UCRL-JC-118313
PREPRINT

Measurements of a 1/4-Scale Model of an Explosives Firing Chamber

John W. Pastrnak
Charles F. Baker
Larry F. Simmons

This paper was prepared for submittal to the
Seventh International Symposium on Interaction of
the Effects of Munitions with Structures
Mannheim, Germany
April 24–28, 1995

January 27, 1995

Lawrence Livermore National Laboratory

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government, nor the University of California, nor any of their employees makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

Measurements of a 1/4-Scale Model of a 60-kg Explosives Firing Chamber

John W. Pastrnak
Charles F. Baker
Larry F. Simmons
Lawrence Livermore National Laboratory
Livermore, CA 94551, USA

Abstract

In anticipation of increasingly stringent environmental regulations, Lawrence Livermore National Laboratory (LLNL) proposes to construct a 60-kg firing chamber to provide blast-effects containment for most of its open-air, high-explosive, firing operations. Even though these operations are within current environmental limits, containment of the blast effects and hazardous debris will further drastically reduce emissions to the environment and minimize the generated hazardous waste.

The major design consideration of such a chamber is its overall structural dynamic response in terms of long-term containment of all blast effects from repeated internal detonations of high explosives. Another concern is how much other portions of the facility outside the firing chamber must be hardened to ensure personnel protection in the event of an accidental detonation while the chamber door is open.

To assess these concerns, a 1/4-scale replica model of the planned contained firing chamber was designed, constructed, and tested with scaled explosive charges ranging from 25 to 125% of the operational explosives limit of 60 kg. From 16 detonations of high explosives, 880 resulting strains, blast pressures, and temperatures within the model were measured to provide information for the final design.

Factors of safety for dynamic yield of the firing chamber structure were calculated and compared to the design criterion of totally elastic response. The rectangular, reinforced-concrete chamber model exhibited a lightly damped vibrational response that placed the structure in alternating cycles of tension and compression. During compression, both the reinforcing steel and the concrete remained elastic. During tension, the reinforcing steel remained elastic, but the concrete elastic limit was exceeded in two areas, the center spans of the ceiling and the north wall, where elastic safety factors as low as 0.66 were obtained, thus indicating that the concrete would be expected to crack in those areas. Indeed, visual post-test inspection of those areas revealed tight cracks in the concrete.

Internal blast pressures averaged 2 to 3 times greater than expected. Quasistatic gas pressures peaked at 18 psig, roughly 86% of the 21 psig predicted by calculation.

Blast overpressures from an accidental detonation scenario ranging from 0.1 to 70 psig were measured during the open-door tests at 22 locations outside the firing chamber model.

These experiments demonstrated that a rectangular, conventionally reinforced, concrete structure can be used as a firing chamber and have validated the conceptual design.

Introduction

This paper is excerpted from a detailed report[1] of the measurements from a 1/4-scale replica model of the firing chamber for the proposed Contained Firing Facility (CFF)[2,3] project at LLNL. The project consists of adding about 2463 m^2 of structural additions to the existing open-air firing facility at Bunker 801, the site of LLNL's existing world-class 17-MeV flash x-ray (FXR) facility. Bunker 801 already contains a variety of high-speed optical and electronic diagnostic equipment, which, together with the FXR, provides a unique diagnostic capability. These additions consist of four components: the firing chamber, a support facility, a diagnostic equipment facility, and an office/conference module, as shown in Figs. 1 and 2.

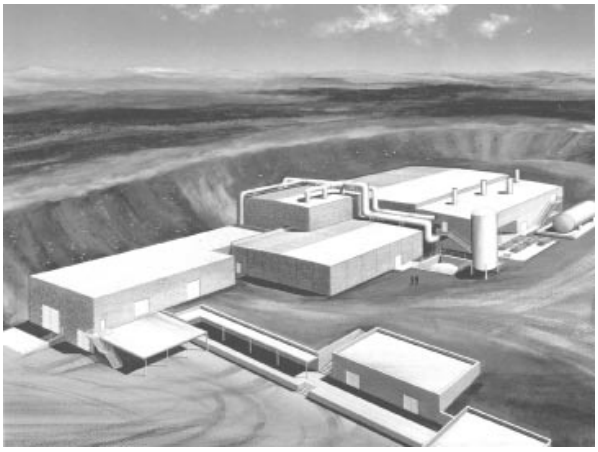

Figure 1. Artist's concept of the CFF.

