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LGGUN User's Manual

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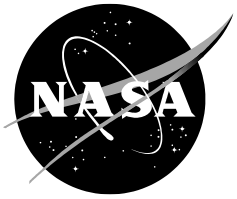

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National Aeronautics and
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1. Introduction

NASA needs to understand hypersonic flight of earth and planetary entry vehicles and hypervelocity impact phenomena of space debris and natural meteoroids on the walls of space vehicles. This can involve test articles being launched at velocities of ~8 km/s or more. Such launches can aid in evaluating new (or existing) designs for earth and planetary entry vehicles. Vehicle static and dynamic stability can be evaluated as well as aerodynamic heating.

The two-stage light gas gun is a well-known method of achieving such high velocity launches. Figure 1 below shows a schematic sketch of a two-stage light gas gun. The gun comprises:

- Powder chamber
- Pump tube with piston
- High pressure coupling cone
- Rupture diaphragm
- Launch tube with projectile

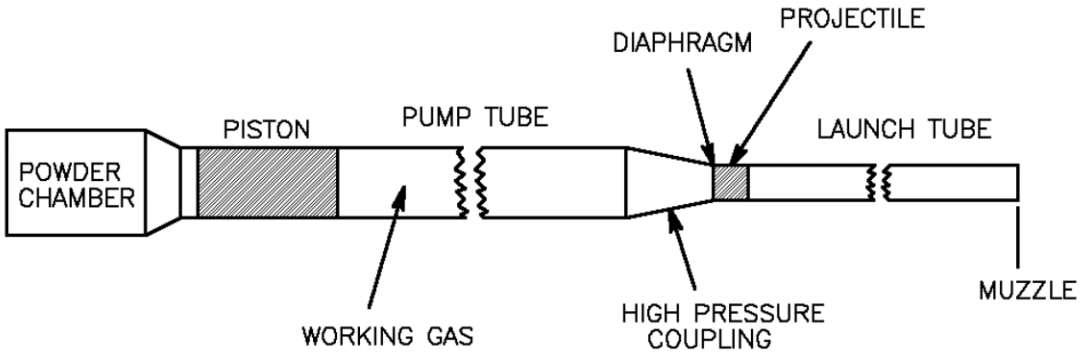

Figure 1. Schematic sketch of a two-stage light gas gun.

The gun operation cycle is as follows:

- Powder burns, accelerates piston
- Piston compresses working gas to very high pressure and temperature
- Diaphragm breaks
- High pressure, high temperature gas accelerates projectile down launch tube

Shots on a two-stage light gas gun (especially on a large gun) can be expensive and time-consuming. It would be desirable to have a computational tool which could predict the performance of such a gun. With this in mind, it was decided to write LGGUN, a code which calculates the internal ballistics of a two-stage light gas gun from the ignition of the powder charge until the second stage projectile exits the muzzle.

LGGUN is a quasi-one-dimensional Godunov code[1] which is second order accurate in time and third order accurate in space, uses realistic equations of state for all media,

includes wall friction and heat transfer for all gas and dense media zones and includes a simple non-equilibrium model for gas phase turbulence. The entire gun is divided into cells by a number of planes normal to the gun axis. The cells are either cylindrical disks or conic frustums or a combination of the two. Gun tube wall heating, melting/ablation and the incorporation of melted wall material (taken to be fine droplets) into the (usually) hydrogen working gas is modelled. It has been extensively validated against analytical solutions and experimental data from the 0.22"/1.28", 0.28"/1.55", 0.50"/2.54", 1.0"/4.0" and 1.5"/6.25" two stage guns at the NASA Ames and Marshall Research Centers operated over a wide range of operating conditions with muzzle velocities of 0.7 to 11.3 km/s. (The two numbers describing each gun are the diameters of the launch tube and of the pump tube.) The code is written in Fortran and CPU times for a total of 138 active computational cells and ~12,500 time steps ranged from 35 to 570 s. The code outputs piston and projectile velocities, maximum gas pressures and temperatures at selected locations and cells, piezometric ratios, snapshots of conditions at specific times and a number of time history files at the projectile base, and at user-selected positions along the gun and for user-selected cells. (The piezometric ratios are the ratios of maximum pressures to the effective average projectile base pressure.) Also given are the maximum gun tube wall and internal temperatures and the profile along the gun of the depth of eroded (melted) wall material during the shot. Since the code is quasi-one-dimensional, errors will be produced if the included cone angle of the tube is greater, at any point, than some critical value. For full (included) angles below about 60 degrees, these errors should be sufficiently small to be acceptable.

2. Code Description

The code is described in considerable detail in Refs. 1 and 2, but is also outlined here. It is a Godunov code, which means that at every time step, at every cell boundary, a Riemann problem is solved in order to obtain the cell boundary fluxes. The Riemann solvers used are very nearly exact. The code is third order accurate in space and uses the MacCormack predictor-corrector scheme,[3] which is second order accurate in time, to advance in time. Most of the time, three different zones are used, each filled with a different media: (1) gunpowder/powder gas, (2) the pump tube piston and (3) the gun working gas plus melted droplets from wall in the pump tube. When a plastic piston is weighted with a metal slug in the rear, four zones are used with the piston made up of two zones, metal aft and plastic forward. Gun working gases H_2, He, N_2 and Ar have been modelled. The projectile is not subdivided into zones, but is treated as a point mass, dynamically.

2.1. Equations of State

The equations of state (EOS) used are as follows. For the powder gas, the Abel volumetric equation of state (Eqn. 1) is used.

$$p(v - b) = \frac{R_u T}{m} \tag{1}$$

p is pressure, v, specific volume, b, molecular volume, R_u, the universal gas constant, T, temperature and m, molecular weight. The absolute enthalpy is determined assuming constant specific heat. The unburned powder is taken to be a constant density, constant internal energy solid at the initial (room temperature) conditions.

For the piston, the Zel'dovich and Raizer three term dense media EOS (see Ref. 4 and Appendices A, B) with the third term neglected is used. From experimental shock Hugoniot data[5] for a given media, a good determination of the constants in this EOS can be made. [Shock Hugoniot data consists of a table (and graphs) of shock velocities, particle velocities, pressures and densities for shocks of different strengths in the media in question.]

For the hydrogen gas, a two-dimensional tabulated EOS of the form T(ρ,e), p(ρ,e) is used (ρ = density, e = internal energy). For the LGGUN code, this EOS was constructed as follows. First, (using Ref. 6) equilibrium calculations were made for point hydrogen molecules (and atoms) over the full required pressure and temperature ranges. Then, a molecular volume term was added which follows the Zel'dovich and Raizer[4] cold pressure-volume relation [Eqn. (2)] for dense media:

$$p = A\left[\left(\frac{\rho}{\rho_0}\right)^n - 1\right] \tag{2}$$

In Eqn. (2), ρ_o is a reference density and A and n are empirical constants for the medium in question. The constants in Eqn. (2) can be obtained using shock Hugoniot data for liquid hydrogen.[5] [Note that ρ in Eqn. (2) is equal to 1/b and is not the overall density of the hydrogen.] This yields an EOS for hydrogen which compares rather well with the tabulated SESAME[7] EOS. When melted wall material is mixed with the hydrogen, a mixture EOS, in which temperatures and pressures of the two components are matched, is created, which is currently used for all two stage gun analyses.

A similar type of EOS was developed for He, N_2 and Ar gun working gases. Here, we use a version of Eqn. (1) in which the molecular volume term, b ($=1/\rho_m$) is compressible according to Eqn. 2. In this case, v $=1/\rho$. Equations (1) and (2) then become Eqns. (3) and (4) below:

$$p\left(\frac{1}{\rho} - \frac{1}{\rho_m}\right) = \frac{R_u T}{m} \tag{3}$$

$$p = A\left[\left(\frac{\rho_m}{\rho_o}\right)^n - 1\right] \tag{4}$$

The constants A, ρ_0 and n in Eqn. (4) can be evaluated by fitting the Zel'dovich and Raizer EOS to shock Hugoniot data for the respective liquified gases. This technique is described in Appendix A. Equation (4) can be integrated to give the pdv work done on the molecules as they are cold compressed from zero pressure to a pressure p. The result is Eqn. (5) below, where e_c is the cold compression energy.

$$e_c = \frac{A}{\rho_0}\left\{\frac{1}{n-1}\left[\left(\frac{\rho_m}{\rho_0}\right)^{n-1} - 1\right] - \left[1 - \frac{\rho_0}{\rho_m}\right]\right\} \quad (5)$$

To get the total gas energy ($e = e_c + e_t$), we must add in the thermal energy term

$$e_t = C_v T = \frac{R_u T}{m(\gamma - 1)} \quad (6)$$

where e_t is the thermal energy, C_V is the specific heat at constant pressure and γ is the specific heat ratio. Using Eqns. (3) - (6), we can construct the EOSs for the pure gases He, N_2 and Ar. When melted wall material is mixed with the gun working gases, a mixture EOS is created, which is currently used for all two stage gun analyses.

