Client: United States Chemical Safety Board

Report Title: Didion Milling Explosion Assessment

Incident: May 31, 2017

Final Report R0

ABS Group Project No. 3953131
Prepared for:

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Executive Summary

ABSG Consulting Inc. (ABS Group) was contracted to conduct a forensic evaluation of the Didion Mill explosion of May 31, 2017 performing the following tasks:

- Assessment of Building Construction and Damage
- Blast Modeling
  - Use of NFPA 68 to evaluate potential explosion scenarios and the effects venting would have had on the consequences and propagation of the event.
  - CFD modeling to evaluate:
    - Explosion in Level 1 of Mill B
    - Explosion in the Multipurpose Building
    - Potential reduction in damage from additional venting

The directional indicator analysis conducted for this investigation is confirming for an explosion origin in Level 1 of Mill B with propagation upward in Mill A and B through the vertical air shafts and into the Multipurpose Building and Mill F through openings between the areas.

The precast elements of the Didion Milling facility included the walls of Mill B and Mill D, and precast Multipurpose Building, Mill F, and the Boiler Room which were not designed to resist the effects of accidental dust explosions nor were connected together in a manner to resist internal pressure loading in a ductile manner.

NFPA 68 analysis of the level 1 of Mill B explosion determined that a minimum cloud volume of approximately 20 to 30 m^3 was predicted to be necessary to produce the observed damage. This cloud size is 2-3% of the total room volume. An explosion in level 1 of Mill B from a full volume dust cloud was predicted to result in a peak pressure of 82 psi accounting only for relief through the vertical air shaft indicating that the dust explosion hazard required engineering controls with vents engineered to protect the structure.

The CFD analysis predicted that the mass of the combustible dust clouds in Level 1 of Mill B most consistent with the observed damage to Levels 1 and 2 was between 40 m^3 (45 lbs.) and 100 m^3 (110 lbs.) of dust. This cloud volume is 4-10% of the volume of level 1 of Mill B main room. Propagation of this explosion to other areas of the mill was required to cause the observed damage to other portions of Didion Milling including Levels 2 through 4 of Mill B, Levels 1 through 5 of Mill A, the Multipurpose Building, and Mill F. Propagation of fire and explosion is consistent with the observed damage, blast directional indicators, and fire directional indicators.

The explosion analysis of the South Gap mill indicated that the maximum flammable mass of ejected dust when the flame front reaches the exit of the South Gap Mill was approximately 5.8 kg (12.8 lb.). This mass is well below the mass calculated to cause the observed damage to Level 1 of Mill B above. Therefore, a combination of dust ejected from the South Gap Mill and fugitive dust within level 1 of Mill B was necessary to cause the initial damaging explosion in level 1 of Mill B.

The minimum volume of a combustible dust cloud in the Multipurpose Building necessary to generate the onset of structural instability and failure was determined to be approximately 70 m^3 at a concentration of 500 gm/ m^3. This equates to 35 kg, or roughly 80 lbs. of dust. The precast elements of the Multipurpose Building were not designed nor connected together in a manner to resist the internal pressure loading in a ductile manner.

Vents were added in the CFD model to the Level 1 of Mill B on the eastern wall to the south of Mill F and the partition wall between the Mill B rooms at level 1. A total vent area of 11 m^2 on the Mill B partition wall and eastern exterior wall at the south end of Mill B was necessary to reduce the pressure in this area of Mill B below that of the walls and doors. Reducing the overpressure to this level would maintain the integrity of these surfaces and openings indicating that engineered venting may have mitigated the propagation of the explosion; however, the air shaft would remain a potential path for fire and overpressure due to the open nature of the system.

Venting of the Multipurpose Building to protect the precast construction would have required approximately 20% of the wall surface area, or 250 m^2 of total vent area, on the north, south, and west walls to protect the precast construction. Proper engineering of vents in the Multipurpose Building in conjunction with additional continuity of the structure could have reduced or eliminated the structural failures.

1 Introduction

ABSG Consulting Inc. (ABS Group) was contracted to support the Chemical Safety and Hazard Investigation Board (CSB) investigation of the May 31, 2017 explosion at the Didion Milling plant in Cambria, Wisconsin which resulted in the deaths of 5 people and extensive damage to the facility.[1] ABS Group also supported the CSB in project 3932927 immediately after the incident by conducting two site visits to survey damage patterns and render a preliminary opinion regarding the location of the explosion origin (Level 1 of Mill B) and blast propagation away from that location into the adjoining mills[2]. This report summarizes the engineering and analysis effort performed in support the CSB investigation.

1.1 Purpose/Objectives

This effort included engineering support and modeling related to the explosion origin, propagation, and resulting structural failures and building collapse.

1.2 Scope

The scope of work included forensic investigation of fire and blast consequences related to the incident and were organized into the following tasks.

- Task 1: Assessment of Building Construction and Damage
- Task 2: Blast Modeling
- Task 3: Recommendations

This scope of work outlined above is detailed in the flow chart presented below in Figure 1-1. A summary of the field investigation performed in Project 3932927 is presented in Section 3. Analysis methodology is discussed in Section 4 with results in Section 5 and findings in Section 6.

The forensic data collected during the site survey was utilized during Task 2 to meet the following objectives:

- Model potential explosion scenarios to estimate blast loading in affected areas.
- Perform structural calculations to estimate blast pressure and impulse combinations that best explain observed damage.
- Reconcile explosion modeling with structural modeling to identify the explosion scenario that is most consistent with the observed damage.

[1] CSB Contract CSB-13-022, Requisition Reference No. CSB-1I25-0029, “Blast Modeling and Analysis”, 9/19/2017.
[2] CSB Contract CSB-17-0023, Requisition Reference No. CSB-1I25-17-0015, “Blast Analysis Consulting to Support.

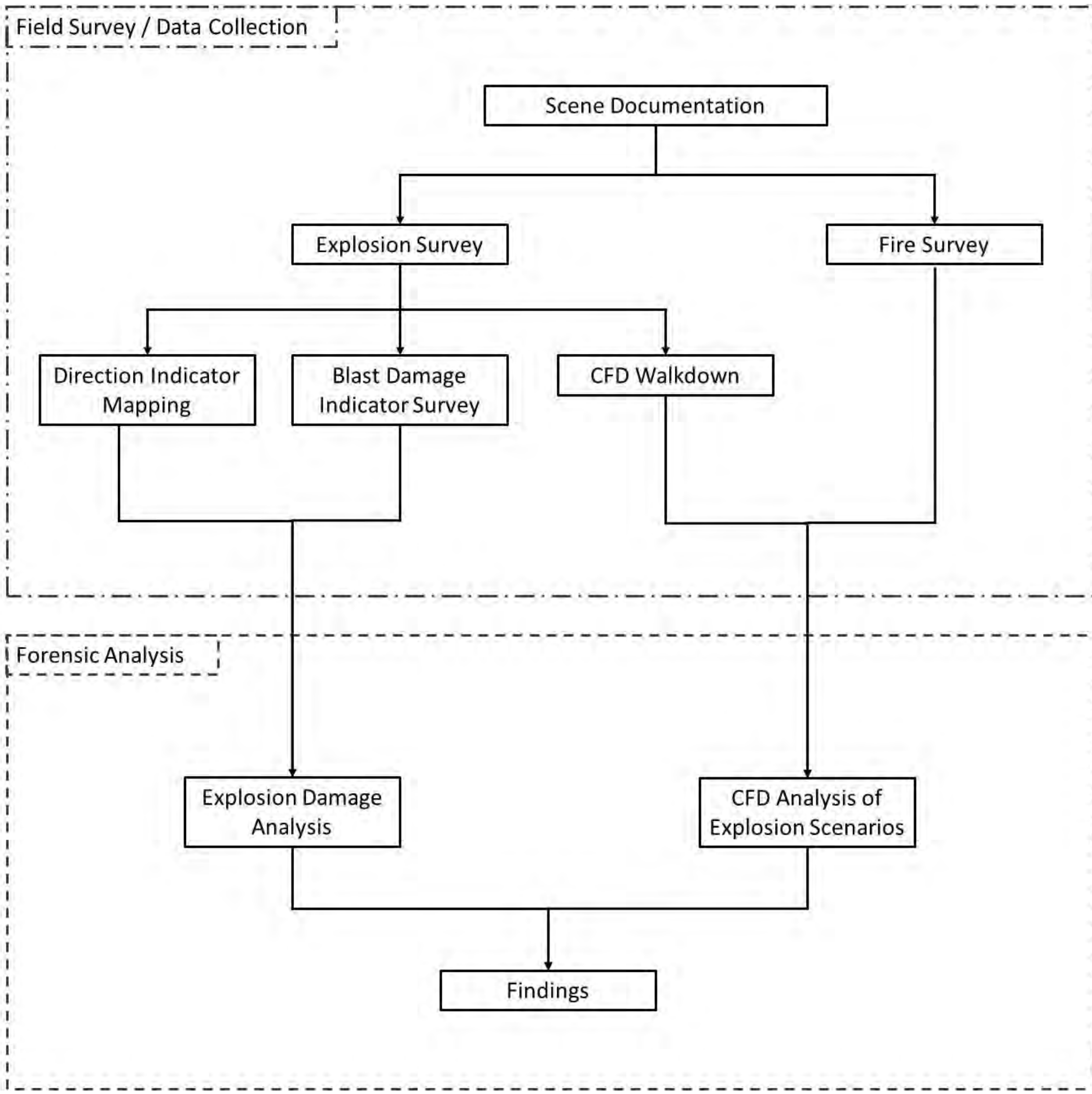


Figure 1-1. ABS Group Scope of Work Flow Chart

1.3 Government Furnished Information

Testing to determine properties of the dust necessary to perform explosion analysis were conducted by ioKinetic[3]. Dust explosivity testing, particle size analysis and bulk density results were provided for the following:

- K_{st} and P_{max} Testing
  - Bran
  - Torit Filter Sample
  - Flour
- Minimum Ignition Energy (MIE)
  - Bran
  - Flour
- Minimum Auto Ignition Energy (MAIE)
  - Bran
- Particle Size Analysis
  - Bran as tested
  - Bran as received
  - Flour as tested
  - Flour as received

The following drawings of the South Gap Mill were provided:

- 7358-L01 – GM-120P Grinding Mill Main Assembly – Wet Version 17 July 1997
- 7350-L02 – GM-120P Grinding Mill Plant Layout # Elevation, 21 July 1997

Drawings were received for the following building sections which are listed in the referenced tables:

- Table 1-1. General Layout Drawings
- Table 1-2. Mill A Drawings
- Table 1-3. Mill B Drawings
- Table 1-4. Mill D Drawings
- Table 1-5. Mill C Drawings
- Table 1-6. Mill F Drawings
- Table 1-7. Boiler House Drawings
- Table 1-8. Warehouse Drawings
- Table 1-9. Bulk Loadout Drawings

[3] ioKinetic, "Combustible Grain Dust Characterization of Didion Manufacturing Dust Samples", isokinetic Project #18065, Michelle R. Murphy.

Table 1-1. General Layout Drawings

Drawing	Sheet No.	Issue Date	Rev. #	Title
DIDION0000370	Sheet 1 of 5	10/07/13	0	1st Floor Layout, Mill Equipment Layout
DIDION0000372	Sheet 2 of 5	10/07/13	0	2nd Floor Layout, Mill Equipment Layout
DIDION0000374	Sheet 3 of 5	10/07/13	0	3rd Floor Layout, Mill Equipment Layout
DIDION0000376	Sheet 4 of 5	10/07/13	0	4th & 5th Floor Layout, Mill Equipment Layout
DIDION0000378	Sheet 5 of 5	10/07/13	0	6th Floor Layout, Mill Equipment Layout
DIDION0000390	Sheet 3 of 4	08/12/13	0	3rd, 4th, 5th & 6th Floor Layout, Existing Filter Placement
DIDION0002042	-	-	-	1st Floor (A and B Mill)
DIDION0002043	-	-	-	2nd Floor (A, B, and C Mill)
DIDION0002044	-	-	-	3rd Floor (A and B Mill)
DIDION0002045	-	-	-	4th Floor (A and B Mill)
DIDION0002046	-	-	-	Section A-A (vertical section thru B Mill)
DIDION0002047	-	-	-	Section B-B (vertical section thru A and B Mill)

Table 1-2. Mill A Drawings

Drawing	Sheet No.	Issue Date	Rev. #	Title
DIDION0000329	2	04/22/91	1	First Floor Plan & Second Floor Plan
DIDION0000330	3	04/22/91	1	Third Floor Plan & Fourth Floor Plan
DIDION0000331	4	04/22/91	1	Fifth Floor Plan & Roof Plan
DIDION0000332	5	04/22/91	1	Building Sections
DIDION0093680	C-1	08/20/91	5	Mill Building Main Slab (1st Floor)
DIDION0093681	C-2	06/14/91	0	Slipform Plan & Wall Diagram
DIDION0093682	C-3	06/14/91	0	Beams & Wall Openings
DIDION0093683	C-4	08/20/91	2	2nd & 3rd Floors
DIDION0093684	C-5	07/26/91	3	4th & 5th Floors
DIDION0093685	C-6	07/25/91	3	Roof Slab
DIDION0093686	C-7	06/17/91	0	Stairway Details
DIDION0093687	JR-1	04/22/91	0	Jackrod Plan
DIDION0093688	S-1	07/17/91	1	Embedded Items
DIDION0093689	S-2	06/27/91	1	Embedded Items
DIDION0093690	S-3	07/11/91	1	Stairway Handrails

Table 1-3. Mill B Drawings

Drawing	Sheet No.	Issue Date	Rev. #	Title
DIDION0002048	S-PC3	03/09/01	A	Processing Area (floor plan and section)
DIDION0002049	S-PC4	03/09/01	A	Reinforcement for Processing Slab
DIDION0002119	S-PC4	06/26/01	B	Reinforcement for Processing Slab
DIDION0002050	S-PC5	06/27/01	B	Processing Area (wall anchor plan)
DIDION0002121	S-PC6	01/17/02	B	Processing Area (5th floor plan and section)
DIDION0002122	S-PC7	01/17/02	B	Reinforcement for Processing Slab (5th floor/roof)
DIDION0002123	S-PC8	01/17/02	B	Processing Area (wall anchor plan, 5th floor/roof)

Table 1-4. Mill D Drawings

Drawing	Sheet No.	Issue Date	Rev. #	Title
DIDION0002082	C1.0	05/31/11	1	Site Plan, Project Location, Notes, Sheet Index & Stamp/Seal
DIDION0002083	F1.0	05/01/11	0	Foundation Plan
DIDION0002084	F2.0	05/01/11	0	Footing Slab Reinforcement Layout
DIDION0002085	F3.0	05/31/11	1	Foundation Details and Notes
DIDION0002086	A1.0	05/01/11	0	1st Floor Plan
DIDION0002087	A2.0	07/12/11	1	2nd Floor Plan
DIDION0002088	A2.1	07/13/11	0	2nd Floor Accessible Route Plan to Existing Stairs
DIDION0002089	A3.0	07/12/11	1	3rd Floor Plan
DIDION0002090	A4.0	07/12/11	1	4th Floor Plan
DIDION0002091	A4.1	07/13/11	0	4th Floor Accessible Route Plan to Existing Stairs
DIDION0002092	A5.0	07/12/11	1	5th Floor/Roof Plan
DIDION0002093	A6.0	05/01/11	0	West & South Elevations
DIDION0002094	A7.0	07/12/11	1	East Elevation
DIDION0002095	A8.0	07/12/11	1	East & North Section Views
DIDION0002096	S2.0	06/14/11	0	2nd Floor Structural Plan
DIDION0002097	S2.1	06/14/11	0	2nd Floor Floor/Wall Dowel Connection Spacing & Details
DIDION0002098	S3.0	06/14/11	0	3rd Floor Structural Plan
DIDION0002099	S3.1	06/14/11	0	3rd Floor Floor/Wall Dowel Connection Spacing & Details
DIDION0002100	S4.0	06/14/11	0	4th Floor Structural Plan
DIDION0002101	S4.1	06/14/11	0	4th Floor Floor/Wall Dowel Connection Spacing & Details
DIDION0002102	S5.0	06/14/11	0	Roof Structural Plan
DIDION0002103	S5.1	06/14/11	0	Roof Floor Floor/Wall Dowel Connection Spacing & Details

Table 1-5. Mill C Drawings

Drawing	Sheet No.	Issue Date	Rev. #	Title
DIDION0002079	100040-1	10/11/10	0	1st Floor C-Mill
DIDION0002080	100040-2	10/11/10	0	2nd Floor C-Mill
DIDION0002081	100040-2	10/11/10	0	Section View C-Mill/Warehouse

Table 1-6. Mill F Drawings

Drawing	Sheet No.	Issue Date	Rev. #	Title
DIDION0002111	C1	12/21/04	0	Plan, Site, 2004 Bran Processing Expansion
DIDION0002104	A1	12/21/04	0	Plan, 1st Floor Building, 2004 Bran Processing Expansion
DIDION0002105	A2	12/21/04	0	Plan, 2nd Floor Building, 2004 Bran Processing Expansion
DIDION0002106	A3	12/21/04	0	Plan, 3rd Floor Building, 2004 Processing Expansion
DIDION0002107	A4	12/21/04	0	Elevation, Exterior East, 2004 Bran Processing Expansion
DIDION0002108	A5	12/21/04	0	Elevation, Exterior South, 2004 Bran Processing Expansion
DIDION0002109	A6	12/21/04	0	Elevation, Exterior North, 2004 Bran Processing Expansion
DIDION0002110	A7	12/21/04	0	Snow Load Diagram & Details, 2004 Bran Processing Expansion
DIDION0002112	F1	12/21/04	0	Plan, Foundation Notes and Information, 2004 Bran Processing Expansion
DIDION0002113	S1	12/21/04	0	Plan, Structural 1st Floor, 2004 Bran Processing Expansion
DIDION0002114	S2	12/21/04	0	Plan, Structural 2nd Floor, 2004 Bran Processing Expansion

Table 1-7. Boiler House Drawings

Drawing	Sheet No.	Issue Date	Rev. #	Title
DIDION0002051	S-1	08/20/94	B	Boiler Walls, Floor, Roof
DIDION0002052	S-2	08/04/94	A	Boiler Foundation
DIDION0002053	S-3	08/14/94	A	Tilt Up Wall Construction

Table 1-8. Warehouse Drawings

Drawing	Sheet No.	Issue Date	Rev. #	Title
DIDION0002115	C-1	11/13/98	B	Site Plan
DIDION0002116	S-1	11/13/98	D	Warehouse Expansion
DIDION0002117	S-2	11/13/98	B	Existing Layout
DIDION0002118	S-3	11/17/98	B	Exterior Elevations

Table 1-9. Bulk Loadout Drawings

Drawing	Sheet No.	Issue Date	Rev. #	Title
-	C1	01/17/06	0	Plan, Site, 2006 Bulk Load-Out Building
-	A1	01/17/06	0	Plan, 1st floor, 2006 Bulk Load-Out Building
-	A2	01/17/06	0	Plan, 2nd floor & 3rd floor Roof, 2006 Bulk Load-Out Building
-	A3	01/17/06	0	Elevation, South Exterior, 2006 Bulk Load-Out Building
-	A4	01/17/06	0	Elevation, North Exterior, 2006 Bulk Load-Out Building
-	A5	01/17/06	0	Elevations, West & East Exterior, 2006 Bulk Load-Out Building
-	F1	01/17/06	0	Plan, Foundation, Information & Notes, 2006 Bulk Load-Out Building
DIDION0002054	C1.0	01/12/13	0	Site Plan, Project Location, Notes, Sheet Index & Stamp/Seal
DIDION0002055	C2.0	01/12/13	0	Project & Plan Review Information
DIDION0002056	F1.0	01/12/13	0	Foundation Plan
DIDION0002057	F2.0	01/12/13	0	Footing Slab Reinforcement Layout
DIDION0002058	F3.0	01/12/13	0	Foundation Details and Notes
DIDION0002059	A1.0	01/12/13	0	1st Floor Plan
DIDION0002060	A2.0	01/12/13	0	2nd Floor Plan
DIDION0002061	A2.1	01/12/13	0	2nd Floor Plan - Accessible Route to Existing Stairs
DIDION0002062	A3.0	01/12/13	0	Roof/3rd Floor Plan
DIDION0002063	A4.0	01/12/13	0	South Elevation View
DIDION0002064	A5.0	01/12/13	0	East Elevation View
DIDION0002065	A6.0	01/12/13	0	Section View - Looking North
DIDION0002066	A7.0	01/12/13	0	Section View - Looking North
DIDION0002067	A8.0	01/12/13	0	Section View
DIDION0002068	A9.0	01/12/13	0	Section Views
DIDION0002069	A10.0	04/15/13	0	Stair Design & Details
DIDION0002070	A11.0	04/15/13	0	Wall Panel Design & Door Schedule
DIDION0002071	S2.0	04/15/13	0	2nd Floor Structural Plan - Overall Area
DIDION0002072	S2.1	04/17/13	0	2nd Floor Structural Plan - Bulk Storage/Load-Out (Middle Area)
DIDION0002073	S2.2	04/17/13	0	2nd Floor Mechanical Level Structural Plan
DIDION0002074	S2.3	04/17/13	0	3rd Level Access Mezzanine Structural Plan (Middle Area)
DIDION0002075	S3.0	04/15/13	0	Roof Structural Plan - Overall Area
DIDION0002076	S3.1	04/17/13	0	Roof Structural Plan - Bulk Storage/Load-Out (Middle Area)
DIDION0002077	S3.2	04/17/13	0	Roof Above Mechanical Level Structural Plan

1.4 Definitions and Acronyms

1.4.1 Acronyms

The following are definitions of several terms used in this document.

- **CAD**: Computer Aided Drafting
- **CFD**: Computational Fluid Dynamics
- **CSB**: United States Chemical Safety and Hazard Investigation Board
- **DustEx**: FLACS-DustEx (formerly DESC) is a computational fluid dynamics (CFD) code for simulating the course of industrial dust explosions in complex geometries.
- **FDIs**: Fire Damage Indicators
- **FLACS**: FLame ACceleration Simulator. A computational fluid dynamics (CFD) code used for explosion and dispersion modeling.
- **NFPA**: National Fire Protection Association
- **SBEDS:** A computer program, distributed by the U.S. Army Corps of Engineers Protective Design Center, which performs SDOF analysis.
- **SDOF**: Single-Degree-of-Freedom, a common dynamic structural analysis method used in blast analysis.

1.4.2 Definitions

- **Blast Indicator:** A damaged or undamaged object that can provide information, through detailed analysis, regarding the applied blast pressure and impulses. See damaged blast indicator and undamaged blast indicator.
- **Blast Impulse:** The integrated area under the blast associated pressure-time curve.
- **Blast Load:** The load applied to a structure or object from a blast wave, which is described by the combination of pressure and either impulse or duration.
- **Blast Pressure:** The peak pressure (above ambient) associated with a blast wave generated by an explosion.
- **Combustion**: A chemical reaction that occurs between a fuel and an oxidizing agent. This reaction can also be described as exothermic decomposition.
- **Confinement**: A physical surface that inhibits the expansion of a flame front of a burning vapor cloud in at least one direction. Examples include solid decks, walls, or enclosures. It should not be confused the traditional process safety related term of confined space (as in "confined space entry permit").
- **Congestion**: A collection of closely spaced objects in the path of the flame front that has the potential to increase flame speed to an extent that it can generate a damaging blast wave.

- **Damaged Blast Indicator**: An object damaged by blast pressure that can provide information, through detailed analysis, regarding the applied pressure and impulses required to cause the observed damage.
- **Directional Indicator:** A damaged object which has been deformed away from an explosion center and hence indicates the direction of blast wave travel. Directional indicators may be used to locate explosion centers.
- **Explosion**: A release of mechanical, chemical, or nuclear energy in a sudden manner resulting in the generation of a blast wave.
- **Free-Field Pressure**: Blast wave pressures which are unimpeded by obstructions in the path of the wave.
- **Impulse**: The integrated area under the blast pressure-time curve.
- **Reflected Pressure:** An amplification of local blast pressure due to interaction of the blast front with a surface or object, such as a building wall. An upper limit occurs for an infinite rigid wall aligned normal to the path of the blast wave. Oblique reflections occur when the interaction is off-normal angle of incidence and typically (but not always) results in less pressure enhancement than does a normal reflection.
- **Reflected Impulse:** The integrated area under the associated reflected blast pressure-time curve.
- **Undamaged Blast Indicator:** An object that remains undamaged after being subjected to blast pressure that can provide information, through detailed analysis, regarding the minimum applied pressure and impulses required to cause the onset of damage which is a threshold that the applied pressures and impulses were below due to the lack of observable damage.

2 Didion Milling Facility Description

The Didion Milling facility was built in stages between 1991 and 2013 with the older portions at the north end and the newer sections at the south end. The facility consisted of several distinct buildings, as shown in Figure 2-1. Mill A, the stairwell and the Mill A air shaft were constructed of cast-in-place reinforced concrete. Mill B consisted of precast concrete walls dowelled into cast-in-place floor slabs that were supported by four cast-in-place concrete columns with drop panels at each column overhead slab interface. The remaining construction of the milling complex including the Warehouse, Boiler Room, and Mills C, D, and F were precast concrete with insulated precast concrete walls. The Warehouse, packaging area and Mill C were part of the Multipurpose Building. The Multipurpose Building roof was constructed of precast hollow core planks resting on precast girders and columns. Each section of the facility is discussed in greater detail in the following sections.

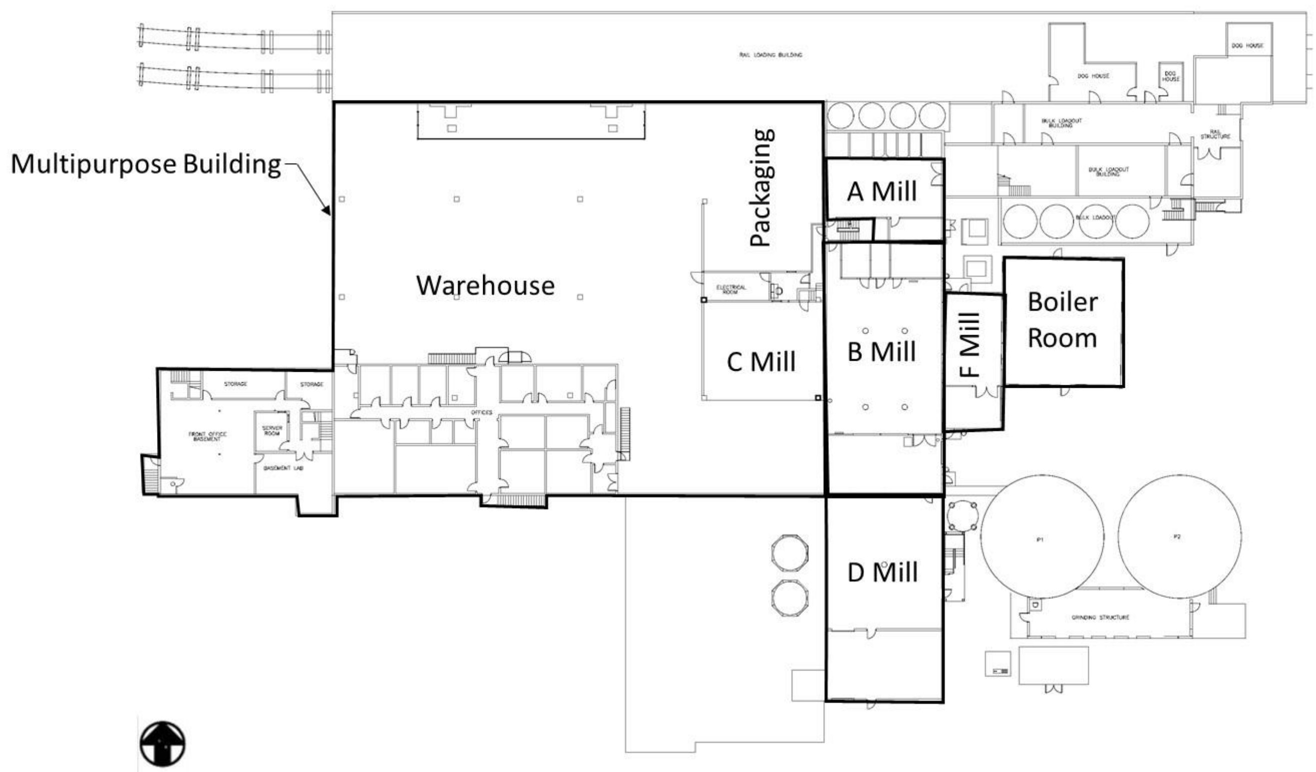


Figure 2-1. Didion Milling Complex Plan View

2.1 Mill A

Mill A was a slip-formed concrete structure that was approximately 39 feet by 42 feet in plan and consisted of 5 interior levels and a filter room on the roof that was enclosed in a metal building. Mill A was designed and constructed in 1991.

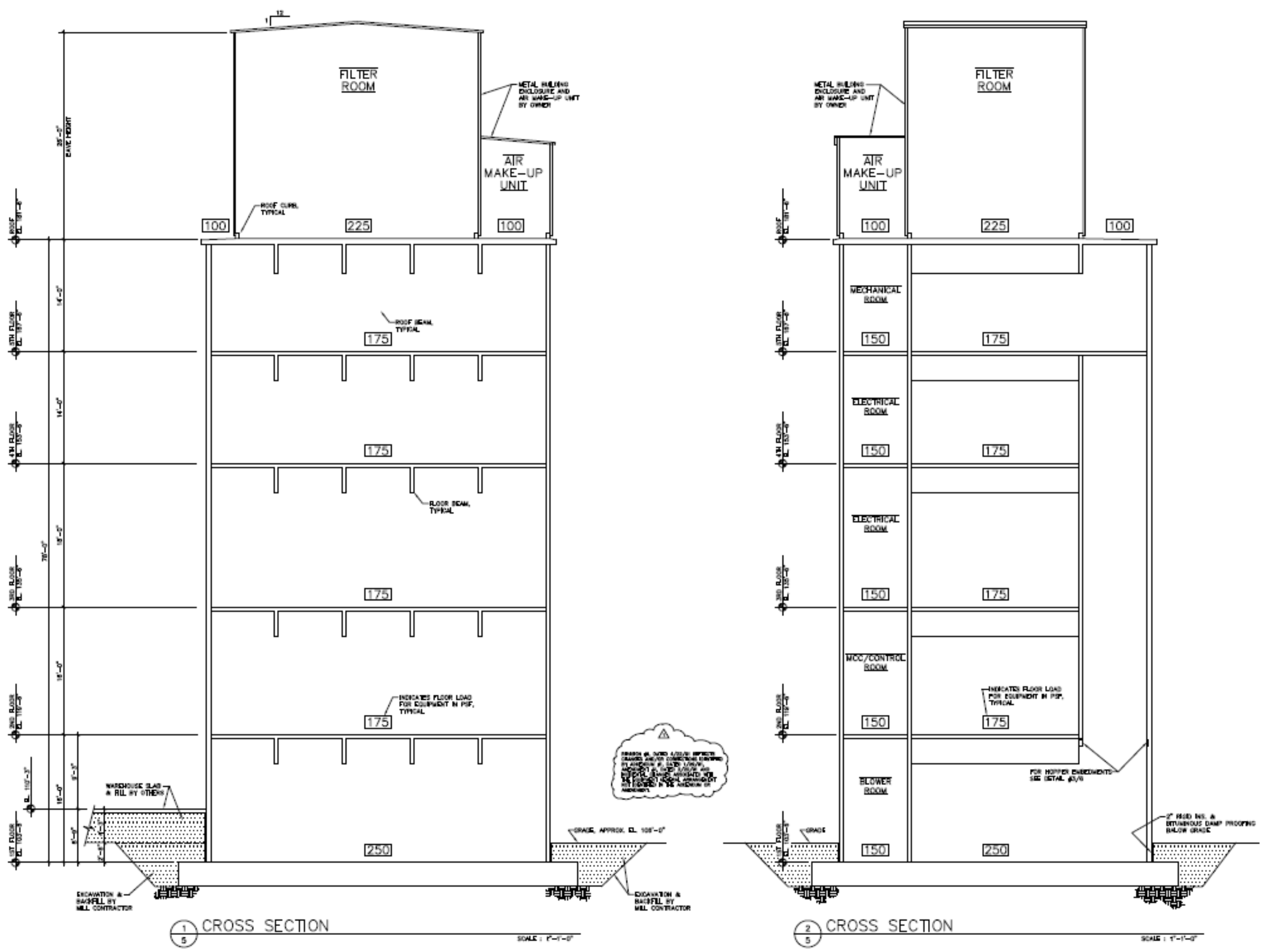


Figure 2-2. Mill A Interior Vertical Cross-Sections

2.2 Mill B

Mill B, which was to the south of Mill A and shared a stairwell, consisted of cast-in-place concrete floor slabs that were supported by four cast-in-place concrete columns with drop caps at each column overhead slab interface. Mill B was designed and constructed in 2001-2002.

