Gas Pressure Testing Program and Measured Gas Pressure Histories

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Background

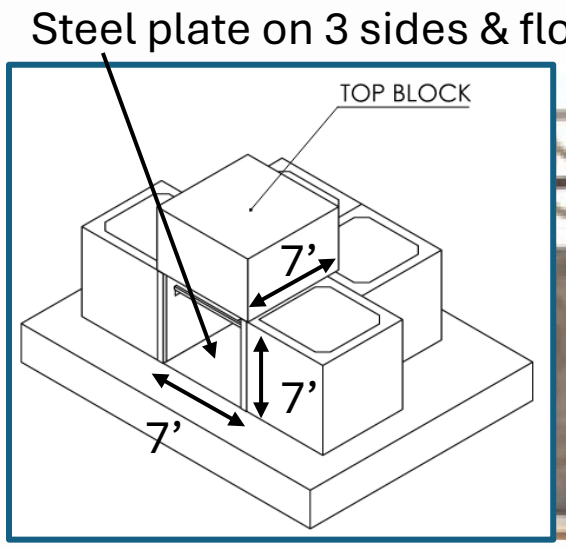
- Internal blast loads from confined detonation consist of shock pressures from shock wave and gas (quasistatic) pressure from confined heat and product gases
  - These two types of pressure are from very different physical phenomena that require separate fast-running calculation methods
- A study in 2019 funded by DDESB concluded existing calculation methods significantly overcalculate measured gas pressures in explosion rooms with significant venting
  - Also limited data for test rooms with large vent areas and low loading densities (ratio of charge weight/room volume)
- Based on 2019 study, DDESB funded a large project in 2020 for gas pressure testing (DDESB Tests) and methodology improvement

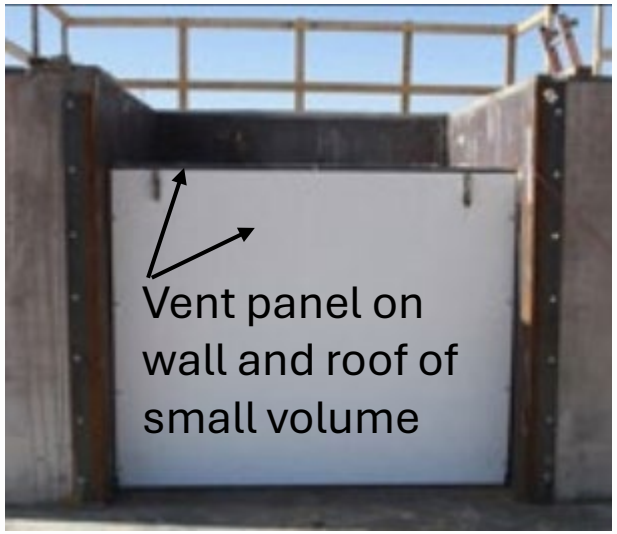
Overview of Testing

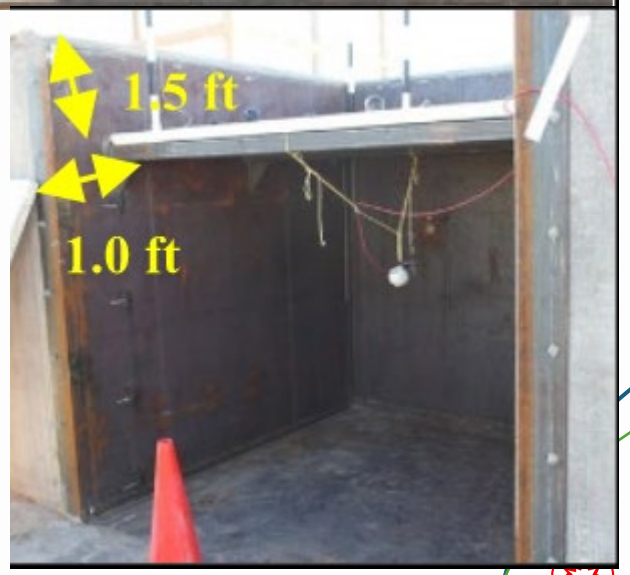
- All testing was conducted by Applied Research Associates (ARA) at Kirtland AFB, New Mexico for Defense Threat Reduction Agency (DTRA) under contract from DDESB
  - ARA conducted all tests and assisted with data reduction
- Goal of testing was to measure gas pressures in test rooms with one and two surfaces covered with lightweight vent panels
  - Tests had "low" loading densities less than 0.022 lb/ft^3
- Two phases of testing
  - Initial tests used special "quasistatic" pressure gages that were not useful
  - Final tests used series of tests with standard piezoelectric blast gages
  - Each series included baseline tests with no gas pressure and vented tests with gas pressure

Test Structure

- Test structure had 3 ft slab with rebar extending into 7 ft cubic culverts on three sides
- Test room lined with steel plate with welded studs extending into holes in culverts
- Culverts filled with concrete
- Additional concrete filled culvert used to cover top surface in many tests







Vent Panels

- 3 vent panel types had 1 psf to 1.5 psf areal weight (at half scale)
  - 2 in. x 1 in. wood stud w/ 0.25 in. thick plywood (6 pieces of plywood)
  - 26 g corrugated steel panels with 1 in. ribs as 12 in. spacing (7 vertical pieces)
  - 0.25 in. thick solid Lexan panel
- 1 heavy vent panel - 0.25 in. thick steel plate (no breakup)
- Vent panels attached with (4) fasteners with 175 lb. tension capacity each

Corrugated steel panel

Wood stud wall panel

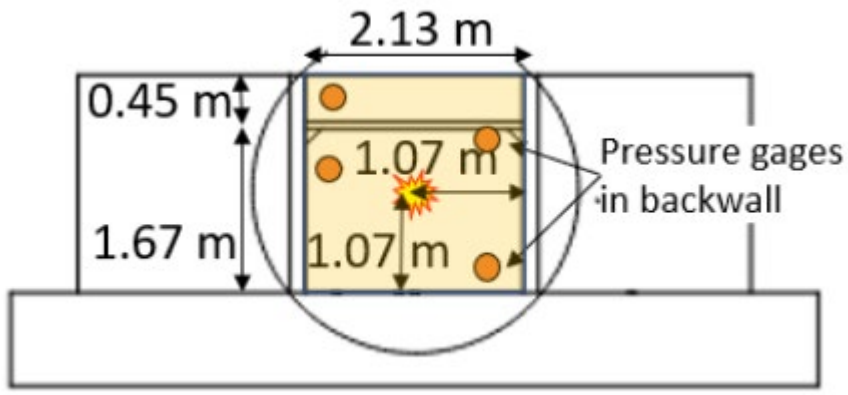
Explosive Charges

- TNT and C4 were spherical charges
- PETN was 1:1 cylindrical charge
- All charges centered in 7 ft cubic volume
  - Same location when volume was reduced
- Explosives had a large range of afterburning heats

Explosive Type	Heat of Detonation (kJ/kg)	Heat of Combustion (kJ/kg)	Afterburning Heat (kJ/kg)
TNT	4480	14,500	10,020
C-4	5410	10,500	5,090
PETN (93% PETN, 7% wax)	5340	8780	3,440

