

# Enclosed Ammonia Vapor Cloud Explosion Testing

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## 1 Introduction and Background

Hydrogen (H<sub>2</sub>) and ammonia (NH<sub>3</sub>) are key energy carriers for modern society as an increased focus on “net-zero” greenhouse gas emissions (specifically carbon dioxide and methane) has resulted in a global push for lower carbon energy vectors, including pure hydrogen and ammonia. Liquid ammonia, having a higher volumetric energy density than liquid hydrogen, is a candidate for carbon-free energy storage, transportation, and fueling applications. Accurately modeling the dispersion, fire, and explosion hazards associated with new and existing ammonia production, consumption, distribution, and transportation networks is a key component to the safe expansion of these networks. This work discusses results obtained through large scale testing performed as part of BakerRisk’s Internal Research (IR) program and how the results compare to methods typically used by industry to quantify the explosion hazards associated with the handling of ammonia.

BakerRisk previously performed unconfined vapor cloud explosion (VCE) testing with ammonia [1]. The unconfined ammonia VCE tests demonstrated that damaging blast loads for unconfined ammonia VCEs would not be expected due to the very low laminar burning velocity (LBV) of ammonia and the resultant low VCE flame speeds. The Baker-Strehlow-Tang (BST) VCE blast load prediction methodology [2, 3], was updated to include a “very low” BST flame speed based on those tests. The results of the unconfined ammonia VCE tests are only applicable to unconfined VCE scenarios. Confined scenarios (i.e., indoor explosions) would behave differently. A BakerRisk IR program was therefore conducted to perform enclosed VCE (i.e., vented deflagration) tests with ammonia. Two configurations were evaluated: a light panel wall/roof fully enclosed rig (6,912 cubic ft) and a solid wall/roof rig (13,600 cubic ft) enclosed by three solid steel walls and a roof with a single open wall. The solid wall/roof tests were carried out using BakerRisk’s Deflagration Load Generator (DLG) test rig. The test matrix for the IR program is shown in Table 1. The test data were compared with calculations based on standard methods commonly applied to predict vented deflagration blast loads. Specifically, the results of these tests were compared to calculations performed using the FLACS computational fluid dynamics (CFD) code [4] and the correlations provided by the National Fire Protection Association Standard on Explosion Protection by Deflagration Venting (NFPA 68) [5].

Table 1. Test Matrix

Rig	Relief Pressure (psig)	Obstacle to Enclosure Surface Area Ratio ( $A_r$ )	Vent Area (ft <sup>2</sup> )	Fuel	Target Fuel Concentration (vol%)
Light Panel Walls/Roof	~0.2	3.7	288*	Ammonia	23.2%
Solid Walls/Roof (DLG)	~0.01	0.7	576		

\*Actual vent area observed during test

## 2 Test Description

The test rig configuration for the light panel wall/roof enclosure consisted of a 24-foot × 24-foot × 12-foot arrangement. The congested volume was constructed using the same cubes from the prior ammonia VCE tests [1]: 6-foot cube frames constructed of 2.5-inch steel square tubes. The congestion was represented by 3-inch nominal PVC pipes in a medium level of congestion (as defined in the BST method), and 32 cubes were arranged to complete the 4 cube × 4 cube × 2 cube volume, as shown in Figure 1. Metal purlin bearing R (PBR) panels were fastened to the test rig frame following industry standard PBR fastening methods, the estimated relief pressure is provided in Table 1. The resulting obstacle to enclosure surface area ratio ( $A_r$ ), which provides a relative congestion measure, is provided in Table 1. The panel-covered rig is also shown in Figure 1. Prior to panel application, a 1-mil thick plastic vapor barrier was put on the rig to minimize leaks of the fuel air mixture. The ignition source was located at grade at the rig center.

