URS 751-4

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EXPERIMENTS TO DETERMINE DEBRIS FORMATION FROM CORRUGATED STEEL AND BRICK WALLS

Final Report

January 1970

OCD Contract No. DAHC20-69-C-0129
OCD Work Unit No. 3313C

URS RESEARCH COMPANY

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by

James E. Edmunds

URS RESEARCH COMPANY
1811 Trousdale Drive
Burlingame, California 94010

for

OFFICE OF CIVIL DEFENSE
Office of the Secretary of the Army
Department of the Army
Washington, D.C. 20310

OCD Contract No. DAHC20-69-C-0129
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OCD REVIEW NOTICE

ABSTRACT

Four corrugated steel industrial-type wall panels were tested in the URS Shock Tunnel Facility to obtain information regarding debris formation and distribution.

Two of the panels, tested at an incident overpressure of about 0.5 psi, were deformed, but remained in place. The other two were torn loose and transported approximately 35 ft at about 2 psi.

The tests showed that there would be a considerable amount of damage to controls and wiring on industrial machinery at incident overpressures of 2.0 psi.

Debris data (crack patterns and fragment sizes and weights) from previous tests of brick wall panels performed for Work Unit 1123D indicate that missiles from brick wall panels can cause severe damage.

URS 731-4
SUMMARY

EXPERIMENTS TO DETERMINE DEBRIS FORMATION FROM CORRUGATED STEEL AND BRICK WALLS

by

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SUMMARY

The objective of this effort was to obtain experimental information regarding debris formation and distribution from corrugated steel industrial-type wall panels, using the URS Shock Tunnel Facility.

The panels were 7 ft, 6 in. high and 10 ft long and were supported on horizontal channels. Four tests were run, two at an average incident overpressure of 0.5 psi, and two at an average incident overpressure of 2.1 psi. These overpressures corresponded to incipient failure and destruction.

The walls tested at the lower overpressure were deformed, but remained in place. The walls tested at the higher overpressure were torn loose and moved about 35 ft, with the majority of the sheets remaining attached to the channels.

From the information gathered, it was concluded that, at incident overpressures of 2.0 psi, the controls and wiring on industrial machinery would be damaged considerably if the machinery were housed in buildings with this type of wall.

Debris data (crack patterns and fragment sizes and weights) from previous tests of brick wall panels performed for Work Unit 1123D are included. These data indicate that fragments of brick walls can be quite large and capable of causing severe missile damage.

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Section 1
OBJECTIVES

The objective of this effort was to obtain experimental information regarding debris formation and distribution. This was to be accomplished by experiments conducted in the URS Shock Tunnel Facility. The information was to be used by the Office of Civil Defense in order to improve the debris prediction techniques and estimates of the damage caused by debris being transported.

The emphasis was to be placed on industrial-type wall panels, since other types of panels (mostly masonry) have been and are being tested in the URS Shock Tunnel for Work Unit 1123E. To gather the pertinent data, the existing methods of determining the debris fragments' initial velocity and size had to be improved. A portion of the effort was devoted towards finding the best way to obtain this information.

Section 2
EXPERIMENTAL PROGRAM

GENERAL

The purpose of these tests was to provide information about debris formation and distribution from industrial-type exterior wall panels. The panels tested were to be different from those that had already been tested in other experimental programs conducted in the URS Shock Tunnel Facility, so brick and wood stud walls were not considered. Concrete or masonry block walls were not tested as it was felt that their response would be quite similar to that of the brick walls that were being tested in an experimental program for Work Unit 1123D.

Metal walls, either corrugated or flat, are common to industrial-type buildings, and it was decided to study these. The flat metal panel wall is becoming popular, because it is more architecturally pleasing than the corrugated type. However, there are many types of flat panels, with various schemes of fastening them to the frame of the building. Included in this category are window walls, which are becoming quite popular in modern building design. These metal walls are designed to resist horizontal wind forces, and their vertical strength is limited to that necessary to support their own weight. They are fastened to the building frame only to the extent necessary to withstand the wind loadings; very little reserve strength is present. Flat metal walls are either bolted to small angles that are bolted to the frame of the building, or spot welded to angles that are welded to the building frame. Corrugated metal sheets are fastened to girts (horizontal members) with self-tapping metal screws, and the girts are bolted or welded to the frame of the building.

It is felt that the method of fastening the corrugated sheeting to the girts provides somewhat more resistance than the method of fastening the flat metal panels. Under a blast loading, the corrugated sheets will deform around the girts and are not likely to become detached until the girts fail. The flat metal panels will shear their connecting bolts and will be free to translate.

Because of the many different kinds of flat metal panel walls and their associated fastening systems, it was decided that testing of a representative type would be quite difficult to accomplish. A flat metal wall for an industrial building was tested as part of Operation TEAPOT in 1955. This was a steel-frame building with aluminum panels (Reynolds-Butler building) having high rib corrugations 12 in. on centers and approximately 1 in. deep. This structure was severely damaged, with much of the siding torn off and permanent frame displacement at an incident overpressure of about 3.0 psi.* The design of a corrugated metal wall, however, is quite straightforward and would be typical of all the corrugated metal industrial walls in existence, thereby permitting extrapolation of the test results to other corrugated walls. Hence the tests were limited to this type of wall.

TEST REQUIREMENTS

The test objectives were to determine the failure patterns of corrugated steel walls. The objectives included determination of the failure overpressure, the load transmitted by the wall before it failed, whether the wall failed as a unit or sheet by sheet, the velocities of the failed pieces, and the strains experienced by the sheets during the failure process.

To accomplish these objectives, the instrumentation had to be improved in two areas. The lighting for the high-speed motion picture photography had to be improved and a method found to measure the initial velocities.

The lighting was improved by adding flash bulbs on the upstream side of the wall. These flashbulbs were placed in a blast-resistant enclosure and fired at the same time the charge was triggered. Two of the problems encountered in trying to observe the wall motions with the side-on camera had been that the smoke (from the detonation) coming through the opening in the failing wall would obscure the wall and that the wall fragments would block out the lights. The upstream lights have helped in both situations, although the smoke problem will always exist to some degree. A camera was

*Johnston, Bruce G., Damage to Commercial and Industrial Buildings Exposed to Nuclear Effects, WT 1189, Federal Civil Defense Administration, Feb 1956.

installed upstream of the test wall location, so that there were now three camera locations for the tests, one upstream, one downstream, and one side-on about 5 ft behind the wall.

Determining the best method to measure initial velocities involved examining several different measuring schemes. In previous tests (Work Unit 1123D), displacement gauges were used that measured only a limited displacement (less than 1/4 in.). This was inadequate, and the gauges were generally destroyed after two or three tests, which was expensive. A method evaluated for measuring velocity (measurement of either velocity, or displacement, as a function of time was desired) was the use of optical displacement techniques. URS has optical displacement followers (Optrons) that can track a target through 5 in. of travel. The Optron is focused on the target, and uses light coming from the target to "lock on" and follow the motion of the target. The Optron needs to have a stable mounting system, and the target needs a constant level of illumination. Since these conditions would be quite difficult to achieve in the environment of the shock tunnel, the idea of using the Optrons was discarded. The use of high-speed motion picture photography against a background grid was not feasible since the lighting conditions cause the cameras to be operated at a speed such that the resolution between frames would be inadequate for precise motion measurements. The scheme that was adopted is based on using a velocity gauge that is attached to a rigid mount on the upstream side of the wall. The movable, or sensing, element of the gauge is attached to the wall. The gauge generates a voltage that is proportional to the relative velocity between the fixed and sensing elements. The limit of travel for this gauge is approximately 4 in., after which a mechanical stop causes it to be separated from the wall. This gauge is manufactured by the G.L. Collins Corporation, Long Beach, Calif.

A shock wave time-of-arrival gauge was developed consisting of two sheets of aluminum foil separated by a small air gap. These sheets are wired to a battery and act as a switch when the shock wave pushes them together.

Two types of crack gauges were developed, although it was not necessary to use them with the corrugated metal panels. The first type consists of a strip of epoxy which is made conductive by the inclusion of very fine aluminum particles. The second type is fabricated by imbedding a very thin (approximately 1/8 in. wide) aluminum foil strip in a brittle epoxy. Both types are fabricated in place on the back of the wall panels, are 18 to 36 in. long, and are placed at the points of anticipated maximum stress. The flow of electricity through the strips is interrupted when the wall cracks, and the time of the crack relative to the time of arrival of the shock wave is recorded.

Strain gauges were also attached to the wall, at the points of maximum and minimum deflection, to monitor strains in the wall. SR-4 strain gauges, made by BLH Electronics, Inc., were used, and their outputs fed into either an oscilliscope or a tape recorder.

The total loads on the panel were monitored by four load cells, one at each panel corner. The load cells were connected to the tape recorder.

DESIGN OF CORRUGATED METAL WALLS

Once the wall type was chosen, it was necessary to design the wall and its supporting structure. The objective was to design a wall representative of what would be found in a typical industrial building (Fig. 1 shows this type of building) and to design the wall section so that its loads and

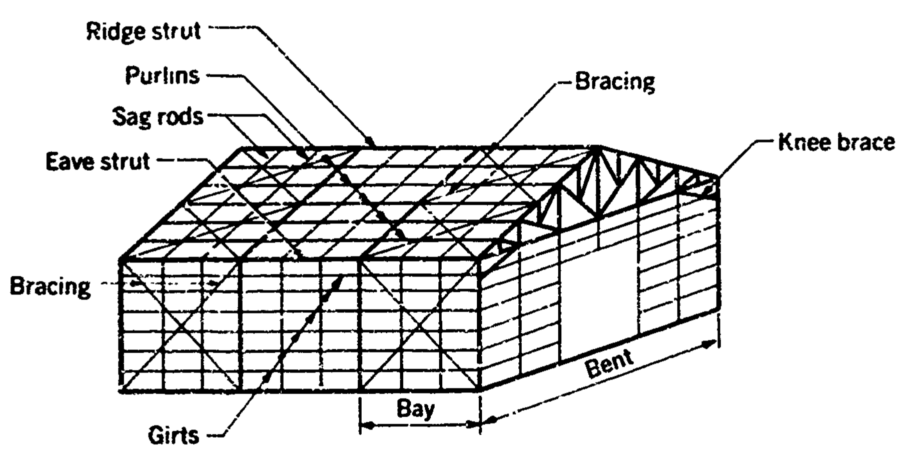

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Fig. 1. Structural Framing for Industrial Building

reactions would be similar to the loads and reactions experienced by a wall section that was part of a full-sized structure. In other words, the wall had to respond just as if it were part of a much larger wall and not just an 8- by 11-ft panel.

The design requirements were for the wall to be capable of withstanding a 30-psf wind load, which was chosen to represent a design wind loading on a building between 30 and 50 ft tall located in the central United States. It was felt that this loading condition would add to the "typicality" of the wall section being tested.

The problem of making the wall section "feel" the same loads it would if it were a portion of a much larger wall was more difficult. The placement of the supports for the wall was the critical item. The open cross section of the tunnel is $8\frac{1}{2}$ by 12 ft, but this was reduced by the permanent supporting framework to an open area of $7\frac{1}{2}$ by 10 ft. It was desirable to have two supporting channels for the wall, but their spacing and orientation (horizontal or vertical) had to be decided. A horizontal position was chosen, both for ease of attaching the channels to the supporting trusses and so that the length of the channels would be great enough to cause them to be stressed somewhat close to yielding. The smallest available channel, oriented vertically, would be capable of withstanding a 45-psf wind load. It was not possible to obtain a channel of small enough cross section to realistically model a wall designed for a 30-psf wind loading. Using a vertically oriented channel, then, would produce atypical failure characteristics under blast loading.

The spacing of the supporting channels was important also. The distances between the channels, and between the channels and the ends of the corrugated sheets, determine the characteristics of the panel loading. In a real wall, a panel is generally supported in three locations — at either end and in the center. An individual panel is not isolated from adjacent panels. There are end and side overlaps, but the end overlaps could not be duplicated in the shock tunnel. It was decided to use full-height panels with the horizontal channels placed at the approximate third-points of the sheets. It was felt that this configuration simulated actual conditions well. The test wall lost strength (compared to an actual wall) because it was not fastened at the top and bottom, thus causing the girts to carry the entire load. However, the top and bottom of the panels deflected, causing the wall loading to be slightly less than it would have been with complete fastening. The loss of strength was probably greater than the decrease in load, but there was probably no significant difference in strength between the test wall and an actual wall.

