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MEMORANDUM REPORT NO. 2599

# COMPUTATIONAL PREDICTIONS OF SHOCK DIFFRACTION LOADING ON AN S-280 ELECTRICAL EQUIPMENT SHELTER

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March 1976



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USA BALLISTIC RESEARCH LABORATORIES
ABERDEEN PROVING GROUND, MARYLAND

# REPORT DOCUMENTATION PAGE

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) ljc

The Los Alamos Scientific Laboratory, under contract to the BRL, utilized a three-dimensional, transient, hydrodynamics computer program, BAAL, developed at LASL, to compute the diffraction loading versus time caused by a one-dimensional 34.475 kPa (5.0 psi) overpressure steady shock wave striking an S-280 Electrical Equipment Shelter. The results of this computation have been placed on a magnetic tape at the BRL. Copies of this tape are available on request. The tape includes an alphanumeric introduction describing the data on the tape and overpressure - time histories for each computational flow

(Item 20 Continued)

field cell that has a coincident face with either the shelter front, top, back, or side face. Also included on the tape is the time history of the resultant force due to overpressure and its effective point of application for each face. Although there are no direct experimental data available for comparison, the pressure - time histories generated appear to be quite good, with the possible exceptions of apparent pressure anomalies at the shelter edges where the flow undergoes a rapid 90 degree expansion, and the late - time pressures computed.

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# 1. INTRODUCTION

The established methods[1] for estimating shock wave diffraction loading on simple structures do not differentiate between two- and three-dimensional geometries. A shock tube study performed at the BRL by Taylor[2] has indicated that significant differences exist in the shock wave diffraction loading - time histories for such structures.

Subsequent to Taylor's shock tube study was the completion of a study at the Los Alamos Scientific Laboratory involving the development by Pracht[3] of a three-dimensional, transient, viscous flow hydrodynamics computer program, BAAL, originally designed to calculate the late-time effects of atmospheric nuclear explosions. The program was modified to permit the inclusion of obstacles, allowing the computation of obstacle surface pressure - time histories for blast loading studies. To explore the possibility of using this hydrocode to determine diffraction loading on simple structures, the Ballistic Research Laboratories contracted with the Los Alamos Scientific Laboratory to perform a test calculation which could be compared with experimental data. Gentry et al[4] simulated one of Taylor's[2] three-dimensional shock tube experiments with a BAAL computer run. This experiment involved a one-dimensional, steady shock wave, of 34.475 kPa (5.0 psi) overpressure, striking a three-dimensional rectangular parallelepiped .2127 m wide, .1062 m high, and .0762 m deep, with the shock traveling in the direction of measure of the depth. Ambient conditions prior to shock arrival were a temperature of 288.16 Kelvin (15C), a pressure of 101.325 kPa (14.696 psi), and no flow. Since the BAAL computation was to be compared to the shock tube measurements, steady flow was specified behind the shock wave.

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[1] *"Design of Structures to Resist the Effects of Atomic Weapons," U.S. Army Corps of Engineers, EM 1110-345-413 (1 July 1959).*

[2] *Taylor, W. J., "A Method for Predicting Blast Loads During the Diffraction Phase," The Shock and Vibration Bulletin, NR.42. Part 4 of 5, Shock and Vibration Center, Naval Research Laboratory, Washington, D. C., p. 135 (January 1972).*

[3] *Pracht, W. E., "Calculating Three-Dimensional Fluid Flows at All Speeds with an Eulerian-Lagrangian Computing Mesh," LA-UR-74-1137, University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico (July 1974).*

[4] *Gentry, R. A., Stein, L. R., and Hirt, C. W., "Three Dimensional Computer Analysis of Shock Loads on a Simple Structure," BRL CR 219, U.S. Army Ballistic Research Laboratories, Aberdeen Proving Ground, MD (March 1975). AD# B003208L.*

The BAAL computer code has the general capability of solving the following system of differential equations in their integral form.

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_j}{\partial x_j} = 0 \ , \qquad (1)$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho u_i u_j - p_{ij}\right) = g_i \rho^{*} \ , \qquad (2)$$

where

$$p_{ij} = - p\delta_{ij} + \tfrac{1}{2} \lambda e_{kk} \delta_{ij} + \mu e_{ij} \ , \qquad (3)$$

$$e_{ij} = \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \ , \qquad (4)$$

and

$$\frac{\partial \rho E}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho u_j E - p_{ij} u_i - \mu B \frac{\partial I}{\partial x_j}\right) = \rho u_j g_j \ , \qquad (5)$$

where

$$E = \tfrac{1}{2} u_i^2 + I \ . \qquad (6)$$

The stress tensor is represented by $p_{ij}$, wherein p is the scalar pressure, and $\lambda$ and $\mu$ are the viscosity coefficients. The term $g_i$ represents the gravitational acceleration, which is neglected here; E is the specific total energy; I is the specific internal energy; $\delta_{ij}$ is the Kronecker delta. The heat conduction term in the energy equation is written as a spatial gradient in I, multiplied by viscosity $\mu$ and an input coefficient B.

The BAAL computations for the shock tube model calculation, and for the S-280 Electrical Equipment Shelter calculation reported here, were made using the above set of differential equations in their integral form, with one major modification. The Navier-Stokes equations, Eqs (2), (3),

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* *For the calculations reported here, the Navier-Stokes equations have been replaced by the inviscid Euler equations, with the added feature of an artificial viscosity being introducted whenever the flow undergoes a deceleration.*

and (4), have been replaced by the inviscid Euler equations, with an artificial viscosity significantly larger than real viscosity being introduced for purposes of numerical stability in regions of high deceleration. The artificial viscosity computed under this criterion is manifested as a simple addition to the scalar pressure. No shearing stresses are calculated. Free slip flow is specified at all boundaries.

These simplifications to the Navier-Stokes equations were deemed expedient because of the large cell sizes dictated by practical computer time and storage limitations. The active computational flow field grid for the shelter calculation consists of 6750 cells, not counting boundary cells, but including those cells occupied by the ½ width shelter. The cells were of varying sizes, with the smallest cell dimension at the shelter boundary being approximately 0.14 m. This smallest cell dimension is estimated to be several times larger than any boundary layer that could develop on the shelter during the shock diffraction phase. The use of the Navier-Stokes equations with a no-slip boundary condition would have resulted in unrealistically large computed boundary layers. A similar situation exists for the shock tube model calculation.

Both computations involved a relatively weak 34.475 kPa (5.0 psi) overpressure shock wave in air. Hence, the polytropic equation of state

$$p = \rho I \ (\gamma - 1) \tag{7}$$

with

$$\gamma = 1.4$$

was used to calculate the scalar pressure.

Comparisons between the computed and experimentally measured pressure - time histories at three points each on the front and back faces of the model are made in Reference 4. Agreement is excellent for all three points on the front face of the model. The theoretical peak reflected overpressure is 78.54 kPa (11.39 psi). The peak experimentally measured overpressure, averaged over these three points, is 75.8 kPa (11.0 psi), approximately 3% below the theoretical peak overpressure. This excellent agreement of the experimentally measured peak with the theoretical peak implies that the experiment yielded accurate data and is a valid standard against which the calculated values may be compared. Using this experimental standard, the following comparisons may be made.

The peak overpressure calculated using the BAAL computer code is 75.1 kPa (10.9 psi), occurring at approximately 50 μs after the theoretical arrival of the shock wave at the front face, and equal to the experimental overpressure for that time. At 200 μs, the computed average overpressure is 1% higher than the experimentally measured average overpressure, 6% lower at 400 μs, 3% higher at 600 μs, and 3% higher at 800 μs.

Agreement between the experimentally measured average overpressure and the calculated average overpressure for the three points on the back face is good, but not as good as that for the front face. For purposes of this comparison, zero time is defined as that time at which the theoretical shock wave reaches the plane of the back surface of the shelter. The computed average overpressure for the three points on the back surface is 21% lower than the experimentally measured overpressure at 100 μs after this redefined reference time, 6% lower at 200 μs, equal at 300 μs, 15% higher at 400 μs, 4% higher at 500 μs, and 6% higher at 600 μs. Shortly thereafter, it was determined that reflected signals were returning from the mesh boundaries, causing spurious pressure rises, and the computation was stopped. There were no experimental measurements made on the top or side faces.

## II. S-280 ELECTRICAL EQUIPMENT SHELTER CALCULATION

The agreement between Taylor's[2] shock tube experiment and the BAAL computer simulation led to the running of a second problem with BAAL, also under contract to the BRL. The results of this second computation are reported here. The three-dimensional rectangular parallelepiped for this computation is a full scale S-280 Electrical Equipment Shelter as shown in Figure 1. The shelter dimensions are width X = 3.6200 m, depth Y = 2.1720 m, and height Z = 2.1085 m. The shelter is sitting on the ground with its largest face, defined here as the front face, oriented so that it is normal to the velocity vector of the oncoming one-dimensional shock wave. A one-half width shelter was used in the computation, taking advantage of the existing plane of symmetry. The active computational flow field consisted of 6750 cells, not counting boundary cells but including those cells occupied by the one-half width S-280 shelter. The one-half width S-280 shelter occupies 7 cells in the X direction, 9 cells in the Y direction, and 7 cells in the Z direction. The cells are of variable size. The upstream end of the computing mesh is 6.27 m removed from the front face of the shelter, and the downstream end of the computing mesh is 12.16 m removed from the back face of the shelter. The top of the computing mesh is 6.34 m removed from the top face of the shelter. One side of the computing mesh, the reflective plane, is coincident with the symmetry plane down the depth of the shelter, and the other side of the computing mesh is 6.20 m removed from the side of the shelter. The computation was started with the shock at the front face, as was the computation for the previously discussed shock tube model.

Surface loadings for a whole shelter are reported here. Initial conditions and shock overpressure are the same as for the calculation involving the smaller shock tube model. The shock tube model does not scale directly to the S-280 shelter. As before, steady flow is specified behind the shock, simulating zero decay blast wave conditions for maximum diffraction loading for that shock overpressure. The time required for the shock to travel the depth of the S-280 shelter, hereafter referred to as the shock traversal time, is slightly over $5.6 \times 10^{-3}$s.

The data tape, available from the BRL on request, includes overpressure - time histories for each computational flow field cell that has one of its faces coincident with the front, top, back, or side face of the S-280 shelter. The tape also includes a time-history of the resultant force due to overpressure for each entire face, and the effective point of application for that force. Other flow field data are not presently available. Although the data are presented as if those overpressures were computed directly on the shelter surface, they are actually computed at the respective flow field cell centers, which are displaced from the shelter surface by one half of the cell dimension in the I, J, or K direction. Figures 2a, 2b, and 2c show the S-280 shelter surface grid spacings, and the cell centers at which surface overpressure - time histories are computed and tabulated.

## III. DISCUSSION

The pressure - time histories for the surfaces of the S-280 shelter as calculated by the BAAL program appear to be quite good in general, although there are no direct experimental data available for comparison. There is, however, one apparent anomaly that appears consistently throughout the pressure - time histories of the BAAL computations for both the three-dimensional shock tube model and the S-280 shelter. Around those model or shelter corners where the flow undergoes a 90 degree expansion, the BAAL program computes unexplained, often sharp, pressure increases seen when comparing the overpressure for the next-to-last flow field cell at the model surface to that for the last flow field cell at the surface prior to the corner. Specifically, the affected rows and columns are the top row of cells on the front face, the last column of cells on the front face, the last row of cells on the top face, and the last column of cells on the side face. These pressure increases are on the order of 10 to 30 percent, using the calculated overpressure for the next-to-last cell in any given case as the basis for comparison. Since it can reasonably be expected that in general there should be a further drop in pressure at these corners rather than a rise, the actual overpressure at these corners may be significantly less than the calculated values. Figures 3a through 3h show a sequential pressure - time history for the fourth row of cells up the side face (the cell centers being at approximately 2/3 of the shelter height), a typical illustration of this anomaly. Shock smearing in the relatively large computational flow field cells is also readily evident.

The cause of this pressure increase has not yet been established, nor has a correction factor been established for modifying these corner effects if, as suspected, they are caused by difficulties in the computational algorithm being utilized. The overpressure data available on magnetic tape is stored as it was presented to the BRL by LASL, with no modifications except for a simple change of units. Resultant force due to overpressure and the effective point of application for each entire shelter face were calculated at the BRL using the overpressure data. These were added to the data tape for the user's convenience.

Figure 4a shows the time history of the resultant force due to overpressure on the front face of the shelter, obtained by making a cell area weighted integration of the overpressure on the front face at each point in time,

$$F = \sum_{i=1}^{N} A_i P_i . \tag{8}$$

Here $A_i$ is the cell area, $P_i$ is the overpressure associated with that cell, and N is the number of cells on the front face. Figure 4b shows the Z location of the effective point of application of the resultant force due to overpressure on the front face, obtained by summing cell area weighted moments,

$$Z_{eff} = \frac{\sum_{i=1}^{N} A_i P_i Z_i}{\sum_{i=1}^{N} A_i P_i} . \tag{9}$$

Here $Z_i$ is the measure of length from the ground to the $i^{th}$ cell center, and the other variables are as defined above. It was expected that Figure 4b would show more of a bias of $Z_{eff}$ toward the ground level at an earlier time than is indicated, since the high pressure should persist longer there. This apparent lack of bias may be due to the high pressure anomaly in the top row of cells. Figures 5a and 5b, 6a and 6b, and 7a, 7b, and 7c show similar data for the top, back, and side faces, respectively.

