Dust or Gas Explosion: Case Study of Dryer Explosion and Design Venting

Scott G. Davis
GexCon US
7735 Old Georgetown Rd., Suite 1010
Bethesda, MD 20814
sgdavis@gexcon.com

Derek Engel and Olav R. Hansen
GexCon US
7735 Old Georgetown Rd., Suite 1010
Bethesda, MD 20814
derek@gexcon.com and olav@gexcon.com

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Scott G. Davis
GexCon US
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sgdavis@gexcon.com

Derek Engel, Olav R. Hansen
GexCon US

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Abstract

A recent explosion occurred in a single burner, recirculating solids ring dryer. No one was reported injured as a result of the explosion, however the explosion caused significant damage to the dryer and minor damage to sections of the facility. Despite the dryer having been designed with seven explosion doors, the explosion caused a section of the dryer recycle duct to rupture and various doors on the dryer equipment to fail. As a result of the blast, two of the explosion doors on the external ring duct were separated from their hinges, with one landing on the upper roof section, while the other fell back through the roof of the facility in the area of workers. A fire in the various sections of ductwork of the dryer ensued just after the explosion, which caused significant damage to the equipment. Fire suppression efforts using water and foam lasted approximately 2 ½ hours when the fire was ultimately extinguished.

Just after the incident the facility owners thought the accident was caused by a dust explosion, as they recently converted to a new process for treating the solid particulates prior to entering the dryer. Moreover, process data also showed that the explosion occurred seconds after a burner trip when air was being added to the dryer to purge the system. The combustion management system utilized an air-to-fuel ratio controller, along with mass flow meters for both combustion air and the natural gas for the burner. This paper describes the investigation into the cause of the explosion and design blast venting used on the dryer. The CFD tool FLACS was used to help evaluate the consequences associated with a dust or gas explosion during the incident. This included analysis of the process data to determine the gas mixture within the dryer at the time of the explosion as well as dust explosion testing of the solid particles in the dryer in order to evaluate its potential contribution. Finally, the deficiencies were identified in the blast vent design employed on the dryer for deflagrations associated with credible gas or dust explosions.

1. Introduction

GexCon engineers were retained to investigate an explosion that occurred at approximately 3:16 am in a process facility. The explosion occurred in one of two single burner, recirculating solids ring dryers. No one was reported injured as a result of the explosion, however the explosion caused significant damage to the dryer and minor damage to sections of the facility. No one was reported injured as a result of the explosion. All four of the explosion panels on the external ring duct, the two explosion panels on the dryer cyclone header, and the pre-separator explosion panel had opened during the explosion. For the purpose of this study, hinged explosion doors and panels are used interchangeably. In addition, a manual entry door into the hot air box was blown open during the explosion. Two of the explosion panels P1 & P2 (discussed later) on the external ring duct were separated from their hinges, with one landing on the upper roof section next to explosion panel P4 (see Figure 1), while the other panel fell back through the roof of the facility (see Figure 2).

Figure 1: Explosion panel (door) from external ring duct that landed on the upper roof

The explosion also caused a section of the recycle duct to rupture near the 90° turn, which can be seen in Figure 3. Plant personnel heard one large "boom" followed by multiple smaller explosions.

Figure 2: Explosion panel (door) that penetrated the roof

Figure 3: Ruptured section of the recycle duct

A fire in the various sections of ductwork of the dryer ensued just after the explosion and caused significant damage to the recirculating dryer. According to the plant personnel, fire suppression efforts using water and foam started at approximately 4:00 am and continued to approximately 6:30 am, when the fire was ultimately extinguished.

Facility personnel indicated that a new process was recently implemented at the facility. As a result of the conversion, the solid material being fed into the dryer was observed to be finer than that previously used. Management suspected that the dust from the new process contributed to the explosion at the facility. As part of this investigation, we evaluated process data and event historian data, combustion management safety controls, and the possible contribution of gas or dried solids to the dryer explosion.

The paper will first give a description of the recirculating dryer. Due to confidentiality issues associated with the incident, a general model of the dryer that captures the major elements and dimensions will be presented. A brief discussion of the process and burner management will be presented, as well as conditions that existed in the dryer on the day of the incident. Next, the CFD explosion simulator tool FLACS was used to evaluate the possible contribution of gas or dust to the resulting explosion within the dryer. Finally, recommendations regarding the design of the dryer's explosion venting are discussed.

2. Facility Dryer and General Process Description

Figure 4 presents a general schematic of the dryer at the facility. The dryer consisted of a natural gas fired burner around which the recirculating flow passed. The combined combustion products of the burner and recirculating flow mixed in the horizontal section of the ductwork and turned 90 degrees vertically at the hot air box. Solid material is added just above the hot air box and the material is conveyed up to the external ring section of the dryer, which has four hinged explosion panels installed on in this section of the duct (P1-P4). Downstream from the external ring, the material flows to a pre-separator, which removes some of the high moisture content material and re-introduces it into the hot box, and has an explosion panel installed (P5). After the pre-separator, the dried material is removed via the two cyclones (with two explosion doors P6, P7) and the remaining gases are circulated back to the burner. There was another door (P8) provided at the hot box to provide access for cleaning and removing accumulated solid material.

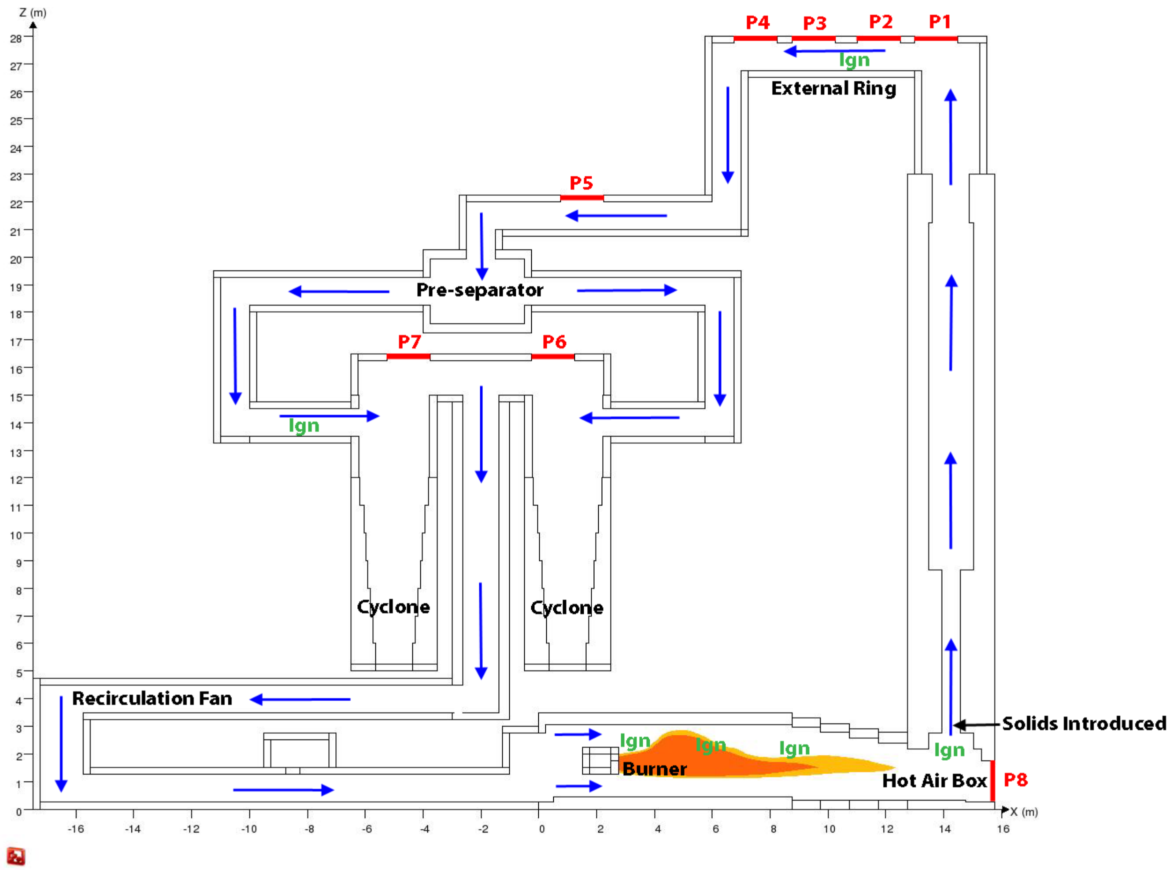

Figure 4: Schematic of facility solids dryer

2.1 Combustion Management for Solids Dryer

A very general description of the combustion management system is provided below. The combustion management system at the facility utilized a ratio controller, which controls the air/fuel ratio to a user-configured set point. The primary process variable is the natural gas flow rate, which is controlled by the process temperature. The combustion airflow is controlled by the air/fuel ratio controller using the pre-configured ratio set point of 15/1. When the natural gas flow rate drops below a user specified value, the combustion airflow rate is no longer controlled to the specified air/fuel ratio but is maintained at a minimum value for safety considerations. This is called thermal turndown and the combustion air will not decrease below this value, irrespective of the gas flow rate.

The combustion air is metered using a mass flow meter, which in turn transmits a signal in the 4 mA to 20 mA range to the ratio controller. The mass flow meter output signal limits of 4 mA and 20 mA correspond to no airflow and maximum airflow conditions, respectively. Based on the measured fuel flow rate, the measured airflow rate and the control condition (thermal turndown or ratio control), the ratio controller will provide an output signal in the 4 mA to 20 mA range to position the combustion air damper. The ratio controller's output signal limits of 4 mA and 20 mA correspond to the fully closed and fully open position of the combustion air damper, respectively.

