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EXPLOSIVE TESTS OF BLAST CELL, NAVAL TORPEDO STATION, BANGOR ANNEX

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Naval Construction Battalion Center
Port Hueneme, CA 93043

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by J. M. Ferritto

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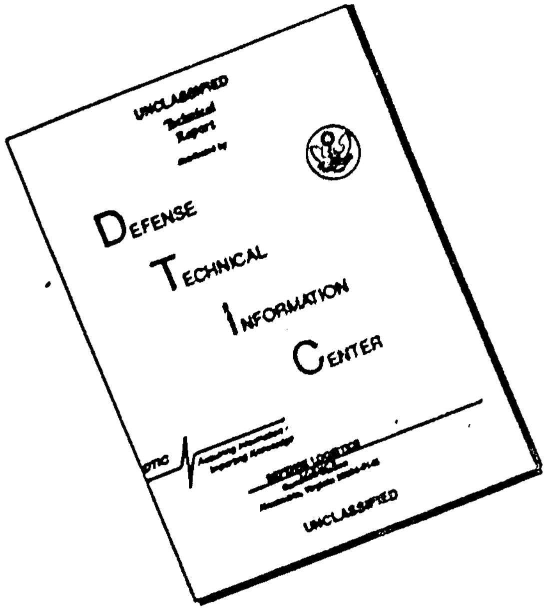

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Blast tests were conducted in blast cells of a typical munitions facility. High-speed camera coverage was made, and pressure measurements were taken. Observed damage was compared with theoretical predictions based on NAVFAC P-397, "Structures to Resist the Effects of Accidental Explosions." The tests indicate that blast pressures will leak out around the blast doors and be of high enough level to cause injury to personnel

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INTRODUCTION

Background

The Department of Defense (DOD) has numerous munitions facilities engaged in the production of the various types of explosives and munitions used by the military services. In most cases the production of ammunition utilizes assembly-line procedures. Projectiles pass through various stages of preparation: filling with explosive, fuzing, marking, and packing. Hazardous operations, such as the filling of the projectile case with explosive in a powder form and the compaction of the powder by hydraulic press, are accomplished in protective cells intended to confine the effects of an accidental explosion. Most of the existing production facilities were built in the 1940's. With few exceptions, the manufacturing technology and existing equipment represent the state-of-the-art as of 1940. The production equipment was operated extensively during World War II, again during the Korean conflict, and recently during the Southeast Asia war. Much of this equipment and the housing structures have been operating beyond their designed capacities [1]. DOD is conducting an ammunition plant modernization program approaching $5 billion with possible expenditures of $500 million a year [2]. The modernization program is intended to greatly enhance safety in the production plants by protective construction, automated processing, and reduction of personnel involved in hazardous operations.

In 1969 a tri-service manual [3] was published to provide guidance to the structural designers of munition plants. The objectives of the manual were to establish design procedures and construction techniques to prevent propagation of explosions from one building, or part of a building, to another; to prevent mass detonations, and to provide protection for personnel and equipment. The manual establishes blast-load parameters required for design of protective structures, provides methods for calculating the dynamic response of concrete walls, and establishes construction details to develop required strength. The design method used accounts for close-in effects of a detonation with its associated high pressures and nonuniformity of loading on protective barriers. A detailed method for assessing the degree of protection afforded by a protective facility did not exist prior to this manual's publication, consequently, the manual represents a significant improvement in design methods. The simplifications made in the development of the design procedures have been presented in the manual. The analysis of a structure using the design procedure will generally result in a conservative estimate of the structure's capacity; therefore, structures designed using these procedures will generally be adequate for blast loads exceeding the assumed load conditions [3]. Certain unknown factors can result in an overestimate of the protective structure's capability to resist the effects of an explosion. These factors (reflections of the shock waves, effects of assumed frangible construction, lack of full shock wave venting, and construction methods) vary for each facility. To compensate for weaknesses resulting from these factors, a recommended increase of 20% is applied to the effective charge weight.

Research is in progress at the Civil Engineering Laboratory (CEL), to determine blast pressures outside the protective cells, the buildup of gas pressure from restricted venting, the effect of frangible construction on pressures within a cell, and explosive equivalency. The results of this research and the research being conducted by other agencies will be added to Reference 3 to continually improve the ability to design a safe facility.

Testing with Full-Scale Structure

Building 30 at the Naval Torpedo Station, Bangor Annex, Washington, was scheduled to be demolished to provide land for new construction. This building contains four blast cells very similar to those existing at many facilities and to those proposed in new construction. Prior to the demolition of the building, CEL was allowed to conduct several tests detonating quantities of explosive in the blast cells. The explosive weights used were on the same order of magnitude as would be expected in medium-caliber projectiles (5-inch) and heavy caliber projectiles (6-inch).

The testing of a full-scale structure afforded an opportunity to observe the structural behavior of the blast cell walls, doors, roof, and structural components. Several accidents have occurred at Naval Ammunition Depot (NAD) facilities in the production of ammunition, however, the damage could not be related to pressures because the explosions were low order and the effective charge weight was unknown. This test provided an opportunity to observe damage from a known high-order detonation and to record pressures associated with it. CEL has conducted test programs to measure the pressures inside and outside of small-scale-model blast cells. The model data can be correlated with the full-scale test data of this test [4 and 5]. The full-scale tests present an advantage in pressure measurement because the effects of interaction of many nonstructural components, such as ceiling and frangible roof, are also shown. This interaction could not be determined in CEL's model tests. Determination of the correct pressure environment behind a blast wall is essential for design of a minimum-cost roof system which will not collapse.

The testing of Building 30 gave an opportunity to assess the design procedure specified in Reference 3 and to identify hazardous areas.

Description of Building 30

Building 30 is a typical munitions building 200 feet long by 50 feet wide, divided into three bays. The north bay contained four reinforced-concrete blast cells (Figures 1, 2, and 3). The walls of the building were constructed of reinforced concrete block and were not load bearing. Steel, wide-flange columns supported steel roof trusses on 20-foot centers. Steel purlins on 4-foot centers spanned the top chords of the roof trusses. Corrugated cement-asbestos roofing sheets 9 feet long were attached to the purlins by bolted clips to form the roof. The pieces of roofing overlapped to prevent leakage of water runoff. Openweb metal joists on 2-foot centers spanned the bottom chords of the roof trusses. Flat cement-asbestos board sheets 4 by 8 feet were clipped to the bottom of the open-web metal joists to form a ceiling. Explosion-proof light fixtures were supported by pipes which were clamped to the purlins and extended through the ceiling.

The cells were constructed as an addition to the building in 1960. They were made of reinforced concrete 24 inches thick with No. 5 reinforcing bars spaced on 10-inch centers on each face of the wall, both horizontally and vertically. The nominal strength of the concrete was rated 3,000 psi at 28 days. Concrete strength was determined to be 6,500 psi by rebound hammer at the time of the test. This is more than twice the design strength but is not uncommon in aged concrete. The cell sidewalls were fixed to the backwall and floor and free on the top and the window side. The backwall extended through the roof. The outer wall of the cell contained a window 6-1/2 by 8 feet, framed in unreinforced masonry concrete block. This is a standard three-wall cell designed to vent through the frangible roof and window in case of an accidental explosion.

In 1972, the cells were upgraded by increasing the backwall height to extend 2 feet above the roof line (see Figure 4). The extension was made to the backwall of all the cells and to the outer sidewalls of Cells 1 and 4. The roof over the cells was raised to the new height. Quarter-inch metal plate was used to divide the cells above the existing concrete sidewalls. An expanded metal grating was used as a debris net to catch falling material in the event of an accidental explosion in an adjacent cell. The grating was tack-welded to angle sections which were bolted to the concrete backwall, welded to the metal plate extensions on the sidewall, and bolted to the concrete-block window wall.

A 1-1/2-inch steel plate, 3 by 6-1/2 feet, suspended by rollers in a track, formed by a wide flange section, served as a blast door. The door was held in place at the bottom by two guides set in the floor. The bearing width of the door on the concrete backwall was 3 inches on the side and 4 inches on the top; no support was provided on the bottom. When the door was closed, approximately 3/8-inch space existed between the door and the backwall on which it was to bear.

A 2- by 3-foot passthrough opening existed in the sidewalls between cells and in the backwall of cell 3. One-inch steel plate supported in brass tracks on each side of the opening were used as doors to close the cell. Bearing width of 1-1/2 inches was provided around the plate.

Partitions between the bays of the building were constructed of reinforced concrete block. A metal fire door was used to separate the bays.

Figure 5 shows selected views of the building before the tests were made.

TEST PROGRAM

Planned Tests

The test program consisted of five 10-pound shots in cell 1 and three 20-pound shots in cell 3. The testing was limited to a maximum charge weight of 20 pounds to minimize noise disturbance to surrounding communities. Predictions of the loading and of the structural behavior were made using the analytical techniques in Reference 3 (see Tables 1, 2, and 3). Visual observation of the damage was correlated with predictions; photographic coverage outside the building and behind the blast cell within the building was provided. Pressure transducers were provided to record the blast pressure.

The charge weight required to cause the blast cell wall to fail with a single detonation was estimated to be about 60 pounds. The cell was not expected to fail with 10- or 20-pound detonations; however, it was expected that sufficient inelastic behavior would occur so that the cell walls would fail by cumulative effects. It was expected that permanent deflection in the blast door could be measured and that the door supports might fail by shearing the concrete. Significant roof damage could occur. The behavior of the debris nets in the cells and the ceiling behind the blast cells was of special interest.

Instrumentation

Twelve channels of pressure data were used to measure the pressure behind the blast cell and in the adjacent cell. Figure 6 shows the location of the instrumentation. Gages were installed to measure the pressure on the outer surface of the roof, above the ceiling, and on the floor. Figure 5 shows the pressure gages installed in gage mounts.

The transducers were connected by cable to amplifiers and a tape recorder located in the south bay. The instrumentation was remotely activated by a switch several hundred feet away. The pressure transducers were manufactured by Bytrex and are specifically designed to measure blast phenomena. They are acceleration resistant, mechanically rugged, and equipped with a heat shield to reduce the effects of thermal radiation. They incorporate semiconductor sensing elements that produce a high electrical output, minimizing system electrical noise. The gages were directly calibrated by static pressurization.

B & F Model 700-SG signal conditioners and B & F Model 702-100-I amplifiers were used in conjunction with a Sangamo Saber 3 tape recorder operated at 120 ips. The electronics had a system capable of flat response to 40 kHz. A Systron-Donner 8150 time code generator provided IRIG-B timing.

Photographic Coverage

Three high-speed cameras were used to provide photographic coverage—two cameras located within the bay containing the blast cells and one outside the building. The camera speeds were calibrated by stroboscope. Figure 2 shows the location of the two cameras in the building. The third camera was located southeast, 200 feet away from the building. All the cameras were remotely controlled by electrical relay.

Explosive

The explosive used was plastic explosive Composition C4, hand-compacted in molds to form spheres. The explosive has a TNT equivalency of 1.19 for pressure and 1.16 for impulse. The charges were electrically detonated by two Engineer Special Number 8 blasting caps placed about 1 inch into the top of the charge. The explosive charge was supported on a stand 3 feet above the ground for all the tests.

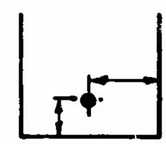
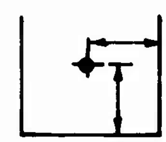
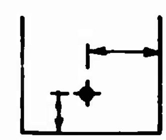
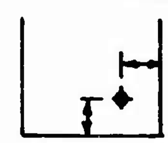
TEST RESULTS

Observed Damage

Shot 1–10 Pounds, Cell 1. Figure 7 gives photographic coverage of the damage caused by shot 1. The

Table 1. Blast Environment Inside Cell, Based on Information in Reference 3

(Plastic explosive Composition C4 used in all shots; only shot 1 had cell roof.)

Shot No.	Parameters	Parameter Values for— Left Wall	Parameter Values for— Back Wall	Parameter Values for— Right Wall	Location of Explosive Charge in Cell
Charge Weight of 10 Pounds					
1	Impulse (psi msec) Pressure (psi) Duration of pressure (msec)	375 129 5.81	495 236 4.20	375 129 5.81	
2, 3, 4, 5	Impulse (psi msec) Pressure (psi) Duration of pressure (msec)	251 107 4.69	369 157 4.69	251 107 4.69	
Charge Weight of 20 Pounds					
6	Impulse (psi msec) Pressure (psi) Duration of pressure (msec)	468 182 5.13	621 335 3.70	468 182 5.13	
7, 8	Impulse (psi msec) Pressure (psi) Duration of pressure (msec)	288 93 6.15	532 188 5.65	410 144 5.65	

explosive was centered between the sidewalls, 2 feet from the backwall. Figure 8 indicates the distance debris was blown from the building. The roof over all the blast cells was blown off. The ceiling of the cell test was blown out. The debris grating in the adjacent cell was still in place although it had become dislodged from its supports. It did catch much of the ceiling blown down; however, the debris grating in cell 3 failed. The debris grating in cell 4 remained and functioned satisfactorily, catching the ceiling blown down.

The 1/4-inch metal plate between cells had been blown over. The unreinforced masonry block framing the window had been blown out in front of cells 1 and 2. The fiberglass windowpanes were blown out whole and did not shatter.

The windows in cells 3 and 4 were blown outward, indicating the pressure spilled over the sidewall across the structure into those cells, rather than out the frangible window wall of the cell and around which would cause the windows to be blown inward. The roof over the pump room adjacent to cell 1 was blown inward; the reinforced masonry block wall of the pump room was deflected outward several inches. The roofing behind the cell had been cracked in places but remained intact. No spalling was observed in this test or any subsequent test.

Table 2. Calculated Resistance Functions, Based on Reference 3

Location	Natural Period (msec)	Ultimate Resistance (psi)	Elastic Deflection (in.)	Stiffness (psi)	Mass (lb-sec^2/in.^{3})	Allowable 2-Degree Deflection (in.)
Sidewall	16.25	20*	0.048	409	2,740	3.77
Backwall	6.34	40*	0.018	3,082	3,138	1.89
Blast door	6.62	270	0.34	780		
Passthrough door	4.5	294	0.31	950		

* Approximate.

Permanent deflections of the sidewalls were measured to be about 3/16 inch outward. No permanent deflection could be measured in the blast door or passthrough door. Window breakage is shown in Figure 9. Figure 10 shows the crack pattern observed in the blast cell walls. The numbers correspond to shot numbers. No evidence was observed of shear failure of the door frame.

Shot 2—10 Pounds, Cell 1. For the second shot the explosive was centered between the sidewalls and between the backwall and window. This shot caused a section of the roofing behind the blast cell to be blown inward (Figure 11). Additional roofing was blown in over the pump room. The passthrough door on the sidewall rebounded off its supports, however, the door on the other side of the wall was still intact. The blast door, although still adequately supported, failed its bottom support guides by outward rebound. Roof failure was noted in the northwest portion of the middle bay. Minor amounts of ceiling were blown down. Figure 10 shows the additional cracking of the cell walls. No measurable additional permanent deflection was noted. The door to the pump room from the main room behind the cells was blown into the building by pressure spilling over the cell wall.

Shot 3—10 Pounds, Cell 1. The explosive was positioned as in shot 2. Roofing was blown off up to almost the ridge line behind the cells. Additional roofing was blown inward in the northeast section of the middle bay. Parts of the ceiling were blown down. The passthrough door on the far side of the sidewall was blown off, leaving an opening into the next cell. The rebound supports of the blast door failed. Cracking of the floor was noted. Figure 12 shows post-shot damage. Figure 10 shows additional cracking to the cell walls; no additional permanent deflection was observed.

Shot 4—10 Pounds, Cell 1. The fourth shot duplicated the position of shot 2. This shot caused additional roof and ceiling damage. Figure 13 shows photographs after the shot. Additional cell-wall cracking is shown in Figure 10.

Shot 5—10 Pounds, Cell 1. The fifth and last shot in cell 1 duplicated the position of shot 2. This shot caused additional roof and ceiling damage. The blast door was still operable although the bottom rebound supports failed. The cell walls did not experience any additional measurable deflections. The cell would still be considered reusable and the amount of damage stabilized such that additional shots of the same size would not cause appreciably more damage to the building.

Shot 6—20 Pounds, Cell 3. The sixth shot was the first shot conducted in cell 3. The 20-pound charge was centered between the sidewalls, 2 feet from the backwall. This shot caused roof and ceiling to be blown down. The frangible window walls of cells 3 and 4 were blown outward. The cell sidewall had a permanent deflection of about 0.5 inch at the top. The passthrough door on the sidewall between cells 3 and 4 rebounded off its supports. The blast

Table 3. Calculated Response, Using the Information From Tables 1 and 2

(Composition C4 plastic explosive used in all tests, single-shot cell capacity is calculated to be 60 pounds.)

Shot No.	Explosive Weight (pounds)	Cell Roof	Location	Calculated Response		Comment
				Maximum Deflection (in.)	Time to Maximum Deflection (msec)	
1	10	Yes	Sidewalls	1.16	20	Shear stress, OK*
			Backwall	0.56	9.56	Shear stress, OK*
			Blast door	0.41	2.9	Shear reaction, OK* Permanent deflection, 0.07 in.
			Passthrough door			Remains elastic Shear reaction, OK*
2, 3 4, 5	10	None	Sidewalls	0.54	13.9	Shear stress, OK*
			Backwall	0.27	7.22	Shear stress, OK*
			Blast door			Remains elastic Supports, OK
			Passthrough door			Remains elastic Supports, OK
6	20	None	Sidewalls	1.85	24.57	Shear stress, OK*
			Backwall	1.13	13.59	Shear stress, OK*
			Blast door	0.65	3.3	Shear reaction, marginally OK Permanent deformation, 0.31 in.
			Passthrough doors Sidewall			At elastic limit Shea[illegible] OK*
			Backwall	0.74		Shear, OK* Maximum permanent deflection, 0.43 in.
7, 8	20	None	Sidewalls, Far side	0.67	15.87	Shear stress, OK*
			Near side	1.38	21.84	Shear stress, OK*
			Backwall	0.73	11.83	Shear stress, OK*
			Blast door			At elastic limit Shear, OK
			Passthrough doors Sidewall			Remains elastic Shear, OK
			Backwall			Remains elastic Shear, OK

* Based on allowable shear stress at supports and distance away from support.

door was still operable. Figure 14 shows photographs after the shot; Figure 15 shows cracks in the cell walls. Window breakage is shown in Figure 16.

Shot 7—20 Pounds, Cell 3. This was the second shot of 20 pounds in cell 3. The charge was positioned 2 feet from the backwall and 2 feet from the sidewall between cells 3 and 2. Some roofing in the middle bay was blown in. Portions of roofing cracked by earlier shots failed. Additional ceiling was blown down; however, most of the roof on the leeward side of the building (east side) was still in place. The blast cell sidewalls had an additional permanent deflection of about 5/32-inch. The passthrough door in the backwall rebounded off its supports. This 2- by 3-foot, 1-inch-thick steel plate has a permanent deformation of ¹ inch at its center. The blast door was still operable with no measurable permanent deflection. The rebound supports failed. Figure 17 shows photographs after the shot.

Shot 8—20 Pounds, Cell 3. This was the last shot in cell 3 and the charge position duplicated shot 7. Additional permanent deflections of 1/16 inch were observed in the sidewalls. Shear cracks were noted around the door frame of the blast door. In one place on the door frame a spall occurred.

Pressure Measurements

Data was reduced and peak pressures obtained. Figures 18 and 19 give the peak pressure on the floor from an average of the 10- and 20-pound tests. This pressure was caused by leakage around the blast door. It is of a high enough level to cause injury. Figure 20 gives the pressure at the ceiling level. Figure 21 gives the pressure on the roof. As noted in Figures 20 and 21, the pressure immediately behind the backwall of the blast cell is higher when the roof is in place over the cell. This is understandable in that the frangible roof remains intact long enough to deflect the pressure wave downward. This would not occur if the roof were not there. Figure 22 shows this. If a roof over the cell does not exist, the shock wave will travel upward, leaving a low-pressure area immediately behind the cell.

Figures 23, 24, and 25 from Reference 5 were "design" predictions which came from CEL model tests. Figures 26, 27, and 28 show this test data with the predictions based on model tests. The increase in pressure behind a cell with a frangible roof was not predicted. This test will be useful in improving the prediction capability. The peak pressures shown in Figures 27 and 28 are predicted very well. The design procedures give a maximum envelope rather than specific values. The low pressure observed in this test is understandable in view of the sloping roof; the predictions were based on a flat roof.

High-Speed Film Coverage

The high-speed film (200 frames per second on cameras inside the building and 64 frames per second outside) were analyzed. The inside cameras showed the fireball and gases leaking aroung the blast door. Figure 29 shows the blast leakage in shot 1 as seen from both camera positions. Figures 30 and 31 show the fireball formation outside the building from 10- and 20-pound detonations, respectively.

DISCUSSION OF TEST RESULTS

As noted above, it was estimated that it would take a 60-pound explosive charge to cause the cell walls to fail in a single shot. The test was limited to a 20-pound maximum. It was planned to cause cell failure by repeated incremental loading. The observed deflections and cracking are much less than those predicted by Reference 3 and as outlined in Table 3. It was expected that some inelastic behavior would occur. The design methods used in Reference 3 rely on the steel reinforcement to provide the only moment capacity. For a rectangular section of width b with the same reinforcement in compression as in tension, the moment is estimated by Equation 5-4 of Reference 3

$$M = \frac{A_s f_s}{b}(d - d')$$

where A_s = area of steel in tension (same as compression steel)

f_s = design stress for reinforcement

d = distance from extreme compression fiber to centroid of tension reinforcement

Table 4. Calculated Response, Using Revised Resistance Statistics

Shot No.	Location	Maximum Dynamic Deflection (in.)
1	Sidewall Backwall	0.2 0.16
2, 3, 4, 5	Sidewall Backwall	0.09 0.08
6	Sidewall Backwall	0.29 0.27
7	Far Sidewall Near Sidewall Backwall	0.10 0.24 0.15

d' = distance from extreme compression fiber to centroid of compression steel

This equation is independent of concrete strength. For large detonations, ultimate strengths have been accurately represented by this equation. Concrete cracking in areas of tensile stress occurs. However, in the relatively low level of loading in this test, failure was not being approached; large-scale cracking and ultimate behavior did not occur. The uncracked concrete load capacity (assuming up to 10% of the compression strength in tension) of the cell walls was 2.4 times the capacity of that from the steel alone. This capacity and its associated stiffness would exist only until the load level was reached to crack the concrete in tension, then the load capacity would revert to that given by the equation. Using the increased capacity of the uncracked wall section, response of the cell walls was calculated (Table 4). These values agree more closely with the observed permanent deflection, assuming very little elastic recovery. However, an important area of difference is shown in Figures 10 and 15; differences exist between the theoretical yield line predicted by analysis and the observed crack pattern.

The blast doors were expected to experience permanent deflection; however, it was assumed that the door would be held rigid against the frame (simple support condition on 3 sides). A space between the door and wall existed; the door underwent rigid body motion in addition to elastic straining. This reduced the effect on the strain energy causing deformation.

The leakage pressure around the blast doors is probably the most serious deficiency noted in the test and affects most existing facilities. Figure 18 shows the pressure levels. Reference 3 gives the following:

Eardrum Rupture

Threshold	5 psi
50%	15 psi

Lung Damage

Threshold	30 to 40 psi
Severe	80 psi

An operator standing behind the backwall would receive threshold lung damage. Personnel in adjacent cells would also receive threshold lung damage.

