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Numerical Studies of Regular and Mach Reflection of Shocks in Aluminum

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Numerical Studies of Regular and Mach Reflection of Shocks in Aluminum

by

Charles L. Mader

ABSTRACT

The regular and Mach reflections of 330 kilobar shocks in aluminum have been studied using a high resolution, Lagrangian, two-dimensional, numerical hydrodynamic code of the MAGEE type. The numerical results compare favorably with the available experimental data.

ACKNOWLEDGMENTS

The author gratefully acknowledges the assistance and contributions of the following Los Alamos Scientific Laboratory personnel: D. Venable and R. W. Taylor of GMX-11, S. R. Orr and G. N. White, Jr., of T-5, F. H. Harlow of T-3, W. C. Davis of GMX-8, and S. D. Gardner of GMX-7.

CONTENTS

FIGURES

I. INTRODUCTION

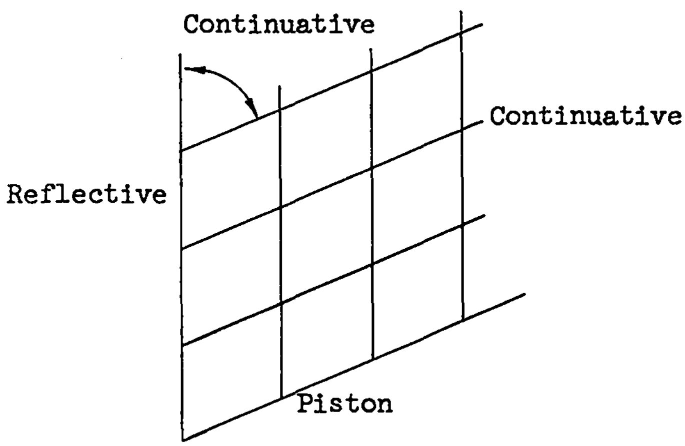
Numerous experimental and theoretical studies of shock reflection in gases are available.[1-7] The interaction of colliding detonation waves in condensed explosives has also been studied experimentally by several investigators.[8-10] Al'Tshuler et al.[11] have experimentally studied the regular and Mach reflections of shocks in aluminum. We have used a two-dimensional Lagrangian hydrodynamics code called 2DL[12] to study numerically the same system that was experimentally studied by the Russians. The numerical results compare favorably with the Russian experimental data.

II. COMPUTATIONAL METHOD

The MAGEE finite difference analogs of the Lagrangian equations of motion of a compressible fluid, developed in Group T-5 during the last 15 years, were used. The particular version of this method used has been described by the author.[12] The equation of state parameters used for aluminum were identical to those described in reference 12.

The problems we are concerned with in this report are exemplified by an applied pressure boundary (hereafter called a piston) with a 330 kilobar pressure normally incident upon one side (which we have taken as bottom) of an aluminum rhombohedron with one reflective side (which we have taken as the left side) and the other sides of semi-infinite extent. Thus the problem becomes a two-dimensional one in the Cartesian coordinates X and Z.

The problems discussed in this report had 50 cells along the X direction and 250 cells along the Z direction. They were run for 1000 cycles, and required approximately 4 hours of IBM 7030 (STRETCH) time each. The Lagrangian cells were parallelpipeds or rhombuses of equal length sides (0.05 cm) with slopes adjusted to give the desired shock collision angle α. A sketch of the mesh is shown below.



III. COLLIDING SHOCK WAVES

Figure 1 shows the computed isobars, Figure 2 the computed isopycnics, and Figure 3 the cell corners (which show fluid distortion) for 330 kilobar shocks in aluminum with a 33.7° collision angle. Regular reflection occurs.

Figure 4 shows the computed isobars, Figure 5 the computed isopycnics, and Figure 6 the cell corners for 330 kilobar shocks in aluminum with a 63.4° collision angle. Mach reflection occurs.

Figure 7 shows the computed isobars, and Figure 8 the cell corners for 330 kilobar shocks in aluminum with a 50° collision angle. Mach reflection occurs.

The computed growth angle ψ of the stem as a function of the collision angle α is shown in Figure 9, compared with the Russian experimental data.[11] The error flags attached to the calculated values are consequences of the cell size, of a smeared shock, and of the curvature of the Mach stems.

The computed peak pressure in the reflected shock or Mach stem as a function of collision angle α is shown in Figure 10, compared with the Russian experimental data.[11] The calculated critical angle is larger than the one reported by the Russians. The flat-topped wave approximation used in the calculations may be responsible for this difference.

Roger Taylor of GMX-11 took PHERMEX[13] radiographs of a system of two P-40 lenses and two pads of Composition B, 4 in. × 4 in. × 8 in. long, detonated simultaneously in contact with a wedge of aluminum. The radiographs were taken after the shock wave had traveled 1 in. into the aluminum. The radiographs were taken along a direction parallel to the intersection of the colliding waves. This provided the density distribution in the interaction region. The x-ray pulse was produced by a burst of 26 MeV electrons impinging on a 3 mm diameter tungsten target resulting in radiation intensities up to 2 roentgens at the aluminum wedge, which was positioned on the beam axis approximately 3 meters from the target. The x-ray film was placed approximately 0.75 meters behind the aluminum wedge in a protective aluminum case. Figure 11 shows the radiograph obtained for regular reflection of two shock waves with a 33.7° collision angle and Figure 12 shows the radiograph obtained for Mach reflection of two shock waves with a 50° collision angle. The Mach stem is approximately 0.5 cm wide with a growth angle of 4°, which agrees with the Russian experimental data and the calculations presented in this report. The density gradients shown in the radiographs are closely reproduced by the calculations. The radiographs do not show the high density zones trailing the interaction points that were observed for colliding detonation waves.[9]

Neither the Russian experiments nor the ones used in the PHERMEX experiments gave flat-topped shock waves as assumed in the calculations. S. D. Gardner of this Laboratory is presently investigating this effect and has an experimental method for producing flat-topped shock waves that should give better data with which to compare the calculations described in this report. In particular it should yield a better experimental critical angle for comparison with the calculated value. Considering the resolution of the calculations and of the experimental data, the calculations are in satisfactory agreement with the experimental evidence.

IV. COLLIDING DETONATION WAVES

These results have encouraged us to undertake a study of colliding detonation waves with resolved reaction zones. Preliminary results of our study of the interaction of nitromethane detonation waves have yielded both regular and Mach reflection of detonation waves with resolved reaction zones for nitromethane. Nitromethane with a 40 kcal/mole activation energy was used so as to have a stable detonation.[14] Additional studies of two-dimensional stability and reflection of detonation waves are in progress.

V. CONCLUSIONS

The results of computations of the regular and Mach reflection of 330 kilobar shocks in aluminum using a two-dimensional, Lagrangian, numerical hydrodynamic model compare favorably with the available experimental data.

The calculated Mach stems are not well described by the usual simple three-shock model. They have significant curvature and hence are better described as a multiple-shock process with a slip region rather than a three-shock process with a slip plane. The absence of a slip plane density discontinuity in the radiographs is experimental evidence of the validity of the calculational model. The calculated growth angle of the Mach stem increases with increasing collision angle up to at least 89°, which is the largest angle for which calculations were performed. A sharp discontinuity in the stem growth angle as a function of collision angle occurs at or near 90°.

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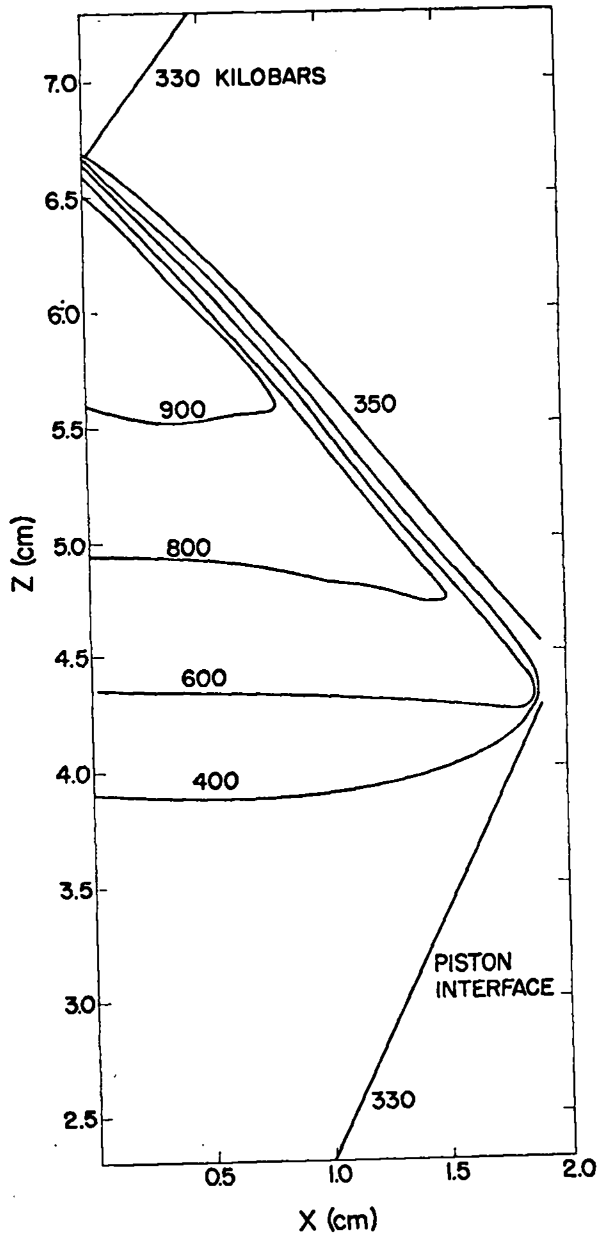


Figure 1. The computed isobars at 5 μsec for 330 kilobar shocks in aluminum with a 33.7° collision angle. Regular reflection occurs. The region at Z = 6.0 between the 900 and the 350 isobars is a result of the shock smear caused by the artificial viscosity.

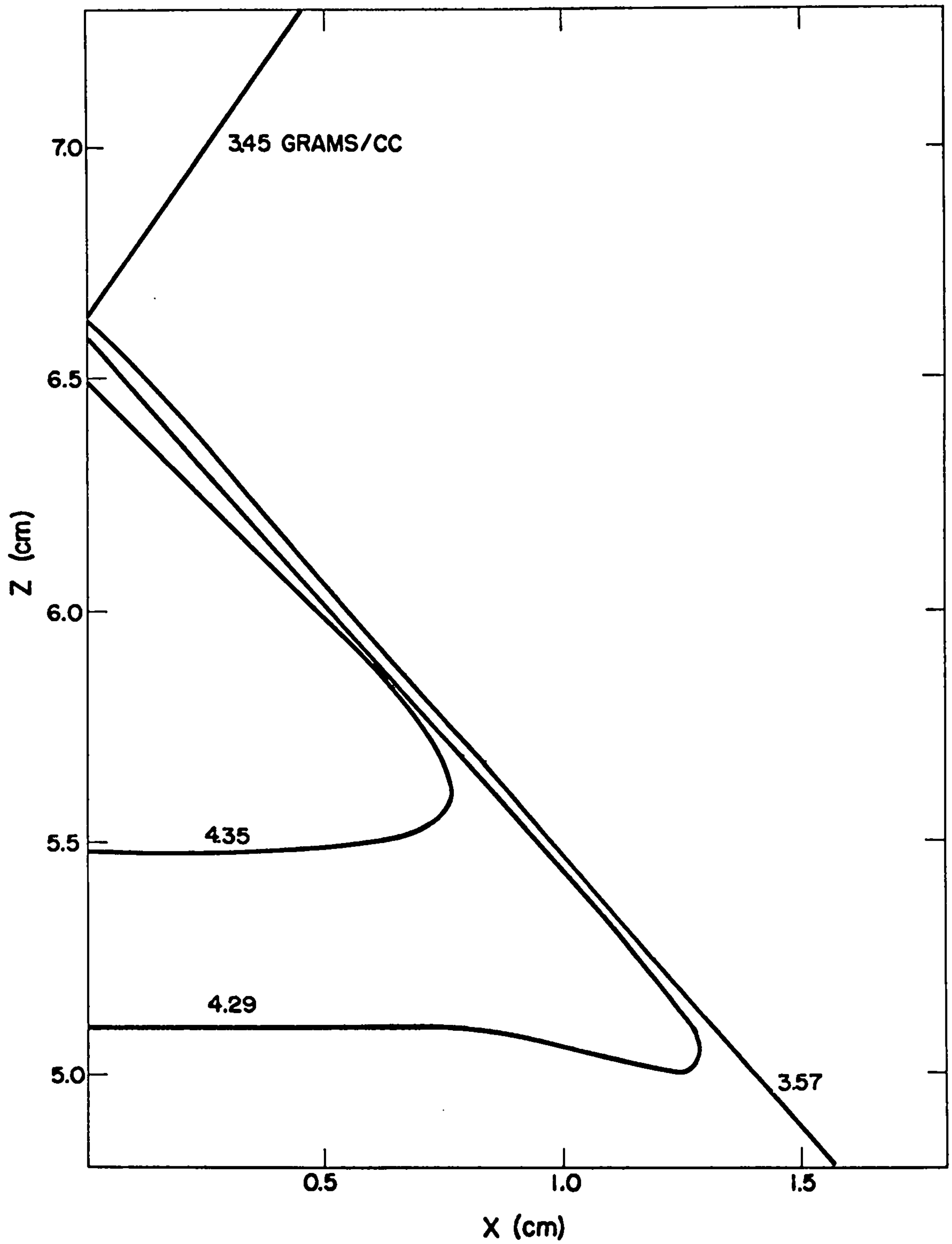


Figure 2. The computed isopycnics for the problem described in Figure 1.