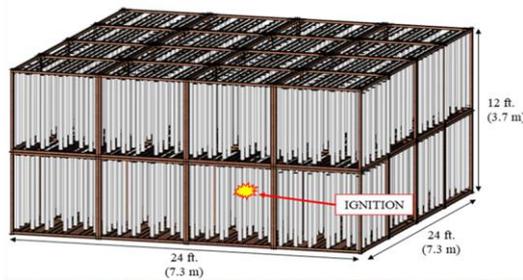


Figure 1. Light Panel Wall/Roof Test Rig

The DLG test rig is an enclosure with three solid walls, a roof, and floor, measuring 48 feet wide, 24 feet deep, and 12 feet tall [6]. Venting was allowed through one of the long walls (i.e., 48-foot  $\times$  12-foot). The venting face of the rig was sealed with a 6-mil thick plastic vapor barrier, which facilitated the formation of a fuel-air mixture inside the test rig, the estimated relief pressure is provided in Table 1. The DLG without plastic vapor barrier is shown in Figure 2. Congestion inside the DLG was provided by an array of vertical cylinders (2.375-inch and 2-inch outer diameter) that occupied the internal volume of the rig. The 2.375-inch outer diameter cylinders were located at the front of the rig (first two rows) to minimize plastic deformation of the cylinders due to repeated loading. The resulting  $A_r$  is provided in Table 1. The ignition source was located at the center of the rear wall, opposite the venting surface.



Figure 2. DLG Rig Test Configuration

Upper and lower fuel concentration acceptance bands were established to minimize the impact of fuel concentration variations. The acceptable concentrations were based on a 1% decrease from the maximum LBV. The target fuel concentration for ammonia tests was 23.2%, with an acceptance range of 22.9% to 23.6%, based on a -1% change from the maximum LBV reported by Duynslaegher [7]. Ten sample points were distributed throughout the DLG, and six through the light panel wall/roof enclosure, to allow the uniformity of the quiescent fuel-air mixture to be verified. Each sample point indicated a fuel-air concentration within the tolerance thresholds prior to ignition. Pressure transducers were fielded inside and outside the test rigs to measure blast loads. A 4K camera, a high-speed (1000 fps) camera and a drone camera were deployed to observe fireball ejection for all tests.

### 3 Predictions

CFD simulations of the tests were performed using the FLACS (FLame ACceleration Simulator) code. FLACS is a CFD tool widely used in industry for gas dispersion and VCE simulations. An overview of the FLACS geometries created for these simulations is shown in Figure 3. The computational mesh was created following the guidelines in the FLACS user's manual [4].

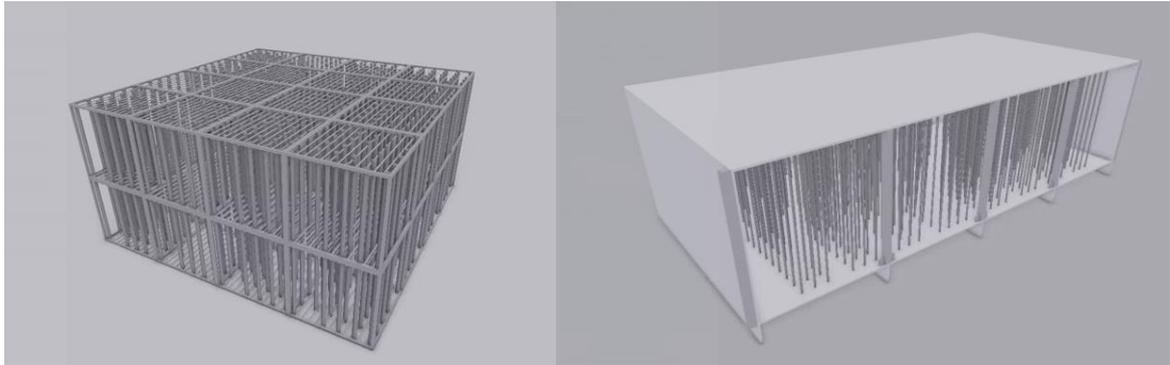


Figure 3. FLACS Geometries - Light Panel Walls/Roof (Left) and DLG (Right) Rigs

The NFPA 68 (2023) correlations for venting deflagrations of gas mixtures were used to predict the internal peak pressure and duration for each test series. The internal peak pressure and duration were then used to determine the corresponding impulse. The panel mass density (parameter required by NFPA 68) of the PBR metal panel used on the light panel wall/roof enclosure was 0.88 lb/ft<sup>2</sup>.