Experimental shock Hugoniot data is available for liquid N_2 in Refs. 5 and 8, for liquid Ar in Refs. 8 - 10 and for liquid He in Refs 11 - 14. Using this data plus the conservation equations of mass, momentum and energy, the after-shock pressure, p_2, internal energy, e_2, and density, ρ_2 can be calculated for each experimental point. Using the EOS Eqns. (3) - (6) above, a second value for the after-shock pressure, $p_2'(\rho_2, e_2)$ can be obtained for each data point. One may then compare the two values of p_2 for every data point. The parameters (primarily ρ_0 and n) are then adjusted to produce the best overall fit of the p_2 values between theory and experiment. Table 1 shows the coefficients of the EOS fits for He, N_2 and Ar.

Table 1. Coefficients in EOSs for He, N_2 and Ar

GAS	A dyne/cm^2	n	ρ_0 g/cm^3	m	γ
He	1.601 x 10^7	4.7	0.1416	4.00	1.667
N_2	1.114 x 10^9	5.7	0.8200	28.0	1.35
Ar	1.931 x 10^9	5.2	1.400	40.0	1.667

Further discussion of the above EOSs can be found in Appendix A.

2.2. Friction and Heat Transfer

Friction and heat transfer to the wall are included for all media. i. e., for

(1) Gunpowder/powder gas
(2) Pump tube piston
(3) Hydrogen gas
(4) Projectile

The models used to calculate friction and heat transfer are described in Appendix B1. Although the projectile is not subdivided into cells, a calculation of the friction and heat transfer from the projectile to the wall is made, based on conditions halfway along the projectile in the axial direction. A simple non-equilibrium turbulence model, described in Appendix B of Ref. 1, is used for the gas phase zones.

2.3. Powder Burn

One option for modelling the powder burn rate is to use the usual ballistics expression (see, for example, Ref. 15)

$$r = bp^n \tag{7}$$

where r is the linear surface regression rate of the powder grain, p is the pressure and b and n are constants given by the maker of the powder or by military testing laboratories.[16-19]

The powder grain is modelled as a cylinder of diameter D_0 and length L_0 (Fig. 2). There can be (or not) n cylindrical perforations of diameter d_0 parallel to the main cylinder axis. For the powders modelled to date, n has been 0, 1 or 7, as specified by the powder manufacturer. For spherical grains, a cylindrical model with length equal to diameter is used (Fig. 2b). Figure 3 shows a 7-perforation grain before burning starts (solid lines) and after burning has caused a retreat of $(w_0 g)/2$ of all surfaces (dashed lines). g is the fraction of the total burn distance burned. g = 0 before burning starts and g = 1 at all burnt. The

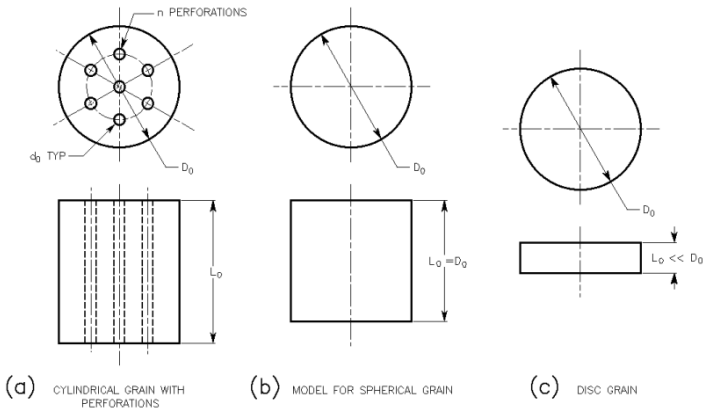

Fig. 2. Modelling of shapes of powder grains.

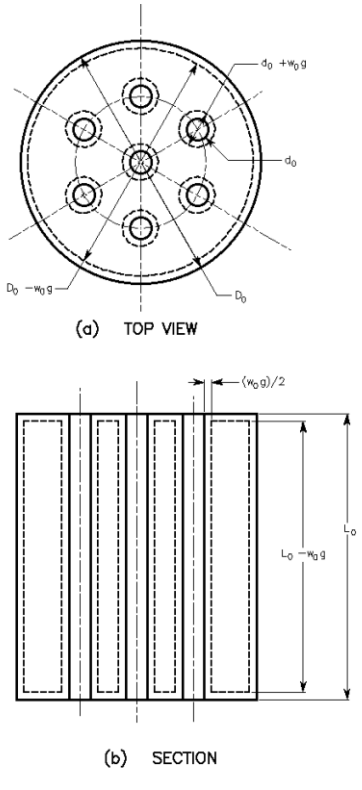

Figure 3. Seven-perforation grain before burning starts (solid lines) and after burning has caused a retreat of ($w_0 g$)/2 of all surfaces (dashed lines).

volume of the grain shown in Fig. 3 after the surface retreat ($w_0 g$)/2 is

$$Volume = \frac{\pi}{4}[(D_0 - w_0 g)^2 - n(d_0 + w_0 g)^2][L_0 - w_0 g] \quad (8)$$

At all burnt (g = 1), w_0 is determined from Eqn. (8) by setting either the first or second square bracket equal to zero. The mass fraction of the unburned powder can be calculated from g using Eqn. (8) and the change in g can be calculated from the burn rate, r in Eqn. (7) and the time step, dt. Thus, we can follow the consumption of the powder. The modelling of the powder grain shape change during burn presented above is ideally correct for cylindrical grains with zero or one perforation(s). For grains with multiple perforations, the burn fronts from the perforations and the outer diameter will intersect at roughly 80% powder burn. Thereafter, the burn front area is essentially unknown and we simply extend the model presented above until the powder grains are entirely consumed. The above analysis is for a uniformly distributed deterrent. If the deterrent concentration varies with position in the grain, b in Eqn. (7) above will vary with position in the grain. An analysis of such a case is presented in Appendix C. Further discussion of both the uniformly distributed and the gradated deterrent cases are also given in Appendix C.

2.4. Gun Tube Heating and Ablation

We now briefly outline the methods used to calculate gun tube heating, gun tube surface melting (ablation) and incorporation of the melted gun metal (taken to be fine droplets) into the gun working gas. These methods are discussed in more detail in Ref. 2. Data bases of gun metal properties are built up. An equation of state for the gun working gas-gun metal mixture is constructed. The heat conduction in the gun tube material is calculated. The heat flux to the wall is matched to the heat lost from the working gas and the amount of gun metal lost (melted) per time step is calculated. For the working gas-gun metal mixture, a simple non-equilibrium turbulence model is used. After all the heat flow and mass flow terms are calculated, the cell center values for all cells are updated. The actual problem is axisymmetric, but a planar, one-dimensional analysis is used for simplicity because the total thickness of the heat conduction zone analyzed is about 1/15th of the tube radius and the thickness within which significant gradients occur is 3 to 5 times smaller still. Thus, the errors caused by using the planar assumption should be quite small, of the order of 1-2% or less.

3. Code Validation

Four code validation efforts were carried out over four different time periods in the life of the code. The first effort is described in considerable detail in Ref. 1 but will also be briefly outlined here. The code was successfully validated against the following analytical solutions.

(1) Reimann's shock tube problem at pressure ratios up to 10^6.
(2) Impact between two dense media plates at closing velocities up to 20 km/sec.
(3) Flow of gas (and CFD cells) through a supersonic convergent-divergent nozzle with an area ratio of 16 to 1.
(4) Exact integration of gunpowder combustion in a closed bomb.

For wall friction, heat transfer and the non-equilibrium turbulence model, no simple analytical solutions exist. The implementation of these calculations in the CFD code was checked by performing complete, six-figure hand calculations of each of these effects for one cell, for one timestep, and comparing the hand calculations against extensive special diagnostics printed out from the CFD code. A few errors were found in this way and corrected.

The code was also verified against data from the NASA Ames Research Center's 0.28"/1.55" and 1.5"/6.25" light gas guns. Particularly for the smaller gun, the data was taken over a considerable range of gun operating conditions. The data included:

(1) Projectile muzzle velocities
(2) Piston velocities at several locations in the pump tube
(3) Powder chamber pressure histories
(4) Pressure histories in the pump tube

The agreement between the experimental data and the CFD code predictions was very good. The comparisons are presented in some detail in Ref. 1.

The second code validation effort is described in considerable detail in Ref. 2 and is briefly outlined here. Forty-five shots with the Ames 0.5”/2.54" light gas gun were modelled with a version of the code which includes bore erosion and the incorporation of the eroded bore material into the hydrogen working gas. (The code used in the first code validation effort did not include bore erosion.) Muzzle velocities for these shots ranged from 4 to 9.5 km/s. The data included:

(1) Projectile muzzle velocities
(2) Piston velocities
(3) Powder chamber maximum pressures
(4) Bore erosion measurements

Experimental and theoretical muzzle velocities were in reasonably good agreement, with most differences being less than 0.5 km/s (out of ~7 km/s) and the worst disagreements being 0.7 km/s. The corresponding piston velocities were in reasonably good agreement, with most differences being less than 25 - 35 m/s (out of ~750 m/s) and the worst disagreements being 50 m/s. The corresponding maximum powder chamber pressures were in reasonably good agreement, with most differences less than 50 bar (out of ~800 bar and the worst disagreements being 70 bar. Experimental and theoretical bore erosion values were mostly within a factor of two of each other, although, in some cases, the shapes of the two corresponding bore erosion curves are rather different. Overall, the agreement between the experimental and CFD gun erosion values was judged to be reasonably good, considering the complexity of the processes modelled and that the CFD erosion calculations were not “tuned” in any way to improve agreement with the experimental results. Overall, the code was judged to predict the experimental results reasonably well.