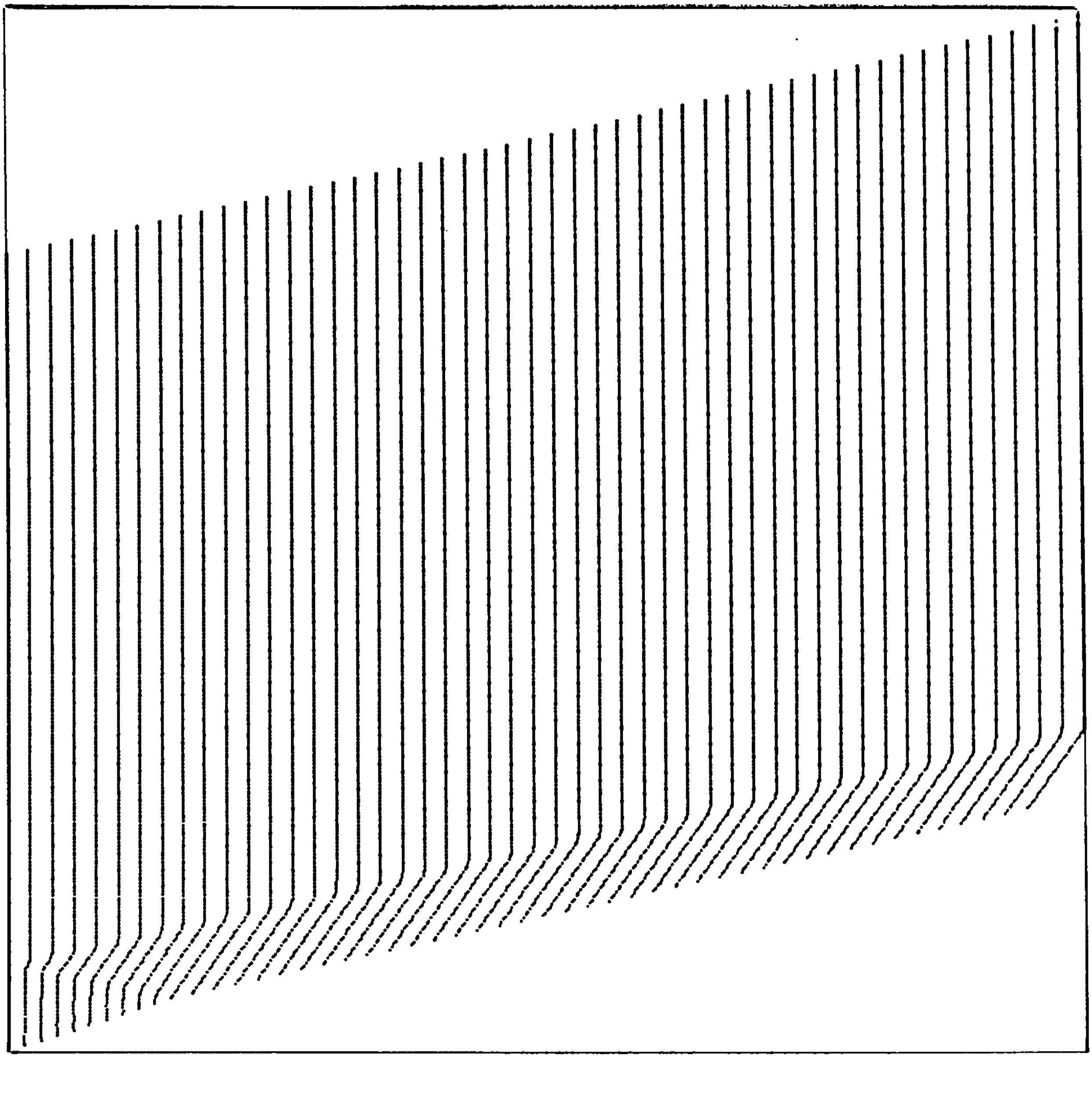
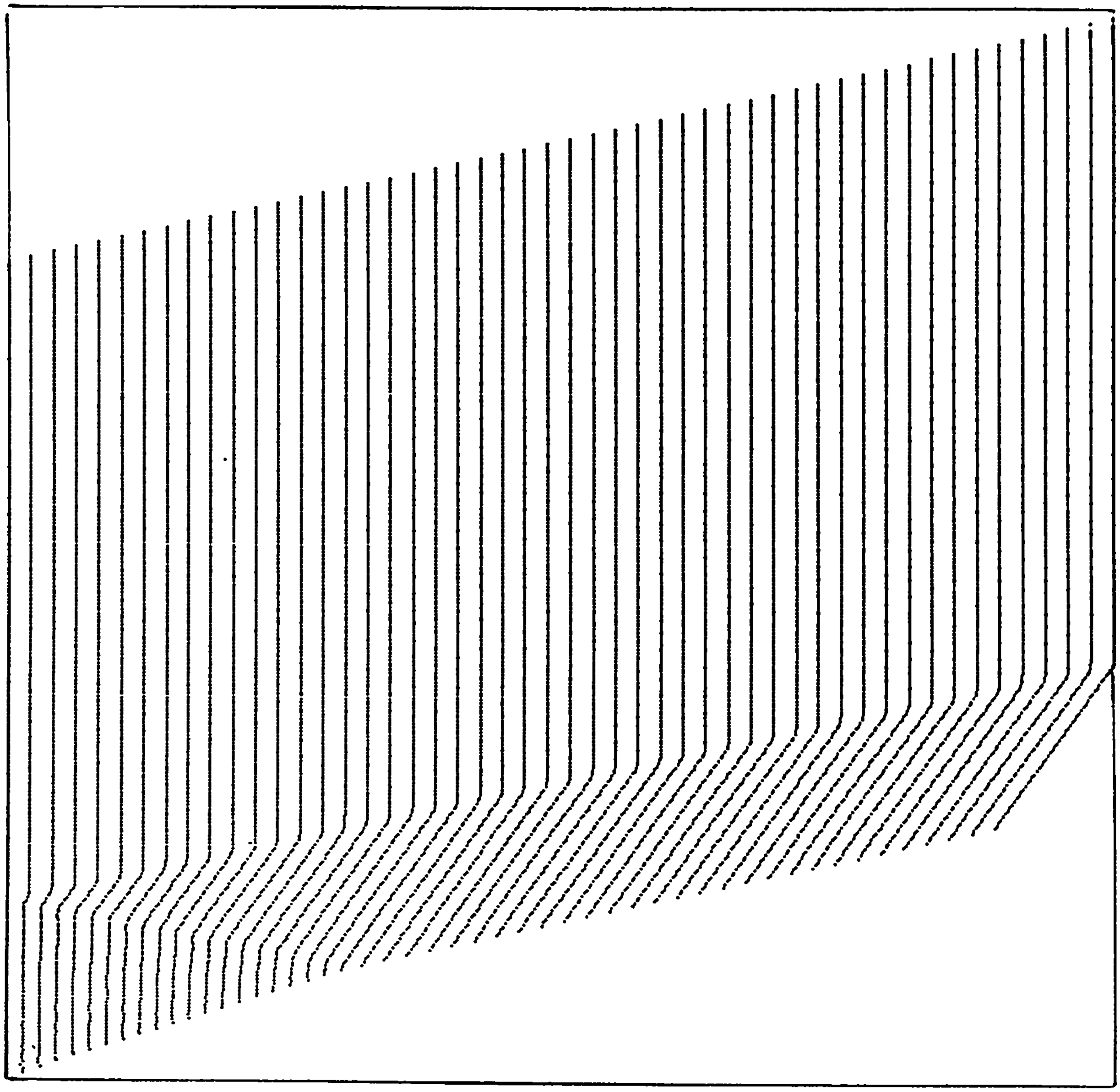
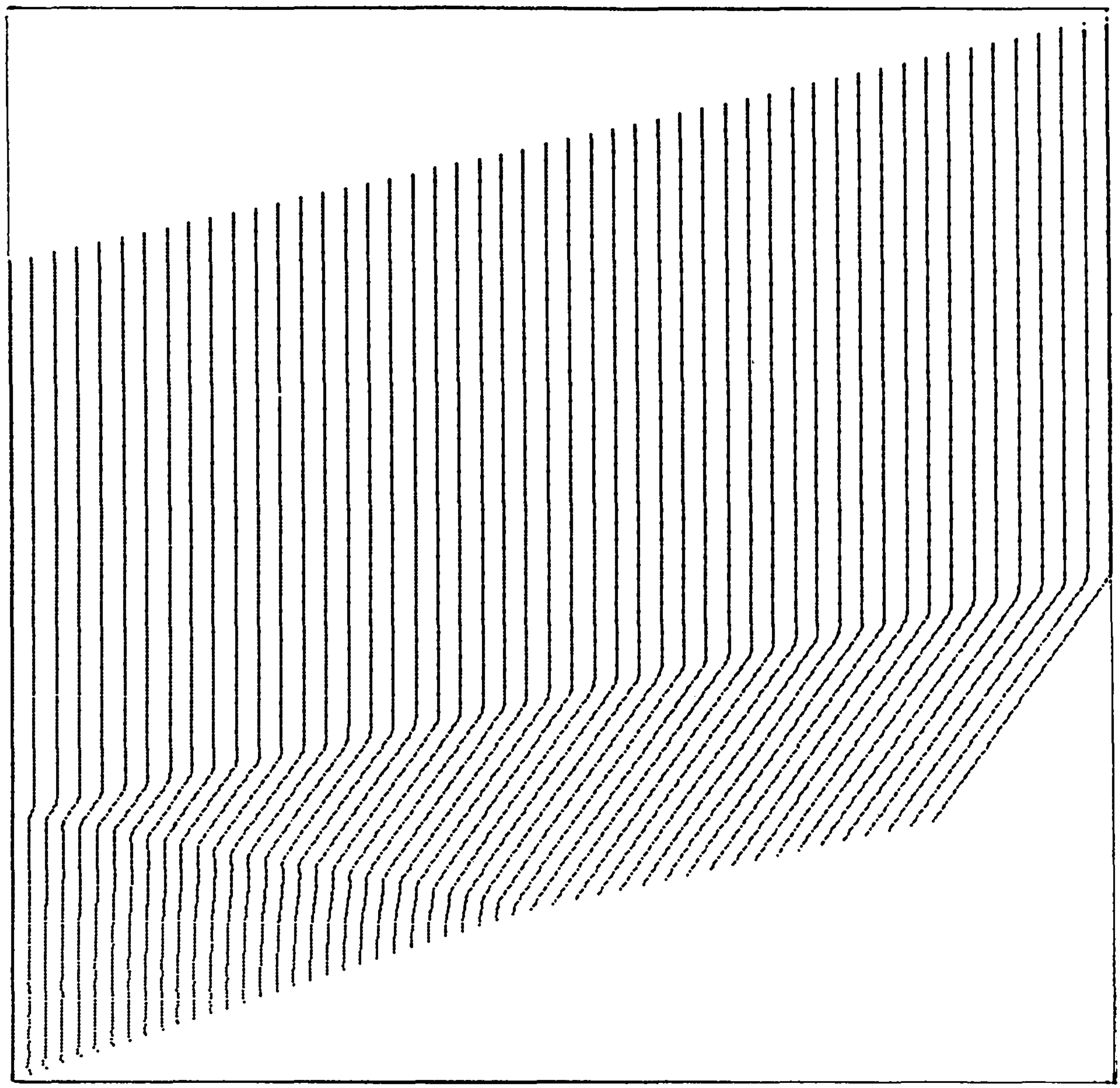


Figure 3. The computed positions of the Lagrangian cell corners at 1, 2, 3, 4, and 5 μsec for the problem described in Figure 1. The X axis is 2.5 cm long and the Z axis is 16.25 cm long. The distortion on the right side at late time results from the interaction of the reflected shock with the continuative boundary.



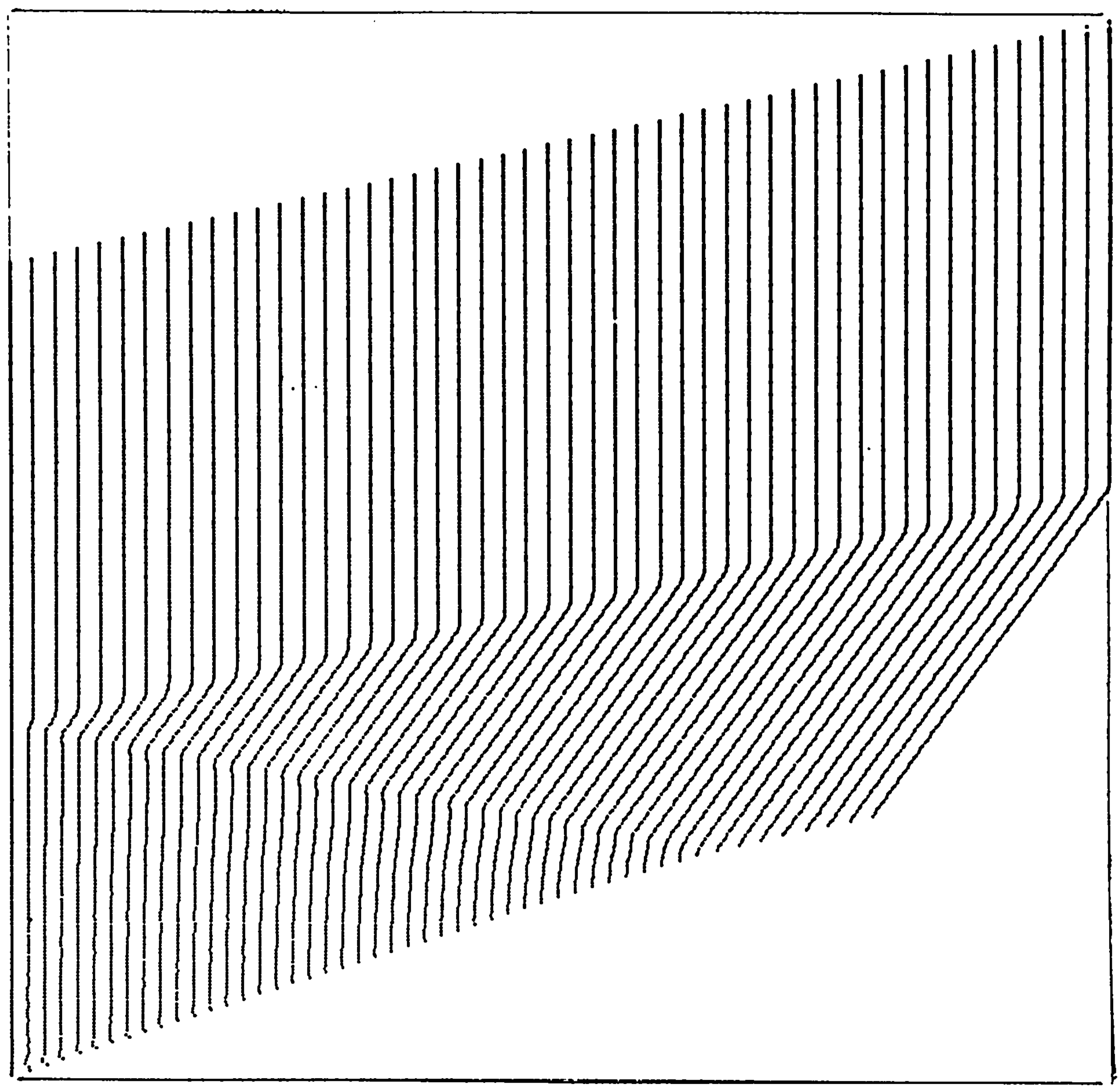
THE TIME IS 2.00000+000 MICROSECONDS AND THE CYCLE NUMBER IS 4.00000+002

Figure 3 continued.