TEST RESULTS

As mentioned, the tests were planned for two different overpressures, 1.5 psi and 2.5 psi. The lower overpressure was to be at the threshold of damage and the higher was to be sufficient to cause destruction. Practically speaking, it is not possible to obtain an exact pressure in the shock tunnel, and furthermore, the nature of the process used is such that these particular overpressures are not within the range of overpressures usually obtained. As may be seen in Fig. 2, 2.5 psi is not realistically attainable since three strands of Primacord will usually give a higher overpressure (about 95 percent of the time) and two strands will virtually never give 2.5 psi. A two and one-half-strand test requires half-strength Primacord, which has very uncertain reliability and is not used. An overpressure of 1.5 psi is attainable about 30 percent of the time with two strands; but since only two tests were planned, these odds were considered too unfavorable. It is possible to utilize a single strand, but the shock wave from this is quite unlike the shock wave from a nuclear weapon, i.e., its rise time is slow and the pulse shape is quite rounded. One strand gives a peak overpressure of about 1 psi.

After some thought concerning these problems, it was decided that it would be better to err on the low side of the desired overpressures rather than the high side. It was almost a certainty that the expected damage would occur at higher overpressures than 1.5 and 2.5 psi. The wall response at the lesser overpressures was less certain, but there was a possibility that the anticipated damage would occur. One strand was expected to give about 1 psi, and two strands were expected to give about 2 psi. If the wall wasn't damaged sufficiently by the two-strand shots, then two additional tests,

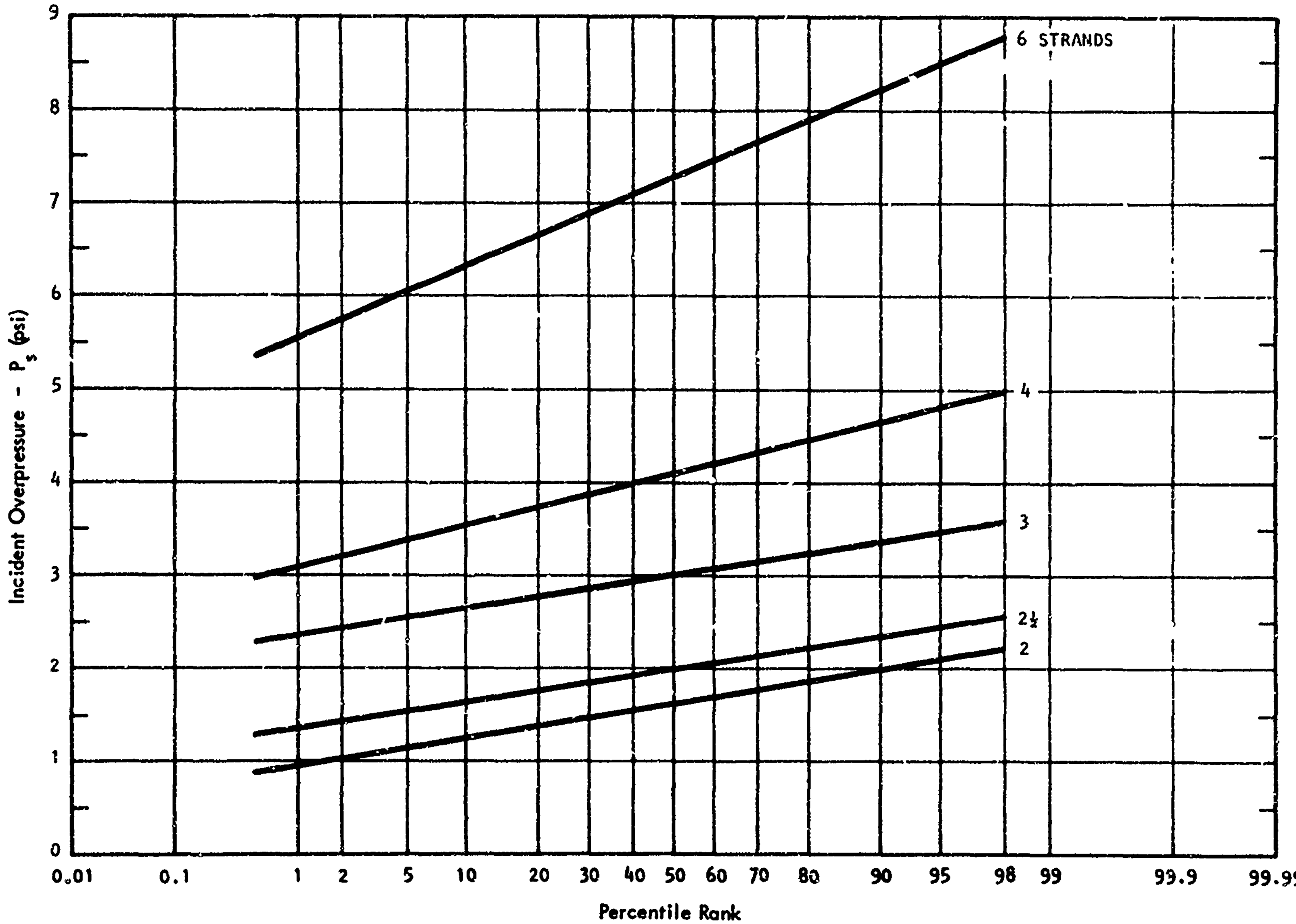

Fig. 2. Distribution Curves Showing Frequency of Occurrence of Overpressures Below a Given Magnitude as a Cumulative Percent of the Total Observations for Various Numbers of Strands of Primacord Ignited

using three strands, could be conducted; if the damage was sufficient, no moretests would be necessary.

The wall configuration was as shown in Fig. 3. The horizontal channels supporting the corrugated sheets were bolted (with 1/4-in. bolts) to vertical 10 in.-wide flange beams, which were fastened to the horizontal trusses that were used to transmit the loads to the load cells. The height of the sheets was made 1 ft less than the height of the tunnel so that as the sheets deflected under the blast loading, they miss the horizontal trusses, which projected 6 in. into the tunnel. This open space was closed off with a timber so that the shock wave loading would not be relieved through the open space, but only by means of the wall failing. It was felt that there was more of a chance of the bottom sheets striking the truss due to gravity forces pulling the wall downwards as it failed; hence the sheets were extended to the ceiling of the tunnel and the timber used to close off the bottom. Pictures of the test setup are shown in Fig. 4. The framework in front of the wall supports the velocity gauge, and the square plate attached to the wall is the time-of-arrival gauge. The wires coming out of the rear of the wall are the strain gauge leads. The sheets are fastened to the wall by Number 14 self-tapping sheet metal screws on 12-in. centers.

The instrumentation was connected to a 14-channel Consolidated Electrodynamics Corporation tape recorder, and dual-channel Tektronix oscilloscopes. A time-mark generator was used to place timing signals on the tape. The instrumentation consisted of:

- five air pressure gauges
- six strain gauges
- four load cells
- one velocity gauge
- one time-of-arrival gauge

The load cells were located at the corners of the wall. Their readings were influenced because of the loading on the surface area of the vertical wide-flange beams and on the horizontal timber used to close the bottom of the wall. Another shortcoming of the load cell readings is that the load

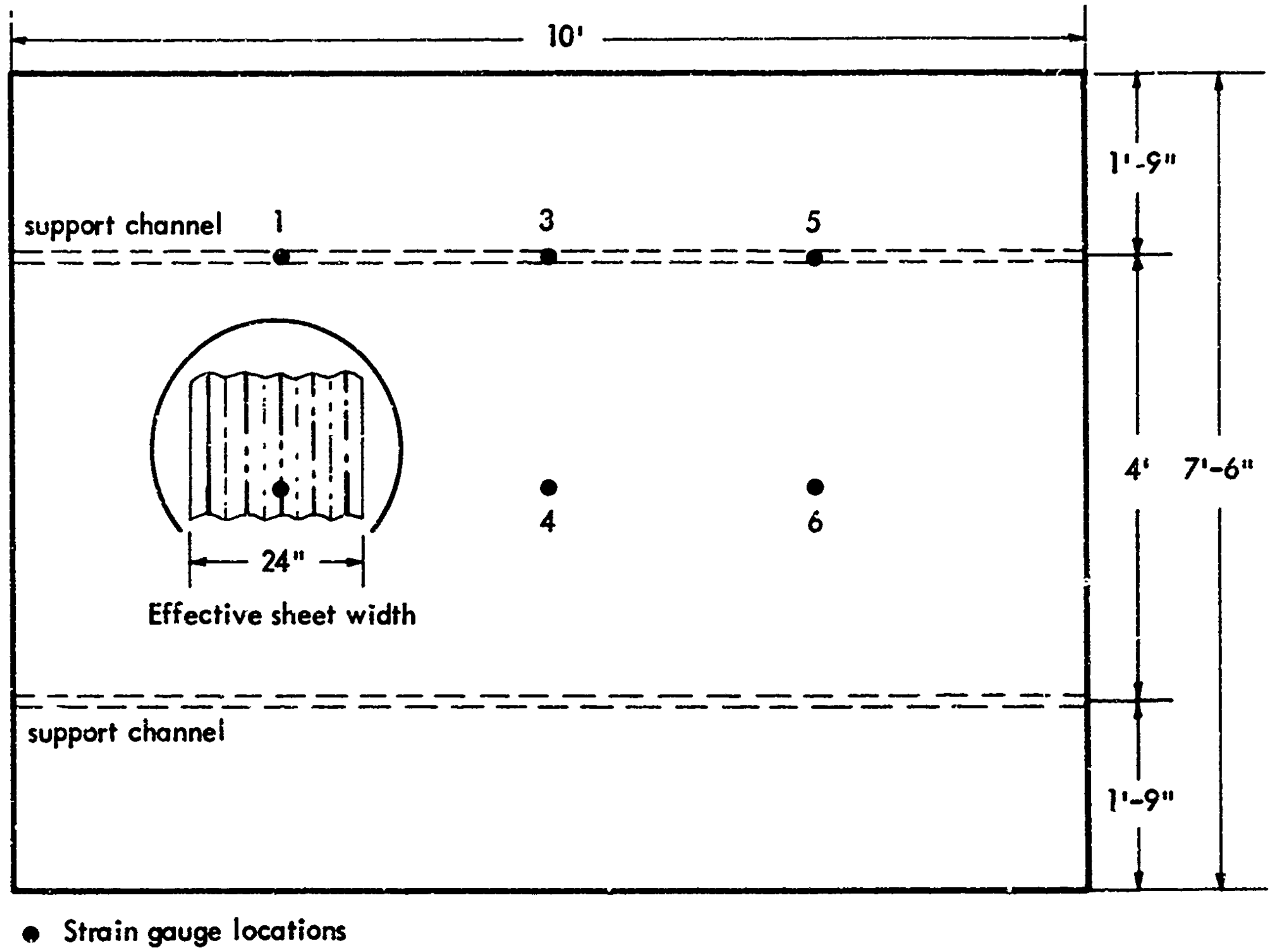

Fig. 3. Corrugated Steel Test Wall

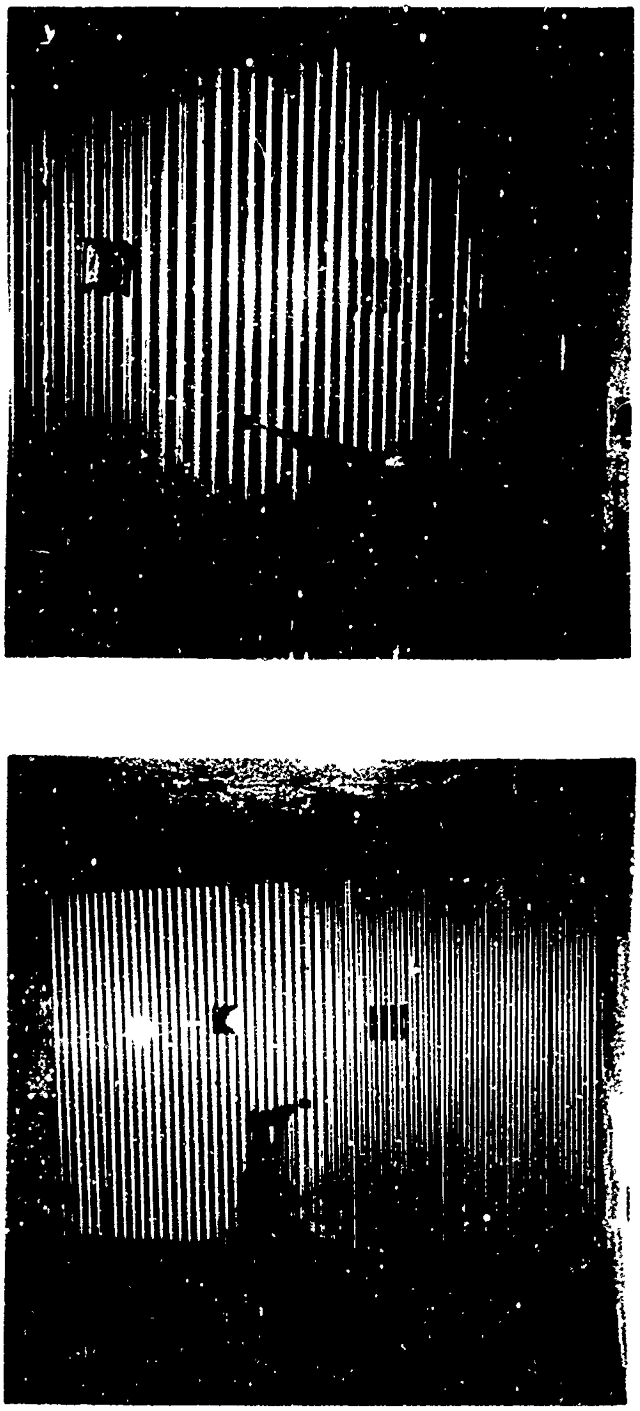

Fig. 4. Pre-test Views of Wall

cells used had a maximum capacity of 200,000 lb, and the maximum reading expected was on the order of 30,000 lb, or about 15 percent of full scale. This meant that their output was very low (especially since a 30,000-lb reading was never achieved), and it was difficult to get a clean trace because of the ambient electronic noise.