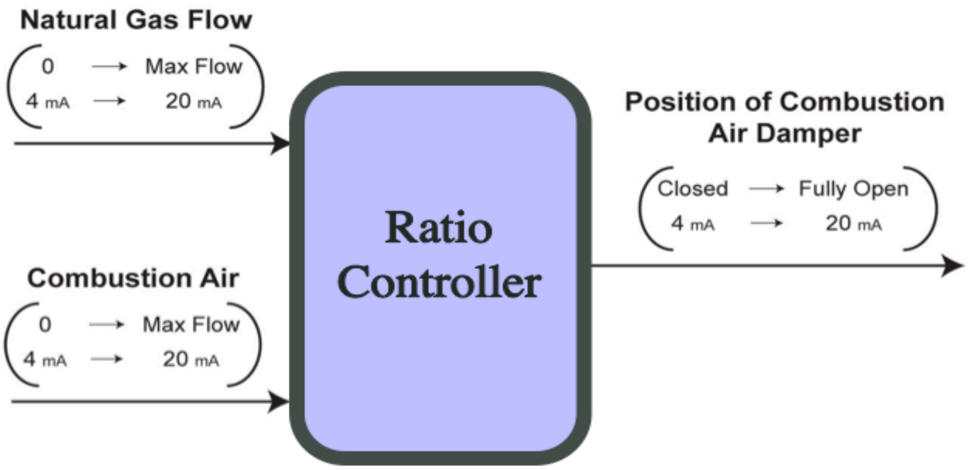

Figure 5: Schematic functionality of the ratio controller

2.1.1 Typical Relight and Burner Data

Figure 6 shows several process variables (gas flow rate, combustion air flow rate, hot box temperature and air/fuel ratio) during a typical relight of the burner in Dryer B. The system is configured for a 10-minute purge period, where the combustion damper is driven to the fully open position and the gas valves are closed, as shown in the shaded areas in Figure 6. The burner is initially relit in a low-fire mode (thermal turndown), where it is maintained for 20 minutes.

After this warm-up period the gas flow rate was increased and product was added to the dryer. As the gas flow rate increased past 18,100 SCFH, the combustion airflow was proportionally controlled to the air/fuel ratio of 15/1. This ratio was maintained fairly steadily while the hot box gradually reached its typical operating temperature of approximately 600 °F. Also shown in Figure 6, is the ratio controller alarm that was specified to activate when the air/fuel ratio drops below a ratio of 10.5/1. To avoid nuisance trips, the air/fuel ratio must remain below this set point for 4 seconds to activate the alarm.

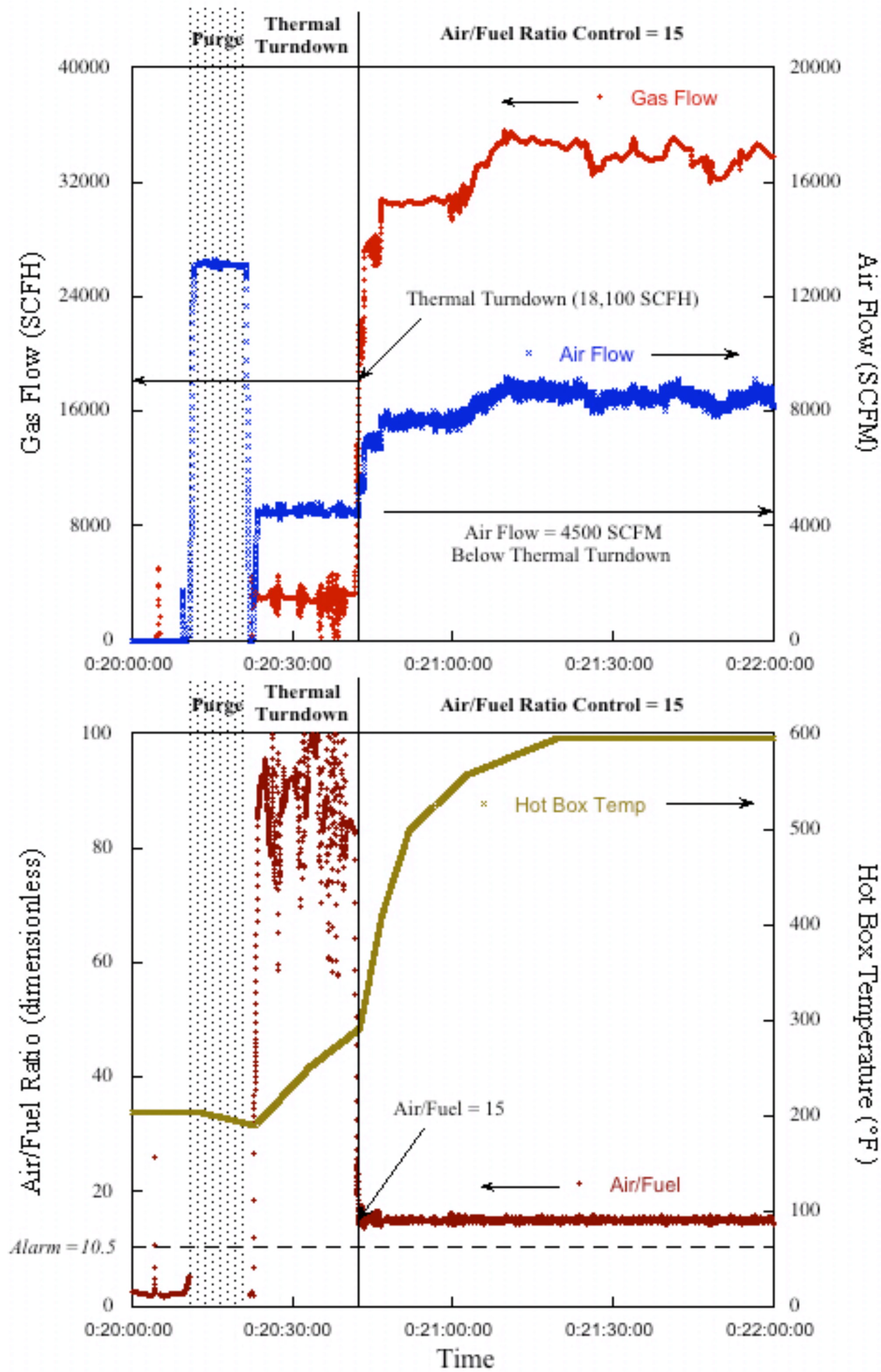

Figure 6: Process data for a typical relight of the dryer

2.2 Process Events Preceding the Explosion

The burner on the dryer was put into purge at approximately 2:51 am, 5 to 6 minutes following a previous burner trip and approximately 25 minutes prior to the explosion. Figure 7 shows several process variables (gas flow rate, combustion air flow rate, hot box temperature and air/fuel ratio) during this particular relight of the burner in Dryer B. Also shown in the top graph of Figure 7 is "Design Air" which is a calculated combustion airflow rate that should have been present during the relight and will be discussed below.

Testing at the facility indicated that the maximum combustion airflow rate when the combustion air damper is fully open is approximately 13,200 SCFM (i.e. during purge period) and is shown by the green line "Design Air" during the purge period. This airflow rate corresponds to a mass flow meter output signal of approximately 18 mA. This means that while the maximum possible airflow rate with the air damper fully open is 13,200 SCFM (as shown by the green line "Design Air" in the purge data), it is below the maximum airflow setting of 15,025 SCFM (20 mA) on the mass flow meter. Therefore during the purge cycle, the data indicate that mass flow meter started transmitting a combustion air signal (in blue) higher than both the maximum possible airflow rate in the dryer (as seen by "Design Air" in the purge period) and the maximum airflow setting of the mass flow meter. During this particular purge period the transmitted combustion airflow signal went as high as 16,621 SCFM, corresponding to an output signal from the mass flow meter of approximately 21.7 mA, which in not only higher than the maximum possible airflow rate of 13,200 SCFM (18 mA) but also higher than the maximum airflow setting of 15,025 SCFM (20 mA) on the meter.

The mass flow meter is designed to automatically check its own operation at timed intervals, and if the diagnostic routine detects a failure in the mass flow meter, the output is driven to either below 3.75 mA or above 21.75 mA, based on its configuration. It was confirmed that the mass flow meter at the facility was set to the default 21.75 mA setting. The 16,621 SCFM (21.7 mA) combustion air signal observed during the purge is consistent with the mass flow meter failing and sending the preset failure mode signal. The gas was maintained at a low firing rate for approximately 10 minutes where the controls would have been in the thermal turndown mode. During the first 3-4 minutes of thermal turndown, the mass flow meter appeared to be functioning properly, resulting in a combustion airflow of approximately 4500 SCFM (consistent with the calculated Design Air). After the initial 3-4 minutes, the data indicates the mass flow meter went into failure mode as observed in the preceding relight. After firing the burner at this low firing rate for approximately 10 minutes, the fire rate was increased.