Figure 8a shows the average overpressure - time history for both the front and back faces. The average overpressure for a given face is calculated by

$$P = \frac{\sum_{i=1}^{N} A_i P_i}{\sum_{i=1}^{N} A_i} . \tag{10}$$

The closest approach of the two curves to one another occurs at approximately $1.9 \times 10^{-2}$s (approximately 3.4 shock traversal times) after shock arrival at the front face. At this time the average overpressures are quite close to the incident shock overpressure of 34.475 kPa, with the front face approximately 11% higher and the back face approximately 4% lower. The front face average overpressure then rises with time during the rest of the computation, indicating an over-relieving of the reflected overpressure, occurring around the $1.9 \times 10^{-2}$s mark. This apparent over-relief and subsequent pressure rise has also been observed experimentally.[2] Figure 8b shows the average overpressure for both the top and side faces versus time. These curves are nearly identical up to approximately $6.0 \times 10^{-3}$s, roughly the shock traversal time. At this time, both curves peak at approximately the incident shock overpressure. This is to be expected, as this represents a loading of the top and side faces equal to the incident shock overpressure as the shock travels down the shelter. Thereafter, the average overpressures for the top and side faces oscillate slightly out of phase with one another just below the incident shock overpressure. These oscillations are probably due to transient waves in the computational flow field.

## IV. CONCLUDING REMARKS

Comparison of the overpressure - time histories measured by Taylor[2] with those generated by Gentry et al[4] using the BAAL computer program indicates that the possibility now exists for supplementing experimental data on simple three-dimensional shapes with computational simulations of actual flow conditions, if it is done carefully and with a full understanding of the limitations of the computational program being used. The report by Gentry et al[4] concerning the shock tube model computation indicates excellent agreement between the computed and experimental overpressure - time histories for the front face. The peak reflected overpressure computed on the front face of S-280 shelter is essentially equal to the theoretical peak reflected overpressure. Taken together, these observations imply that the BAAL computation for the front face loading of the S-280 shelter is an accurate simulation of the loading to be expected under actual conditions. As noted earlier, the computed overpressure - time histories of the top and side faces of the S-280 shelter agree well with expectations on theoretical grounds, and thus may also be regarded as accurate. The only obvious discrepancies in the overpressure - time histories for the front, top, and side faces are the pressure anomalies at those corners where the flow undergoes a 90 degree expansion.

As indicated previously in the report by Gentry et al[4], the BAAL computation for the overpressure - time history on the back face of the shock tube model did not agree as well with experiment as did that for the front face of the model, particularly at late time near the edge of the model. This is not surprising. For a target of this general shape with this type of loading, it is to be expected that viscous effects will be most pronounced on the back surface. Because of practical computer time and storage limitations, it was necessary to use a computational grid with relatively large cell sizes. This was also the case for the S-280 shelter computation. For both computations the smallest cell dimensions were significantly larger than any boundary layers that would be generated under actual flow conditions. There was also considerable numerical diffusion of the shock wave in these necessarily large grids. As a consequence, the addition of the viscous terms in the Navier-Stokes equations would add only complexity and additional computational time to the computer solution, but not accuracy. For these reasons, the Navier-Stokes equations were replaced by the inviscid Euler equations, using artificial viscosity for numerical stability. Since the computation for the shock tube model did not simulate viscous effects, it is understandable that the computed pressure - time history for the back face did not agree as well with experiment as did that for the front face. These difficulties are not unique to BAAL, but rather are common to all simulations of high Reynolds number flow.

For the same reasons, it can be expected that the computational predictions for the pressure - time history on the back face of the S-280 shelter will also be found at variance with experimental measurements, once they are made. Nonetheless, the pressure - time histories presented here, as computed using the BAAL computer program, represent the best estimate to date of the shock diffraction loadingon an S-280 Electrical Equipment Shelter.

## V. ACKNOWLEDGEMENTS

Thanks are extended to R. A. Gentry, L. R. Stern, and C. W. Hirt of the Los Alamos Scientific Laboratory for their cooperation in performing these computations for the BRL. The assistance of Mr. John Wortman in generating the data tapes and plots has been most appreciated. Thanks are also extended to Mr. Noel Ethridge for his advice and contributions.

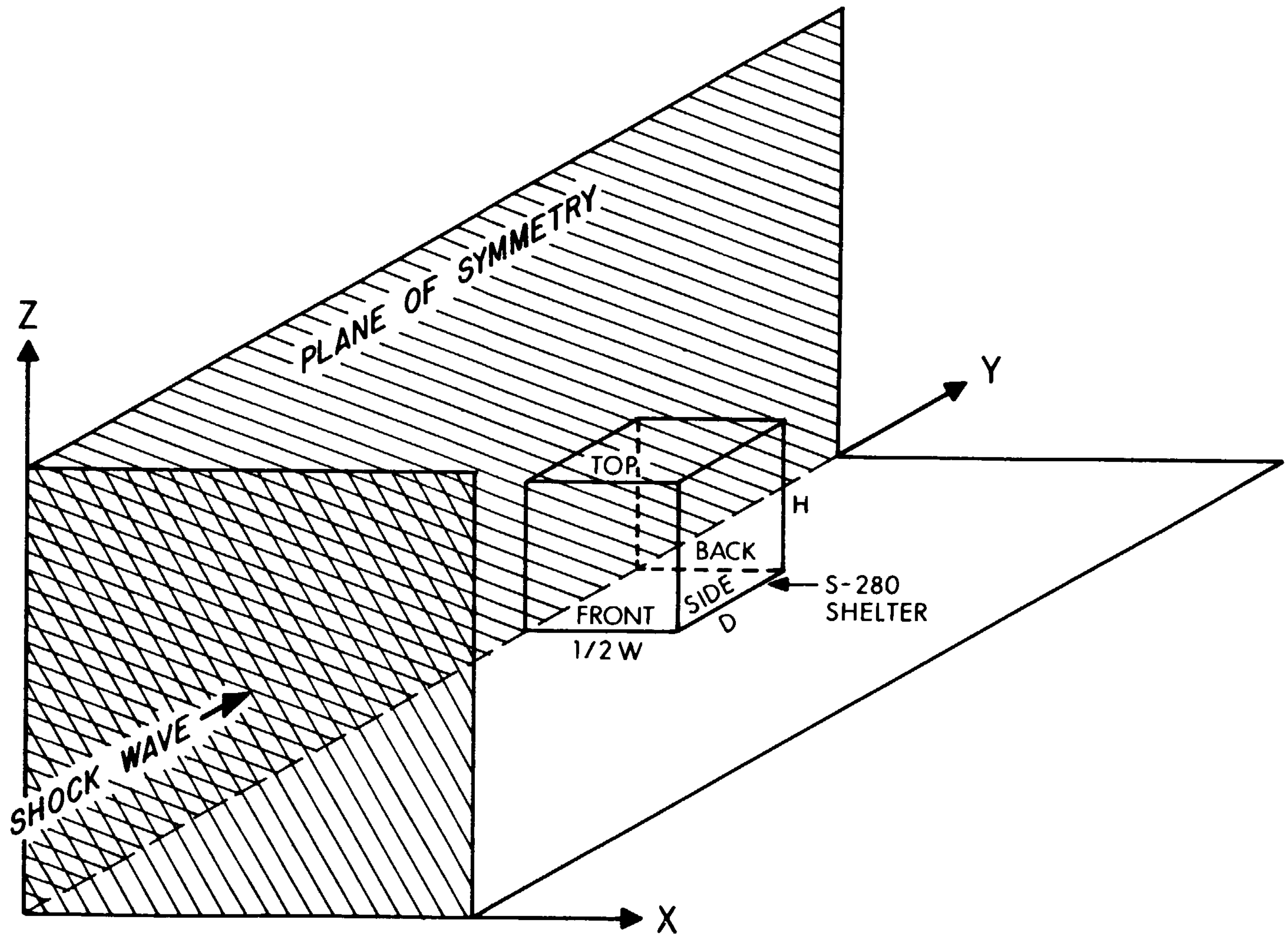


Figure 1. S-280 Electrical Equipment Shelter in the computational flow field.

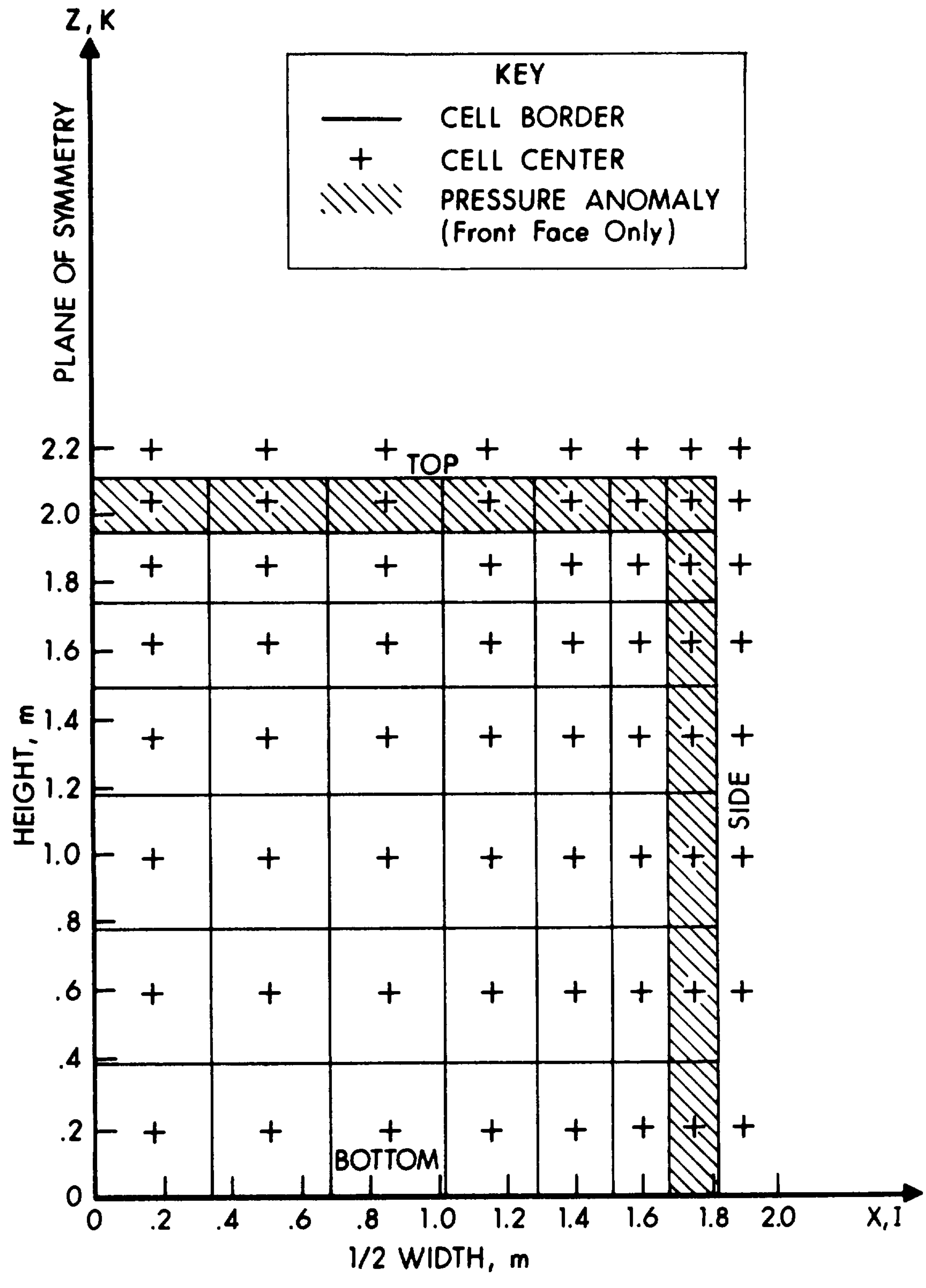


Figure 2a. Computational grid, front face. (Identical back face.)

