Client: United States Chemical Safety Board

Report Title: AB Specialty Silicones Explosion Assessment

Incident: May 3, 2019

Final Report Revision 1

ABS Group Project No. 4282052
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Executive Summary

ABSG Consulting Inc. (ABS Group) was contracted to conduct a forensic evaluation of the AB Specialty Silicones, LLC explosion of May 03, 2019 performing the following tasks:

- Field Investigation
  - Assessment of Building Construction and Damage
  - Identify Blast Indicators and Directional Indicators on-site and off-site
- Blast Modeling
  - CFD modeling to evaluate the following potential flammable releases:
    - Methane Explosion in the Low Bay Processing Area
    - Hydrogen Gas Explosion in the Low Bay Processing Area

Directional indicator analysis of the AB Specialty facility indicated the generation of the highest overpressures was located between Tank S4 and S2 of the low bay process area.

The natural gas explosion scenario was modeled by filling the entire Processing Area of the Low Bay with a methane gas cloud to establish an upper bound in judging viability of a natural gas event. Comparison of the predicted blast loads from the CFD methane model to the blast loads determined that the observed/measured damage to the blast indicators does not support the likelihood of a natural gas explosion. This eliminates natural gas as the potential flammable gas source of the explosion.

Hydrogen gas cloud volumes of 22900, 26800, 27880, and 39540 ft^3 were evaluated. Volumes were based on gas present inside the Processing Area near the ceiling and/or gas from floor to ceiling in the area centered between Tank S4 and S2. The size of the flammable cloud was varied to compare with blast damage results. The mass of the flammable gas cloud most consistent with the observed damage to on-site and off-site facilities was approximately 27,000 ft^3 (41 lbs) of hydrogen gas. This cloud volume represents about 25% of the volume of Processing Area of the Low Bay. There was no evidence that a flammable could was formed outside of the Processing Area.

The flame speed represents the intensity of the explosion. Three different flame speeds of 0.59, 0.7, and 0.9 Mach (M_f) were modeled based on the combination of fuel reactivity, congestion, and confinement noted in the Process Area. A flame speed of 0.7 (M_f) produced the blast loads most consistent with the observed damage.

Ignition locations are often not located at the explosion center of flammable gas clouds. Combustion of flammable gas may burn into areas of higher congestion or confinement which accelerate the flame resulting in damaging overpressure. Consequently, ignition of the flammable gas cloud was simulated in two separate locations. The first was between Tank S4 and S2 where heavy damage was evident on tanks and equipment radiating away from this central point. The second ignition location was simulated in the western quarter of the upper cloud (cloud formed along the ceiling) west of Tank R5. This was done to determine if the damage observed off-site, particularly at the American Outfitters and Eagle

Foods building, was affected by an offset ignition location resulting in the observed damage. Results indicate that the ignition likely initiated in western portion of the Low Bay Processing Area burning and accelerated eastward.

An explosion of about 27,000 ft^3 of hydrogen gas centered in the Processing Area of the Low Bay portion of the facility is most consistent with the observed damage. An explosion involving natural gas of any volume within the Processing Area in the Low Bay was not consistent with the observed damage and was eliminated as a potential fuel source of the explosion.

1 Introduction

ABSG Consulting Inc. (ABS Group) was contracted by the Chemical Safety and Hazard Investigation Board (CSB) to support the investigation of the May 3, 2019 explosion at the AB Specialty Silicones (AB Specialty) facility in Waukegan Illinois [1]. The explosion and subsequent fire resulted in the deaths of 4 people, seriously injury to one other person, and extensive damage to the facility and adjacent businesses. ABS Group conducted two site visits to support a forensic investigation of the explosion which included surveying damage patterns at the explosion origin as well as blast damage away from the facility at nearby properties.

1.1 Goal/Objective

The goal of the forensic investigation was to determine which potential flammable gas and volume of gas was most consistent with the explosion consequences. This report summarizes the engineering and analysis effort performed in support of the CSB investigation.

1.2 Scope

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

- Task 1: Forensic Field Investigation
- Task 2: Blast Damage Indicator Assessment
- Task 3: CFD Modeling of Explosion Scenarios
- Task 4: Reporting
- Task 5: Project Management

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 Task 1 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 to meet the following objectives:

- Perform structural calculations to estimate blast pressure and impulse combinations that best explain the observed damage.
- Model potential explosion scenarios to determine the corresponding blast loads associated with the observed damage.
- Reconcile explosion modeling with structural modeling to identify the explosion scenario that is most consistent with the observed damage.

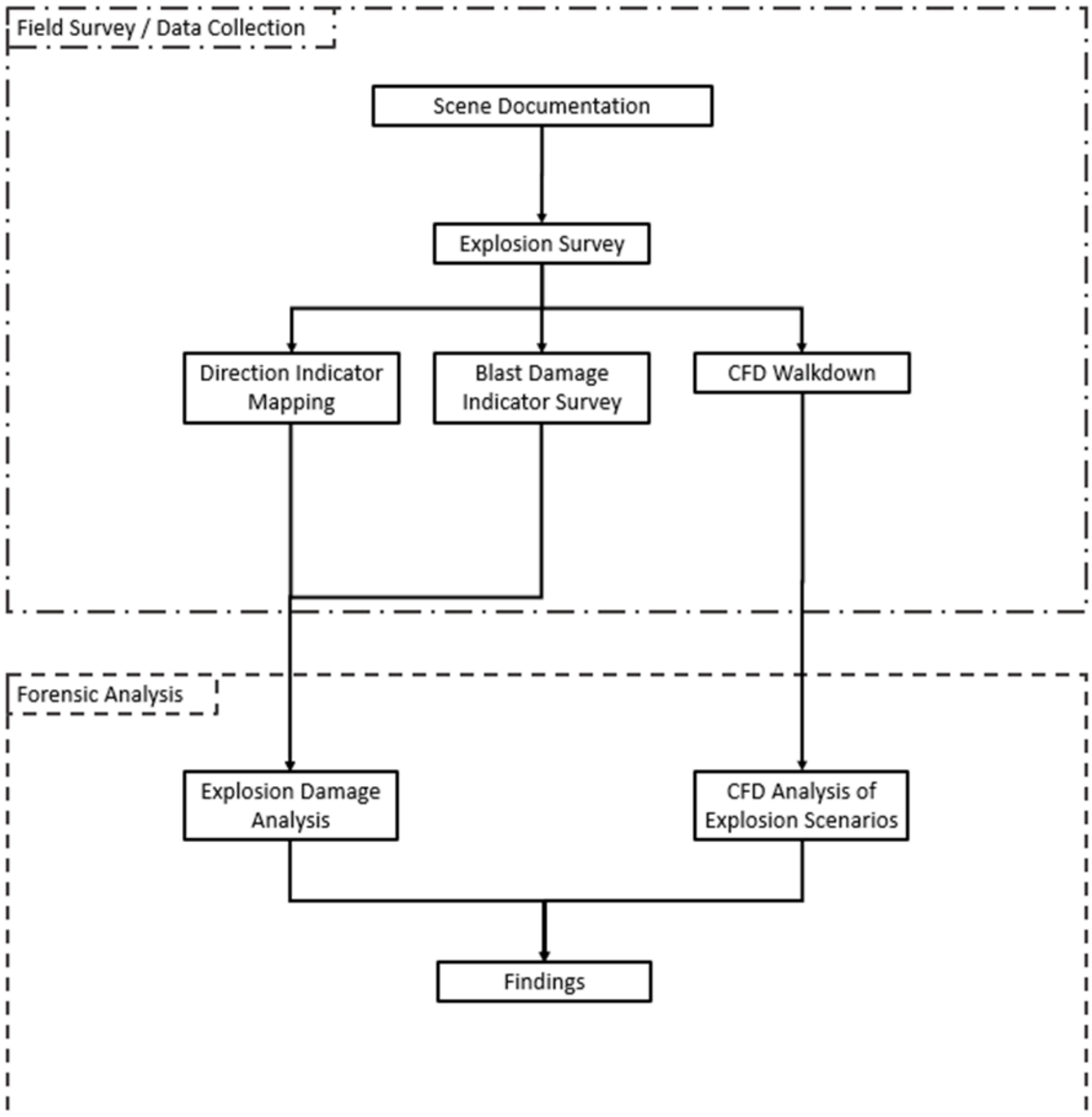


Figure 1-1. ABS Group Scope of Workflow Chart

1.3 Government Furnished Information

The CSB provided basic information on the AB Specialty Facility construction as well as media of the explosion consequences, fire department incident, and investigation reports as follows:

Drawings received for the building layout are listed in Table 1-1.

Table 1-1. General Facility Drawings

CSB Designation	Sheet No.	Issue Date	Title
CSB_0002543	1	07/15/1977	Original Building, Site Development Plan
CSB_0002544	3	07/15/1977	Original Building Floor Plan
CSB_0002545	A-2	06/08/2017	New Floor Plan
CSB_0002546	NA	NA	Equipment Layout (South Building)
CSB_0002547	NA	NA	Peripheral Equipment Layout (South Building)
CSB_0002548	A0	09/20/2010	Site Plan
CSB_0002549	A1	09/20/2010	North Building Floor Plan
CSB_0002549	NA	NA	Equipment Layout (North Building)

The following videos were provided by CSB:

- Initial blast- slow motion.mp4 – Security camera footage from Woodland Foods approximately 1000 ft to the southeast
- Morning (3).MP4 – Drone video of incident site flyover morning of 05/04/2019

In addition, copies of the local fire department incident reports and Fire Investigation Report were provided including the following.

- DFM Zupec Investigation Report Amended.pdf[2]
- 3790 Sunset NFIRS report FULL with casualties.pdf[3]

CSB publication of AB Specialty Silicones Factual Update[4] was also provided.

1.4 Definitions and Acronyms

1.4.1 Acronyms

The following are acronyms used in this document.

- **BST**: Baker-Strehlow-Tang methodology
- **CAD**: Computer Aided Drafting
- **CEBAM**: The Computational Explosion and Blast Assessment Model
- **CFD**: Computational Fluid Dynamics
- **CSB**: United States Chemical Safety and Hazard Investigation Board
- **LEL:** Lower Explosion Limit
- **M_f**: Flame speed relative to a fixed observer, expressed as a Mach number
- **ms**: Milliseconds
- **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.
- **LEL**: Lower Explosion Limit
- **UEL**: Up per Explosion Limit
- **SDOF**: Single-Degree-of-Freedom, a common dynamic structural analysis method used in blast analysis.

1.4.2 Definitions

Definitions of key terms:

- **Blast Indicator:** A damaged or undamaged object that can provide information, through detailed analysis, regarding 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.
- **Deflagration**: combustion which propagates through a gas or across the surface of an explosive at subsonic speeds, driven by the transfer of heat.
- **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.
- **Flame Speed**: measured rate of expansion of the flame front in a combustion
- **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 AB Specialty Facility Description

The AB Specialty facility consisted of two structural systems. For the purposes of the investigation, these are referred to as the Low Bay structure and the High Bay structure. A general floor plan of the facility highlighting the building structures is shown in Figure 2-1. The Low Bay structure was located on the southern side of the facility with floor plan dimensions of approximately 150 ft by 100 ft with a roof height of about 16 ft. The Low Bay contained two primary areas including the processing area on the east side of the floor plan and the Labs and support offices on the west side of the floor plan. It was constructed of steel frames with masonry walls and brick veneer on the south and west walls. The east wall consisted of steel girts and insulated metal wall panels. The north wall was open to the High Bay structure on the north side of the facility. The roof was a corrugated metal deck with built up gravel roofing supported by open web steel joists. A small penthouse was constructed over the southeast corner. The penthouse was a light gage steel pre-engineered structure.

The High Bay structure was located on the northern portion of the facility and was approximately 150 ft by 94.5ft by 40 ft tall. The high bay functioned as a warehouse for raw materials, stored finish product, and shipping. It was constructed of a pre-engineered steel frame with cold formed girts and purlins supported corrugated metal wall panels and roof panels.

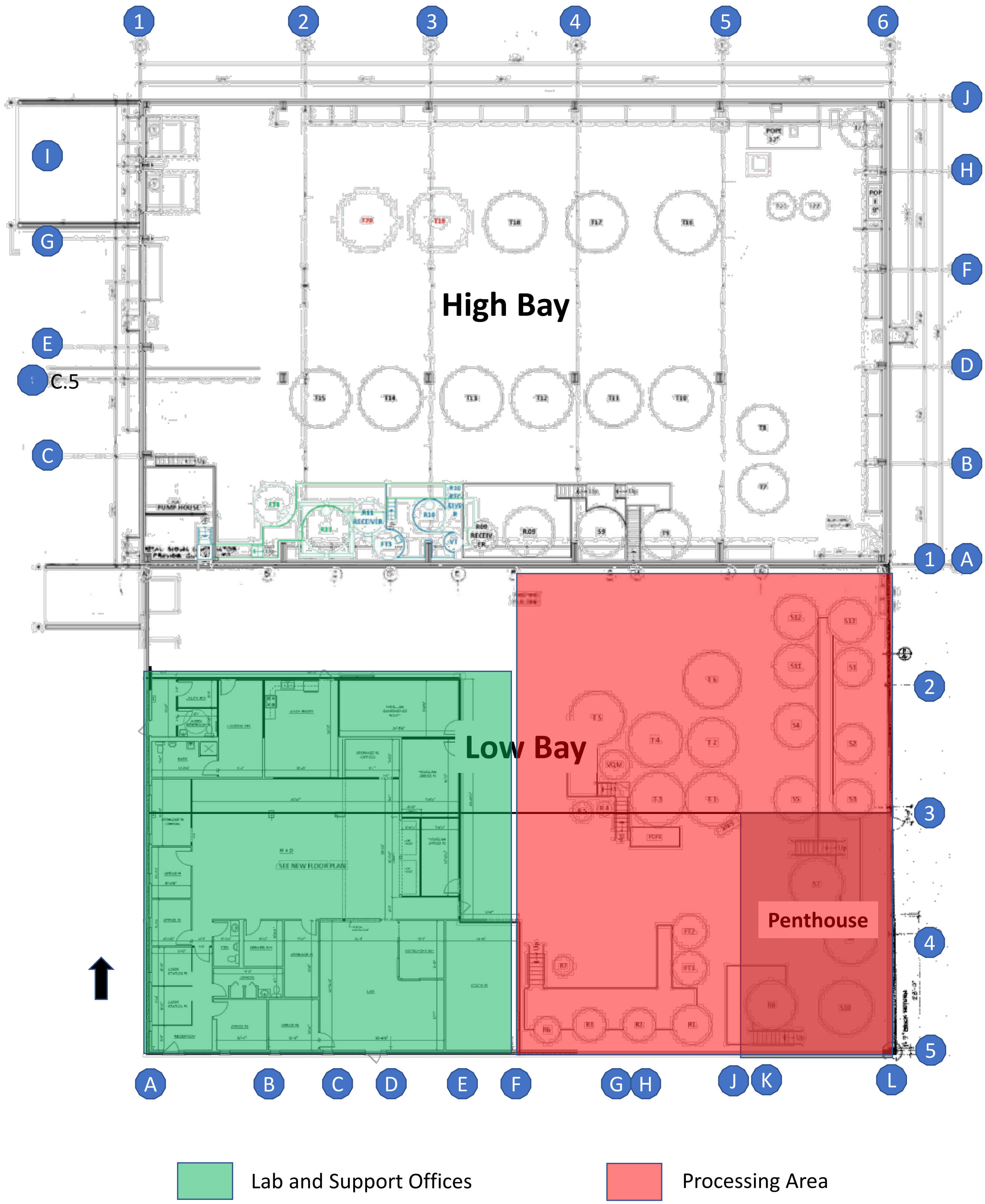


Figure 2-1. AB Specialty Facility General Floor Plan

3 Site Survey and Data Collection

Site surveys were conducted by the ABS Group team on June 11-13 and July 09-12, 2019 to observe the explosion scene and collect information to support the forensic analysis as detailed in the following sections.

On-site survey of explosion damage included documentation of blast indicators and directional indicators within the interior of High Bay and Low Bay, exterior façade and facility debris patterns. Observations were also made for development of the CFD model including equipment location, congestion, confinement, and openings between structures. Due to the extent of the damage to the facility, entries were limited to the High Bay area and portions of the Low Bay to minimize exposure of the investigation team to potential collapse hazards.

Off-site surveys were also conducted of nearby structures to document blast damage to neighboring buildings affected by the explosion.

3.1 Damage Observations

The explosion resulted in the complete structural failure and subsequent collapse of the Low Bay structure. A large portion of the roof was destroyed by the event and the west, south, and east walls were blown outward away from the building creating a significant debris field extending several hundred feet away from the building.

All the metal deck walls of the High Bay were ripped off the girts of the structure by the overpressure. A majority of the girts were deformed outward from the interior of the building. Approximately two thirds of the roof decking were dislodged and thrown from the roof. The southeastern corner of the High Bay was observed to have more significant damage than the remainder of the structure. Girts in this area had larger deformations as well as several experiencing failed connections. An overhead view of the AB Specialty facility damage and collapse is shown below in Figure 3-1, the damage to the west façade is shown in Figure 3-2, and damage to the south façade is shown in Figure 3-3 below.

Figure 3-1. Overhead Drone Photo of AB Specialty Facility Collapse

Figure 3-2. AB Specialty Facility Building West Façade

Figure 3-3. AB Specialty Facility Building South Façade

3.2 Directional Indicators

Directional indicators are objects that are deformed by the blast wave in the direction of travel of the wave and are mapped to aid in the identification of explosion centers and origins. Experience was used to identify situations that can affect the direction of damage, such as blast reflections off nearby surfaces and structural rebound. Large flammable cloud explosions may envelop multiple regions of confinement and produce multiple explosion centers.

ABS Consulting mapped directional indicators in the accessible portions of the Low Bay and High Bay structures in order to determine the origin of the damaging explosion overpressure. Process tanks, exterior walls, and roof members were all significant blast direction indicators. In addition, debris patterns also illustrated the primary direction of the blast.

As a general observation, the directional indicators are consistent with an explosion in the eastern portion of the Low Bay building. Multiple process tanks were damaged on the surfaces facing the area just east of Column Line K and just south of Column Line 2 in the Low Bay. Table 3-1 is a summary of the primary Directional Indicators. Figure 3-4 shows the general floor plan with the Directional Indicators overlaid and examples of directional indicators are provided in Figure 3-5. Photographs of the directional indicators can be found in the Appendix.