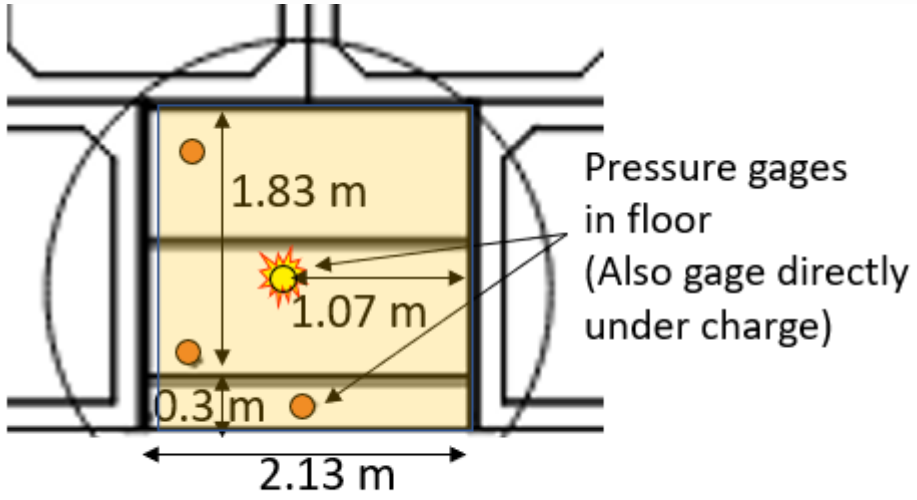
Blast Gages

- Gage locations same for all tests
- Initially 2 piezoelectric blast pressure gages + 6 quasistatic pressure gages
- Thereafter all 8 gages were piezoelectric blast pressure gages



Elevation View

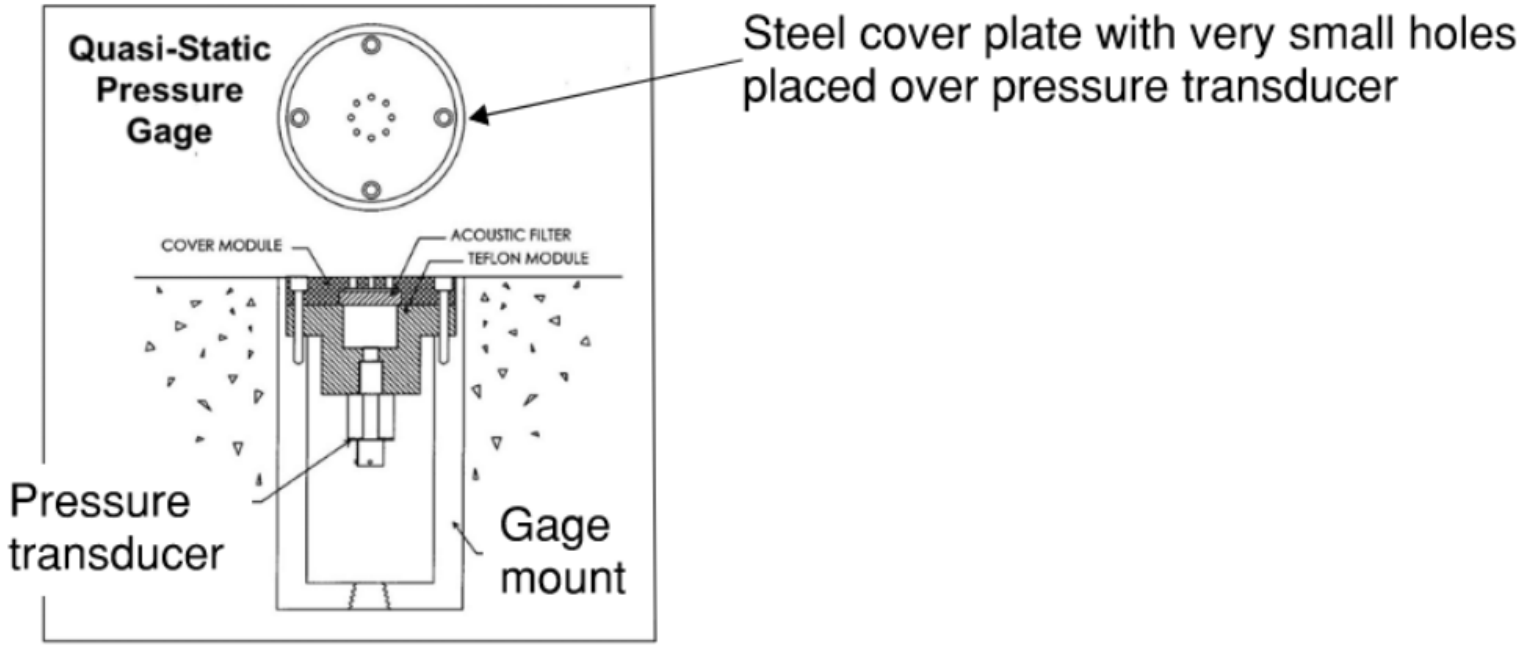
2.13 m = 7 ft
1.07 m = 3.5 ft
1.67 m = 5.5 ft
1.83 m = 6 ft



Plan View

Initial Tests

- First 15 vented tests used quasistatic pressure gages originally developed to measure longer duration quasistatic pressures
- Gas pressure vented quickly over same time frame required for pressure to enter/exit through small holes in front of pressure



Final Tests

- Tests were conducted in “series” to separate out gas pressure from shock pressure. Each series included:
  - One “Baseline test” with one side open so that only measured shock pressures
  - Multiple otherwise very similar confined “Vented tests” where one or two sides of test structure were covered with vent panels
- Gas pressure histories were determined by subtracting average of all measured pressure histories in each Vented test from average all measured pressure histories in Baseline test
  - Subtracted pressure histories for vented tests have small amount of unintended shock pressure from shock wave reflected off vent wall prior to its failure
- Final tests included 43 tests in 11 series