If one considers the marginal attachment of the debris nets, they performed well. This test shows debris nets will work but must be anchored to substantial objects that will not be dislodged.

Screens used to prevent flying glass must be on the inside of the building, not on the outside as was the case in the middle and south bays of the building.

Reference 3 was conservative in this case; ultimate capacity predictions from a single loading condition were not evaluated. The formation of yield lines was not clearly evident and should be questioned. This is an area where more experimental testing is necessary.

Samples of corrugated cement asbestos roofing and flat cement asbestos ceiling board were brought back to the laboratory for testing. The tests indicated that the roofing when used in continuous spans of 48 inches would have an ultimate resistance of 1.02 psi and a natural period in flexure of 107 msec. This would be expected to fail at about 6-psi overpressure. The ceiling board when used in continuous spans over 24 inches would have an ultimate resistance of 0.835 psi and a natural period of 129 msec. This would be expected to fail at about 5-psi overpressure. The load test and observed damage agree in that Figure 20 shows regions of pressure above 6 psi on the roof; these regions were observed as having the most roof damage.

CONCLUSIONS

1. The high pressures leaking out around the blast doors would injure an operator in the vicinity of the door. Proper seals must be used to protect personnel in the area immediately behind the doors.

2. Debris screens must be attached to substantial structural members which will remain in place.

3. The formation of yield lines used as the basis of the calculation of wall capacity should be investigated. The computation of wall stiffness should also be reviewed. Both of these areas can significantly influence the behavior of a wall, as noted in this test.

4. Conventional corrugated cement asbestos roofing can withstand up to 6-psi dynamic overpressure with only minor damage.

5. Areas of conventional construction adjacent to blast cells can survive reasonably well.

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2. Arthur Mendolia. 'A new approach to explosives safety," paper presented at the Fifteenth Explosive Safety Seminar. Department of Defense Explosive Safety Board, San Francisco, CA, Sep 1973.

3. Departments of the Army, Navy, and Air Force. TM5-1300, NAVFAC P-397, and AFM 88-22: Structures to resist the effects of accidental explosions. Washington, DC, Jun 1969.

4. Naval Civil Engineering Laboratory. Technical Report R-780: Determination of blast leakage pressures and fragment velocity for fully vented and partially vented protective cubicles, by J. M. Ferritto. Port Hueneme, CA, Nov 1972.

5. Civil Engineering Laboratory. Technical Report: Blast environment from fully and partially vented explosions in cubicles, by W. A. Keenan and J. E. Tancreto. Port Hueneme, CA. (To be published.)

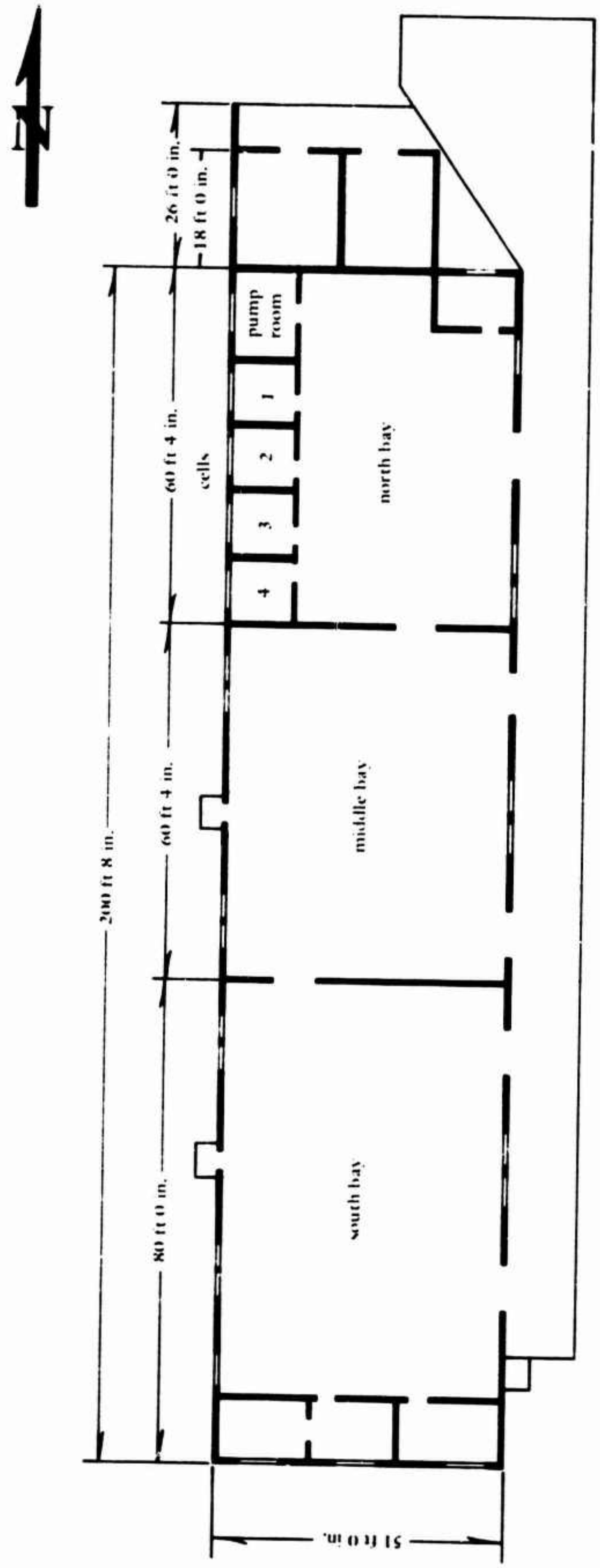


Figure 1. Plan of Building 30. Descriptions of cells 1 through 4 are found in Figure 2.

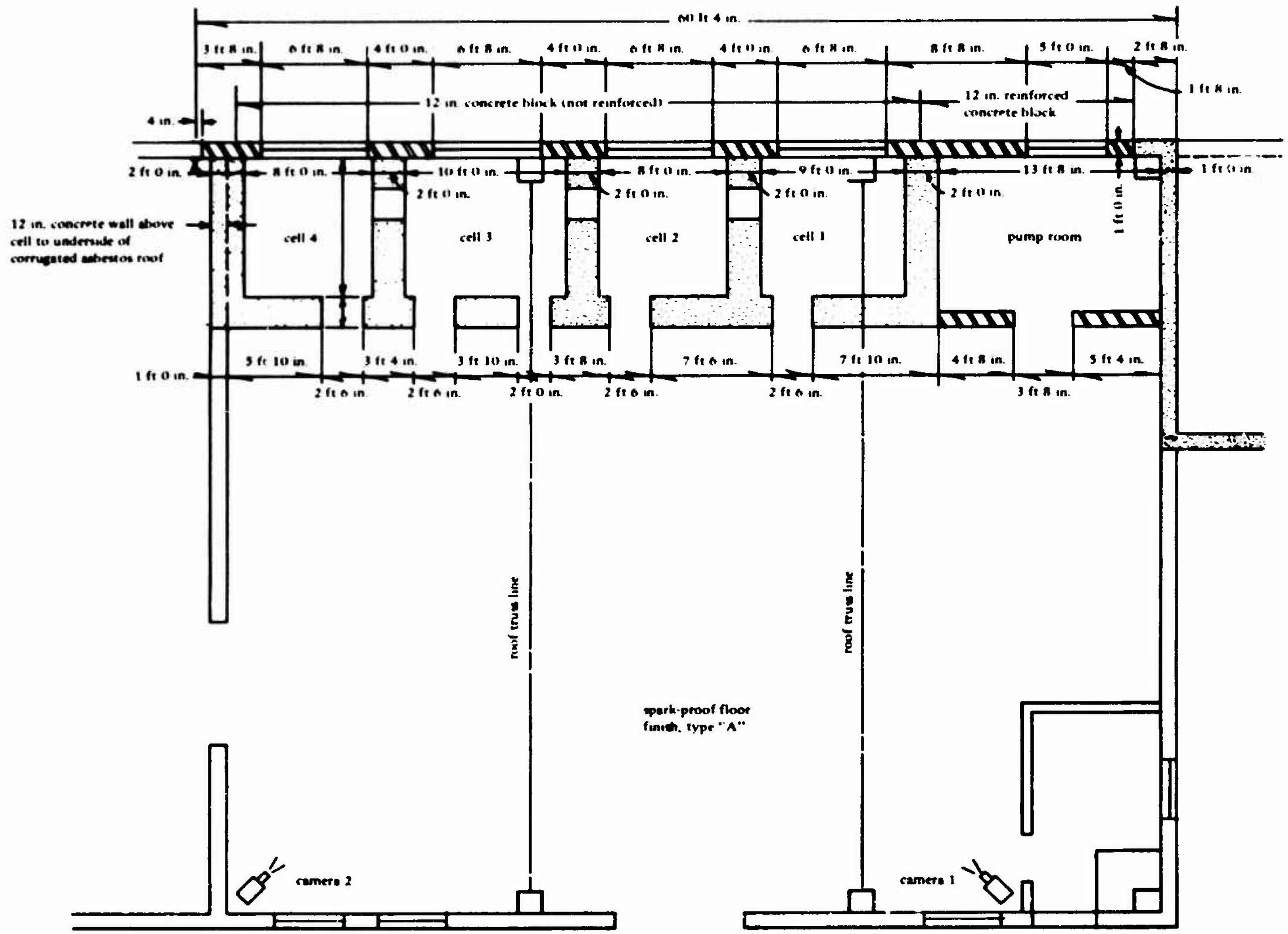


Figure 2. Floor plan of north bay portion of Building 30.

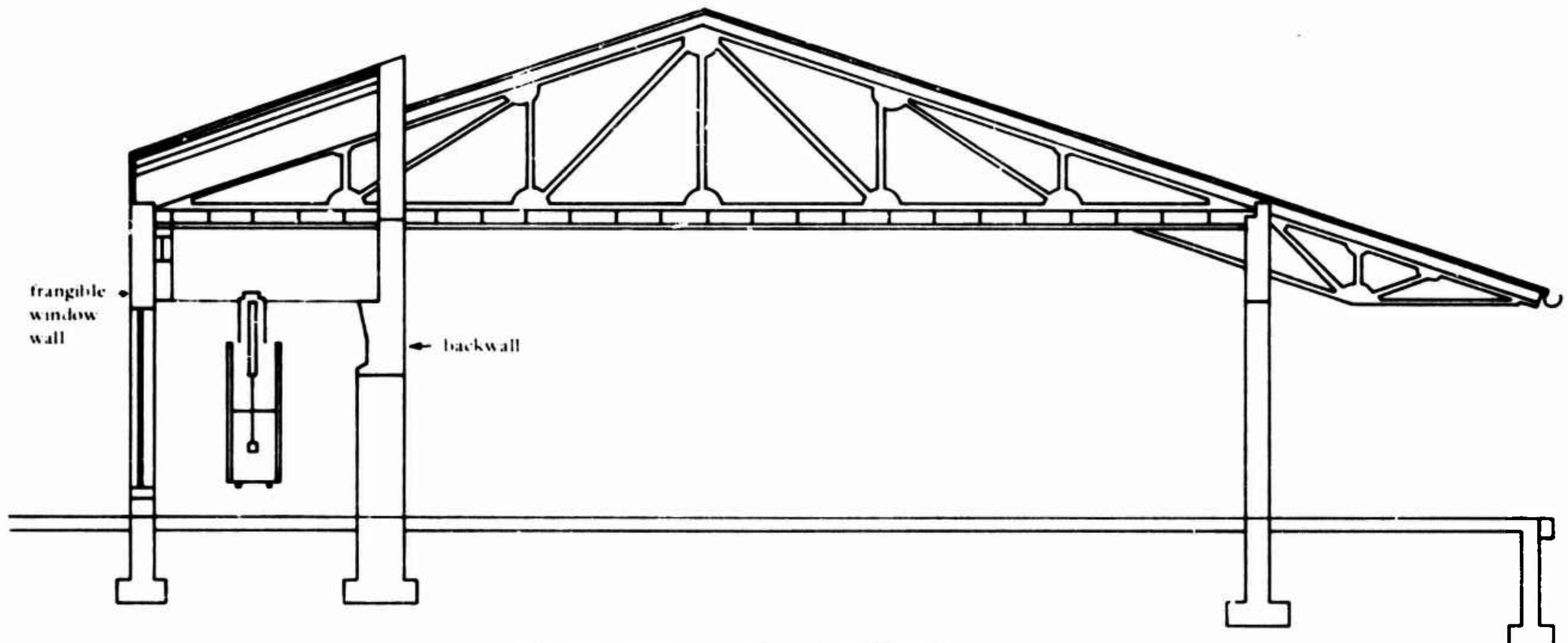


Figure 3. Section view through Building 30.

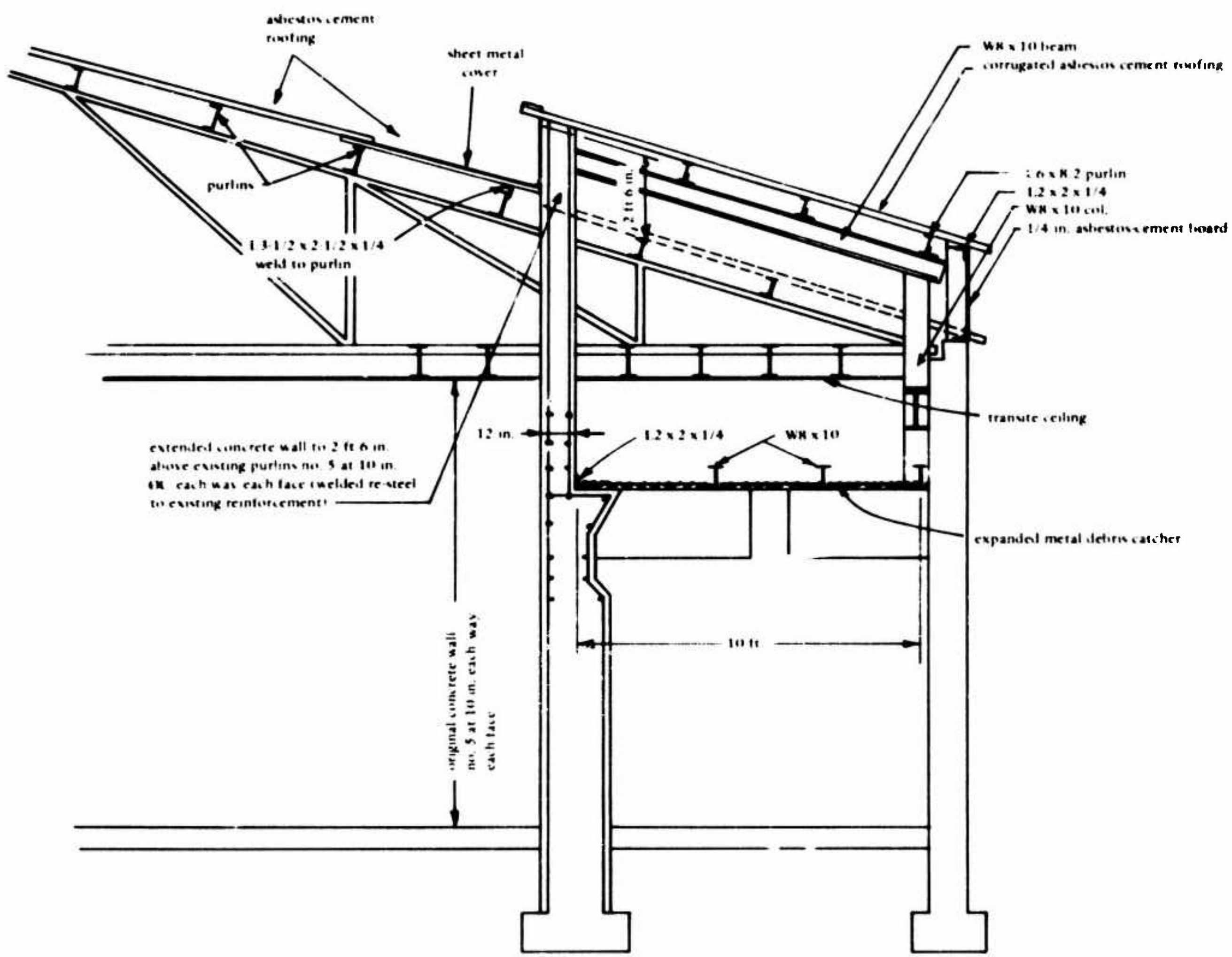
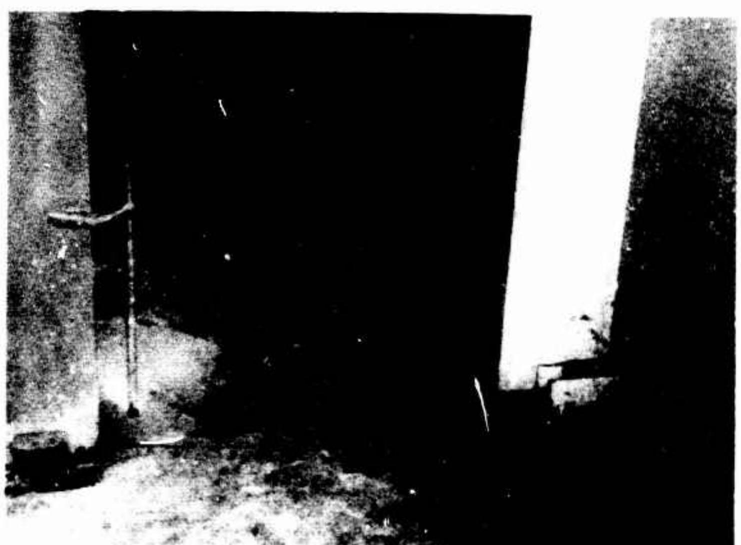


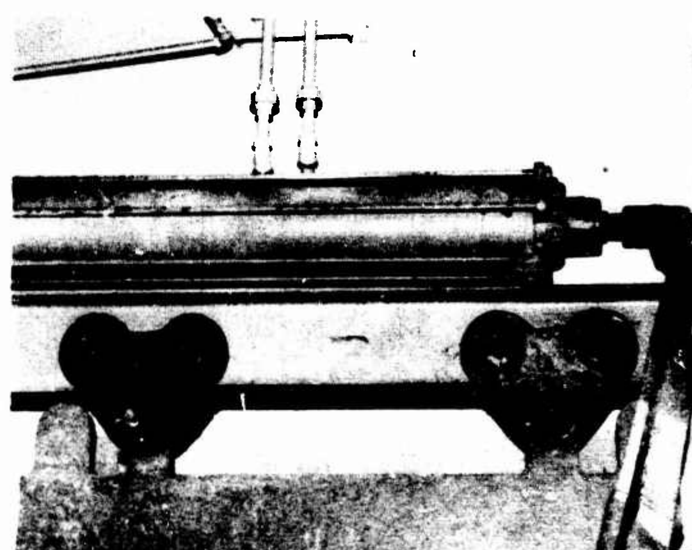
Figure 4. Section view through a cell in Building 30.

Exterior of building looking south.

Exterior of building looking north.

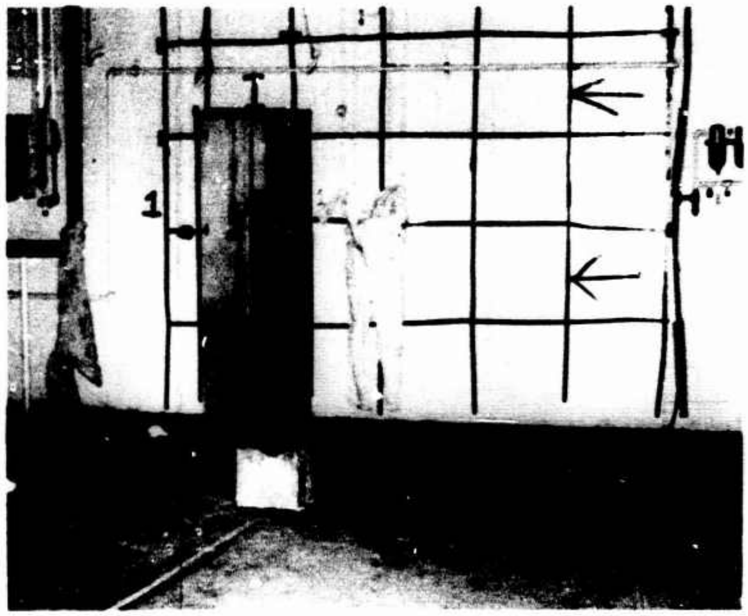


Restraint at bottom of blast door.

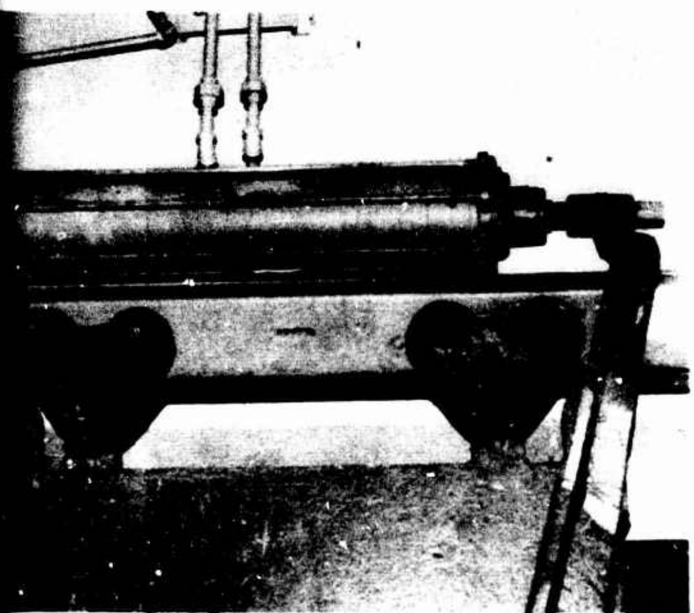


Door track and hydraulic closing ram.

Exterior of building looking north.



Testcell 1 and pressure transducer.



Door track and hydraulic closing ram.

Figure 5. Variety of views of Building 30 before the tests.

