panel consisting of technical experts in the field and members of the NFPA Technical Committees which will ensure the quality of the work and that the work is relevant to implementation in NFPA standards and codes.

This paper reports the work in progress. The equations, analyses and preliminary conclusions presented herein are based on a review of the documents available at the time this paper was prepared, and are subject to change after Project Panel input, or the validation testing which will be conducted during the second phase of this project.

III. An introduction to the New Strawman Methodology

The objective of the method is to estimate the amount of dust that can be removed from dust layers by a primary event such as a pressure vessel burst, or a primary explosion. The prediction will obviously depend on the nature and the strength of the primary event, the air velocity it induces over the layer as a function of location and time, and the resistance of the dust in the layer against entrainment.

Mathematically, if a primary event is capable of inducing velocity u=u(x,y,t) over the layer, and the entrainment mass flux for the particular dust is given by the expression m” = m”(u), then the total mass of dust removed from the layer, M, can be expressed as:

$$M = \int\int\int m''[u(x,y,t)] \cdot dx \cdot dy \cdot dt \qquad (1)$$

Since such a rigorous approach is impractical for the anticipated end users, a simplified approach was sought. The simplification was achieved by narrowing down the initiating events to a few typical primary event scenarios. Additional simplification was achieved by breaking the methodology into several components and further simplifying them. These components include:

- Estimation of threshold entrainment velocity for dust
- Estimation of entrained mass flux
- Estimation of the flow velocity and duration induced by the primary event
- Estimation of total entrained mass

While this approach can result in some loss of generality and precision, its ease of use is obviously a major benefit.

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IV. Estimation of Threshold Entrainment Velocity for Dust

Empirical algebraic relationships proposed by Kalman et al (2005) were selected for use in this phase of the project. Three expressions were provided for different particle size groups, accounting for particle size and particle density. An additional equation was provided to account for the particle shape for the large particle regime.

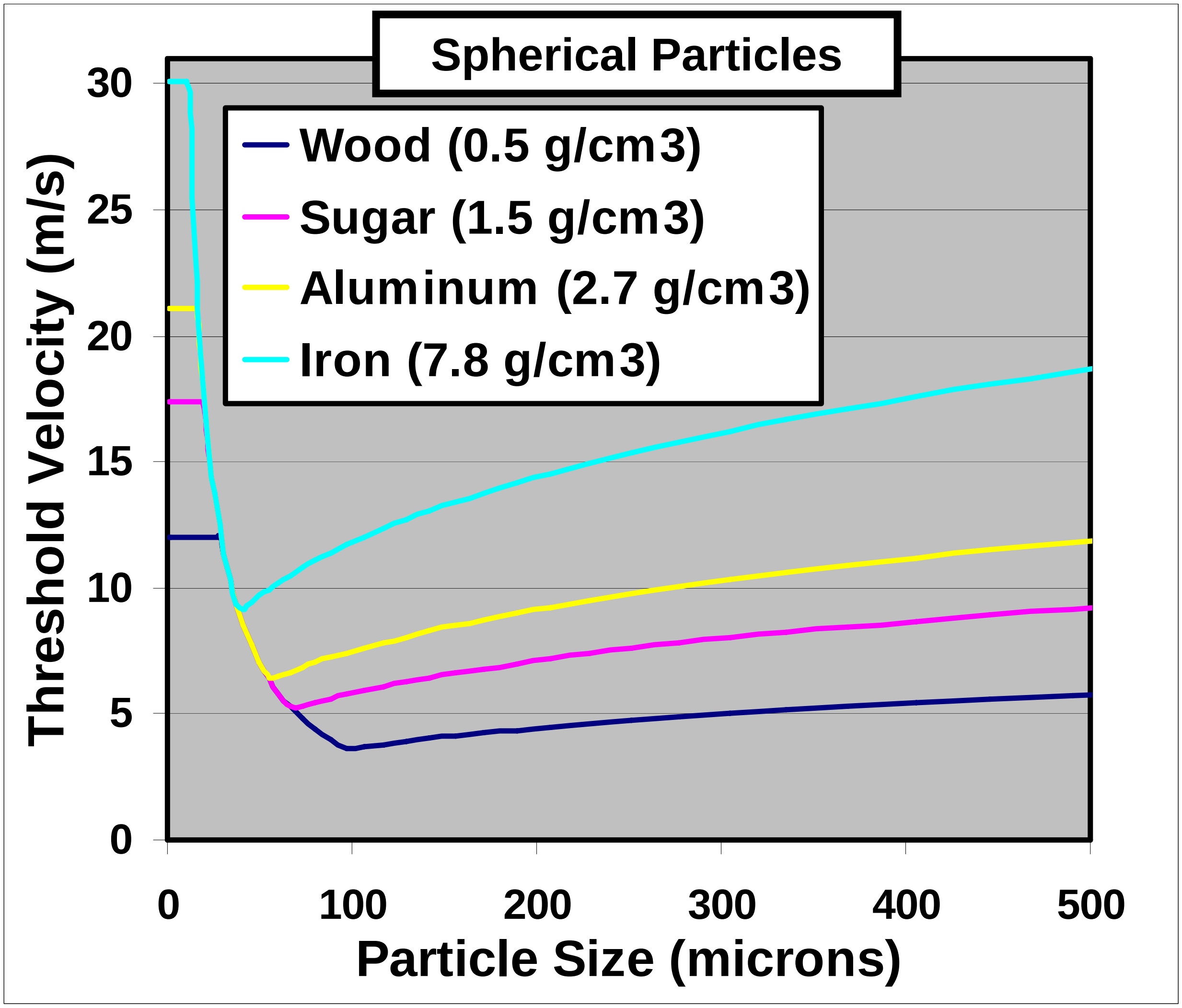

Figure 1. Calculated threshold entrainment velocity as a function of particle size and particle density