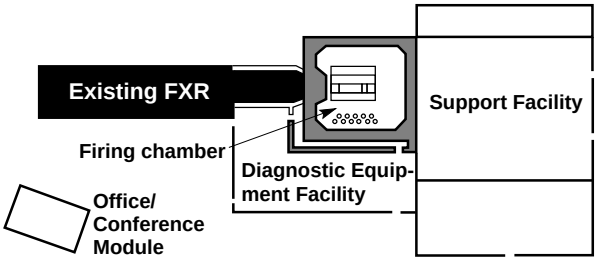

Figure 2. Plan view of the proposed additions to Bunker 801.

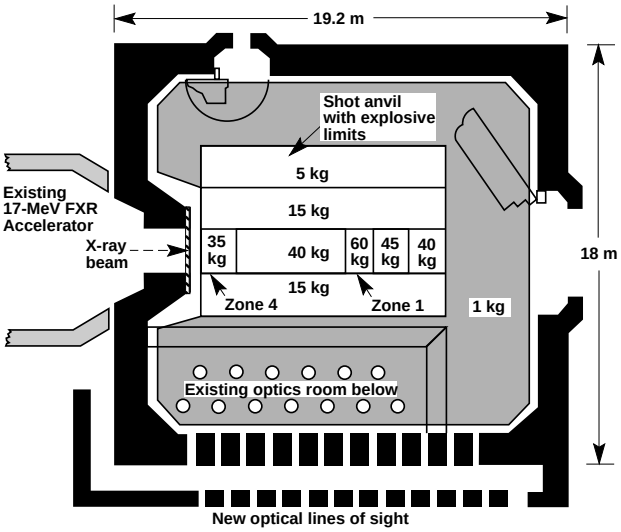

Figure 3. Plan view of the firing chamber, showing explosive quantity zones, with corresponding mass limits.

The heart of the CFF is the firing chamber (see Fig. 3). Slightly larger than half a gymnasium, the firing chamber will contain the blast overpressure and fragmentation effects from detonations of cased explosive charges up to 60 kg. The inside surfaces of the chamber will be protected from high-velocity shrapnel from detonating cased explosives. To permit repetitive firings, all main structural elements of the firing chamber are designed to remain elastic when subjected to blast. Detonations will be conducted above a 150-mm-thick, steel firing surface (the shot anvil) embedded in the floor.

Explosive quantity zones, with capabilities for operational masses up to 60 kg of PBX-9404 (a plastic-bonded explosive containing 94% HMX)[4] are shown in Fig. 3 for detonations at the nominal distance of 1.22 m above the anvil. Separate, general-purpose, removable shielding will protect interior surfaces of the firing chamber from high-velocity fragments. A key aspect of the CFF is that the rectangular firing chamber will be made of low-cost conventional reinforced concrete, as opposed to labor-intensive laced reinforcement, commonly found in many blast-resistant structures. From a materials standpoint, a spherical chamber shape would be more efficient, but a rectangular shape is cheaper, provides easier and more desirable setup and working surfaces, and encompasses existing diagnostic systems. The thickness of the reinforced concrete walls, ceiling, and floor of the chamber are 1.22, 1.37, and 1.83 m, respectively. The locations of existing camera ports and the end of the FXR accelerator (see Fig. 2), all of which must be in the chamber, led to the selection of a chamber area of about 344 m^2, with an interior height of 9.5 m.

Scale Model Testing

It is customary and is good engineering practice to build and test scale models of high-value, blast-resistant structures before the actual full-size structure is constructed. Testing of an instrumented scale model is particularly useful in verifying the preliminary design because it reveals potential construction defects and provides the best estimate of the actual blast loading environment for use in the final design. Recent experience from qualification testing of the contained firing vessels in the High-Explosives Applications Facility (HEAF)[5] at the LLNL main site indicates that, in some regions, the highest measured strains occur after the shock loading has passed and are due primarily to the vibrational modes of the structure that are excited by the detonation. To evaluate the CDR chamber design, an instrumented 1/4-scale replica model of the firing chamber was designed, constructed, instrumented with strain gauges, pressure transducers, and temperature gauges (see Fig. 4).