Final Test Series Matrix

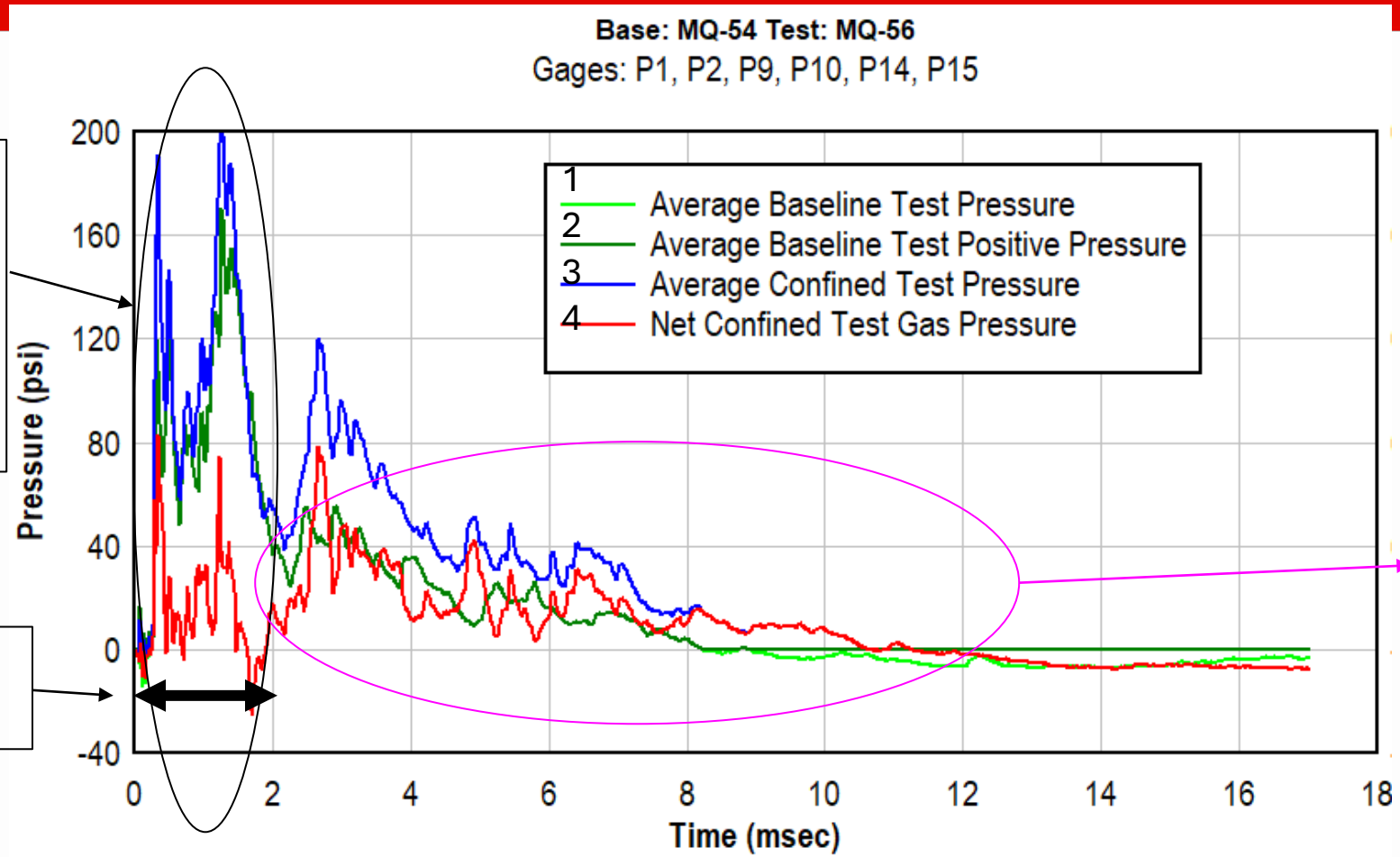
Group	Test	Charge		Nominal Dimensions	Room Volume (ft^3)	Loading Density (lb/ft^3)	No. of Vent Panels	Front Wall		Roof	
		Weight (lb)	Type[1]					Type[1]	Dimensions (ft)[2]	Type[1]	Dimensions (ft)[3]
1	10A	1.2	C4	5.5 x 7 x 6	231	0.0052	0	Open	5.5 ft x7 ft	Rigid	6 ft x7 ft
	5A	1.2	C4	5.5 x 7 x 6	231	0.0052	2	1/4" steel	5.5 ft x7 ft	1/4" steel	6 ft x7 ft
	6A	1.2	C4	5.5 x 7 x 6	231	0.0052	2	26-gauge metal	5.5 ft x7 ft	26-gauge metal	6 ft x7 ft
2	11A	3.6	C4	5.5 x 7 x 6	231	0.0156	0	Open	5.5 ft x7 ft	Rigid	6 ft x7 ft
	13A	3.6	C4	5.5 x 7 x 6	231	0.0156	1	1/4" Lexan	5.5 ft x7 ft	Rigid	6 ft x7 ft
	15A	3.6	C4	5.5 x 7 x 6	231	0.0156	2	1/4" Lexan	5.5 ft x7 ft	1/4" Lexan	6 ft x7 ft
3	16	5	C4	5.5 x 7 x 6	231	0.0216	0	Open	5.5 ft x7 ft	Rigid	6 ft x7 ft
	17	5	C4	5.5 x 7 x 6	231	0.0216	2	1/4" steel	5.5 ft x7 ft	1/4" steel	6 ft x7 ft
	18	5	C4	5.5 x 7 x 6	231	0.0216	2	26-gauge metal	5.5 ft x7 ft	26-gauge metal	6 ft x7 ft
	19	5	C4	5.5 x 7 x 6	231	0.0216	1	26-gauge metal	5.5 ft x7 ft	Rigid	6 ft x7 ft
	20	5	C4	5.5 x 7 x 6	231	0.0216	1	1/4" steel.	5.5 ft x7 ft	Rigid	6 ft x7 ft
4	22	1.2	C4	7 x 7 x 7	340	0.0035	0	RP	7 ft x7 ft	Open	7 ft x7 ft
	8A	1.2	C4	7 x 7 x 7	360	0.0033	2	¼" plywood	7 ft x7 ft	¼" plywood	7 ft x7 ft
	23	1.2	C4	7 x 7 x 7	340	0.0035	1	RP	7 ft x7 ft	26-gauge metal	7 ft x7 ft
	24	1.2	C4	7 x 7 x 7	340	0.0035	1	RP	7 ft x7 ft	¼" Lexan	7 ft x7 ft
5	25	5	C4	7 x 7 x 7	340	0.0147	0	RP	7 ft x7 ft	Open	7 ft x7 ft
	21	5	C4	7 x 7 x 7	352	0.0142	1	26-gauge metal	7 ft x7 ft	Rigid	7 ft x7 ft
	26	5	C4	7 x 7 x 7	340	0.0147	1	RP	7 ft x7 ft	26-gauge metal	7 ft x7 ft
	27	5	C4	7 x 7 x 7	340	0.0147	1	RP	7 ft x7 ft	¼" Lexan panel	7 ft x7 ft
6	33	1.14	TNT	7 x 7 x 7	340	0.0034	0	RP	7 ft x7 ft	Open	7 ft x7 ft
	34	1.14	TNT	7 x 7 x 7	360	0.0032	2	¼" plywood	7 ft x7 ft	¼" plywood	7 ft x7 ft
	35	1.14	TNT	7 x 7 x 7	347	0.0033	1	RP	7 ft x7 ft	¼" plywood	7 ft x7 ft
	36	1.16	TNT	7 x 7 x 7	340	0.0034	1	RP	7 ft x7 ft	1/4" Lexan	7 ft x7 ft

Final Tests (Cont'd)