The end users of this methodology are expected to refer to a chart similar to that shown in Figure 1, which was created using the Kalman et al equations. For example, if the particular dust were made up of atomized aluminum particles of 100-micron diameter, then no entrainment would be expected so long as the free stream velocity, U_t, over the layer is below 7.5 m/s, as read from Figure 1. Alternatively, the minimum value of the appropriate curve can be used for poly-disperse materials. For nearly spherical particles, the minimum threshold velocity (in m/s) is:

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$$U_t = 0.46\ \rho_p^{1/3} \qquad (2)$$

and it corresponds to the optimal particle size (in meters):

$$D_{opt} = 7.9 * 10^{-4}\ \ \rho_p^{-1/3}$$

Where ρ_p is the particle density in kg/m3. In applications where dust particles are expected to be removed as agglomerates, substituting particle density with bulk density may be more appropriate. Non-spherical particle shapes are treated using a correction factor based on the particle sphericity.

V. Estimation of the entrained mass flux

Inspired by the literature reviewed in the first task of this project, the following equation was selected to estimate the entrainment mass flux[1]:

$$m'' = 0.0017*\rho*U*(U^{1/2} - U_t^2 / U^{3/2}) \qquad U > U_t \qquad (3)$$

where:
m” entrained mass flux in kg/m2-s
ρ gas density in kg/m3
U free stream velocity in m/s
U_t threshold velocity in m/s determined from Figure 1 or Equation 2.

This equation predicts that the entrainment mass flux is proportional to the 1.5 power of the free stream velocity and goes to zero when the free stream velocity approaches the threshold velocity.

VI. Comparisons with Large Scale Explosion Data

The Equations (2) and (3) represent the essence of the new strawman methodology. Their predictions are compared to the available test data in this section.

The National Institute for Occupational Safety and Health (NIOSH), Office of Mine Safety and Health Research (OMSHR) has conducted large-scale dust explosion tests in an experimental mine (Cashdollar et. al, 2010). Before each test, the first 12 m section of the mine gallery, starting at the face (closed end) was filled with 10% methane in air mixture. Test mixtures of coal and rock dust for dust flammability studies were distributed from 12 to 250 meters from the face with a coal nominal dust loading of 200 g/m3. Approximately half of the coal dust and rock dust mixtures was loaded on shelves suspended from the roof with the other half applied to the floor. The methane air mixture was ignited with electric matches located at the closed end of the mine.

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[1] The rate of mass removal per unit area per unit time.

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Based on personal communications with Marcia Harris, a Research Engineer with OMSHR, the dust removal experiments within the NIOSH experimental mine were setup and conducted in the following manner (Harris et. al, 2009). The dust bed for the dust removal tests was prepared at a location 250 ft from the face (ignition end) between two parallel aluminum rails, 1-inch high by 100-inches long, attached to the mine floor 22-inches apart. The dust was placed between the rails and leveled; creating a 1-inch deep layer. Before and after the explosion test, the dust layer depth was measured, to within ± 0.1 mm accuracy, at stations 24”, 36”, 48”, 60”, 72”, 84” and 96”. The difference at each station was attributed to the dust removal due to explosion. Time resolved gas flow velocity induced by the primary explosion near the dust bed was also recorded using a bi-directional velocity probe.

Figure 2 was generated from the gas velocity data logged near the dust bed (containing a 35% coal dust 65% rock dust mixture) during the experimental mine test 511. The dust removal rate (mass per unit area per unit time can be estimated as a function of time, by inserting the instantaneous gas velocity and gas density into Equation (3). Equation (2) estimates the threshold velocity to be 6.4 m/s. Integrating the dust removal rate over time one can obtain the cumulative mass removal per unit area (kg/m2) as a function of time. Dust bed bulk density of 850 kg/m3 was used to convert the cumulative mass removal to dust removal depth shown in Figure 2. Our strawman methodology is seen to predict that the particular explosion created in this test will remove approximately top 2 mm of the 25 mm thick dust bed, corresponding to an 8% entrainment fraction.