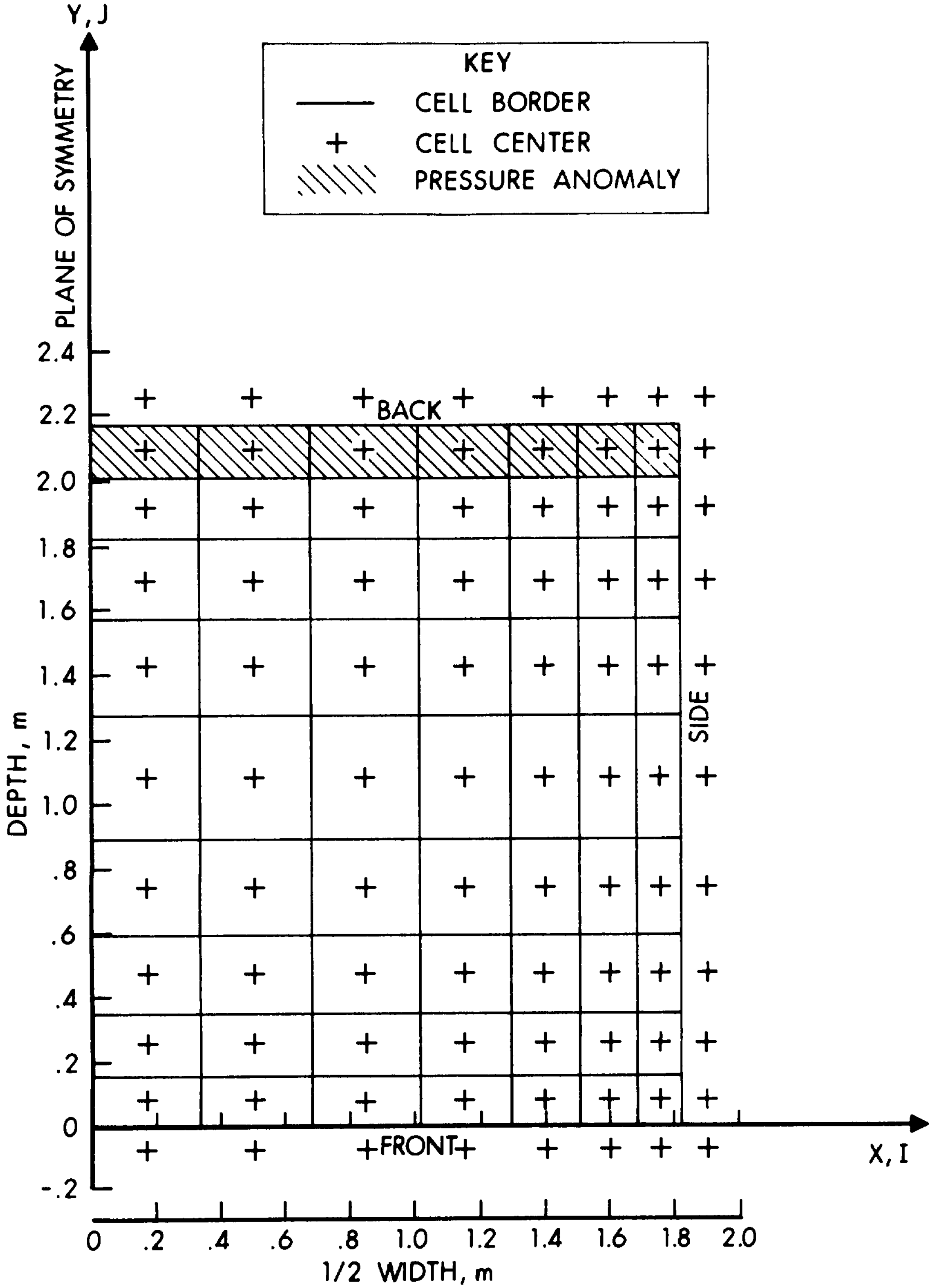


Figure 2b. Computational grid, top face.

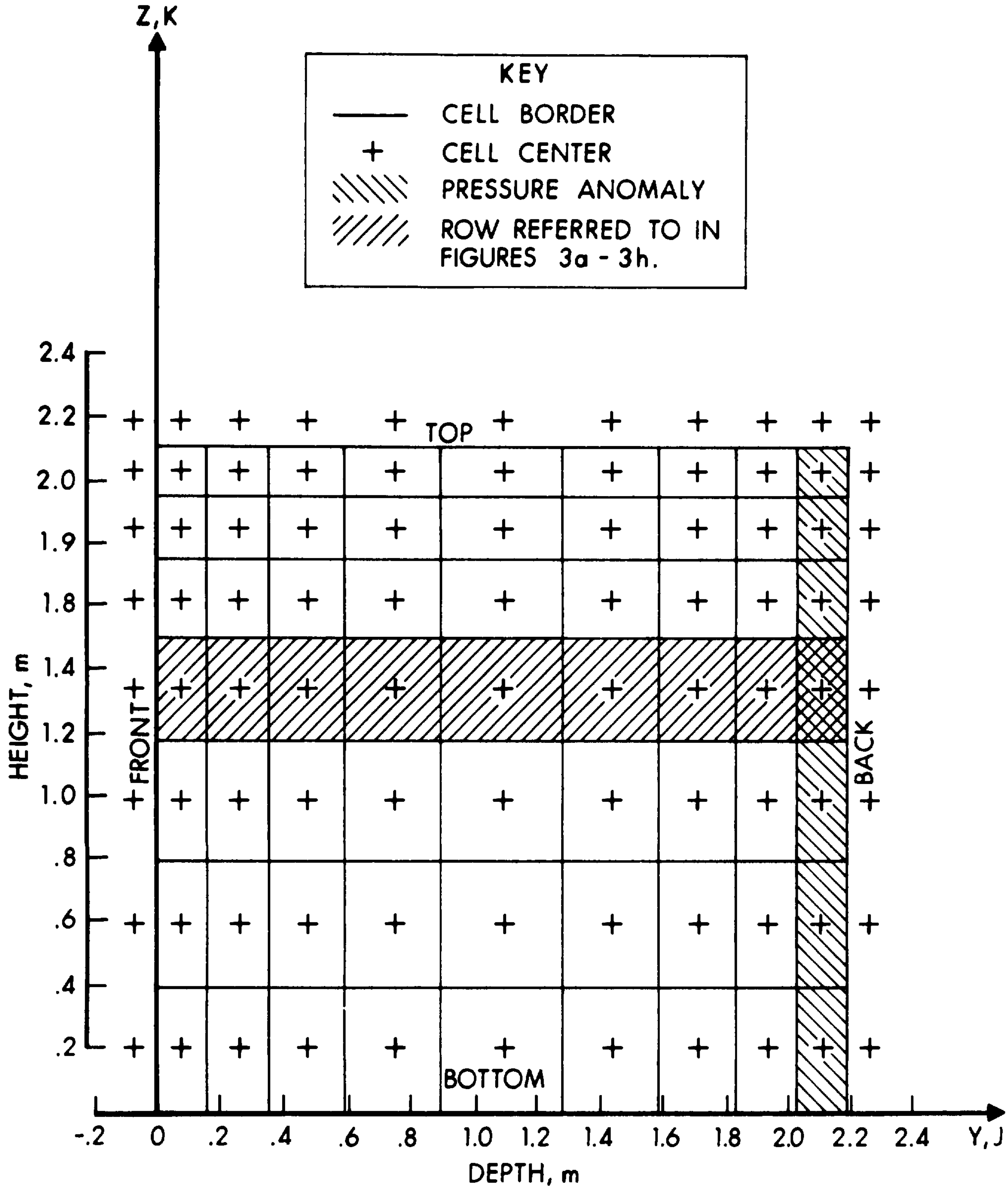


Figure 2c. Computational grid, side face.

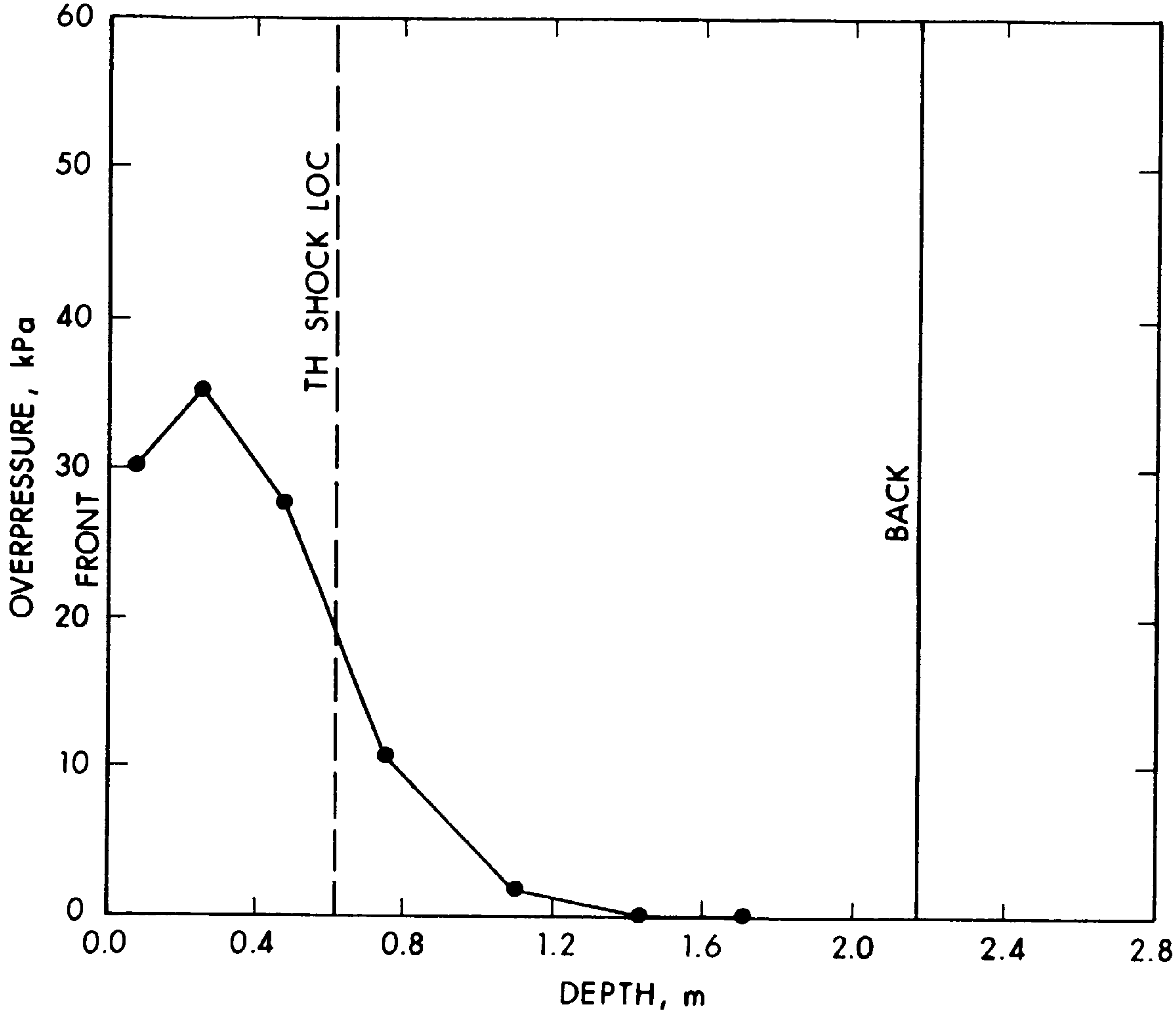


Figure 3a. Overpressure along the fourth row up the side face of the S-280 shelter. Time = 1.57 x $10^{-3}$ s after shock arrival at the front face.

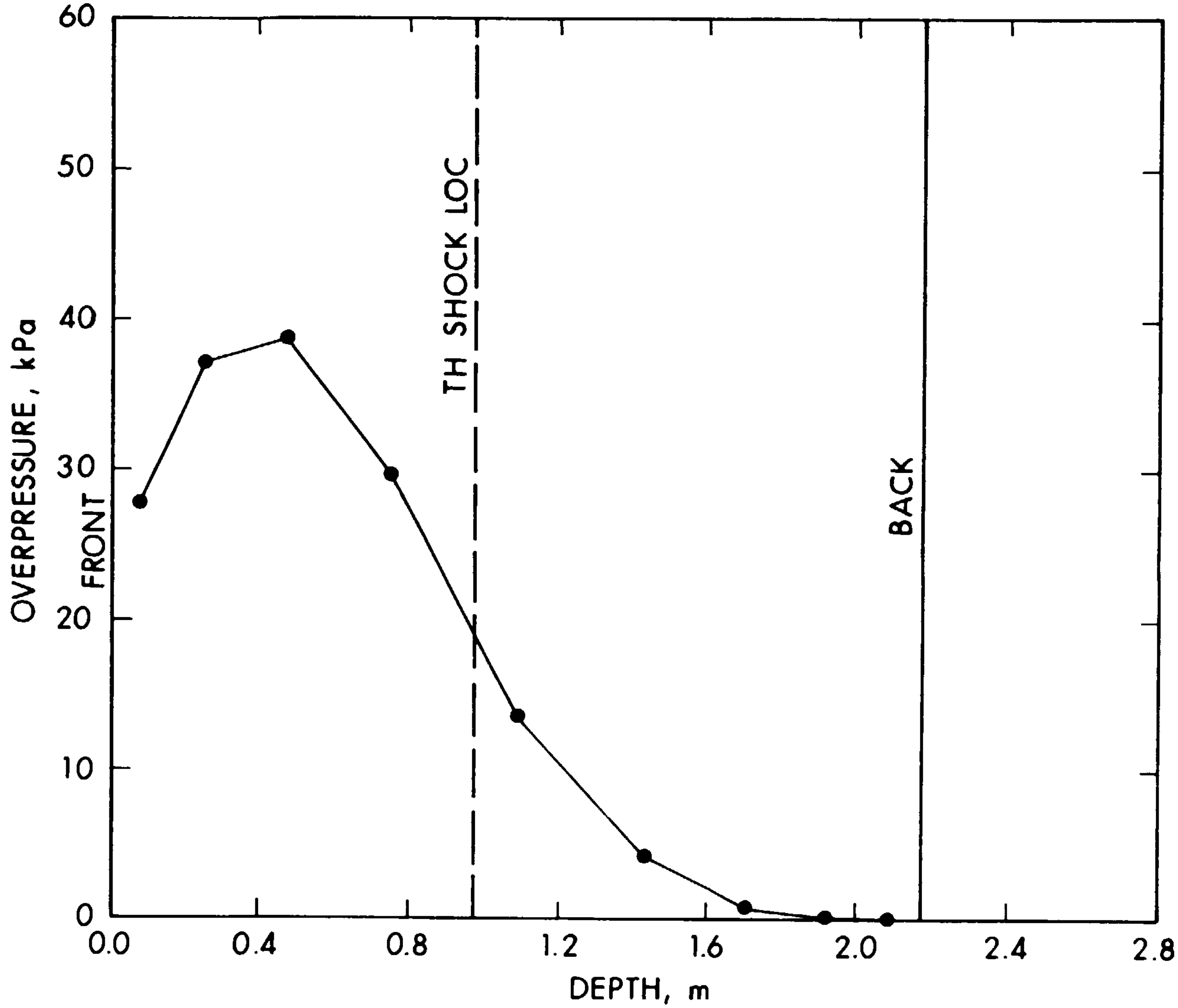


Figure 3b. Overpressure along the fourth row up the side face of the S-280 shelter. Time = $2.51 \times 10^{-3}$ s after shock arrival at the front face.