Group	Test	Charge		Nominal Dimensions	Room Volume (ft^3)	Loading Density (lb/ft^3)	No. of Vent Panels	Front Wall		Roof	
		Weight (lb)	Type[1]					Type[1]	Dimensions (ft)[2]	Type[1]	Dimensions (ft)[3]
7	37	2.62	TNT	5.5 x 7 x 6	231	0.0113	0	Open	5.5 ft x7 ft	Rigid	6 ft x7 ft
	38	2.6	TNT	5.5 x 7 x 6	241	0.0108	2	¼" plywood	5.5 ft x7 ft	¼" plywood	6 ft x7 ft
	39	2.6	TNT	5.5 x 7 x 6	231	0.0113	2	¼" Lexan	5.5 ft x7 ft	¼" Lexan	6 ft x7 ft
	40	2.6	TNT	5.5 x 7 x 6	236	0.011	1	¼" plywood	5.5 ft x7 ft	Rigid	6 ft x7 ft
	41	2.6	TNT	5.5 x 7 x 6	231	0.0113	1	¼" plywood	5.5 ft x7 ft	Rigid	6 ft x7 ft
8	42	3.44	TNT	7 x 7 x 7	340	0.0101	0	RP	7 ft x7 ft	Open	7 ft x7 ft
	43	3.44	TNT	7 x 7 x 7	347	0.0099	2	26-gauge metal	7 ft x7 ft	26-gauge metal	7 ft x7 ft
	44	3.42	TNT	7 x 7 x 7	340	0.0101	1	RP	7 ft x7 ft	26-gauge metal)	7 ft x7 ft
	45	3.42	TNT	7 x 7 x 7	340	0.0101	1	RP	7 ft x7 ft	¼" Lexan	7 ft x7 ft
9	46	1.2	PETN	7 x 7 x 7	346	0.0035	0	Open	7 ft x7 ft	RP	7 ft x7 ft
	47	1.2	PETN	7 x 7 x 7	360	0.0033	2	¼" plywood	7 ft x7 ft	¼" plywood	7 ft x7 ft
	48	1.2	PETN	7 x 7 x 7	346	0.0035	1	¼" plywood	7 ft x7 ft	RP	7 ft x7 ft
	49	1.2	PETN	7 x 7 x 7	346	0.0035	1	¼" steel	7 ft x7 ft	RP	7 ft x7 ft
10	50	2.74	PETN	7 x 7 x 7	340	0.0081	0	RP	7 ft x7 ft	Open	7 ft x7 ft
	51	2.74	PETN	7 x 7 x 7	347	0.0079	2	26-gauge metal	7 ft x7 ft	26-gauge metal	7 ft x7 ft
	52	2.74	PETN	7 x 7 x 7	340	0.0081	1	RP	7 ft x7 ft	26-gauge metal	7 ft x7 ft
	53	2.74	PETN	7 x 7 x 7	347	0.0079	1	RP	7 ft x7 ft	¼" plywood	7 ft x7 ft
11	54	3.6	PETN	5.5 x 7 x 6	231	0.0156	0	Open	5.5 ft x7 ft	Rigid	6 ft x7 ft
	55	3.6	PETN	5.5 x 7 x 6	231	0.0156	1	26-gauge metal	5.5 ft x7 ft	Rigid	6 ft x7 ft
	56	3.6	PETN	5.5 x 7 x 6	231	0.0156	1	¼" Lexan	5.5 ft x7 ft	Rigid	6 ft x7 ft

RP = steel plate that does not fail (responds elastically with measured maximum deflection history)

Example of Measured Average Pressure Histories



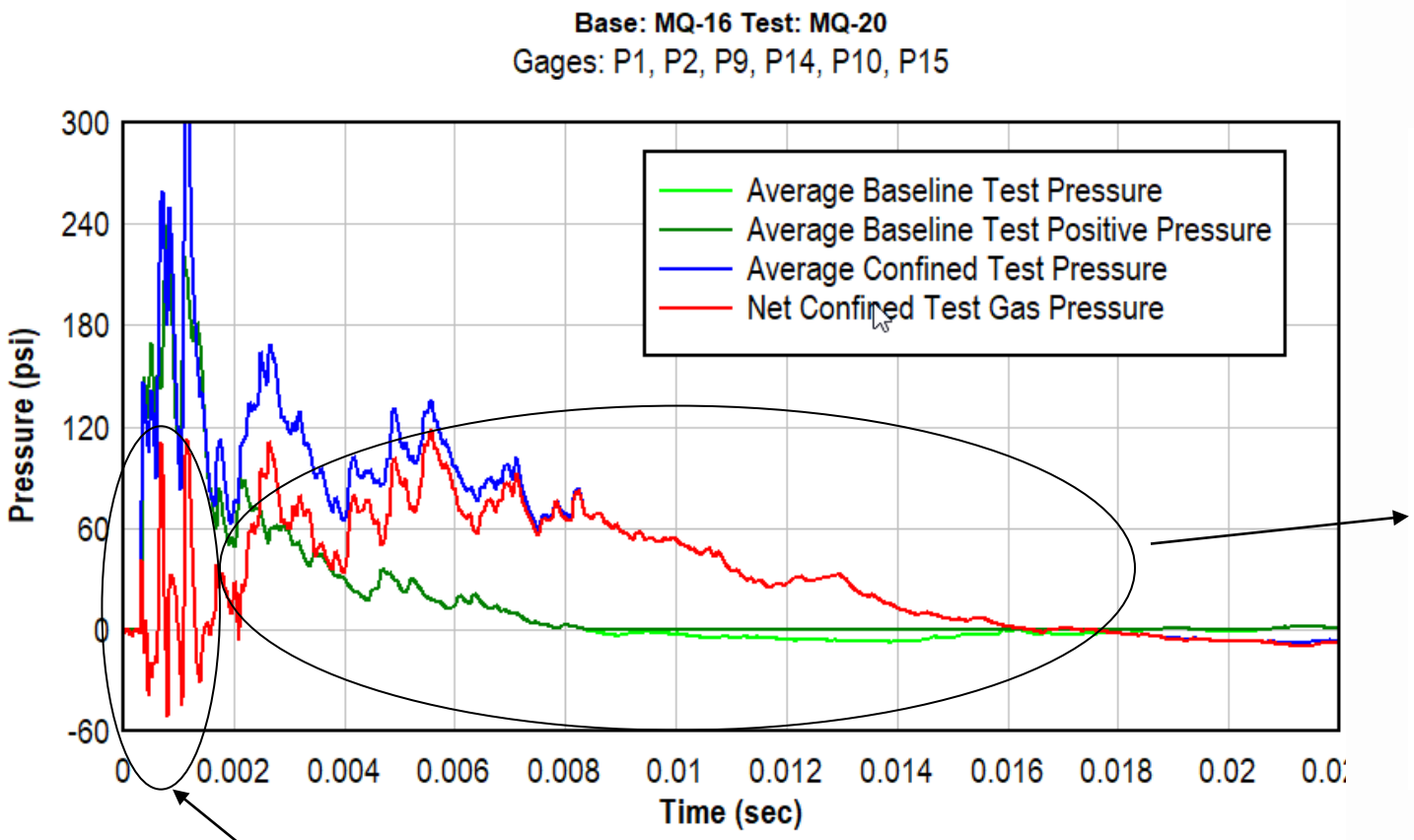
No gas pressure for initial 2 msec where blue & green curves very similar

Gas pressure "arrival time"

This part of **red curve** was curve-fit to determine **"measured" gas pressure**

1. Average time history of all internal gages in baseline test
2. Same as No. 1 except negative phase set to zero
3. Average time history of all internal gages in confined test
4. Net pressure history (approx. gas pressure history) = Avg confined – Avg baseline positive pressure only