The third code validation effort is described in considerable detail in Ref. 20 and also briefly outlined here. In Ref. 20, experimental and CFD piston and muzzle velocities for the NASA Ames 0.22”/1.28”, 0.28”/1.55”, 0.50”/2.54”, 1.00”/4.00” and 1.50”/6.25” guns are compared. The agreement between the experimental and CFD piston velocities was judged to be very good. Ninety percent of the 50 data points showed differences of less than ±20 m/s, 3 points had differences of 25 – 30 m/s and 2 data points had differences of 45 and 50 m/s. Overall, the agreement between the experimental and CFD muzzle velocities over the wide velocity range of 3 to 11 km/s was judged to be very good. The differences between the experimental and CFD muzzle velocities were 0.35 km/s or less for 74% of the data points, 0.35 - 0.5 km/s for 18% of the data points and 0.5 - 0.7 km/s for 4 out of 50 data points. It must be pointed out that, for muzzle velocities above 6 – 7 km/s, the gun code must take into account erosion of the steel gun tube wall material and the incorporation of it into the hydrogen working gas of the gun. This weighs down the working medium of the gun and leads to substantial reductions in muzzle velocity below those calculated without gun tube erosion.

The fourth code validation effort has not yet been presented in the literature but enters new territory and, hence, will be briefly described here. The object in this study was to achieve low muzzle velocities (1 - 2.5 km/s). The guns used were the NASA Ames 0.30"/2.5" vertical gun (Ref. 21) and the NASA Marshall 0.22"/0.787" gun. In addition to

shots with hydrogen working gas, shots were made with helium, nitrogen and argon working gases. Muzzle velocities of 1.8 - 5.7 km/s were achieved with hydrogen, velocities of 1.1 - 4.0 km/s with helium, velocities of 1.7 - 2.4 km/s with nitrogen and velocities of 0.7 - 2.0 km/s with argon. These shots were modelled with the CFD code. The overall effects of changing the powder load and the working gas were well predicted by the code. The disagreements between experimental and CFD muzzle velocities were mostly in the range of 5 - 10%, but with hydrogen and at velocities of 2.5 to 5.7 km/s, ranged up to 10 - 18%, versus a consistent 5 - 10% for the third code validation effort. The Ames vertical gun has a previous history (when operated with hydrogen) of producing highly variable muzzle velocities. In addition, at the lowest velocities (with the lowest powder loads), there is some evidence of incomplete and erratic powder burn.

4. Set Up of Input Files Used in Light Gas Gun Code

4.1. Introduction

The code requires three input files, ONED1D.DAT, ONED1DE.DAT and WAHE1D.DAT. It is assumed that the user has a functioning set of input files to start with (i.e., a set of input files that produces a valid solution.) A valid set of input (and output) files prepared on 3/30/18 is provided with the code package. The main content of these input and output files is given in Appendix H. Details of these input and output files are given in Appendices I and J, respectively.

ONED1D.DAT basically defines the overall problem, ONED1DE.DAT defines the EOSs (equations of states) (although some EOS data is in ONED1D.DAT) and WAHE1D.DAT defines the wall heating.

Here, we give the method of setting up the input variables grouped in the following way:

Gun
- Dimensions
- Whisker gauge locations
- Diaphragm location, burst pressure
- Material - steel, rhenium, tantalum
- Parameters for wall heat conduction problem

Gunpowder
- Grain dimensions
- Energy release
- Burn rate

Piston
- Dimensions (lands, shank)
- Location
- Properties (modulus, yield strength, Poisson's ratio, friction coefficient)

Projectile
- Dimensions
- Mass
- Properties (modulus, yield strength, Poisson's ratio, friction coefficient)

Working media

EOS (equation of state) for powder gas
EOS for piston
EOS for He, N_2, Ar, H_2
Set working media density, internal energy
Viscosity

The following sections give steps to be performed if a complete change of every group was to be made. In normal use of the code one or more groups, such as the piston group, will be kept constant between various series of CFD runs. All quantities are in cgs units. In a number of cases herein, numerical examples are given to clarify procedures. These calculations are made for the gun and operating condition defined by the sample input files. The results of these calculations will likely be very different for the user's gun and gun operating conditions.

Before proceeding, we define several of the important variables and give pointers to where information on the code subroutines can be found:

NZ = number of zones in the CFD calculation (= 3 for our example case - powder/powder gas, piston and gun working gas)
NC(NZ) = number of cells in each zone (= 32, 32, 80 for our example case). Note that the two end cells of each zone are "ghost" cells and serve only to set zone boundary conditions.
NCOM(NZ) = number of components in each zone (= 2, 1, 2 for our example case). Examples of zones with two components are powder/powder gas and gun working gas/ablated steel droplets.

Appendix E gives a list of the subroutines used in the code LGGUN. Appendix F gives a list of the subroutines used in the code LGGUN in the past which are now not invoked (not used). They have been kept in the code package because (to date) we have not had time to "clean up" the code, for example, to eliminate conditional calls to subroutines which are now not used. Appendix G gives the order in which major subroutines are called by the main program in the LGGUN code (flow chart).

4.2. Gun

Figure 4 below shows a sketch (not to scale) of a two stage light gas gun with key dimensions labelled. All the dimensions shown in Figure 4 (plus additional data) must be

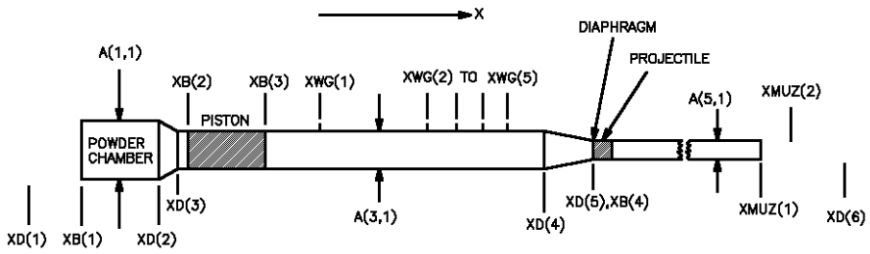

Figure 4. Sketch of a two stage light gas gun with key dimensions labelled.

available for the gun to be modelled. The values of the variables discussed in the first part of this section are to be entered into the input file ONED1D.DAT. A list of the input variables is found in Appendix I. A sample ONED1D.DAT file is presented in Appendix K. We now return to the main discussion of this section. XD(2) through XD(5) are the x-coordinates of the break points (cylinder to cone) of the gun tube profile. XD(1) and XD(6) must be outside all other x-dimensions in the figure. ND is the total number of cylindrical and conical tube sections modelled and is 5 for the case in point. NTD(1) through NTD(5) give the type of gun profile between successive pairs of XDs. For the gun profile of Fig. 4, the NTDs, in order, are 2 1 2 1 2, with 2 denoting cylinder and 1 denoting cone. For the cylindrical sections of the gun tube, A(1,1), A(3,1) and A(5,1) are the tube diameters as shown in the figure. For the cones, the gun tube diameter at any point is A(2,1)*x + A(2,2) or A(4,1)*x + A(4,2), as the case may be, where x is the distance along the gun, in cm. Apart from the seven A(n,m) values mentioned above, all other A(n,m) values are zero. The A(n,m)s for the cones are easily determined by fitting a (diameter) = A(2,1)*x+A(2,2) (for example) expression to the two ends of the cone. XMUZ(1) is the x-coordinate of the gun muzzle, but the CFD solution is carried out until the projectile base reaches XMUZ(2) and then parameters are interpolated back to XMUZ(1) to give muzzle exit values. The difference between XMUZ(2) and XMUZ(1) is generally about 10% of the gun total length.

The five XWG(n) values are the x-coordinates of the whisker gauges (or whatever piston passage detectors are used). Whisker gauge number 1 cannot be uprange of the initial location of the front of the piston or the code will fail. It is suggested that NXWG be kept at 5 and if there are less than five whisker gauges, just insert extra x-coordinates into the input file, as long as they are in the pump tube and not in the high pressure coupling cone.

XB(1) through XB(4) are the initial positions of the zone boundaries, in cm. XB(1) is the position of the blind end of the powder breech, XB(2) is the initial position of the boundary between the powder/powder gas zone and the piston, XB(3) is the initial position of the boundary between the piston and the gun working gas and XB(4) is the initial position of the diaphragm and the projectile base. See Sec. 6 for the determination of XB(3). Two variants of the gun shape configuration of Fig. 4 should be mentioned. First, one may eliminate the chambrage cone just downrange of the powder chamber. Second, the high pressure coupling cone [between XD(4) and XD(5)] can be represented by two cone frustums with different slopes joined together instead of just one cone frustum as in Fig. 4. In one case, this was found to give a better match to the profile of the high pressure coupling than a single frustum.