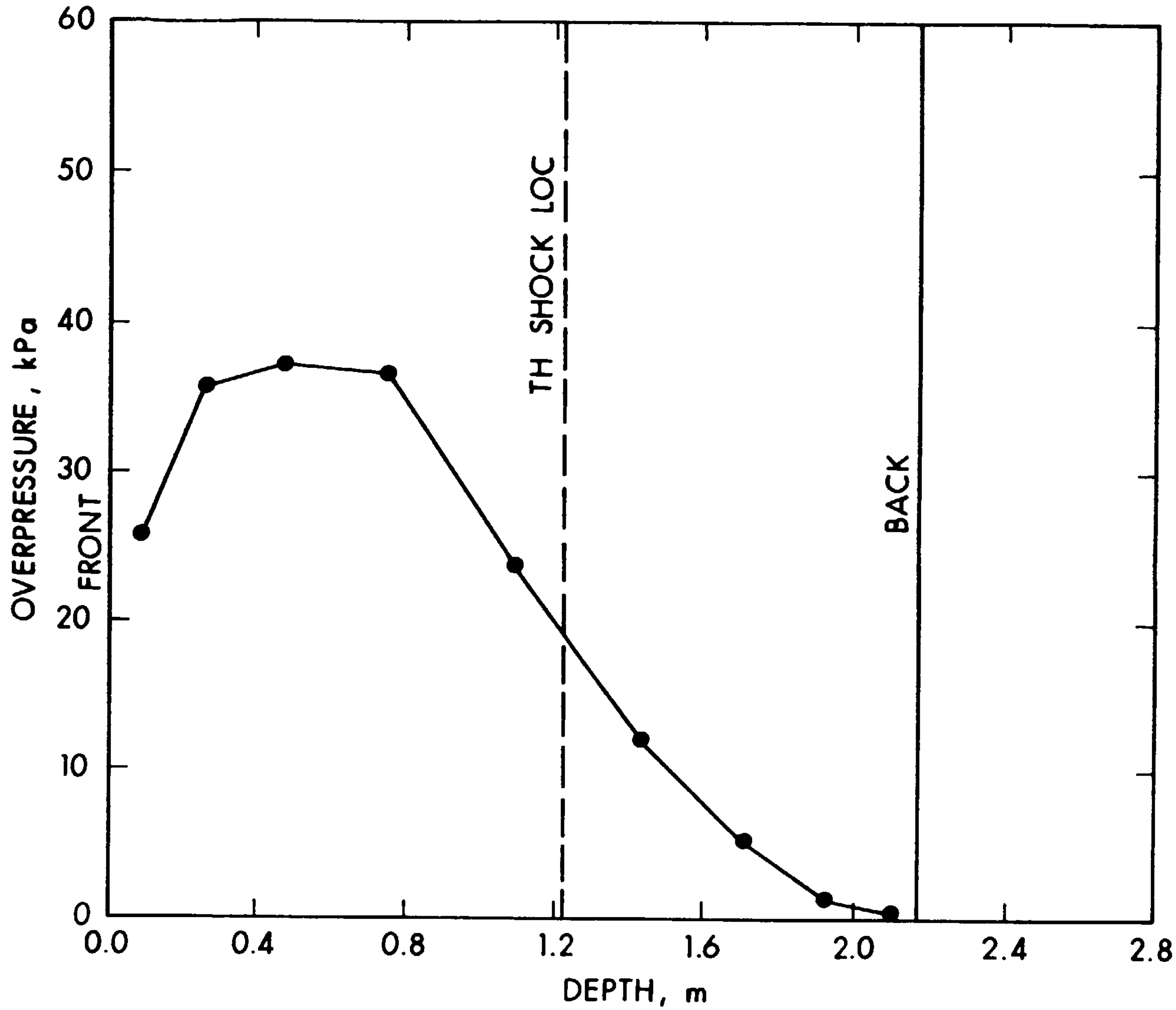


Figure 3c. Overpressure along the fourth row up the side face of the S-280 shelter. Time = $3.14 \times 10^{-3}$ s after shock arrival at the front face.

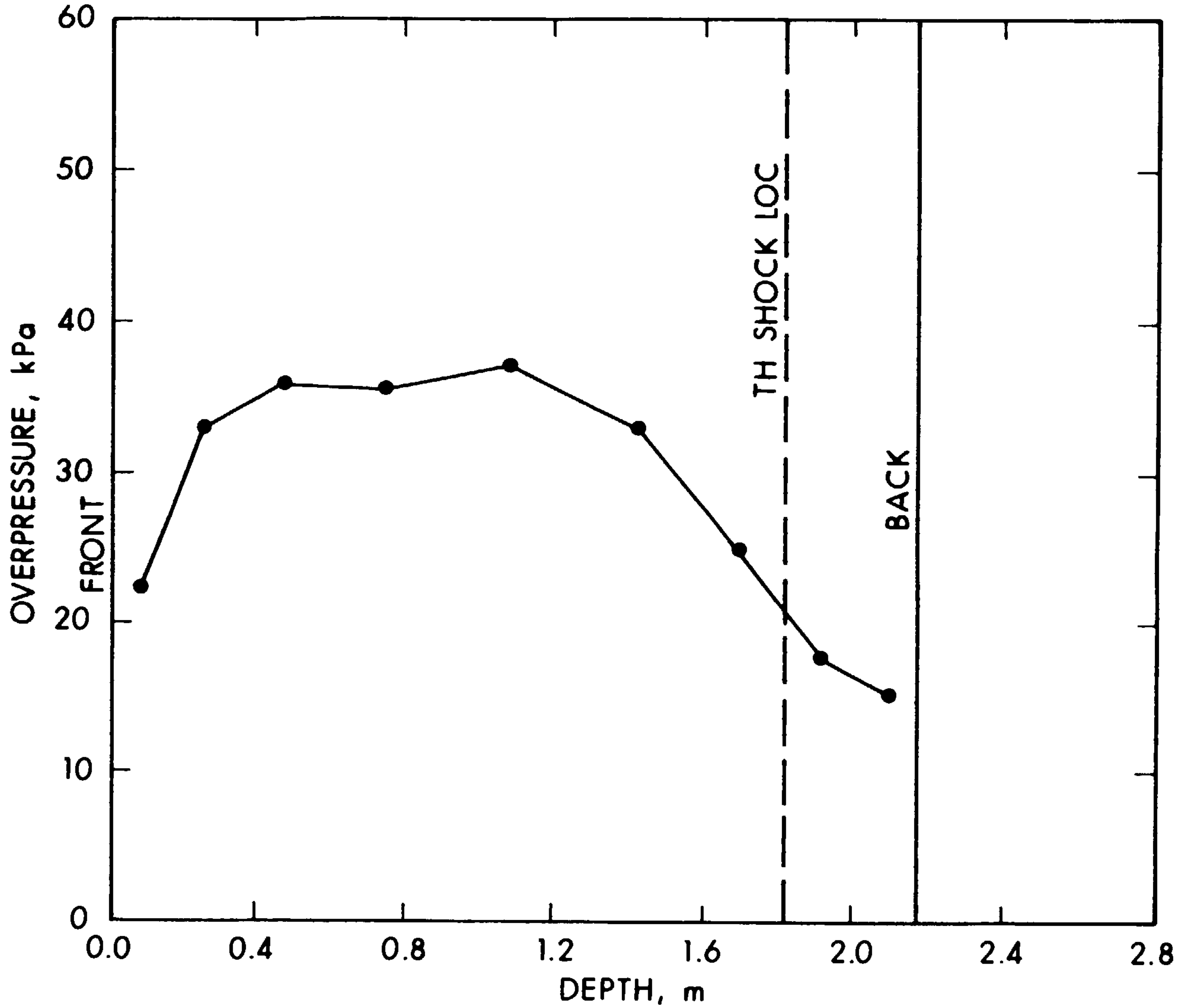


Figure 3d. Overpressure along the fourth row up the side face of the S-280 shelter. Time = 4.71 x $10^{-3}$ s after shock arrival at the front face.

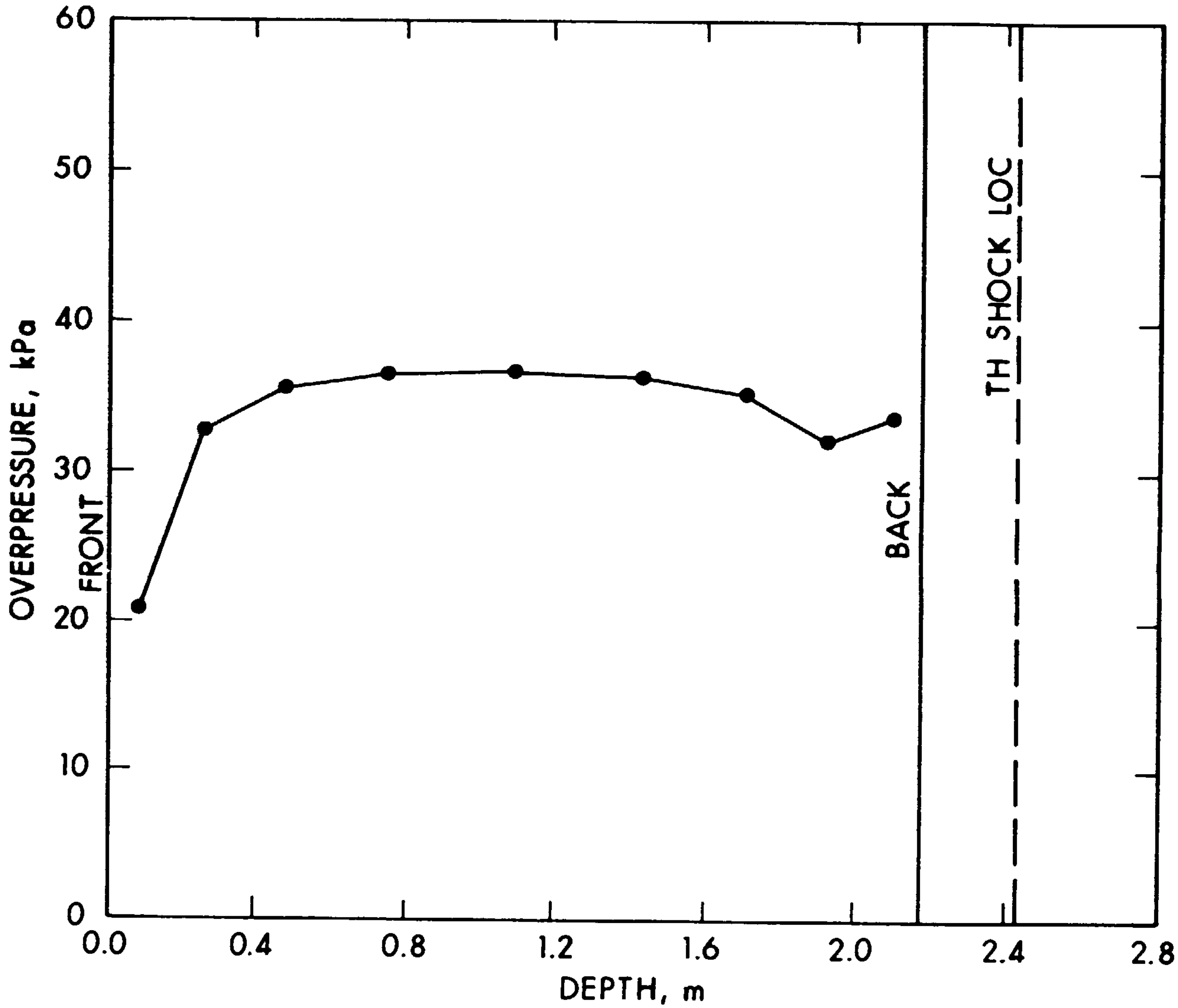


Figure 3e. Overpressure along the fourth row up the side face of the S-280 shelter. Time = 6.29 x $10^{-3}$ s after shock arrival at the front face.