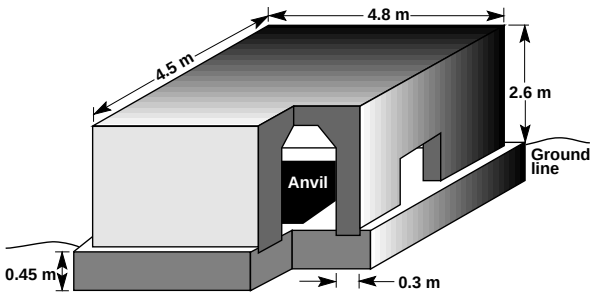

Figure 4. 1/4-scale model of the firing chamber.

Closed- and open-door tests were conducted by detonating high-explosive charges within the model. For the closed-door experiments, the chamber was sealed to measure the normal maximum interior pressures, strains, and temperatures that would be expected on a routine, day-to-day basis (100%) and from certification over-tests[6] at 125%. Blast loadings due to reflections from the ceiling and walls occurred, as did long-term quasistatic gas loading resulting from confinement.

The chamber door was left open during some experiments, and blast pressures were measured that could affect adjacent structures if an accidental detonation occurs while a shot is being set up in the firing chamber. These blast measurements will be used by the architect/engineer (A/E) to assess and design adequate facility hardening (i.e., protection for those personnel who would not be directly involved in the pending explosive experiment, especially personnel in the locker room, the clean diagnostics area, and the small office/conference area).

Experimental Setup

Twelve closed-door and four open-door tests were performed at four scaled levels: 25%, 50%, 100%, and 125% of the CFF operational explosive mass limit of 60 kg of PBX-9404 were performed within the instrumented 1/4-scale chamber model. The charges were all spherical, double, center-detonated, bare C4 explosive, which was used because it was readily available and closely matched the heat of detonation of PBX-9404. For each test, the charge was supported from ceiling hooks by lightweight strings so that the center of the charge was 12 in. above the top surface of the shot anvil. Two charge locations were used to provide the worst-case loading on the 1/4-scale structure. The first and largest charge location was in CDR zone 1 near the center of the anvil (see Fig. 5). This represented the maximum operational charge limit of 60 kg of PBX-9404 and thus provided the worst-case global loading on the structure. The second location, with smaller charge amounts, was in CDR zone 4, near the bullnose, simulating close-in, highly localized loading on the bullnose. Table 1 shows the test matrix.

Table 1. 1/4-scale model testing matrix.[7]

	Amount of C4 (lb)	Max. equiv. TNT (lb)	% operational charge weight	Z_{min} (ft/lb$^{1/3}$)
Closed door	0.30	0.39	25	1.25
	0.52	0.67	25	1.14
	0.52	0.67	25	1.14
	0.60	0.78	50	1.00
	1.03	1.34	50	0.91
	1.03	1.34	50	0.91
	1.21	1.57	100	0.79
	2.07	2.58	100	0.72
	2.07	2.58	100	0.72
	1.51	1.96	125	0.73
	2.58	3.36	125	0.67
	2.58	3.36	125	0.67
Open door	2.07	2.58	100	0.72
	2.07	2.58	100	0.72
	2.07	2.58	100	0.72
	2.07	2.58	100	0.72

