Quantifying the Effectiveness of Explosion Protection Measures

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1. INTRODUCTION

In industrial processing of flammable materials there is an attendant risk of ignitions leading to explosion consequences. A key process plant design objective is to minimise the risk and consequence arising from any ignition by the incorporation of efficacious explosion prevention and explosion protection measures.

There exists a substantive literature that details the effectiveness of explosion protection measures and robust guidance that leads to viable and secure explosion safety at the plant component level. Much of this detail is engrossed in our NFPA Codes [1-4] that establish a best practice framework for industry.

In practice design engineers are challenged by the scale of this task – particularly when considering the complexity of many of our industrial processes. The challenge is compounded because the design demand is not always intuitive or apparent. The authors have advocated the use of a risk modelling tool which sets out to quantify and interrogate the standing residual risk that the elected safety measures would fail to mitigate an explosion consequence. This approach can assist practitioners in ascribing efficacious explosion protection.

2. THE CALCULATION TOOL

The calculation methodology and its strict mathematical interpretation has been previously described [5-7] and is summarised herein. It provides for a representation of any process by a set of vertices (the processing vessels) and connections (all of the ducts and communition equipment) between these vertices.

2.1 Directed Graph Representation

Process plants under study are represented by a connected, directed graph [8]. In the representational architecture, each vessel in the system is defined as a vertex. In the event of an ignition, the edges between the vertices represent possible paths of flame propagation (e.g. duct-work between connected vessels). Between any pair of adjacent vertices, there are two directed edges in opposite directions. Each edge is associated with a weighting which represents the directional probability of flame propagating along the connection. Figure 1 shows a schematic of a typical spray drying process which Date et al [7] described to clarify the mathematical basis of this deterministic method. Here a wet dairy product is spray dried, and then passes through two fluid bed driers that further reduce the moisture content of the final product. Dust content in the drying air is separated by a ganged pair of cyclones, and returned via a fines return line to the spray drier.

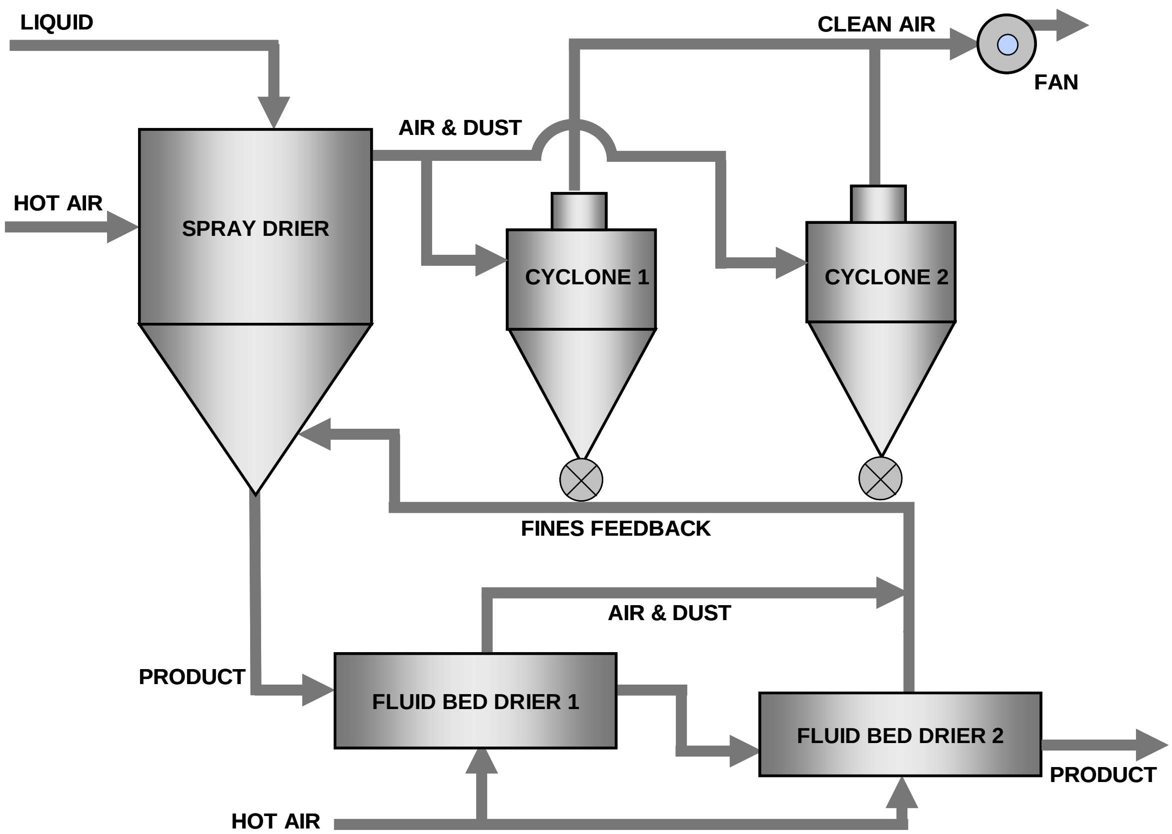

Figure 1: Schematic representation of an example spray drying process. The arrows represent the flow directions through the process plant.