The air pressure gauges were located as shown in Fig. 5. Gauge number 1 was located 25.6 ft in front of the wall, gauge number 7 at 1.7 ft in front, and gauge number 11 at 3.7 ft in front. Gauge number 9 was located 1.7 ft behind the wall, and gauge number 10 was 6.7 ft behind. The purpose of the gauges in front of the wall was to determine the incident overpressure on the wall. The gauges behind the wall wer to determine the rate of pressure buildup behind the wall. If the buildup was slow, then the potential damage to equipment due to overpressure effects behind the wall would be less than if there was a rapid buildup.

The data from the tests are presented in Table 1. Four tests are listed, although five were actually run. The first one resulted in very little data and was considered to be more of a "shakedown" test. These data were obtained from the tape recorder and oscilliscope records taken during the tests. Occasionally the gauges did not operate and this is indicated by the dash in the column. The problem with the strain gauges is one of proper bonding to the corrugated galvanized sheet metal walls. Proper bonding requires extremely careful surface preparation. It wasn't possible to test the bond of the strain gauges adequately without the possibility of loosening them and endangering the integrity of the bond during the actual test. For Test 4, the type of strain gauge used was changed from a foil-type to a wire-type, which gave better results. The locations of the strain gauges are indicated in Fig. 1.

The test objectives were met, even though the instrumentation did not perform to expectation. These objectives were to test a corrugated steel wall at an overpressure less than failure and at an overpressure greater than failure. The tests at the lower overpressure bent the sheets and the horizontal channels, but the wall remained in place. The higher overpressures caused the sheets, together with the horizontal channels, to be torn loose

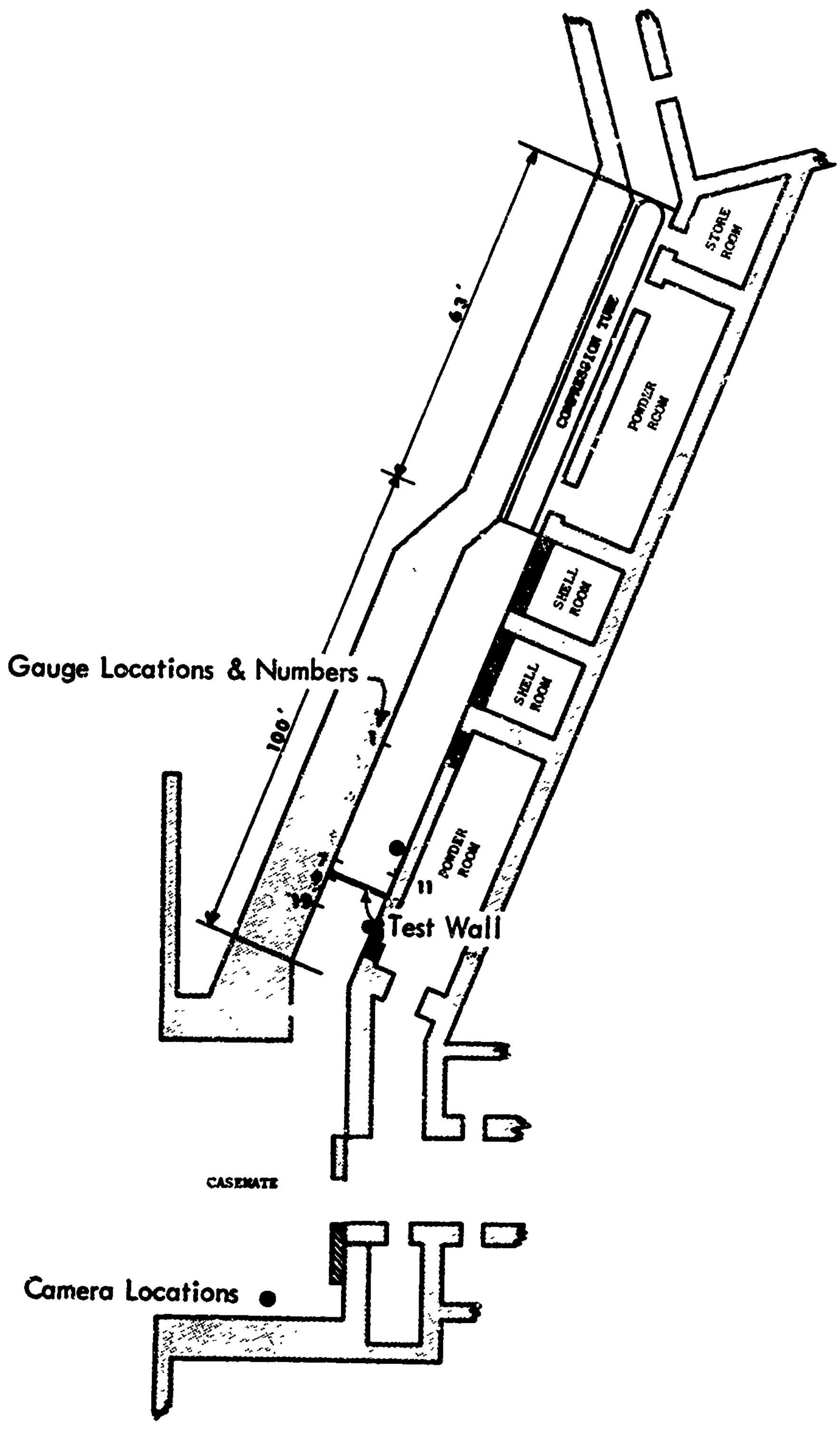

Fig. 5. Plan View of Shock Tunnel Facility

Table 1

TEST RESULTS

Gauge Description	Test 1	Test 2	Test 3	Test 4	Remarks
Air Pressure Gauge #1	0.8 psi	0.5 psi	2.1 psi	2.3 psi	All air pressure read-
Air Pressure Gauge #7	0.4 psi	0.6 psi	2.1 psi	2.2 psi	ings are for incident
Air Pressure Gauge #11	0.2 psi	0.3 psi	1.8 psi	1.9 psi	overpressures.
Air Pressure Gauge #9	-	0.4 psi	1.3 psi	0.8 psi	Test 4 goes off scale.
Air Pressure Gauge #10	0.6 psi	-	2.7 psi	1.1 psi	
Load Cell #1	-	2,000 lb	5,500 lb	8,000 lb	
Load Cell #2	500 lb	8,000 lb	4,600 lb	2,000 lb	
Load Cell #3	3,000 lb	18,500 lb	15,000 lb	20,500 lb	
Load Cell #4	1,000 lb	2,000 lb	-	6,500 lb	
Strain Gauge #1	3.52×10^{-3} in./in.	6.32×10^{-3} in./in.	2.17×10^{-3} in./in.	1.83×10^{-3} in./in.	
Strain Gauge #2	-	-	-	3.36×10^{-3} in./in.	
Strain Gauge #3	-	-	-	3.19×10^{-3} in./in.	
Strain Gauge #4	-	2.15×10^{-3} in./in.	-	0.996×10^{-3} in./in.	
Strain Gauge #5	-	-	2.67×10^{-3} in./in.	1.59×10^{-3} in./in.	
Strain Gauge #6	-	-	8.59×10^{-3} in./in.	-	
Velocity Gauge	124 in./sec	276 in./sec	658 in./sec	660 in./sec	Test 1 goes off scale at 124 in./sec

and translated down the tunnel (Fig. 6). The load on the horizontal channels caused shearing of the 1/2-in. bolts fastening them to the vertical supports. In Test 3, the sheets were still attached to the channels after the assembly came to rest; in Test 4, some of the sheets came off of the channels.

The air pressure gauge readings indicate the unreliability of the single-strand detonations. Adding to this problem is the electronic noise that accompanies low output. The amplification necessary to produce a readable signal also amplifies the "noise," making it more difficult to pick the correct peak. Tests 3 and 4, with the higher overpressures were more consistent. Gauges 1, 7, and 11 were in front of the wall. Thus the overpressures indicated for these gauges were incident overpressures. Gauges 9 and 10 are behind the wall and do not sense any reflected pressure, but a slow buildup as the wall deflects.

The load cell readings, for reasons discussed previously, vary considerably and are not reliable. The loss of these data is not critical, however, since the very low overpressures at which the walls become debris are not great enough to produce a loading sufficient to damage the building frame.

The strain gauge readings also vary considerably, and it is more difficult to determine the reasons for this. Bonding problems could be responsible. The theoretical maximum elastic strain is approximately 1×10^{-3} in./in. The theoretical ultimate strain is approximately 200×10^{-3} in./in. The strain gauges were located where the strain would be the greatest. However, the corrugated sheets did not bend exactly as expected. As may be seen in Fig. 7, the bends were abrupt, not gradual as might be anticipated.* Also, the sections of the sheets that were not bent remained fairly straight. The bends did not appear in the same place for each test; consequently it was a matter of chance whether or not the strain gauges were located on a bend.

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* Although this picture is of a wall (Test 2) that did not tear loose, those that did tear loose were bent in the same way.

Fig. 6. Post-test View of Wall Translated Down Tunnel

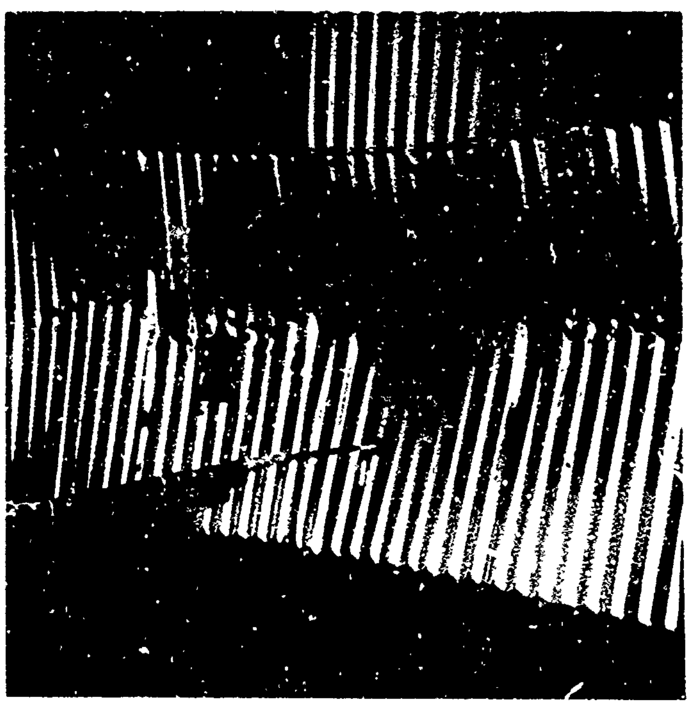

Fig. 7. Post-test View of Non-failing Wall

If they were, or almost were, the strain reading would be large; if they weren't, the strain reading would be small. For this reason there is no correlation between the strain gauge readings.

DISCUSSION OF TEST RESULTS

As stated, the primary test objectives were achieved. There were two tests in which the wall failed, and two in which it didn't. The manner in which the wall failed was as expected. The sheets deflected around the horizontal channels, and the entire assembly failed by shearing the bolts fastening the channels to the vertical columns. The average incident overpressures for these tests were approximately 0.5 psi for the no-failure case and approximately 2.1 psi for the failure case. Comparing these to the overpressures predicted by using the data from Hiroshima and Nagasaki and the weapons tests in which there were few failures at less than 1.5 psi and all walls failed at 2.5 psi* leads one to suspect that the empirically derived overpressures could be high. Many more tests than were performed in this study would be necessary to confirm this, and for the purposes of this report, the critical overpressures will remain at 1.5 and 2.5 psi.

Since numerical data were lacking, the high-speed photography was important in analyzing the tests. One finding from the motion pictures was that the walls did not tear loose from the vertical supports until the positive phase was almost complete. Consequently, the walls were only transported a short distance, about 8 ft, before they struck the ground in an essential horizontal position. They slid along the floor of the tunnel for approximately 30 ft more before coming to rest. Had the duration of the positive phase been much longer (a megaton-size weapon would have a duration at least fifty times longer than that obtained for these tests in the shock tunnel), then both the panels and the individual sheets would have been translated a much greater distance. As it was, the panels got essentially no aerodynamic translation ascribable to the blast force. The blast force was little more than enough to shear the bolts that connected the panels to the vertical supports.