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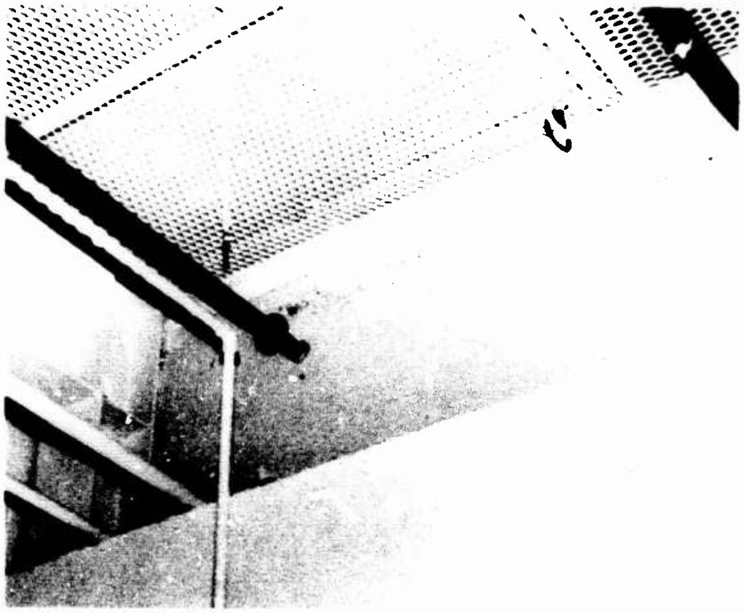
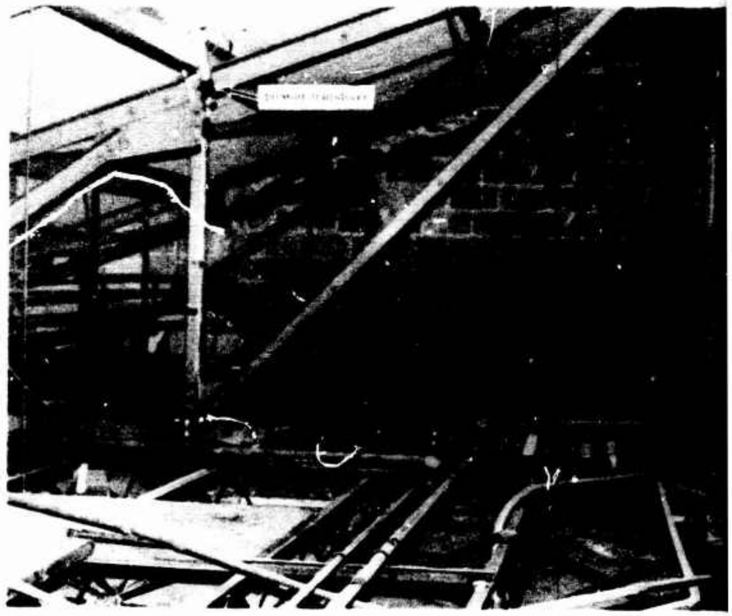
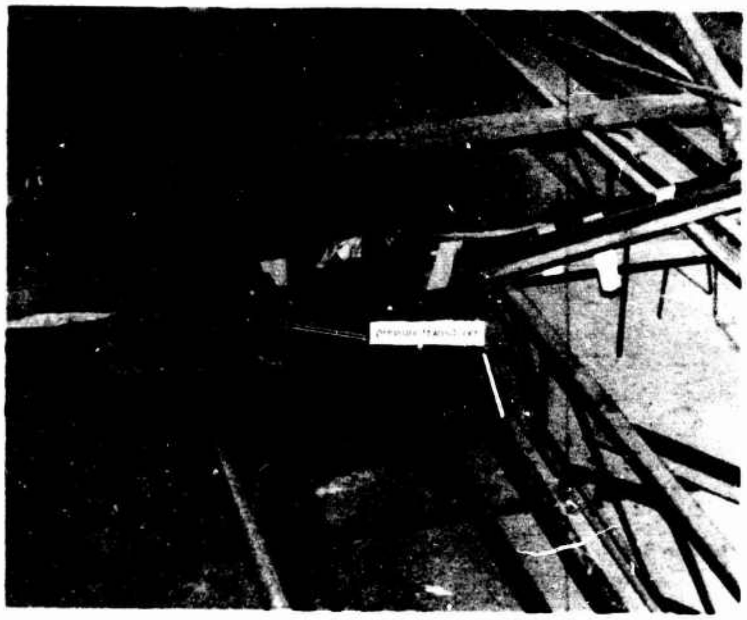


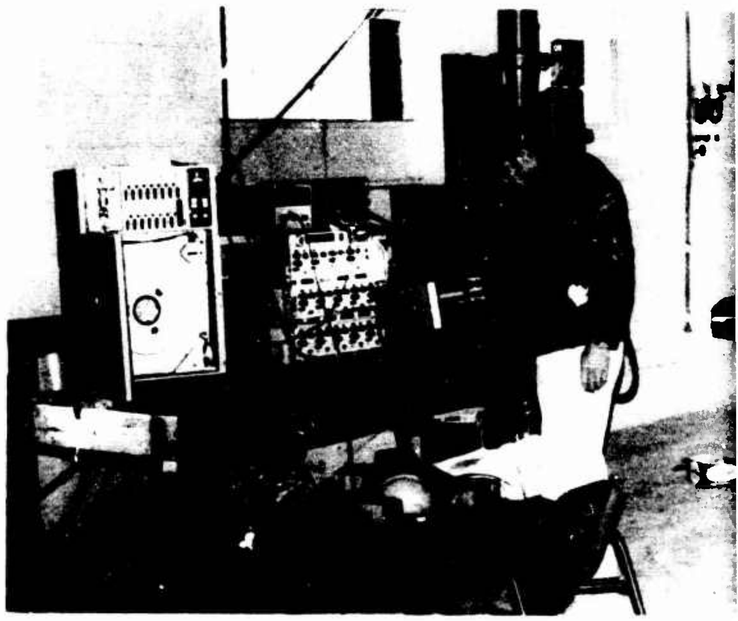
Debris net in blast cell.



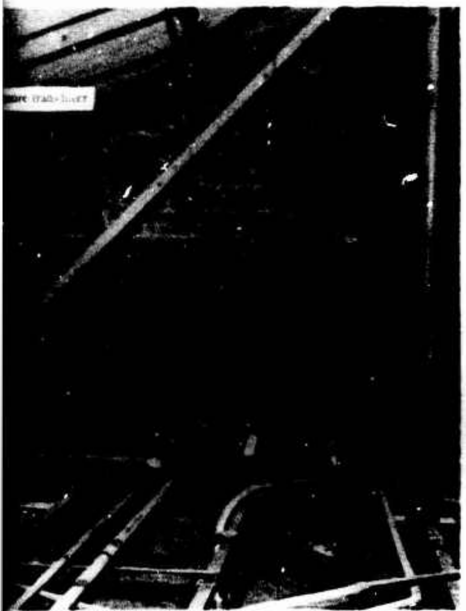
West side of interior of roof.



View of pressure transducer.



Instrumentation in south bay.



ide of interior of roof.

East side of interior of roof.

tation in south bay.

Figure 5 (cont).

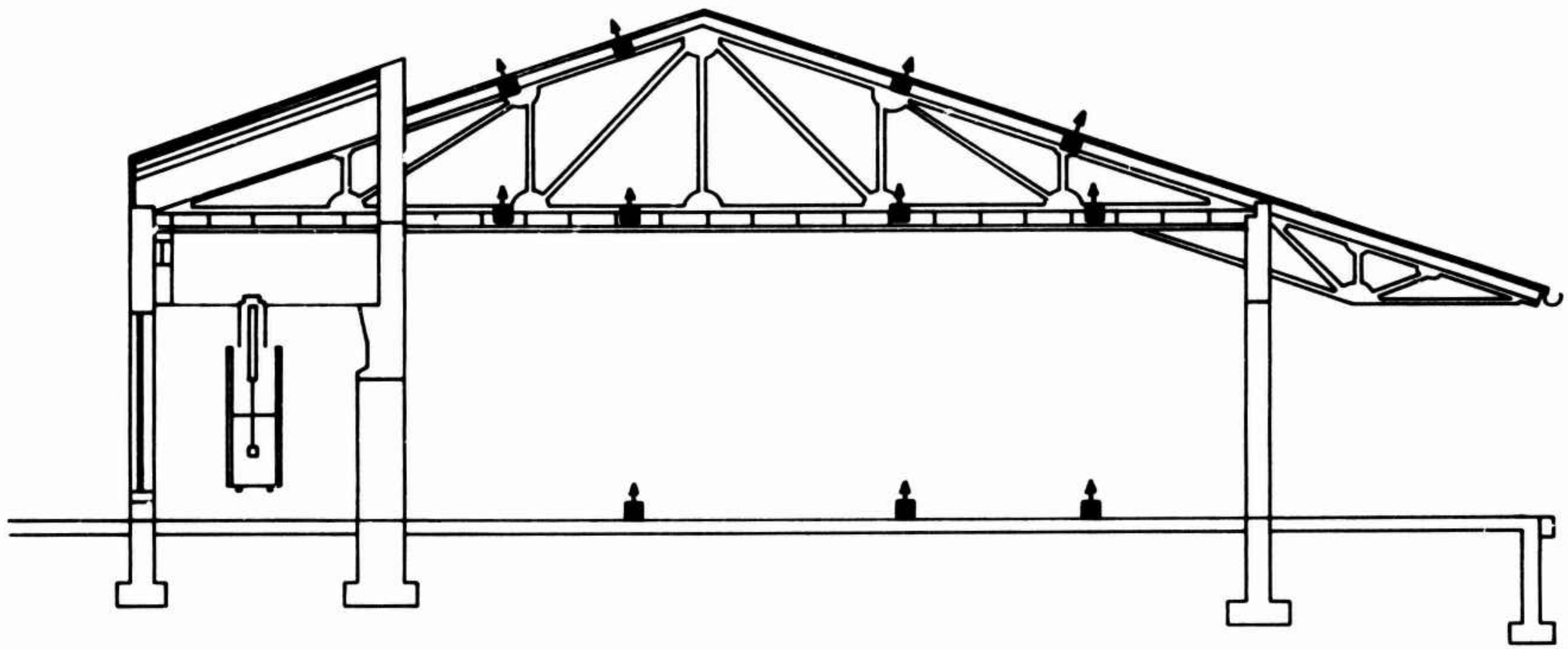
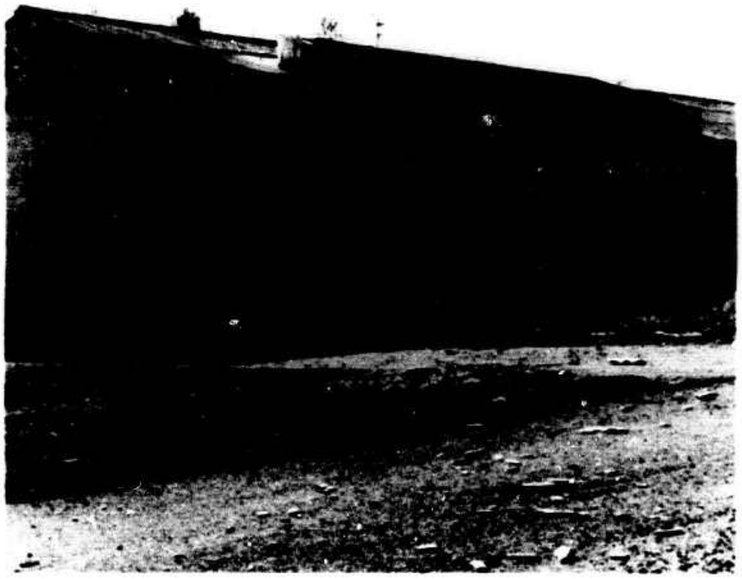
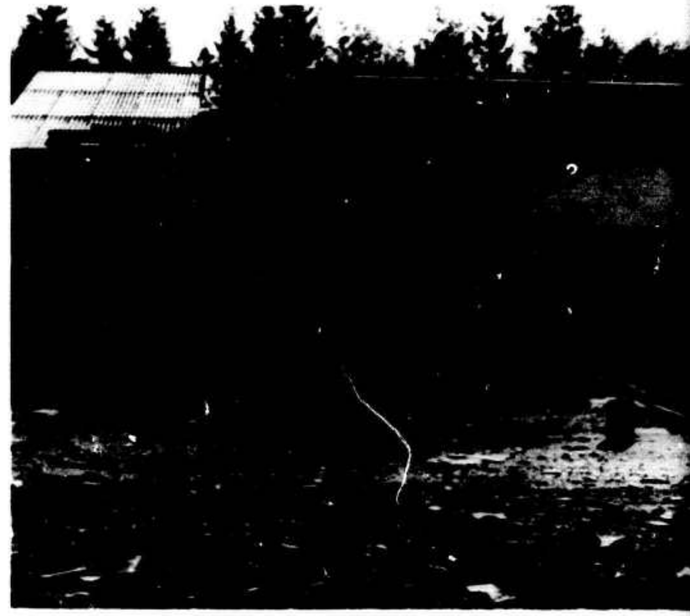


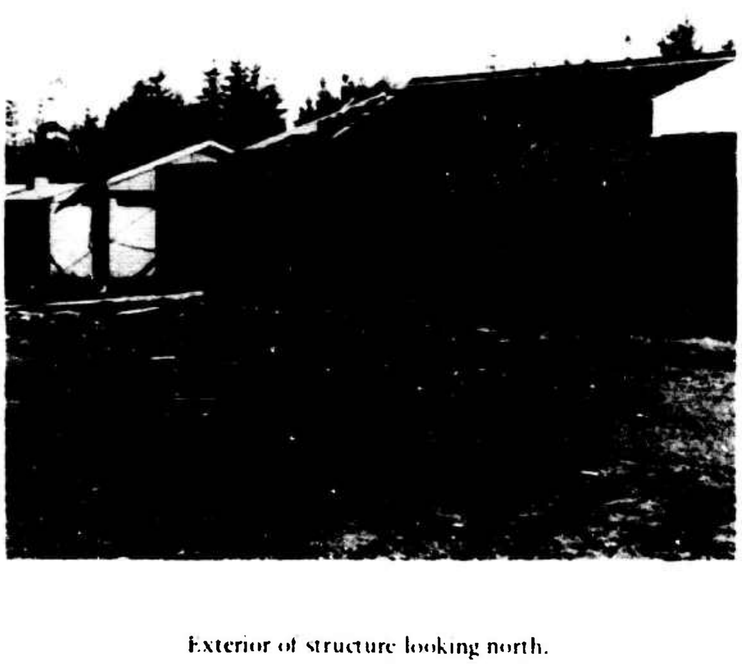
Figure 6. Location and direction of pressure transducers.



Exterior of structure looking south.



Exterior of structure looking east.



Exterior of structure looking north.

Exterior cell 1.

ucture looking east.

Close-up of exterior.

ior cell 1.

Figure 7. Observed damage after shot 1.

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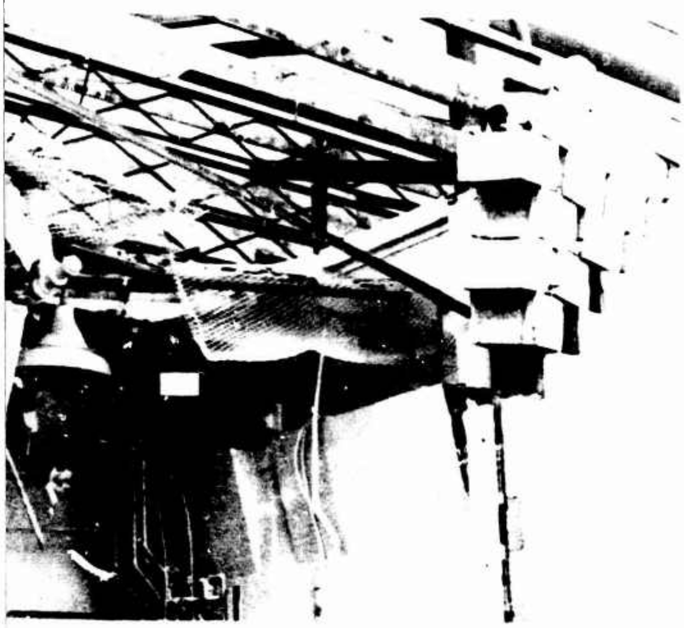
Exterior view of movement of exterior wall.

View of interior of cell 3.

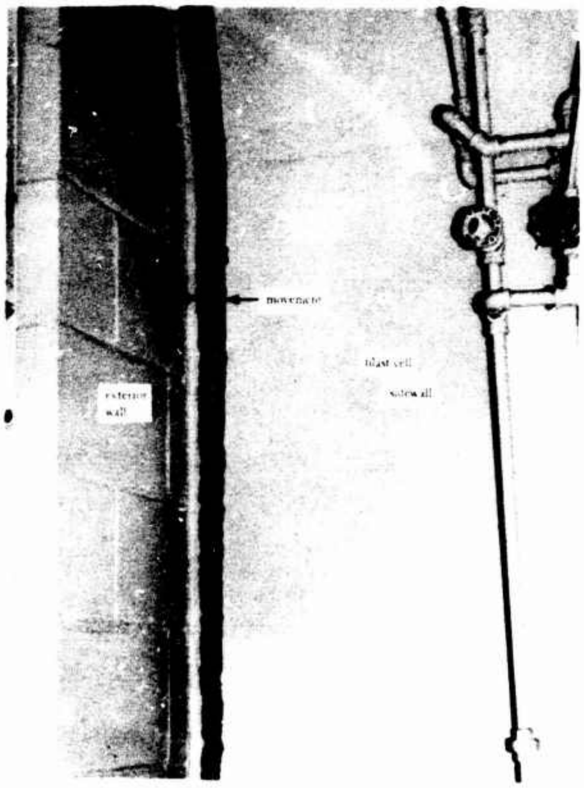


Exterior of cell 2.

Debris net in cell 3.

Figure 7 (cont).

View of interior of cell 3.



Interior view of exterior wall movement.

Debris net in cell 3.

Debris net in cell 3.

Figure 7 (cont).

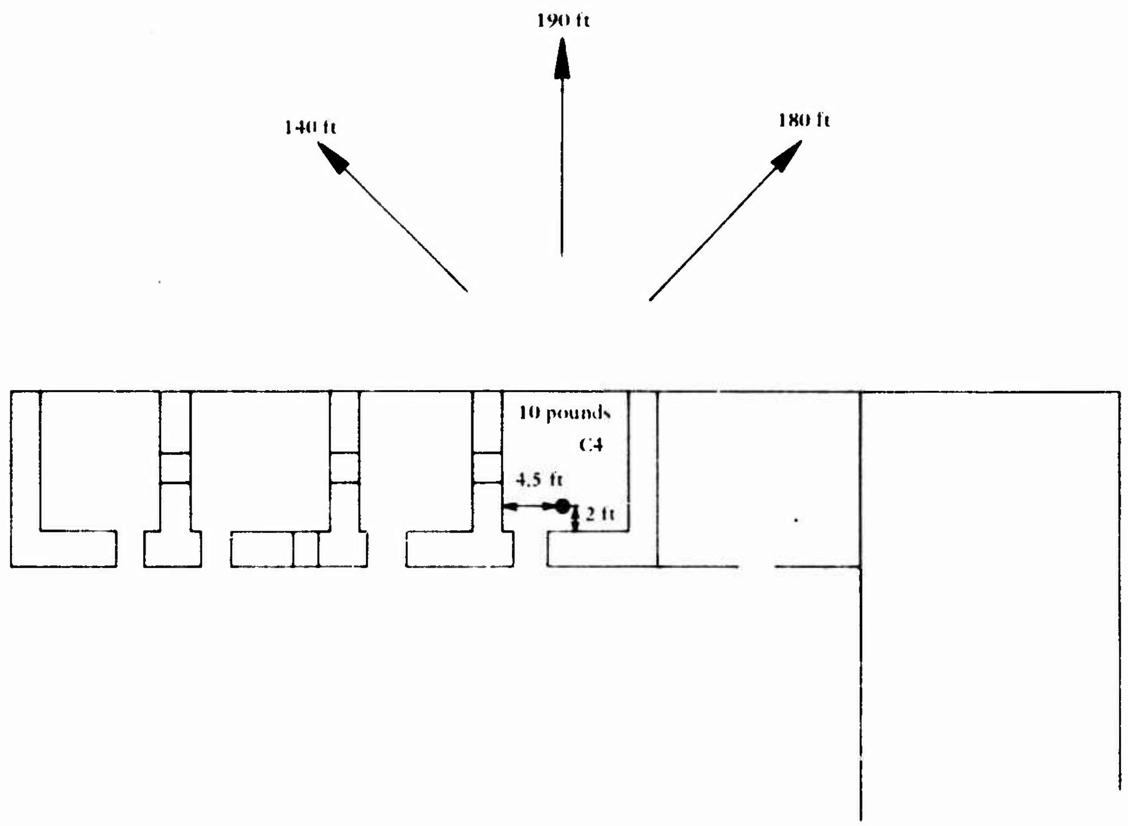


Figure 8. Distance of travel of building debris, shot 1.