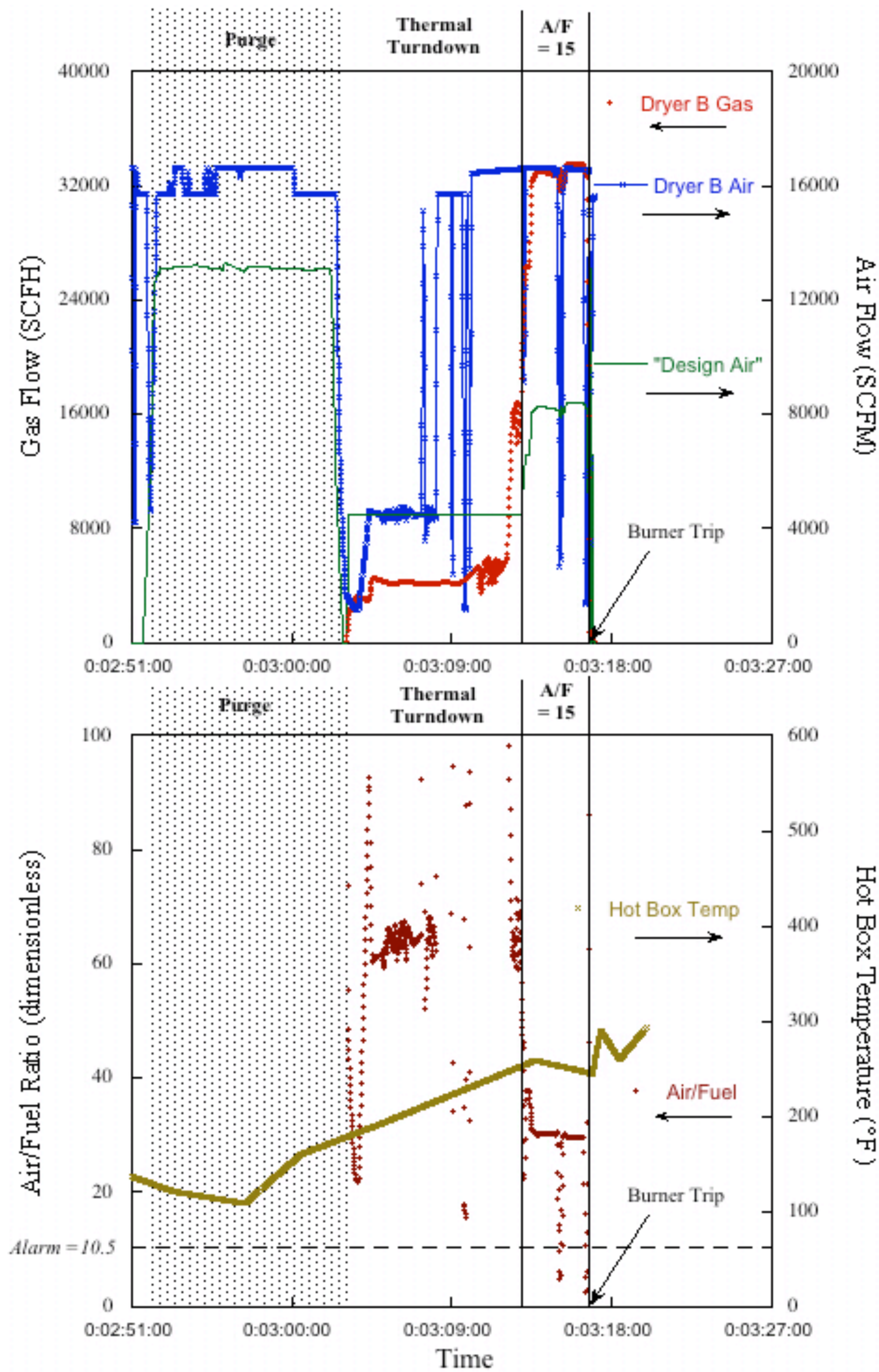

Figure 7: Process data for the 2:51 am relight on the day of the incident

The process data suggests that the mass flow meter continued to fail for about 4 minutes until the burner tripped at approximately 3:16 am. The mass flow meter was not continuously in the failure mode and would occasionally transmit the actual signal. The ratio controller has a programmed over-range alarm programmed into the unit. The over-range alarm was set to activate at signal equal to or greater than 23.5 mA. However, during the failure mode of the mass flow meter during this particular relight, it transmitted signals at approximately 21.7 mA (less than 23.5 mA). When receiving this signal, the response of the ratio controller was to drive the combustion air damper to the closed position in an attempt to maintain the pre-determined air/fuel ratio set point.

Despite the possibility of the recorded process data not capturing all the details of the combustion air, it did record on at least three occasions when the mass flow meter was operating and the air/fuel ratio dropped below the alarm setting of 10.5/1. For the first two occasions, the data indicates that the alarm did not activate because the mass flow meter did not stay in this mode for 4 seconds. Before 4 seconds had passed, the mass flow meter went back into failure mode and transmitted a combustion air signal of approximately 21.7 mA, thus resulting in artificially high air/fuel ratios. Right before the burner trip, the recorded air/fuel ratio dropped as low as 2.4, corresponding to an equivalence ratio of 4.1 or an extreme fuel rich condition. Fuel rich conditions lead to incomplete combustion, including unburned natural gas, hydrogen and carbon monoxide. If the recorded signals from the mass flow meter are valid, extreme fuel rich conditions led to unburned natural gas, hydrogen and carbon monoxide being circulated in the dryer in an oxygen-starved environment.

According to the process data log, the dryer was put into cool down mode approximately 3 seconds after the burner tripped. In this mode, the combustion air damper was driven to the full open position, adding air to the oxygen-starved environment filled with incomplete combustion products, such as, unburned natural gas, hydrogen and carbon monoxide. Approximately 8 seconds after putting the dryer into cool down mode the historian log recorded the near-simultaneous opening of the four explosion doors on the external ring (P1-P4) and two explosion doors on the cyclone (P6-P7). The explosion door on the pre-separator (P5) opened approximately two seconds after the other doors. This is consistent with the explosion doors attempting to vent the resulting overpressure due to the deflagration in the dryer. One interesting observation is that P5 opens at nearly the same instant as when one of the cyclone doors closes, then P5 closes 0.3 seconds later. There are two possible explanations for this phenomena: (1) the explosion panel switch “stuck” and did not record the opening of P5 at the time P1-P4 & P6-P7 opened or (2) there was a weak overpressure that barely opened P5 and soon after closed.

Assuming the recorded signals from the air mass flow meter are valid, there is strong evidence to suggest that the addition of air to the extreme fuel-rich (oxygen-starved) conditions in the dryer ultimately resulted in a mixture within the flammability regime and ignited. While the most likely ignition source was the hot surfaces around the burner section, smoldering material that accumulates on the sides of the duct are also known to flare up as air is added back into the dryer. Another possible, yet less likely scenario, involves a malfunction of the burner management system that allowed for inaccurate recordings of the mass flow meter. Therefore there is a remote possibility that the dryer burner tripped for some other reason and a dust explosion occurred during the purge of the dryer. The CFD explosion and dispersion simulator FLACS was used to evaluate both potential explosion scenarios. These explosion analyses are presented next.

3. Evaluating Explosion Scenarios in the Dryer

The explosion scenarios were evaluated using CFD tool FLACS [1, 2, 3], which can evaluate the explosion dynamics and venting within process equipment for both gas and dust explosions. FLACS has been continuously developed since 1982, and is today a leading CFD-tool for vapor cloud explosion modeling. Dust explosions are modeled using the DESC module of FLACS [4, 5]. In addition to evaluating the actual explosion itself, FLACS was used to evaluate the flow conditions and product distribution within the dryer just prior to ignition using the dispersion models.

In order to evaluate the dynamics of the explosion and explosion venting, key parameters of the explosion panels had to be included in the simulations. Hinged explosion panels can be specified in FLACS (shown in Figure 4), where the time dependent vent area is calculated based on the momentum of the venting flow and the specifications of the explosion panel. The facility owner provided the weight of each panel and the static opening pressure was estimated to be approximately 50 mbar. For the incident dryer, the maximum design pressure allowed during deflagration venting was not provided and recommendations provided by NFPA 68 *Guide for Venting of Deflagrations* were used in the present study. Per NFPA 68, the maximum pressure (P_{red}) allowed during deflagration venting of gases or dusts in ducts operating at or near atmospheric pressure is 170 mbar (2.5 psi). In addition, the static opening pressure for explosion vent panels should be as far below P_{red} as practical and consistent with operating pressure, but be at least 50% lower than P_{red} or 85 mbar. For the given flow conditions within the dryer, it is estimated that stagnation pressures in the bends could reach as high as 20 mbar (not including the solids). We therefore assume 50 mbar as the static opening pressure for the explosion panels (P1-P7).

The first scenario that was evaluated was the gas explosion case, where the recorded process data is assumed to be an accurate representation of what occurred on the day of the incident. The second scenario assumes that the burner management systems failed for another unexplained reason and the explosion was caused by an accumulation and ignition of dust that occurred at the time of air purging during the relight sequence. In addition to evaluating the worst-case dust concentrations that could have existed at the time of the incident, we also evaluated the dryer explosion vent design with respect dust explosions in general.

3.1 Gas Explosion Scenario

As previously stated, the recorded process data indicates that the mass flow meter had failed, causing the ratio controller to close the combustion damper. The last recorded air flow measurement indicated the burner was operating at a very fuel rich condition (equivalence ratio of 4.1), which resulted in unburned natural gas, hydrogen and carbon monoxide to be circulated in an oxygen-starved environment.

It is assumed that the dryer had been operating near these conditions for quite some time, hence a near homogenous mixture of products were being circulated throughout the dryer. After the burner tripped, the combustion air damper was opened to a maximum for approximately 8 seconds prior to the explosion panels opening. The details of how the resulting gas cloud was estimated are presented next.

3.1.1 Gas cloud estimate

To estimate the chemical composition that would have been present within the dryer prior to the burner trip, the STANJAN equilibrium code was employed. We assumed that the entire fuel-rich mixture (equivalence ratio = 4.1) was allowed to react to equilibrium. In addition, facility records indicate that a certain amount of air leaks into the dryer (suction side of the recirculation fan), as the oxygen levels are typically 3% higher than expected during normal operation. The gas mixture employed in the present paper that was used to estimate the mixture being transported in the dryer prior to the purge is given in Table 1.