Failure of the connections between the Mill B precast wall panels and the Mill B floor slabs were observed after the Didion explosion. A perspective of the failure at level 2 of Mill B is provided in Figure 2-3 and shown in detail in Figure 2-4. Provided drawings show the precast wall panel connection to be an embedded #4 reinforcing bar dowel secured with adhesive at each floor slab at various spacing along the perimeter of Mill B. The dowels were specified to be drilled into the walls using the Hilti HVA capsule adhesive system with 4 ¼ in. embedment into the walls, as shown in Figure 2-5.

Figure 2-3. Mill B Wall Panel to Level 2 Slab Connection Failure Perspective

Figure 2-4. Mill B Wall Panel to Level 2 Slab Connection Failure Detail

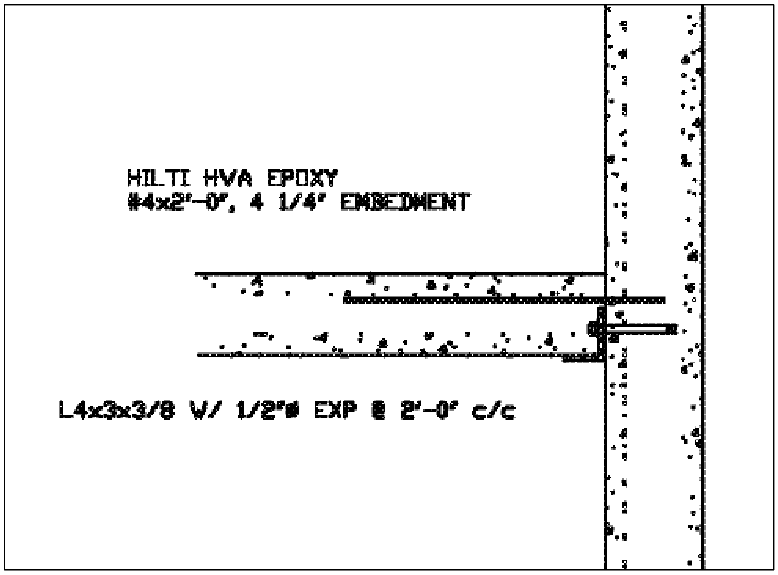


Figure 2-5. Typical Precast Wall Panel Connection to Floor Slab

Both the west and east facades of Mill B collapsed at the 4th level as shown in Figure 2-6 and Figure 2-7, respectively. The Mill B wall panels at the 4th level rested on the 4th floor slab and abutted the 5th level / roof as shown in the drawing section in Figure 2-8. The bottom of the 4th level wall connection to the 4th floor slab was assumed to be (2) #7x10 in. long dowel pins per 9 ft. wide panel (similar to Mill F detail 2/A6). The dowels at the bottom of the wall panel are visible in Figure 2-9. The dowels extended vertically into the top of the slab and were assumed to be centered on the 9-¼ in. thick wall.

The top of the 4th level wall connection to the 5th floor/Roof slab was detailed on the original Mill B drawings with the #4 horizontal dowels into the face of the wall with 4 ¼ in. embedment and are shown in Figure 2-10. The wall panels extended 6 in. above the top of 5th/Roof slab. The spacing of these dowels varied along the east and west facades resulting in varying wall connection capacities.

Figure 2-6. Mill B West Façade at 4th Level

Figure 2-7. Mill B East Façade at 4th Level

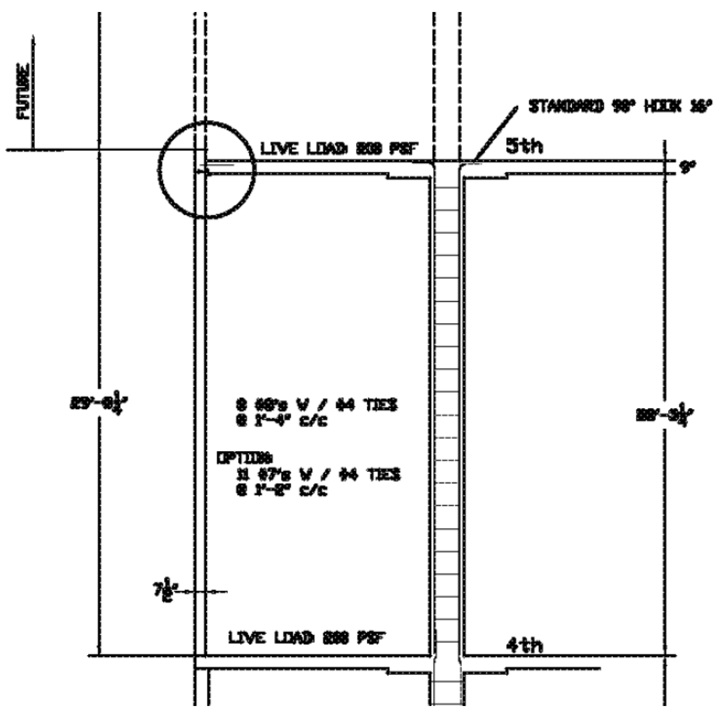


Figure 2-8. Mill B Precast Wall Panel Connections at 4th Level

(a)

(b)

Figure 2-9. Mill B Wall Panel Bottom Connection at 4th Level (a) West Façade (b) East Facade


(a)

(b)

Figure 2-10. Mill B Wall Panel Roof Slab (a) West Façade (b) East Façade

2.1 Mill D

Mill D, which was to the south of Mill B, completed the main milling building with Mills A and B and was similar to Mill B in construction. Mill D was designed and constructed in 2011. All of the floor and roof slabs were cast-in-place slabs. The floors had a single interior cast-in-place column at the north half of the building and there was an interior precast wall that supported the floors from the foundation up to the underside of the 4th floor at the south end of Mill D. An additional interior concrete column extended from the 4th floor to the roof above the interior precast wall. The perimeter precast wall panels were continuous from the cast-in-place concrete stem wall up to the underside of the 4th floor. An additional set of panels were supported on top of the 4th floor slab and extended to the roof.

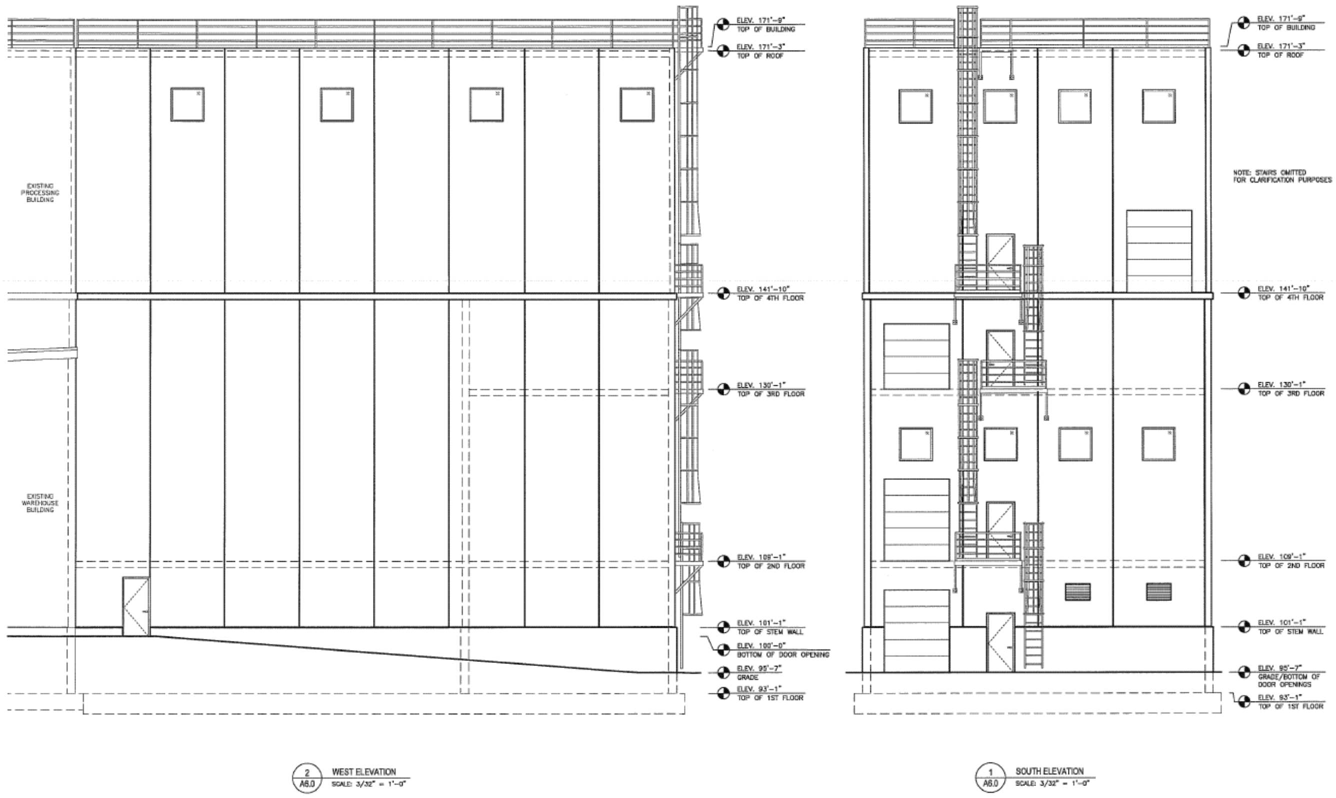


Figure 2-11. Mill D Exterior Elevations

2.2 Mill C

Mill C was located inside the Multipurpose Building, west of Mill B. Mill C measured approximately 68 feet by 44 feet in plan and consisted of two levels. The building was precast tilt-up construction similar in construction to Mills B and D. Mill C was designed and constructed in 2010.

2.3 Mill F

Mill F, located between Mill B and the Boiler Room was a pre-cast concrete structure. Mill F was designed and constructed in 2004. The 2nd floor slab was cast-in-place and the 3rd floor and roof slabs were hollow-core planks that also included a 2 in. topping slab. The east wall of Mill F was supported by the west wall of the Boiler Room as shown in Figure 2-12.

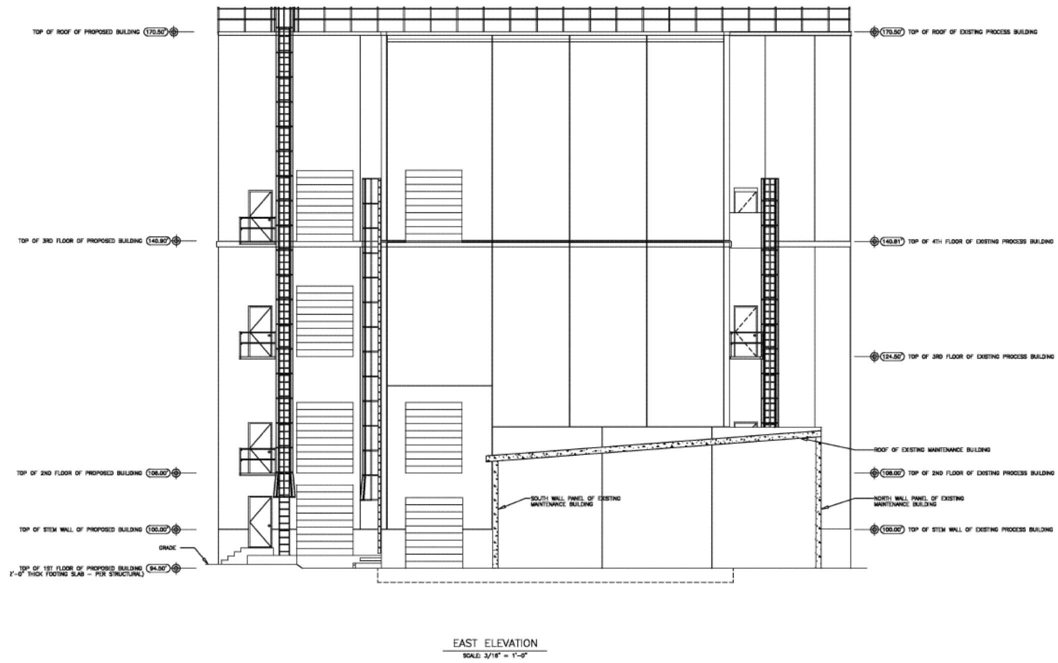


Figure 2-12. Mill F East Elevation

2.4 Boiler Room

The Boiler Room was a single story precast tilt-up one story building located to the east of Mill F. The Boiler Room was constructed in 1994 with insulated concrete precast tilt-up walls and 10 in. hollow core plank roof that spanned east to west and were supported on steel angles anchored to the walls.

2.5 Multipurpose Building

The Multipurpose Building was a precast tilt-up concrete structure designed in 1998 to replace a smaller metal warehouse building that was west of Mill A. The Multipurpose Building structure was a tall one-story building measuring 175 ft. in the east-west direction by 140 ft. in the north-south direction and was located directly west of the Mill A and Mill B structures. A low roof lean-to load-out cover over two rail lines was attached at the north side of the Multipurpose Building. A low roof loading dock cover was attached at the north end of the west elevation along with a low roof office area at the south end of the west elevation.

The Multipurpose Building consisted of four 35 ft. wide bays. The bays were formed by the exterior walls at the north and south elevations and three interior precast column/beam lines. There were five 24 in. x24 in. precast columns in each column line. The four precast beams in each line were not dimensioned on the drawings but based on photos appeared to be approximately 36 in. wide by 48 in. tall and were simply supported beams bearing directly on top of the columns. Column spacing was 41 ft. and 44 ft. on center with the end bays being slightly narrower to so that the outer columns were inside the building's east and west walls. The roof was formed by 12 in. deep hollow core planks, shown in Figure 2-13, spanning between the north and south bearing walls and interior column/beam grid lines. No topping slab was used on top of the hollow core planks.

Figure 2-13. Multipurpose Building Hollow Core Roof Plank

The outer walls of the Multipurpose Building were 12 in. thick tilt-up insulated panels consisting of an 8 in. interior layer of structural concrete, 2 in. rigid insulation, and a 2 in. exterior layer of concrete.

The available drawings do not show any information regarding connections between precast elements. Therefore, a detailed review of photos taken after the explosion and collapse was performed to look for evidence of precast connections that may have been used. This photo review along with a precast concrete literature search forms the basis of the following conclusions about the precast construction of the Multipurpose Building. Based on the shape and configuration of the hollow core slab and holes observed in the collapsed structure, the manufacturer of the hollow core slabs used at the Multipurpose Building was most likely Spancrete. Their corporate headquarters is located in near Cambria in Milwaukee, Wisconsin.

2.5.1 Beam to Column Connections:

The beam to column connections were simple bearing connections as shown in Figure 2-14. In a typical precast beam to column connection, the precast beam sits on a bearing pad on top of the column. The beam is dropped over a dowel that extends out of the top of the column. The dowel goes into a vertical tube placed through the depth of the beam. Once the beam is set in place, this tube is grouted solid to prevent the beam from shifting off the column. (See the attached Spancrete typical detail BC-8 in Figure 2-15.)

Figure 2-14. Failed Multipurpose Building Beam to Column Joint

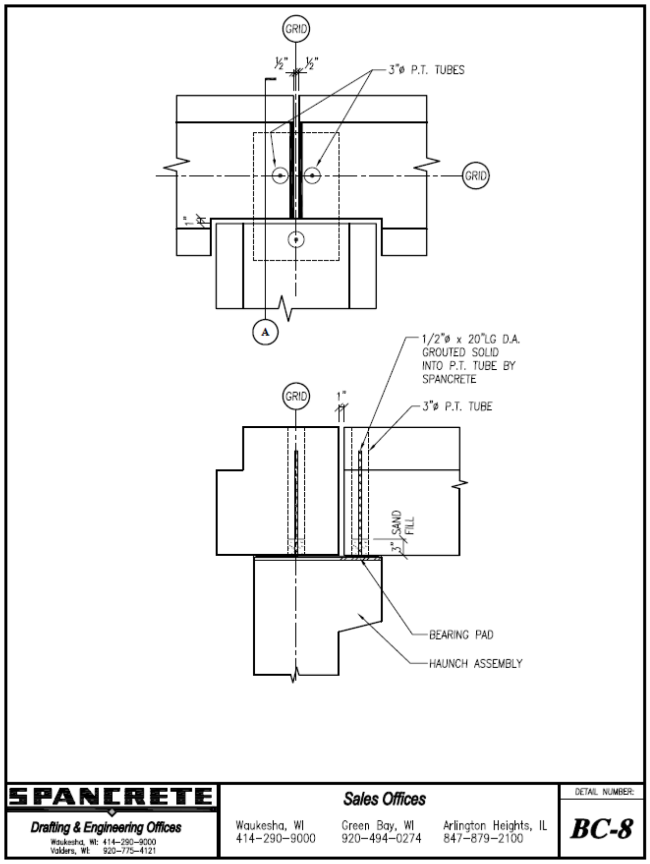


Figure 2-15. Spancrete Typical Beam to Column Detail

In the few bays in which the beam was dislodged from the columns, the grout hole in the bottom of the beam is observable in the overhead drone photos shown in Figure 2-16. It is noted that there does not appear to be grout visible in the holes. Dowels extending from the top of the columns are visible in the photographs, including the example in Figure 2-17. However, the grout holes in the beams appear to be ungrouted when viewed from the underside of the beam. Therefore, it is concluded that the beams were resting on top of the columns with little to no physical connection between elements other than an ungrouted dowel.

Figure 2-16. Multipurpose Building Beam Grout Hole

Figure 2-17. Multipurpose Building Top of Column with Visible Dowel

2.5.2 Hollow Core Slab to Beam connections:

The hollow core slab to precast beam connections were simple bearing connections. The building section on the available drawings shows the hollow core slab planks extending over and splicing at the midpoint of the precast beams, with no physical connection to the precast beam. This is consistent with a typical hollow core slab on precast beam detail from Spancrete which shows a simple bearing strip supporting the end of the hollow core slab. See the attached Spancrete typical detail H-35 in Figure 2-18.

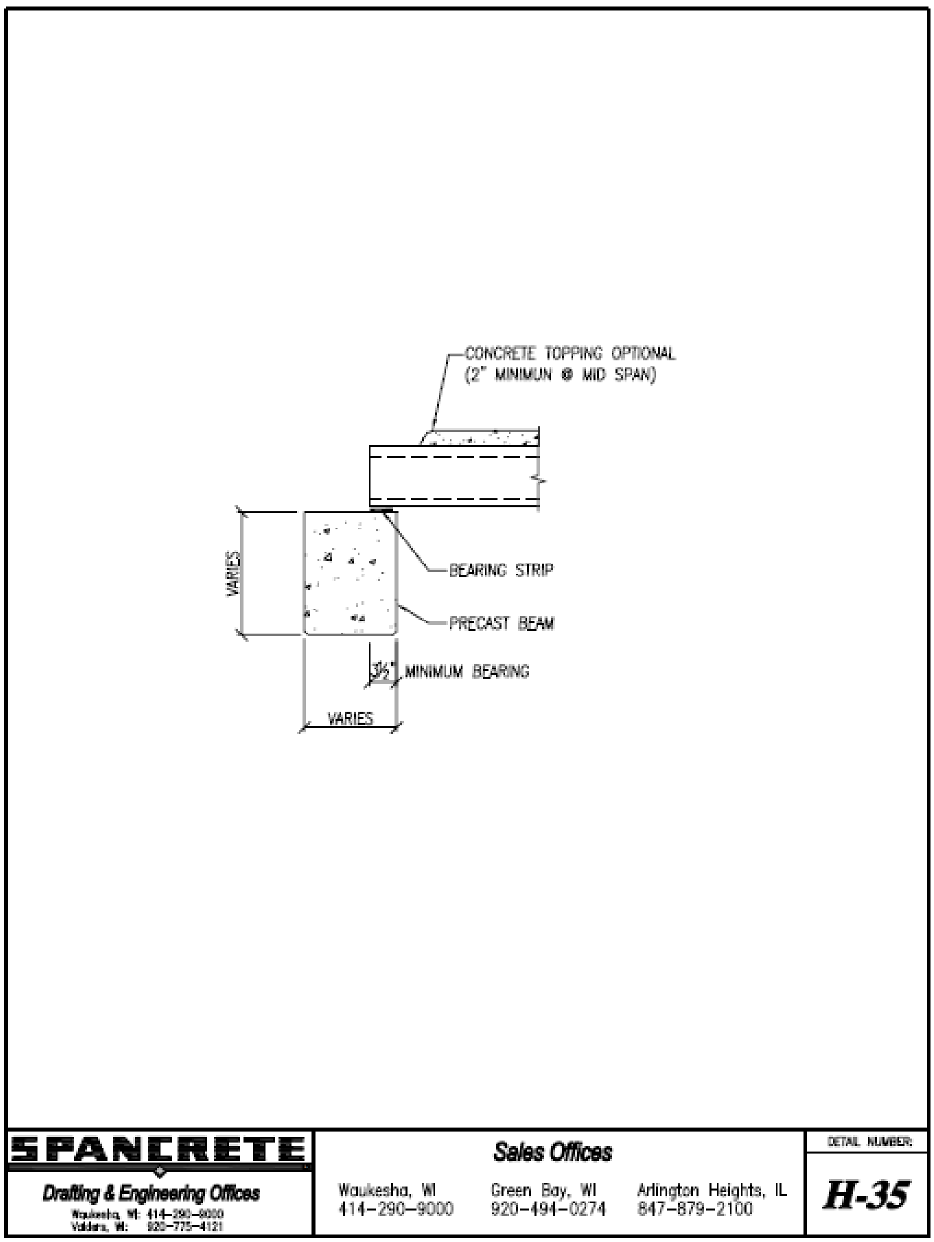


Figure 2-18. Spancrete Typical Hollow Core Plank to Precast Beam Bearing Detail

In a number of overhead aerial photographs, including the one provided in Figure 2-19, it is evident that the top of the exposed concrete beams are smooth and free from any extended dowels (or spalled concrete suggesting the presence of dowels). There are also no embedded corner angles to which the underside of the hollow core slabs could have been welded. Therefore, it is concluded that the hollow core slabs were simply resting on top of the precast beams with no physical connection between elements.

Figure 2-19. Top of Multipurpose Building Beams

2.5.3 Hollow Core Slab to Perpendicular Wall connections:

The hollow core slab to perpendicular wall connections were simple bearing connections. The building section shown on the available drawings shows the hollow core slab extending over the top of the north and south precast bearing walls with no physical connection to the precast wall referenced. This is consistent with a typical hollow core slab on wall detail from Spancrete which shows a simple bearing strip supporting the hollow core slab over the supporting walls as referenced in Spancrete typical detail H-4 shown in Figure 2-20.

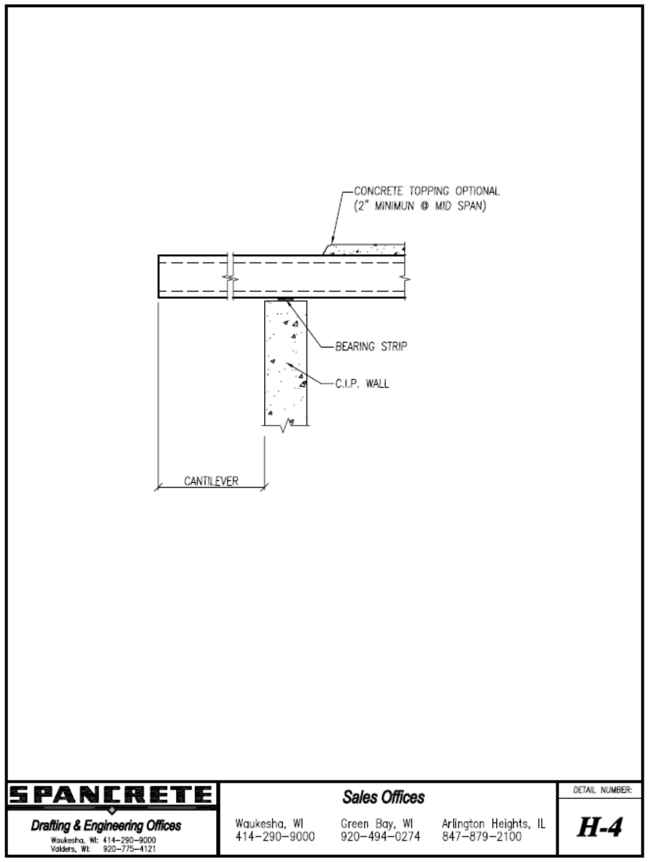


Figure 2-20. Spancrete Typical Hollow Core Slab to Perpendicular Wall Bearing Connection

In a few photographs, as shown in Figure 2-21, small rebar dowels sticking out of the top of the exposed concrete walls can be seen. These bars were likely used to tie the wall to the slabs for out-of-plane wall loads. The bars appear to be #3 or #4 bars at approximately 4 ft. on center (which matches the width of the hollow core slab panels). Therefore, it is concluded that each hollow core slab plank was connected to the walls by extending the rebar dowel through the slab into the top of the walls as shown in Spancrete typical detail H-6 in Figure 2-22. It is unclear whether any grout was placed around the dowel inside the hollow core slab cavity.

Figure 2-21. Multipurpose Building Load Bearing Wall Dowels into Hollow Core Planks

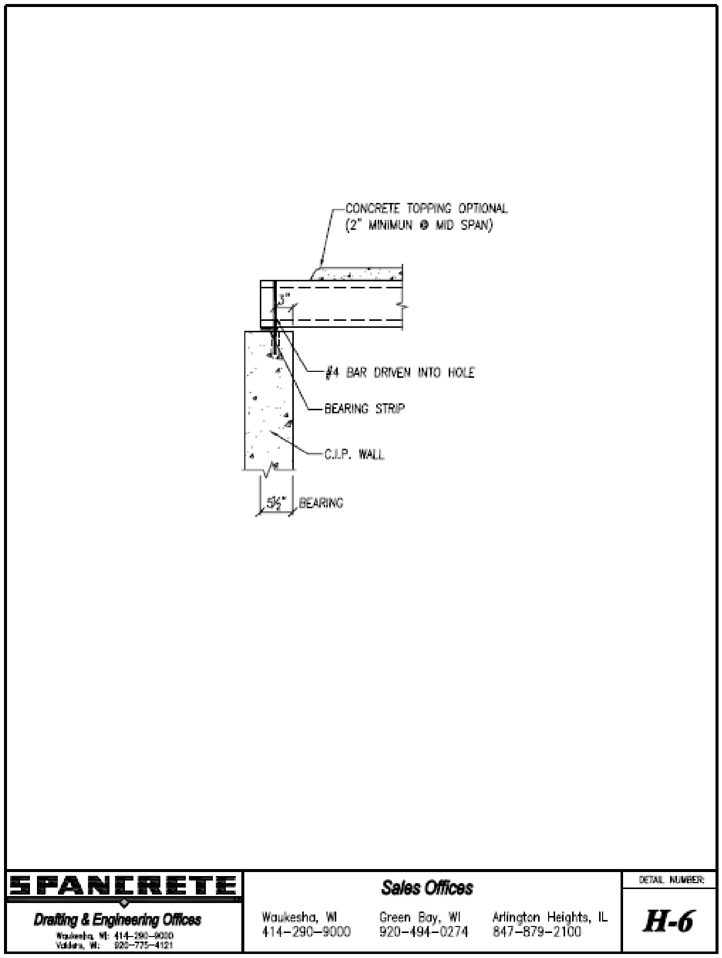


Figure 2-22. Spancrete Typical Hollow Core Plank to Precast Wall Detail

2.5.4 Hollow Core Slab to Parallel Wall Connections:

The hollow core slab to parallel wall connections were simple bearing connections. There are no building sections shown on the available drawings showing the hollow core slab extending over the top of the east and west precast non-bearing walls. Based on photographs and a review of typical Spancrete details it is likely rebar dowels were extended through the slab into the top of the walls similar to the perpendicular walls (see Spancrete typical detail H-13).

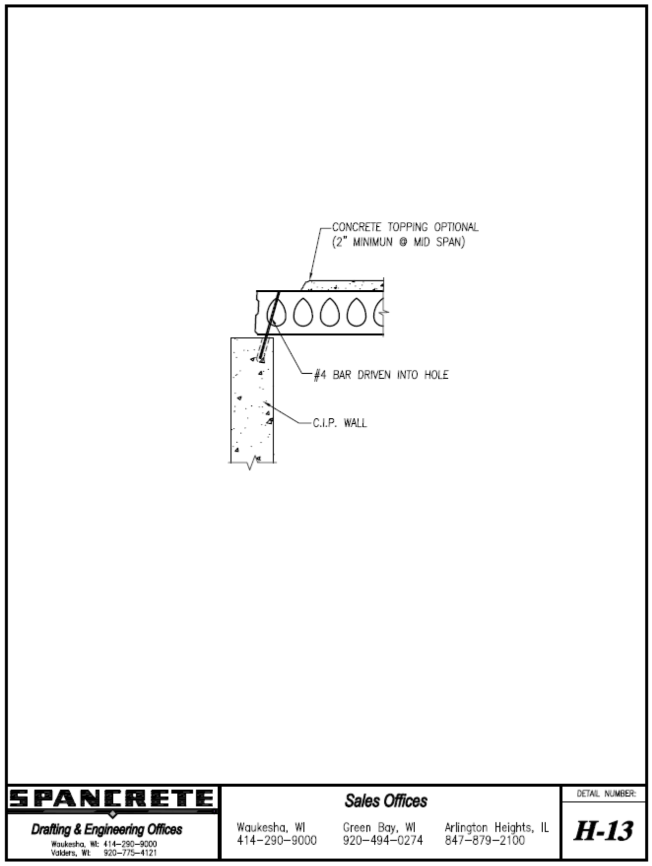


Figure 2-23. Spancrete Typical Hollow Core Slab to Parallel Wall Bearing Connections

3 Site Survey and Data Collection

Site surveys were conducted by the ABS Group team on June 7-8 and June 12-15, 2017. The site surveys were conducted to collect information from the explosion scene to support the forensic analysis as detailed in the following sections.

