Inherently Safer Plant Equipment Layout to Minimize the Hazards from Vapor Cloud Explosions

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It is possible to minimize the blast loads from a potential vapor cloud explosion by careful examination of equipment layout and structural designs. These inherently safer facilities have the advantage of reducing the potential consequences to occupied support buildings, and off site. This paper will review the conclusions from two studies using computational fluid dynamics modeling to demonstrate the impact of potential improvements.

Background

Our understanding of the mechanism by which Vapor Cloud Explosions generate damaging pressures has improved greatly in recent years. We now understand that a combination of vapor cloud confinement and obstacles provide an environment where a turbulent and fast burning flame front develops. The speed of that flame front ultimately determines the ability of the burning cloud to develop damaging pressure waves.

As Process Hazards Analyses are conducted, and siting decisions revisited, we have been given the opportunity to review our earlier decisions with improved tools and knowledge. In many cases, we have found that decisions made based on the TNT Equivalent method were reasonable or on the side of conservatism.

We have also uncovered potential hazards that were previously not understood due to the state of the technology at that time. Some of these cases have shown up in facilities where the total amount of flammables is considered small relative to facilities historically considered as having major vapor cloud explosion hazards. In addition, the confined and/or congested volume of equipment that is considered for explosion modeling is also relatively small. Modeling of vapor cloud explosions where the flammable mass of concern is less than 1000 lbs shows that these have the potential to generate explosions that can significantly damage nearby buildings.

We know, qualitatively, that if we reduce the confinement and/or congestion in the facility, we have the potential to reduce the maximum pressures that can be generated in a vapor cloud explosion. These changes can make a facility inherently safer. Such a facility may spend less money on blast protection of buildings, or lay out their facility on a reduced footprint, compared to facilities that have not made these considerations. Although we would prefer to invest in prevention, the industry has demonstrated that despite out best efforts, facilities will periodically loose containment of hazardous materials, and on occasion, vapor cloud explosions will occur.

The difficulty associated with investing in the process of making these type of mitigation decisions lies in predicting how those changes have reduced the potential explosion consequences, and translating that information into a usable package for designers.

Two such cases will be discussed in this paper. In each case, computational fluid dynamics modeling was utilized to help quantify the benefit of proposed changes to the facility.

Case 1 – Confinement Reduction

Background Information

Referring to Figure 1.0, the ground floor process structure central to the picture has the potential for a vapor cloud explosion due to the fact that this portion of the process contains sufficient quantities of high-pressure flammable gases with a maximum laminar burning velocity of ~35 cm/sec. The structure is 20 m (l) x 12 m (w) x 4 m (h). This structure has a solid concrete roof, and a portion of one wall (to the left) is made of cinder block. The scenario evaluated was ignition of a stoichiometric cloud of flammable in air of equivalent dimensions to the Potential Explosion Site (PES). Due to the orientation and extremely low congestion and confinement of neighboring process structures, these were not considered for their contribution to a potential explosion in this analysis.