Table 3-1. AB Specialty Directional Indicator Summary

Directional Indicator Number	Description
A	Exterior Walls of Low Bay and High Bay Building
B	Tank S12
C	Tank T6
D	Tank T2
E	Tank S4
F	Tank S5
G	Tank S2
H	Tank S1
I	Tank S13
J	High Bay Ceiling Fan
K	Roof Panels of High Bay

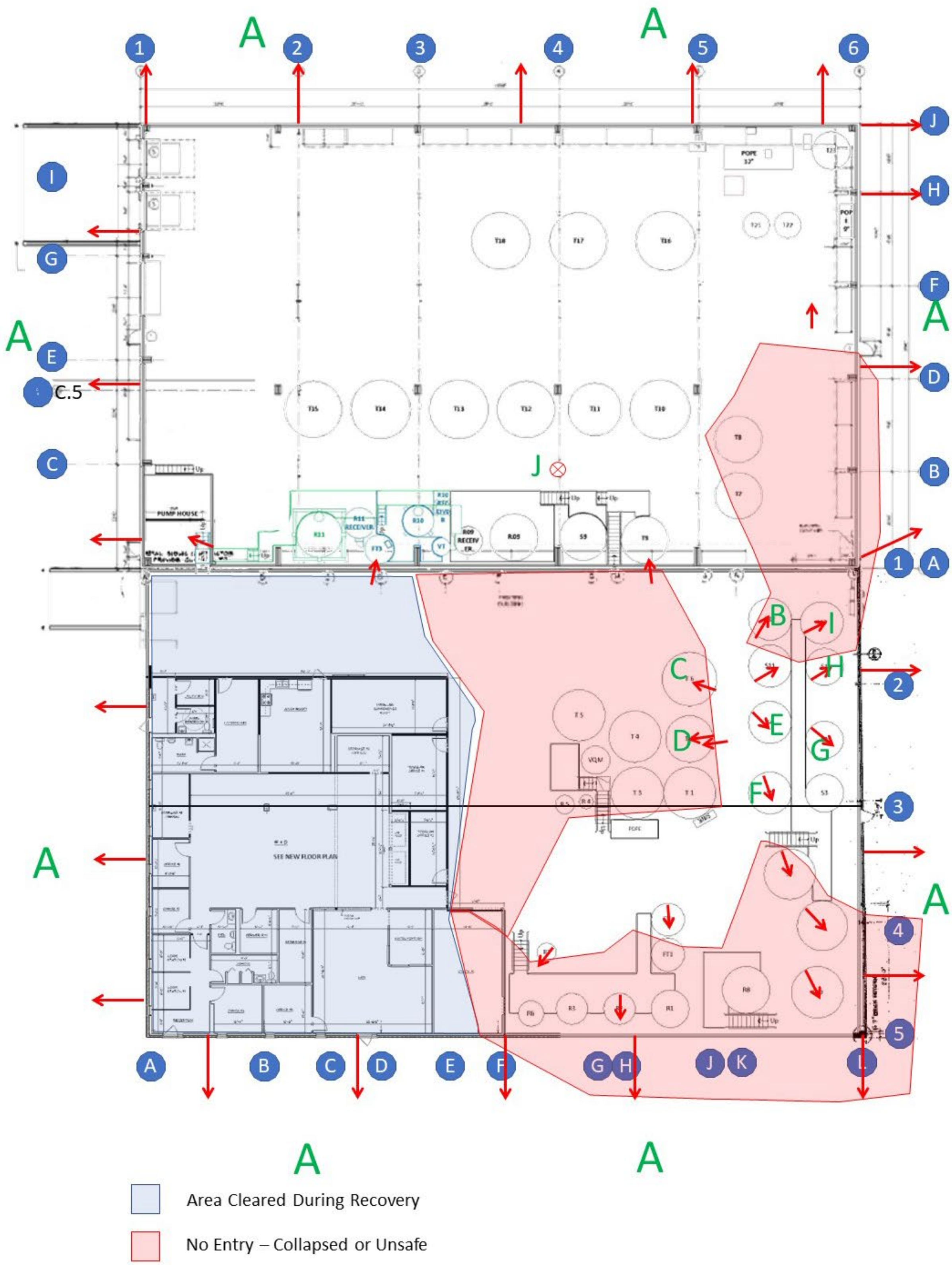


Figure 3-4. AB Specialty Directional Indicator Plan

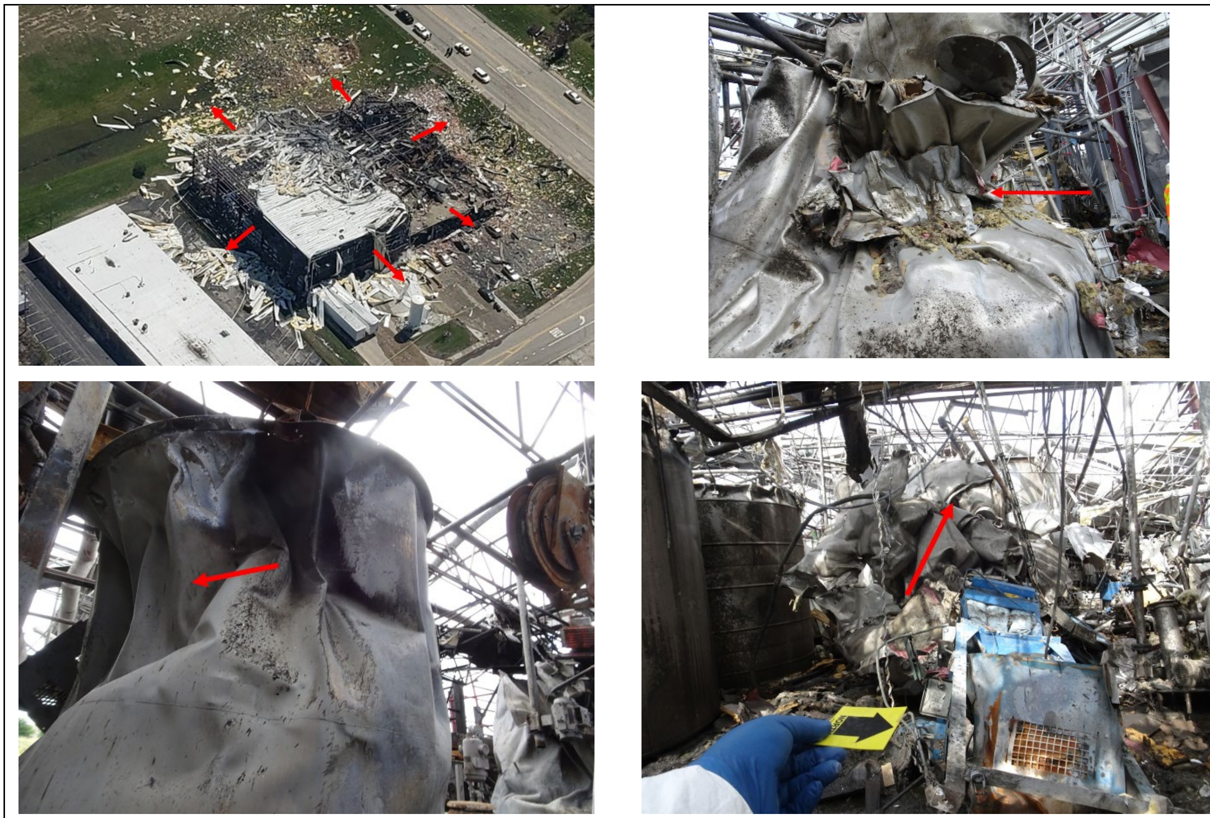


Figure 3-5. Directional Indicator Examples

3.3 Blast Indicators

The site survey included documentation of blast indicators 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 undamaged by blast and their state of damage can be used as a measure of the blast pressure and impulse at their location. 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. An undamaged blast indicator is an object that remains undamaged after being subjected to blast pressure providing information regarding the minimum applied pressure and impulses required to cause the onset of damage. 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.

Structural analyses were conducted on the blast indicators to calculate applied blast pressure and impulse combinations that can result in the observed indicator 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 idealized conditions. Variations in boundary conditions can affect the computed pressure and impulse values.

Blast indicators are presented in the following sections along with summary photographs included in the appendix. Surfaces representing the blast indicators are placed in the CFD model with probes to provide the peak pressure and total impulse. The blast loads predicted by the CFD for each indicator are utilized to evaluate which explosion scenario in the process area of the Low Bay is most consistent with the observed damage at the AB Specialty facility.

3.3.1 On-site Blast Indicators

ABS Consulting surveyed a number of blast indicators inside the Low Bay and High Bay areas of the AB Specialty facility. Reliable blast indicators are not severely damaged by the explosion and had consistent boundary conditions and loaded area. There were a handful of reliable damaged blast indicators such as electrical cabinet doors, electrical boxes, job boxes, and various structural members of the High Bay building. Damaged blast indicators in the survey are summarized below in Figure 3-6 and identified in Table 3-2 below. Examples of indicators provided in Figure 3-7 indicate that an explosion in the process area was severe enough to cause complete structural failure of the Low Bay as well as significant damage in the High Bay.

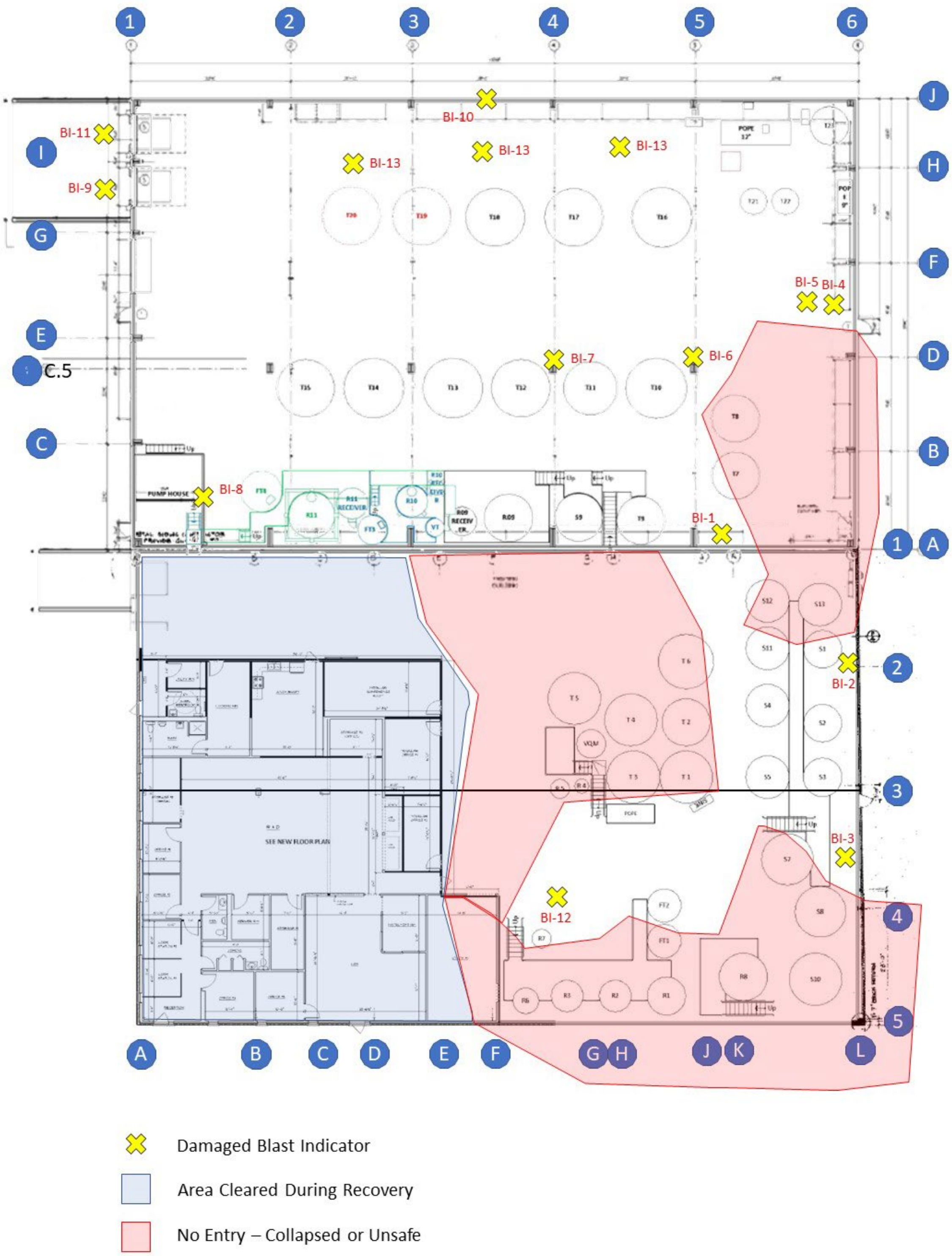


Figure 3-6. AB Specialty On-site Damaged Blast Indicators

Table 3-2. AB Specialty On-site Blast Indicator Summary

Blast Indicator Number	Description
BI-1	Steel Wall – White “Bldg” or Shed
BI-2	Electrical Box Panel
BI-3	Blue Top of flammables cabinet
BI-4	Job Box
BI-5	Delta JobSite Box
BI-6	Electrical Box Panel – Unitron Controls
BI-7	Electrical Box Panel
BI-8	Metal Studs on Interior Room
BI-9	Box Trailer – Parked in loading dock
BI-10	High Bay Girt
BI-11	Box Trailer – Parked in loading dock
BI-12	Electrical Box Panel
BI-13	High Bay Purlins

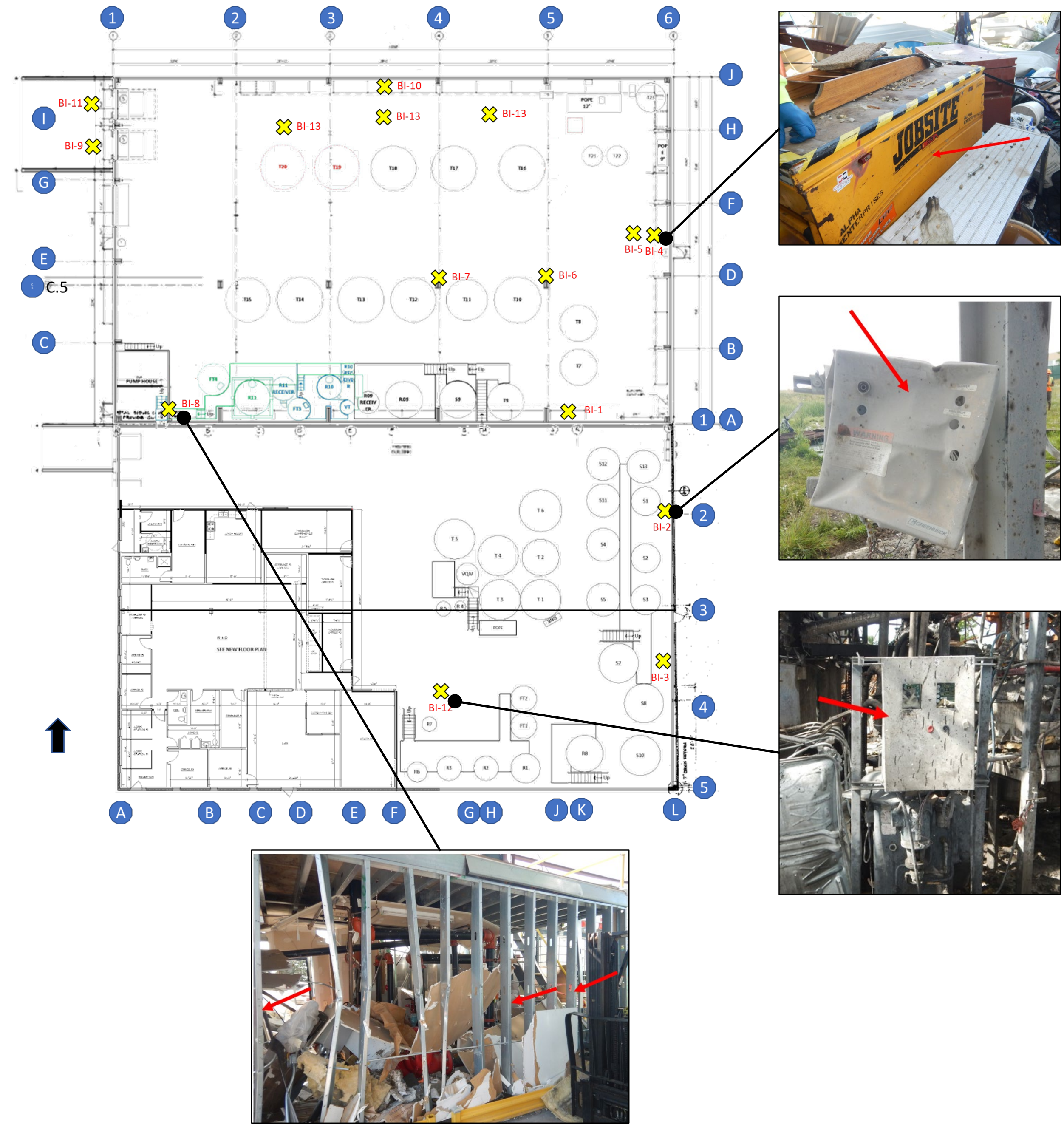


Figure 3-7. AB Specialty On-site Exemplar Blast Indicators

3.3.2 Offsite Blast Indicators

In addition to blast indicators in the facility, ABS Consulting surveyed a number of blast indicators at nearby buildings including damaged blast indicators that sustained some permanent deformation during the event. The survey similarly included documentation of blast indicators with photographs and field notes, and measurement of permanent deformations if applicable. The purpose of the offsite evaluation was to provide data at farther distances from the explosion that can be used to supplement the onsite blast and directional indicators and assist in determining the severity of the explosion in terms of observed pressure and impulse.

There were five local businesses which sustained damage where a blast indicator was observed. Damaged and undamaged building components windows, roof joists, structural steel members, and masonry walls were identified. A map of the offsite locations surveyed is shown in Figure 3-8. The off-site blast indicator survey is summarized below in Table 3-3. Maps of blast indicator locations in each of the buildings shown in Figure 3-9 through Figure 3-13.