Figure 2 shows the corresponding directed graph representation for this process. Vertices are just abstract representations of the plant vessels, and each vertex has multiple edges.

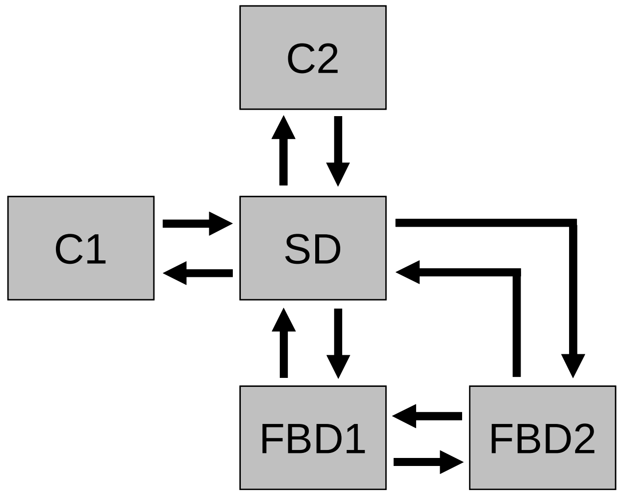

Figure 2: The directed graph representation of the spray drying example. The vertices are labelled according to Figure 1.

2.2 Description of the Calculation Methodology

- The explosion challenge relies on the measured explosibility parameters* of P_{max} and K_{max}, which are considered as representative worse case for the application in question.

- An unmitigated explosion (failure) is defined as any occurrence at any vertex where the reduced explosion pressure, P_{red}, of a suppressed or vented explosion is greater than the pressure shock resistance, P_s, of the plant item – i.e the design inequality $P_{red} \leq P_s$ is **NOT** met.

- Explosion propagation down a connection is considered unmitigated in any occurrence where the elapsed time to establish an explosion isolation barrier, t_b, is greater than the time to transition flame to the barrier location, t_f – i.e. the design inequality $t_b \leq t_f$ is **NOT** met.

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* Industry practice [9,10] is to quantify material explosibility by a measurement of the maximum explosion pressure, P_{max}, and the explosibility rate constant $K_{max}=(dP/dt)_{max}.V^{2/3}$ of a turbulent explosion in a closed volume, V.

- Given an ignition event at a vertex, an unmitigated explosion is assumed to occur when any one component[†] of the explosion protection system fails, be it an explosion vent device, explosion detector, explosion suppressor or control panel. The method uses each component's reported MTBF[‡] (mission critical failures only) as a proxy for their risk of failure.

- The model treats all failures equally and ascribes no consequence specific to the failure scenario. In reality many of the envisioned failures will only represent inconvenience (such as some minor plant distortion) but some would be catastrophic.

- In the cases where there are multiple flame paths between adjacent vessels, these paths are considered independently and the total probability of flame transfer determined by summing over all paths.

2.3 The Calculation Basis (Overview)

Each vessel or plant item i (vertex i) within the process plant, together with its associated explosion protection system is characterised by a set of parameters.

$Q_E(i)$ is the ignition probability in vertex i. For a given process plant and over a given unit of time we assume that $\sum_i Q_E(i) = 1$, i.e. that there will be one ignition occurrence somewhere in the process plant against which we seek to determine the residual risk that the resulting explosion will not be mitigated at one (or more) of the vertices.

The risk of failure of any vertex i due to ignition in vertex j, is denoted $R_{i,j}$ and can be computed as the sum of the risk of hardware failure, $Q_h(i)$, and the risk of inadequate explosion protection (the second term in Equation 1):

$$R_{i,j} = Q_h(i) + (1 - Q_h(i)) \times Q_{vessel}(i,j) \qquad \text{Equation 1}$$

where $Q_{vessel}(i,j)$ represents the proximity of P_{red} to P_s in the system design and accounts for any intentional design safety factors in our computation of residual risk; and $Q_h(i)$ can be calculated from Equation 2

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† Designs with any hardware redundancy require a failure of both components.

‡ MTBF – Mean Time Between Failure

$$Q_h(i) = \alpha(i) + (1-\alpha(i)\beta(i) + (1-\alpha(i))(1-\beta(i))\gamma(i) \qquad \text{Equation 2}$$

The terms in Equation 2 for $Q_h(i)$ represent the hardware failure exposures of vent panels, α, explosion detectors, β, and explosion suppressors, γ as installed as part of the explosion protection measures. $Q_h(i)$ as a whole represents the probability that an unmitigated explosion occurs in vessel i due to hardware failure.