#### 4 Results and Discussion

Exemplar internal pressure histories for Test B01 (Light Panel Walls/Roof Rig) and Test A01 (DLG Rig) are provided in Figure 4 and Figure 5, respectively. The slow speed of the deflagration resulted in the pressure peaks arriving near the end of the pre-programmed three second data acquisition window. The measured peak pressures for all internal transducers were used to determine an average internal peak pressure for each test, and subsequently for each test series. One test was completed with the Light Panel Walls/Roof Rig configuration, and two tests were completed with the DLG rig. The maximum impulse (integration of pressure with respect to time) for each internal transducer was calculated based on the positive phase of the measured pressure history, and the average internal impulse was then determined for each test and each test series. The resulting average internal peak pressure and impulse for all test series, along with the predictions from the FLACS CFD code and NFPA 68, are provided in Table 2.

Table 2. Average Internal Peak Pressure, Impulse and Equivalent Duration

Test Rig	Test Data			FLACS			NFPA 68		
	Pressure (psig)	Impulse (psi-ms)	Equivalent Duration (ms)	Pressure (psig)	Impulse (psi-ms)	Equivalent Duration (ms)	Pressure (psig)	Impulse (psi-ms)	Equivalent Duration (ms)
Light Panel Walls/Roof	0.2	75	702	0.2	49	429	0.75	144	383
DLG	0.06	17	536	0.09	32	688	0.36	101	112