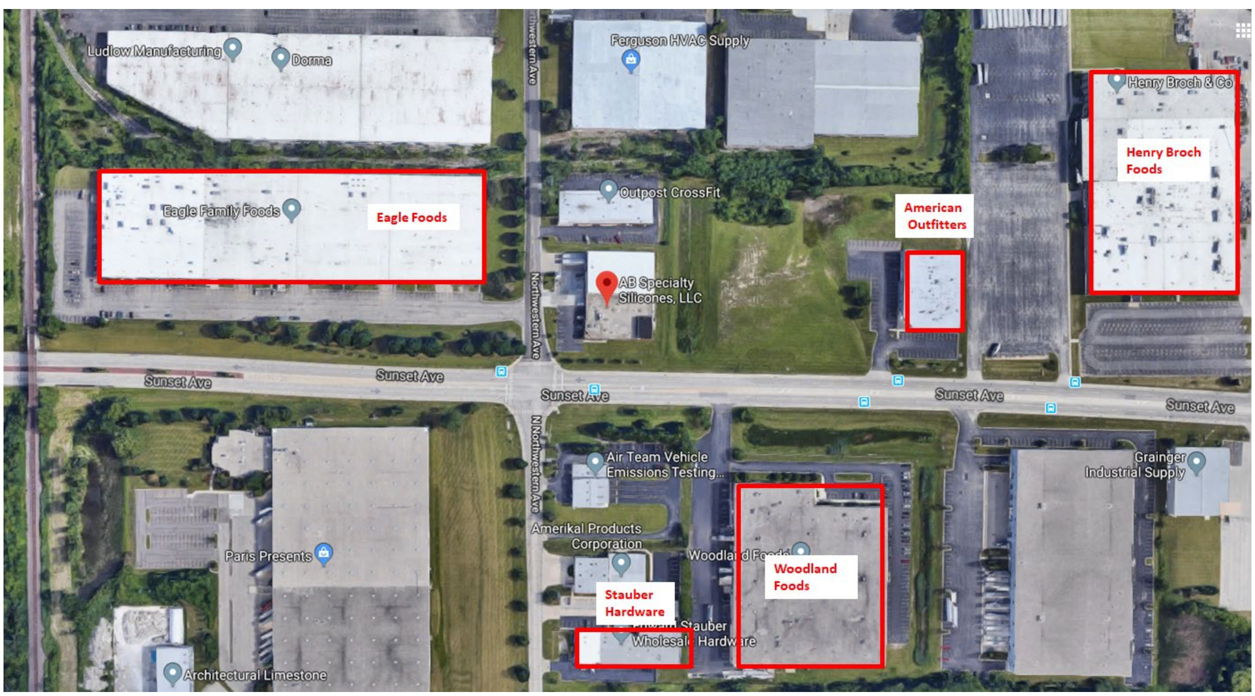


Figure 3-8. AB Specialty Off-Site Businesses Surveyed for Blast Indicators

Table 3-3. AB Specialty Offsite Blast Indicator Summary

ID	Description	Location
American Outfitters		
AO-1	44”x66” IGU Windows	South and West Wall
AO-2	58”x70” IGU Windows	Front Entry - SW Corner
AO-3	OWSJ	Roof
AO-4	Steel Girts	North Wall
AO-5	Hollow Metal Man Door	West Wall
Eagle Foods		
EF-1	CMU/Brick Walls	East Wall
EF-2	Steel Girts	East Wall
EF-3	Hollow Metal Man Door	East Wall
EF-4	OWSJ	Roof
EF-5	46”x54” Window	SE Corner South Wall Entry
EF-6	31.5”x54” Window	SE Corner South Wall Entry
EF-7	31”x76” Glass Door	SE Corner South Wall Entry
Woodland Foods		
WF-1	39”x44” IGU Window	North Wall
WF-2	45”x55” IGU Windows (Curtain Wall)	North Wall
WF-3	Horizontal Steel Beam 24ft Span (Curtain Wall)	North Wall
WF-4	Horizontal Steel Beam 19.5ft Span (Curtain Wall)	
WF-5	Steel Column (Curtain Wall)	North Wall
WF-6	OWSJ	North Wall
Stauber Wholesale		
SW-1	41.5”x44 IGU Windows	North Wall
SW-2	Corrugated Metal Wall Panel	North Wall
SW-3	Rollup Door	North Wall
SW-4	Rollup Door	South Wall
Henry Broch Foods		
HB-1	49”x69” Window	West Wall
HB-2	63”x79” Window	West Wall
HB-3	33”x134” Window	West Wall

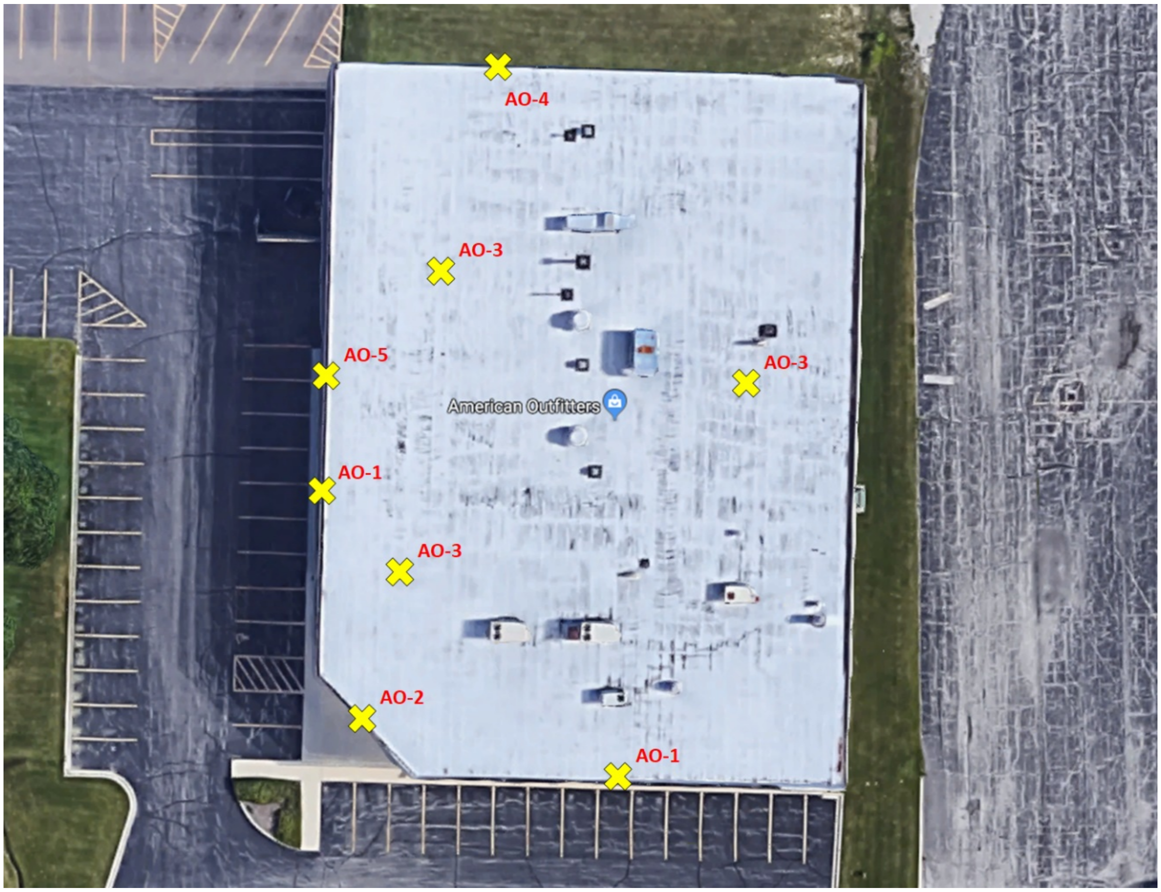


Figure 3-9. American Outfitters Blast Indicators

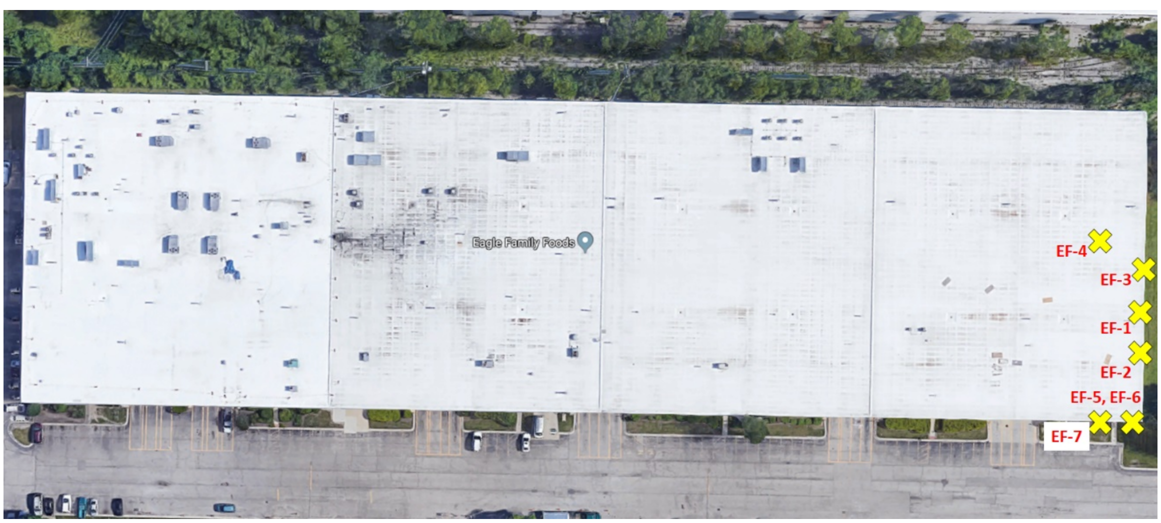


Figure 3-10. Eagle Foods Blast Indicators

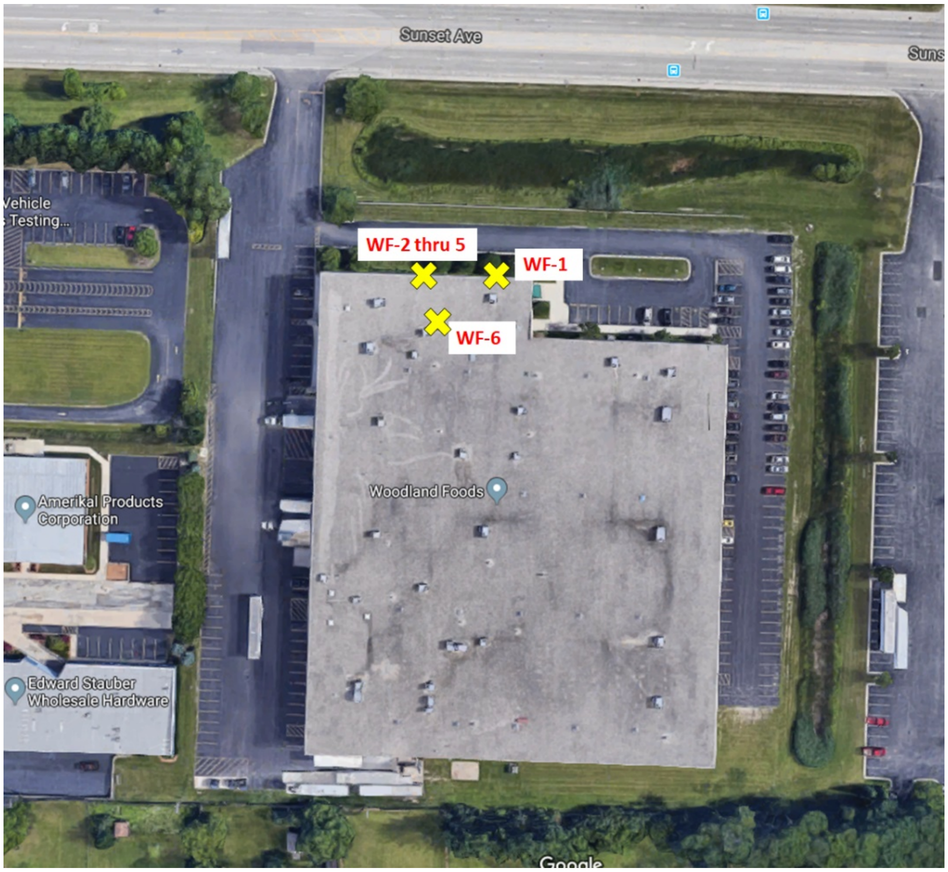


Figure 3-11. Woodland Foods Blast Indicators

Figure 3-12. Stauber Wholesale Hardware Blast Indicators

Figure 3-13. Henry Broch Foods Blast Indicators

The three off-site locations closest to the AB Specialty facility provided the most suitable far-field blast indictors and included American Outfitters, Eagle Foods, and Woodland foods. At the American Outfitters building, there were broken and unbroken windows along with slightly damaged and undamaged roof joists. Examples of these off-site blast indicators are shown in Figure 3-9.

Two blast indicators from the Eagle Foods building directly faced the ABS Specialty facility were evaluated. The lower portion of the east façade wall was a concrete masonry block walls with a brick façade up to a height of 8 feet. This wall was cracked and permanently deformed from the explosion event. The horizontal steel girt supporting the block walls at the 8-foot height was undamaged. The insulated metal deck wall above the 8-foot girt was deformed heavily and the deformations were too severe to allow it to be included in the blast indicator analysis. Examples of the Eagle Food building blast indicators are shown in Figure 3-15.

Windows on the Woodland Foods building were observed to be both broken and unbroken on the north elevation. A few smaller sized windows on the first-floor level near the center of the building (in the east-west direction) were broken while larger windows located in the curtain walls further west on the north elevation were undamaged. Examples of the Woodland Foods off-site blast indicators are shown in Figure 3-16.

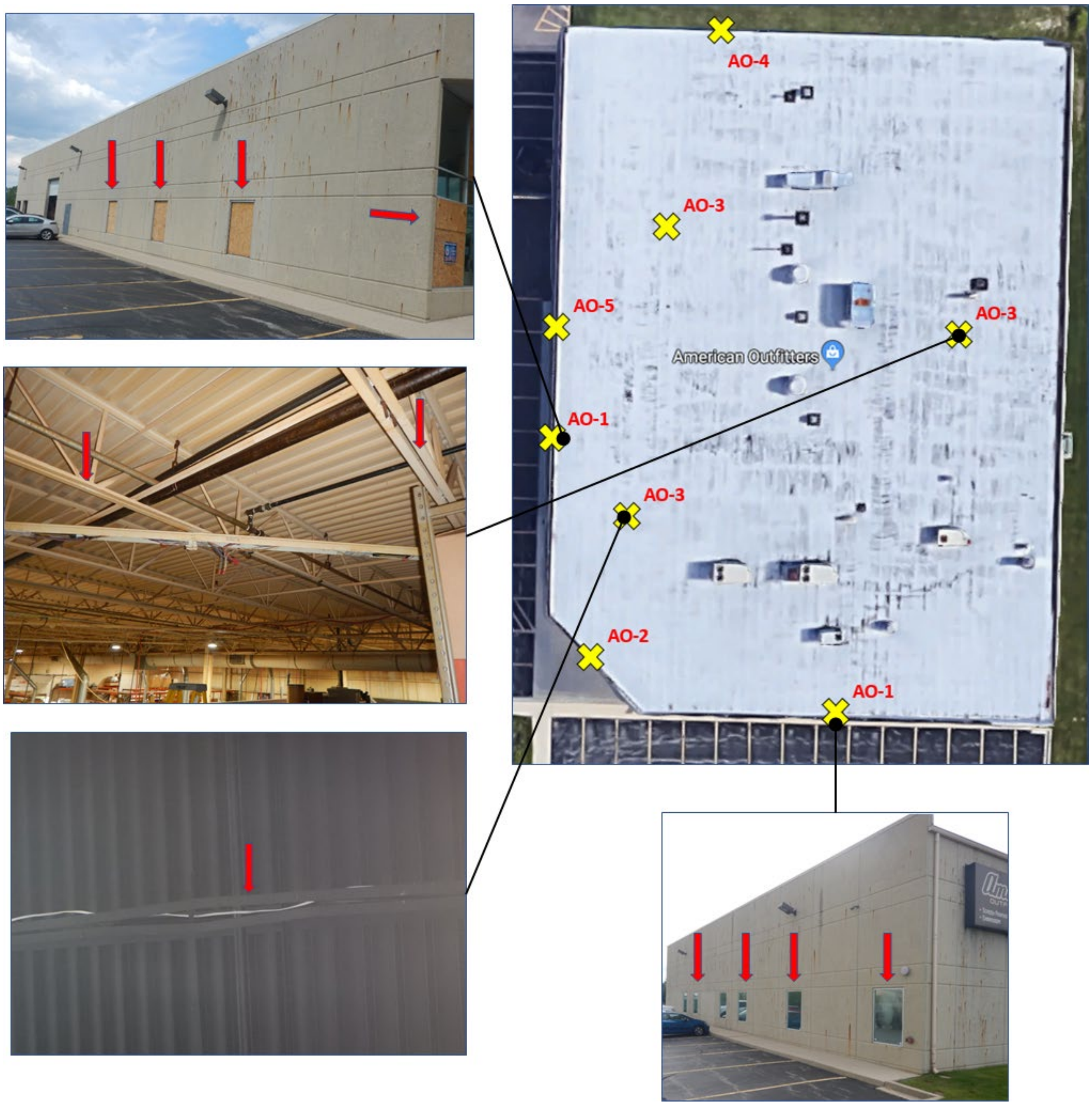


Figure 3-14. Examples of American Outfitters Off-site Blast Indicators

Figure 3-15. Examples of Eagle Foods Off-site Blast Indicators

Figure 3-16. Examples of Woodland Foods Off-site Blast Indicators

3.3.3 CFD Walkdown

The AB Specialty Low and High Bay areas were surveyed to document information required to support modeling of potential explosion scenarios using computational fluid dynamics (CFD). Each region within the building was surveyed to determine the levels of congestion and confinement consistent with the CFD method. Congestion and confinement levels, along with the fuel type, were inputs to determine the flame speed(s) used in the CFD model.

Confinement is specified as one dimensional expansion (1-D), two-dimensional expansion (2-D), or three-dimensional expansion (3-D), in reference to the ability for an ignited cloud to expand away from the ignition source. For example, a fire in a pipe can only expand along the length of the pipe, or 1-D. An ignited cloud under a strong concrete deck, for example, cannot expand vertically but can expand horizontally in two dimensions (2-D). An ignited cloud in the open can expand vertically and horizontally in three dimensions (3-D). 1-D results in higher flame speed than 2-D, and 2-D confinement produces higher flame speed than 3-D.

Congestion refers to the obstacles that obstruct the passage of the flame front enough to create turbulence and increase flame speed without preventing expansion [[5]]. Congestion is specified as either Low, Medium, or High and relates to the generation of turbulence which increases flame speed. The higher the congestion, the greater the flame speed.

In qualitative terms Low, Medium, and High congestions are described below:

- Low
  - An area easy to walk through relatively unimpeded with one or two "layers" of obstacles.
- Medium
  - An area that is cumbersome to walk through and often requires taking an indirect path with several “layers” of obstacles.
- High
  - An area where it is not possible to walk through due to insufficient space to pass between obstacle and successive layers prevent transit through the area. Moreover, repeated layers of closely spaced obstacles block line of sight from one edge of the congested zone to the opposite side.

4 Methodology

CFD was utilized to model the explosion, propagation of overpressures on-site and off-site. This provides a means to evaluate which flammable gas, volume of gas, explosion intensity, and directionality that most consistently matches observed damage.