Table 1: Estimated gas composition within the dryer (prior to purge)

Species	Composition of gas in dryer (ER = 4.1)
Hydrogen (H_2)	23.7%
Oxygen (O_2)	3.0%
Water (H_2O)	2.3%
Methane (CH_4)	5.0%
Carbon Monoxide (CO)	10.7%
Carbon dioxide (CO_2)	2.3%
Nitrogen (N_2)	53.0%

As nitrogen from a reaction product cannot easily be input into the gas cloud mixture in FLACS, it was replaced by approximately 75% water by mole. Given nitrogen and water are essentially inerts for combustion processes and that water has a slightly higher heat capacity per mole than nitrogen, this change should have a negligible effect on the reactivity and explosion results.

This gas mixture would have been present throughout the dryer as the recirculation dryer remained in operation after the burner trip. For the simulations, the gas mixture was allowed to circulate for approximately 30 seconds to establish a fully developed flow field within the dryer prior the air purge. The temperature measured in the dryer at the hot air box was approximately 250°F (121°C) at the time of the incident and this temperature was used for all simulations. After 30 seconds air was introduced through the burner at a rate of 13,200 SCFM, corresponding to the air damper being fully open (purge). Air was introduced for approximately 7-8 seconds, after which the mixture was ignited and the explosion was modeled.

In Figure 8 the development of the gas mixture during the 8-second air purge is shown. Initially the whole system is filled with a fuel-rich composition with approximately 10 times more fuel than optimum for combustion. The gas mixture, with large fractions of hydrogen and CO, is estimated to be flammable at equivalence ratios (ER) from 0.5 (the lower flammability limit – LFL) to 4.7 (the upper flammability limit – UFL). The highest burning velocity is estimated to occur at ER=1.5. For concentrations near the flammability limits (e.g. ER above 3.5) one can expect quite slow, if any, flame propagation, which will likely be dominated by the strong circulation flow of the dryer system. The high turbulence levels within the dryer may also prevent ignition of such weakly burning mixtures. As the air purge continues, the equivalence ratio continues to decrease. Once the ER is approximately 3 or below more reactive mixtures that that could pose an explosion risk are expected.

As the air purge at the burner is initiated, the simulation results shows a small air pocket downstream of the burner that quickly gets diluted to non-flammable or barely flammable concentrations. Once this barely flammable plug of gas (that has the additional air from the purge) has circulated one loop in the system and starts receiving air injected from the purge for the second time, a much more reactive pocket of flammable fuel-air is formed. Both from process data and the simulation results, it can be seen that it takes approximately 6 seconds for the flow within the dryer to complete one loop in the system. The simulations show that the highly flammable pocket of fuel-air grows rapidly after 6 seconds. The explosion takes place approximately 8 seconds after the air purge at the burner is started. However, if ignition had been further delayed to say 10 seconds, a much larger flammable gas cloud would have been present and a much stronger explosion could have occurred. In Figure 9 the development of the flammable cloud downstream of the burner air purge is shown for the studied ignition locations.

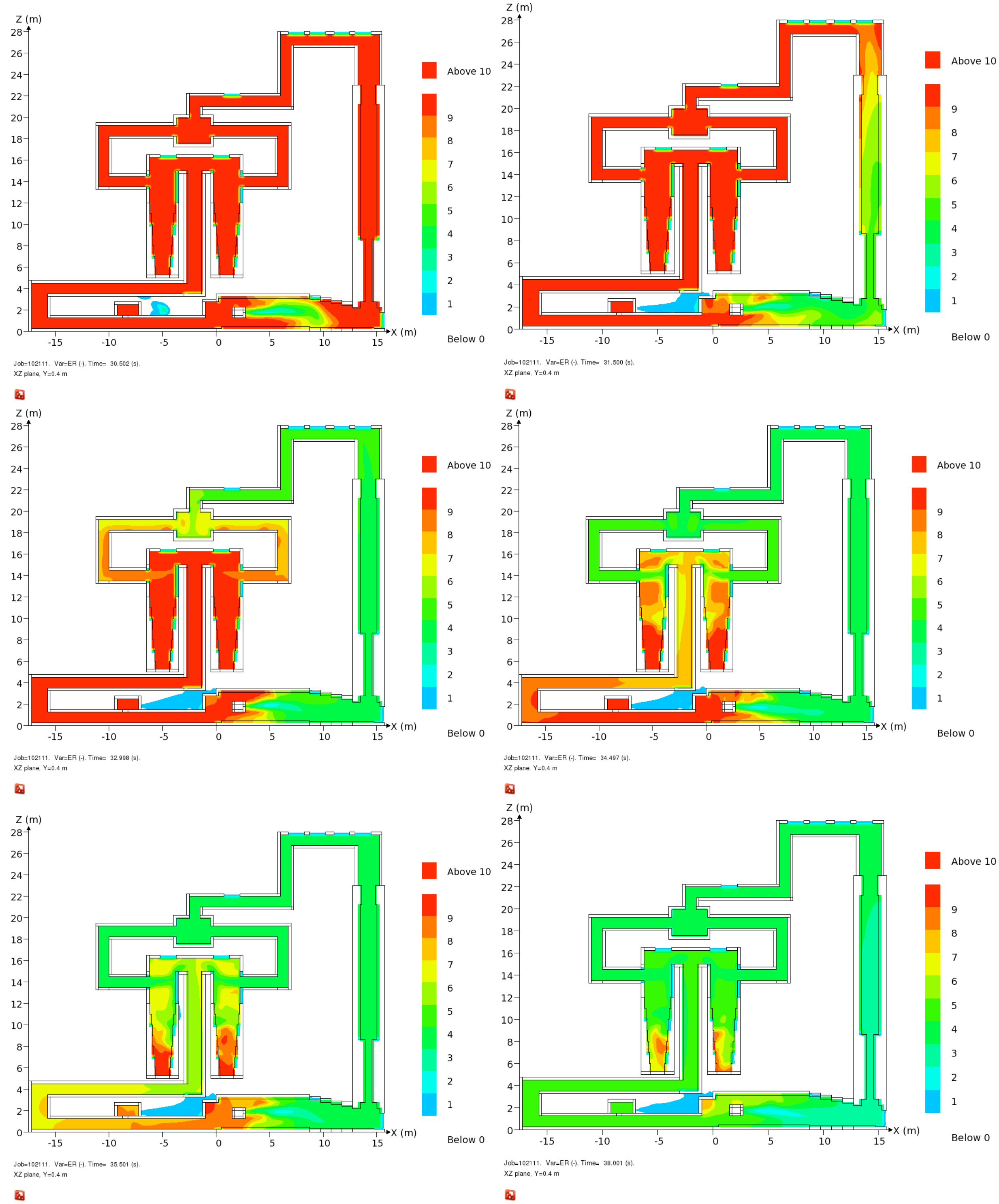

Figure 8: Simulated fuel-air ratio (equivalence ratio) in system during 8 seconds of air purging (starting at time=30s). The estimated flammable range for the actual mixture is from ER=0.5 (LFL) to ER=4.7 (UFL)

While the current simulations confirmed the formation of a highly flammable pocket of fuel-air, the next step will be to ignite some of the simulated mixtures to see if the flame and pressure development can explain the observed damage and explosion panel behavior. Of particular interest is the observation about explosion panel opening times, as panels 1-4 and 6-7 opened almost simultaneously, whereas there was a delay to the opening of panel 5. In addition, significant damage to the recycle duct was observed, which is located a small distance upstream of the burner. Since the flammable gas cloud for the incident time scales (6-8 seconds) will be located mainly downstream of the burner (initially between the burner and hot box and later in the duct towards the external ring panels 1-4), and the burner itself is one of the more likely sources for ignition, this may limit the number of scenarios to be studied.

For the given incident, the gas cloud should not be too large, as this would cause more damage to the dryer than what was observed, and would also result in the opening of explosion panel 5 shortly after panels 1-4. Furthermore, both the observed damage upstream of the burner and the fact that explosion panels 6-7 at the cyclones opened nearly simultaneously to panels 1-4, would require that the “origin” of the strong flame acceleration is some distance slightly downstream of the burner. Alternatively, if the explosion would initiate right at the burner, the directional effect of the explosion would make it hard to explain the damage and panel opening sequence upstream of the burner. Still the ignition source could originate right at the burner, but the initial flame development may be slow leading to stronger flame propagation some moments later when the flame ball has been transported a few meters downstream of the burner.

There are some uncertain parameters in the present work, yet the ignition appears to have occurred approximately 7.5 to 8.0 seconds after the burner air purge was initiated. While the ignition location is in the region downstream of the burner, its exact location is not known. In addition, small deviations exist in our modeled dryer (e.g., definition of bends) and there are uncertainties associated with the exact composition of the gases circulating within the dryer. Therefore, we also evaluated small deviations in ignition time compared to observed times. More specifically, we evaluated a few different ignition locations and ignition times to see if ignition scenarios can be determined that partly or fully explain the observed damage level and sequence of explosion panel opening. One additional parameter that is not known is the opening characteristics for the access door in the hot box (P8). If this door is stronger than the vent panels this can have a significant effect on explosion pressures since the door is very close to the assumed gas cloud location and ignition. For most cases, this door has been assumed to have the same strength as the explosion panels (50 mbar), but sensitivity calculations have been performed with a higher opening pressure (100 mbar).