On-site survey of explosion damage included documentation of blast indicators, directional indicators and fire indicators within the interior of Mill A and Mill B as well as the exterior of the Didion facility. Observations were also made for development of the CFD model including openings between structures. Due to the extent of the damage to the facility, entries were limited to levels 1 through 3 of Mill B and 1 through 5 of Mill A to minimize exposure of the investigation team to potential collapse hazards. No entry was made into level 4 of Mill B, the southern portion of B Mill, D Mill, F Mill, the Boiler Room or Multipurpose Building.

Propagation of the explosion resulted in the complete collapse of the overhead concrete roof of the Mutipurpose Building, Mill F, and the Boiler Room. Precast walls of Mill B collapsed above the 3rd level and were failed at the south end of Mill B on both the west and east facades. Mill D precast panel connections failed and the wall panels were deflected at the 2nd level. Mill D was determined (by others) to be too unstable for entry and demolition of this mill was planned. An overhead view of the milling complex damage and collapse is shown in Figure 3-1. Damage to the west façade is shown in Figure 3-2, and the east façade in Figure 3-3.

Figure 3-1. Overhead Photo of Didion Milling Complex Collapse

Figure 3-2. Milling Building West Façade

Figure 3-3. Milling Building East Façade

3.1 Directional Indicators

Directional indicators are mapped to aid in the identification of explosion centers and origins and are deformed by the blast wave in the direction of travel of the wave and aid in identifying the explosion source(s) or location(s). Experience is used to identify situations that can affect the direction of damage, such as blast reflections off nearby surfaces and structural rebound. Large dust cloud explosions may envelop multiple regions of confinement and produce multiple explosion centers.

ABS Group mapped directional indicators within the accessible portions of Mill A and Mill B to determine the room of origin of the damaging explosion. Hollow metal doors proved to be a significant directional indicator in addition to openings into the vertical air shafts between Mills A and B, which are highlighted in Figure 3-4. Directionality of fire at the air shaft openings was also documented.

Directional indicators for each level are presented in the following sections along with summary photographs. The directional indicator analysis is confirming for an explosion origin in Level 1 of Mill B with propagation upward in Mill A and B through the vertical air shafts and into the packaging area and Mill F through openings between the areas.

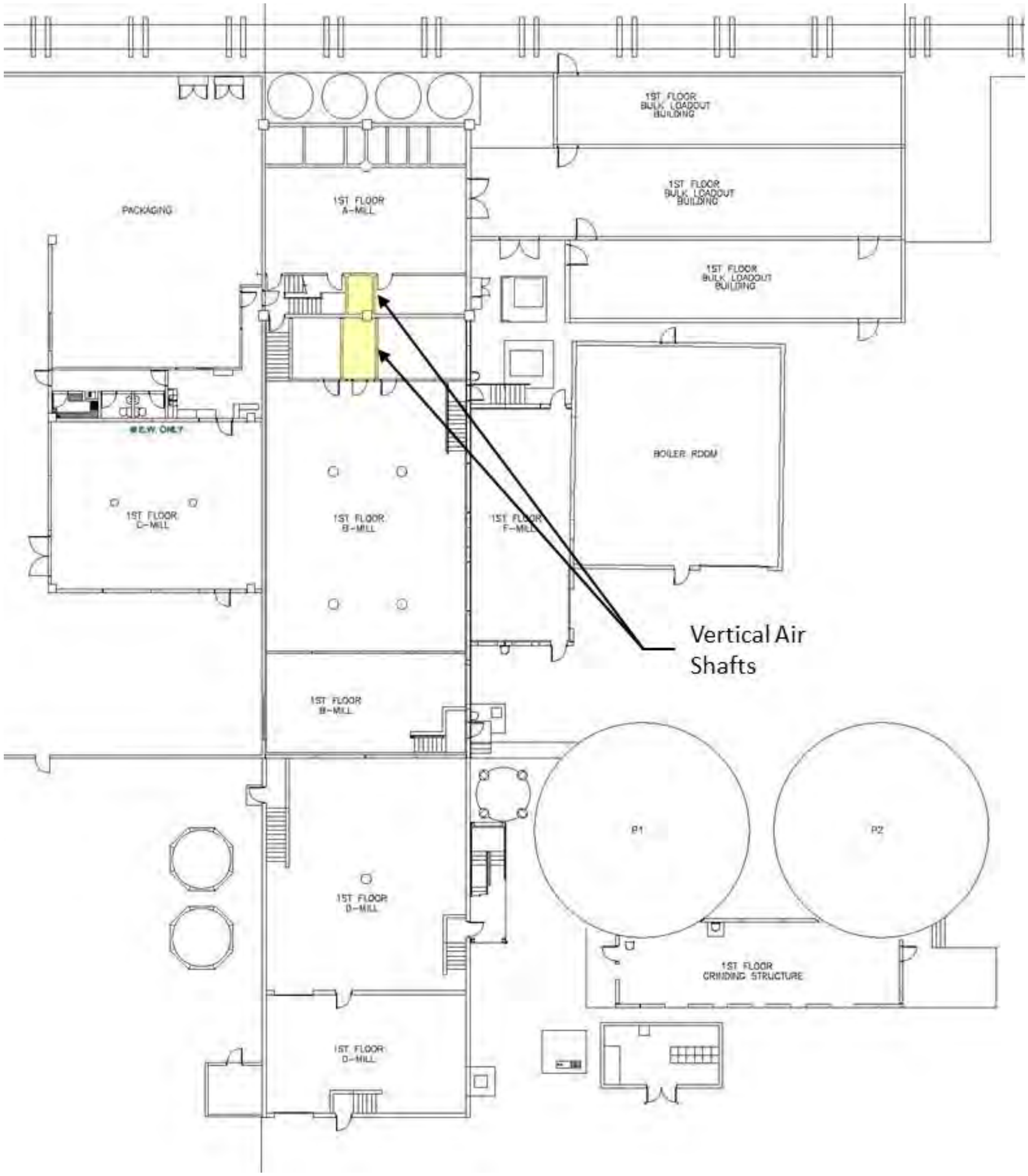


Figure 3-4. Didion Milling Floor Plan Highlighting Vertical Air Shaft Between Mill A & B

3.1.1 Mill A & B First Level Directional Indicators

Directional indicators for the first level of Mill A and Mill B as well as the truck bulk loading are presented in Figure 3-5 and identified in Table 3-1 below. Exemplar indicators provided in Figure 3-6 indicate that overpressure which initiated in Level 1 of Mill B entered the vertical air shaft and exited the air shaft into Level 1 of Mill A. In addition, fire damage to the piping to the exterior of the Level 1 Mill B air shaft opening, highlighted in Figure 3-7, is consistent with a flame traveling from Mill B into the air shaft. The piping was also charred on the mill side of the pipe highlighted in Figure 3-7. The directional indicators are consistent with an explosion occurring in Level 1 of Mill B.

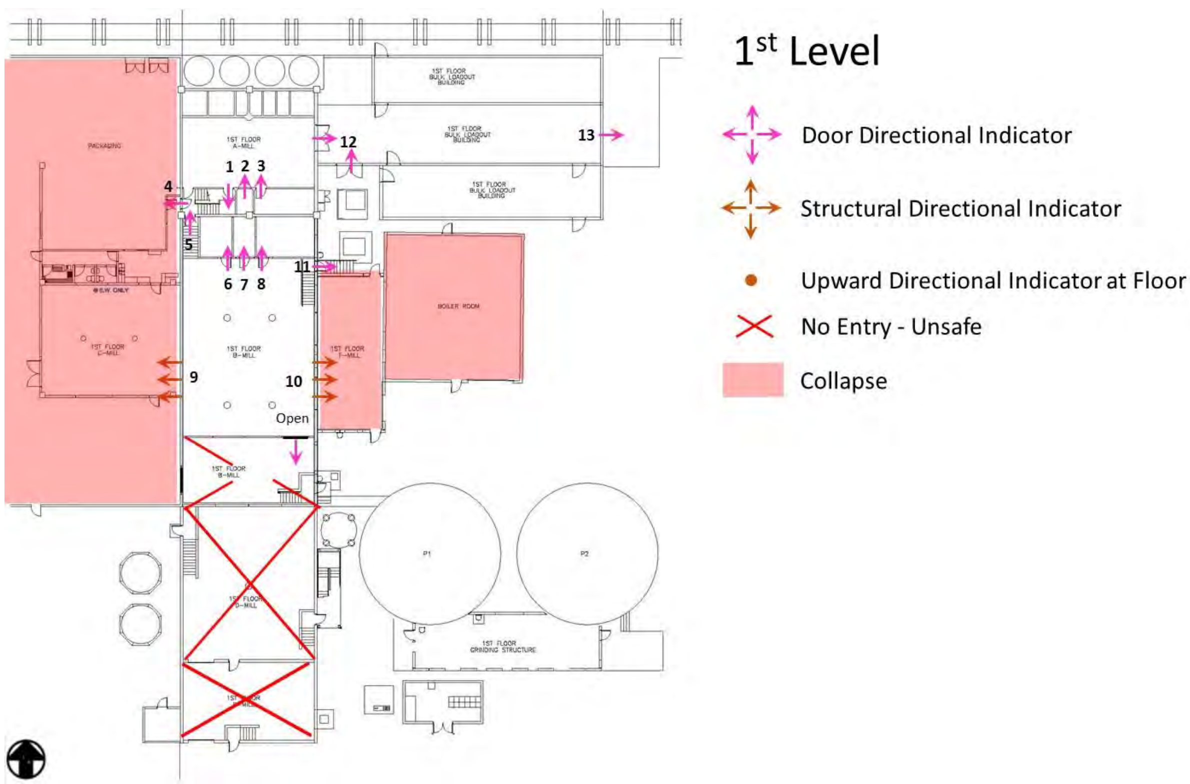


Figure 3-5. Level 1 of Mill A & B Directional Indicators

Table 3-1. Level 1 of Mill A & B Directional Indicator Summary

Directional Indicator Number	Description
1	Mill A stairwell entry door
2	Air shaft access door
3	Mill A switchgear access door
4	Packaging / C Mill stairwell entry door
5	Mill B stairwell entry door
6	Mill B electrical room access door
7	Mill B air shaft access door
8	Mill B switchgear access door
9	Mill B west wall
10	Mill B east wall
11	Mill B to Mill F access door
12	Bulk load out mill access doors
13	Load out truck windshield and dash

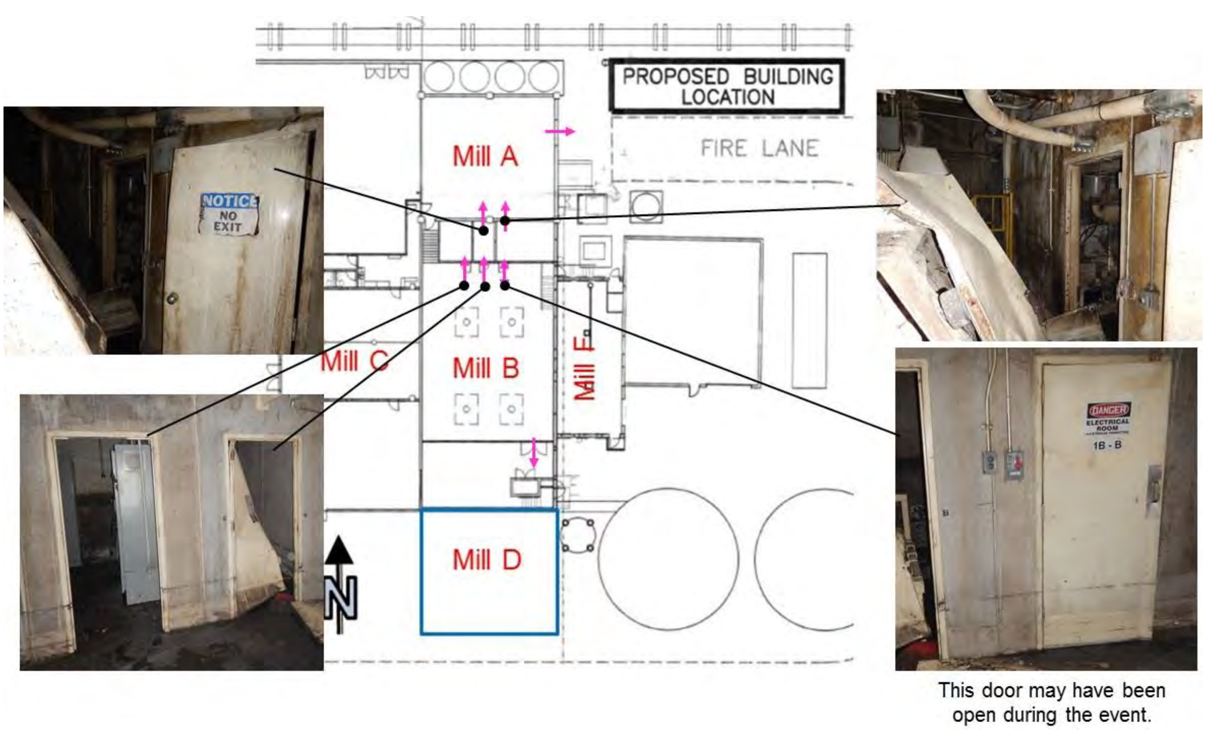


Figure 3-6. Mill A and Mill B Level 1 Exemplar Directional Indicators

Figure 3-7. Mill B Level 1 Air Shaft Opening Fire Directional Indicator

3.1.2 Mill A & B Second Level Directional Indicators

Directional indicators for the second level of Mill A and Mill B as well as the truck bulk loading are presented in Figure 3-8 and identified in Table 3-2 below. Exemplar indicators provided in Figure 3-9 indicate that overpressure entered Level 2 of Mill A and Mill B from the vertical air shaft. The door between Level 2 of Mill B and the stairwell is indicative of overpressure in Level 2 of Mill B. The air shaft on the Mill B side at Level 2 clearly indicates fire travelling vertically in the air shaft upward from the first to second levels as indicated by the fire damage to the underside of the horizontal piping which is shown in Figure 3-10. The air shaft opening at Level 2 of Mill A is shown in Figure 3-11 and the opening between the air shaft and Mill B is shown in Figure 3-12. Both air shaft openings clearly show indications of heat travelling from the air shaft into Mill A and Mill B at the second level of the mill. The directional indicators are consistent with an explosion propagating into Level 2 of Mill A and B from the vertical air shaft.

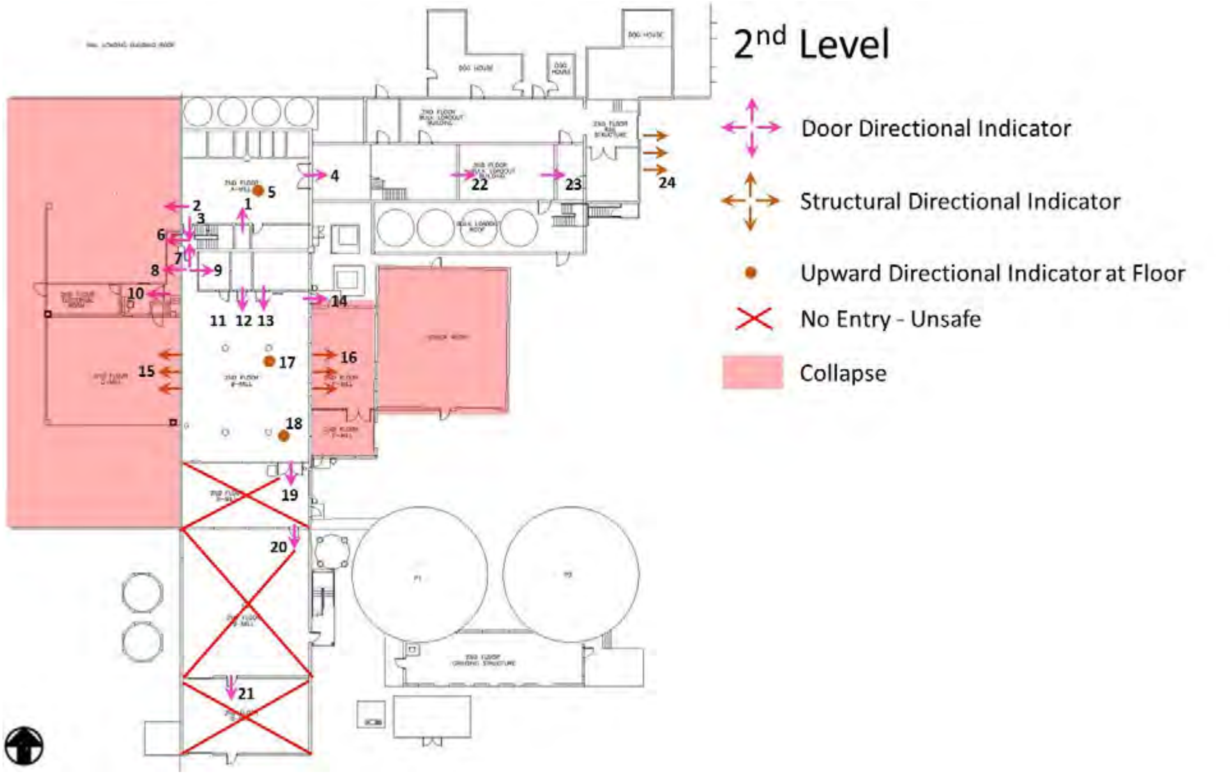


Figure 3-8. Level 2 of Mill A & B Directional Indicators

Table 3-2. Level 2 of Mill A & B Directional Indicator Summary

Directional Indicator Number	Description
1	Mill A air shaft access door
2	Mill A to Packaging Area roll-up door
3	Mill A stairwell entry door
4	Mill A to Bulk Loadout access double door
5	Mill A floor plate upward and dislodged
6	Packaging / C Mill stairwell entry door
7	Mill B stairwell entry door
8	Mill B west wall masonry infill
9	Mil B electrical room wall masonry infill
10	Mill C electrical area access double door
11	Mill B electrical room access door
12	Mill B air shaft access door
13	Mill B switchgear access door
14	Mill B to Mill F access door
15	Mill B west wall
16	Mill B east wall
17	Mill B floor cover plate upward off hole
18	Mill B floor cover plate upward off hole
19	Mill B south double door
20	Mill B to Mill D access door
21	Mill D interior door
22	Bulk Loadout partition wall and door
23	Bulk Loadout partition wall and door
24	Bulk Loadout 2^{nd} level east metal wall

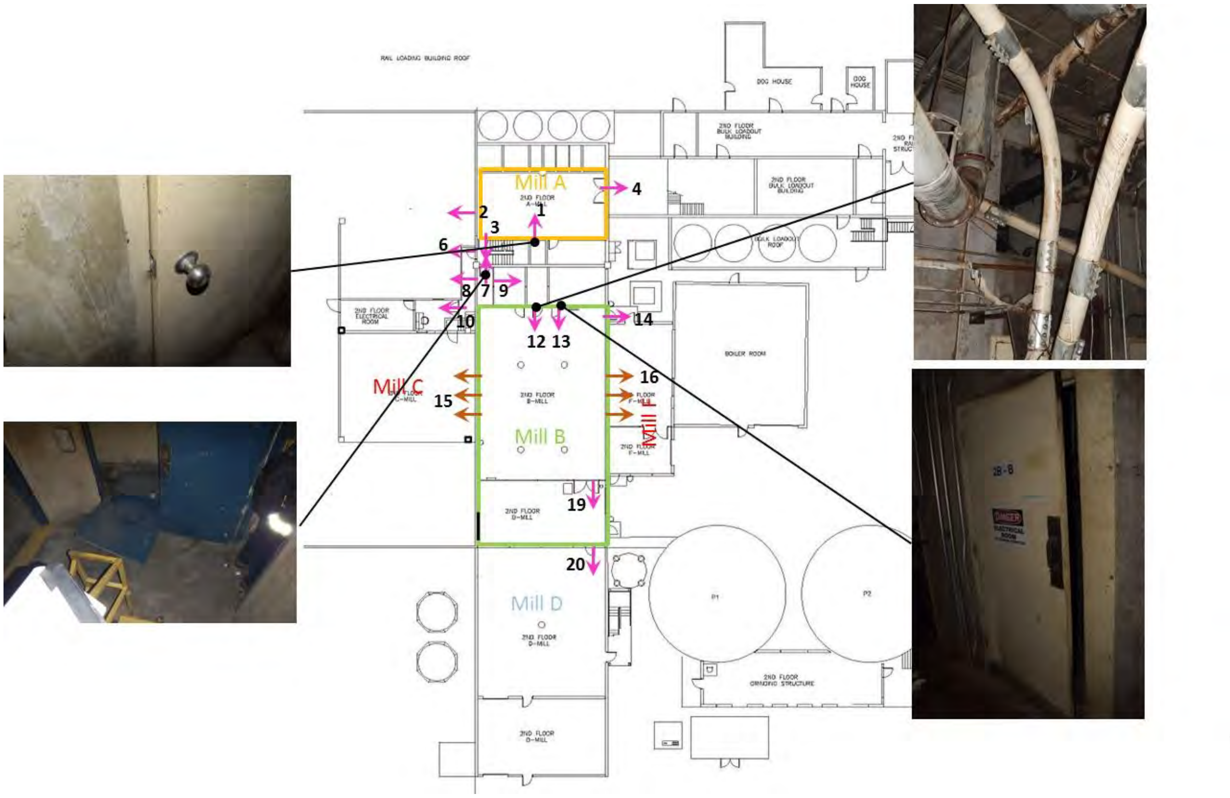


Figure 3-9. Mill A and Mill B Level 2 Exemplar Directional Indicators

Figure 3-10. Mill B Level 2 Air Shaft Fire Directional Indicator

Figure 3-11. Mill A Level 2 Air Shaft Opening Fire Directional Indicator

Figure 3-12. Mill B Level 2 Air Shaft Opening Fire Directional Indicator

3.1.3 Mill A & B Third Level Directional Indicators

Directional indicators for the third level of Mill A and Mill B are presented in Figure 3-13 and identified in Table 3-3 below. Examples of the directional indicators are shown in Figure 3-14. Fire exiting the vertical air shaft into both Mill A and Mill B at the third level was indicated by melting of pipe coverings and scorching as shown in Figure 3-15 and Figure 3-16, respectively. These directional indicators are consistent with an explosion propagating into Level 3 of Mill A and Mill B from the vertical air shaft.

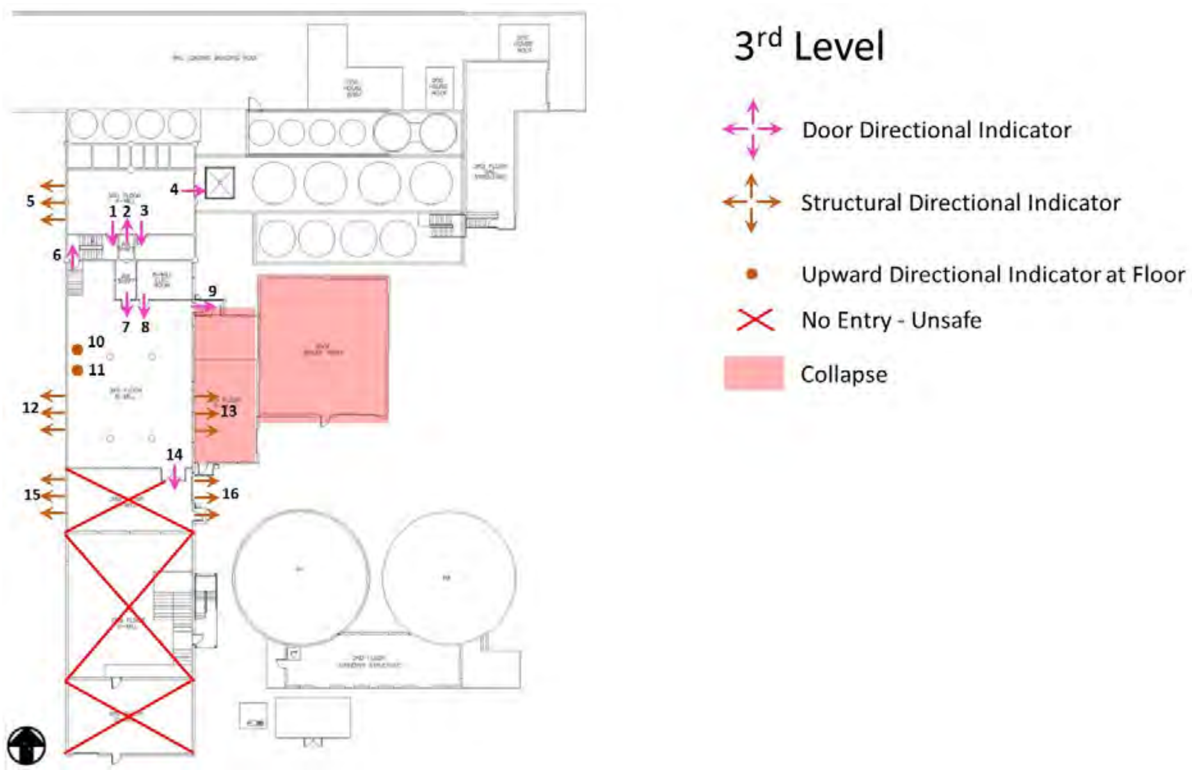


Figure 3-13. Level 3 of Mill A & B Directional Indicators

Table 3-3. Level 3 of Mill A & B Directional Indicator Summary

Directional Indicator Number	Description
1	Mill A stairwell entry door
2	Mill A opening to air shaft
3	Mill A switchgear access door
4	Mill A to Bulk Loadout roll-up door
5	Mill A west wall
6	Mill B stairwell entry door
7	Mill B air shaft access door
8	Mill B switchgear access door
9	Mill B to Mill F access door
10	Mill B cover plate upward off hole
11	Mill B electrical room access door
12	Mill B air shaft access door
13	Mill B switchgear access door
14	Mill B to Mill F access door
15	Mill B west wall
16	Mill B east wall

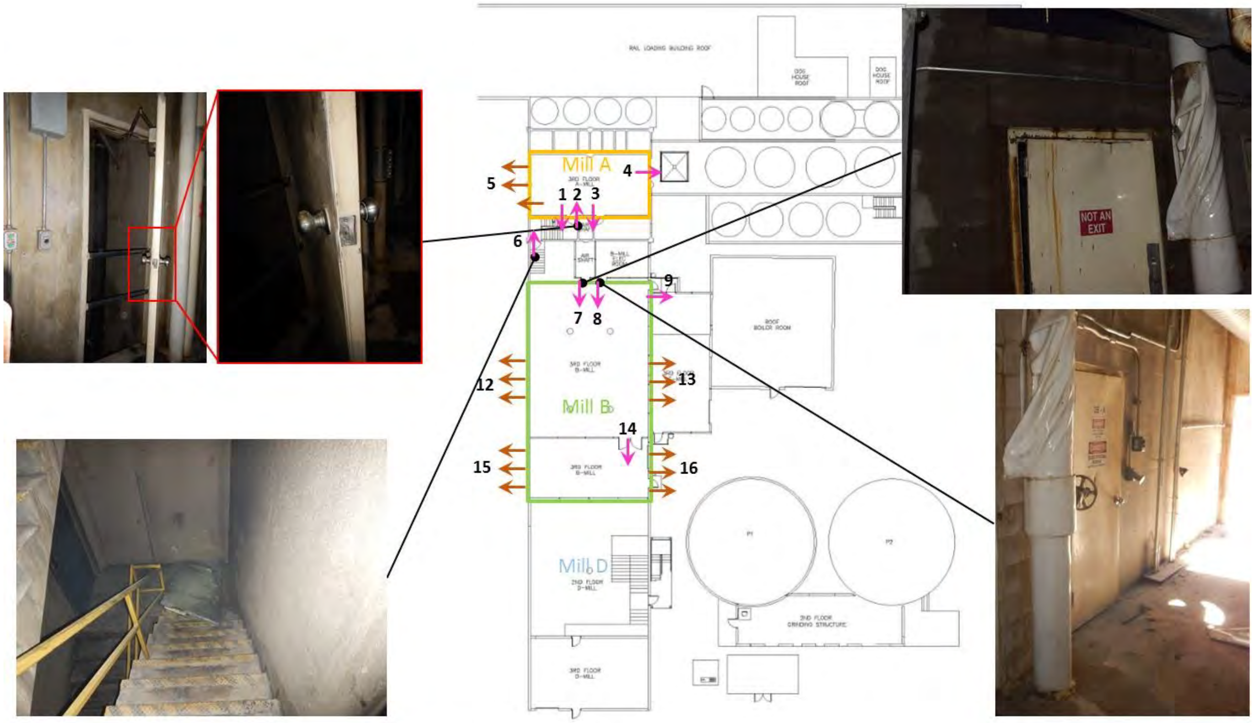


Figure 3-14. Mill A and Mill B Level 3 Exemplar Directional Indicators

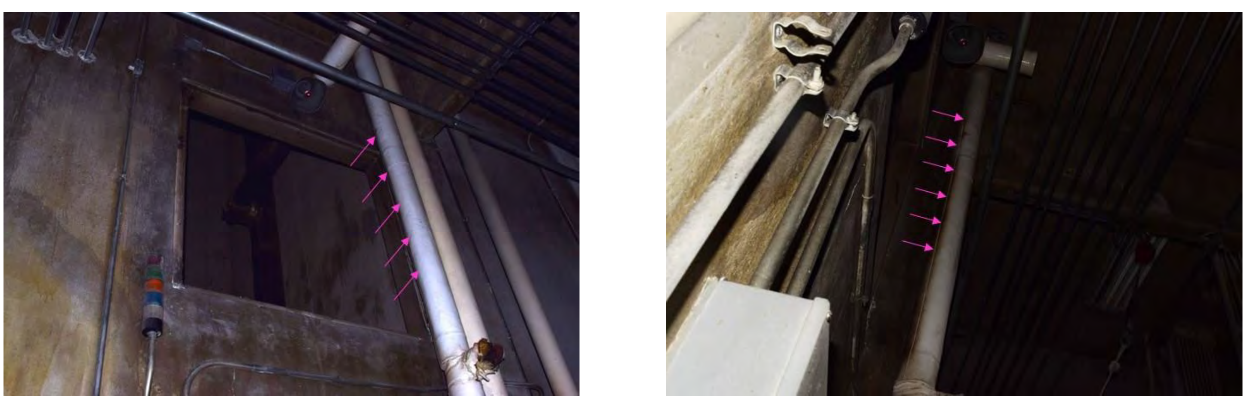


Figure 3-15. Mill A Level 3 Air Shaft Opening Fire Directional Indicator

Figure 3-16. Mill B Level 3 Air Shaft Opening Fire Directional Indicator

3.1.4 Mill A & B Fourth Level Directional Indicators

Level 4 of Mill B could not be accessed safely due to the collapsed side walls and unprotected fall hazards. Drone photos were reviewed in lieu of access. Directional indicators for the fourth level of Mill A and Mill B are presented in Figure 3-17 and identified in Table 3-4 below and examples are provided in Figure 3-18. The exemplar directional indicators show overpressure in the air shaft pushing out of the air shaft into Mill B and overpressure in Mill A that forced the west Wall of Mill A away from the slab. Fire exiting the air shaft into the fourth level of Mill A is evident as shown in Figure 3-19; however, the drone photographs of the fourth level Mill B opening, provided in Figure 3-20, were inconclusive for fire indicators due to the range from which the photographs were taken. The directional indicators are consistent with an explosion propagating into Level 4 of Mill A and Mill B from the vertical air shaft.