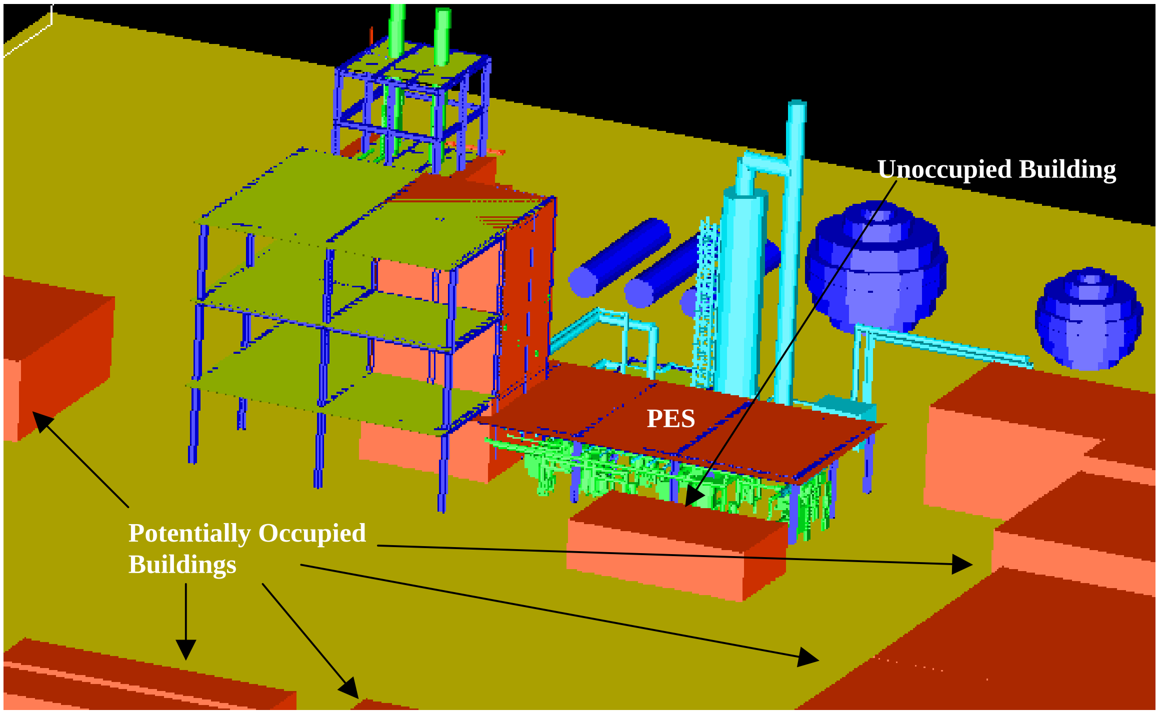

Figure 1.0 – Plant Layout and Potential Explosion Site (PES).

Computational Fluid Dynamics was considered for the following reasons.

- The vertical wall of the PES and the adjacent unoccupied structure could tend to focus the blast toward the buildings located directly opposite.

- Major pieces of equipment within the structure (Figure 2.0) are oriented perpendicular to the length of the structure. These may facilitate venting of the gas and minimize the pressure development.
- It is helpful to quantify the effect of reflection of the blast waves in close to the explosion.
- A portion of the concrete roof could be removed and replaced with a metal roof that could blow off to reduce the pressure. The CFD model would provide a basis to judge the improvements.

Explosion simulations were performed using FLACS 98 as developed by Christian Michelsen Research.

The Potential Explosion Site (PES) consists of several major pieces of equipment, process vessels, and interconnected piping. The basic arrangement of equipment is shown in Figure 2.0.

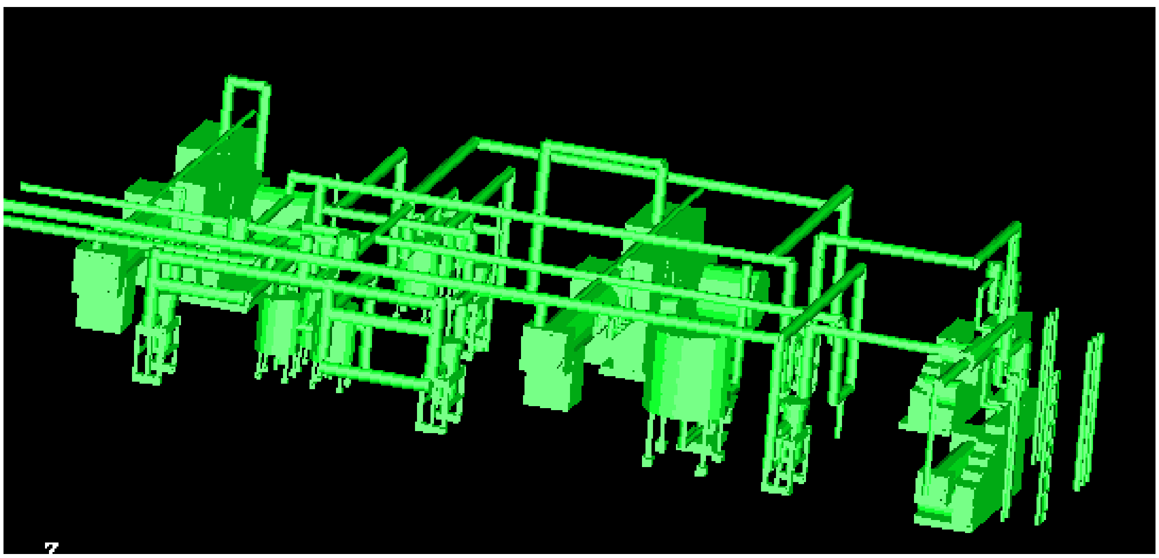

Figure 2.0 – Isometric view of Potential Explosion Site minus confinement, structural steel, and piping from support systems (air, steam, etc.).

After construction of the model, the volume blockage of the PES was determined to be 5.0%, while the area blockage was determined to be ~10.0%.

