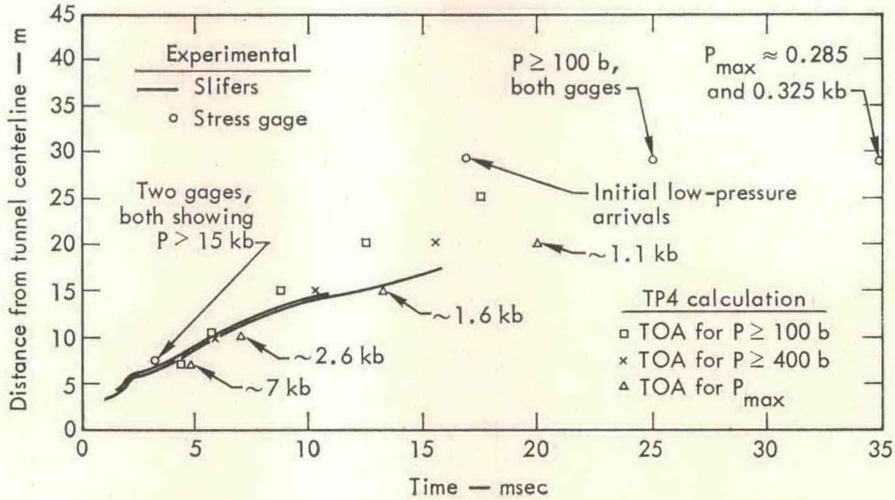

Fig. 16. Free-field measurements and calculated results for the vertical instrumentation hole.

culations indicate that some mass flow reverses direction at late times, the amount is small. Thus, most of the mass flow should end up at roughly the farthest position attained in the tunnel. The higher concentration of ablated chemical tracers near the end of the tunnel (see Figure 7) appears to be consistent with this result.

The TP4 calculation indicated that 4×10^{18} ergs of energy (approx. 5%) were transferred to the walls of the tunnel by heat transfer during the calculated 2.8-msec transit of the air shock down the tunnel. The calculation indicated that about ½ ton of wall material entered the flow during this interval. The mass addition rate exponentially decreases with time, and at 20 msec, approximately 1 ton of material had been entrained. Information from Table 1, which infers the amount of ablated material from the chemical tracers, can be used to estimate the amount of entrained wall material. Such rough estimates appear to be consistent with the 1-ton value calculated by TP4 for the entrained wall material at 20 msec.

At 20 msec, the TP4 calculation indicated that only a few per cent of the total energy was in kinetic energy. Most of this kinetic energy was located behind the shock front in the media (in Tensor) surrounding the tunnel, not in the tunnel gas (not in Pufl). In the calculation, approximately 17% of the energy was located at an axial position *beyond* 22 meters down the tunnel. Since no postshot drill holes were dug into the side of the cavity away from the tunnel, the total volume of the final cavity can only be estimated. Let us generously assume that the final main cavity is spherical with a 22-meter radius (the maximum radius indicated by postshot drill samples in Figure 7) and a volume of 4.5×10^4 m^3. The volume of the final tunnel beyond 22 meters also can be obtained from the radii given in Figure 7; it is found to be about 6.7×10^3 m^3. This is approximately 15% of the estimated main cavity volume. Thus, assuming that energy scales like the volume, both the calculations and the postshot drill samples indicate that at least ~15% of the energy was preferentially channeled down the tunnel.

CONCLUSIONS

By both calculation and experimental evidence, the initial shock traveled outward in the alluvium at about 2 m/msec. This is over 50 times slower than the initial 130-m/msec (Mach 380) velocity of the air shock. When the air shock reached the end of the tunnel (122 meters, ~3.5 msec), the shock in alluvium had traveled only 7.5 meters from the working point. The calculations and chemical-tracer analysis likewise agree that significant ablation occurred during the air-shock transit down the tunnel and that ablation has a primary effect in attenuating the air shock.