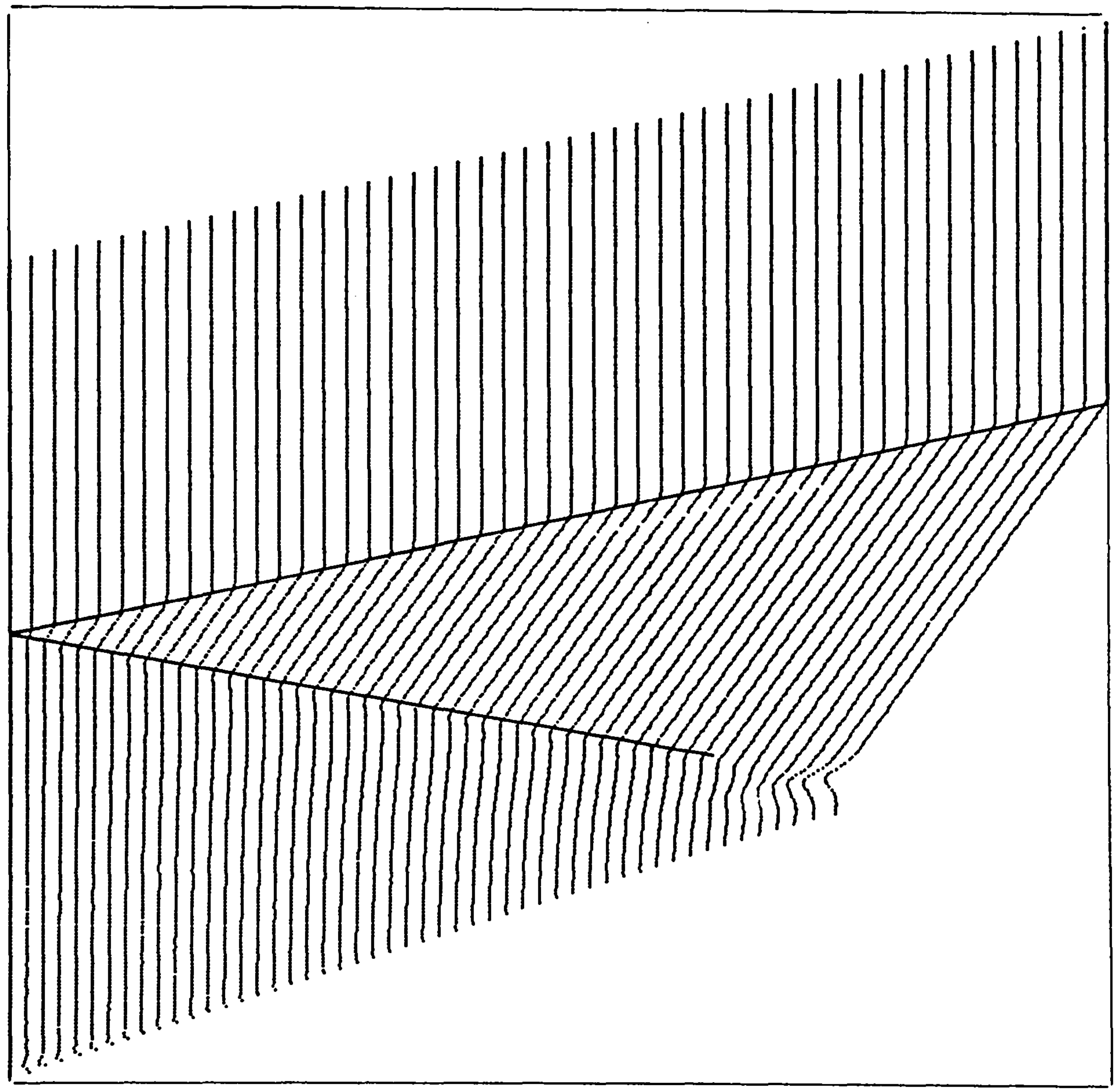
THE TIME IS 3.00000+000 MICROSECONDS AND THE CYCLE NUMBER IS 6.00000+002

Figure 3 continued.



THE TIME IS 4.00000+000 MICROSECONDS   AND THE CYCLE NUMBER IS 8.00000+002

Figure 3 continued.



THE TIME IS 5.00000+000 MICROSECONDS AND THE CYCLE NUMBER IS 1.00000+003

Figure 3 continued.

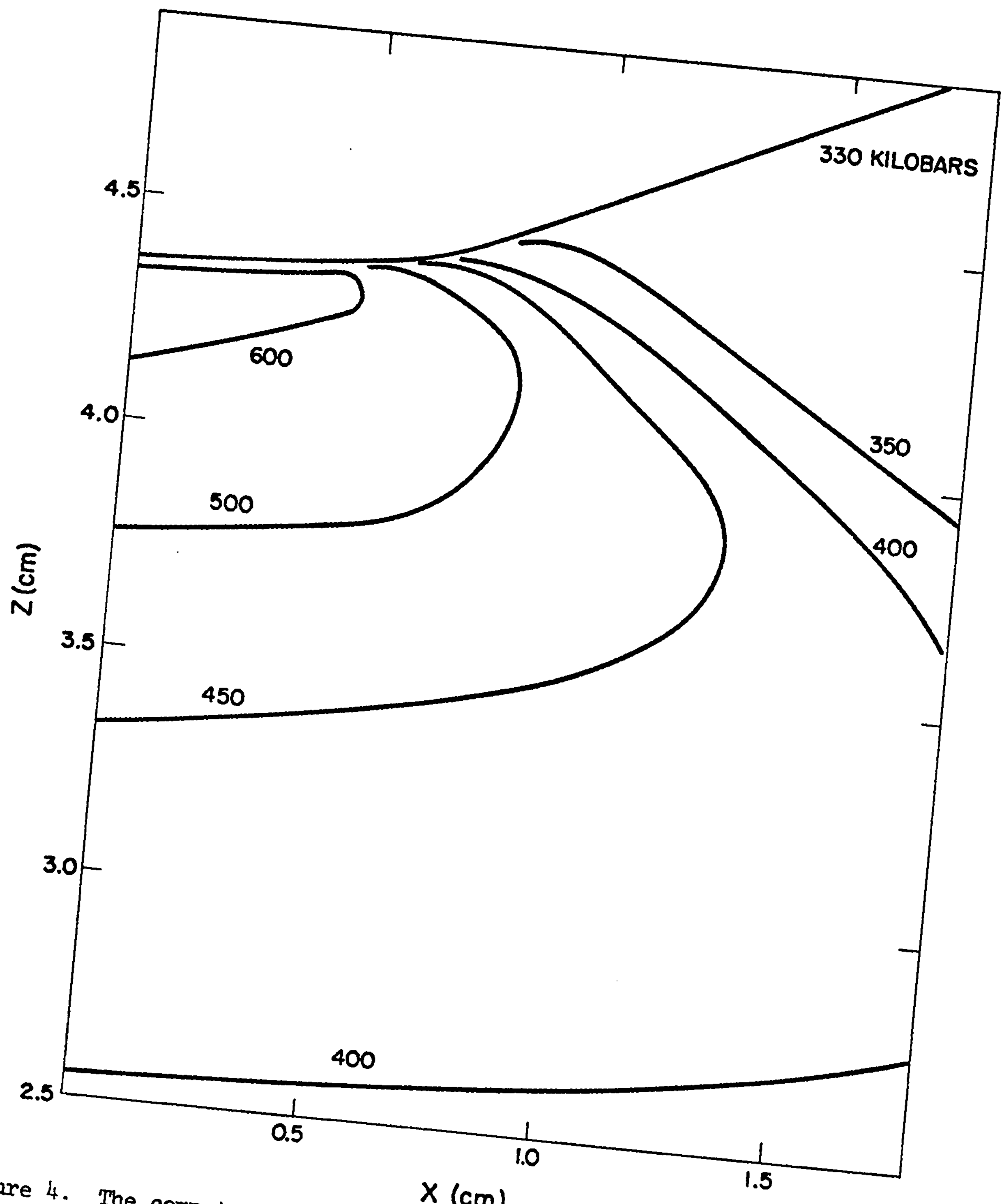


Figure 4. The computed isobars at 5 μsec for 330 kilobar shocks in aluminum with a 63.4° collision angle. Mach reflection occurs.