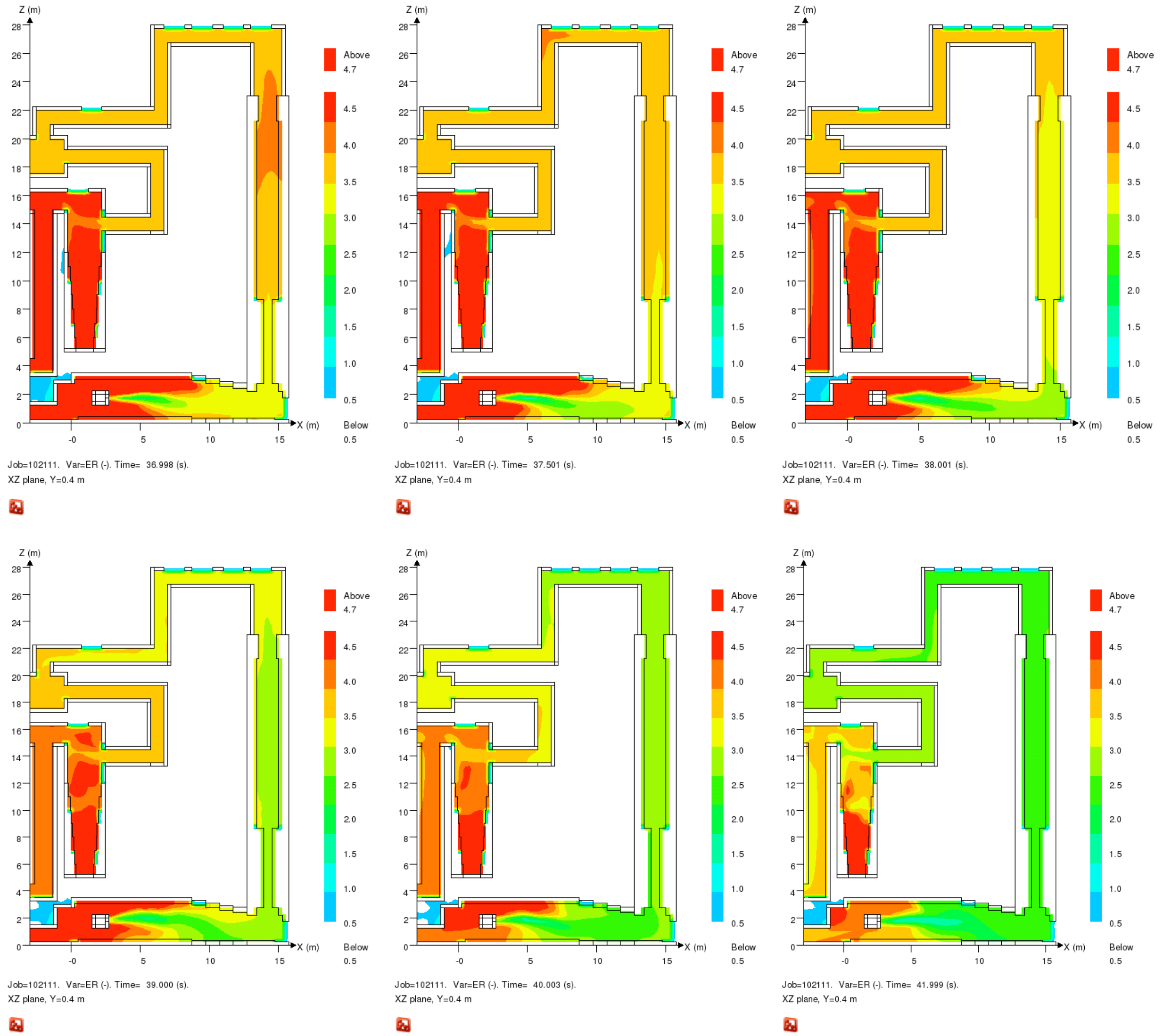

Figure 9: Gas cloud concentrations downstream of air purge location at different studied ignition times, 7s, 7.5s, 8.0s, 9.0s, 10s and 12s. The estimated flammable range for the actual mixture is from ER=0.5 (LFL) to ER=4.7 (UFL)

3.1.1 The study of ignition scenarios at different times

Given that ignition likely took place in the region between the burner and hot box, a number of ignition scenarios were simulated (see Figure 4). Ignition locations near the burner (2.5m, 5m, 10m) and more downstream of the burner were studied. For selected scenarios the strength of the access door to the hot box was increased from 50 to 100 mbar to see how this would influence the explosion development. In Figure 10 the maximum reported pressures and vent panel pressures for one of the scenarios ignited at 7.0 seconds are shown. Note that the explosion panel pressure will go to zero once the panel is opened, and that pressures reported higher than the 50 mbar opening pressure are caused by inertia. With ignition at 7.0 seconds near the burner, the maximum pressures reach approximately the minimum NFPA 68 recommended design strength for such equipment (2.5 psi = 170 mbar). By moving the ignition point 2.5m downstream for this same case, the pressure level increases somewhat, and even more if ignition location is moved 5m downstream of burner. With the ignition location moved to the end of the hot box (10m downstream of burner) the ignition region seems to be pushed downstream into a less flammable region. This leads to a 3-second delay before a significantly stronger explosion is seen as more air has been mixed into the gas at this stage.

All the scenarios with ignition at 7.0 seconds within 2.5m of the burner can replicate many of the characteristics of the explosion. Panels 1-4 (red in the panel pressure plots) and 6-7 (blue), in addition to the hot box access door (orange), opened, whereas panel 5 (black) in general did not yield for these scenarios. There is however a 100ms time delay from the opening of panels 1-4 to the opening of panels 6-7 (these were reported to have near-simultaneous opening times in the incident). The exact resolution for the recorded event log is unknown and this scenario may be close to the actual opening times. For all these scenarios the pressure level is around or slightly above the required design strength as recommended by NFPA 68. However, we do not have sufficient knowledge about the actual design strength to judge whether these pressure loads may explain the observed damage to the dryer. The ignition located 5m downstream from the burner also shows many characteristics similar to those observed in the previous case, except that panel 5 yielded within 90ms of panel P1. This scenario may be consistent with the explosion panel switch being "stuck" and not properly recording the opening of P5.

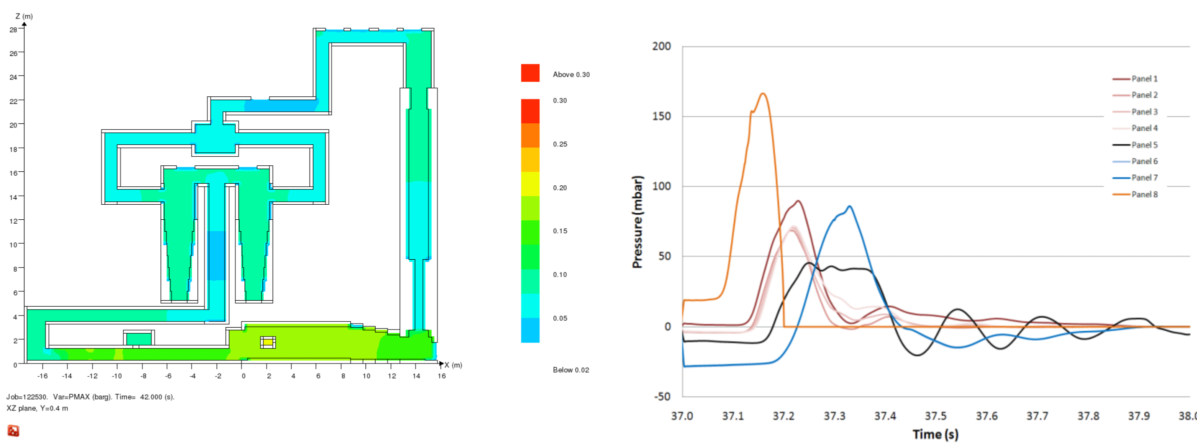

Figure 10: Explosion scenario with ignition at 7s (ignition position is 2.5m downstream of burner and door opening pressure 100 mbar). The left picture shows the distribution of maximum pressure seen in the system during the explosions, whereas the right picture shows the recorded explosion panel pressures.

Seven different ignition scenarios with ignition at 7.5 seconds were simulated. Two of these cases are shown in Figure 11. In general, very similar trends as those reported for the 7.0-second ignition time are observed, except that pressure levels are slightly higher. This may be more realistic with regard to the observed damage to the duct upstream of the burner, however, due to the increasing pressure, panel 5 starts opening at times very close to panels 1-4. The first scenario shown in Figure 11 is one example of this group of scenarios.

At one ignition location for the 7.5-second ignition case, panel 5 did not open with panels 1-4 but opened 3 seconds later consistent to what was recorded in the process data. This scenario is with the ignition in the bend downstream from the hot box and this case is shown in Figure 11. Here it can be seen that panels 1-4 and the access door (P8) open early, and that panels 5, 6 and 7 open violently 3 seconds later. In the actual explosion only panel 5 opened with a delay at the same time an explosion panel for the cyclone closed. Therefore this scenario has been ruled out as it does not properly reconcile the sequence of events and includes a potentially unrealistic ignition source remote from the burner.