The risk of failure of any vertex due to an ignition in vertex i may be denoted by δ_i and can be computed as:

$$\delta_i = Q_E(i)\left(R_{i,i} + (1-R_{i,i}) \sum_{j\in\Phi_i} Q^s(i,j) R_{j,i} \right) \qquad \text{Equation 3}$$

where Φ_i denotes the set of vertices adjacent to vertex i and $Q^s(i,j)$ represents the total flame propagation probability from vessel i to j and will be dependent on the geometric configuration and the explosion hazard, together with the reliability of any explosion isolation hardware.

Each $R_{j,i}$ is computed using Equation 1. Note that the first term in Equation 3 represents an event where an ignition in vertex i causes an unmitigated explosion in the vertex i and the second term with the summation over j represents an event where there is no unmitigated explosion in vertex i given an ignition in the same vertex, however, the flame propagates to a connected vertex j causing an unmitigated explosion in vertex j.

Instead of computing the “per-ignition” risk (due to ignition in vertex i), δ_i, one may choose to compute the “per-vertex” risk, i.e. total risk of failure in each vertex due to ignition in the same vertex or in any of the connecting vertices. Denoting this risk with ς_i, we arrive at Equation 4

$$\varsigma_i = Q_E(i) R_{i,i} + \sum_{i\in\Phi_j} Q_E(j)(1-R_{j,j}) Q^s(j,i) R_{i,j} \qquad \text{Equation 4}$$

The overall residual risk R can be computed via Equation 5 where we have chosen to sum over ς_i. A summation over δ_i with appropriate inclusion of the probability of failure of the suppression system control panel would yield the same results as Equation 5.

$$R = \sum_j \left\{ \pi(j) + (1 - \pi(j)) \sum_{i \in \Psi_j} \varsigma_i \right\} \qquad \text{Equation 5}$$

where π is the probability of failure of the suppression system control panel. The summation is over all control panel zones and $\Psi_1, \Psi_2, \ldots$ represent the MTBF for each control zone.

Lade et al [6] described a milling process with envisioned explosion protection measures and de-convolutes the residual risk of failure to mitigate using this method, see Figure 3 and Table 1.

For this example we see a well protected plant segment where each of the vertices has an equivalent SIL2 (safety integrity level) or higher rating, but the overall process segment itself is only at SIL1.

