UNITED STATES ATOMIC ENERGY COMMISSION

AECD-3643

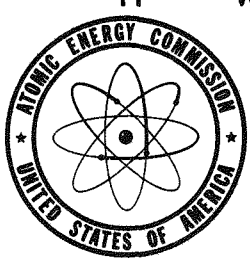
THE EFFECT OF ATOMIC WEAPONS ON GLAZING AND WINDOW CONSTRUCTION

Annex 3.5 — Scientific Director's Report of Atomic Weapon Tests at Eniwetok, 1951

By
Walton C. Clark

August 1951

General Services Administration
Washington, D. C.



Technical Information Service, Oak Ridge, Tennessee

Subject Category, ENGINEERING.

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Walton C. Clark, Public Buildings Service

Approved by: Sherwood B. Smith, Director, Program 3 and Alvin C. Graves, Scientific Director

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AECD-3643

THE EFFECT OF ATOMIC WEAPONS ON GLAZING AND WINDOW CONSTRUCTION

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CONTENTS

Abstract

A OBJECTIVE

This investigation was undertaken to determine the relative resistance of different types of commercial windows and glazing to an atomic blast, also to determine what degree of protection from flying glass is provided by Venetian blinds, insect screens, and wire netting.

B PROCEDURE

Various types of windows glazed with plastic and different kinds of glass were installed on four sides of a test structure, which was exposed to the blast of an atomic weapon. The photographic record and detailed description of the windows before and after the blast included in this report provide a basis for evaluating comparative damage.

C CONCLUSIONS

1. In supporting static loads tempered glass has about 4½ times the strength of ¼ in. plate; ¼ in. wire glass, ¼ in. safety glass, and ¼ in. plate have equal strength; and double-strength glass has only one-fourth the strength of ¼ in. plate. The results of the test seem to indicate that the resistances of these different types of glass to an atomic blast were approximately proportional to their strength in supporting static loads.

2. If a sash perpendicular to the blast can swing with the blast, without too much resistance, into a position parallel to the direction of the blast, the glass is less likely to be broken. Casement sashes on the front and rear of a building which are open parallel to the direction of a blast at the time of the explosion are less likely to be damaged.

3. Glass mounted in a flexible frame is likely to be broken if the frame is distorted by the blast, whereas the same size pane may be undamaged if installed in a more rigid frame.

4. Fragments from wire or safety glass are not so dangerous to personnel as the larger fragments from other types of glass.

5. Plastic, being more resilient than glass, is less likely to break, and fragments, being lighter and not so sharp, are less likely to cause injuries. Plastic ⅛ in. thick, 11¼ by $15\,^{7}/_{16}$ in., was undamaged, and ¼ in. wire glass of the same size was shattered and blown out of the frame.

6. Commercial types of Venetian blinds and insect screens afforded little or no protection against flying glass fragments at the distance of the test structure from ground zero. However, it is thought that a blind with some of the parts reinforced and properly anchored to the window opening would give some protection at distances greater than 3 miles from ground zero. The blind, if closed, gives full protection at 2 miles against the heat waves, which last only a few seconds; and the blast wave, which travels at a much slower rate, may not reach the building and damage the blind before the heat waves have dissipated.

7. Wire netting with ¼ in. mesh installed on the inside of window openings proved effective in stopping all except very small glass fragments.

8. Lightweight, double-hung, wooden windows with sashes glazed with small panes supported by narrow muntins offer little resistance to an atomic blast.

9. Much valuable data were derived from the investigation; however, on account of the limited time in which the test had to be prepared, only a few of the elements of the window problem were covered. It is recommended that additional investigations on this subject be undertaken in order to design windows that will be more resistant to an atomic blast and less hazardous to occupants of buildings where windows are installed.

Chapter 1

Introduction

1.1 OBJECTIVE

The purpose of this test was to determine the resistance of various types of glazing and different types of wood, steel, and aluminum window construction to the effects of an atomic blast. The purpose was also to determine what protection from flying glass will be provided by mounting Venetian blinds, insect screens, and ¼ in. mesh wire netting on the inside of window openings.

1.2 JUSTIFICATION

The data secured from this test will serve as a guide to architects and engineers who design new and remodel existing buildings that may be subjected to an atomic attack. The results of the test will also give an indication of the extent of the hazard to occupants near windows in a building which may be exposed to an atomic blast and means of reducing such hazard.

1.3 REFERENCES

Investigations have been made in recent years to determine the resistance of windows and glass to high-explosive blasts, and the results of some of these tests may be found in the following listed publications:

"Glass and Glass Substitutes" (Office of Civilian Defense, November 1941)

"Report of Blast Tests in Glass" (Office of Chief of Engineers, War Department, March 1943)

"Antiscatter Treatment for Glass" (National Bureau of Standards, June 1944)

"Igloo Tests" (Arco, Idaho: Army-Navy Explosives Safety Board, 1945; Revised November 1947)

"Igloo and Revetment Tests" (Army-Navy Explosives Safety Board, October 1946)

"Glass and Plaster Damage" (Armed Services Explosives Safety Board, March 1950)

"Structural Defense", by D. G. Christopherson (British Ministry of Home Security Research and Experiments Department, 1946)

"Explosion Tests on Glass Windows", by N. J. Thompson and E. W. Cousins, Journal of the American Ceramics Society, XXXII (1949), 313–15.

Chapter 2

Experimental Procedure

2.1 DESCRIPTION OF TEST STRUCTURE

The windows included in this test were mounted in a prefabricated structure 8 ft wide, 8 ft high, and 40 ft long, with four interior partitions on 8 ft centers which divided the building into five equal cubes. The structure was not designed to simulate any building used as a home or as an office, it being merely a frame to support the windows during the blast. The building was constructed of panels approximately 8 ft square and 5½ in. thick made of two sheets of ¾ in. plywood nailed and glued to 2 by 4 in. studs, 16 in. on centers. The panels were held together by angle-iron clips and ½ in. bolts. The building was anchored to the ground by means of four pairs of ½ in. steel cables connected to four pieces of wooden piling buried 3 ft deep. Details of the structure and anchorage are shown on Drawing 31–1 of Appendix A.

2.2 LOCATION OF STRUCTURE

The building was erected so that the blast would be at right angles to the long side, and there was no obstruction on the blast side, so that the full effect of the shock wave from the atomic weapon would be transmitted to the structure. Knowing that windows are relatively fragile and are usually not designed to withstand pressures exerted by winds in excess of 75 mph, the test structure was located at a distance where it was expected that the windows would be only partially damaged. The original plans contemplated the erection of three structures at distances where the estimated damage would be slight, moderate, and severe, but this proved impractical and only one structure was located at the middle position.

2.3 DESCRIPTION OF WINDOWS AND GLAZING

The following listed windows were installed in the test structure, and the details of the frames and glazing are shown on Drawings 31–1 and 31–2 of Appendix A. The double-strength glass was 0.118 in. thick and all tempered, plate, polished wire, and safety glass was ¼ in. thick.

2.3.1 List of Windows

Two double-hung wooden windows of lightweight sections glazed with double-strength panes, 10⅔ by 15 in.

Two lightweight, outswinging, aluminum casements glazed with double-strength, plate, and wire glass, and plastic, approximately 11½ by 16 in. One piece of plastic was ⅛ in. thick and the other was $^1/_{10}$ in. thick.

Two architectural projected steel windows glazed with plate, safety, wire, and double-strength glass, approximately 15 by 40 in.

Two heavyweight, inswinging, aluminum casements glazed with tempered and wire glass, 19⅝ by 61⅝ in.

Two outswinging aluminum casements with an inswinging hopper vent, glazed with safety, wire, plate, and double-strength glass. Panes in the casement section were 21 by 45½ in., and the hopper vent was $12^9/_{16}$ by $44^1/_{16}$ in.

Two louvered windows of three sections, the two upper sections swinging out and the lower section swinging in, glazed with plate, wire, safety, and double-strength glass, $18^9/_{16}$ by $32^{15}/_{16}$ in.

Two heavyweight, steel, double-hung windows glazed with safety, plate, wire, and double-strength glass, 19½ by 30¾ in.

Three 12 by 12 in. panes of "Flex-duplate" were installed in the front wall panel of Room 2 in the space around inswinging casement window 4. "Flex-duplate" is made by applying ⅛ in. plate glass on each side of a plastic sheet and cutting the inner piece of glass and the plastic along the diagonals of the square. The plastic extended beyond the two pieces of plate glass about 1 in. and was held in the panel by nailing wood strips over the plastic around the opening which was 12½ by 12½ in. As the glass was only 12 in. square there was a ¼ in. space between the edge of the opening and the edge of the plate glass.

2.4 DESCRIPTION OF WIRE NETTING, VENETIAN BLINDS, AND SCREENS

Wire netting with ¼ in. mesh was installed on the inside of the two double-hung wooden windows, one lightweight aluminum casement, and the two architectural projected steel windows. The netting was held firmly in place by placing it under the eight clamps around each window frame and staples were also driven on 4 in. centers around the edge of netting.

A wooden Venetian blind was installed on the inside of lightweight aluminum casement window 2 and commercial-type, metallic Venetian blinds were installed on the inside of the two heavy-duty, inswinging, aluminum casement windows 4 and 5 and on one steel, double-hung window 8. All the blinds were let down and the slats closed before the blast. The bottom rail of one blind was attached to the wall at both ends with two clamps.

Insect screens of Monel metal or aluminum were mounted with the standard type of metal clips on the inside of windows 2, 5, 6, 7, 10, 13, 14, and 15.

Chapter 3

Test Results and Discussion

3.1 DESCRIPTION OF DAMAGE

The shock wave enveloped the entire building almost instantaneously, and all the glass on the four sides of the building that was broken was forced inward, except in one free-swinging casement sash. This sash was on the rear face of the structure and was opened inward before the blast so that it was perpendicular to the rear wall. The sash was slammed shut and all panes were broken, with the fragments falling to the ground outside the building.

There was, of course, much heavier damage on the front face than on the rear of the structure. Of the 28 panes of glass in the windows on the front, 21 were broken, and on the rear only 5 were broken out of 30 installed, although many panes on the rear face were made of thinner glass than those on the front. All the double-strength glass mounted in light wooden frames in the ends of the building was broken. One of the two pieces of plastic in window 2 on the front of the building was broken.

3.2 DISCUSSION OF PRESSURES

Many of the fragments of glass were found outside the structure, and it is thought that the blast passed over the building so quickly that the pieces were blown outward by the expanding air trapped within the building before the fragments had time to fall to the floor. This was particularly noticeable on the windows in the end of the building which had ¼ in. mesh wire netting nailed across the inside of the opening. This wire screen was bent inward by the blast, and it appears that before the fragments of glass that were projected against the netting could fall to the sill, the air on the inside expanded so quickly that the fragments from the windows were blown 4 to 6 ft beyond the wall.

On the rear of the building there was a canopy window of three sections, with the two upper sections designed to swing outward together and the independent lower section to swing in. The glass in the upper section was blown in, and yet the lock on these sections was broken by an outward pressure and the two sections were pushed out as shown in Figs. 3.50 and 3.55. The following comments on this reversal of pressure in the test structure have been made by C. W. Lampson of the Ballistic Research Laboratories at Aberdeen, Maryland:

> The general impression that one has from these photographs of the results of an atomic blast on various window materials and mountings is that the diffraction of the blast wave and the formation of vortices about the corners produce an extremely rapid reversal of load on those portions of the structure which are on the sides and rear relative to the direction of propagation of blast. Windows in general have periods which are less than the reversal times, so that they follow the forces without appreciable lag. The inertia of the debris in many cases is such that reversal of aerodynamic forces may occur before the pieces fall to the ground, so that the location of the debris is no indication of the mode of failure. The formation of vortices reduces the pressure over a localized area, whereas the flow of air through openings in the front permits a pressure build up inside the structure, thus producing a possible reversal of aerodynamic forces acting on the area. The behavior of the glass after failure is con-

sistent with this hypothesis, as is other evidence arising from shock-tube studies; however, the phenomena on the front side must be somewhat different since no vortices are formed here to reverse the pressure gradient, and any glass found outside the windows must have been caught by some means and then gently blown outward on the passage of the suction phase.

3.3 POSITIVE AND NEGATIVE WIND

There was little or no indication of the strength of the positive wind, as there was no debris blown against the front of the building and little sand was blown on the inside, nor was any trash left adhering to an insect screen on the blast side. There was some evidence of the negative wind, as one of the wire insect screens mounted in one of the casement windows which was opened on the rear of the building was covered on the outside with small pieces of leaf mold, which was blown in from some underbrush about 50 ft to the rear of the building. (See Figs. 3.50 and 3.52.)

3.4 PHOTOGRAPHS WITH COMMENTS

Photographs (Figs. 3.1 to 3.58) with descriptive titles and comments show the structure, windows, blinds, and screens before and after the blast. There was no damage to the test structure in which the windows were installed, and the building was forced backward only ⅛ in. by the blast. The numbers on the white cards shown in the photographs refer to the rooms, 1 to 5, of the building. For example, "Front 5" indicates that the picture shows the front wall of room 5. The rooms and windows are numbered on Drawing 31–1 of Appendix A.

Chapter 4

Summary with Conclusions and Recommendations

4.1 STRENGTH OF GLASS AND PLASTIC

Tempered glass was undamaged on the front of the structure facing the blast. The locks on one of the inswinging casements glazed with tempered glass were broken by the blast and the sash swung inward; however, the glass was unbroken. The locks and hinges of another inswinging sash glazed with tempered glass were broken off and the sash was blown across the room, but the tempered glass was unbroken. On the rear of the building a sash with tempered glass was opened inward before the blast, so that the leaf was parallel to the line of the blast. However, there was no friction arm on the leaf, and it was slammed shut with such violence that the glass was broken and most of the pieces fell to the ground outside of the building.

In supporting static loads tempered glass has about 4½ times the strength of ¼ in. plate; ¼ in. wire glass, ¼ in. safety glass, and ¼ in. plate have equal strength; and double-strength glass has only one-fourth the strength of ¼ in. plate. The results of the test seem to indicate that the resistances of these different types of glass to an atomic blast were approximately proportional to their strength in supporting static loads.

4.2 FRAGMENTATION OF GLASS AND PLASTIC

The fragments from wire and safety glass would not have been so dangerous to personnel as the flying pieces of plate or double-strength glass, which were larger and had sharper corners. Plastic, $^{1}/_{10}$ by 11⅞ by $15^{7}/_{16}$ in., was blown out of a frame and broken into about eight pieces. A piece of plastic, ⅛ by 11¼ by $15^{7}/_{16}$ in., was undamaged, while a piece of ¼ in. wire glass of equal size in the same frame was blown out. Plastic, being more resilient than glass, is less likely to break, and the fragments are lighter and less likely to cause injury to personnel.

4.3 STRENGTH OF WINDOW CONSTRUCTION

The aluminum and steel windows on the blast side were little damaged if glazed with double-strength glass or plastic. However, most of the muntins or meeting rails were bent or twisted if glazed with ¼ in. tempered, plate, wire, or safety glass unless the sash could swing with the blast. The window sections on the blast side which were not damaged, although glazed with ¼ in. glass, were the upper and lower fixed units of the architectural projected steel window and the upper sash of the steel, double-hung window with one section glazed with double-strength glass and one with ¼ in. plate glass.

There was little damage to the windows in the rear of the building, and only five panes were broken; three of these were in the sash that was slammed shut. The other two panes which were broken were of double-strength glass. The operator arm on the open sash of lightweight casement window 10 was broken, and the lock on canopy window 15 was forced open. The sashes in inswinging casement window 13, were forced inward ½ in. against the locks. The closed sash on outswinging

casement window 14 was pushed outward about ½ in.

The commercial-type, lightweight, double-hung wooden window with sashes glazed with small panes supported by narrow muntins has little strength to resist a blast. If the window is open and the sashes are opposite, the resistance is increased. Such windows installed in the ends of the structure parallel to the blast were almost completely destroyed, although the window that was open suffered less damage.

4.4 RIGIDITY OF WINDOW FRAMES

Steel architectural projected window 3 had plate glass in the upper section, two panes of safety glass in the ventilator section (separated by a lightweight muntin), and a piece of wire glass in the lower section. All glass pieces were approximately 16 by 40 in. The upper and lower panes were not damaged although the safety glass in the ventilator was destroyed when the muntin was bent inward by the blast. Wire glass only 11¼ by $15^{7}/_{16}$ in. was blown out of a lightweight aluminum casement adjacent to the steel window when the aluminum muntin bent inward. Glass mounted in a flexible frame is likely to be broken if the frame is distorted by the blast, whereas the same size pane may be undamaged if installed in a more rigid frame.

4.5 POSITION OF WINDOWS RELATIVE TO BLAST

Casement sashes on the blast side which were opened outward parallel to the blast were not damaged. A casement sash on window 4, glazed with tempered glass, was forced open and swung inward without being damaged. If the casement sash referred to in Sec. 4.1 had been equipped with some type of a lock or friction arm to hold it open, it probably would not have been slammed shut and there would have been no glass breakage. Other sashes in the rear of the building which were opened outward parallel to the blast were only slightly damaged, and none of the glass was broken. (See Sec. 4.3.) If a sash perpendicular to the blast can swing, without too much resistance, into a parallel position, the glazing will be less likely to be damaged.

4.6 PROTECTIVE SCREENS AND VENETIAN BLINDS

Pieces of ¼ in. mesh wire netting mounted on the inside of the windows in the end of the structure were bowed inward by the blast and one piece was split along one side. However, these screens prevented all but the smaller fragments of broken glass from being projected into the rooms. A similar piece of netting installed on the inside of the architectural projected window 3 prevented the two panes of safety glass from being blown into the room after they were torn out of the frames.

All five Venetian blinds were almost completely destroyed and afforded little or no protection from flying fragments of glass. One blind was torn loose at the head, and the supporting cords and tapes were broken on the other blinds, letting the slats fall to the floor. In many cases the slats were broken or twisted out of shape, as shown in the photographs, and two of the aluminum slats were pierced by fragments of glass. However, it is thought that a blind with some of the parts reinforced and properly anchored to the window opening would give some protection at distances greater than 3 miles from ground zero. The blind, if closed, gives full protection at 2 miles against the heat waves, which last only a few seconds; and the blast wave, which travels at a much slower rate, may not reach the building and damage the blind before the heat waves have dissipated.

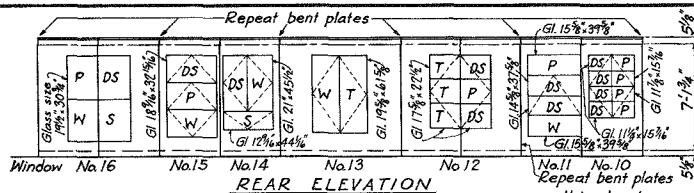
Insect screens, being held in place with lightweight clips, were torn from the frames and were little or no protection from flying glass. The blast had little effect on a screen over a window that was opened before the explosion.

4.7 RECOMMENDATIONS FOR ADDITIONAL TESTS

The time allowed for assembling the windows and erecting the building used in this test was very limited and only a few of the elements of the window problem were covered by this investigation. It is, therefore, recommended that additional investigations on this subject be undertaken in order to secure data for designing windows that will be more resistant to atomic blasts and less hazardous to the occupants of buildings where the windows are installed.

Further investigations should include:

1. The resistance of glazing and window construction at distances of 3, 4, and 5 miles from an atomic weapon.
2. The protection provided by specially designed Venetian blinds, wire screens, and other types of shielding devices installed on the inside of windows located at various distances from a blast.
3. The performance of specially designed windows that will swing with the blast and yet remain closed against wind storms.
4. The performance of windows glazed with combinations of plastic and glass, with glass reinforced with strips applied to the surface, with different thicknesses of plastic, and with two panes of glass separated by a narrow air space.
5. The protection provided by blinds or shutters installed on the outside of windows.



REAR ELEVATION
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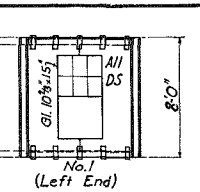
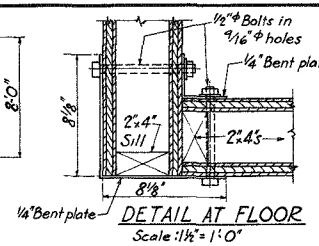
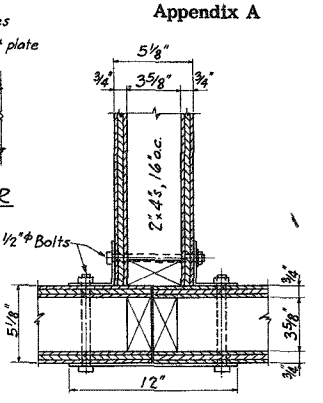


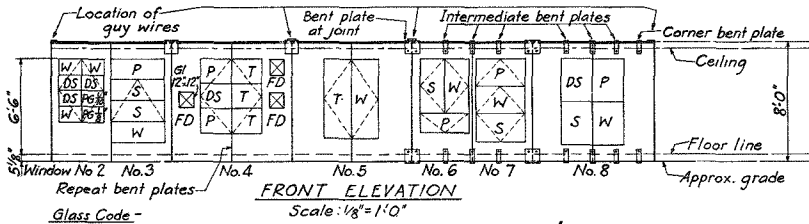
ELEVATION
Scale : 1/8"=1'-0"



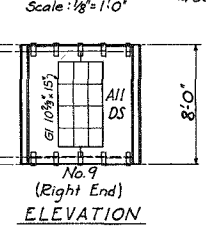
DETAIL AT FLOOR
Scale : 1 1/2"= 1'-0"



VERTICAL SECTION OF FLOOR AT PARTITION
Scale : 1 1/2"= 1'-0"



FRONT ELEVATION
Scale : 1/8"=1'-0"



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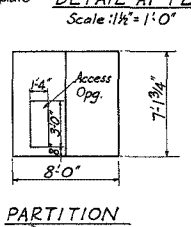
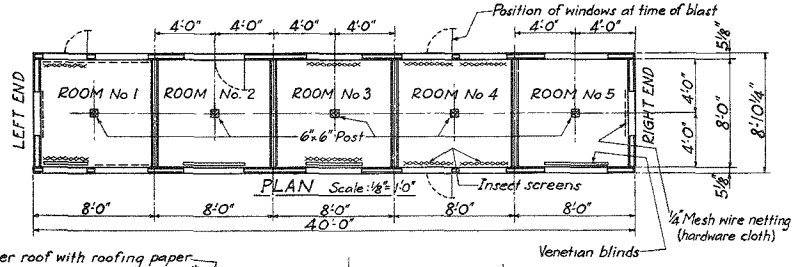
Scale : 1/8"=1'-0"



PARTITION

Glass Code -
P - Polished plate
W - Polished wire
S - Safety glass
T - Tempered
DS - Double strength glass
PG - "Plexiglas"
FD - "Flex-Duplate"



PLAN Scale : 1/8"= 1'-0"

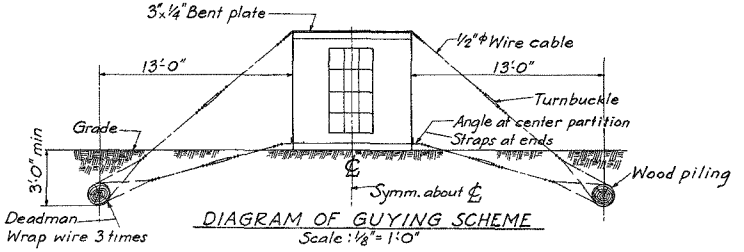
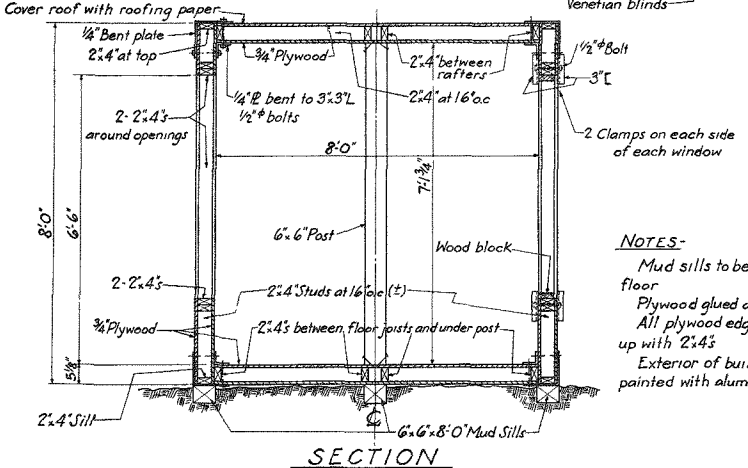


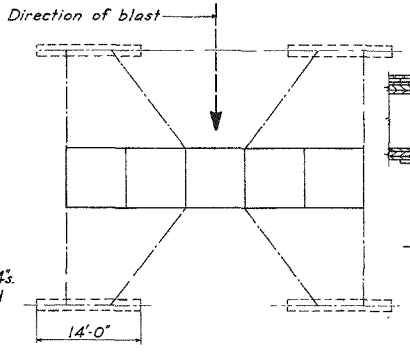
DIAGRAM OF GUYING SCHEME
Scale : 1/8"= 1'-0"

Note: Guy wires to be located at ends of building and over two center partitions.