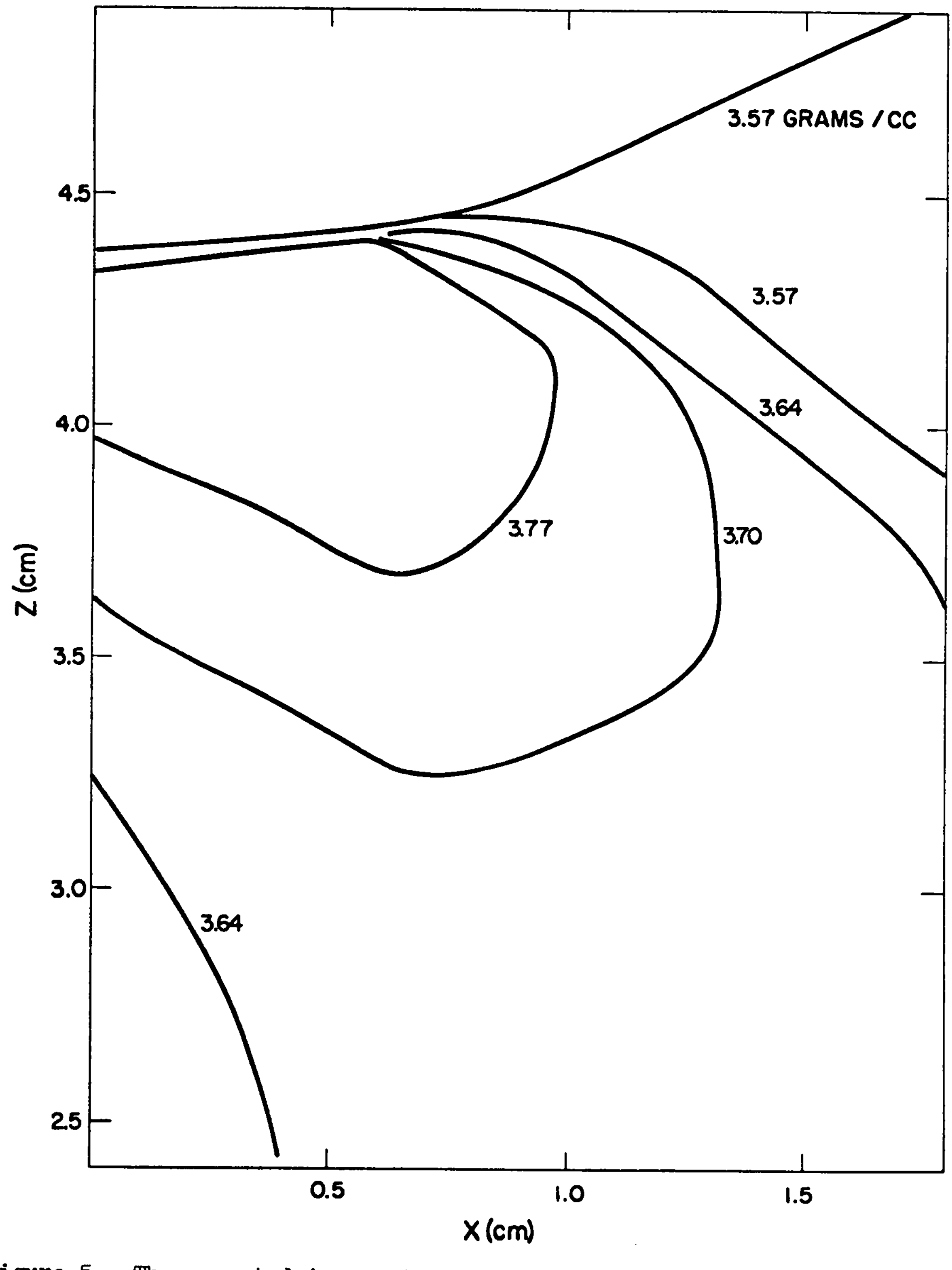
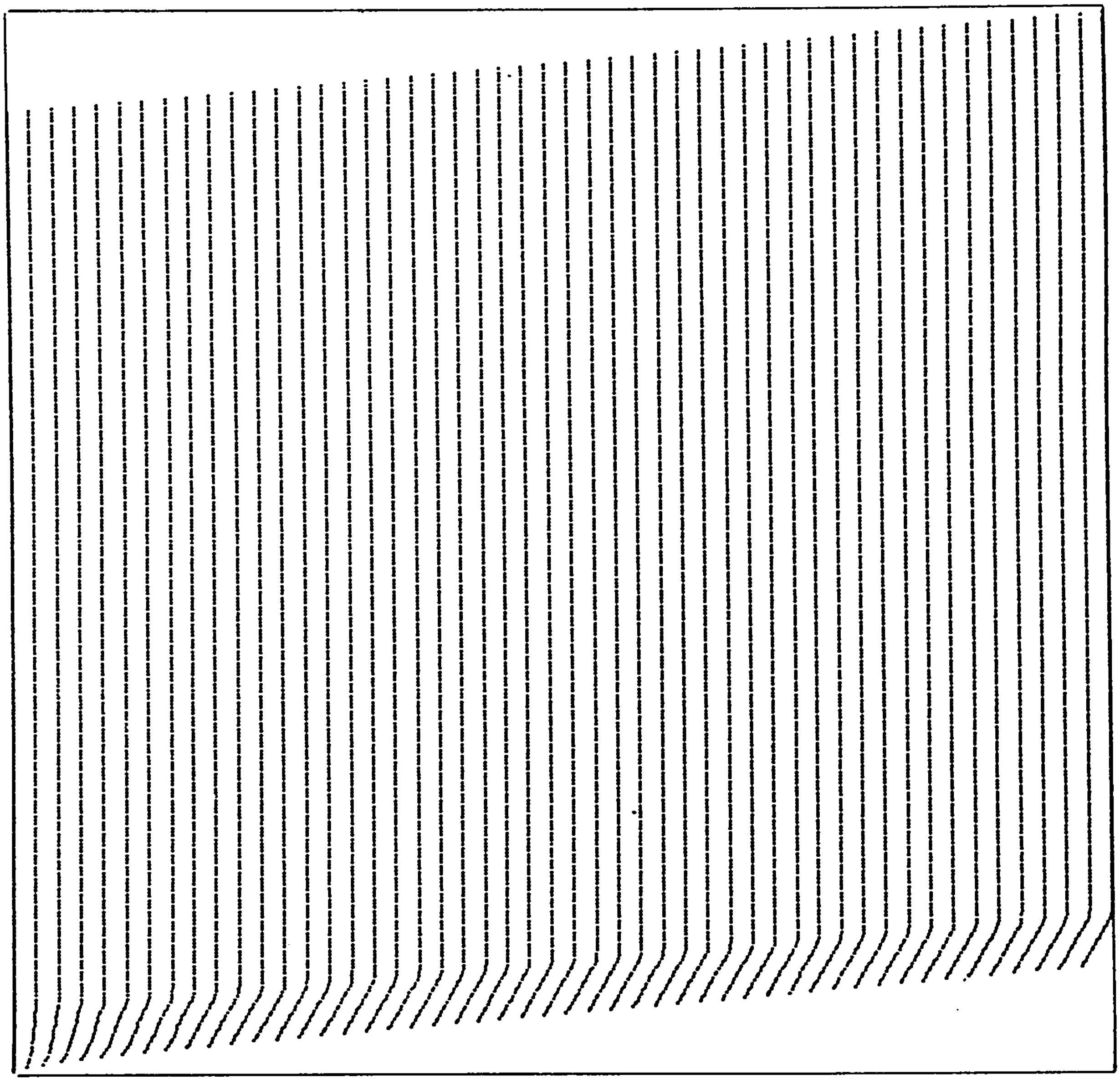
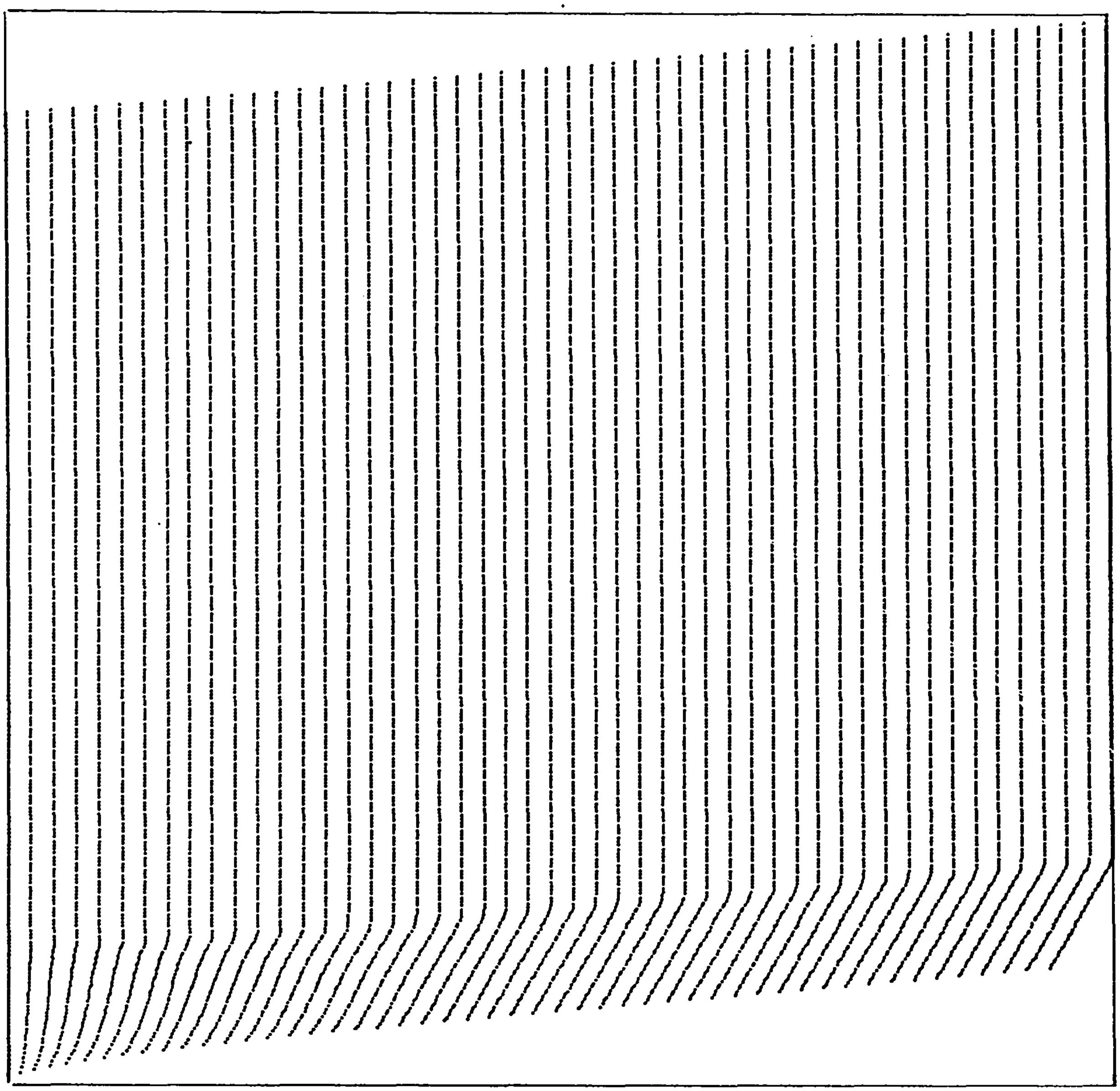


Figure 5. The computed isopycnics for the problem described in Figure 4.



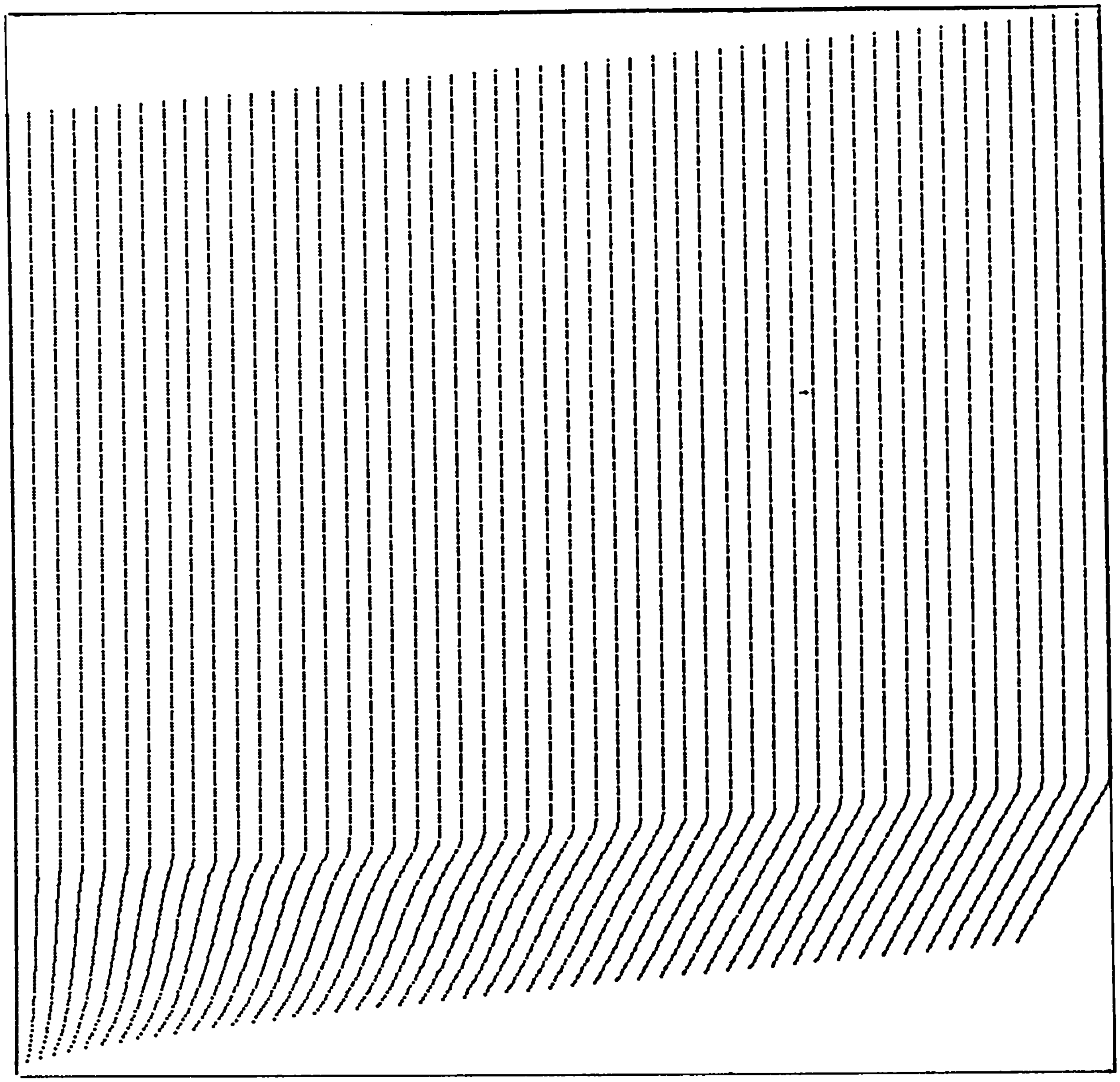
THE TIME IS 1.00000+000 MICROSECONDS AND THE CYCLE NUMBER IS 2.00000+002

Figure 6. The computed positions of the Lagrangian cell corners at 1, 2, 3, 4, and 5 μsec for the problem described in Figure 4. The X axis is 2.5 cm long and the Z axis is 13.75 cm long.



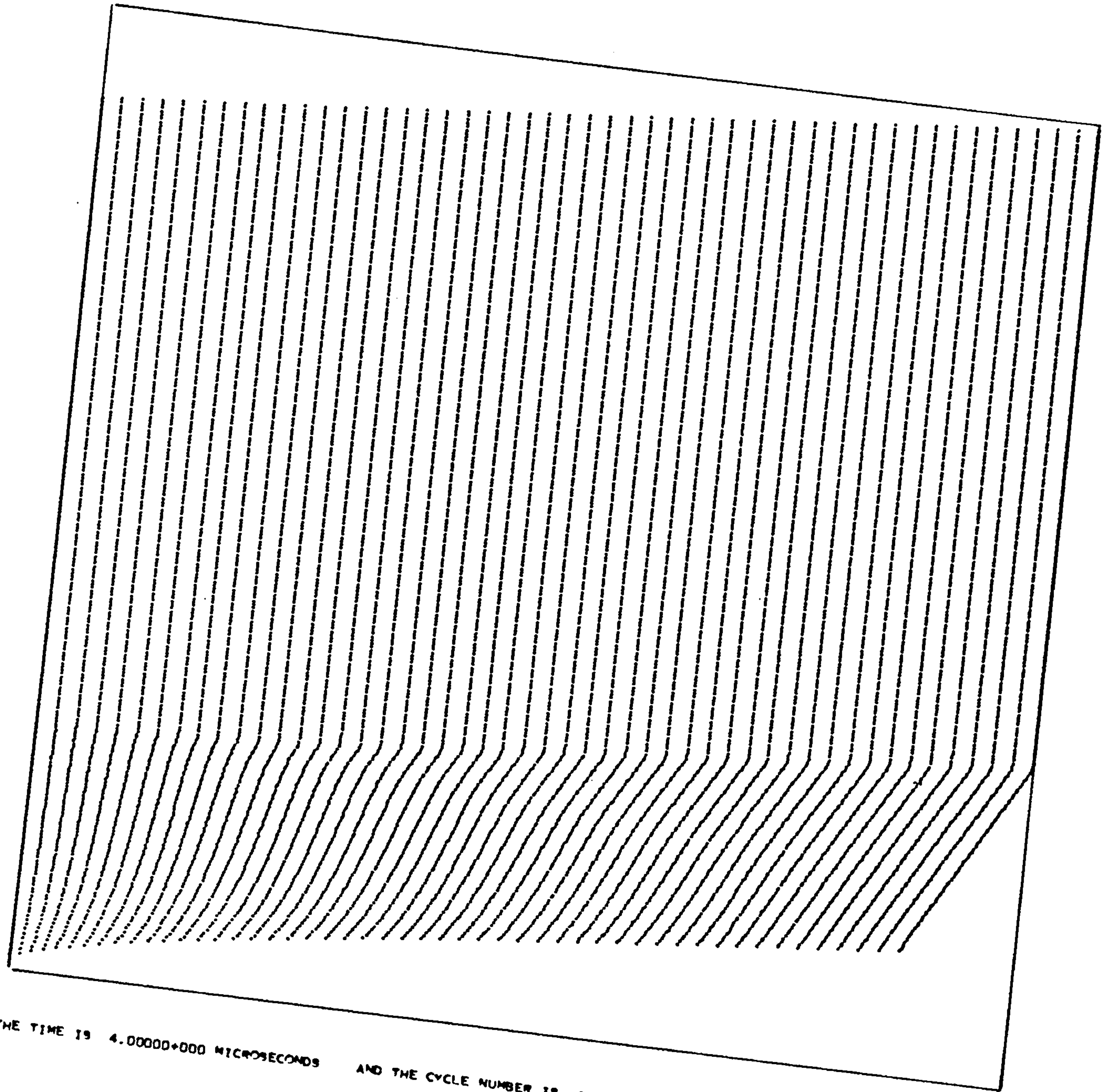
THE TIME IS 2.00000+000 MICROSECONDS AND THE CYCLE NUMBER IS 4.00000+002

Figure 6 continued.



