NWC TP 6076

LEVEL III

ESKIMO V

MAGAZINE SEPARATION TEST

by

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and

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Test and Evaluation Directorate

FEBRUARY 1979

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NAVAL WEAPONS CENTER
CHINA LAKE, CALIFORNIA 93555

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Naval Weapons Center

AN ACTIVITY OF THE NAVAL MATERIAL COMMAND

FOREWORD

This report describes a full-scale magazine test conducted at the Naval Weapons Center in August 1977. The test work was conducted for the Department of Defense Explosives Safety Board (DDESB) using funds provided by that organization. The work was identified by Army Program Element Number 6.57.02.A and Project and Test Area Number 4A765702M857.

From data derived from the test, DDESB gained considerable information on explosive hazards and storage magazine criteria.

This report has been reviewed for technical accuracy by DDESB staff member Dr. Thomas A. Zaker. Dr. Zaker also played a major role in the design of the test.

Colonel Philip G. Kelley, Jr., USA, Chairman of DDESB, provided technical, administrative, and policy guidance during the preparation, execution and reporting of the test.

Approved by
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1 February 1979

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(U) *ESKIMO V Magazine Separation Test*, by F. H. Weals and Bill Finder. China Lake, Calif., Naval Weapons Center, February 1979. 78 pp. (NWC TP 6076, publication UNCLASSIFIED.)

(U) In an instrumented test conducted in August 1977 at the Naval Weapons Center, approximately 75,000 pounds (34 000 kilograms) of trinitrotoluene (TNT) explosives were detonated. The explosives were contained in a hemisphere built of 9,376, 8-pound (3.6-kilogram) demolition blocks, and were detonated by means of an initiation system located at the center of the hemisphere. Principal objectives of the test were to justify removal of concrete thrust beams from an oval steel-arch igloo and to demonstrate the safety of applying current side-to-side separation distances to concrete-arch igloos which have never been tested at those distances.

~~(U)~~ Additionally, the test demonstrated the greater safety of earth-covered storage as opposed to above-ground storage.

CONTENTS

INTRODUCTION

At the request of the Department of Defense Explosives Safety Board (DDESB), the Naval Weapons Center (NWC) conducted a large-scale explosives hazard test known as ESKIMO V (ESKIMO is an acronym for Explosive Safety Knowledge IMprovement Operation). The test was carried out in August 1977 at the Randsburg Wash Test Range, and was the fifth in a series of full-scale tests for earth-covered magazines sponsored by the DDESB.

ESKIMO I,[1] the first test, was conducted in December 1971 to determine a safe, practicable minimum separation distance for face-on exposures of the U.S. Army standard steel-arch magazines. Explosion communication occurred to an acceptor igloo of this design at a distance in feet equal to $1.25 \times W^{1/3}$, in which W is the weight in pounds of the high explosive in storage, but failed to occur at a distance of $2.0 \times W^{1/3}$ to the rear of the donor. Further, the test revealed that safety and economy might be increased through improved design for closer balance in strength between the doors and headwall of the magazine. (A minimum separation distance in feet equal to $1.25 \times W^{1/3}$ in customary units is equal to approximately 0.5 in metric units, in which the separation distance is in meters and W is in kilograms.)

ESKIMO II was conducted in May 1973 to appraise magazine door and headwall designs.[2] A large, single-leaf sliding door withstood the blast with minor distortion, although the accompanying headwall sustained severe damage. A Stradley-type headwall, on the other hand, incurred only minor damage. In addition, the noncircular (oval) steel arch tested with the Stradley headwall withstood the blast without breakup or severe distortion.

ESKIMO III,[3] conducted in June 1974, further extended the study of explosive-storage magazines using information derived from ESKIMO I and II. A further test of the oval arch and Stradley-type headwall. ESKIMO III used structures remaining from ESKIMO II, rebuilt as necessary, as well as new construction of a light-gauge, deeply corrugated, steel-arch magazine. Igloo B, the oval-arch magazine tested in ESKIMO II, was fitted with a newly designed Stradley-type headwall with a single-leaf sliding door. ESKIMO II proved that the Stradley-type headwall could withstand a face-on impulse of 1,750 psi-ms (12 066 kPa·ms) and that the steel oval-arch igloo could withstand the face-on impulses generated by that charge. ESKIMO III tested the ability of the new headwall to withstand the side-on blast imposed by the explosion of an adjacent magazine.

[1] Naval Weapons Center. *ESKIMO I Magazine Separation Test*, by Frederick H. Weals. China Lake, Calif., NWC, April 1973. 84 pp. (NWC TP 5430, publication UNCLASSIFIED.)

[2] Naval Weapons Center. *ESKIMO II Magazine Separation Test*, by Frederick H. Weals. China Lake, Calif., NWC, September 1974. 90 pp. (NWC TP 5557, publication UNCLASSIFIED.)

[3] Naval Weapons Center. *ESKIMO III Magazine Separation Test*, by Frederick H. Weals. China Lake, Calif., NWC, February 1976. 70 pp. (NWC TP 5771, publication UNCLASSIFIED.)

ESKIMO IV,[4] conducted in September 1975, continued the study of explosive storage magazines, using information from the prior tests in the ESKIMO series. The door and headwall combination used on the oval-arch magazine was again tested in ESKIMO IV but with face-on blast loading as compared with the side-on loading experienced with ESKIMO III. The door that had fallen off its supports in ESKIMO III was rehung in position. ESKIMO IV provided the initial test of the combination of a newly designed headwall and single-piece sliding door under face-on loading. ESKIMO IV also included a rebuilt standard headwall and doors (OCE standard drawing 33-15-64) as a control structure, and a single-piece sliding door remaining from ESKIMO III, in combination with a rebuilt standard headwall. The response of the three magazines was essentially as expected, with only minor damage occurring to two of the three. The third magazine experienced door failure and presented unacceptable hazards to stored sensitive materials.

GENERAL DESCRIPTION

ESKIMO V was a continuation of the study of explosive-storage magazines, using information from the prior ESKIMO tests. The oval steel-arch igloo used in ESKIMO III (side-on loading) and ESKIMO IV (headwall loading) was again tested. The earth cover was removed, the concrete thrust beams were removed, and the dirt fill was replaced. ESKIMO V also included a newly constructed magazine of the FRELOC concrete-arch type. Since door response was not a concern in this test, nonpermanent steel doors were spot-welded and/or bolted to the door openings of both igloos.

This report discusses ESKIMO V, its objectives, procedures and results, and the conclusions drawn from these results.

TEST OBJECTIVES

The main purposes of this test were (1) to validate and justify the removal of the costly concrete thrust beams from the oval steel-arch igloo, and (2) to demonstrate the safety of applying current side-to-side separation distances to concrete-arch igloos, which had never been tested at such small separations. A secondary purpose was to demonstrate once again at full-scale the greater safety of earth-covered storage as compared with above-ground storage.

TEST LAYOUT

TEST ARRAY

The ESKIMO V test array consisted of two magazine structures each side-on to the explosion source at centerline separations of 155 feet (47 meters) as shown in Figures 1 and 2. The northwest igloo (Igloo A) was of the FRELOC concrete-arch type constructed especially for this test. The southeast igloo (Igloo B) was the oval steel-arch structure used in ESKIMO II, III, and IV, but modified

[4] Naval Weapons Center. *ESKIMO IV Magazine Separation Test*, by F. H. Weals and C. H. Wilson. China Lake, Calif., NWC, March 1977. 52 pp. (NWC TP 5873, publication UNCLASSIFIED.)

by removing the concrete thrust beams (Figure 3). Only slight damage occurred to this magazine during ESKIMO II, III, and IV, and consequently it was deemed usable for ESKIMO V. The magazines are 80 feet (24 meters) long and were fitted with a nonpermanent steel door spot welded and/or bolted rigidly in place in the door opening.

The array was designed to simulate the conditions of ESKIMO III in which the explosion source consisted of 350,000 pounds (159 100 kilograms) of Tritonal contained in stacked M117 bombs and placed inside an 80-foot-long (24-meter-long), lightweight, 14-gauge, deeply corrugated, steel-arch igloo. Magazines in ESKIMO III were separated by a scaled distance in feet of 1.25 X $W^{1/3}$.

FRELOC CONSTRUCTION

The FRELOC magazine, a noncircular concrete arch magazine, was constructed in accordance with U.S. Army Engineer Command, Europe, Drawing 33-15-13. The magazine, with a nominal span of 26 feet (8 meters), is 80 feet (24 meters) long and has a rise of 14.5 feet (4.4 meters) above the interior floor, which is at the same elevation as the exterior ground surface. The sidewalls are straight and vertical to an elevation of 8 feet (2 meters) above the floor. The arch was covered by 2 feet (0.6 meter) of compacted soil with a horizontal soil layer out to the vertical sides of the arch and then tapered downward at a slope of 2:1 to intersect the original ground level (Figure 4). The concrete pour was completed in five phases:

1. Footings
2. Vertical sidewalls and rear wall
3. Floor
4. Rear half of arch
5. Front half of arch and headwall

In the process of pouring the rear half of the arch, voids were produced due in part to a failure of the concrete to flow around the reinforcing bar (Figures 5 and 6). Factors contributing to this problem included an aggregate maximum size (1.5 inches (3.75 centimeters)) too large to permit the concrete to flow around the reinforcing bars and the dryness of the plywood forms that caused the moisture content of the concrete to be absorbed into the form. Vibration procedures during pouring also may have contributed to the problem.

The obvious voids were subsequently chipped out and filled with pneumatically placed concrete. Figure 7 illustrates the patches on the outside portion of the arch. To prevent the reoccurrence of this problem in pouring the front half of the arch, a smaller aggregate (3/4 inch (2 centimeters)) was used, forms were soaked with water prior to pouring, and Pozzolan was added to the concrete mix to facilitate easy flow. No voids were detected in the pour of the front half of the arch and the headwall.

OVAL STEEL-ARCH MAGAZINE

The oval steel-arch magazine used in ESKIMO V had been tested previously in ESKIMO series II, III, and IV. Since only minimal damage to the magazine had occurred in the previous tests, the magazine was determined to be acceptable for further testing. The original magazine was modified by removing the concrete thrust beams, necessitating the removal and replacement of the earth cover.

The oval steel-arch magazine was constructed of 1-gauge corrugated steel and had a length of 80 feet (24 meters), a nominal span of 26 feet (8 meters), and a height of 14.5 feet (4.4 meters) from the interior floor to the arch. Figure 8 shows a cross-section of the magazine.

EXPLOSION SOURCE

The donor charge consisted of an above-ground hemispherical stack of TNT with an approximate weight of 75,000 pounds (34 000 kilograms). To assure reasonable approximation to the desired weight, a randomly selected number of individual blocks were weighed prior to stacking. Average weight of these blocks was 8.06 pounds (3.7 kilograms), with the lightest block weighing 7.73 pounds (3.5 kilograms) and the heaviest weighing 8.44 pounds (3.8 kilograms). A total of 9,376 blocks were used in the stack (Figures 9, 10, and 11); the stacking pattern was designed by DDESB. MO34 demolition blocks were furnished by the sponsor from U.S. Army sources at Letterkenny Army Depot, Chambersburg, Pa. A total of 9,216 blocks were shipped specifically for the ESKIMO V test; the remaining 159 blocks came from supplies left over from ESKIMO IV.

An explosive detonator and booster system was provided to ensure safe, reliable initiation at the center of the charge. A newly designed slide-tray arrangement was utilized to insert 27 pounds (12.24 kilograms) of C-4 explosive directly under, and in contact with, the center of the stack. P-11 detonators were attached to primacord and embedded in the C-4. The primacord was initiated from the firing lines by electric detonators.

Donor size and positioning was determined by model studies conducted at Aberdeen Proving Ground, Md., to generate the same loadings on the acceptor igloos as were experienced from the ESKIMO III donor.

INSTRUMENTATION

BLAST

Near Field

Kistler-type piezoelectric gauges were placed in the earth-fill over each magazine to measure blast overpressure and impulse (Figure 12). Gauge locations and specifics are given in Figures 13 and 14. In addition, four soil stress gauges were implanted in the earth-fill over Igloo A (Figure 15) to measure blast pressure attenuation at various depths and in various directions.

In addition, a special gauge fixture was constructed that contained two Bytrex blast gauges at right angles to each other. These gauges were used to measure reflected and incident overpressures and to confirm the theoretical value of normal reflection coefficient at a pressure level associated with the minimum distance permitted for front-to-rear separation of earth-covered magazines. Overpressures of interest were 44 psi (303 kPa) incident and 170 psi (1172 kPa) reflected, assuming a barometric pressure of 940 millibars (94 kPa). It was determined that these values should be obtained at a distance of 202 feet (61.5 meters) from the center of the donor stack.

Kistler gauge fixture construction is shown in Figure 16; Figure 17 shows the gauge fixture in place. (See Figure 2 for the Bytrex gauge location relative to the test array.)

Far Field

Twenty-one Ballistic Research Laboratories (BRL) mechanical, self-recording blast gauges were placed on three radials, 45 degrees apart, and intersecting at the donor center. These gauges were positioned so as to yield the approximate pressure values as were experienced in ESKIMO IV. BRL gauge layout is shown in Figure 18.

MAGAZINE RESPONSE

Each of two test magazines was equipped with a wide variety of instruments to measure the response of the magazine when subjected to blast loading. These instruments included strain gauges attached to the reinforcing bar of the FRELOC (Igloo A), linear displacement gauges in both magazines, and velocity gauges and accelerometers in both magazines. In addition, photo-optical methods were used to measure sidewall displacement. Figures 19 and 20 show the relative location of each of the different types of instruments. Figures 21 through 25 show each of the different types of instruments in place. An ion probe was embedded in the donor stack and its output was recorded on each analog recording tape along with IRIG format-B timing to provide a "zero-time" indicator and consequently a way by which all event times could be correlated.

DETONATION

The donor charge was initiated at approximately 1300 hours PDT (2000 hours GMT) on 17 August 1977, 1 hour behind schedule. Weather conditions at the time consisted of intermittent rain and drizzle with the cloud base at approximately 5,000 feet (1520 meters) AGL over ground zero. The test area was affected by tropical storm Doreen, which resulted in local precipitation of 0.92 inch (2.3 centimeters).

A blast refocusing program was run through the NWC UNIVAC 110 computer several times on the morning of the test to determine the possibility of refocusing at populated areas in the vicinity of the test. The last data received prior to donor initiation indicated no refocusing in areas of interest, and the test proceeded to conclusion. Figures 26 through 29, taken at intervals of 0.25 second, show the blast sequence as seen from a helicopter. The "steam" cloud appearing around the fireball and interior to the blast wave front is thought to be a result of the extremely heavy concentration of water vapor in the air at the time of the test.

OBSERVED TEST RESULTS

Damage to both magazines was determined visually to be minimal. Concrete spalling was observed on the interior headwall of the FRELOC (Igloo A) at the edge of the door (Figure 30). This spalling, however, was probably a result of the concrete being too thin over the reinforcing bar at that point (a discrepancy in the separation distance of the forms from the rebar, which made it more susceptible to blast damage). Some minor cracking was observed at the intersection of the donor side pilaster and the headwall. The voids in the FRELOC that had been filled appeared to hold, and the joint between the two separate concrete pours remained intact.

In the oval-steel arch magazine, Igloo B, several additional cracks were observed in the headwall, and the separation between the headwall and the floor increased slightly; however, prior removal of the concrete thrust beams did not appear to affect the performance of the oval steel-arch igloo, which remained structurally intact and experienced no significant arch movement.

Since the headwall/door units were not being directly tested in ESKIMO V, doors were fitted to both magazines by bolting and/or spot welding in place. The door used on the oval steel arch had been used in previous tests and was somewhat distorted. Both doors had access holes cut into them that were covered by bolt-on hatch covers. Following detonation, it was noted that the door on the FRELOC had swung open 90 degrees away from the donor and the door of the oval steel arch appeared to have fallen straight out along the longitudinal axis of the magazine (Figure 31).

Crater size appeared somewhat larger than anticipated with a rim-to-rim diameter of 88 feet (26.8 meters) and a maximum depth of 14 feet (4.3 meters) relative to the pretest ground elevation. Surveyed crater contours along two radials are shown in Figure 32. (See Figure 31 for a post-test site overview of the crater.)

STATIC MEASUREMENTS OF STRUCTURAL RESPONSE

A contour survey of the interior of each magazine was conducted prior to the test and was repeated after the test. Table 1 shows the resultant displacements at various locations in both magazines.

Maximum permanent displacement of the FRELOC appears to have occurred 20 feet (6 meters) from the headwall on the side away from the donor at approximately 10 feet (3 meters) above the floor, and amounted to 0.09 foot (2.7 centimeters). Maximum permanent displacement of the oval steel arch appears to have occurred at the top of the arch, 40 feet (12 meters) from the headwall, and amounted to 0.15 foot (4.6 centimeters). Both displacements indicate a relative decrease in the distance separating the point of measurement on the arch and the central reference point located on the floor of the igloo.

DATA DERIVED FROM INSTRUMENTATION

Far-Field Blast Data

With the exception of the gauges located at the 1,898-foot (579-meter) distance on the NW and SW radials (see Figure 18), all BRL self-recording mechanical blast gauges functioned properly. Table 2 provides a summary of the far-field blast-gauge data; Figure 33 provides a graphic display of overpressure versus scaled distance. Figures 34 through 38 provide individual gauge plots of overpressure versus time.

Near-Field Blast Data

The special gauge fixture with the two Bytrex blast gauges was to measure reflected overpressure and incident overpressure, but because of the adverse weather conditions water apparently entered the gauge meant to measure incident overpressure and rendered that gauge inoperative. (See Figure 2 for the location of that gauge fixture.) The Kistler-type piezoelectric blast gauges were placed on and around the berm covering of each magazine. Tables 3 and 4 provide a summary of the near-field, blast-gauge data for the FRELOC and oval steel-arch magazines, respectively. Figures 39 and 40 provide a comparison between near-field overpressure and near-field impulse, versus the derived standard curve for a 75,000-pound (34 000-kilogram) hemispherical donor stack.

Figures 41 through 45 provide graphic displays of selected overpressure and impulse data from the near-field blast gauges.

The gauge that measured reflected overpressure and located in the special gauge fixture is referred to as gauge number 18, Igloo B.

The character of the pressure-time histories in ESKIMO V is generally consistent with results from comparable locations in scale model tests for ESKIMO III conducted at BRL.[5] Comparisons between ESKIMO V and scale model tests are shown in Figure 46. Both test results showed higher than side-on values of overpressure and impulse on the earth side slopes facing the blast, where reflection of the vertical incident wave front occurs. Both tests also showed a small impulse past the leeward side of the slope break from incline to horizontal at the position marked by gauge 7 on both Igloo A and Igloo B, i.e., the impulse was small relative to the overpressure, the time of arrival, and the impulse expected from hemispherical charges at this scaled distance. This sharp change in impulse from the slope facing the blast to the described horizontal positions atop the earth-fill makes it somewhat difficult to compare air blast impulses with impulses sensed under the earth-fill. Comparisons between soil-stress data and corresponding pressure data (Table 5) using averaged values are made in Table 6.

Strain Gauges

Electronic strain gauges were attached to the steel reinforcing bar of the FRELOC magazine at several locations (see Figures 19 and 21). Several of the gauges failed to operate properly, and data on others were of questionable value. A possible reason for this may have been damage incurred during the concrete pour. A summary of strain-gauge data appears in Table 7. Figures 47 through 48 provide graphic displays of that data.

[5] Ballistic Research Laboratory. *Blast Loading on Model Earth-Covered Magazine*, by Charles N. Kingery. Aberdeen Proving Ground, Md., BRL, August 1978. (ARBRL-TR-02092, publication UNCLASSIFIED.)

Soil-Stress Gauges

Kulite Semiconductor soil-stress gauges were buried in the earth cover of the FRELOC magazine (see Figure 15). Gauges SS1 and SS4 were to be located near the base of the donor-side sidewall. However, because the gauges were received late and because of the time allotted for emplacing the earth cover, these gauges were located in the vicinity of SS2. Table 5 provides a summary of soil stress-gauge data and corresponding near-field, pressure-gauge data. It was felt that comparisons between SS1, SS2, and SS4 and corresponding Kistler pressure data required an averaging of pressure gauges P6 and P7. These comparisons are given in Table 6. Figures 49 and 50 provide a graphic display of the soil stress-gauge data.

Linear-Motion Gauges

Linear-motion gauges were placed in several locations in both test magazines (see Figures 19 and 20). Horizontal gauges were mounted on a steel rail that was suspended by chains attached to the arch. The gauges were connected to the sidewall by a universal joint (see Figure 22). Vertical gauges placed across the joint of a telescoping pipe arrangement (see Figure 23) recorded a composite of both arch and floor motion. A summary of linear-motion data is given in Tables 8 and 9. Figures 51 through 53 provide a graphic display of the linear-motion data.

Velocity Gauges

Pendulum-type velocity gauges (see Figure 25) were installed at several locations in both magazines (see Figures 19 and 20) to record velocity data in two directions. Data obtained from the oval steel-arch igloo were extremely noisy and required smoothing so as to derive some of the values. Smoothing was accomplished over a 1-millisecond time interval using an eleven-point sliding linear fit. Some areas of the data were not amenable to smoothing techniques, and usable data from these areas were consequently derived from "eyeball" smoothing of the plotted data.

Tables 10 and 11 provide a summary of the velocity data. A comparison between the linear-motion-gauge data and integrals of the velocity data showed good correlation between the two. Figure 54 provides a graphic display of the comparison between FRELOC sidewall linear-motion gauge D2 and the integral from V4, the corresponding horizontal velocity gauge. Figure 55 illustrates the comparison between FRELOC vertical linear-motion gauge D1 and the sum of the integrals of velocity gauges V1 and V7. The sum represents relative floor and arch motion. As can be seen, there is relatively strong agreement between linear-motion-gauge data and that derived by integrating velocity-gauge data. It does appear, however, that the integrated data are of lower amplitude and exhibit a time lag.

Accelerometers

Accelerometers were placed in both magazines at several locations (see Figures 19 and 20). Because of a malfunction in the recording system, calibration data for accelerometers located in the FRELOC magazine were lost. As a result, there was no way of converting recorded data to engineering units and those data are not included in this report. Accelerometer data obtained from the oval steel-arch igloo were extremely noisy and not amenable to smoothing techniques. These data were considered meaningless and consequently were omitted from this report.

Comparison Between Predicted Magazine Response and Magazine Response Derived From Instrumentation, FRELOC Igloo A

A comparison was made between actual magazine response and the response predicted by the Civil Engineering Laboratory, Port Hueneme, Calif. (Appendix A). The results are given in Table 12.

Photo-optical Data

Several cameras (16-, 35-, and 70-mm) were positioned around the area to record the test event. Although no data were directly derived from these cameras, they were helpful in providing documentary coverage of the test area and blast sequence.

Additionally, 16-mm cameras were positioned inside each magazine at the quarter points to record sidewall motion. A black-on-white stripe was painted on the sidewall and a 3-inch-diameter (7.6 centimeters) pendulum was suspended from the arch as a "static" reference point. The camera at each point was positioned to have its optical axis normal to a line between the pendulum and the stripe (see Figure 25). It was expected that sidewall motion could be derived from this arrangement. However, motion of the floor resulted in movement of the camera platform and these data, too, were of questionable value. This technique may yield valid data in future tests if a stationary platform for the camera can be established.

CONCLUSIONS

The blast produced by the donor stack of explosives was essentially as predicted and acceptably simulated conditions at a scaled distance of 1.25 ft/lb$^{1/3}$ to the side of the donor magazine as in ESKIMO III. ESKIMO III contained 750-pound (340-kilogram) bombs filled with a total of 350,000 pounds (159 000 kilograms) of Tritonal.

Structural response of the FRELOC magazine (Igloo A) was well within acceptable limits. This structure is considered to be adequate to protect all magazine stores against the propagation of an explosion under the conditions simulated and blast effects produced on the test. The measured response of the magazine was similar, in general form, to that predicted by prior analysis.

The response of the oval steel arch (Igloo B) without concrete thrust beams was also well within acceptable limits, with measured additional deflection from the ESKIMO V test being slight. Comparison between response of the steel arch and the concrete thrust beams in ESKIMO III showed that the absence of concrete thrust beams will not significantly affect the response of this type of structure under blast loads comparable to, or less than, those of ESKIMO III and ESKIMO V.

TABLE 1. Surveyed Arch Movement in Centimeters Relative to Centerline of Igloo Floor.

Position (deg. from centerline)	Front-quarter point, 6.1 meters from headwall		Midpoint, 12.2 meters from headwall		Rear-quarter point, 18.3 meters from headwall	
	Decrease, cm	Increase, cm	Decrease, cm	Increase, cm	Decrease, cm	Increase, cm
Igloo A						
1. 20	0.91	. . .	. . .	1.52	1.52	. . .
2. 40	1.83	. . .	1.83	. . .	1.22	. . .
3. 60	2.13	. . .	2.13	. . .	0.91	. . .
4. 90	2.44	. . .	2.44	. . .	1.22	. . .
5. 120	2.13	. . .	0.91	. . .	1.22	. . .
6. 140	2.74	. . .	0.61	. . .	0.00	. . .
7. 160	0.00	. . .	1.52	. . .	0.00	. . .
Igloo B						
1. 10	0.00	. . .	1.22	. . .	0.00	. . .
2. 20	0.61	. . .	0.00	. . .	0.00	. . .
3. 40	. . .	0.30	0.61	. . .	0.00	. . .
4. 60	1.52	. . .	3.35	. . .	1.22	. . .
5. 90	0.91	. . .	4.57	. . .	2.13	. . .
6. 120	. . .	0.61	1.52	. . .	1.22	. . .
7. 140	. . .	0.30	0.91	. . .	. . .	0.61
8. 160	1.22	. . .	0.91	. . .	1.22	. . .
9. 170	1.52	. . .	0.30	. . .	0.30	. . .

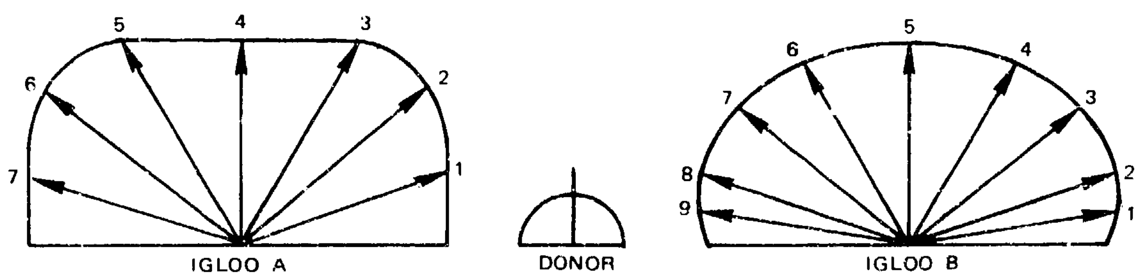


TABLE 2. Summary of Far-Field BRL Pressure-Gauge Data.