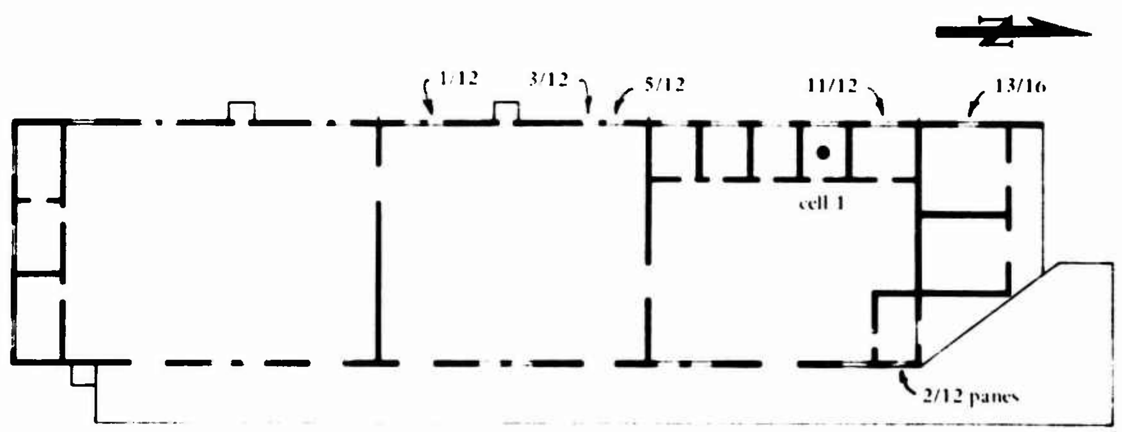
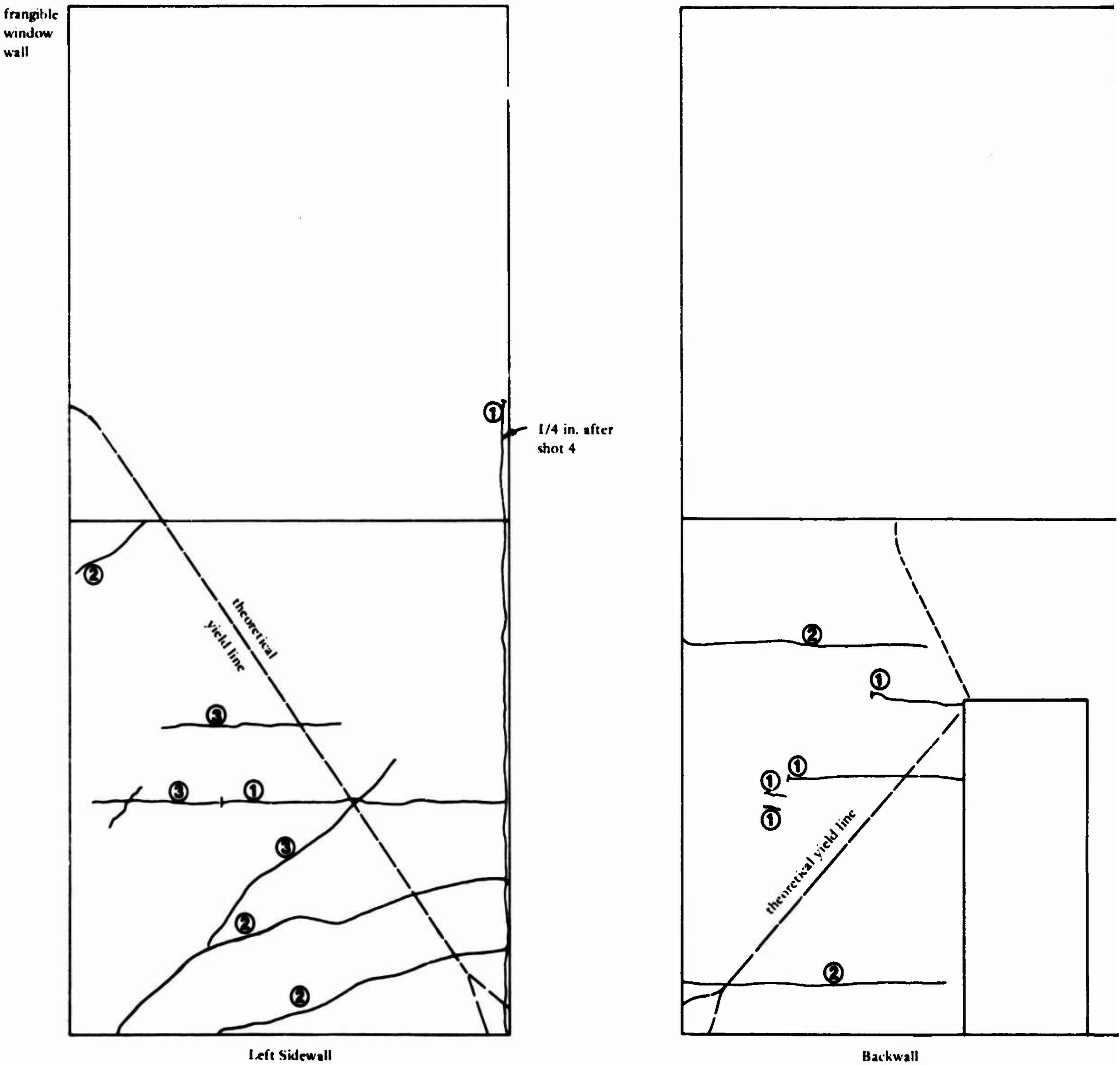
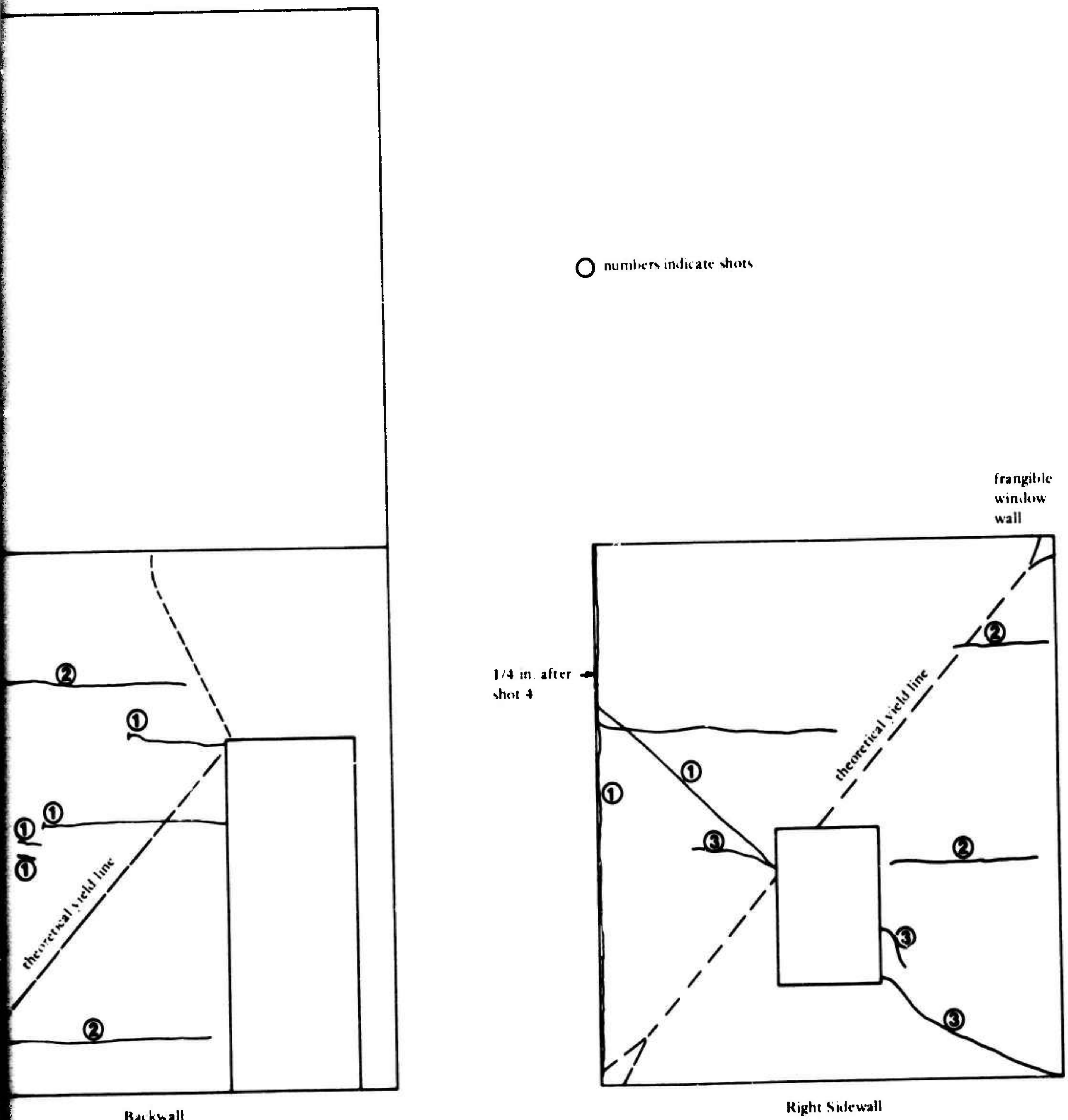


Figure 9. Window breakage from shot 1. Definition of numbers: 1/12 = of twelve original intact panes, one pane was broken.



(a) Inside cell.

Figure 10. Crack patterns in walls of cell 1 after 10-pound deto



(a) Inside cell.

ack patterns in walls of cell 1 after 10-pound detonations.

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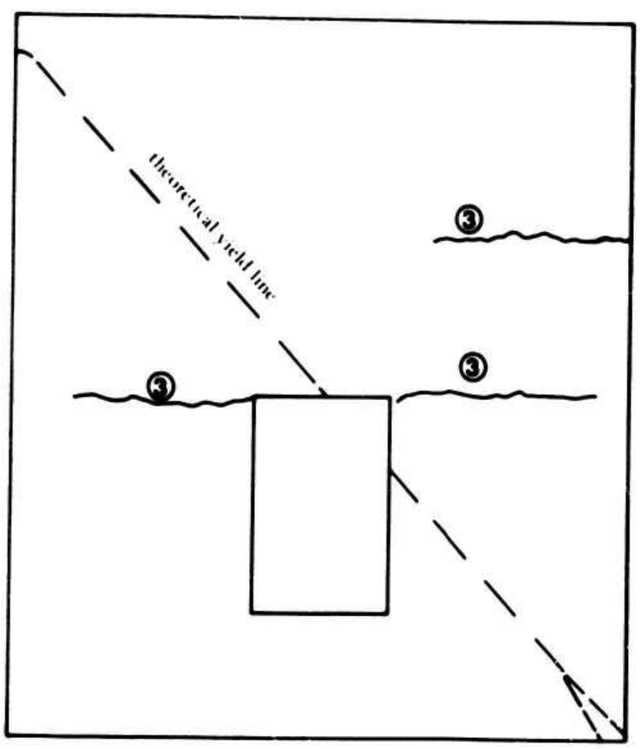
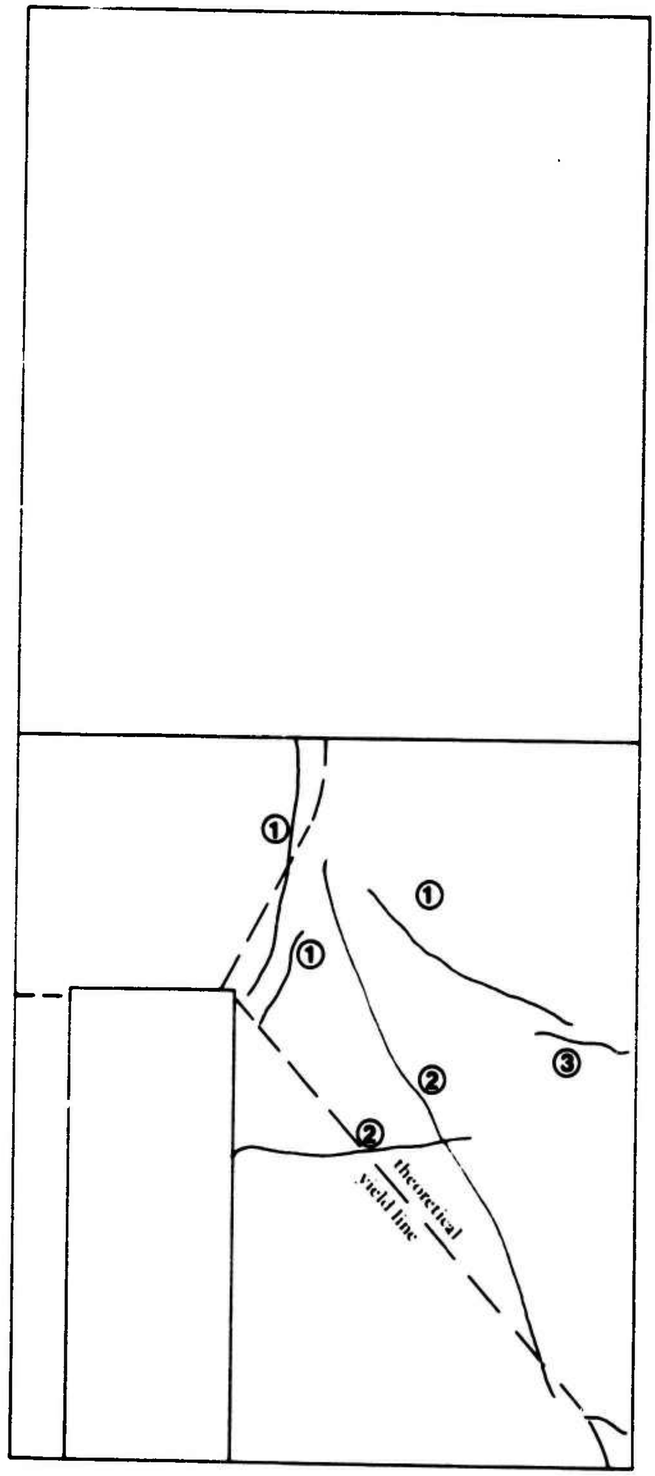
frangible window wall



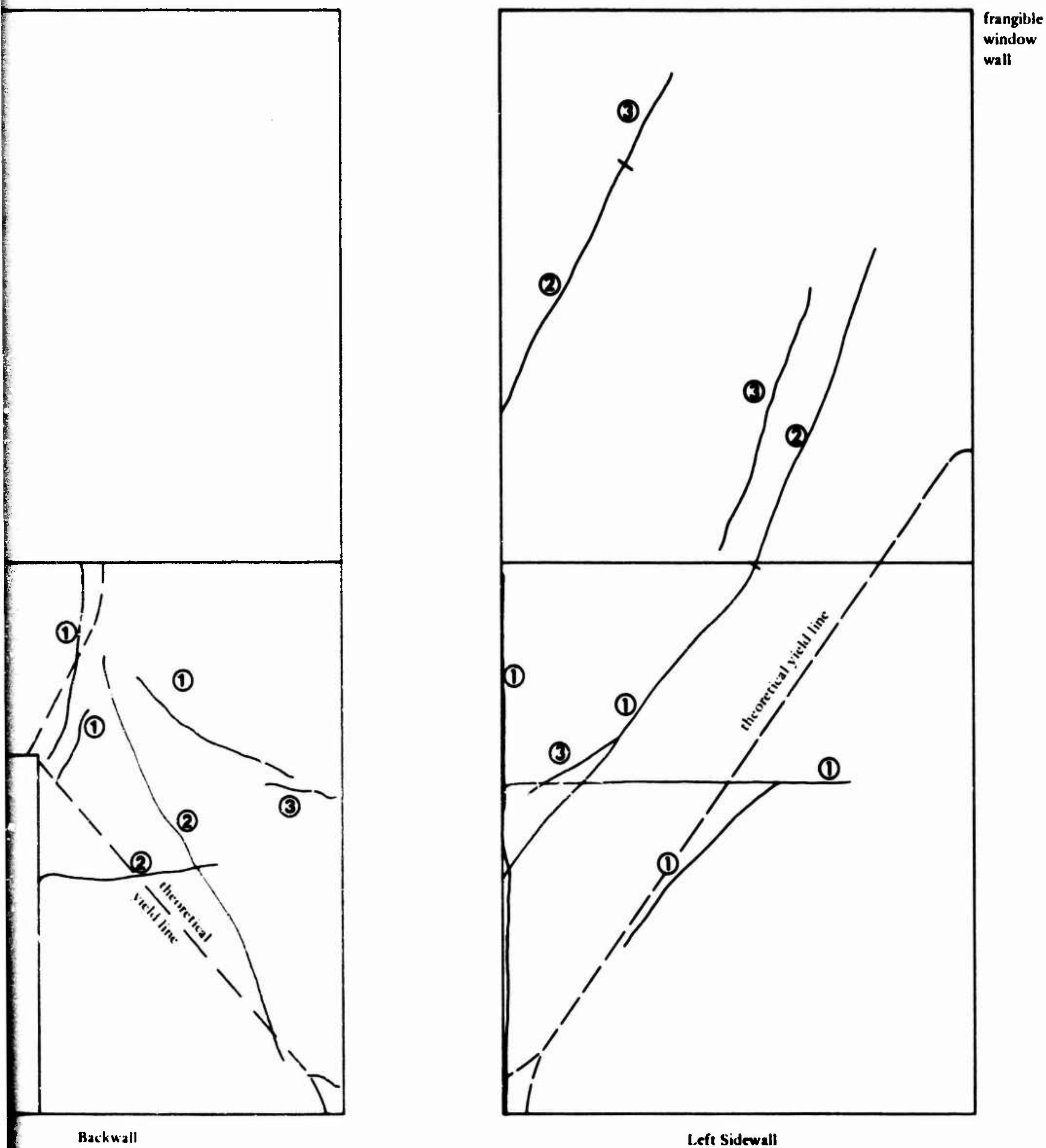
Right Sidewall



Backwall

(b) Outside cell.

Figure 10 (cont).



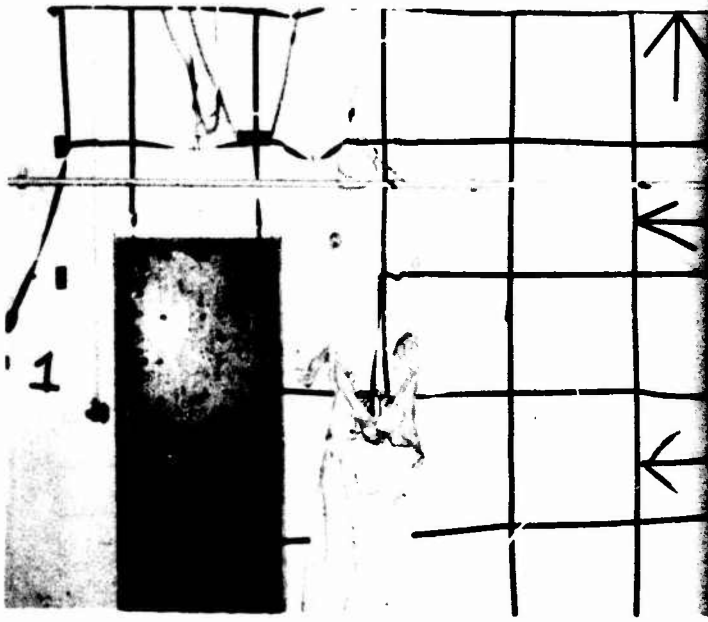
(b) Outside cell.

Figure 10 (cont).

Cell 1 and cell 2.

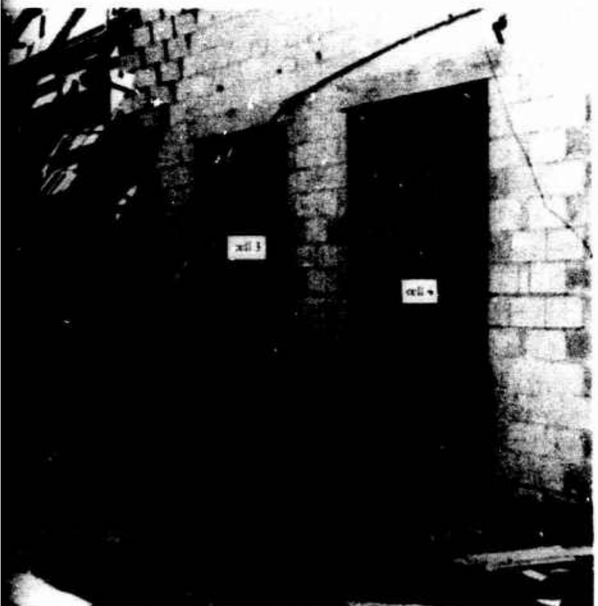
Exterior of structure facing north.

Interior roof damage facing north.

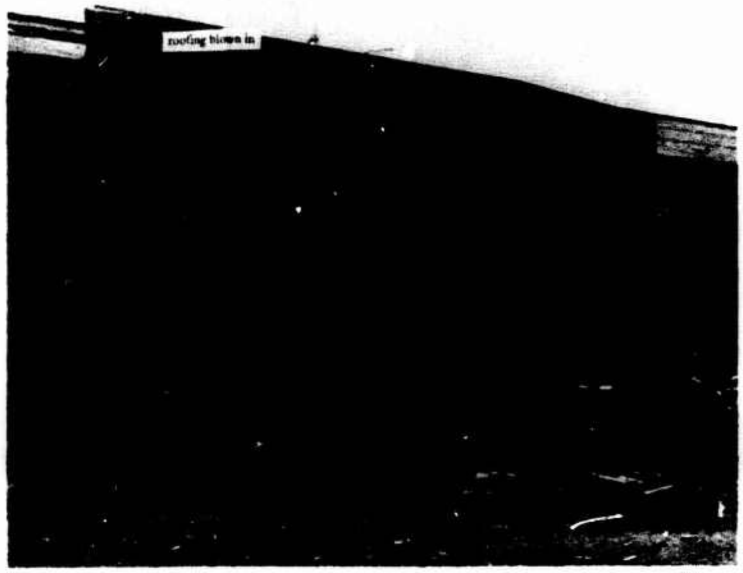


Crack in cell walls.

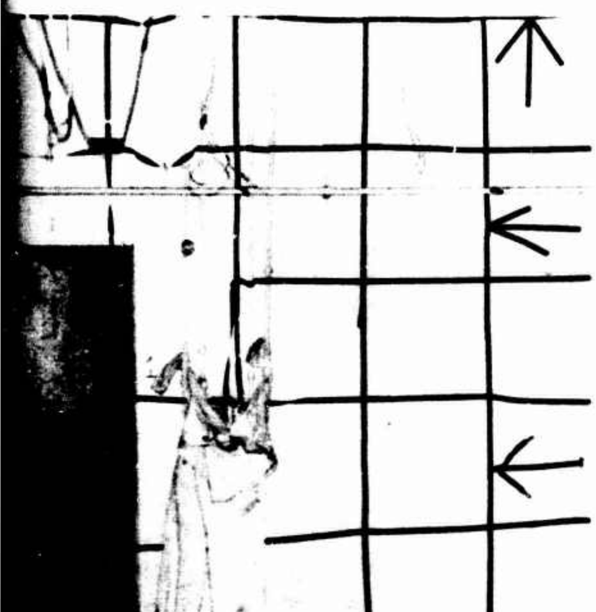
Figure 11. Observed damage after shot 2.



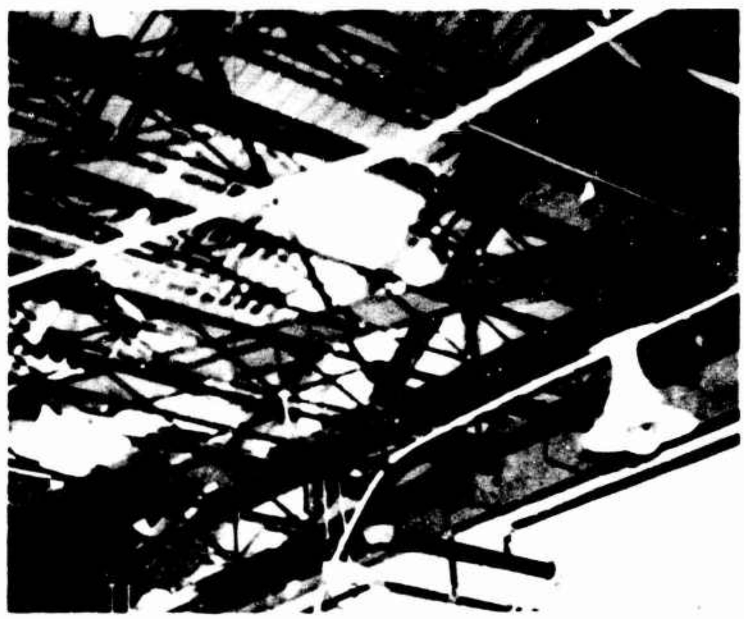
Exterior of structure facing north.



Exterior of structure facing south.



Crack in cell walls.



Middle bay roof damage.

Figure 11. Observed damage after shot 2.

Exterior of structure facing east.

Cells 1 and 2.

Interior ceiling damage.

Cracks in sidewall.

Rebound of passth

Figure 12. Observed damage after shot 3.

Cells 1 and 2.

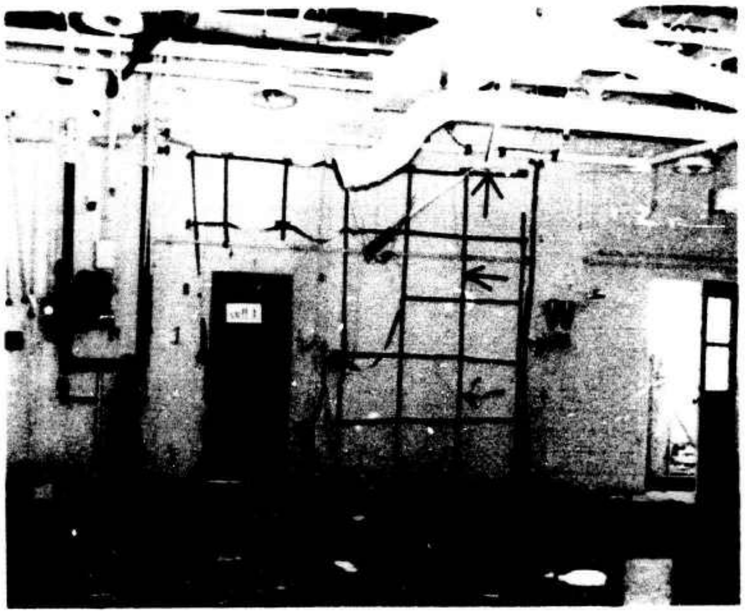
Interior roof failure.

ks in sidewall.

Rebound of passthrough door.

Roof damage of middle bay.

Figure 12. Observed damage after shot 3.