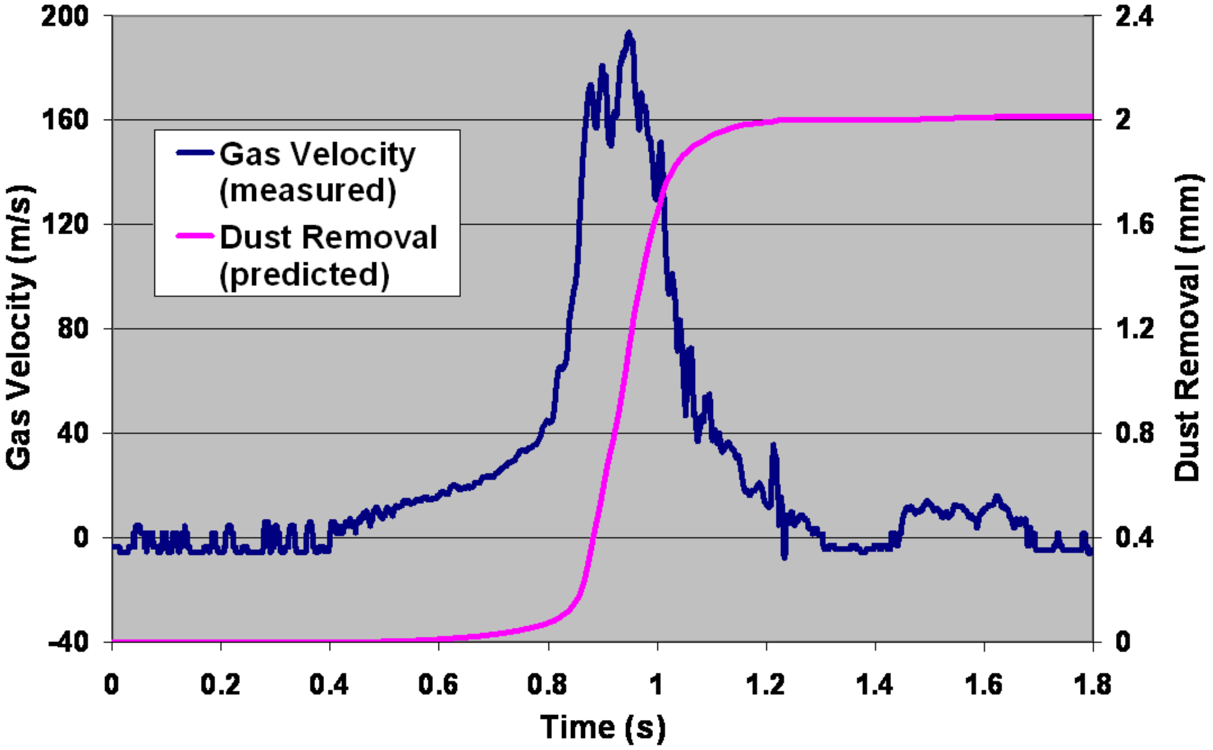

Figure 2. Gas velocity recorded near the dust bed during the experimental mine test 511.

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Figure 3 shows the experimental dust removal depths determined from pre and post explosion depth measurements (Harris, 2010). The strawman methodology is seen to provide a reasonable representation of the data.

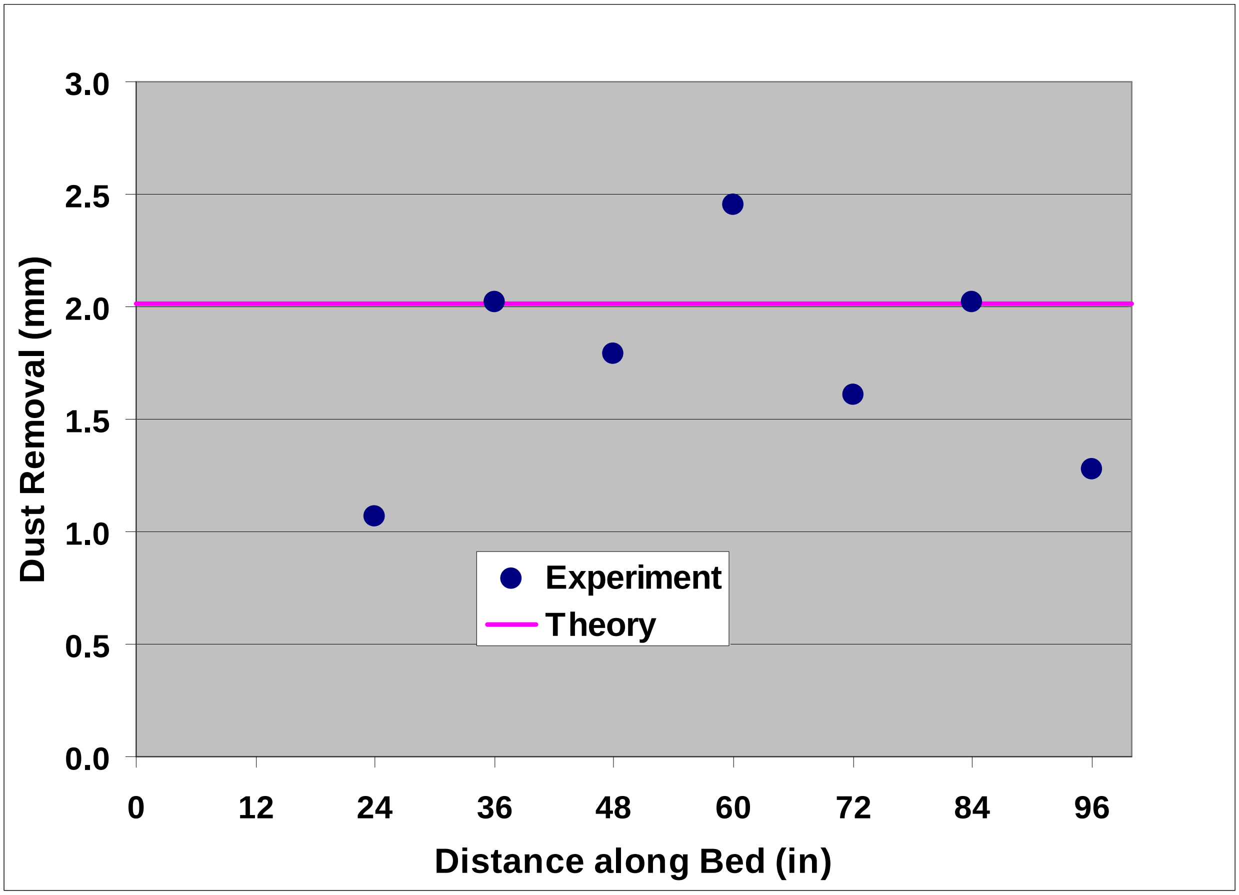

Figure 3. Experimental mine and theoretical dust removal depths for test 511.