4.1 Explosion Damage Analysis

A quantitative assessment of surveyed structural components was performed which included a dynamic elastic-plastic single-degree-of-freedom (SDOF) analysis of each selected damaged and undamaged blast indicator using the SBEDS[6] 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 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. The P-I diagram is an iso-damage curve, connecting all of the unique pressure-impulse pairs that are calculated from the damage indicators, and 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 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.

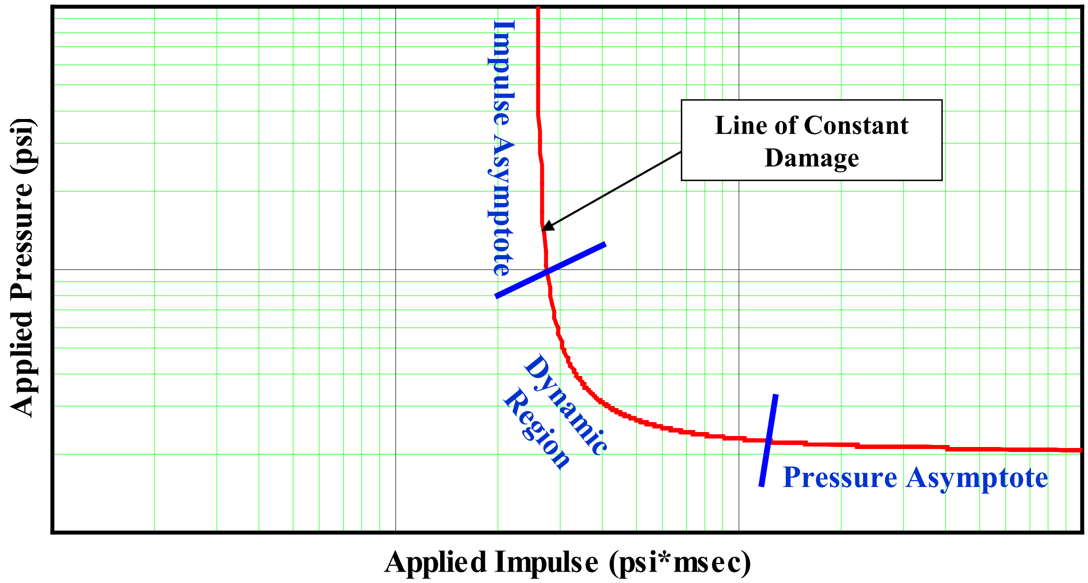
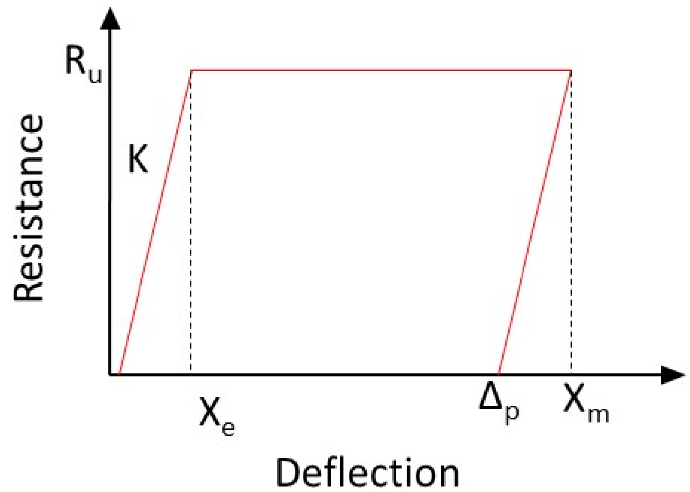


Figure 4-1. Example Pressure-Impulse (P-i) Iso-Damage Diagram

For damaged load indicators, the permanent deformation of a given indicator is obtained from the indicator's resistance-deflection curve, an example of which is shown in Figure 4-2. Deformations measured in the field are permanent plastic deformations which occurred after the observed indicator undergoes elastic rebound.

Damaged blast indicators were measured, as shown below in Figure 4-3, to determine the permanent deformation. The P-i diagram is developed for the peak response of the component, which differs from the permanent deformation due to elastic recovery after blast load dissipates, as shown in Figure 4-2.



K	= Stiffness per unit loaded area
R_u	= Ultimate resistance per unit loaded area
X_e	= Elastic deflection limit
X_m	= Maximum displacement
Δ_p	= Permanent deformation measured in the field

Figure 4-2. Typical Resistance-Deflection Curve

Figure 4-3. Measuring of Damaged Load Indicators

A qualitative blast damage assessment was performed for the High bay and Low Bay wall panels by comparing fastener's connection capacity (as determined by AISI 2001 Specification Section E4, Screws[7]) to blast pressures applied to the interior of the panels. It was observed on the site inspection that a majority of the wall panels of the High Bay were torn off and fasteners remained attached to the structural girts as shown in Figure 4-4. A similar condition was also observed on the insulated metal panels walls on the east elevation of the Low Bay. Fasteners that attached the structural girts to the panels were also found remaining on these girts. For these cases, by determining the tear out capacity of panel over the connection, a minimum threshold of the pressure applied to the internal surface of the wall panels was established.

Figure 4-4. High Bay Metal Panel Connec

4.2 Explosion Scenario Analysis

The explosion scenario analysis was performed by selecting potential flammable clouds, referred to as scenarios, for use in the assessment. The purpose was to model each scenario, compare with the results of the structural analysis, and determine which scenario is most consistent with the blast and directional indicator analysis.

Two different flammable gas types were simulated in explosion scenario analyses, natural gas and hydrogen. The AB Specialty facility was supplied with natural gas through an exterior meter from local utilities. A large cloud of methane in the Low Bay was evaluated to determine whether the explosion could have been caused by a leaking gas line within the Process Area. Natural gas is composed of primarily methane but may contain other small amounts of inert and flammable gases. In most utilities, it is greater than 90% methane. One hundred percent (100%) Methane was conservatively used to simulate the natural gas cloud.

Just prior to the explosion event, it was reported by AB Specialty workers that a potential problem was occurring with a mixing process[4]. Generation of hydrogen gas was considered a possible consequence of an unexpected chemical reaction of the particular mixing process and materials in use at the time. Hydrogen gas clouds were modeled to determine if gas produced from an unexpected chemical reaction in the mixing process could generate an explosion resulting in the damage to the facility and off-site.

The explosion scenarios were analyzed using CFD modeling. CFD modeling is considered to be the best approach given the type of flammable gas, presence of confinement, and reflecting surfaces versus blast curve methods or other CFD codes. The Computational Explosion and Blast Assessment Model (CEBAM) was utilized for the CFD modeling. CEBAM was developed specifically for explosion modeling, including vapor cloud explosions (VCEs), high explosives, and pressure vessel bursts. Mathematical and physics solution methods incorporated in the code for VCEs are described in Ref. [8]. CEBAM predictions compared with large scale explosion data are summarized in Ref. [9] and [10]. Ref. [11] reviews application of computational modeling with CEBAM for flammable gas vapor cloud explosion accident investigations.

CEBAM allows the user to:

- Input geometries of buildings, vessels, equipment and other objects that will affect the propagation of the blast.
- Specify the threat/hazard in terms of its location, size and composition.
- Specify the ignition location
- Produce a pressure-time dependent prediction of the blast wave propagation through first-principle calculations.

Key factors such as blast focusing, shielding, and diffraction are resolved by CEBAM in determining the blast wave propagation. Flammable cloud volumes, shapes, locations, and ignition locations were varied to find the most consistent blast source with the observed damage.

4.2.1 Model of the Facility

The CFD analysis of the explosion scenarios required a three-dimensional (3D) model of the process areas. A 3D model of the Low Bay and High Bay areas was created in CEBAM along with the principal equipment within using photographs and notes taken during the site visit. Congestion (as described in Section 3.3.3) in the Process Area and confinement (from the roof and floor) of the cloud was utilized to assign the flame speed of the deflagration/explosion in the areas with flammable gas.

The CEBAM 3D model included the following features:

- Walls, floors, and roofs throughout the process building were represented in CEBAM as a series of panels (Figure 4-5). Objects that affect the confinement of gas and combustion were modeled.
- Equipment representing the approximate large-scale congestion inside the buildings (Figure 4-6). Objects that affect combustions and blast wave formation, reformation, and travel were modeled.
- Each panel was assigned failure criteria (as previously discussed), in terms of the pressure required to structurally fail or release a panel. The represented panel is released in the CFD model by overpressure to create vent paths that open up due to panel failure. The panels are represented geometrically as a series of triangles for each surface. The size and number of the triangles is based on the size of the overall geometry and special discrimination. This allows for the partial failing of a structural surface (i.e. a deck plate) or the transient failing of a complete surface during the event. Within the model, these plates fail when the input pressure is reached (over an average of the surface area, the triangular plate). At that time the panel is removed from the geometry of the model and the pressure wave/combustion can propagate beyond/through the failed surface.
- Separate rooms for Low Bay and High Bay areas.
- Propagation paths for explosion overpressure and products between Low Bay and High Bay (Figure 4-7).
- Target boxes were placed at locations of blast indicators considered in the blast-structural analysis to record pressure-time histories of blast loading in the simulation.

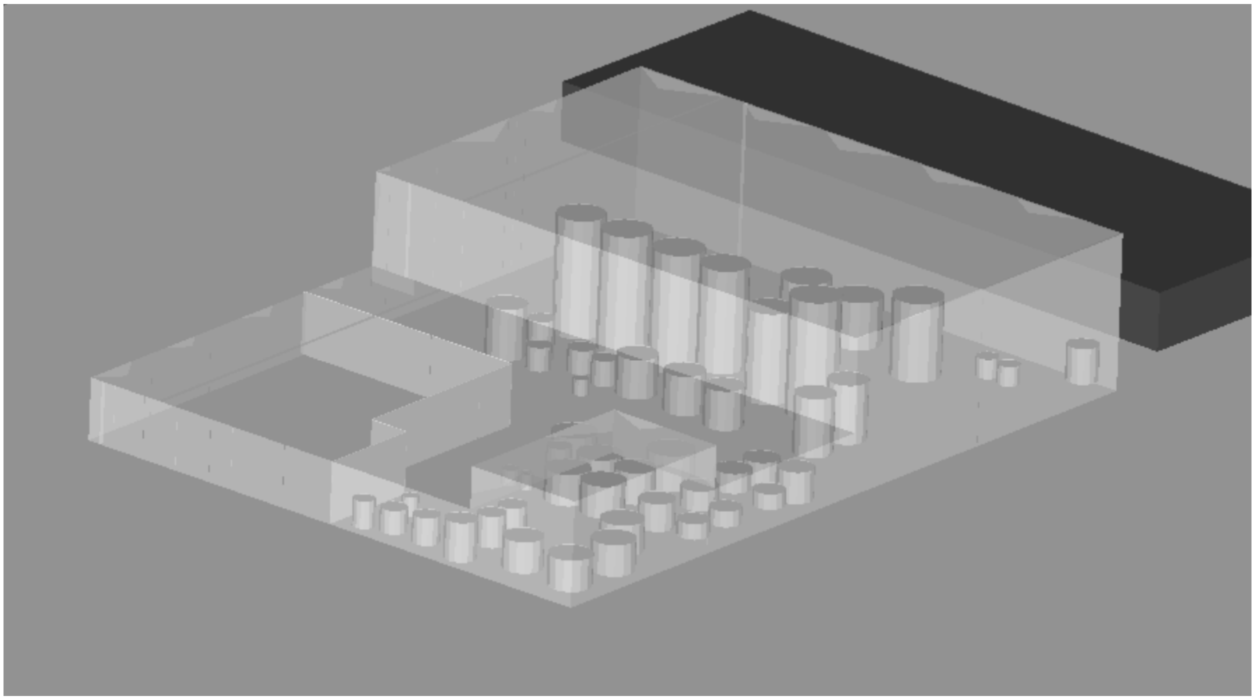


Figure 4-5. Overall View of the CEBAM Model

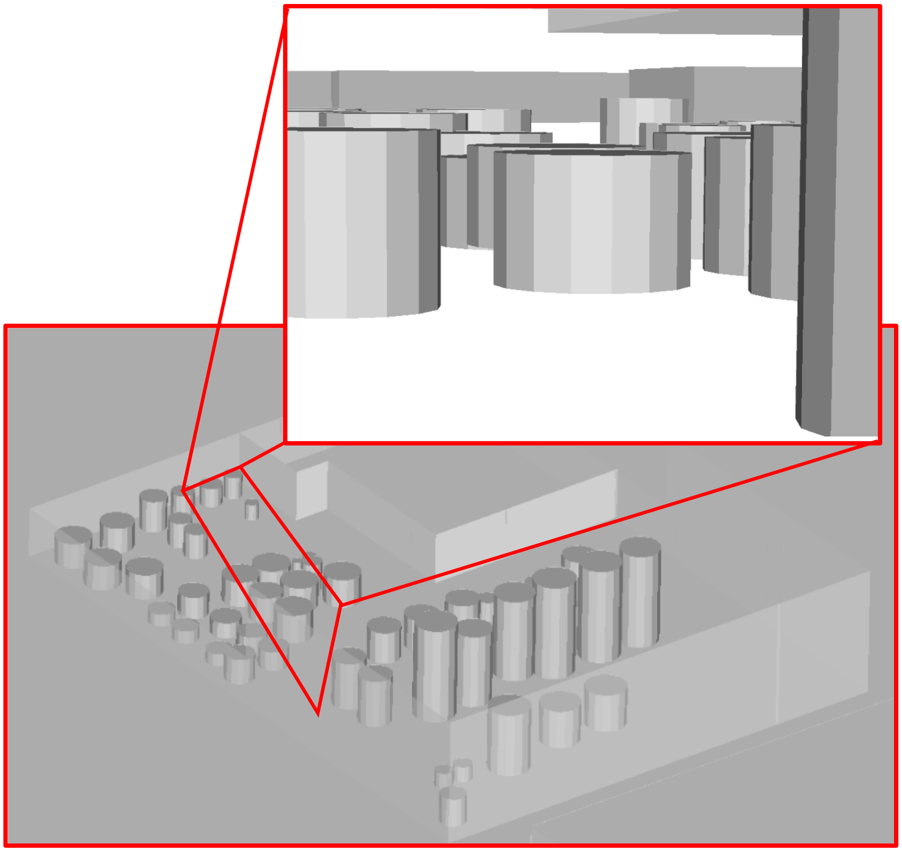


Figure 4-6. Example of Equipment in CFD Model

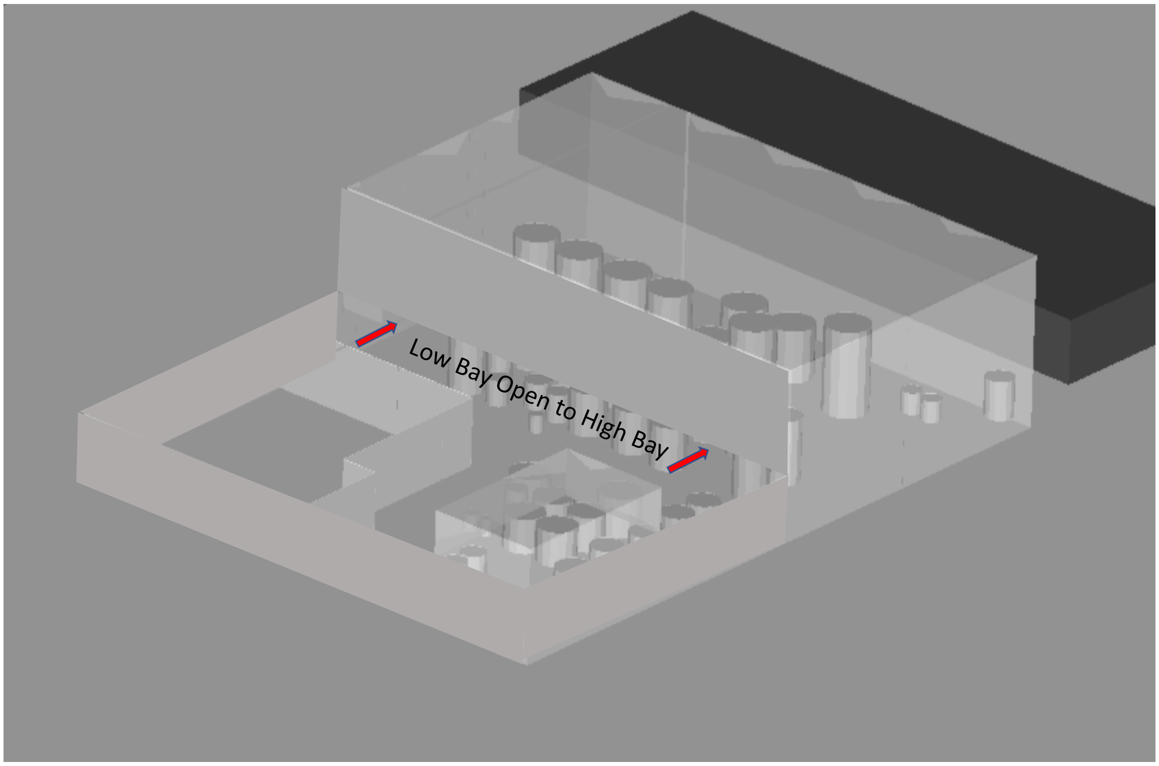


Figure 4-7. Propagation Path Between Low Bay and High Bay

The CEBAM model utilizes the Baker-Strehlow-Tang (BST) rules for congestion, confinement, and reactivity to define the burn rate (flame speed) of the energetic material. The BST rules were applied based on the observed geometry of this incident and the fuel involved (as discussed in Section 3.3.3).

The modeling utilized an ideal cloud (uniform, stoichiometric mix) to approximate the explosion incident that certainly involved a non-uniform mix of fuel and air. The flammable cloud would have included a range of conditions between the lower and upper explosion limits (LEL and UEL) of fuel in air. For hydrogen-air mix, the LEL and UEL are approximately 4% to 75% (volume percent) with a stoichiometric mix at approximately 30% [[5]]. For methane-air mix, the LEL and UEL are approximately 5% to 15% with a stoichiometric mix at 9.5%.

4.2.2 CFD Analysis of Methane Explosion in the Low Bay

Methane is a relatively low reactivity fuel. Based on the plans and site observations of the Low Bay building processing area, there was Low congestion (see Section 3.3.3), and 2-D confinement (see Section 3.3.3) with only the roof preventing expansion. This being the case, a very large amount of methane would be required to generate the explosion to cause the observed damage. Conservatively, the entire processing area of the low bay was filled floor to ceiling with a stoichiometric mixture of methane and oxygen. The resulting cloud was approximately 141,730 ft^3 and is shown in in Figure 4-8.