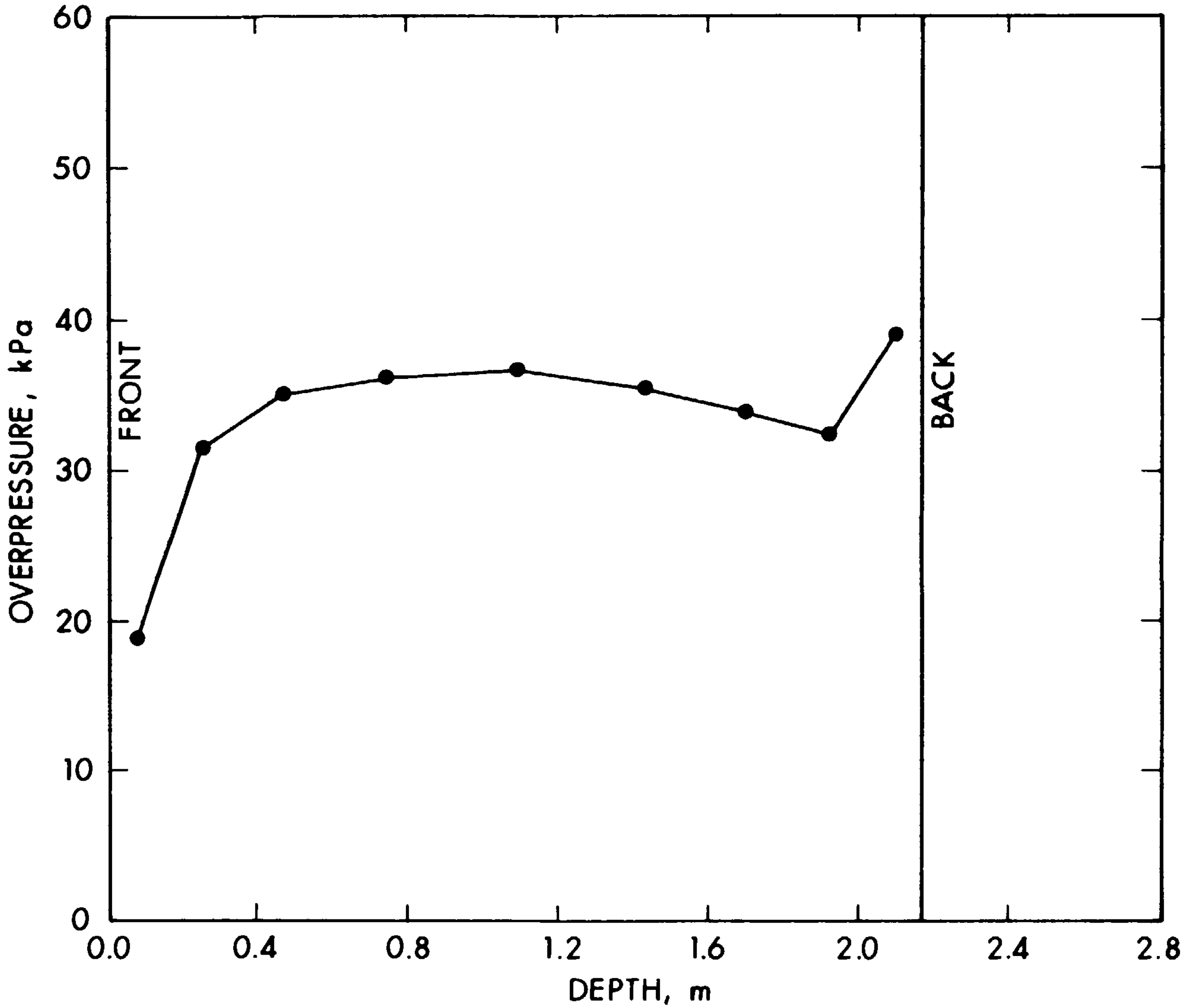


Figure 3f. Overpressure along the fourth row up the side face of the S-280 shelter. Time = $7.86 \times 10^{-3}$ s after shock arrival at the front face.

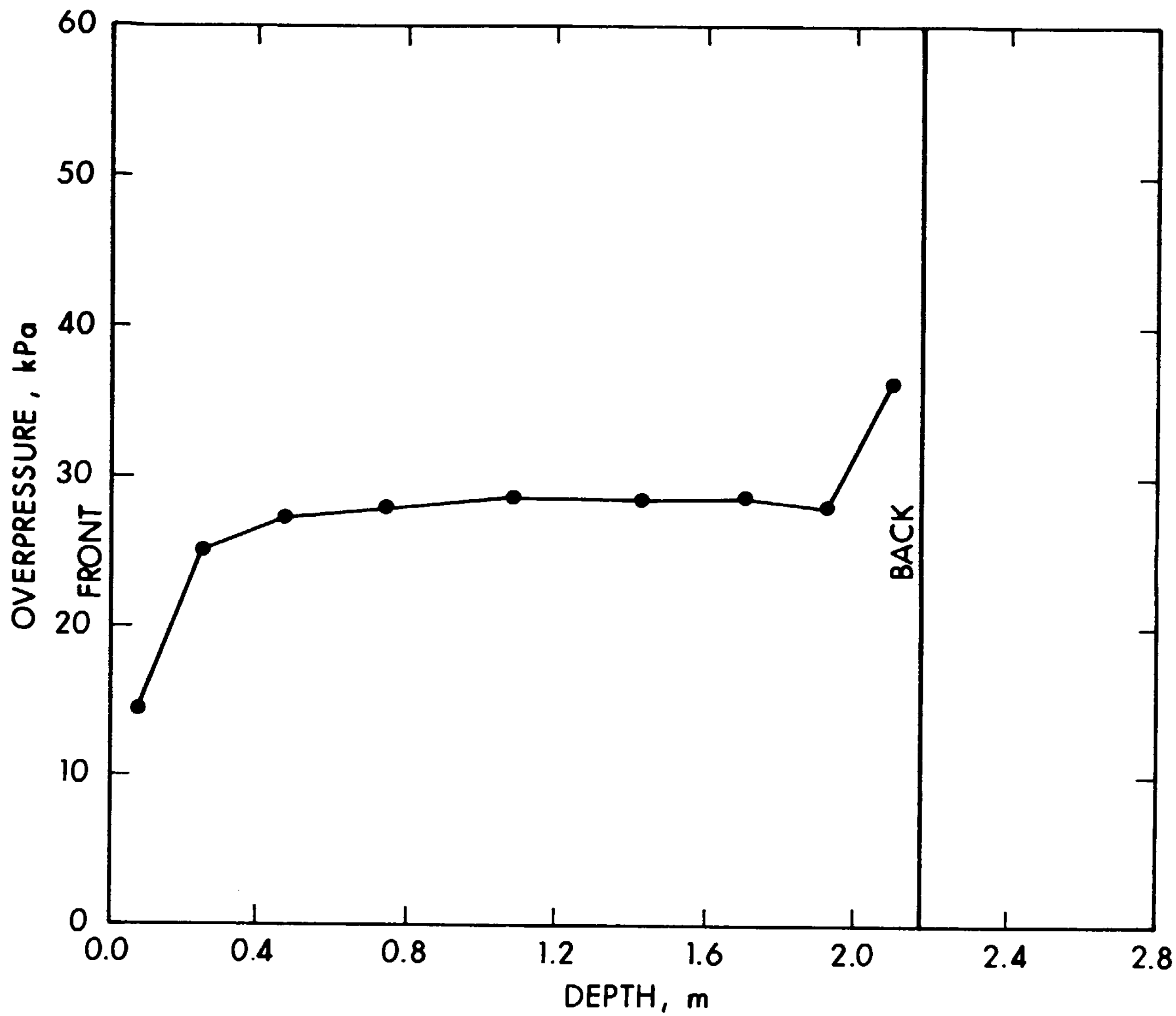


Figure 3g. Overpressure along the fourth row up the side face of the S-280 shelter. Time = 15.71 x $10^{-3}$ s after shock arrival at the front face.

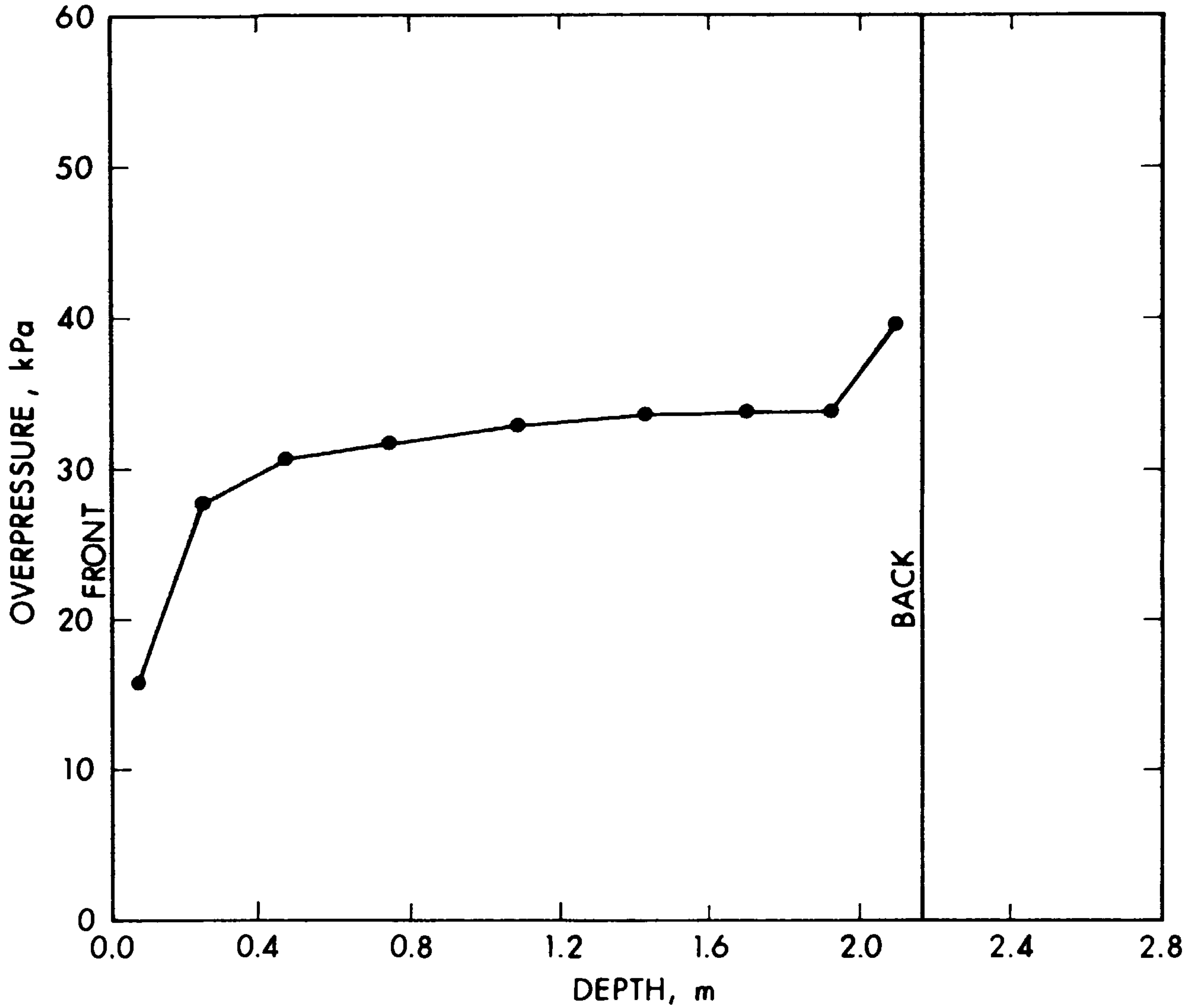


Figure 3h. Overpressure along the fourth row up the side face of the S-280 shelter. Time = 33.63 x $10^{-3}$ s after shock arrival at the front face.