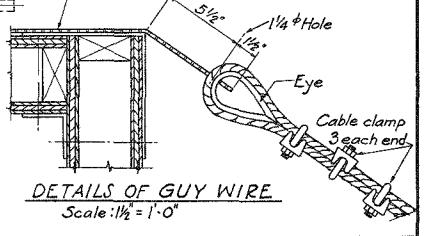


SECTION
Scale : 3/8"= 1'-0"

NOTES-
Mud sills to be connected to floor
Plywood glued and nailed to 2"x4"s.
All plywood edges to be backed up with 2"x4"s
Exterior of building and roof painted with aluminum paint.



PLAN OF GUYING SCHEME
Scale : 1/16"= 1'-0"



DETAILS OF GUY WIRE
Scale : 1 1/2" = 1'-0"

GENERAL SERVICES ADMINISTRATION PUBLIC BUILDINGS SERVICE - WASHINGTON D C	
PROJECT	WINDOW TEST STRUCTURE
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PROJ. NO.	49QX-99017 FILE NO.
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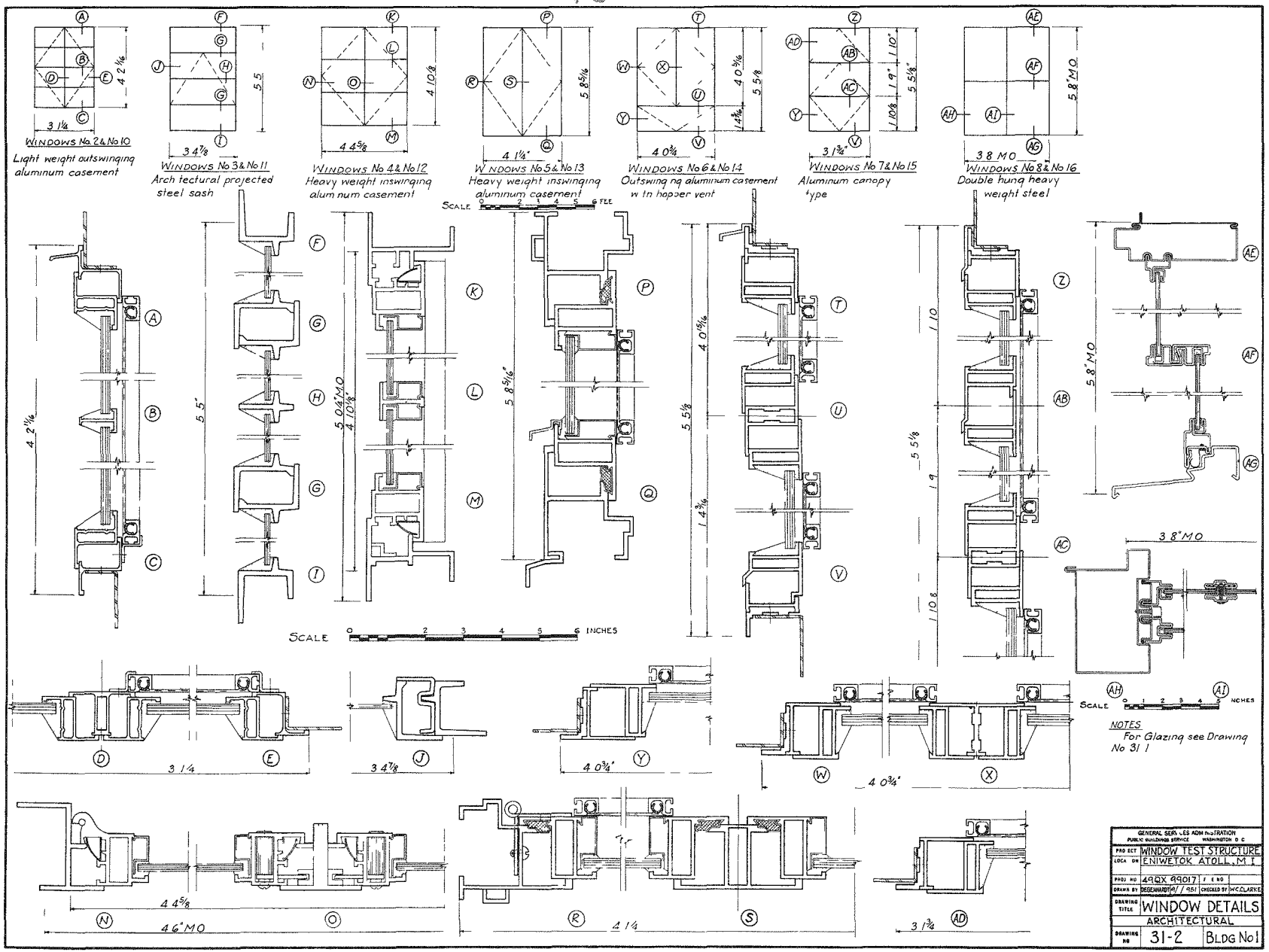
WINDOWS No 2 & No 10
Light weight outswinging aluminum casement
WINDOWS No 3 & No 11
Arch tectural projected steel sash
WINDOWS No 4 & No 12
Heavy weight inswinging alum num casement
WINDOWS No 5 & No 13
Heavy weight inswinging aluminum casement
WINDOWS No 6 & No 14
Outswing ng aluminum casement w th hopper vent
WINDOWS No 7 & No 15
Aluminum canopy type
WINDOWS No 8 & No 16
Double hung heavy weight steel
SCALE 0 1 2 3 4 5 6 FEE
SCALE 0 1 2 3 4 5 6 INCHES
NOTES
For Glazing see Drawing No 31 1
GENERAL SERVICES ADMINISTRATION
PUBLIC BUILDINGS SERVICE WASHINGTON D C
PROJECT WINDOW TEST STRUCTURE
LOCATION ENIWETOK ATOLL, M I
PROJ NO 49QX 99017
DRAWN BY DEGENHARDT / / 451 CHECKED BY WC CLARKE
DRAWING TITLE WINDOW DETAILS ARCHITECTURAL
DRAWING NO 31-2 BLDG No 1

Appendix B

The side on peak pressure was estimated at 2 psi and the positive maximum wind at 105 ft/sec with a duration of 1½ sec. These data were derived from Interferometer Gauge Pressure-Time measurements, GREENHOUSE Project 8.2B. The reflected pressure was estimated at 4.2 psi, and the negative maximum wind at 30 ft/sec.