Simulation Results

The simulations were set up to measure the average pressures developed on the wall surfaces of neighboring buildings. FLACS pressure panels are used for this purpose. Illustrations of the plant buildings and corresponding panels are shown in Figure 3.0

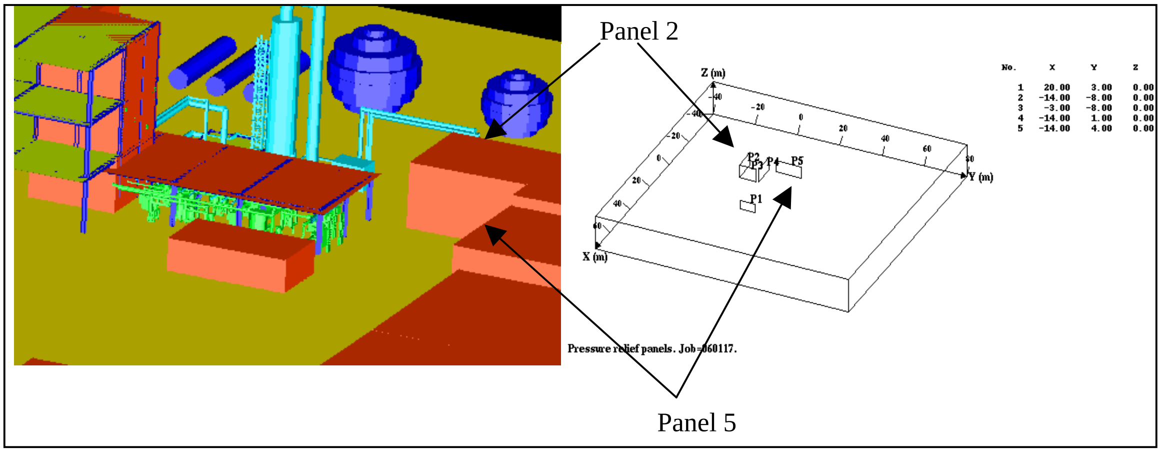

Figure 3.0 – Close-up of plant geometry (left) with FLACS pressure panels (right). Panels 2,3,4 and 5 correspond to the walls of the nearest building to the right of the geometry above. Panel 1 corresponds to the only vertical wall of the PES to the left of the geometry.

Various ignition locations were selected to understand the worst case ignition location. In this case, the worst case location was found to be on the centerline to the width of the PES approximately 25% of the length from the vertical wall. This location was mildly worse than central ignition or ignition near to the wall. These simulations suggested that significant damage to neighboring buildings was possible from the worst case event.

A measure of inherent safety can be introduced by reducing the confinement from the roof. For a number of reasons, a roof on this structure is desired by operations and maintenance. Piping above a portion the roof (not visible in the model.), does not permit the entire roof to be replaced, therefore; it was decided to model a lightweight sheet metal panel that would replace ½ the width of the roof (Figure 4). This portion of the roof is completely clear of obstructions. The weight of the panel (2.45 lb/ft^2 or 12 kg/m^2) and release pressure (0.4 psi or 2760 Pa) are specified in the program so that equations conserving mass, momentum, and energy can be satisfied. The panel was modeled as one piece, which is intended to be a conservative assumption.

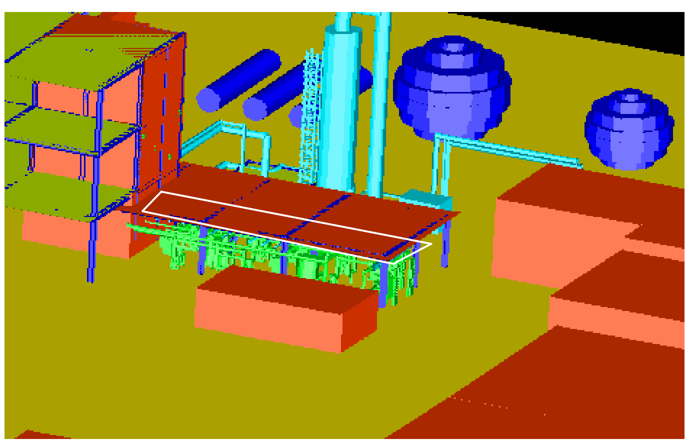

Figure 4.0 – The location of the roof blowout panel is shown in the white outline.

The average panel pressure and impulse from the worst case simulation is shown below.

	P2 Pres	P2 Imp	P3 Pres	P3 Imp	P4 Pres	P4 Imp	P5 Pres	P5 Imp
Solid Roof	0.5	28.1	1.4	74.4	1.3	76.5	1.3	66.3
Partially Vented Roof	0.4	23.5	1.0	56.7	0.8	52.6	0.7	43.6

Table 1.0 – Average Pressure (psi) and Impulse (psi-msec) on wall panels P2-P5.

Panels P3-P5 are those that would be damaged significantly in the solid roof case. By partially venting the roof, an improvement in peak pressure on the wall panels of 29 to 46% is realized with improvement in impulse betweeen 24 and 34%. While in absolute terms, these changes may seem small, based on the construction of the buildings, we concluded that strictly on consequences we could avoid the need for upgrades to the building structures by installing a partially vented roof.