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* Edmunds, J. E., C. K. Wiehle, and K. Kaplan, Structural Debris Caused by Nuclear Blast, URS 639-4, Contract No. OCD-PS-64-19, URS Corporation, Burlingame, Calif., Oct 1964.

This fact makes predictions of transport distance based on these test results impossible. It was hoped that the velocities of the panels, as they came free and were translated down the tunnel, could be obtained; but once the panels came loose, there was very little of the shock wave's translational energy remaining. There was a slight amount of strain energy that was released when the connecting bolts sheared, adding some impetus to the panel. However, this was barely discernible in the high-speed photography and not measurable at all.

Section 3

DEBRIS FRAGMENTS FROM BRICK WALLS

As a part of this study, a review was made of the debris data resulting from previous tests of brick wall panels. These data consist of motion picture films of the tests, and post-test surveys of the wall fragments.

The data include a brief description of the tests, a bar chart showing the weight of the fragments as a function of distance from the initial position of the wall, a tabulated listing of the debris data consisting of the distance each piece was translated and the weight and number of bricks in each piece, and sketches of the walls' initial crack patterns (derived from the high-speed motion picture films). Some post-test still photographs are also included.

Of primary interest to this study were the number of pieces that the brick walls generated upon failure. This number was obtained by study of the high-speed films. The number of pieces counted after the test was not as significant, since the initial few large pieces were broken into many small pieces due to impact with the walls and floors of the tunnel. The initial number of pieces may be predicted through application of the theory of the bending of beams and plates, in which a panel supported at opposite ends (a beam) will have maximum stresses (and hence will break) in the center. A rectangular panel supported on all four sides with the edges restrained from moving (a plate) will have maximum stresses in the central portion. These stresses are fairly uniform over the central portion, causing a rectangular section to break out, as in Wall 30 (p. 57).

From the limited number of tests on plates, it appears that the number of fragments is dependent on the incident overpressure, that is, the higher the overpressure, the larger the number of fragments. For beams, however, the number of fragments is essentially independent of the incident overpressure, that number being two, or three at most.

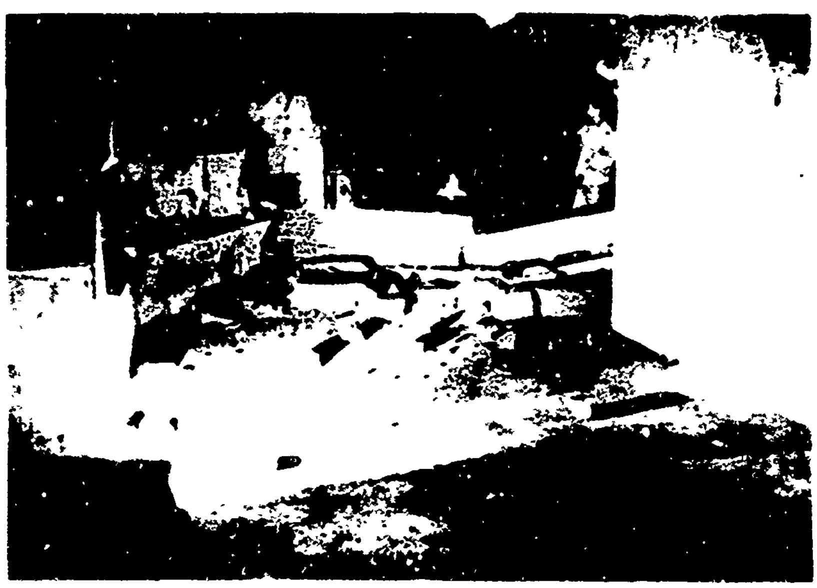
WALL PANEL TEST REPORT

Wall Number 1

Type of Wall: 8-in. nonreinforced brick with simple beam support condition.

Peak Reflected Overpressure: 3 psi

Results: First crack appeared at height of ~ 5-1/2 ft and was essentially horizontal across width of wall. The wall failed and the majority of the brick was found within ~ 20 ft of the original wall location. Several large pieces of the wall landed within first 4 ft (on truss). See photo below.



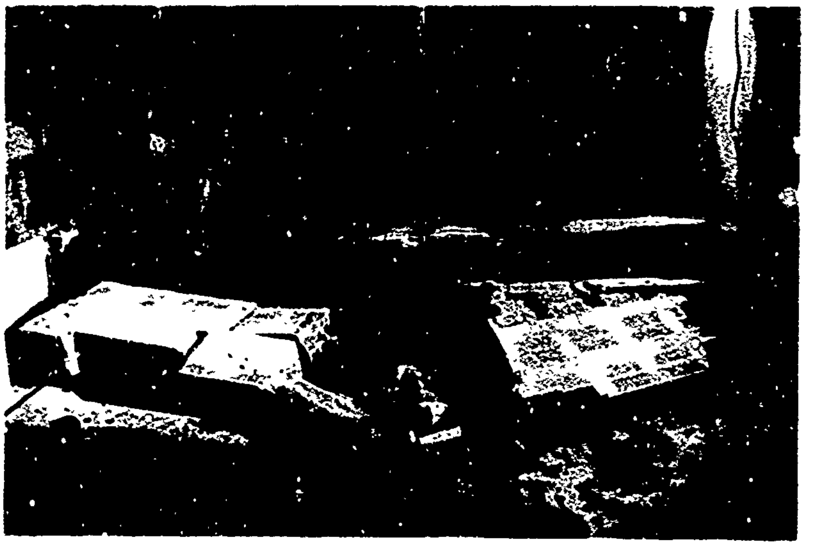
WALL PANEL TEST REPORT

Wall Number 2

Type of Wall: 8-in. nonreinforced brick with simple beam support condition.

Peak Reflected Overpressure: ~ 3.5 psi

Results: The first crack was a staggered horizontal line at a height of ~ 4 ft. The wall failed and the majority of the brick was found within 20 ft of the original wall location, with several large pieces on the lower truss (see photo).



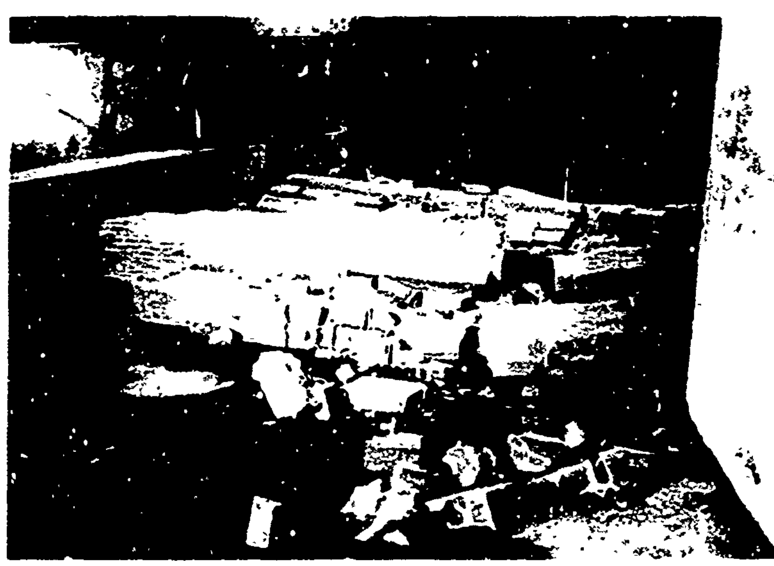
WALL PANEL TEST REPORT

Wall Number 3

Type of Wall: 8-in. nonreinforced brick with simple beam support condition.

Peak Reflected Overpressure: ~ 3.5 psi

Results: The first crack appeared as a horizontal line at a height of ~ 4 ft. The wall failed, and the majority of the brick was found within 20 ft of the original wall location. A few pieces remained within 4 ft of their original location, but the majority of the debris was recovered at distances between 4 and 15 ft. (See photo)



WALL PANEL TEST REPORT

Wall Number 4

Type of Wall: 8-in. nonreinforced brick with simple beam support condition.

Peak Reflected Overpressure: 10 psi

Results: First cracks were two horizontal lines at heights of ~ 4 and ~ 5.3 ft. The wall failed and debris scattered as far as 77 ft. (See photo below).

WALL NO. 4

DEBRIS SURVEY

Distance Feet From Wall	Number of Bricks	Weight Lb.	Distance Feet From Wall	Number of Bricks	Weight Lb.
77	1	8.05	44	8	64.40
77	4	32.20	34	1	8.05
77	3.5	28.18	34	4	32.20
62	1	8.05	34	3	24.15
54	1	8.05	33	6	48.30
54	10	80.50	33	14	112.70
54	3	24.15	33	14	112.70
52	11	88.55	32	50	402.50
52	12	96.60	32	1	8.05
51	1	8.05	32	16	128.80
49	15	120.75	30	2-Singles	8.05
47	2	16.10	29	3-Singles	8.05
47	1	8.05	29	6.5	52.33
47	10	80.50	29	20	161.00
46	60	483.00	27	4	32.20
46	1	8.05	27	2	16.10
44	2	16.10	25	1	8.05

WALL NO. 4 Cont.

DEBRIS SURVEY

Distance Feet From Wall	Number of Bricks	Weight Lb.	Distance Feet From Wall	Number of Bricks	Weight Lb.
25	3	24.15			
24	5	40.25			
24	8	64.40			
23	2-Singles	8.05			
23	2	16.10			

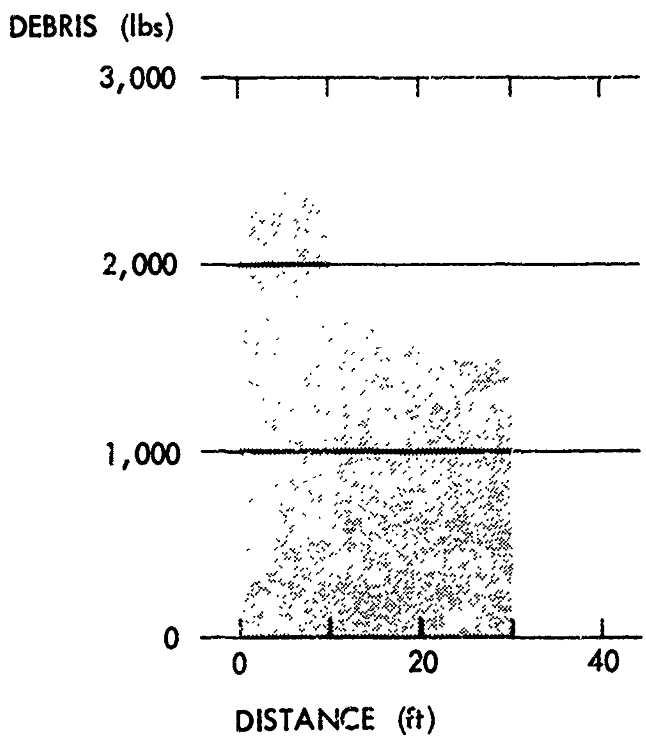
WALL PANEL TEST REPORT

Wall Number 5

Type of Wall: 8-in. nonreinforced brick with simple beam support condition.

Peak Reflected Overpressure: 3.6 psi

Results: The wall collapsed and debris scattered to 24 ft (See debris distribution chart below).



Debris Distribution, Wall Number 5

WALL NO. 5

DEBRIS SURVEY

Distance Feet From Wall	Number of Bricks	Weight Lb.
24	5	40.25
24	2	16.10
20	100	805.00
20	85	684.25
18	80	644.00
18	10	80.50
12	80	644.00
12	16	128.80
12	7	56.35
12	6	48.30
12	12	96.60
9	40	322.00
9	14	112.70
9	12	96.60
9	12	96.60
9	16	128.80
9	14	112.70

Distance Feet From Wall	Number of Bricks	Weight Lb.
6	10	80.50
5	15	120.75
0-4	170*	1,368.50

*On truss size distance not known.