Interior of building.

Exterior cells 1 and 2.

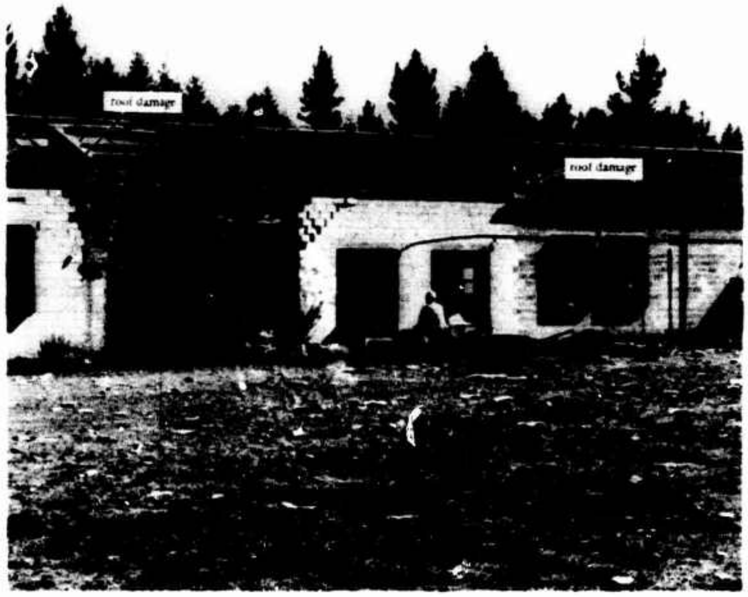
Cell 1.

Cell 2.

Interior ce

Figure 13. Observed damage after shot 4.

Exterior cells 1 and 2.



Exterior cells 1, 2, 3, and 4.

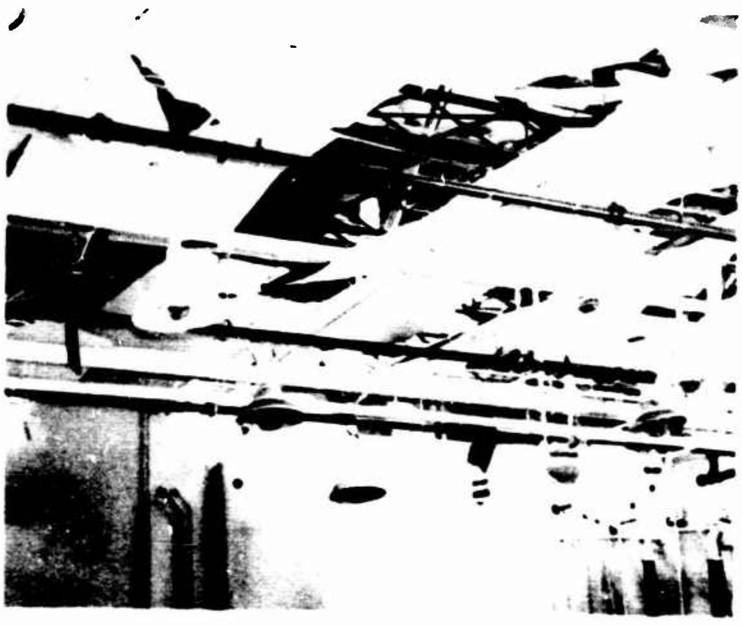
Interior ceiling damage.

Exterior wall damage looking north.

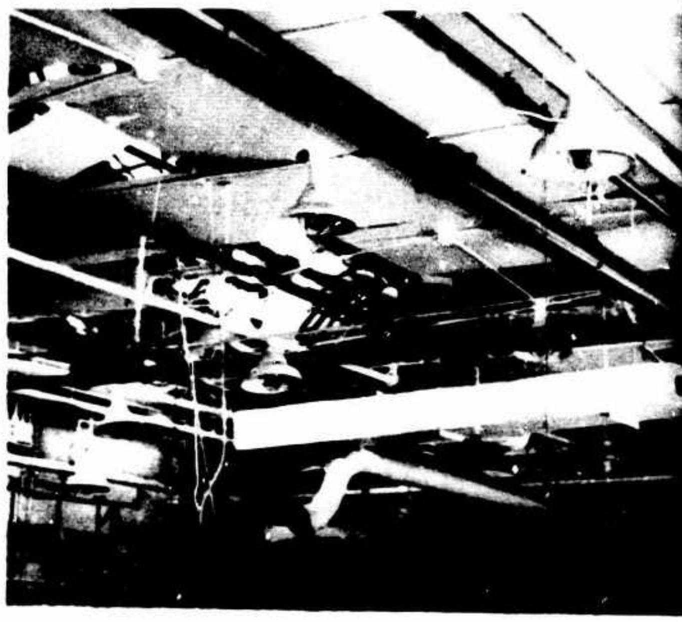
Observed damage after shot 4.

Exterior cells 1 and 2.

Exterior cells 3 and 4.



Interior ceiling damage behind cell.



Interior ceiling damage behind cell.

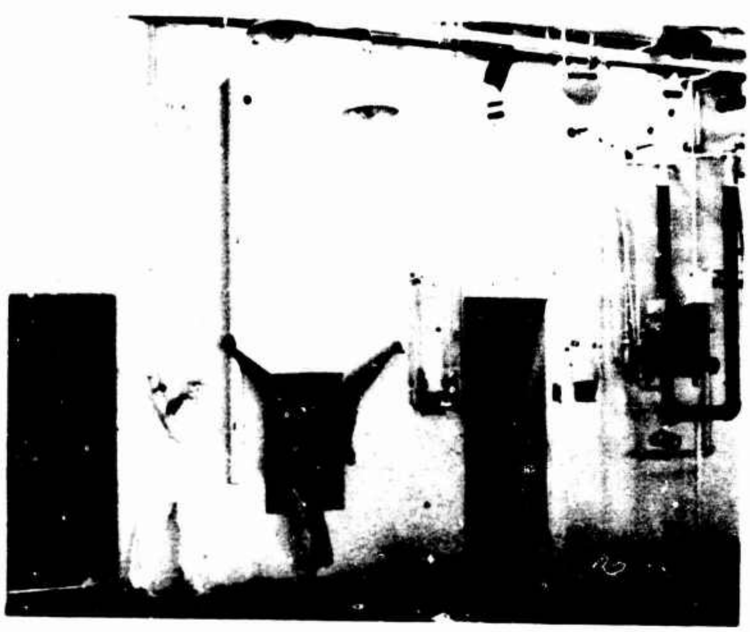
Figure 14. Observed damage after shot 6.

ls 3 and 4.

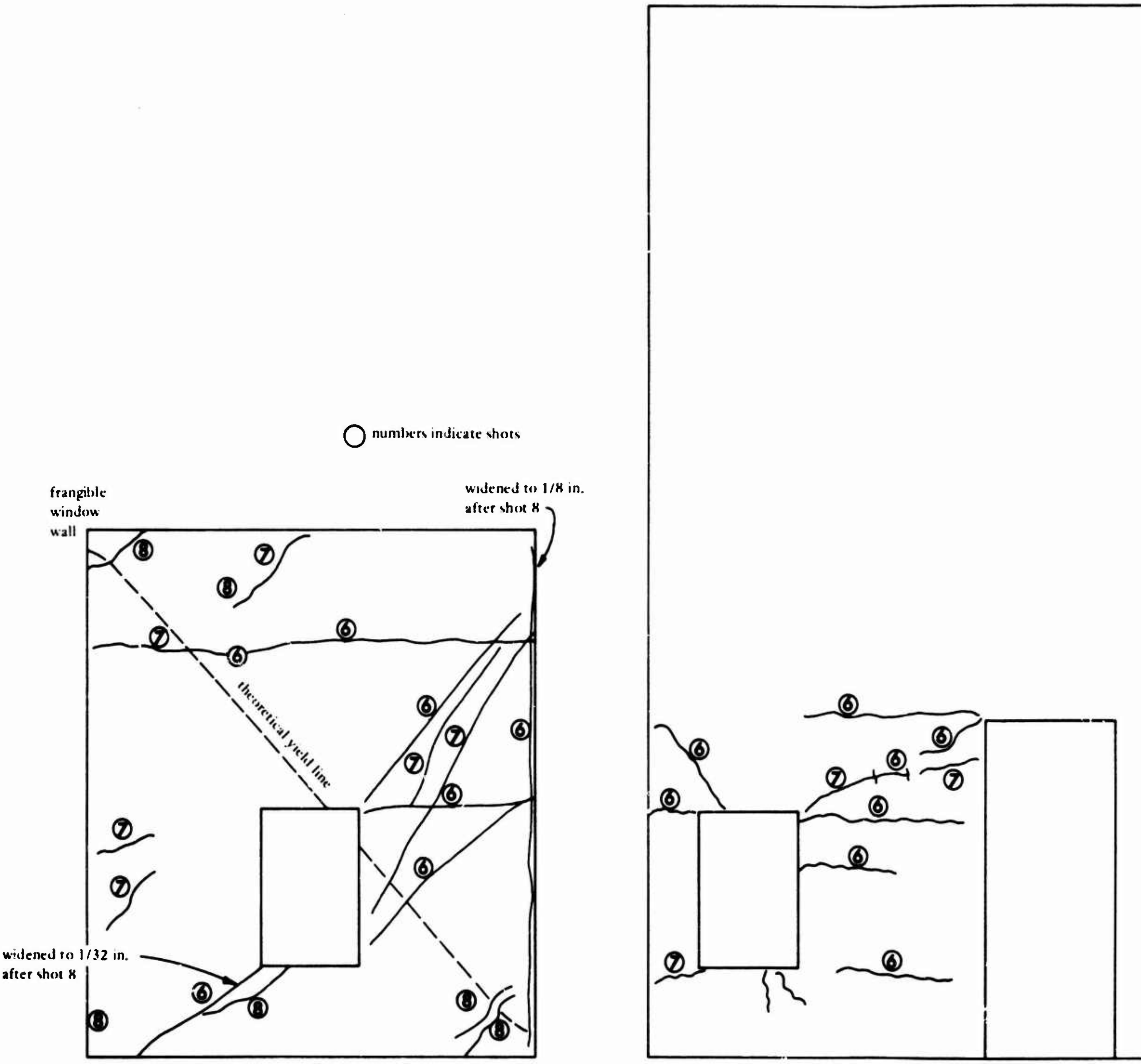
Exterior wall looking east.

mage behind cell.

lamage after shot 6.

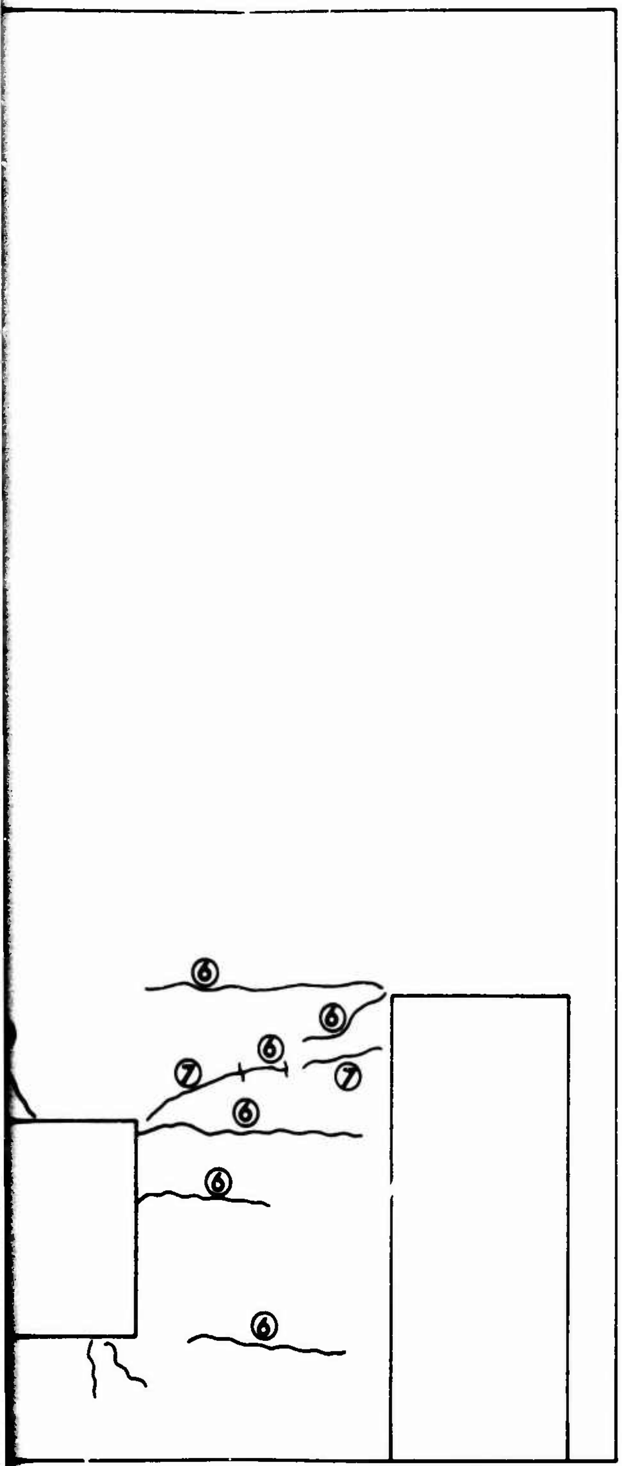


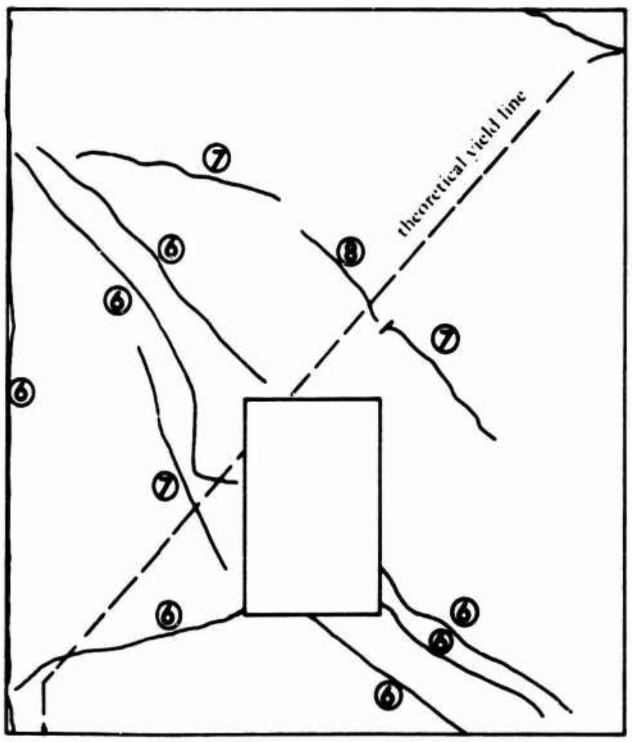
Blast cell interior wall.



(a) Inside cell.

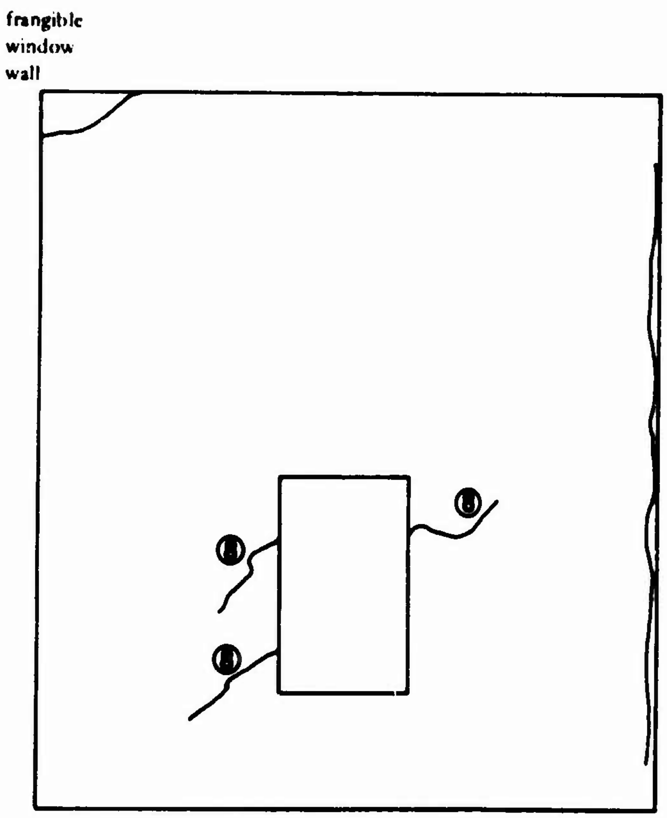
Figure 15. Crack patterns in the walls of cell 3 after 20-pound detonatior



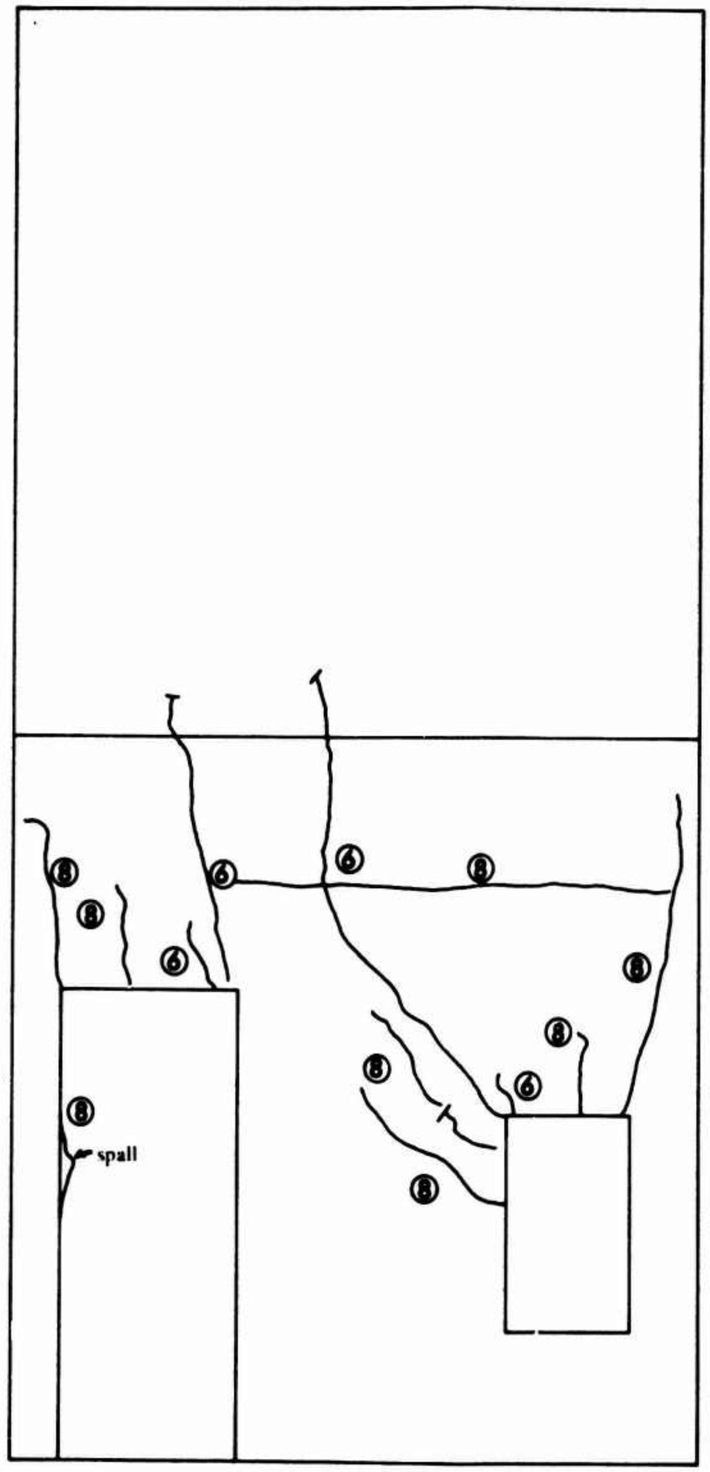


(a) Inside cell.

Crack patterns in the walls of cell 3 after 20-pound detonations.



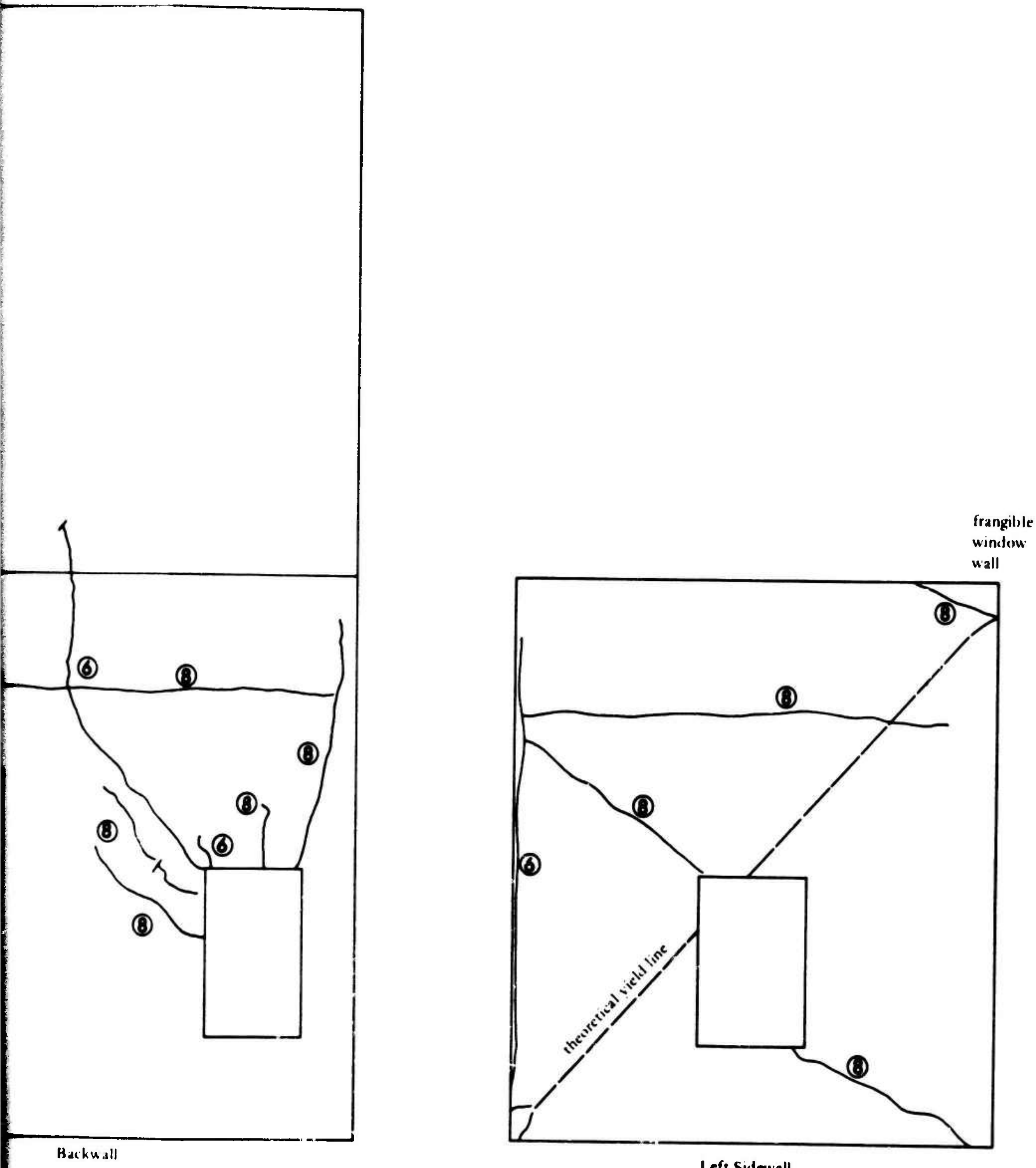
Right Sidewall



Backwall

(b) Outside cell.