THE TIME IS 3.00000+000 MICROSECONDS AND THE CYCLE NUMBER IS 6.00000+002

Figure 6 continued.



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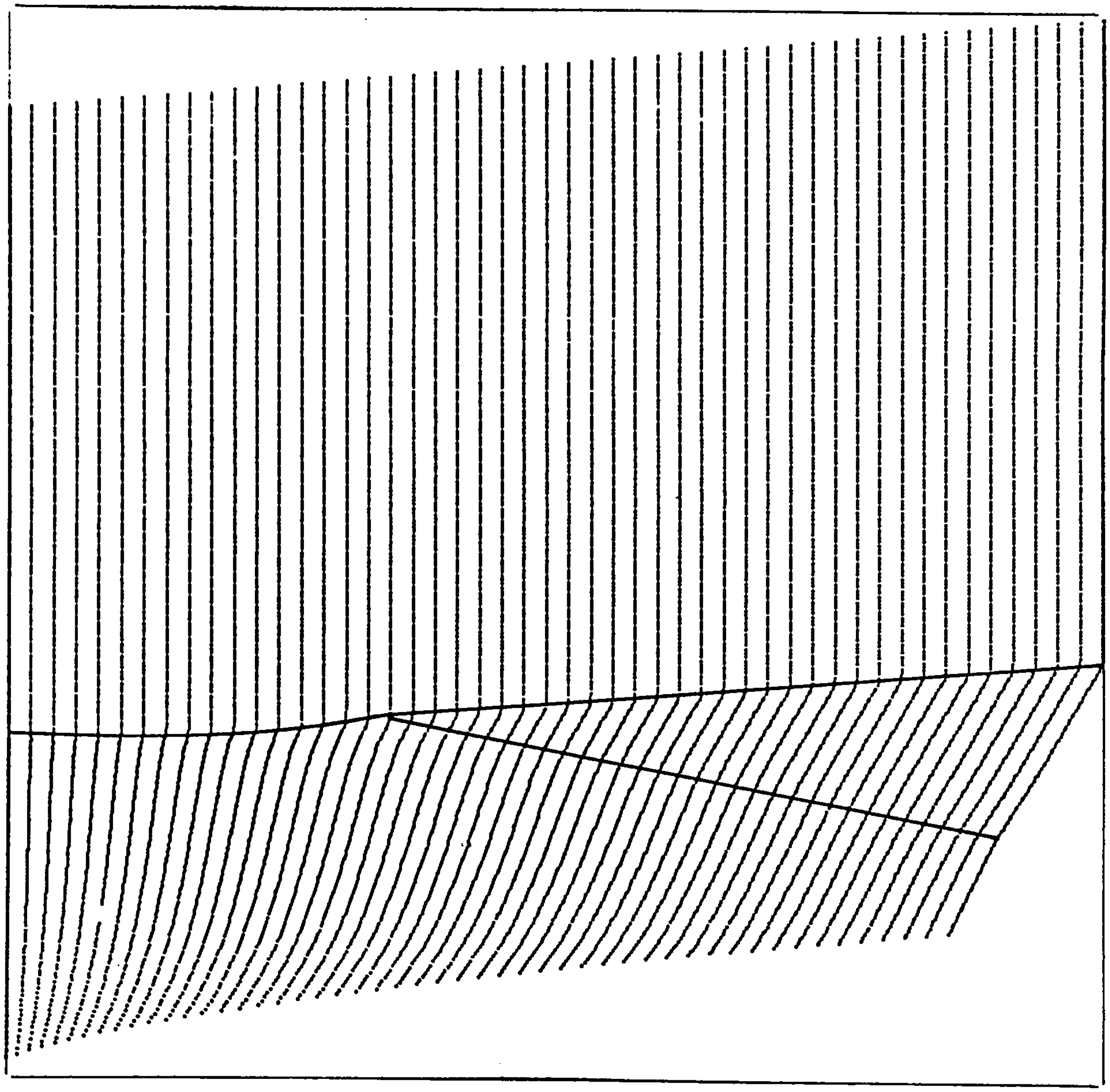


THE TIME IS 5.00000+000 MICROSECONDS AND THE CYCLE NUMBER IS 1.00000+003

Figure 6 continued.

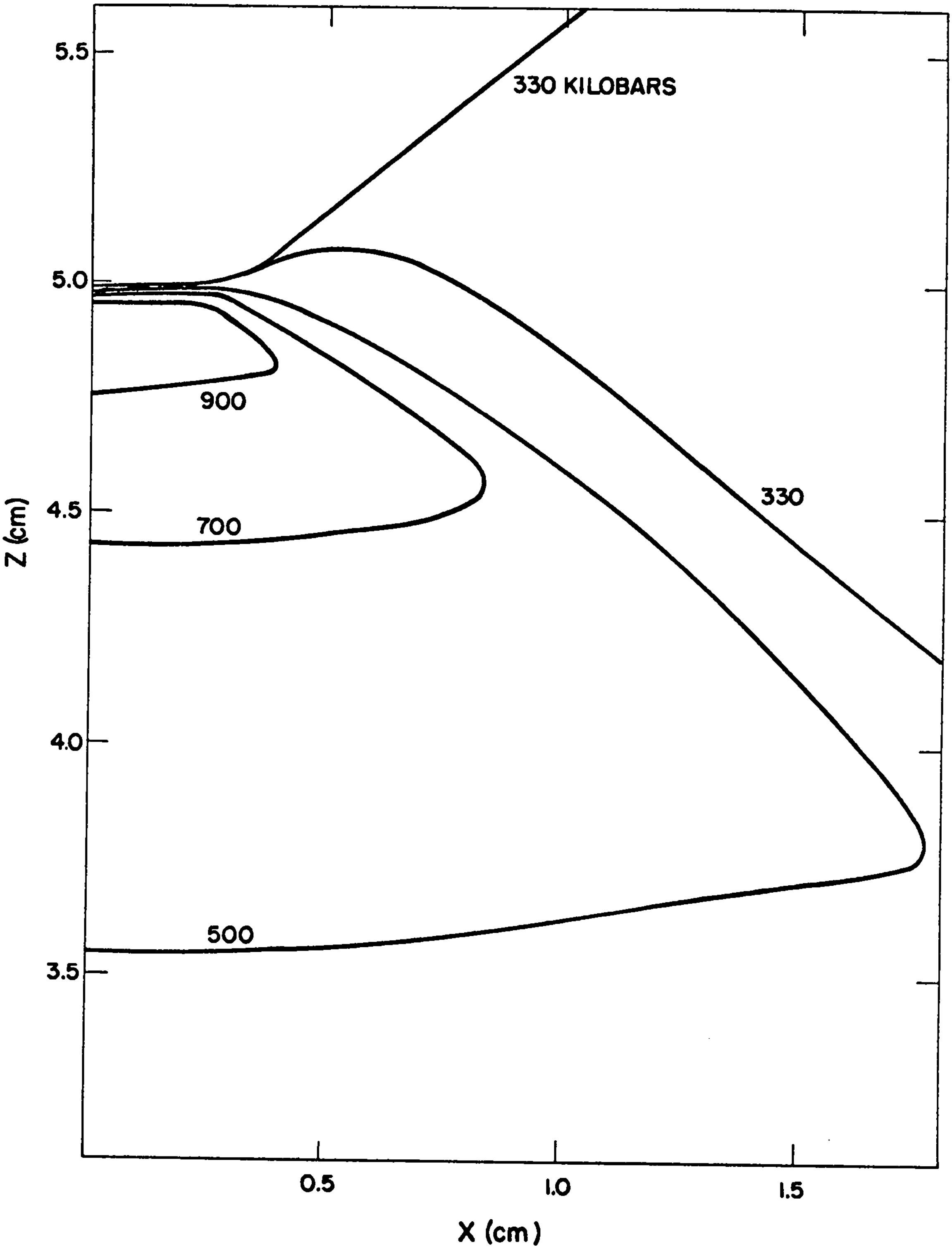
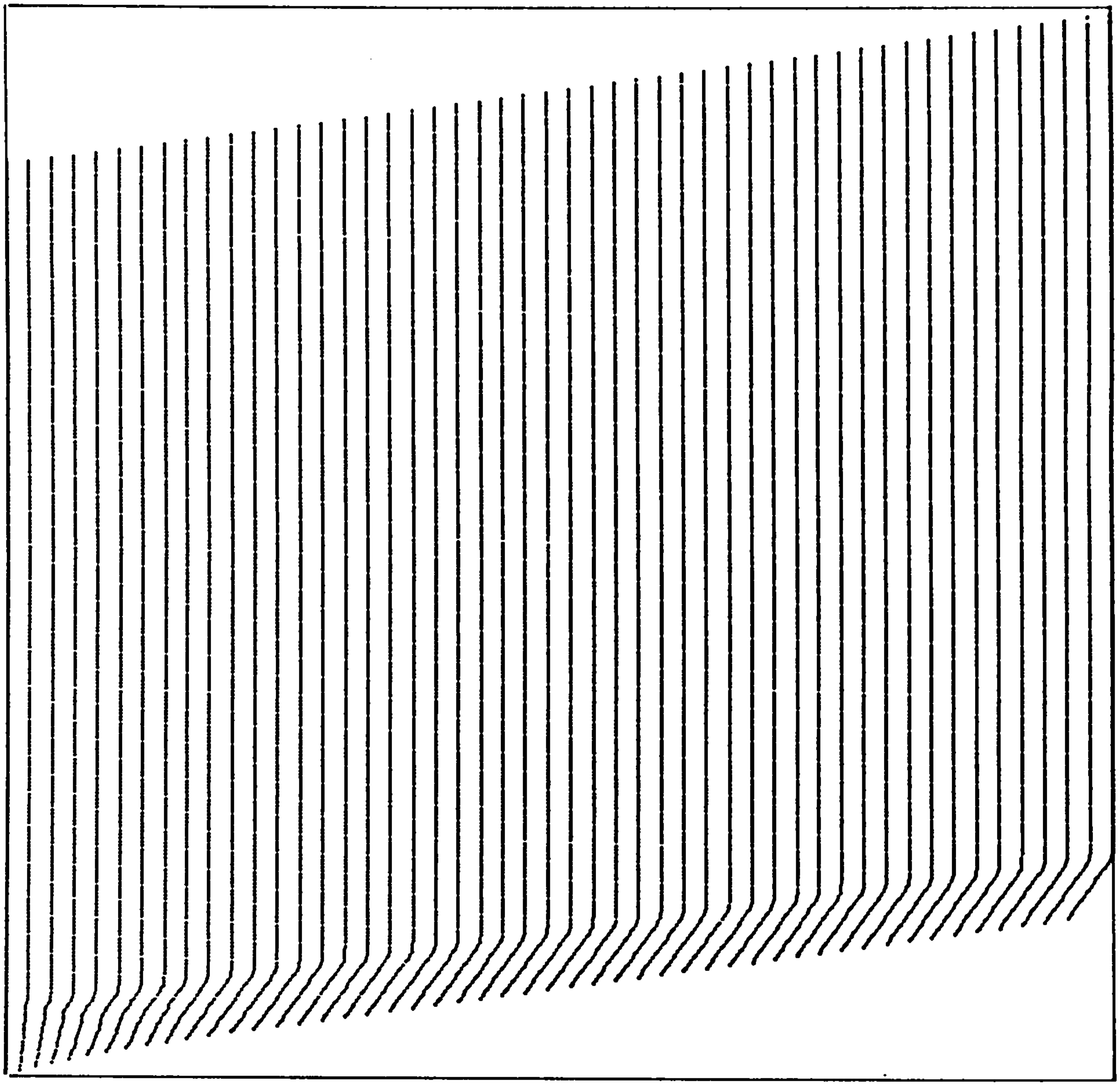
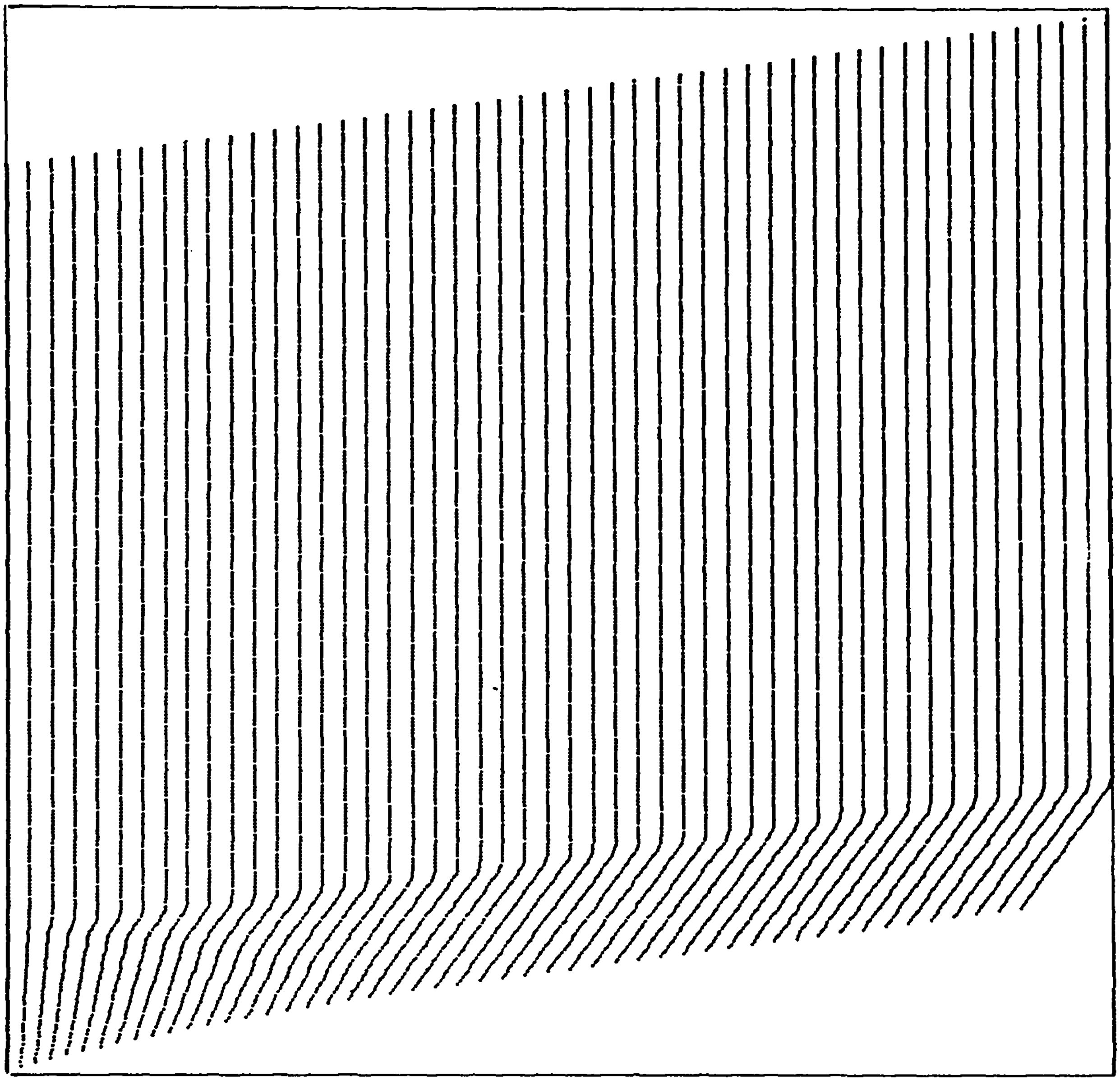