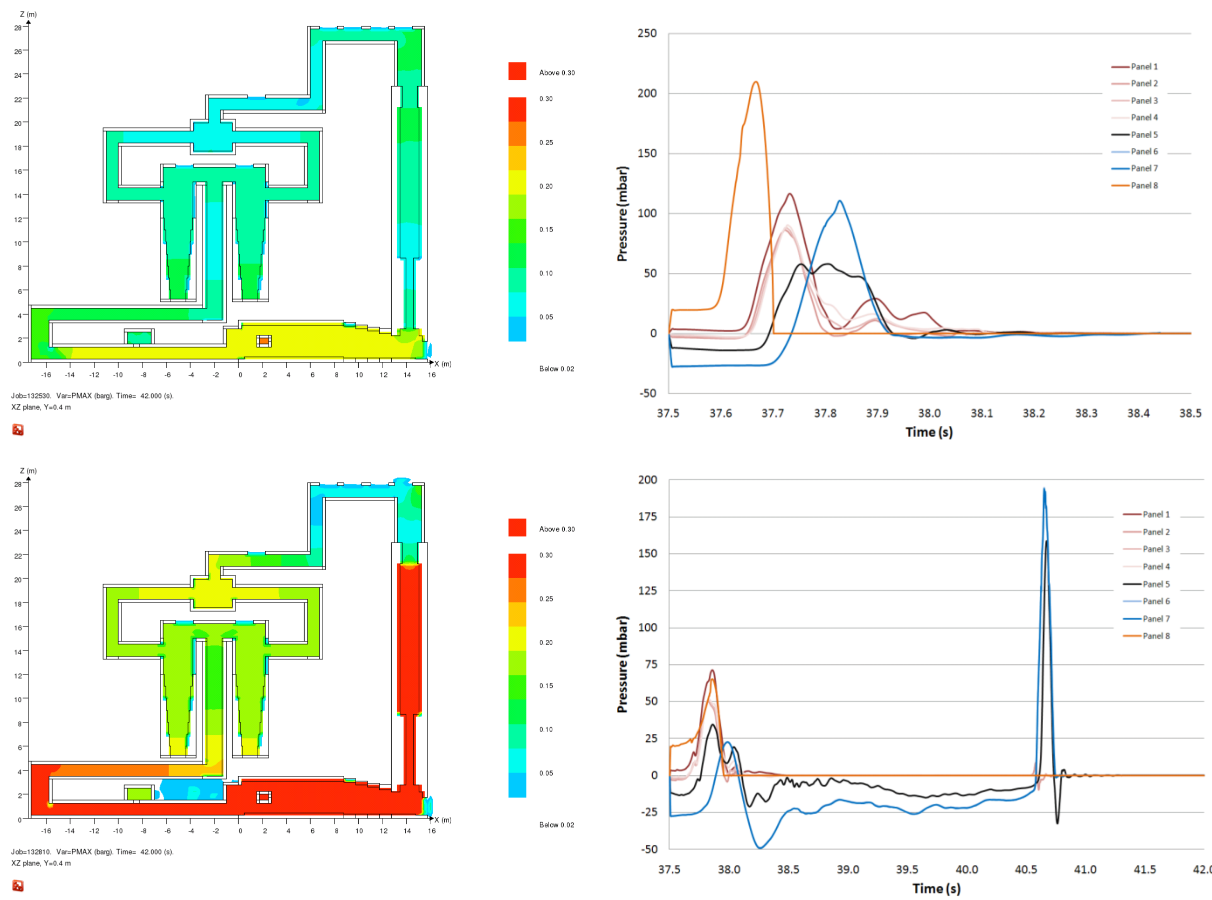

Figure 11: Two explosion scenarios with ignition at 7.5s. The left pictures show the distribution of maximum pressure seen in the system during the explosions, whereas the right pictures show the recorded explosion panel pressures. The upper plot is for ignition 2.5m downstream of burner and door opening pressure 100 mbar, whereas the lower plot is for ignition just downstream of the hot box with door opening pressure 50 mbar.

Three different scenarios with ignition at 8.0s were simulated. Two of these cases are shown in Figure 12. For ignition near the burner, similar trends as seen with the 7.0- and 7.5-second ignition cases were observed, which can be seen in the upper plots of Figure 12. Explosion pressures increase considerably if the ignition location is moved further downstream of the burner, where the pressure distribution for ignition located 5m downstream of burner is shown in the lower plot of Figure 12. High pressures reach panels 1-4, and these could help explain that the hinges of panel 1 broke and made the panel into a projectile during the explosion. For scenarios with an even more delayed ignition, the flammable gas cloud at the time of ignition is larger and more severe explosions are observed. These severe explosions are not consistent with the observed damage.

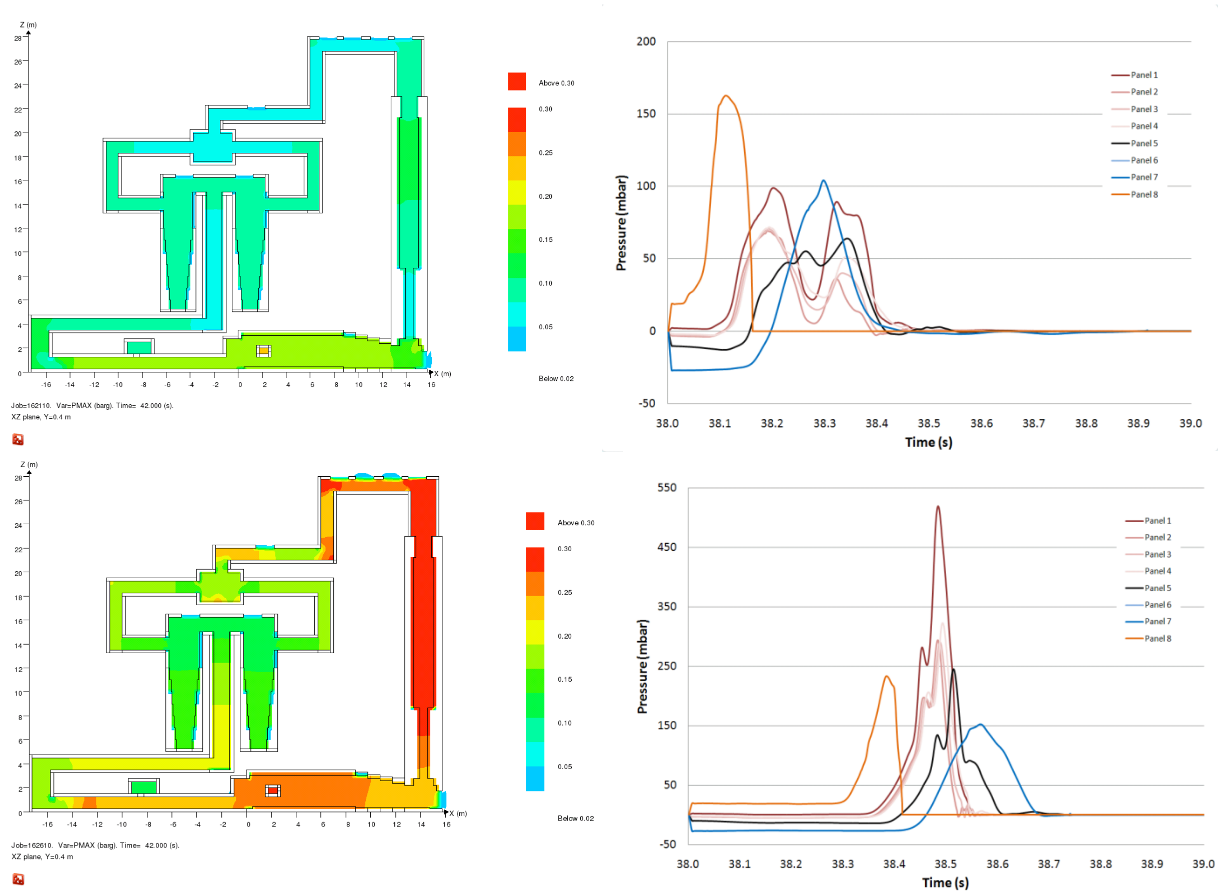

Figure 12: Two explosion scenarios with ignition at 8.0s. The left pictures show the distribution of maximum pressure seen in the system during the explosions, whereas the right pictures show the recorded explosion panel pressures. The upper plots are for ignition near the burner, whereas the lower plots are for ignition 5m downstream of the burner (door opening pressure is 50 mbar in both cases).

As a conclusion the simulations can clearly help explain much of what occurred in the explosion. The observed 8-second delay between the initiation of the burner air purge and the opening of the explosion panels is very consistent with the time it takes to create a highly reactive gas cloud downstream of the burner. A few seconds earlier the fuel-rich gas has only been purged with air once and there is practically no flammable gas cloud region. A few seconds later, the flammable gas cloud downstream of the burner has grown too large, and the consequences of such an explosion would likely be more severe than observed. FLACS simulations accurately captured this development within the dryer.

With regard to the explosion scenarios, it can be seen that many of the scenarios with ignitions at 7, 7.5 and 8 seconds near the burner (which is the most likely ignition source) result in pressures and panel behavior very similar to what was observed in the explosion. It is unclear from the process data if panel P5 did open at times close to P1-P4, but was not properly recorded ("stuck" switch), or that P5 was opened after a 2-second delay by a fairly weak overpressure. Due to the very limited window, our limited simulations on either side of the optimal window appear to show that either panel sequence may be possible. More importantly, the limited simulations performed can thus explain most elements and governing physics observed in the explosion. Significantly more detail would be required to identify the "exact" scenario. In addition, due to some uncertainties in flow parameters and reported variables from the incident, as well as smaller deviations in the definition of the system for the simulations, we cannot expect to be able to explain such a complex event to the last detail.

3.2 Dust Explosion Scenario

On the day of the incident, the possibility of a dust explosion resulting from the burner management systems failing for an unexplained reason was evaluated. Under this condition, dust could be lifted and transported during the operation of the fan and while the purge was adding oxygen back into the system during the relight of the system. Under normal conditions, dust would only be present in any significant quantities from the location at the hot box where it is added, through the exit of the cyclones, which includes the volume of the cyclones. Filling the entire dryer with significant concentrations of dust could only occur if the cyclones were clogged and the dust just passed through the dryer. While there was no evidence to suggest the cyclones were clogged, we also evaluated this scenario in an effort to evaluate the worst-case size dust cloud that could be present within the dryer at the time of the incident. In order to perform dust explosion simulations the explosivity of the dust needed to first be evaluated.

3.2.1 Dust analysis

Two representative dust samples from within the dryer having moisture contents of 10% and 7% were evaluated, along with a conservatively dry sample (taken from the process after being dried in the dryer and fluidized bed) of 6% moisture content. It is recommended that explosibility and ignition studies be conducted on a sample having particle size distribution that represents a conservatively small sample size of what is found in the industrial application. This practice assures that the material hazard assessment is conservative. For the three samples, the fractions of the samples that passed through a 40 mesh (475 microns) screen (the smallest screen possible to sieve this dust) were tested. The explosibility and ignition characteristics of the three samples were tested to: ASTM E-1226 maximum explosion pressure P_{max}, maximum rate of pressure rise R_{max} and maximum volume scaled rate of pressure rise K_{ST}, and ASTM E-1515 Minimum Explosible Concentration (MEC) of combustible dusts. The results for the tests are presented in Table 2.