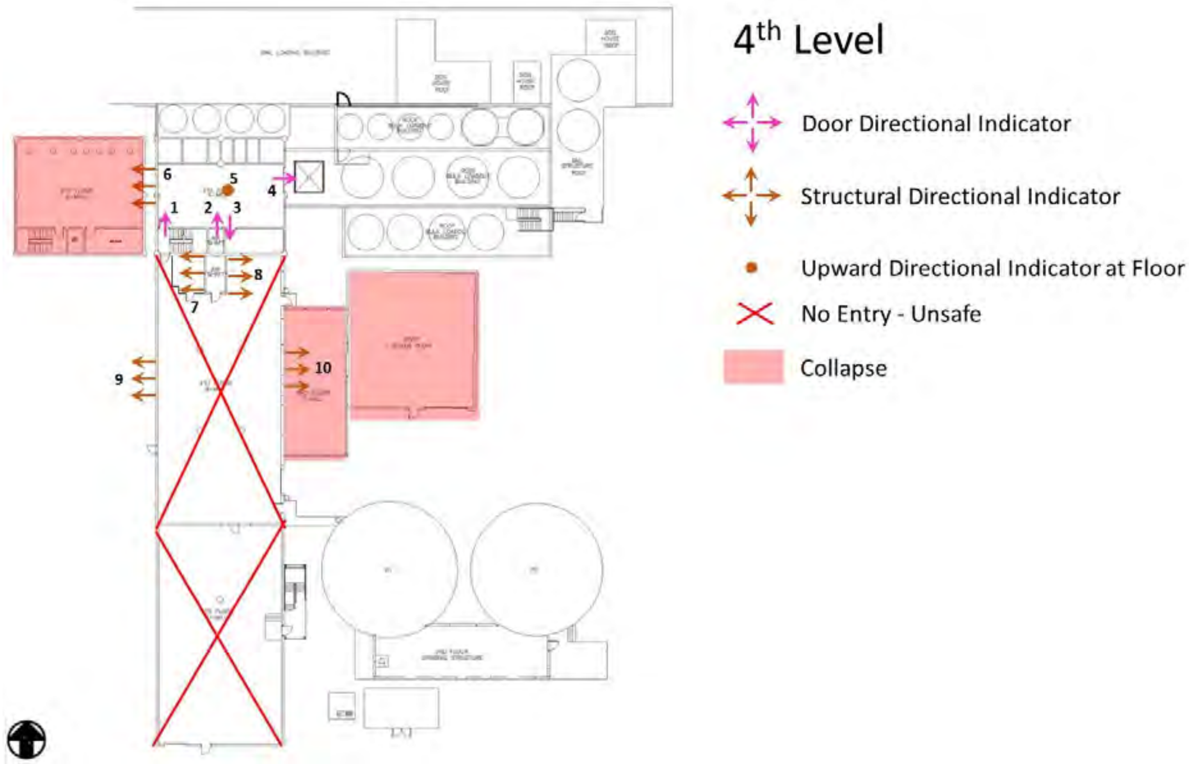


Figure 3-17. Level 4 of Mill A & B Directional Indicators

Table 3-4. Level 4 of Mill A & B Directional Indicator Summary

Directional Indicator Number	Description
1	Mill A stairwell entry door
2	Mill A opening to air shaft
3	Mill A switchgear access door
4	Mill A to Bulk Loadout roll-up door
5	Mill A cover plate upward off hole
6	Mill A West Wall
7	Mill B air shaft west wall
8	Mill B air shaft east wall
9	Mill B west wall
10	Mill B east wall

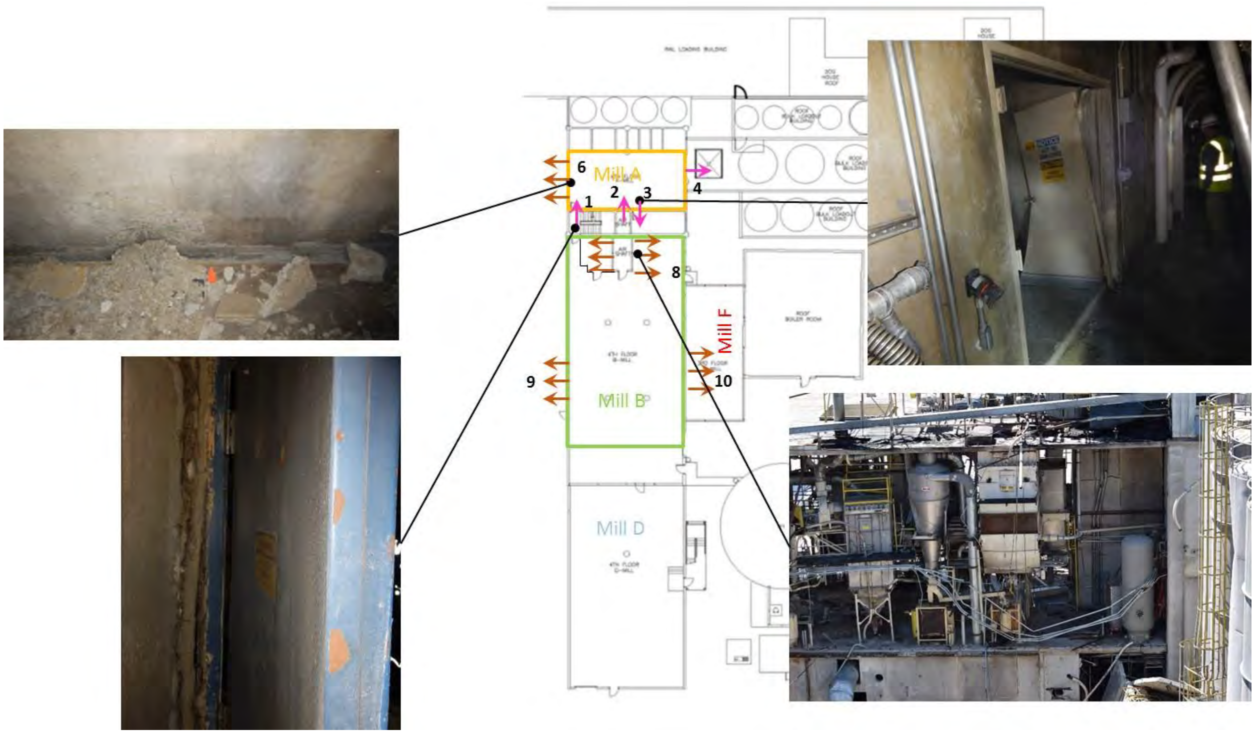


Figure 3-18. Mill A and Mill B Level 4 Exemplar Directional Indicators

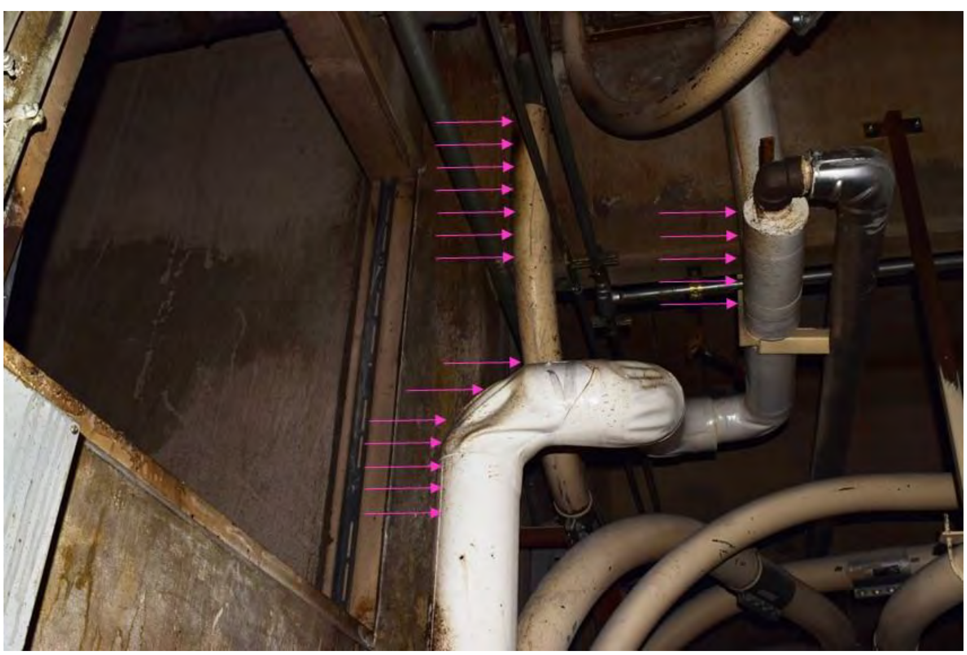


Figure 3-19. Mill A Level 4 Air Shaft Opening Fire Directional Indicator

Figure 3-20. Mill B Level 4 Air Shaft Opening

3.1.5 Mill A Fifth Level Directional Indicators

Directional indicators for the fifth level of Mill A are presented in Figure 3-21 and identified in Table 3-5 below. Examples of the observed directional indicators on level 5 of Mill A indicate overpressure proceeding from the vertical air shaft into Mill A as shown in Figure 3-23. The directional indicators are consistent with an explosion propagating into Level 5 of Mill A from the vertical air shaft.

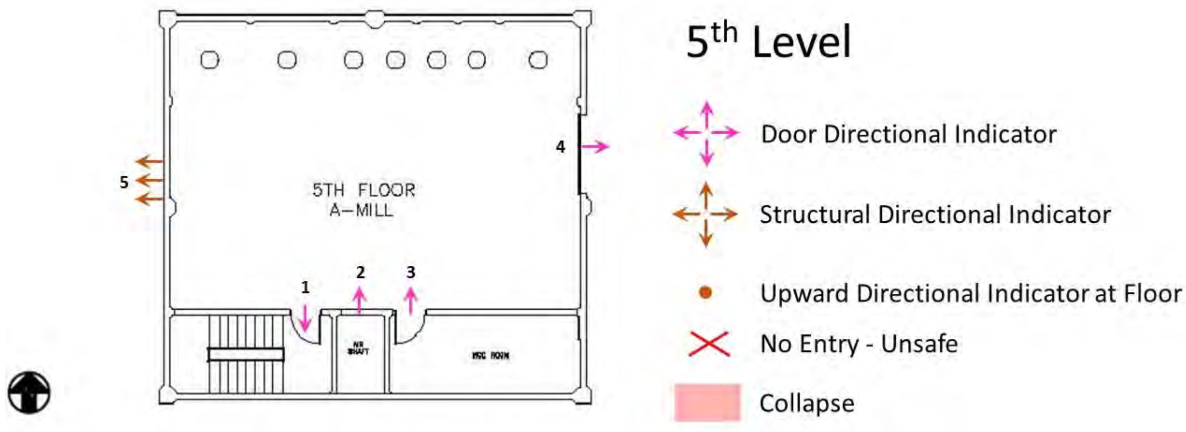


Figure 3-21. Level 5 of Mill A & B Directional Indicators

Table 3-5. Level 5 of Mill A Directional Indicator Summary

Directional Indicator Number	Description
1	Mill A stairwell entry door
2	Mill A opening to air shaft
3	Mill A switchgear access door
4	Mill A to east roll-up door
5	Mill A west wall

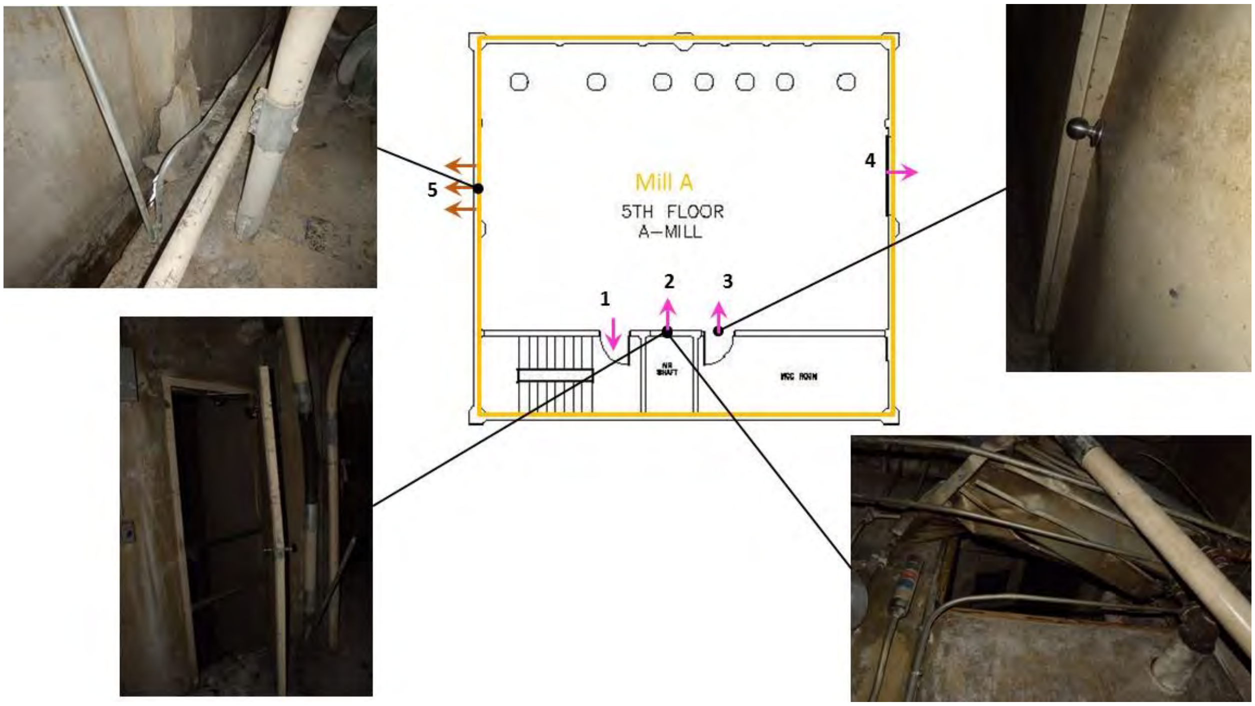


Figure 3-22. Mill A Level 5 Exemplar Directional Indicators

Figure 3-23. Mill A Level 5 Air Shaft Opening Directional Indicator

3.1.6 Mill A Sixth Level Directional Indicators

The sixth level of Mill A could not be accessed due to overhead hazards as shown below in Figure 3-24.

Figure 3-24. Mill A Level 6 Access

3.2 Blast Indicators

The site survey included documentation of damage with photographs and field notes, and measurement of permanent deformations if applicable. The purpose of the evaluation was to provide data that can be used to determine the severity of the explosion in terms of observed pressure and impulse.

Blast indicators are objects either damaged or un-damaged by blast and their state of damage can be used as a measure of the blast pressure and impulse experienced by the object. Often, an object can be both a blast indicator and a directional indicator.

Blast indicators included both qualitative and quantitative measures of blast pressure and impulse. Qualitative blast indicators demonstrate relative levels of damage (e.g., minor, moderate, severe, blowout). Quantitative blast indicators have measurable deformations (obtained in the field survey) and can be analyzed to estimate or bound the applied blast loading magnitude.

The most reliable blast indicators are those with reasonable permanent deformations, such that the response mode (bending, membrane, etc.) can be identified and modeled. Heavily damaged or totally failed components often have response modes that cannot be easily modeled to allow load prediction. The Mill B walls and stairwell doors did allow quantitative comparisons of blast loads even though the damage was heavy. The estimate of the blast pressure and impulse necessary to cause the onset of failure was determined which represents a threshold value, or minimum required to cause the observed failure.

The information collected in the field was used for structural analyses to calculate blast load pressure and impulse combinations that can result in the observed component damage. This process, repeated at a variety of locations, provides feedback to the independent explosion analyses to help determine which evaluated scenario(s) are most consistent with the observed damage.

Pressures and impulses calculated using blast indicators are the applied loads, which are dependent upon orientation of the blast indicator to the path of the blast wave. It is not unusual to find scatter in the predicted values, where side-by-side load indicators have different calculated loads. This scatter is due to numerous reasons including approximations in calculations or accuracy of field measurements. Often the boundary condition for a component may not be truly fixed or simple, but rather some fixity between these types. Variations in boundary conditions can affect the computed pressure and impulse values.

Blast indicators identified in Mill A and Mill B at Didion Milling were both damaged and undamaged. A damaged blast indicator is an object damaged by blast pressure that can provide information, through detailed analysis, regarding the applied pressure and impulses required to cause the observed damage. Examples of damaged blast indicators include stairwell doors, precast walls of Mill B, and cast in place concrete walls in Mill A.

An undamaged blast indicator is an object that remains undamaged after being subjected to blast pressure that can provide information regarding the minimum applied pressure and impulses required to cause the onset of damage. These pressure and impulses represent a threshold that the applied pressures and impulses were below due to the lack of observable damage. These values represent a maximum pressure and impulse that could have occurred. Undamaged electrical boxes were observed in Mill B and Mill A at Didion.

Blast indicators for each level are presented in the following sections along with summary photographs. The blast indicators are incorporated into the CFD model and utilized to evaluate the severity of the damaging explosion in Level 1 of Mill B and whether propagation of explosion was required in order to produce the observed damage at Didion Milling.

3.2.1 Mill A & B First Level Blast Indicators

Blast indicators for the first level of Mill A and Mill B are presented in Figure 3-25 and identified in Table 3-6 below. Examples of indicators provided in Figure 3-26 indicate that an explosion in Level 1 of Mill B was severe enough to cause significant damage to the stairwell door as well as the doors to the air shaft and electrical rooms. Overpressure in Level 1 of Mill B damaged the double door between Mill A and the bulk loading. In addition, a significant overpressure event occurred in the east electrical room attached to Mill A.

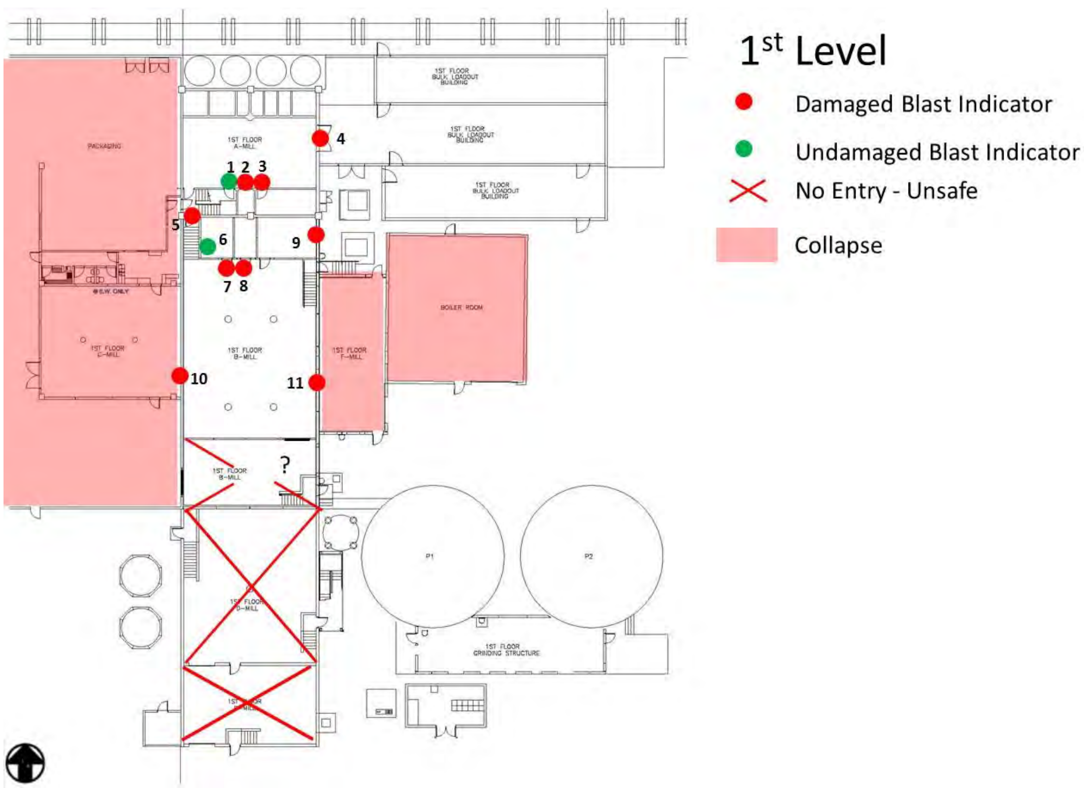


Figure 3-25. Level 1 of Mill A & B Blast Damage Indicators

Table 3-6. Level 1 of Mill A & B Blast Damage Indicator Summary

Directional Indicator Number	Description
1	Mill A stairwell entry door
2	Mill A air shaft door
3	Mill A switchgear access door
4	Mill A to east double door
5	Mill B stairwell entry door
6	Mill B electrical cabinet undamaged
7	Mill B electrical room door
8	Mill B air shaft door
9	Mill B switchgear room electrical cabinet
10	Mill B west wall
11	Mill B east wall

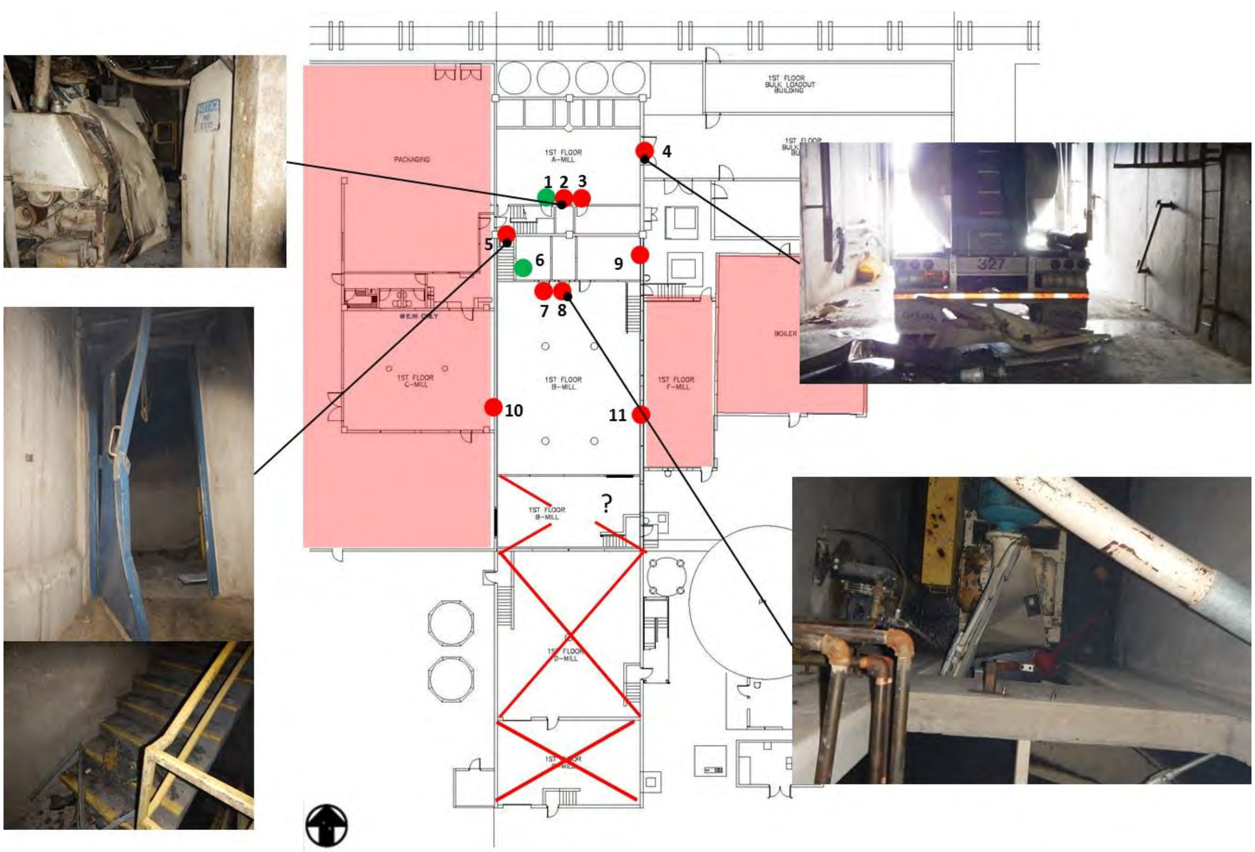


Figure 3-26. Mill A and Mill B Level 1 Exemplar Blast Indicators

3.2.2 Mill A & B Second Level Blast Indicators

Blast indicators for the second level of Mill A and B are presented in Figure 3-27 and identified in Table 3-7 below. Examples of indicators provided in Figure 3-28 indicate that overpressure in level two of Mill B was substantial enough to force the entry door through the frame into the stairwell but did not result in permanent deformation to the undamaged electrical boxes. In addition, the west precast wall of Mill B was separated from the 2nd level slab. Overpressure in Level 2 of Mill A unseated the entry door with sufficient energy for the door to strike the jamb at the stairway landing that led to the corridor and the control room. Not shown in Figure 3-28 is the roll up door on the west face of Mill A that was pushed through the tracks into the packaging area of the Multipurpose Building.

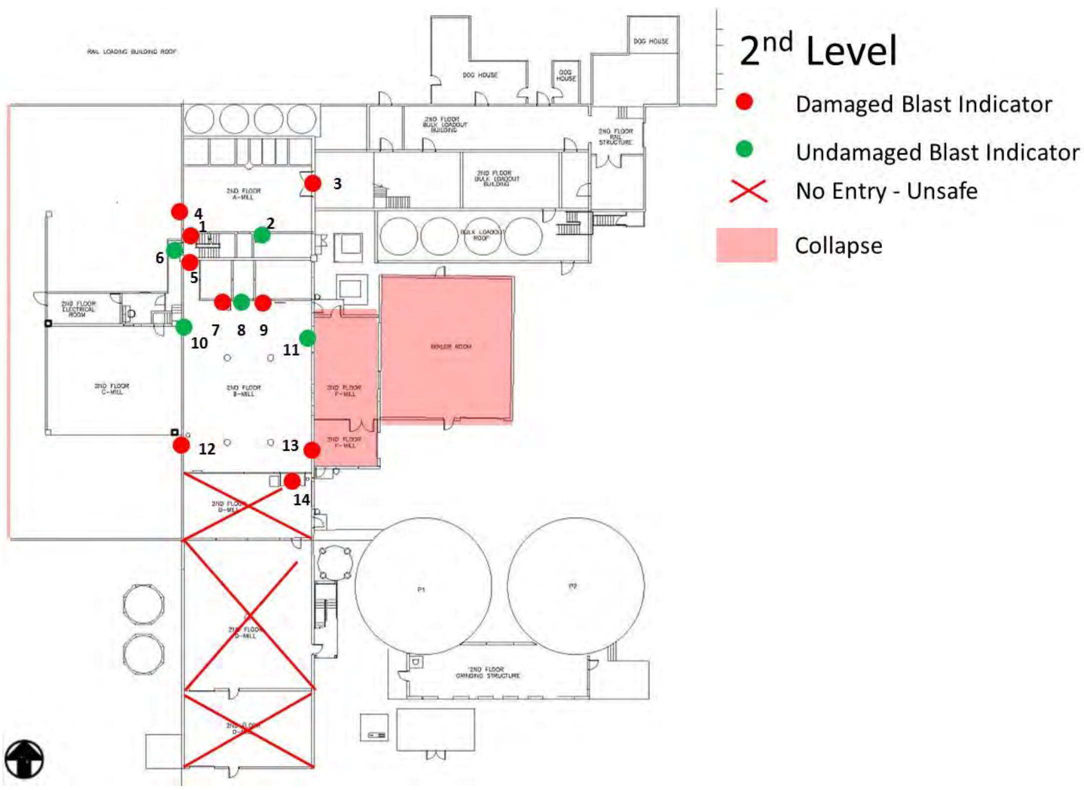


Figure 3-27. Level 2 of Mill A & B Blast Damage Indicators

Table 3-7. Level 2 of Mill A & B Blast Damage Indicator Summary

Directional Indicator Number	Description
1	Mill A stairwell entry door
2	Mill A switchgear access door
3	Mill A to east double door
4	Mill A roll-up door to Packaging
5	Mill B stairwell entry door
6	Packaging / C Mill stairwell entry door
7	Mill B electrical room door
8	Mill B air shaft door
9	Mill B switchgear room electrical cabinet
10	Electrical box cover – undamaged
11	Electrical box cover – undamaged
12	Mill B west wall
13	Mill B east wall
14	Mill B south double door

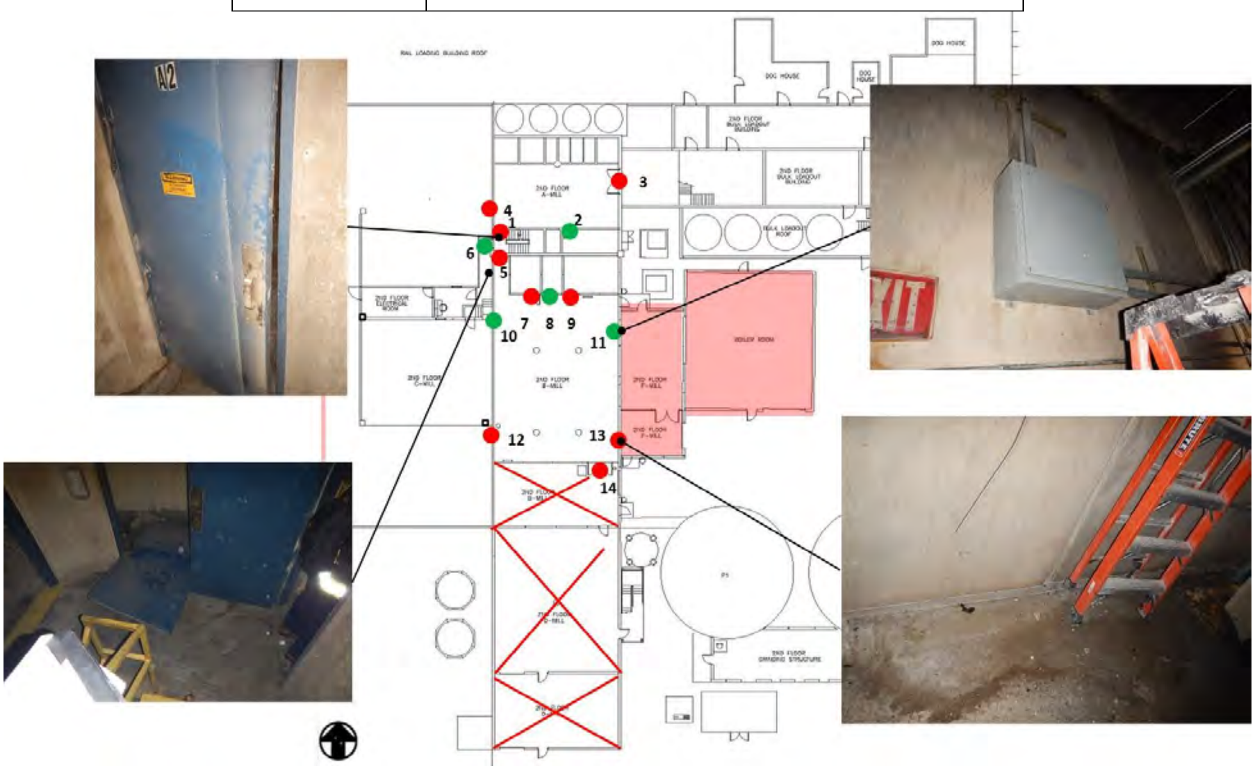


Figure 3-28. Mill A and Mill B Level 2 Exemplar Blast Indicators

3.2.3 Mill A & B Third Level Blast Indicators

Blast indicators for the third level of Mill A and Mill B are presented in Figure 3-29 and identified in Table 3-8 below. Exemplars of the directional indicators are shown in Figure 3-30. Overpressure in Mill B pushed the stairwell entry door through the frame with such force that the entry door separated from the hinges and came to rest on the landing between levels 3 and 2 of the stairwell. The electrical boxes in Mill B were undamaged by the overpressure. The overpressure in Mill A at the third level was sufficient to damage the third level west wall at the ceiling (4th level slab) and fail the double doors on the east face.