18

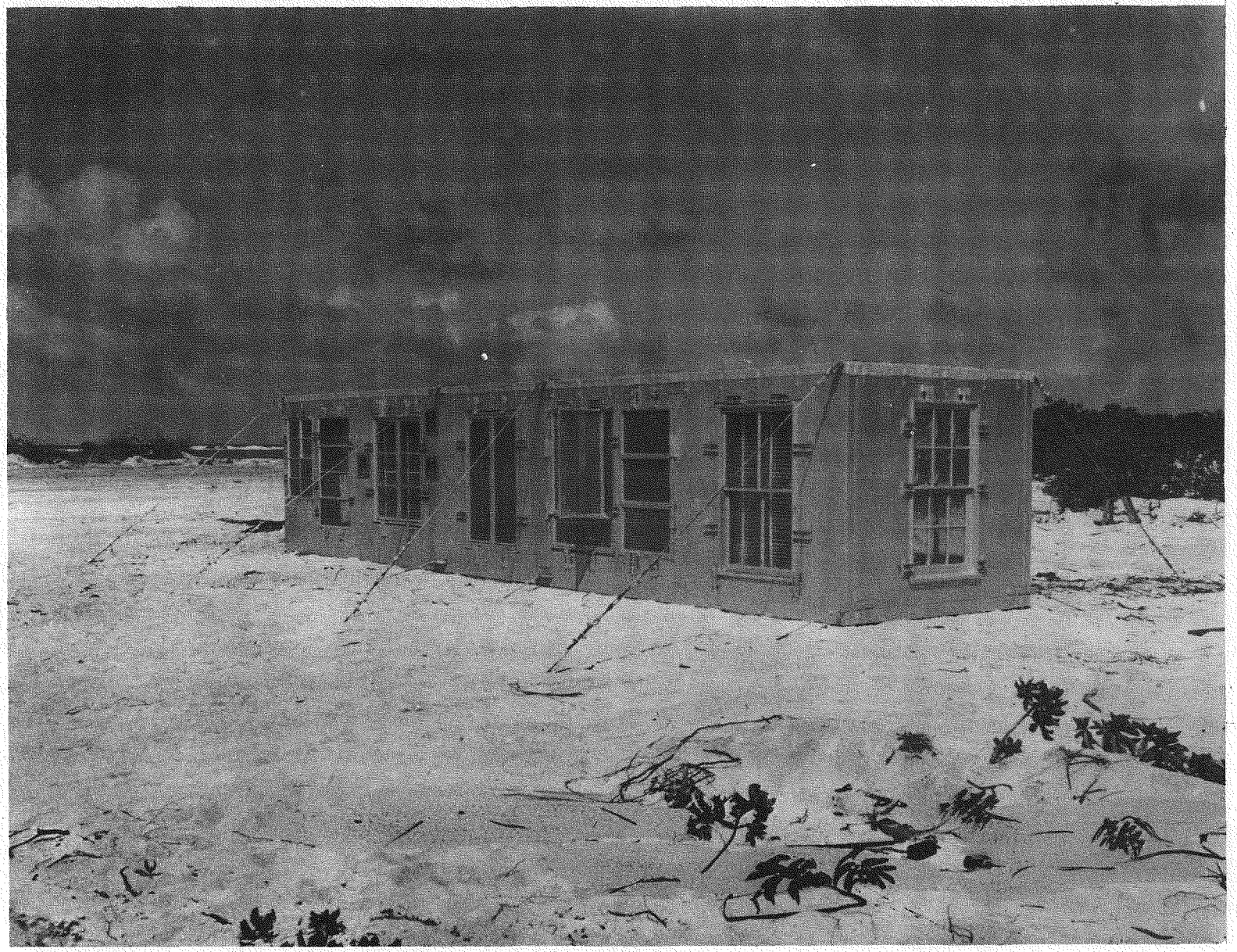

FIG. 3.1 Front of the Building before the Blast

FIG 3.2 Front of the Building after the Blast

20

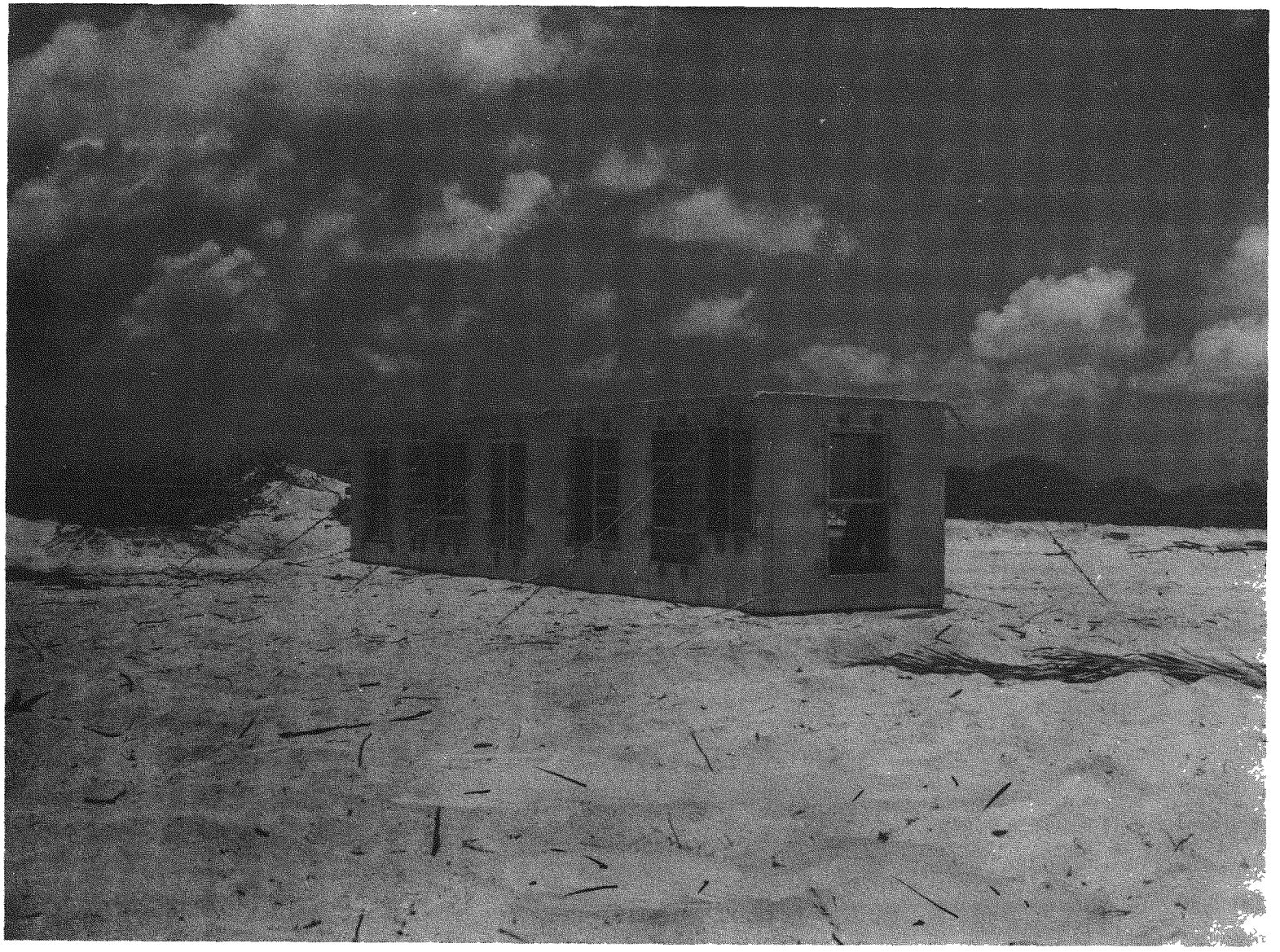

FIG. 3.3 Rear of the Building before the Blast

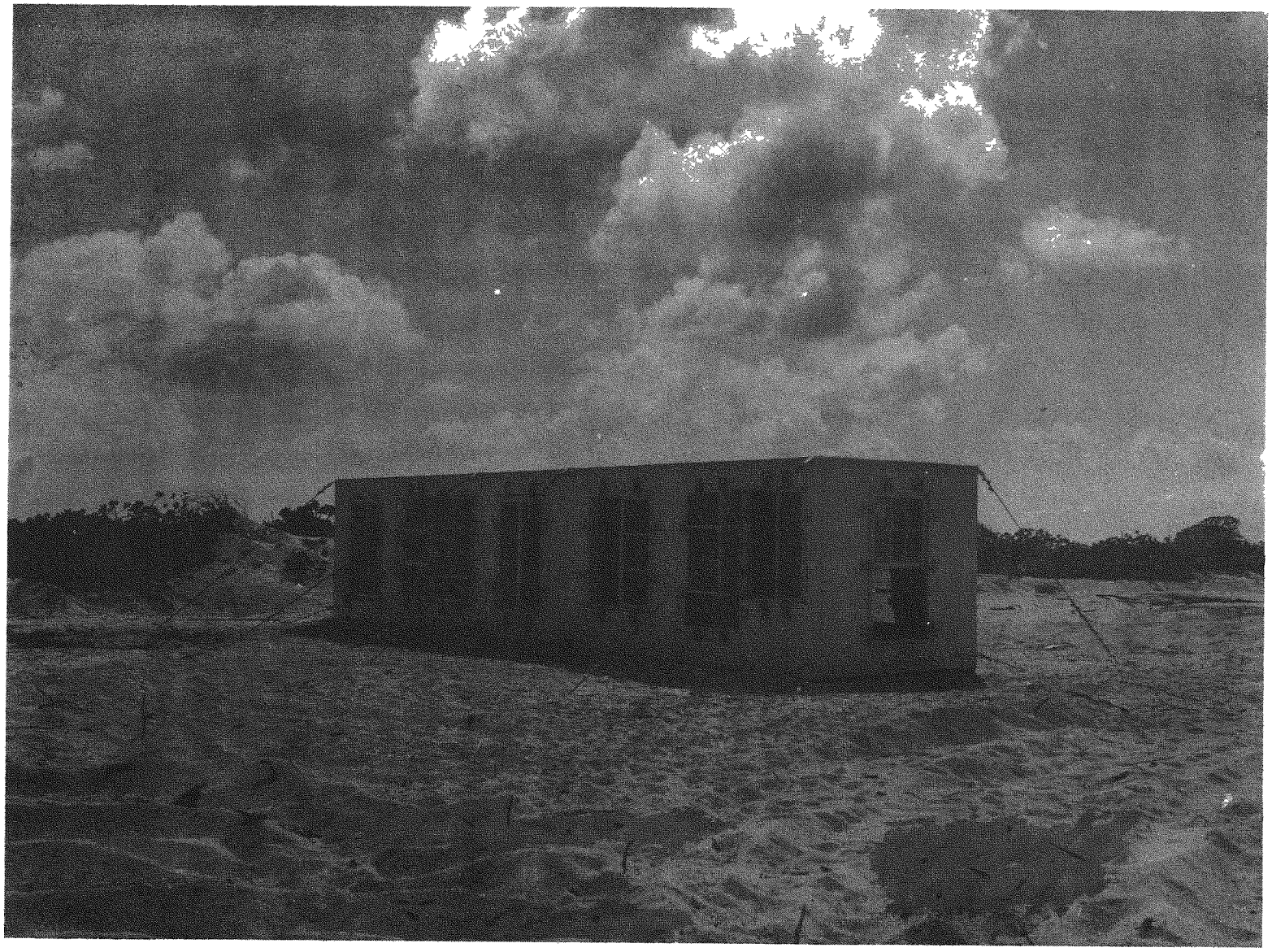

FIG 3.4 Rear of the Building after the Blast

FIG. 3.5 Front of the Building after the Blast from the Air

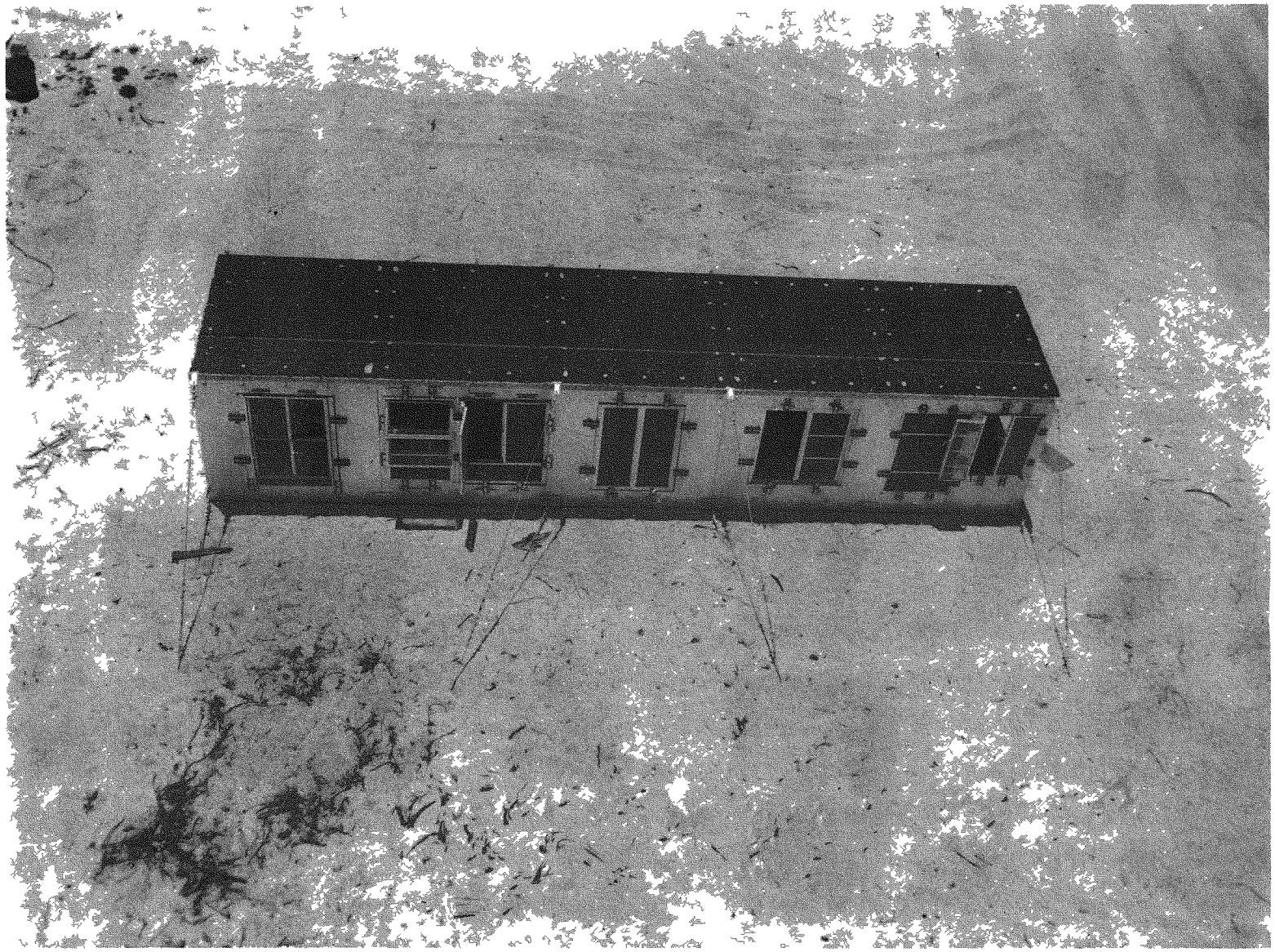

FIG 3 6 Rear of the Building after the Blast from the Air

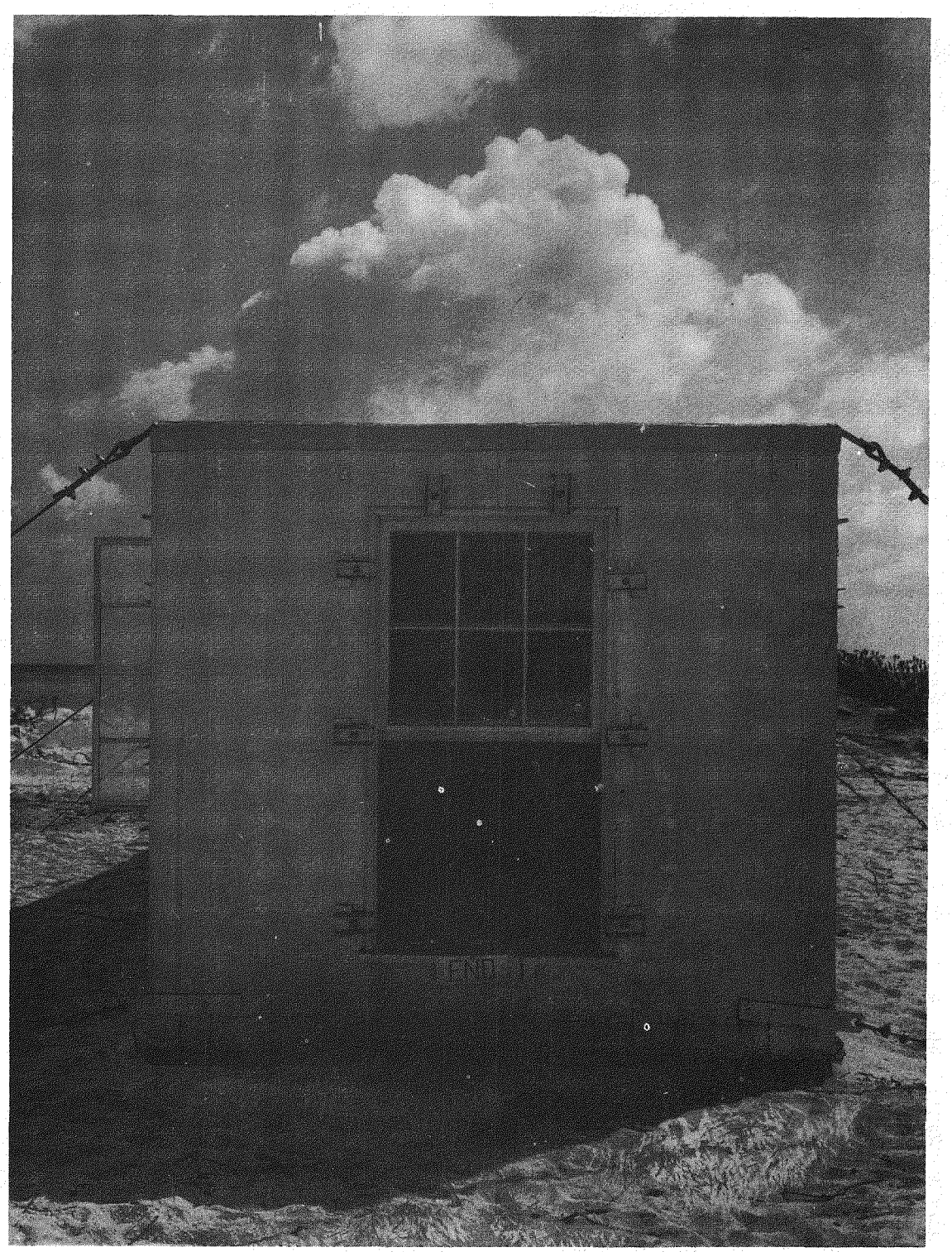

FIG. 3.7 Outside of Double-hung Wooden Window 1 before the Blast. This was a commercial-grade wooden window such as is used in moderately priced residences. The frame was made of members 1⅛ in. thick and glazed with double-strength glass 10⅞ by 15 in. The lower sash was raised before the blast.

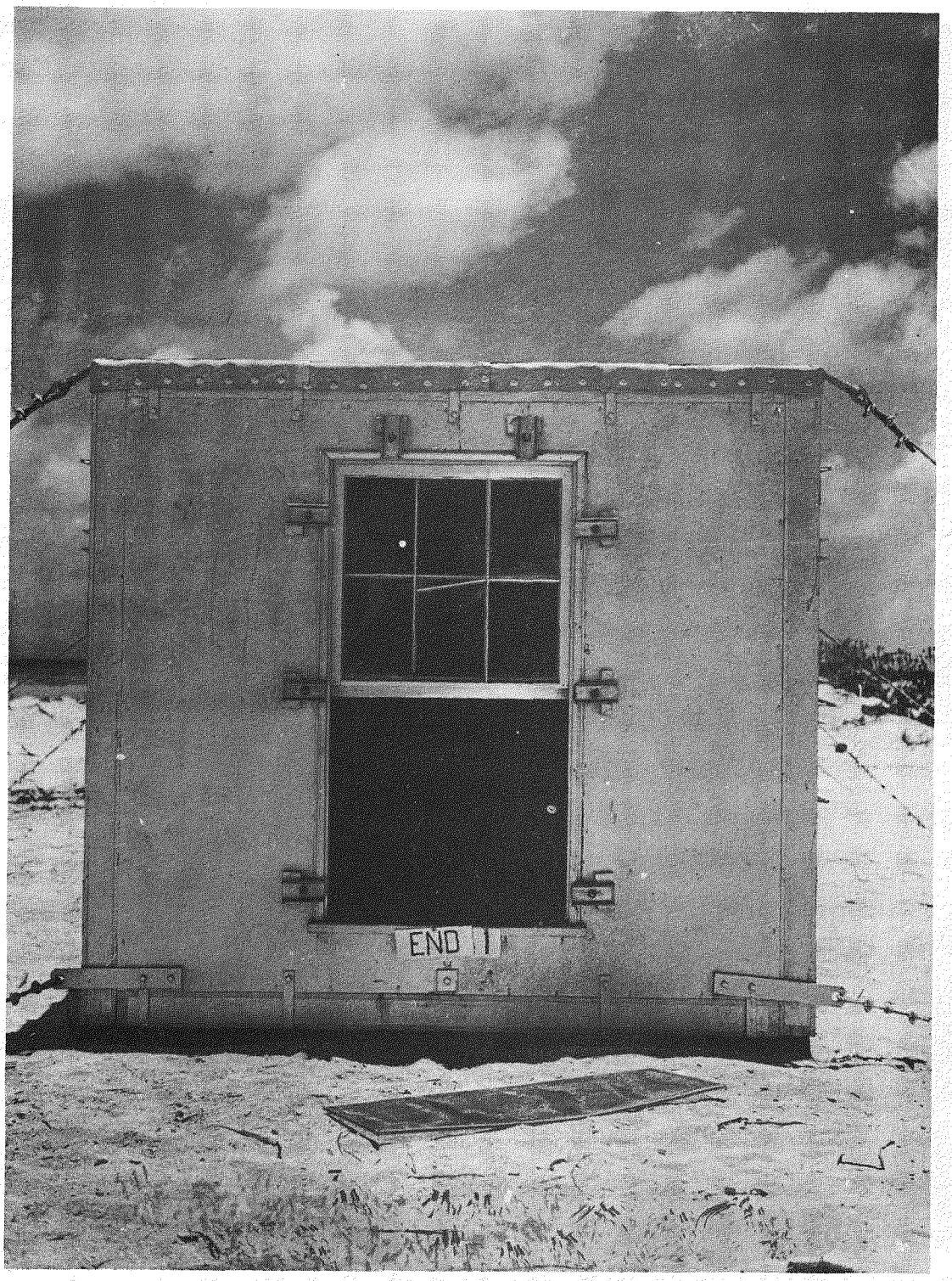

FIG. 3.8 Outside of Double-hung Wooden Window 1 after the Blast. The aluminum wire insect screen on the ground was blown through the opening below the raised sash in the end of the building. The screen was originally installed on the casement window 2 on the front of the building.

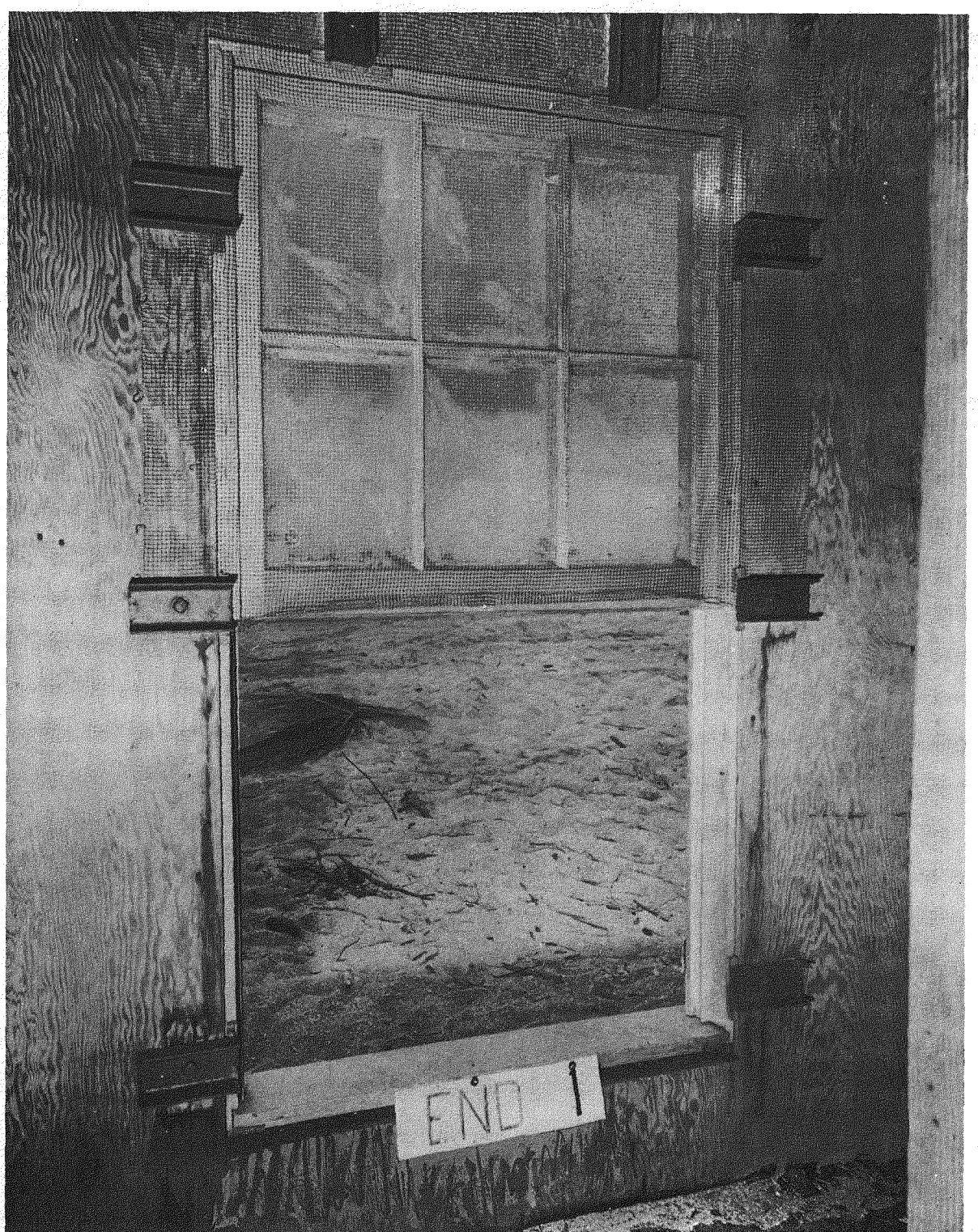

FIG. 3.9 Inside of Double-hung Wooden Window 1 before the Blast. Wire netting with ¼ in. mesh was mounted on the inside to stop flying fragments from entering the room.

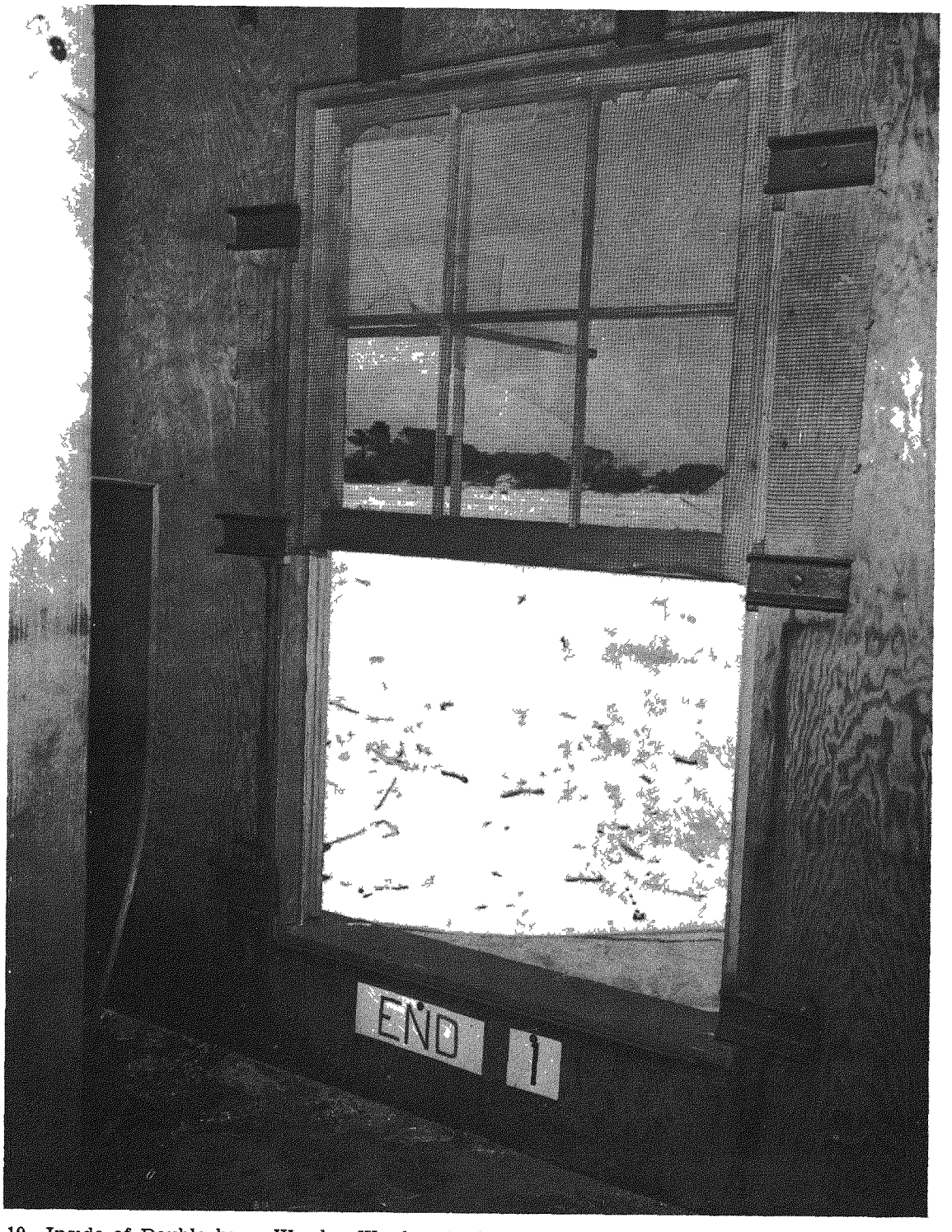

FIG 3 10 Inside of Double-hung Wooden Window 1 after the Blast The ¼ in mesh wire netting was undamaged All the glass fragments and pieces of muntins torn loose from the sash were blown outward, apparently by the expanding air within the room after the shock front passed, before the pieces could fall vertically This debris was on the sand outside the building about 4 ft from the face of the wall.

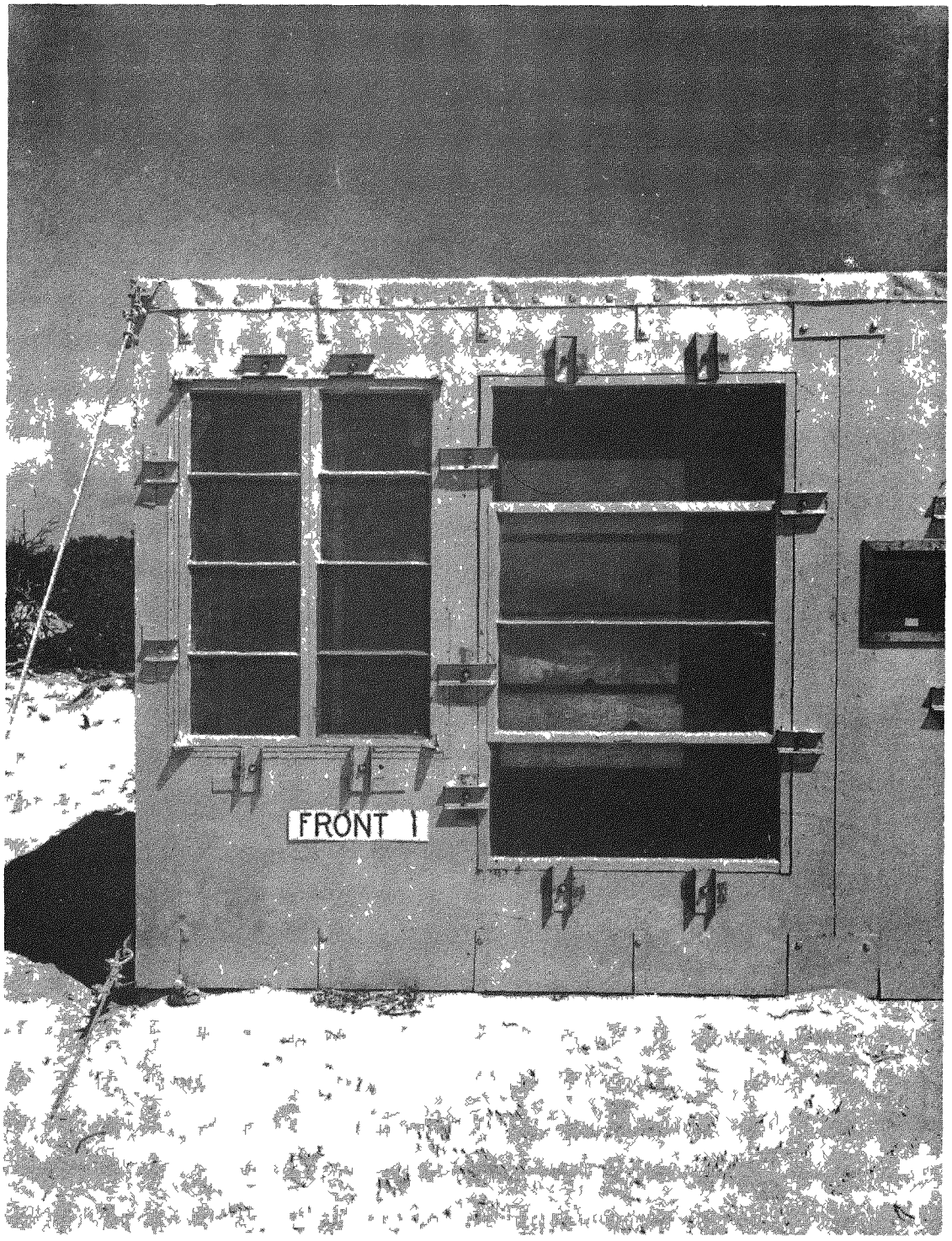

FIG 3 11 Outside of Casement Window 2 and Architectural Projected Window 3 before the Blast Window 2 is a lightweight aluminum, outswinging casement window used principally in small residences. Window 3 is an architectural projected steel window with two center panes of safety glass mounted in the ventilator section The top pane was plate glass 14⅝ by 37⅝ in , and the lower pane was polished wire glass

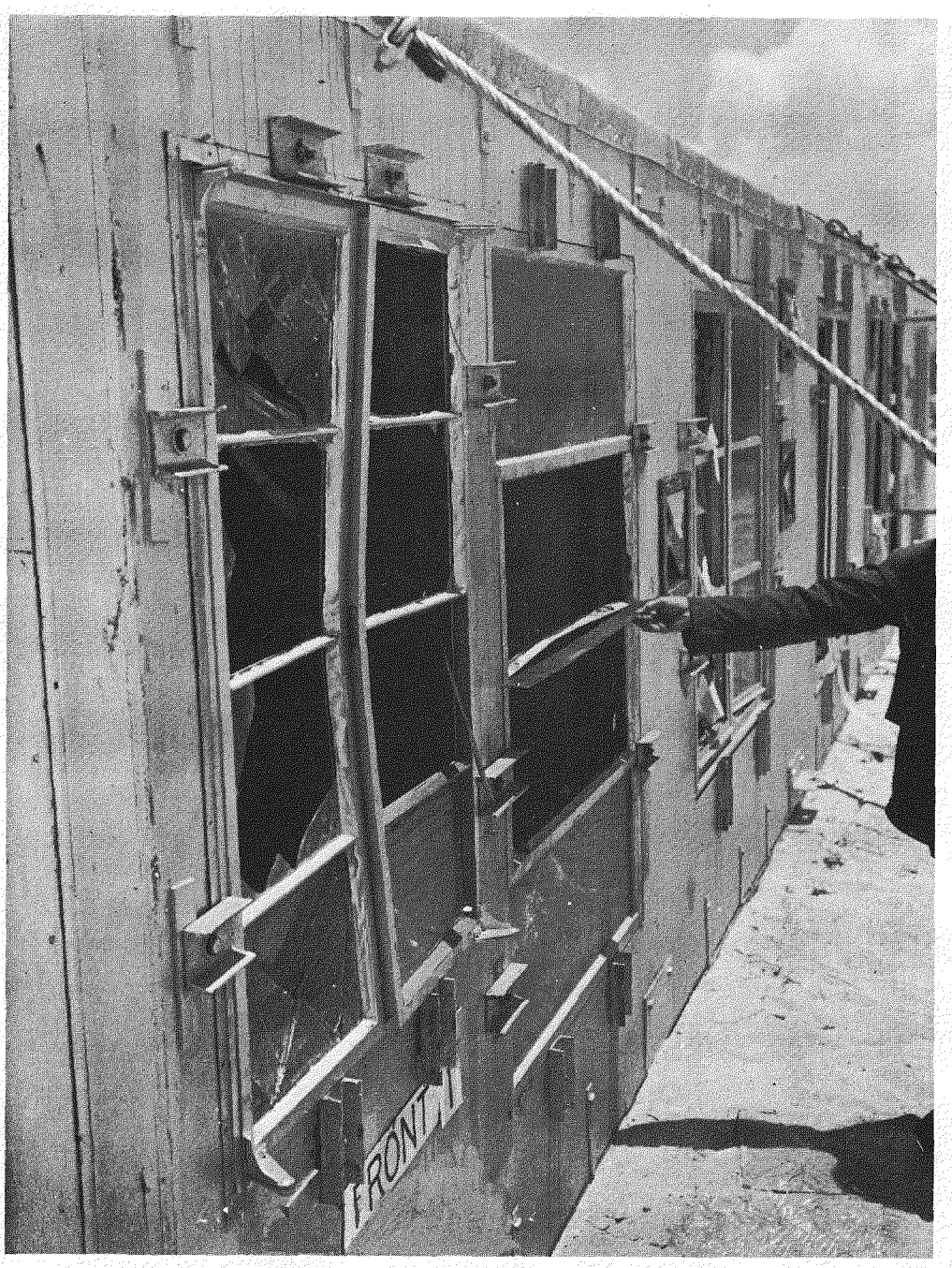

FIG. 3.12 Outside of Casement Window 2 and Architectural Projected Window 3 after the Blast. On the right-hand sash, the upper wire glass pane was blown out, as well as the double-strength glass in the second opening, and the 1/10 in. plastic in the third opening. The ⅛ in. thick plastic in the fourth opening was undamaged. The center meeting rail was bent approximately 2 in. out of line. The upper and lower panes on window 3 were undamaged, and the two sections of safety glass in the ventilator were broken in a large number of fragments less than ½ in. square. The plastic, however, held these fragments together in one sheet. The lower piece of safety glass fell between the lower pane of the window and the wire screen on the inside. The upper sheet of safety glass fell to the ground and can be seen in the shadow of the man's hand.