There are four RTCF(n) values. Two of these, RTCF(2) and RTCF(4), are tube radii (in cm) of the pump tube and launch tube, respectively. The remaining two RTCF(n) values are not used. RTCF(2) must be set to A(3,1)/2 and RTCF(4) must be set to A(5,1)/2. There are NPLOTX XXPLOT(n) values, where NPLOTX can range from 5 to 468. The first 5 of these are the x locations, to be selected by the user, where pressure history files are generated. The remaining XXPLOT(n) values are the x locations, also to be selected by the user, where maximum pressures are calculated and are used to make a profile of maximum pressures along the entire length of the gun. One can also run the code with NPLOTX equal to 5 and, in this case, the time histories will be generated but no profile of maximum pressures along the gun will be generated. Further details are given in Appendix D1. Often, the x-coordinates selected are in the powder chamber or in the high pressure coupling,

where pressures are very high. We note that, if XXPLOT(n) is outside the length of the gun, the pressure for that n will always be set to zero.

There are five pairs of values IWHHZ(n), IWHHC(n). These are the zone numbers and cell numbers, to be selected by the user, where history files of all variables are generated. Zone end cells (not ghost cells - see Appendix E) are often chosen for these histories, for examples IWHHZ(n) = 3, IWHHC(n) = 2 or IWHHZ(n) = 3, IWHHC(n) = 79 for a zone with NC = 80. It is suggested that, IWWH, which is the number of multi-variable histories to be generated, be kept at five.

Several parameters must be properly set to have the diaphragm rupture correctly. The pressure being compared with the diaphragm rupture pressure is the pressure in the most downrange internal cell of the gun working gas zone. For a three (four) zone setup with NC = 80 for the working gas zone, that cell designation would be zone 3 (4), cell 79. Thus, in the ONE1D.DAT input file, we must have NZBKPR = 3 (4), NCBKPR = 79. Also, we must set IBKVAL = 0, indicating the condition before diaphragm rupture obtains. Upon diaphragm rupture, IBKVAL is set to 1. The boundary condition at the downrange end of the working gas zone NTB(3,2) [NTB(4,2)] must change from 1 (blind end) to 10 (accelerating projectile) upon diaphragm rupture. To accomplish this we must set NBCCH1 = 3 (4) and NBCCH2 = 3 (4) in the input file. Note that if there were a different number of zones or cells, one or more of NZBKPR, NCBKPR, NBCCH1 and NBCCH2 would change. PBKVAL is set equal to the diaphragm rupture pressure in dynes/cm^2.

4.3. Variables to Modify in WAHE1D.DAT - given in Secs. 4.3 to 4.8

All of the input variables discussed in Section 4.2 above are found in the input file ONED1D.DAT. We now discuss other input variables relating to the gun which are found in the input file WAHE1D.DAT. A list of the input variables is found in Appendix I. A sample WAHE1D.DAT file is presented in Appendix K. Most of the input variables in WAHE1D.DAT deal with the properties of the barrel wall material and do not have to be changed if the wall material remains unchanged. However, one should check that the correct input file is being used as WAHE1D.DAT. Three versions of this file exist - WAHE1D.DAT (for gun steel), WAHE1DRERE.DAT (for rhenium) and WAHE1DTATA.DAT (for tantalum). Within WAHE1D.DAT (the active file for the solution at hand), check the values of ZMWHYD and ZMWSTE. The former should be the molecular weight of the working gas and latter, the molecular weight of the gun tube material. In many cases, even while keeping the same gun material, variables have to be changed because of differing dimensions of guns being modelled. We first list these variables in the order that they appear in WAHE1D.DAT, i.e:

NXSTEE NYSTEE DYSTE1 RDYSTE
XSTEEL (400 entries)
NCXST1 NCXST2 NCYST1 NCYST2
ZMWHYD ZMWSTE

We then discuss these variables in four groups as listed below:

Variables dealing with specifying axial (x) dimensions

Variables dealing with specifying radial (y) dimensions
Variables specifying where the output profiles will be taken (profiles are saved in output files WAHE1OP and WAHE1OHA)
Variables giving molecular weights

The variables will be discussed in the following sections for the benchmark shot of our benchmark gun which is studied herein. Details are given below.

4.4. Axial Dimension Variables

These variables are NXSTEE and XSTEEL. The latter variable is a subscripted variable and has NXSTEE entries. In the current version of the code, NXSTEE, the number of wall cells in the x-direction, is taken to be 400. The XSTEEL values are the axial locations along the gun where radial heat conduction and wall erosion calculations are performed. Our benchmark gun has the blind end of the powder breech located at x = 0.0 cm. The small end of the high pressure coupling is located at x = 1081.514 cm and the muzzle is located at 1336.744 cm. Thus, the barrel length is 255.23 cm. (For reference, the powder chamber diameter is 5.08 cm, the pump tube diameter is 6.4465 cm and the launch tube diameter is 0.7112 cm.)

We have selected XSTEEL(1) to be -100.0 cm, i.e, 100 cm beyond the blind end of the powder breech. XSTEEL(201) was set to 1081.514 cm, i.e, at the small end of the high pressure coupling. XSTEEL(400) was set to be 1496 cm, i.e, roughly 160 cm beyond the gun muzzle and roughly 70 cm beyond XMUZ(2), where the calculation normally stops (see Appendix I). The gun wall cell x-array [XSTEEL(n)] must extend from uprange of XB(1) to downrange of XMUZ(2). The XSTEEL array is created in a small program and is pasted into the WAHE1D.DAT profile.

Often, we have used a configuration in which the distances between the successive XSTEEL values decrease by a constant ratio from XSTEEL(1) to XSTEEL(201) and then increase by a constant ratio to XSTEEL(400). This results in XSTEEL(2) - XSTEEL(1) ~ 30 cm, XSTEEL(202) - XSTEEL(201) ~ 0.5 cm and XSTEEL(400) - XSTEEL(399) ~ 20 cm. For our example case herein, we have not done this, but rather, have kept the length of all steel cells constant at 4.0 cm. This is simpler to set up, but has reduced resolution in the region of the high pressure coupling. There has been no evidence that using steel cells of a constant length impairs the quality of the gun analyses.

4.5. Radial Dimension Variables

These variables are NYSTEE, DYSTE1 and RDYSTE. NYSTEE is the number of cells in the radial direction extending inwards from the barrel wall surface (including one ghost cell). NYSTEE is currently set to 18. The cell with a y-number of 1 is a ghost cell, inside the radius of the surface of the barrel wall. The first real cell within the barrel wall material has a y-number of 2. Hence, there are 17 real cells within the barrel wall material, with y-number from 2 to 18. DYSTE1 is the width of the first real cell (with a y-number of 2) within the barrel wall material. Successive cells inwards from the first real cell have successively greater widths by the ratio RDYSTE. That is, RDYSTE is equal to (width of cell with y-number of 3)/(width of cell with y-number of 2) = (width of cell with y-number of 4)/(width of cell with y-number of 3), etc. For our benchmark gun, DYSTE1 = 0.001170

cm and RDYSTE = 1.1.

It is suggested to keep NYSTEE at 18 and RDYSTE at 1.1. These values have worked well for us and do not need to be changed for guns of different sizes. DYSTE1 should simply be scaled with the duration of the gun launch cycle to the 0.5 power. As a rough approximation for similar muzzle velocities, the duration of the gun launch cycle is proportional to the gun length. Hence, DYSTE1 should be scaled with the gun length to the 0.5 power.

4.6. Variables Specifying Where the Output Profiles in WAHE1OP and WAHE1OHA Will be Taken

These variables are NCXST1, NCXST2, NCYST1 and NCYST2. NCXST1 and NCXST2 are the x-position numbers at which profiles of temperature versus y-position are printed out in WAHE1OHA. NCYST1 and NCYST2 are the y-position cell numbers at which profiles of temperature versus x-position are printed out in WAHE1OP. For our benchmark gun CFD run, these variables were set to 115, 136, 2 and 6, respectively. These variables can be set to any number within the total ranges available (400 and 18, respectively, for our benchmark gun case). Generally, we have set NCXST1 and NCXST2 to allow us to study regions in the high pressure coupling and launch tube where the temperatures and heat fluxes are highest. NCYST1 and NCYST2 have generally been set fairly near the barrel wall surface to allow one to study higher temperature regions. Setting NCYST2 to 18 allows one to examine the temperature at the deepest cell calculated inside the barrel wall material. For all cases that we have calculated, the temperatures at all cells with y-numbers of 18 are within 1 K of the initial barrel wall temperature, indicating that no significant heat has penetrated this deep into the barrel wall material. Hence, the total depth of the unsteady heat conduction calculation is sufficient to accurately model the heat conduction process.

4.7. Variables Specifying Molecular Weights

These variables are ZMWHYD and ZMWSTE. These are the molecular weights of the gun working gas and the gun tube metal, respectively. The entries in WAHE1D.DAT must correspond to the actual molecular weights of the materials in question.

4.8. Refractory Metal Guns

The file WAHE1D.DAT is for a gun material of gun steel (e.g., AISI 4340 steel). The files WAHE1DRERE.DAT and WAHE1DTATA.DAT are for rhenium and tantalum gun materials, respectively. To change the gun material, copy WAHE1D.DAT to a file with some other name (for storage) and copy WAHE1DRERE.DAT or WAHE1DTATA.DAT to WAHE1D.DAT, depending on the desired gun material. Use of the refractory gun materials is predicted to improve muzzle velocities and reduce gun erosion.[22,23] Tantalum has better mechanical properties than rhenium[23]. For a refractory gun metal gun, the entire gun is taken to be made of refractory metal, since, at present, the code cannot handle two different gun materials. However, for the powder breech and pump tube (usually made of

steel), this material error makes very little difference in the solutions, since these components never reach their melting points.