Another large-scale explosion study, where the quantity of dust removal was carefully measured, was Tamanini (1983) mentioned above. The tests were conducted in an 8’ by 8’ by 80 feet long gallery connected at one end to a 2250 ft3 chamber. The other end of the gallery was open to atmosphere. Before each test, a uniform layer of cornstarch was laid on the gallery floor using a modified lawn spreader. After each test, the gallery was swept and the dust residue was collected and weighed. Primary explosion was created by igniting a cornstarch cloud (nominally 125 g/m3) formed in the primary chamber. The table below, taken from Tamanini 1983, lists the tests performed, the amount of cornstarch spread over the gallery floor (first column), and the amount of cornstarch picked up (second column) by the explosion, reported as a corresponding average concentration in the gallery.

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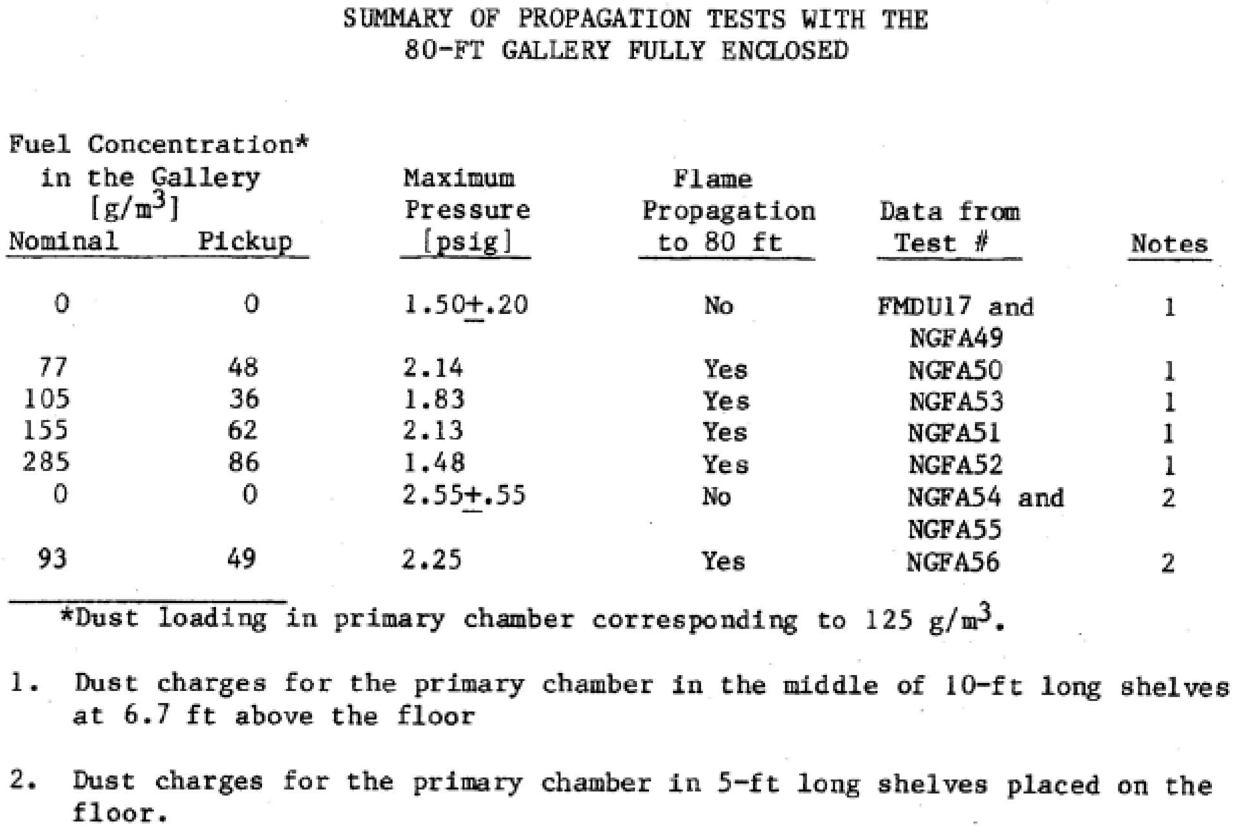

SUMMARY OF PROPAGATION TESTS WITH THE
80-FT GALLERY FULLY ENCLOSED

Fuel Concentration* in the Gallery [g/m^3]		Maximum Pressure [psig]	Flame Propagation to 80 ft	Data from Test #	Notes
Nominal	Pickup				
0	0	1.50±.20	No	FMDU17 and NGFA49	1
77	48	2.14	Yes	NGFA50	1
105	36	1.83	Yes	NGFA53	1
155	62	2.13	Yes	NGFA51	1
285	86	1.48	Yes	NGFA52	1
0	0	2.55±.55	No	NGFA54 and NGFA55	2
93	49	2.25	Yes	NGFA56	2

*Dust loading in primary chamber corresponding to 125 g/m^3.

1. Dust charges for the primary chamber in the middle of 10-ft long shelves at 6.7 ft above the floor

2. Dust charges for the primary chamber in 5-ft long shelves placed on the floor.

The concentrations reported in the first two columns can be converted into layer densities by multiplying them by the gallery height of 8 ft, or 2.4 m. For example, for the last test in the table (NGFA56), 227 g/m2 (i.e. 93 g/m3 X 2.4 m) cornstarch was spread over the floor, and explosion removed 119 g/m2, corresponding to an entrainment fraction of 53%.