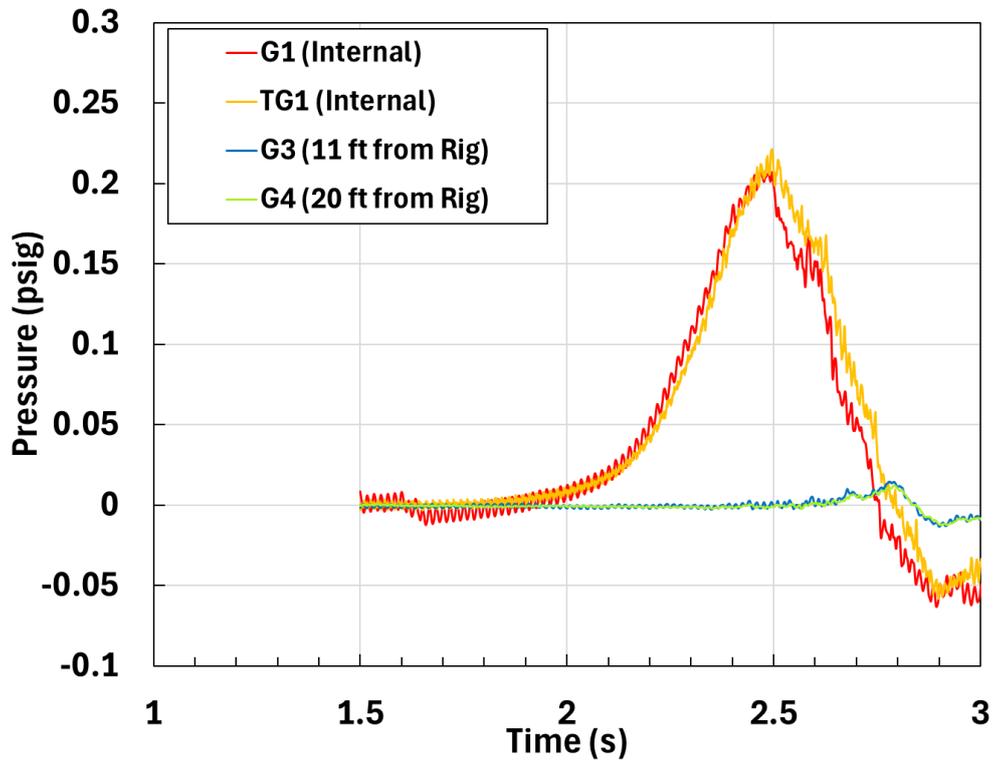


Figure 4. Pressure Histories Inside the Light Panel Walls/Roof Rig for Test B01

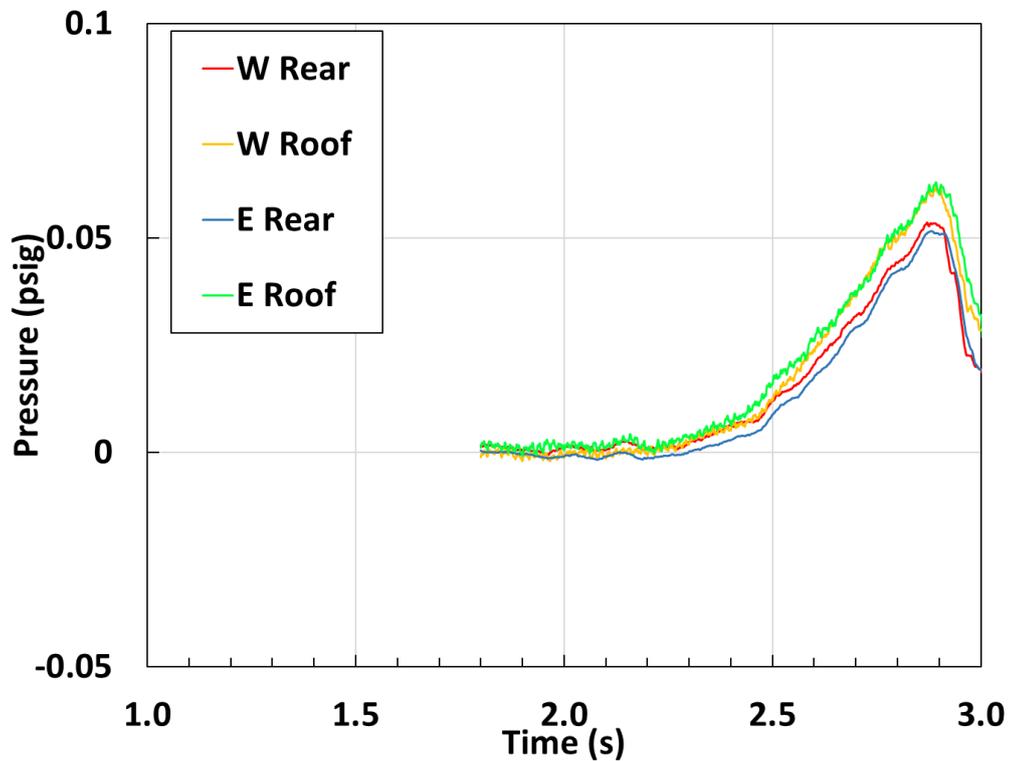


Figure 5. Pressure Histories Inside the DLG Rig for Test A01

Select still frames from the drone videos are provided in Figure 6 and Figure 7, for the Light Panel Walls/Roof Rig test B01 and the DLG rig test A02, respectively. During the light panel wall/roof test series, only a portion of the roof (approximately 288 ft<sup>2</sup>) opened allowing for venting (as shown in Figure 6). The resulting average internal peak pressure was approximately 0.2 psig. That is, a portion of the panels opening was sufficient to vent the deflagration, and the peak pressure did not rise to the level required for all panels to release. Predictions made using FLACS and NFPA 68 were adjusted to account for the smaller than anticipated vent area (i.e., the simulations were revised to match the test condition), however a sensitivity analysis showed negligible change to the predicted peak pressures from FLACS and NFPA 68 when the vent area was increased to include all the walls and roof.