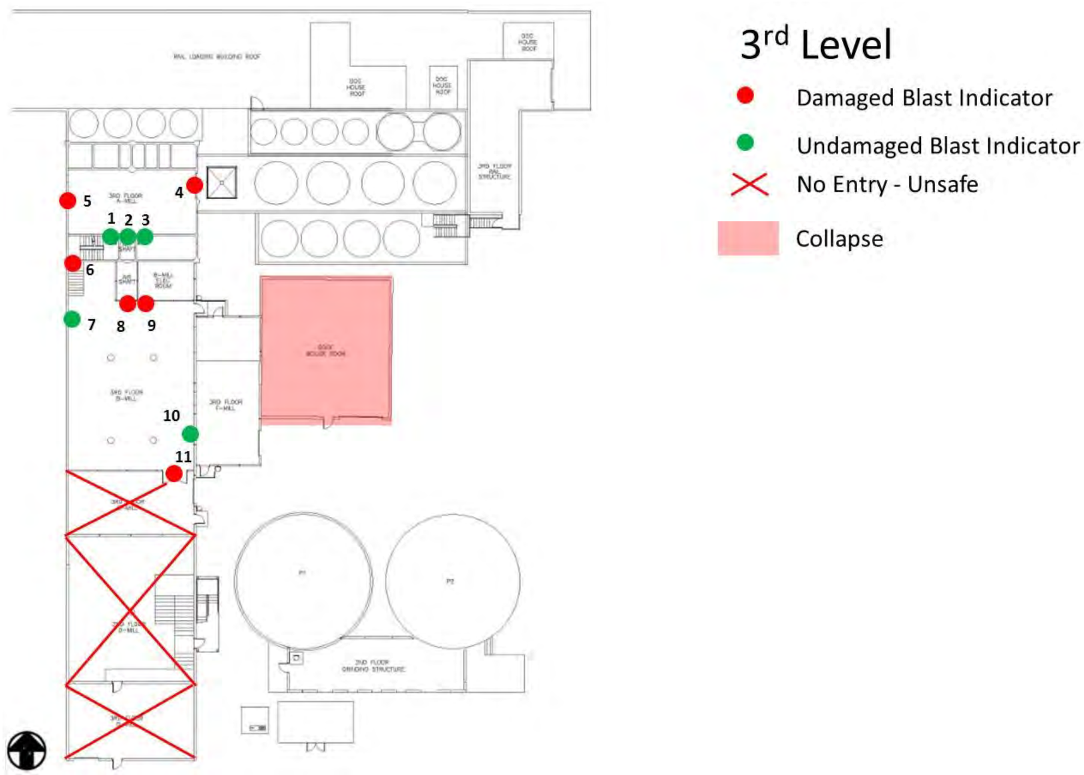


Figure 3-29. Level 3 of Mill A & B Blast Damage Indicators

Table 3-8. Level 3 of Mill A & B Blast Damage Indicator Summary

Directional Indicator Number	Description
1	Mill A stairwell entry door
2	Mill A air shaft door
3	Mill A switchgear access door
4	Mill A to east double door
5	Mill A west wall
6	Mill B stairwell entry door
7	Electrical box cover – undamaged
8	Mill B electrical room door
9	Mill B air shaft door
10	Electrical box cover – undamaged
11	Mill B south double door

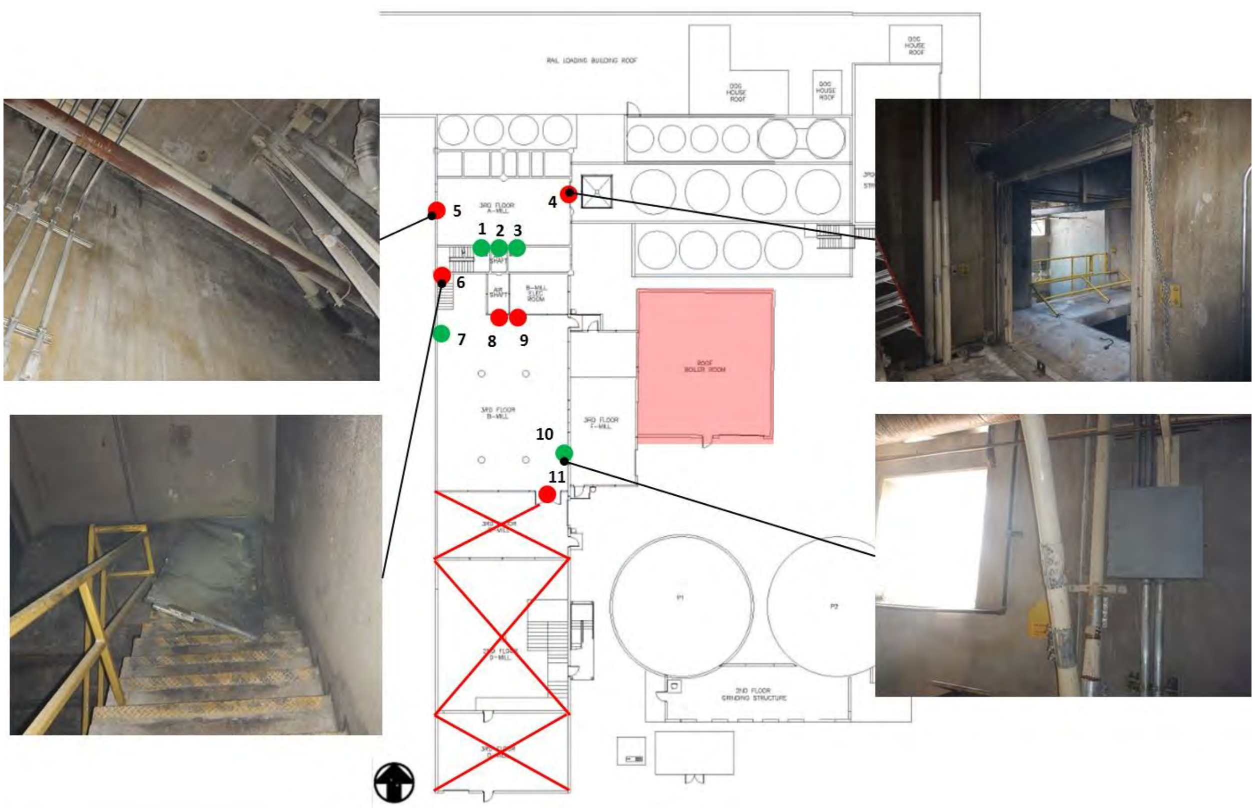


Figure 3-30. Mill A and Mill B Level 3 Exemplar Blast Indicators

3.2.4 Mill A & B Fourth Level Blast Indicators

Level 4 of Mill B could not be accessed safely due to the collapsed side walls and unprotected fall hazards. Drone photos were reviewed in lieu of access. Blast indicators for the fourth level of Mill A and Mill B are presented in Figure 3-31 and identified in Table 3-9 below and examples are provided in Figure 3-32. The exemplar blast indicators show that overpressure the 4th level of Mill B was insufficient to damage the stairwell entry door and only slightly damage the HVAC ducting above the mechanical rooms. Overpressure in Mill A at the 4th level separated the west concrete wall from the 4th level floor slab, pushed the electrical room double doors through the opening into the electrical room, but did not damage the electrical box on the west wall.

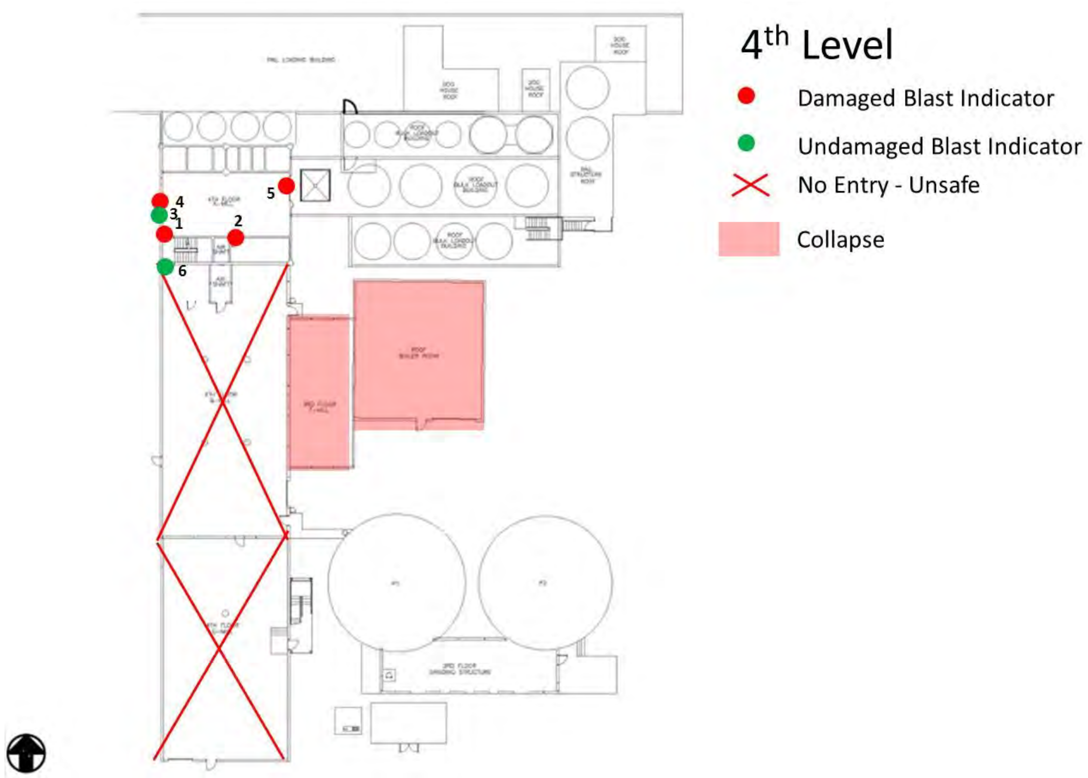


Figure 3-31. Level 4 of Mill A & B Blast Damage Indicators

Table 3-9. Level 4 of Mill A & B Blast Damage Indicator Summary

Directional Indicator Number	Description
1	Mill A stairwell entry door
2	Mill A switchgear access door
3	Electrical Box
4	Mill A west wall
5	Mill A east door
6	Mill B stairwell entry door

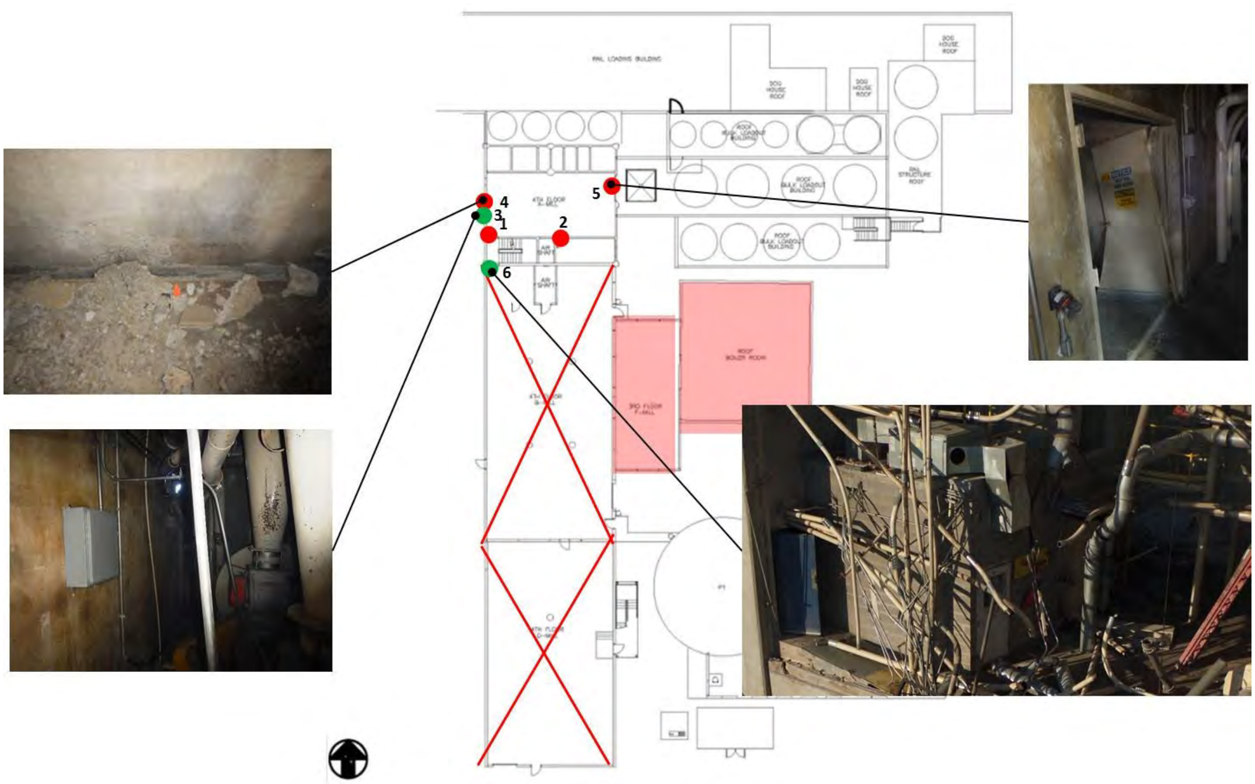


Figure 3-32. Mill A and Mill B Level 4 Exemplar Blast Indicators

3.2.5 Mill A Fifth Level Blast Indicators

Blast indicators for the fifth level of Mill A are presented in Figure 3-33 and identified in Table 3-10 below. Examples of the observed blast indicators on level 5 of Mill A again indicate overpressure separated the west wall from the Mill A slab, this time at the 5th level. The overpressure failed the east view windows and door as shown in Figure 3-34 and damaged the air shaft door between Mill A and the air shaft.

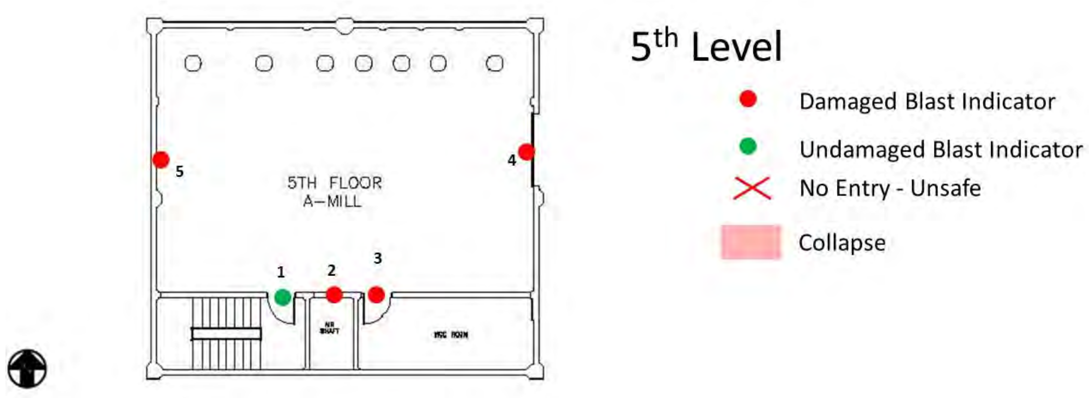


Figure 3-33. Level 5 of Mill A & B Blast Damage Indicators

Table 3-10. Level 5 of Mill A & B Blast Damage Indicator Summary

Directional Indicator Number	Description
1	Mill A stairwell entry door
2	Mill A air shaft access door
3	Mill A switchgear access door
4	Mill A to east roll-up door
5	Mill A west wall

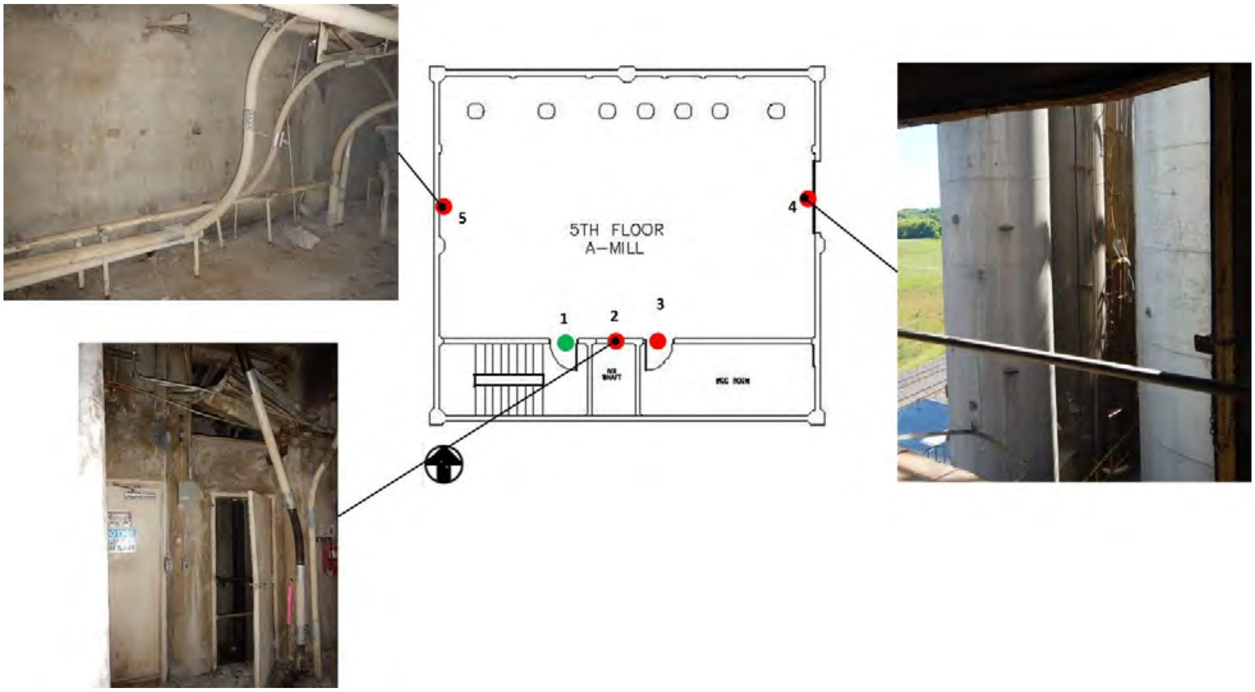


Figure 3-34. Mill A and Mill B Level 5 Exemplar Blast Indicators

3.3 Fire Survey

ABS Group conducted a fire damage survey within the mill. Fire damage indicators are broken into three groups. Low fire damage indicators include damaged papers, straw and plastics, soot, and bubbled or charred rubber conduit (Figure 3-35). Medium fire damage indicators include charred wood, and bubbled industrial coating on steel (Figure 3-36). High fire damage indicators include charred or burned steel (coating burned off), warped or ruptured pipe, and warped or torn structure (Figure 3-37). These levels allowed for a map to be generated that demonstrated fire locations and severity (heat).

The maps in Figure 3-38 through Figure 3-42 show fire damage on the levels of Mill A and Mill B. The first level of Mill B had more extensive fire damage than the remainder of Mill A and Mill B. The Transformer room adjacent to the bulk loading area showed signs of an intense fire that may have been the result of an increase in fuel loading ignited by the fire traversing through the facility. The fire damage indicators from within Mill A and Mill B are consistent with a prolonged fire in Level 1 of Mill B.

Figure 3-35. Example of Low Fire Damage Indicator (Melted Plastic)

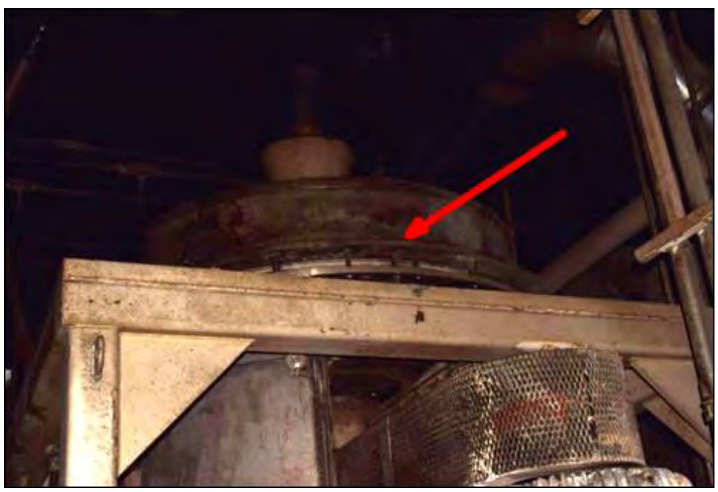


Figure 3-36. Example of Medium and High Fire Damage Indicator (Bubbled and Lost Coating)

Figure 3-37. Example of High Fire Damage Indicator (Spalled Concrete)

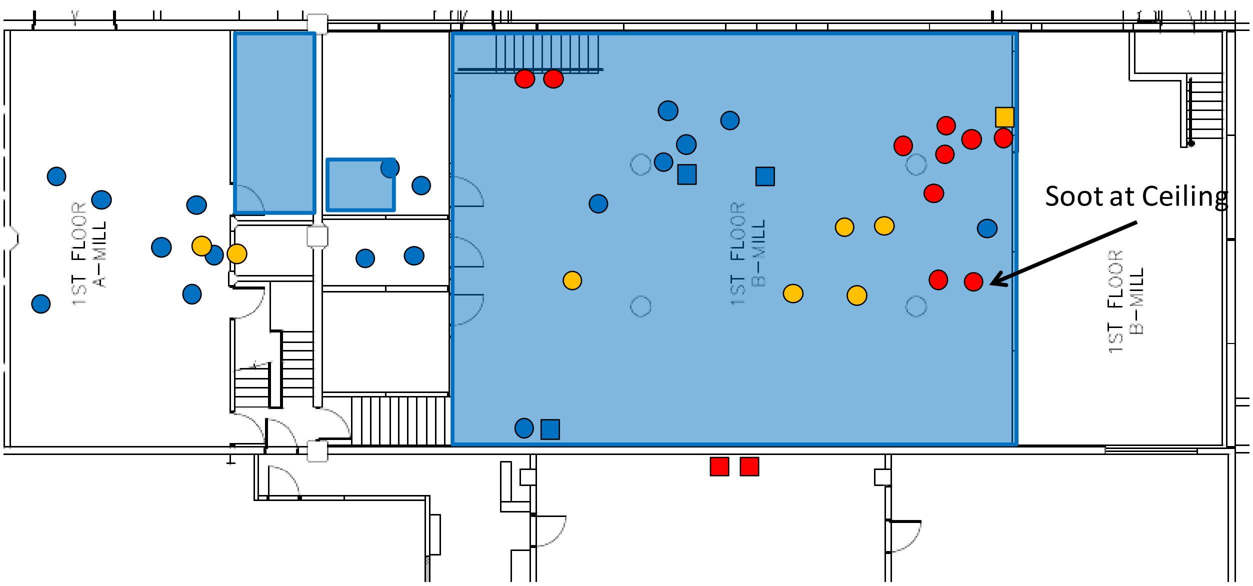


Figure 3-38. Level 1 A and B Mill (Low – Blue, Medium – Orange, High – Red)

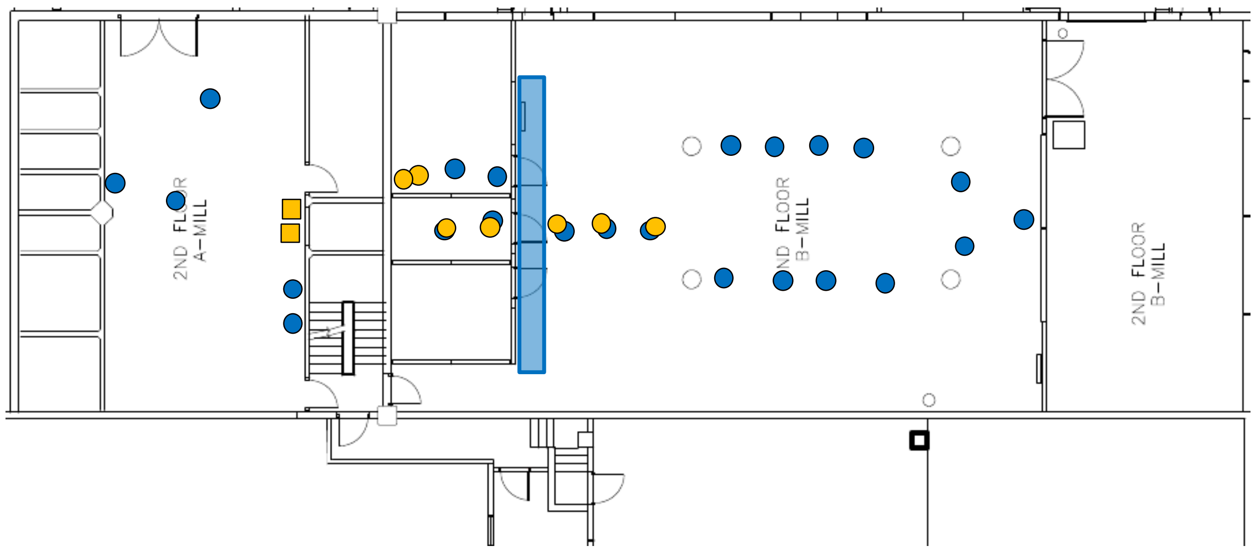


Figure 3-39. Level 2 A and B Mill (Low - Blue, Medium - Orange, High - Red)

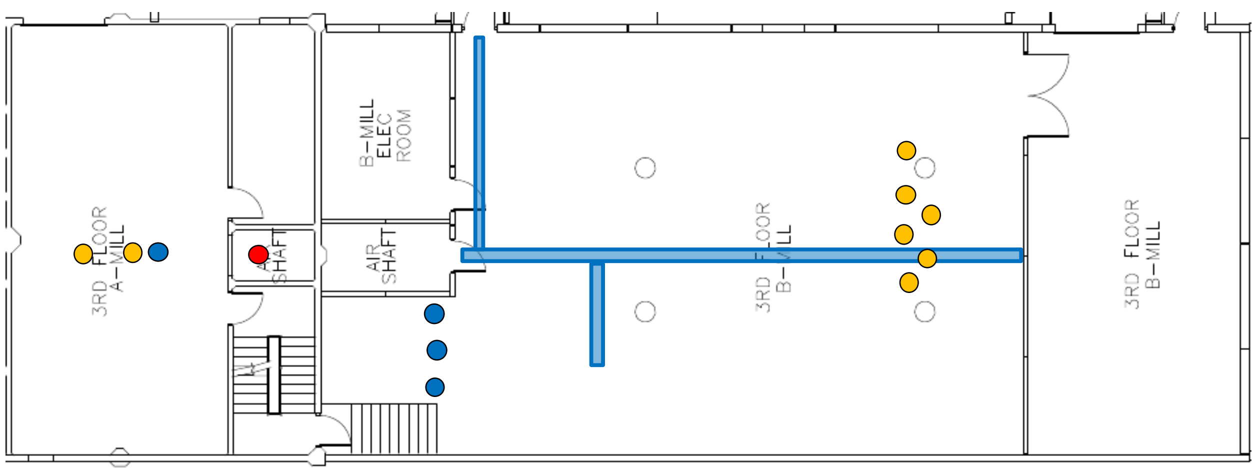


Figure 3-40. Level 3 A and B Mill (Low - Blue, Medium - Orange, High - Red)

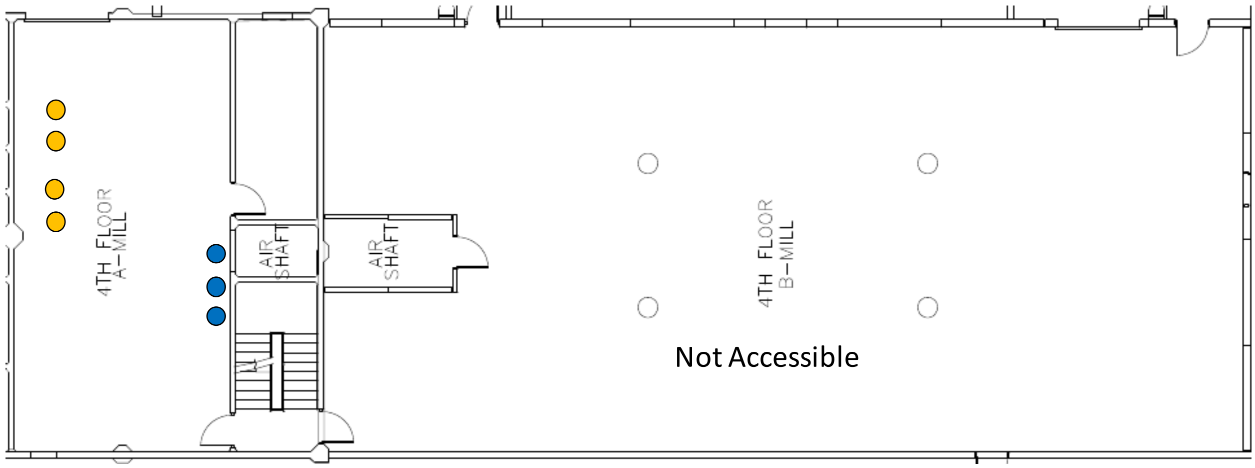


Figure 3-41. Level 4 A and B Mill (Low - Blue, Medium - Orange, High - Red)

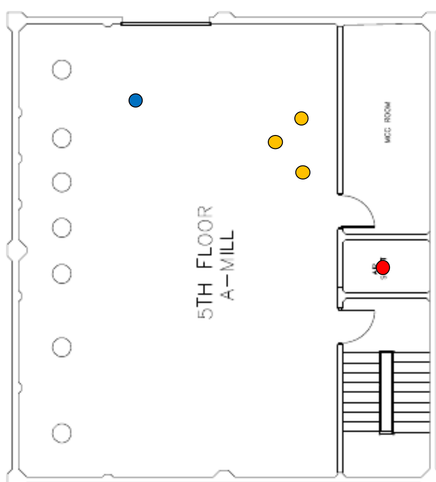


Figure 3-42. Level 5 A Mill (Low - Blue, Medium - Orange, High - Red)

4 Methodology

Blast modeling was performed using two methodologies. The first was the methodology provided in NFPA 68 which is an industry guidance document for design of facilities with internal gas and dust explosion hazards. The methodology was used to evaluate potential explosion scenarios and the effects of venting on the consequences and propagation of the event. The second approach utilized computational fluid dynamics (CFD) to model the explosions, propagation of overpressure, fire, and whether propagation of explosion is required to result in the observed damage.