Case 2 – Equipment Arrangement, Confinement Reduction and Cloud Location

Background Information – Existing Equipment and Proposed Changes to Equipment and Confinement

The manufacturing structure of Figure 5.0 was the subject of a study to minimize the damage potential of a potential vapor cloud explosion in the outer manufacturing structure between the solid decking of the top floor, and the ground.

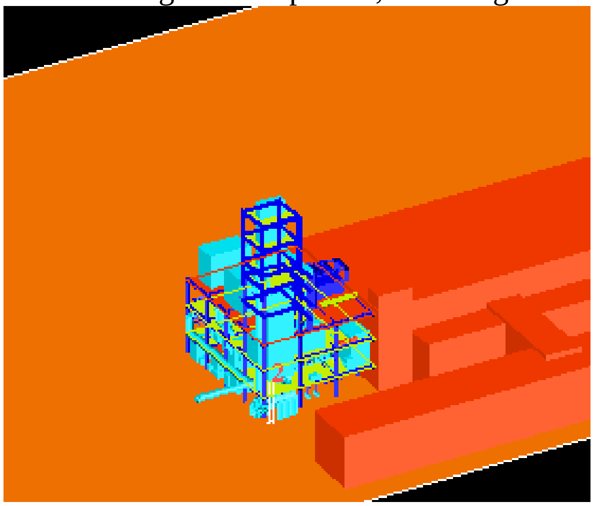

Figure 5.0 – Case 2 Potential Explosion Site

The average area blockage ratio within the PES is ~13.0 %, with a volume blockage of ~5%.

Figures 6.0, 7.0, and 8.0 show the location of major pieces of equipment on the 1st, 2nd, and 3rd, floors respectively. Not all sources of congestion can be shown in these views since only those intersecting with the plane are represented, but they do provide a feel for the location of large objects.

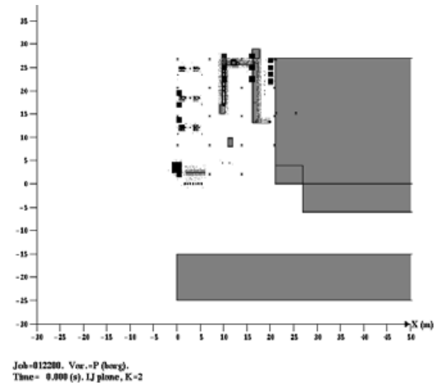

Figure 6.0 – 1st Floor location of major equipment.

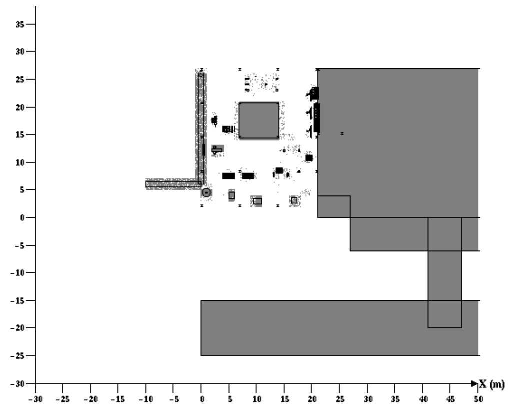

Figure 7.0 – 2nd Floor location of major equipment.

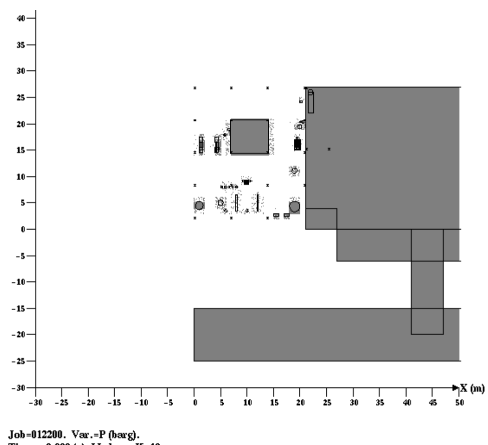

Figure 8.0 – 3rd Floor Location of major equipment.

There exists on the 1st Floor, a large piece of equipment that shows up as a U-shaped object in the upper right-hand corner of the outer structure (Figure 6.0). A plant project was being considered that would remove a significant portion of this equipment, and replace it with an additional steel structure and piping running vertically up the outer structure as shown in Figures 9.0, 10.0, and 11.0. There is a significant amount of piping associated with the existing equipment (not shown on this view) that could be eliminated, shortened, and rerouted. As a result, the revised plant structure would be significantly less congested on the 1st Floor, with only a relatively minor addition to congestion running vertically up the perimeter of structure.