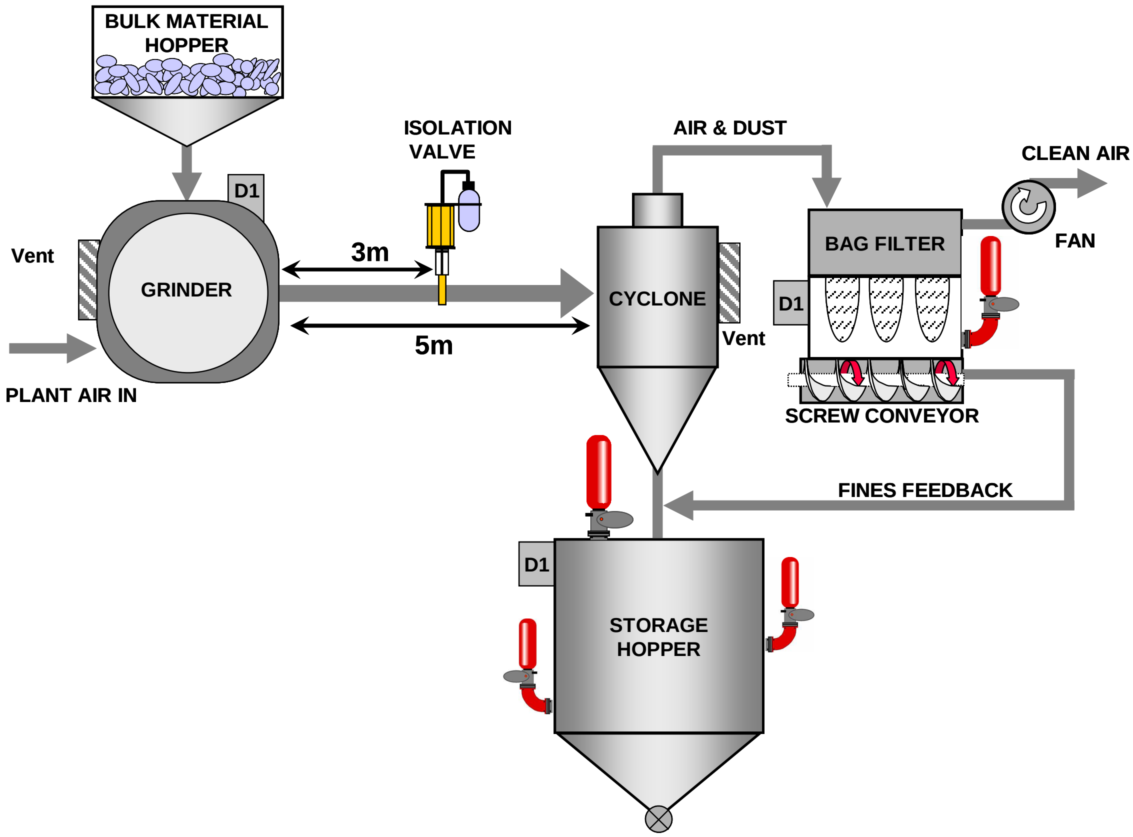

Figure 3: Schematic representation of a milling and collection process [6] with envisioned explosion protection measures. The grey arrows represent material flow through the plant. d represents the installed distance of the isolation barrier from the Grinder.

Table 1: Calculated residual risks all for vertices shown in Figure 3 on a per vertex basis (ς_i) together with the overall risk

Vertex	ς_i **(vertex basis)**
Grinder	2.79×10^{-3}
Cyclone	4.95×10^{-3}
Bag Filter	7.10×10^{-3}
Storage Hopper	5.43×10^{-5}
Overall Residual Risk, R	1.50×10^{-2}

To assist in our appreciation of the value of such analyses, let us consider a plant segment of just two connected vessels as shown in Figure 4 – each with an explosion vent sized in accordance with the prevailing NFPA codes.

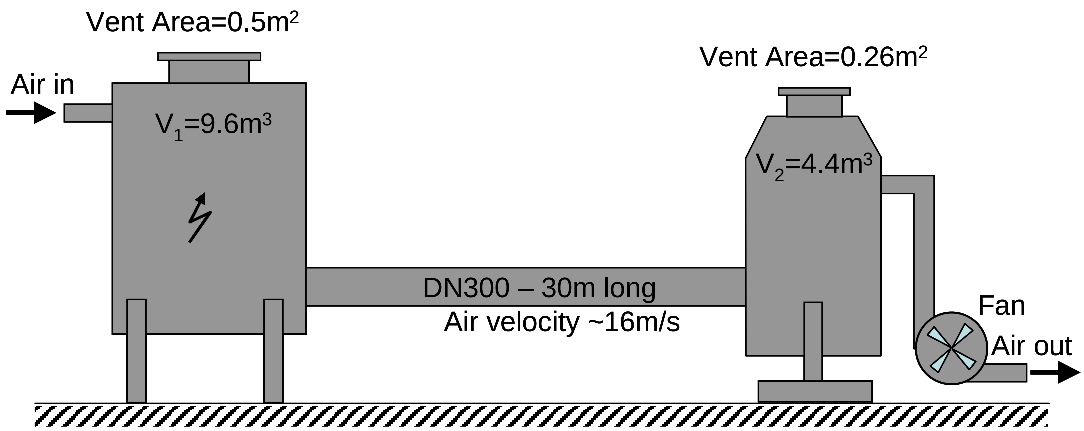

Figure 4: Schematic representation of a 9.6m^3 (V_1) connected via a 30m long DN300 duct to a secondary vessel V_2 (4.4m^3). Both V_1 and V_2 have a pressure shock resistance P_s~0.6bar and vent areas calculated based on a material explosibility of K_{max}=160 bar m/s.

We know that for such a configuration with an ignition in V_1, there is a high risk of flame propagation from V_1 to V_2 [11,12], and that such a connected vessel explosion will result in a very intense explosion in V_2. Strict application of the current explosion venting guidance, however would prescribe a 0.26m^2 vent panel on V_2. Application of the described tool with the datum set of input values to this scenario delivers up a calculated (theoretical) residual risk of the protection (in this case the two explosion vent panels) failing to mitigate, see Table 2.

Table 2: Calculated residual risks for vertices V_1 and V_2 in Figure 4 assuming an equal ignition probability in both vertices.

Plant Component	**Residual Risk** ς_i
V_1	8.7×10^{-2}
V_2	1.1×10^{-1}
Overall Residual Risk, R	1.97×10^{-1}

The overall residual risk that the explosion protection measures fail to mitigate is the arithmetic sum of the risks at each vertex of the plant segment. In this case the analysis teaches that there is around a 1 in 5 chance that any ignition will result in an explosion that is not fully mitigated, which is entirely reasonable because of the high probability of a flame propagation between V_1 and V_2 leading to enhanced connected vessel explosions.

The inclusion of an explosion isolation measure between these two vessels would be expected to significantly reduce this residual risk. Figure 5 shows the application of a triggered extinguishing barrier installed along the 30m interconnection.