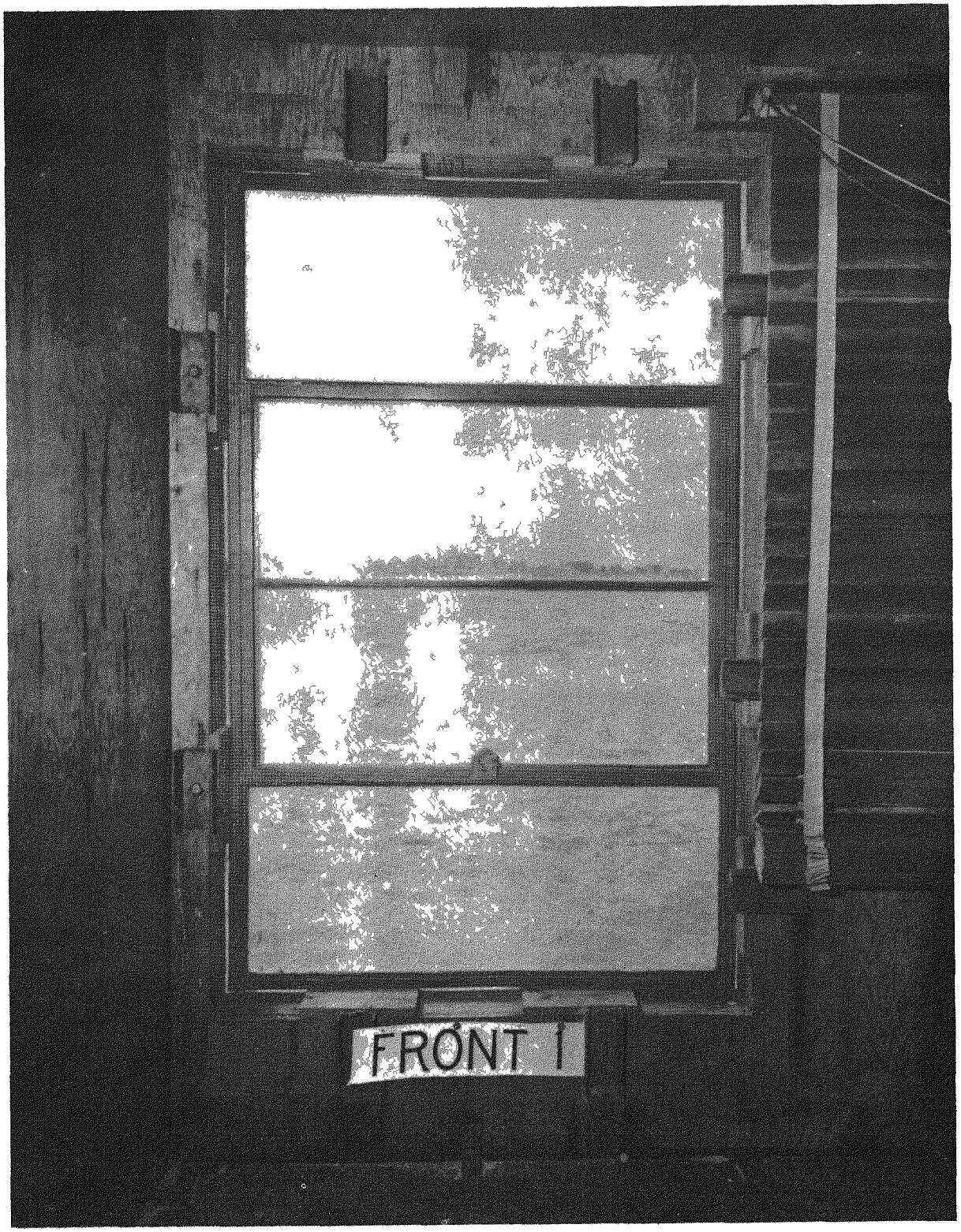

FIG 3 13 Inside of Architectural Projected Window 3 before the Blast Wire netting with ¼ in mesh was installed on the inside of the opening

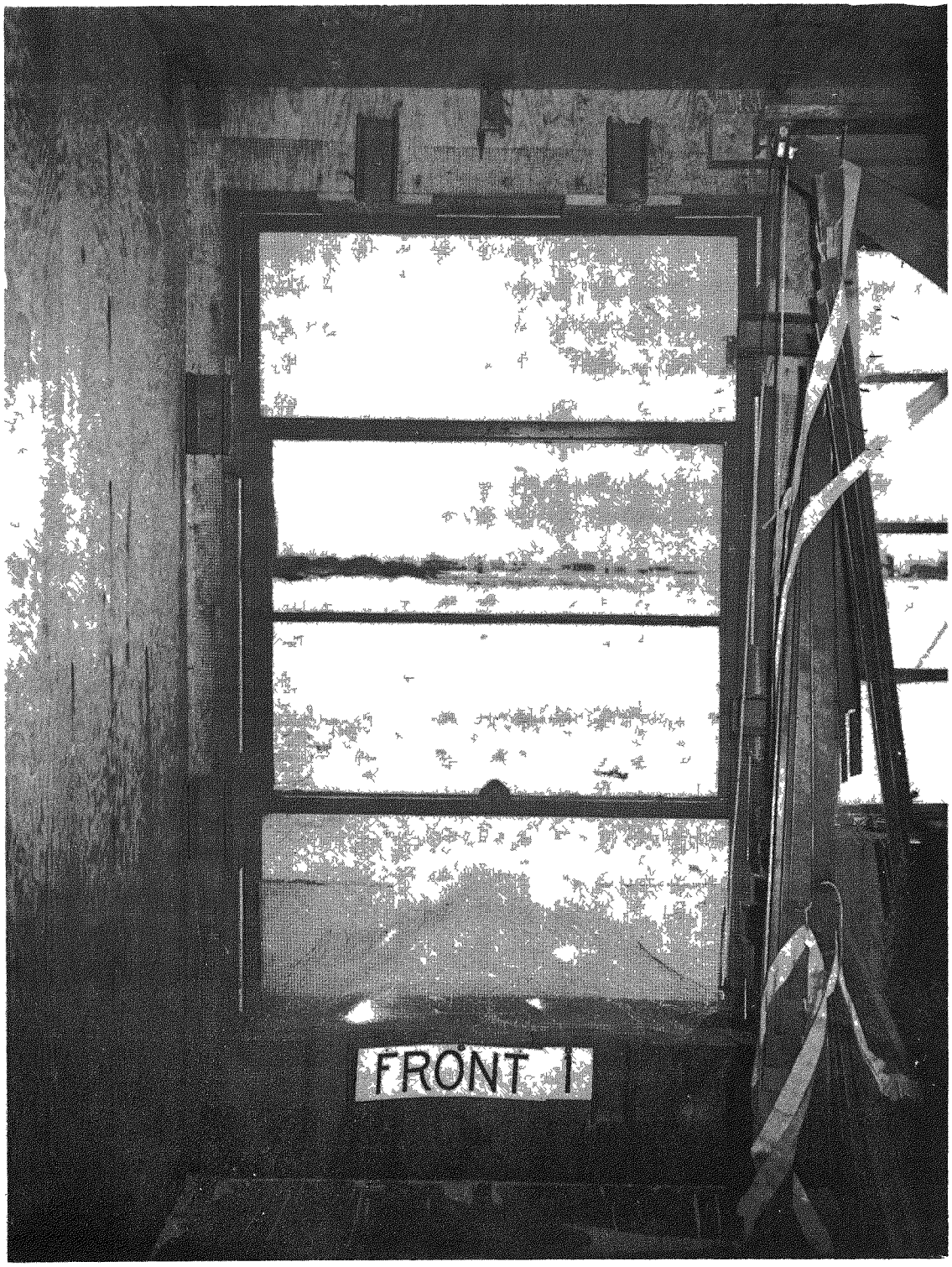

FIG 3 14 Inside of Architectural Projected Window 3 after the Blast The ¼ in mesh wire netting is intact, and the lower section of the crushed safety glass dropped to a position between the wire netting and the wire glass pane, which was unbroken

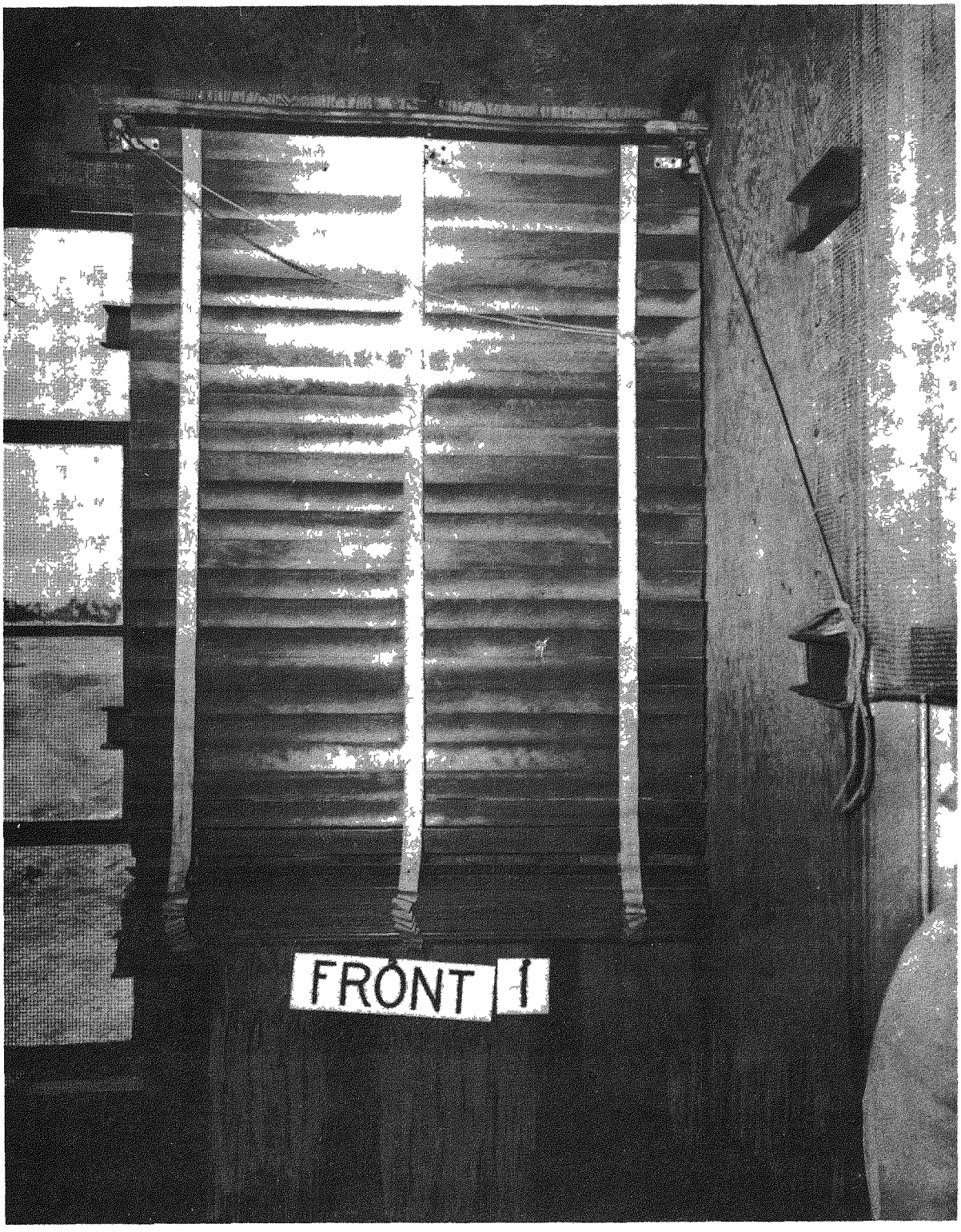

FIG 3 15 Inside of Casement Window 2 before the Blast A wooden Venetian blind was mounted over the opening

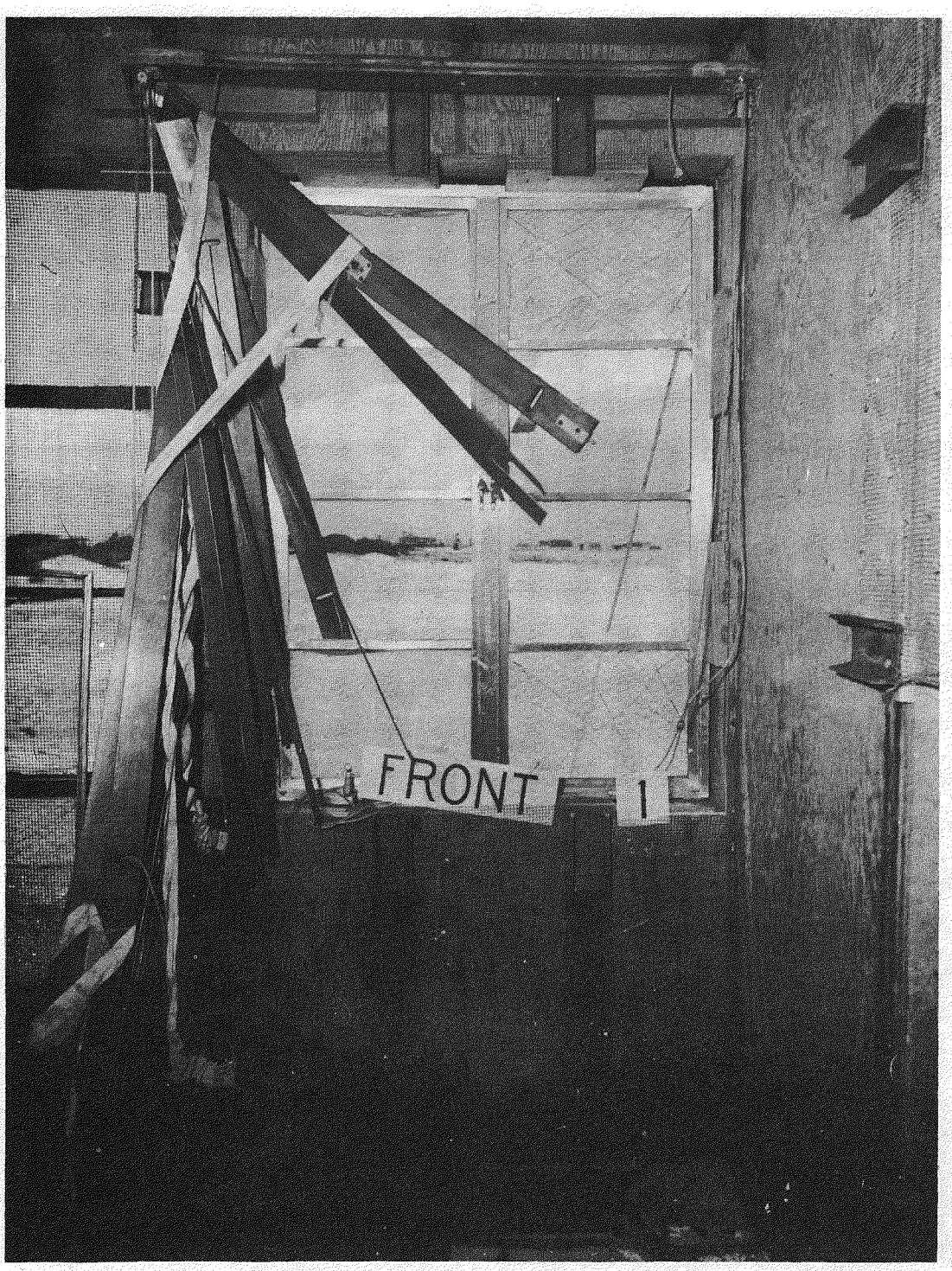

FIG. 3.16 Inside of Casement Window 2 after the Blast. The Venetian blind was completely wrecked, one side being torn from the wall, and the supporting cords broken off so that it was hanging by the connections on the left side only. Below the window sill the fragments of the 1/10 in. plastic which were mounted on the wall after the blast can be seen faintly. The plastic was broken in only about eight pieces, which fell to the floor near the center of the room.

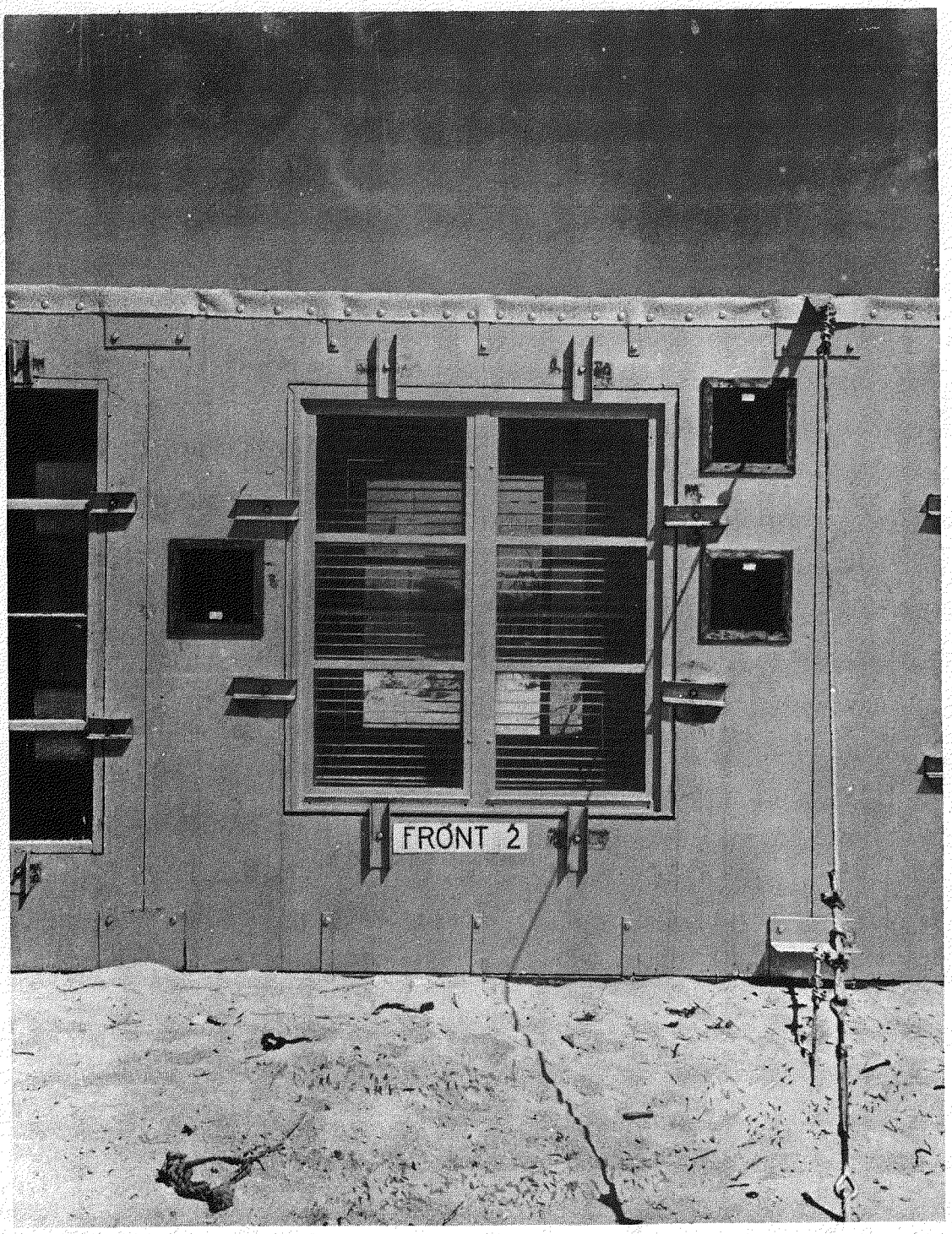

FIG. 3.17 Outside of Heavy Inswinging Casement Window 4 before the Blast. This aluminum casement is designed for office buildings and hospitals. The sash on the left was glazed with plate glass in the top and bottom openings and double-strength glass in the center. The sash on the right side was glazed with tempered glass. All pieces of glass were 17⅝ by 22½ in. In the three openings in the wall surrounding this window were installed pieces of specially prepared glass panels known as "Flex-Duplate" made by applying ⅛ in. plate glass on both sides of a plastic sheet. (See Sec. 2.3.)