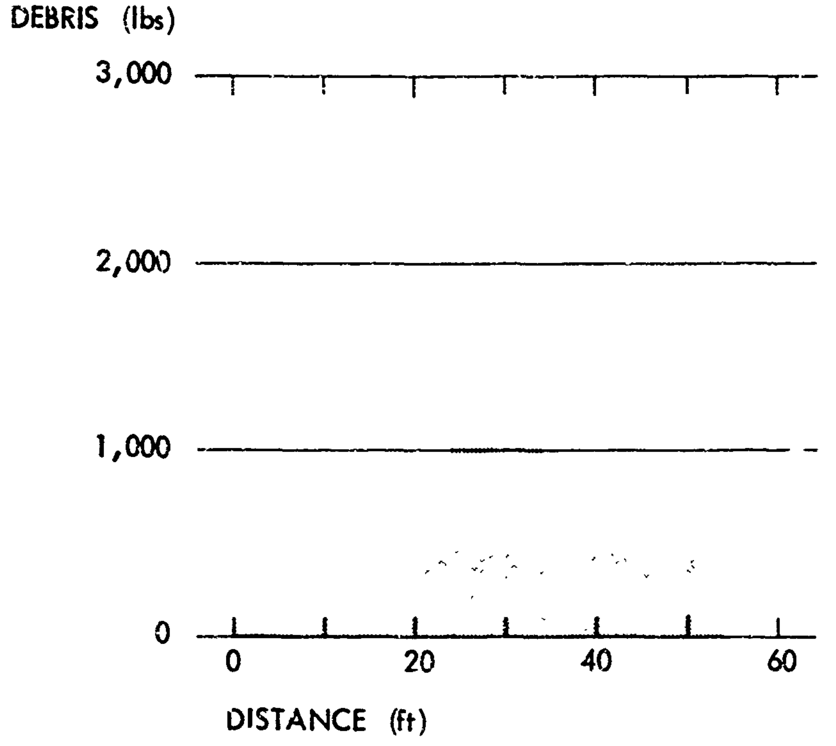
WALL PANEL TEST REPORT

Wall Number 6

Type of Wall: 8-in. nonreinforced brick with simple beam support condition.

Peak Reflected Overpressure: 10.1 psi

Results: First cracks appeared as horizontal lines at heights of ~ 4 and ~ 6 ft. The wall failed and debris scattered to 54 ft. (See debris distribution chart below).



Debris Distribution, Wall Number 6

WALL NO. 6

DEBRIS SURVEY

Distance Feet From Wall	Number of Bricks	Weight Lb.	Distance Feet From Wall	Number of Bricks	Weight Lb.
54	6	48.30	44-49	2	16.10
54	5	40.25		4	32.20
49-54	2	16.10		3	24.15
	21	169.05		5	40.25
	4	32.20		10	80.50
	4	32.20		1	8.05
	3	24.15		5	40.25
	1.5	12.08		1	8.05
	10	80.50		1	8.05
	4	32.20		3	24.15
	5	40.25		1	8.05
	4.5	36.23	44	1	8.05
	15	120.75	44	2	16.10
	4	32.20	44	3	24.15
	3	24.15	39-44	32	257.60
49	6	48.30		2	16.10

WALL NO. 6 Cont.

DEBRIS SURVEY

Distance Feet From Wall	Number of Bricks	Weight Lb.	Distance Feet From Wall	Number of Bricks	Weight Lb.
39-44	5	40.25	34	2	16.10
	16	128.80	24-34	10	80.50
	10	80.50		8	64.40
	15	120.75		8	64.40
	2	16.10		10	80.50
	2	16.10		36	289.80
	8	64.40		100	805.00
39	5	40.25		18	144.90
39	11 Broken Fragments			5	40.25
39	2-Singles	8.05		5	40.25
39	2	16.10		3	24.15
39	4 Broken Fragments			4	32.20
34-39	16	128.80		3	24.15
	20	161.00	24-34	12	96.60
34	15 Broken Fragments			20-Singles	
34	5	40.25		20	161.00

WALL NO. 6 Cont.

DEBRIS SURVEY

Distance Feet From Wall	Number of Bricks	Weight Lb.	Distance Feet From Wall	Number of Bricks	Weight Lb.
24-34	30	241.50			
	20-Singles				
14-24	10	80.50			
	4-Singles				
	2-Singles				
	40-Singles				
	40	322.00			
	8	64.40			
	10	80.50			
	26-Singles				
	4	32.20			
0-14	47-Singles				

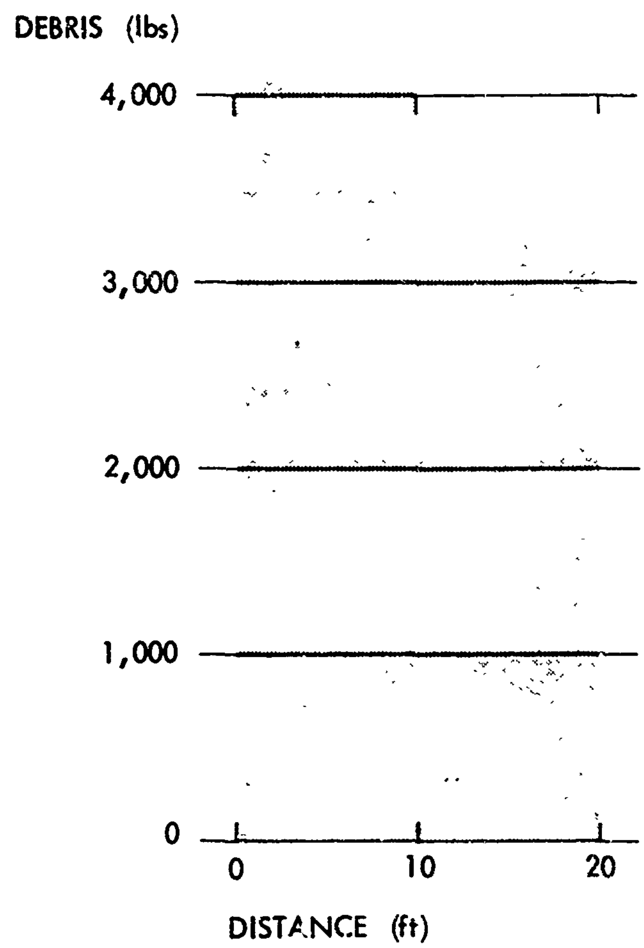
WALL PANEL TEST REPORT

Wall Number 7

Type of Wall: 8-in. nonreinforced brick with simple beam support condition.

Peak Reflected Overpressure: 3.6 psi

Results: The initial crack appeared horizontally at a height of ~ 4 ft. The wall failed and debris scattered to 19 ft. (See debris distribution chart below).



Debris Distribution, Wall Number 7

WALL NO. 7

DEBRIS SURVEY

Distance Feet From Wall	Number of Bricks	Weight Lb.	Distance Feet From Wall	Number of Bricks	Weight Lb.
19	1	8.05	12	18 Fragments	
18	7	56.35	12	200	1,610.00
16	1	8.05	10	40	322.00
14	4	32.20	10	25	201.25
14	6	48.30	9	15	120.75
14	14	122.70	9	44	354.20
14	5	40.25	9	39	313.95
14	4	32.20	7	35 Fragments	
14	4	32.20	5	60	483.00
14	20	161.00	5	28	225.40
14	4	32.20	0-4	300	2,415.00
14	6	48.30			
14	48	386.40			
14	60	483.00			
12	10	80.50			
12	20	161.00			

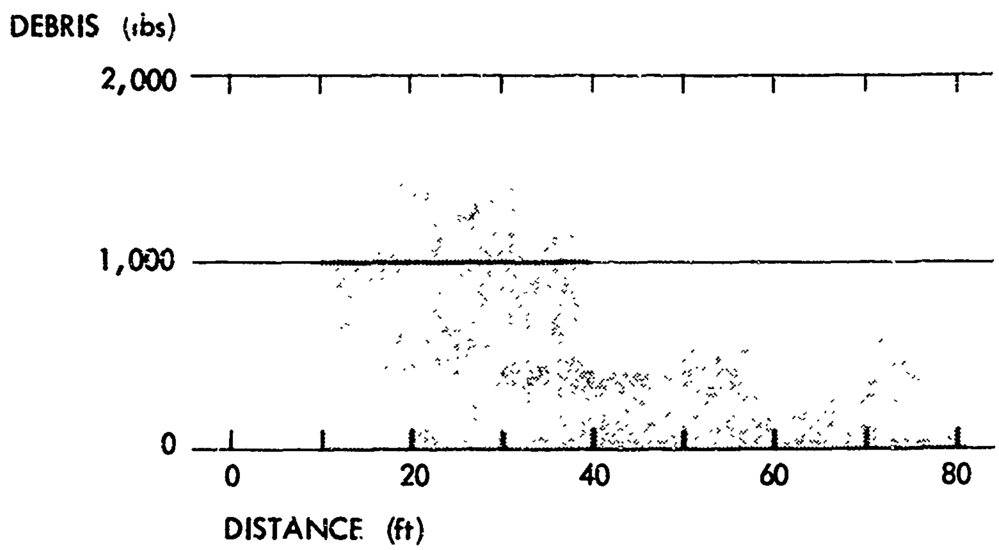
WALL PANEL TEST REPORT

Wall Number 20

Type of Wall: 8-in. reinforced brick with simple beam support conditions.

Measured Peak Reflected Overpressure: 10.3 psi

Results: Two essentially horizontal cracks occurred initially at heights of ~ 3 and ~ 5 ft. The wall failed, scattering debris to ~ 80 ft. (See debris distribution chart below).



Debris Distribution, Wall Number 20

WALL NO. 20

DEBRIS SURVEY

Distance Feet From Wall	Number of Bricks	Weight Lb.	Distance Feet From Wall	Number of Bricks	Weight Lb.
81	4-Singles		56	2	16.1
81	4	32.2	56	4	32.2
80	12	96.6	56	2	16.1
77	9	72.5	54	2	16.1
77	7	56.4	54	16	128.8
77	4	32.2	52	5-Singles	
77	2	16.1	51	12	96.6
76	37	297.9	50	15	120.8
75	10	80.5	49	2	16.1
70	4	32.2	48	5	40.3
69	14	112.7	47	1	8.1
69	7	56.4	47	3	24.2
65	4	32.2	44	8	64.4
64	10	80.5	44	4	32.2
61	1	8.1	43	5	40.3
58	14	112.7	42	4-Singles	

WALL NO. 2C Cont.

DEBRIS SURVEY

Distance Feet From Wall	Number of Bricks	Weight Lb.	Distance Feet From Wall	Number of Bricks	Weight Lb.
42	3	24.2	34	11	88.6
40	6	48.3	32	27	217.4
40	4	32.2	32	3	24.2
39	18	144.9	31	49	394.5
38	7	56.4	31	6	48.3
38	1	8.1	30	3-Singles	8.1
36	3	24.2	30	16	128.8
36	1	8.1	30	8	64.4
36	2	16.1	29	6	48.3
36	3	24.2	26	14	112.7
36	4	32.2	26	2	16.1
36	7	56.4	25	5	40.3
35	2	16.1	25	9	72.5
35	15	120.8	25	19	153.0
35	15	120.8	25	16	128.8
34	5	40.3	23	15	120.8

WALL NO. 20 Cont.

DEBRIS SURVEY

Distance Feet From Wall	Number of Bricks	Weight Lb.
23	71	571.6
21	4	32.2
21	10	80.5
20	6	48.3
20	20	161.0
20	1	8.1
19	29	233.5
18	9	72.5
18	2	16.1
17	4	32.2
17	8	64.4
16	19	153.0
16	16	128.8
15	9	72.5
15	12	96.6
14	6	48.3
14	4	32.2
13	29	233.5
12	15	120.8
12	3	24.2
11	1	8.1

0-10 Small Fragments Only.

WALL PANEL TEST REPORT

Wall Number 21

Type of Wall: 8-in. nonreinforced brick with simple beam support condition.

Measured Peak Reflected Overpressure: 3.5 psi

Results: The wall failed near the middle. The upper half broke into five sections, one piece weighing ~1,600 lb and two pieces weighing ~400 lb each. The lower half of the wall fell over and remained almost entirely on the lower truss. The base of the wall moved approximately 6 in. from point of origin.

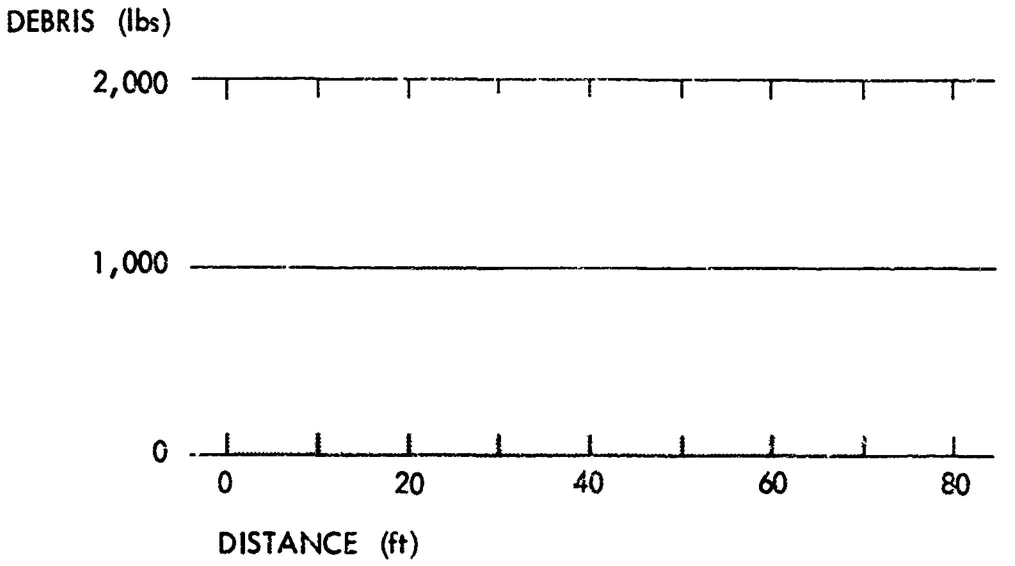
WALL PANEL TEST REPORT

Wall Number 22

Type of Wall: 8-in. nonreinforced brick with simple beam support condition.

