

coefficient of friction.

Conservation of energy.

$$\frac{\partial e}{\partial t} = \frac{1}{m} \left\{ \phi m' S [(u - u_w)^2 / 2 + (e_w - e)] - p \frac{\partial V}{\partial t} + T_w S |u| + H' \right\} \quad (\text{A3})$$

The specific internal energy, e , is modified by: the entering mass, whose specific internal energy is e_w and whose velocity is u_w ; volume changes; irreversible dissipative work done on a zone by the tunnel surface stresses; and (H' = energy/time) energy sources or sinks.

Equation of state. The functions can be any equation or table for each material present.

Heat transfer. The energy sink H' can be due to turbulent convective heat flux q_c and a radiative heat flux q_r . These heat fluxes transfer energy through the surface area S of the zone that is in contact with the tunnel walls. The heat fluxes are calculated by *Bond, Watson and Welch* [1965], *Schlichting* [1960], and *Rose and Offenhartz* [1959]

$$H' = -S(q_c + q_r) = -S \left(\frac{C_H \gamma p u}{\gamma - 1} + \frac{4\sigma T^4}{3\rho K_R(R/2)} \right) \quad (\text{A4})$$

where p is pressure, u is particle velocity, γ is the ratio of specific heats, C_H is the dimensionless coefficient of turbulent heat transfer (the Stanton number), σ is the Stefan-Boltzmann constant, T is the temperature of the gas, and K_R is the Rosseland mean opacity, which is obtained from a temperature- and density-dependent table.

Ablation mass flux. The mass flux that enters the flow, m' , is related to H' by

$$m' = \frac{q_c + q_r}{q^*} = -\frac{H'}{Sq^*} \quad (\text{A5})$$

where

$$q^* = E_v + \eta h \quad (\text{A6})$$

and q^* is the energy required to ablate a unit mass of wall material, E_v is the total specific heat required to vaporize wall material ($E_v \approx 10^{11}$ ergs/g for rock), h is the specific total enthalpy of the gas flow in the tunnel, and η is the turbulent transpiration coefficient ($\eta \approx 0.2$ for rock) [*Rose and Offenhartz*, 1959].

APPENDIX B. TURBULENT DIFFUSION OF ABLATED WALL MASS

A set of hypothetical Eulerian regions are considered axially along the walls of the tunnel. When ablation starts in one of these regions, the time T_s is noted. Then, at any later time T the time interval $T_t = T - T_s$ can be calculated. T_t is the time during which turbulent diffusion has carried gas a distance Y [*Schlichting*, 1960], measured from the wall, where

$$Y = R \left\{ 1 - \left[1 - \frac{T_t u (C_f/2)^{1/2}}{2R} \right]^2 \right\} = R[1 - (1 - \beta)]^2 \quad (\text{B1})$$

and R is pipe radius, u is free stream velocity, $C_f/2$ is the dimensionless coefficient of friction, and all quantities are averaged over the Puff zones within a hypothetical Eulerian wall region.

Until the mass leaving the wall diffuses to the center of the pipe, the calculated ablation mass flux has only a partial effect on the total Puff zone. It is assumed that this partial effect is proportional to the volume of the Puff zone that the entering mass occupies at any time. The ratio of the volume occupied by the entering mass to the volume of the inside of the pipe is denoted by ϕ and calculated for each Eulerian region by

$$\phi = 1 - (R - Y)^2 / R^2 = 1 - (1 - \beta)^4 \quad (\text{B2})$$

The ablation mass fluxes, calculated for each Lagrangian Puff zone by equation A5, are multiplied by the appropriate ϕ , depending on the Eulerian region in which the almost-Lagrangian Puff zone is located.

Acknowledgments. A complete list of the people who contributed to Marvel would easily extend to over a hundred names, and such a list is virtually impossible to compile. Each person mentioned below relied on many others, and it was this combined effort of many individuals that made Marvel possible. L. A. Rogers, project physicist, and R. S. Guido, project engineer, led the program. P. D. Compton worked extensively with us on both the design and instrumentation; G. T. Pelsor, S. Sack, and F. C. Cook, on design of the homogeneous source region; F. E. Locke, on chemical tracers; B. C. Maranville, D. R. Garner, and J. B. Currey, on engineering and emplacement of instrumentation; and J. N. Vierra and J. B. Carson, on electronic recording. Field operations and mining were performed by the Reynolds

Electric and Engineering Company. The miners working on Marvel contributed through many efforts not normally required; without their careful and willing help, the Marvel design could not have been implemented. H. G. Hicks was responsible for the postshot drilling and data analysis. L. K. Barr, E. A. Reed, and J. G. Shaw worked with the code development and numerical calculations. C. L. Myers typed many of our papers for Marvel.