Figure 6. Photos Light Panel Walls/Roof Rig Test B01

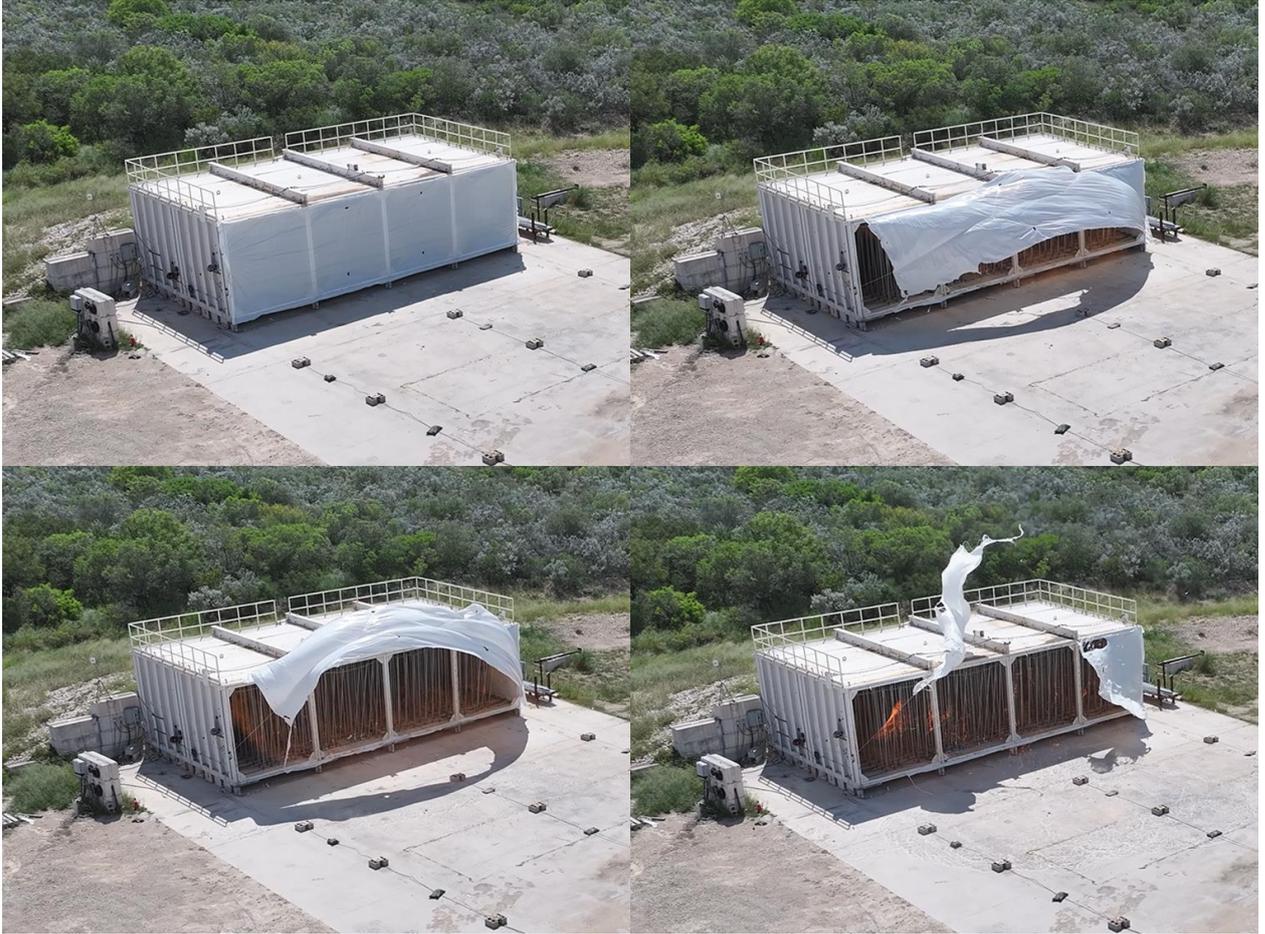


Figure 7. Photos DLG Rig Test A02

Internal pressure histories predicted using FLACS are provided in Figure 8 and Figure 9 for the Light Panel Walls/Roof Rig and DLG Rig, respectively. The FLACS wave shape predictions are in good agreement with the test data for the DLG tests, with FLACS predicting higher peak pressures and longer durations for internal gauges. The wave shape predicted by FLACS for the Light Panel test is not in good agreement with the test data, but the peak pressure predicted by FLACS is good agreement with the measured value.

Selected time stamps for 3D maximum pressure and combustion product (i.e., flame) contours for the FLACS simulations are provided in Figure 10 and Figure 11. These figures show the blast wave and fireball exiting the test rigs through the venting surfaces (i.e., light metal panels/plastic).