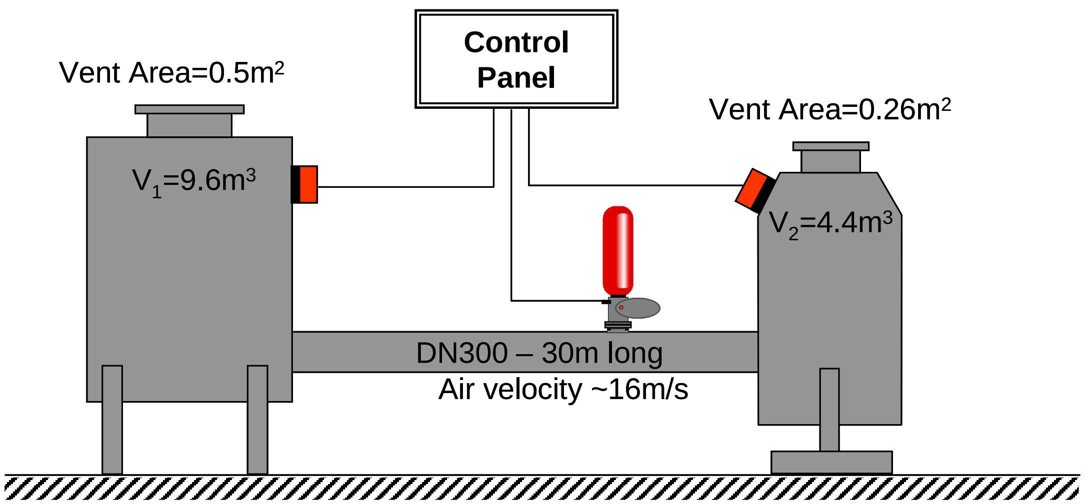

Figure 5: Schematic representation of a 9.6m^3 connected via a 30m long DN300 duct to a secondary vessel V_2 (4.4m^3) whereby pressure detectors are employed to trigger a suppressant barrier on the connecting duct work.

Table 3 shows that this additional explosion protection expedient reduces the residual risk of an unmitigated explosion by almost two orders of magnitude.

Table 3: Calculated residual risks for vertices V_1 and V_2 in Figure 5 assuming an equal ignition probability in both vertices.

Plant Component	Residual Risk ς_i
V_1	1.4×10^{-3}
V_2	1.2×10^{-3}
Overall Residual Risk, R	2.6×10^{-3}

Date et al. [7] analyses a more complex application – the spray drier shown in Figure 1 with the envisioned explosion protection measures and logical zones of protection shown in Figure 6 - deconvolutes risk from a perspective of per ignition in each vertex, δ_i, and per vertex ς_i – see Table 4.