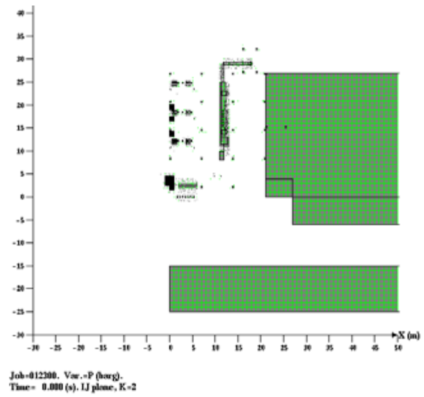

Figure 9.0 – 1st Floor after equipment rearrangement.

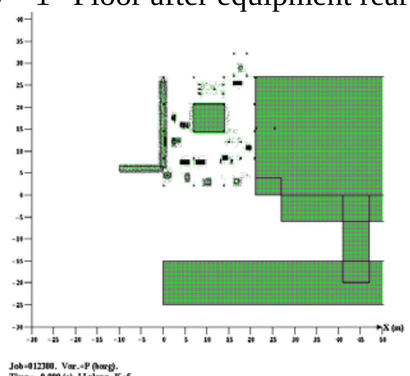

Figure 10.0 – 2nd Floor after equipment rearrangement.

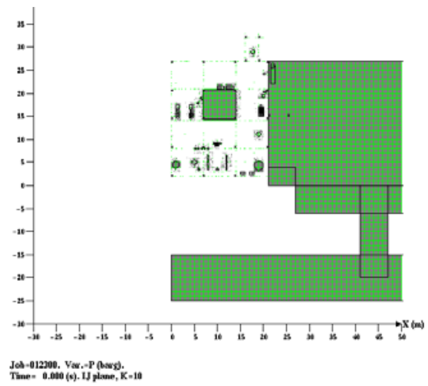

Figure 11.0 – 3rd Floor after equipment rearrangement.

In addition, we considered the potential benefit of removing some of the confinement from the top floor concrete, and replacing it with grated decking. Figure 12.0 shows the plan view of the proposed vented top floor. Referring to Figure 12.0 the existing Top Floor was solid except for the lower left corner that consisted of grating.

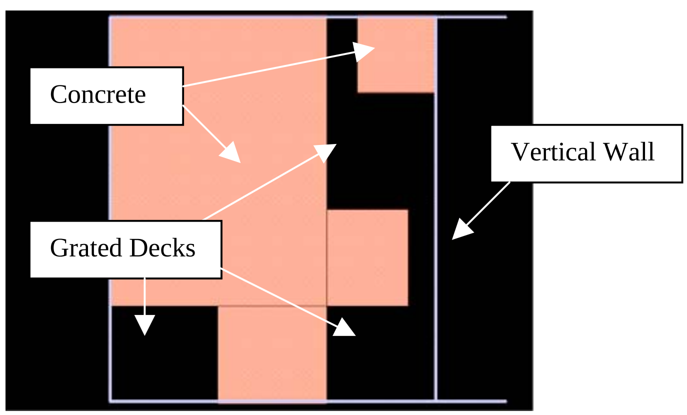

Figure 12.0 – Vented Top Floor

Simulation Results – Equipment Rearrangement and Confinement Reduction

The evaluation of explosion damage potential was conducted in the outer structure to with the following objectives.

- Minimize the effect of an explosion on the building connected to the outer structure.
- Minimize the effect of an explosion as it propagates in the far field.

The outer manufacturing structure contains an array of infrared flammability detectors with automatic interlock and isolation capability to minimize the quantity of flammable hydrocarbons that could potentially be released. Based on process conditions, leak potential, and mitigation systems, we have chosen a release quantity for evaluation that is equivalent to a stoichiometric mixture of flammable in air with a volume of 1600 m^3 (56500 ft^3). This corresponds to a cubical gas cloud with one side of 11.7 m (38 ft).

As in Case 1, the location of optimum ignition was determined, and found to be near and central to the vertical wall that separates the outer structure from the manufacturing building. The gas cloud is also located against and central to the vertical wall.

FLACS pressure panels set up to estimate the average pressure on the wall separating the manufacturing building from the outer structure. Figure 13.0 illustrates the location of the 12 panels versus the floors.