Measured Peak Reflected Overpressure: 10 psi

Results: Two initial horizontal cracks were noted at heights of ~3 ft and 6.5 ft. The wall failed and scattered debris to 70 ft. (See debris distribution chart below).



Debris Distribution, Wall Number 22

WALL NO. 22

DEBRIS SURVEY

Distance Feet From Wall	Number of Bricks	Weight Lb.	Distance Feet From Wall	Number of Bricks	Weight Lb.
70	95	764.8	35	4	32.2
62	3	24.2	35	11	88.6
59	4	32.2	34	11	88.6
58	2	16.1	33	13	104.7
58	3	24.2	70	95	764.8
56	3-Singles	8.1	62	3	24.2
55	107	861.4	59	4	32.2
51	3	24.2	53	2	16.1
48	4-Singles	8.1	58	3	24.2
48	3	64.4	56	3-Singles	8.1
47	7	56.4	55	107	861.4
46	6	48.3	51	3	24.2
41	5	40.3	48	4-Singles	8.1
40	30	241.5	48	8	64.4
39	10	80.5	47	7	56.4
38	16	128.8	46	6	48.3
38	4	32.2	41	5	40.3

WALL NO. 22 Cont.

DEBRIS SURVEY

Distance Feet From Wall	Number of Bricks	Weight Lb.	Distance Feet From Wall	Number of Bricks	Weight Lb.
40	30	241.5	5	11	88.6
39	10	80.5	3	36	289.8
38	16	128.8	0-5	10-Singles	
38	4	32.2			
35	4	32.2			
35	11	88.6			
34	11	88.6			
33	13	104.7			
19	20	161.0			
14	6	48.3			
14	18	144.9			
14	3	24.2			
13	6	48.3			
11	9	72.5			
9	9	72.5			
9	44	354.2			

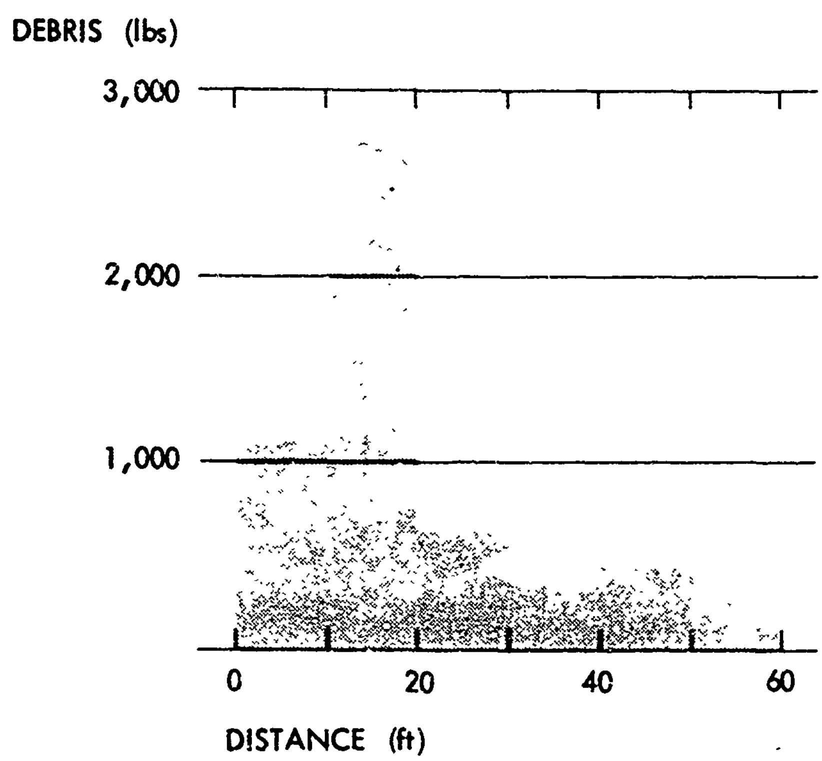
WALL PANEL TEST REPORT

Wall Number 23

Type of Wall: 8-in. nonreinforced brick with simple plate mounting condition.

Measured Peak Reflected Overpressure: 10.9 psi

Results: Initial cracks formed as shown in sketch below. The wall failed, and debris was scattered to 57 ft. (See debris distribution chart).



Debris Distribution, Wall Number 23

WALL NO. 23

DEBRIS SURVEY

Distance Feet From Wall	Number of Bricks	Weight Lb.	Distance Feet From Wall	Number of Bricks	Weight Lb.
57	2	16.1	34	6	48.3
55	2	16.1	32	28	225.4
55	1	8.1	28	12	96.6
55	31	249.6	27	31	249.6
50	12	96.6	26	2	16.1
49	2-Singles	8.1	26	2	16.1
47	11	88.6	26	2	16.1
47	6	48.3	26	5-Singles	8.1
47	2	16.1	24	1	8.05
44	8	64.4	23	6	48.30
44	2	16.1	21	15	120.75
44	2-Singles	8.1	20	32	257.60
42	4	32.2	20	22	177.10
41	16	128.8	18	49	394.45
40	4-Singles	8.1	18	41	330.05
36	1	8.1	15	5	40.25

WALL NO. 23 Cont.

DEBRIS SURVEY

Distance Feet From Wall	Number of Bricks	Weight Lb.	Distance Feet From Wall	Number of Bricks	Weight Lb.
13	27	217.35	5	16	128.80
12	7	56.35	3	13	104.65
12	20	161.00			
12	15	120.75			
12	20	161.00			
12	27	217.35			
11	9	72.45			
11	47	378.35			
10-20	17-Singles				
10	17	136.85			
9	21	169.05			
9	3	24.15			
9	22	177.10			
7	14	112.70			
7	15	120.75			
5	16	128.80			

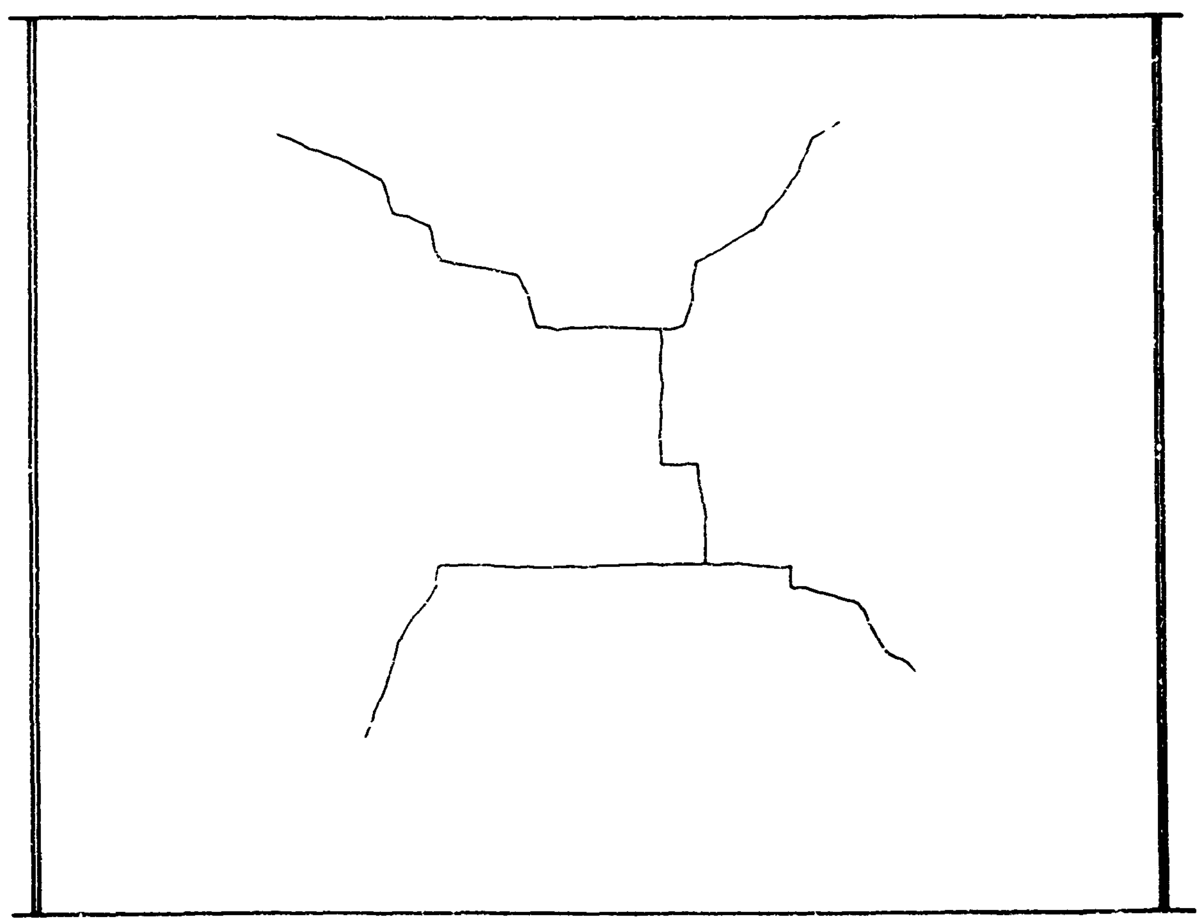
WALL PANEL TEST REPORT

Wall Number 24

Type of Wall: 8-in. nonreinforced brick with simple plate mounting system (corners restrained).

Measured Peak Reflected Overpressure: 3.2 psi

Results: The wall cracked as shown in the sketch below but did not collapse. (The wall failed on second test at 3.0 psi peak reflected overpressure).



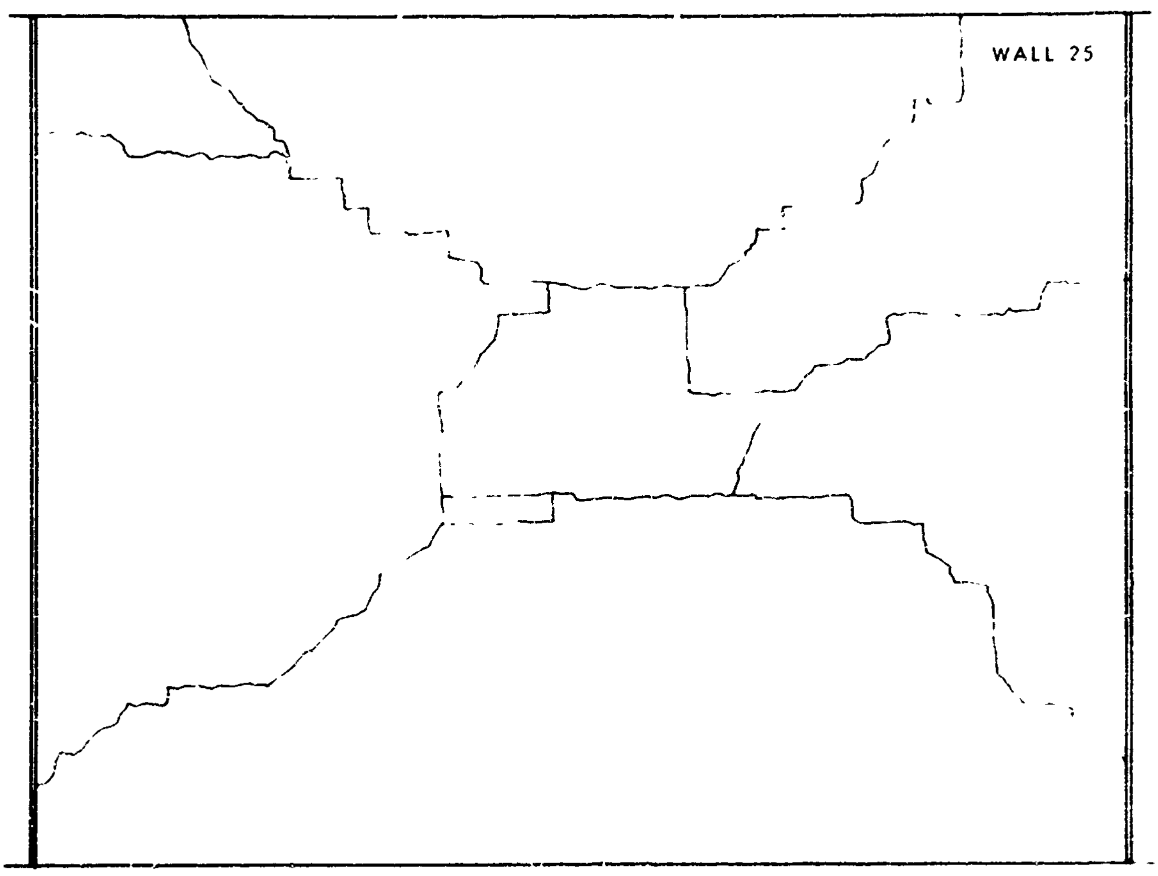
WALL PANEL TEST REPORT

Wall Number 25

Type of Wall: 8-in. nonreinforced brick with simple plate mounting (corners restrained).