FIG 3 18 Outside of Inswinging Casement Window 4 after the Blast All glass was broken out of the left-hand sash, and the right-hand sash was undamaged except for the broken catches which allowed the sash to swing inward with the blast After the shock front passed this sash was partially closed, probably by the negative wind, trapping some slats of the blind between the sash and the frame The center meeting rail of this window was deflected about ½ in The outer glasses in the three 12 in square openings surrounding this window were broken along the diagonal lines and forced in Later some of the triangular sections were pushed outward

FIG. 3.19 Inside of Inswinging Casement Window 4 before the Blast. A metal Venetian blind was mounted over the opening. One sash was blocked in place by means of two pieces of 2 by 4 in. planks shown in the photograph.

FIG. 3.20 Inside of Inswinging Casement Window 4 after the Blast. Some fragments of glass punctured the aluminum slats of the Venetian blind, which offered little protection against the flying glass.

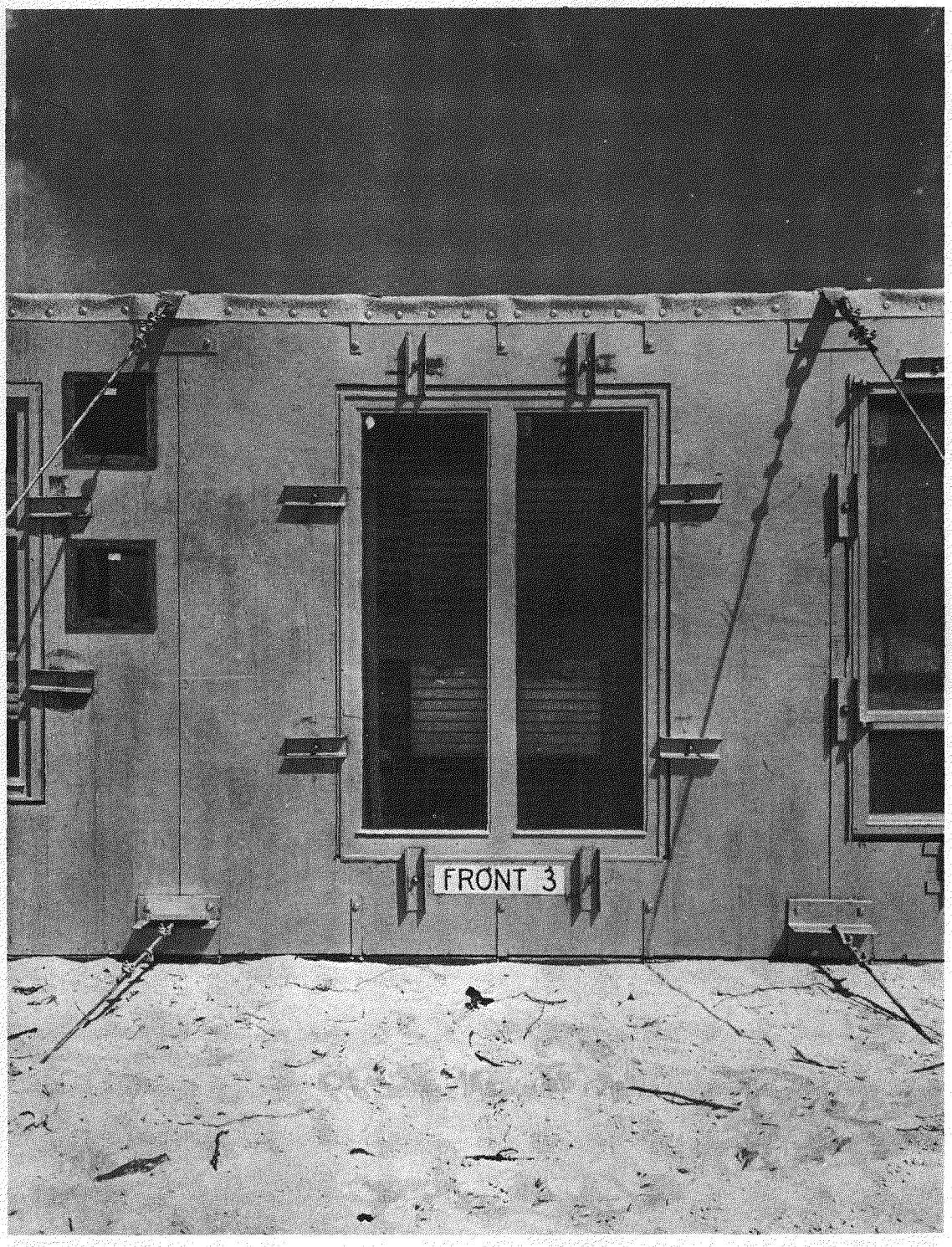

FIG. 3.21 Outside of Inswinging Casement Window 5 before the Blast. This window was constructed of heavy weight aluminum sections with hinges spot-welded to the frame and to the sash. The left-hand sash was glazed with tempered glass and the right-hand sash with wire glass. The glass sections measured $19\frac{5}{8}$ by $61\frac{5}{8}$ in.

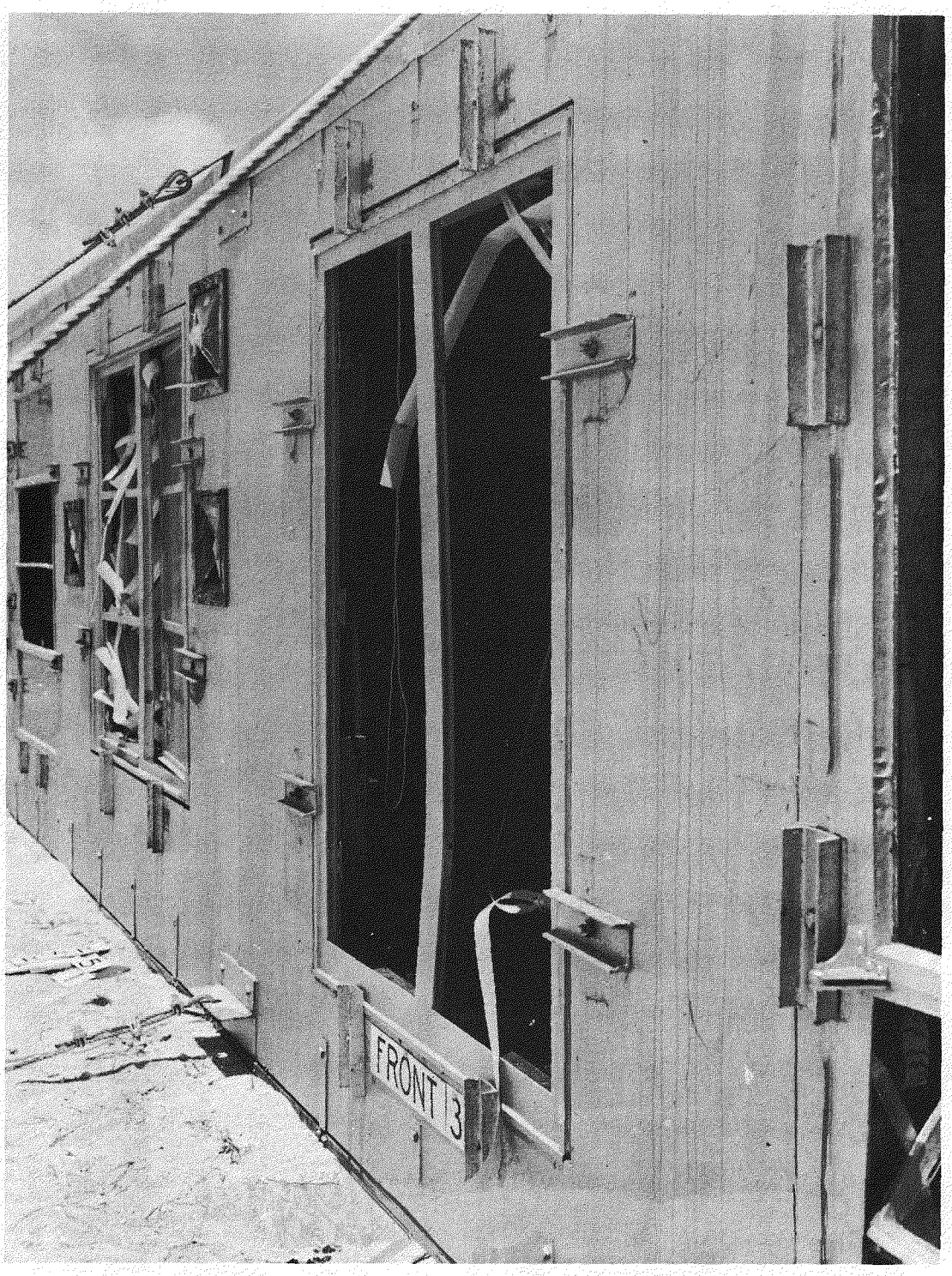

FIG. 3.22 Outside of Casement Window 5 after the Blast. The left-hand sash of this window was broken from the hinges and thrown across the room. The tempered glass in this sash was not broken. The locks on the right-hand sash were torn loose, and the wire glass was broken out of the frame. The center meeting rail was deflected about 1½ in. out of line.

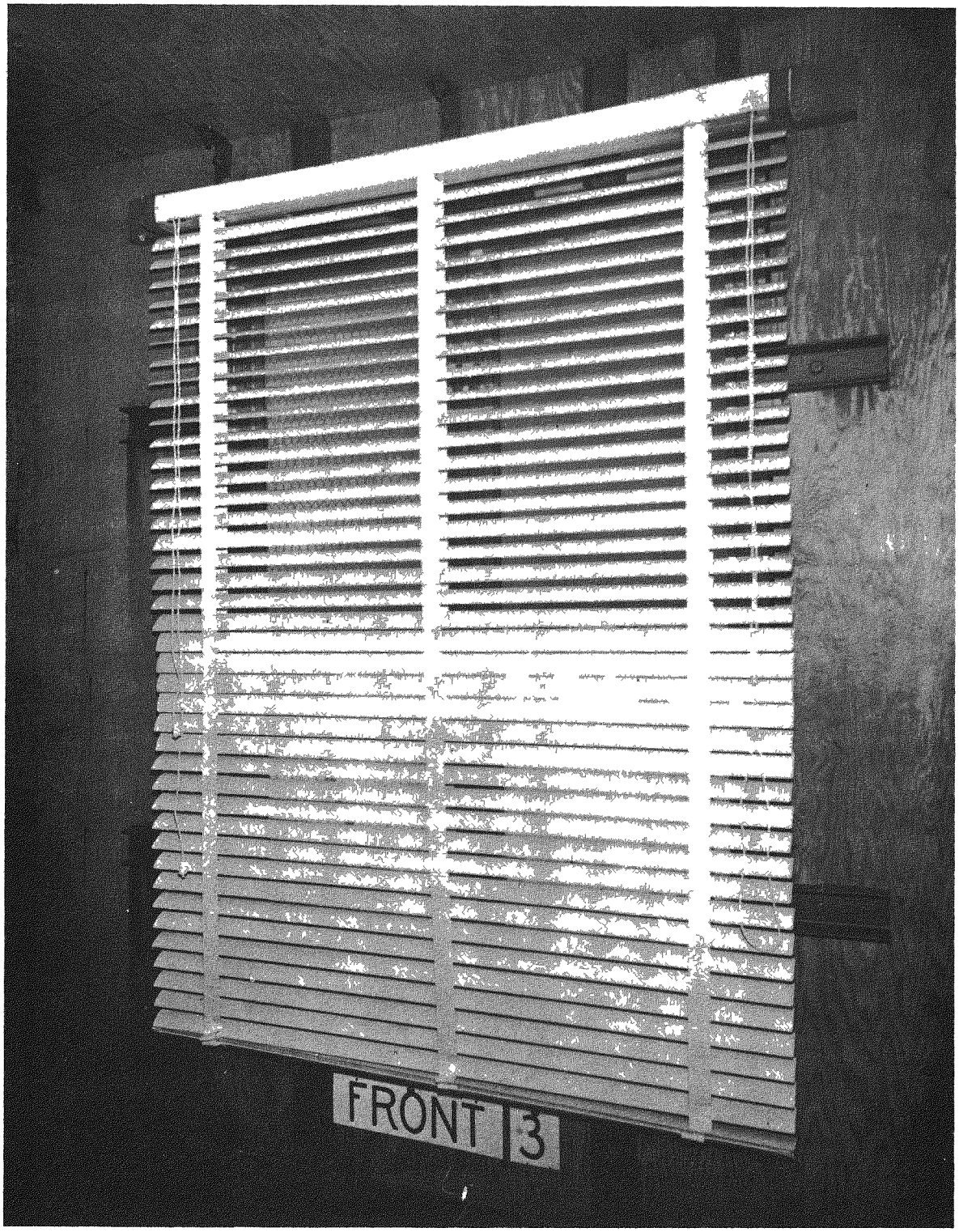

FIG 3 23 Inside of Inswinging Casement Window 5 before the Blast A metal Venetian blind was installed over the opening

FIG. 3.24 Inside of Window 5 after the Blast. The Venetian blind was completely wrecked. Some of the glass fragments of the wire glass section were imbedded in the partition running perpendicular to the front wall just beyond the limit of the picture on the left side.

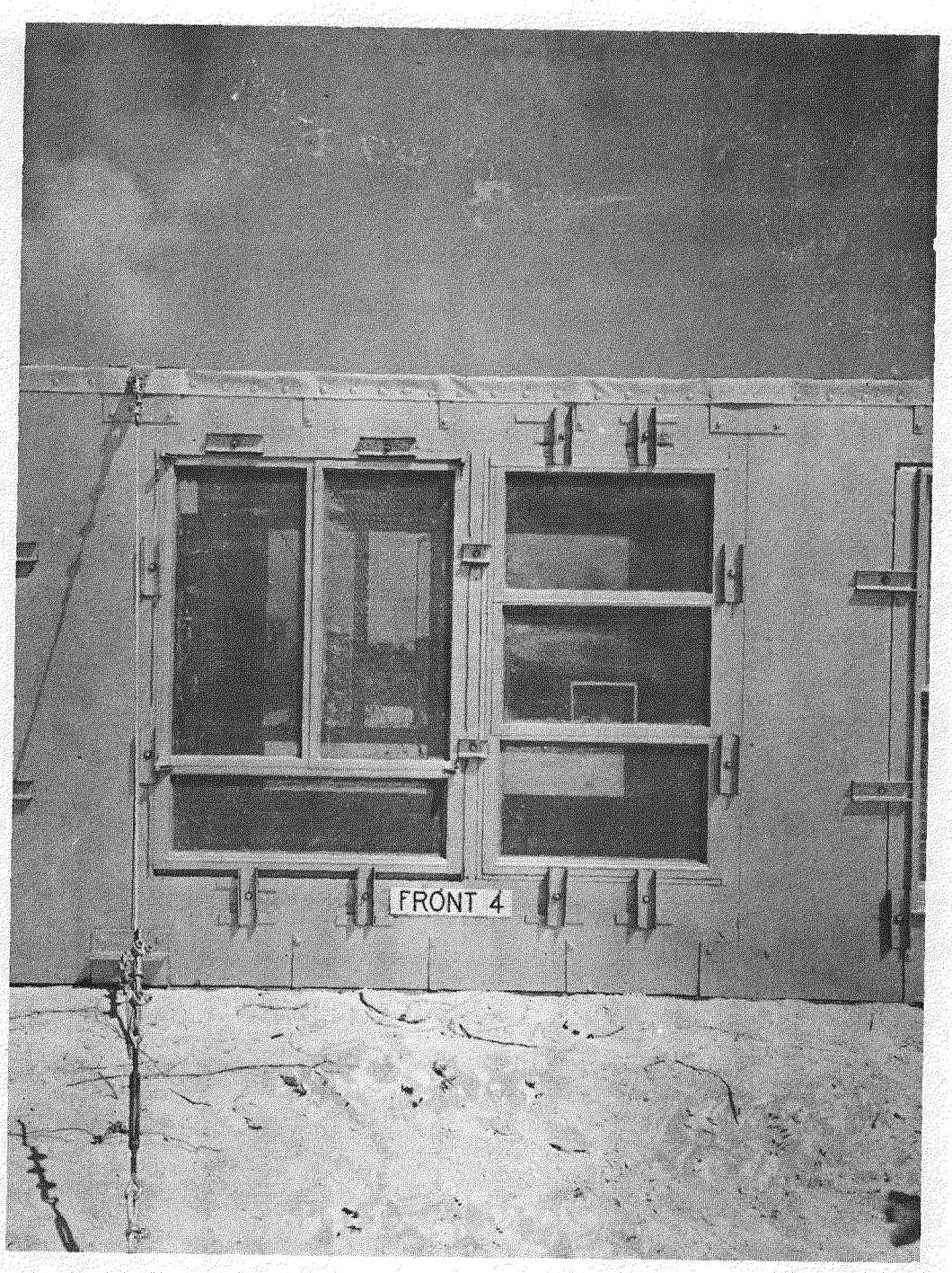

FIG. 3.25 Outside of Casement Window 6 and Canopy Window 7 before the Blast. Window 6 is a heavyweight aluminum inswinging casement, with an inswinging hopper vent at the bottom. The left-hand sash of window 6 was glazed with safety glass and the right-hand sash with wire glass. Plate glass was used in the hopper vent. Before the blast the right-hand sash of the casement was opened so that it would be parallel to the blast. Window 7 was a lightweight aluminum canopy window with two upper sections swinging outward and the lower section swinging inward. Plate glass, wire glass, and safety glass, 18 9/16 by 32 15/16 in., were installed in the frame.

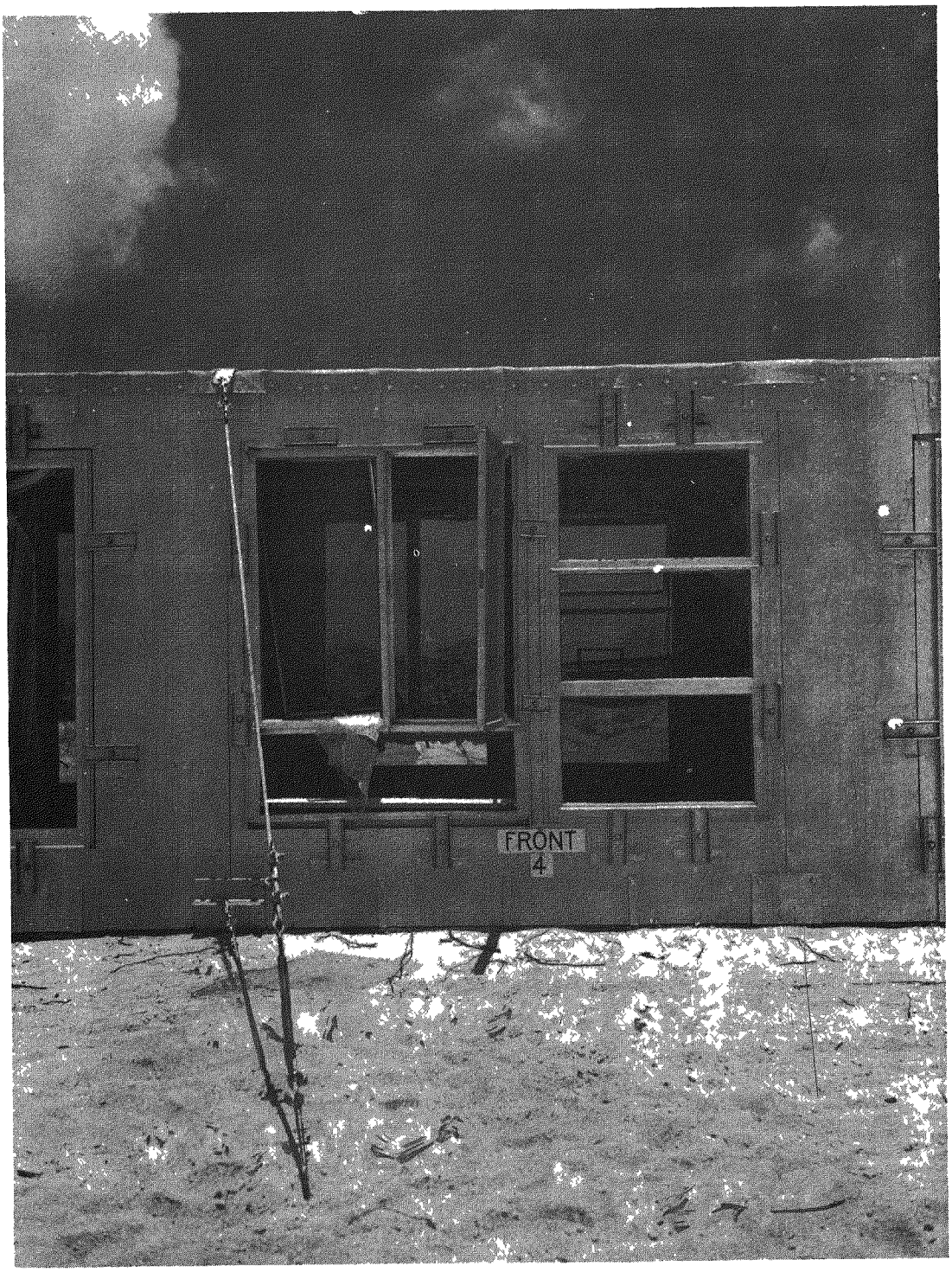

FIG 3 26 Outside of Casement Window 6 and Canopy Window 7 after the Blast The safety glass in the right-hand sash of the casement was shattered and fell to the sill as shown in the photograph The right-hand sash of the casement was undamaged and the glass in the hopper vent was broken out All glass was broken out of window 7, however, the frame was undamaged

FIG. 3.27 Inside of Casement Window 6 before the Blast

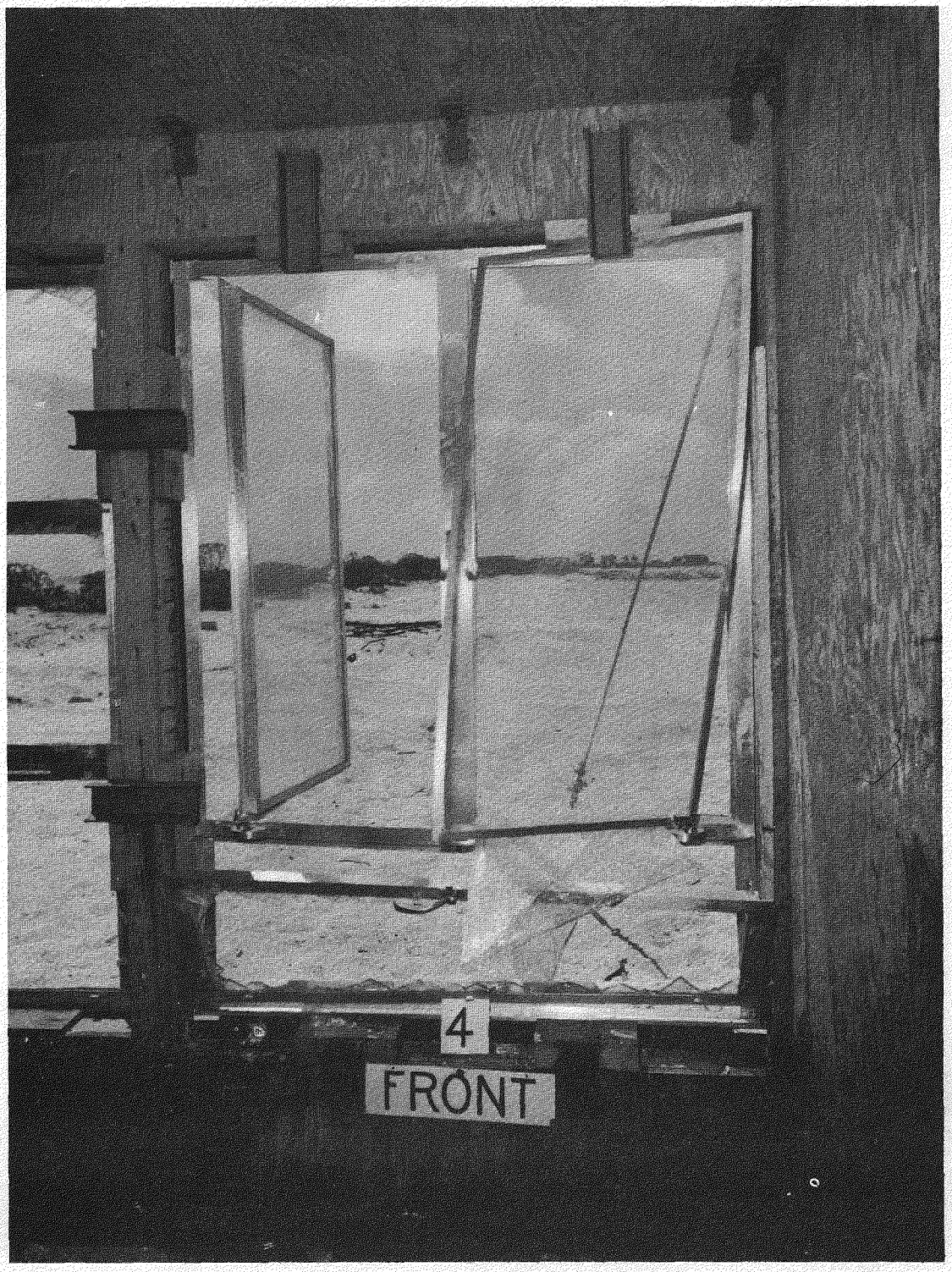

FIG. 3.28 Inside of Casement Window 6 after the Blast. The left-hand sash of the window was opened outward perpendicular to the wall before the blast and was undamaged. The latch on the hopper vent was broken as the sash was forced open.