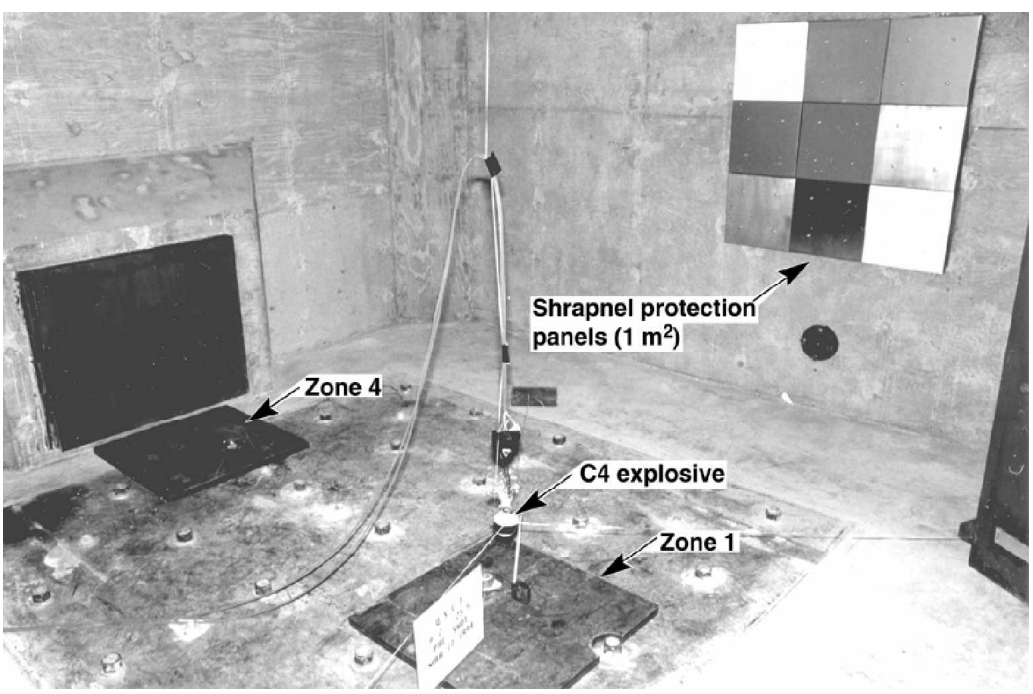

Figure 5. Explosive charge positioned in zone 1 prior to detonation.

Instrumentation

Instrumentation for the 1/4-scale model consisted of 60 channels of strain gauges, thermocouples, and pressure transducers. Strains were measured in the concrete, on the rebar, on the anvil hold-down bolts, and on the bullnose and sealing doors. Five blast and two quasistatic pressure measurements were made at key locations on the inside surfaces of the chamber. For the open-door tests, exterior blast measurements were made. For the closed-door tests, average interior air temperature was measured by using ceiling-mounted thermocouples.

For the four open-door tests, six torpedo ballistic-type pressure transducers were mounted 1.5 ft above ground and generally were positioned by aiming the normal to each transducer diaphragm toward the door opening. External blast pressures were measured at 22 distinct locations and orientations, as shown in Fig. 6.

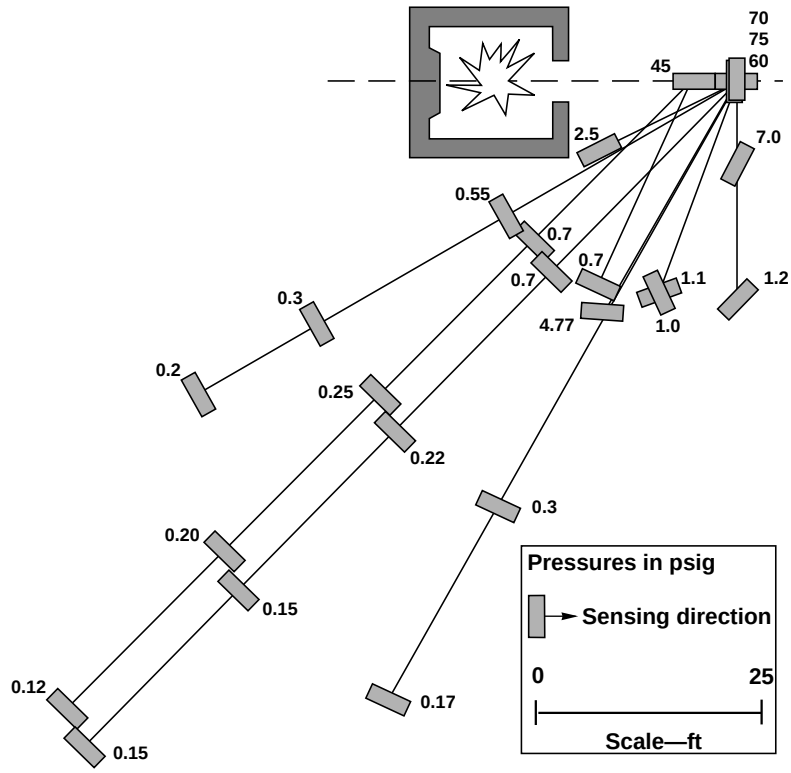

Figure 6. Open-door test pressures map.

Empirical Results

To access and evaluate the original nonyielding criteria, safety factors for tensile and compressive dynamic yielding were calculated. Safety factors less than 1 indicate yielding. Peak internal blast pressures from the closed-door tests are tabulated in Table 2. Peak external blast pressures from the open-door tests are indicated on Fig. 6. Figure 7 shows peak quasistatic pressure as a function of charge weight. Figure 8 (a) contains a typical quasistatic pressure-time plot for a 125% charge in zone 1.