Position identification	Distance from center of donor		Scaled distance, $D/W^{1/3}$ [a]	Maximum overpressure direct readings		Maximum overpressure machine extrapolated		Impulse[b]		Positive pulse duration	
	ft	m		psi	kPa	psi	kPa	psi-ms	kPa·ms	Direct reading, ms	Machine extrapolated, ms
NW1	316	96	7.48	16.4	113.1	18.1	124.6	388.4	2678.1	71.4	74.2
NW2	422	129	9.98	9.7	66.6	9.9	68.1	286.7	1977.0	90.7	91.9
NW3	569	173	13.46	6.7	46.3	6.6	45.6	243.1	1676.3	112.2	122.5
NW4	759	231	17.96	3.7	25.2	3.8	26.4	186.0	1282.2	130.2	142.7
NW5	1,054	321	24.94	2.5	17.4	2.4	16.3	114.0	785.7	130.5	139.9
NW6	1,392	424	32.93	1.6	11.2	1.7	11.5	100.6	693.3	150.1	182.2
NW7[c]	1,898	579	44.91	1.4	9.9	...	...	...	...	...	...
W1	316	96	7.48	13.0	89.7	15.7	108.4	379.8	2618.4	60.7	61.9
W2	422	129	9.98	11.6	80.0	11.4	78.9	282.6	1948.4	89.4	89.5
W3	569	173	13.46	6.9	47.4	6.5	44.7	227.1	1565.9	103.0	107.8
W4	759	231	17.96	4.4	30.0	3.9	27.2	197.9	1364.3	136.6	147.4
W5	1,054	321	24.94	2.1	14.8	2.3	15.9	121.7	838.8	130.9	151.6
W6	1,392	424	32.93	1.7	11.5	1.7	11.9	88.8	612.1	139.0	157.4
W7	1,898	579	44.91	1.0	7.2	1.1	7.8	61.6	424.9	150.2	147.7
SW1	316	96	7.48	17.5	120.7	21.0	144.5	346.3	2387.5	58.9	58.0
SW2	422	129	9.98	9.5	65.7	8.9	61.4	282.0	1944.3	86.3	93.0
SW3	569	173	13.46	5.9	40.5	6.2	42.4	255.0	1758.3	124.9	121.2
SW4	759	231	17.96	3.5	24.4	3.9	26.5	181.1	1248.6	128.3	137.0
SW5	1,054	321	24.94	3.0	21.0	2.8	19.6	132.0	910.0	130.6	142.3
SW6	1,392	424	32.93	2.2	15.1	1.9	13.3	103.4	712.7	155.5	165.9
SW7[c]	1,898	579	44.91	2.0	13.6	...	...	...	...	...	...

[a] W = 75,000 lbs (34 318 kg).

[b] From direct readings.

[c] Gauge did not run—only peak pressure available.

TABLE 3. Summary of Near-Field Pressure Data From Electronic Gauges, FRELOC Igloo A.

Gauge number	Radial distance from donor		Pressure wave arrival, ms	Peak overpressure		Time of peak overpressure, ms	First positive pressure duration, ms	Impulse	
	ft	m		psi	kPa			psi-ms	kPa·ms
1	100	30.5	12.5	237	1635	14.3	38.5	1,165	9029
2	115	35.1	15.8	276	1901	17.6	41.8	1,343	9257
5	120.9	38.7	19.7	276	1900	20.2	34.5	1,344	9269
6	135.7	41.4	22.1	287	1979	22.6	29.9	1,331	9179
7	145.2	44.3	24.9	152	1047	25.2	15.4	336	2316
8	168.7	51.4	31.9	77	532	32.3	39.3	476	3279
9	157	47.9	28.2	108	745	28.7	26.9	483	3332
13	165.4	50.4	31.7	102	705	32.2	20.7	463	3190
15	185.3	56.5	41.9	50	346	42.3	51.3	567	3908
16	215	65.5	55.9	57	392	56.3	49.8	604	4163

TABLE 4. Summary of Near-Field Pressure Data From Electronic Gauges and Gauge Fixture West of Donor, Steel-Arch Igloo B.

Gauge number	Radial distance from donor		Pressure wave arrival, ms	Peak overpressure		Time of peak overpressure, ms	First positive pressure duration, ms	Impulse	
	ft	m		psi	kPa			psi-ms	kPa·ms
3	125	38.1	18.3	216	1492	18.9	29.9	1,246	8590
4	123.7	37.7	18.0	202	1390	18.4	28.7	1,355	9340
6	133.4	40.7	20.6	163	1123	20.9	25.2	895	6171
7	143.9	43.9	23.6	122	840	23.9	44.4	358	2466
11	156.1	47.6	28.6	125	860	29.0	32.9	588	4052
12	160.1	48.8	32.6	78	539	32.8	39.0	380	2619
13	163.8	49.9	30.3	99	683	30.6	22.9	624	4301
14	174.8	53.3	34.7	56	383	35.0	19.1	206	1422
17[a]	Gauge did not function								
18[b]	206.7	63.0	48.5	196	1350	49.5	51.1	1,211	8351

[a]Gauge fixture, incident pressure.
[b]Gauge fixture, reflected pressure.

TABLE 5. Summary of Soil Stress and Corresponding Near-Field Pressure Data, FRELOC Igloo A.

Gauge number	Location	Pressure wave arrival, ms	Peak overpressure		Time of peak overpressure, ms	First positive pressure duration, ms	Impulse	
			psi	kPa			psi-ms	kPa·ms
			Soil Stress					
SS1[a]	1.5 ft (0.2 m) below surface, 2.5 ft (0.76 m) from arch on curve of arch, donor side. Vertical axis.	29.3	43	295[b]	34.5[b]	110.0	680	4688
SS2[a]	3.5 ft (1 m) below surface, 0.5 ft (0.15 m) from arch on curve of arch, donor side. Axis normal to arch.	29.2	47	322	37.6	82.8	532	3667
SS3[a]	1.5 ft (0.2 m) below surface, 0.5 ft (0.15 m) from arch at top of arch. Vertical axis.	33.6	41	280	35.2	49.2	314	2162
SS4[a]	1.5 ft (0.2 m) below surface, 2.5 ft (0.76 m) from arch on curve of arch, donor side. Horizontal side.	29.7	34	232	30.8	81.9	543	3746
			Near-Field Pressure					
P6	44.1 m (145 ft) from donor, top of slope donor side, 40 ft (12 m) from headwall.	22.1	287	1979	22.6	29.9	1,331	9179
P7	44.3 m (145 ft) from donor, top of arch donor side, 40 ft (12 m) from headwall.	24.9	152	1047	25.2	15.4	336	2316
P9	47.9 m (157 ft) from donor, center of arch, 60 ft (18 m) from headwall.	28.2	108	745	28.7	26.9	483	3332
Average of P6 and P7	...	...	219	1513	...	...	834	5748

[a] Soil stress gauges located 40 ft (12 m) from headwall.

[b] Data saturated. True values will be somewhat higher than indicated. Time of peak overpressure accurate to ±40 ms.

TABLE 6. Comparison Between Soil Stress and Near-Field Pressure Data, FRELOC Igloo A.

Gauges compared	Time delta for pressure wave arrival, ms	Ratio of peak overpressures, soil stress:near-field pressure	Time delta for peak overpressure, ms	Time delta for first positive pressure duration, ms	Ratio of [illegible], soil stress:near-field pressure
SS1 and average of P6 and P7	4.4	0.20[a]	9.3[a]	94.6	0.82[a]
SS2 and average of P6 and P7	4.3	0.21	12.4	67.4	0.64
SS3 and P9	5.4	0.38	6.5	22.3	0.65
SS4 and average of P6 and P7	4.8	0.16	5.6	66.5	0.65

[a] Values approximate due to saturation of soil-stress gauge. Ratio should be somewhat higher.

TABLE 7. Summary of Strain Gauge Data, FRELOC Igloo A.

Gauge[a]	Location[b]	Peak tension,[c] μ-strain	Time of peak tension, ms	Peak compression, μ-strain	Time of peak compression, ms	Permanent "set"[d] μ-strain
S1	Donor side sidewall, outer rebar, 2.5 ft (0.76 m) from floor.	201	72.6	134	33.1	. . .
S2	Donor side sidewall, inner rebar, 2.5 ft (0.76 m) from floor.	66	118.6	148	34.7	≅−40
S5	Top of arch, outer rebar.	181	188.4	347	35.0	. . .
S6	Top of arch, inner rebar.	560	69.1	215	193.7	. . .
S7	Curve of arch away from donor, outer rebar.	≅15[e]	≅190[e]	80	42.6	≅−5
S8	Curve of arch away from donor, inner rebar.	145	162.2	549	45.1	. . .
S9	Sidewall away from donor, outer rebar, 5.5 ft (1.6 m) from floor.	94	159.8	216	39.8	. . .
S10	Sidewall away from donor, inner rebar, 5.5 ft (1.6 m) from floor.	383	63.9	29	34.7	≅−155
S14	Top of arch, inner rebar.	2266	117.9	1255	46.5	. . .

[a] Gauges S3–S4, S11–S13 failed to operate and/or provide data.
[b] All gauges listed except S14 located 40 ft (12 m) from headwall. S14 located 2 ft (0.6 m) from headwall.
[c] Sign convention on corresponding plots: "−" indicates tension, "+" indicates compression.
[d] Missing values indicate data was still changing at 350 ms. "−" indicates tension, "+" indicates compression.
[e] Curve remained relatively "flat" for an extended period of time.

TABLE 8. Summary of Linear-Motion Gauge Data, FRELOC Igloo A.

Gauge identification	Type of motion	Sign convention	Maximum positive deflection, cm	Time of maximum positive deflection, ms	Maximum negative deflection, cm	Time of maximum negative deflection, ms	Maximum velocity (derived), cm/s	Time of maximum velocity, ms
D1[a]	Relative motion between floor and top of arch at centerline.	(+) Arch and floor moving apart (−) Arch and floor moving together	2.67	69	−0.12	220	106	≅45
D2[a]	Horizontal motion of donor side sidewall.	(+) Towards donor (−) Away from donor	1.0	68	. . .	. . .	87	≅39
D3[a]	Horizontal motion of far side sidewall.	Gauge did not function						

[a] Gauge located 12.2 m (40 ft) from headwall.

TABLE 9. Summary of Linear-Motion Gauge Data, *Oval Steel-Arch Igloo B.*

Gauge identification	Type of motion	Sign convention	Maximum positive deflection, cm	Time of maximum positive deflection, ms	Maximum negative deflection, cm	Time of maximum negative deflection, ms	Maximum velocity (derived), cm/s	Time of maximum velocity, ms
D1	Horizontal motion of donor side sidewall, 6.1 m (20 ft) from headwall	(+) Away from donor (−) Toward donor	2.2	346	−0.2	190	21.8	60 240
D2	Relative motion between floor and top of arch at centerline, 6.1 m (20 ft) from headwall	(+) Arch and floor moving together (−) Arch and Floor moving apart	4.6	80	−5.9	339	200	40
D3	Horizontal motion of donor side sidewall, 18.3 m (60 ft) from headwall	(+) Away from donor (−) Toward donor	1.1	345	−0.9	220	29	50 270
D4	Relative motion between floor and top of arch at centerline, 18.3 m (60 ft) from headwall	(+) Arch and floor moving together (−) Arch and floor moving apart	3.6	65	−1.0	307	230	45
D5	Horizontal motion of donor side sidewall, 12.2 m (40 ft) from headwall	(+) Away from donor (−) Toward donor	1.3 1.1	96 316	−0.8	208	22.2	60 250
D6	Relative motion between floor and top of arch at centerline, 12.2 m (40 ft) from headwall	(+) Arch and floor moving together (−) Arch and floor moving apart	3.3	51 160	. . .	. . .	300	43
D7	Horizontal motion of far side sidewall, 12.2 m (40 ft) from headwall	(+) Toward donor (−) Away from donor	1.46	73	−2.0	325	86	≅46

TABLE 10. Summary of Velocity Gauge Data, FRELOC Igloo A.

Gauge identification	Type of motion and location[a]	Sign convention	Apparent first motion, ms	Maximum positive velocity, cm/s	Time of maximum positive velocity, ms	Maximum negative velocity, cm/s	Time of maximum negative velocity, ms	Maximum deflection (integrated), cm	Time of maximum deflection, ms	Maximum acceleration (derived), g	Time of maximum acceleration, ms
V1	Vertical velocity, top of arch	(+) Downward (−) Upward	31.2	74.1	35.1	−21.0	131.0	1.7	≅73.0[b]	32.7	≅33.1
V3	Vertical velocity, donor side sidewall	(+) Downward (−) Upward	30.2	68.9	≅36.5	−24.6	98.7	1.4	≅76.5	18.8	≅32.8
V4	Horizontal velocity, donor side sidewall	(+) Away from donor (−) Toward donor	33.6	55.9	37.0	−13.1	224.0	0.7	≅63.2	22.0	≅36.6
V5	Vertical velocity, floor, donor side	(+) Upward (−) Downward	Not well defined	30.8	45.2	−21.9	105.5	0.8	≅86.8	5.6	≅41.0
V6	Horizontal velocity, floor, donor side	(+) Away from donor (−) Toward donor	Not well defined	13.5	54.3	−8.0	183.8	0.5	≅148.9	3.9	≅105.0
V7	Vertical velocity, floor, central	(+) Upward (−) Downward	43.4	20.0	98.0	−9.6	55.2 120.3	0.2	≅104.7	−4.1	≅101.4

[a] All gauges 12.2 m (40 ft) from headwall.
[b] All approximate values indicate data remained constant in excess of 2 ms.

TABLE 11. Summary of Velocity Gauge Data, Oval Steel-Arch Igloo B.

Gauge identification	Type of motion and location	Sign convention	Current first motion, ms	Maximum positive velocity, cm/s	Time of maximum positive velocity, ms	Maximum negative velocity, cm/s	Time of maximum negative velocity, ms	Maximum deflection (integrated), cm	Time of maximum deflection, ms	Maximum acceleration (derived), g	Time of maximum acceleration, ms
V1	Vertical velocity, top of arch, 6.1 m (20 ft) from headwall	(+) Downward (−) Upward	31.0	88.6[a]	34.2[a]	−30.0[b]	230[b]	2.06	120	28.2	32.6
V2	Vertical velocity, top of arch, 18.3 m (60 ft) from headwall	(+) Downward (−) Upward	29.9	118.4[a]	39.6[a]	−20.0[b]	230[b]	2.20	60	40.4	31.1
V3	Vertical velocity, top of arch, 12.2 m (40 ft) from headwall	(+) Downward (−) Upward	29.5	167.6[a]	32.7[a]	−29.0[b]	270[b]	3.73	184.2	53.4	31.1
V4	Horizontal velocity, donor side sidewall, 12.2 m (40 ft) from headwall	(+) Away from donor (−) Toward donor	35.9	48.0	40.0	−11.0	147	≥1.5[c]	≥350[c]	24.1	35.8
V5	Horizontal velocity, floor, donor side, 12.2 m (40 ft) from headwall	(+) Away from donor (−) Toward donor	Not well defined	8.0	70.0	−5.0	196.7	≥1.1[c]	≥350[c]	0.5	55.0
V6	Vertical velocity, floor, center, 12.2 m (40 ft) from headwall	(+) Upward (−) Downward	Not well defined	30.0	188.3	−18.3	140	≥4.6[c]	≥350[c]	−4.2	194.2

[a] Derived by smooth data.
[b] Analog derivation. Data not amenable to smoothing. Values are approximate.
[c] Values increasing or stable at end of data (350 ms).

TABLE 12. Summary Comparison Between Measured Gauge Peak Values Versus CEL Predictions.

Gauge and type of measurement	Predicted value	Measured value
S-1, strain	+190 μ-strain[a]	+134 μ-strain
S-2, strain	−320 μ-strain[a]	−66 μ-strain
S-5, strain	+150 μ-strain[a]	+347 μ-strain
S-6, strain	−1500 μ-strain[a]	−560 μ-strain
S-7, strain	−850 μ-strain[a]	−15 μ-strain
S-8, strain	+450 μ-strain[a]	+549 μ-strain
S-9, strain	+270 μ-strain[a]	+216 μ-strain
S-10, strain	−780 μ-strain[a]	−383 μ-strain
SS-2, soil stress	345 kPa	322 kPa
SS-3, soil stress	345 kPa	280 kPa
V-1, velocity	50 cm/s	74.1 cm/s
V-3, velocity	28 cm/s	68.9 cm/s
V-4, velocity	28 cm/s	55.9 cm/s
V-5, velocity	28 cm/s	30.8 cm/s
V-6, velocity	28 cm/s	13.5 cm/s
V-7, velocity	28 cm/s	20.0 cm/s
D-1, deflection	2.5 cm	2.67 cm
D-2, deflection	1.3 cm	1.0 cm

[a] + indicates compression, − indicates tension.

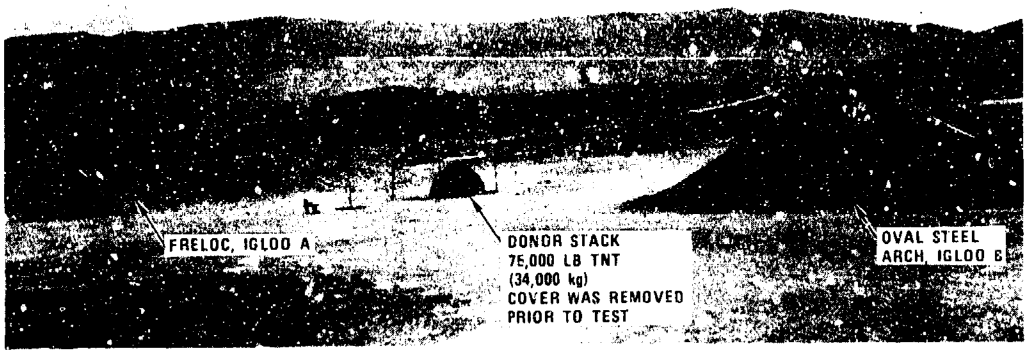


FIGURE 1. Pretest Site Overview.

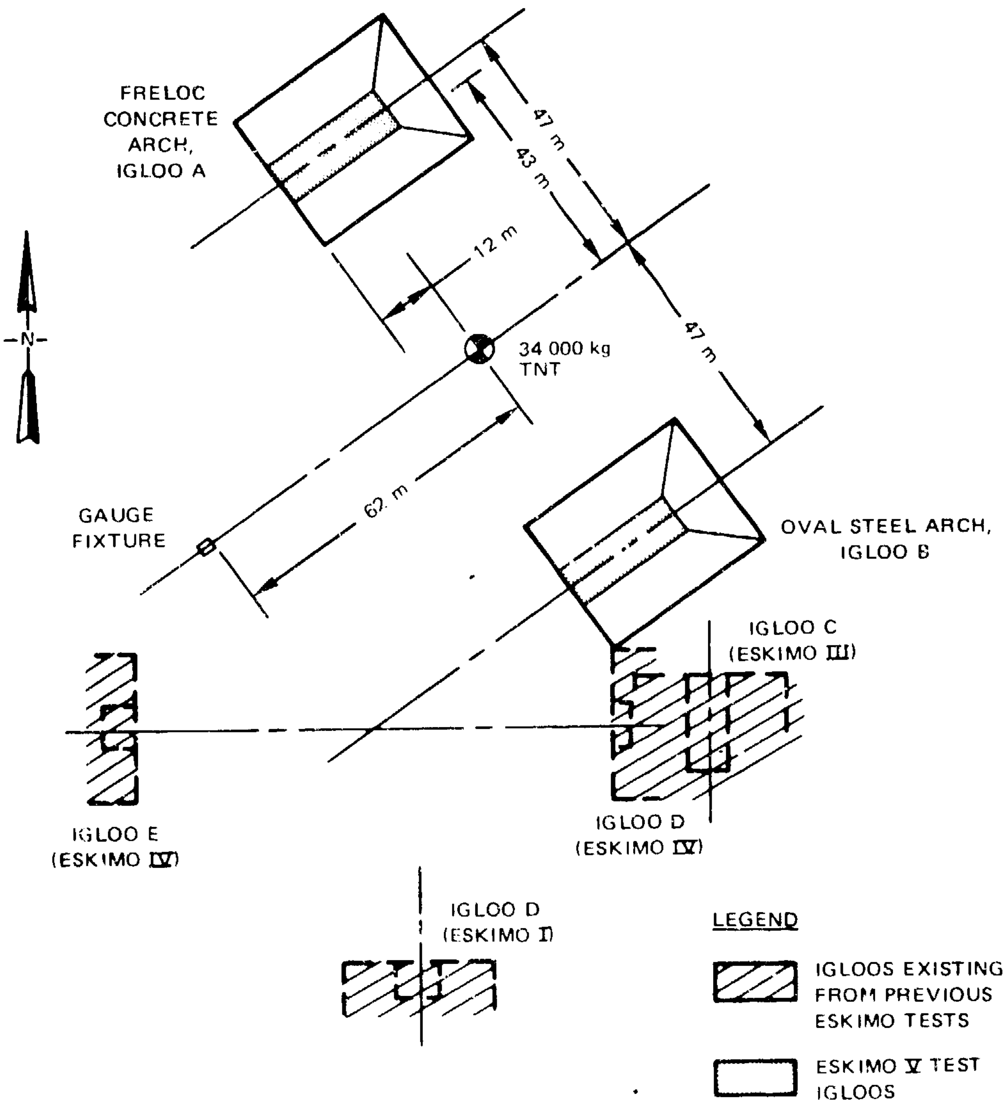


FIGURE 2. ESKIMO V Test Area Layout.

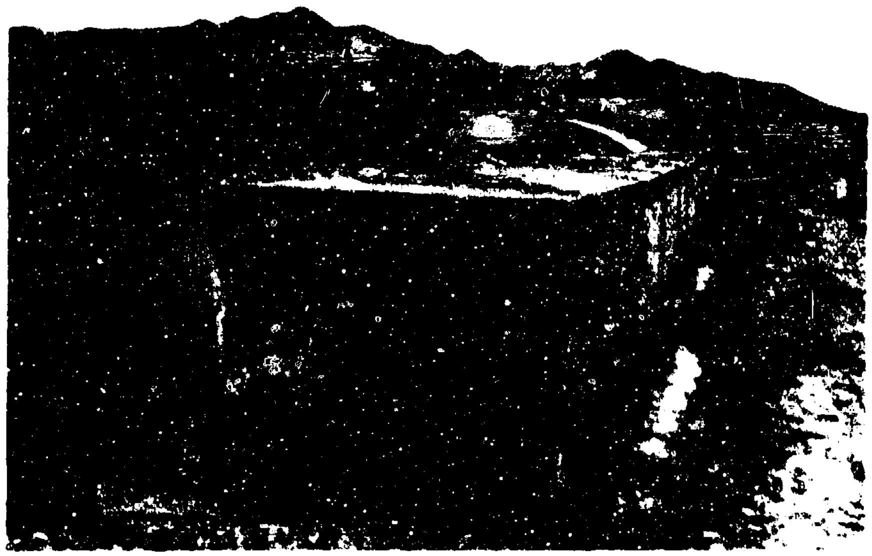


FIGURE 3. Concrete Thrust Beam on Oval Steel-Arch Igloo, Removed for ESKIMO V Test.

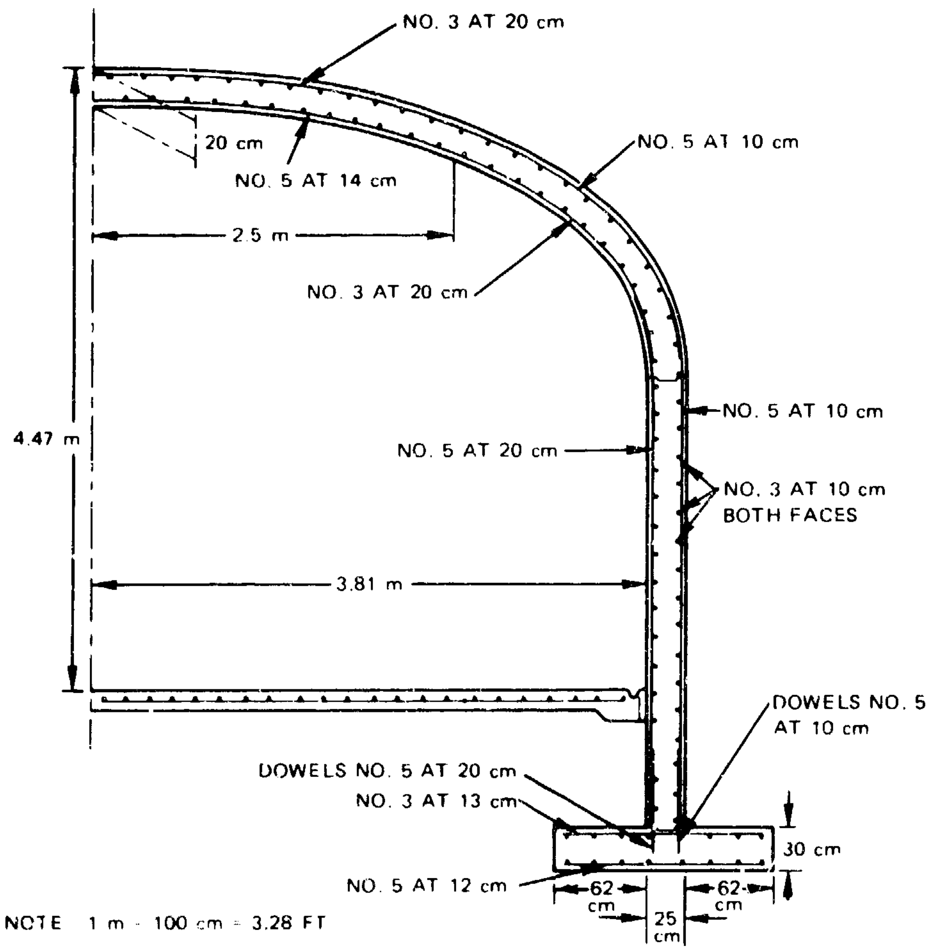


FIGURE 4. Half-Section of FRELOC Igloo Test Structure.

FIGURE 5. Concrete Voids, FRELOC Igloo.

FIGURE 6. Poor Concrete Flow Between Arch and Sidewall, FRELOC Igloo.

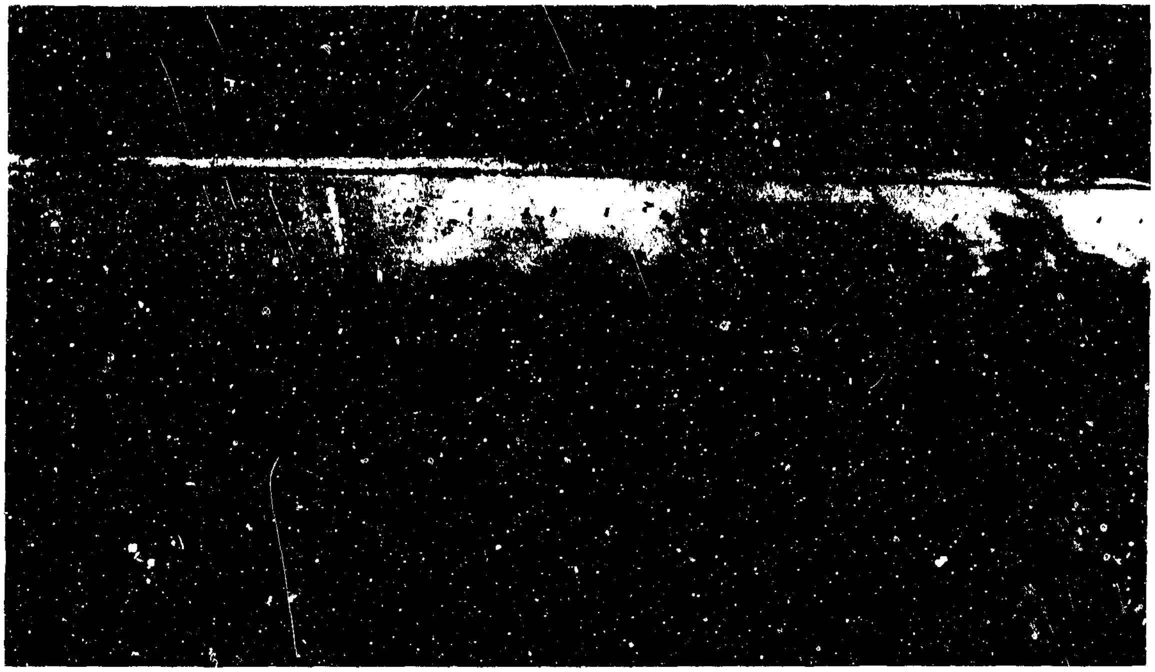


FIGURE 7. Exterior Concrete Patches, FRELOC Igloo.