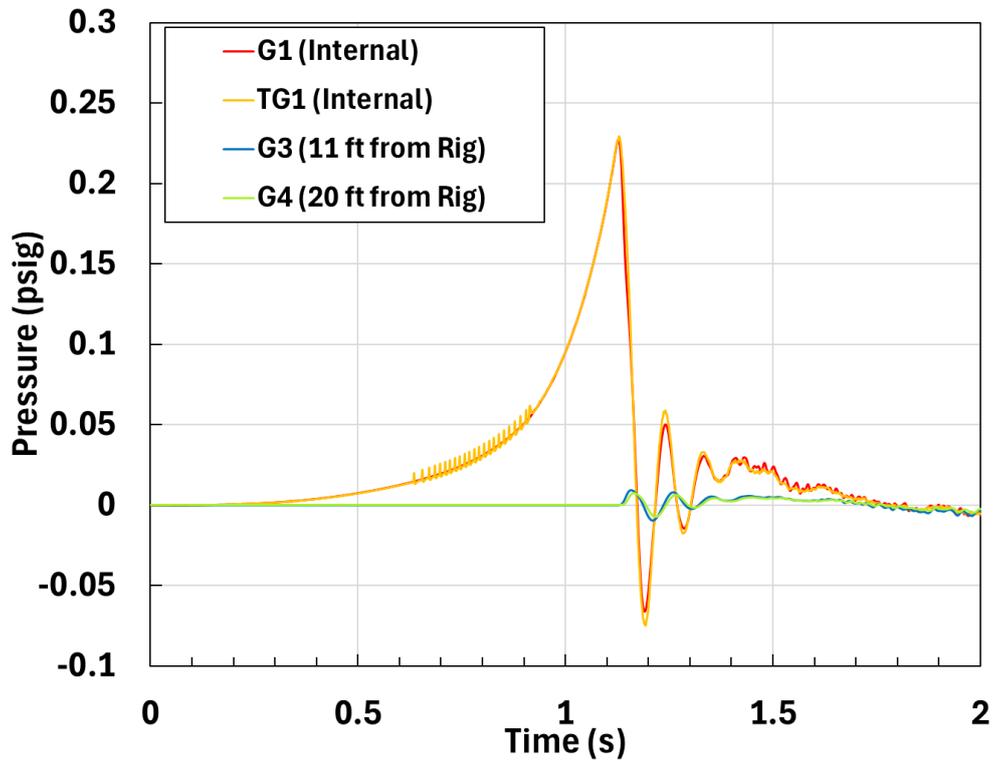


Figure 8. FLACS Predicted Pressure Histories Inside Light Panel Walls/Roof Rig

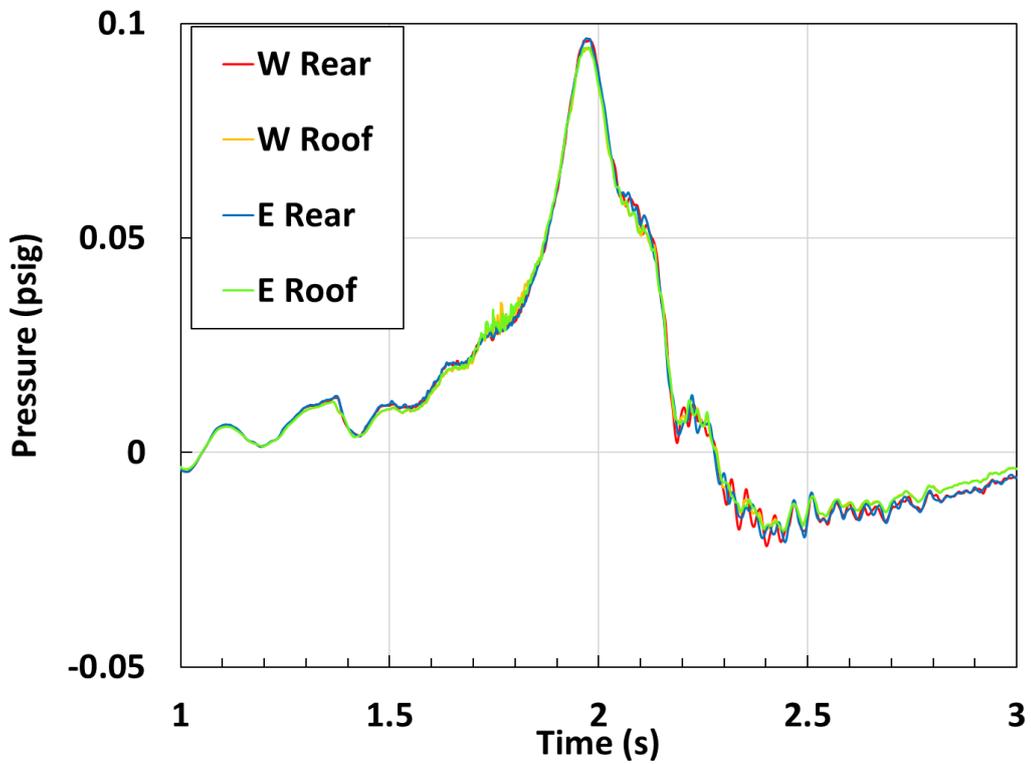