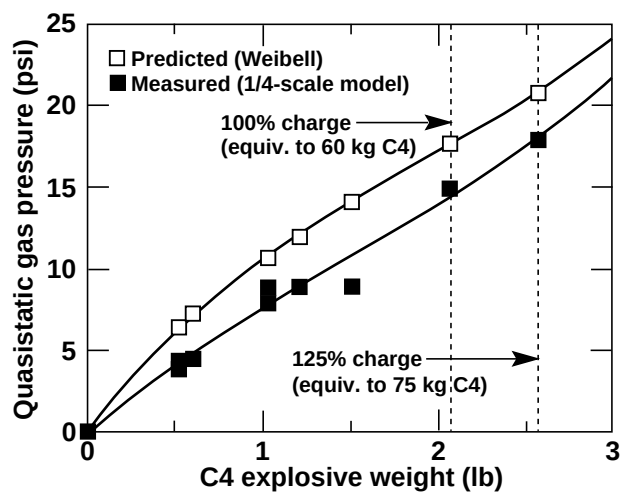

Figure 7. Predicted and measured quasistatic gas pressure for the 1/4-scale model.

Table 2. Measured peak internal blast pressures (psig).

C4 explosive wt (lb)	0.52	0.52	0.3	1.03	1.03	0.6	2.07	2.07	1.21	1.51	2.58	2.58
% of full-scale chg.		25			50			100			125	
Zone	1	1	4	1	1	4	1	1	4	4	1	1
Bullnose	—	—	3612	318	282	1686	550	420	8723	15,322	—	—
Ceiling	—	38	33	—	—	—	77	102	79	94	185	188
North wall, zone 1 shot elev.	—	61	—	211	218	65	1185	305	201	133	445	423
Door	—	64	—	323	707	139	1259	335	100	—	1138	267
South wall, midspan	—	45	15	115	93	51	190	186	76	—	217	230

(—) indicates data not available.

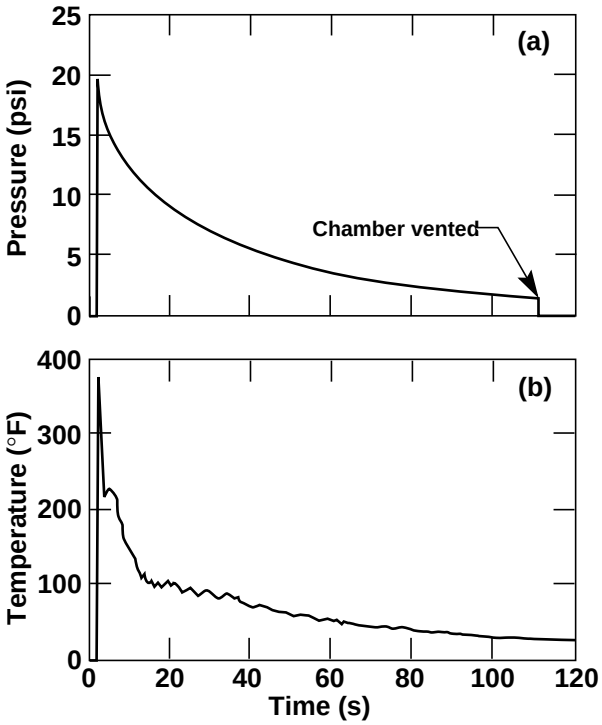

Figure 8. Typical quasistatic pressure and temperature records for 125% charge.

Observations and Conclusions

1. Based on the safety factors for dynamic ***compressive*** yield), no compression problems occur in the steel reinforcing or the concrete. The safety factors calculated from the 100% and 125% testing levels range from 2.6 to 647. The worst case (SF = 2.6) was measured in the concrete at the center of the ceiling near the inside reinforcing mat.

2. Based on the safety factors for dynamic ***tensile*** yield, no tension problems occur in the steel reinforcing. However, the safety factors for dynamic tensile yielding in seven areas of the center spans of the north wall and ceiling are less than 1, especially at the 100% and 125% testing levels, showing that blast-induced cracking of the concrete is likely to initiate in these areas. Because the firing chamber is symmetrical, the following observations for the north wall also apply to the south wall.