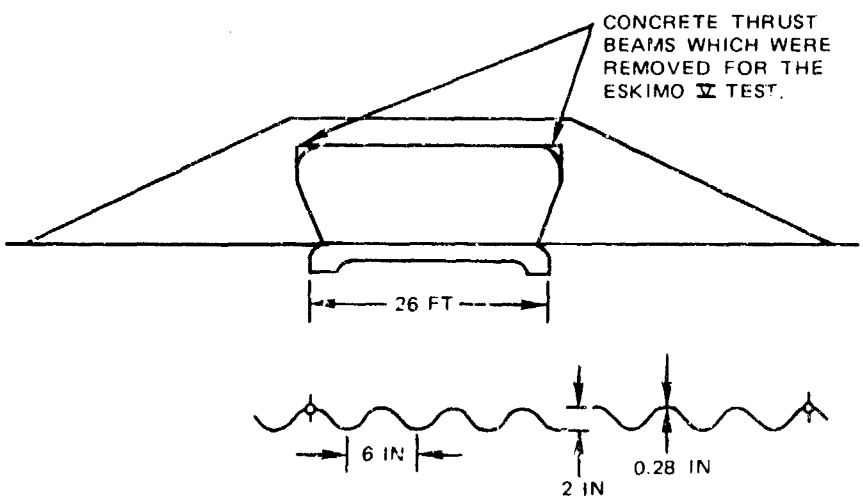


FIGURE 8. Cross Section of Oval Steel-Arch Magazine.

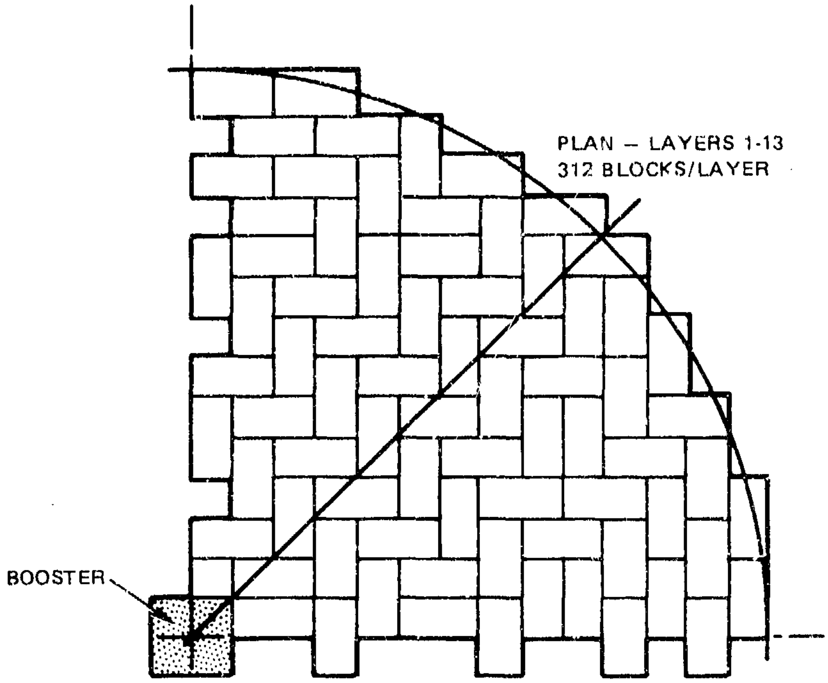


FIGURE 9. Horizontal Section of One Quadrant, TNT Donor Stack.

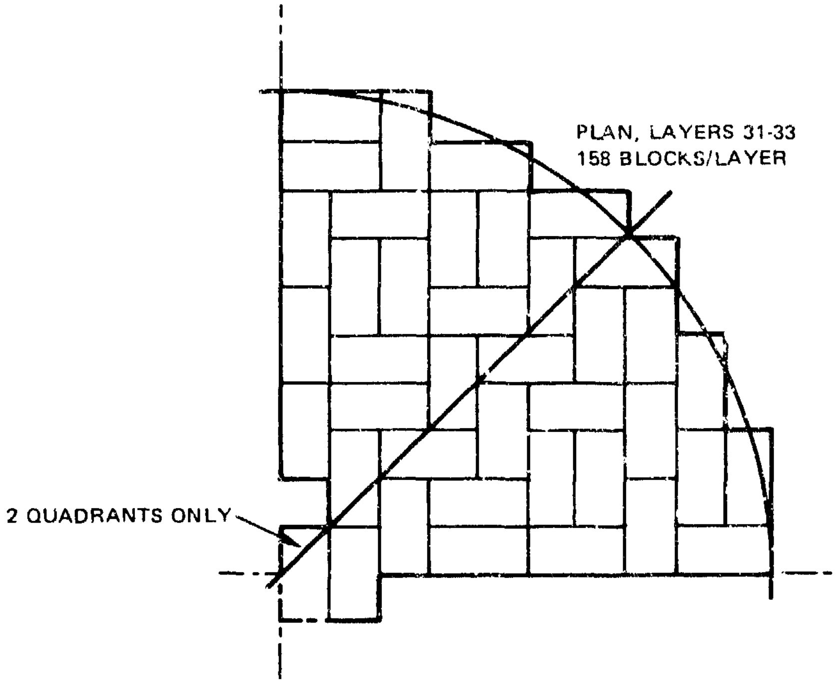


FIGURE 10. Horizontal Section of One Quadrant, Midheight of TNT Donor Stack.

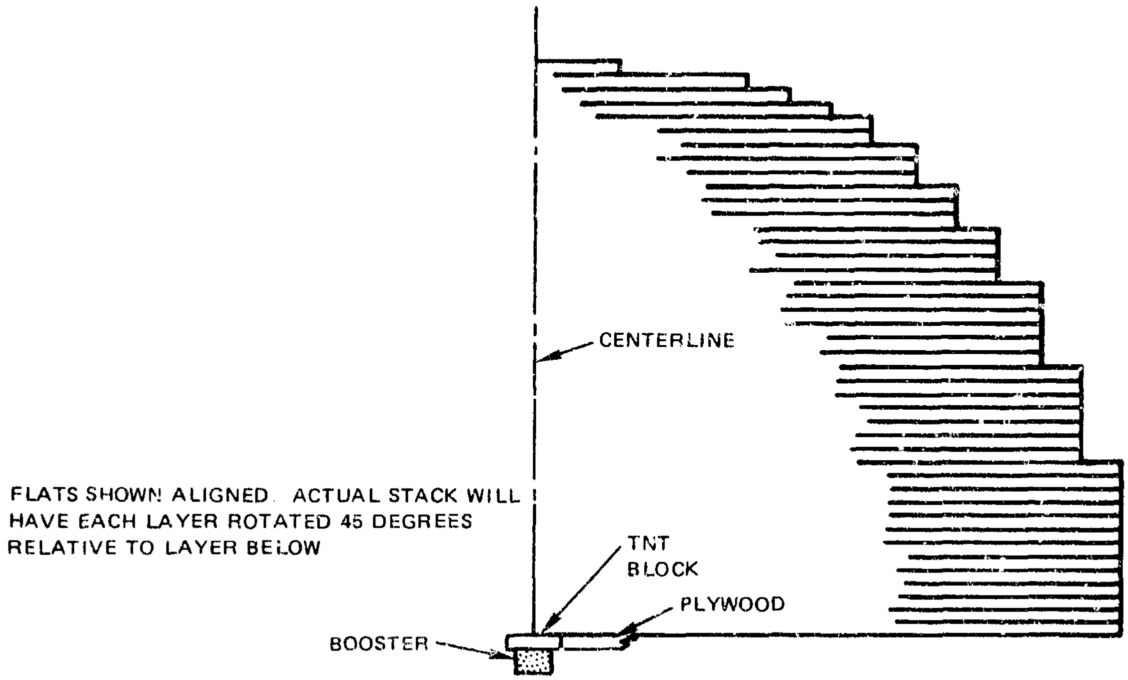


FIGURE 11. Vertical Section of One-Half TNT Donor Stack.

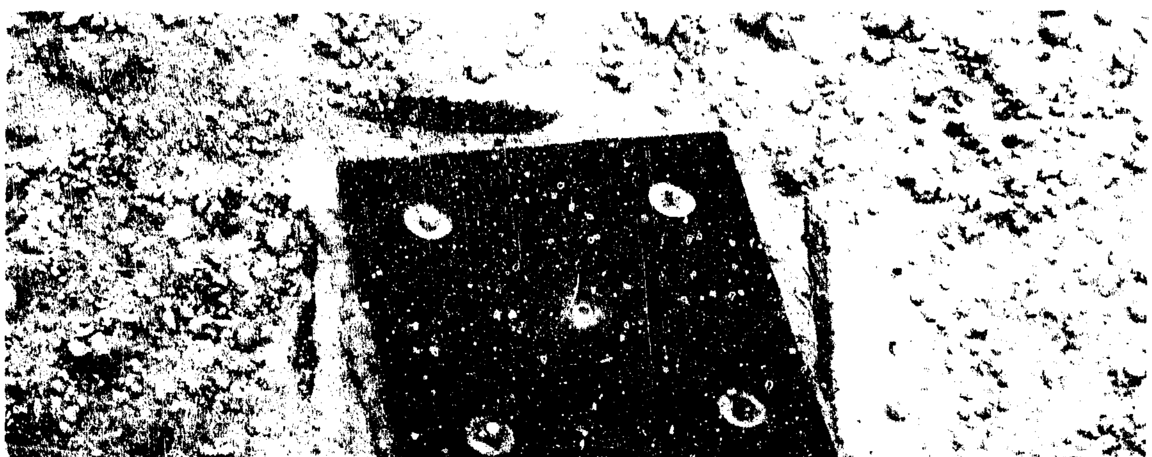


FIGURE 12. Kistler Near-Field Blast Gauge Set into Igloo Earth Cover.

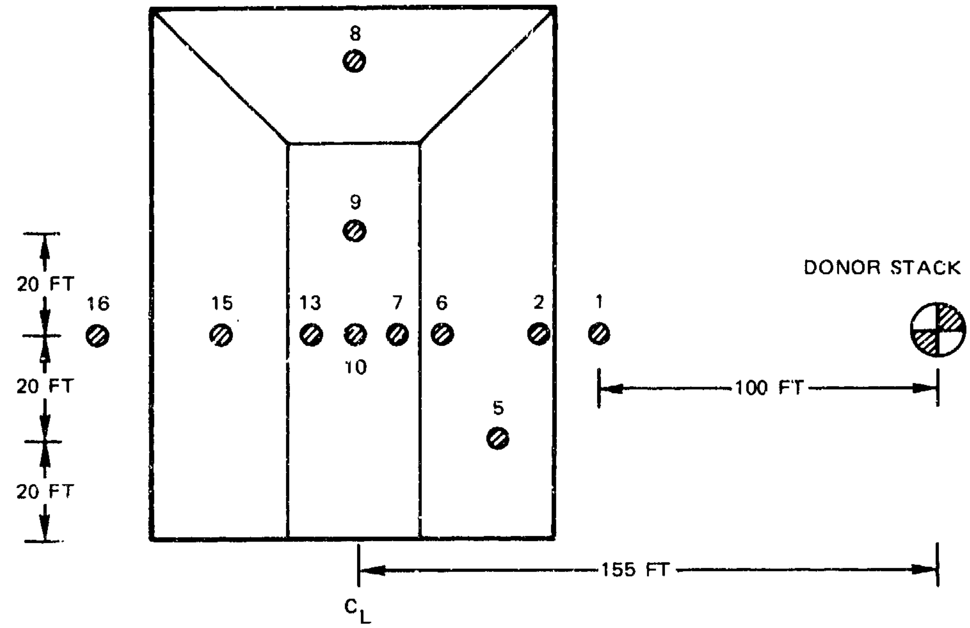


FIGURE 13. Electronic Blast Gauge Layout on FRELOC Igloo.

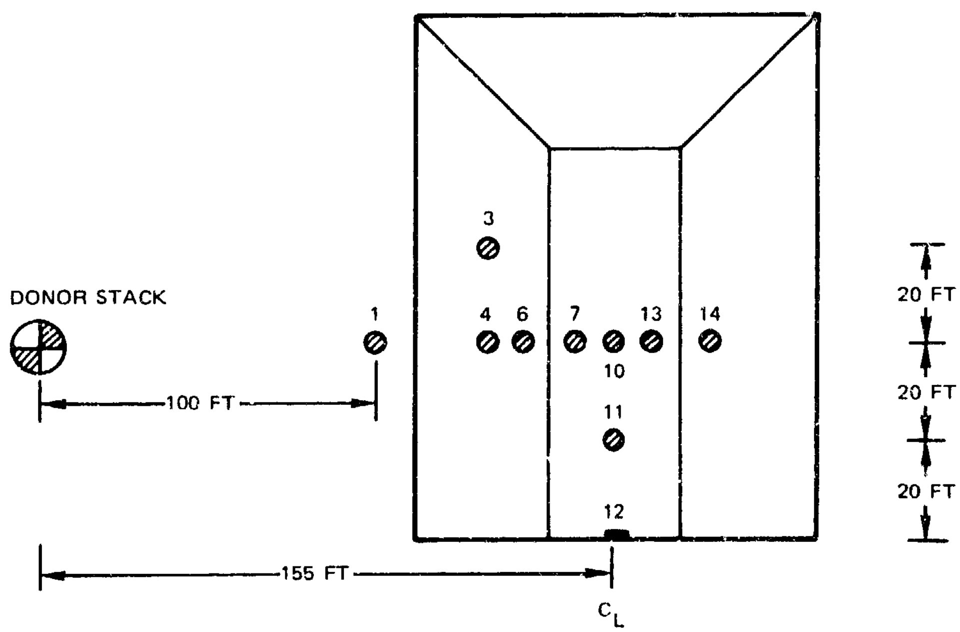


FIGURE 14. Electronic Blast Gauge Layout on Oval Steel-Arch Igloo.

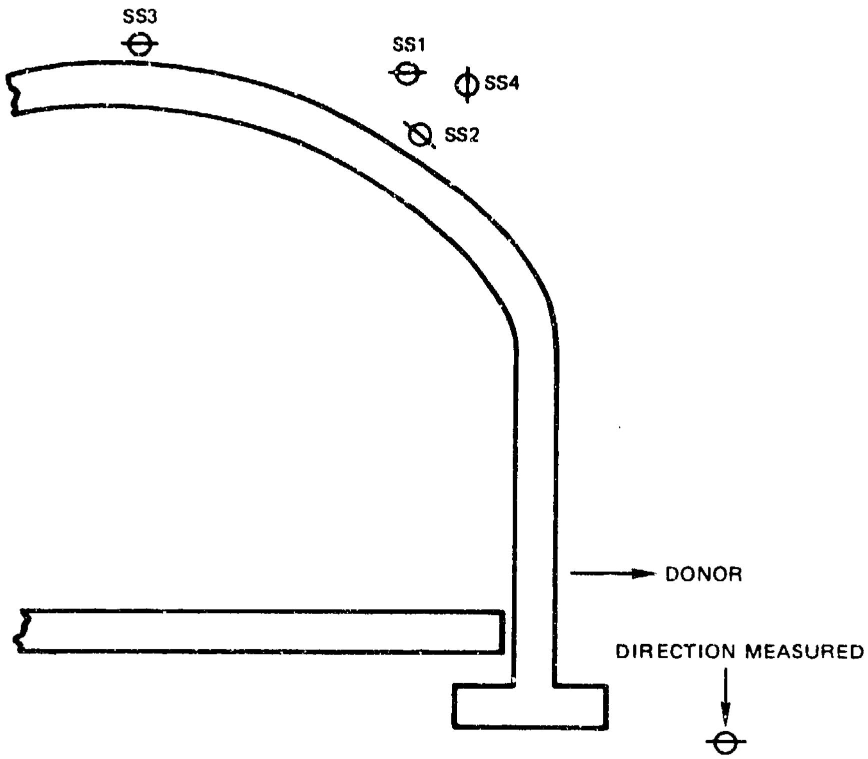


FIGURE 15. Soil Stress Gauge Locations, FRELOC Igloo.

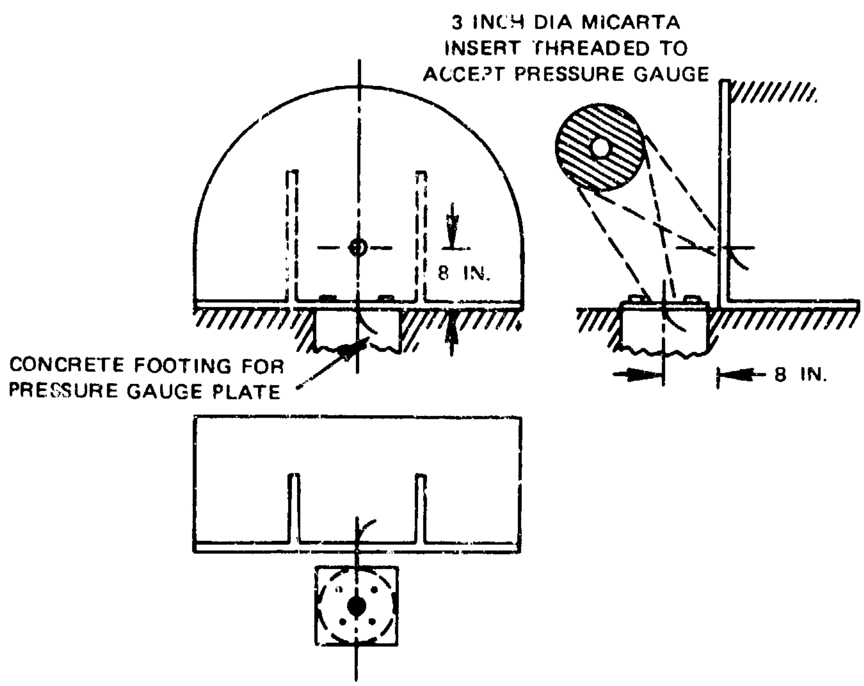


FIGURE 16. Gauge Fixture for Incident and Reflected Pressure Measurements.

FIGURE 17. Far-Field Blast-Gauge Fixture.

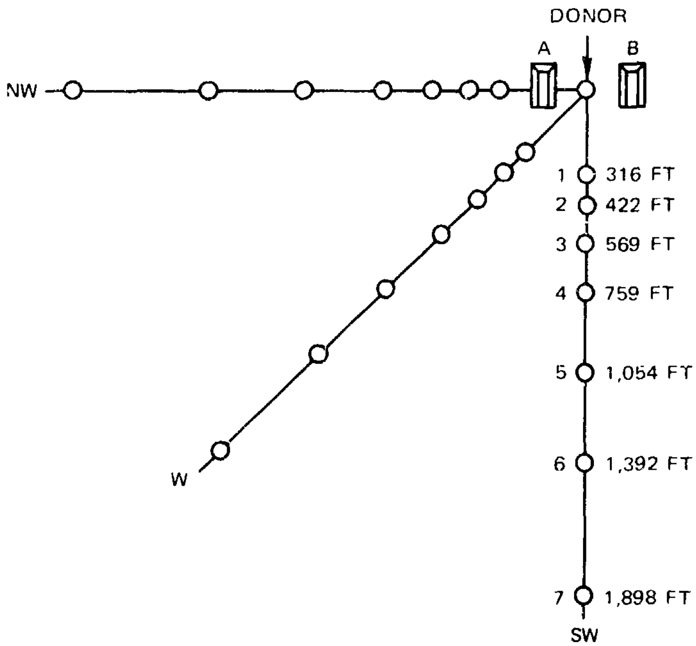


FIGURE 18. BRL, Self-Recording, Blast-Gauge Layout.

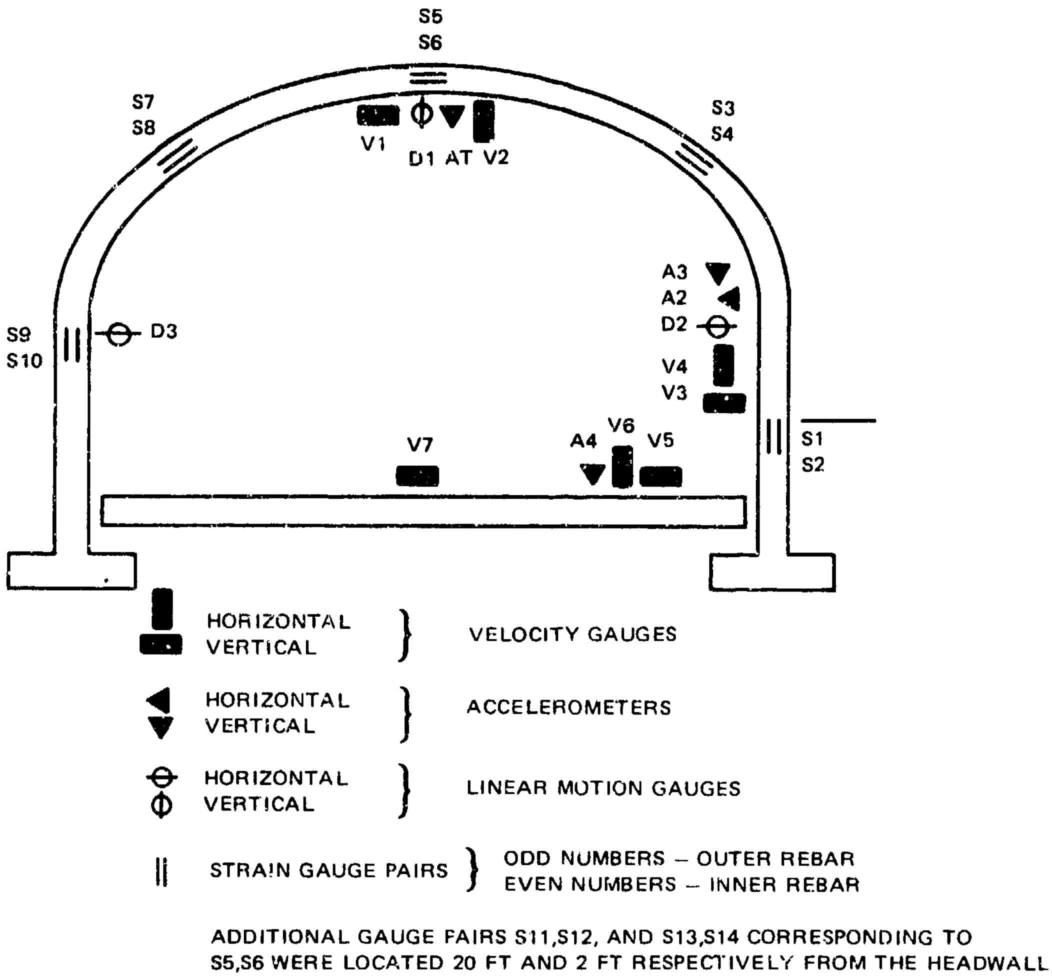


FIGURE 19. Motion Instrumentation Installed in FRELOC Igloo.

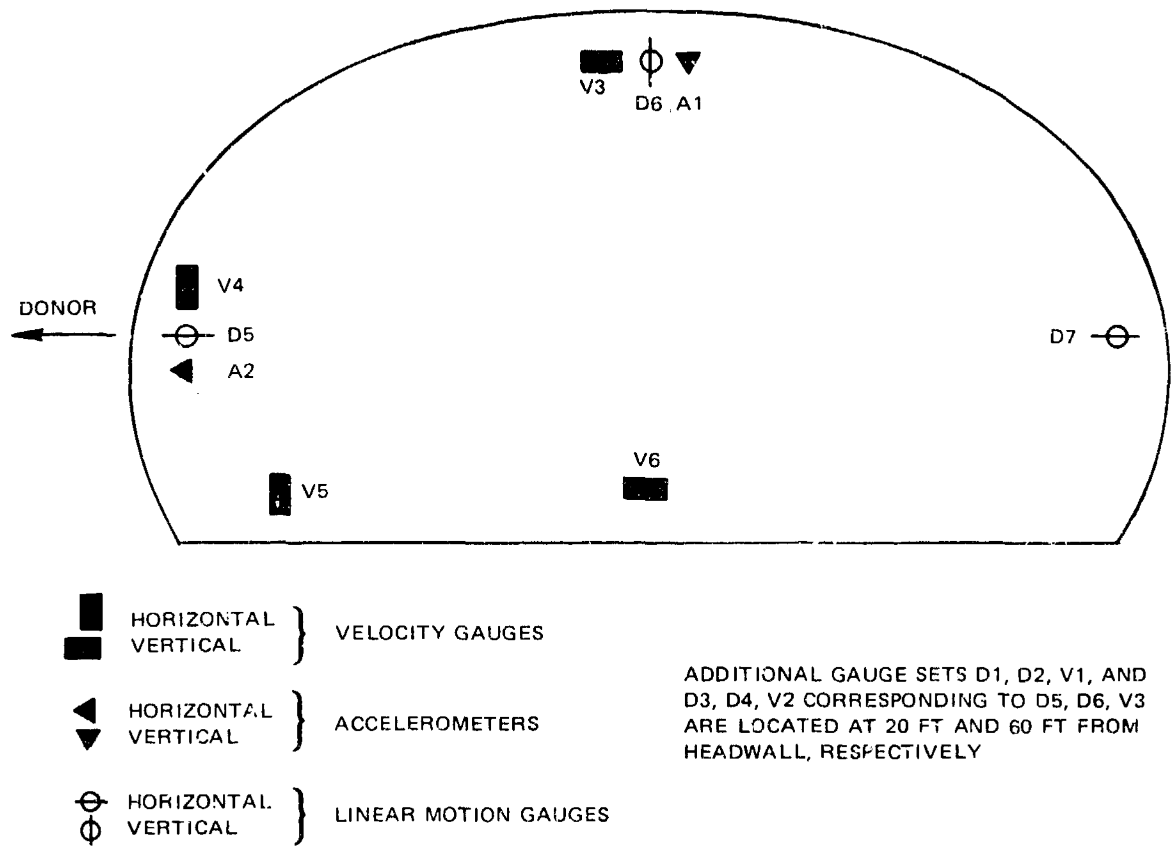


FIGURE 20. Motion Instrumentation Installed in Oval Steel-Arch Igloo.

