Preface

This report describes the work performed in the first phase of the Fire Protection Research Foundation project entitled Dust Explosion Hazard Assessment Methodology.

Dust explosions occur only when a number of preceding events take place almost simultaneously. A comprehensive generic chain of events that can lead to an explosion is described in Chapter 17-8 of NFPA Handbook of Fire Protection.

Unless dust is kept suspended in the air by design, most dust explosions start with a disturbance that raises dust into suspension. The disturbance could be as simple as the rupture of a compressed air line, a mechanical jolt to beams where dust layers have accumulated, or a small explosion somewhere else in the plant. Once subjected to the disturbance, the amount of dust entrained (removed) from the deposit depends predominantly on the magnitude and the severity of the disturbance. Other parameters such dust and layer properties can also play a role on the dust entrainment rates.

Once the dust is lifted off from the layer, it mixes with air and can form explosible pockets in the enclosure. The size of the explosible cloud volume is controlled by the dust entrainment rate and the existing air motion in the enclosure (e.g. ventilation/recirculation), or that induced by the primary disturbance.

Once created, an explosible dust cloud can be ignited by a number of possible ignition sources. In critical applications or for hard to ignite dusts, credible strength of ignition sources can be evaluated and compared to the ignition requirement of the particular dust cloud. Though seldom done, such an exercise may reveal whether elimination of ignition sources is a viable prevention method for the particular application. While NFPA standards encourage ignition control to reduce the frequency of the incidents, they generally assume that an ignition source may exist despite the presence of an ignition source control program.

Once ignition takes place, the reaction front (flame) moves into the unburnt dust cloud with a well-defined velocity, called the burning velocity. If the enclosure is practically unvented, the maximum explosion pressure is related to the heat of combustion of the dust cloud. Fully confined deflagrations of dust clouds occupying a substantial portion of the enclosure volume commonly develop pressures in the range of seven to ten times the initial absolute pressure, or 100 to 140 psig (7 to 10 barg). If the enclosure has large openings (deflagration vents), then the maximum explosion pressure is substantially reduced depending on the burning velocity and the maximum flame surface area. Pre-existing turbulence conditions inside the enclosure, turbulence induced by flame propagation, and the geometry of the enclosure can increase both the burning velocity and the maximum flame surface area.

Process enclosures are seldom designed for pressure containment. Pressures at which enclosure failure occurs can be quite low, particularly for enclosures of rectangular sheet metal construction. These can fail completely at internal pressures of a few pounds per square inch. Typically, buildings can tolerate only a fraction of 1 psi pressure.

While properly designed deflagration vents can successfully limit the peak pressure rise to a level that can be tolerated by the enclosure, an explosible dust cloud occupying a substantial portion of the compartment volume is never allowed in occupied enclosures, because it is capable of producing untenable conditions in the entire volume. Combustible dust occupancy standards promulgated by NFPA recognize this fact and impose restrictions on dust accumulations, currently specified as the threshold layer thickness and areas. 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 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 standards or other relevant safety codes. 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 scope of the first phase of the project is limited to a study of those combustible dusts covered under the scopes of NFPA Standards 61, 484, 654 and 664 which include dusts encountered in agricultural and food processing, combustible metals, wood processing and wood-working facilities. However, since these standards cover dusts exhibiting a wide spectrum of properties, the project results could be extrapolated to most other dusts. In fact, large scale test data for coal dust rock dust mixtures as well as sand and soil were used in the preliminary validation of the strawman method described in this report.

As apparent from the objective, the biggest challenge in a project of this sort is to simplify the models to an extent that would be suitable for incorporation in NFPA Standards and Codes. This is a difficult task to accomplish for two reasons:

1) the level of complication that is suitable for incorporation in NFPA Standards is at best a subjective concept, and
2) simplification often comes at a cost of loss of generality, and added conservatism for some applications.

Many valuable discussions with the project panel helped the author develop a strawman method which provides a good balance between the two desirable but competing features: simplicity versus generality.

Acceptable simplicity was achieved by assuming all entrained dust enters into a dust cloud, which is always at the worst-case concentration for the particular combustible dust. The more dust is entrained, the bigger the cloud is. This assumption is conservative but obviates the need for complex tools such as computational fluid dynamics to calculate the development of the entrained dust cloud. This assumption also allows ready use of the partial volume deflagration concepts and equations provided in NFPA 68, a published consensus standard.

Hence, the strawman method is essentially reduced to two components:

a. selection of the types, magnitudes and durations of the maximum credible disturbances
b. calculation of the mass of the dust entrained from the deposits.

The first component depends on the primary event scenarios that are credible for the specific occupancy and are expected to evolve through the consensus process. To demonstrate the concepts in this report, two most common scenarios were selected after conferring with the project panel.

First scenario is the catastrophic burst of indoor equipment. Resulting blast wave propagates over the dust layer and raises all of it or a portion of it into suspension. A worked out example included in the report demonstrates how the amount of dust lifted from the layer can be estimated by relying on published pressure vessel burst nomograms to calculate the magnitude of the air velocity pulse and its duration.

The second scenario is the deflagration venting from a room into a building covered with combustible dust deposits. In the worked out example included in the report, the flow field induced by the vent discharge is approximated by using axial jet correlations, and its duration is calculated using an equation provided in NFPA 68.

The second component of the strawman method is the calculation of the mass of the dust entrained from the deposits. An extensive international literature review was carried out on relevant research on airflow induced dust entrainment rates. Effects of factors such as aerodynamic flow and boundary layer characteristics, dust particle size and shape, and dispersibility were examined. Since the dust entrainment occurs deep in the boundary layer, friction velocity rather than the free stream velocity is the more appropriate parameter to correlate the entrainment rate. On the other hand, most users of the NFPA standards are not anticipated to be versatile in using aerodynamics concepts encompassing the friction velocity. Therefore, an additional simplification is introduced by translating the selected entrainment rate correlation to free stream velocity. The selected equation was also modified for low flow velocities so that entrainment rate tends to zero at the threshold velocity.

The following equation is proposed to estimate the entrainment mass flux[1] until the validation tests are completed in the next phase of this project:

$$m = 0.002 * \rho * U * \left(U^{1/2} - U_t^2/U^{3/2}\right) \quad U > U_t \tag{1}$$

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

where:

m'' entrained mass flux in kg/m2-s
ρ gas density in kg/m3
free stream velocity in m/s
U_t threshold velocity in m/s.

The threshold velocity, U_t, is the minimum air velocity at which dust removal from the layer begins, and it depends on factors such as particle size, particle shape and particle density. The report provides algebraic correlations and charts to estimate this parameter.

Predictions of the strawman method is compared to available large scale coal dust and cornstarch explosion test data. Good agreement was observed. Nevertheless, additional tests are recommended to validate equation (1) further.

The new strawman method described in this report represents a paradigm shift in dust explosion hazard assessment. The approach used in current NFPA standards implicitly assumes that the dust explosion hazard is primarily related to the thickness of the dust layers, or the total mass of the dust accumulations. The new strawman method, on the other hand, primarily determines the maximum amount of dust an initial disturbance can raise into a cloud. If that quantity is large enough to create an explosion risk, then the explosion hazard can still be averted by controlling the amount of dust accumulations.

In other words, the new strawman method is capable of estimating the fraction of the dust accumulations that can become airborne, a parameter also known as the entrainment fraction. Predicted entrainment fraction values range anywhere from zero to one, depending on a number of parameters including dust characteristics, layer thickness, geometry, as well as type, magnitude and the duration of the maximum credible disturbance.

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