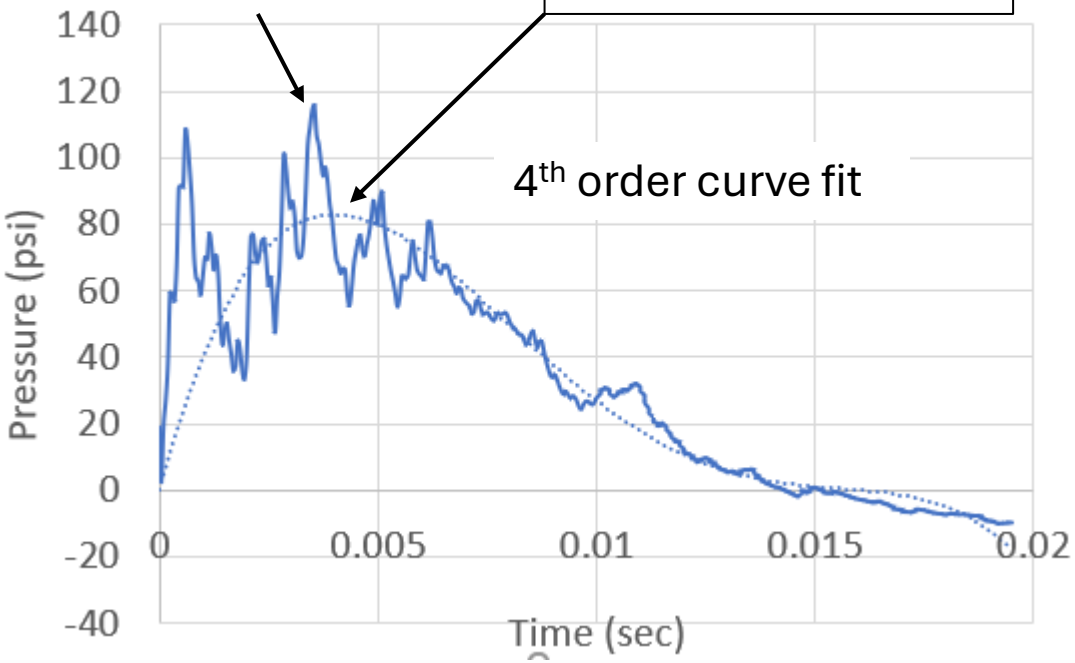
Example of Curve-fit to Net Pressure History = Gas Pressure



No gas pressure for initial 2 msec where blue & green curves very similar

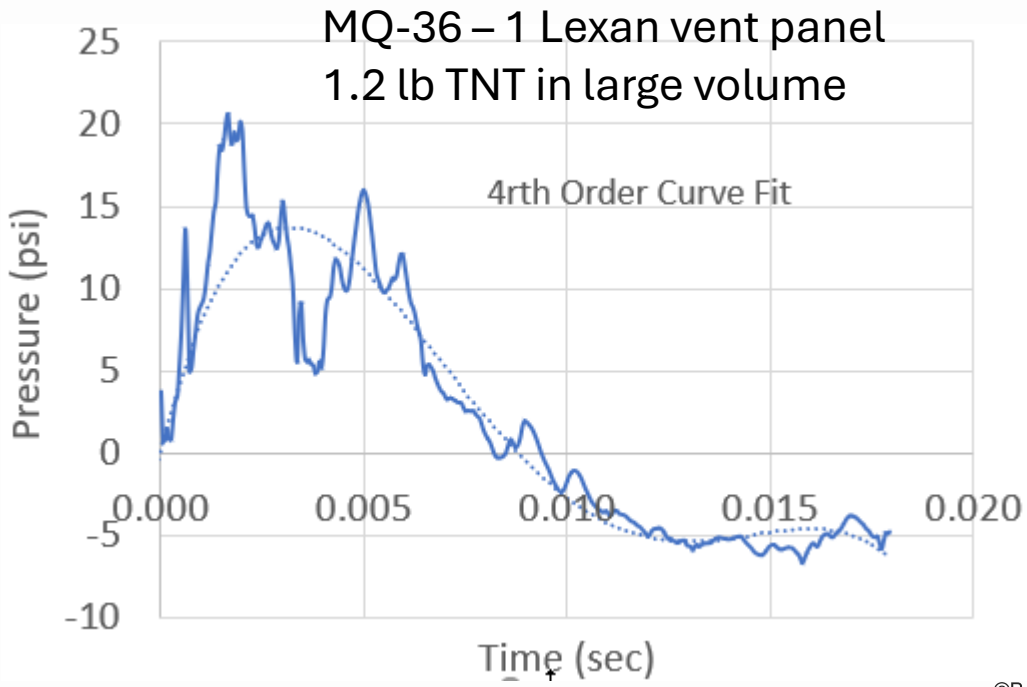
This is same as red curve to the left

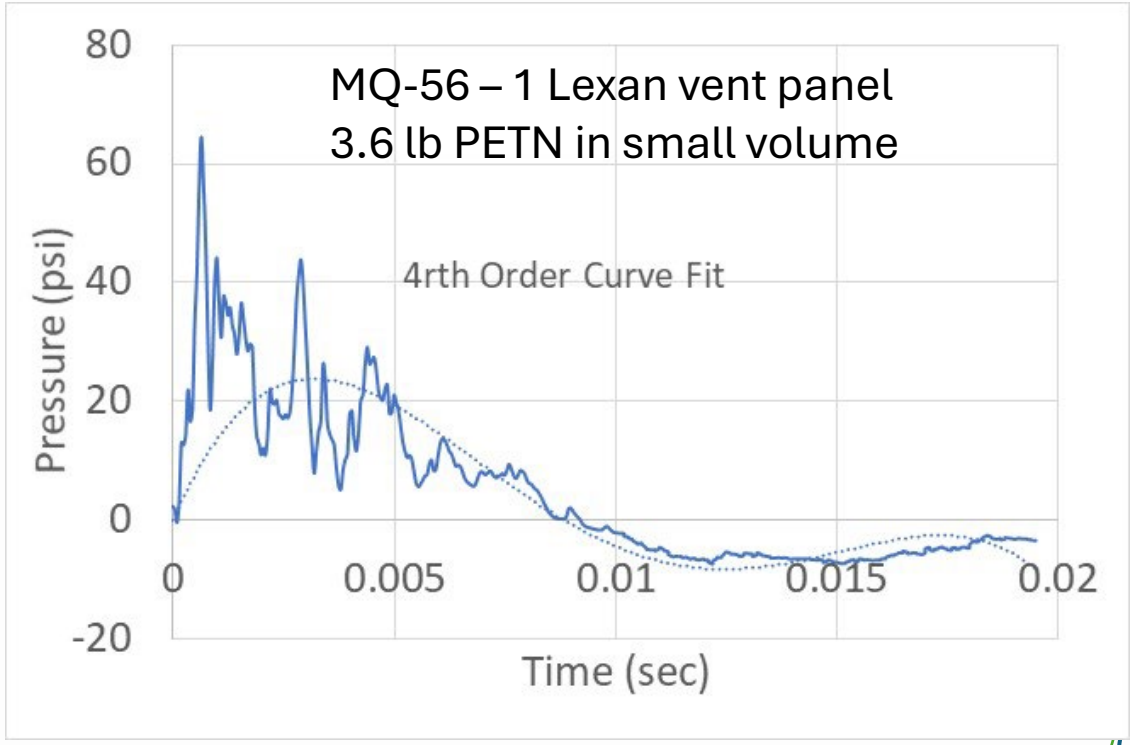
Curve fit = Measured gas pressure history