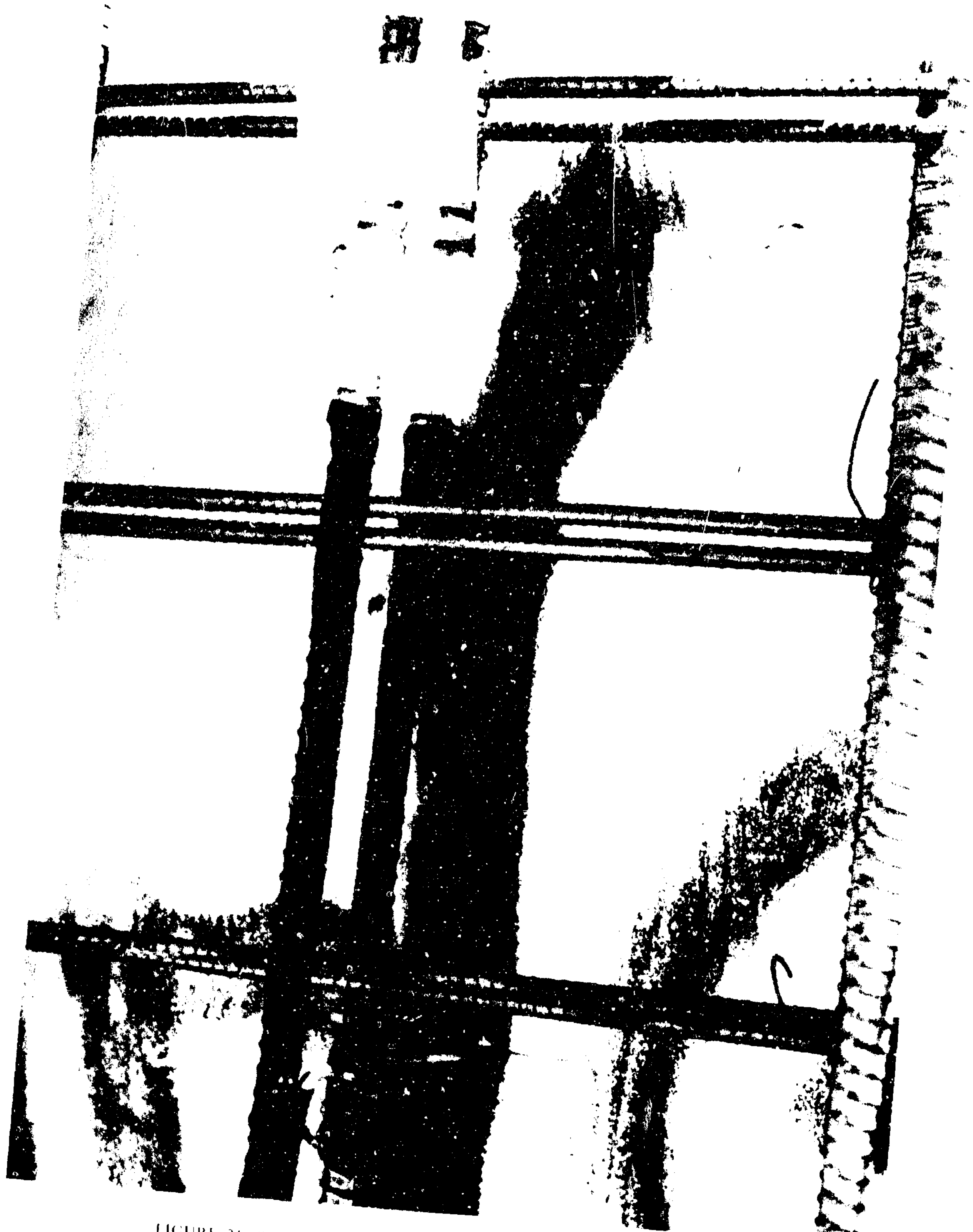


FIGURE 21. Strain Gauge Installation Prior to Concrete Pour, FRELOC Igloo.

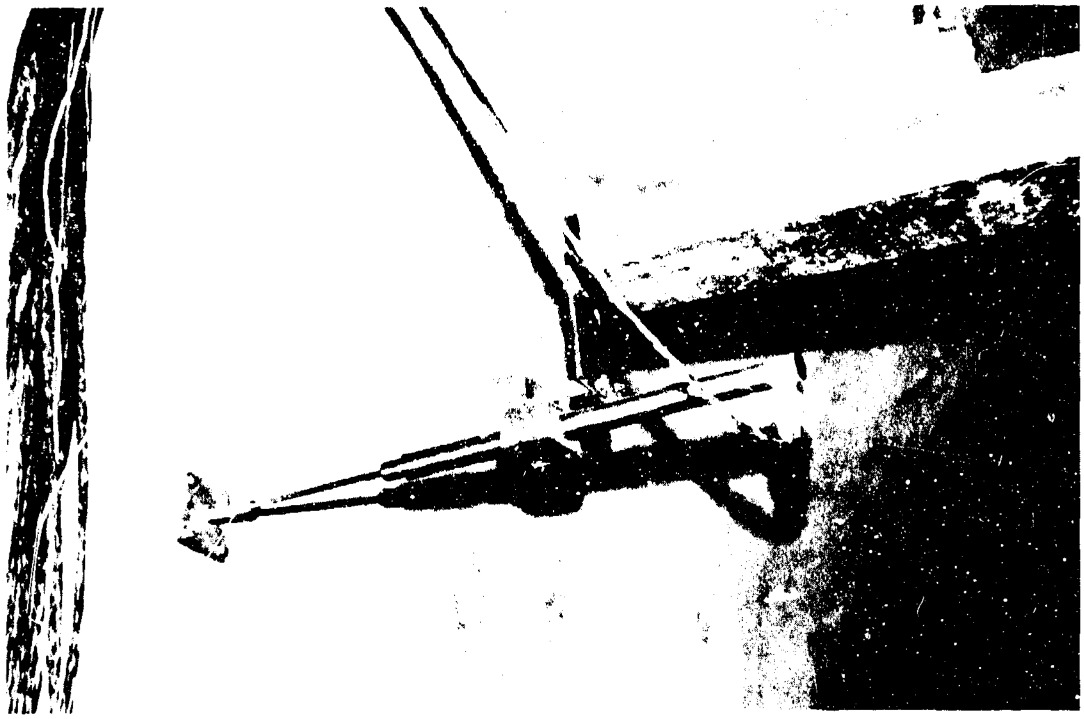


FIGURE 22. Horizontal Linear-Motion Gauge Installation, ERFLOC Igloo.

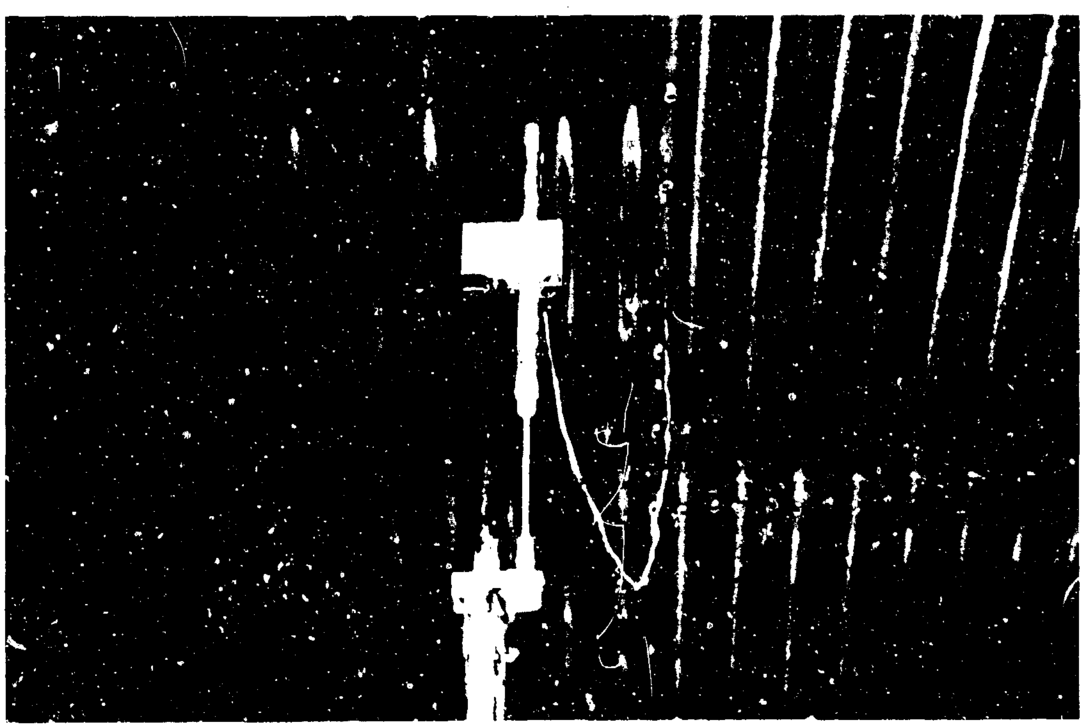


FIGURE 23. Vertical Linear-Motion Gauge in Place in Oval Steel-Arch Igloo.

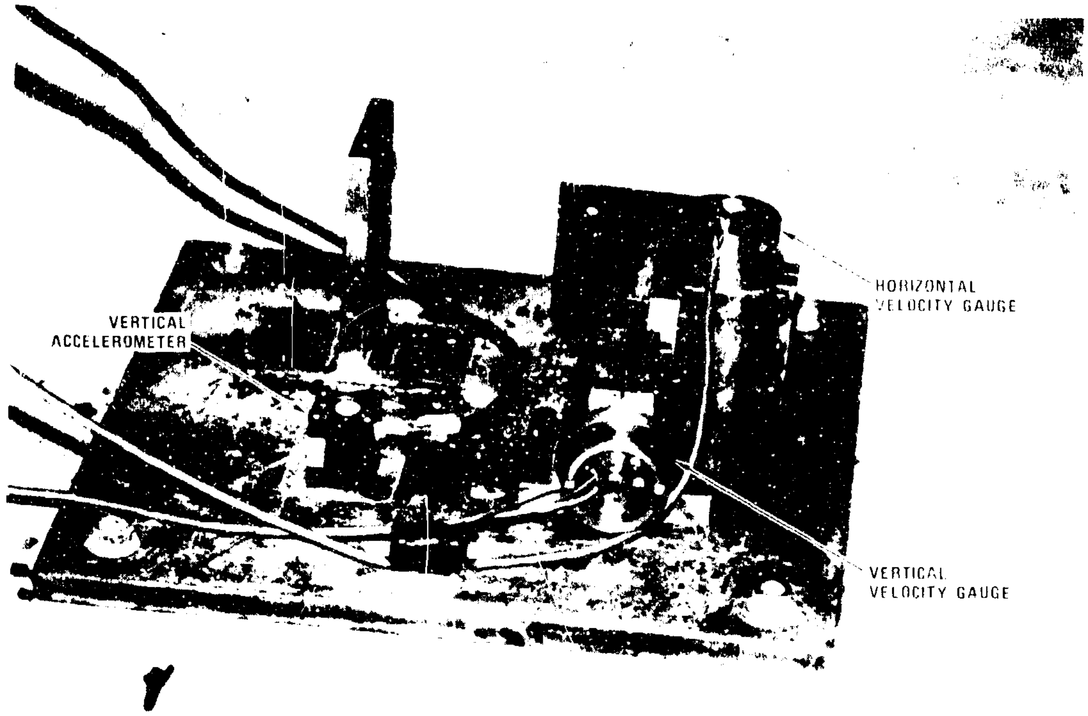


FIGURE 24. Velocity Gauge and Accelerometer Installation.

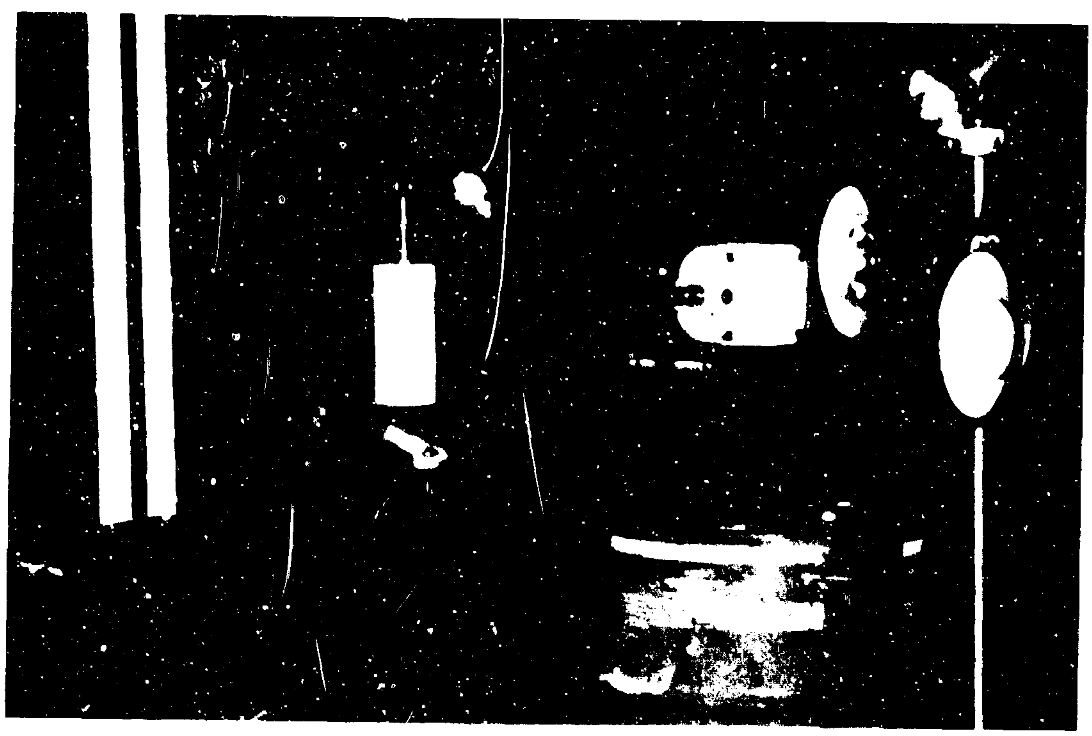


FIGURE 25. Interior Motion Picture Camera REFLOC Igloo, Showing Camera, Reference Stripe, and Pendulum

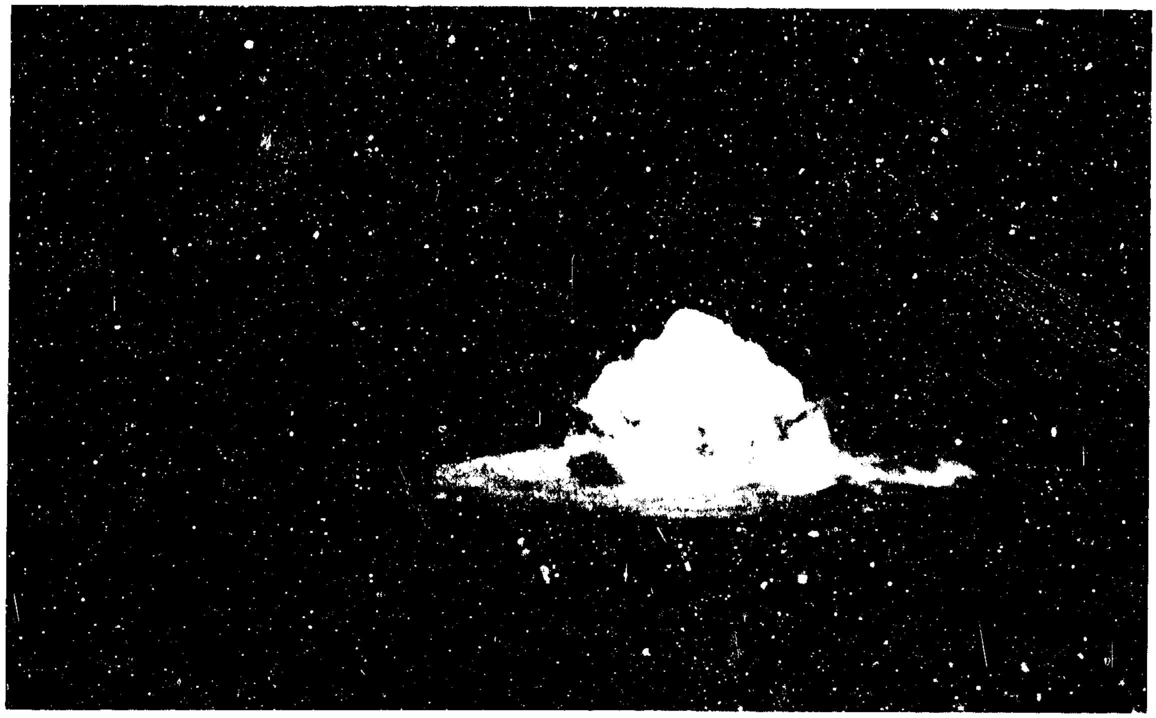


FIGURE 26. Blast Sequence, Approximately T_0 + 0.05 Second.

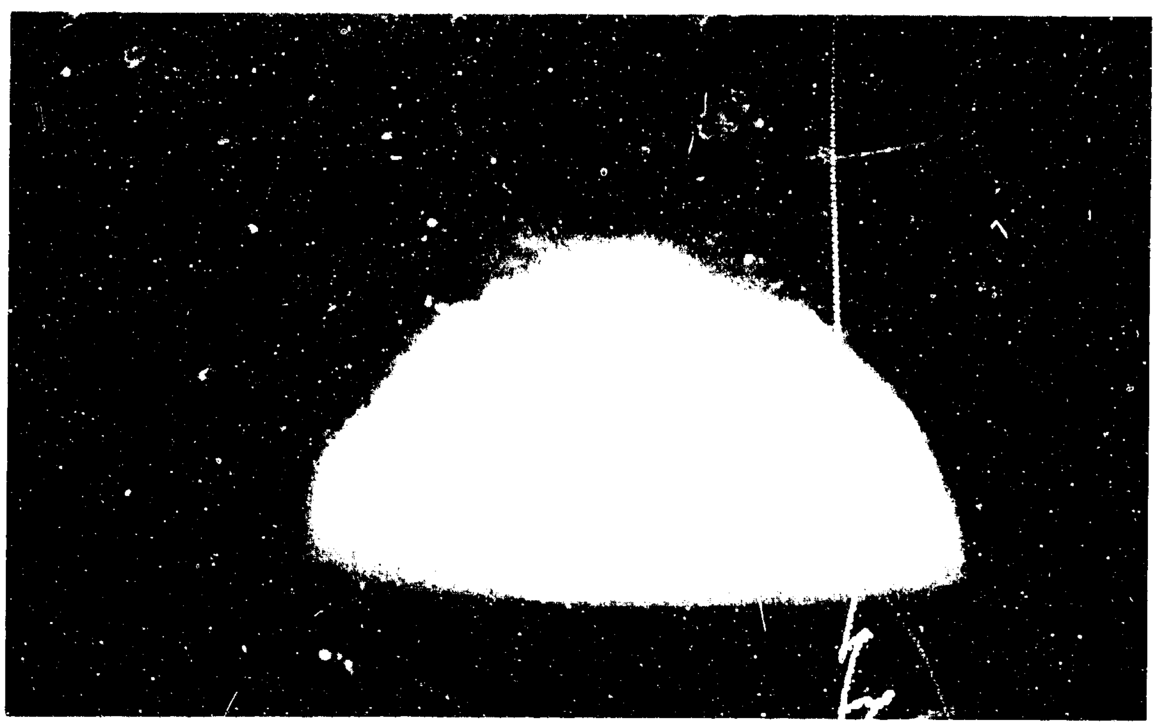


FIGURE 27. Blast Sequence, Approximately T_0 + [illegible] Second. Note formation of vapor cloud around [illegible].

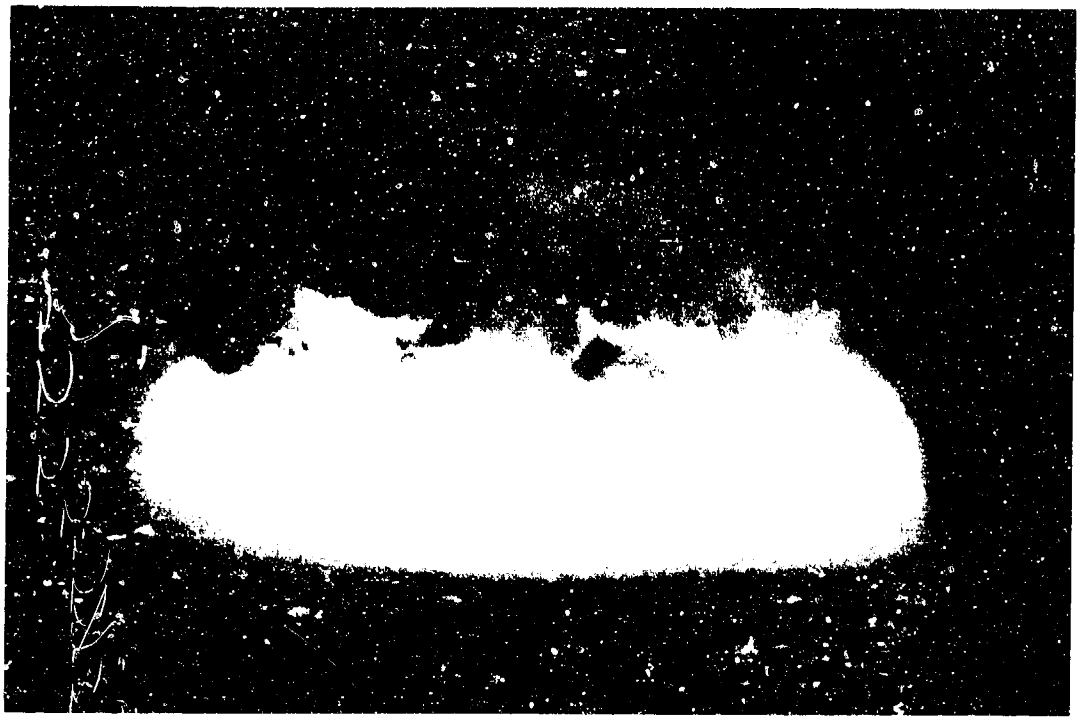


FIGURE 28. Blast Sequence, Approximately T_0 + 0.58 Second

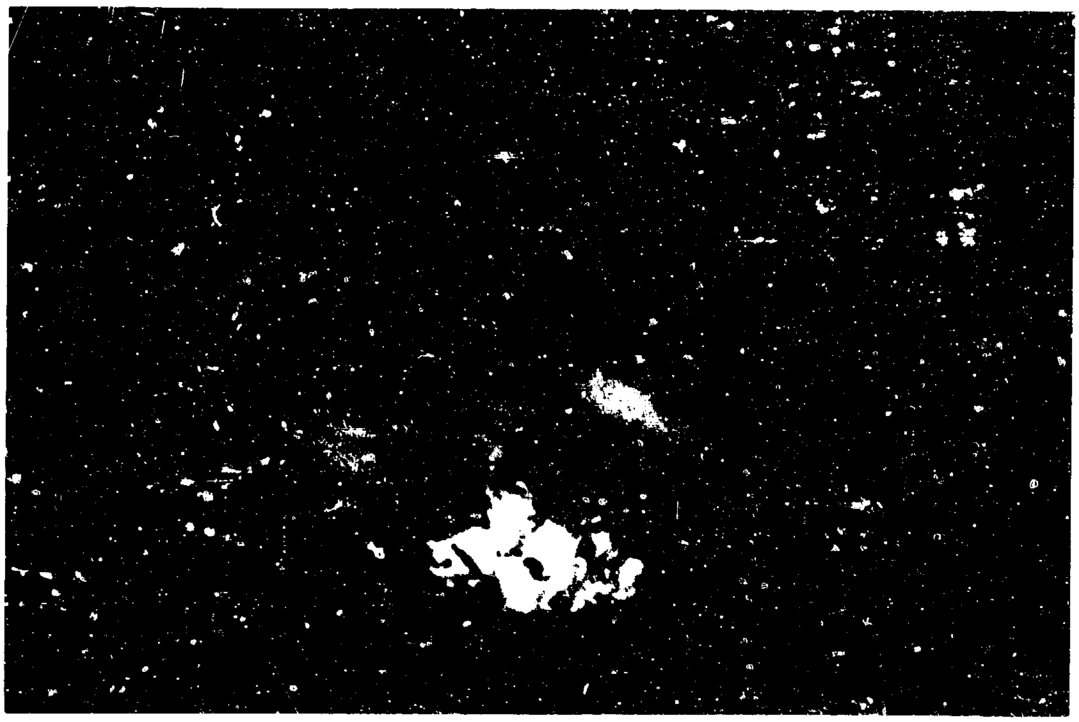


FIGURE 29. Blast Sequence, Approximately T_0 + 0.80 Second. Note [illegible] cloud.

FIGURE 30. Interior Headwall Spalling, FRELOC Igloo.

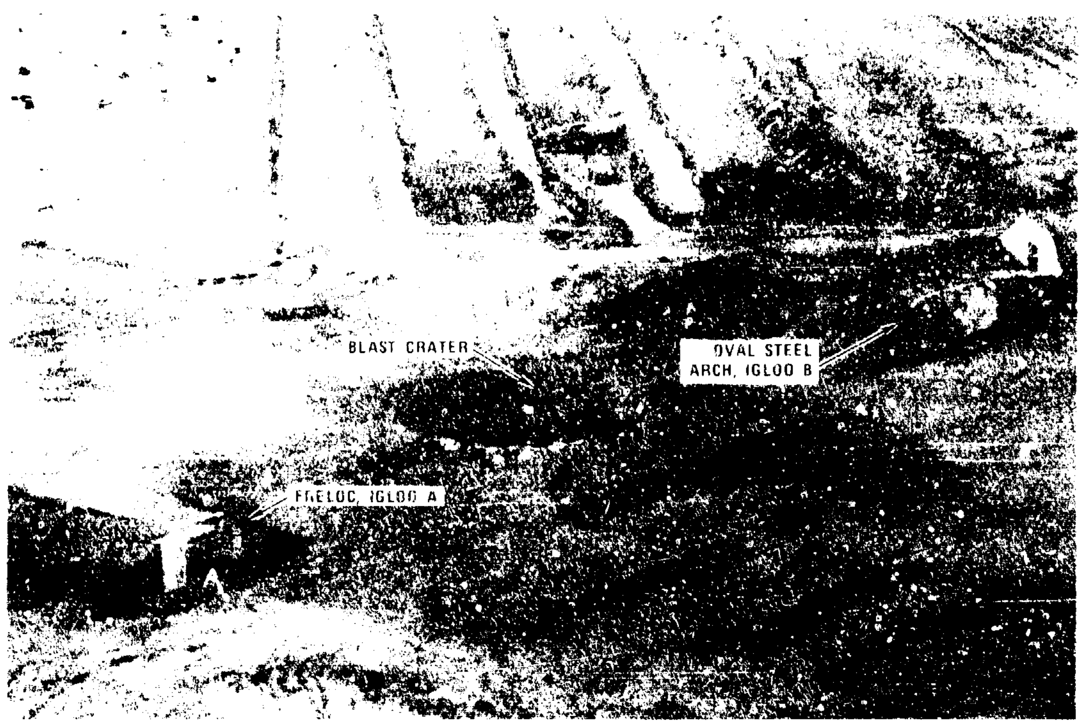
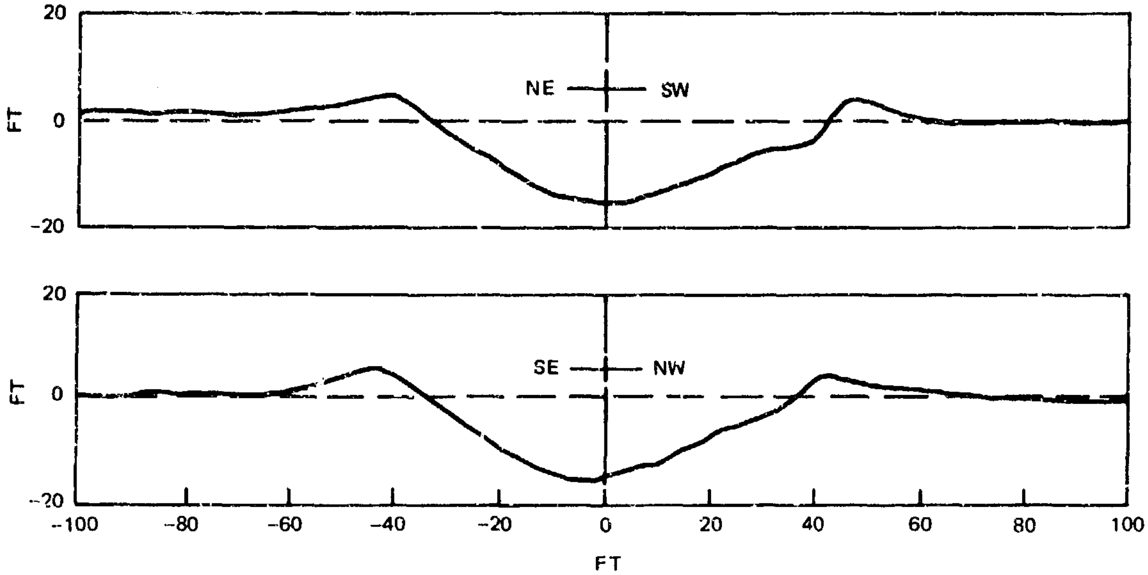


FIGURE 31. Post-Test Site Overview.