Figure 7. The computed isobars at 5 μsec for 330 kilobar shocks in aluminum with a 50° collision angle. Mach reflections occurs.



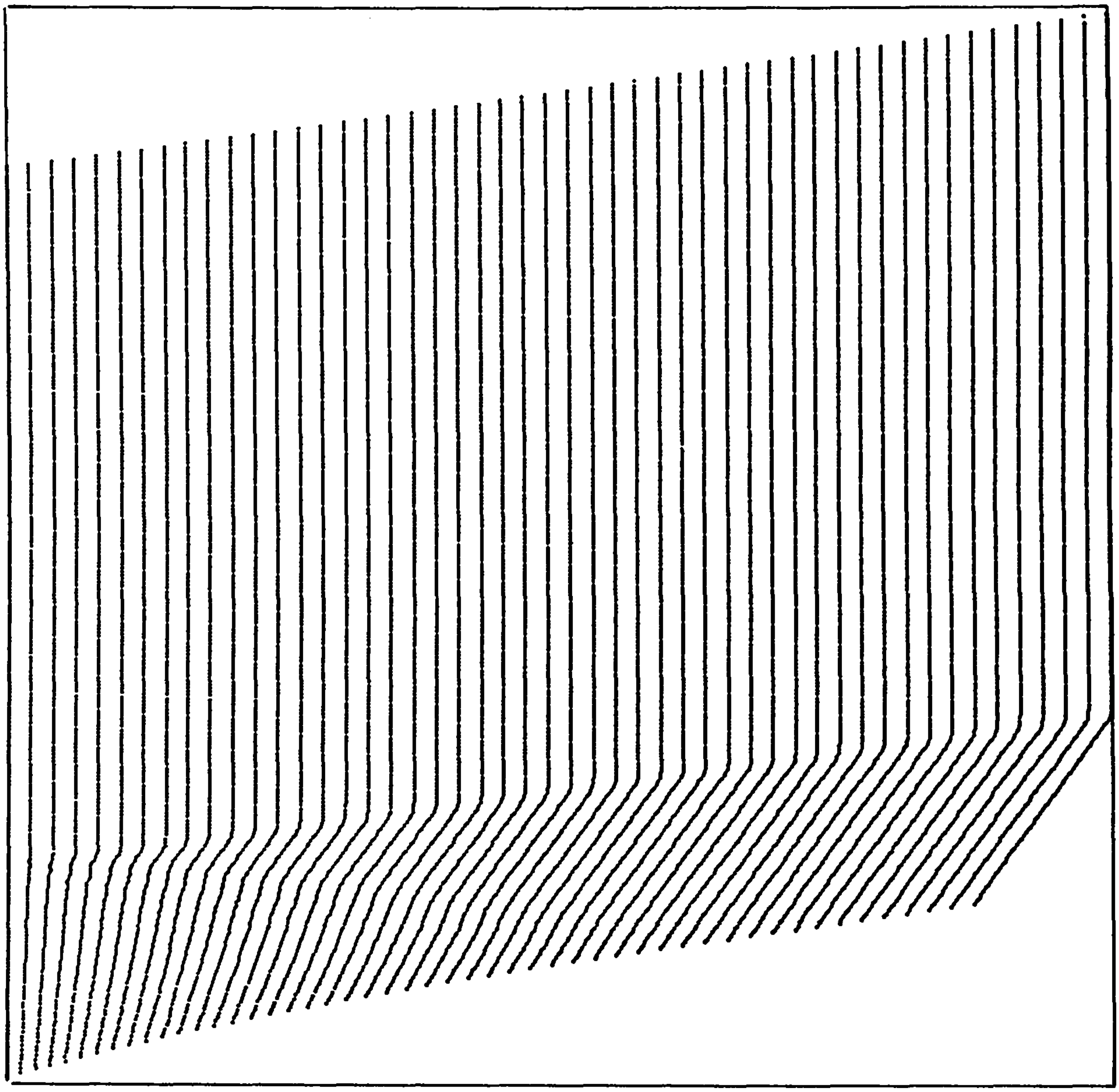
THE TIME IS 1.00000+000 MICROSECONDS AND THE CYCLE NUMBER IS 2.00000+002

Figure 8. The computed positions of the Lagrangian cell corners at 1, 2, 3, 5, and 6 μsec for the problem described in Figure 7. The X axis is 2.5 cm long and the Z axis is 14.6 cm long.



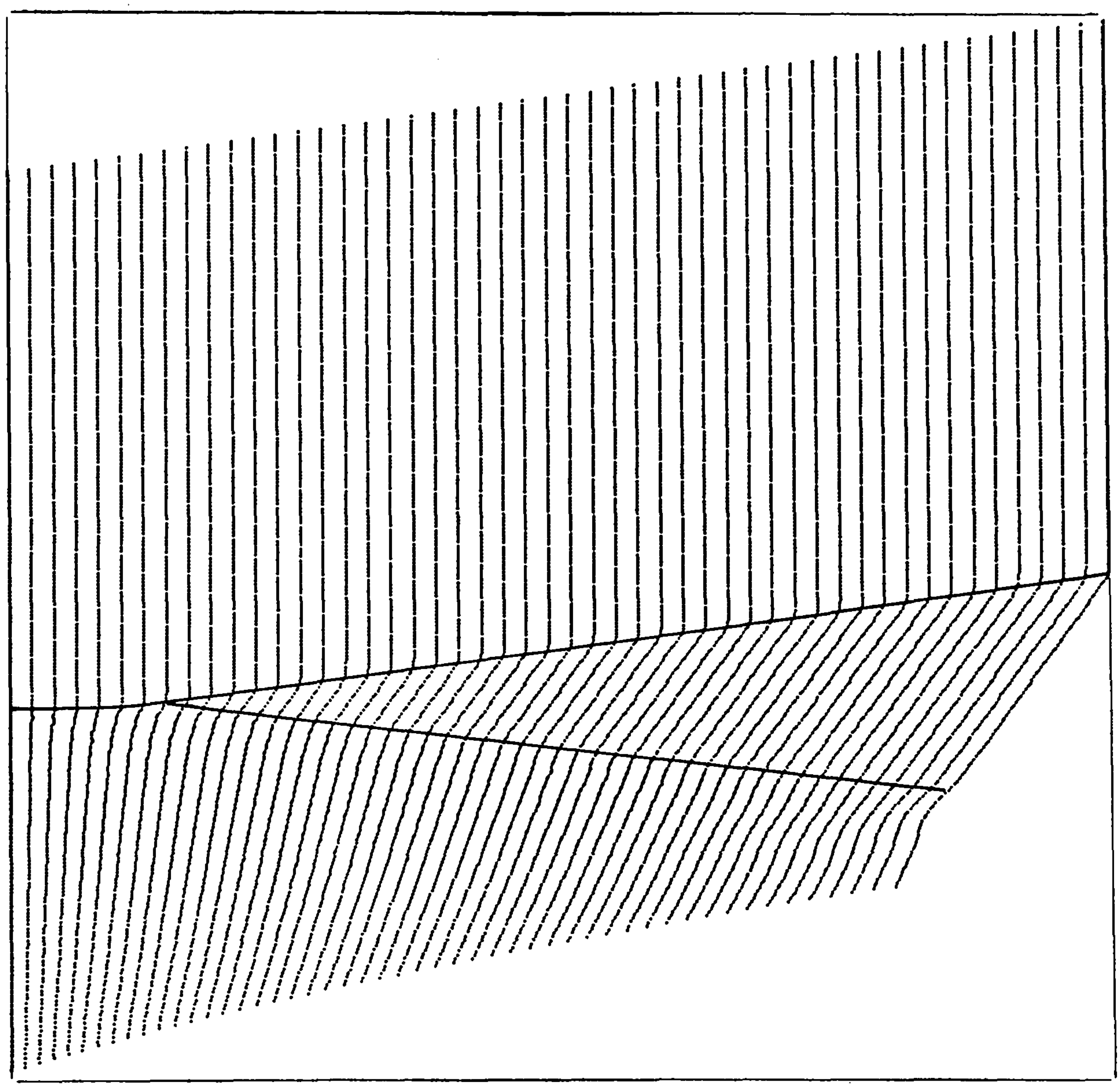
THE TIME IS 2.00000+000 MICROSECONDS AND THE CYCLE NUMBER IS 4.00000+002

Figure 8 continued.



THE TIME IS 3.00000+000 MICROSECONDS AND THE CYCLE NUMBER IS 6.00000+002

Figure 8 continued.



THE TIME IS 5.00000+000 MICROSECONDS AND THE CYCLE NUMBER IS 1.00000+003

Figure 8 continued.

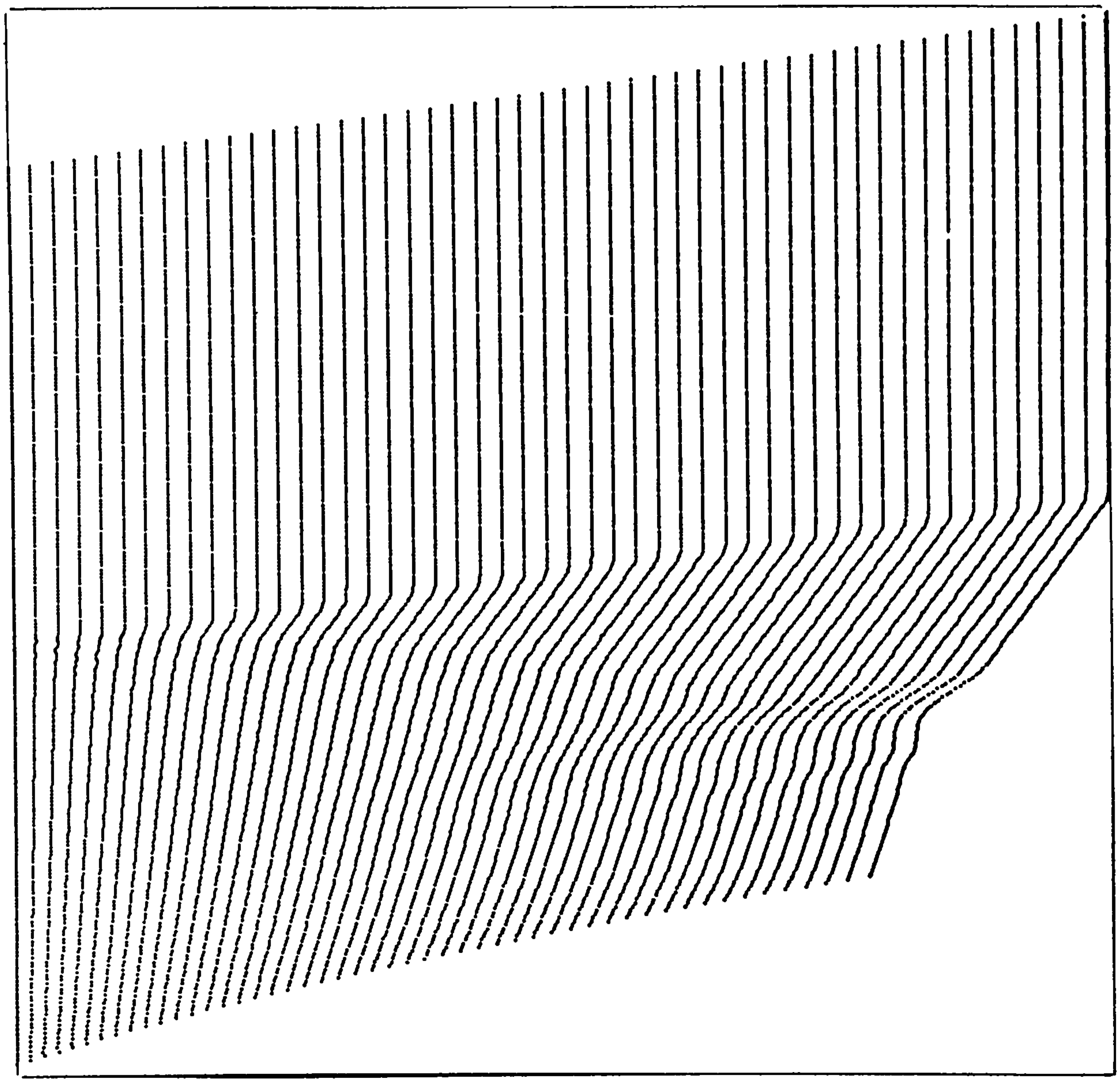


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Figure 8 continued.