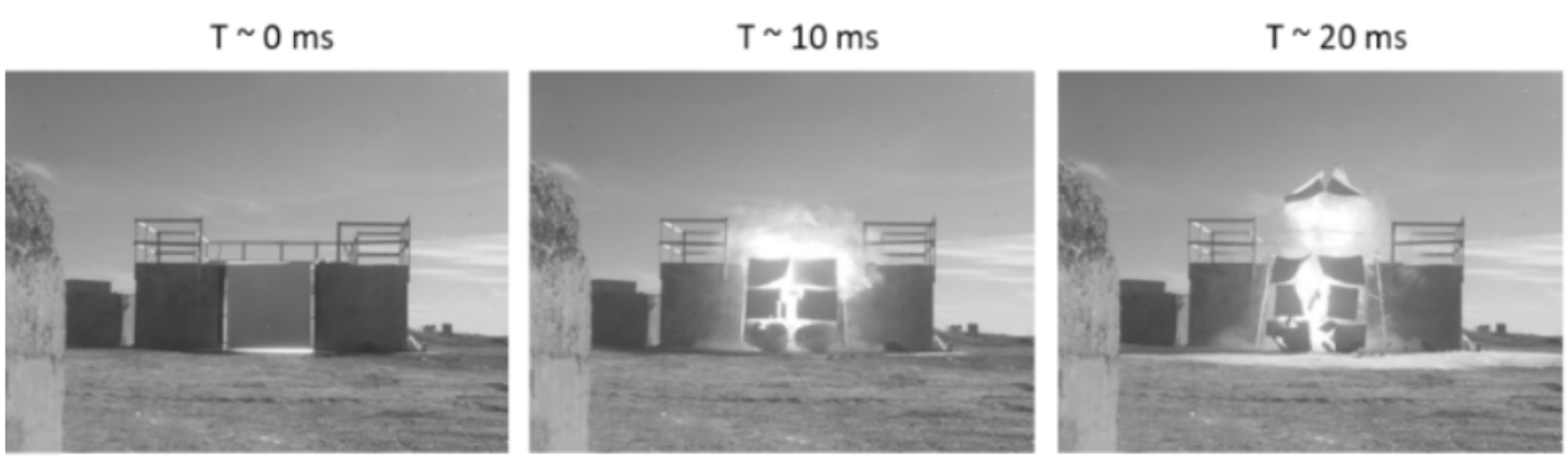
Curve-fits Through Average Measured Net Pressure Histories

- 4th order curve-fits through relevant portion of net gas pressure histories predominantly used to determine measured gas pressure
  - Initial zero net pressure history deleted and curve-fits forced through (0,0) point
  - Measured peak gas pressure and impulse determined from curve-fits



