grams, which indicates an initial density of $\rho = 1.3$ g/cm^3.

A variety of other materials was present in the source region, and an accurate equation of state for this region would be difficult to obtain. Therefore, to simulate the first 100 μsec of the source region, a constant value for γ was used and the pressure was calculated by $p = (\gamma - 1) \rho_e$. Two calculations with $\gamma = 1.5$ and 1.7 were performed, which gave nearly identical results at 100 μsec. The larger γ gave larger initial pressures, which acted to drive the shock down the tunnel faster. However, the larger pressure also acted to push out the walls of the cavity and tunnel at a more rapid rate, thereby relieving itself faster.

One-dimensional studies [*Butkovich*, 1967] indicate that within about 100 μsec, the ground shock from a 2.2-kT energy source can vaporize approximately 150 tons of alluvium. During this initial vaporization period, the various gases in the source are undoubtedly undergoing a very violent mixing. Within a few tens of microseconds, the source region contains a much larger mass of vaporized rock than the initial mass of source-region materials. The source region gas may then be represented by an equation of state for SiO_2 [*Butkovich*, 1967].

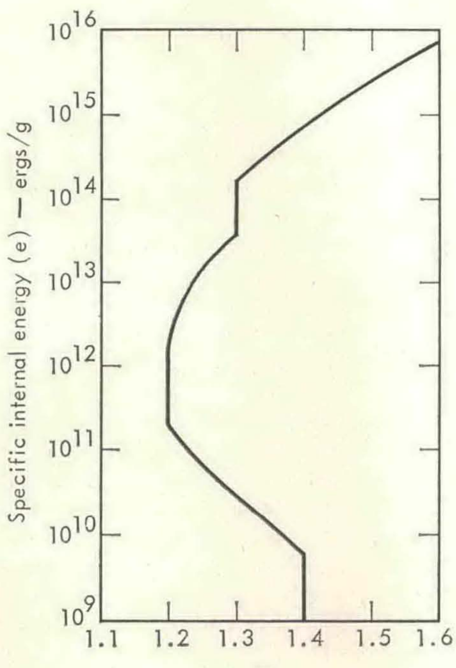

Fig. 12. Equation of state for air used by Pufl, specific internal energy as a function of γ: where $P = e\,(\gamma - 1)\rho$.

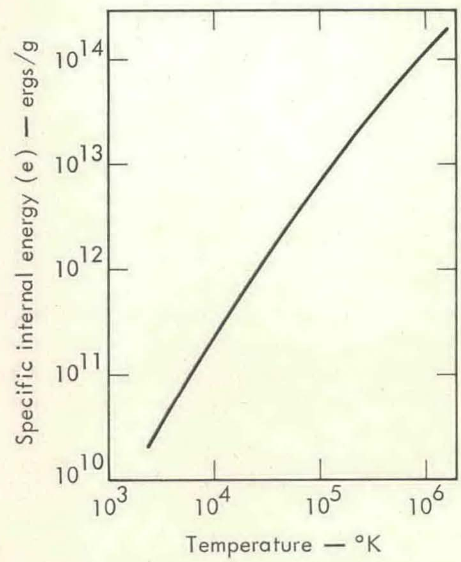

Fig. 13. Relationship used in Pufl to obtain temperature for a given specific internal energy.

At 100 μsec, the two calculations with $\gamma =$ 1.5 and 1.7 indicate a radial vaporization contour that corresponds favorably to the 150 tons of vaporized mass indicated by the one-dimensional calculations. Because a considerable amount of vaporized rock gas is undoubtedly mixed with the source-region gases by 100 μsec, and because Tensor zones at present have no provision for varying their masses, these constant γ calculations were terminated at 100 μsec.

The Pufl and Tensor results at 100 μsec were combined, and the problem was rezoned to include the vaporized wall material in Pufl. This combination was performed by conservation of internal energies, momentums, and total masses of the vaporized material over each of about 75 axial sections of the problem. These rezoned conditions, which are shown in Figure 14, represent Marvel at 100 μsec. These conditions are used as the initial conditions for the remaining calculations.

Calculations and Comparison with Data

The remaining calculations simulate the air shock and flow of gas down the tunnel. By comparison of various calculational results, the relative effects of radial expansion, heat transfer, and mass entrainment can be observed.