0 REPRESENTS ORIGINAL PRETEST POSITION
OF THE DONOR STACK CENTER

FIGURE 32. Donor Contours.

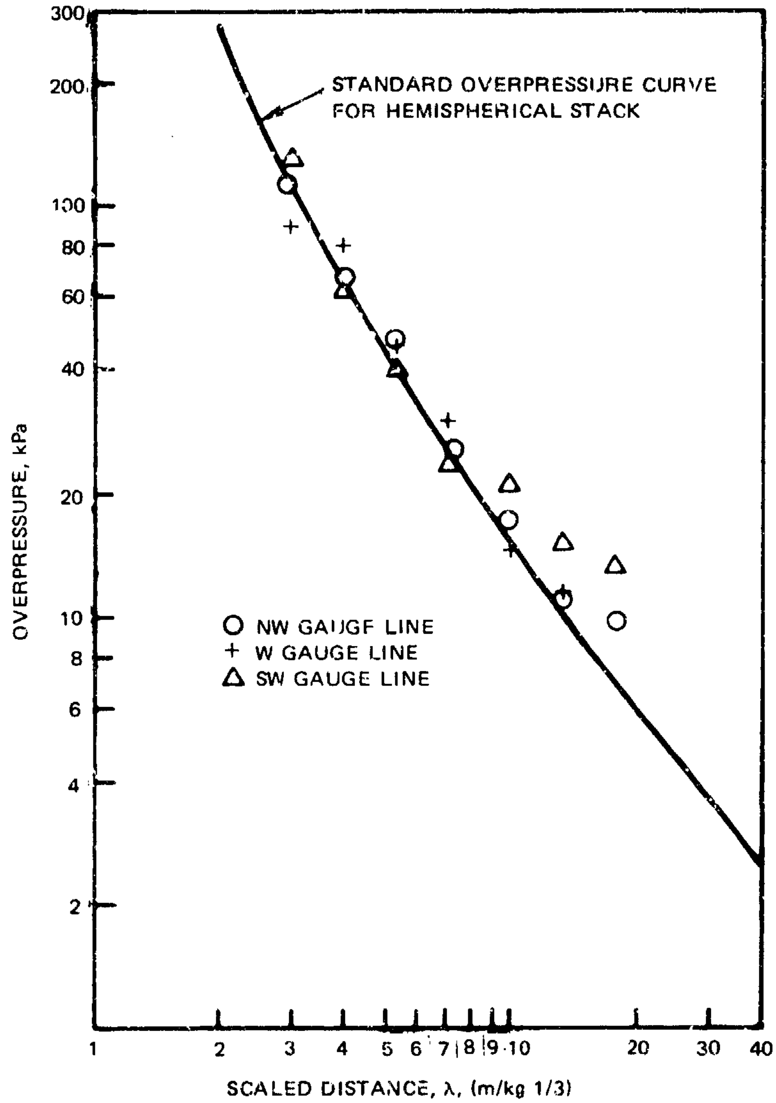


FIGURE 33. Plot of Far-Field Overpressure Recorded by BRL Gauges, Versus Scaled Distance.

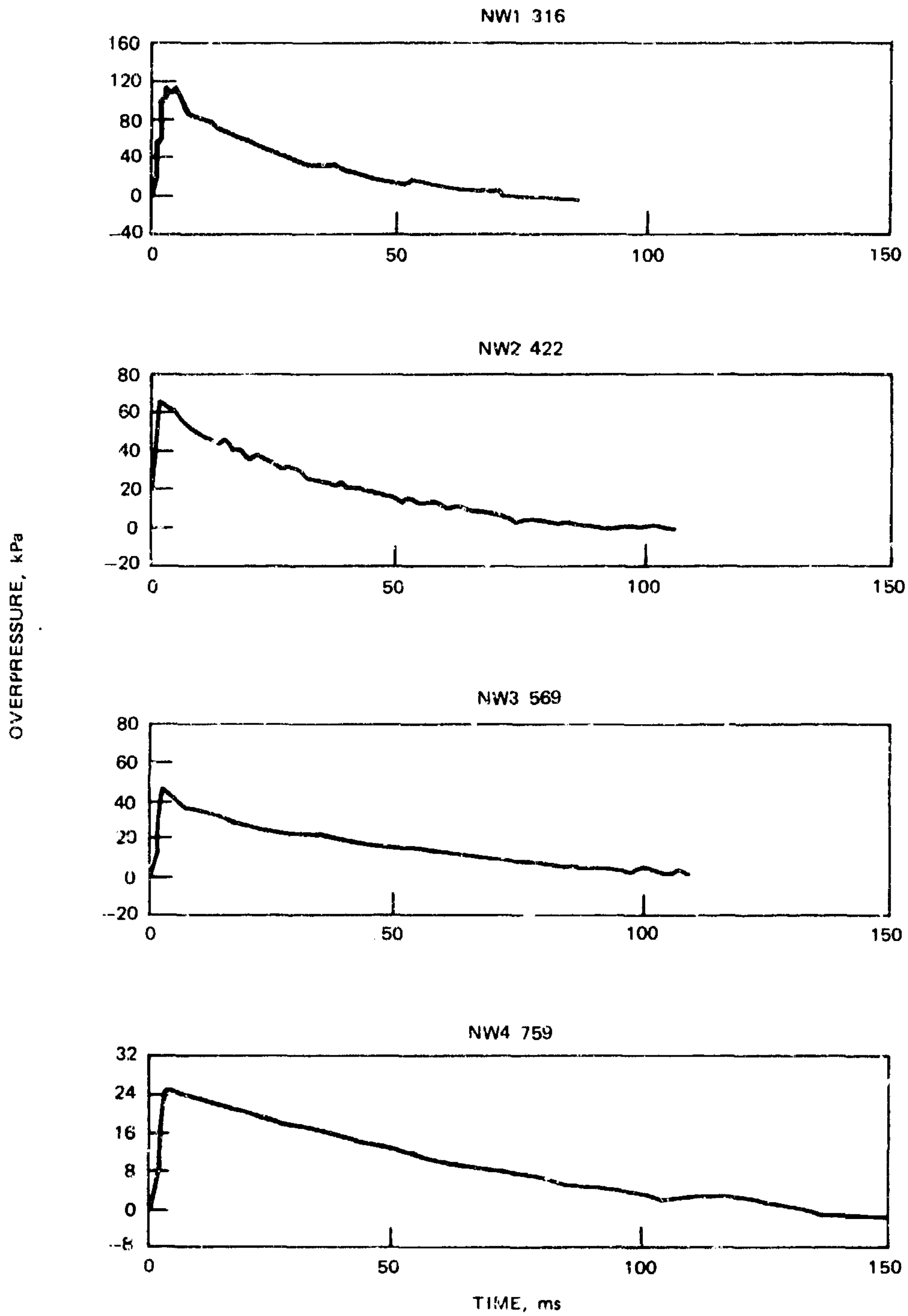


FIGURE 34. Data Plots for Far-Field Blast Gauges NW1 Through NW4.

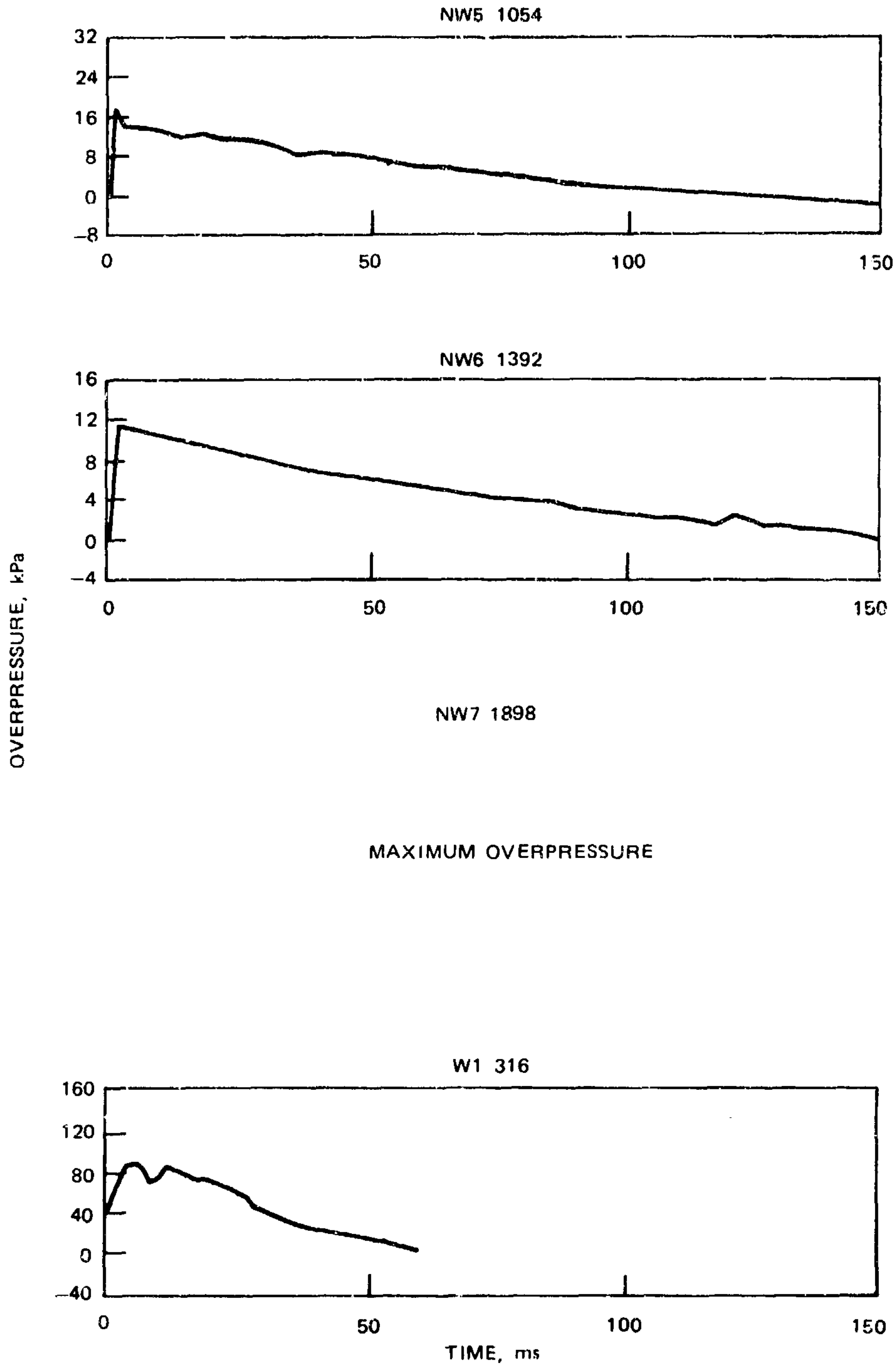


FIGURE 35. Data Plots for Far-Field Blast Gauges NW5, NW6, and W1.

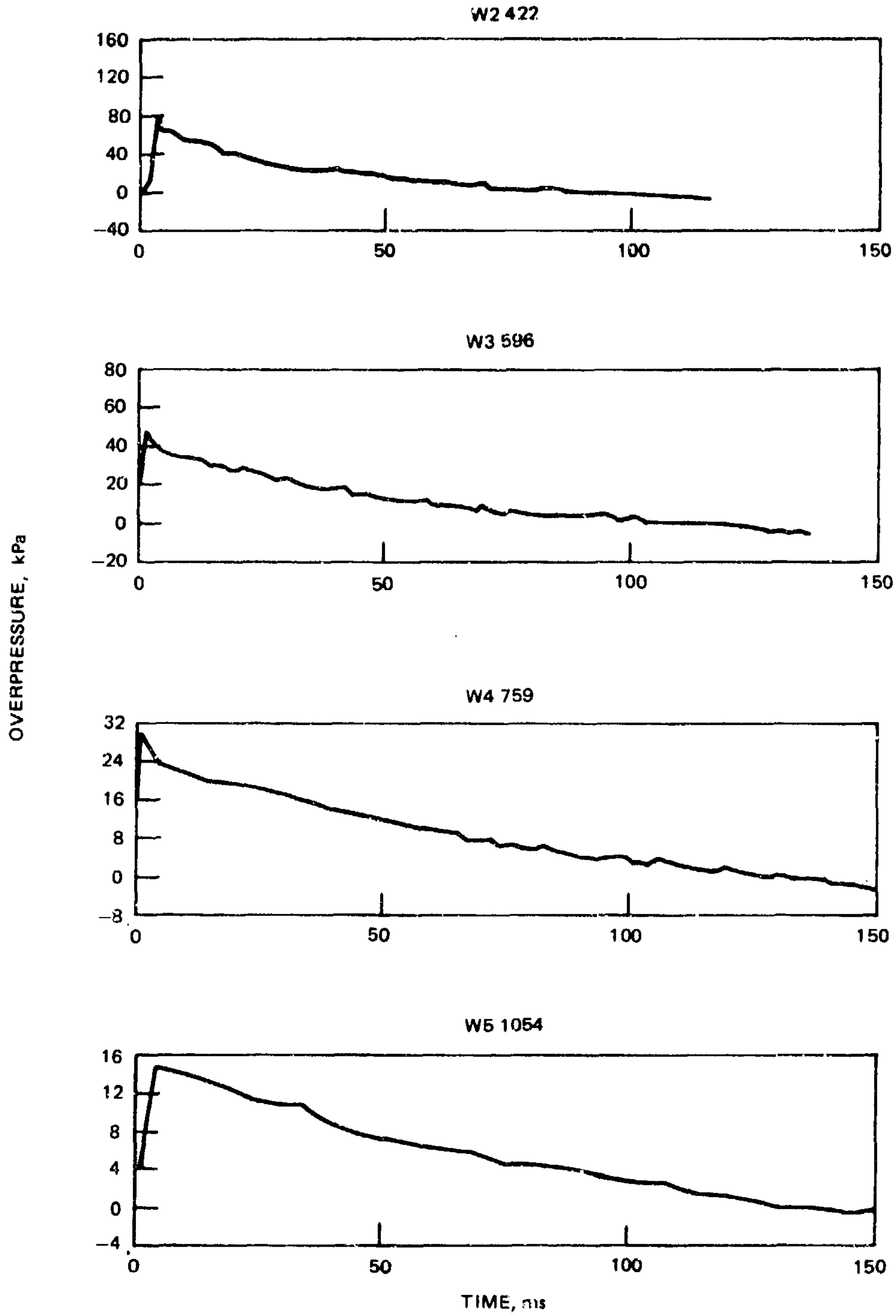


FIGURE 36. Data Plots for Far-Field Blast Gauges W2 Through W5.

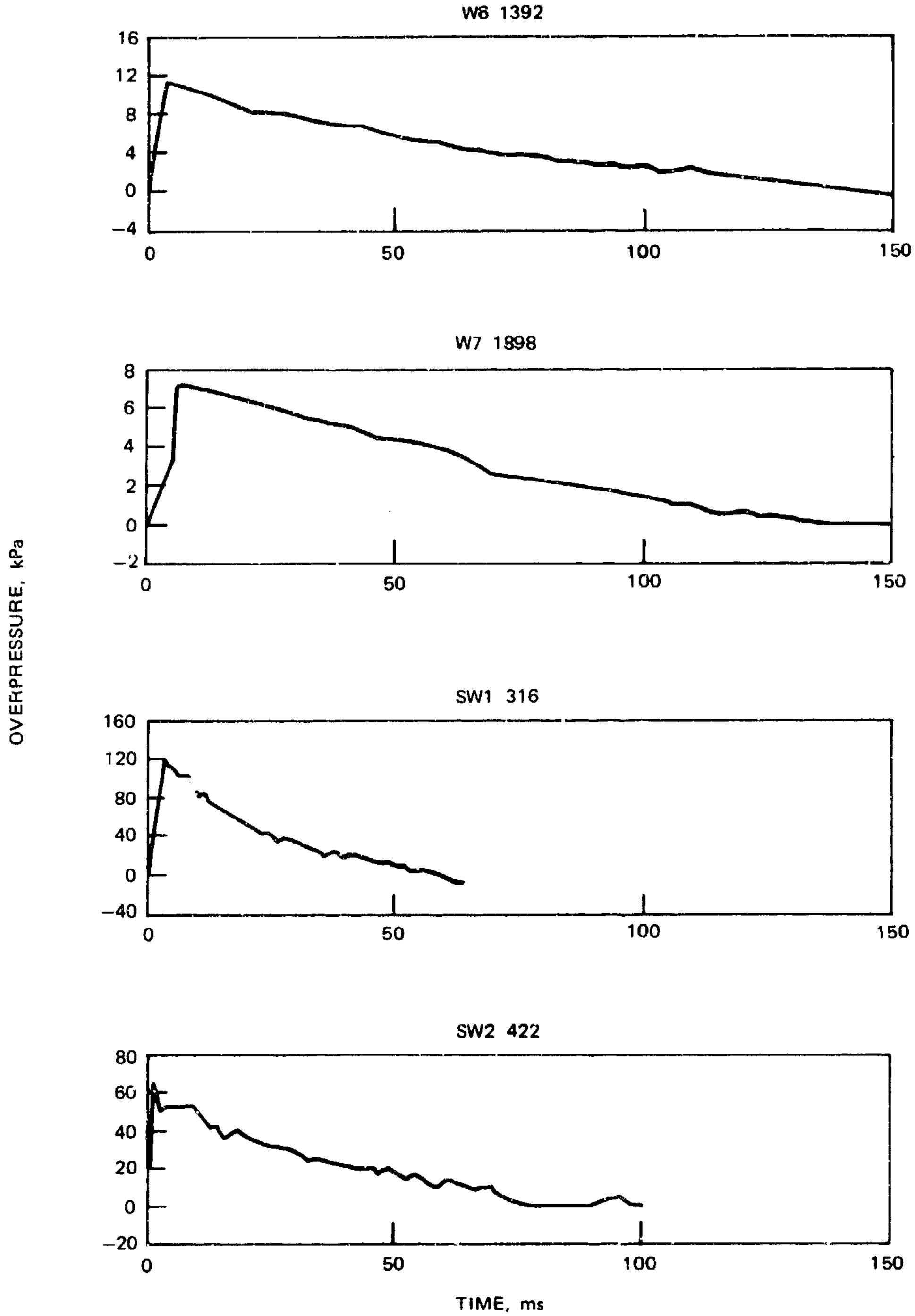


FIGURE 37. Data Plots for Far-Field Blast Gauges W6, W7, SW1, and SW2.

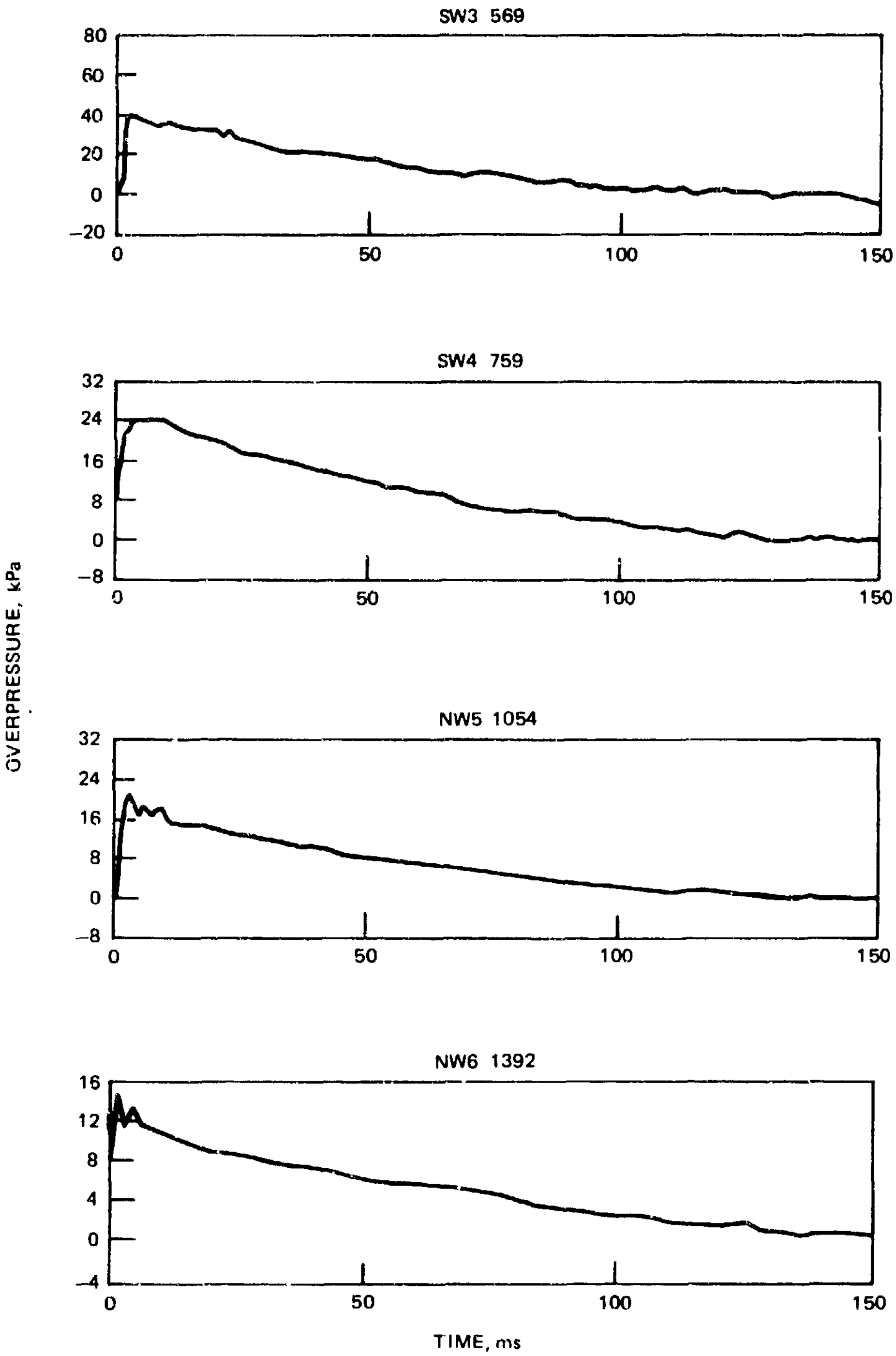


FIGURE 38. Data Plots for Far-Field Blast Gauges SW3, Through SW6.

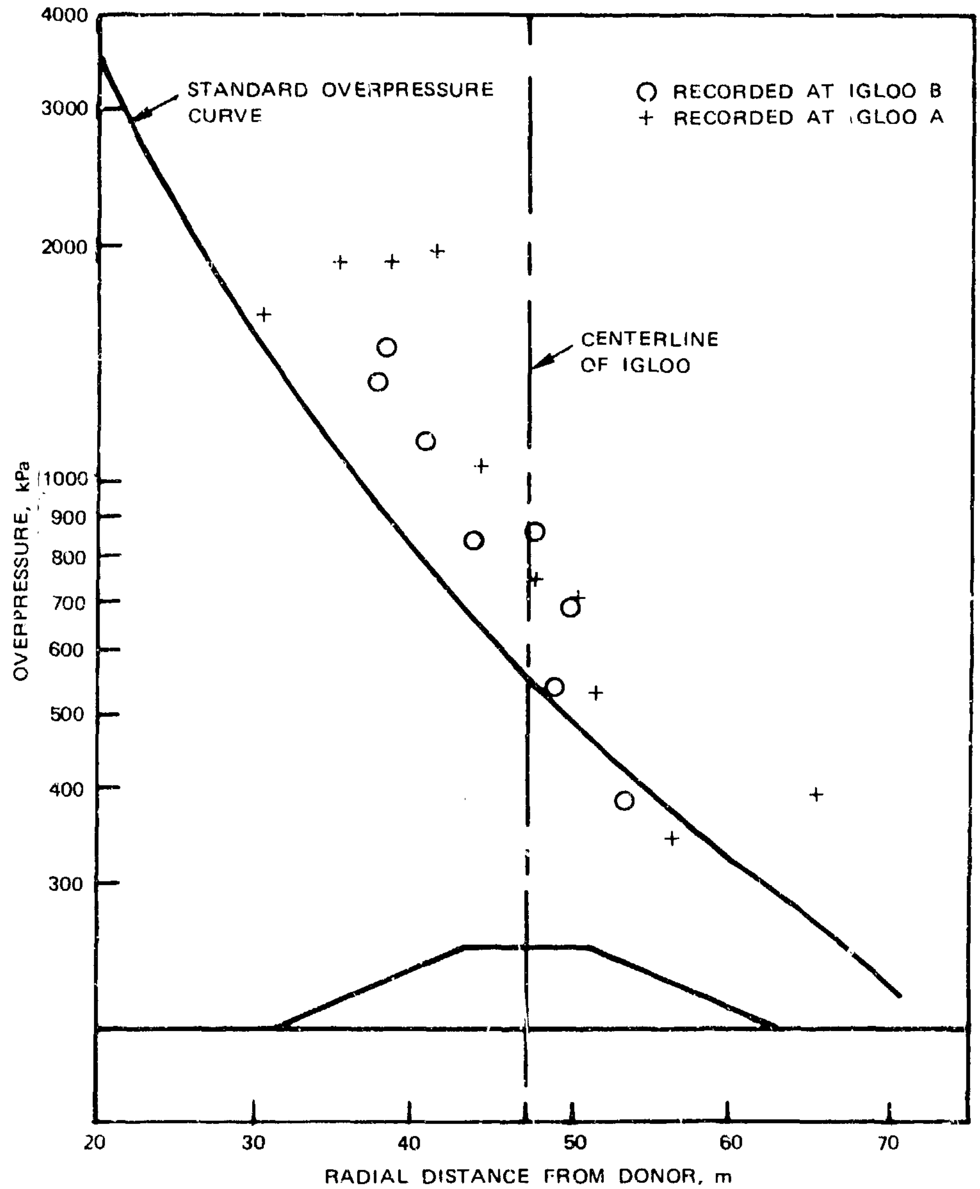


FIGURE 39. Plot of Near-Field Overpressure Recorded by Electronic Gauges, Compared With Derived Standard Curve for Hemispherical Stacks. (BRL Report 1344, September 1966.)