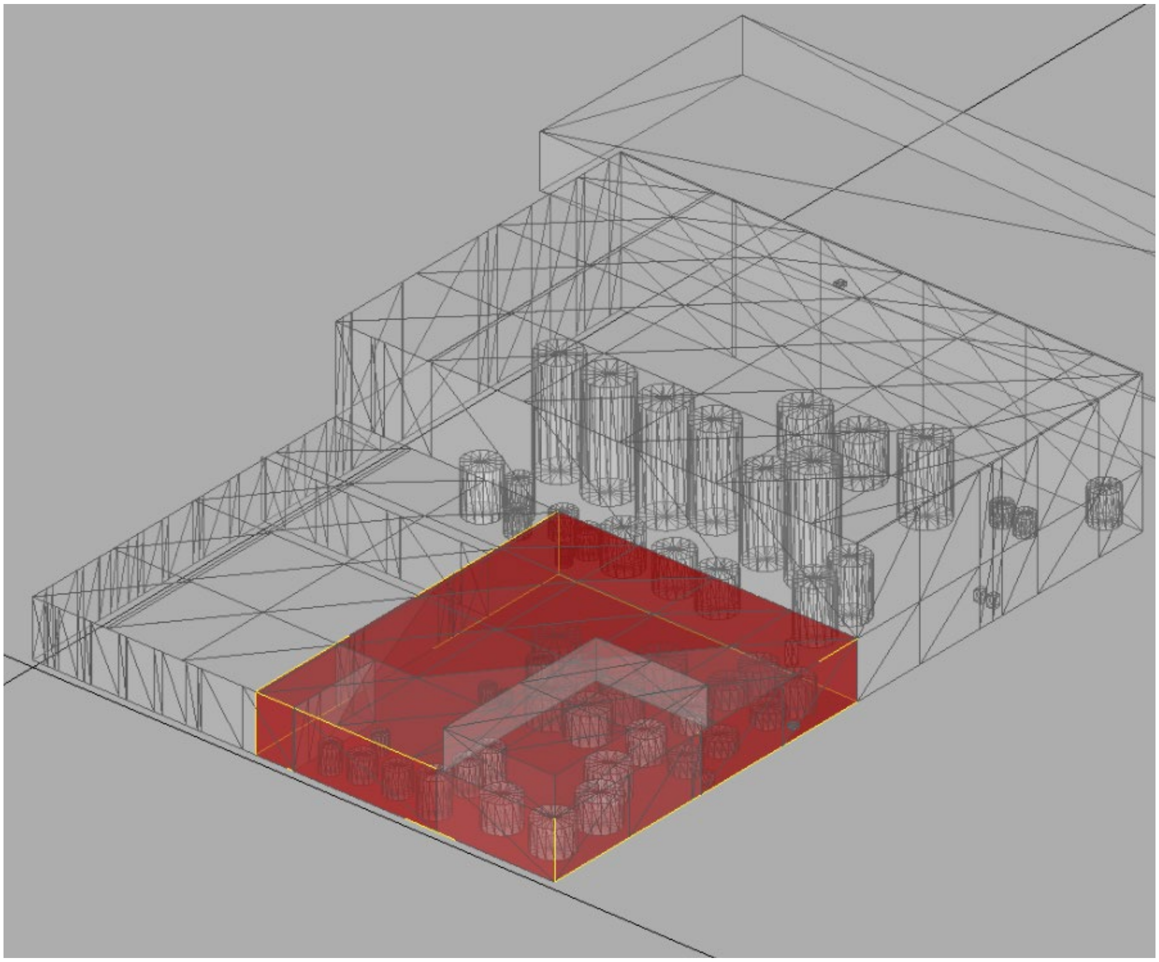


Figure 4-8. CFD Methane Cloud Model in the Low Bay

4.2.3 CFD Analysis of Hydrogen Explosion in the Low Bay

A hydrogen gas explosion was also modeled in the Low Bay. Hydrogen is significantly lighter than air and would be expected to rise and flood portions of the ceiling. For the purposes of this discussion, the cloud formed along the ceiling is referred to as the upper cloud. A portion of the flammable cloud was assumed to disperse around source of gas generation over an area immediately surrounding the source upward. This portion of the cloud is referred to as the lower cloud. CSB's investigation[[4]] reported the possibility of some materials being spilled out of the reactor vessel onto the floor and foaming. It is postulated that hydrogen was emanating from the vessel port that was open to the room and from contents on the floor. Therefore, the lower cloud was assumed to be able to form near the floor and rise to the ceiling. A sketch of the upper and lower cloud concept is shown in Figure 4-9.

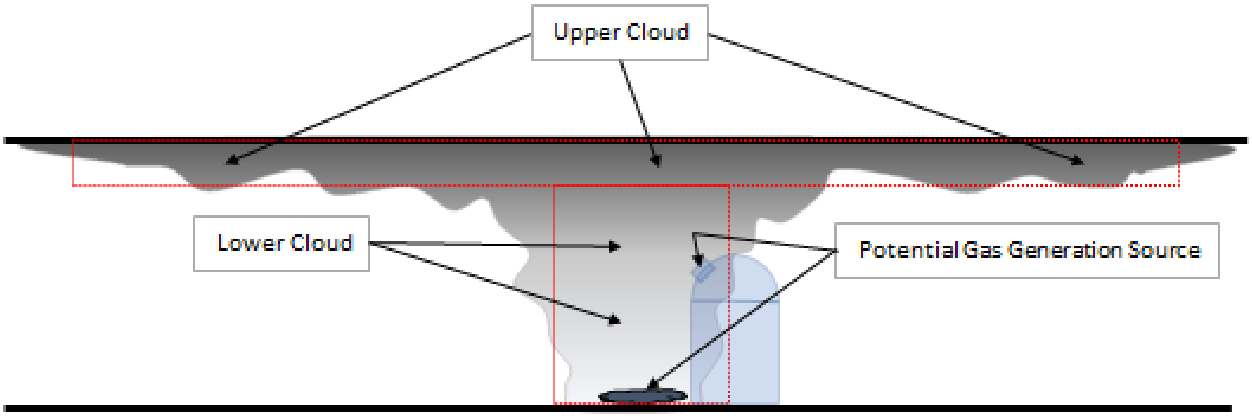


Figure 4-9. Upper and Lower Flammable Gas Cloud Model Concept

Ignition location of the flammable cloud plays an important part of the blast wave propagation. Start of ignition was originally modeled in the area between Tank S4 and S2 where heavy damage is evident on tanks and equipment radiating away from a central point. Blast loads at a specific point may be enhanced at locations beyond the flammable cloud in the direction of the flame travel. The longer the flame burns through the cloud in one direction, the more the energy the blast wave forming in front of it will develop. An ignition point, selected in the western quarter of the upper cloud (west of Tank R5), was assessed to determine if the damage observed off-site, particularly at the American Outfitters and Eagle Foods building, was affected by an offset ignition location. Ignition points modeled are illustrated in Figure 4-10.

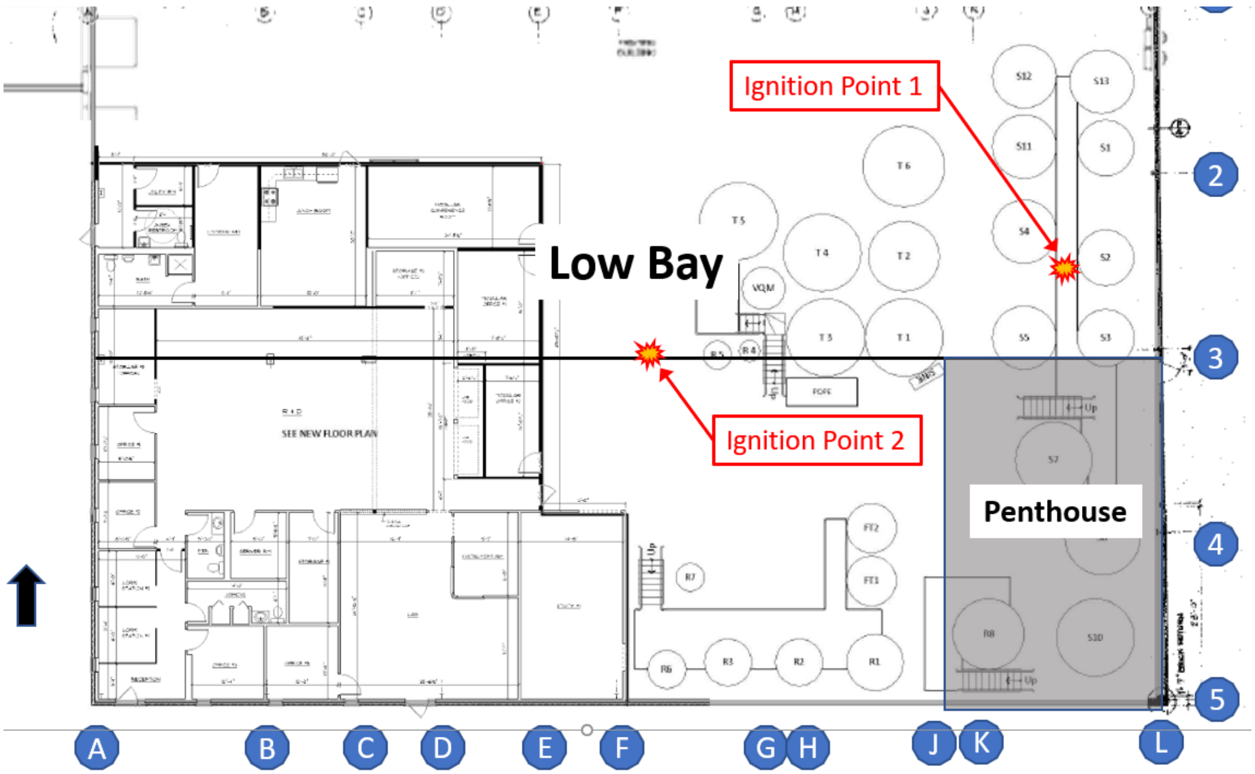


Figure 4-10. Ignition Points Evaluated with Flammable Hydrogen Cloud(s)

Analyses were performed varying the sizes of upper cloud and lower cloud as well ignition location and flame speed of the event. The purpose was to model each scenario and use the resulting blast loads to compare with the results of the blast and directional indicators in order to identify the scenario that was most consistent with the observed damage.

A number of preliminary models were run to develop and refine the CFD model. Parameters such as grid size, model extents, and several initial scenario variations were tested prior to final development of the CFD models.

One large methane gas explosion and eight hydrogen gas explosion scenarios were evaluated in the final CFD model. The first scenario (1001) was based on a large stoichiometric methane/air cloud. The remaining scenarios are flammable hydrogen clouds with a stoichiometric mixture with air. Each of the hydrogen gas scenarios included an upper cloud and a lower cloud except for scenario 1005 which only included a floor to ceiling lower cloud. A summary of the cloud sizes, flame speeds, and ignition location are shown in Table 4-1.

The scenarios selected for assessment are as follows:

- Scenario 1001 is a large methane cloud approximately 141,730 ft^3 as discussed in 4.2.2.
- Scenarios 1002 and 1003 includes an upper cloud and lower cloud of 21,600 ft^3 and 1,300 ft^3, respectively. Ignition for Scenario 1002 was at Location 1 and Location 2 for Scenario 1003 (Figure 4-11).
- Scenario 1004 is similar to 1002 with a higher flame speed.
- Scenario 1005 is a floor to ceiling cloud with a volume of 22,932 ft^3 with ignition at Location 1 (Figure 4-12).
- Scenario 1006 is like 1003 with a higher flame speed.
- Scenario 1007 include an upper cloud of 21,600 ft^3 and lower cloud of 5,200 ft^3. Ignition is at Location 2 (Figure 4-13).
- Scenario 1007a is the same as 1007 with a slightly large upper cloud of 22,680 ft^3.
- Scenario 1008 is based on Scenario 1007 but included filling the Penthouse on the southeast corner of the Low Bay with hydrogen gas adding a volume of 16,640 ft^3 (Figure 4-14).
- Scenarios 1109 and 1009a are similar to 1007 and 1007a with ignition at Location 1.

The CFD model utilized flame speeds based on the BST rules with inputs for the hydrogen scenarios as follows:

- Fuel Reactivity –
  - High Reactivity used for all hydrogen scenarios
- Congestion
  - All scenarios utilized low congestion throughout the flammable clouds
- Confinement
  - For all scenarios, confinement under the Low Bay roof is 2-D.

The BST designates a flame speed of 0.59 (M_f) for the combination of High Fuel reactivity, Low congestion, and 2-D confinement (See Section 3.3.3). However, due to the sensitivity of hydrogen, an increase in either congestion or confinement predicts the cloud would transition to a detonation (DDT) with flame speeds exceeding 1.0 (M_f) or even higher. Observed damage to the site did not support a strong detonation explosion. Therefore, flame speeds evaluations were limited to 0.59, 0.7, and 0.9 (M_f) as reasonable deflagration and possible low DDT reactions.

Table 4-1. Explosion Scenarios Modeled

Scenario Designation	Flammable Gas	Upper Cloud Dimensions (ft)	Lower Cloud Dimensions (ft)	Flame speed (M_f)	Ignition Location
1001	Methane	NA[1]	86x103x16	0.27	1
1002	Hydrogen	80x90x3	10x10x13	0.59	1
1003	Hydrogen	80x90x3	10x10x13	0.59	2
1004	Hydrogen	80x90x3	10x10x13	0.9	1
1005	Hydrogen	NA[1]	42x42x13	0.59	1
1006	Hydrogen	80x90x3	10x10x13	0.7	2
1007	Hydrogen	80x90x3	20x20x13	0.7	2
1007a	Hydrogen	84x90x3	20x20x13	0.7	2
1008	Hydrogen	80x90x3& Penthouse[2]	10x10x13	0.7	2
1009	Hydrogen	80x90x3	20x20x13	0.7	1
1009a	Hydrogen	84x90x3	20x20x13	0.7	1

[1]Floor to Ceiling Cloud – No Upper Cloud Distinction
[2]Volume of Penthouse also Filled with Gas

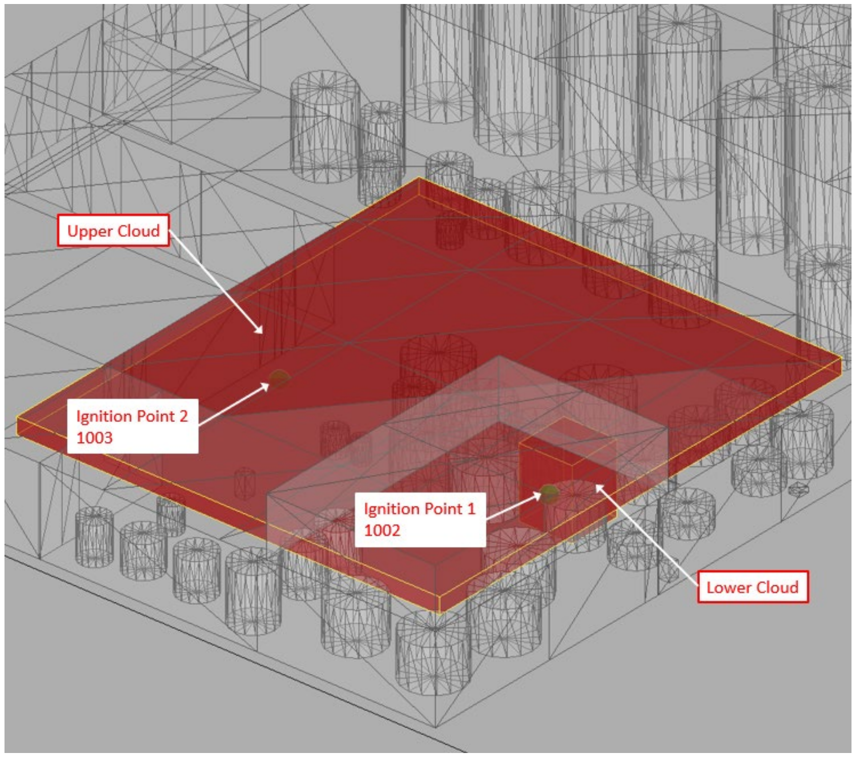


Figure 4-11. Scenario 1002 and 1003 Flammable Hydrogen Cloud(s) and Ignition Points