Tamanini measured the pressure development in the primary chamber as well as at four different stations along the gallery. The data from test NGFA56 is shown in Figure 4. An examination of this pressure data reveals the following:

- There are no significant differences among the primary pressure pulses experienced in the primary chamber and at upstream stations in the gallery,
- Primary pressure pulse travels downstream at approximately sound speed, and
- The period of the Helmholtz oscillations are substantially smaller than the period of the primary pulse.

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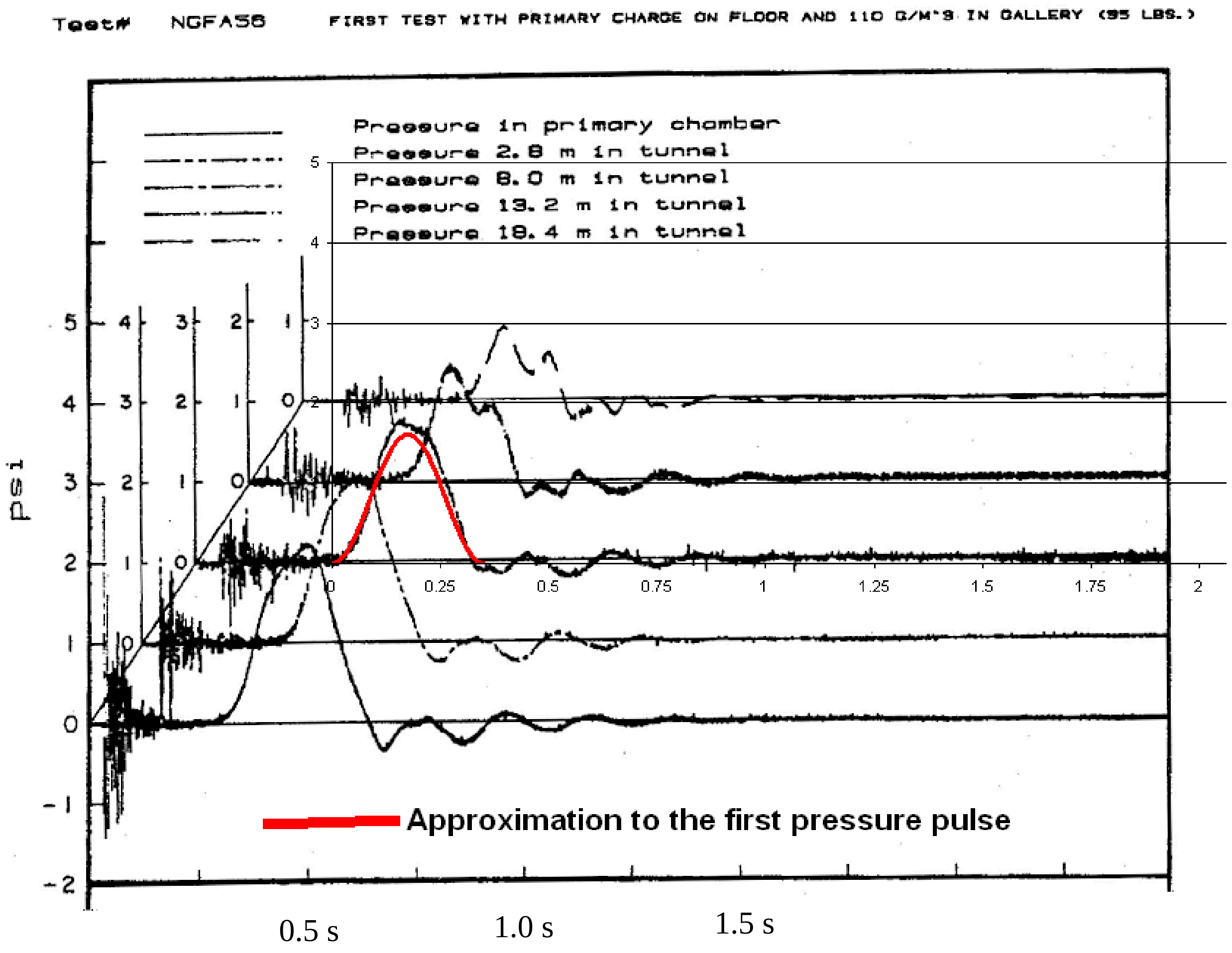

Figure 4. Pressure data from test NGFA56.

These observations suggest that gas velocity in the gallery might be estimated using the acoustic approximation for a simple wave defined by the measured pressure pulse. The red curve superimposed, in Figure 4, on the pressure trace recorded at 8.0 m in the tunnel represents our approximation to the time resolved pressure data in the gallery. For cornstarch, Equation 2 predicts a threshold velocity of 5.3 m/s. Resulting entrainment predictions are compared to the data in Figure 5. The abscissa in Figure 5 corresponds to the peak pressure Tamanini recorded at the 8 m station. The agreement between the data and predictions is encouraging but may be fortuitous owing to the uncertainty in the gas velocity estimation.