This approach allowed evaluation of the blast loads produced by the more commonly used NFPA 68 methodology compared with the more complex CFD simulation.

4.1 Explosion Damage Analysis

A quantitative assessment of surveyed damaged structural components was performed which included a dynamic elastic-plastic single-degree-of-freedom (SDOF) analysis of each damaged and undamaged blast indicator using the SBEDS[4] computer program. The component's structural properties such as cross-section, span, material properties and supported mass are inputs to the SDOF analysis. SBEDS is used to determine all of the combinations of applied pressure and impulse that would cause the observed damage. These pressure and impulse pairs are plotted to form a pressure-impulse (P-i) diagram. Any P-i pair on the diagram will result in the same damage level for the component. This iso-damage curve, connecting all of the unique pressure-impulse pairs that are calculated from the damage indicators, is used to evaluate potential explosion scenarios to determine if they would produce more or less damage than observed in the field.

A P-i diagram (Figure 4-1) divides the plot area into two regions:

1. Loads in the area above and to the right of a curve will produce greater response/damage than that observed.
2. Loads in the area below and to the left of the curve will produce less response/damage than that observed.

The pressure asymptote of the P-i diagram represents the applied pressure necessary to cause the observed damage for cases when the load duration is much longer than the natural period

[4] PDC-TR-06-08, "Single Degree of Freedom Structural Response Limits for Antiterrorism Design", U.S. Army Corps of Engineers PDC, Rev. 1, Jan 2008.

of the component. The impulse asymptote applies to cases where the load duration is much shorter than the natural period. The dynamic range is between these two extremes and in these cases the component response is dictated by both the specific values of pressure and impulse.

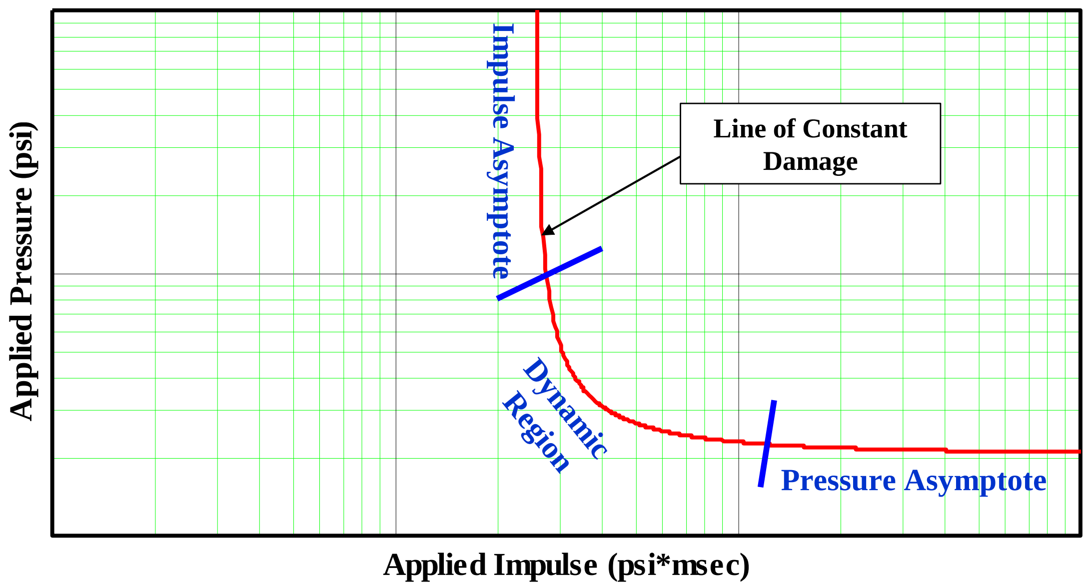


Figure 4-1. Example Pressure-Impulse (P-i) Iso-Damage Diagram

4.1.1 Mill B Precast Walls

Ultimate capacity (failure) loads for the connections and corresponding capacity per unit area (pressures) were calculated for each spacing condition that existed for the embedded adhesive dowels. Connection strengths were evaluated by eliminating strength reduction factors (i.e. ϕ=1.0) to calculate the ultimate connection capacities, assuming proper installation. SDOF properties developed for the precast wall panels were limited to the connection capacity per unit loaded area at the elastic limit of the connection (i.e. ductility ratio of 1). Although panels were continuous across floor levels (multi-span) the capacities were evaluated for load at one level of the mill at a time to account for differences in timing between overpressure events at different levels of Mill B. The P-i diagram for Mill B wall panel at Level 2 and 3 of Mill B is provided in Figure 4-2. The P-i diagram for the 4th level is shown in Figure 4-3. The pressure asymptote for the 2nd and 3rd levels is much higher than for levels 4 due to differences in the connections as discussed in Section 2.2.

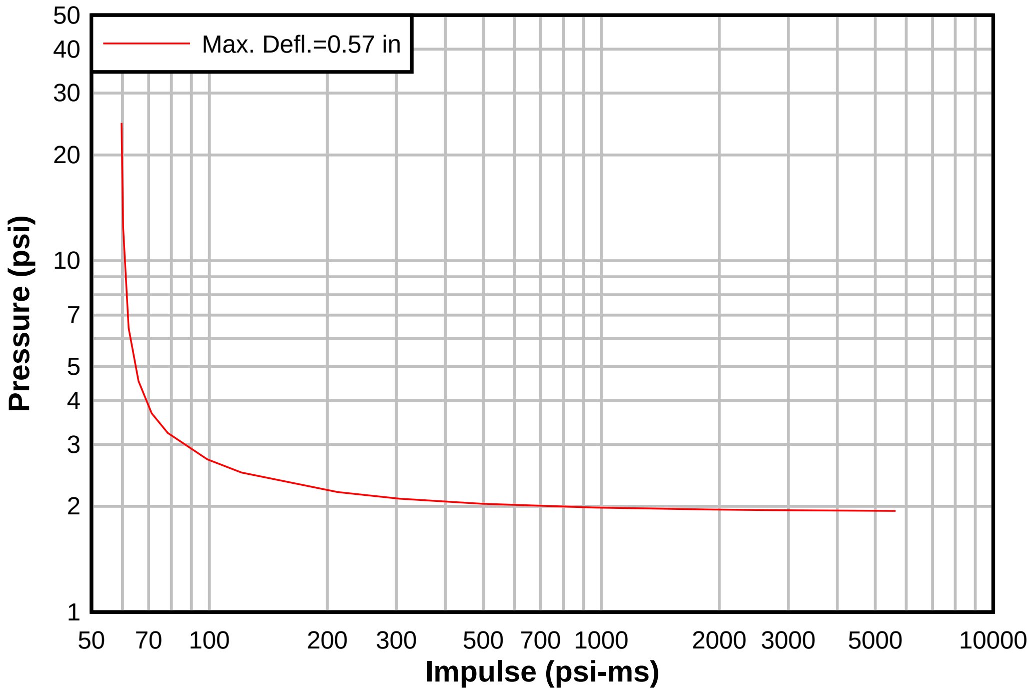


Figure 4-2. Mill B Precast Wall Capacity at 2nd and 3rd Level (2 ft. fastener spacing)

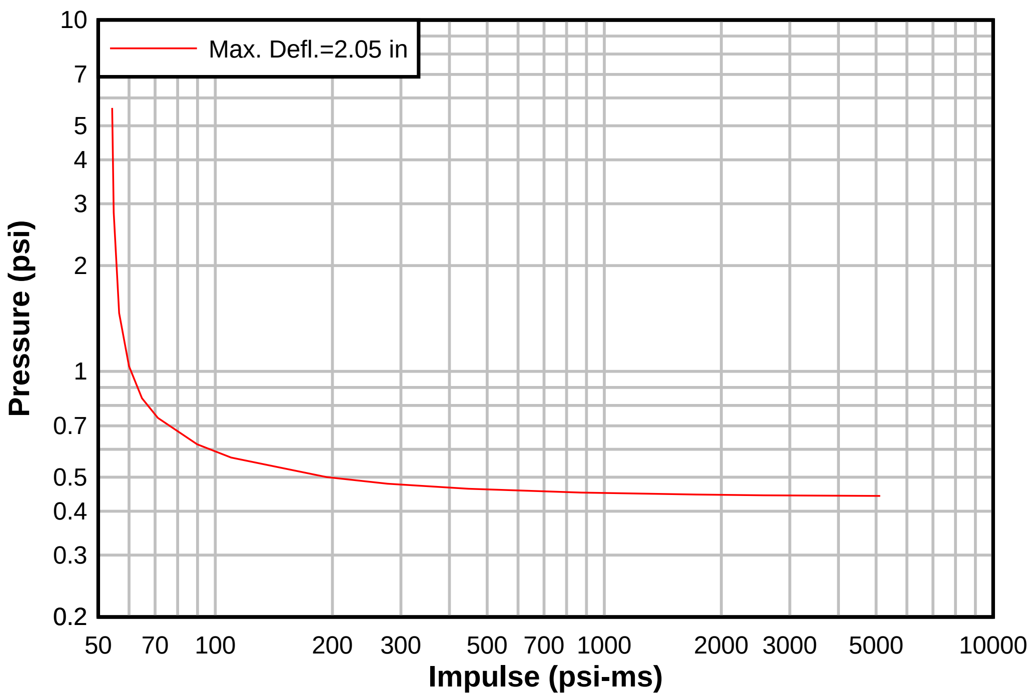


Figure 4-3. Mill B Precast Walls at 4th Level

4.1.2 Mill Doors

A qualitative blast damage assessment was performed for the mill doors by classifying the door damage according to the component damage level definitions in ASTM F2247[5] (Table 4-1). Applied load P-i diagrams, shown below in Figure 4-4, developed by the U.S. Army Corps of Engineers (USACE)[6] were utilized. The door P-i diagrams illustrated in Figure 4-4 are for 16 gauge polystyrene doors and the stairwell doors in the Didion mill were measured to be 15 gauge while the doors to the mill rooms and air shaft were measured to be 18 gauge. The 16 gauge polystyrene doors from the PDC are adequate models for the doors at Didion based upon reported test results that included 18 gauge doors[6].

Table 4-1. ASTM Door Damage Level Categories

ASTM Category	Detailed Description
I	The door panel is operable and has no permanent deformation.
II	The door panel has some permanent deformation. The door panel is operable.
III	The door panel is permanently deformed. The door panel is inoperable.
IV	The door panel is severely deformed. The door panel is inoperable. The door panel is not forced through the door frame opening.
V	The door panel is forced through the door frame opening and may become a flying debris hazard.

[5] ASTM F2247-18, Standard Test Method for Metal Doors Used in Blast Resistant Applications (Equivalent Static Load Method), ASTM International, West Conshohocken, PA, 2018, www.astm.org.

[6] PDC-TR-06-01, "Methodology Manual for the Single-Degree-of-Freedom Blast Effects Design Spreadsheets, Rev. 3 December 2014.

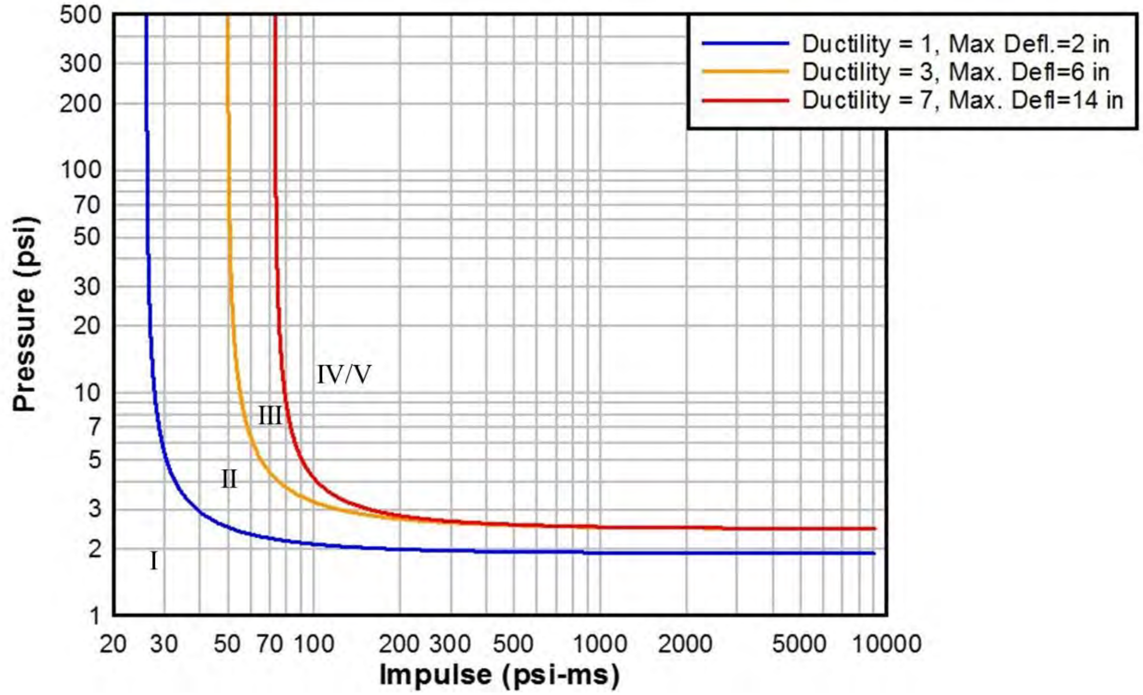


Figure 4-4. Applied Load Pressure Impulse Diagram for 16 Ga. Polystyrene Door.

4.1.3 Electrical Boxes

Electrical junction boxes were observed with undamaged doors at levels 2 and 3 of Mill B as well as level 4 of Mill A. An example is provided in Figure 4-5. The electrical box door was measured in the field and analyzed as a two way flat plate. The box is undamaged; therefore, the analysis was performed to the elastic limit to indicate the threshold at which damage to the electrical box would be observable indicating an upper limit to the applied blast loads at this location. A P-i diagram for the electrical boxes is presented in Figure 4-6.

Figure 4-5. Mill B Undamaged Electrical Junction Box

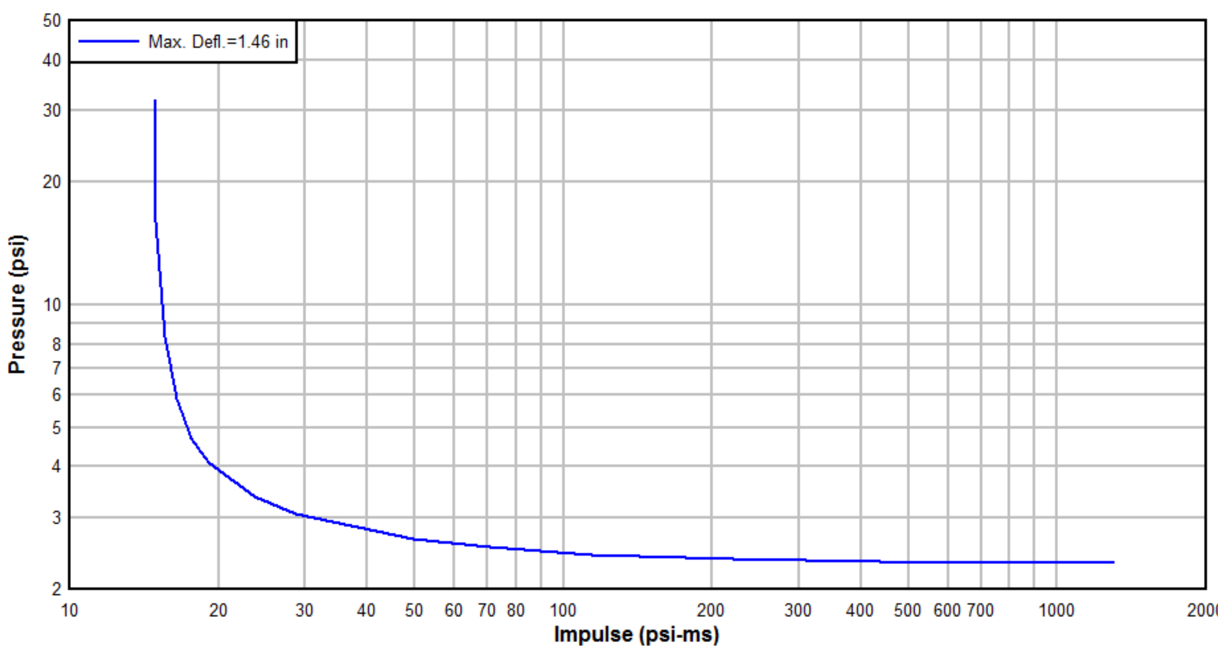


Figure 4-6. Undamaged Electrical Box Pressure Impulse Diagram

4.2 NFPA 68 Evaluation of Explosion in Level 1 of Mill B

4.2.1 NFPA 68 Methodology

The National Fire Protection Association (NFPA) 68 (2018)[7] is a standard on explosion protection by deflagration venting used by the industry to evaluate and protect against internal gas and dust explosion hazards. NFPA 68 provides analysis methods for determining the necessary vent area (A_v) to prevent the pressure rise (P_{red}) in the building/equipment from exceeding a specified value.

4.2.2 Analysis Approach

The first task was to find the pressure associated with an explosion in Level 1 of Mill B using the NFPA 68 methods. The methodology determines a reduced peak pressure (P_{red}) in an enclosed area which results from venting. The reduction in pressure is a function of the maximum pressure (P_{max}) in an unvented enclosure, the amount of vent area provided, and the pressure at which the vent opens, (also called the activation pressure, P_{stat}). Since the calculations are designed to determine the necessary vent area given a desired P_{red}, an iterative approach was used to solve for the P_{red} given the available 3 m^2 of vent area in the vertical vent shaft. A room volume of 1,025 m^3 was used along with a deflagration index (K_{st}) of 150 bar-m/sec, P_{max} of 8 bar, and P_{stat} of 0.01 psi (vent area is initially open to the vertical vent shaft and no effective pressure resistance for the vent). Calculations included the effects of the room aspect ratio (L/D = 2.5) and a 1.7 factor applied to vent area for dust explosions in buildings in accordance with the methodology.

The second task was to evaluate the necessary vent area to maintain a P_{red} gauge pressure of ≤ 2.5 psi which is the pressure asymptote for doors on level 1 of Mill B based on the observed damage indicators. Vents were assumed to be located at the end of the room due to interference from the Mutipurpose Building and Mill F preventing continuous vents along the walls. A P_{stat} of 0.2 psi was assumed for the vents along with a mass of 2 lb./ft^2. Both values were chosen as representative of an engineered venting panel.

Both of the above tasks assumed the room was full of dust. NFPA 68 has methods for a partial fill fraction; however, the objective was to show the worst case impact for conditions which existed at the time of the incident and the potential impact of additional venting. Results of the analysis are provided in section 5.1

[7] NFPA 68, "Standard on Explosion Protection by Deflagration Venting", National Fire Protection Association, 2018.

4.3 CFD Modeling

Computational Fluid Dynamics (CFD) modeling for the investigation included a number of simulation cases to identify the scenario that best explains the series of events (structural failure and blast propagations) that occurred. The FLame ACceleration Simulator (FLACS) DustEx CFD computer code was used for internal dust explosion analyses. FLACS is a widely used commercial software for the numerical analysis of dispersion and explosion events in the process industries. Development work on the FLACS code has been underway since the early 1980's, primarily in response to explosions in offshore production platforms. The DustEx code specializes in dust explosions, calculating explosion pressure and other flow parameters as a function of time and space for modeled geometry. It accounts for the interaction between flame, vent areas and obstacles such as equipment and pipe work.

The simulation cases evaluated during the analysis were:

- Case 1 - An explosion in the South Gap Mill to evaluate whether an explosion within the equipment can release enough flammable dust to support an explosion in Level 1 of Mill B.
- Case 2 - An explosion in Level 1 of Mill B to determine the minimum amount of combustible dust required to be consistent with the observed damage in Level 1 of Mill B. The overpressures from this case were also used to determine whether a single explosion within Level 1 of Mill B was consistent with the observed damage to the remainder of Mill A and Mill B and the Multipurpose Building or if propagation of fire and explosion to adjacent areas was required to explain the damage to the rest of the Didion facility.
- Case 3 – An explosion in the Multipurpose Building was evaluated to determine the amount of combustible dust necessary to initiate the observed collapse of the Multipurpose Building.
- Case 4 – A vented release using the dust volume determined from Case 2 which best matched the observed damage with additional vent relief area to mitigate the explosion.
- Case 5 - An explosion which includes propagation of fire and blast from each area to the next by including a dust volume in each area and linking those volumes with dust in the vertical vent shaft.

4.3.1 Model of the Facility

The CFD explosion study required a three-dimensional (3D) model of the process areas. ABS Group created a 3D CAD model of the mill areas and principal equipment within using photographs and notes taken during the site visit. To approximate the congestion in some areas with significant amounts of piping, a grid of piping-objects was used in the model to represent the actual piping. The 3D model was then imported into FLACS DustEx and used for the explosion simulations.

The 3D model included the following features:

- Piping and equipment representing the approximate congestion inside the mill (Figure 4-7).
- Walls, floors, and roofs throughout the process building were represented in FLACS as a series of panels (Figure 4-8). Each panel was assigned failure criteria, in terms of both pressure and impulse, required to structurally fail or release a panel. This allowed for simulation of the panel being released in the CFD model to create vent paths as panels fail. FLACS utilizes the mass per unit area of each panel to account for inertial resistance to movement of the panel away from its original position and thereby accounts for the effect of panel movement on venting.
- Separate rooms for each mill area and a central stairwell with ventilation duct (Figure 4-9).
- Propagation paths for explosion overpressure and products between mill rooms and the Multipurpose Building (Figure 4-10).

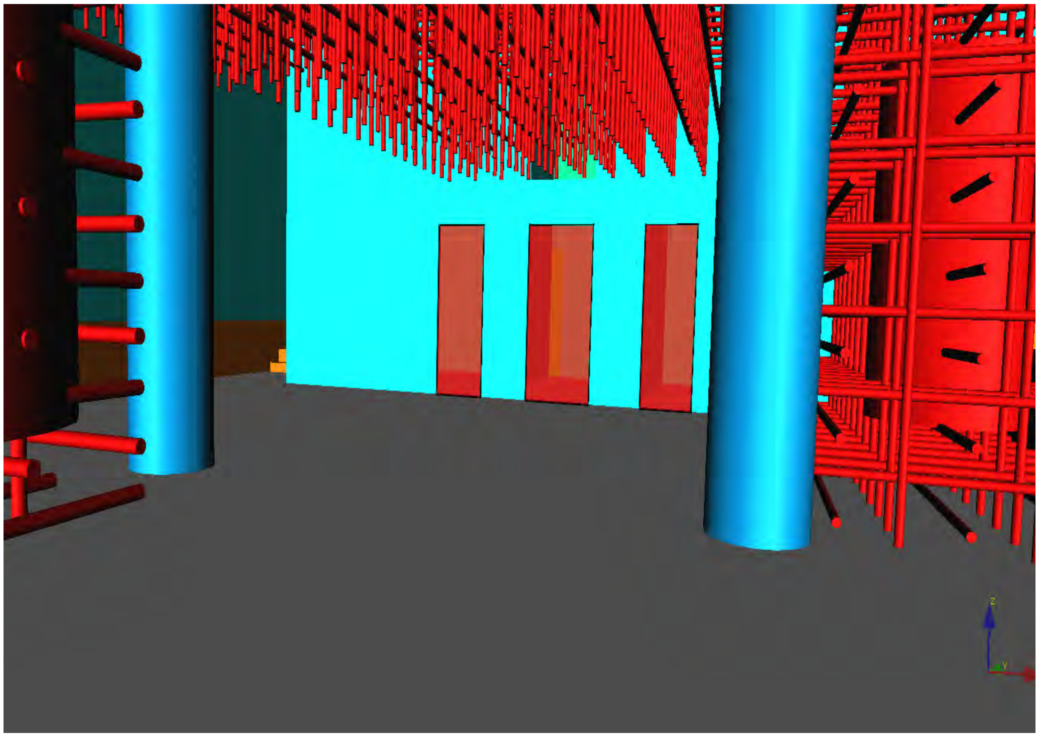


Figure 4-7. Example of Equipment and Piping

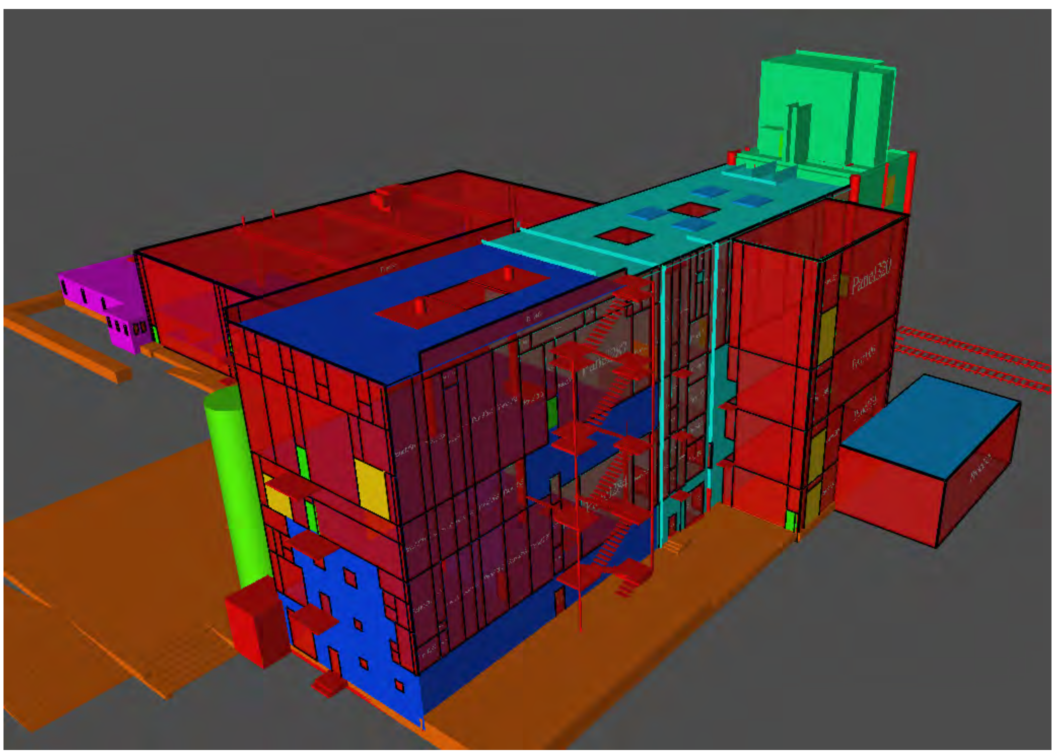


Figure 4-8. Overall View of the DustEx Model

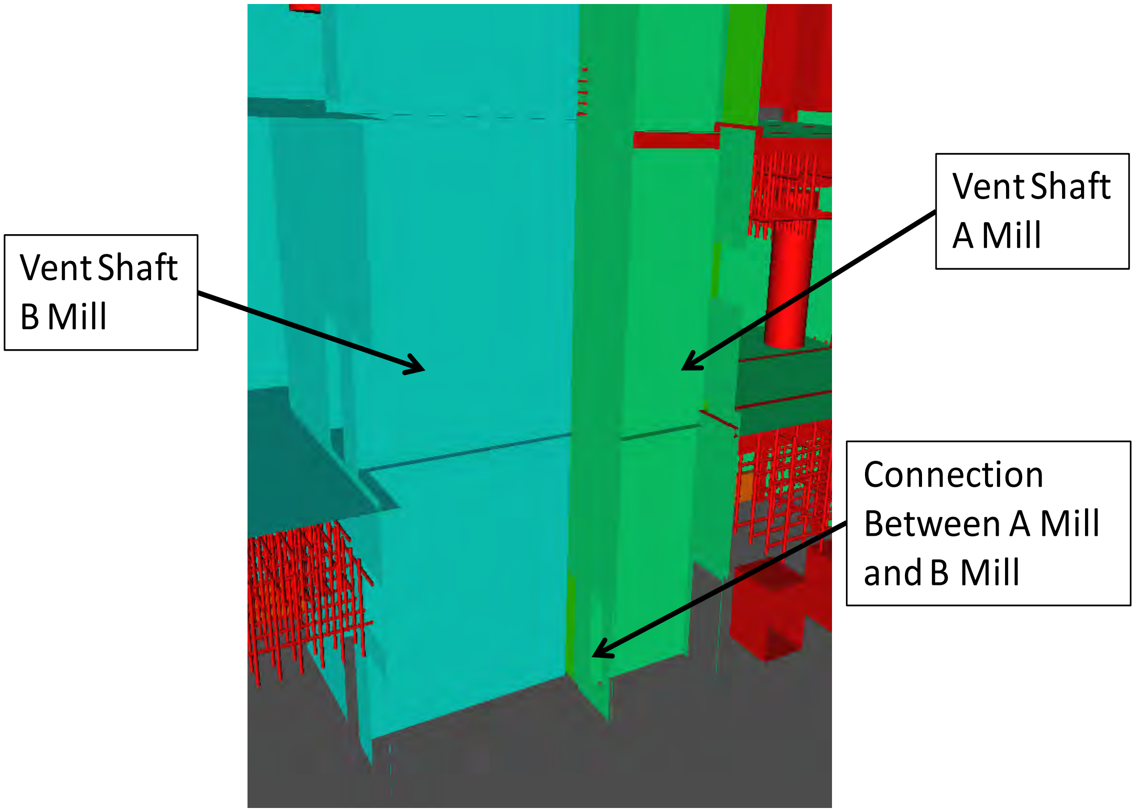


Figure 4-9. Mill A and B Vertical Section through Air Shaft

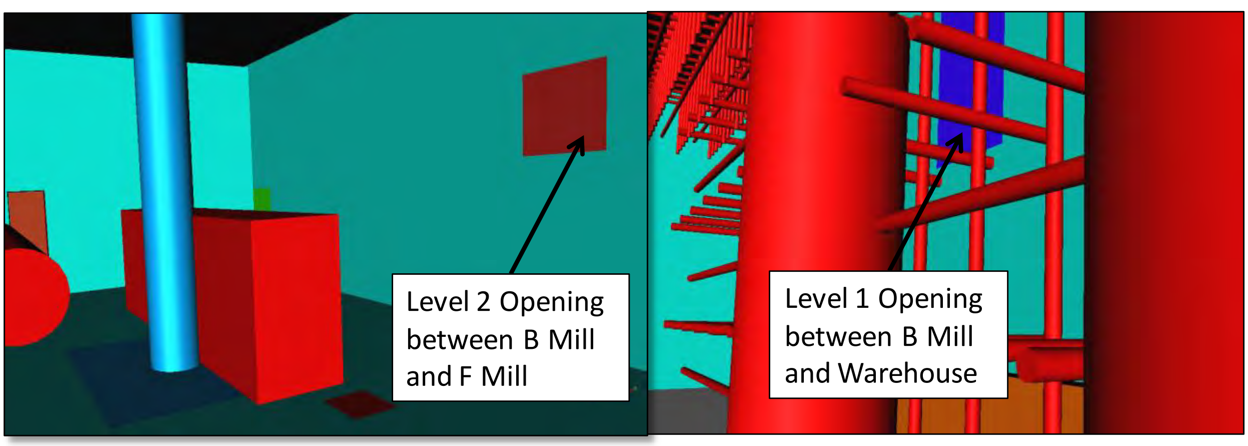


Figure 4-10. Vertical Section Through Multipurpose Building and Mills

4.3.2 Dust Model Source Term

The dust source term for the simulations was based on key characteristics of the dust at the Didion facility. These characteristics, maximum pressure (P_{max}) and deflagration index (K_{st}) were experimentally determined using a 20 liter bomb test[3].The K_{st} value is an indication of the pressure rise within the room while P_{max} is the highest pressure experimentally determined within the cloud. Tests included bran from the bran system, flour from other parts of the facility, and dust from the torit filter. The bran system was observed to have a release during the event from the south gap mill by eye witnesses[8], but the bran tested is from a finished bag of bran and not specifically from the Gap Mill during production. The torit filter collects fugitive dust from the area including the first level of Mill B. The dust in the torit filter is expected to have characteristics of dust in Mill B. The dust source term in the model is most closely related to this dust. Flour was tested to determine whether variability in product explosivities (Kst and P_{max}) were of enough significance to require modeling different dust values in different rooms of the mill. The values for the different dusts were proximate such that this was deemed unnecessary.