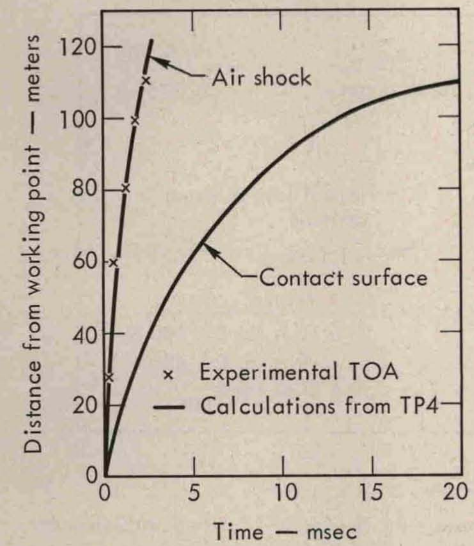

Fig. 17. Air-shock and contact-surface time of arrival.

The experimental and calculational results indicate that the emplacement of a nuclear explosive in a nonspherical initial geometry can result in significant nonspherical effects on the surrounding media. In Marvel, approximately 15% of the energy was channeled to distances beyond the main cavity radius. Energy was preferentially channeled down the tunnel, primarily because the velocity of the air shock in the tunnel was higher than the velocity of the alluvium shock.

If the shock in the surrounding media were to get ahead of the shock in the tunnel, the developed pressure gradient (existing between the 1 bar of tunnel air and the higher pressures behind the alluvium shock) would act to close the tunnel. A closure of the tunnel would inhibit the preferential flow of energy down the tunnel. Thus, the equation of state and the other properties of the materials immediately surrounding the energy source and the conditions in the tunnel can both be significant in determining the distribution of energy. However, we feel that, in Marvel, the large density difference between alluvium and air had the first-order effect on the initial shock velocities and the preferential distribution of energy. Since the densities of rocks are comparable to alluvium ($\rho \sim 2$ g/cm^3), it is felt that performing Marvel in a different media would not result in a significantly different distribution of energy. (Calculational parameter studies indicate that this is the case.) However, other effects that are more strongly material dependent, such as the extent of cracking, may significantly differ in different types of rock.

Whether significantly more energy could be channeled down a tunnel designed, for instance, twice as long as Marvel still remains to be answered.

Since flow in the tunnel would scale approximately as the ratio of the length to diameter, a tunnel of significantly smaller diameter would cause a faster attenuation. If this attenuation is fast enough, the shock in the surrounding material might overtake the tunnel shock in some designed instances. In such a case, the energy distribution could be significantly different.

The favorable agreement of the experimental data with the numerical simulation indicates that the Tensor-Pufl code can be used as a predictive technique for similar emplacements.

Marvel demonstrated the feasibility of hydrodynamically tailoring energy from a nuclear source. Economically tailoring nuclear energy for a particular application, such as mining or gas stimulation, is a fundamental goal of Plowshare.

APPENDIX A. PUFL CONSERVATION EQUATIONS

Pufl Equations

Conservation of mass.

$$\frac{\partial \rho}{\partial t} = \frac{1}{V}\left(-\rho\,\frac{\partial V}{\partial t} + \phi m' S\right) \qquad \text{(A1)}$$

$\phi m'S$ describes the change in density ρ due to the mass flux m'. The zone has a volume V and contacts the tunnel walls over a surface area. ϕ is defined in appendix B.

The momentum equation.

$$\frac{\partial u}{\partial t} = \frac{1}{m}\left[\phi m' S(u_w - u) - V\,\frac{\partial p}{\partial x} - T_w S\right] \qquad \text{(A2)}$$

The axial particle velocity u is modified by: the entering mass, whose axial velocity is u_w; the axial pressure gradient; and frictional stresses. $T_w = \frac{1}{2} C_f \rho u^2$, and C_f is the dimensionless