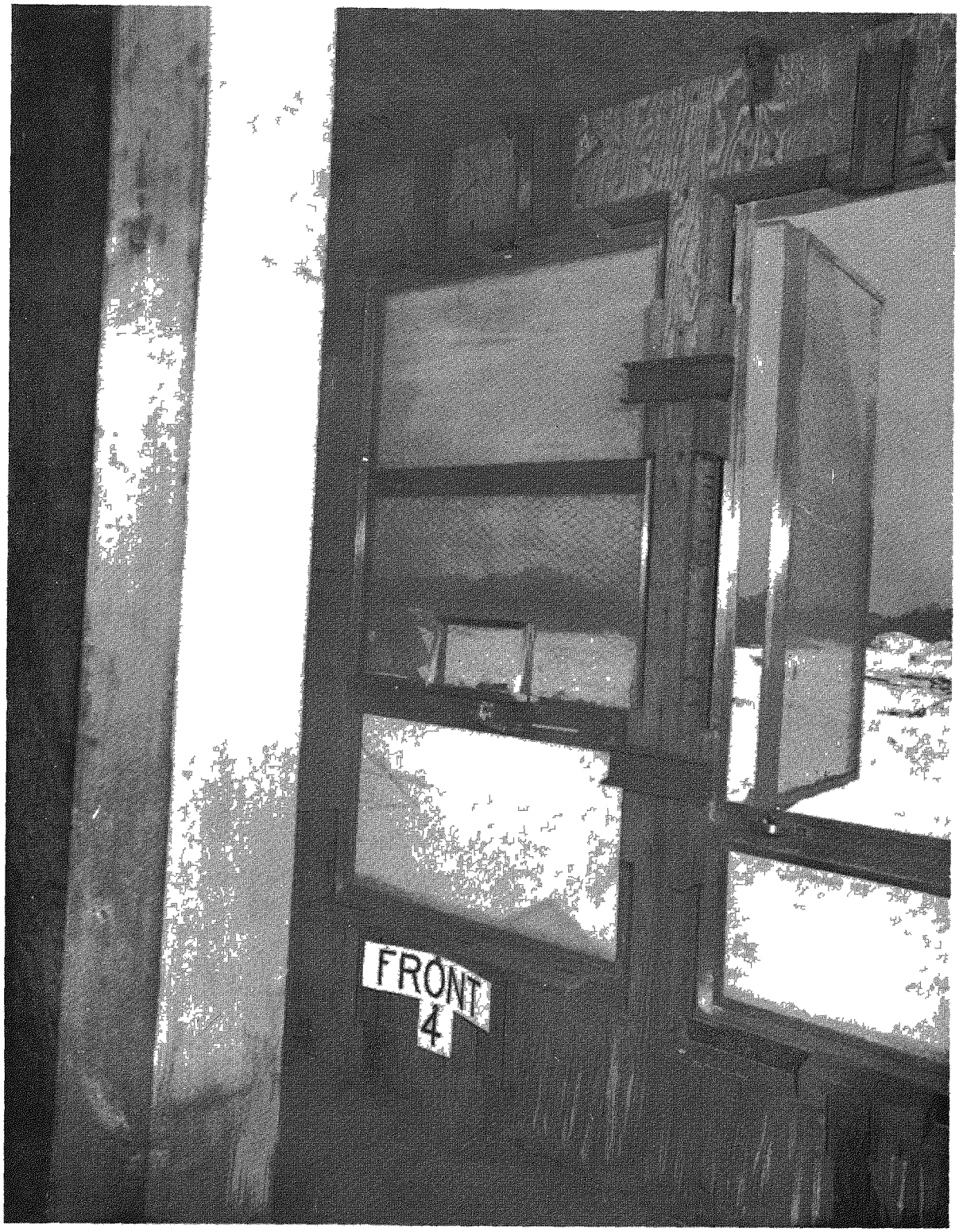

FIG 3 29 Inside of Canopy Window 7 and Part of Casement Window 6 before the Blast

FIG 3 30 Close-up of Casement Window 6 after the Blast The insect screen was partially torn from the frame, and no trash was deposited on the outer surface by the positive wind The bottom rail of the casement opening was bent about 2 in out of line

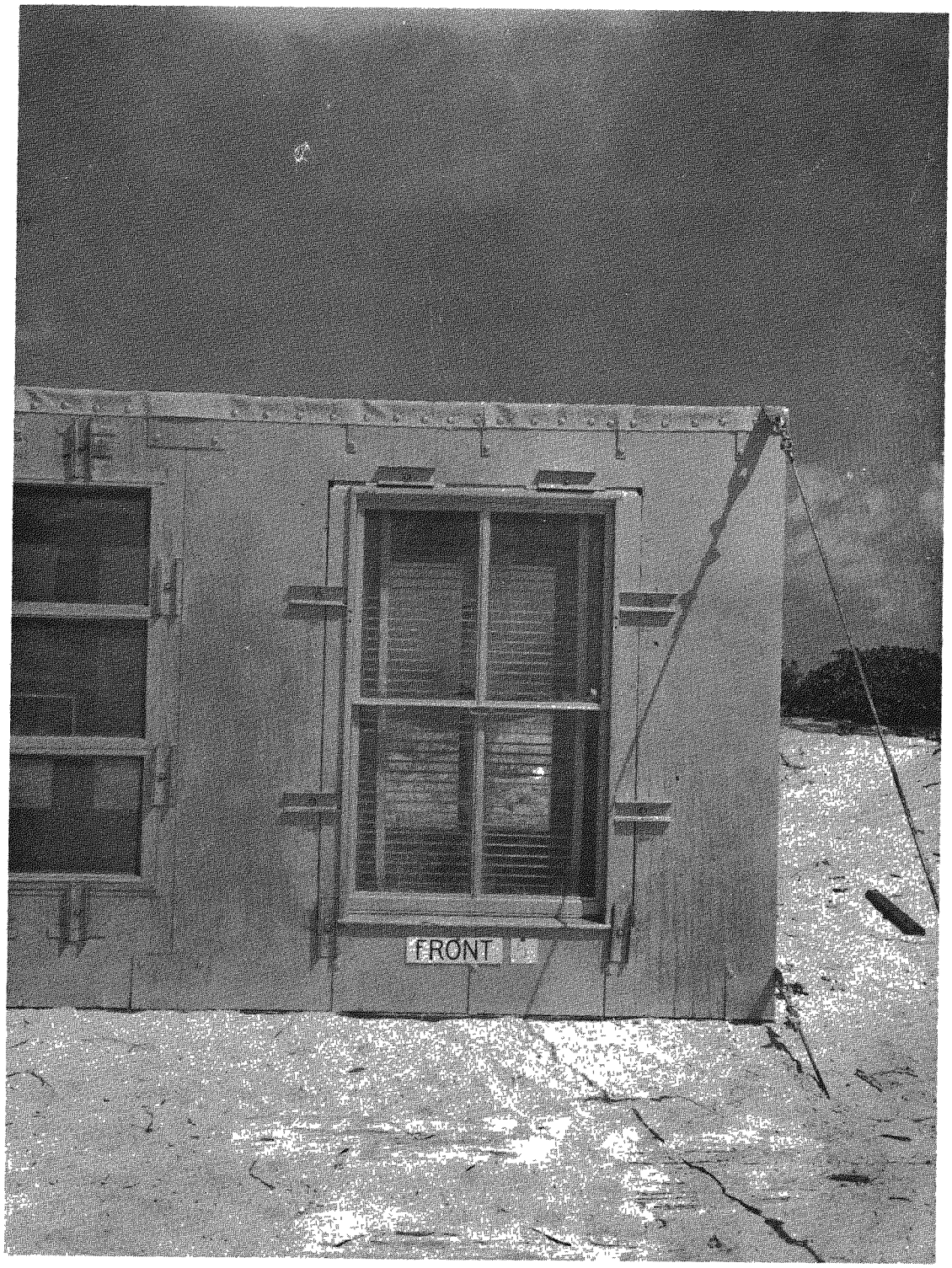

FIG. 3.31 Outside of Double-hung Steel Window 8 before the Blast. This was a heavyweight steel double-hung window glazed with double-strength and plate glass in the upper sash and safety and wire glass in the lower sash. Panes were 19½ by 30¾ in.

FIG. 3.32 Outside of Double-hung Window 8 after the Blast. All panes of glass were blown from the frame and the lower muntin was torn loose from the bottom rail of the sash.

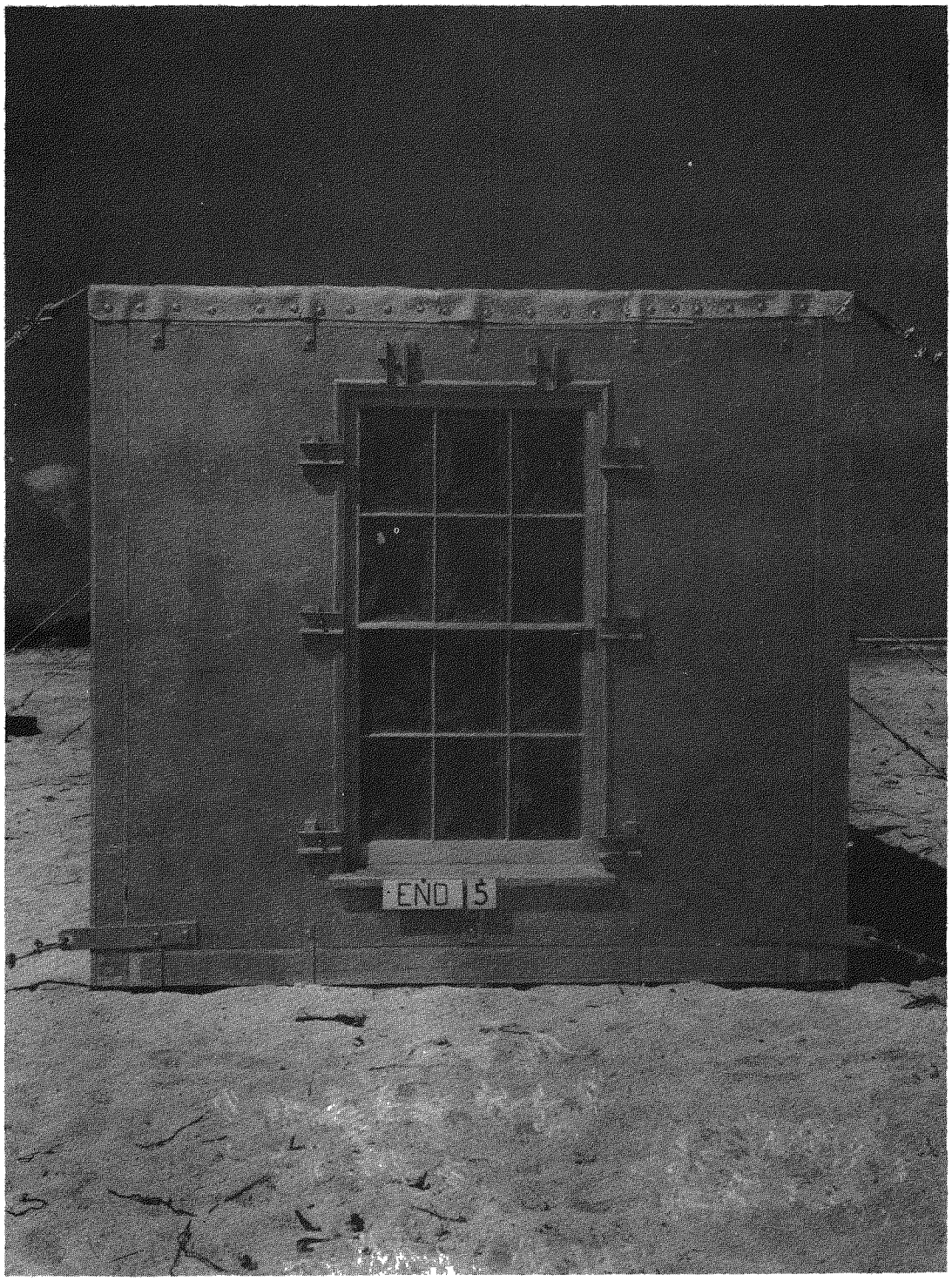

FIG. 3.33 Outside of Double-hung Window 9 before the Blast. This was a commercial-grade, wooden, double-hung window like window 1 at the other end of the building. It was glazed with double-strength glass. On the inside of the window opening, ¼ in. mesh wire netting was mounted to prevent the glass from flying into the building.

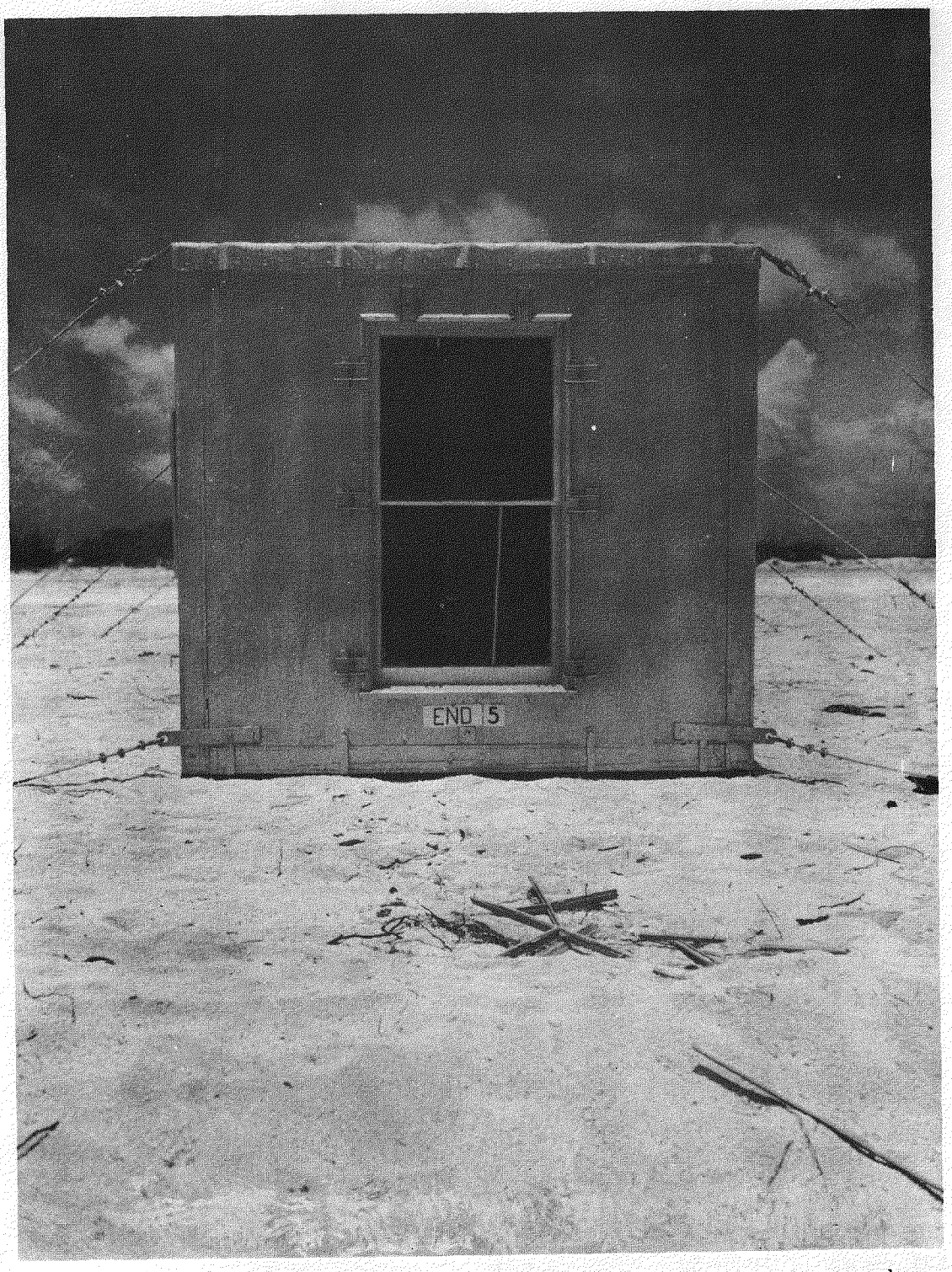

FIG. 3.34 Outside of Double-hung Window 9 after the Blast. The debris in the foreground was about 6 ft from the building and was composed of glass fragments and muntins that apparently were blown outward by the expansion of the air after the shock wave had passed and before gravity could pull the fragments down to the window sill.

FIG. 3.35 A Close-up of Outside of Window 9 after the Blast. The wire screen was bent inward by the blast and split along one side.

FIG. 3.36 Inside of Double-hung Window 8 after the Blast. The Venetian blind mounted over the window opening was torn loose from the brackets at the top and fell to the floor. Glass was scattered over the entire room, and the Venetian blind apparently offered little resistance to the flying fragments.

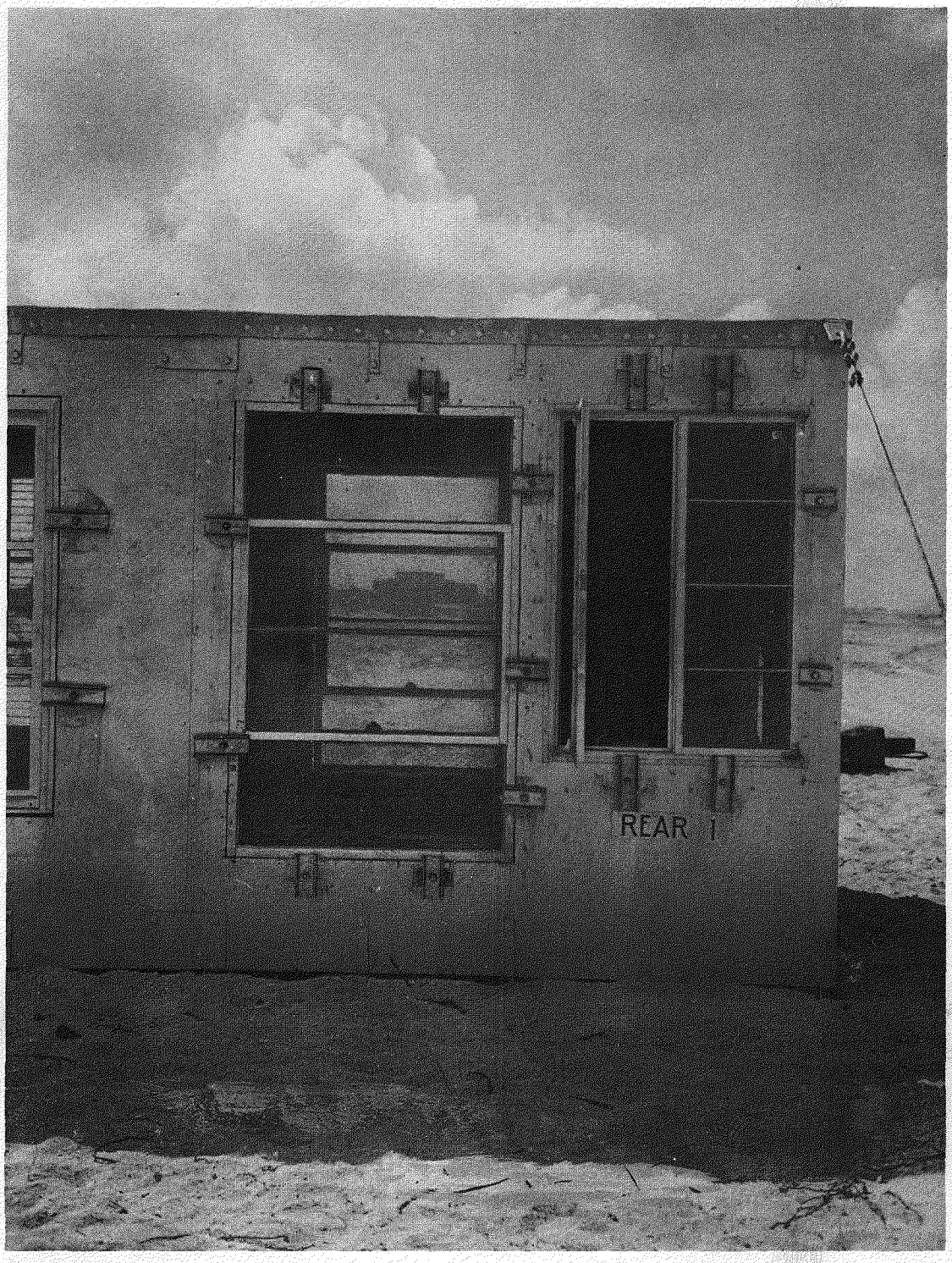

FIG. 3.37 Outside of Casement Window 10 and Architectural Projected Window 11 before the Blast. Window 10 was a duplicate of window 2 except that the right-hand sash was glazed with plate glass and the left-hand sash with double-strength glass. The left-hand sash was opened at right angles to the building before the blast. Window 11 was a duplicate of window 3 except that the top pane was plate glass, the ventilator panes were double-strength glass. and the lower pane was wired glass.