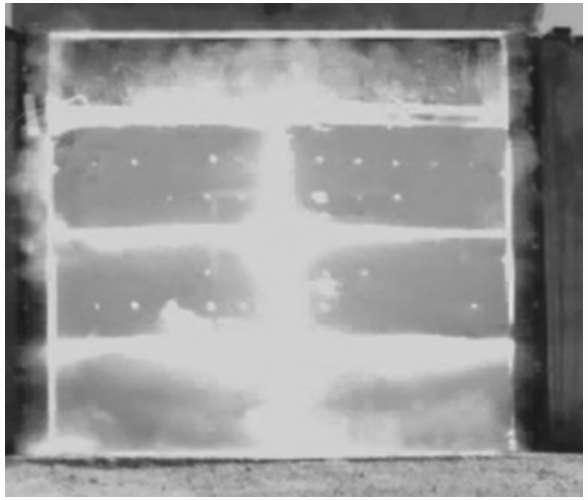


Vent Wall Breakup at Low Loading Density

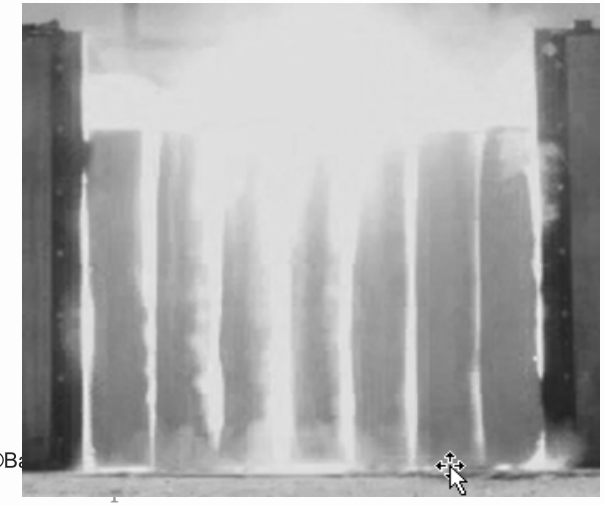


Smallest loading density (0.0052 lb/ft^3) with plywood wall and roof panels

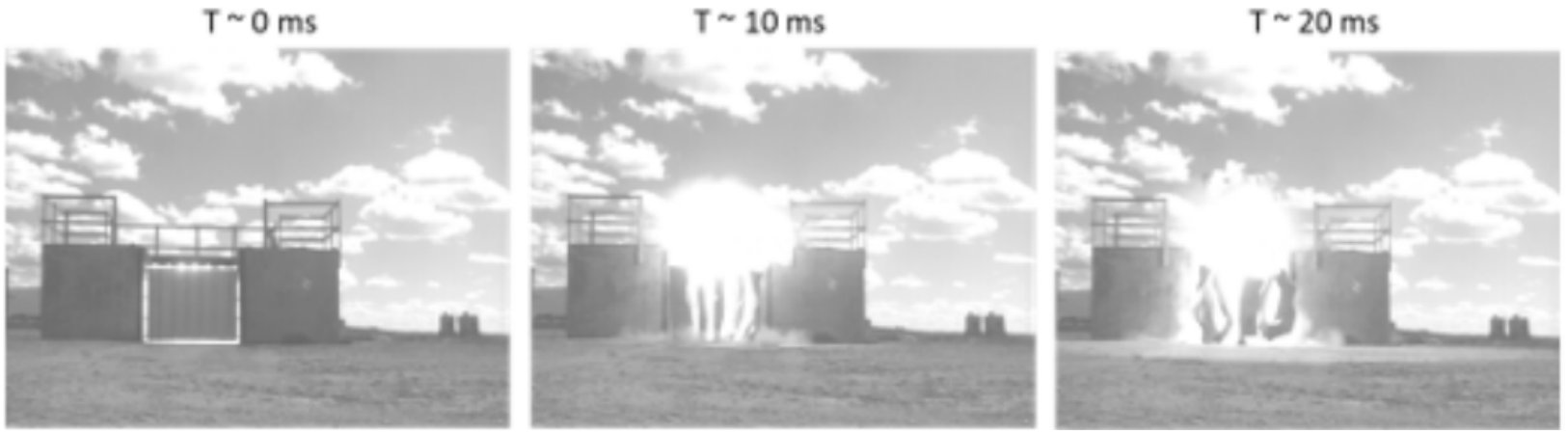
Wood panels supported by wood studs



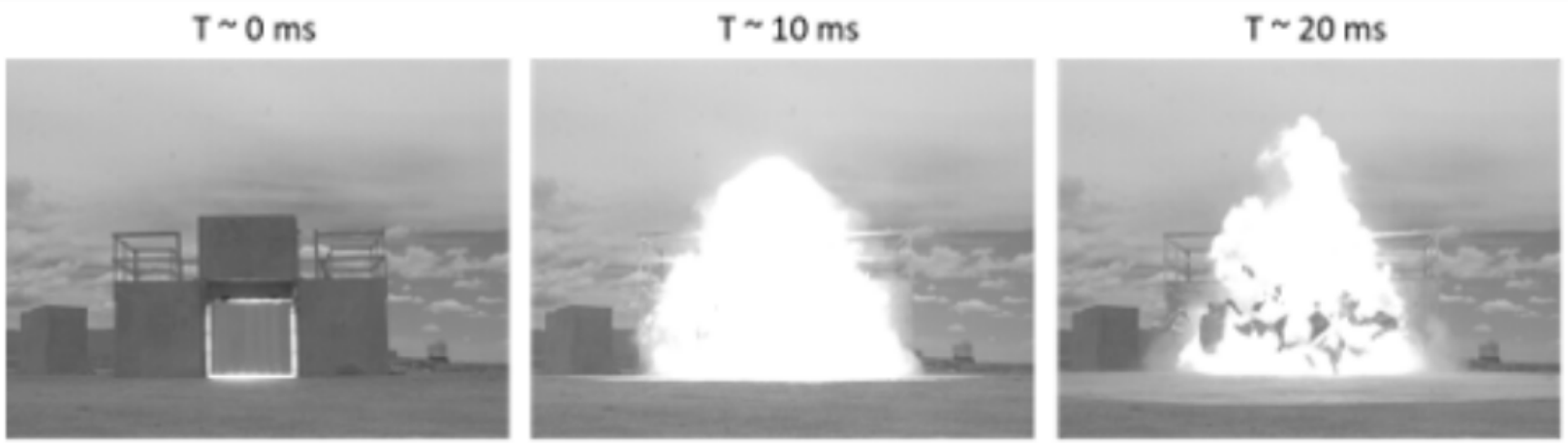
Metal panels



Vent Wall Breakup Increases with Loading Density



Smallest loading density (0.0052 lb/ft^3) with corrugated steel wall and roof panels



Intermediate loading density (0.0155 lb/ft^3) with corrugated steel wall panels

Measured Gas Pressure Test Data

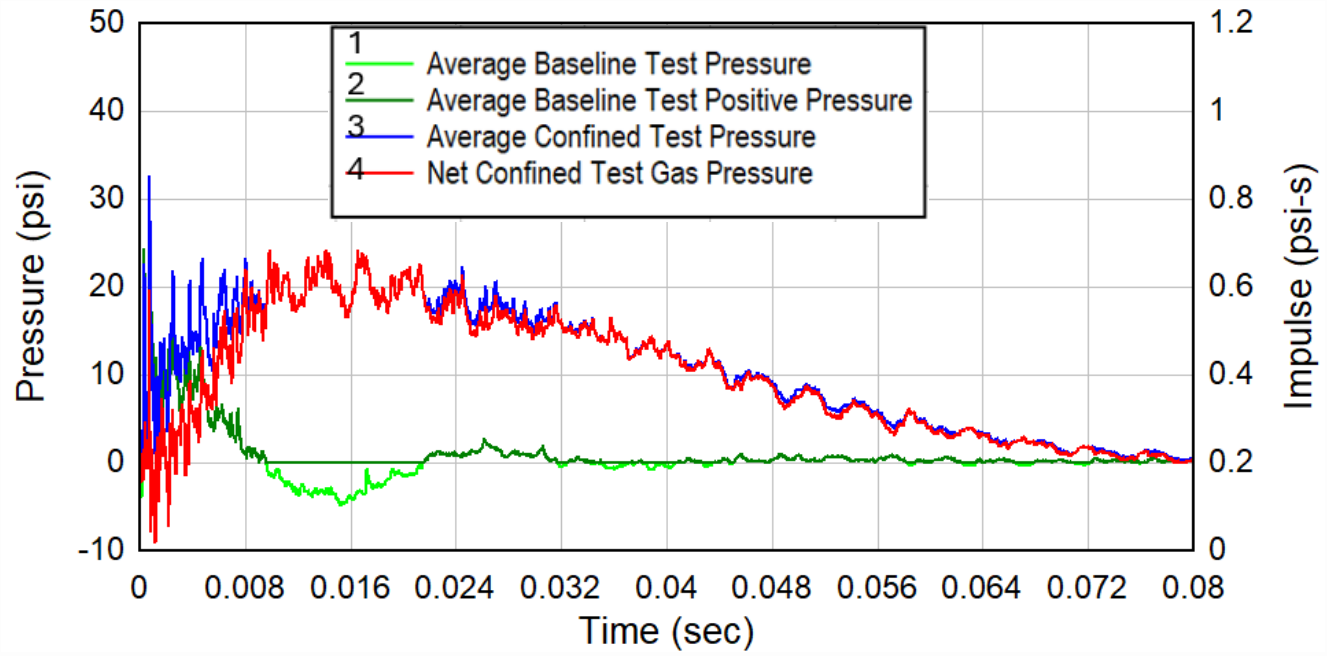
Test	Load Density (lb/ft^3)	Room Volume (ft3)	Vent Panel Area (ft2)	Total Blast Pressure		Quasistatic Pressure (psi-ms)				Maximum Velocity (ft/s)	
				Peak Pressure (psi)	Impulse (psi-ms)	Peak Pressure (psi)	Impulse (psi-ms)	Arrival Time (ms)	Rise Time (ms)	Wall Panel	Roof Panel
10A	0.0052	231	0	173	149						
5A	0.0052	231	80.5	156	408	27	245	2.8	4.5	144	147
6A	0.0052	231	80.5	174	165	6	12			422	380
11A	0.0156	231	0	429	309						
13A	0.0156	231	38.5	421	496	26.5	142	2.4	2.1	775	
15A	0.0156	231	80.5	449	339	27	34			697	732
16	0.0216	231	80.5	526	407						
17	0.0216	231	80.5	570	870	60	395	2.1	3.3	330	331
18	0.0216	231	38.5	592	371	23	24			831	969
19	0.0216	231	38.5	518	535	18	95	2.3	1.9	1300	
20	0.0216	343	49	590	1114	81	630	2.2	4.0	390	
21	0.0142	231	80.5	557	494	20	103	2.8	2.0	993	
22	0.0035	343	0	152	127						
8A	0.0033	343	98	178	147	5	15			385	375
23	0.0035	343	49	134	202	11.2	60	3.4	2.1		437
24	0.0035	343	49	135	212	13	71	3.5	2.4		458
25	0.0147	343	0	513	358						
26	0.0147	343	49	561	485	20	98	2.4	1.9		1163
27	0.0147	343	49	731	532	18	85	2.3	2		1191
33	0.0034	343	0	174	145						
34	0.0032	346.9	98.56	128	124	5	22			338	317
35	0.0033	346.9	49	90	175	11.6	59	3.6	1.6		362
36	0.0034	341	49	72	186	13.7	75	3.6	2.7		242