At the 100% and 125% testing levels, the vertical strain in the north wall outer concrete center span exceeded dynamic yield four out of six times, giving consistently low safety factors in the range of 0.86 to 0.66. In only one experiment out of the six did the inner concrete gauge in this same area produce an unacceptable SF of 0.96. In the horizontal direction (east-west), the inner

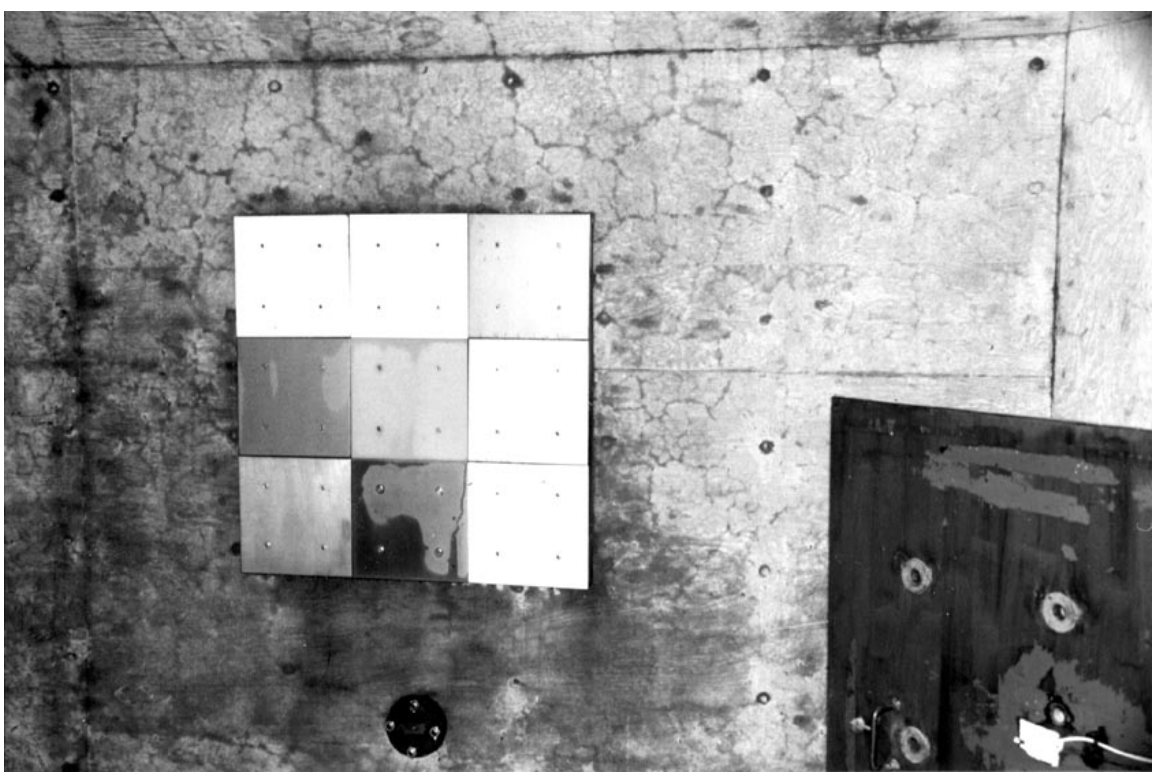

Figure 9. Interior cracks in north wall after 100% charge level experiments.

concrete gauge indicated yielding (SF = 0.93, 0.80) only for the two zone-1 experiments at the 100% level. At the 125% level, these safety factors increased to 1.81 and 1.69 for zone 1.

Similarly low safety factors (0.84, 0.87) also were measured in the upper concrete of the ceiling for the two 100% test levels in zone 1. At the 125% level, the safety factors for the outer concrete increased to 1.32 and 1.24, apparently at the expense of the inner concrete safety factors, which deceased to 0.95 and 0.88. From these observations, it appears that cracking of the ceiling concrete initiated at the outer surface and eventually advanced through the ceiling to the inner surface. To enhance the visual effects of the cracks, the concrete was moistened and photograghed during different stages of drying before the 125% shot levels (see Fig. 9).

4. At the 50% shot level, low tensile safety factors for dynamic yielding (0.91, 0.97) were recorded in the bottom of the concrete floor. This was consistent with results from earlier testing.[8] When a previously developed blast-attenuation system was used for the other 10 experiments above the 50% level, the lowest factor of safety increased to 2.08 for the 125% level.