FIG 3.38 Outside of Casement Window 10 and Architectural Projected Window 11 after the Blast. There was no damage to either of these windows except that the operator on the open sash of the casement was broken and the center meeting rail was bent inward slightly

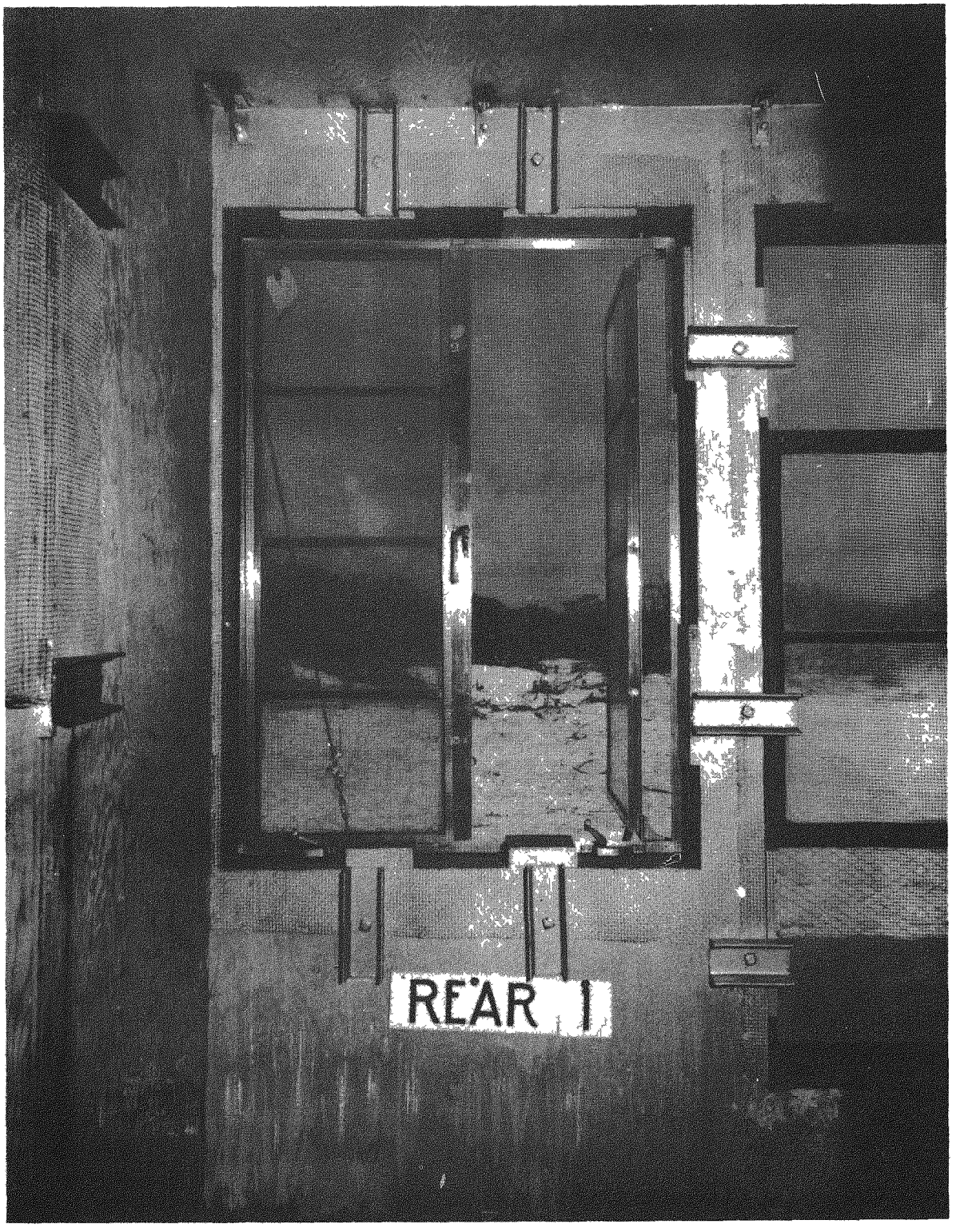

FIG 3.39 Inside of Casement Window 10 before the Blast The sash on the right-hand side was opened perpendicular to the building wall

FIG. 3.40 Inside of Casement Window 10 after the Blast

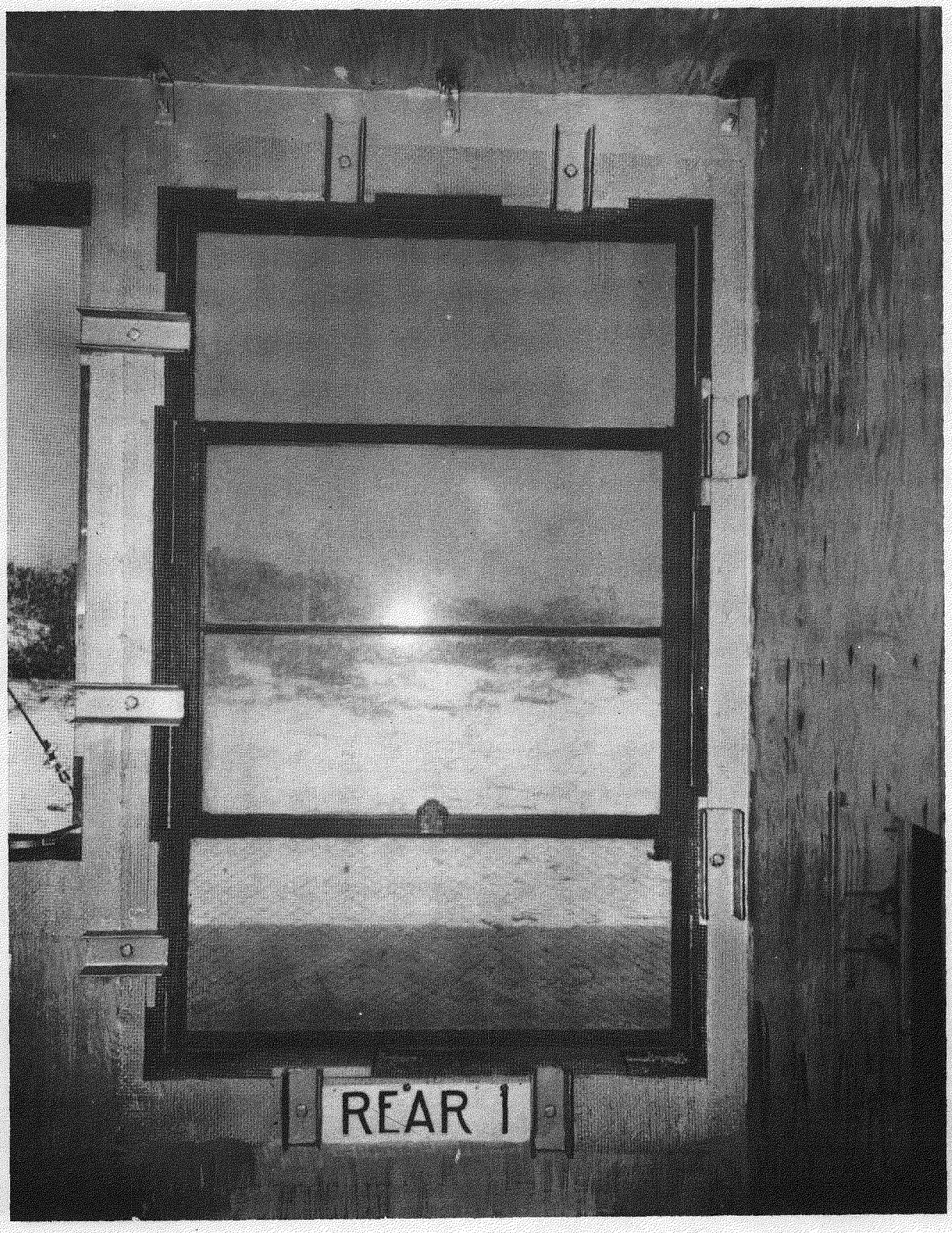

FIG. 3.41 Inside of Window 11 before the Blast

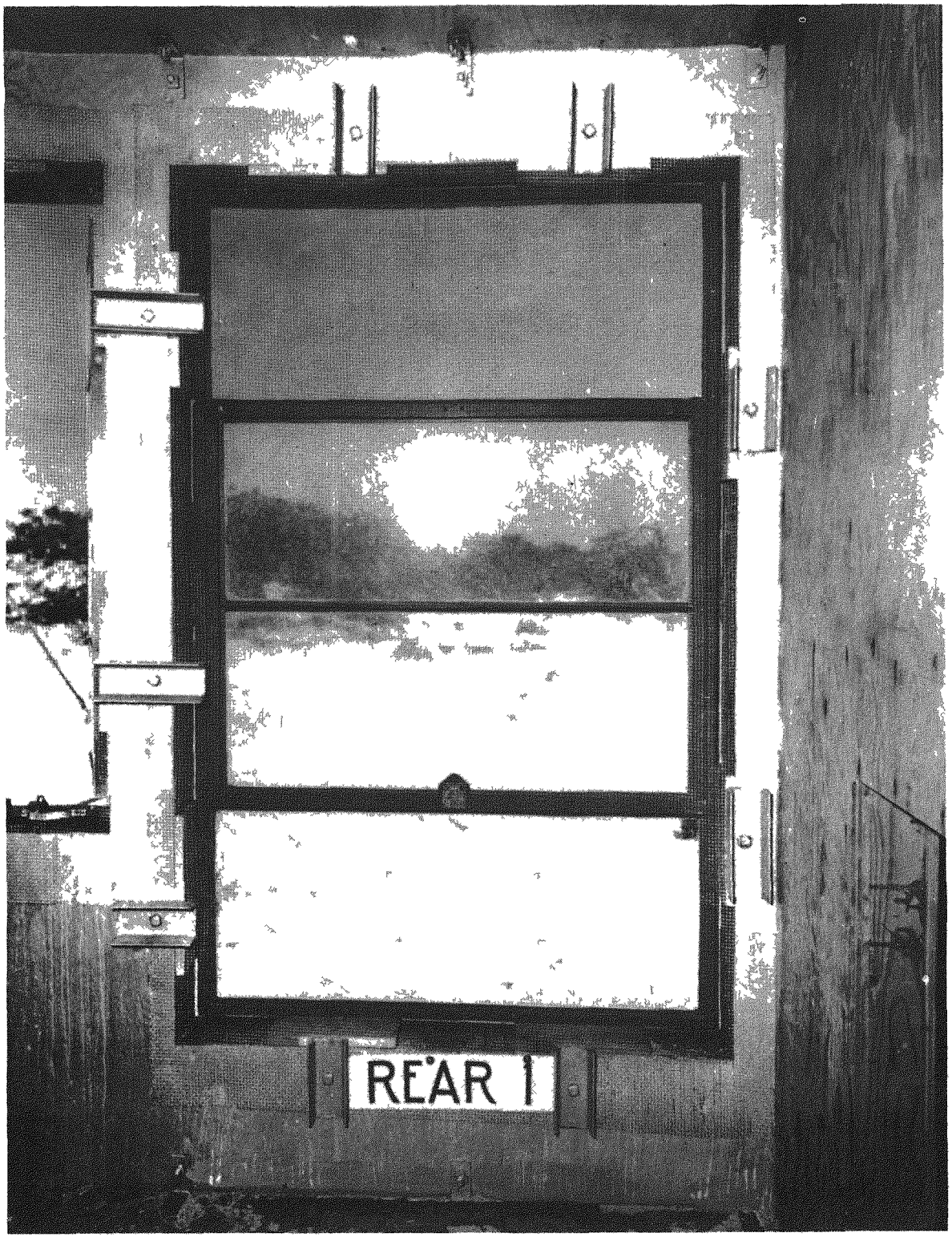

FIG 3 42 Inside of Window 11 after the Blast There was no apparent damage to this unit.

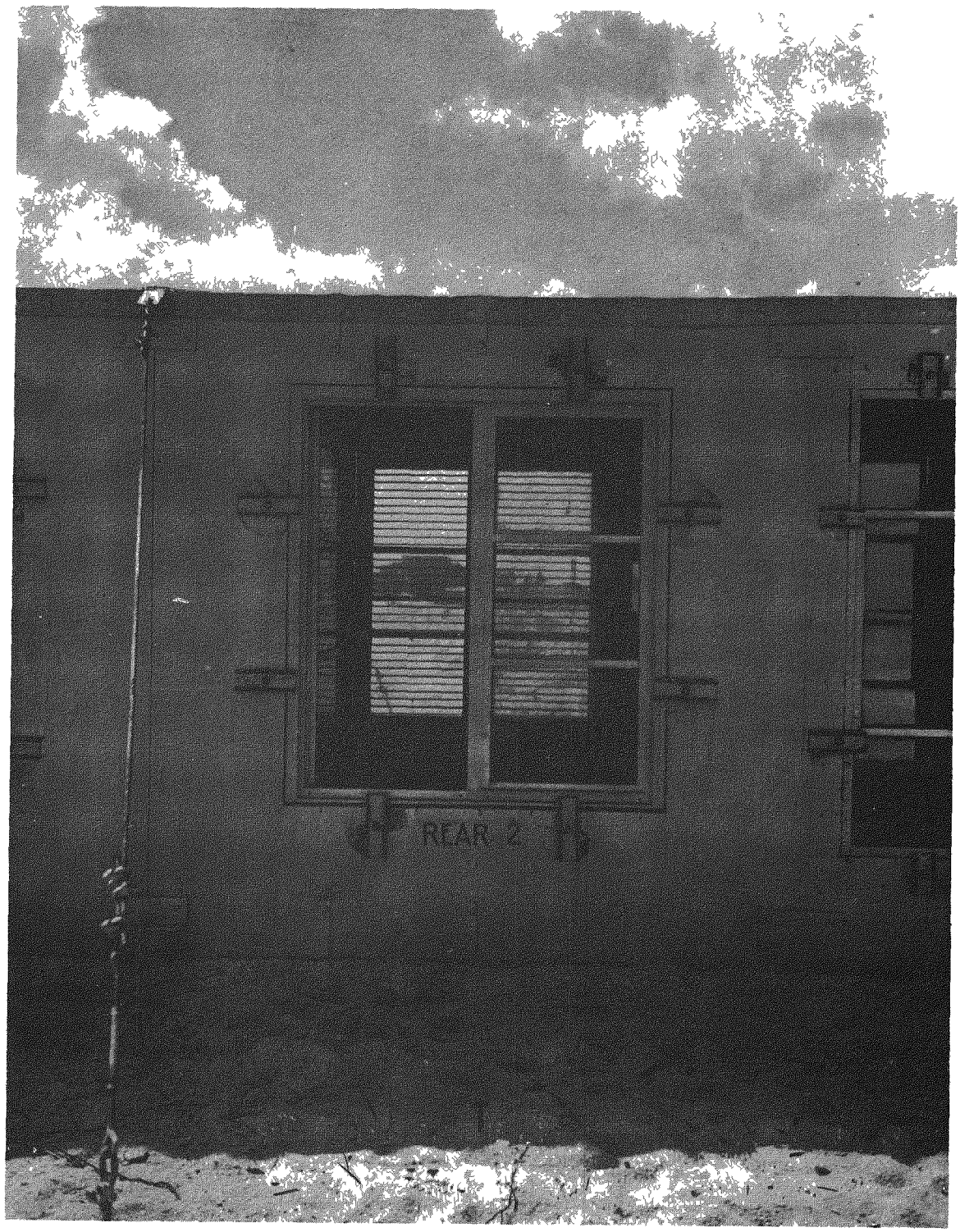

FIG. 3.43 Outside of Inswinging Casement Window 12 before the Blast. This was a duplicate of window 4 except that the left-hand sash was glazed with tempered glass and the right-hand sash was glazed with double-strength glass at the top and bottom, with a plate-glass unit in the center opening. The sash on the left was opened inward prior to the blast.

FIG 3 44 Inside of Window 12 after the Blast Possibly either the shock wave or the expansion of the air within the building after the shock wave passed slammed the open sash of this window shut with such violence that all the glass was broken and the fragments fell to the ground outside of the building The negative wind blowing against this free-swinging sash evidently returned it to its original position

FIG. 3.45 Outside of Casement Window 13 before the Blast. This is a duplicate of window 5 except that the left-hand sash was glazed with tempered glass and the right-hand sash with wire glass.

FIG 3 46 Outside of Casement Window 13 after the Blast The pressure of the shock wave apparently forced both sashes of this casement inward against the latches approximately ½ in There was, however, no breakage of the glass

FIG. 3.47 Inside of Casement Window 13 before the Blast. This window was a duplicate of window 5 with wire glass on the left and tempered glass on the right.

FIG 3 48 Inside of Casement Window 13 after the Blast The sash on the extreme left with only the corner showing is the one which was torn from the frame of window 5 on the front of the building

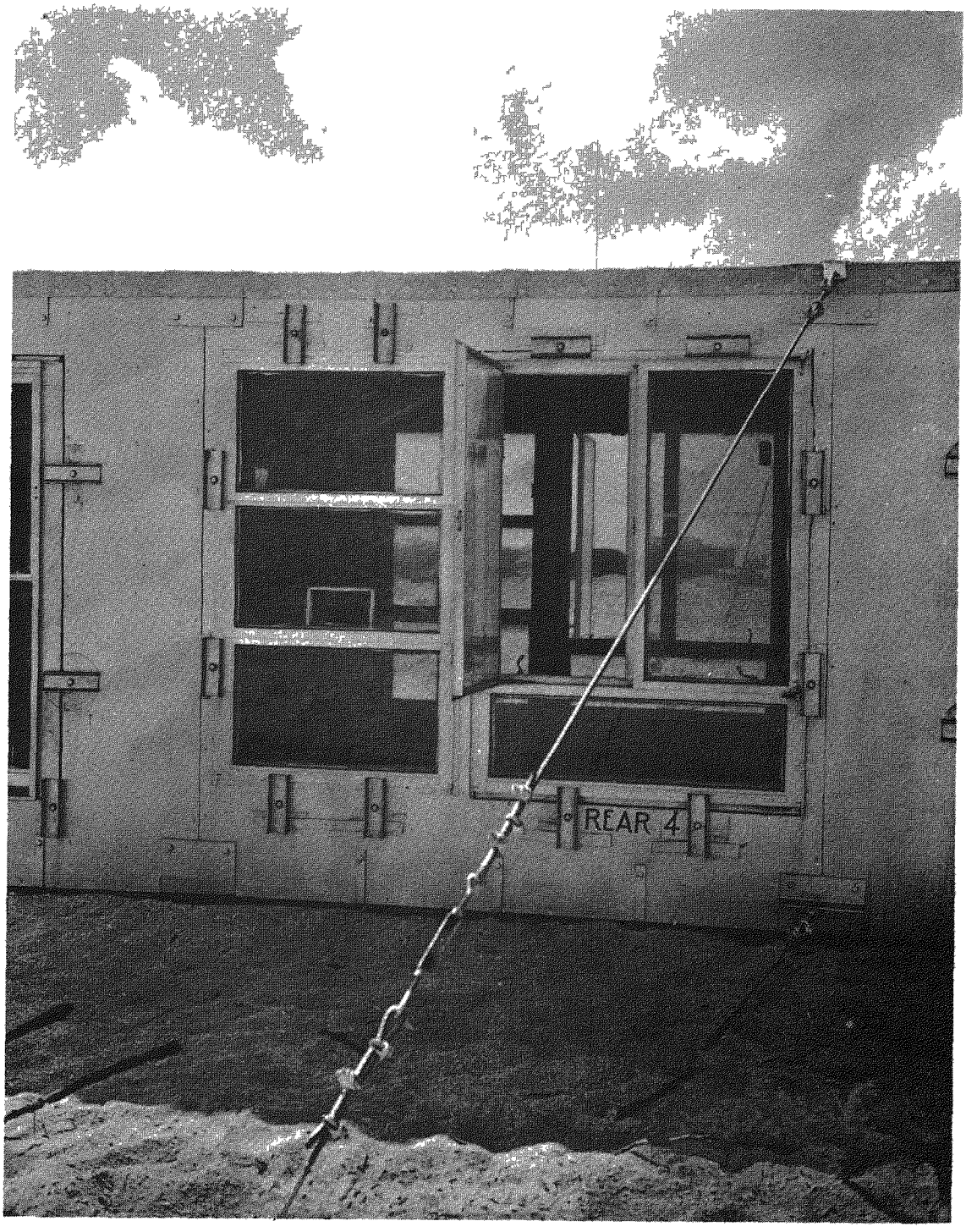

FIG 3 49 Outside of Casement Window 14 and Canopy Window 15 before the Blast. Window 14 was a duplicate of window 6 except that the left-hand sash was glazed with double-strength glass and the right-hand sash with wire glass. The hopper vent was glazed with safety glass. The left-hand sash of the casement was opened before the blast. Window 15 was a duplicate of canopy window 7 except that the upper pane was of double-strength glass, the middle pane of plate glass, and the lower pane of wire glass.

FIG. 3.50 Outside of Windows 14 and 15 after the Blast. Window 14 was undamaged. The upper glass in window 15 was blown in. The expanding air in the room following the blast apparently tore the catch loose, which locked the two upper ventilators in place and opened the window, as shown in the photograph. The insect screen over the opening in window 14 was covered with fine debris which was probably picked up by the negative wind and deposited on the outside surface of the screen.