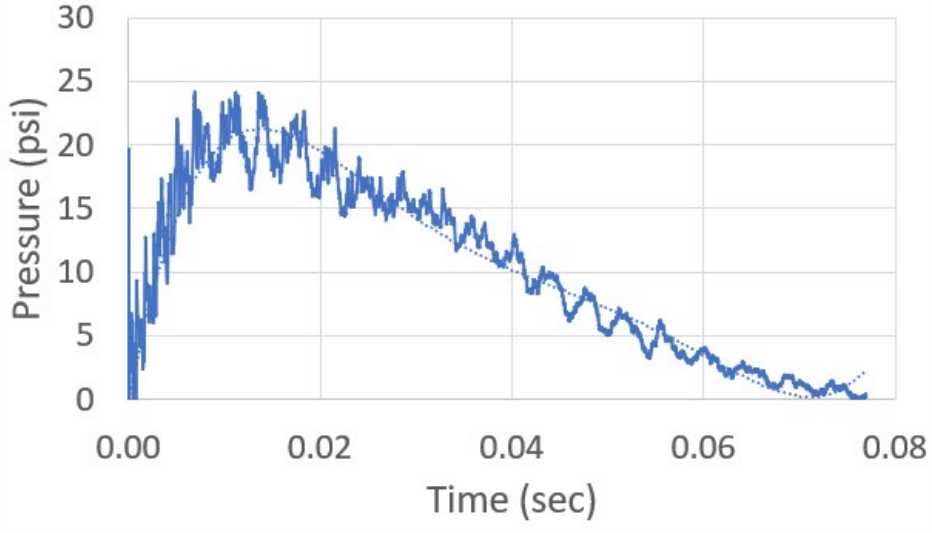
Measured Gas Pressure Test Data (Cont'd)

Test	Load Density (lb/ft^3)	Room Volume (ft3)	Vent Panel Area (ft2)	Total Blast Pressure		Quasistatic Pressure (psi-ms)				Maximum Velocity (ft/s)	
				Peak Pressure (psi)	Impulse (psi-ms)	Peak Pressure (psi)	Impulse (psi-ms)	Arrival Time (ms)	Rise Time (ms)	Wall Panel	Roof Panel
37	0.0113	231	0	238	261						
38	0.0108	236	81.34	253	252	11	12			563	597
39	0.0113	236	81.34	258	272	13	19			443	553
40	0.011	236	39.34	189	349	18	115	2.5	2.8	661	
41	0.0113	231	38.5	275	392	20	111	2.5	2	572	
42	0.0101	338.1	0	314	244						
43	0.0099	338.1	97.3	309	271	15	28			511	646
44	0.0101	338.1	49	320	357	17	94	2.8	1.7		473
45	0.0101	340.1	49	280	338	21	123	2.6	1.9		810
46	0.0035	350.8	0	238	184						
47	0.0033	350.8	99.12	230	146	5	19			422	394
48	0.0035	350.8	50.12	339	244	10.9	54	3.5	3.8	370	
49	0.0035	345	49.28	236	395	22	226	3.3	4.0	152	
50	0.0081	338.1	0	197	175						
51	0.0079	338.1	97.3	471	291	13.4	28			430	438
52	0.0081	338.1	49	262	321	17	85	2.5	2.2		539
53	0.0079	346.9	49	387	338	22	83	2.9	1.6		866
54	0.0156	231	0	376	299						
55	0.0156	231	38.5	842	449	16	80	2.3	2.1	547	
56	0.0156	231	38.5	504	487	23.7	130	2	2.5	570	

Fully Confined Gas Pressure Tests

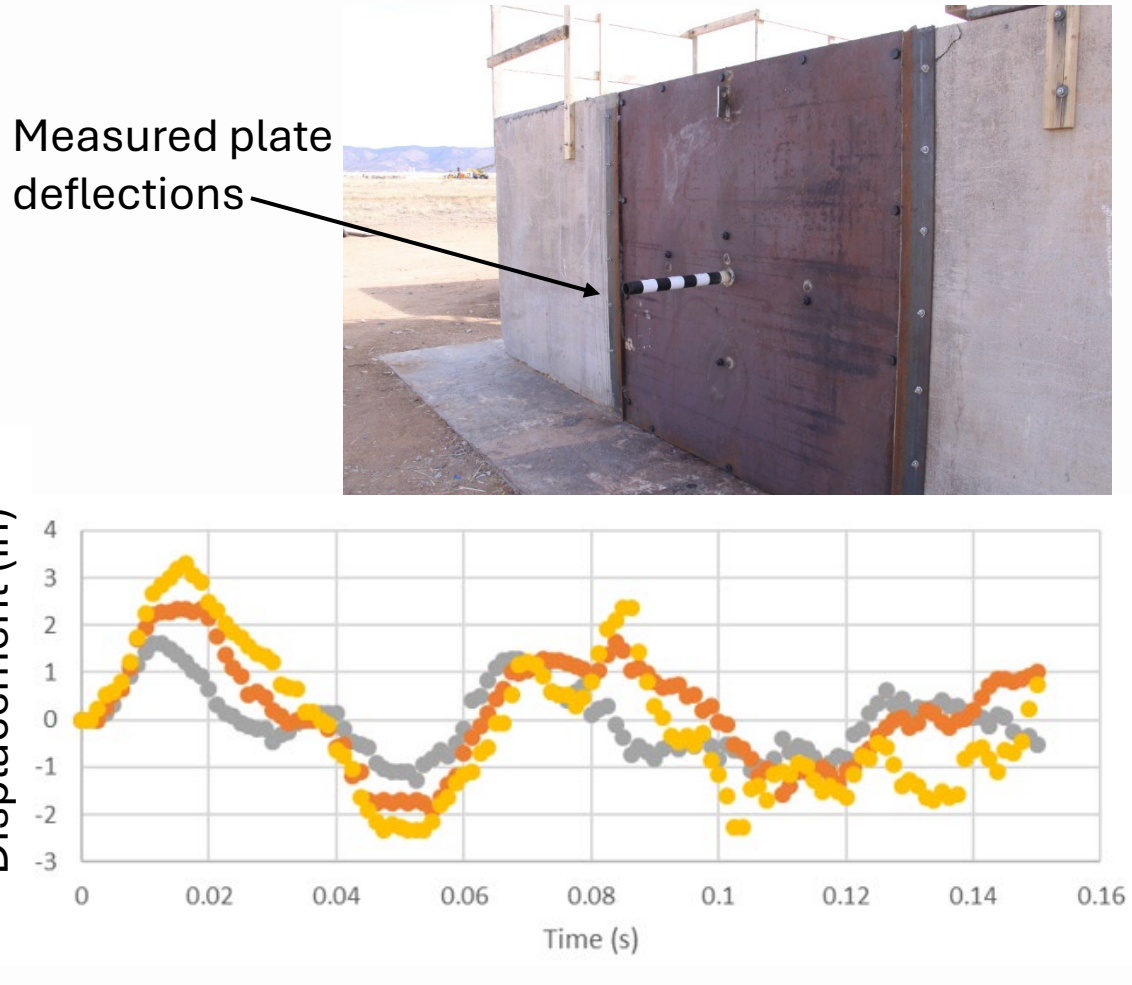
Test	Charge		Room Volume (ft^3)	Loading Density (lb/ft^3)	Uncovered Vent Area (ft^2)	Measured Gas Pressure	
	Weight (lb)	Type				Pieak Pressure (psi)	Impulse (psi-ms)
60	0.25	PETN	160	0.0016	1.48	21.0	788
61	0.5	PETN	159	0.0031	1.41	38.0	1430
62	0.5	PETN	358	0.0014	1.46	12.7	479
66	0.25	TNT	161	0.0016	1.78	17.7	540
67	0.5	TNT	161	0.0031	1.95	30.4	806
68	0.5	TNT	360	0.0014	1.90	15.1	605





Measured Max. Displacements for Steel Plates

- Rigid side of test structure had elastic responding steel plate in some tests
- Heavy gusseted steel angle connections so plate considered 3 side fixed
- SDOF analyses with symmetric measured blast pressures on opposite face of test structure matched measured deflections



Measured Maximum Steel Plate Displacements