The first calculation, TP1, is an idealized case and may be used as a basis for comparison. In TP1, the friction, heat transfer, and mass addition terms were suppressed by setting $C_f = \sigma = C_H = 0$ and $\eta = \infty$ in equations A1–A6. As seen in Figure 15, air-shock velocity in this calculation is nearly unattenuated. The slight attenuation observed in this calculation is due to radial expansion of the cavity and tunnel walls, which reduces the pressure behind the shock. For comparison, the data from Figure 8 are also shown.

In the second calculation, TP2, the effect of heat transfer in attenuating the air shock is

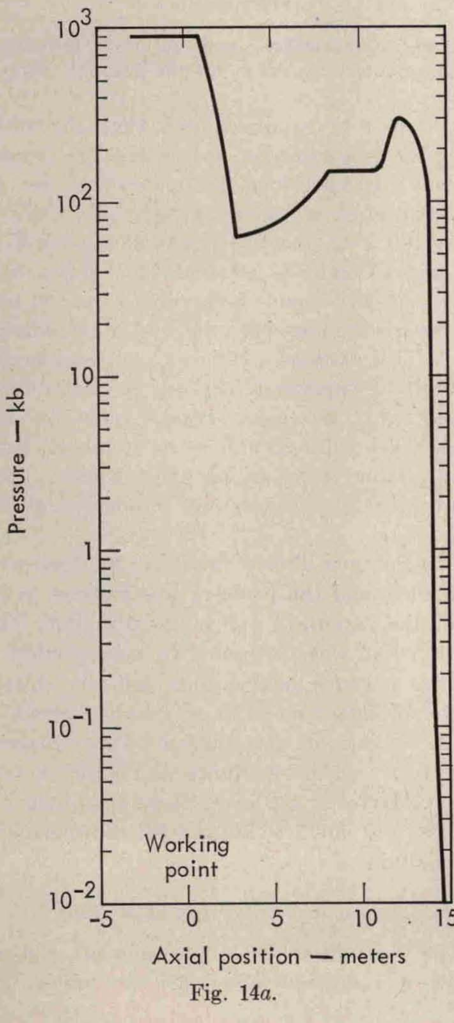

Fig. 14*a*.

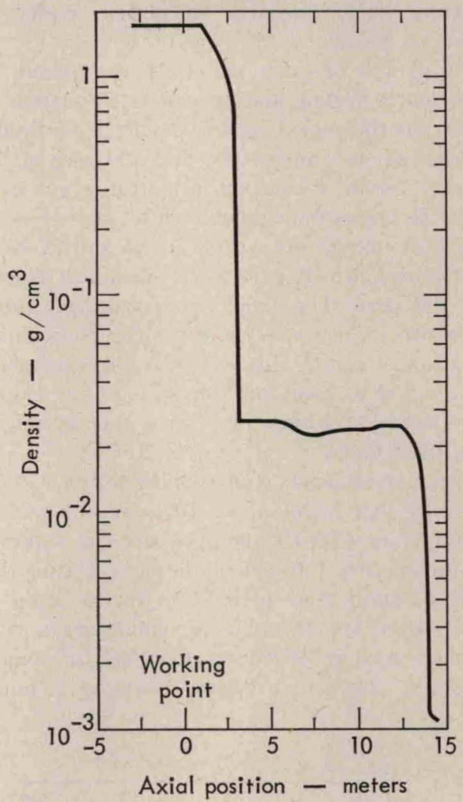

Fig. 14*b*.

investigated. As mentioned in section 1, the average offset in joining the sections of the tunnel was less than 0.3 cm. The 0.3-cm offsets were treated in the calculations as an average roughness, rather than as discontinuities. An estimate of 0.3 cm as the maximum surface roughness k_s gives a radius-to-surface-roughness ratio, $r/k_s = 170$. For turbulent flow with $r/k_s = 170$, a dimensionless coefficient of friction of $C_f/2 = 0.003$ is reasonable [*Schlichting*, 1960]. Invoking Reynolds's analogy (which assumes that the same mechanism induces the transfer of heat and momentum in turbulent flow), the dimensionless coefficient of heat transfer C_H is assumed to be $C_H = C_f/2 = 0.003$. These values are used for the dimensionless coefficients in the TP2 calculation. By setting the turbulent transpiration coefficient $\eta = \infty$ in TP2, mass addition is suppressed, and the effect of heat transfer may be examined.

Shock-arrival results from TP2 are shown in Figure 15, where it is seen that without mass addition, heat transfer does not account for the