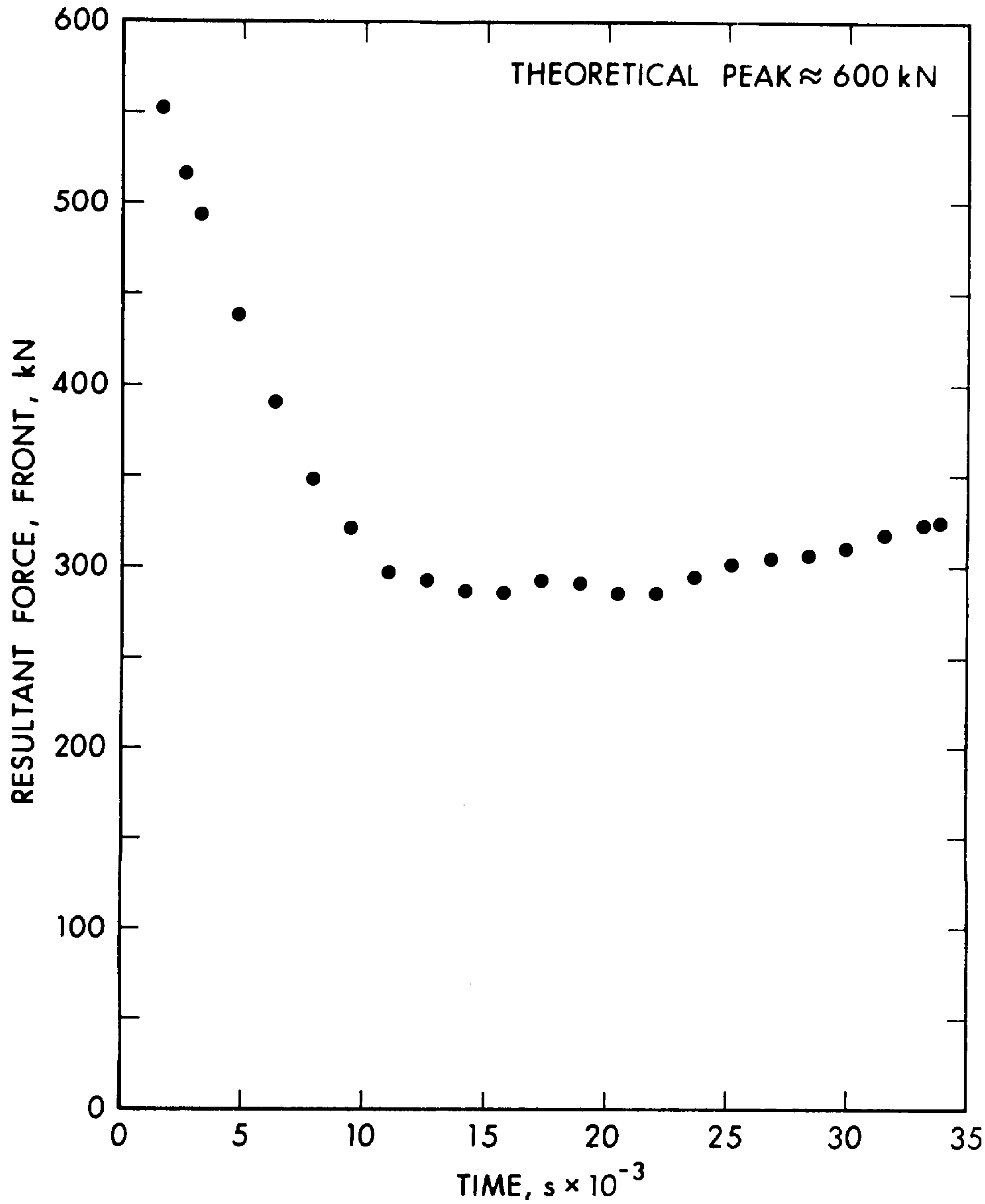


Figure 4a. The resultant force due to overpressure versus time for the front face.

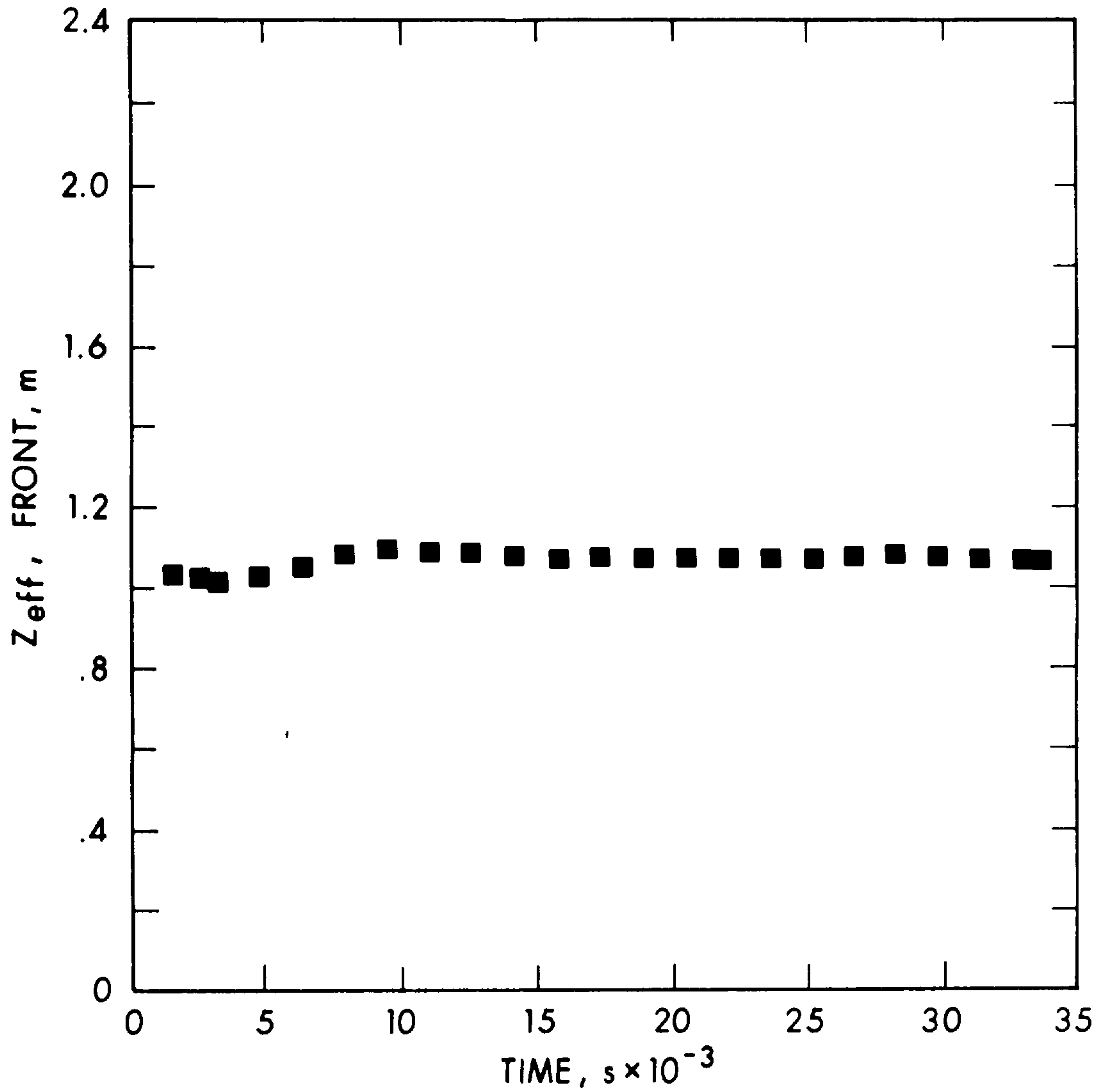


Figure 4b. The Z location of the effective point of application of the resultant force due to overpressure versus time for the front face.

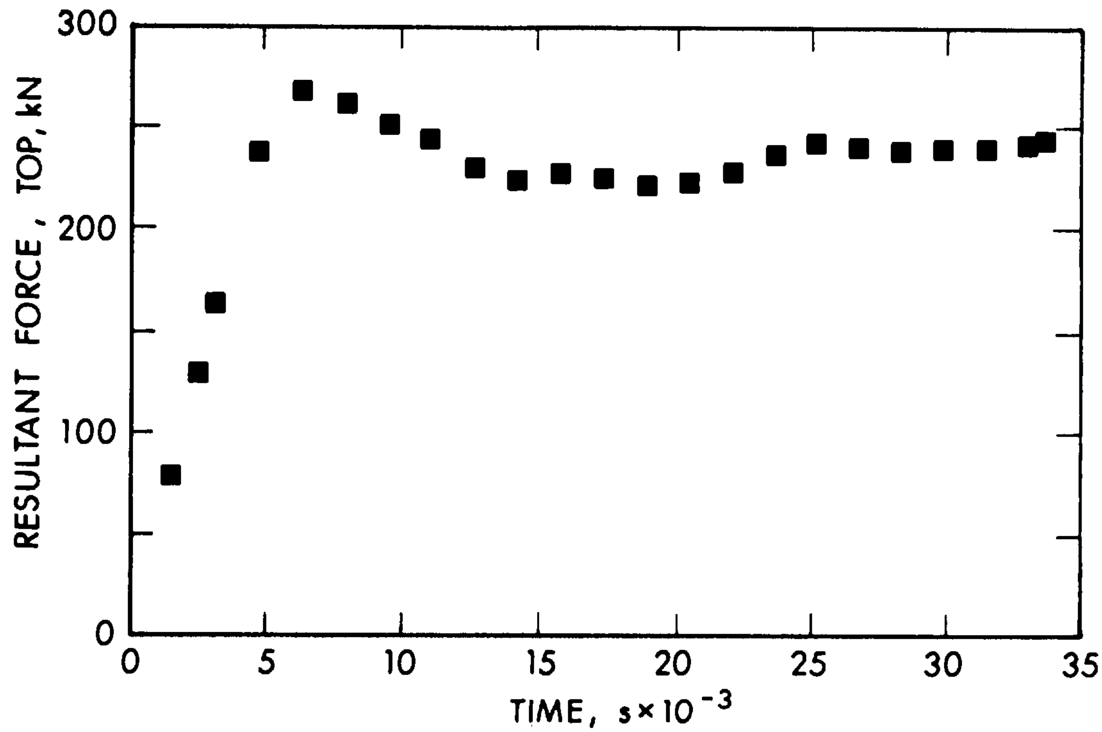


Figure 5a. The resultant force due to overpressure versus time for the top face.

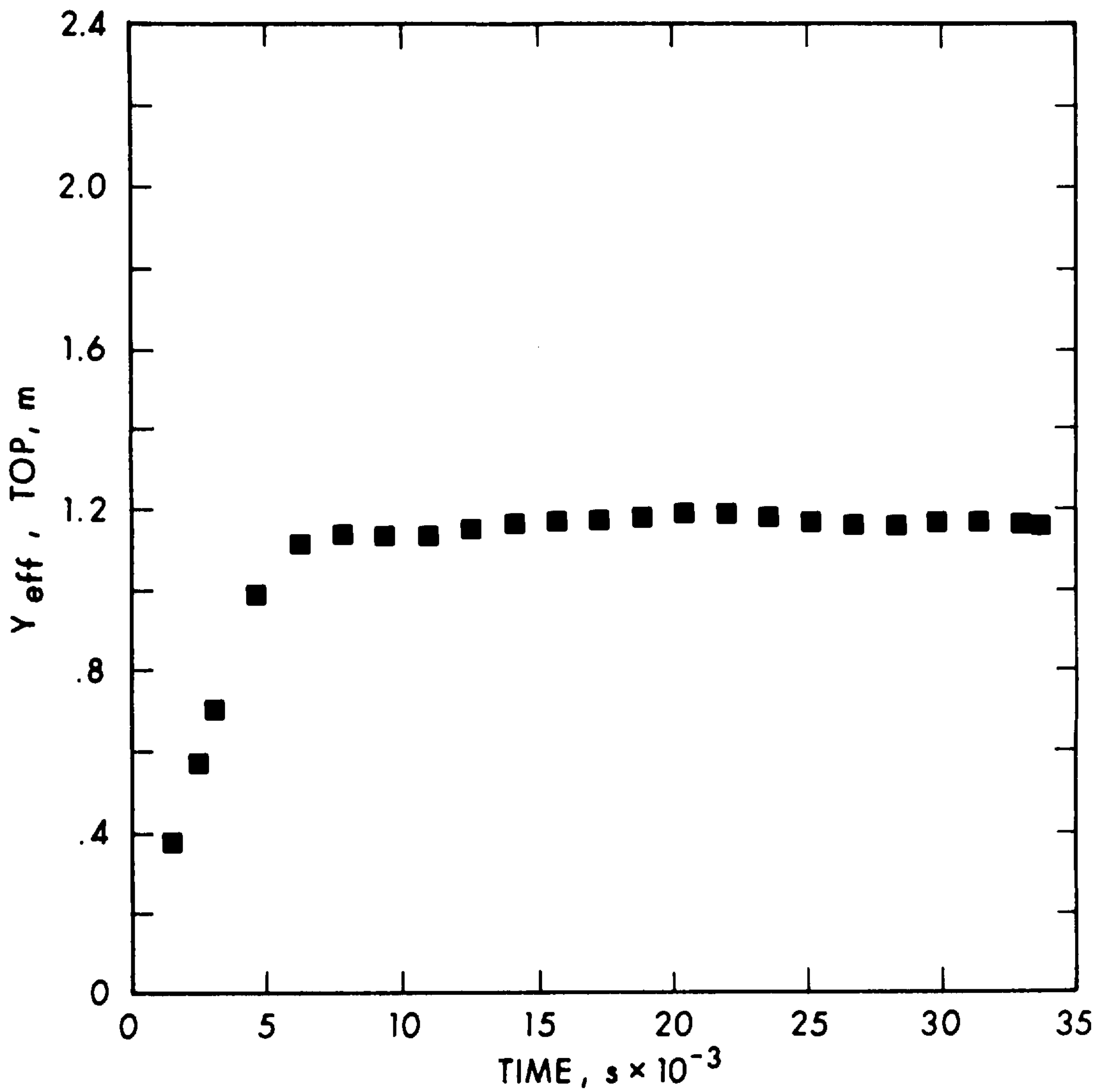


Figure 5b. The Y location of the effective point of application of the resultant force due to overpressure versus time for the top face.