Measured Peak Reflected Overpressure: 3.6 psi

Results: Wall cracked as shown in sketch below but did not collapse.



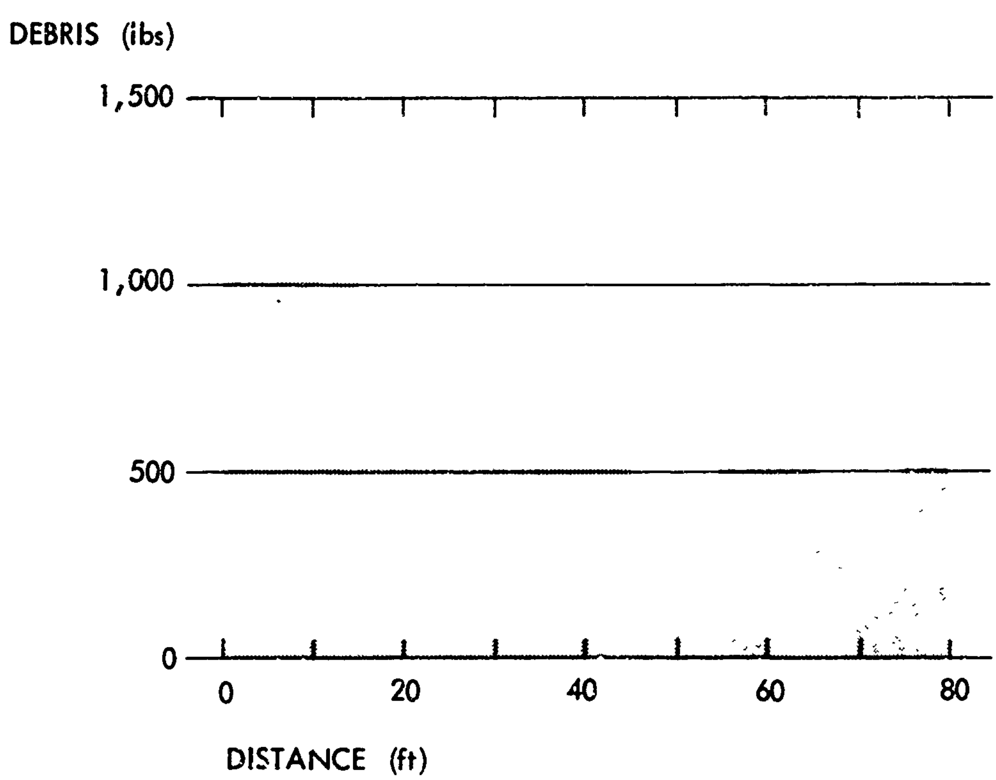
WALL PANEL TEST REPORT

Wall Number 26

Type of Wall: 8-in. reinforced brick with simple plate support condition (corners restrained).

Measured Peak Reflected Overpressure: ~ 15 psi

Results: The wall failed, and debris scattered to 80 ft. (See debris distribution chart below).



Debris Distribution, Wall Number 26

WALL NO. 26

DEBRIS SURVEY

Distance Feet From Wall	Number of Bricks	Weight Lb.	Distance Feet From Wall	Number of Bricks	Weight Lb.
75-80	5	40.25	55-65	16	128.80
	5	40.25		3	24.15
	6	48.30		2	16.10
	9	72.45	45-55	33	265.65
	10	80.50		6	48.30
	45	362.25		6	48 30
	4	32.20	35-45	12	96.60
65-75	7	56.35		12	96.60
	6	48.30		15	120.75
	5	40.25		11	88.55
	11	88.55		35	281.75
	10	80.50		6	48.30
55-65	32	257.60	25-35	27	217.35
	8	64.40		42	338.10
	16	128.80		8	64.40
	6	48.30		9	72.45
	26	209.30	15-25	45	362.25

WALL NO. 26 Cont.

DEBRIS SURVEY

Distance Feet From Wall	Number of Bricks	Weight Lb.	Distance Feet From Wall	Number of Bricks	Weight Lb.
15-25	32	257.60			
	4	32.20			
0-15	9	72.45			
	46	370.30			
	2	16.10			
	23	185.15			
	24	193.20			
	6	48.30			
	14	112.70			
	9	72.45			
	2	16.10			

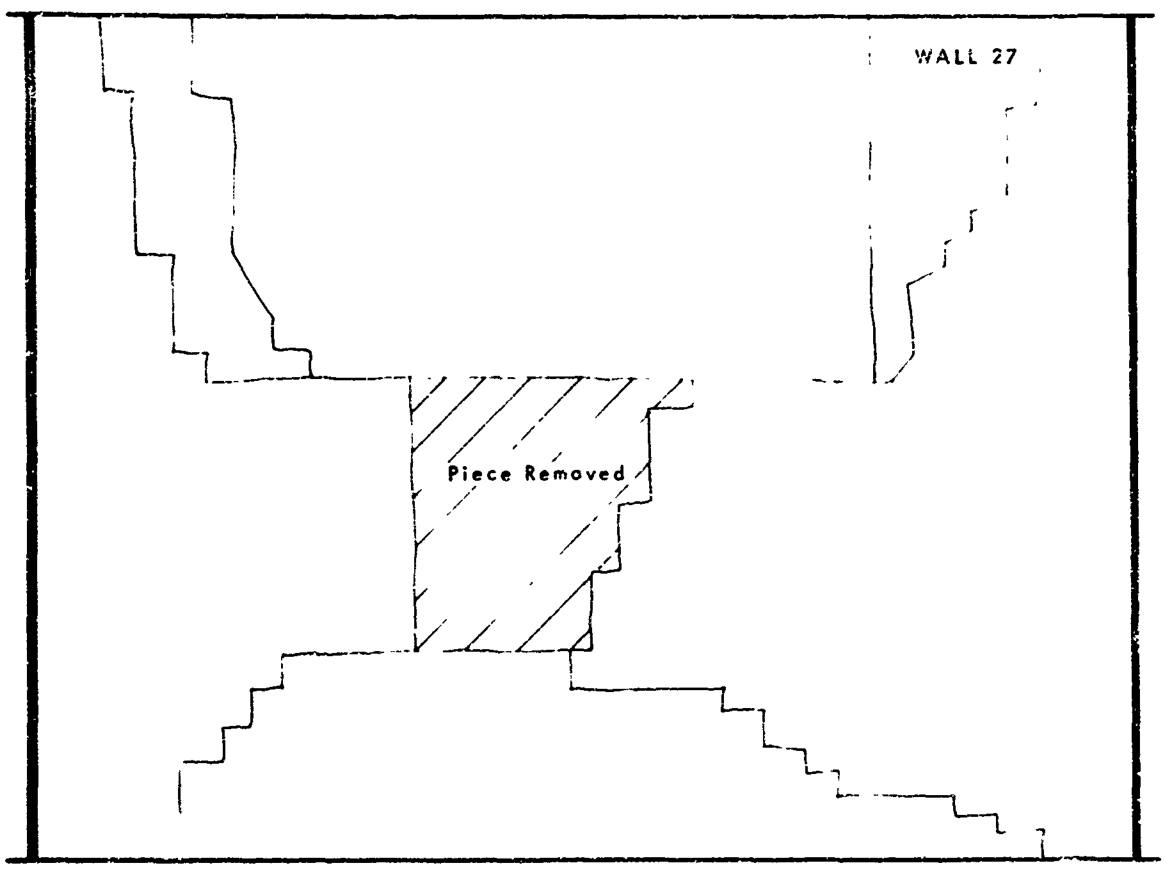
WALL PANEL TEST REPORT

Wall Number 27

Type of Wall: 8-in. nonreinforced brick with simple plate support condition (corners restrained).

Measured Peak Reflected Overpressure: ~ 3.5 psi

Results: The wall cracked, and a section weighing ~ 500 lb fell out of the center. The remainder of the wall stayed in place. (See crack pattern sketch below).



WALL PANEL TEST REPORT

Wall Number 28

Type of Wall: 8-in. reinforced brick with simple plate mounting condition (corners restrained).

Measured Peak Reflected Overpressure: 4 psi

Results: The wall failed, and seven wall fragments, weighing a total of ~ 1900 lb, landed within 8 ft of the wall. The remainder of the bricks stayed in the frame.

WALL NO. 28 DEBRIS SURVEY

Distance Feet From Wall	Number of Bricks	Weight Lb.*	Distance Feet From Wall	Number of Bricks	Weight Lb.
0-8	94	847			
	33	270.5			
	22	178			
	36	290.5			
	11	89			
	11	90.5			
	21	165			

Remainder of bricks still in frame.

*Actual scale measurements.

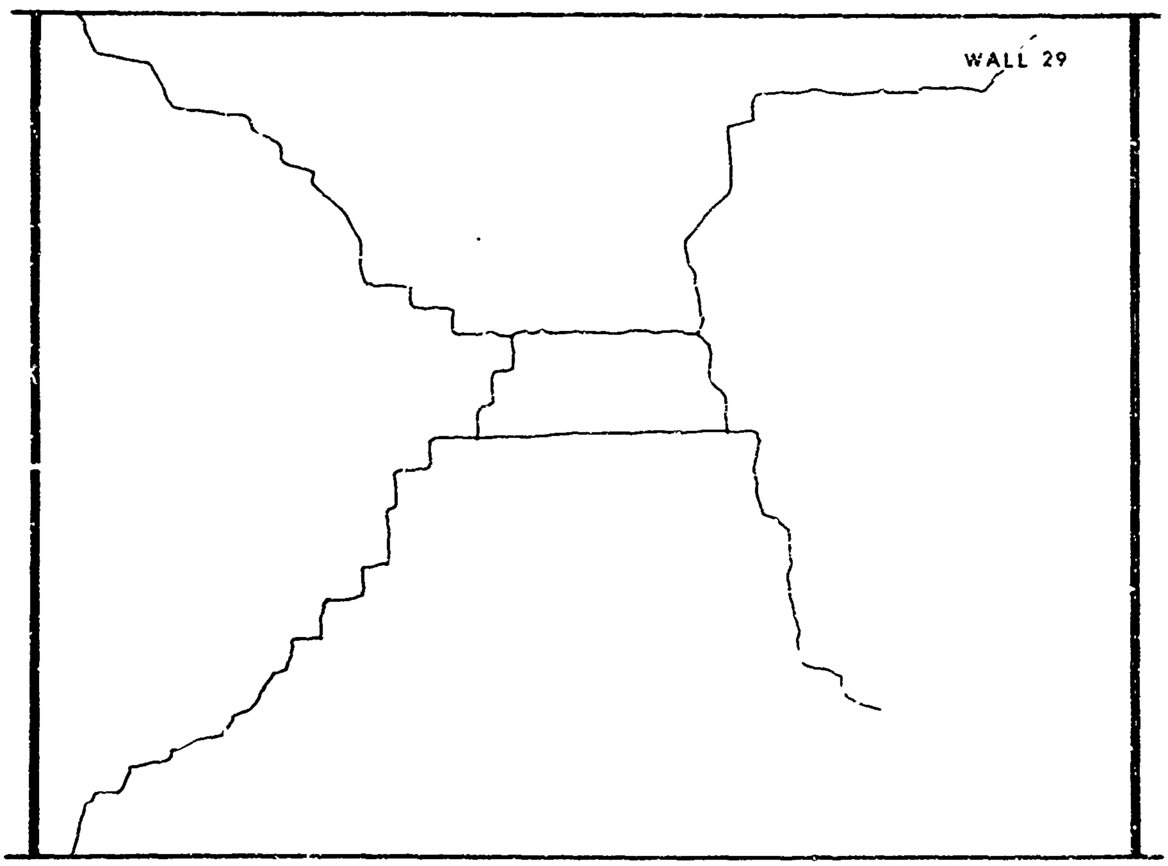
WALL PANEL TEST REPORT

Wall Number 29

Type of Wall: 8-in. nonreinforced brick with simple plate mounting system (corners restrained).

Measured Peak Reflected Overpressure: 3.8 psi

Results: The wall cracked but did not collapse. (See crack pattern sketch below). A second test on this same wall at a peak reflected overpressure of 4.2 psi caused about 350 bricks to fall out of the wall, all landing within 10 ft.