Figure 9. FLACS Predicted Pressure Histories Inside DLG Rig

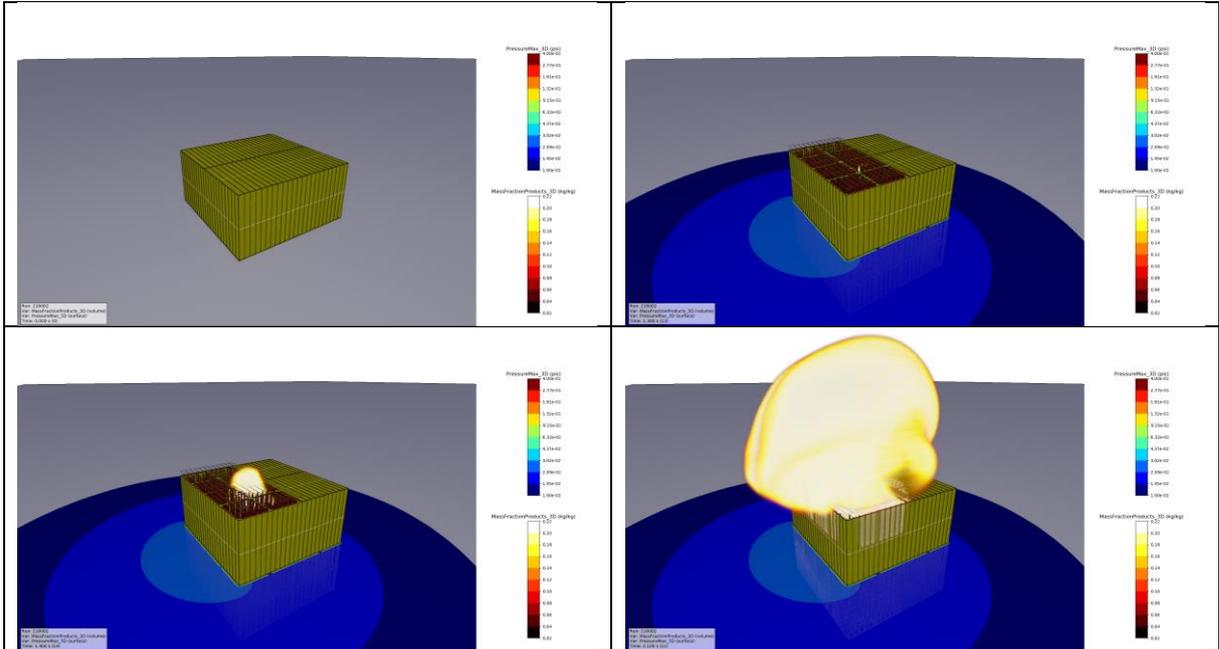


Figure 10. Light Panel Walls/Roof Rig FLACS Simulation Max Pressure and Burned Products Contours at Selected Times