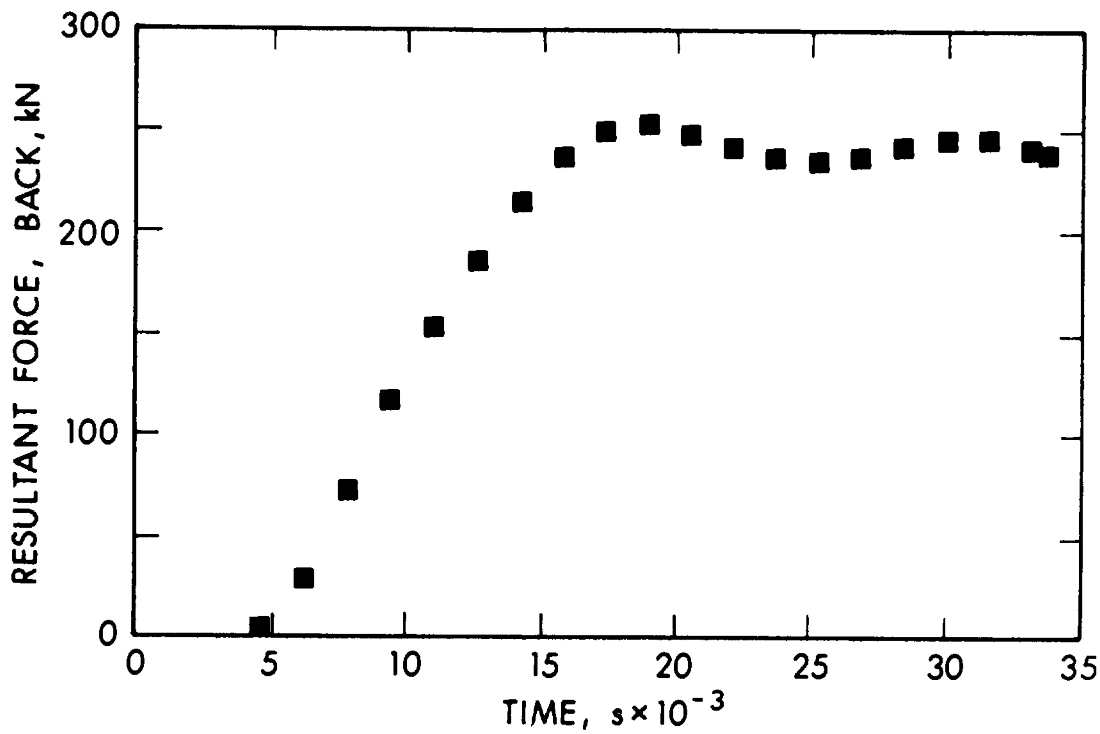


Figure 6a. The resultant force due to overpressure versus time for the back face.

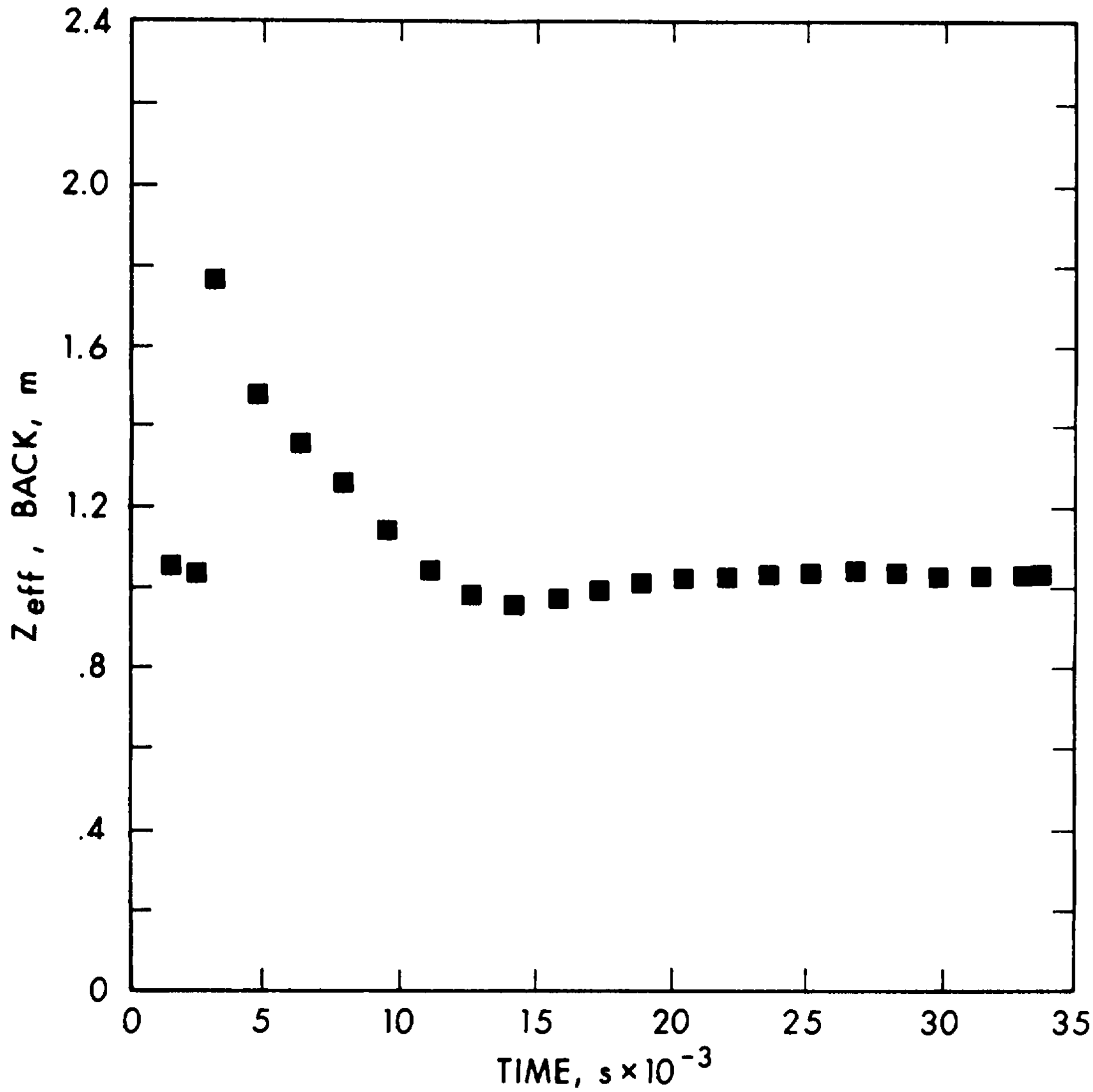


Figure 6b. The Z location of the effective point of application of the resultant force due to overpressure versus time for the back face.

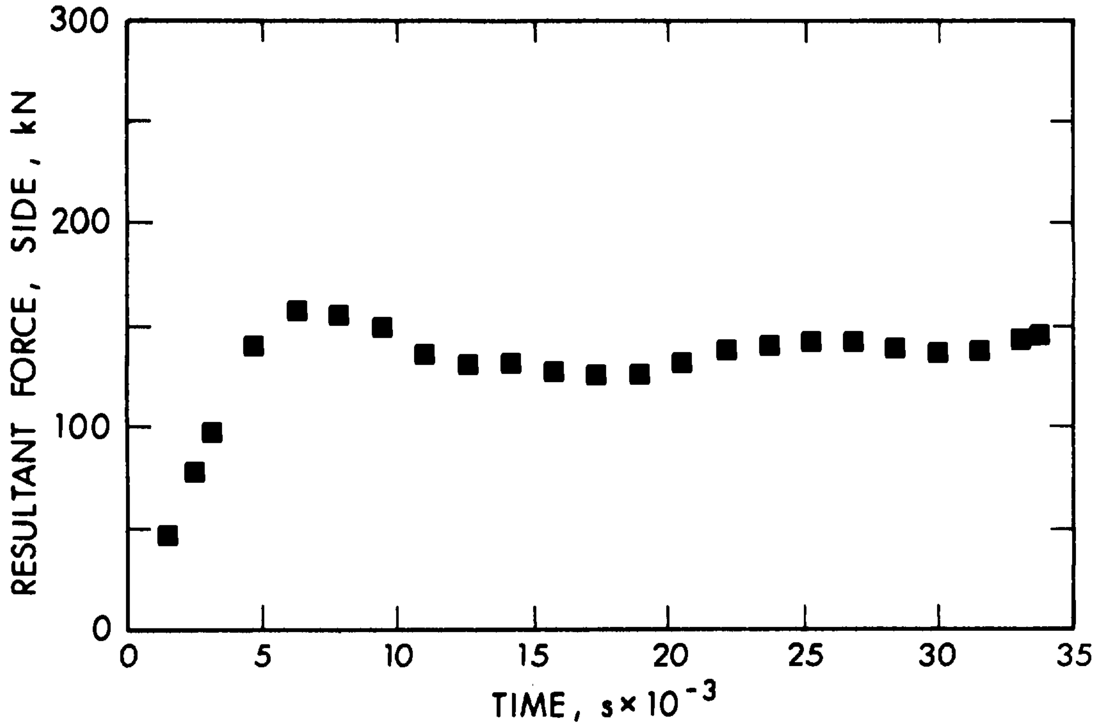


Figure 7a. The resultant force due to overpressure versus time for the side face.

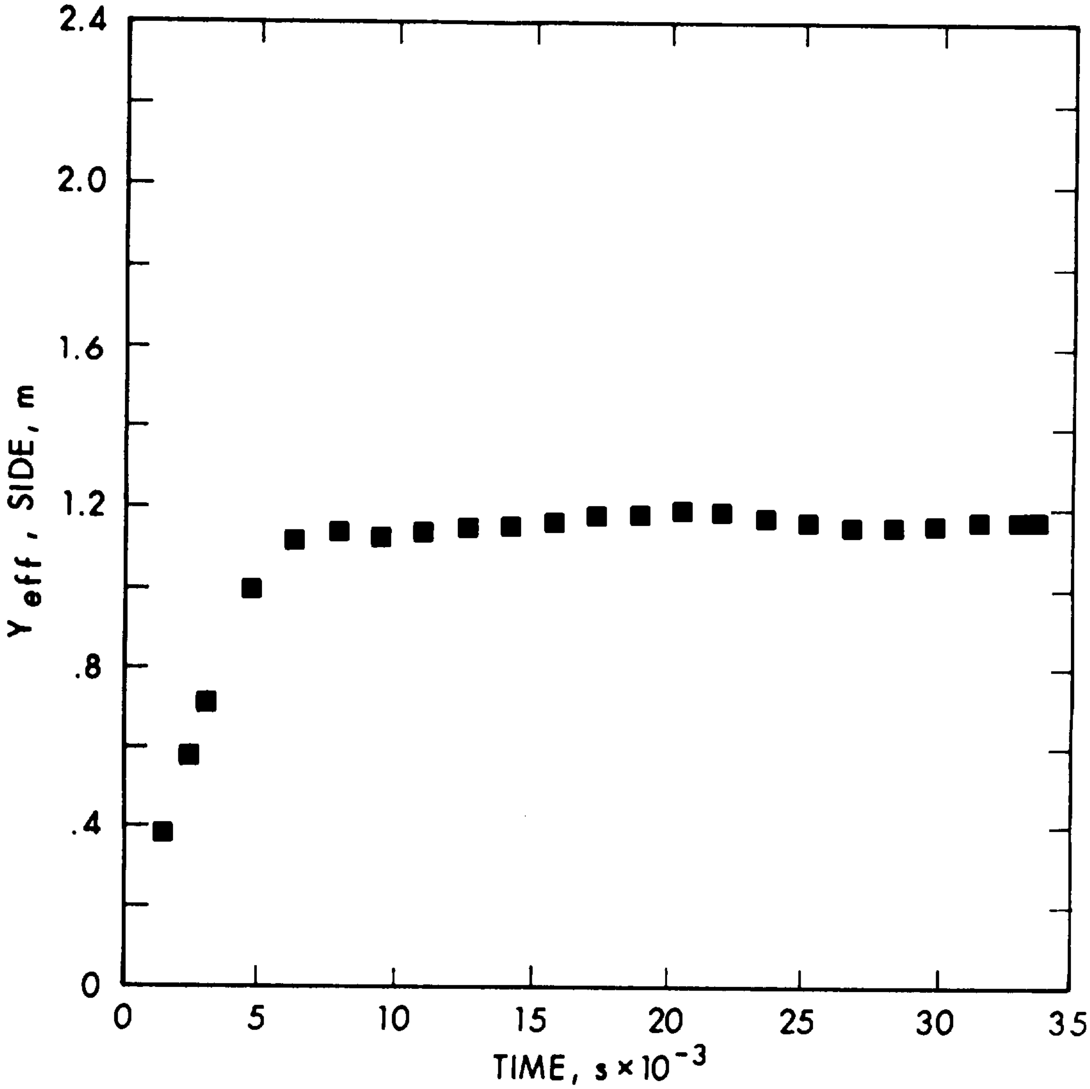


Figure 7b. The Y location of the effective point of application of the resultant force due to overpressure versus time for the side face.