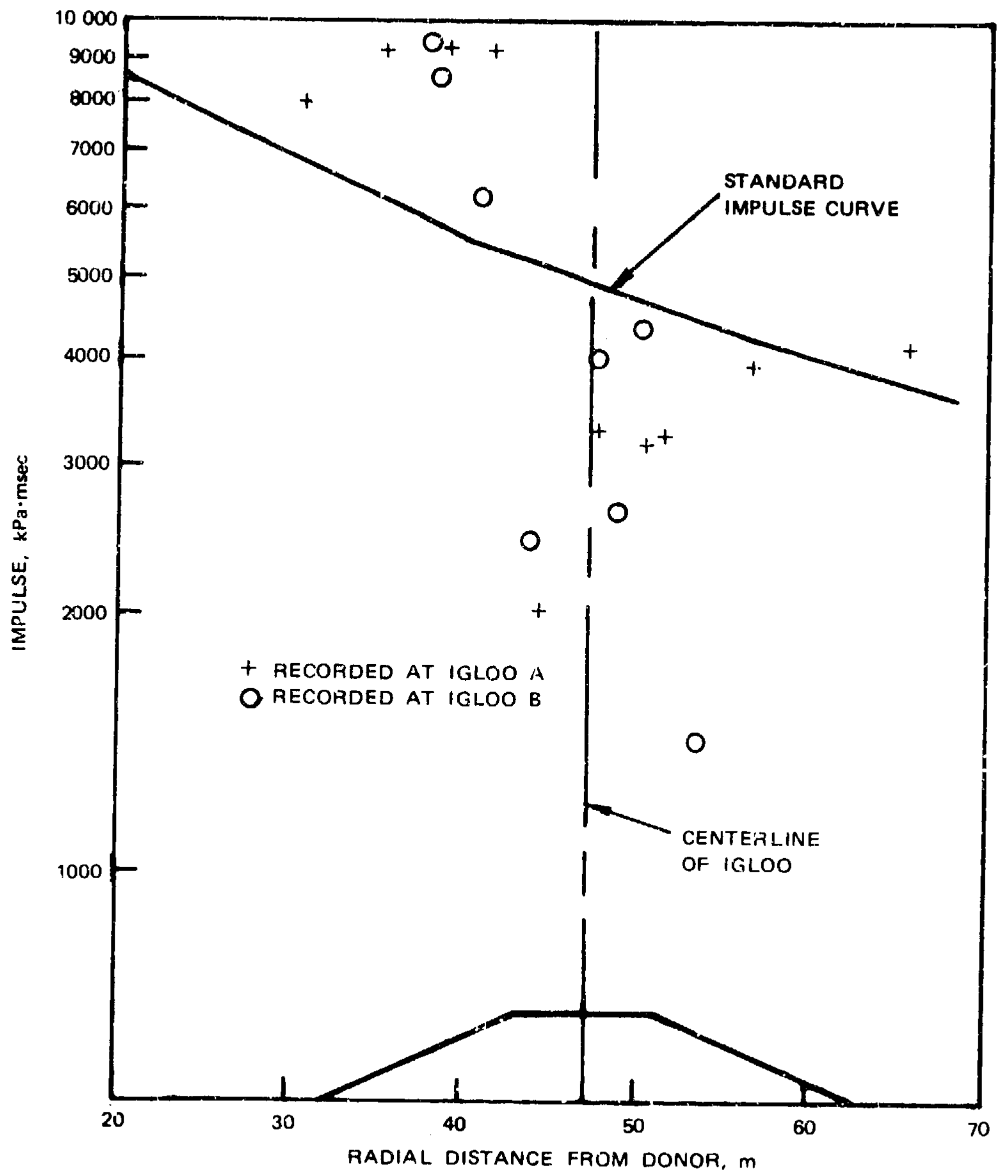


FIGURE 40. Plot of Near-Field Impulse Versus Distance, Compared With Derived Standard Curve for Hemispherical Stacks. (BRL Report 1344, September 1966.)

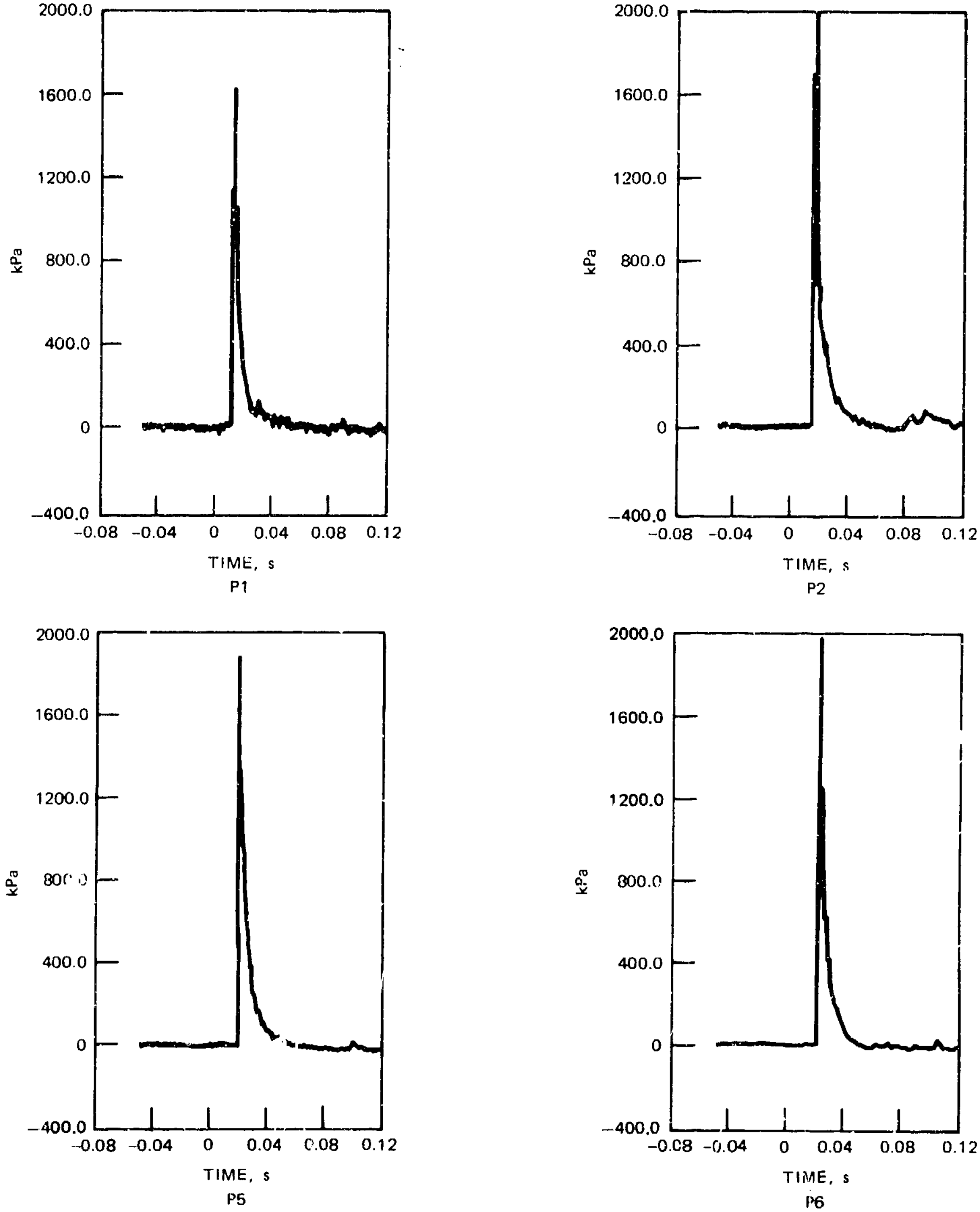


FIGURE 41. Overpressure Gauges P1, P2, P5, and P6, Igloo A.

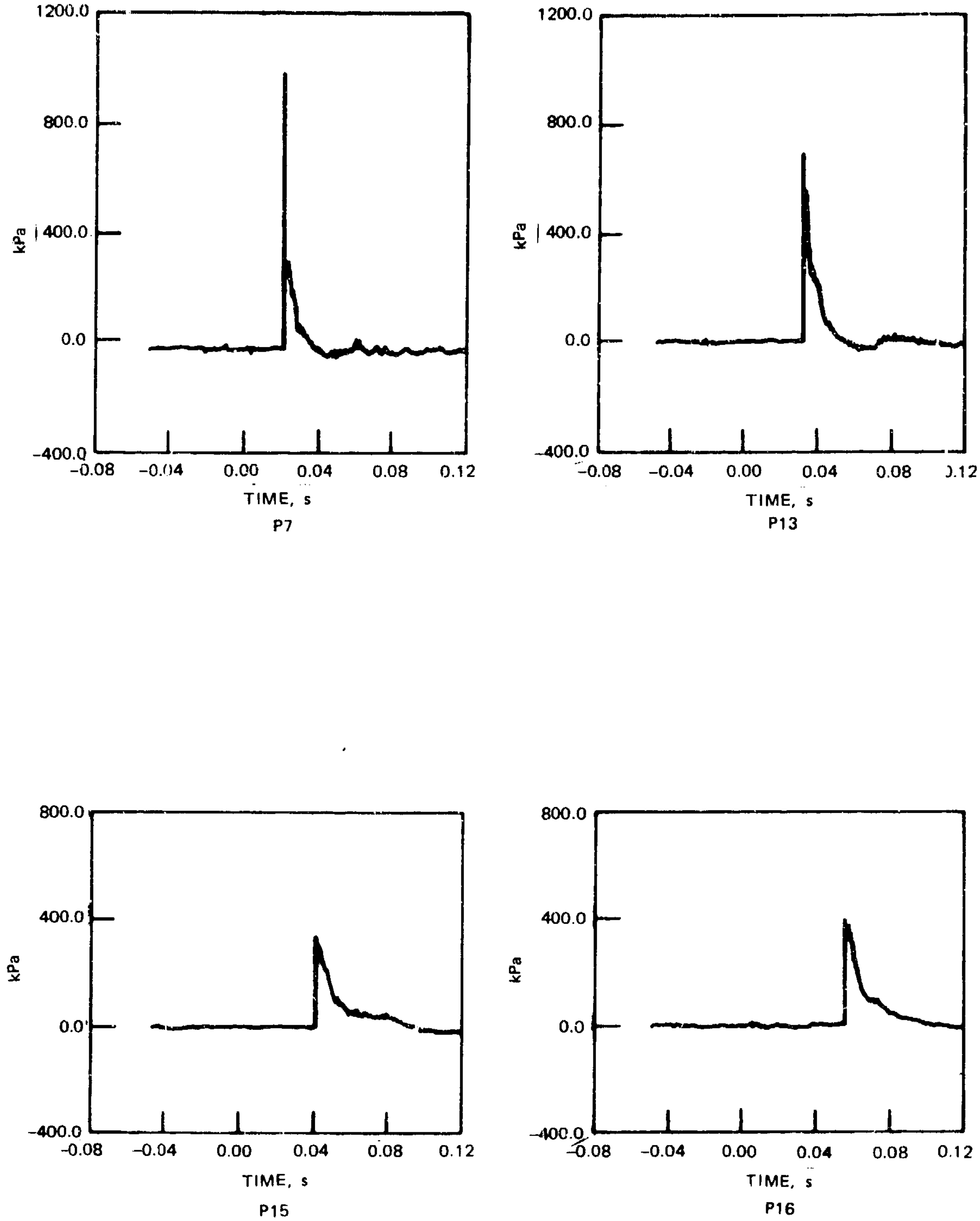


FIGURE 42. Overpressure Gauges P7, P13, P15, and P16, Igloo A.

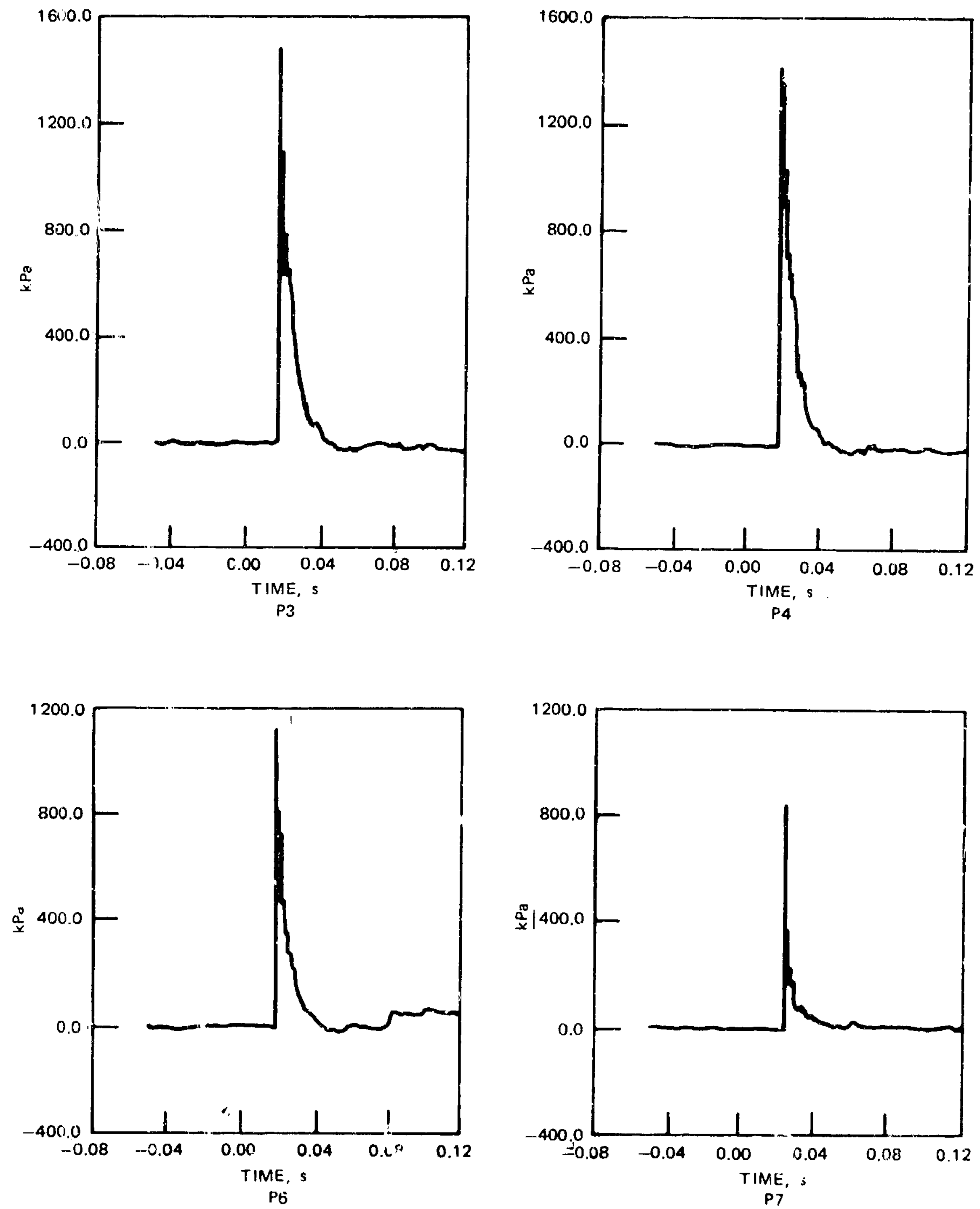


FIGURE 43. Overpressure Gauges P3, P4, P6, and P7, Igloo B.

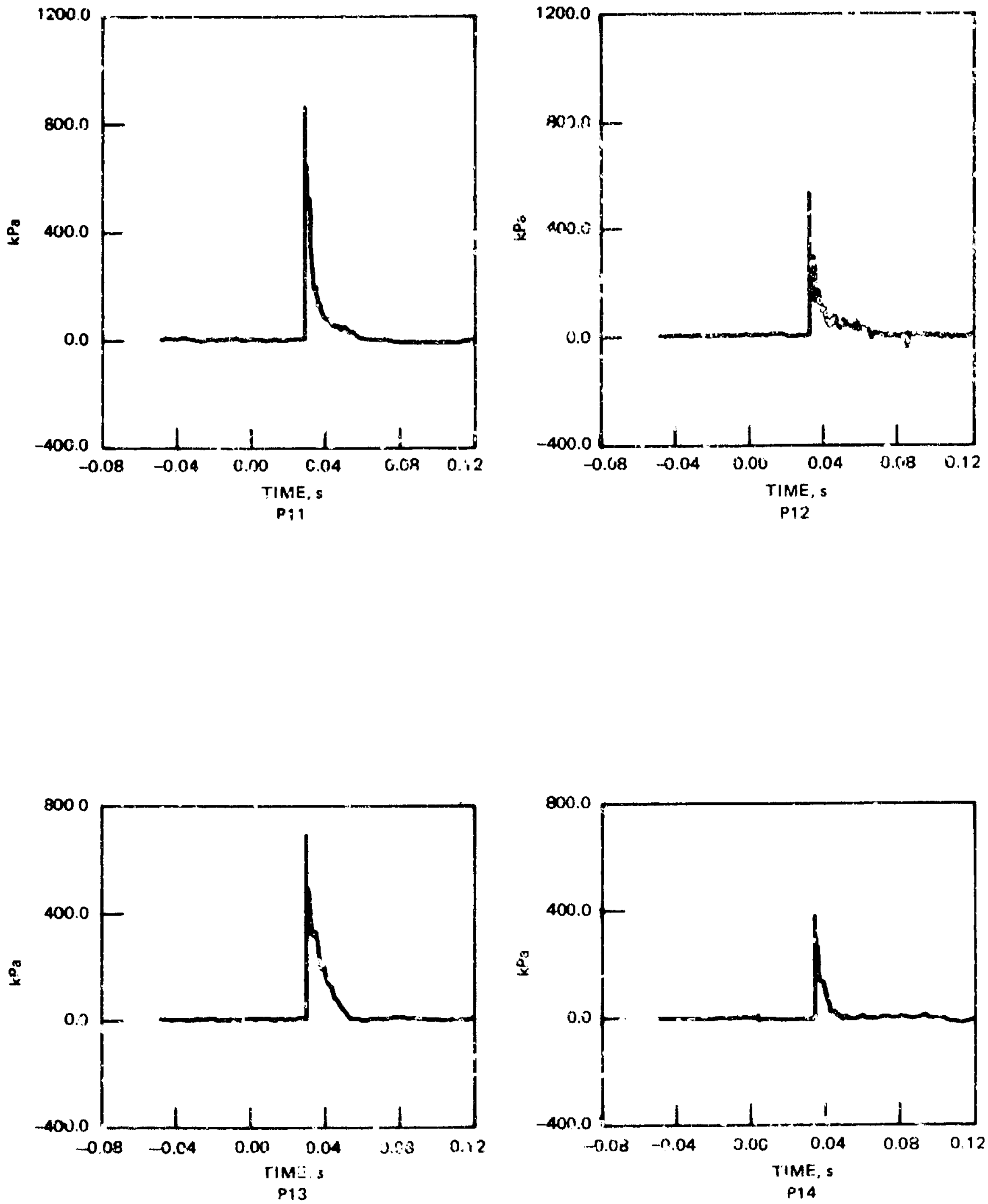


FIGURE 44. Overpressure Gauges P11, P12, P13, and P14, Igloo B.

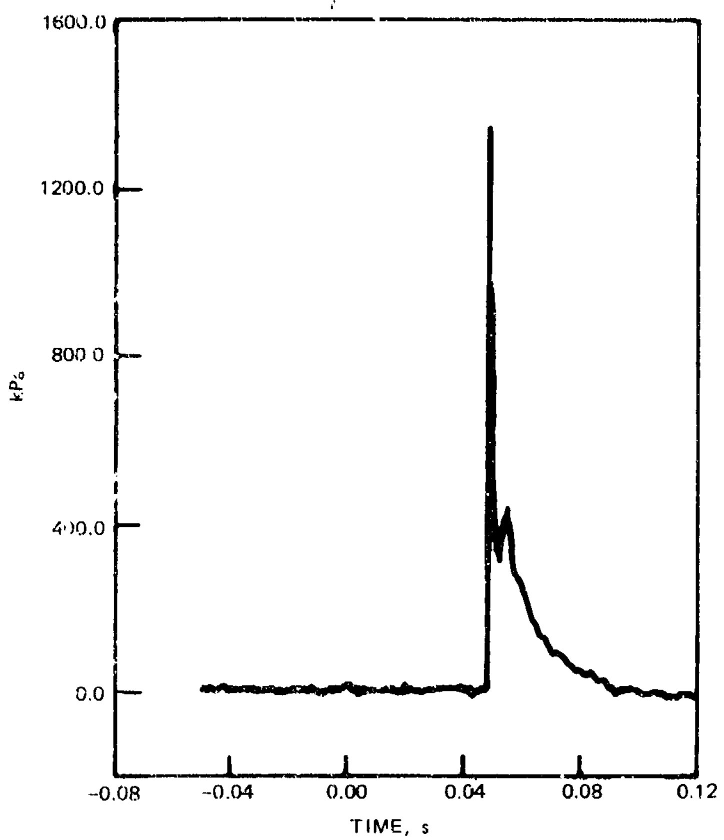


FIGURE 45. Overpressure Gauge P18, Igloo B.

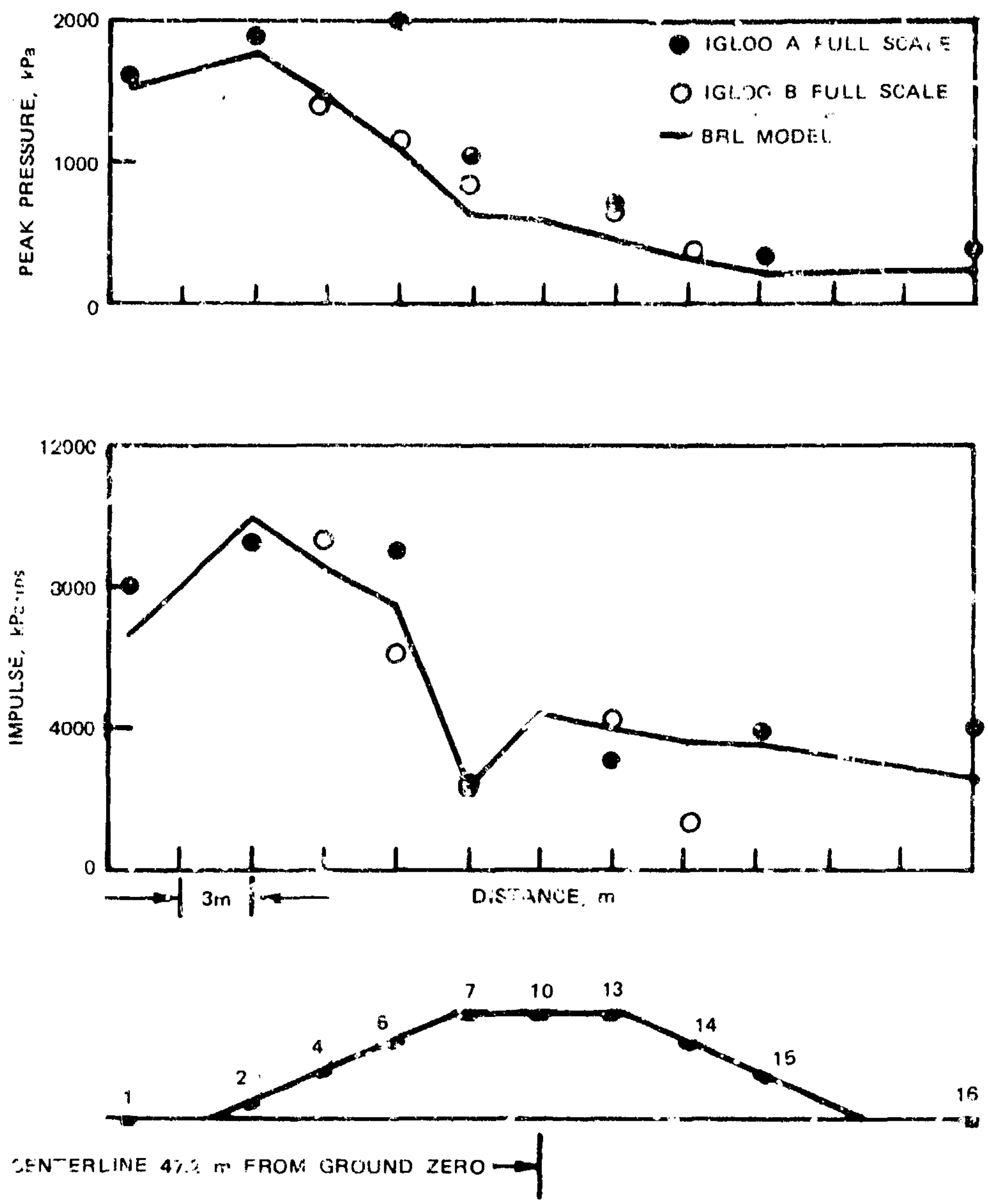


FIGURE 46. Comparison Between BRL Model Predictions and Actual Full-Scale Results.

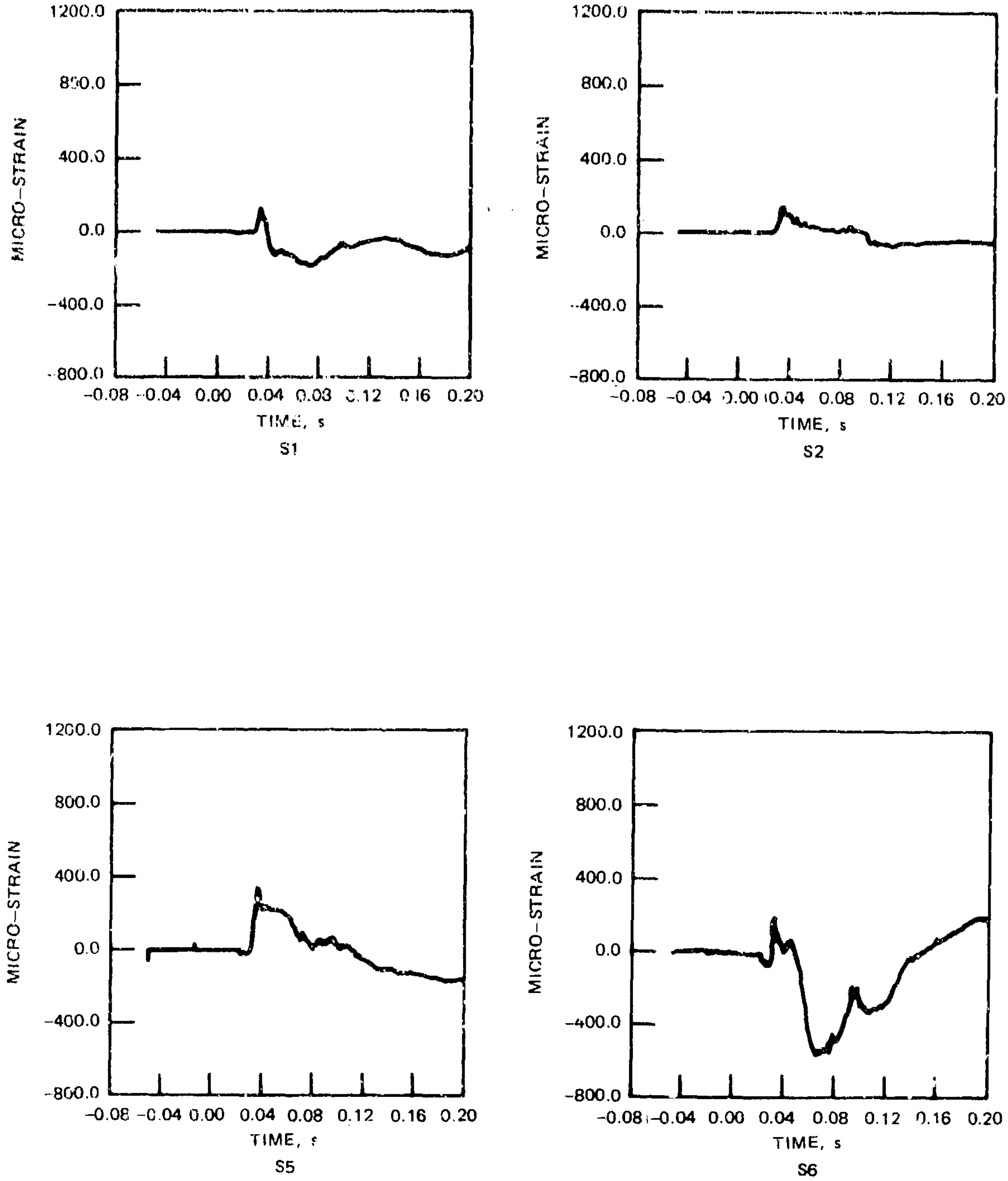


FIGURE 47. Data Plots for Strain Gauges S1, S2, S5, and S6.