5. On the basis of the measured strain in a single anvil anchor bolt in zone 1, the number of anchor bolts should be increased. It appears that significant rebounding of the anvil occurs, which induces very high tensile forces and yielding in the anchor bolts. By adding more bolts, thus decreasing the spacing between bolts, the tensile rebound forces are expected to be spread out more uniformly within the concrete below the anvil. The tranfer of these tensile rebound forces into the concrete through an insufficient number of anchor bolts is speculated to cause highly localized yielding, leading to through-thickness cracking, as observed during previous floor section testing.[8]

6. As expected from cracked section concrete design, it appears that tensile yielding (cracking) of the concrete increases the damping of the vibrational response of the structure. This can be seen Fig. 10, which gives a chronology of the vertical strain in the outer concrete of the north wall prior to and during yielding, and also gives evidence of strain relaxation and redistribution by the reduction in the peak strain value from (a) to (b). It is not clear that this cracked section behavior is desirable from a repeated use standpoint, in that it may not be compatible with the original design criterion of infinite-life elastic response. Clearly, the long-term behavior after cracking has not been tested in these experiments, and further study is recommended.

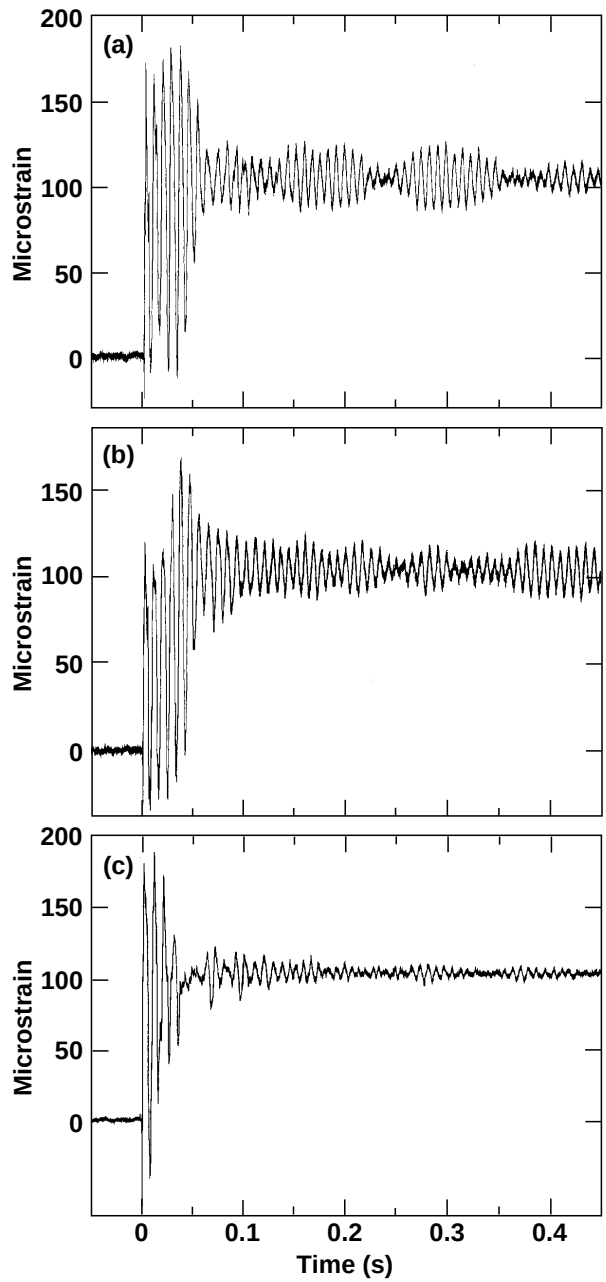

Figure 10. Increase in damping due to suspected cracking of the concrete in the north wall of the chamber (gauge C7): (a) Test 7 (100%), (b) Test 8 (100%), (c) Test 16 (125%).

7. Various high-temperature coatings were applied to the nine mild-steel shrapnel protection plates mounted in the north inside wall of the chamber. These coatings, which were all at a scaled distance of about 4.5 $ft/lb^{1/3}$ from a charge in zone 1, performed equally well and showed no signs of burning from the detonation fireball.

High-temperature paint was applied to the inside surface of the bullnose door, which was at a scaled distance of 0.73 $ft/lb^{1/3}$ from zone 4. Due

to its proximity to the charge, the paint showed some signs of ablation and burning.