DustEx contains a library of dusts with adjustable parameters including reactivity but these do not have P_{max} and K_{st} values. To determine which dust to use and adjustments to characteristic parameters, the 20 liter bomb test was modeled in DustEx. Different concentrations of a similar dust from the DustEx library were used in a series of simulations. P_{max} and K_{st} were recorded from probes in the simulation and compared to the experimental values. Dust reactivity was raised or lowered for subsequent simulations until the P_{max} and K_{st} values from the analysis compared well with the experimental values.

Figure 4-11 shows a comparison of bran, flour, and dust from the torit filter to the dust modeled in the simulations. The modeled dust more closely resembles the deflagration index (K_{st}) values in the torit filter but the maximum pressure from the analysis slightly exceeded the experimental values.

[8] U.S CSB, "Didion Milling Factual Investigation Update", April 30,2018.

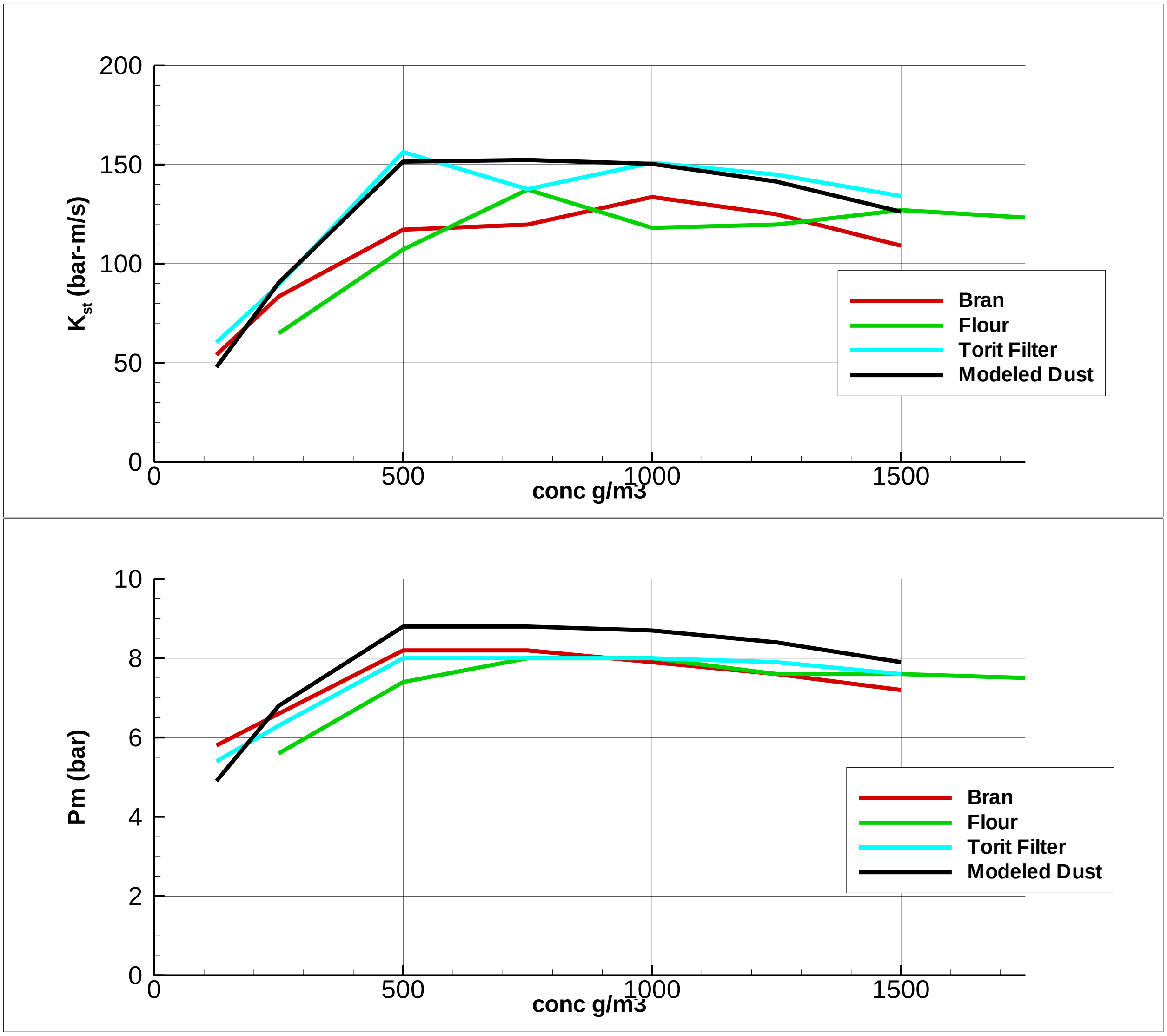


Figure 4-11. K_{st} and P_{max} comparrison for Modeled Dust and Dust on-site

4.3.3 CFD Analysis of an Explosion in the South Gap Mill

The purpose of the model was to evaluate whether an explosion within the South Gap Mill can release enough flammable dust to support the explosion in Level 1 of Mill B. The South Gap Mill CAD model was prepared using drawings of the Gap Mill provided by the CSB. A release location was added at the top of the Gap Mill corresponding to the diameter of the air intake. A cloud of dust was added to the volume and an ignition was located at the bottom of the volume. The concentration within the Gap Mill was 2 kg/m^3, the maximum concentration that this material will burn (effectively a rich concentration)[3].

The total mass of dust outside of the Gap Mill was determined and compared to minimum amounts of dust from other simulations to determine if the observed damage could be explained based only on the dust ejected from the South Gap Mill.

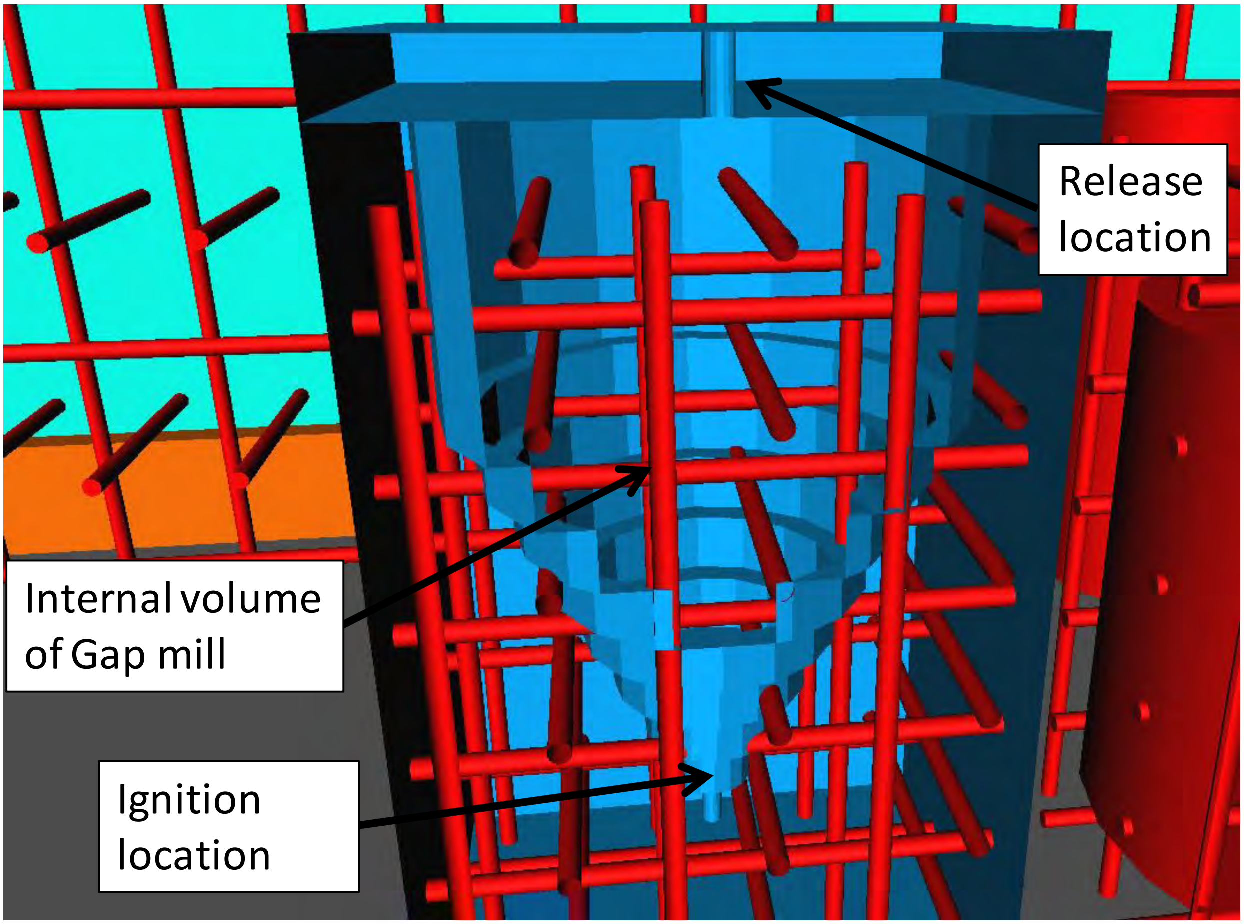
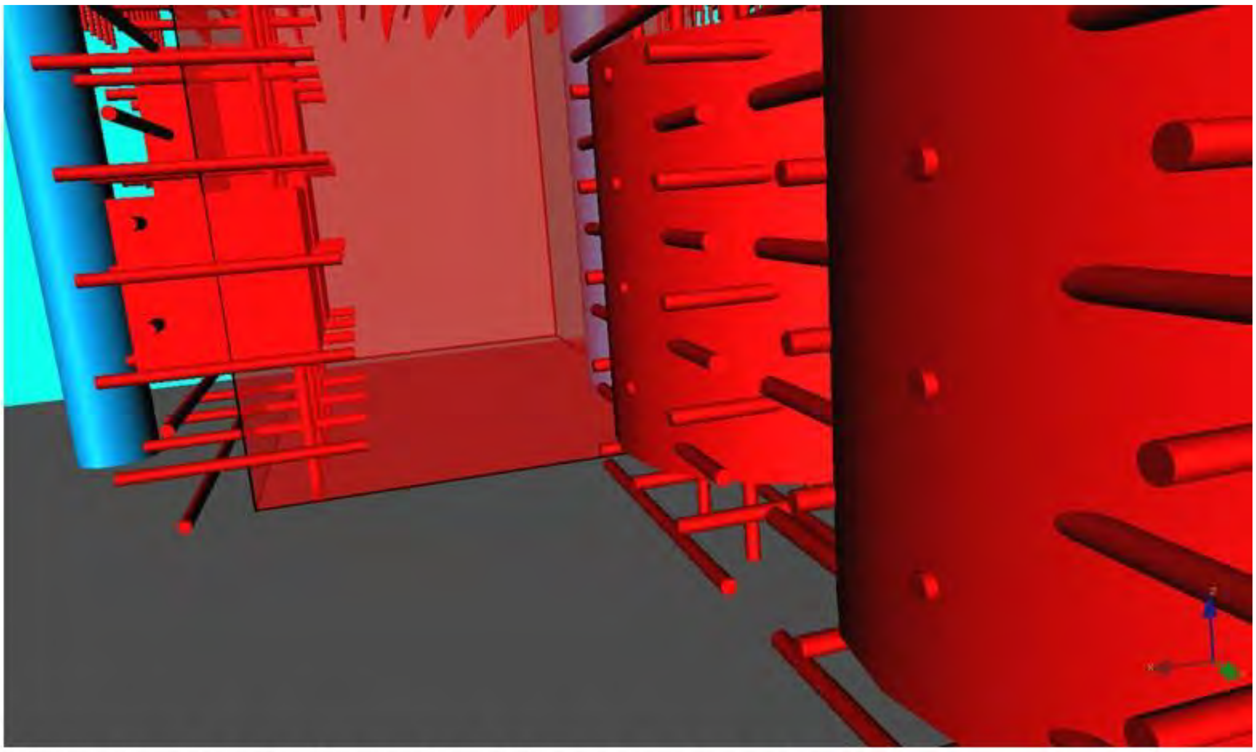


Figure 4-12. The Model of the Gap Mill

4.3.4 CFD Analysis of an Explosion in Level 1 of Mill B

The purpose of this model was to evaluate the minimum amount of combustible dust required to be consistent with the observed damage in Level 1 of Mill B. The overpressures from this case were also evaluated to determine whether a single explosion in Level 1 of Mill B is consistent with the observed damage or if propagation of the fire and explosion into adjacent areas was required to explain the damage to the rest of the Didion facility. Flammable dust clouds of varying sizes were modeled within Level 1 of Mill B to determine the size of the cloud which best matches the observed damage. Applied pressures were measured in the model where damage indicators were located. Figure 4-13 shows one of the flammable clouds (translucent red) near the South Gap Mill.

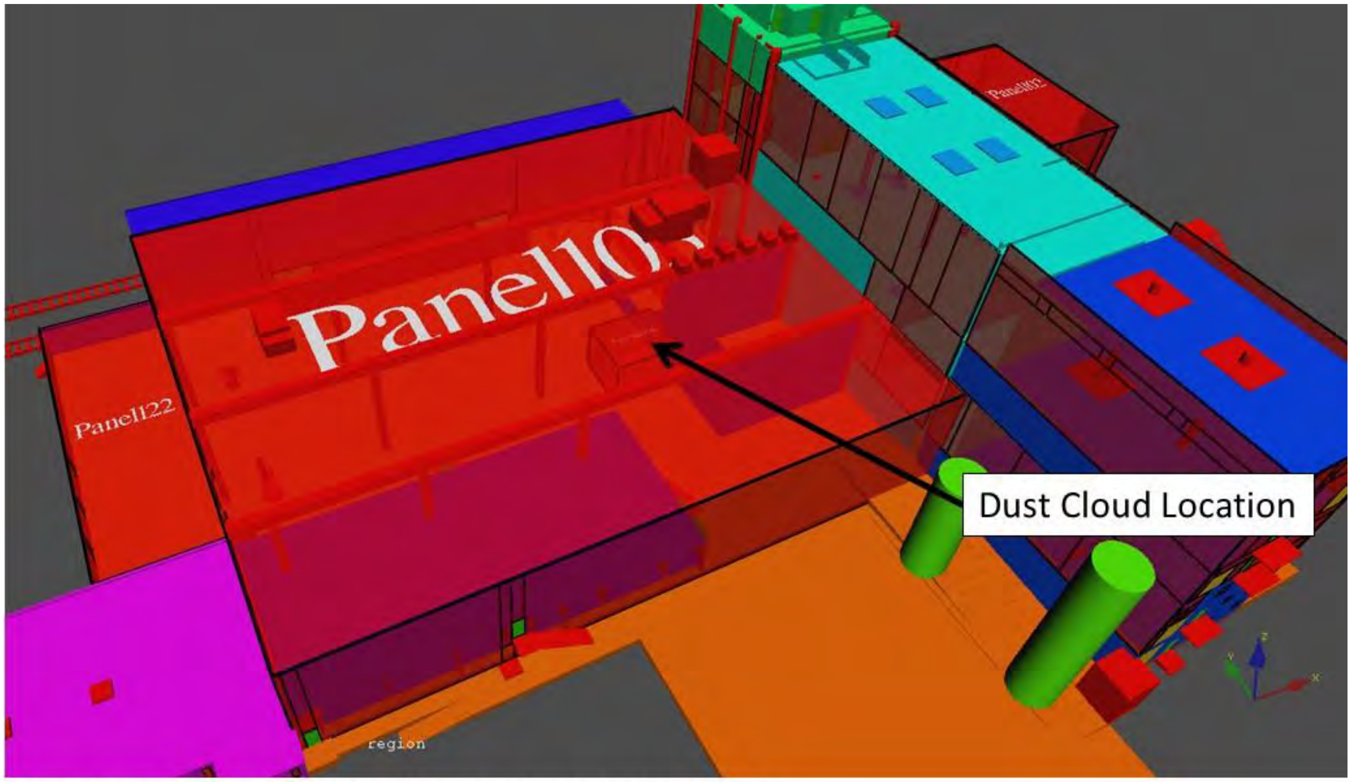


Note: Figure indicates the location of the dust cloud but not the volume.

Figure 4-13. Model for Explosion in Level 1 of Mill B

4.3.5 An Explosion in the Multipurpose Building

A simulation model was developed to determine the minimum amount of combustible dust required to initiate a collapse of the Multipurpose Building. Flammable dust clouds of varying sizes were modeled and the walls and roof of the Multipurpose Building were modeled as of venting panels. The size of the dust cloud was iterated to find the minimum cloud required to generate the onset of failures. Figure 4-14 shows the flammable dust cloud location within the model.



Note: Figure indicates the location of the dust cloud but not the volume.

Figure 4-14. Model for the Explosion in the Multipurpose Building

4.3.6 Vented Explosion in Level 1 of Mill B and Multipurpose Building

A simulation was performed to determine if venting from Level 1 of Mill B or (separately) if venting from the Multipurpose Building, would be capable of reducing the predicted applied loads and resulting damage for these areas. The dust volumes determined from Sections 4.3.4 and 4.3.5, which best represented the observed damage, were used in these venting models. Additional vent locations (0.13 psig release pressure) were added to allow for pressure relief. Figure 4-15 and Figure 4-16 show the additional vents in Level 1 of Mill B and the Multipurpose Building.

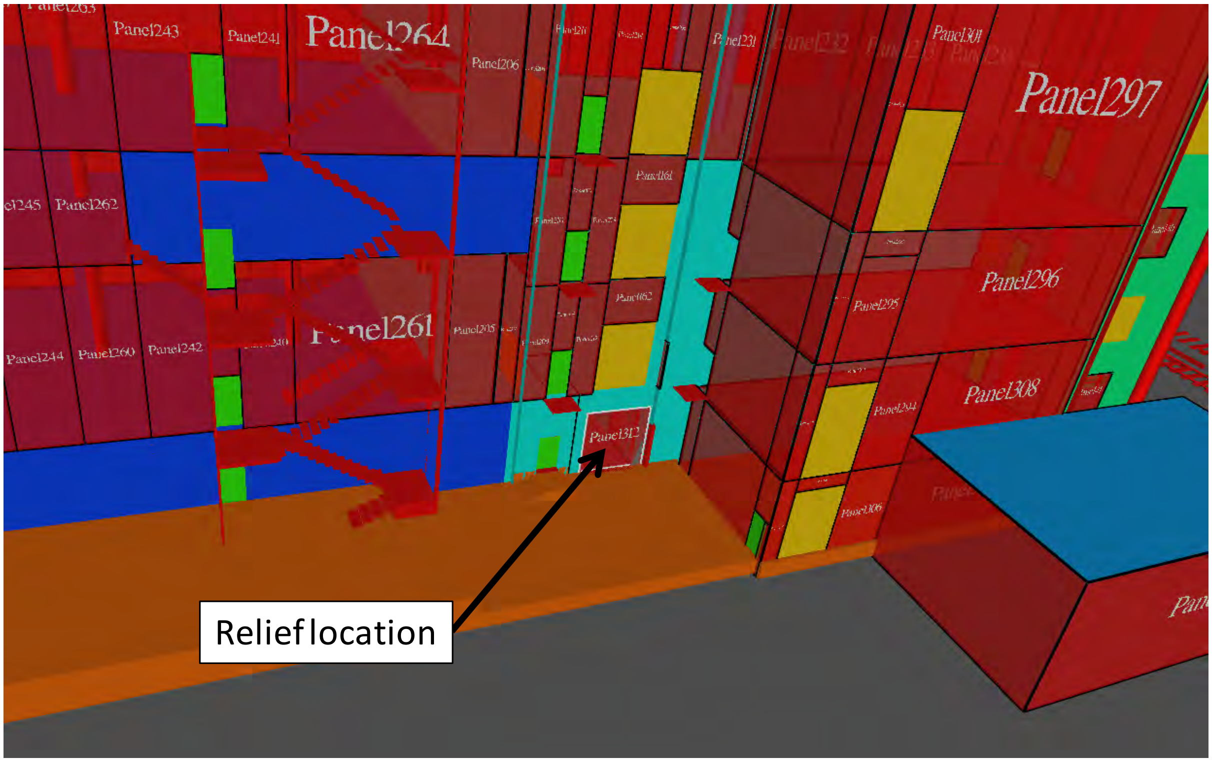


Figure 4-15. Location of Additional Vent in Level 1 of Mill B

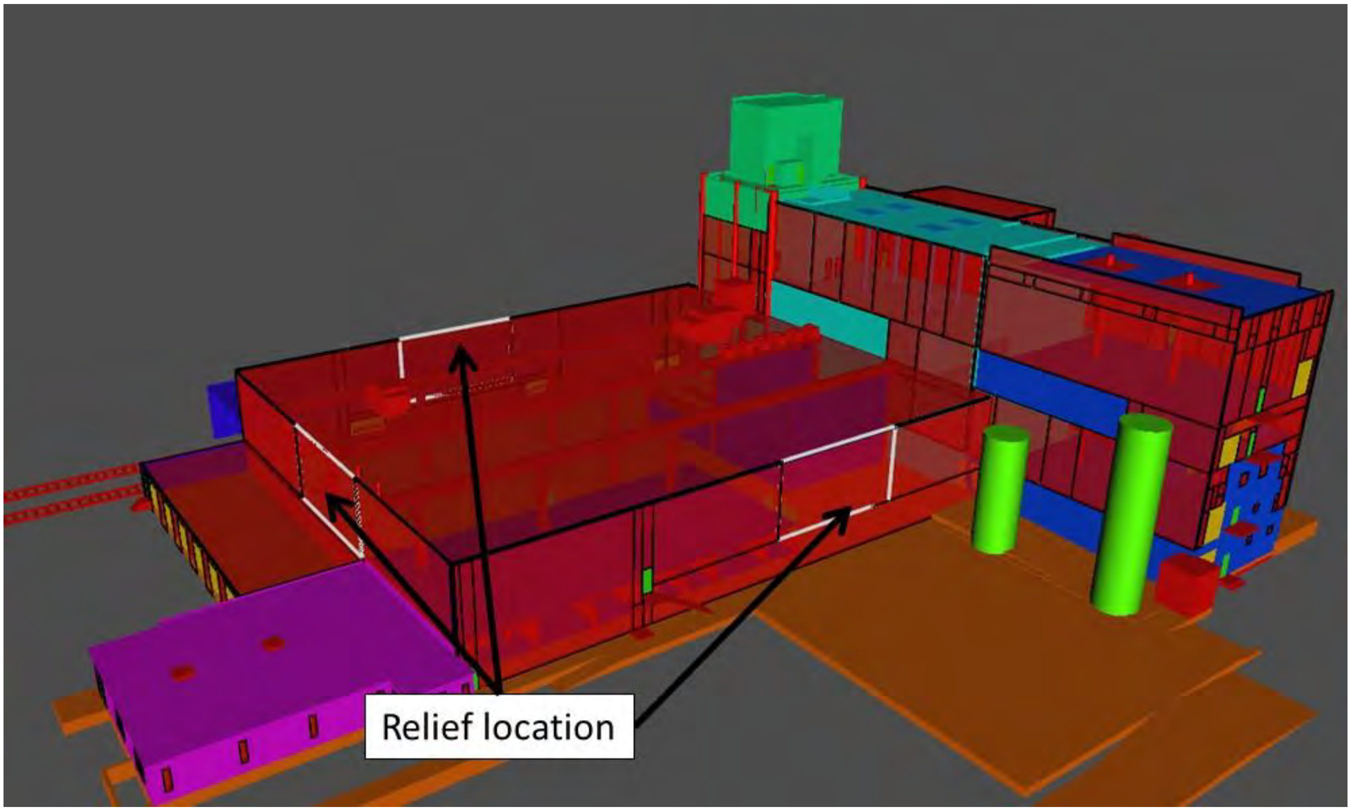


Figure 4-16. Location of Additional Vents in Multipurpose Building

4.3.7 An Explosion with Propagation Between Mill Rooms

A simulation was prepared to show potential propagation of flame and explosion between Mill rooms. The 49 m^3 cloud was placed in the first three levels of Mill B. Clouds were also placed in the corresponding levels of Mill A; however the volumes were reduced proportionately to the volume of Mill A to Mill B for each level. Figure 4-17 show the individual clouds in Mill B separated by failing doors, walls, and floors. The vertical vent shaft connecting the various Mill rooms and floors was filled with dust and ignition was initiated in Level 1 of Mill B.

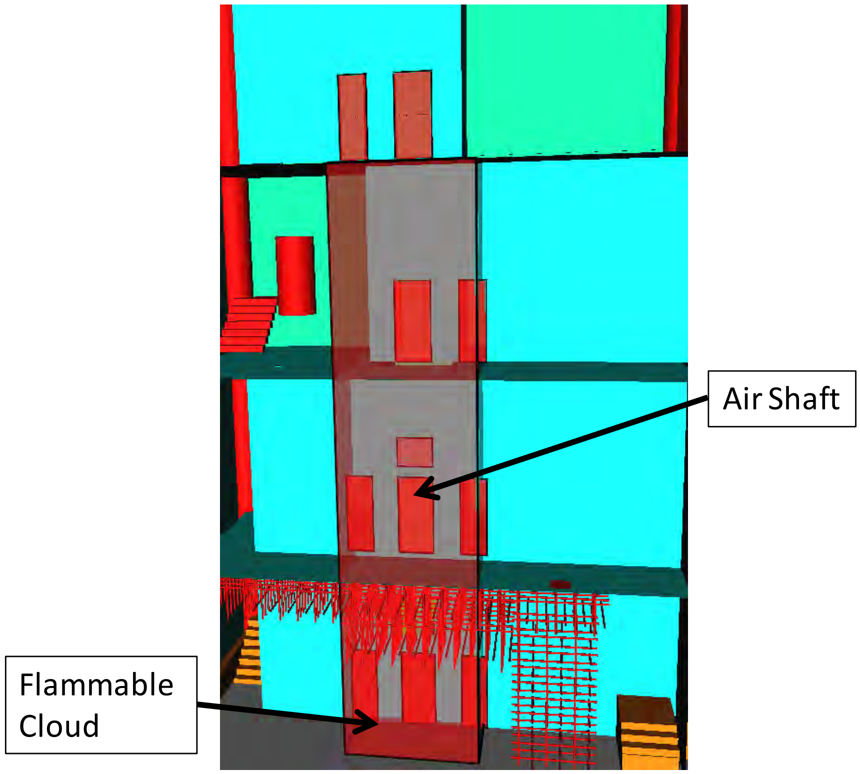


Figure 4-17. Flammable Cloud Extending Through Three Levels Encompassing Air Vent Shaft

5 Results

5.1 NFPA 68 Evaluation

Using NFPA 68[7] a partial volume cloud of 2 to 3% of the full volume of level 1 Mill B, which is 20 m^3 to 30 m^3, was predicted to result in the onset of the observed door damage in level 1 of Mill B. This represents a very low partial fill fraction (Xr) below which the NFPA analysis begins to break down and produce inconsistent results. A full volume dust cloud in level 1 of Mill B was predicted to result in a peak pressure of 82 psi. This takes into account relief only through the vertical vent shaft.

To reduce the predicted pressure for a full volume dust explosion in level 1 of Mill B to 2.5 psi, the limit of the doors, a vent area of 42 m^2 is required. This vent area is much higher than the available area on the south of Mill B where vent panels could have been located.

The required vent area for partial fill fractions of 25%, and 10% were 32 m^2 and 26 m^2, respectively, for vents located at the end of the room. If the facility were designed such that vents could be placed along the long dimension of the room (which reduces the L/D in the calculations to 1) then the necessary vent area for a 10% fill fraction would be 19 m^2. This area, divided among multiple vents, only represents 12 % of the area of the two N-S walls in Level 1 of Mill B. Evaluation of the NFPA methodology for this facility indicates that properly engineered vents could have controlled the peak internal pressures if performed in conjunction with structural design of the mill enclosure.

5.2 An Explosion in the South Gap Mill

An explosion ignited at the base of the South Gap Mill which is located in level 1 of Mill B. As the material burns within the Gap Mill, unburned dust is ejected into level 1 of Mill B as the flame front progresses from the bottom of the Gap Mill. The maximum flammable mass of ejected dust when the flame front reaches the exit of the mill was tracked. Figure 5-1 shows the location of the dust cloud at the maximum flammable mass and the corresponding vertical section through the South Gap Mill and Mill B is shown in Figure 5-2. The total mass of dust expelled from the South Gap Mill into level 1 of Mill B was approximately 5.8 kg (12.8 lb.). This mass is well below the minimum mass of dust in level 1 of Mill B necessary to cause the observed damage as described in Section 5.3.