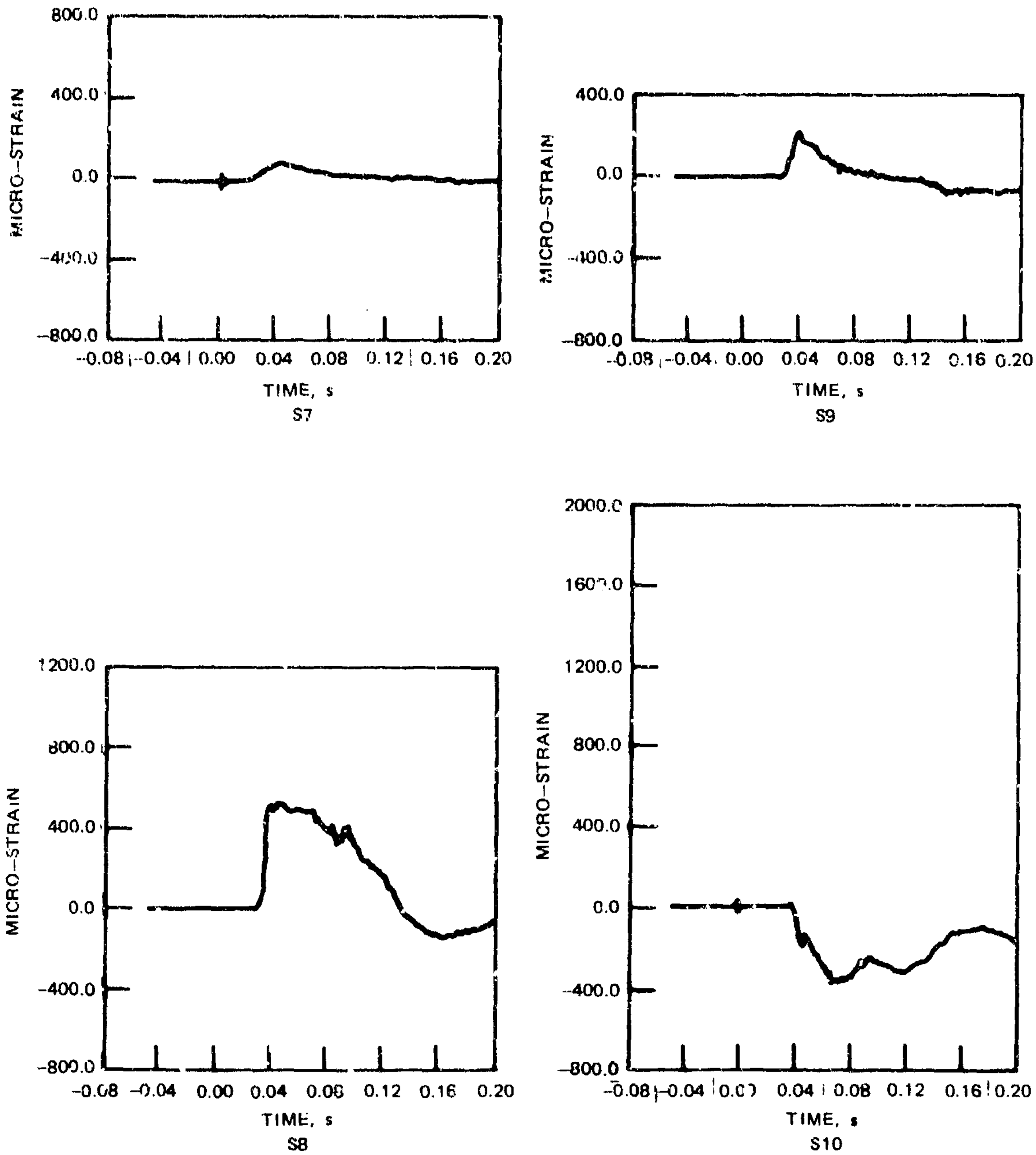


FIGURE 48. Data Plots for Strain Gauges S7, S8, S9, and S10.

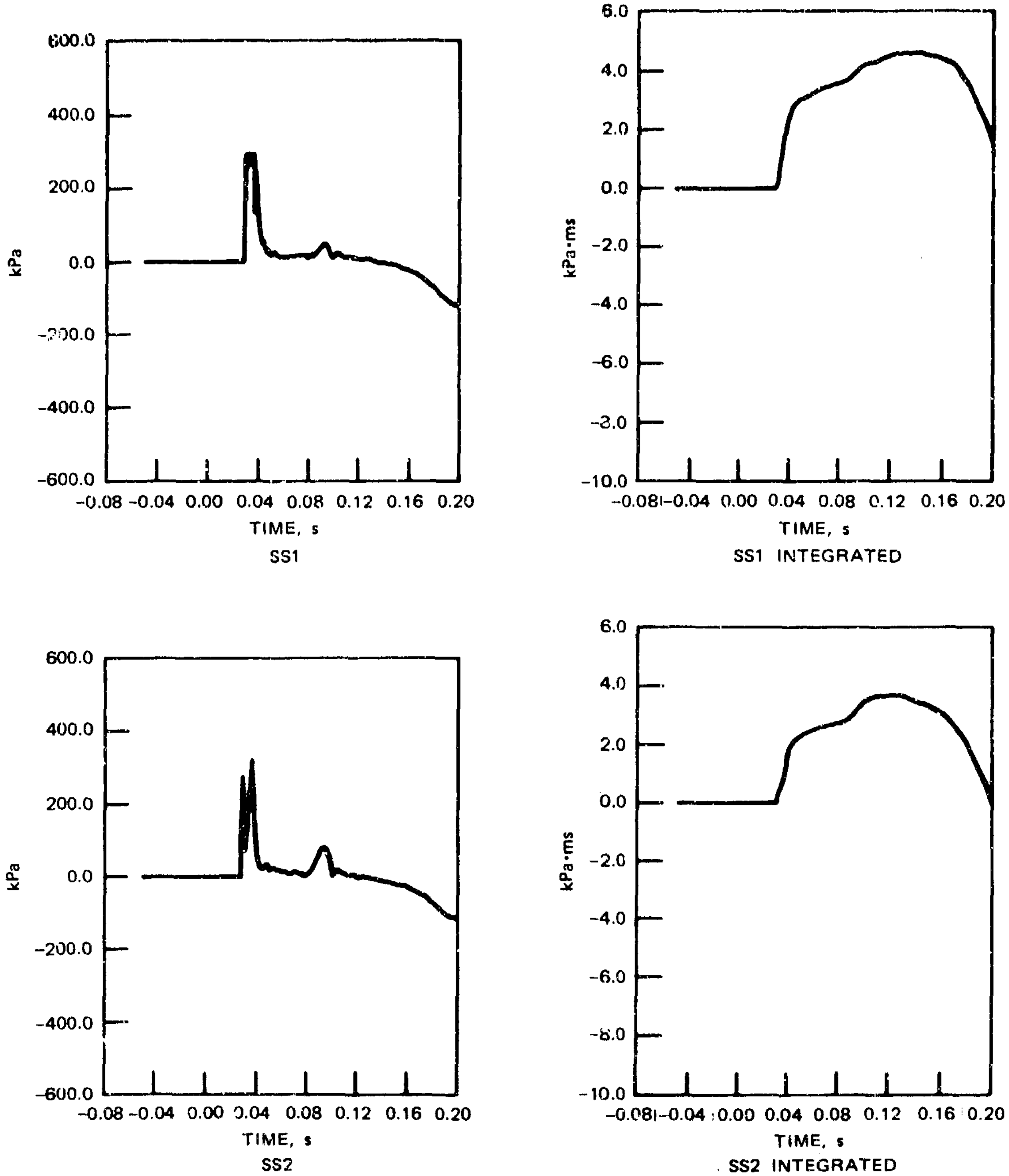


FIGURE 49. Data Plots for Soil-Stress Gauges SS1 and SS2.

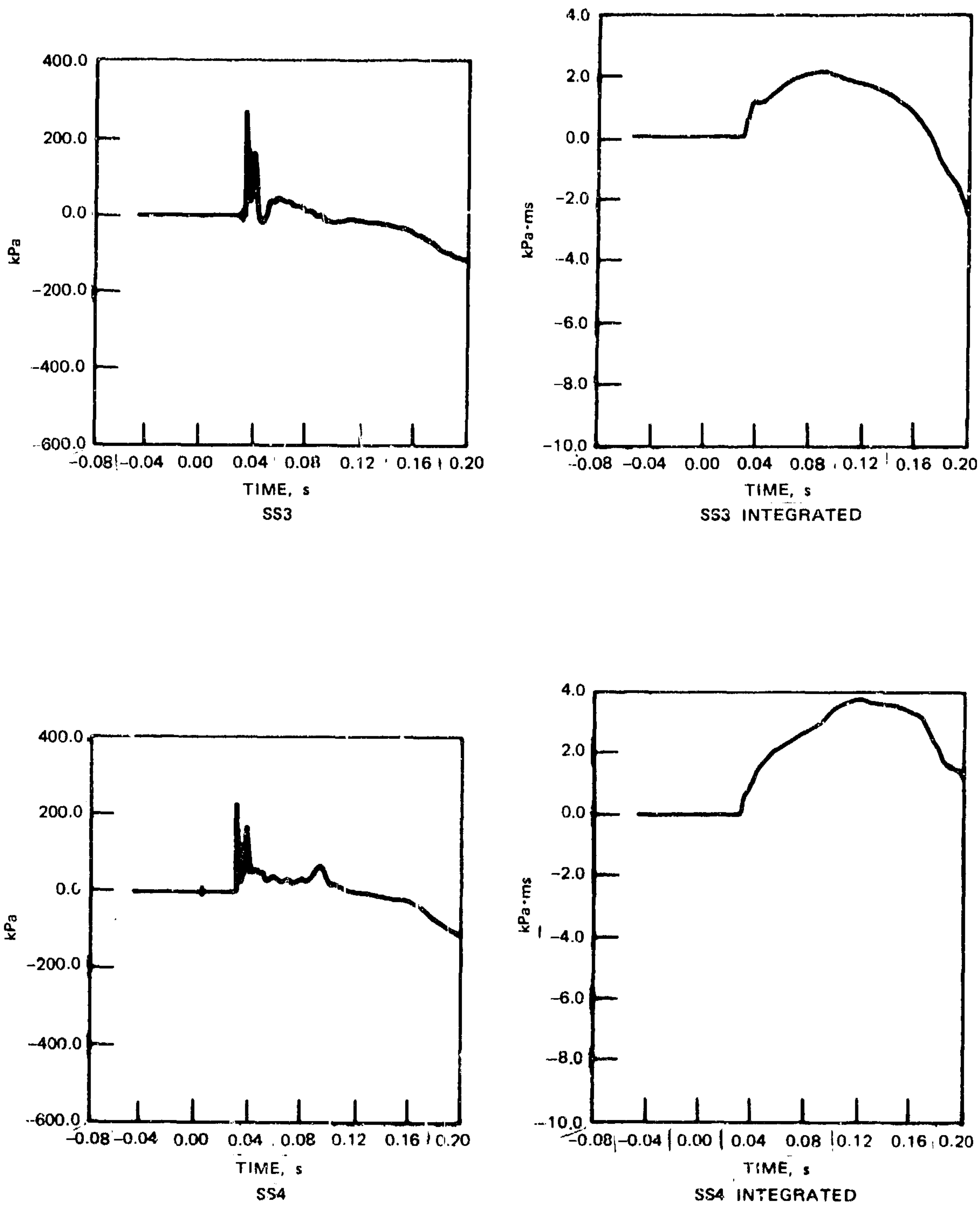


FIGURE 50. Data Plots for Soil-Stress Gauges SS3 and SS4.

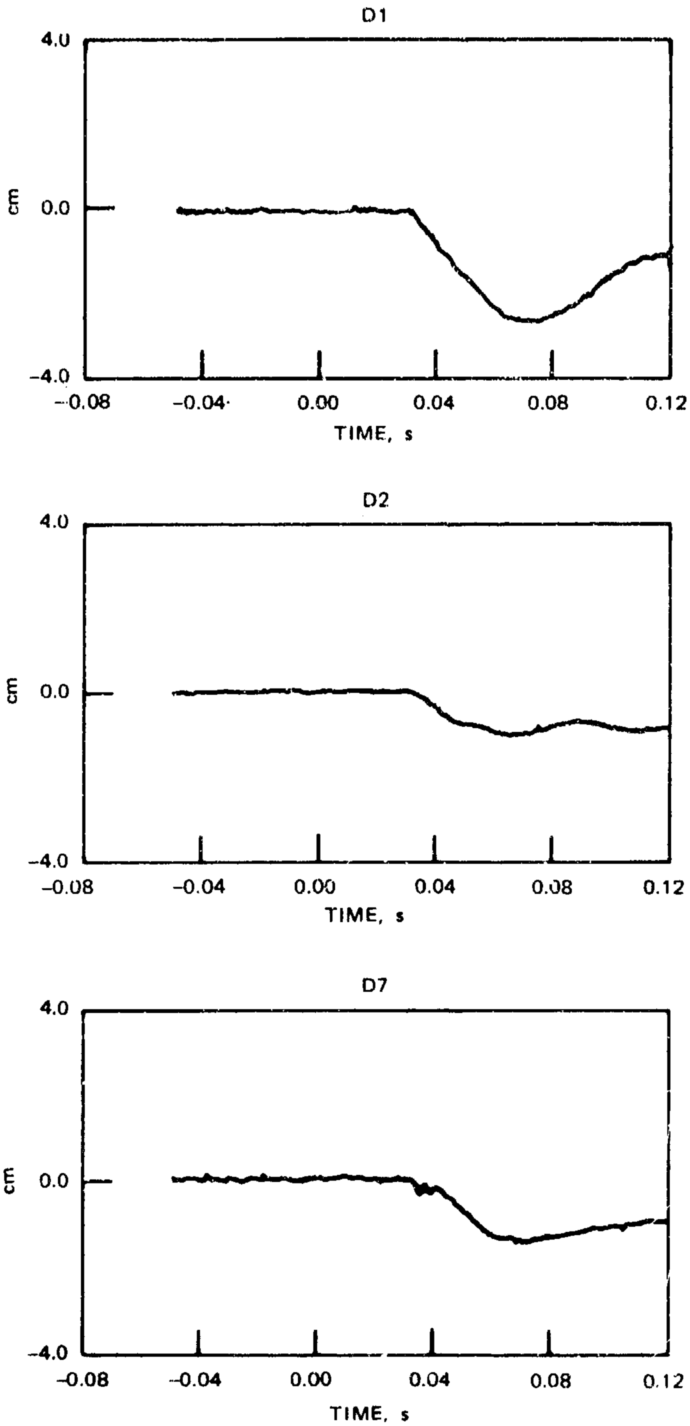


FIGURE 51. Data Plots for Deflection Gauges D1, D2, and D7, Igloo A.

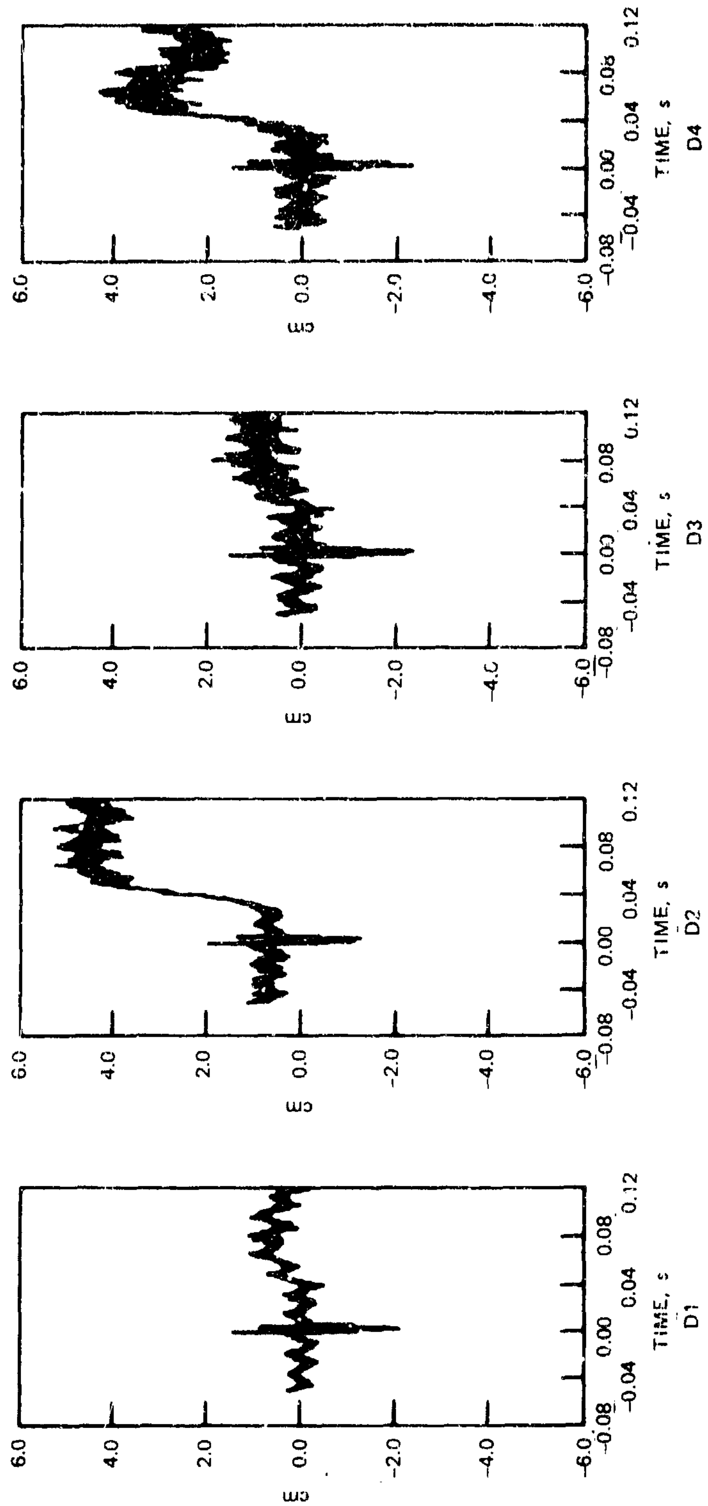


FIGURE 52. Data Plots for Deflection Gauges D1, D2, D3, and D4, Igloo B.

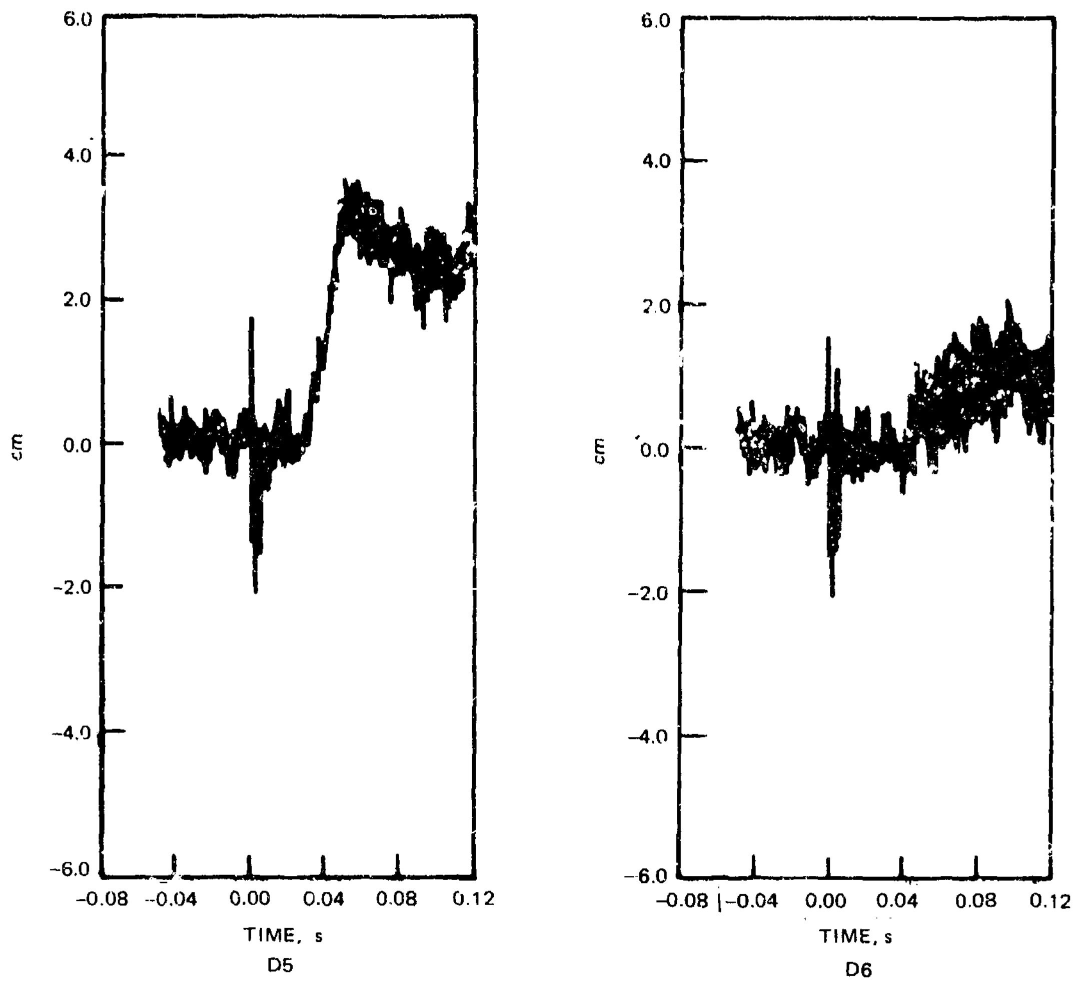


FIGURE 53. Data Plots for Deflection Gauges D5 and D6, Igloo B.

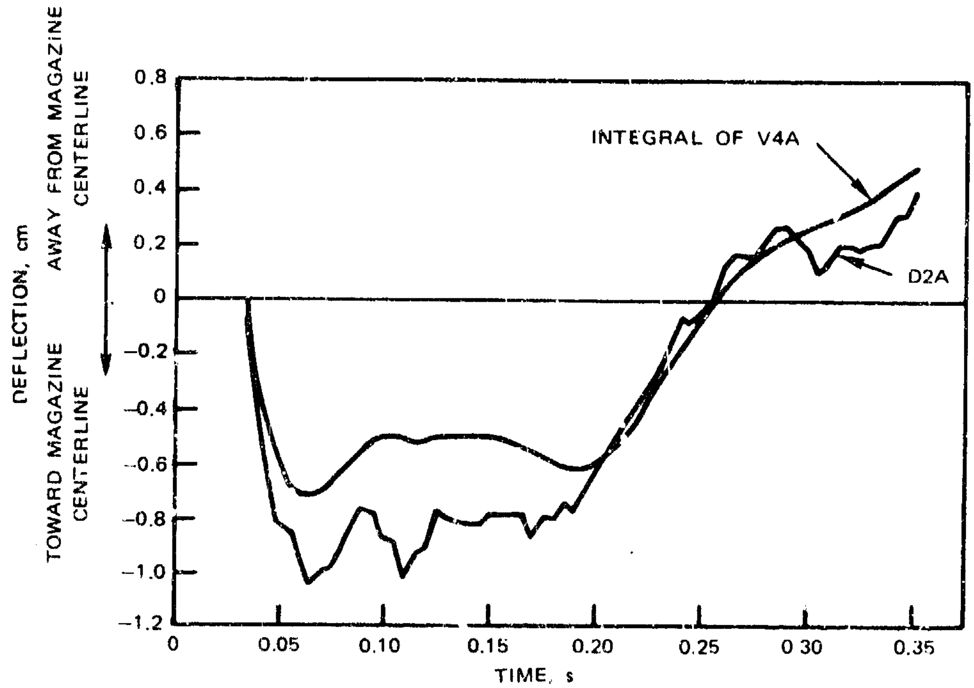


FIGURE 54. Comparison Between Sidewall Deflection Gauge D2 and Integral of Velocity Gauge V4 Located on Donor Side, 40 Feet From Headwall, FRELOC Igloo A.

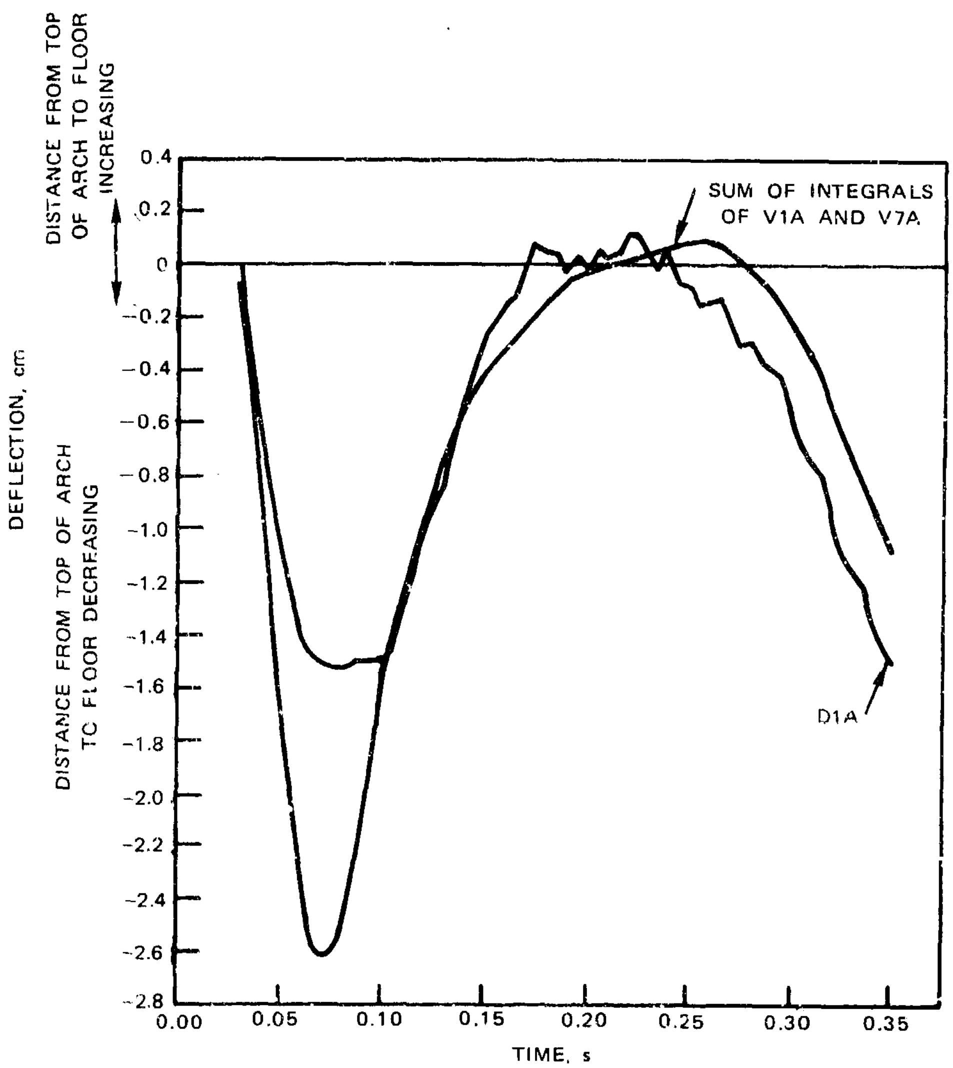


FIGURE 55. Comparison Between Arch/Floor Deflection Gauge D1 and the Sum of the Integrals of Velocity Gauges V1 and V7 Located 40 Feet From Headwall, FRELOC Igloo A.