9. The measured peak internal blast pressures and those calculated were compared by using the SHOCK[9] computer program at the 100% shot level for detonations in zones 1 and 4. SHOCK was the program used in the CDR to calculate the load pressures and impulses for the chamber design. Table 3 shows the ratio of measured to predicted pressures. For close-in loading at scaled distances less than 1.0 ft/lb$^{1/3}$, the measurements are close to those predicted (85%). In the far-range loading regime, the measurements are on the average 2.8 times higher than predicted by SHOCK. The most likely explanation for this large discrepancy is the use of electrician's tape over the face of the pressure-sensing diaphragm to eliminate the temperature effects from the fireball. The tape may have mass-loaded the sensor and thus changed its effective calibration.

10. Quasistatic gas pressure measured during the experiments tracked the predicted pressures fairly well. Figure 11 shows a reasonable correlation of the peak values for measured quasistatic pressure and temperature vs charge weight. At the 125% shot level, the measured pressure was 18 psig vs 21 psig calculated via the Weibell formula. As expected, the quasistatic pressure due to the hot products of combustion decreases as the gases cool (see Fig. 8).

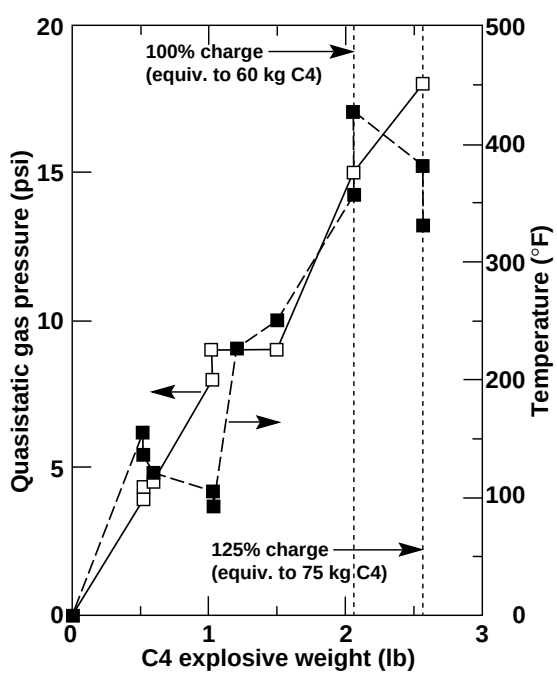

Figure 11. Correlation between peak quasistatic pressure and temperature for the 1/4-scale model.

Table 3. Measured and predicted internal blast pressures for 100% full-scale charge.

	Measured data (psig)		SHOCK prediction (psig)		Ratio of prediction	
	Shot zone		Shot zone		Shot zone	
Location	1	4	1	4	1	4
Bullnose	420	8723	138	10,258	3.04	0.85
Ceiling	102	79	124	34	0.82	2.32
N. wall, zone 1 shot elev.	305	201	138	41	2.21	4.93
Door	335	100	136	21	2.46	4.67
S. wall, midspan	186	76	56	39	3.31	1.93

Acknowledgment

This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

Footnotes and References

1. J. W. Pastrnak, C. F. Baker, and L. F. Simmons, *Empirical Validation of the Conceptual Design of the LLNL 60-kg Contained Firing Facility*,Lawrence Livermore National Laboratory, Livermore, CA, UCRL-ID-119432 (1995).
2. *Site 300 Contained Firing Facilities—Conceptual Design Report*, U.S. Department of Energy Project Number 94-SAN-LLN-02, prepared by Holmes & Narver Architects-Engineers (1992).
3. The design of this facility is governed by DOE requirements and regulations found in DOE 5481.1B, DOE 5430.1A, DOE 6430.1A, DOE/AD-0006/1, DOE/EV-0043, DOE/EV-06194 (*DOE Explosives Safety Manual*), DOE/NEPA, and 10CFR Part 435 (*Energy Conservation Report*).
4. Composition of HMX: octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine.
5. The High-Explosives Application Facility can detonate up to 10 kg of high explosive in stainless-steel firing vessels.
6. *Health & Safety Manual*, Lawrence Livermore National Laboratory, Livermore, CA (1990), chapter 6.26.
7. J. W. Pastrnak, 1/4 Scale Model Project Plan (1993).
8. J. W. Pastrnak, C. F. Baker, and L. F. Simmons, *Quarter Scale Close-in Blast loading Experiments in Support of the Planned Contained Firing Facility*, Lawrence Livermore National Laboratory, UCRL-JC-116822 (1994).
9. SHOCK Users Manual, Naval Civil Engineering Laboratory, Port Hueneme, CA.., Version 1.0 (1988).

Technical Information Department • **Lawrence Livermore National Laboratory**
University of California • Livermore, California 94551