Table 2: Dust Explosibility and Ignition Results

Test	Dust 6%	Dust 7%	Dust 10%
P_{max} (bar-gauge)	6.8	6.6	6.4
R_{max} (bar/s)	89	72	72
K_{ST} (bar-m/s)	24	20	19
Dust Class	St-1	St-1	St-1
MEC (g/m^3)	53	53	61
%Moisture	6.5	7.0	9.6
Explosion Severity	0.19	0.15	0.15

P_{max}, R_{max} and K_{ST} are standard baseline parameters used in determining the explosibility of dusts, and are required values for the DESC (FLACS) simulations. Explosion Severity is defined as the ratio of the product of the P_{max} and R_{max} of a dust sample relative to that of Pittsburgh Seam Coal. Dusts with an explosion severity less than 0.5 are typically classified as having a weak dust explosion hazard [6]. This low rate of pressure rise is most likely due to the actual diameter size of the dust product, with possible contributions due to the moisture levels and volatility of the dust. Smaller diameter dust particles typically have higher rates of pressure rise when ignited due to increased surface area. The smallest dust samples from the dryer were only capable of passing through a 40-mesh screen, indicating that the most conservative and smallest diameter dust sample has about a factor of 6 larger diameter than the ASTM standard (200 mesh screen). If smaller particle size dust or dryer dust is able to accumulate in the process, it may represent a greater dust explosion hazard than the samples measured. It can further be mentioned that the procedure for determining dust reactivity may be questionable for such low reactivities, both due to the influence of the two 5kJ pyrotechnic igniters used in the testing as well as the given turbulence levels from the time of ignition to the end of the test. For low reactivity dusts, the turbulence levels may decay within the test apparatus by the time the flame fully develops, as compared to more reactive dusts. In addition, the shape of the flame may be far from spherical as is assumed. For our base case simulation we have therefore doubled the highest measured K_{ST} to 50 bar-m/s in an effort to conservatively overestimate the dust explosion hazard. We have also included a sensitivity study with a K_{ST} of 100 bar-m/s, which would be close to the reactivity expected for a dry dust sample having a significantly smaller particle size.

In the present study, we have assumed that the maximum reactivity occurs at a dust concentration around 500 g/m^3, which was also confirmed from testing. This concentration in air was used in all dust cloud simulations within the dryer. At the time of the explosion, product was not being fed into the dryer but this serves as a reasonable estimate to maximize the effects of a dust explosion. In order to evaluate the possible contribution of dust to the present explosion, two different dust clouds were evaluated within dryer at the measured dryer temperature of 250°F (121°C) at the time of the explosion. The first dust cloud represents the likely worst-case cloud, had dust been lifted and transported within the dryer. The point where the dust is introduced and finally removed by the cyclones would bound the size of the cloud. The second scenario assumes an even more unlikely event that lifted and transported dust is present throughout the dryer, which could only occur if the cyclones were clogged. Dust cloud explosions were evaluated with the K_{ST} value that is doubled relative to the experimentally determined value (50 bar-m/s) as well as the 100 bar-m/s. Each cloud was evaluated at three different ignition points: (a) one near the burner due to hot surface ignition for the full dust cloud or from smoldering ignition at the hot air box for the more representative dust cloud; (b) smoldering flare up/ignition from accumulated material in the external ring duct, and (c) smoldering flare up/ignition from accumulated material in the entrance to the cyclones.

3.2.2 The simulation of dust explosion scenarios

A total of 36 different dust explosion simulations were carried out. Two very conservative assumptions on gas cloud size were investigated (dust cloud filling half of the system and the full system). For each case two dust reactivities were studied (K_{ST} = 50 bar-m/s and 100 bar-m/s). For the scenarios with a dust cloud filling the entire system, the normal process flow with turbulence is modeled prior to ignition. For the scenarios with half of the dryer filled with dust, the flow is defined to be quiescent, but with representative turbulence parameters for the process flow situation. For each of these scenarios three different ignition locations were simulated at three different initial temperatures. The temperatures were 20°C (ambient), 120°C (condition at time of explosion) and 315°C (typical operating conditions). The purposes of the simulations were both to see if a dust explosion could have caused the actual explosion, but also to evaluate if the vent design seemed appropriate for the actual dust reactivity and system layout.

In Figure 13 the maximum pressures observed in the dryer are reported for all simulated dust explosion scenarios for an initial temperature of 120°C. Provided the NFPA 68 recommendations on system strength are followed (system should withstand 2.5 psi), the simulations predicted that the system should generally be well designed to resist dust explosions for dusts with a K_{ST} of 50 bar-m/s, which is double the reactivity reported for the actual dust. The dust cloud sizes and conditions were overly conservative (filling the whole dryer with worst-case reactivity dust).

In Figure 14 some simulation results are shown, in both cases with the “realistic” flammable dust cloud assumption covering the region from the exit of the hot box to the cyclones. The initial temperature in the dryer is 120°C and a normal air atmosphere is assumed. The latter is a very conservative assumption as the process is normally oxygen starved. The first scenario is with a dust reactivity K_{ST} of 50 bar-m/s and ignition at the exit of the hot box. From the plots it can be seen that the explosion pressures are well controlled by the explosion vent panels, and the maximum pressure reported in the dryer is less than twice the panel opening pressure of 50 mbar.

The dust explosion scenarios with K_{ST} of 50 bar-m/s generally generate too low pressures to explain the observed damage from the incident studied. The fact that the real dust was measured to have a significantly lower reactivity, and that there was an oxygen-starved atmosphere in the dryer, should further rule out a dust explosion scenario as a cause of the incident.

In Figure 13 it can also be seen that if the dust reactivity is doubled (K_{ST} = 100 bar-m/s), the explosion pressures are predicted to increase almost one order of magnitude for some scenarios.

The second scenario shown in Figure 14 is one of the sensitivity calculations with the significantly higher dust reactivity (K_{ST} = 100 bar-m/s) and ignition near the cyclones. In this simulation overpressures of more than 1 bar are predicted between the cyclones and explosion panel 5. Explosion panels 1-4 have a positive effect of reducing the pressure level and keeping pressures below 0.5 bar in the pipes down towards the hot box.

The simulations at 20°C and 315°C initial temperature generally show similar trends, but have some small differences. An increase in temperature will generally increase the reactivity of the mixture, whereas the reduced density (and thus lower heat of combustion) will contribute to lower flame speeds, therefore the combined effect for a change in temperature for such scenarios is not obvious. Most of the cases in this study show a moderate reduction in overpressures with increased temperature, while some local pressures may increase.

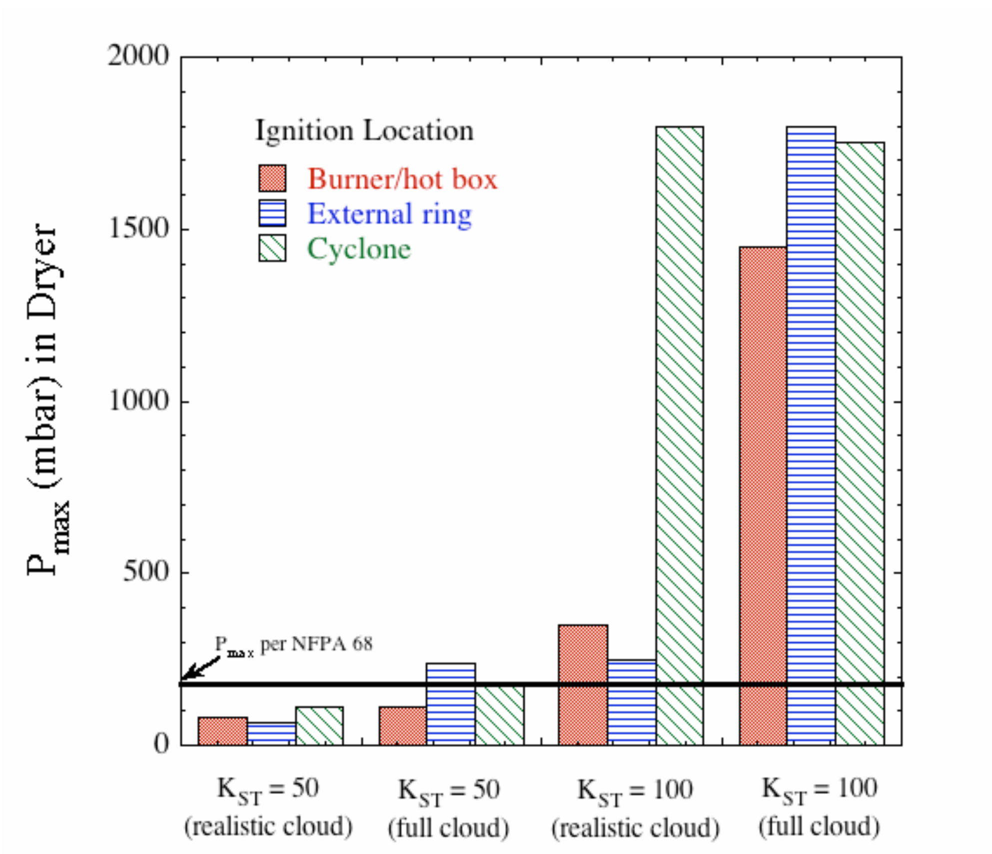

Figure 13: Overview of overpressures obtained in simulated dust explosion scenarios at initial temperature 120°C.