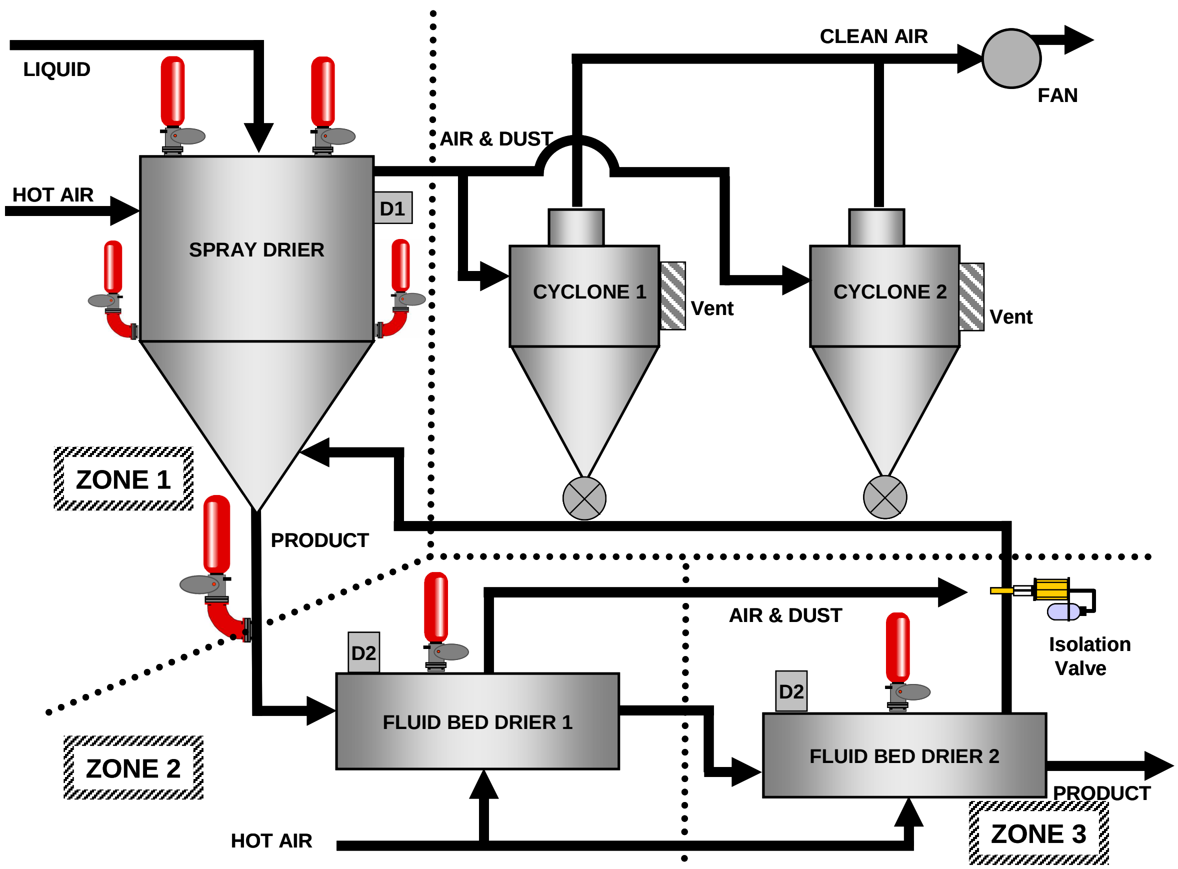

Figure 6: Schematic of a simple spray drier process with envisioned explosion protection measures.

Table 4: Calculated residual risks all for vertices shown in Figure 5 on a per ignition (δ_i) and per vertex basis (ς_i)

Vertex	δ_i (ignition basis)	ς_i (vertex basis)
Spray Drier	3.41×10^{-3}	1.11×10^{-4}
Cyclone 1	6.49×10^{-3}	7.95×10^{-3}
Cyclone 2	6.26×10^{-3}	7.77×10^{-3}
Fluid Bed Drier 1	3.14×10^{-3}	4.64×10^{-4}
Fluid Bed Drier 2	3.14×10^{-3}	4.64×10^{-4}
Overall Residual Risk, R		1.68×10^{-2}

Such analyses are specific to the detail of the process and the pertinence of the input parameters. They can deliver up a systematic de-convolution of the overall residual risk, and can assist in driving down such risk by a relentless pursuit of the higher risk elements of the application.

3.0 CHALLENGING THE IMPLICIT ASSUMPTIONS

If reliance is to be placed on a risk model of this type, then the validity of its assumptions must be understood. The risk model accounts for:

- Hardware failure
- Ineffective protection of vertices – where the design inequality $P_{red} \leq P_s$ is compromised
- Ineffective protection of connections – where the design inequality $t_b \leq t_f$ is compromised

It derives a residual risk that the protection fails to mitigate based on the contributions of the risks of the above, but does not represent any consequence of said failures.

It is clearly the case that a calculation of residual risk is mathematically tractable for any reasonable set of assumptions, and that the value of the output is therefore dependent on the rationale of the assumptions. It is important, therefore, to review the assumptions, consider their validity and their sensitivity to the output projections. The basis of this approach to ascribing efficacious explosion protection is to assume that there will be an ignition occurrence, somewhere in the process segment under consideration, and to use the derived probability that the resultant explosion will not be mitigated as a proxy for ascribing residual risk.

Clearly for any deterministic measure of the exposure it is necessary to condition a derived residual risk by the expected frequency of occurrence of ignitions. This is somewhat intangible. It will be a function of the type of process, the scale and complexity of the process, and the rigour of control and maintenance practices. Ascribing the residual risk that an ignition will lead to an unmitigated explosion consequence is thus just a first step in the determinant. We examine below the assumptions within the calculation method.

3.1 Ignition Location Assumption

The described model considers only ignition scenarios at vertices. Any ignition in an interconnection is expected to become an ignition at one or more vertices, and the outcome (risk of failure to mitigate) is thus the consequence of said ignition(s). This represents a reasonable basis to proceed provided that an ignition in an interconnection will not result in pressure or flame damage to the interconnection prior to its propagation to a vertex. This assumption would breakdown for long interconnections (where flame acceleration could transition to a detonation).

3.2 Ignition Probability Assumption

The described model relies on the historical evidence of ignition occurrences to ascribe the relative probability of ignition based on the vertex duty cycle. Clearly processes vulnerable to mechanical spark, frictional heating and/or glowing ember ignitions have a higher incidence of ignition relative to processes such as dust separation and pneumatic transport. One such approximation extracted from the data reported in [13,14] is shown in Table 5.

Table 5: Normalised ignition probabilities for different generic plant processes.