4.9. Gunpowder

The next four sections (Secs. 4.9 - 4.12) discuss variables to modify in ONED1D.DAT and ONED1DE.DAT. The present section deals with the gunpowders.

Properties of various gunpowders are given in references 16 - 19 and 24 - 31. If one can find all the data needed for the powder to be used, that data can be used in the code simulations. If one can't find that data, but one has the composition of the powder to be used, one can search for a powder that has a composition close to that of the powder to be used and for which data is available and use that data. If data is not available on the powder to be used, but the powder is composed primarily of nitrocellulose (NC), nitroglycerine (NG) and dibutylphthalate (DBP)(deterrent), one may use the correlation of Refs. 18 and 19 to calculate the burn rate of the powder. This correlation is given in Appendix C, Eqns. (7) - (10).

The data needed for the powder are as follows. The powder grains are assumed to be right circular cylinders which may have one or more circular perforations parallel to the axis of the cylinder (see Appendix C). Many powders have this type of geometry. Spherical powder grains are approximated by a cylinder without perforations and with diameter equal to length. Disc grains are directly simulated by this model, but the grain length can be much less than the grain diameter. The values of the variables discussed below are (with the exception of e_{solid} = E1SOL) to be taken from the source data and inserted in the input file ONED1DE.DAT.

Outside diameter of grain, D_o, insert as DDPOW, 5th line from bottom

Diameter of perforation(s), d_o, insert as DPOW, 5th line from bottom

Length of grain, L_o, insert as ZLPOW, 4th line from bottom

Number of perforations, n, insert as ZNPOW, 4th line from bottom

Web thickness of grain, w_o - calculate from Eqns. (3) and (4) from Appendix C, take smaller value, insert as WPOW, 4th line from bottom. Note that if WPOW is taken from Eqn. (3), NLDSW must be set to 0; otherwise, NLDSW must be set to 1.

Solid density of grain, ρ_{solid}, insert as R1SOL, 11th line from top

Internal energy of grain at room temperature, e_{solid}, suggest use value of 0.3148×10^{10} erg/cm, based on specific heat of nitroguanidine (see Appendix I, section on ONED1DE.DAT), insert as E1SOL, 11th line from top

Heat of explosion of powder, insert as ECPOW, 5th line from bottom

Molecular weight of powder gas, m, insert as ZMW, 6th and 7th line from top

Specific heat ratio of powder gas, γ, insert as G, 6th and 7th line from top

Covolume of powder gas, b (cm^3/g), insert as BCO, 6th and 7th line from top

The burning rate of many gunpowders is given as

$$r = a + bp^n \quad (9)$$

where r is the linear burning rate, p is the pressure and a, b and n are constants. The burning rate constants a and b for powders are given in the original references in various units, but one must convert them so that the final unit system is as follows. r and a are in cm/sec, p is in dynes/cm^2 and b is in (cm/sec)/[(dynes/cm^2)^n]. For the powders modelled by us to date, a has been zero. We now continue the variable list.

First constant in powder burn rate equation, a, insert as APOW, 4th line from bottom
Second constant in powder burn rate equation, b, insert as BPOW, 4th line from bottom
Exponent in powder burn rate equation, n, insert as ZNXPOW, 4th line from bottom

There is an option to use a gradated, instead of uniformly distributed deterrent. In this case, NGRSW, second line from bottom, file ONED1DE.DAT, must be set to 1 and GLIM, ZMAXDT, BPOW2 and EFFDET must be set to appropriate values. This option is discussed in Appendix C. If NGRSW is set to zero, the deterrent is uniformly distributed and GLIM, ZMAXDT, BPOW2 and EFFDET are not used.

All of the variables discussed in Sec. 4.9 up to this point are to be inserted into the input file ONED1DE.DAT. The remainder of this section deals with the input variables that are related to the gunpowder and are to be inserted into the input file ONED1D.DAT. These variables are RII, UII, EII, GPOWI and INIB in one block of data with eight lines and ZMII in another block of data with eight lines. NINIB = 4, 2, 2 are the number of lines for each zone in the RII to INIB data block. The sum of the NINIBs is 8, which corresponds to the eight lines of data.) For each of these two blocks of data, only the first four lines refer to the gunpowder/powder gas zone and only these lines will be discussed at this point. In the sample input file, there are two different initial conditions in the gunpowder/powder gas zone. One set of initial conditions applies in the uprange part of the powder breech and a second set applies in the downrange part. This technique is used to simulate a powder load with considerable empty space ("ullage") downrange of the powder charge. The "empty space" must contain a small density of powder - the code will fail if this region has zero density. The four values of INIB determine the location of the boundary between the two sets of initial conditions. The first two values of INIB define the inclusive range of cell numbers where the uprange initial conditions apply. In the sample file, these numbers are -200 and 4. Since the initialization is performed only over the cell number range of 2 to NC - 1, where NC is the number of cells in the zone in question, for the case in point, the uprange initial conditions will be applied to cells 2, 3 and 4. The second two values of INIB define the inclusive range of cell numbers where the downrange initial conditions apply. In the sample file, these numbers are 5 and 200. For the case in point, the downrange initial conditions will be applied to cells 5 through 31 (= NC - 1).

To insert the proper densities in the two parts of the powder/powder gas zone, the volumes of the two parts must be known. Figure 5 below shows the powder/powder gas and piston zones and the arrangement of the cells in each zone. The cells are of uniform

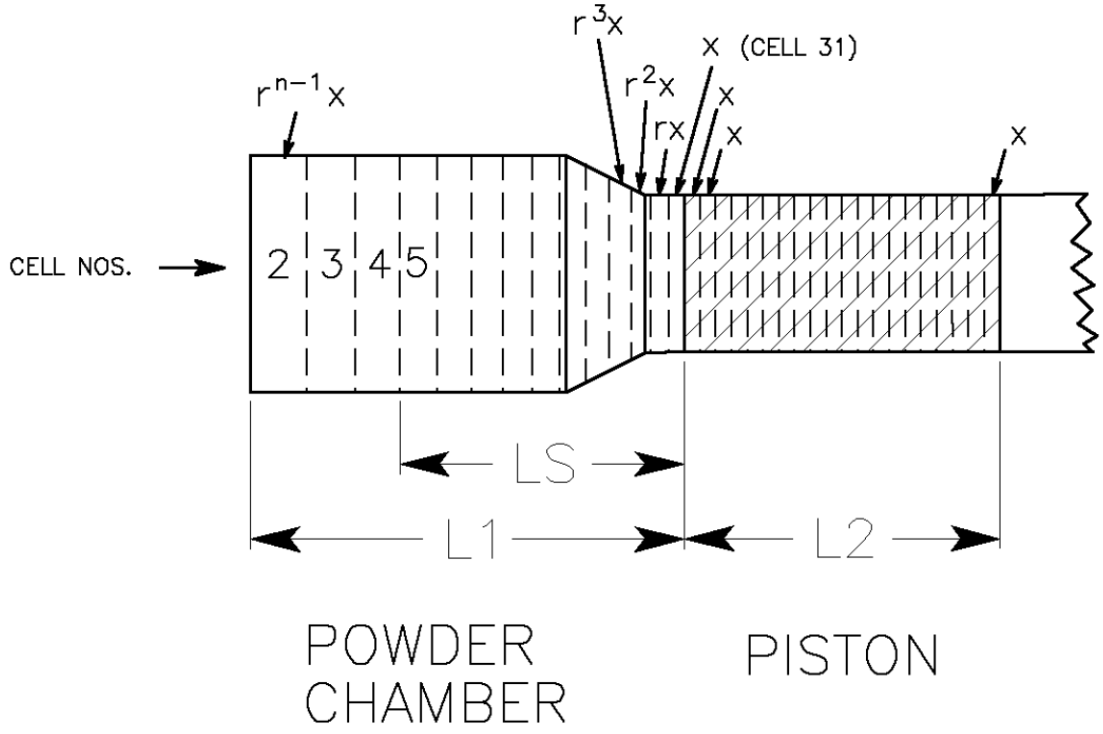

Figure 5. Powder/powder gas and piston zones and cell arrangements in each zone.

length (x) in the piston zone and of steadily increasing length (by the ratio r) as one moves uprange in the powder zone. At the zone boundary the cell lengths in the two zones are matched. In the sample file ONED1D.DAT, NC for each zone is 32, meaning that there 30 fully active internal cells in each zone. From the piston zone, x can determined from

$$x = \frac{L2}{30} \tag{10}$$

By summing up the cell lengths in the powder zone and making a transformation, we can arrive at

$$L1 = \frac{x(1 - r^{30})}{1 - r} \tag{11}$$

Solving by iteration, we can determine r. For the sample file case, with the boundary between the powder sub-zones between cells 4 and 5, LS can be determined from

$$LS = \frac{x(1 - r^{27})}{1 - r} \tag{12}$$

With LS known, using the other dimensions of the powder breech, the volumes of the two sub-zones of the powder zone can be calculated. Call the uprange sub-zone volume v_1 and the downrange sub-zone volume v_2. Let the corresponding powder densities be ρ_1 and ρ_2. Summing up the masses of powder in the two sub-zones, we have

$$\rho_1 v_1 + \rho_2 v_2 = m \tag{13}$$

where m is the total mass of the powder charge. To solve for ρ_1 and ρ_2, we need one more condition. This can be knowing ρ_1, knowing ρ_2 or knowing the ratio of the two densities. For the sample file case, we have chosen $\rho_1 = 0.75851$ g/cm^3, close to the bulk density of the IMR 4227 powder being modelled, which is 0.855 g/cm^3 (reference 25). Using the total powder charge mass, 34.57 g, in Eqn. (13), we find $\rho_2 = 0.00521$ g/cm^3. ρ_1 corresponds to the first two values of RII (in the first two lines) in the sample file ONED1D.DAT. ρ_2 corresponds to the third and fourth values of RII in the sample file.