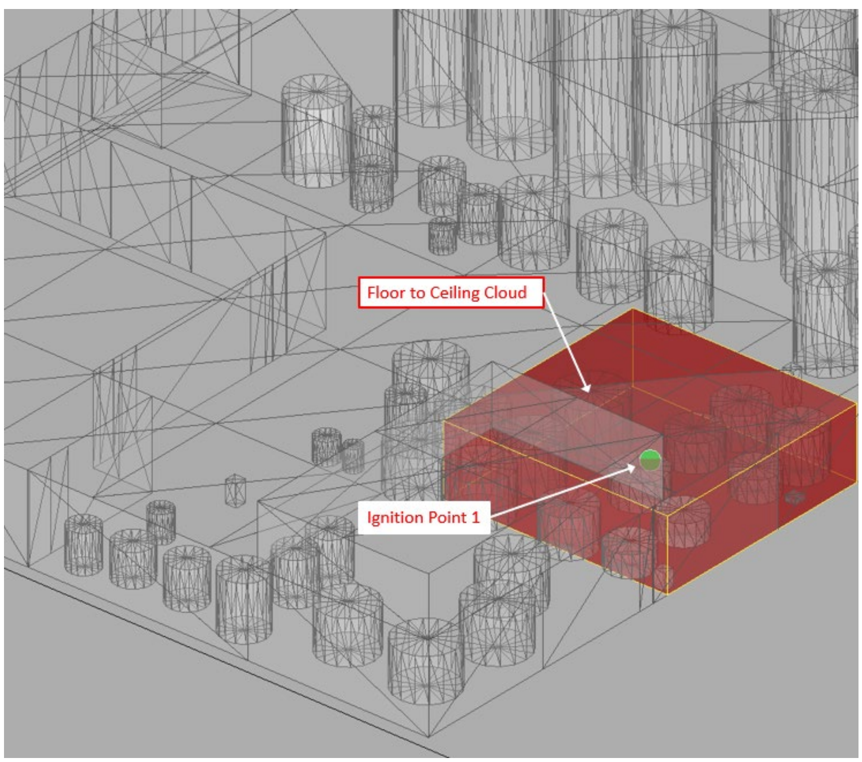


Figure 4-12. Scenario 1005 Floor to Ceiling Hydrogen Cloud(s) and Ignition Point

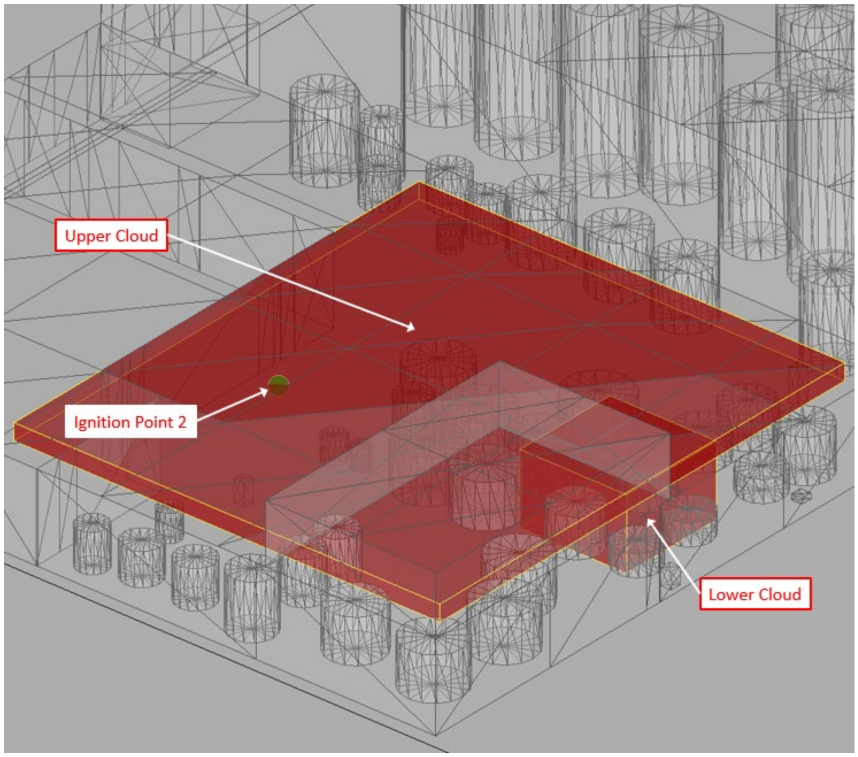


Figure 4-13. Scenario 1007 Flammable Hydrogen Cloud(s) and Ignition Point

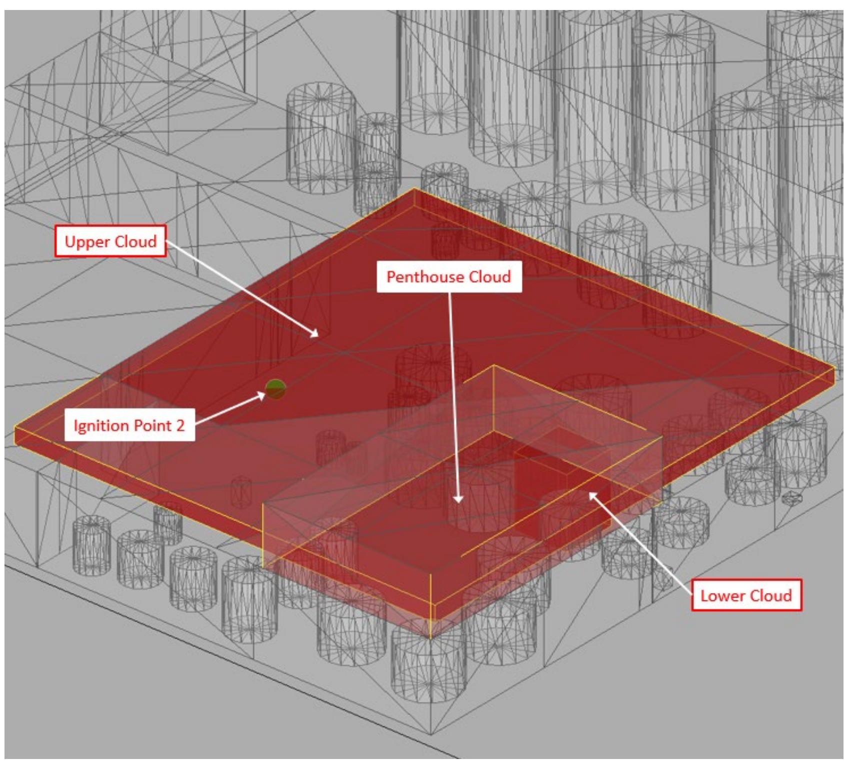


Figure 4-14. Scenario 1008 Flammable Hydrogen Cloud(s) and Ignition Point

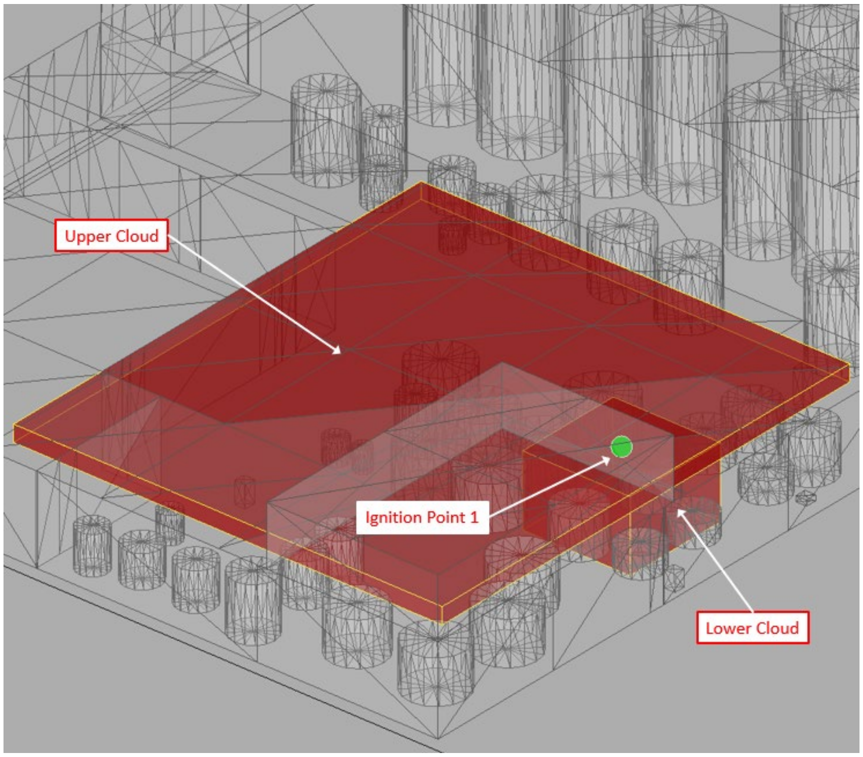


Figure 4-15. Scenario 1009 Flammable Hydrogen Cloud(s) and Ignition Point

5 Results

The CFD explosion modeling of each scenario generated ground plane blast contours which illustrated in the sequence of Figure 5-1 to Figure 5-9. The CFD model included “targets” to represent the blast indicators that were evaluated separately by P-i diagrams. Targets on each of the blast indicator surfaces were included in the model collecting the applied loading to be evaluated. Figure 5-10 is an example of predicted applied pressure-time histories and resulting impulse on the face of a target after ignition of the vapor cloud. The graph shows the applied pressure histories for a target representing blast indicator BI-2 (electrical junction box, see Table 3-2) and is labeled BI-2. The pressure-time history for the front panel (west facing surface) is plotted. Note that time history starts at time zero and the pressure increases at about 100 ms. Time zero is at the onset of ignition of the flammable cloud and the 100ms represents the time of arrival for the blast wave at BI-2. The west face of BI-2 receives the highest pressure and impulse loads, which is reasonable since that side faces the explosion. This data is used in a later example in Section 5.3 to describe the comparison of CFD results and blast indicator structural analysis.