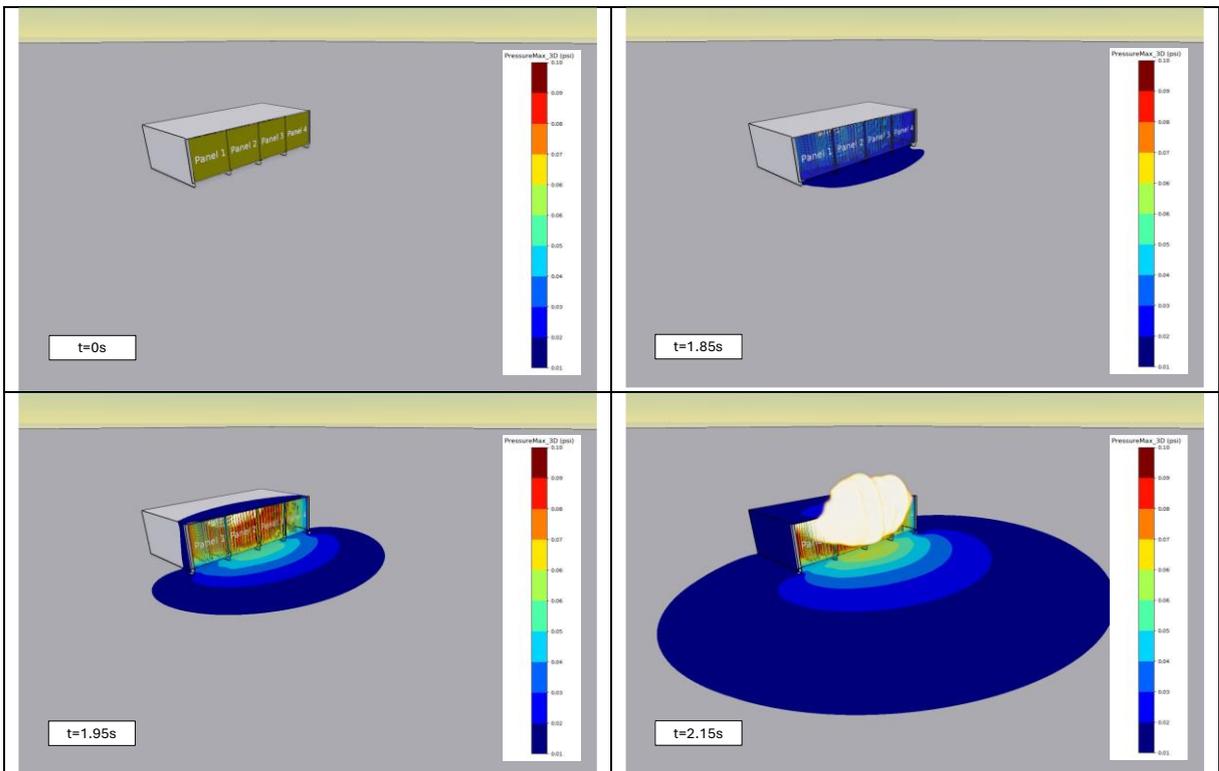


Figure 11. DLG Rig FLACS Simulation Max Pressure and Burned Products Contours at Selected Times

## 5 Key Findings

For the DLG test series, the average internal peak pressure was <0.1 psig. This result was consistent with prior testing performed in a confined/vented geometry [8]. The FLACS peak pressure predictions for the DLG test showed to be conservative (0.09 psig vs 0.06 psig), while the wave shape showed general good agreement. The NFPA 68 predictions for pressure/impulse (duration) were conservative, for both the light panel wall/roof and DLG test series. Both test series indicate that ammonia does not pose a significant explosion hazard when sufficient venting is provided; however, a confined ammonia VCE could cause catastrophic enclosure failure if sufficient venting is not provided, achieving a maximum deflagration pressure of 78 psig (5.4 barg) in the absence of any venting [5]. The test data from both rigs can also be used to update the “very low” BST flame speed values for confined VCEs.

## 6 Acknowledgments

This work was made possible by the BakerRisk IR program. We would also like to acknowledge other testing work completed for the ERC (Explosion Research Cooperative). The ERC is a joint industry research program started by BakerRisk in 1993 to serve as a resource for the oil, gas, and chemical processing industries to come together and share research, experiences, and best practices. The ERC research supports improvements in explosion hazard models, structural damage, injury models, and structural design techniques to mitigate these hazards.

## References

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