FIG. 3.51 Inside of Casement Window 14 before the Blast

FIG. 3 52 Inside of Window 14 after the Blast Debris on the outside of the insect screen is visible, as previously noted

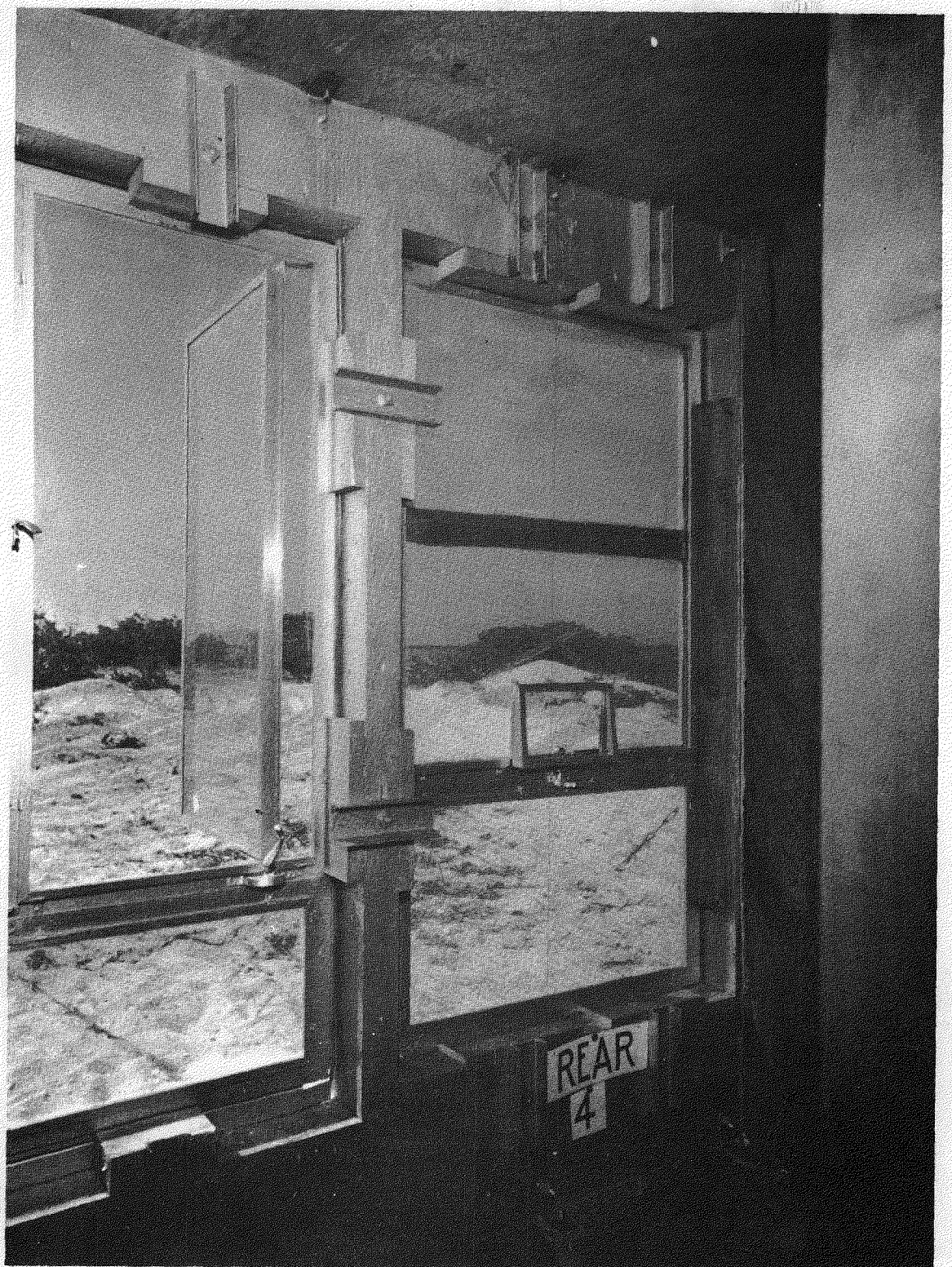

FIG. 3.53 Inside of Canopy Window 15 before the Blast

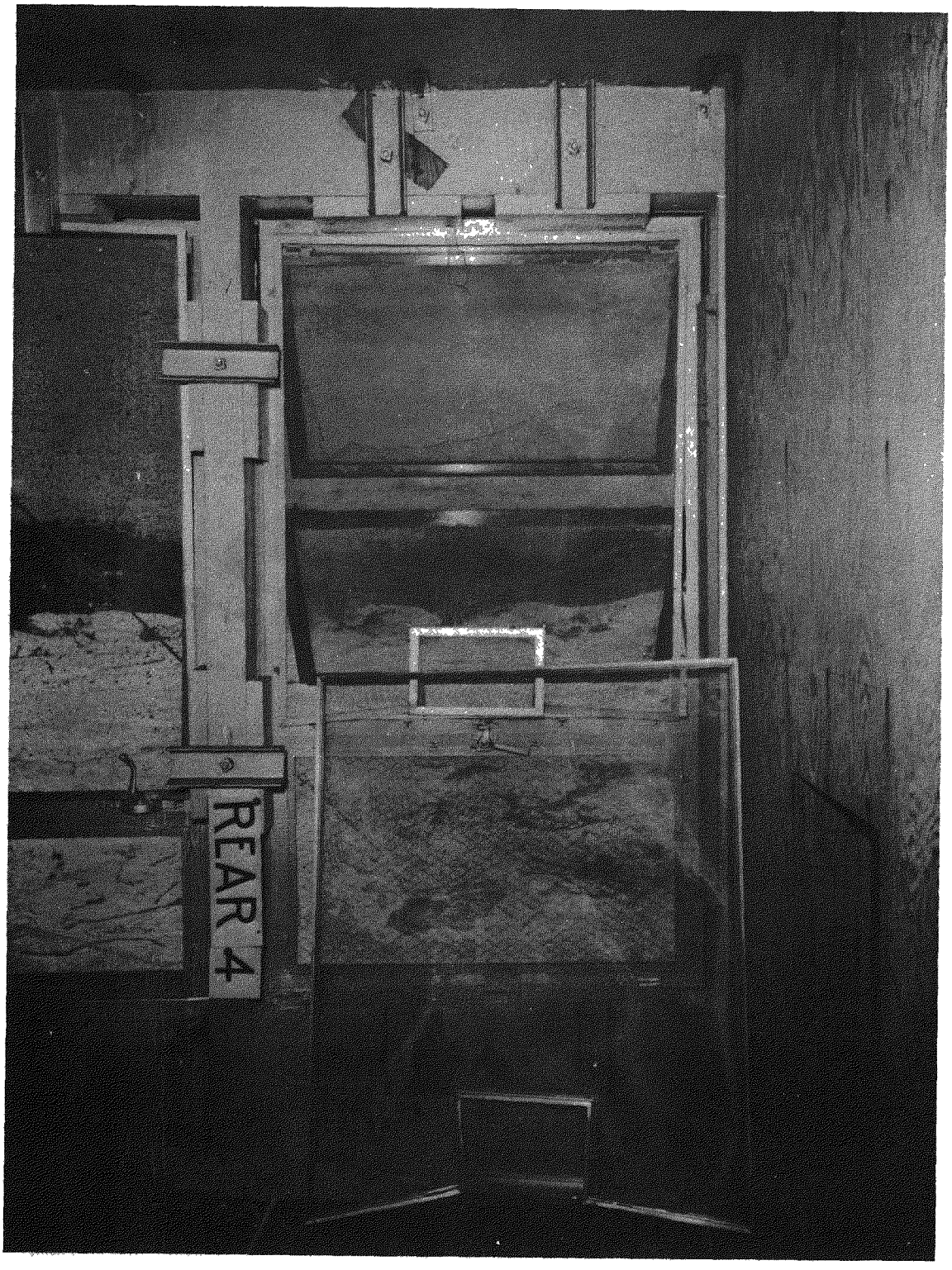

FIG. 3.54 Inside of Window 15 after the Blast. The insect screen mounted on the window was torn loose from the frame and dropped to the floor.

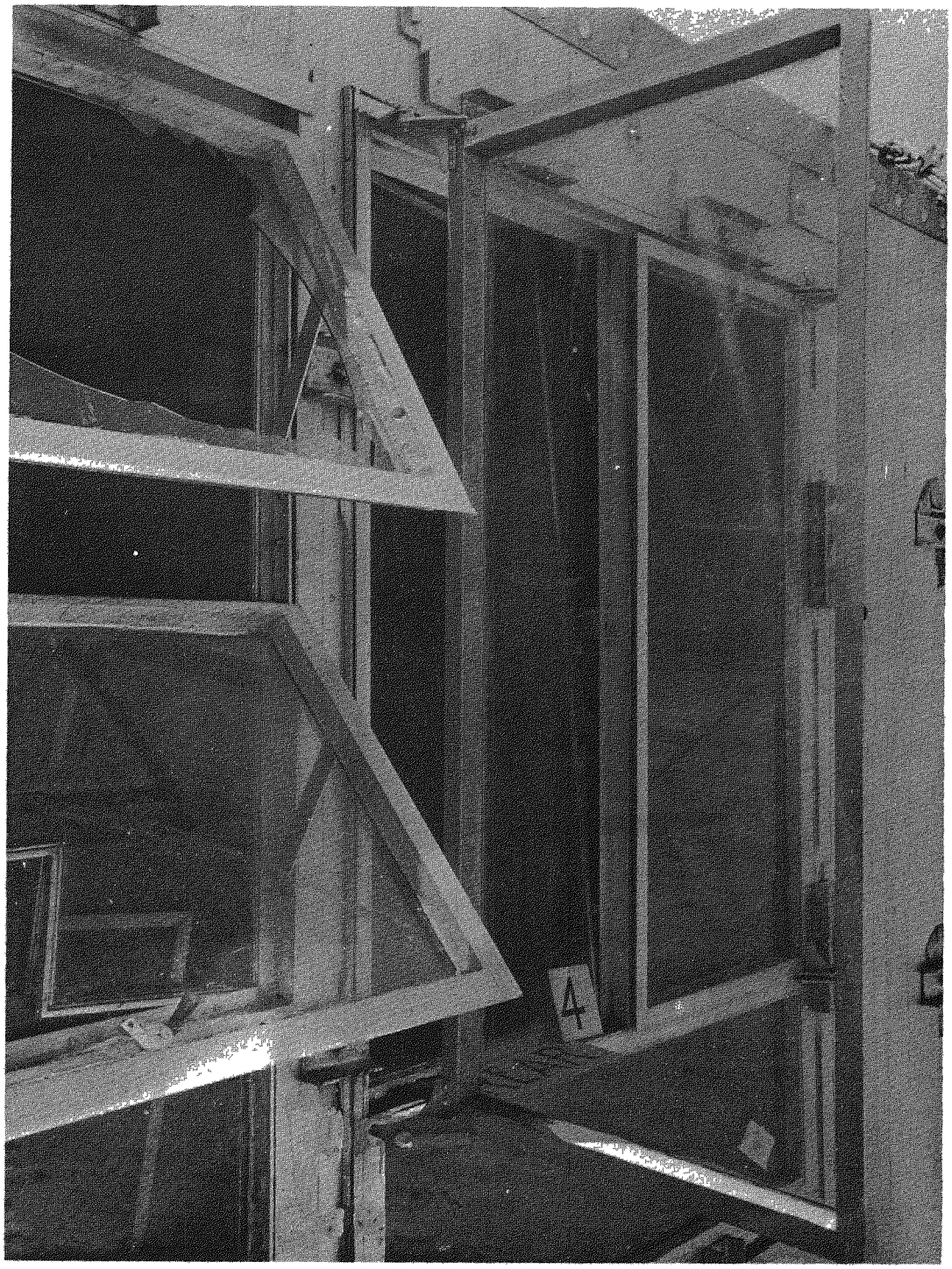

FIG. 3.55 A Close-up of the Outside of Windows 14 and 15 after the Blast. The right-hand sash of the casement was sprung outward about ½ in., possibly due to the expanding air in the structure after the shock wave passed. Apparently the outward pressure of the expanding air also broke the catch on the middle ventilator section of the canopy window and both upper and middle sections moved outward together, as they are connected by a vertical bar so that a movement in one sash causes a corresponding motion in the other sash.

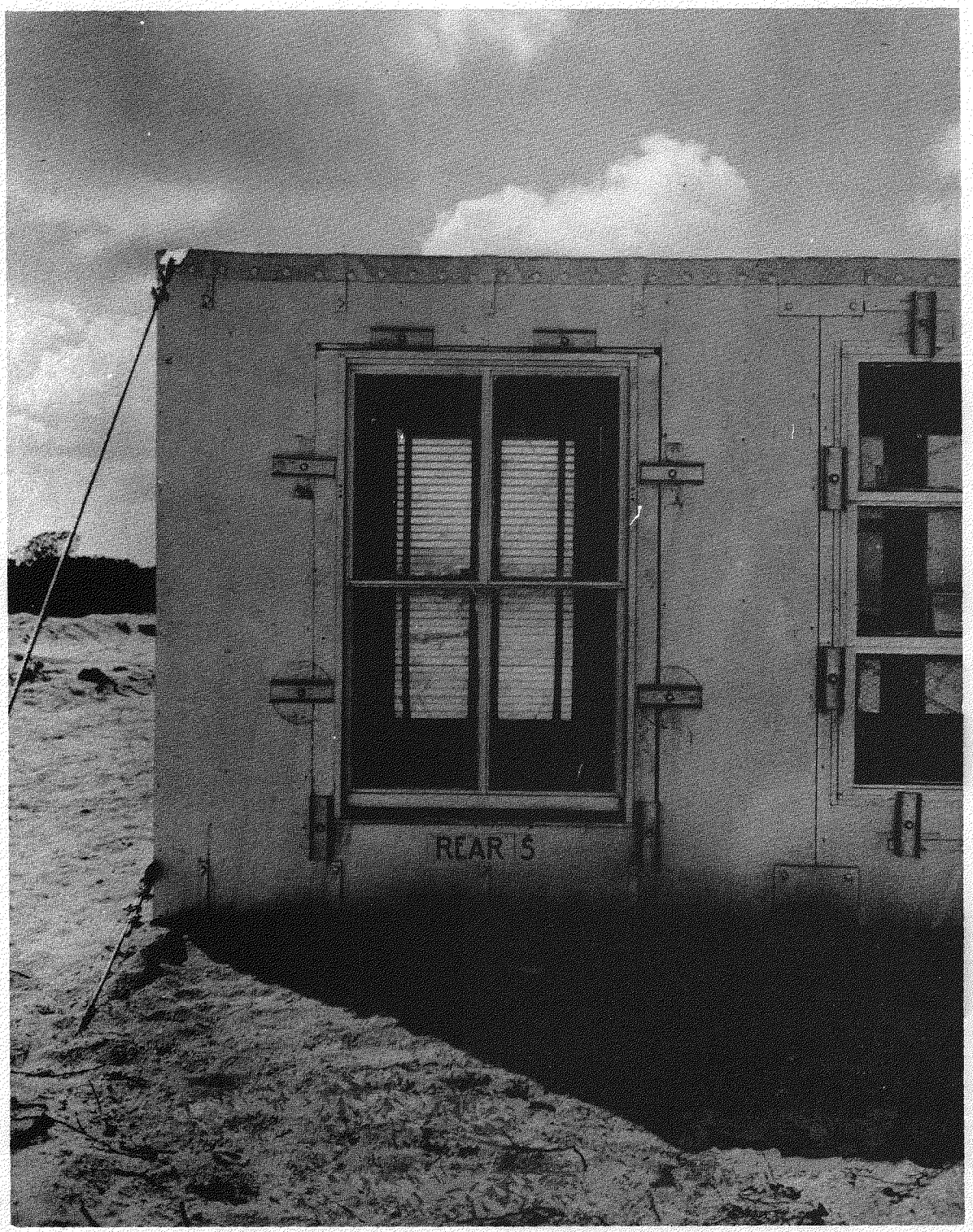

FIG. 3.56 Outside of Double-hung Window 16 before the Blast. This was a duplicate of window 8, except that the upper sash was glazed with plate glass on the left and double-strength glass on the right. The lower sash had wire glass on the left and safety glass on the right.

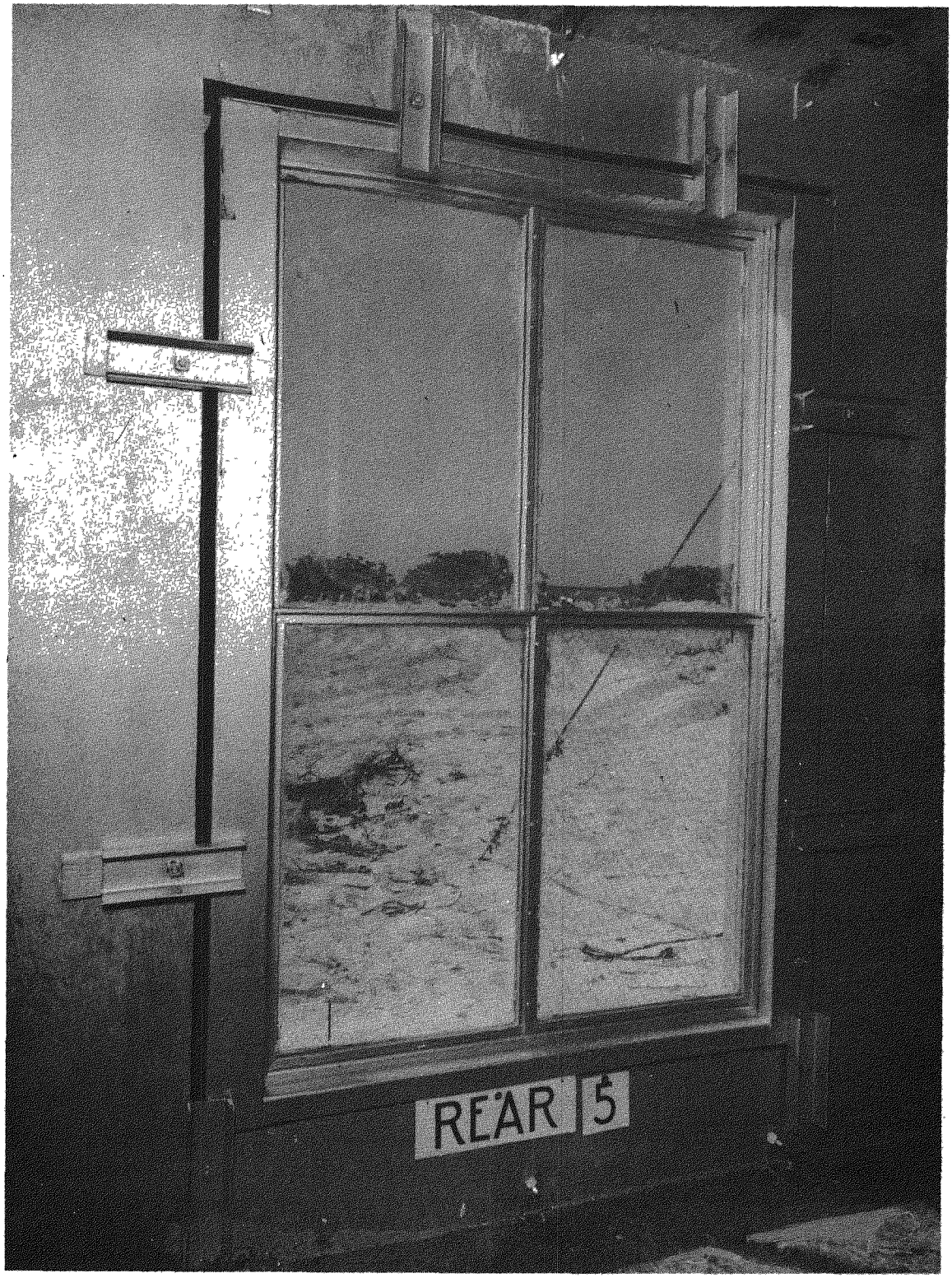

FIG. 3.57 Inside of Steel Double-hung Window 16 before the Blast

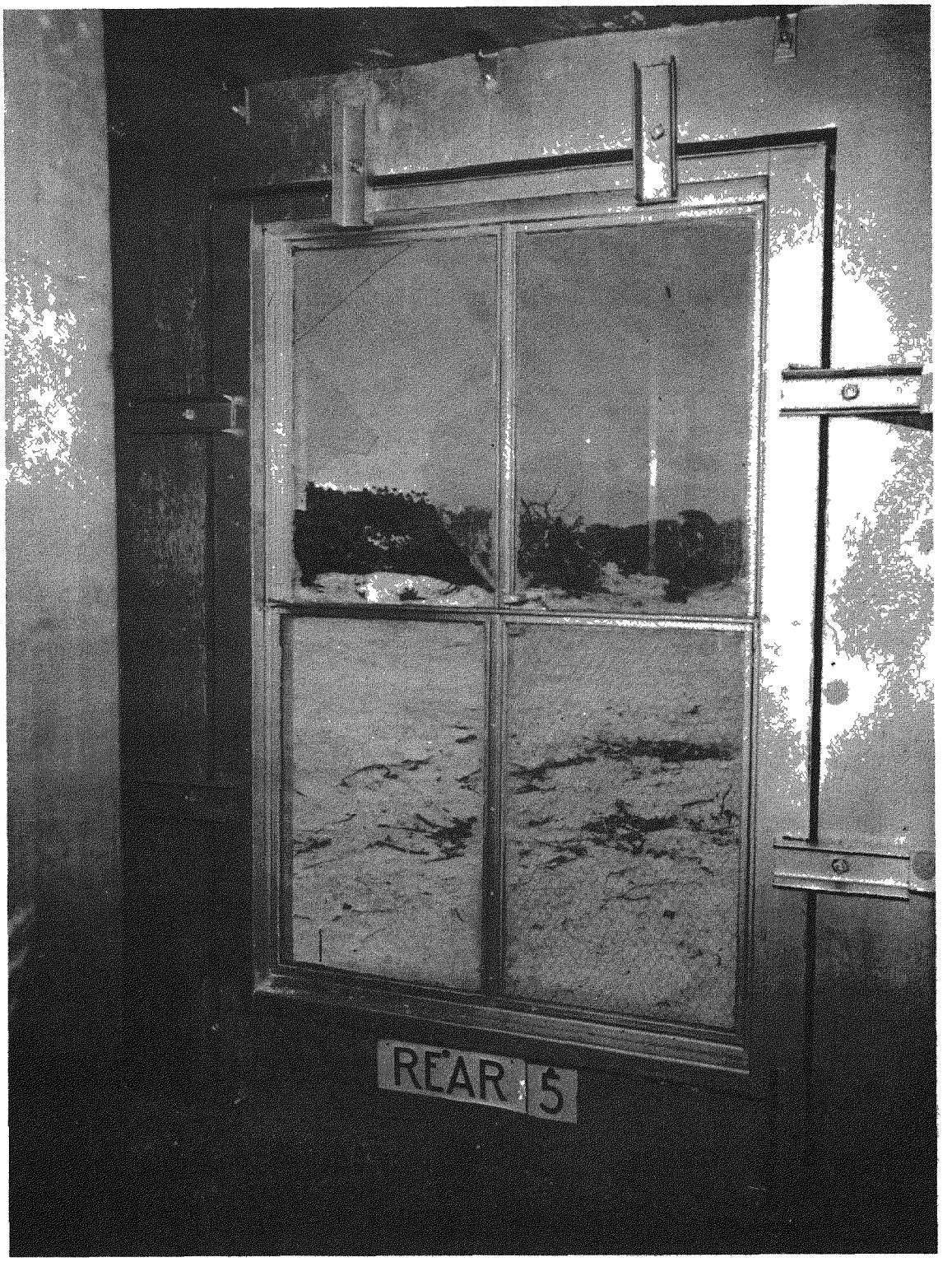

FIG. 3.58 Inside of Window 16 after the Blast. The double-strength glass in the upper sash was forced inward, and the fragments fell inside of the building. The other three panes of ¼ in. glass were unbroken.

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