If the powder is assumed to be uniformly distributed in the powder breech, determination of the RIIs is very much simpler. One takes the mass of the powder charge, divides by the total powder breech volume and the resultant powder density is input for all four RII values in ONED1D.DAT. In this case, the INIB values may be kept at -200, 4, 5, 200. We have found it necessary to have a small fraction of the powder burnt in the initialization of the cells within the powder breech. If there is zero powder gas in a powder zone cell, the equation of state will crash with a divide by zero. We have found that in the powder/powder gas zone initial mass fractions of 0.99 powder, 0.01 powder gas are very satisfactory. 0.99 is to be inserted in the first column of the first four rows of ZMII and 0.01 is to be inserted in the second column of the first four rows of ZMII. It should not be necessary to change these values.

The EII values are the internal energy of the powder/powder gas cells, allowing for the combustion of 1% of the powder. Thus, (initial energy of powder cells after 1% combustion) = (initial energy of powder cells with no combustion) + 0.01 x (heat of combustion). The heat of combustion is taken to be equal to the heat of explosion. Thus, EII (in ONED1D.DAT) = E1SOL (in ONED1DE.DAT) x 0.01 x ECPOW (in ONED1DE.DAT). For the sample file case, EII (in ONED1D.DAT) = 0.3148 x 10^{10} + 0.01 x 3.7674 x 10^{10} = 3.5247 x 10^{10} erg/g. This value is to be inserted into the first four entries of the third column of the RII, UII, EII, GPOW, INIB block. All UII's in this data block should set to zero, since there is no motion before the code starts to calculate.

At the beginning of the calculation, the powder grains do not have their initial shapes, since, for each grain, 0.01 x (mass of grain) has been consumed. In Appendix C, the following equation was developed. It relates the mass fractions of the unburned powder (m_1, m_2) at the beginning and ending of a burn time step in the code. The variables with 0 subscript are grain dimensions before the 1% initial burn. g_1 and g_2 are the fractions of the grain web thickness consumed at the beginning and end of the burn timestep.

$$m_2 = m_1 \frac{[(D_0 - w_0 g_2)^2 - n(d_0 + w_0 g_2)^2][L_0 - w_0 g_2]}{[(D_0 - w_0 g_1)^2 - n(d_0 + w_0 g_1)^2][L_0 - w_0 g_1]} \quad (14)$$

We apply Eqn. (14) between the condition before and after the 1% initial burn. We replace g_2 by g, set g_1 to zero and set m_2/m_1 to 0.99. This results in Eqn. (15).

$$0.99 = \frac{[(D_0 - w_0 g)^2 - n(d_0 + w_0 g)^2]}{[D_0^2 - n d_0^2]} \frac{[L_0 - w_0 g]}{L_0} \quad (15)$$

Solving Eqn. (15) for g (= GPOWI) by iteration yields the value of GPOWI needed to insert in ONED1D.DAT in the RII to INIB data block. This is the fraction of the web depth which needs to burn to reduce the grain mass 1%. This value is to be inserted in the first four entries in the fourth column of the RII to INIB data block.

4.10. Piston

A representative piston of the type used at the NASA Ames Research Center is shown in Fig. 6(a). There are lands at the front and rear of the piston and a conical Bridgman seal at the front of the piston. The one-dimensional code cannot handle the conical seal, so, for the code runs, the simplified piston shown in Fig. 6(b) is used. Land diameters (which are equal for the front and rear lands), land lengths and the shank diameters are equal between the real and the simplified pistons. The overall piston lengths are not equal for the two pistons, but the masses of the two pistons are set to be equal. The piston friction is calculated based on the piston shape shown in Fig. 6(b), but the main one-dimensional CFD solution cannot handle the steps between the shank and the lands. Thus, for the main CFD solution, the gun tube is always completely filled by the working media. Hence, the overall length of the simplified piston must be based on the actual piston mass and density and the full area of the pump tube. (Note that the piston dimensions shown in Fig. 6 and to be entered into the input file ONED1D.DAT are the unstressed values at room temperature, not the values which obtain when the piston is jammed into the pump tube.)

The friction force on the piston depends on the piston diameters versus the pump tube diameter. Piston cells with the land diameter will experience different friction forces than those with the shank diameter. Figure 7 shows the cell arrangement and piston diameters for the rear part of the piston. For cells number 2 to 6, the piston diameter is D(rear land) and for cells 8 through the forward end of the shank, the piston diameter is D(shank). For cell 7 an averaged piston diameter is taken, according to Eqn. (16).

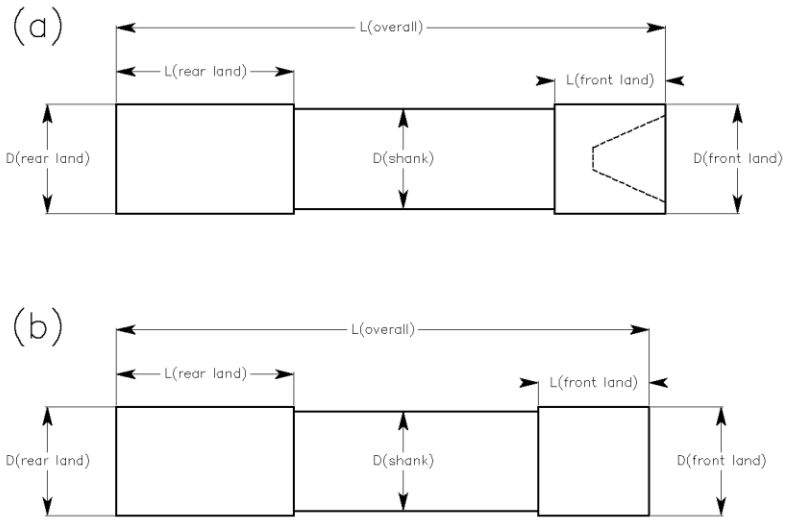

Fig. 6. (a) A representative piston of the type used at the NASA Ames Research Center.
(b) Simplified piston used in CFD calculations.

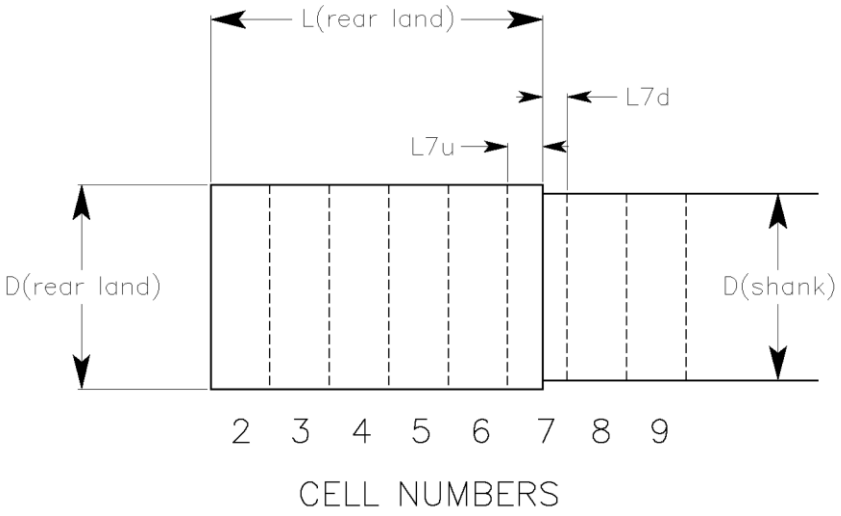

Figure 7. The cell arrangement and piston diameters for the rear part of the piston.

$$D7 = \frac{D(rear\ land)*L7u+D(shank)*L7d}{L7u+L7d} \tag{16}$$

A similar calculation must be made to determine the piston diameter of the cell which straddles the step between the shank and the forward land. At this point, piston diameters for all cells are known. For historical reasons, radii instead of diameters are to be entered in the input file ONED1D.DAT. They are to be entered in the NSRFCF, RPCFI data block.