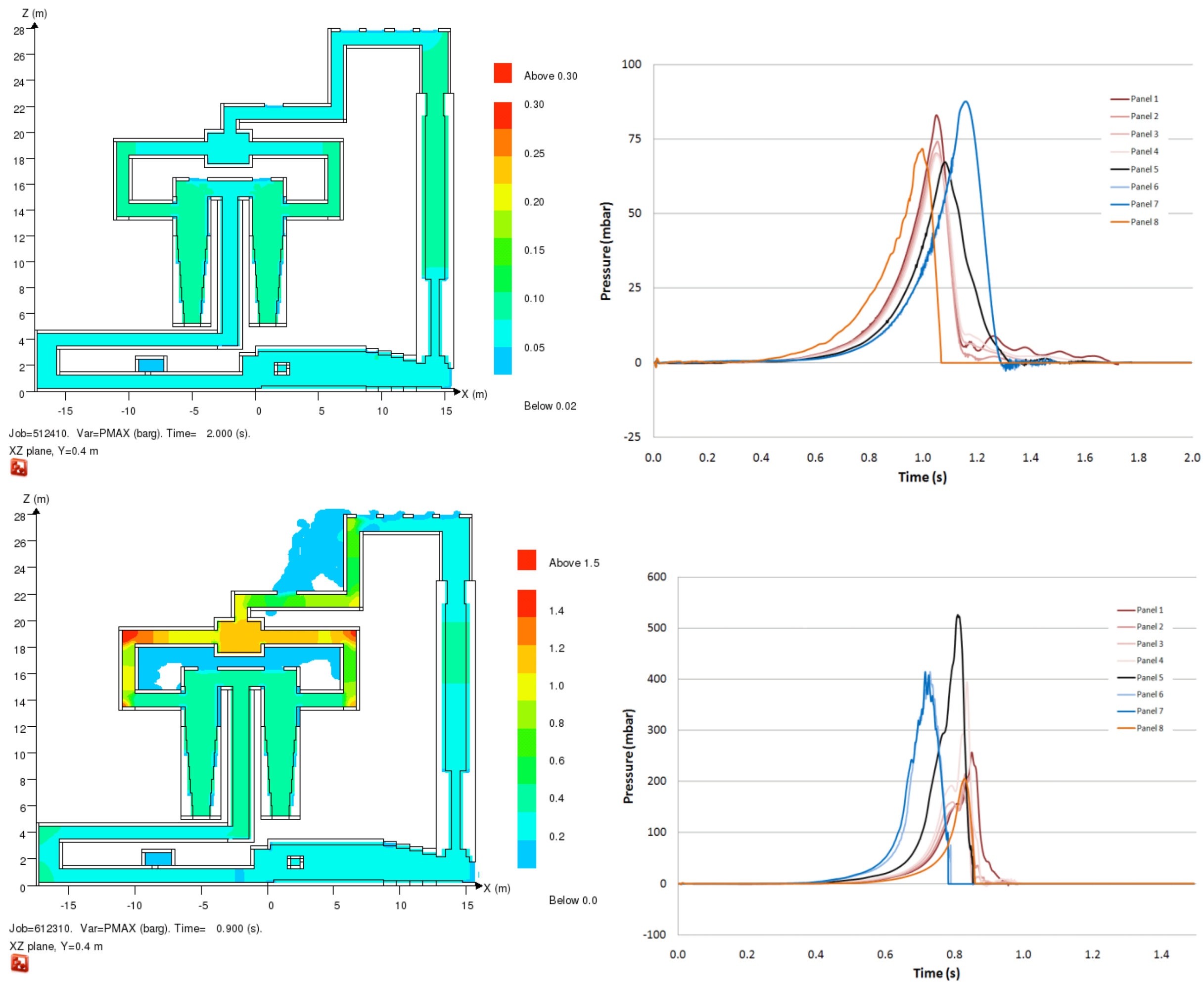

Figure 14: Dust explosion scenarios with realistic dust cloud between hot box and cyclones. The upper plots show predicted explosion pressures for K_{ST} = 50 bar-m/s dust with ignition near the hot box, while the lower plots show predicted pressures for K_{ST} = 100 bar-m/s dust with ignition near the cyclones. Left plots are showing maximum pressure distribution in system during explosion, the right plots show vent panel pressure during explosion.

3.3 Further Comments Regarding Explosion Vent Design

The incident caused significant damage and created numerous hazards. Some notable events included the failure of two explosion panels that became massive projectiles and the hot air box door blowing open and venting flames/hot combustion products into the facility. Explosion vents are to be located or retained so that personnel are not exposed to injury by operation of the vents. If the access door to the hot box is to be used as an explosion vent in the current configuration, personnel in front of the opening could be exposed to venting products of combustion and flames (see Figure 15).

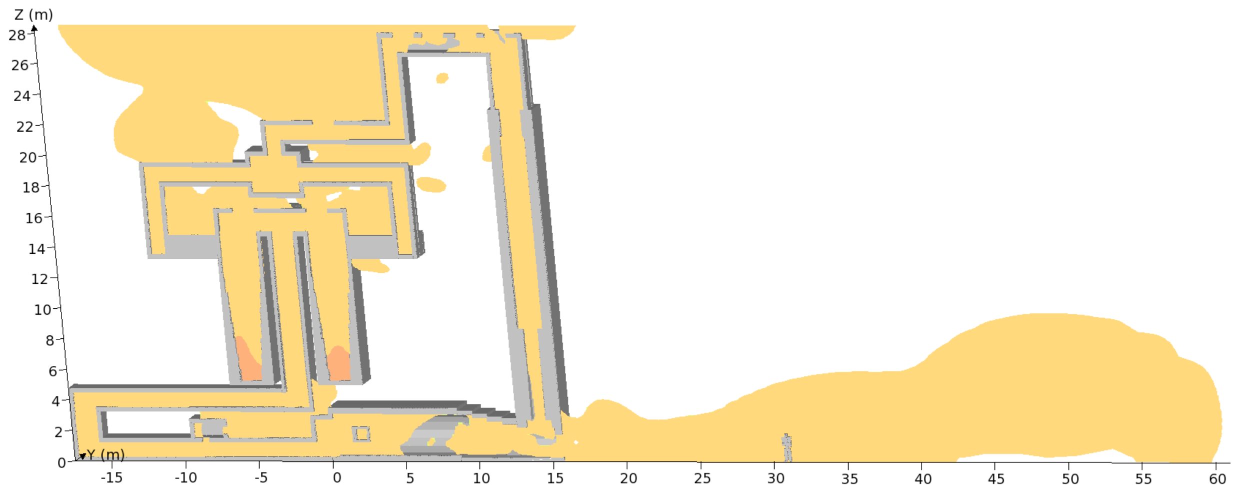

Figure 15: Venting of products of combustion and flames during a dust deflagration via the access door in the hot box. Note the representative employee at 31 m.

4. Conclusion and Recommendations

The cause of the given dryer explosion was a result of a failing mass flow meter for the combustion air, which caused the combustion air damper to close resulting in insufficient combustion air being supplied to the dryer (an extreme fuel rich condition in the dryer). This resulted in unburned natural gas, hydrogen and carbon monoxide being circulated in the dryer, which caused the burner to trip and the gases subsequently ignited after air was reintroduced into dryer. The explosion simulation tool FLACS confirmed that the likely source of the ignition was the area of the burner. In fact, FLACS simulations accurately captured the flammable mixture development in the dryer and reconciled the narrow window of a flammable fuel-air cloud that forms approximately 7-8 seconds after the air purge is initiated. In addition, explosion simulations near the most-likely ignition source, the vicinity of the burner, resulted in explosion dynamics that predicted the near simultaneous opening of the explosion vent panels on the external ring duct and in the cyclone header. While it is unclear from the process data if panel P5 did open at times close to P1-P4 (stuck switch), or that P5 was opened after a 2-second delay by a fairly weak overpressure, our limited simulations on either side of the optimal explosion window appear to show that either panel sequence may be possible.

It is unlikely that the dust found in the dryer had any significant contribution to this incident. There was no evidence that significant dust was suspended and being transported in the dryer at the time of the incident, and even if a dust cloud with conservatively high combustibility (smallest available particle size, lowest moisture content, optimal dust concentration) was present, the explosion consequence predicted by DESC cannot explain the damage to the dryer. This is consistent with the measured low combustion severity of the dust found in the dryer given these conservative combustible conditions.

The following recommendations were provided to the facility owners in order to prevent future events and minimize explosion consequences:

1. The dryer and its explosion venting are not designed for accumulation of combustible gases within the dryer. The dryer combustion management system should be designed to significantly reduce the likelihood of this condition within the dryer. This can be accomplished by employing the following:

    a. On the dryers that use the incident flow meter for combustion air and the incident air-to-fuel ratio controller, the internal jumper pins for the Failure Mode Alarm on the mass flow meter should be set to the low position for combustion air (output signal driven below 3.75 mA). In the event the ratio controller interpreted this as an actual signal, it would drive the air damper fully open causing fuel-lean conditions to exist in the dryer.

    b. The over/under range signals emitted from the mass flow meters need to be detected by the combustion management system and initiate a burner shutdown.

2. The designer of the dryer should have provided a sufficient means of securing the explosion doors on the ring dryers and failed to meet the requirements of NFPA 68 *Guide for Venting of Deflagrations*, which states, "For personnel safety, the door or panel should be designed to remain intact and to stay attached."

3. The door to the hot box should be vented outside the facility, in the event it blows open during the venting of a dryer deflagration. This access door failed to meet the requirements of NFPA 86 *Ovens and Dryers*, which states, "Explosion-relief vents shall be located or retained so that personnel are not exposed to injury by operation of the vents." While the door to the hot box may not have originally been considered an explosion vent, it can however serve such a purpose and safety design needs to be considered.

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