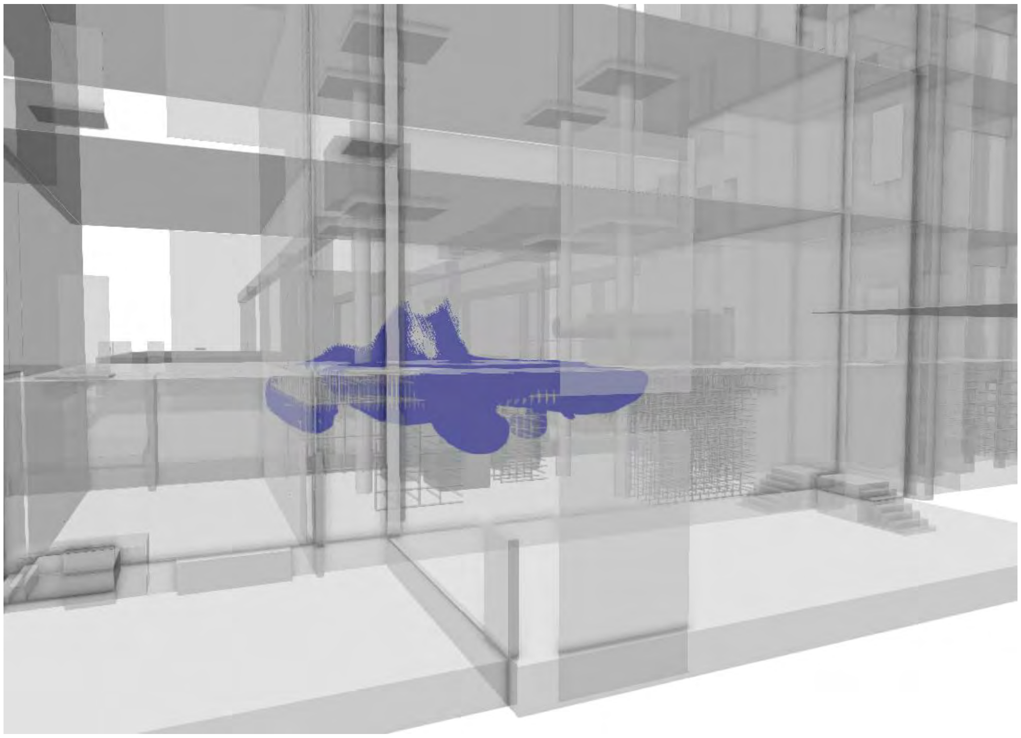


Figure 5-1. Dust Cloud Released from the South Gap Mill

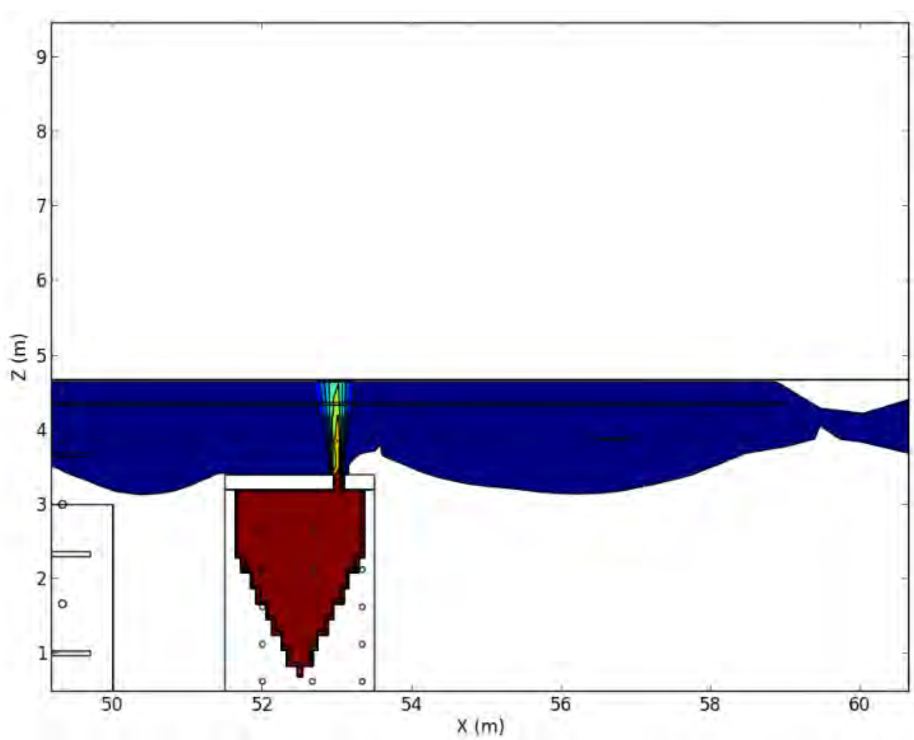


Figure 5-2. Vertical Section of South Gap Mill Dust Cloud Released into Mill B

5.3 An Explosion in Level 1 of Mill B

Five scenarios of varying dust cloud sizes were evaluated in Level 1 of Mill B as identified in Table 5-1. Applied pressures and impulses determined in the analysis at locations of the damage indicators are shown in Table 5-2. The stairwell doors and air shaft and electrical room doors were the primary damage indicators evaluated. These doors were severely deformed in the explosion consistent with ASTM Level IV damage. The P-i diagrams for the stairwell door is provided in Figure 5-3 and the air shaft and electrical room doors in Figure 5-4. Scenario 610016, a 33 m^3 dust cloud, was insufficient to cause the observed damage to the doors; however, the remaining scenarios were consistent with the observed damage in Level 1 of Mill B. This places the lower bound of dust mass above 33 m^3.

The damage to the stairwell door at Level 2 of Mill B, which was forced though the frame and thrown into the stairwell landing, is consistent with ASTM Level V damage. Applied blast loads on the stairwell door for each scenario are presented in Figure 5-5. None of the evaluated scenarios are capable of explaining the observed damage to the stairwell door at Level 2 of Mill B.

Applied blast loads on the P-i diagram for the undamaged electrical box at Level 2 of Mill B nearest the stairwell are shown in Figure 5-6. Scenario 610115 with the 100 m^3 cloud is predicted to cause loads which would produce damage and is inconsistent with this undamaged blast indicator. All other scenarios fall below the P-i diagram in Figure 5-6 and are consistent with this undamaged blast indicator. This would place the maximum dust volume between 67 m^3 and 100 m^3.

The blast indicator assessment of the scenarios in Table 5-1 indicate that the evaluated dust cloud most consistent with the observed damage in Levels 1 and 2 of Mill B was between 40 m^3 (45 lbs.) and 100 m^3 (110 lbs.). Further, to explain the damage to the remainder of the Mill, including Levels 2 through 4 of Mill B, Levels 1 through 5 of Mill A, the Multipurpose Building and Mill F requires propagation of the explosion from Level 1 of Mill B to other rooms within the Mills. This is evident due the 100 m^3 cloud in scenario 610115 being insufficient to cause the observed damage to Level 2 of Mill B but exceeding the threshold of damage to the undamaged electrical box in Level 2 of Mill B.

A sensitivity study was also conducted to evaluate the effect of congestion in the model from piping. The resulting dust masses from the model with reduced piping congestion (lower speed deflagration) were on the same order of magnitude. Therefore, the results are based upon the best estimate of the congestion with an upper mass limit of 110 lbs.

Table 5-1. Level 1 Mill B Explosion Scenarios

Scenario	Dust Cloud Volume	Concentration of Cloud	Mass of Dust in Cloud
610016	33 m^3	500 gm/m^3	16.5 kg (36.4 lb.)
610019	41 m^3		20.5 kg (45 lb.)
610017	49 m^3		24.5 kg (54 lb.)
610015	67 m^3		33.5 kg (74 lb.)
610115	100 m^3		50 kg (110 lb.)

Table 5-2. Explosion Scenario Applied Pressures and Impulses on Key Blast Indicators

Damage Indicator	Scenario and Cloud Volume	Applied Impulse (psi*ms)	Applied Pressure (psi)
Level 1 Mill B Stairwell Door ASTM Level IV Damage	610016 (33 m^3)	283	0.9
	610019 (41 m^3)	122	2.5
	610017 (49 m^3)	122	2.5
	610015 (67 m^3)	222	2.5
	610115 (100 m^3)	200	3.2
Level 1 Mill B Electrical Rooms and Air Shaft Doors ASTM Level IV Damage	610016 (33 m^3)	286	0.9
	610019 (41 m^3)	437	2.6
	610017 (49 m^3)	490	2.6
	610015 (67 m^3)	655	2.6
	610115 (100 m^3)	1142	7.9
Level 2 Mill B Stairwell Door ASTM Level V Damage	610016 (33 m^3)	185	0.5
	610019 (41 m^3)	214	1.1
	610017 (49 m^3)	229	1.3
	610015 (67 m^3)	339	1.4
	610115 (100 m^3)	200	1.7
Level 2 Mill B Electrical Box Undamaged	610016 (33 m^3)	191	0.6
	610019 (41 m^3)	280	1.5
	610017 (49 m^3)	303	1.5
	610015 (67 m^3)	426	1.8
	610115 (100 m^3)	351	3.2

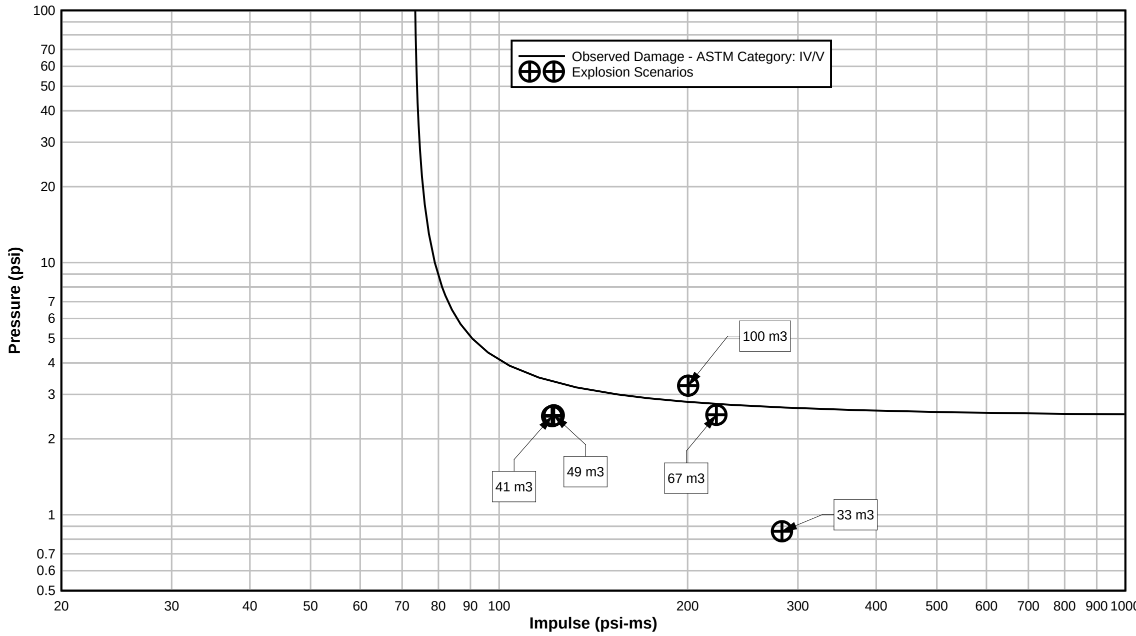


Figure 5-3. Level 1 Mill B Stairwell Door P-i Diagram and Scenarios

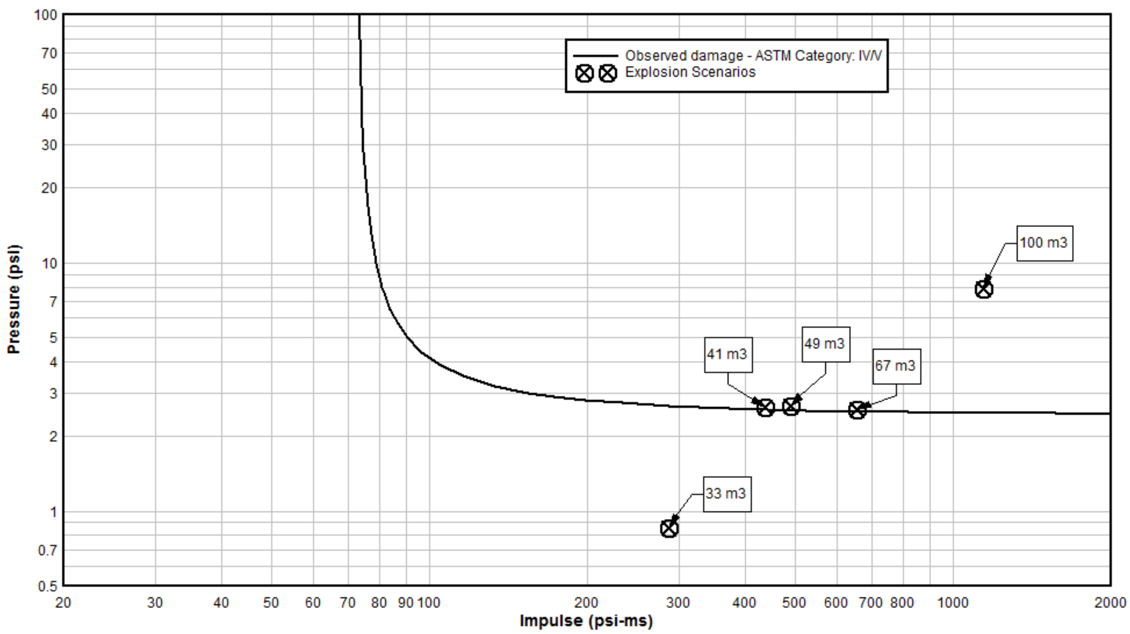


Figure 5-4. Level 1 Mill B Doors at Electrical Rooms and Air Shaft P-i Diagram and Scenarios

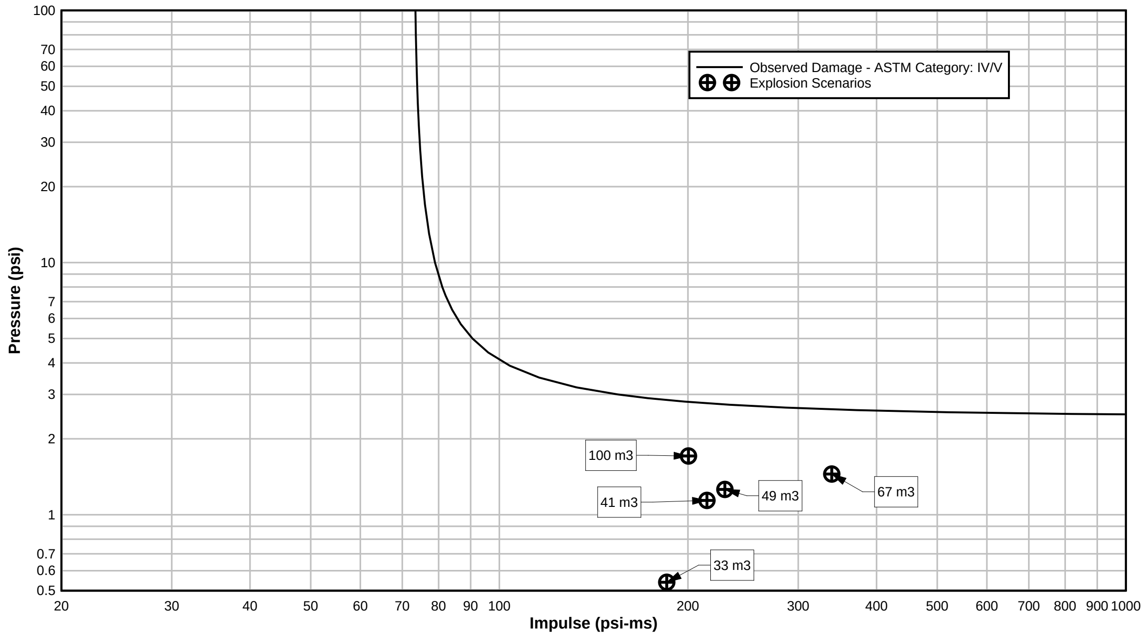


Figure 5-5. Level 2 Mill B Stairwell Door P-i Diagram and Scenarios

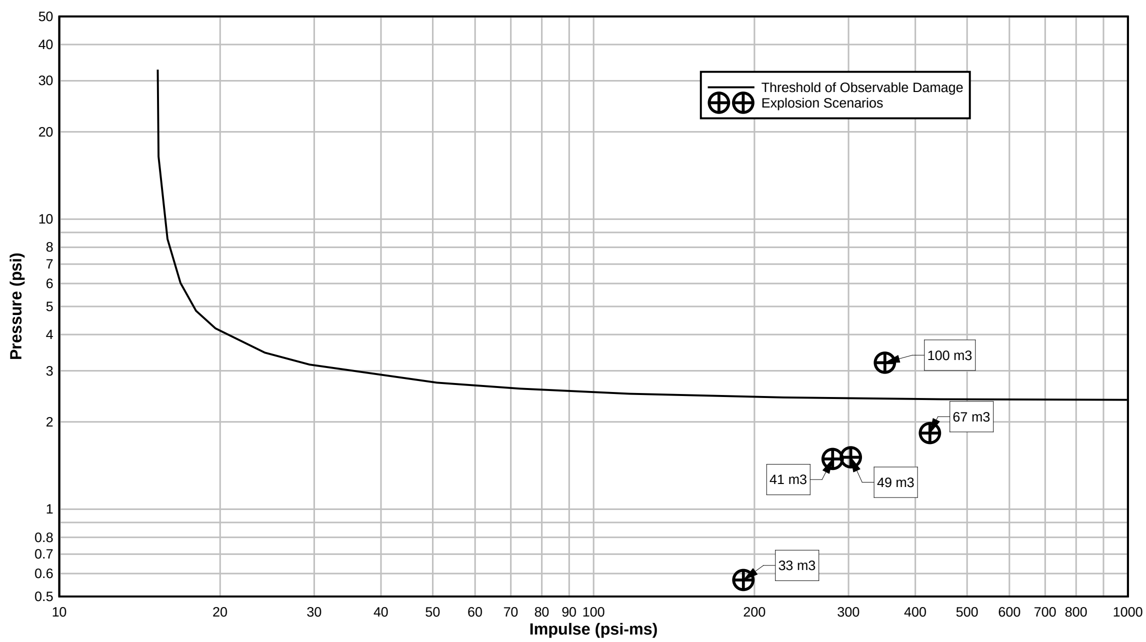


Figure 5-6. Level 2 Mill B Undamaged Electrical Box P-i Diagram and Loads

5.4 An Explosion in the Multipurpose Building

The Multipurpose BUilding construction was described in Section 2.5. Based on photos of the Multipurpose Building roof slab debris, the hollow core slabs did not contain any prestressing tendons at the top of the typical roof slabs, only at the bottom, which is standard hollow core slab construction. Top tendons are only used if required for locations where negative moment is expected. For simple beams there is no expected negative moment due to gravity loading. Therefore load from beneath on the hollow core roof slabs (an internal load) would fail at low overpressure due to tension on the top of the slab. With the prestressing tendons at the bottom of the slab and an upward pressure, the induced compression from the tendons add to the load reversal and accelerate the upward failure mode. Further, the ends of the planks were not significantly restrained therefore the entire roof could simply uplift off the supports as a consequence of internal pressure and then impact the beams after the load subsided shearing off the ends. The dynamic enhancement of the load (dynamic load factor - DLF) results in a peak pressure less than the weight of the roof component to cause the initiation of uplift.

The end bay adjacent to the bearing walls did not add significant resistance to resist the internal pressures of the blast since the out-of-plane resistance of the assumed rebar dowel is negligible when consideration is given to roof uplift and separation from the wall. Since both the interior roof bays and the outer roof bays have essentially the same damage pattern, the uplift on the roof failure scenario is more likely to be the main failure mechanism of the Multipurpose Building.

The predicted blast loads from the CFD model determined the minimum volume of a combustible dust cloud in the Multipurpose Building necessary to generate the onset of structural instability and failure was approximately 70 m^3 of dust at a concentration of 500 gm/m^3. This equates to 35 kg, or roughly 80 lbs. of dust. The precast elements of the Multipurpose Building were not designed nor connected together in a manner to resist the internal pressure loading in a ductile manner.

5.5 Vented Explosion in Level 1 of Mill B and Multipurpose Building

5.5.1 Vented Explosion in Level 1 of Mill B

Vents were added to the CFD model of level 1 of Mill B to determine the reduced pressures. One vent was added to the southern wall measuring 11 m^2. This reduced the pressure at the doors to 1.7 psi for the 67 m^3 dust cloud. This is below the 2.5 psi from the unvented simulation (Section 5.3) and would result in integrity of the door opening being maintained.

5.5.2 Vented Explosion in the Multipurpose Building

Three vents were added to the Multipurpose Building on the north, south, and west walls. In total, the vents measure 245 m^2. Figure 5-7 shows the result after the 67 m^3 explosion from Section 5.4. The vent panels have opened up but the rest of the structure is below the calculated failure loads. Therefore, proper design of engineered vents in the Multipurpose Building in conjunction with additional continuity of the structure could have reduced or eliminated the structural failures.

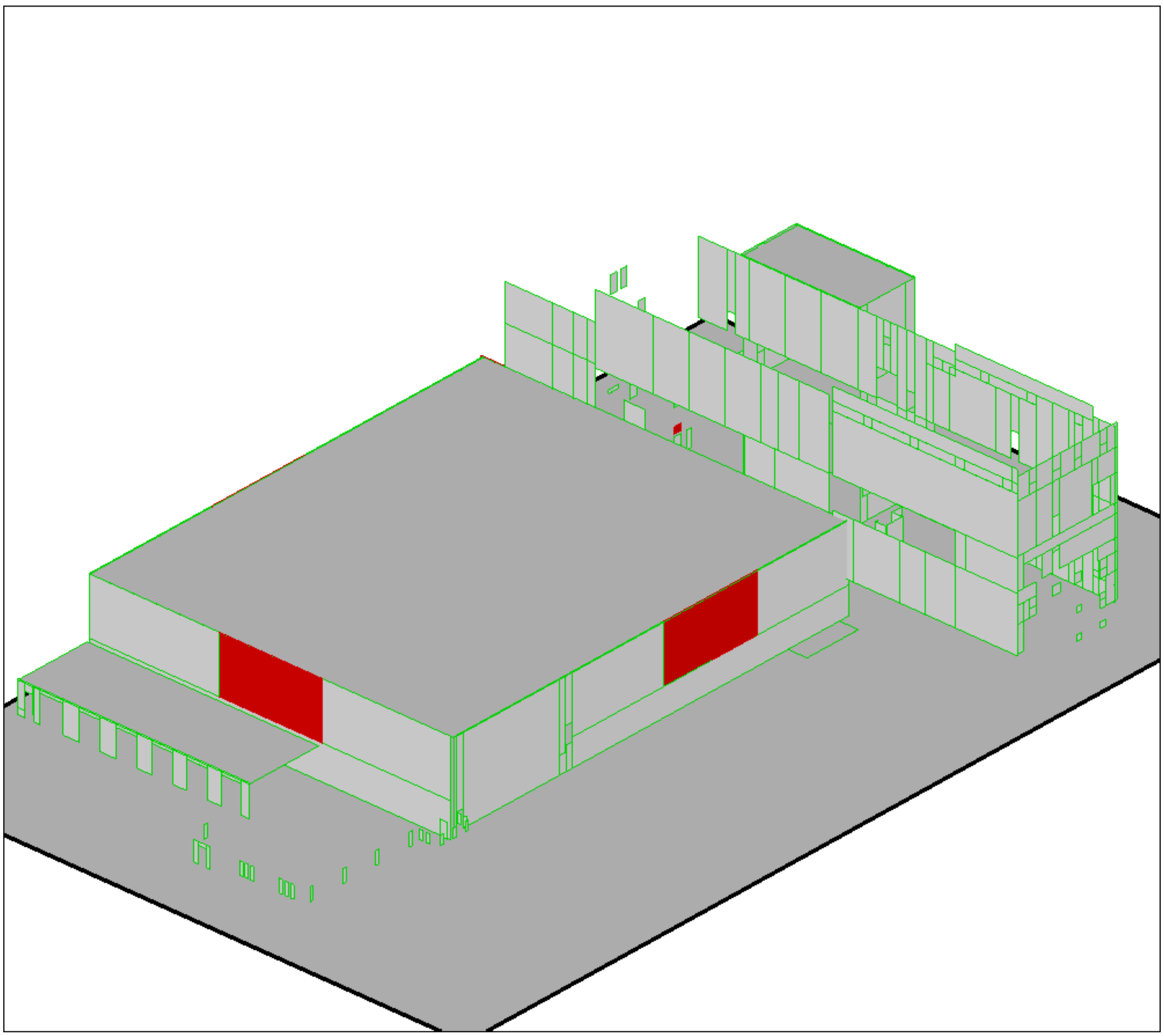


Figure 5-7. Vented Multipurpose Building Failure Patterns (in Red)

5.6 An Explosion with Propagation between Mill Rooms

The progression of an explosion, initiated on Level 1 of Mill B, to the third level and separated by vent shaft doors, floors, and walls is shown in Figure 5-8. As the pressure loads fail doors and the flame front propagates through the air shaft and ignites additional dust, pressure is increased throughout Mill A and Mill B. This result is consistent with the observed damage and directional indicators.

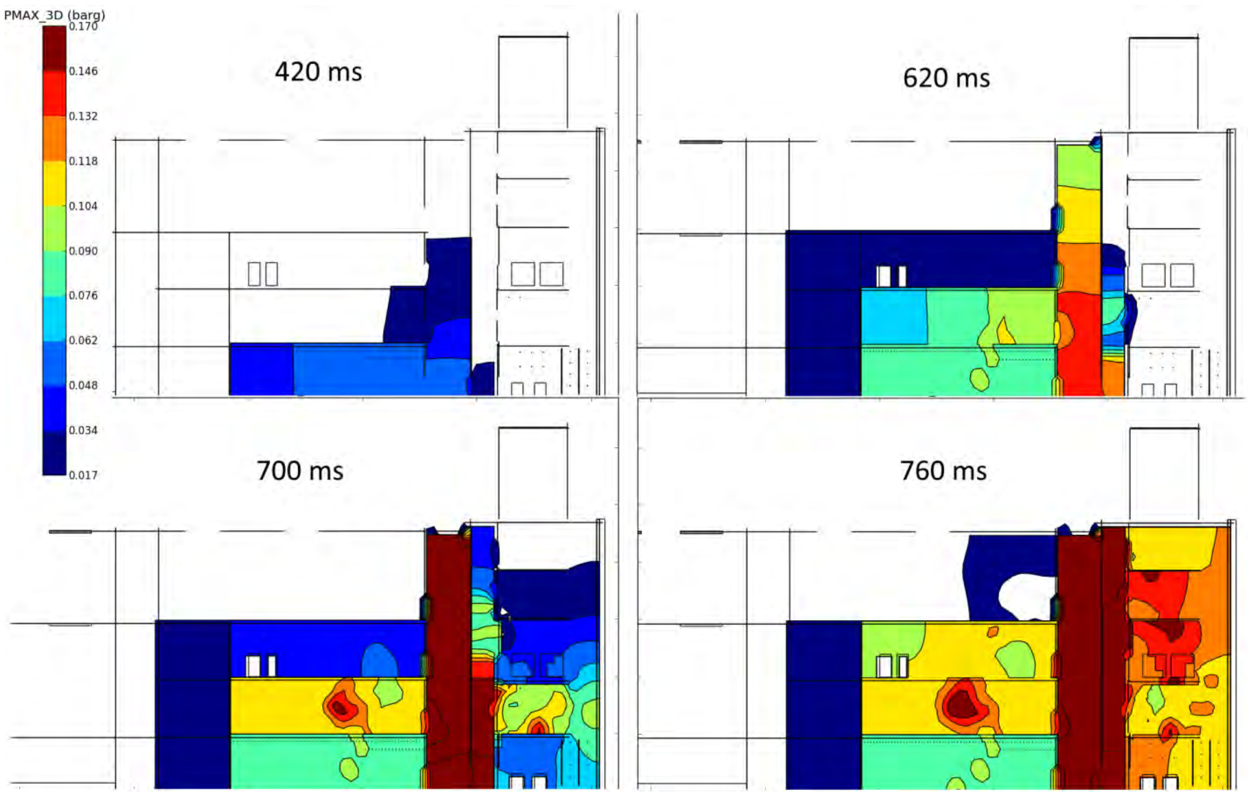


Figure 5-8. Progression of Pressure through the Vertical Vent Shaft

6 Findings

The precast elements of the Didion Milling facility included the walls of Mill B and Mill D, and Mill F, the Boiler Room and Multipurpose Building which were not designed to resist the effects of an accidental dust explosions nor were connected together in a manner to resist internal pressure loading in a ductile manner.

Using NFPA 68[7] methods and restricting the cloud size to the full volume of level 1 of Mill B, the peak pressure expected from an explosion within Level 1 of Mill B would be 82 psi. This takes into account relief only through the vertical air shaft. A partial volume cloud of 2 to 3% of the full volume of level 1 Mill B, which is 20-30 m^3, was predicted to explain the onset of the observed door damage in level 1 of Mill B by NFPA methodology.

The CFD analysis predicted that the mass of the combustible dust clouds in Level 1 of Mill B most consistent with the observed damage to Levels 1 and 2 was between 40 m^3 (45 lbs.) and 100 m^3 (110 lbs.) of dust. This cloud volume is 4-10% of the volume of level 1 of Mill B main room. Propagation of this explosion to other areas of the mill was required to cause the observed damage to other portions of Didion Milling including Levels 2 through 4 of Mill B, Levels 1 through 5 of Mill A, the Multipurpose Building and Mill F. Propagation of explosion is consistent with the observed damage, blast directional indicators, and fire directional indicators.

The explosion analysis of the South Gap mill indicated that the maximum flammable mass of ejected dust when the flame front reaches the exit of the South Gap Mill was approximately 5.8 kg (12.8 lb.). This mass is well below the mass calculated to cause the observed damage to Level 1 of Mill B above. Therefore, a combination of dust ejected from the South Gap Mill and fugitive dust within level 1 of Mill B was necessary to cause the initial damaging explosion in level 1 of Mill B.

The minimum volume of a combustible dust cloud in the Multipurpose Building necessary to generate the onset of structural instability and failure was determined to be approximately 70 m^3 at a concentration of 500 gm/ m^3. This equates to 35 kg, or roughly 80 lbs. of dust.

Vents were added in the CFD model to the Level 1 of Mill B. One vent was added to the southern wall measuring 11 m^2. This reduced the pressure in this area of Mill B below that of the walls and doors which would maintain the integrity of these surfaces and openings indicating that engineered venting may have mitigated the propagation of the explosion;

however, the air shaft would remain a potential path for fire and overpressure due to the open nature of the system.

Venting of the Multipurpose Building to protect the precast construction would have required approximately 20 percent of the wall surface area, or 250 m^2 of total vent area, on the north, south, and west walls to protect the precast construction. Proper design of engineered vents in the Multipurpose Building in conjunction with additional continuity of the structure could have reduced or eliminated the structural failures.

7 References

1. CSB Contract CSB-13-022, Requisition Reference No. CSB-1I25-0029, "Blast Modeling and Analysis", 9/19/2017.

2. CSB Contract CSB-17-0023, Requisition Reference No. CSB-1I25-17-0015, "Blast Analysis Consulting to Support.

3. ioKinetic, "Combustible Grain Dust Characterization of Didion Manufacturing Dust Samples", isokinetic Project #18065, Michelle R. Murphy.

4. PDC-TR-06-08, "Single Degree of Freedom Structural Response Limits for Antiterrorism Design", U.S. Army Corps of Engineers PDC, Rev. 1, Jan 2008.

5. ASTM F2247-18, Standard Test Method for Metal Doors Used in Blast Resistant Applications (Equivalent Static Load Method), ASTM International, West Conshohocken, PA, 2018, www.astm.org.

6. PDC-TR-06-01, "Methodology Manual for the Single-Degree-of-Freedom Blast Effects Design Spreadsheets, Rev. 3 December 2014.

7. NFPA 68, "Standard on Explosion Protection by Deflagration Venting", National Fire Protection Association, 2018.

8 U.S CSB, "Didion Milling Factual Investigation Update", April 30,2018.