This data block is preceded by the NRPCF data block with the entries 1 5 1 1. These numbers refer to the number of cells for which radii are given in the three zones of the calculation plus for the projectile. For the powder/powder gas zone, the gun working gas zone and the projectile, the number of RPCFIs is one, for the piston, it is five. In the NSRFCF, RPCFI data block in the sample input file ONED1D.DAT, the following numbers are to be found. These are cell numbers and radii, in order. The first and seventh rows refer to the powder/powder gas and gun working gas zones and these radii are place holders which are not used in the calculations. The last row refers to the projectile and we usually set the projectile radius equal to the launch tube radius, as was done for our sample case. Rows two through six refer to the piston and we work with these five rows in the following discussion.

```
1   1.5
1   1.97100
9   1.95830
10  1.9475
27  1.95680
28  1.97100
1   1.5
1   .355600
```

These entries indicate that:

Cells 2 to 8 have radii of 1.971 cm.
Cell 9 has a radius of 1.9583 cm
Cells 10 to 26 have radii of 1.9475 cm.
Cell 27 has a radius of 1.9568 cm
Cells 28 to 31 have radii of 1.971 cm.

Unfortunately, the cell number for the rear land-shank step for Fig. 7 (a concept-only sketch) does not correspond to that in the ONED1D.DAT file. For the user's gun and operating conditions, he must insert his own values for NSRFCF and RPCFI in the input file ONED1D.DAT. If there are no lands on the piston, the entries for RPCFI in ONED1D.DAT which refer to the piston (2nd through 6th lines in this case) will all be the same. The land radius (or the piston radius if there are no lands) given as RPCFI (a room temperature, no stress value) can exceed the tube radius if the piston is cooled in a freezer, inserted into the pump tube and allowed to warm up.

In Fig. 4 (Sec. 4.2), we see that the two ends of the piston are located at x-coordinates XB(2) and XB(3). XB(2) is simply the customary location of the rear of the piston - XB(2) = 19.596 cm in the sample ONED1D.DAT file. For the simplified piston of the case in point, L(overall) = 17.787 cm. XB(3) = XB(2) + L(overall) = 19.596 + 17.787 = 37.383 cm. The user must insert his corresponding value of XB(3) into ONED1D.DAT.

A number of values for piston properties must be inserted into the input files. Table 2 gives the variable names, values, where they are discussed and where they are to be entered.

Table 2. Values of various properties for the high density polyethylene (HDPE) piston.

Variable	Symbol	Symbol in FORTRAN, row where located	Page no. in Appendix C where relevant FORTRAN file located	Value	Units	Input file in which entered	Section nos., page nos. for description of variable
Modulus of elasticity	E	ECF (2nd row)	81	8.6224×10^{9}	$dynes/cm^2$	ONED1D.DAT	5.1, 31
Yield strength	σ_y	SYCF (2nd row)	81	2.1×10^{8}	$dynes/cm^2$	ONED1D.DAT	5.1, 31
Poisson's ratio	ν	POICF (2nd row)	81	0.4		ONED1D.DAT	5.1, 34
Prefactor for high speed friction coeff. (μ_{hs})	A ; $\mu_{hs}=Au^{.4224}$	ADFCF (2nd row)	81	1.625	$(cm/s)^{.4224}$	ONED1D.DAT	5.1, 34
Low speed friction coefficient	μ_{ls}	ZMSCF (2nd row)	81	0.0359		ONED1D.DAT	5.1, 34
Initial cell density	ρ_1	RII (5th, 6th rows)	80	0.9442	g/cm^3	ONED1D.DAT	5.1, 24
Initial cell internal energy	e_1	EII (5th, 6th rows)	80	1.00×10^{9}	erg/g	ONED1D.DAT	5.1, 24
Limiting negative pressure		PLIM00 (2nd row)	83	-2.10×10^{8}	$dynes/cm^2$	ONED1DE.DAT	5.2, 41, 42
Second limiting negative pressure		PLIMO2 (2nd row)	83	-1.68×10^{8}	$dynes/cm^2$	ONED1DE.DAT	5.2, 41, 42
Limiting sound speed squared		C2LIMO (2nd row)	83	2.25×10^{10}	$(cm/s)^2$	ONED1DE.DAT	5.2, 42, 43
Second limiting sound speed squared		C2LIM2 (2nd row)	83	2.475×10^{10}	$(cm/s)^2$	ONED1DE.DAT	5.2, 42, 43

The variables are discussed in some detail in Appendix I; we briefly run through them here. ECF, SYCF and RII can be obtained from the literature. POICF can be obtained from longitudinal and shear sound speed data. ADFCF and ZMSCF are constants of the friction model. These often have to be tuned to match experimental and theoretical piston velocities. The values shown here have worked well for the NASA Ames 0.28"/1.550" gun and could be used as a starting point for other guns using HDPE pistons. We have generally kept the ratio of these two constants the same and varied them together. EII is generally varied to make the initial temperature of the piston plastic equal to 295 K. To avoid code instabilities, PLIMOO and PLIMO2 define the maximum magnitude negative pressure obtained when the piston material is greatly expanded. We have found that PLIMOO = -SYCF and PLIMO2 = -0.8 x SYCF (as shown in Table 2) have worked well for us. For highly extended piston plastic, it is also necessary to keep the sound speed from dropping too low to avoid instabilities. In the input file ONED1DE.DAT, two values for limiting sound speeds squared are given. These are C2LIMO = 0.225×10^{11} cm^2/s^2 and C2LIM2 = 0.2475×10^{11} cm^2/s^2. They are to be entered in the fifteenth line, third and fourth entries in ONED1DE.DAT. These values produce a minimum sound speed of 1.5×10^{5} cm/s. Further discussion of these limiting techniques is given in Appendix I.

If one is using HDPE pistons, the data shown in Table 2 should be a good start, although ADFCF and ZMSCF very likely will need to be tuned. If the piston material is different, the user will have to set up his own data set corresponding to the data of Table 2.

The procedure described above can be used when the piston comprises only one component or part. In this case, the piston could be made of plastic (e.g., epoxy or polyethylene), metal (e.g., steel or aluminum) or a plastic matrix/metal shot mixture. If the piston has two parts or components (e.g., a plastic slug forward and a metal weight aft), the above piston design procedure (given for a single component piston) must be performed twice, once for each of the two parts of the piston.

4.11. Projectile

The projectile is modelled as a simple cylindrical slug. A number of values for the properties of the projectile plastic (here, taken to be polycarbonate) and the projectile dimensions and mass must be inserted into the input files. Table 3 gives the variable names, values, where they are discussed and where they are to be entered.

Table 3. Values of various characteristics and material properties for the polycarbonate projectile.

Variable	Symbol	Symbol in FORTRAN, row where located	Page no. in Appendix C where relevant FORTRAN file located	Value	Units	Input file in which entered	Section nos., page nos. for description of variable
Modulus of elasticity	E	ECF (4th row)	81	2.2935×10^{10}	$dynes/cm^2$	ONED1D.DAT	5.1, 31
Yield strength	σ_y	SYCF (4th row)	81	3.02×10^{8}	$dynes/cm^2$	ONED1D.DAT	5.1, 31
Poisson's ratio	ν	POICF (4th row)	81	0.403		ONED1D.DAT	5.1, 34
Prefactor for high speed friction coeff. (μ_{hs})	A ; $\mu_{hs}=Au^{-.4224}$	ADFCF (4th row)	81	2.264	$(cm/s)^{.4224}$	ONED1D.DAT	5.1, 34
Low speed friction coefficient	μ_{ls}	ZMSCF (4th row)	81	0.05		ONED1D.DAT	5.1, 34
Projectile mass	m_{pr}	ZMPROJ	80	0.3325	g	ONED1D.DAT	5.1, 27
Projectile length	L_{pr}	ZLPROJ	80	0.6764	cm	ONED1D.DAT	5.1, 27
Projectile diameter	D_{pr}	RPCFI (8th row)	81	0.3556	cm	ONED1D.DAT	5.1, 32

The variables are discussed in some detail in Appendix I; we briefly run through them here. ECF and SYCF can be obtained from the literature. POICF can be obtained from longitudinal and shear sound speed data. ADFCF and ZMSCF are constants of the friction model. We have not changed these values for years and they have proven very satisfactory for six different guns modelled at NASA Ames. If it is necessary to tune these parameters, it is suggested that they be varied together, i.e. maintaining the ratio of the two variables. ZMPROJ, the projectile mass, is self-explanatory. We take the projectile to completely fill the launch tube, and then, have used the material density to calculate the projectile length, ZLPROJ. That was done for the case for which data is shown in Table 3, for a polycarbonate density of 1.20 g/cm^3. Generally, the projectile radius, RPCFI, is taken to be equal to the launch tube radius, 0.5 x A(5,1) (see Sec. 4.2). RPCFI can be made larger than this, simulating jamming of the projectile into the launch tube (either by cooling or hammering). In the vast majority of cases (many guns, wide range of operating conditions) the method given in Ref. 1, pp. 40 - 41 for calculating the projectile friction gives very good results. However, there are conditions in which the projectile friction can be overestimated by the code. This can occur when a heavy projectile is simulated by a long projectile made of light plastic. In this case, it appears that the frictional force along the cylinder surface can be over-estimated by the model, leading to muzzle velocities that are too low. A fix for this was to shorten the model length by a factor of 2, (from L/D = 2.0 to L/D = 1.0) while keeping the model mass fixed. This brought the muzzle velocity back into line. Changing the L/D in this way is a good test to see if this calculation problems exists. For the same projectile mass, the muzzle velocity should change very little, other parameters being unchanged.