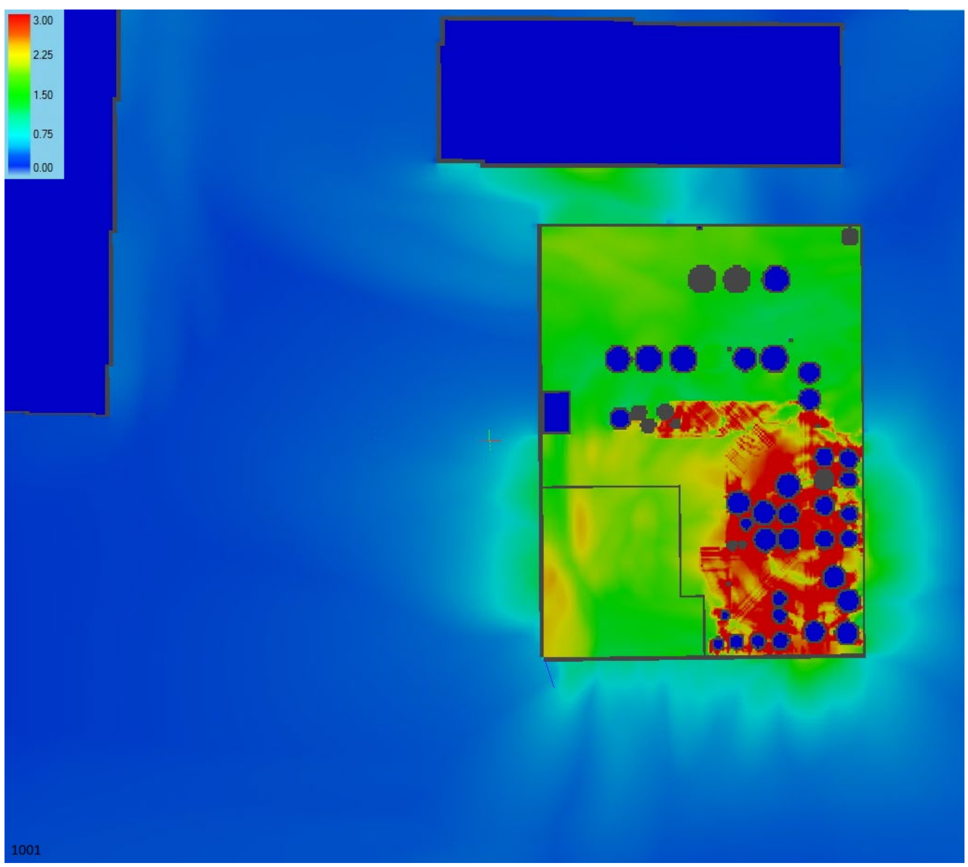


Figure 5-1. Scenario 1001 Pressure Contours at Ground Floor Level

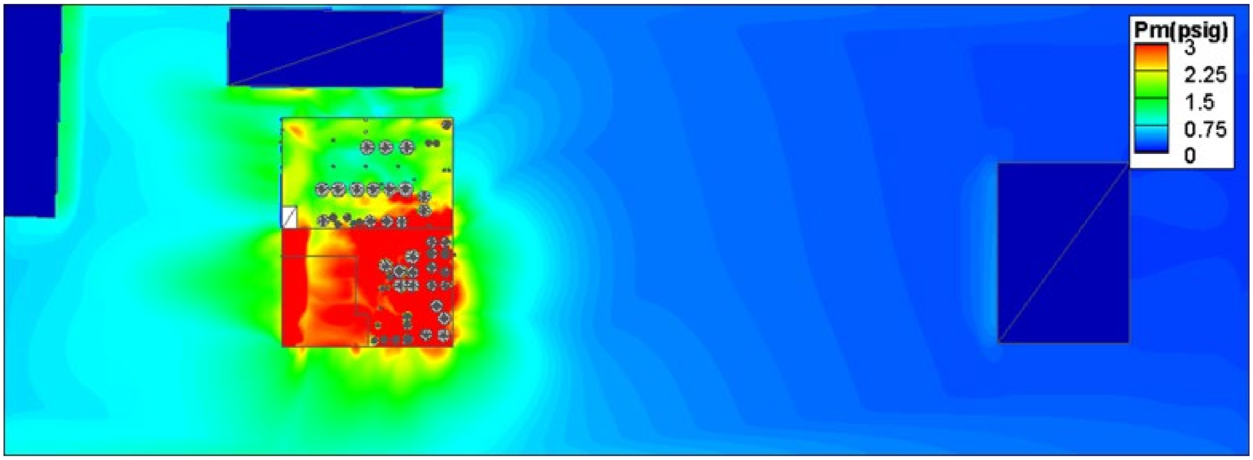


Figure 5-2. Scenario 1002 Pressure Contours at Ground Floor Level

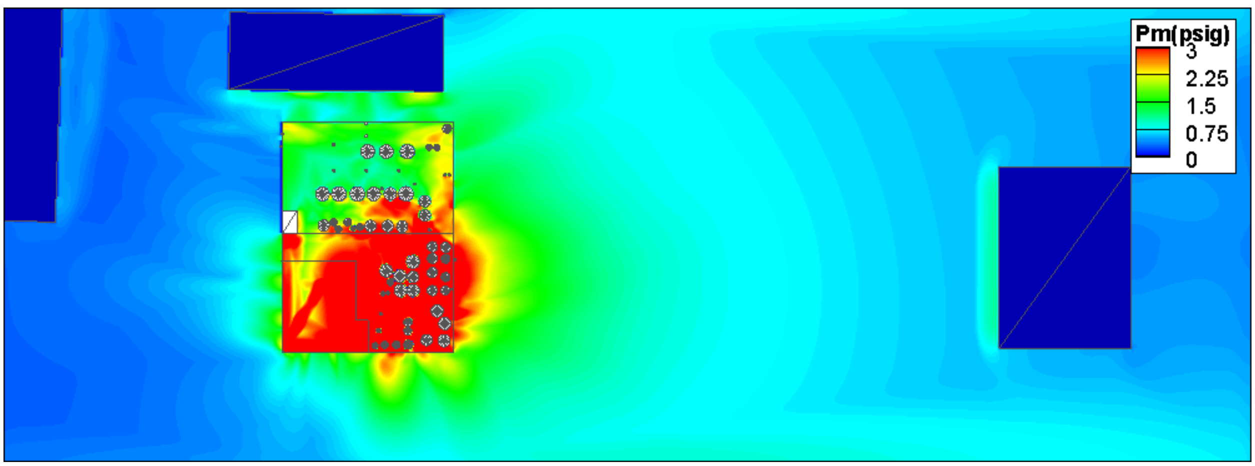


Figure 5-3. Scenario 1003 Pressure Contours at Ground Floor Level

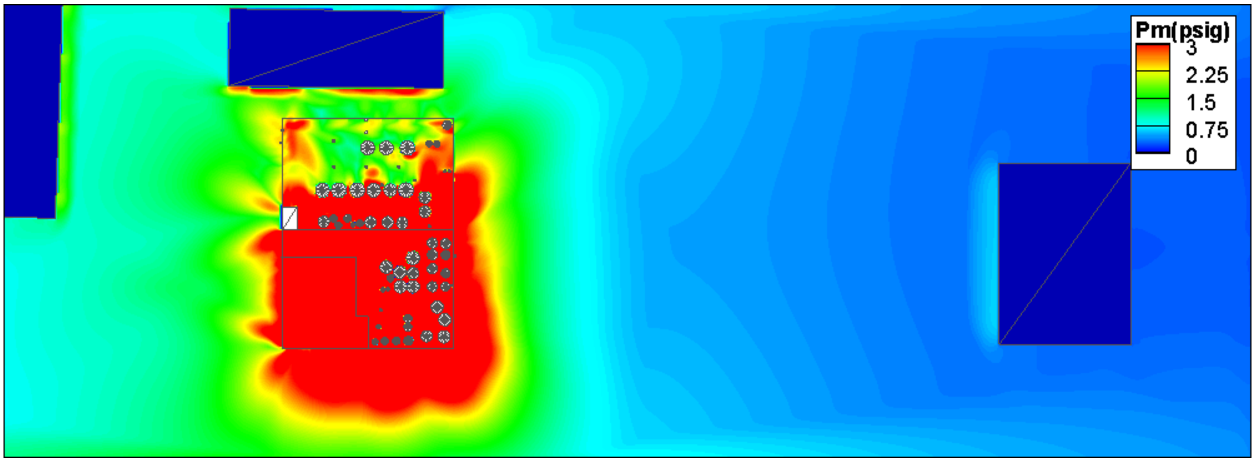


Figure 5-4. Scenario 1004 Pressure Contours at Ground Floor Level

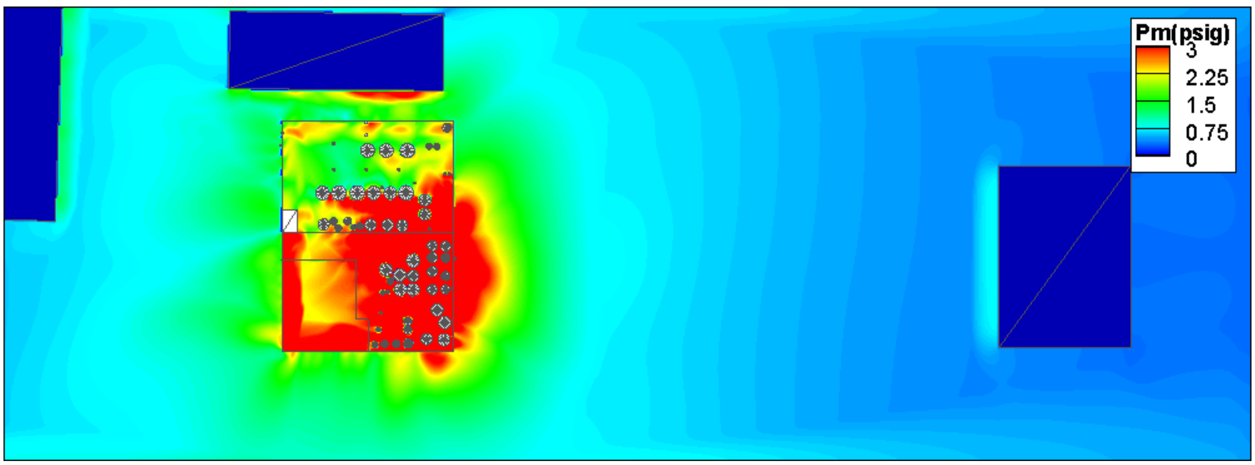


Figure 5-5. Scenario 1005 Pressure Contours at Ground Floor Level

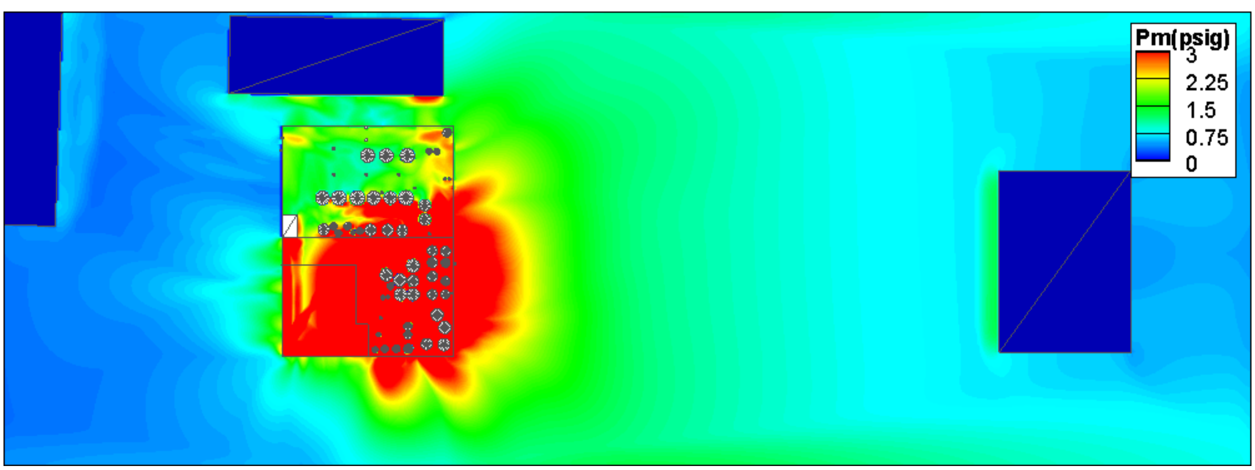


Figure 5-6. Scenario 1006 Pressure Contours at Ground Floor Level

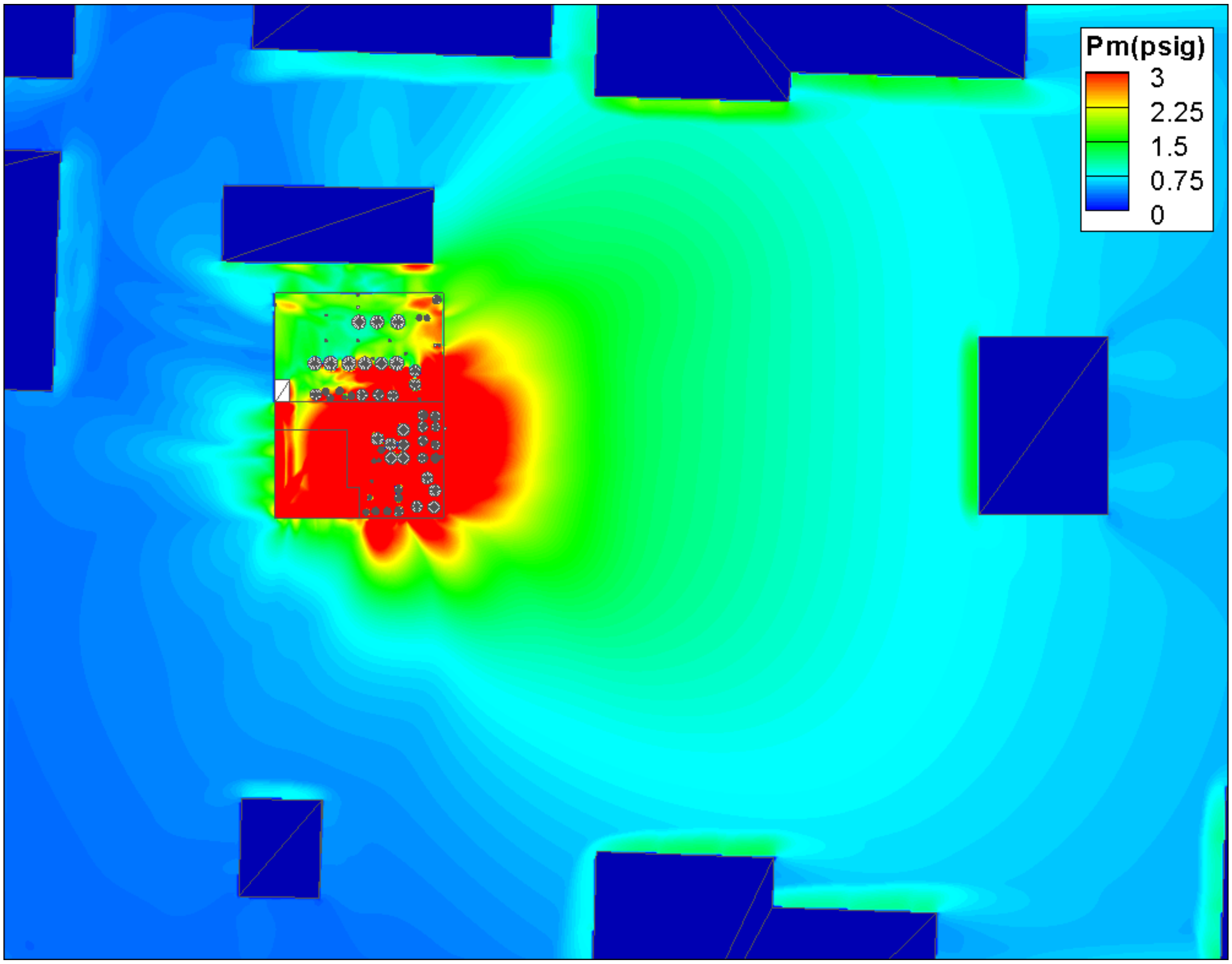


Figure 5-7. Scenario 1007 Pressure Contours at Ground Floor Level

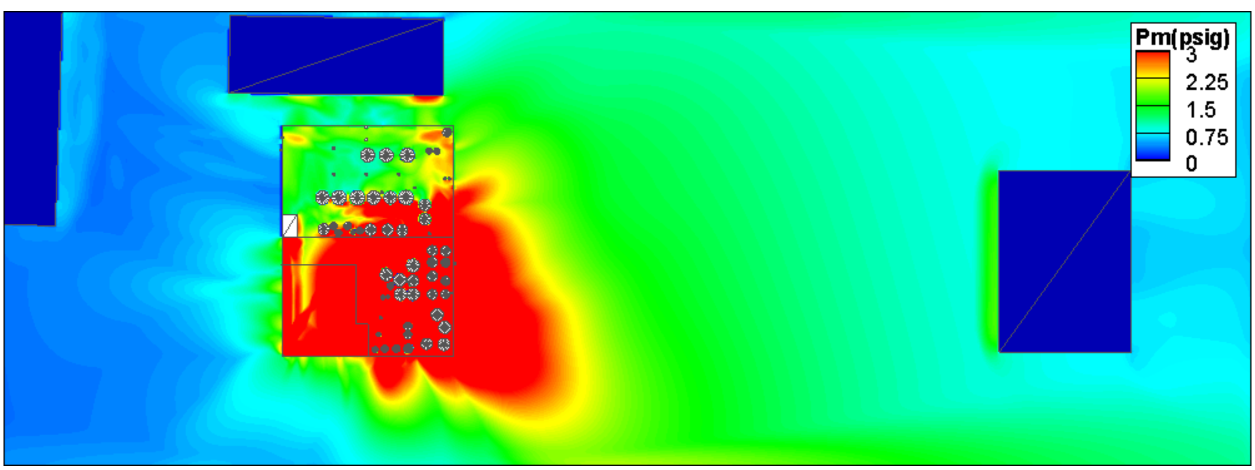


Figure 5-8. Scenario 1008 Pressure Contours at Ground Floor Level

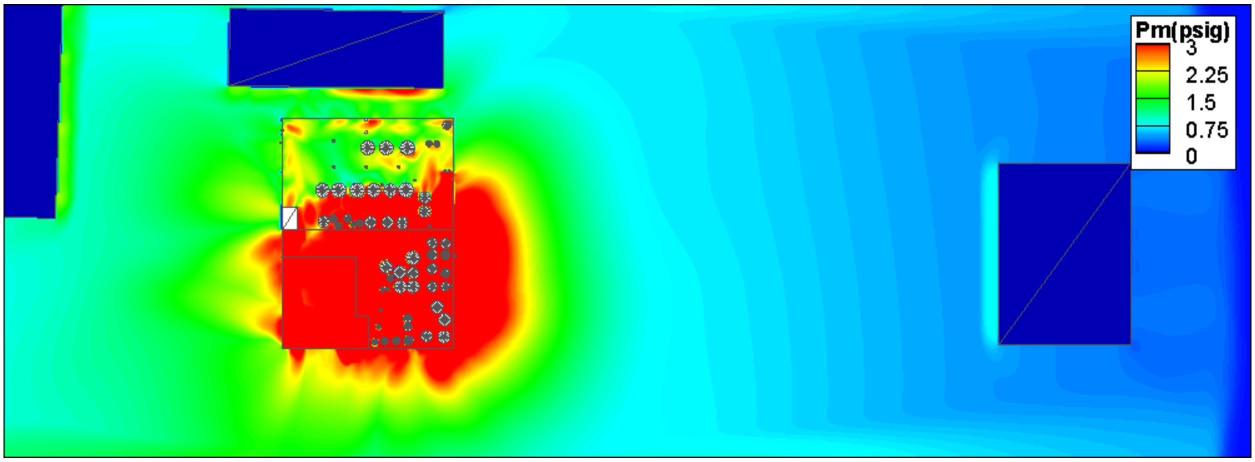


Figure 5-9. Scenario 1009 Pressure Contours at Ground Floor Level

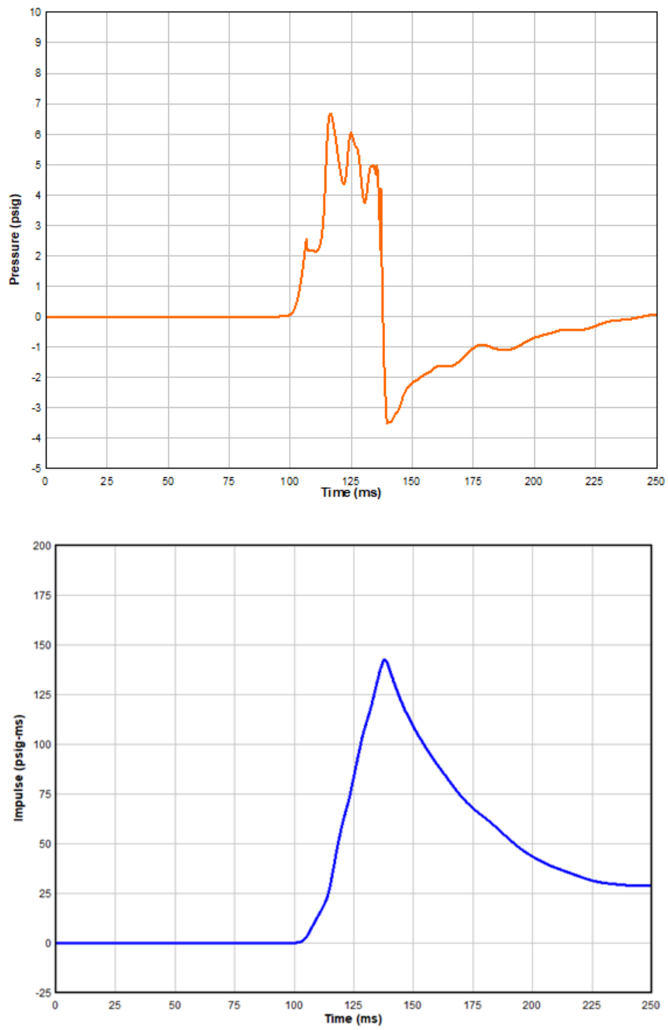


Figure 5-10. Blast Indicator BI-2 Target Surface Loading (Scenario 1007) (Pressure-time History Above and Impulse Below)

5.1 Explosion Scenario Evaluation

Explosion scenarios were evaluated by determining which blast indicators were consistent with the explosion modeling results. Figure 5-11 shows on-site blast indicators that were evaluated. The blast indicators denoted by a black "X" were included in the CFD model as targets and applied pressures and impulses were predicted. Indicators with a yellow "X" were measured but were not included in the CFD model and evaluations. Blast indicators marked by the yellow "X" were also observed and measured. However, structural analysis of the indicator did not produce practical results which was due to various factors including but not limited to varying loaded area, varying boundary conditions, multiple modes of response or failure, excessive damage, or large disparity between capacity of the indicator and overpressure.

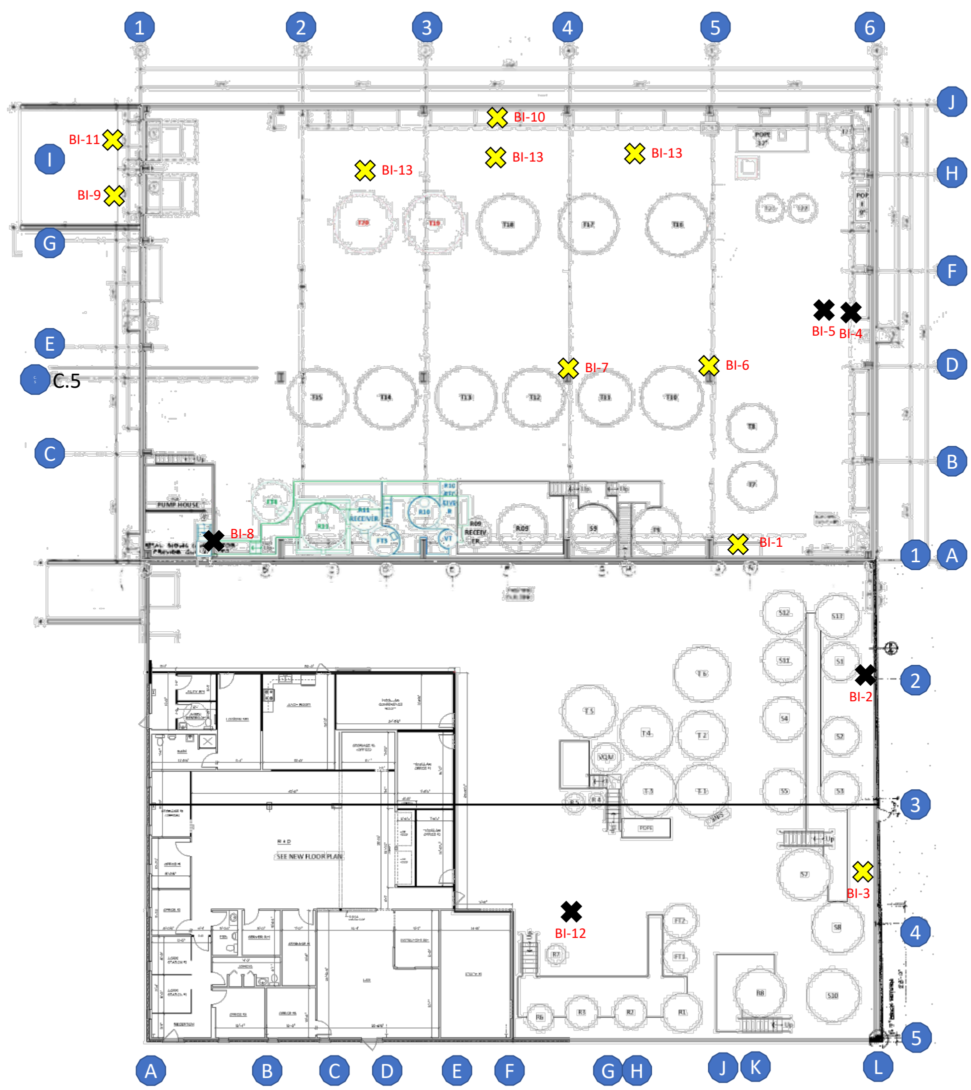


Figure 5-11. On-Site Blast Indicators – Black Evaluated

Blast indicator BI-12 was an electrical control box in the southwest region of the process area, shown in Figure 5-12. The P-i diagram was created for the control box north face and plotted along with the CFD blast loads in Figure 5-13. The P-i diagram falls between Scenarios 1001, 1002, 1003,1005, and 1009 (&1009a) plotting below the curve. Scenarios 1004, 1006, 1007(&1007a), and 1008 plotting above the line. Scenario 1004 is essentially closest to the P-i curve as measured in log space. However, the control box was supported by two square tubing vertical struts cantilevered from the floor. The struts would also have bent away from the blast absorbing energy and reducing additional blast to create the damage to the front control panel. This resulted in consistency with Scenarios 1006, 1007, and 1008 for this specific comparison.

Blast indicator BI-8 was metal wall studs located on the southwest corner of the High Bay adjacent to the connection to the Low Bay. The metal stud wall is shown in Figure 5-14. This blast indicator is unique in that the two P-i diagrams were generated for the observed damage (two different studs with slightly different damage) could be plotted on the same chart and compared to the same applied blast loads, due to the close proximity of their location and orientation within the High Bay. The intersection of the two P-i diagrams, shown below in Figure 5-15, indicated the theoretical blast pressure and impulse at the location of blast indicator BI-8. It is noted that Scenarios 1007(&1007a) and 1008 are the most proximate to the two curves with Scenario 1006 just below.

a

b

Figure 5-12. Blast Indicator BI-12 North Face - Front View (a) and Side View (b)

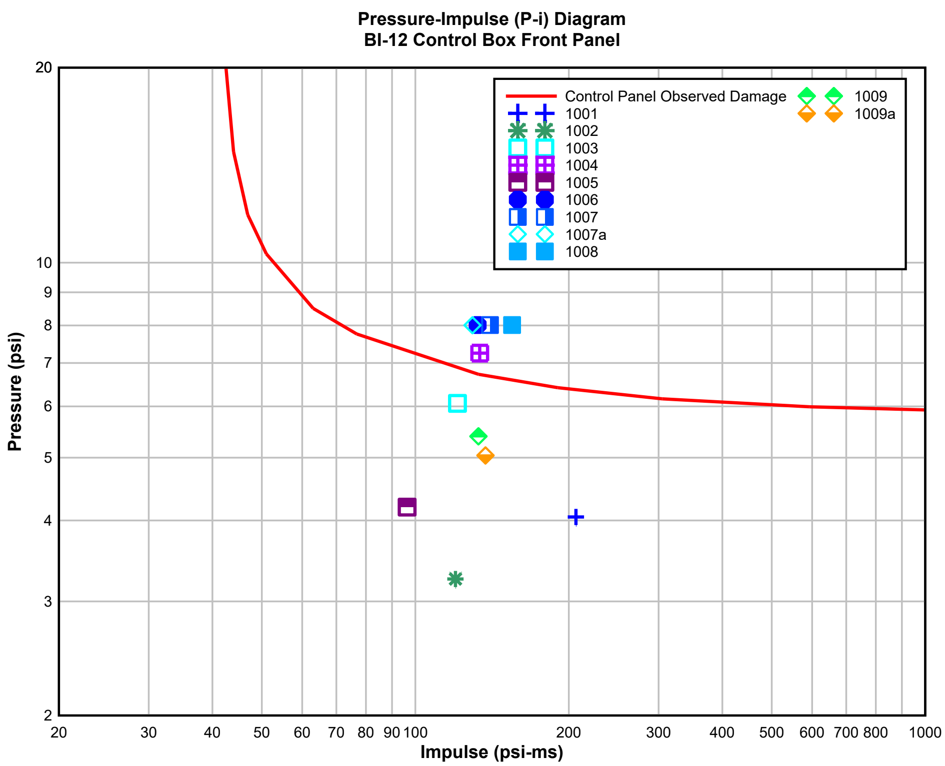


Figure 5-13. Blast Indicator BI-12 North Face P-i Diagrams and CFD Applied Loads

a b

Figure 5-14. Blast Indicator BI-8 East Face - Front View (a) and Side View (b)

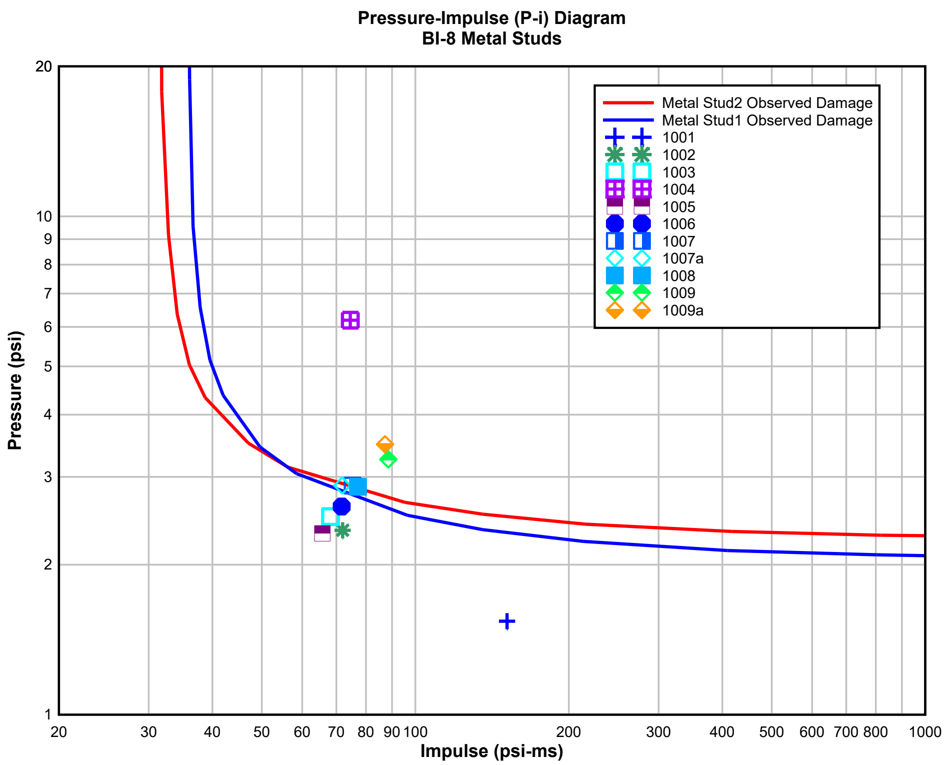


Figure 5-15. Blast Indicator BI-8 East Face P-i Diagrams and CFD Applied Loads

Similarly, off-site blast indicators at the American Outfitters, Eagle Foods, and Woodland Foods buildings were assessed. Off-site indicators that were evaluated are shown in Figure 5-16, Figure 5-17, and Figure 5-18. Select examples are discussed in the following paragraphs and evaluated blast indicator P-i diagrams are provided in Appendix B.