Figure 15 (cont).



(b) Outside cell.

Figure 15 (cont).

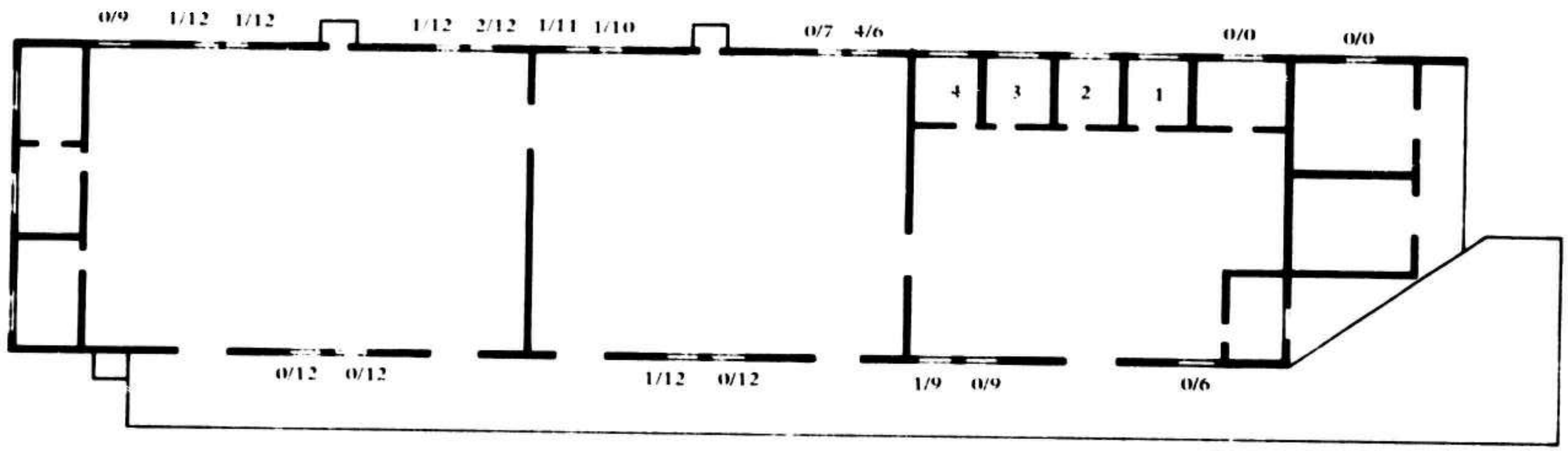
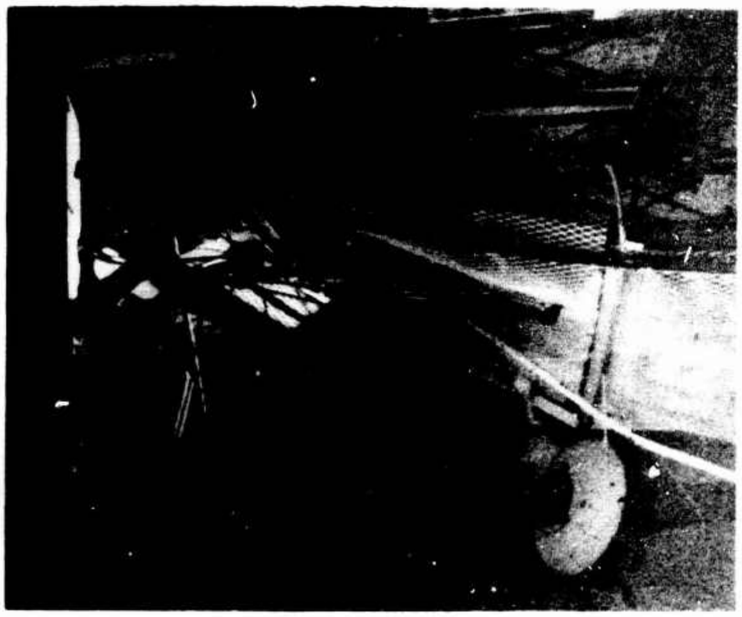
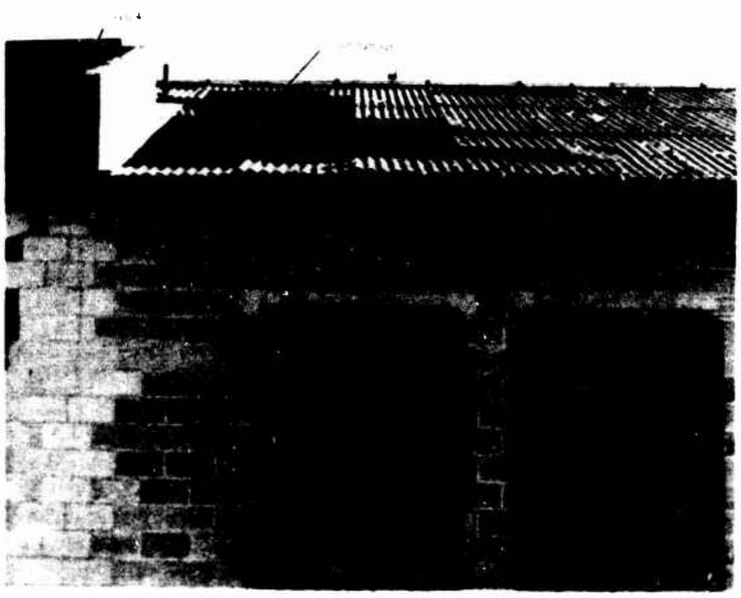


Figure 16. Window breakage after shot 6.

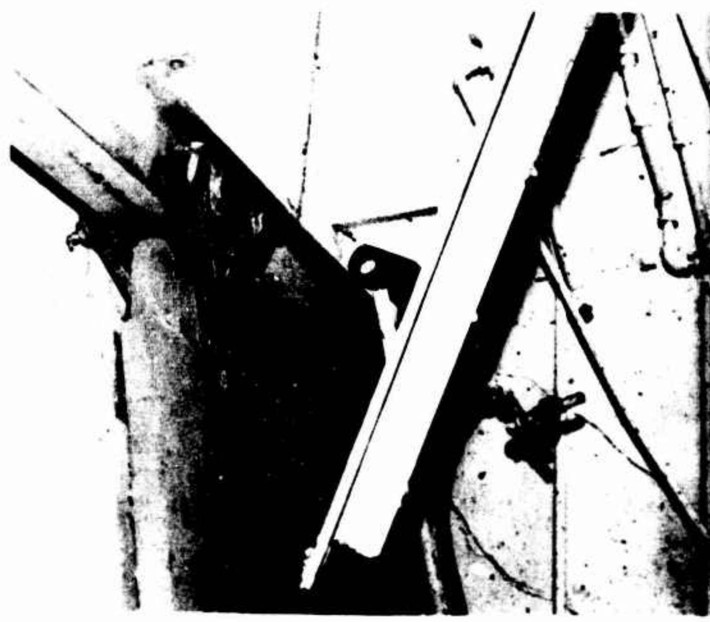


Debris net cell 4.

Exterior cells 3 and 4.

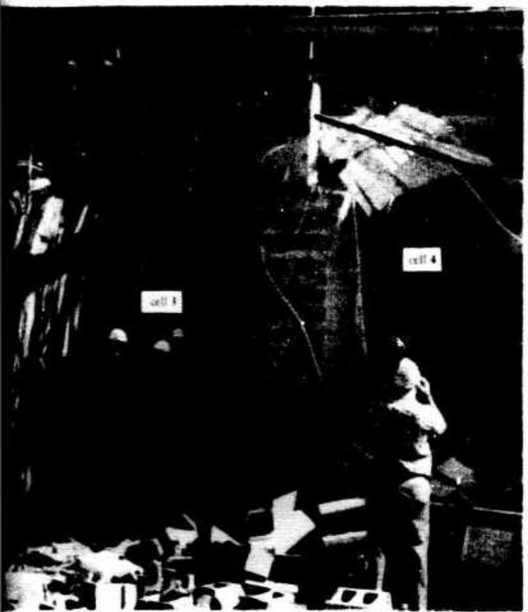


Exterior structure looking east.



Blast door cell 3.

Figure 17. Observed damage after shot 7.



Exterior cells 3 and 4.

Cell 3.

Blast door cell 3.

Blast door cell 3.

17. Observed damage after shot 7.

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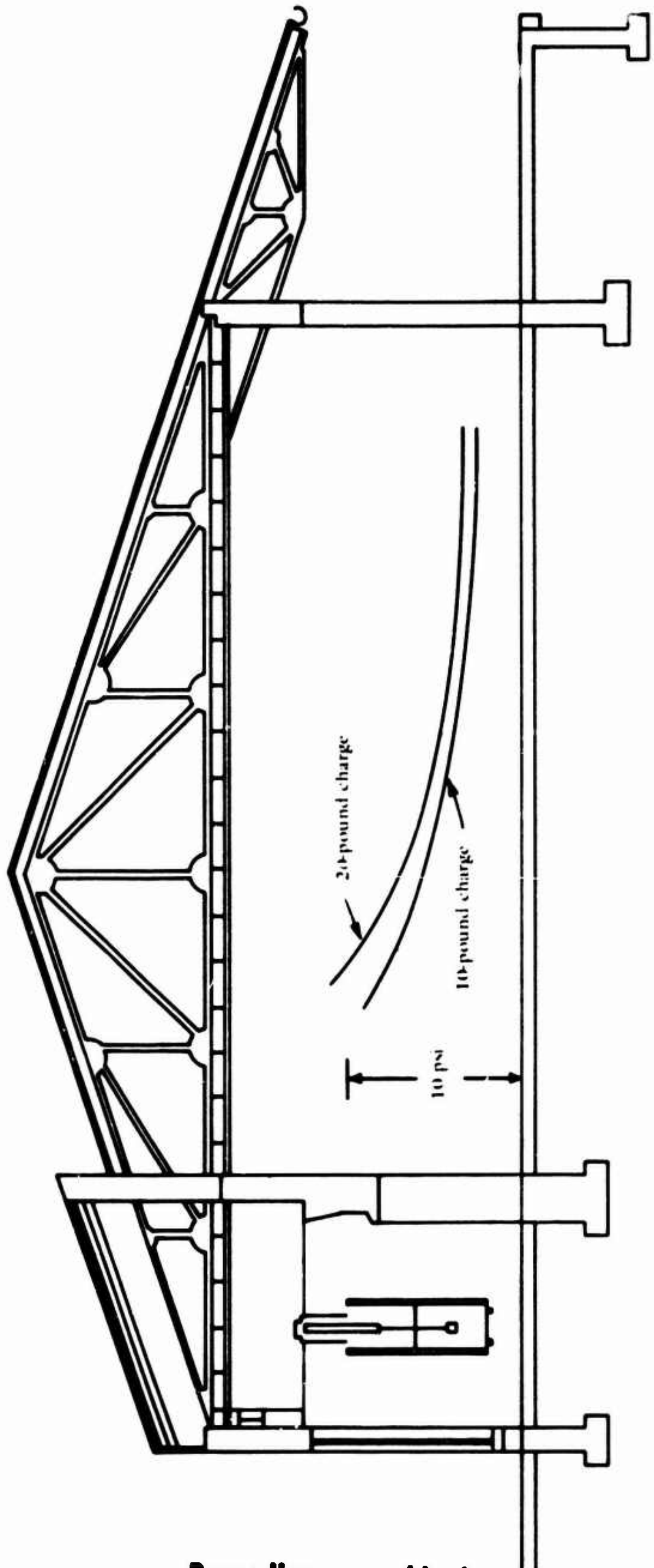

Figure 18. Peak pressure at floor level.

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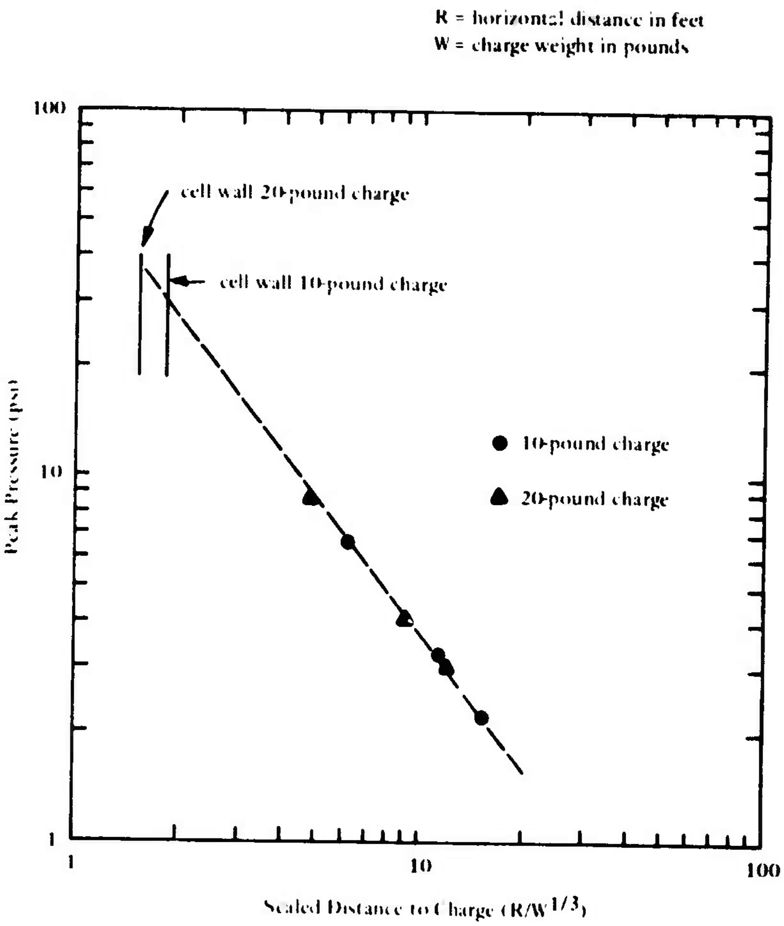


Figure 19. Pressure/distance for leakage pressure around door.

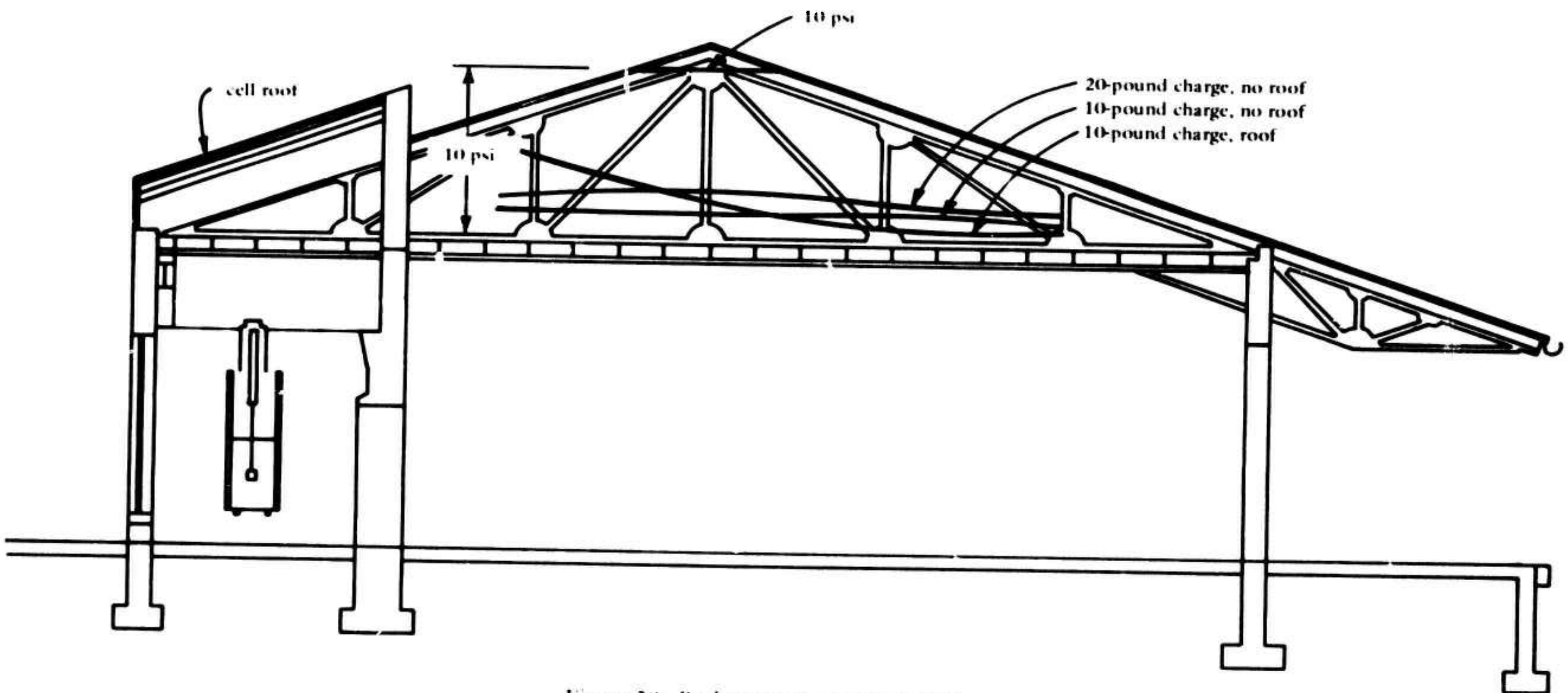


Figure 20. Peak pressure at ceiling level.

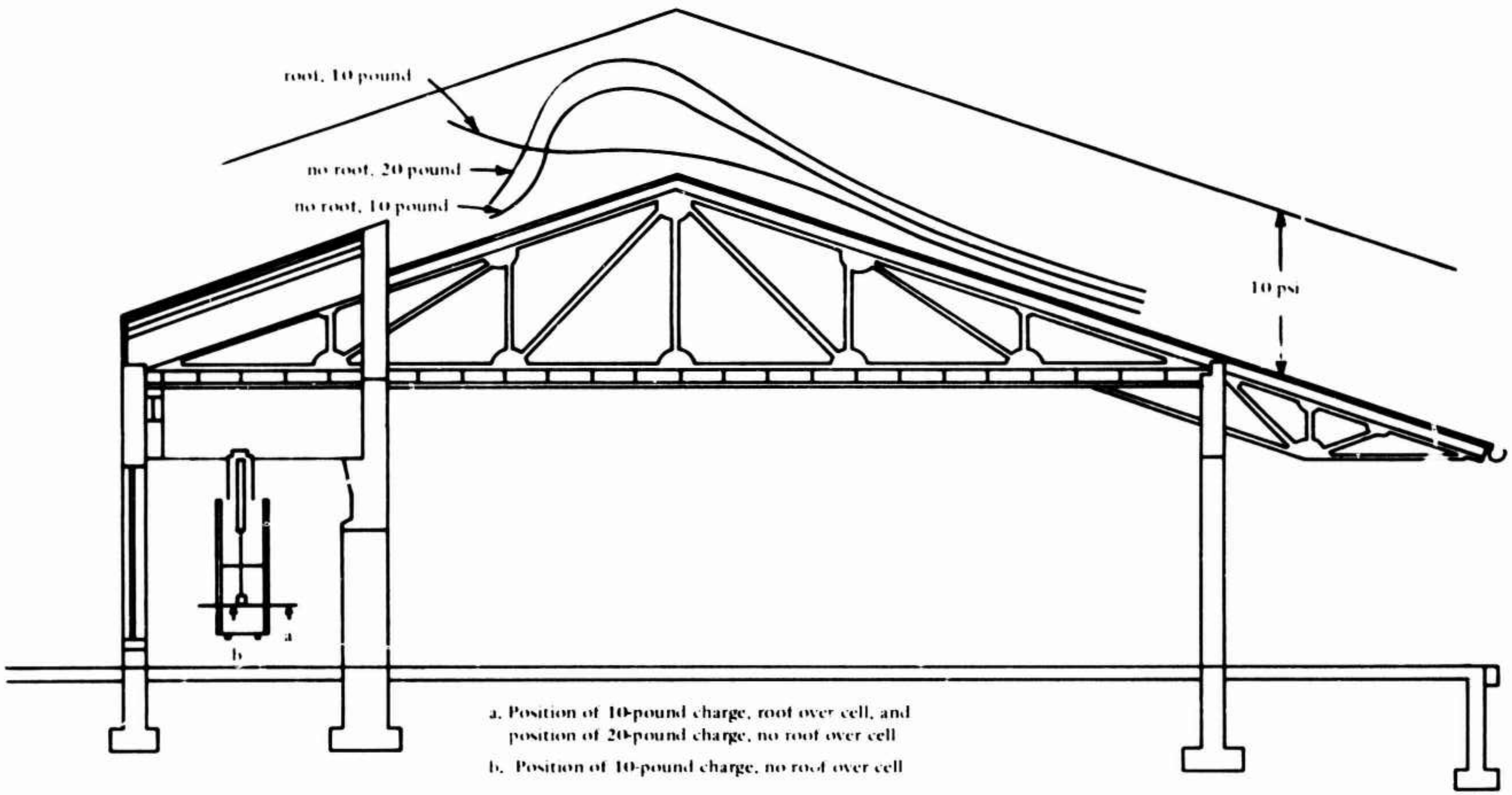
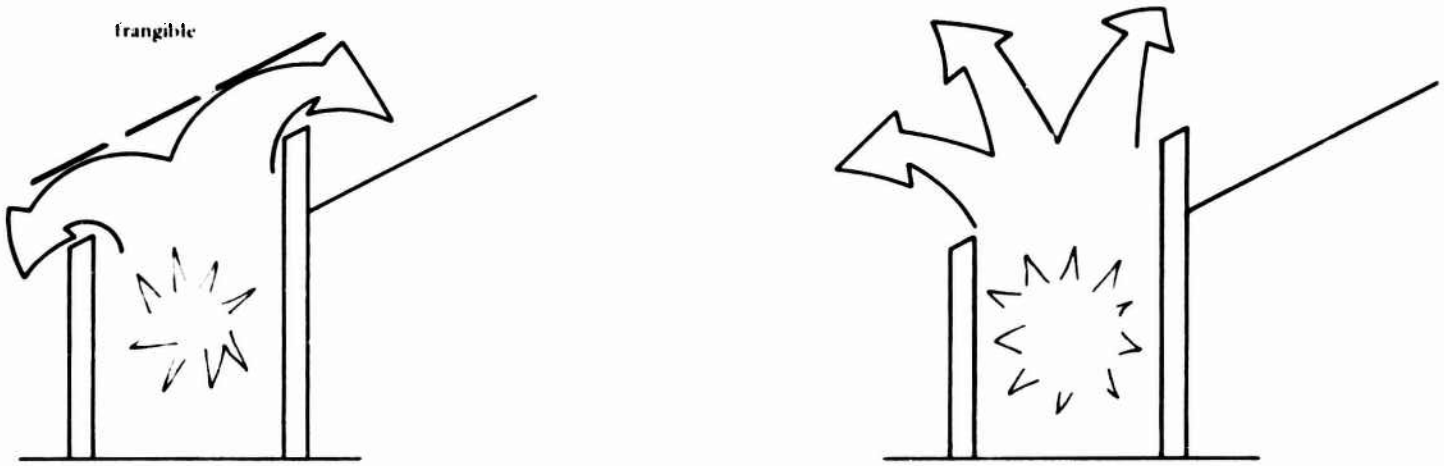


Figure 21. Peak pressure on roof.