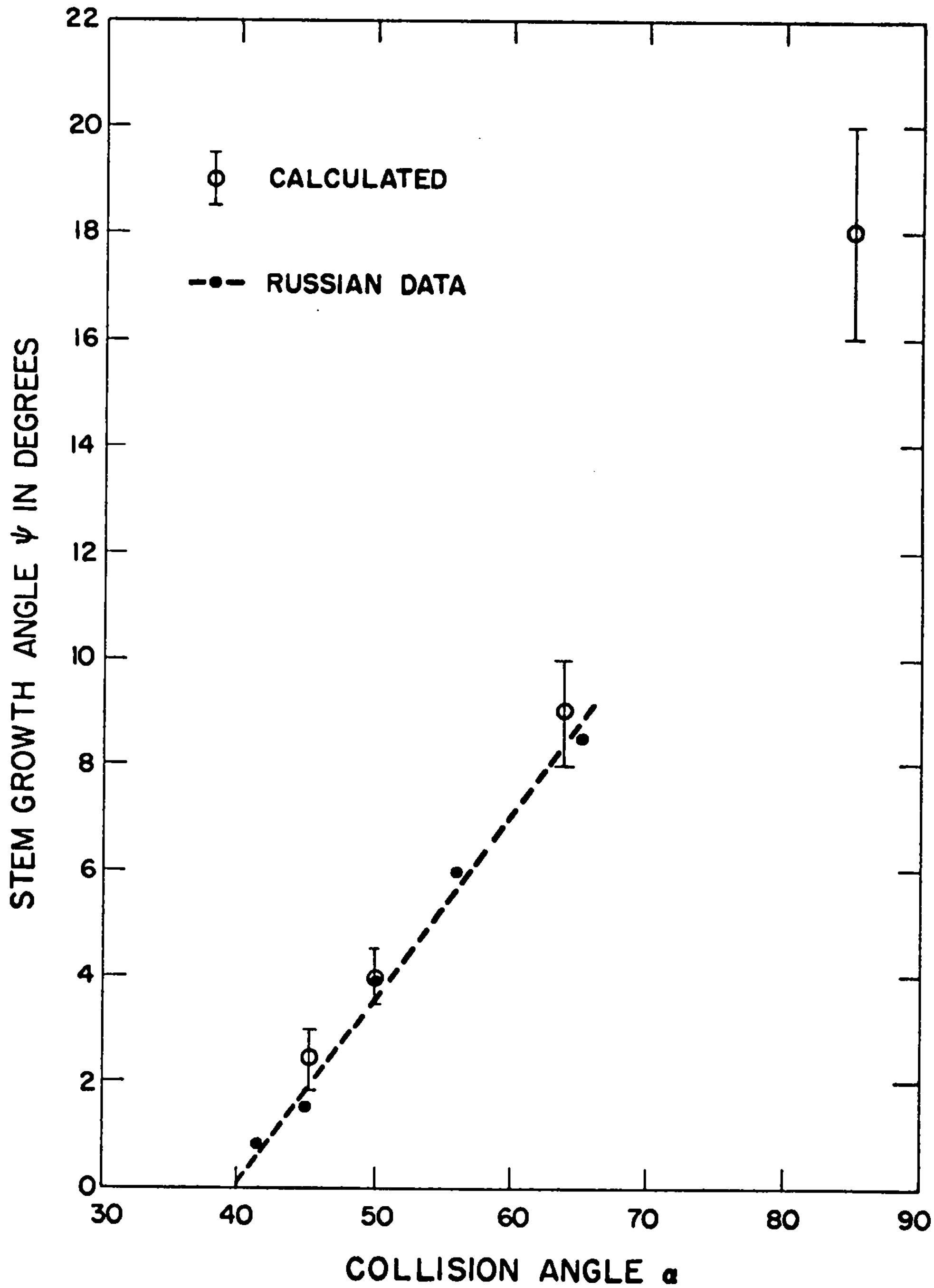


Figure 9. The computed growth angle ψ of the stems as a function of collision angle α of 330 kilobar shocks in aluminum. The Russian experimental data are also shown.

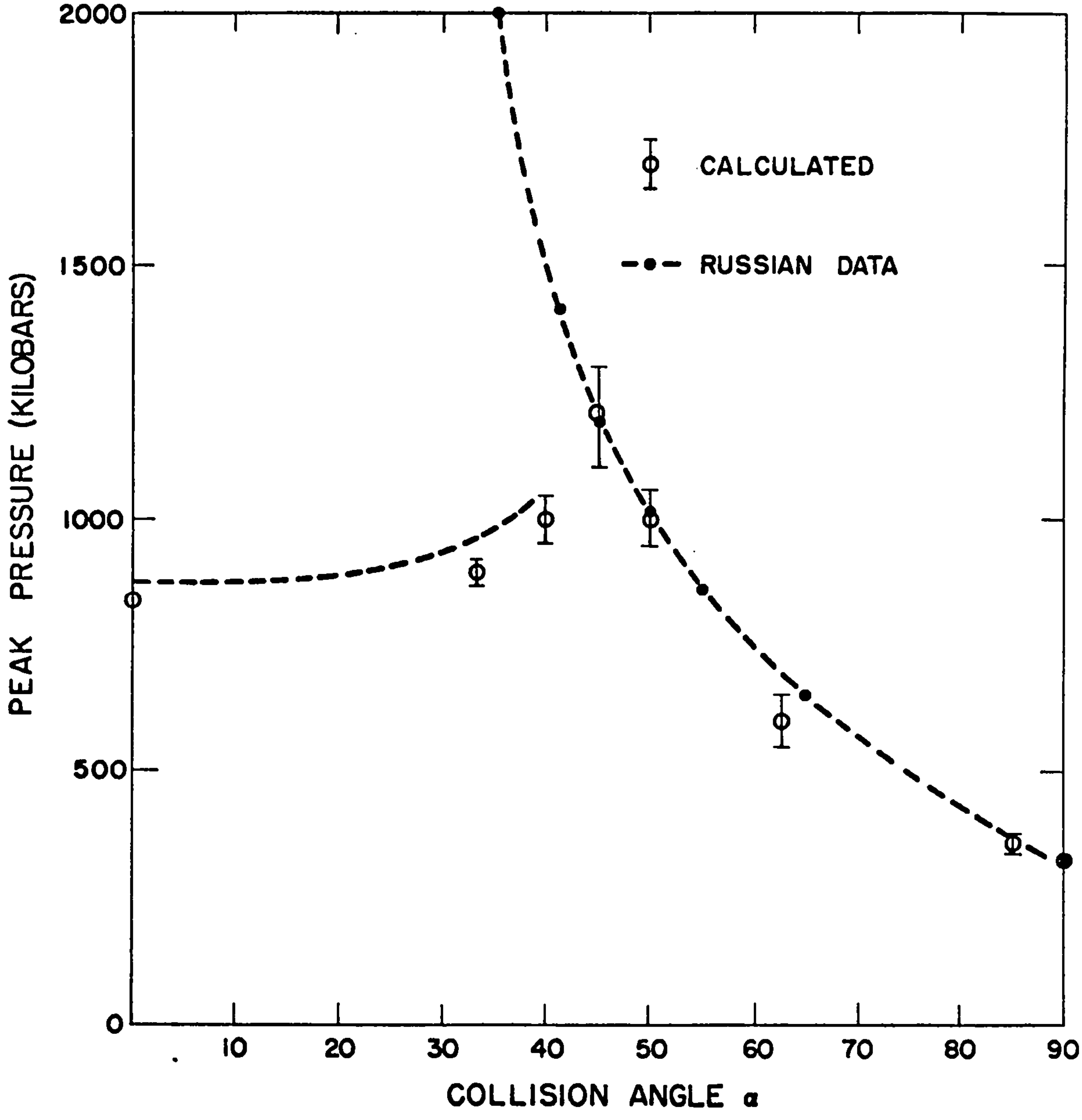


Figure 10. The computed peak pressure as a function of collision angle α of 330 kilobar shocks in aluminum. The Russian experimental data are also shown.

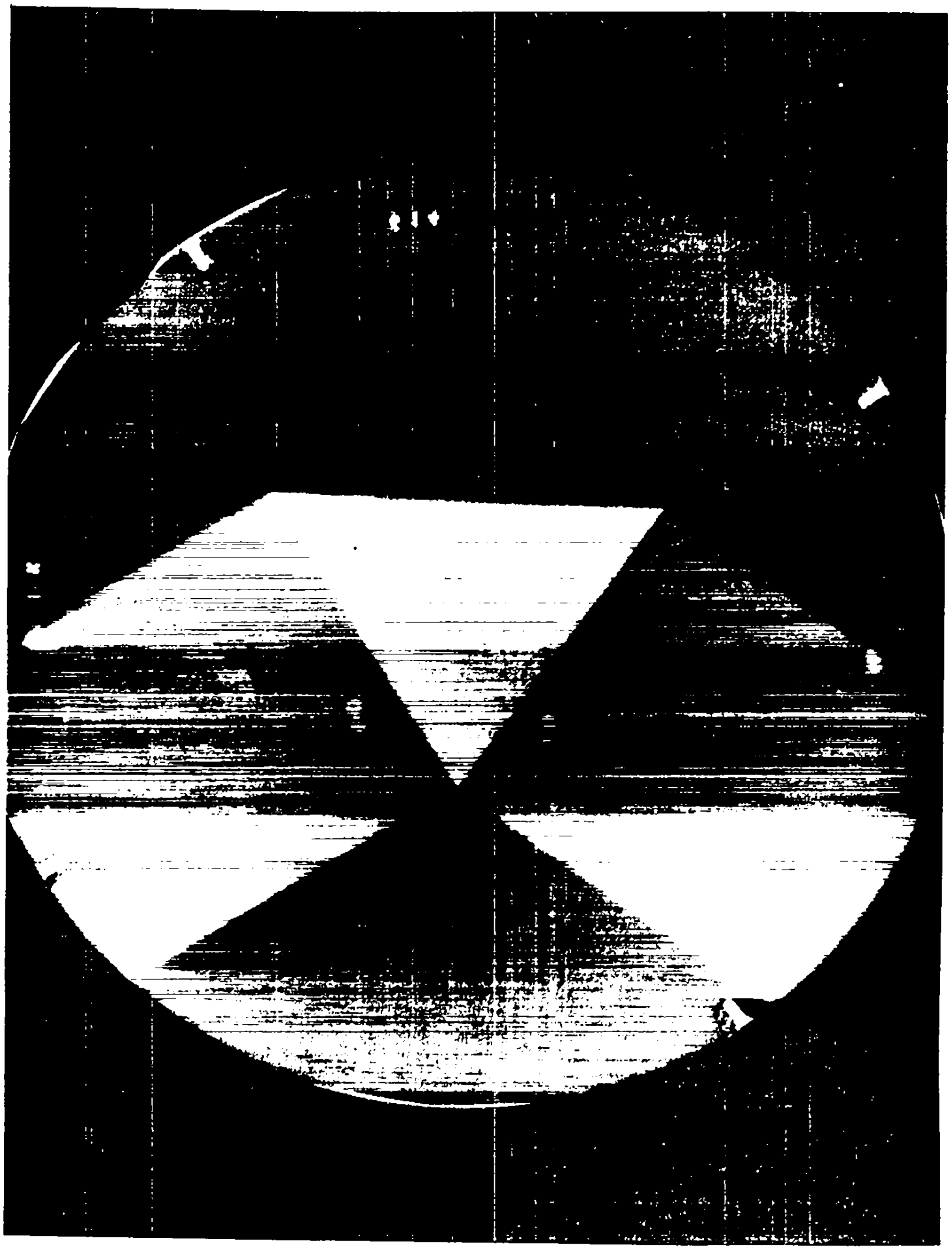
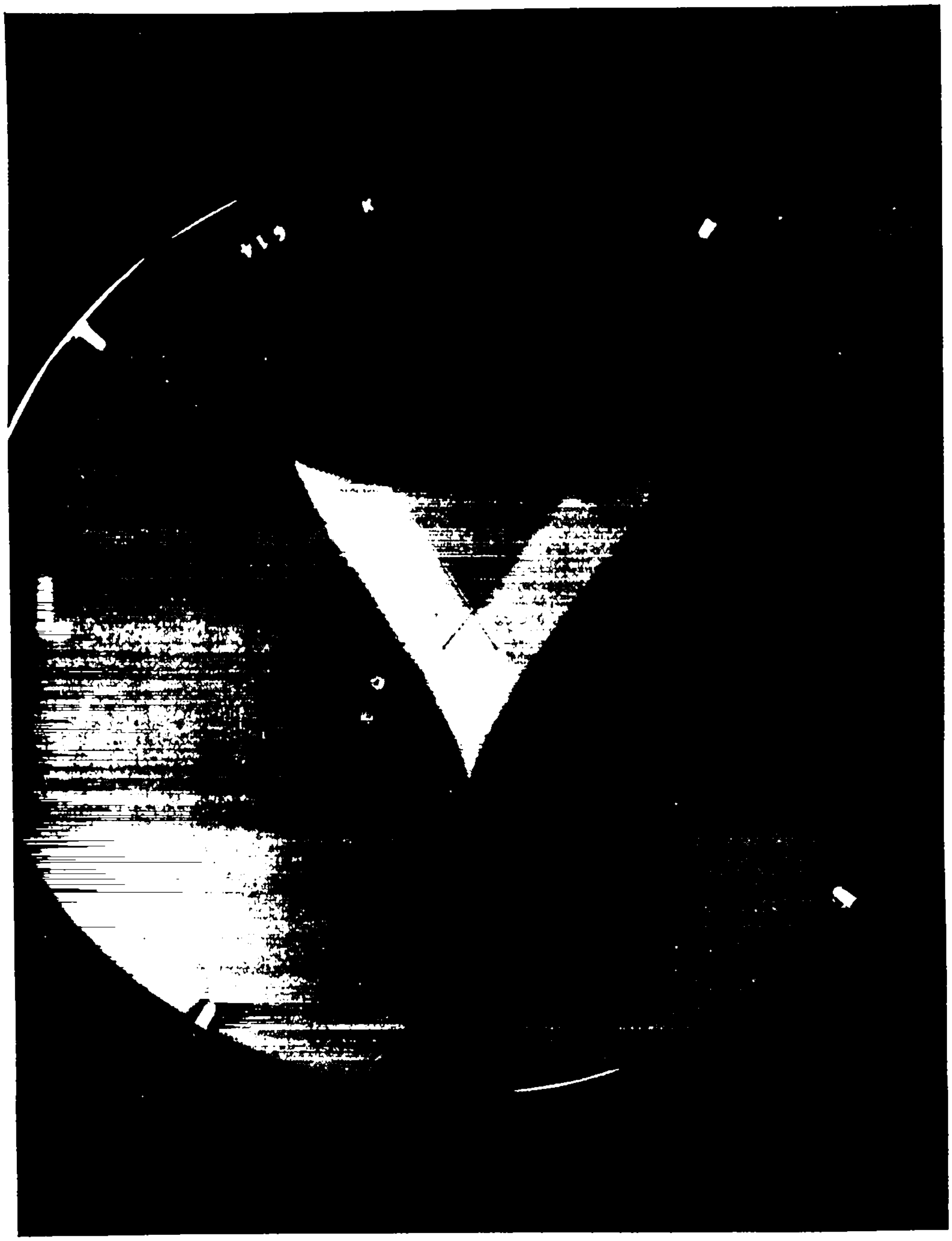