Process Category	Example Plant	Normalised Ignition Probability
Mechanical working, high speed	Micronisers, Pin mills, Grinders, Hammer mills	31%
Mechanical working, low speed	Communition equipment, Elevators, Fans	25%
Forced heating	Spray, bed, ring dryers, T>100°C	25%
Dust separation	Filters, Sieves, Separators, Classifiers	9%
Pneumatic transport	Cyclones, Transport ducts	7%
Bulk storage	Silos, Bins, Hoppers	3%

Note that this simple treatment makes no allowance for the scale of the respective plant components and also presumes that any ignition is equally probable at all locations within the said component. Risk models would benefit from a more rigorous quantification of ignition probabilities.

3.3 Parametric Uncertainty Assumption

The nominated values of each of the key parameters P_{max}, K_{max}, P_{red}, P_s, t_b and t_f are assumed to represent the 2σ limit value from a normal distribution (i.e. 95% confidence that said elected values are not understated), and the default value for the standard deviation, σ, is set as 10% of the parametric mean.

The examination of representative experimental data sets - in this case the measured explosibility of a turbulent starch dust in a 6.2m^3 vessel, and the suppression of this explosion using a proprietary explosion suppression system[§] demonstrates the reasonableness of this assumption, see Table 6.

[§] Two 16kg explosion suppressors with a 75mm outlet charged with KIDDEx™ suppressant with an actuation pressure of 0.1bar(g).

Table 6: Experimental data for unsuppressed and suppressed high turbulence maize starch explosions in a 6.2m^2 vessel.

	P_{max}	K_{max}	P_{red}
Type of Test	Unsuppressed	Unsuppressed	Suppressed
Number of tests / n	6	6	4
Mean value / x	8.66 (bar)	302 (bar m s^{-1})	0.49 (bar)
Standard deviation / σ	0.21 (bar)	17.7 (bar m s^{-1})	0.07 (bar)
x/σ	2.4%	5.9%	14.8%

It is often the case that the uncertainty in the quantification of pressure shock resistance, P_s, for plant components is greater than this default value, and in such cases practitioners would be advised to elect a more conservative criterion.

3.4 Connectivity Assumption

The risk is computed over all flame paths between each of the adjacent (directly connected) vertices. For each connection there are three alternative outcomes:

- Flame propagates from the ignition location (vertex i) to the connected vertex (vertex j) and causes a sympathetic explosion in the connected vertex that is more intense than would have been the outcome of a point ignition in vertex j. This consequence is referred to as "flame jet ignition" and arises because the connected vertex experiences both pre-compression from the upstream explosion and a jet of flame blasted into the vertex as an ignition scenario [11,12]. The consequence is an intensified explosion that is substantially more challenging for any installed explosion protection on this vertex.

- Flame propagates from the ignition location (vertex i) to the connected vertex (vertex j) with little blast effect and gives rise to a sympathetic explosion in the connected vessel that is no more intense than would have been the outcome of a point ignition in that connected vertex.

- Flame propagation collapses in the connection and there is no sympathetic ignition in vertex j.

The purpose of an explosion isolation measure such as a triggered gate valve or an extinguishing barrier is to minimise the risk of flame propagation, and thus the occurrence of a sympathetic explosion. In the case where such isolation fails because the criteria $t_b \leq t_f$ is not met, the action of the barrier will nevertheless substantially reduce the risk of a flame jet ignition induced enhanced explosion because it reduces the blast impact, and in the case of the extinguishing barrier provies some pre-inerting of vertex j.

Risk models are reliant on the corpus of experimental data, and validated computation fluid dynamic (CFD) modelling tools like FLACS [15] (and the dust variant DESC) to assist in ascribing the flame connectivity expectation. They would clearly benefit from an increased corpus of test data and/or improved CFD treatments. Provided that connectivity assumptions are reasonable, however, risk models can deliver systematic projections of the residual risk map.

3.5 First Order Assumption

The described calculation method considers that for any ignition in a vertex i only the probabilities of an unmitigated explosion at this vertex and in all adjacent connected vertices j, contribute to the risk of failure. Thus the only flame paths considered are those between directly connected vertices.

The calculation method is fully tractable for secondary or tertiary order assumptions. It can be shown that in practice this extension has a minimal impact on the derived residual risks.

4.0 BENEFITS TO OVERALL PROCESS SAFETY INTEGRITY LEVEL (SIL)

Quantifying the efficacy of explosion protection measures and their impact on the residual risk that pertains is complex. The use of a systematic methodology has been described, and the assumptions implicit in such a method explored. Whilst there is a necessity to accept certain assumptions, the method provides a systematic means to permit the comparison between explosion protection options, and importantly, to assist the design engineer to focus on those aspects of any protection system that make the greatest contribution to residual risk. The benefits of explosion protection options are not always intuitive, and by the adoption of a systematic means to ascribe risk better choices are more probable.

It could be argued that the method is restrictive simply because of the disconnect between risk and consequence – clearly the primary aim is not so much to reduce risk of failure but to reduce risk of high consequence failure. To that end it is evident that a quantification of the overall risk, and most importantly the major contributors to this risk, is a valuable step. Moreover, as explained above, the risk determinate does not address the absolute frequency of expected ignition occurrences, and its interpretation must be conditioned by this consideration.