(a) With roof.

(b) Without roof.

Figure 22. Comparison of shock waves for cells with and without a cell roof.

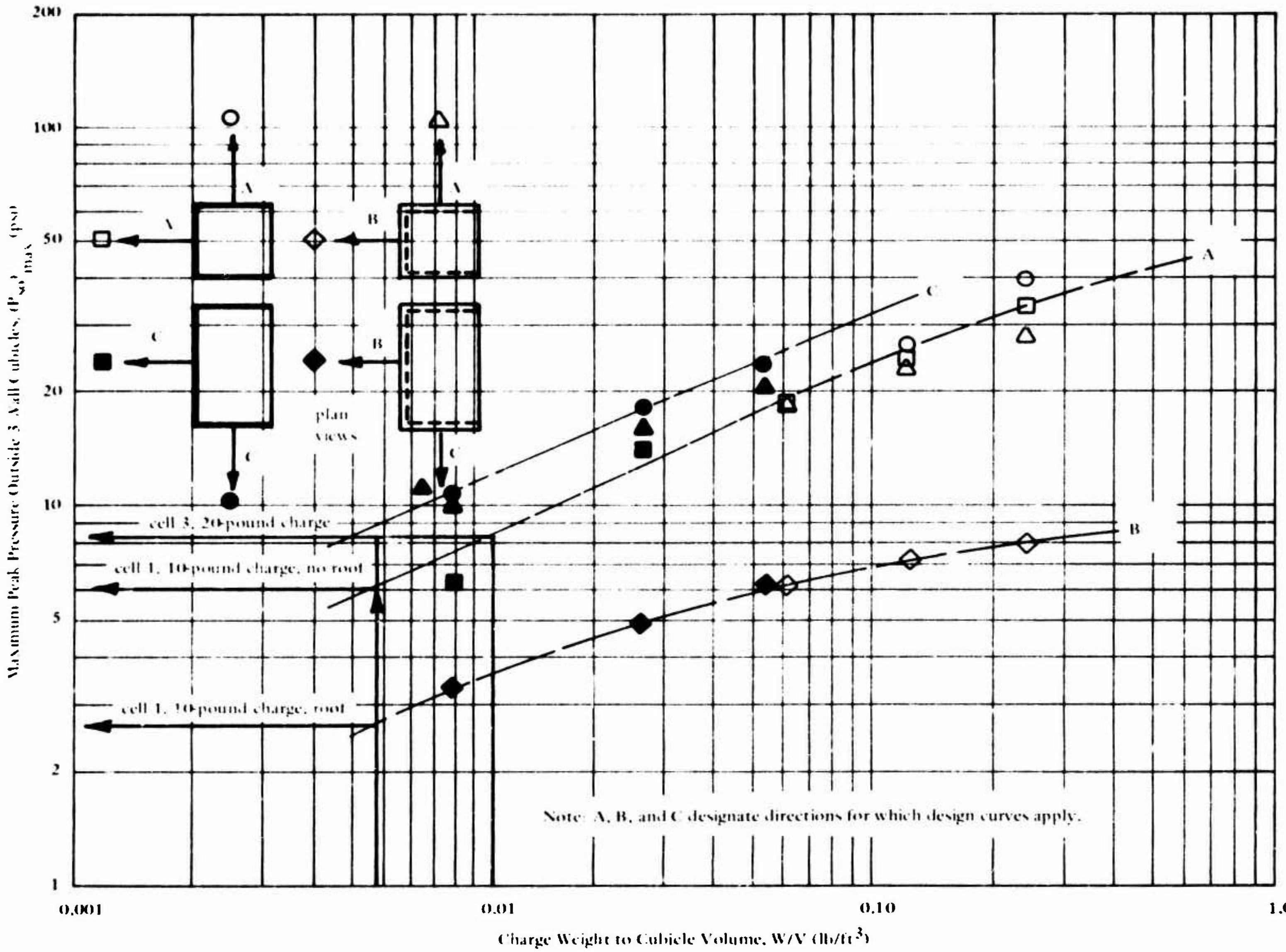


Figure 23. Envelope curves for maximum peak pressure outside 3-wall cubicles during explosion of 10- and 20-pound charges.

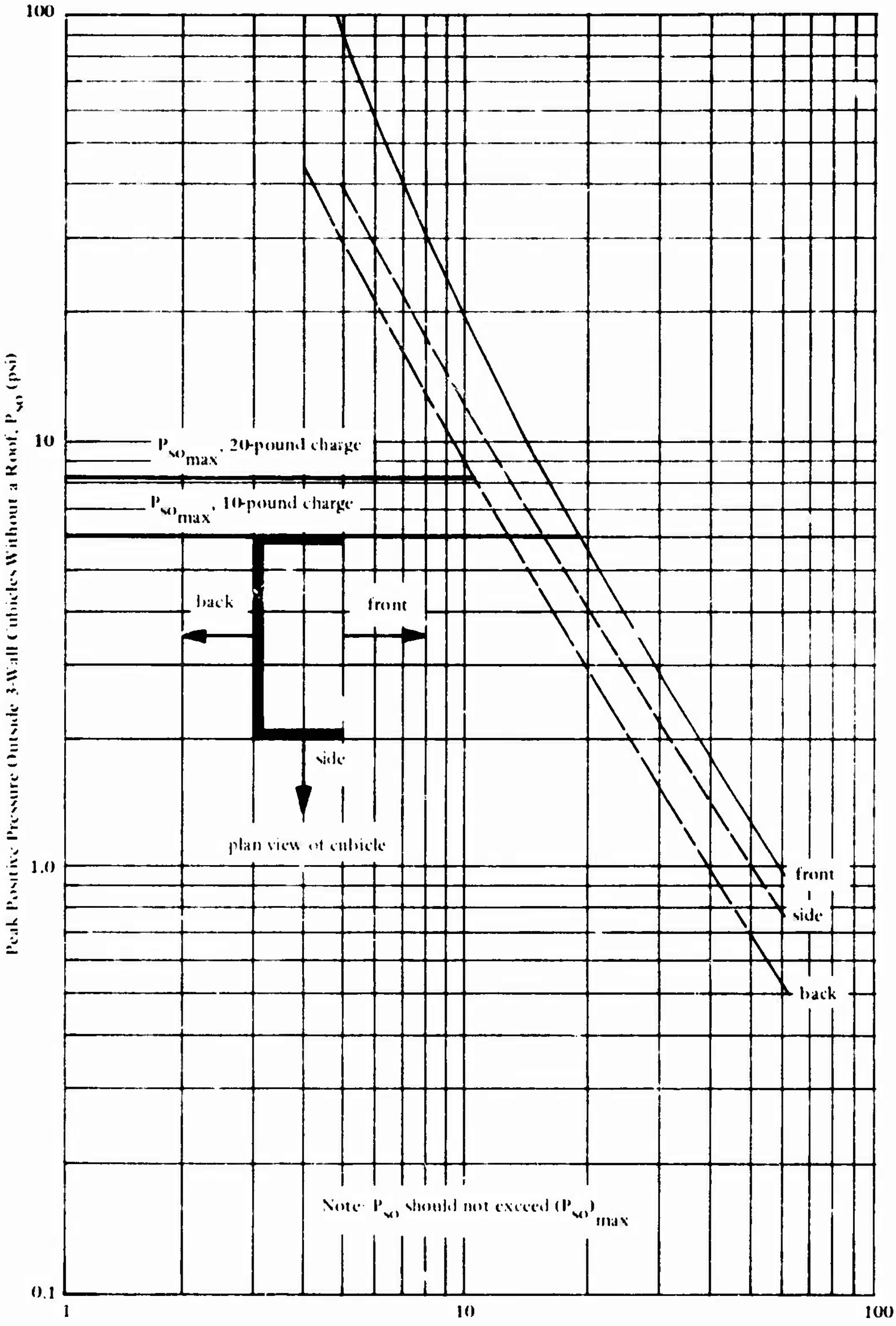


Figure 24. Envelope curves for peak positive pressure outside 3-wall cubicles without a roof during explosion of 10- and 20-pound charges.

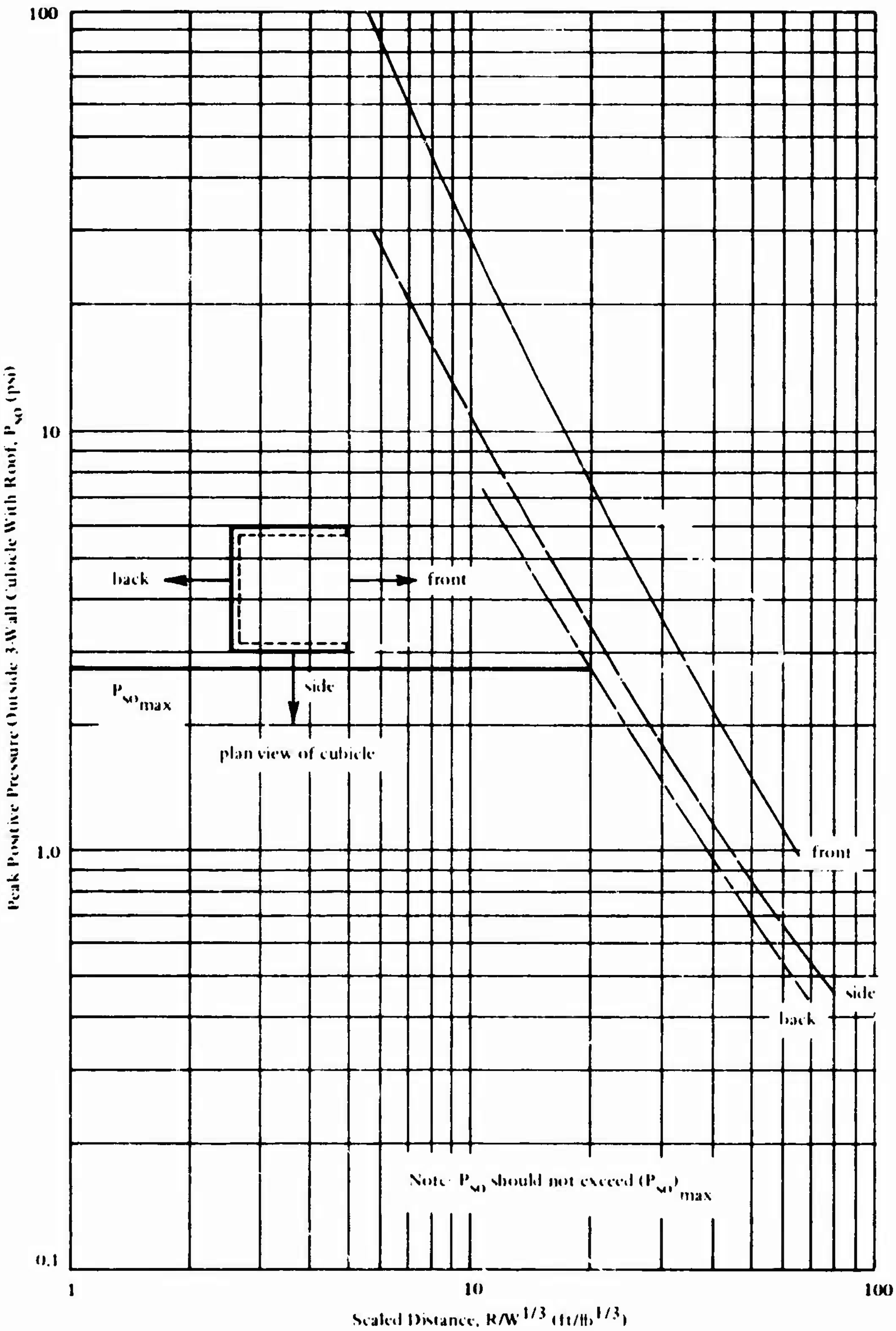


Figure 25. Envelope curves for peak positive pressure outside 3-wall cubicles with a roof.

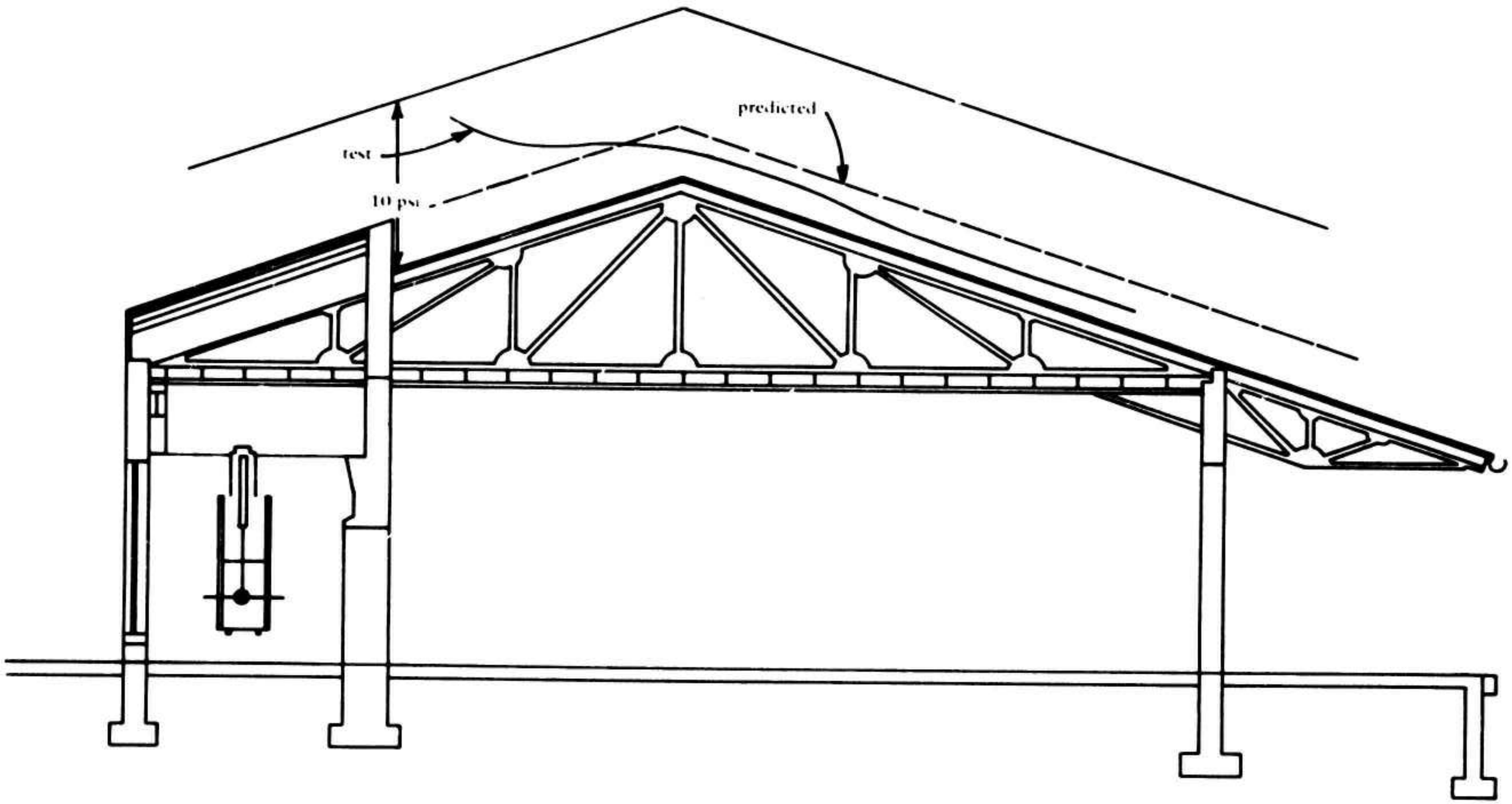


Figure 26. Comparison of predicted and actual test curves for explosion of 10-pound charge in cell with a roof.

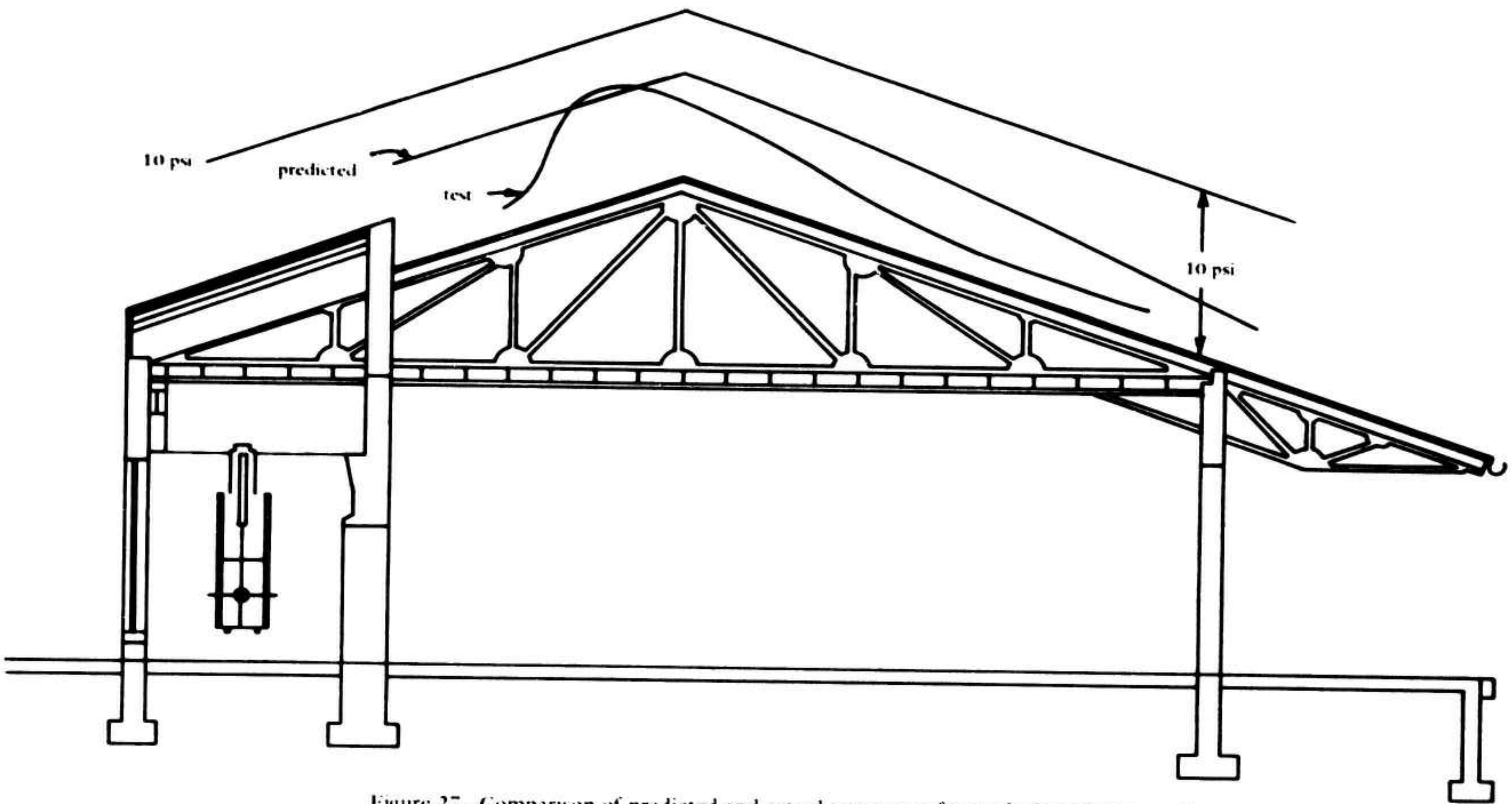


Figure 27. Comparison of predicted and actual test curves for explosion of 10-pound charge in cell without a roof.

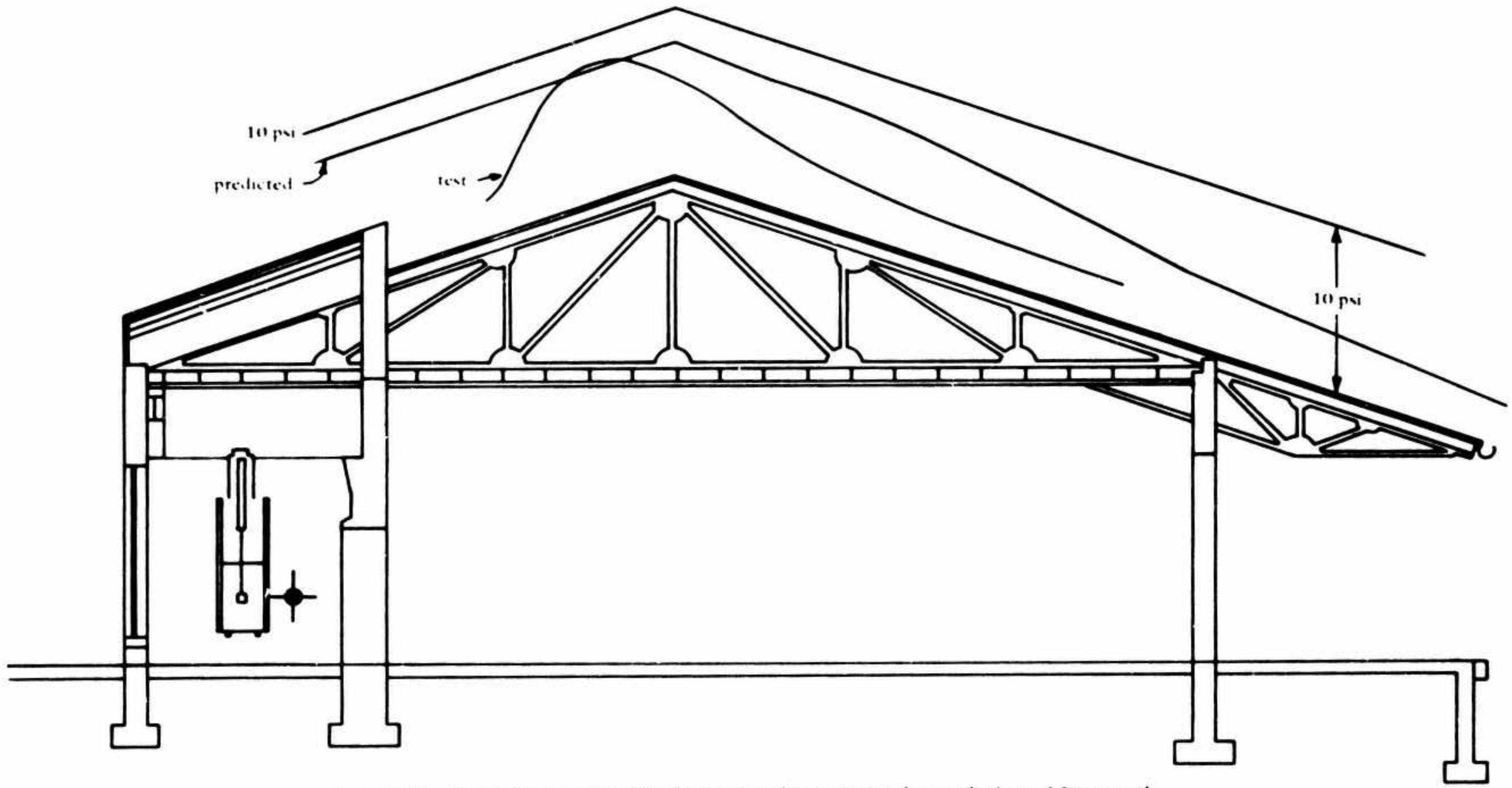
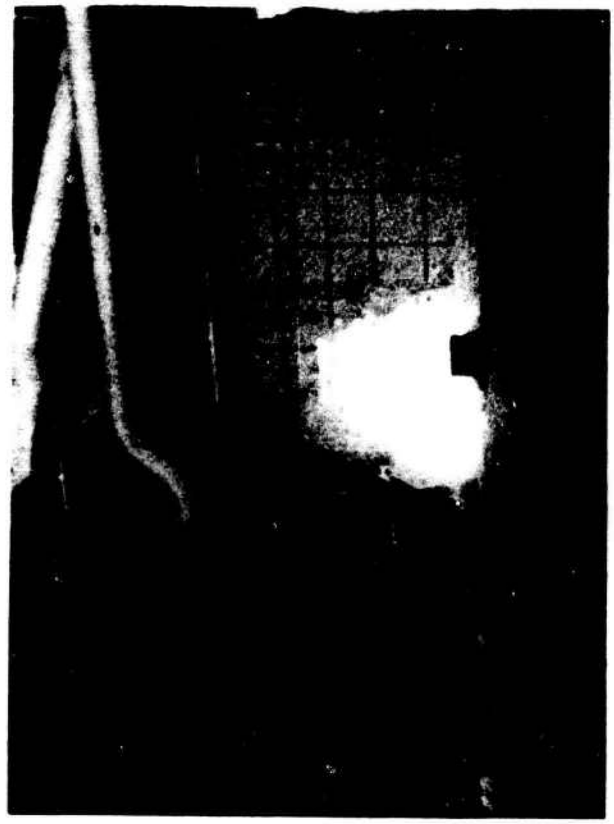


Figure 28. Comparison of predicted and actual test curves for explosion of 20-pound charge in cell without a roof.