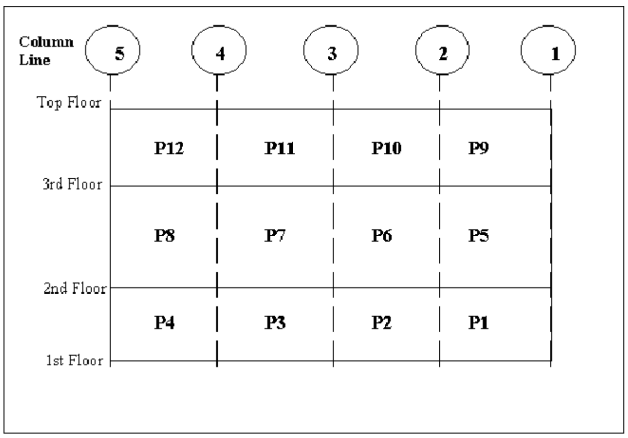

Figure 13.0 – Pressure Panels 1-12 as defined for computer simulation. The view is as if one was looking through the outer structure at the manufacturing building.

Pressure versus time traces are calculated during the simulation, and the resulting positive and negative phase pressure and impulse are tabulated for each pressure panel. The results of the base line case (prior to changes) are shown in Table 2.0. Greatest wall effects are seen towards the center of the wall, with symmetrical decay of pressure and impulse towards the vertical edges of the wall. Due to the confinement of the top deck, the average pressure and impulse between floors are essentially identical.

Panel	Positive Phase P_{max} (psi)	Positive Impulse (psi-msec)	Negative Phase P_{max} (psi)	Negative Impulse (psi-msec)
1	2.3	240	-1.3	-102
2	2.5	284	-1.4	-106
3	2.5	284	-1.3	-106
4	2.2	222	-1.3	-99
5	2.2	238	-1.3	-99
6	2.5	284	-1.3	-105
7	2.6	279	-1.3	-104
8	2.3	223	-1.2	-96
9	2.2	236	-1.3	-99
10	2.5	282	-1.3	-105
11	2.6	278	-1.3	-104
12	2.3	207	-1.2	-92
1st Floor Average	2.4	258	-1.3	-103
2nd Floor Average	2.4	257	-1.3	-101
3rd Floor Average	2.4	251	-1.3	-100
Average Overall	2.4	255	-1.3	-101

Table 2.0 – Simulated blast characteristics of explosion before changes.

Table 3.0 shows the results from the simulation with reduced obstacles on the 1st floor and changes to equipment per Figures 6 – 11.

Panel	Positive Phase P_{max} (psi)	Positive Impulse (psi-msec)	Negative Phase P_{max} (psi)	Negative Impulse (psi-msec)
1	1.9	214	-1.2	-156
2	2.2	254	-1.3	-162
3	2.2	254	-1.3	-162
4	1.9	213	-1.2	-154
5	1.8	212	-1.2	-152
6	2.1	253	-1.2	-159
7	2.1	253	-1.2	-160
8	1.9	214	-1.2	-150
9	1.9	211	-1.2	-149
10	2.2	251	-1.2	-157
11	2.2	252	-1.2	-158
12	1.8	199	-1.1	-141
1st Floor Average	2.1	235	-1.2	-159
2nd Floor Average	2.0	234	-1.2	-155
3rd Floor Average	2.0	229	-1.2	-151
Average Overall	2.0	232	-1.2	-155

Table 3.0 – Simulated blast characteristics of explosion from reduced congestion.

This change resulted in a 17% improvement in peak positive phase pressure and a 9% improvement in the positive phase impulse.

Table 4.0 shows the results from venting the top deck.

Panel	Positive Phase P_{max} (psi)	Positive Impulse (psi-msec)	Negative Phase P_{max} (psi)	Negative Impulse (psi-msec)
1	2.3	205	-1.1	-138
2	2.4	246	-1.1	-135
3	2.4	247	-1.0	-128
4	2.1	195	-1.0	-121
5	2.0	200	-1.0	-130
6	2.2	238	-1.0	-127
7	2.2	232	-1.0	-121
8	2.0	189	-0.9	-113
9	1.8	184	-0.9	-119
10	2.0	218	-0.9	-118
11	2.0	207	-0.9	-110
12	1.8	166	-0.8	-102
1st Floor Average	2.3	224	-1.0	-130
2nd Floor Average	2.1	215	-1.0	-122
3rd Floor Average	1.9	194	-0.9	-112
Average Overall	2.1	210	-1.0	-121

Table 4.0 – Simulated blast characteristics of explosion from venting the top deck.

Note that versus the two previous simulations, venting the top deck preferentially reduces the pressure and impulse towards the top of the wall. From a structural standpoint, this should result is a lower bending moment on the vertical support beams.

Table 5.0 shows the combined effect of both changes.