Figure 5-16. Off-Site Blast Indicators at American Outfitters– Black Evaluated

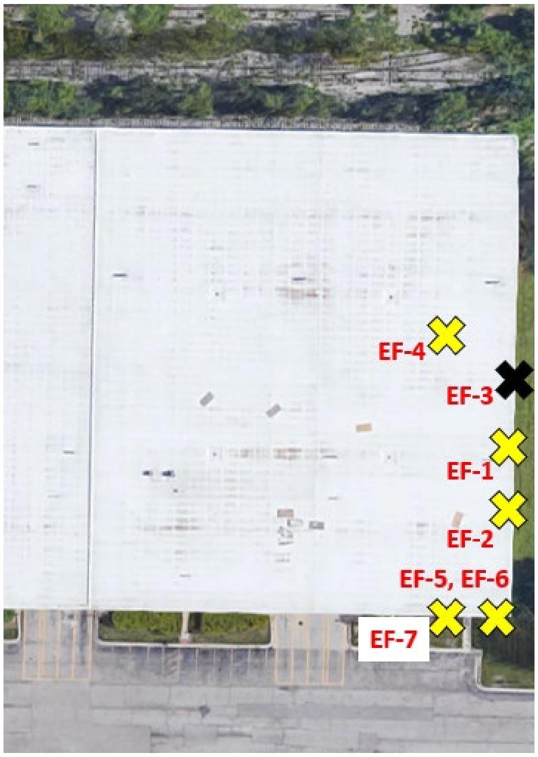


Figure 5-17. Off-Site Blast Indicators at Eagle Foods– Black Evaluated

Figure 5-18. Off-Site Blast Indicators at Woodland Foods– Black Evaluated

Off-site blast indicator AO-1 was a set of windows on the west face of the American Outfitters building as shown in Figure 5-19. Glazing in the windows was an insulated glass unit (IGU). All the windows on this face of the building were broken. Most of the broken glass was reported to be lying on the ground outside of the building after the explosion. This indicates that the blast wave was strong enough to break the windows but not energetic enough to accelerate and propel the glass into the building. Two P-i diagrams were developed for the typical window in the west elevation of the building. The first set of P-i data represent the threshold for breakage (Condition 1-2) of the window glazing and the second represents threshold for glass debris beyond 1 meter (Condition 2-3a) into the building. The P-i diagrams and explosion scenario blast loads at this location are shown in Figure 5-20. Only Scenarios 1006, 1007(&1007a), and 1008 showed pressure and impulses over the window breakage threshold. The higher blast loads of Scenario 1008 would indicate that the glass would have been propelled more into the building than was observed. Thus, Scenarios 1006 and 1007(&1007a) are most consistent with the window damage observed at this location.

Off-site blast indicator EF-1 was an unreinforced concrete masonry unit (cmu) wall with brick veneer on the lower portion of the east elevation of the Eagle Foods building, shown in Figure 5-21. Eagle Foods is located to the west across Northwestern Avenue from the AB Specialty facility. Blast indicator EF-2 was a hot rolled steel girt supporting the top of the cmu wall at about 8 ft above the floor slab and supporting the metal wall panels above shown in Figure 5-22. Two sets of P-i data were developed for the cmu walls; the threshold of damage and observed damaged curves. The steel girt did not show signs of permanent damage, so, a threshold for damage curve was used for comparison with CFD applied loads. Figure 5-23 shows the P-i diagrams and CFD applied loads for the cmu walls and steel girt. Scenario 1001 blast loads are close to the cmu wall damage threshold curve. Scenarios 1002, 1004, 1005, 1009(&1009a) loads exceed the observed cmu damage curve and not consistent with the damage. Scenarios 1006, 1007(&1007a), and 1008 are the most consistent with undamaged cmu blast indicator. All the scenarios are below the threshold of damage for the steel girt which is consistent with lack of permanent damage to the member.

Figure 5-19. Blast Indicator AO-1 West Elevation - Elevation View (a) and Close-in View (b)

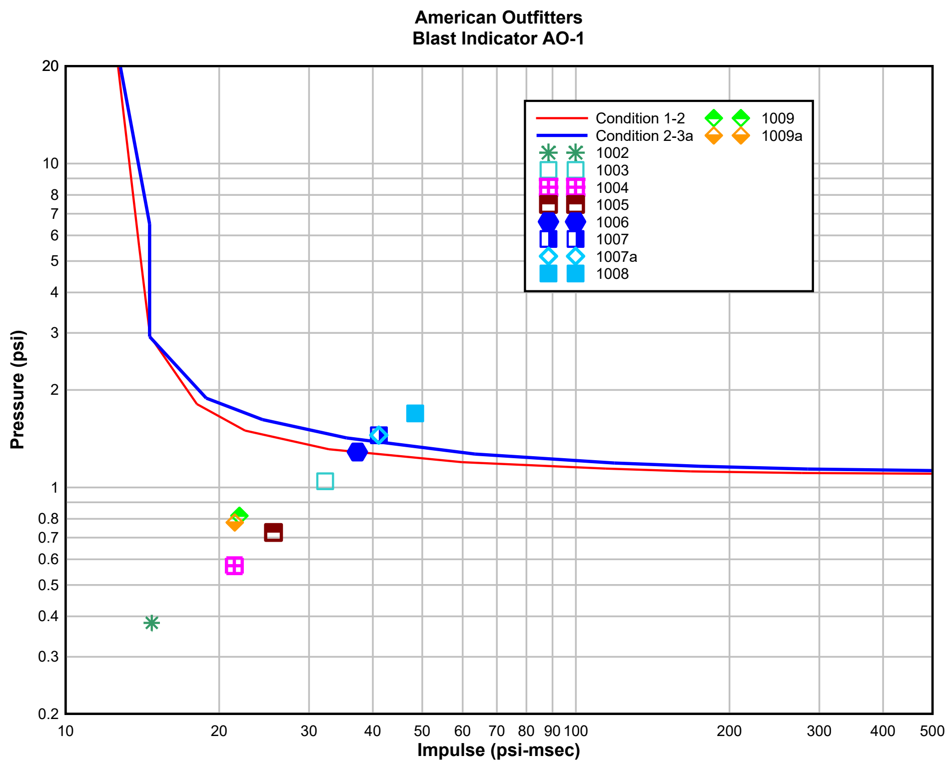


Figure 5-20. Blast Indicator AO-1 West Face P-i Diagrams and CFD Applied Loads

a

b

Figure 5-21. Blast Indicator EF-1 East Elevation - Elevation View (a) and Close-in View (b)

Figure 5-22. Blast Indicator EF-2

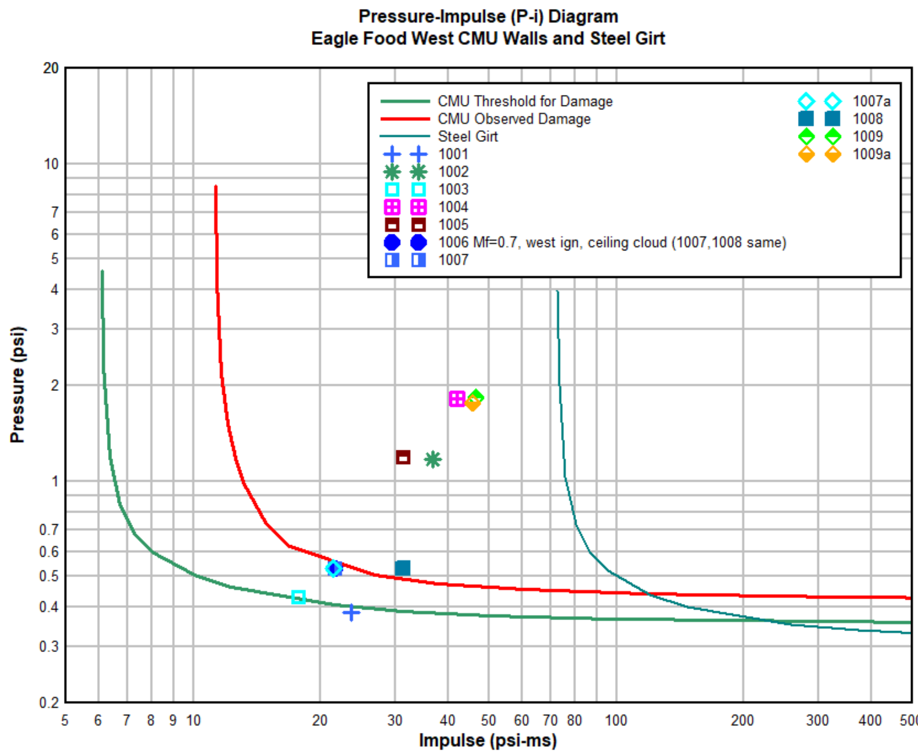


Figure 5-23. Blast Indicator EF-1 and EF-2 East Face P-i Diagrams and CFD Applied Loads

Each blast indicator was evaluated in a similar manner for the predicted blast loads and the scenario(s) that were most consistent with the observed damage were noted. The results are summarized below in Table 5-1. For damaged blast indicators, the blast scenarios that were determined to be reasonably consistent with the measured damage P-i diagram was noted in the table with an “X” and shaded green. Inspection of Table 5-1 shows that although other scenarios are consistent with some of the observed damage, Scenario 1007 and 1007a are most consistent with the observed damage.

Table 5-1. Blast Indicator Scenario Evaluation Summary

Scenario	Blast Indicator										
	BI-2	**BI-4**	**BI-5**	**BI-8**	**BI-12**	**HB_{Panels}**	**AO-1**	**AO-2**	**A0-3**	**EF-1**	**WF-1**
1001		X	X								
1002		X	X								
1003		X									
1004					X	X					
1005	X					X					
1006				X	X	X	X	X	X	X	X
1007	X			X	X	X	X	X	X	X	X
1007a	X			X	X	X	X	X	X	X	X
1008				X	X	X	X		X	X	X
1009	X			X		X					
1009a	X			X		X					

X Consistent with observed damage

5.2 Ignition Source

Candidate ignition sources were researched and identified. Potential ignition sources include but not are not limited to the following:

- Improperly classified electrical outlets, lighting, switches, etc. The AB Specialty facility did not utilize explosion proof electrical. Thus, any electrical item could have been a potential ignition source
- Mechanical systems such as HVAC handlers, motors, mixers, etc. were also not classified explosion proof. Thus, numerous mechanical items could also have been a potential ignition source.
- Sparks: Dropped / thrown tools or flammable gas interaction with objects that may cause sparks.
- Electrostatic discharge: A buildup of static charge can develop from variety of sources (e.g., lack of grounding, lack of humidity, etc.).
- Machinery and tools: Forklifts, cutting torches, and numerous other items capable of creating heat or sparks were present in the building
- Personal electronic devices such as cell phones, radios, handheld testing equipment, etc. were also a potential source

Due to numerous potential ignition sources and large area which flammable gas may have been introduced, it was not possible to identify the specific ignition source.

5.3 Methane Gas Explosion in Low Bay Results

A methane gas explosion scenario was evaluated in the Low Bay processing area of the AB Specialty Facility as described in Section 4.2.2 and summarized in Table 4-1.

The flame speed of a vapor cloud explosion/deflagration is dependent upon the fuel type, congestion of the volume, and confinement as discussed previously. Natural gas is a low reactivity fuel, congestion was observed to be Low, and confinement was 2-D (floor and ceiling). With these parameters, a Low congestion flame speed of 0.078 (M_f) is appropriate. However, a higher Low-Medium congestion flame speed of 0.27 (M_f) was modeled to evaluate the natural gas at a higher flame speed than predicated by the conditions for establishing an upper bound in assessing the viability of a natural gas event.

Comparison of the predicted blast loads from the CFD model to the blast loads determined to cause the observed damage was performed as discussed in 5.1. Based on the predicted blast loads for Scenario 1001, the observed/measured damage to the blast indicators do not support the possibility of a natural gas explosion, eliminating natural gas from consideration as a potential fuel source of the explosion.

5.4 Hydrogen Gas Explosion in Low Bay Results

Multiple hydrogen gas cloud explosions were modeled in the Low Bay processing area of the AB Specialty Facility as described in Section 4.2.3 and summarized in Table 4-1. Comparisons of CFD applied blast loads to both on-site and off-site blast indicator P-i damage curves reveals that Scenarios 1007 & 1007a are most consistent with the observed damage from the event. This represents an upper cloud of hydrogen gas dispersed near the ceiling of the Low Bay processing area with a lower cloud in and around the area where the batch of materials was mixing/reacting. Results indicate that the ignition likely initiated in the western portion of the processing area (ignition Location 2) and propagated in all directions. However, enhanced pressure waves were pushed toward the east due to the longer flame travel distance in that direction.

6 Findings

Site surveys were conducted by the ABS Group team on June 11-13 and July 09-12, 2019 to observe the explosion scene and collect information to support the forensic. Explosion damage, blast indicators and directional indicators were observed and documented within facility. The observations made also aided in the development of the CFD model including equipment location, congestion, confinement, and openings between structures. Off-site surveys were also conducted of nearby structures to collect blast indicators at neighboring buildings affected by the explosion.

6.1 Evaluation of Potential Methane Explosion

A worst-case flammable methane cloud filling the Processing Area from floor to ceiling with a stoichiometric mixture of methane and air was evaluated. A conservative flame speed of 0.27 (M_f) was utilized to establish an upper bound in judging viability of a natural gas event. Comparison of the blast loads developed in the CFD model and the observed/measured damage to the blast indicators does not support the scenario of a natural gas explosion eliminating it as a potential fuel source of the explosion.

6.2 Evaluation of Potential Hydrogen Explosion

Explosion modeling showed that a flammable hydrogen cloud explosion in the Low Bay processing area is most consistent with the observed damage. The overall flammable cloud was modeled in two volumes; the upper cloud (gas that rose and formed along the ceiling), and a lower cloud (gas that dispersed around the source at the tank and reacting materials on the floor). Based on observed and measured damage hydrogen was distributed over a large portion of the Process Area of the Low Bay building. See Section 4.2.3 for detailed discussion of the flammable cloud size.

Hydrogen is a high reactivity fuel, which along with confinement and congestion, contributed to the severity of the explosion. Blast calculations indicate that the explosion intensity was consistent with a flame speed of 0.7(M_f) (flame speed evaluation is discussed Section 4.2.3).

6.3 Mass of Flammable Gas Contributing to the Explosion

The blast modeling determined that a flammable vapor cloud with a mass of approximately 41 to 42 lbs of hydrogen stoichiometrically mixed with air contributed to producing the damaging blast wave. That mix fills a volume of between approximately 26,800 to 27,880 ft^3. The modeling utilized an ideal cloud (uniform, stoichiometric mix) to approximate the real circumstances that involved a non-uniform mix of hydrogen and air. Due to the wide range of flammable limits for hydrogen, this was a necessary and reasonable assumption.

6.1 Potential Ignition Sources

A number of potential ignition sources were identified as described in Section 5.2. Based on eyewitness statements and timing of explosion [4], it was determined that ignition occurred after a flammable gas cloud could have formed. The amount of time from start of hydrogen release to ignition cannot be quantified since a definitive chronological sequence is not available and exact time of hydrogen production is not identifiable. Due to numerous potential ignition sources and Process Area which flammable gas may have been introduced, it was not possible to identify the specific ignition source.

7 References

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5 “Guidelines for Evaluating the Characteristics of Vapor Cloud Explosions, Flash Fires, and BLEVEs,” Center for Chemical Process Safety of the American Institute of Chemical Engineers, 1994.

6 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.

7 American Iron and Steel Institute, “North American Specification for the Design of Cold Formed Steel Structural Members.”, 2007 Edition, ANSI S100-2007.

8 Clutter, J.K., and Luckritz, R.T. "Comparison of a Reduced Explosion Model to Blast Curve and Experimental Data," Journal of Hazardous Materials, Vol. 79, Oct 2000, pp. 41-61.

9 Clutter, J.K., "A Reduced Combustion Model for Vapor Cloud Explosions Validated Against Full-Scale Data," Journal of Loss Prevention in the Process Industries, Vol. 14, Feb 2001, pp. 181-192.

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