2



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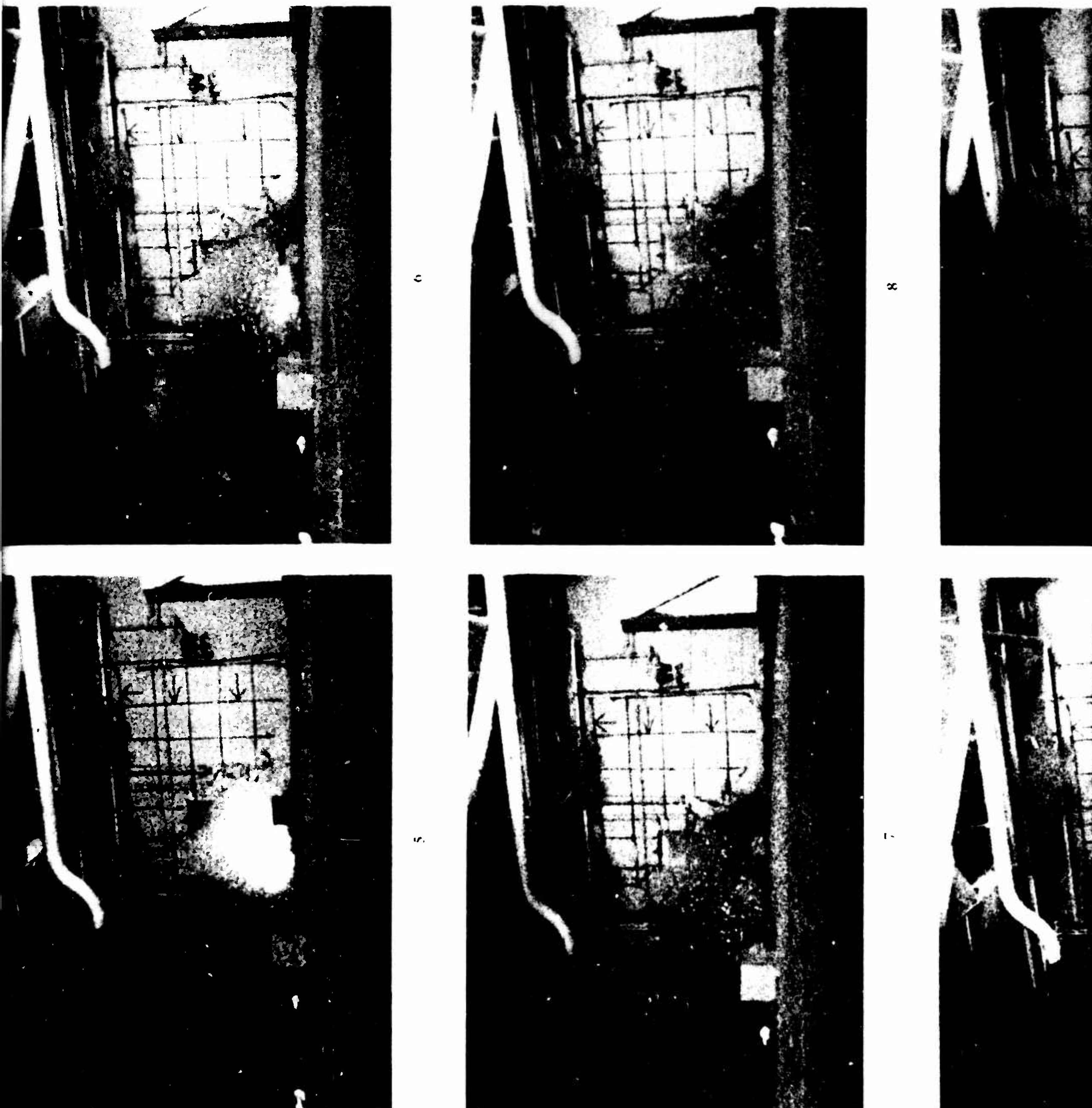
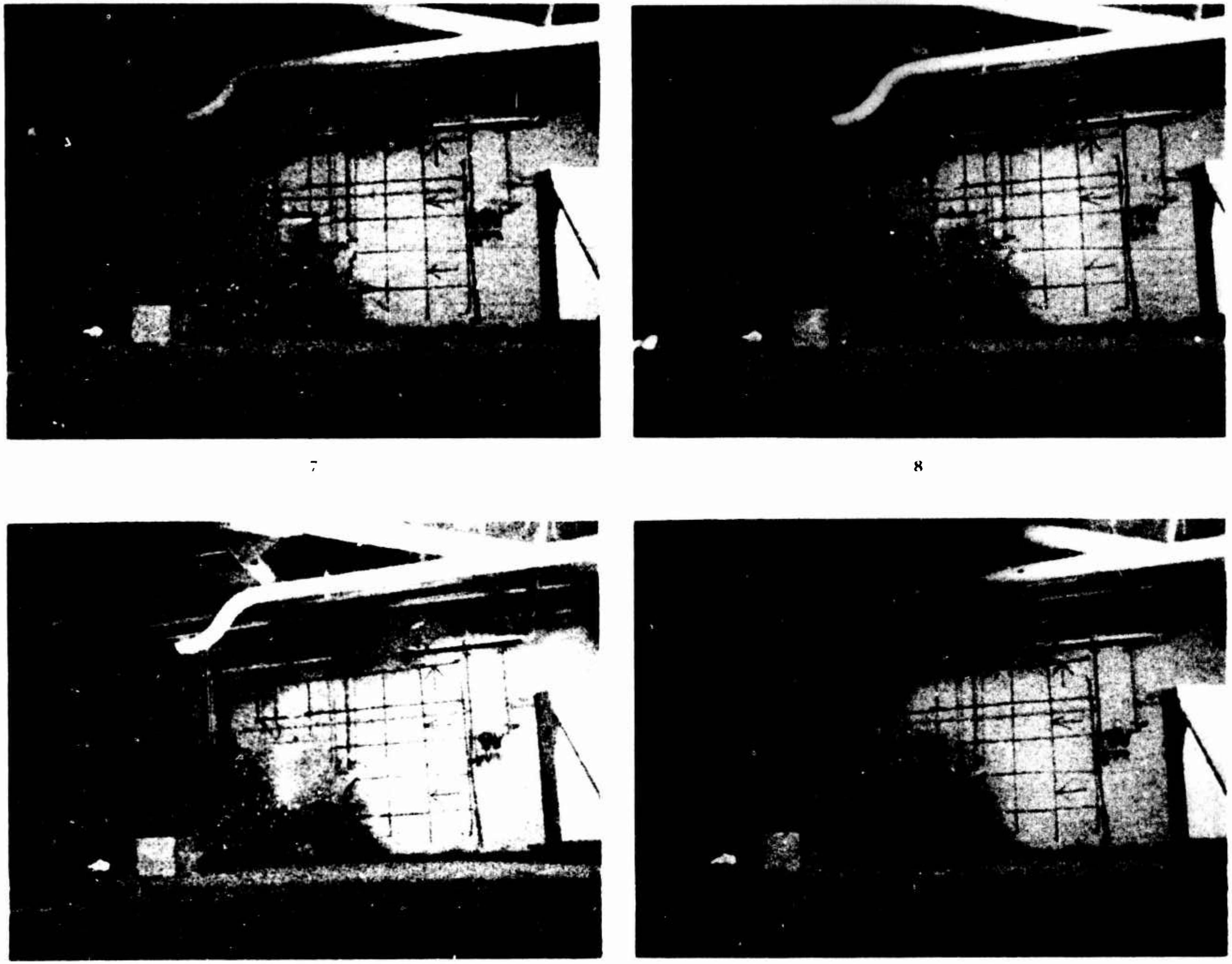


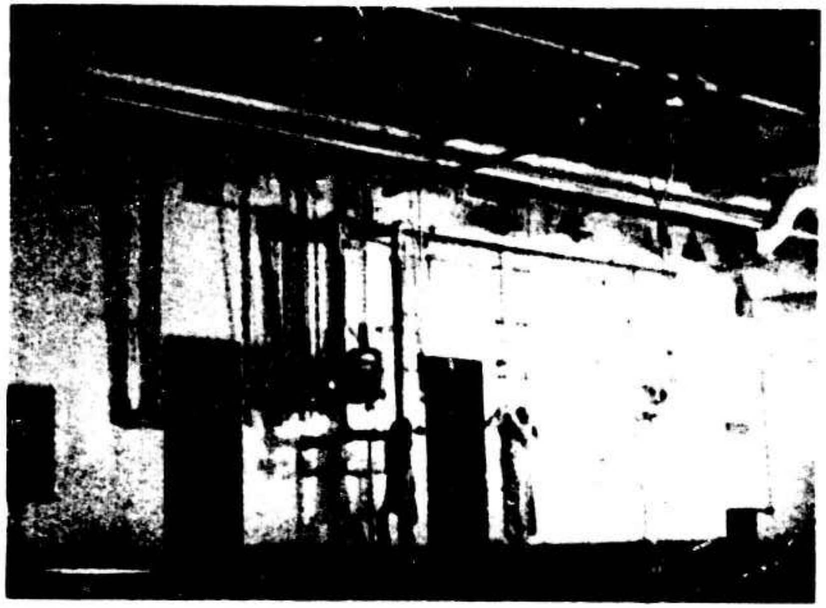


7 8

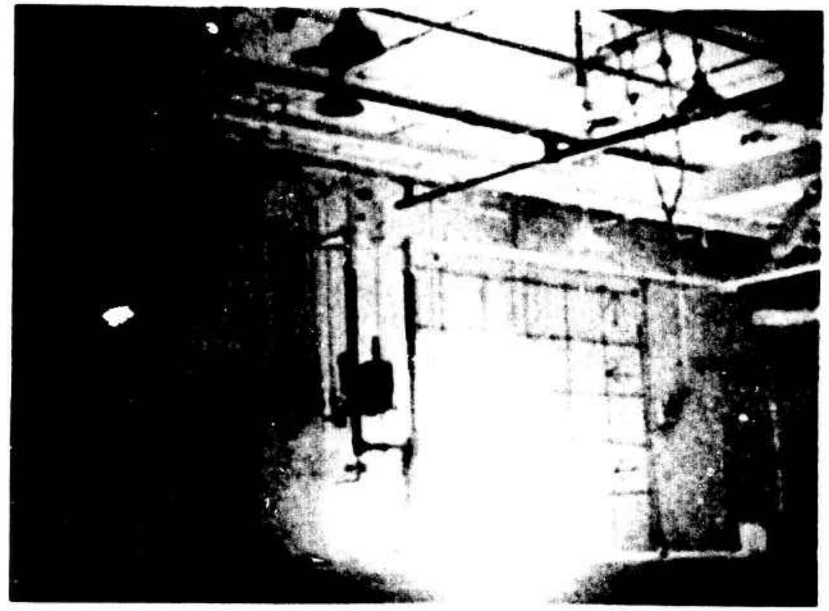
9 10

(a) Camera 1.

Figure 29. Series of photographs showing gas leakage from under the blast door from two camera positions.



1



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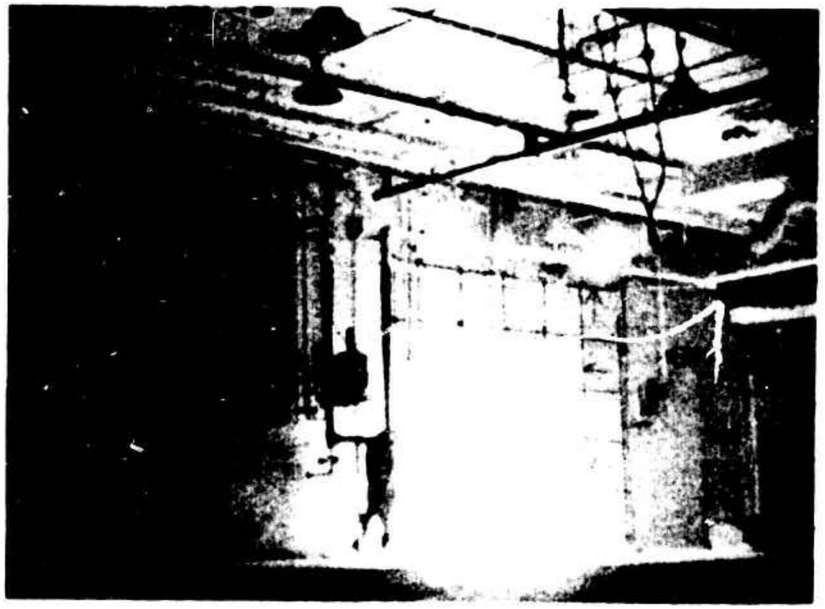
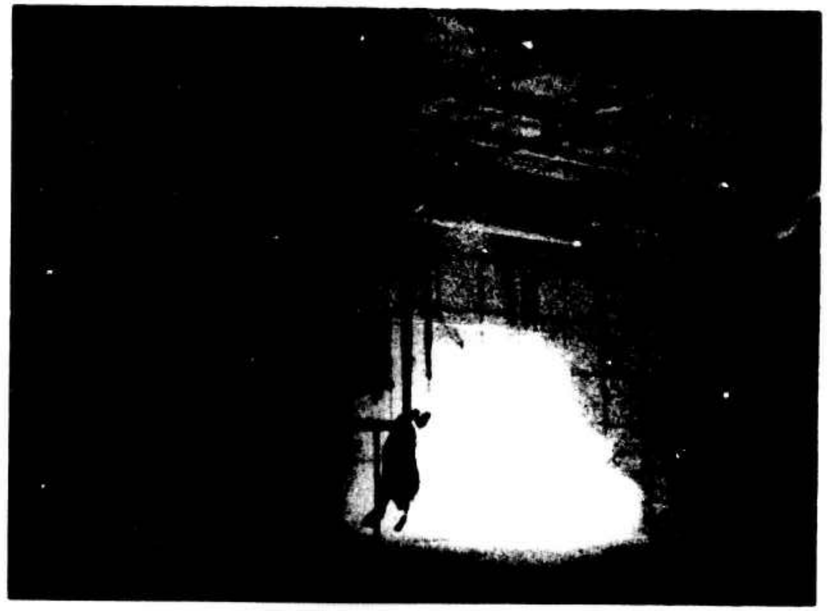
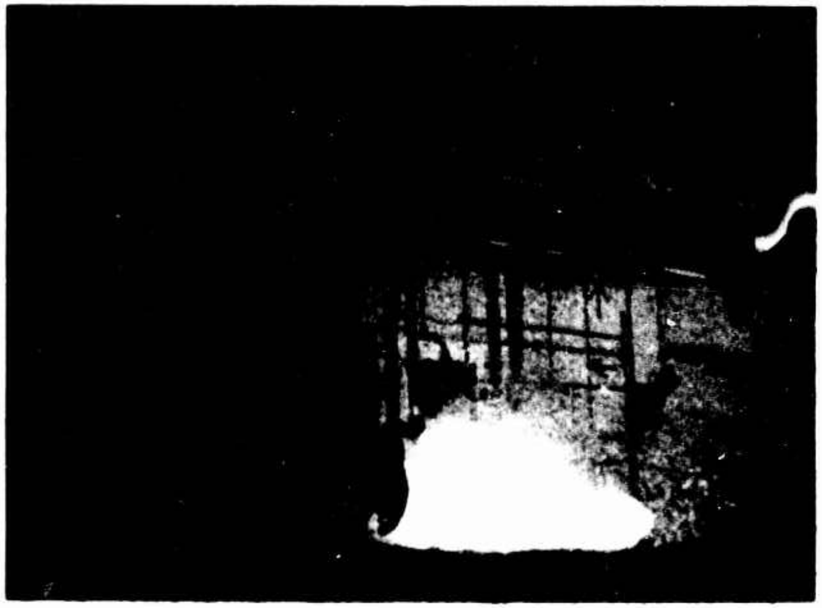


3



4



5

6

7

8

5

6

7

8

9

10

(b) Camera 2.

Figure 29 (cont).

1

2

3

4

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8

9

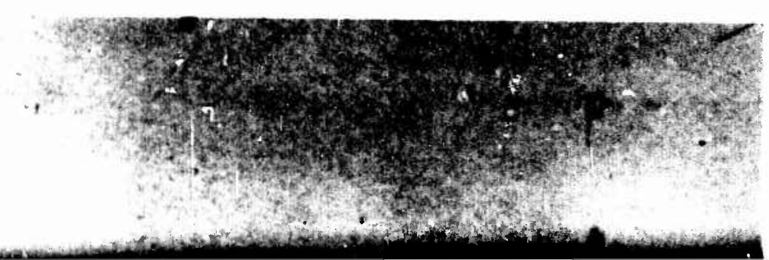
Figure 30. Series of photographs showing fireball formation outside of building at detonation of 10-pound charge.

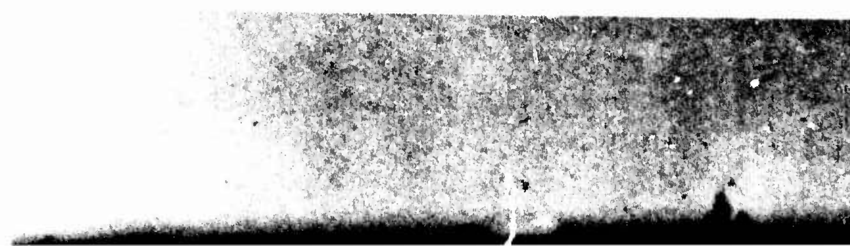
1

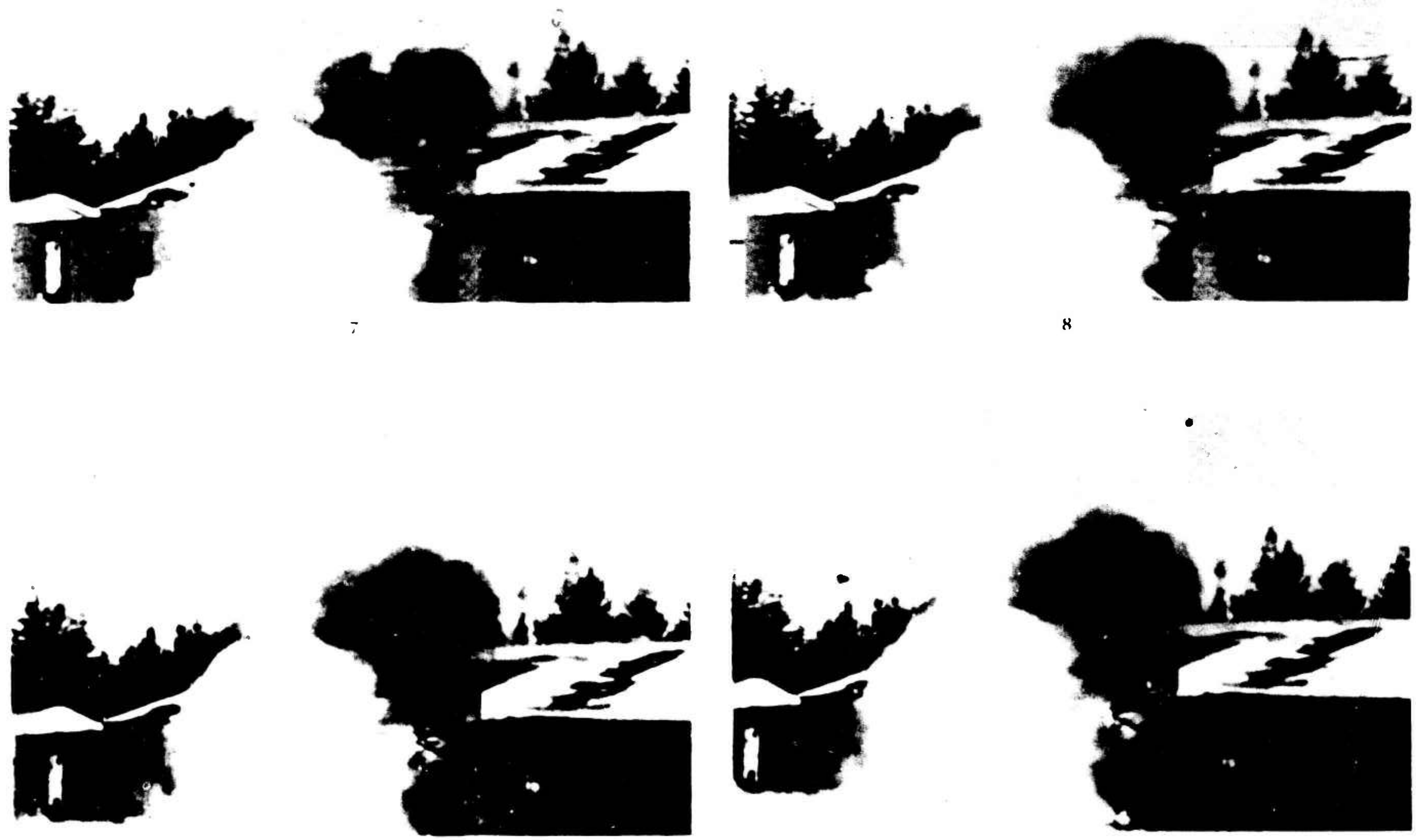
2

3

4







7 8 9 10

Figure 31. Series of photographs showing fireball formation outside of building at detonation of 20-pound charge.