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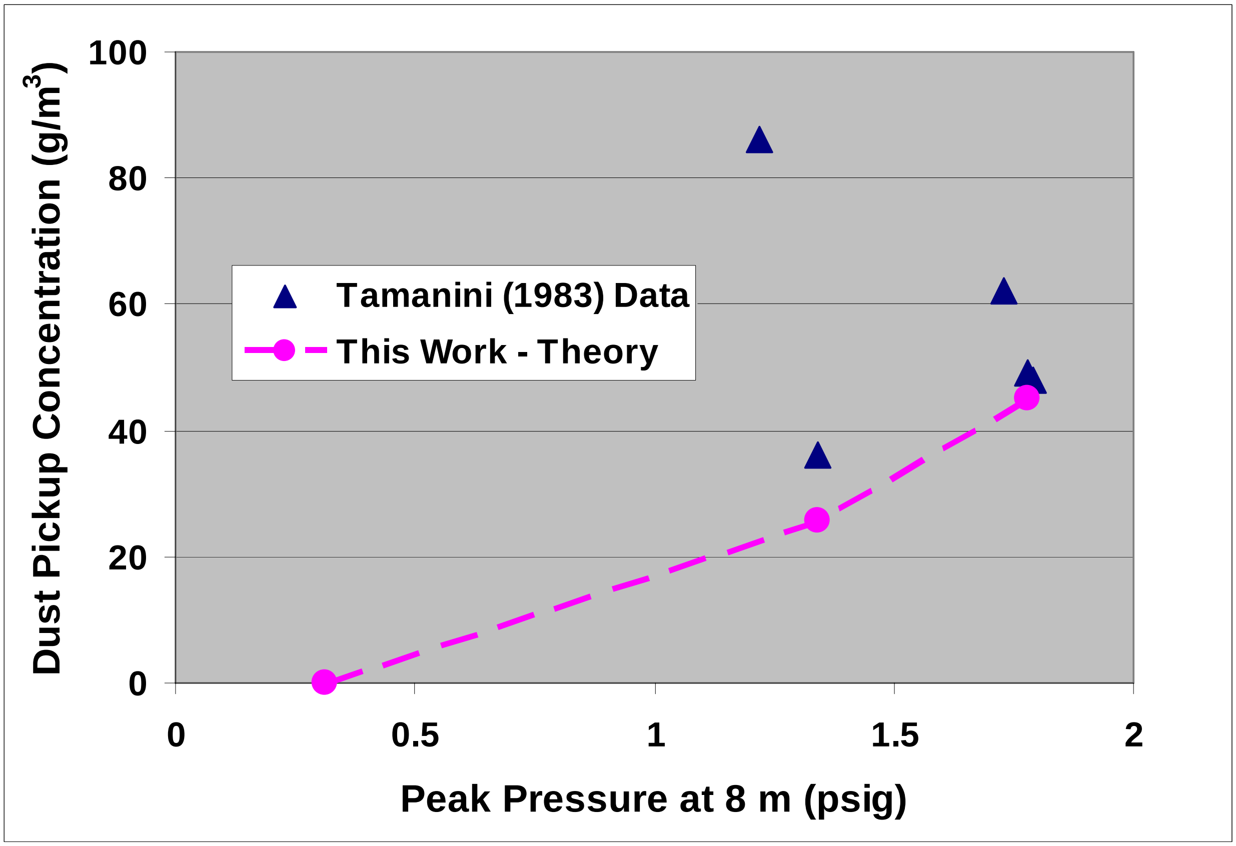

Figure 5. Comparison of the cornstarch entrainment predictions with Tamanini data.

VII. Estimation of the dust entrainment caused by a typical primary event scenario

To demonstrate the use of the new strawman methodology for industrial applications, catastrophic burst scenario of an indoor equipment will be examined here. Assume that a 74 ft3 dust collector sitting on the floor, in the middle of plant bursts at 0.5 barg. The floor of the plant is covered with a thick layer of aluminum dust made up of 100 micron spherical particles. In this scenario, the Baker-Strehlow method for bursting spheres can be used. If the burst is caused by an internal deflagration, the average temperature inside the enclosure depends on the availability of venting prior to burst. In this analysis, the enclosure contents were assumed to be at the ambient temperature and have the specific heat ratio of 1.4 prior to the burst, since this produces results that are more conservative. Effects of any combustion or shock wave reflections after the burst are ignored. For the burst pressure of 0.5 barg, Baker-Strehlow method predicts a maximum side-on pressure of 0.22 barg, approximately one-half of the burst pressure.

Since the dust collector is sitting on the floor, we can approximate the geometry as a hemisphere as shown in Figure 6. The hemispherical treatment accounts for the confinement of the blast wave due to floor by doubling the dust collector size, but ignores effects such as oblique and mach reflections. For the dust collector volume of 74 ft3, then the hemisphere radius is 1 m.

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Figure 7 shows the peak pressure field predicted by the Baker-Strehlow method. The peak velocity field is ideally calculated using the shock relations. However, since the peak pressures are low, acoustic approximation is adequate in this case:

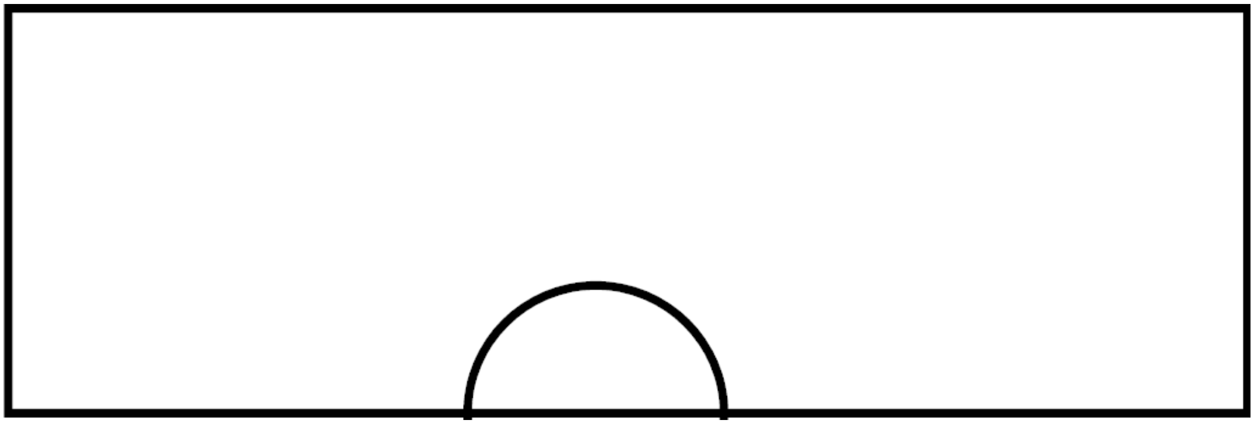

Figure 6. Hemispherical vessel burst in the middle of the plant.