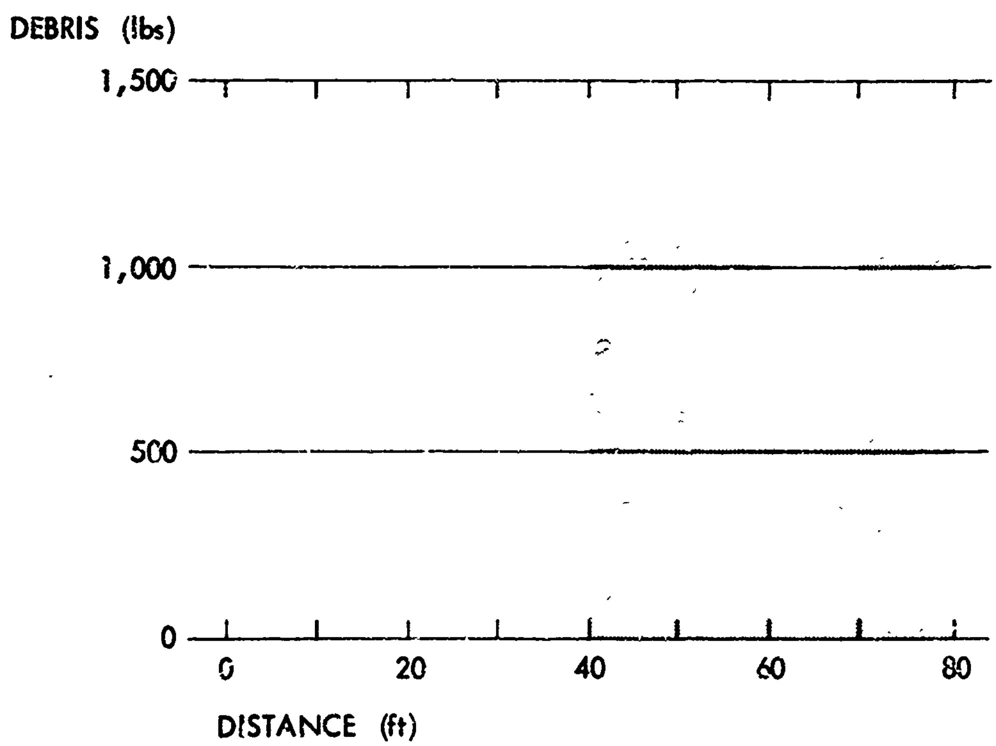
WALL PANEL TEST REPORT

Wall Number 30

Type of Wall: 8-in. nonreinforced brick with simple plate mounting system (corners restrained).

Measured Peak Reflected Overpressure: ~15 psi

Results: The wall failed and debris scattered more than 70 ft. (See distribution chart and initial crack pattern sketch below).



Debris Distribution, Wall Number 30

WALL NO. 30

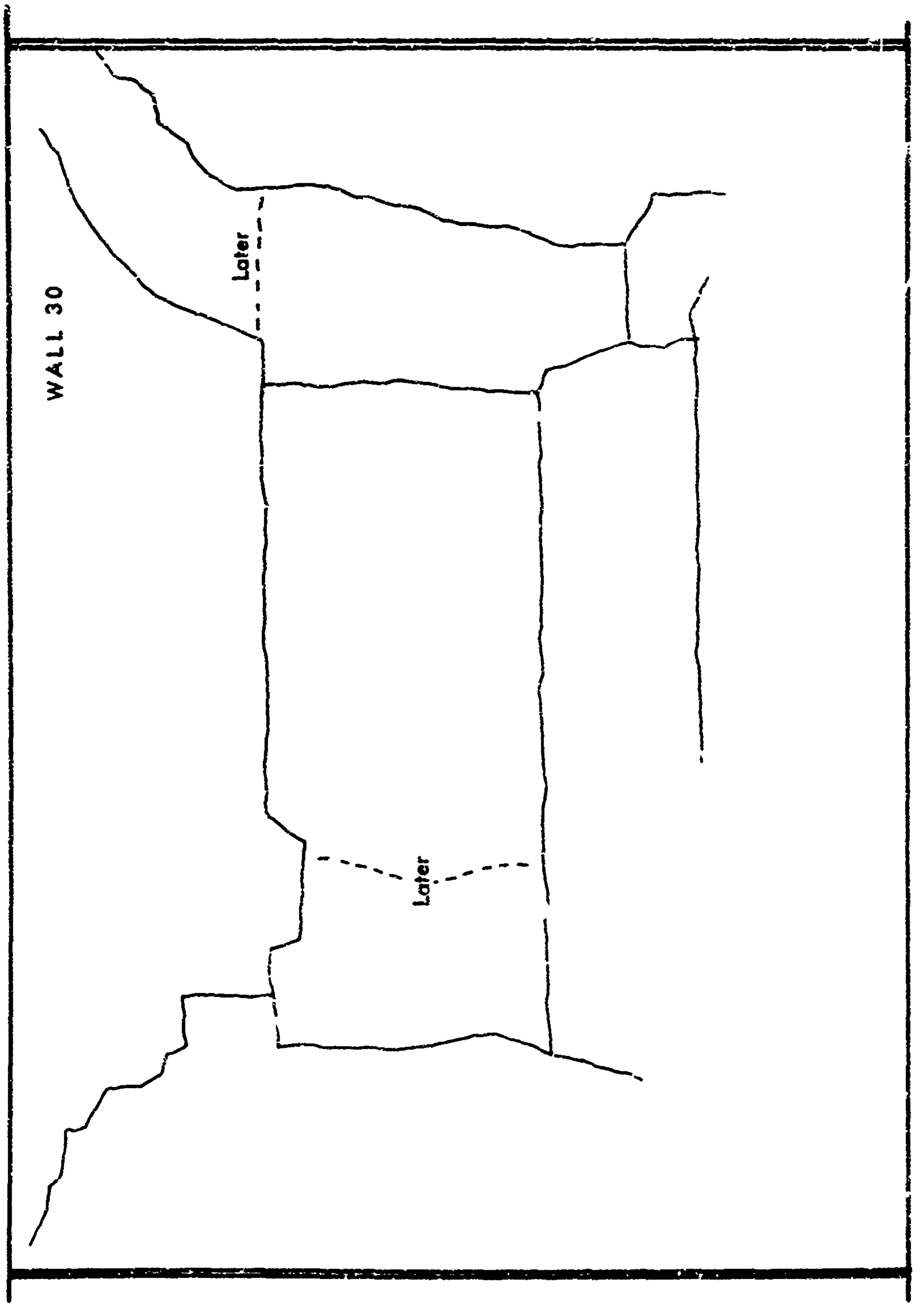
DEBRIS SURVEY

Distance Feet From Wall	Number of Bricks	Weight Lb.	Distance Feet From Wall	Number of Bricks	Weight Lb.
>70		47	60-70		7
		68			8
		11			149
		47			37
		15			312
		16	50-60		529
		21			54
		71			28
		83			56
		14			39
		255			89
		143			118
		185			186
		110	40-50		445
		151			23
60-70		34			67
		6			32

WALL NO. 30 Cont.

DEBRIS SURVEY

Distance Feet From Wall	Number of Bricks	Weight Lb.	Distance Feet From Wall	Number of Bricks	Weight Lb.
40-50		26			
		72			
		366			
		124			
		220			


WALL 30
Later
Later

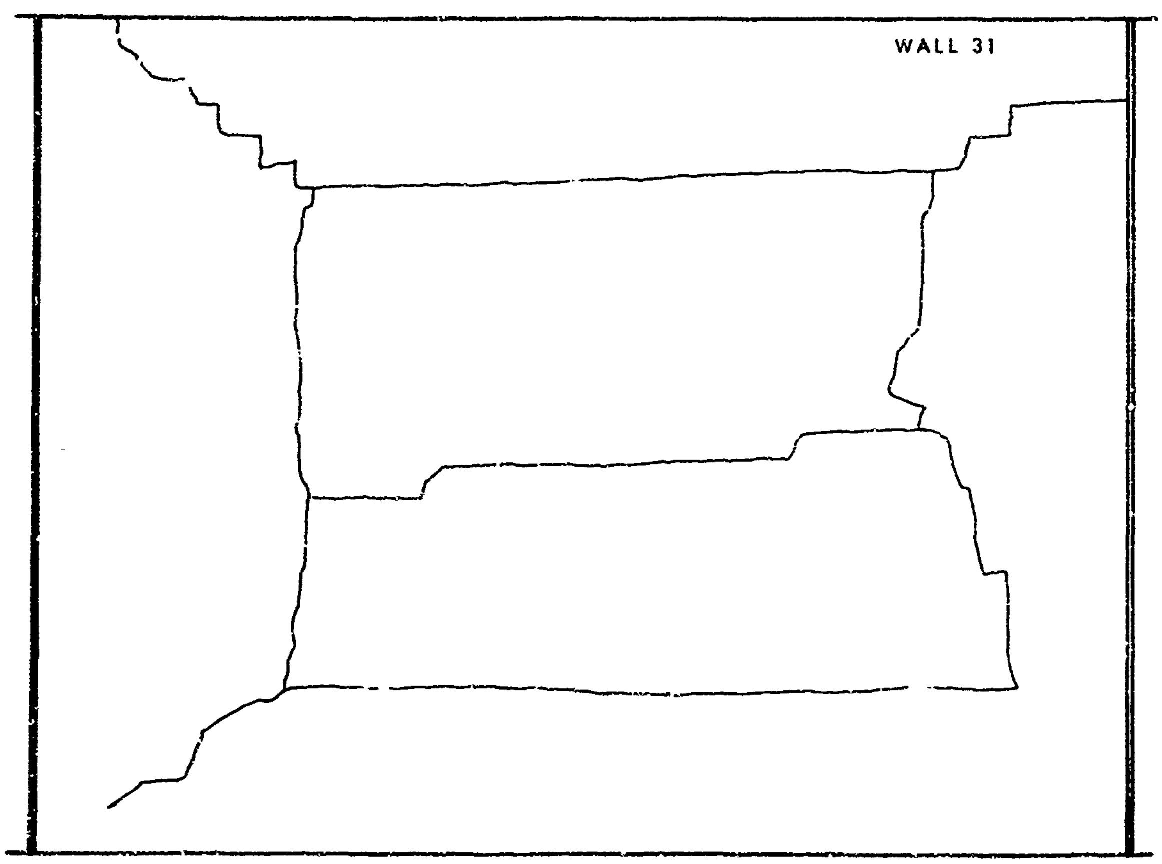
WALL PANEL TEST REPORT

Wall Number 31

Type of Wall: 8-in. nonreinforced brick with simple plate mounting system (corners restrained).

Measured Peak Reflected Overpressure: 15 psi

Results: The wall failed. (See initial crack pattern sketch.)



WALL PANEL TEST REPORT

Wall Number 32

Type of Wall: 8-in. nonreinforced brick with simple plate mounting system (corners restrained).

Measured Peak Reflected Overpressure: 9.3 psi

Results: The wall failed.

Section 4
CONCLUSIONS

The objective of this effort was to obtain experimental debris formation and distribution information for walls common to industrial buildings, i.e., corrugated metal wall panels.

Four tests showed that the incident overpressures that had been assumed in previous debris studies for the initiation and completion of corrugated metal wall failure (1.5 psi and 2.5 psi respectively) are reasonable. For the tests in this study, the average incident overpressures for the initiation and completion of failure were 0.5 psi and 2.1 psi respectively.

One of the main concerns about the debris potential of corrugated metal industrial walls is the damage that the wall panels will cause to machinery inside the building. The machinery itself won't be damaged significantly, but controls, wiring, and piping would be damaged considerably due to airborne debris. In the shock tunnel tests, although the positive phase ended at approximately the same time as the panels tore loose, the momentum imparted to the panels was sufficient to cause them to slide along the tunnel floor for 20 to 25 ft. This indicates that, with a long duration pulse, the panels would travel a long distance and possess sufficient momentum to cause a considerable amount of damage to light objects in their path of travel. The conclusion is that, above 2 psi, sufficient damage would be caused to any equipment in a building having corrugated metal walls to require extensive repairs before the equipment could be used again. The damage would not be so much to the equipment itself as to the electrical wiring and controls, and to air and liquid piping.

The data from the tests of the brick wall panels indicate that missiles from these panels will be quite large — on the order of half a panel for panels supported as a beam and at least a foot square for panels supported as a plate. Missiles this large will cause severe damage to anything they strike. The tests show wall failure (and hence the possibility of missile damage) at incident overpressures as low as 1.5 to 2.0 psi.

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13. ABSTRACT

Four corrugated steel industrial-type wall panels were tested in the URS Shock Tunnel Facility to obtain information regarding debris formation and distribution.

Two of the panels, tested at an incident overpressure of about 0.5 psi were deformed, but remained in place. The other two were torn loose and transported approximately 35 ft at about 2 psi.

The tests showed that there would be a considerable amount of damage to controls and wiring on industrial machinery at incident overpressures of 2.0 psi.

Debris data (crack patterns and fragment sizes and weights) from previous tests of brick wall panels performed for Work Unit 1123D indicate that missiles from brick wall panels can cause severe damage.

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