The work was performed under the auspices of the U.S. Atomic Energy Commission.

REFERENCES

- Bass, R. C., Additional Hugoniot data for geologic material, *Sandia Corp. Rep. SC-RR-66-548*, 1966.
- Bass, R. C., H. L. Hawk, and A. J. Chabai, *Sandia Corp. Rep. SC-RR-4903*, 1963.
- Bond, J. W., Jr., K. M. Watson, and J. A. Welch, Jr., *Atomic Theory of Gas Dynamics*, 518 pp., Addison-Wesley, Reading, Mass., 1965.
- Butkovich, T. R., Calculation of the shock wave from an underground nuclear explosion in granite, *J. Geophys. Res.*, **70**, 885-892, 1965.
- Butkovich, T. R., The gas equation of state for natural materials, *Lawrence Radiat. Lab. Rep. UCRL-14729*, 1967.
- Cherry, J. T., Computer calculations of explosion-produced craters, *Int. J. Rock Mech. Mining Sci.*, **4**, 1-22, 1967.
- Crowley, B. K., PUFL, an 'almost-Lagrangian' gasdynamic calculation for pipe flows with mass entrainment, *J. Comp. Phys.*, **2**, 61-86, 1967.
- Crowley, B. K., and L. K. Barr, TENSOR-PUFL: Boundary condition linked codes, *J. Comput. Phys.*, **7**, 167-171, 1971.
- Fenter, F. W., The thermodynamic properties of high-temperature air, *Chance Vought Res. Center Rep. RE-1R-14*, 1961.
- Gilmore, F. P., Equilibrium composition of thermodynamic properties of air to 24,000°K, *Rand Corp. Rep. RM-1543*, 1955.
- Glenn, H. D., and B. K. Crowley, Marvel—Nuclear driven shock-tube experiment, *J. Appl. Phys.*, **41**, 689-697, 1970.
- Heusinkveld, M., and F. Holzer, A method of continuous shock front position measurement, *Rev. Sci. Instrum.*, **35**, 1105-1107, 1964.
- McQueen, R. G., and S. P. March, Equation of state of Nevada alluvium, *Los Alamos Sci. Lab. Rep. LAMS-2760*, 1961.
- Maenchen, G., and S. Sack, The Tensor code, in *Methods of Computational Physics*, vol. 3, p. 181, Academic, New York, 1964.
- Petersen, C. F., W. J. Murri, and R. W. Gates, Dynamic properties of rocks, *Def. At. Support Agency Rep. 2298, SRI-PGU-6273*, 1969.
- Rodean, H. C., Understanding and constructively using the effects of underground nuclear explosions, *Rev. Geophys.*, **6**, 401-445, 1968.
- Rogers, L. A., Free-field motion near a nuclear explosion in salt: Project Salmon, *J. Geophys. Res.*, **71**, 3415-3426, 1966.
- Rose, P. H., and E. Offenhartz, Ablation measurements in turbulent flow, *Avco-Everett Res. Lab. Rep. AVCO-PR-114*, 1959.
- Schlichting, H., *Boundary Layer Theory*, McGraw-Hill, pp. 457-557, New York, 1960.
- Shipmen, F. H., W. M. Isbell, and A. H. Jones, High-pressure Hugoniot measurements for several Nevada Test Site rocks, *Def. At. Support Agency Rep. 2214, MSL 68-15*, 1969.
- Stephens, D. R., E. M. Lilley, and H. Louis, Pressure-volume equation of state of consolidated and fractured rocks to 40 kbar, *Int. J. Rock Mech. Mining Sci.*, **7**, 275-296, 1970.
- von Neumann, J., and R. D. Richtmyer, A method for the numerical calculation of hydrodynamic shock, *J. Appl. Phys.*, **21**, 232-237, 1950.

(Received October 26, 1970;
revised February 3, 1971.)