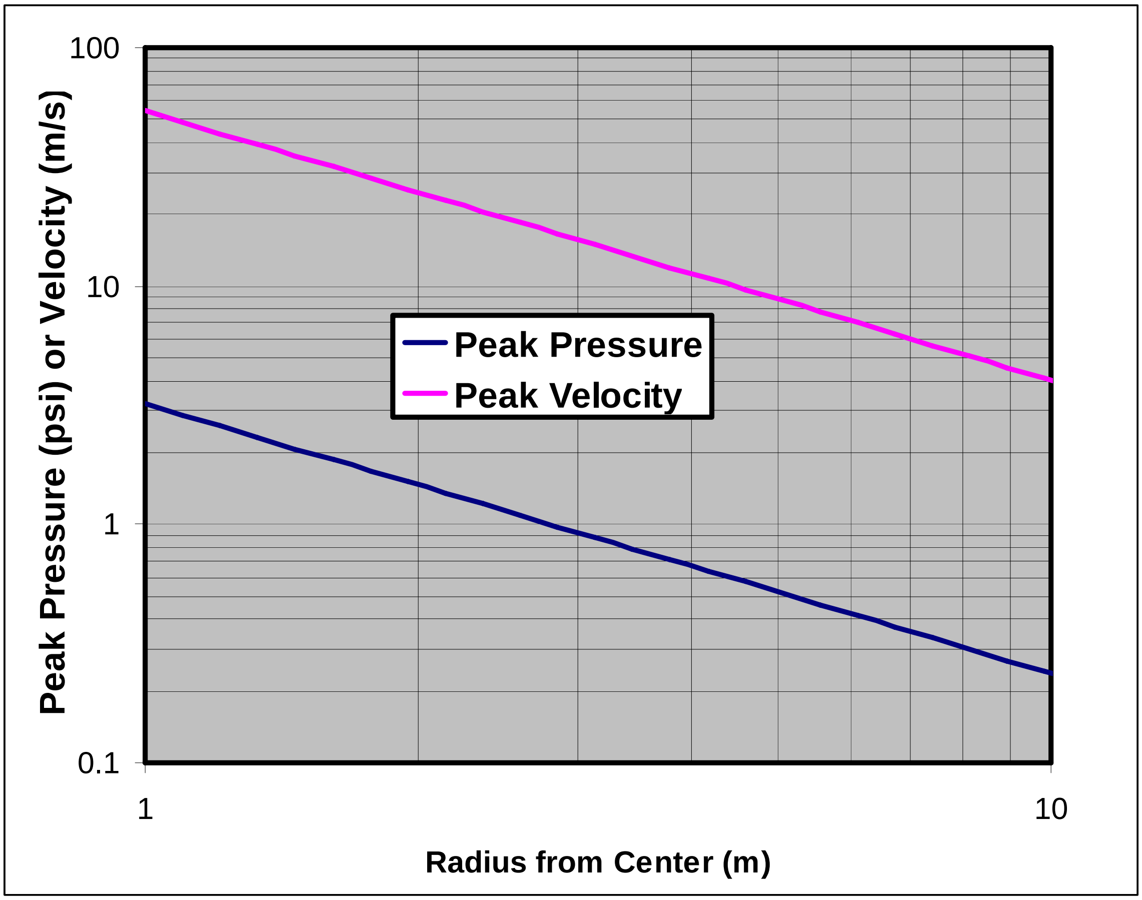

Figure 7. Peak pressure and velocity fields created by a 74 ft3 hemispherical enclosure burst at 0.5 bar pressure.

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$$U = \frac{\Delta P}{\rho \cdot a} \qquad (4)$$

Where:
U=U(r): peak free stream velocity (m/s) at radius r
ΔP=ΔP(r): peak pressure rise (Pa) at radius r
ρ: density of air (1.2 kg/m3), and
a=340 m/s speed of sound in air.

The peak velocity field calculated using the acoustic approximation is also shown in Figure 7. The peak velocity is seen to be equal to the 7.5 m/s threshold velocity, for the 100-micron Aluminum dust example above, at a radius of 5.6 meters. Therefore, beyond the 5.6 m "threshold radius[2]", our methodology predicts no entrainment. Peak velocity never exceed 54 m/s, a value determined strictly by the burst pressure.

Figure 8 shows the local peak entrainment flux calculated using Equation (3).

At a given location, both the overpressure and velocity suddenly jump from zero to their respective peak values, and start decaying exponentially. After a finite period both the overpressure and velocity go through zero and change sign. For the sake of simplicity here, we will assume the peak overpressure and velocity at a given radius remain constant for a finite period. Its duration can be estimated from the peak overpressure and impulse values predicted by the Baker-Strehlow model. Assuming a triangular waveform:

Duration, Δt = 2* Impulse / (Peak Overpressure) (5)

It should be pointed out that this is a very conservative assumption for the dust entrainment calculations. For the present example, a duration Δt = 0.0028 sec is predicted.

Figure 9 shows the local entrained mass per unit area for the 100-micron Aluminum dust, and is calculated by multiplying the flux shown in Figure 8 with the 0.0028 second duration.