Panel	Positive Phase P_{max} (psi)	Positive Impulse (psi-msec)	Negative Phase P_{max} (psi)	Negative Impulse (psi-msec)
1	1.6	192	-1.0	-128
2	1.9	230	-1.0	-133
3	2.0	231	-1.0	-132
4	2.0	194	-1.0	-125
5	1.5	186	-0.9	-120
6	1.8	220	-1.0	-124
7	1.9	220	-1.0	-123
8	1.8	188	-0.9	-117
9	1.4	171	-0.8	-107
10	1.6	201	-0.9	-111
11	1.6	193	-0.8	-106
12	1.6	161	-0.8	-100
1st Floor Average	1.9	212	-1.0	-130
2nd Floor Average	1.7	204	-1.0	-121
3rd Floor Average	1.6	182	-0.8	-106
Average Overall	1.7	198	-0.9	-118

Table 5.0 – Simulation results from reduced confinement and congestion.

The peak positive and negative phase pressure has been reduced nearly 30%, with a 22% reduction in positive phase impulse.

It was also desired to understand the effects of these events on the sides of the building, and in the far field.

Monitor points (Figure 14.0) were set up in the simulations to develop this information. At each monitor point, the pressure versus time history for the simulation is calculated and stored.

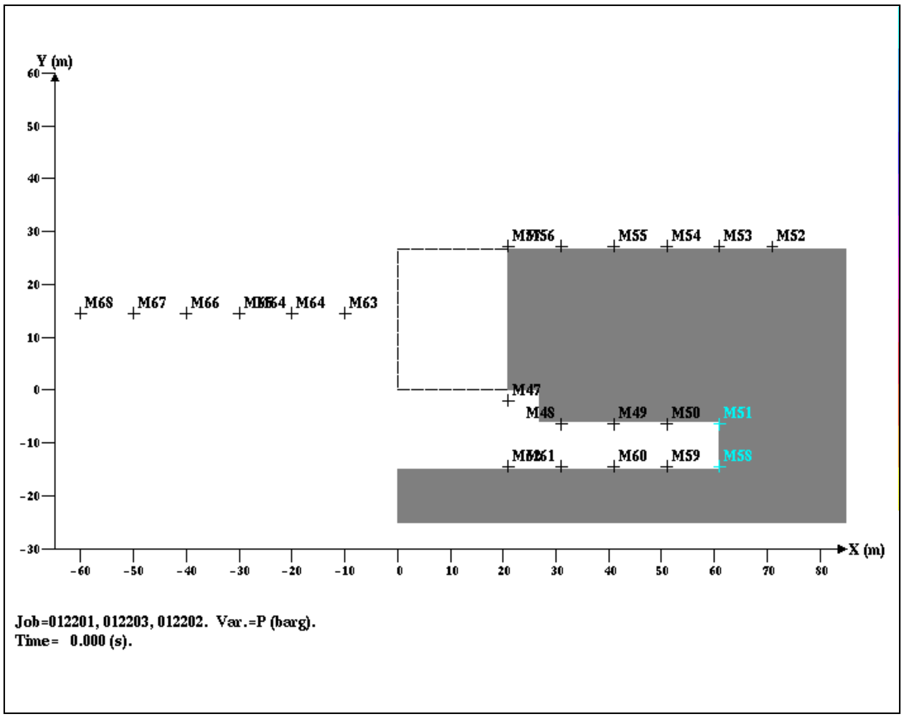

Figure 14.0 - Monitor Point locations for FLACS multiblock simulations.

A pressure time versus trace is calculated for each monitor point. The tabulated results for the positive phase pressure and impulse at each monitor point location are shown in Tables 6.0, 7.0 and 8.0.

Job #	012200		012300		012100		012400	
	Existing		**Reduced Congestion**		**Reduced Confinement**		**Combined Changes**	
	P (psi)	**I** (psi-msec)	**P** (psi)	**I** (psi-msec)	**P** (psi)	**I** (psi-msec)	**P** (psi)	**I** (psi-msec)
M47	2.37	155	1.77	150	1.48	127	1.30	121
M48	1.50	105	1.36	95	1.24	89	1.07	79
M49	1.42	86	1.28	80	1.12	73	0.91	69
M50	0.76	49	0.70	46	0.67	46	0.58	43
M51	0.53	44	0.71	42	0.71	42	0.58	40
M58	0.53	44	0.71	42	0.71	42	0.58	40
M59	0.76	48	0.73	46	0.66	46	0.58	43
M60	1.30	86	1.28	80	1.07	74	0.93	69
M61	1.50	113	1.43	95	1.26	96	1.05	80
M62	2.22	160	2.18	140	1.74	128	1.43	120

Table 6.0 - Far field positive phase pressure and impulse between buildings.