The described method herein permits a means to quantify risk of vertex failure (irrespective of where ignition is envisioned), and can be used to assist in ascribing efficacious explosion protection. In the spray drier example the greatest consequence (both risk to personnel and cost of business recovery) would be substantive damage or destruction of the very large spray drying tower. Although, relative to the risk of failures at other vertices, this is already a low exposure (in this case $1.1x10^{-4}$), it would be prudent to consider actions that could further reduce this contributing risk. In the example, the spray drier is fitted with an explosion suppression system and the key contributors to this risk element will be the hardware's intrinsic reliability and the safety factor between the expected worse case suppressed explosion pressure, P_{red}, and the tower's internal pressure shock resistance, P_s. The former can be addressed by the selection of proprietary hardware that has higher intrinsic reliability and/or by the inclusion of some redundancy. The latter can be addressed by changing the suppression system design to reduce P_{red}, or by specifying/strengthening the tower construction for a higher P_s. Table 7 below shows the theoretical impact of such change options that would form part of the users' final consideration and election of operational practice for this application.

Table 7: Impact of residual risk of the spray drier shown in Figure 6 with re-specification of hardware reliability and re-specification of reduced explosion pressure, P_{red}.

	ς_i
Spray Drier ς_i datum – see Table 4	1.11×10^{-4}
Revision A: Re-specification of explosion suppression system with higher reliability components such that hardware MTBF is increased by factor of 2 on this vertex.	5.55×10^{-5}
Revision B: Re-specification of explosion suppression system such that the expected worse case P_{red} = 50% P_s	7.89×10^{-5}
Impact of BOTH Revision A and B.	3.45×10^{-5}

Interrogating the risk of failure at each vertex assists in opining on consequence. The evolutionary next step for industrial explosion protection would be to migrate today's capability towards an "expert system" design tool that can maximise safety provisions by taking account of both the risks and consequences and deliver up robust cost/benefit projections. The authors contend that this evolution is now within sight.

5.0 ACKNOWLEDGEMENTS

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6.0 REFERENCES

1. NFPA 61: (2008) Standard for the Prevention of Fires and Dust Explosions in Agricultural and Food Processing Facilities, National Fire Protection Association, Quincy, MA.

2. NFPA 654: (2006) Standard for the Prevention of Fire and Dust Explosions from the Manufacturing, Processing, and Handling of Combustible Particulate Solids, National Fire Protection Association, Quincy, MA.

3. NFPA 68: (2007) Standard on Explosion Protection by Deflagration Venting, National Fire Protection Association, Quincy, MA.

4. NFPA 69: (2006) Standard on Explosion Prevention Systems, National Fire Protection Association, Quincy, MA.

5. Ganguly, T., Date, P., Mitra, G., Lade, R. J. and Moore, P. E., (2007), "A method for computing the residual risk of safety system failure" in `Proceedings of 12th International Symposium on Loss Prevention and Safety Promotion in the Process Industries'

6. Lade, R. and Moore, P., (2008), "A methodology to guide industrial explosion safety system design", Hazard XX: Process Safety and Environment Protection' IChemE No 154.

7. Date, P., Lade, R. J., Moore, P. E., and Mitra, G., (2009), "Modelling the Residual Risk of Safety System Failure", submitted to Journal of Loss Prevention.

8. West, D. (2001), *Introduction to Graph Theory*, Prentice Hall.

9. ISO 6184: Parts 1-3 (1985) Explosion Protection Systems – Determination of Explosion Indices of Combustible Mixtures in Air.

10. ASTM E1226, Standard Test Method for pressure and rate of pressure rise for combustible dusts, ASTM International, Conchehocken, PA.

11. Holbrow, P., Andrews, S., Lunn, G. A., 1996, “Dust Explosions in Interconnected Vented Vessels”, J Loss Prevention Process Industries, 9(1): 91-103.

12. Lunn, G. A., Holbrow, P., Andrews, S., Gummer, J., 1996, “Dust Explosions in Totally Enclosed Interconnected Vessel Systems”, J Loss Prevention Process Industries, 9(1): 45-58.

13. Berufsgenossenschaftliches Institut für Arbeitssicherheit – Report NR. (1982) 4/82 Dokumentation Staubexplosionen, Analyse und Einzelfalldarstellung, ISSN 0173-0487.

14. Berufsgenossenschaftliches Institut für Arbeitssicherheit – Report NR. (1997) 11/97 Dokumentation Staubexplosionen, Analyse und Einzelfalldarstellung, ISSN 0173-0387 (ISBN 3-88383-463-7).

15. FLACS: (FLame ACceleration Simulator), (2005) Gexcon AS, Bergen, Norway.