Figure 11. The PHERMEX radiograph of the regular reflection of 330 kilobar shocks in aluminum with a 33.7° collision angle. The initial shot geometry is shown on the first radiograph. The outline of the shocks has been sketched on the second radiograph since the reproduction is poor.



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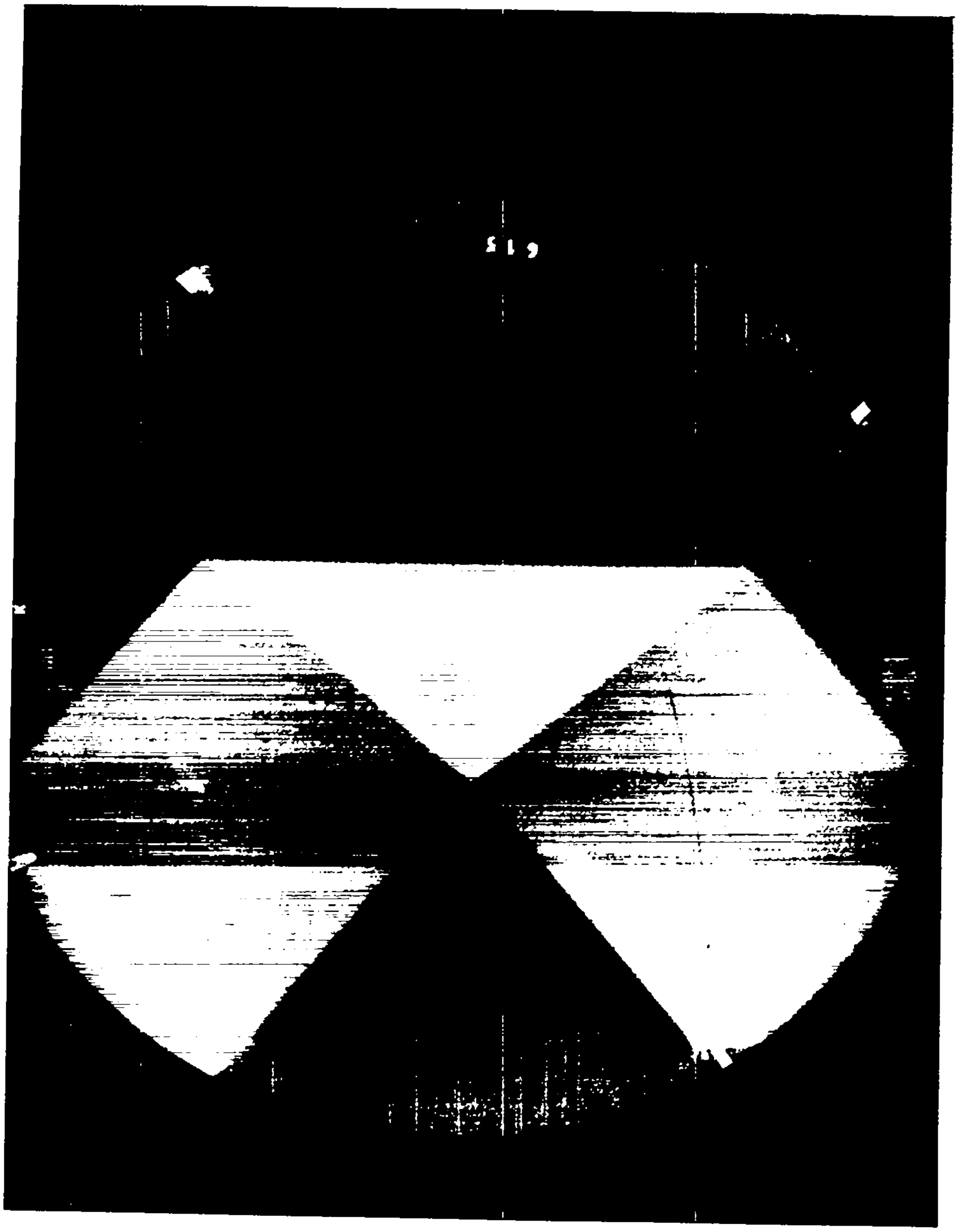
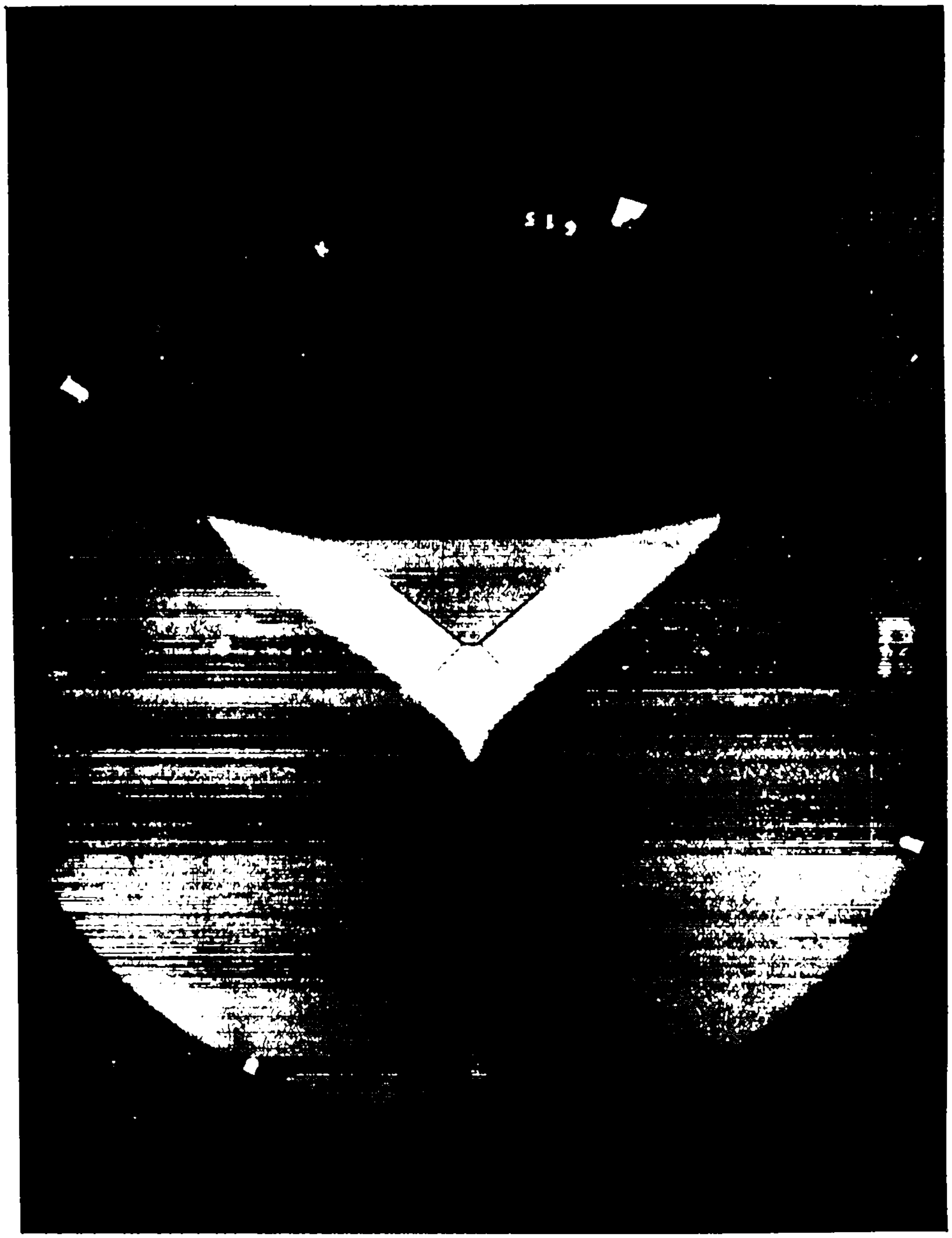


Figure 12. The PHERMEX radiograph of the Mach reflection of 330 kilobar shocks in aluminum with a 50° collision angle. The initial shot geometry is shown in the first radiograph. The outline of the shocks has been sketched on the second radiograph since the reproduction is poor. The third print shows the stem detail of the second radiograph as obtained using high contrast photographic processing.



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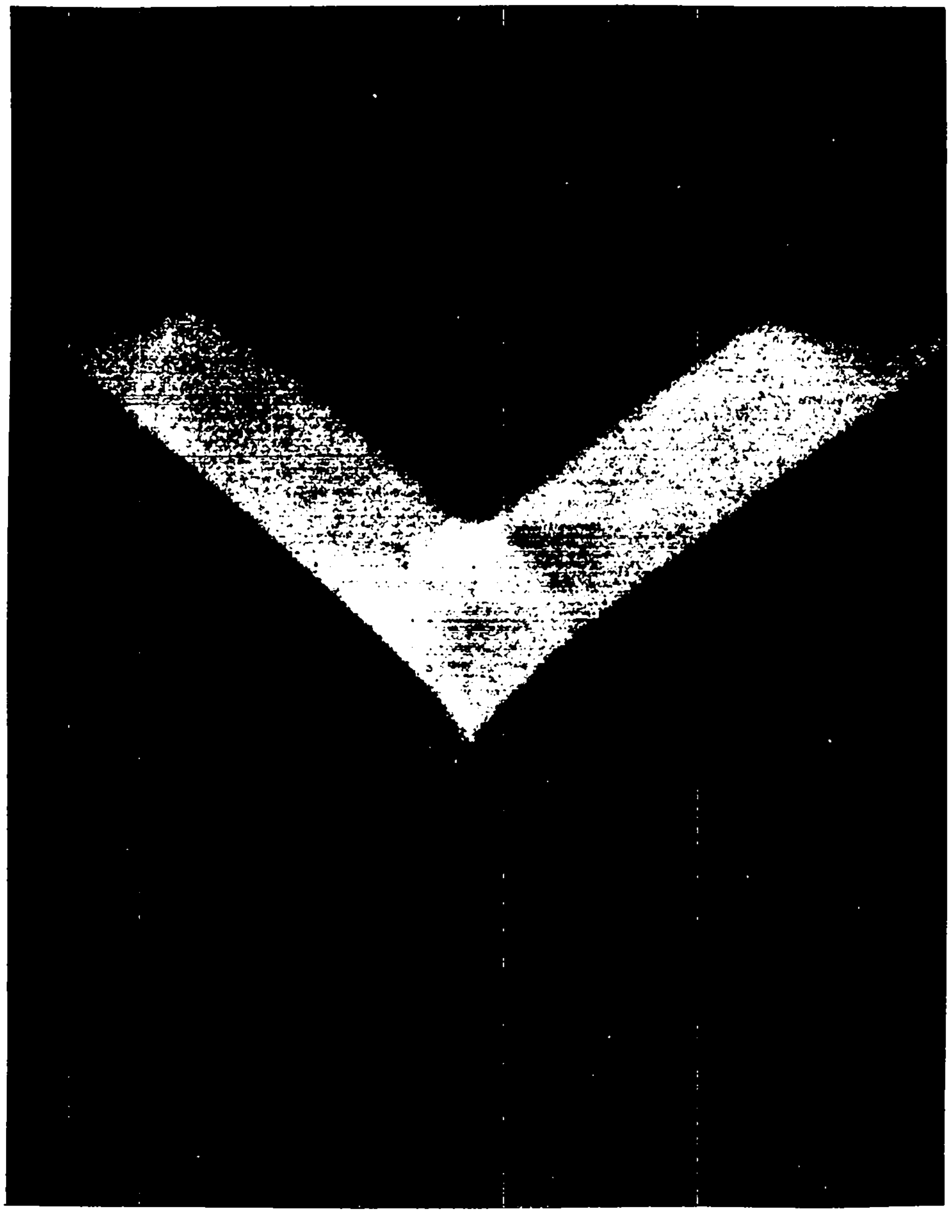

Figure 12 continued.