Appendix A

ANALYTICAL EFFORT IN SUPPORT OF ESKIMO V

by
Robert Odello
Civil Engineering Laboratory
Naval Construction Battalion Center
Port Hueneme, California

Transmitted to NWC in January 1977 as CEL Technical Memorandum M-51-77-2.

INTRODUCTION

This study is an analytical effort in support of ESKIMO V, a high-explosive field test conducted by the Naval Weapons Center (NWC), China Lake, Calif., for the Department of Defense Explosives Safety Board (DDESB). The purpose of the field test is to evaluate the structural response of two earth-covered explosives storage magazines to side-on blast loading. The magazines are a corrugated steel-arch type and a reinforced concrete-arch type. This report documents the analysis of the concrete-arch magazine.

The arch that was analyzed has a nominal span of 26 feet (8.0 meters) and a rise of 14.7 feet (4.5 meters) above the interior floor, which is at the same elevation as the exterior ground surface. The sidewalls are straight and vertical to an elevation of 8 feet (2.4 meters) above the floor. Figure A-1 shows a cross-section of the arch. Further geometric and reinforcing details can be obtained from U.S. Army Engineer Division, Europe, Drawing 33-03-30, Sheet A-11, Sheet 14 of 28, copies of which are available at NWC. The arch is covered with 2 feet (0.6 meter) of compacted soil over the crown. A horizontal soil layer out to the vertical sides of the arch tapers downward at a slope of 2:1 until it intersects the original ground level.

The blast loading on the arch is expected to simulate the loads on Igloo A and Igloo B in the ESKIMO III test (Reference 1). The explosive charge was chosen to be a bare charge that would simulate the actual igloo detonated in the previous test. Due to their complexity, structural response calculations were based on an average overpressure wave shape from Reference 1.

This study provides recommendations for active and passive measurements on the test structure. The final product consists of recommendations for gauge types, and positions and ranges. The authors also present their recommendations for the relative importance of each measurement.

ANALYSIS

The analytical efforts were divided into two separate areas: ground shock and structural response. Each analysis and its associated results are discussed in the following sections.

GROUND SHOCK

The ground shock analysis was based on the prediction methods described in Reference 2. Equations for air-blast induced ground shock were based on one-dimensional wave propagation theory, and equations for direct induced ground shock were based on empirical data.

Several assumptions were made in arriving at the ground shock predictions. The explosive was assumed to be a hemispherical unconfined surface charge. Air-blast parameters were obtained from Reference 3. Scaled ranges for the given charge weight were selected on the basis of maintaining the approximate air-blast impulse as measured on ESKIMO III structures: 650 psi-msec (4500 kPa·msec). The ground medium was assumed to be dry soil with a density of 121 lb/ft^3 (1940 kg/m^3) and a compression wave speed of 2,700 ft/s (820 m/s). The resulting ground shock peak values are given in Table A-1.

Table A-1 data are for near-surface ground motions in undisturbed soil equidistant from ground zero as the igloo. Within the accuracy range of the prediction equations, these data represent the expected values of ground shock that the igloo will experience. The data on which the equations were based have scatter bands of approximately a factor of five for accelerations, two for velocities, and three for displacements. The estimates are of sufficient accuracy for selecting gauge and calibration ranges.

FINITE ELEMENT ANALYSIS

The reinforced concrete-arch magazine shown in Figure A-1 was modeled using the finite-element code NONSAP (Reference 4). A plane-strain, linear elastic analysis was performed to assist in determining critical locations and magnitudes of structural response.

The model is shown in Figure A-2. It is composed of four-node, quadrilateral, plane-strain elements. Since the overpressure propagates perpendicular to the magazine axis, the model represents a section that is far enough from the end walls to be modeled with a plane-strain idealization. Note that all cross-sections of the igloo shown in this report are drawn with the blast wave approaching from the left. The soil overburden is treated as a linear elastic material. The reinforced concrete arch is represented by linear elastic-equivalent beam elements. Bending stiffness for the beam elements was based on the average of the cracked and uncracked transformed areas.

The incident traveling overpressure wave (Figure A-3) was an idealization of the average measured wave forms on Igloos A and B in Reference 1. The wave travels across the structure at approximately the same speed as the measured overpressure pulse in the previous tests. Thus, the loading function is a realistic approximation of actual test conditions.

Dynamic response over a 50-millisecond range was obtained using an unconditionally stable numerical integration scheme, the Wilson θ method. A solution step size of 0.1 millisecond for 500 steps was used.

The model's dynamic response to the traveling overpressure wave predicts peak structural response as indicated in Figures A-4 and A-5. Figure A-4 shows the exaggerated deflected shape of the arch at the time of maximum vertical deformation at the crown. Figure A-5 shows the bending moments at the same time.

The data presented in these figures are more of qualitative value and should not be looked on in a rigid quantitative sense. For example, the spikes in Figure A-5 should be "smoothed" to yield a more realistic moment curve. The moment spikes are created by the coarseness of the finite element mesh, in that a tangent mismatch exists at adjacent beam elements in the arch.

The general shapes of the deflection and moment diagrams may be assumed to be reasonable and useful in determining the placement of test instrumentation. It was also assumed reasonable to consider model structural response to be conservative, thereby aiding in selecting gauge ranging. Any more reliance upon this linear elastic analysis would be untenable. Additionally, more sophisticated modeling is beyond the scope of the present effort.

From the qualified findings of the model dynamic response and the ground shock analysis, predictions of response ranges were made. Critical points of interest on structural survivability were also determined.

RECOMMENDATIONS

MEASUREMENT OBJECTIVES

The primary objective for the recommended measurements is to obtain data to determine if the concrete-arch igloo can survive the blast effects of an accidental explosion in an adjacent igloo. The primary criterion for survivability is that sensitive explosives stored within the igloo would not detonate. Conceivably, detonation of the contents could result if catastrophic structural failure of extremely large deflections occur. Severe ground shock might also cause such a detonation.

A second objective of the measurements is to determine the structural response of the igloo. If the structure survives, the data will indicate the degree of conservatism. Conversely, if the structure does not survive, the data will help in determining how and why it failed. In either case, structural response measurements will contribute to design improvements.

A third objective is to provide data that can be compared with analytical results. The ultimate goal is to develop sufficient confidence in analytical tecnniques so that costly test programs can be minimized. ESKIMO V test data are not expected to correlate quantitatively with the analysis presented in this report, because numerous simplifying assumptions were made to minimize the time and cost of the analysis. However, if sufficient structural response measurements are made on this and other tests, data will be available for comparison with more detailed analyses which could include nonlinear and three-dimensional effects.

TRANSDUCERS

Several different types of electronic transducers are recommended for this test: strain gauges, velocity gauges, accelerometers, deflection gauges, and soil-stress gauges. Each type is discussed briefly.

Strain gauges are of the standard resistance-wire or foil-gauges type. All strain gauges should be bonded to the reinforcing bars and protected according to manufacturer recommendations. Each gauge location should consist of two gauges in series, one on each side of the reinforcing bar (e.g., position 1S6 of Figure A-6 consists of two strain gauges). This will compensate for localized bending in the bar.

Velocity gauges are of the pendulum type normally used in ground shock tests. The gauges consist of a pendulum suspended in a viscous fluid which creates an overdamped system so the displacement of the pendulum is proportional to the velocity. The vertical velocity gauge includes a spring which compensates for gravitational effects on the pendulum.

Accelerometers should be of the damped strain gauge type and have a maximum range of 100 *g* with a frequency response up to 1,000 hertz.

Deflection gauges may be linear-motion potentiometers or linear variable differential transformers. The instruments should be mounted on relatively rigid frames to minimize effects of lateral motion and relative displacement in the frame. Mounting designs should also be able to accommodate limited cross-axis motion. Calibrated proximity sensors might prove useful for displacement measurements since they do not require a structural link between moving and reference surfaces. Manufacturer data indicate the devices would perform well in the test environment.

Soil stress gauges are of the type developed by the U.S. Army Corps of Engineers Waterways Experiment Station. The low range S-E gauge would be most appropriate for this application. The gauges are available through GSA.

GAUGE LOCATIONS

It is recommended that most active electronic instrumentation be located at one cross-section of the arch which is equidistant from the headwall and the end wall of the igloo. Additional locations near the headwall and halfway between the headwall and center are also suggested for limited gauging. Transducer locations and orientations are located as shown in Figure A-6. Table A-2 lists the recommended gauges, expected peak values, and priorities. The gauges are placed in priority groups with Priority 1 as the most important, and priorities also assigned within each group. A brief explanation of each measurement or groups of measurements follows.

The strain gauges on the reinforcing bars are the most important. They are placed at locations that the analysis indicates as experiencing the greatest bending moments and thrust in arch sections. Gauges S3 through S8 are placed in Priority 1, because they are at the most highly stressed sections.

Measurements of the crown deflection is relatively important because it is the expected point of maximum deflection. Horizontal deflection of the sidewall is also of value in evaluating structural performance, but is of lesser importance.

Velocity measurements provide data on structural motion, but more importantly, the data can be integrated to provide additional displacement and distortion data. Gauges V1 and V4 provide checks on gauges D1 and D2. Subtracting integrated data of V1 and V7 would provide a better check on D1. Gauges V3 through V6 provide information which defines relative motion between the arch and the interior slab.

Accelerometers are intended to provide data on shock experienced by the structure. These data would be useful for designing attachments to the interior of the igloo and would permit definition of the average response spectrum for the structure.

Data from the soil-stress gauges are expected to be valuable in understanding the manner in which loads are transmitted to the structure by the earth berm. The data could be compared with results of computer analyses to guide design modifications.

It is also recommended that several mechanical, passive, or photographic measurements be made in addition to the electronic transducer measurements. Scratch gauges or rotating drum gauges could provide additional relative displacement data. The former uses a scribe attached to one portion of the structure for tracing the relative displacement pattern on a plate attached to an adjacent portion. This device describes the displacement signature in two dimensions, but it does not give a time history. The rotating drum gauge uses a scribe to trace a displacement pattern on a rotating drum which is turned by a battery powered motor. This gauge provides a time history, but only gives displacements in one dimension.

CONCLUDING REMARKS

The results presented in this report are best estimates of the ground shock and structural response of the concrete-arch igloo which is to be tested in ESKIMO V. Recommendations for gauge locations and expected values were the result of both analytical efforts and engineering judgment. Implementation of these recommendations is expected to provide adequate data for a thorough post-shot evaluation of the igloos' behavior under blast loading.

Civil Engineering Laboratory, January 1977

TABLE A-1. Estimates for Near-Surface Ground Motions.

Charge size	34 000 kg (75,000 lb)
Scaled range	2.3 m/kg$^{1/3}$ (5.9 ft/lb$^{1/3}$)
Air-blast arrival	70 ms
Ground shock arrival	93 ms
Vertical air-blast ground shock	
Acceleration	16 *g*
Velocity	0.13 m/s (5.0 in/s)
Displacement	3.0 mm (0.12 in.)
Vertical direct induced ground shock	
Acceleration	6.8 *g*
Velocity	0.27 m/s (10.5 in/s)
Displacement	20 mm (0.8 in.)
Horizontal air-blast ground shock	
Acceleration	16 *g*
Velocity	9.13 m/s (5.0 in/s)
Displacement	3.0 mm (0.12 in.)
Horizontal direct induced ground shock	
Acceleration	3.4 *g*
Velocity	0.27 m/s (10.5 in/s)
Displacement	20 mm (0.8 in.)

TABLE A-2. Gauge Recommendations for 34 000-kg (75,000-lb) Charge.

Gauge[a]	Measurement	Expected peak	Priority	Actual performance in ESKIMO V
1S6	Strain	1,500 μ-strain tension	1	Functioned
1S5	Strain	150 μ-strain compression	1	Functioned
1S7	Strain	850 μ-strain tension	1	Functioned
1S8	Strain	450 μ-strain compression	1	Functioned
1S3	Strain	850 μ-strain tension	1	Failed
1S4	Strain	450 μ-strain compression	1	Failed
D1	Crown deflection	25 mm (1.0 in.)	2[b]	Functioned
V1	Vertical velocity	0.5 m/s (21 in/s)	2	Functioned
V4	Horizontal velocity	0.28 m/s (11 in/s)	2	Functioned
A1	Vertical acceleration	32 *g*	2	Failed
2S6	Strain	1,500 μ-strain tension	3	Failed
2S5	Strain	150 μ-strain compression	3	Failed
3S6	Strain	1,500 μ-strain tension	3	Functioned
3S5	Strain	150 μ-strain compression	3	Failed
D2	Lateral deflection	13 mm (0.5 in)	3	Functioned
V7	Vertical velocity	0.28 m/s (11 in/s)	3	Functioned
V2	Horizontal velocity	0.28 m/s (11 in/s)	3	Failed
1S9	Strain	270 μ-strain compression	4	Functioned
1S10	Strain	780 μ-strain tension	4	Functioned
1S1	Strain	190 μ-strain compression	4	Functioned
1S2	Strain	320 μ-strain tension	4	Functioned
A3	Vertical acceleration	32 *g*	4	Failed
A2	Horizontal acceleration	32 *g*	4	Failed
SS2	Soil stress	345 kPa (50 psi)	4	Functioned
SS3	Soil stress	345 kPa (50 psi)	4	Functioned
V3	Vertical velocity	0.28 m/s (11 in/s)	4	Functioned
V5	Vertical velocity	0.28 m/s (11 in/s)	5	Functioned
V6	Horizontal velocity	0.28 m/s (11 in/s)	5	Functioned
SS1	Soil stress	210 kPa (30 psi)	5[c]	Functioned
SS4	Soil stress	210 kPa (30 psi)	5[c]	Functioned
A4	Vertical acceleration	11 *g*	5	Failed

[a] Prefix on strain gauges is as follows:
1 = Midlength cross section
2 = Halfway between midsection and headwall
3 = Near face of headwall

[b] Measured composite of floor and roof motion.

[c] Relocated in proximity to SS2.

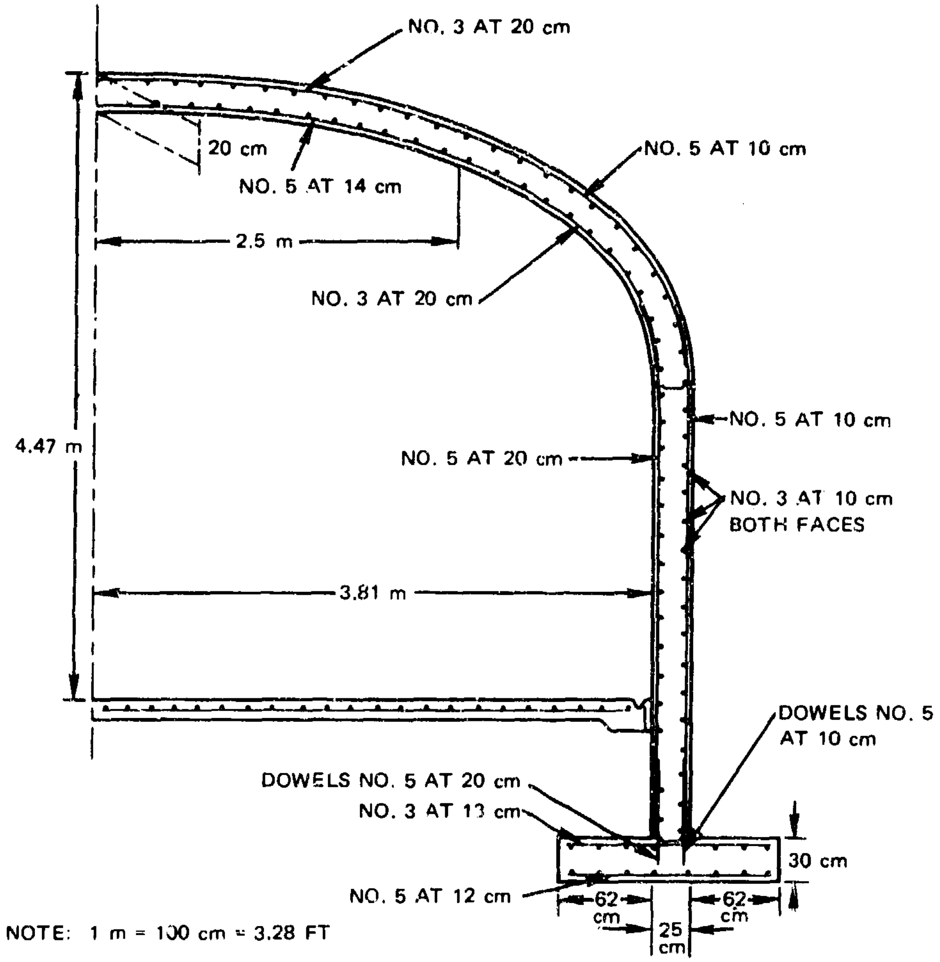


FIGURE A-1. Half-Section of Test Structure.

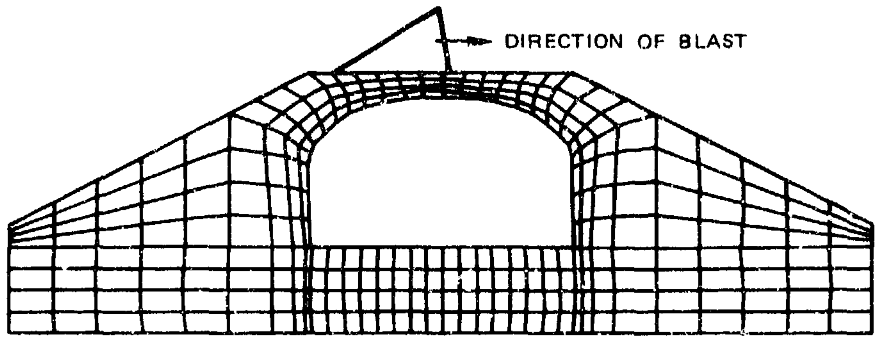


FIGURE A-2. Finite Element Model of Structure and Earth Mound.

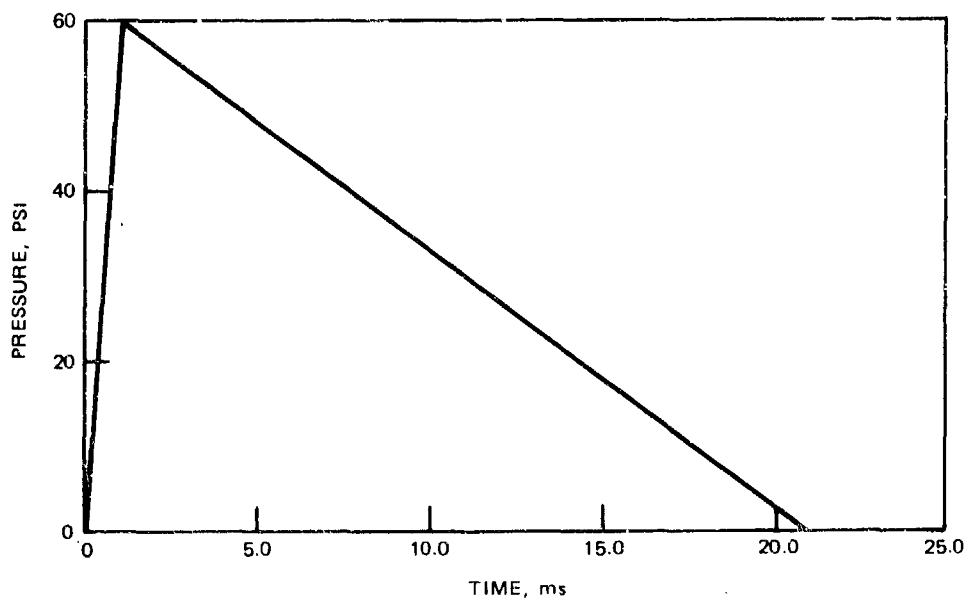


FIGURE A-3. Idealized Incident Wave.

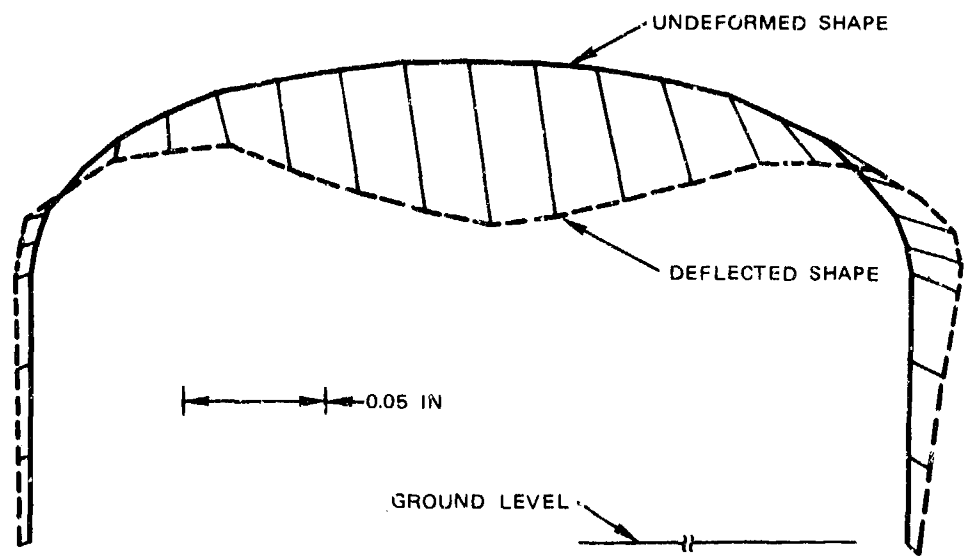


FIGURE A-4. Deflected Slope of Igloo.

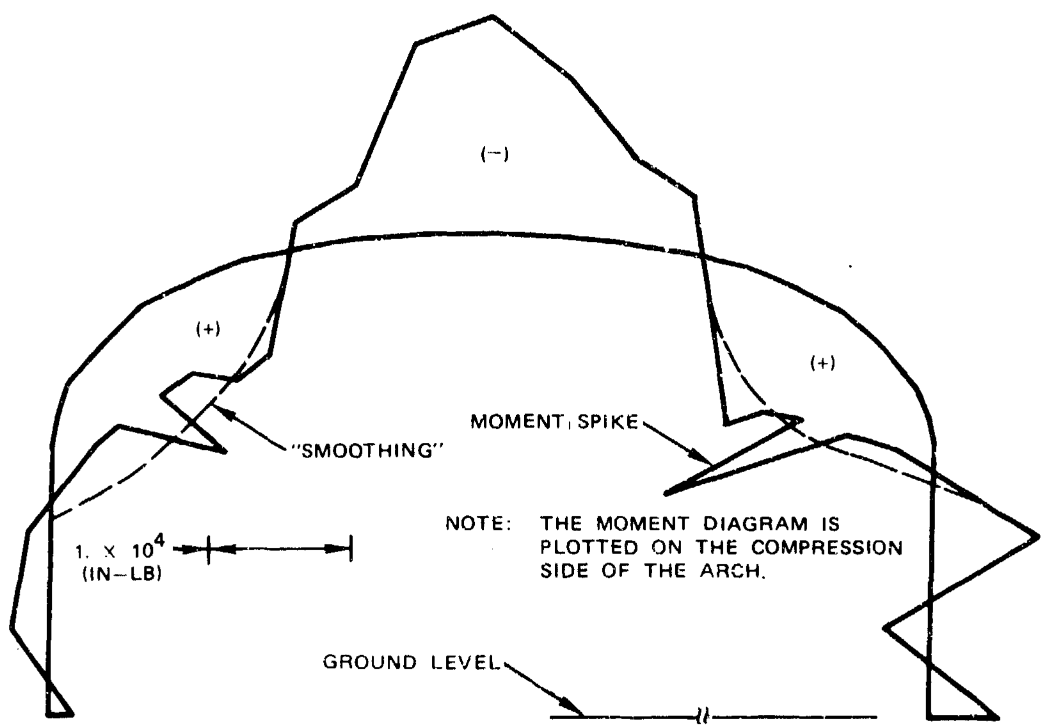


FIGURE A-5. Moment Diagram of Maximum Response

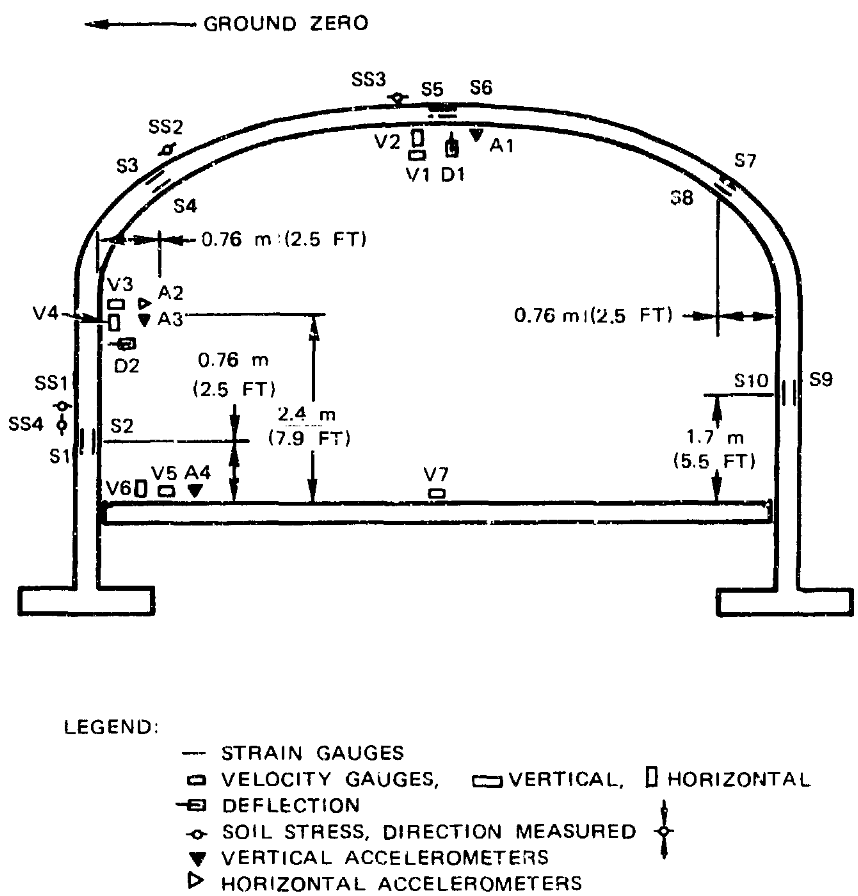


FIGURE A-6. Gauge Locations.

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