Total mass is calculated by integrating the values shown in Figure 9 over the radius and is calculated to be only 7.5 grams. In other words, the new strawman methodology predicts no secondary explosion hazard for this scenario.

VIII. Summary of Conclusions

A simple strawman methodology being developed in the course of the Fire Protection Research Foundation project was described. The methodology appears to provide a good representation of the available test data. Additional tests needed to validate the methodology are being planned and will be carried out in a future phase of this project.

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[2] The threshold radius scales with the cube root of the bursting enclosure volume, and can conceivably be utilized to establish safe separation distances.

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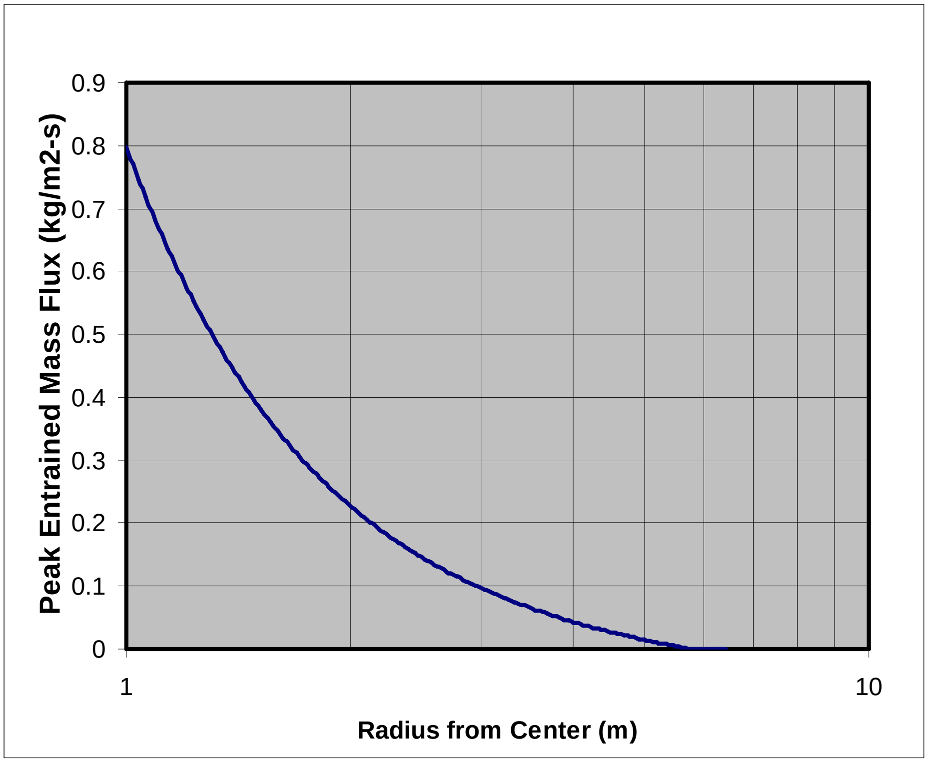

Figure 8. Local peak entrainment mass flux for the 100-micron Aluminum dust

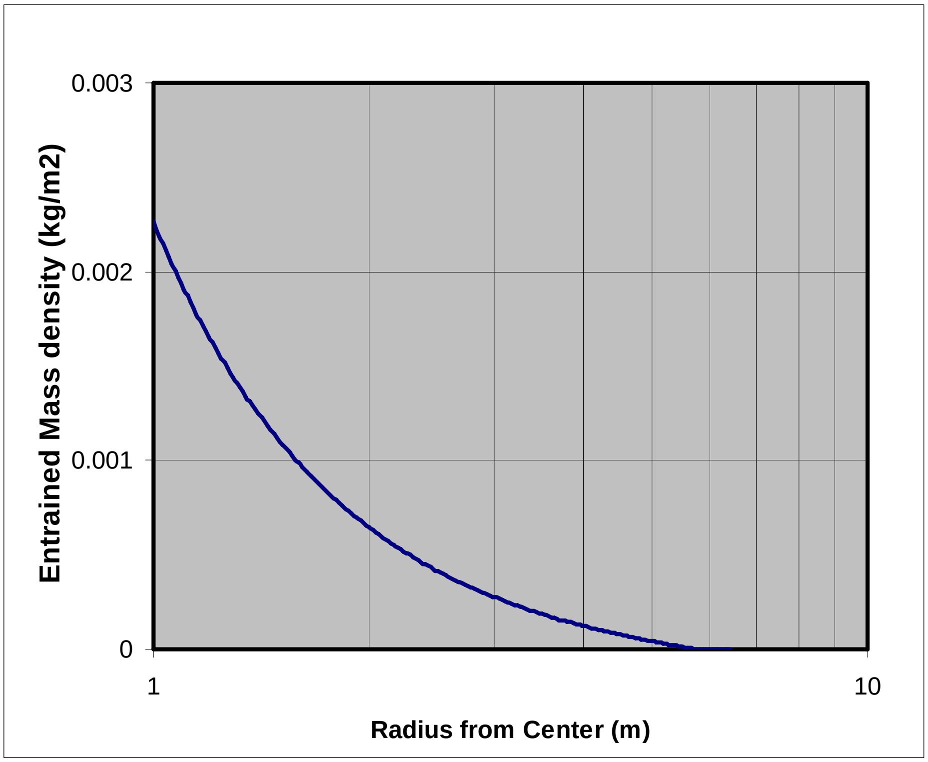

Figure 9. Local entrained mass per unit area for the 100-micron Aluminum dust

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