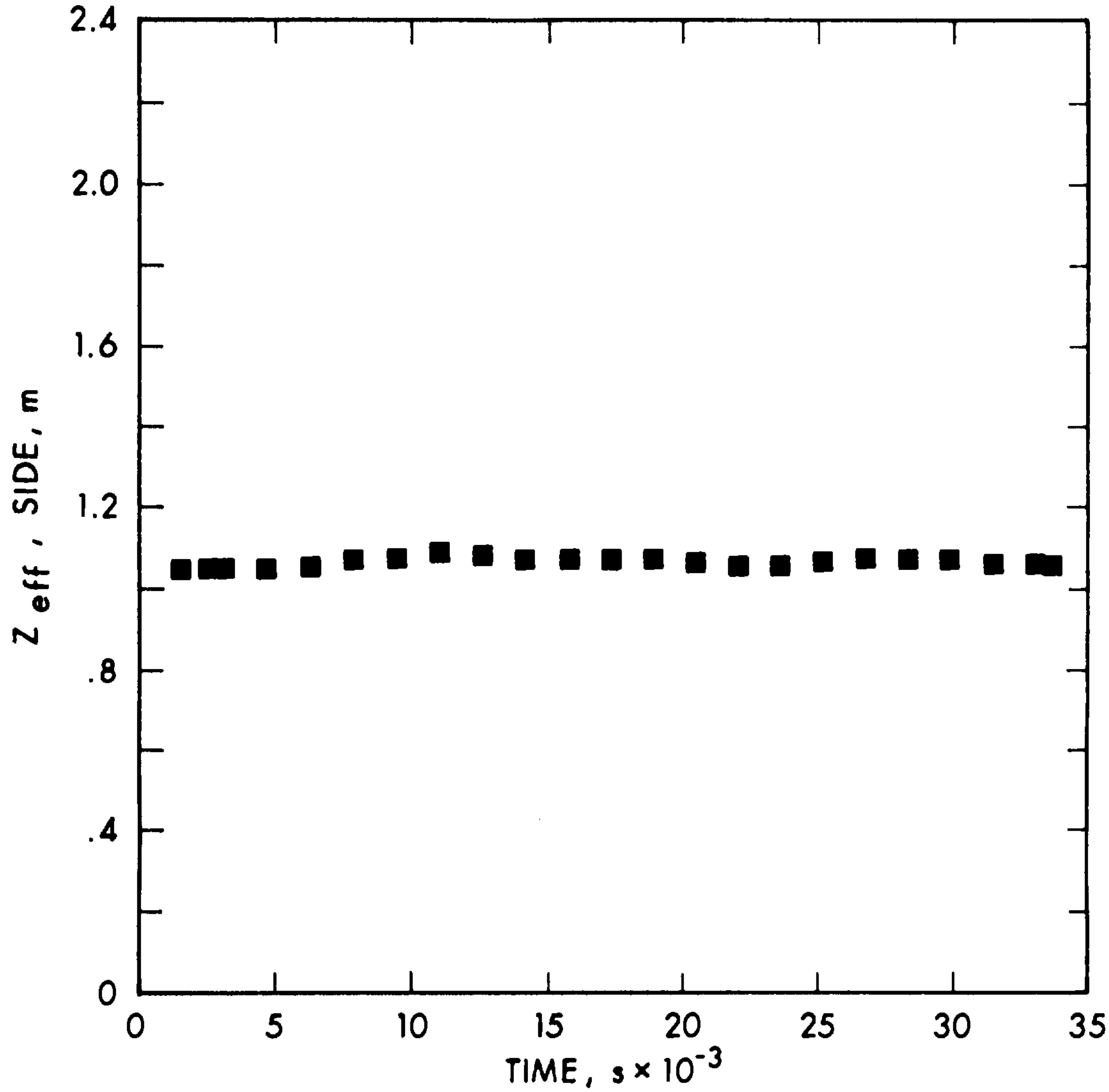


Figure 7c. The Z location of the effective point of application of the resultant force due to overpressure versus time for the side face.

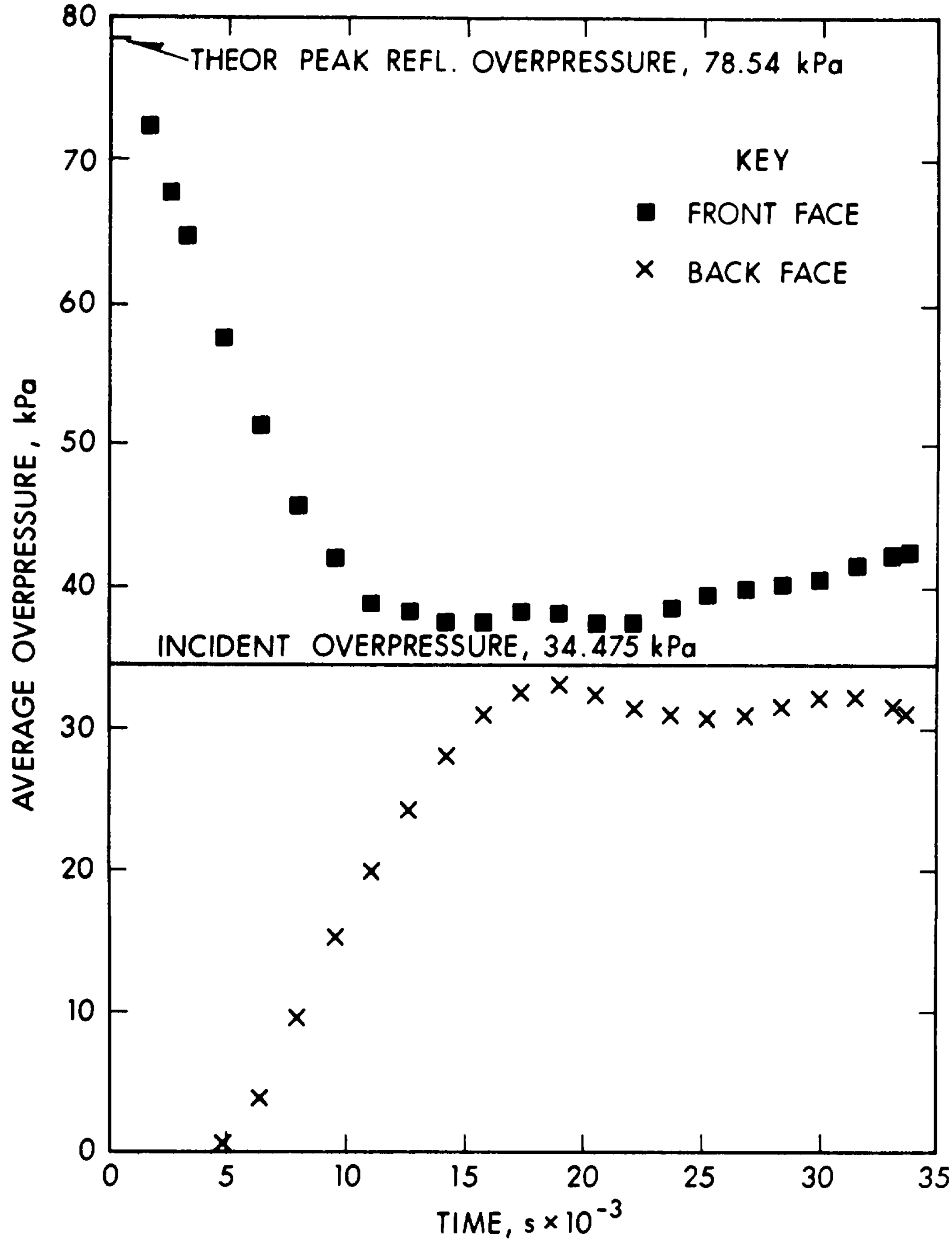


Figure 8a. Comparative plot of average overpressure on the front and back faces versus time.

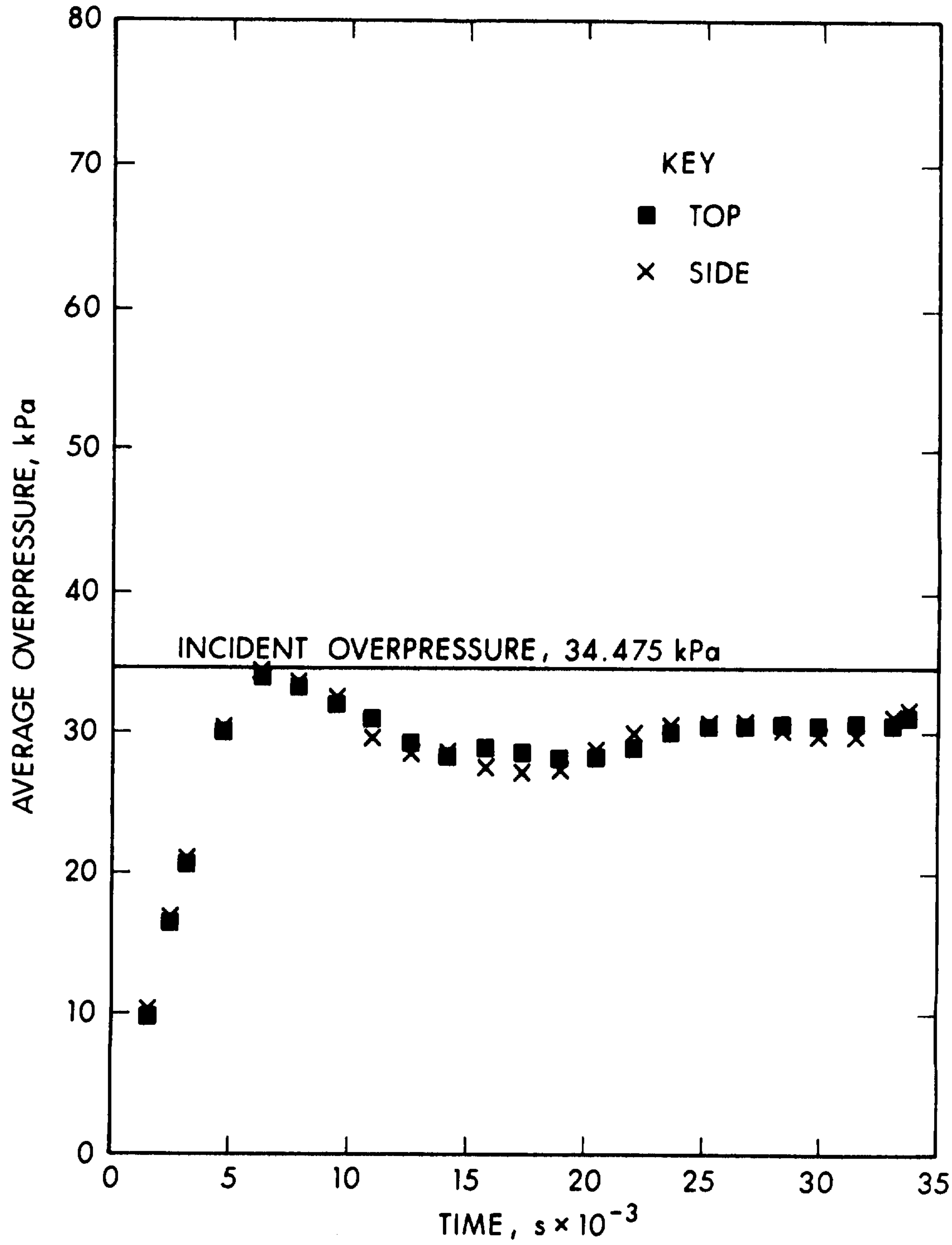


Figure 8b. Comparative plot of average overpressure on the top and side faces versus time.

# APPENDIX

A magnetic data tape has been prepared containing the results of the BAAL computation for the shock diffraction loading of a steady, one-dimensional, 34.475 kPa (5.0 psi) overpressure shock wave on an S-280 Electrical Equipment Shelter. Copies of this tape are available upon request. Send tape requests, referring to this document, to:

Director
Ballistic Research Laboratories
Aberdeen Proving Ground, MD 21005
ATTN: AMXBR-TB, Mr. R. E. Lottero

The data tape contains two general sets of information. The first set consists of 102 lines of alphanumeric data describing the numeric data to follow. The alphanumeric data is written so that the tape can serve as a self-contained, clearly interpretable document. When the tape is used as a numeric data source, these 102 lines of alphanumeric data may be skipped, going directly to the first line of numeric data.

The second set of information contains the numeric data, all pertaining to the loading on an S-280 Electrical Equipment Shelter caused by a 34.475 kPa (5.0 psi) steady shock wave. There are cell center overpressures for each flow field cell that has a face coincident with a shelter face for each of 23 points in time. Also included are resultant force due to overpressure for each entire shelter face, and the effective point of application of that force. The 23 points in time represent approximately every fifth computational cycle. The computational time stepping was implicit.

The data is written in a card image format. The tape is 7 track, 800 BPI, even parity, BCD code (IBM 1401), unlabeled, with 80 character lines, and a blocking factor = 1.

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