Job #	012200		012300		012100		012400	
	Existing		**Reduced Congestion**		**Reduced Confinement**		**Combined Changes**	
	P (psi)	**I** (psi-msec)	**P** (psi)	**I** (psi-msec)	**P** (psi)	**I** (psi-msec)	**P** (psi)	**I** (psi-msec)
M52	0.28	18	0.29	16	0.29	19	0.28	19
M53	0.36	22	0.37	21	0.35	23	0.35	23
M54	0.47	30	0.48	28	0.44	30	0.44	29
M55	0.66	43	0.67	39	0.58	40	0.57	38
M56	0.79	54	1.00	60	0.79	57	0.79	53
M57	0.87	71	1.23	77	0.87	65	0.91	67

Table 7.0 - Far field positive phase pressure and impulse along the long wall of building.

Job #	012200		012300		012100		012400	
	Existing		**Reduced Congestion**		**Reduced Confinement**		**Combined Changes**	
	P (psi)	**I** (psi-msec)	**P** (psi)	**I** (psi-msec)	**P** (psi)	**I** (psi-msec)	**P** (psi)	**I** (psi-msec)
M63	1.98	100	1.63	99	1.58	87	1.27	83
M64	1.44	72	1.19	69	1.19	62	0.98	60
M65	1.09	52	.0.92	51	0.89	47	0.75	46
M66	0.85	42	0.74	41	0.72	38	0.60	36
M67	0.69	33	0.61	33	0.58	31	0.50	30
M68	0.57	26	0.51	26	0.49	25	0.41	24

Table 8.0 - Far field positive phase pressure and impulse in the “strong” direction of the blast.

Tables 6.0 and 7.0 represent values that take into account the dynamic effect of pressure on the adjacent surfaces, and are therefore representative of reflected blast loading.

The monitor points associated with Table 8.0 do not have buildings near them and are more representative of free field values. Since they are located opposite the vertical wall, they represent the strongest direction of the blast.

Background Information – Effect of Cloud Location

After the previous analysis, we came to the realization that by making the proposed piping changes, potential sources of hot and high-pressure flammables could be limited to the outer manufacturing bays. This change improves inherent safety by making releases more likely to be diluted by wind and directed out of the structure. In addition, it is possible to erect a lightweight vertical vapor barrier that could separate the perimeter bays with leak potential from the interior of the structure. Such a barrier would give way upon a deflagration in the outer bays to minimize the confinement of the cloud after it ignites. Figure 15.0 shows the proposed location for the vapor barrier.

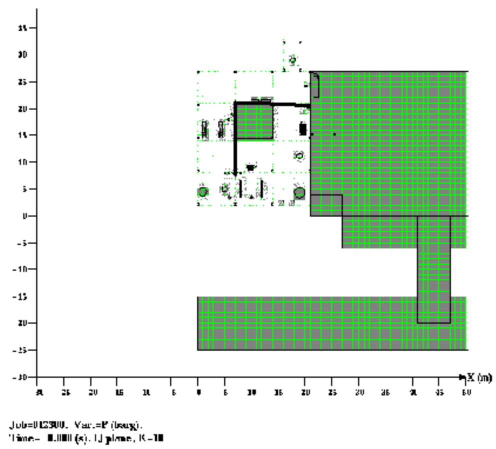

Figure 15.0 – Proposed vapor barrier location.

A vapor cloud of equivalent volume to that earlier simulated would occupy the volume of 9 bays. By “moving” the potential location of the cloud, peak pressures from a potential explosion would be reduced from the following effects.

- More of the unburned gas is pushed out of the confined and congested volume prior to combustion, preventing it from participating in pressure development.
- The shape of the initial cloud is such that the potential horizontal run-up distance for flame speed development is significantly reduced.
- The level of congestion in many of the outer bays is low relative to the interior of the structure.

Simulations of the effects of such a barrier versus a number of ignition locations indicate that for this process, peak explosion pressures on the vertical wall would be 0.5-0.8 psi. This is below the design strength of the wall. While this solution shows promise, caution is warranted.

- Application of such a barrier inhibits natural ventilation throughout the process unit. This could negatively impact the consequences of releases of flammable liquids or toxic materials within the vapor barrier.
- Location of the barrier should take into account that releases could be directed into the wind and redirected back into the process unit.

- In cases of moderate to high congestion or with fuels of higher reactivity, damaging explosion pressures may still be generated.
- This method does nothing to reduce the hazard to individuals in the open who would be exposed to the flash fire effects.

Conclusions

The variables associated with this inherently safer design process are complex. The process requires careful consideration, sophisticated tools, and experience to turn qualitative considerations into a design basis. The greatest benefit can be made early in the design process, to minimize the impact of those changes on project scope and timing.

From the cases discussed, it is clear that the damage potential of vapor cloud explosions can be significantly reduced through an explosion sensitivity analysis of equipment location, arrangement, and confinement in our manufacturing processes.

References

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