If one is using polycarbonate projectiles, the data of the first five lines shown in Table 3 should be a good start. If the piston material is different, the user will have to set up his own data set corresponding to the data of Table 3.

4.12. Working Media - Equations of State (EOS), Viscosities

For the powder/powder gas zone, we use the Abel EOS for the gas and a constant energy, constant density model for the unburned powder grains. This is discussed in some detail in Appendix A. For the powder zone, the variables for which values need to be inserted in the file ONED1DE.DAT are given in Sec. 4.9. The NTEOS value, which identifies the EOS option to be used, is 8 in this case. This value is to be inserted in the second line, first entry in the file ONED1DE.DAT.

For the piston zone, we use the Zel'dovich and Raizer three term EOS with the third term dropped. This EOS is discussed in some detail in Appendix B. Our coefficients for fits to the EOSs for pistons of epoxy, polyethylene, aluminum and iron are given Table 4 below. These values are to be inserted in the input file ONED1DE.DAT. The NTEOS for this EOS is 1, to be entered in the third line, first entry (and fourth line, first entry if there are two piston zones). The bottom four lines of Table 4 give the correspondence of the variable names and the location(s) where the variable is to be entered in ONED1DE.DAT. For example ρ_o corresponds to ROZZX in ONED1DE.DAT and the values must be put in line 7, entry 1 and line 8, entry 1 in ONED1DE.DAT for a two zone piston. For a one zone piston, the ρ_o value must be put in line 6, entry 1.

Table 4. Coefficients in EOSs for epoxy, polyethylene, aluminum and iron.

Material	ρ g/cm^3	ρ_o g/cm^3	A_1 dynes/cm^2	n	A_2 dynes/cm^2	m	G_1	G_2 cm^3/g
Epoxy	1.185	1.1875607	1.920E+10	3.6	3.840E+09	6	0.8	0
Poly-e	0.954	0.9578335	1.679E+10	3.6	3.360E+09	6	1.2	0
Alum.	2.784	2.830049	1.259E+11	3.6	2.520E+10	6	10.5	-2
Iron	7.856	7.9474191	2.646E+11	3.6	5.292E+10	6	2.613	-0.0625
FORTRAN		ROZZX	AA1ZZX	ZNZZX	AA2ZZX	ZMZZX	GRZZ1X	GRZZ2X
Location 2		L7 E1	L7 E4	L7 E2	L7 E5	L7 E3	L15 E1	L15 E2
Location 2		L8 E1	L8 E4	L8 E2	L8 E5	L8 E3	L16 E1	L16 E2
Location 1		L6 E1	L6 E4	L6 E2	L6 E5	L6 E3	L12 E1	L12 E2

* "FORTRAN" denotes FORTRAN name in input file ONED1DE.DAT

† "Location 2" denotes line number and entry number in ONED1DE.DAT for a two zone piston

†† "Location 1" denotes line number and entry number in ONED1DE.DAT for a one zone piston

The constants T2CXN1 - T2CXN4 in the fits of the of the temperature as a function of the internal energy, $T = T(e_{thermal})$, are given in Table 5 below. The locations where these

variables are to be placed in ONED1DE.DAT are given at the bottom of Table 5 in the same way they were given in Table 4. Further discussion of the constants T2CXN1 - T2CXN4 is given in Appendix B.

Table 5. Constants T2CXN1 - T2CXN4 for epoxy, polyethylene, aluminum and iron.

Material	T2CXN1	T2CXN2	T2CXN3	T2CXN4
Epoxy	6.324E-03	200	2.000E+07	4.000E+09
Poly-e	5.574E-03	180	2.317E+07	4.170E+09
Alum.	6.988E-03	120	9.837E+06	1.180E+09
Iron	9.649E-03	125	5.370E+06	6.710E+08
Location 2	L11 E1	L11 E2	L11 E3	L11 E4
Location 2	L12 E1	L12 E2	L12 E3	L12 E4
Location 1	L9 E1	L9 E2	L9 E3	L9 E4

If we use one of the working gases shown in Table 6, instead of hydrogen, we use a version of Eqn. (1) (Sec. 2.1) in which the molecular volume term is compressible. The development of this EOS is given in Sec. 2.1, Eqns. (1) - (6). We have made fits of the various coefficients of this EOS to data for the three gases shown in Table 6. For the gas chosen, the coefficients of the table are to be inserted in the input file ONED1DE.DAT. The locations where these variables are to be placed in ONED1DE.DAT are given at the bottom of Table 6 in the same way they were given in Table 4. The NTEOS for this EOS for pure gases is 3. This NTEOS is not normally used in the code, due to the incorporation of eroded wall material into the working gas. An EOS which can handle the gas/eroded wall mixture with the gases shown in Table 6 has a NTEOS of 5. This number is to be entered in the fifth or fourth line (depending on the number of piston zones), first entry of ONED1DE.DAT.

Table 6. Coefficients in EOSs for He, N_2 and Ar

GAS	A dyne/cm^2	n	ρ_0 g/cm^3	m	γ
He	1.601 x 10^7	4.7	0.1416	4.00	1.667
N_2	1.114 x 10^9	5.7	0.8200	28.0	1.35
Ar	1.931 x 10^9	5.2	1.400	40.0	1.667
FORTRAN	AA	ZN	RO	ZMW	G
Location 2	L5 E2	L5 E4	L5 E3	L28 E1	L28 E2
Location 1	L4 E2	L4 E4	L4 E3	L22 E1	L22 E2

* "FORTRAN" denotes FORTRAN name in input file ONED1DE.DAT
† "Location 2" denotes line number and entry number in ONED1DE.DAT for a two zone piston
†† "Location 1" denotes line number and entry number in ONED1DE.DAT for a one zone piston

For pure hydrogen gas, a two-dimensional tabulated EOS of the form $T(\rho,e)$, $p(\rho,e)$ is used. The development of this EOS is given in Appendix A. The tabulated data is to be found in ~19,000 lines of ONED1DE.DAT and no hydrogen EOS data needs to be inserted by the user. The NTEOS for this EOS for pure hydrogen is 6. When melted wall material is mixed with the hydrogen, a mixture EOS is created, for which the NTEOS is 9. This number is to be entered in the fourth line, first entry of ONED1DE.DAT.

In the input file ONED1D.DAT, it is necessary to insert the initial values of the density and internal energy for the working gas. These are the RII and EII values in the seventh and eighth rows of the RII, UII, EII, GPOWI, INIB block. The RIIs can be calculated using the ideal gas law. The EIIs can be calculated using data from the JANAF tables.[32]

Appendix D presents a discussion of our method to develop fits to viscosity data for He, H_2, N_2, Ar and powder gas. The coefficients of the fits are given in Table 1 of Appendix D. The viscosity coefficients appear in two three-line blocks in the input file ONED1D.DAT. The first block contains the coefficients VIS(NZ,1), VIS(NZ,2) and two non-viscosity variables. The second block contains the coefficients VIS(NZ,3) through VIS(NZ,6). One should check that the correct sets of viscosity coefficients have been loaded into ONED1D.DAT, especially after changing the working gas.

5. Final Check of Input Variables

In Section 4 (subsections 4.1 to 4.12) the setting of most of the important input variables has been discussed. However, Sec. 4 is not exhaustive. When the code is first set up, the settings of the input variables in the three input files should be checked against the exhaustive Appendix I. (Note that only the variables marked with a dagger in Appendix I need to be checked.) After the initial Appendix I check, it is usually not necessary to check variables that are not in Sec. 4, but are in Appendix I with daggers. The Appendix I check should, however, be made from time to time. Note that Appendix I provides considerable further explanations and amplifications of the material of Sec. 4.

6. Gun Operating Parameters Which Can Be Varied

Gun operating parameters which can be varied include

1. Powder mass
2. Piston mass
3. Working gas pressure
4. Gunpowder (burn rate)
5. Working gas
6. Pump tube length and diameter
7. Break valve rupture pressure
8. Projectile mass

Often, in assessing a new gun or a radically different gun operating condition, we perform a survey by varying piston mass and gas pressure on a square grid of values and, for each pair of values, varying the powder mass over 6 to 10 values. This generally gives a rough idea where the sweet spot(s) is (are). Changing the type of gunpowder seems to produce gun performance changes that can be cancelled out by changing the powder mass. Changing the working gas from the usual hydrogen to helium, nitrogen or argon can produce much lower muzzle velocities than are usual for two-stage guns. However, in some cases, that is the desired goal. If the pump tube length is shortened and the working gas fill pressure is correspondingly raised, a large reduction in gun erosion can be obtained in some cases.[33] By varying the break valve rupture pressure, it may be possible to minimize the maximum projectile base pressure. This was found to be the case for CFD results for the NASA Ames 0.5"/2.54" gun for the conditions described in Ref. 34. In this case, the optimum rupture pressure was 5.0 ksi. The projectile mass is obviously a very important parameter with respect to the muzzle velocity, as is evidenced in the graph of Ref. 35. However, in many cases, the projectile mass is determined by considerations other than the highest possible muzzle velocity, and there is little freedom to vary this mass.

7. Suggestions for Operation of Code

7.1. Selection of Numbers of Cells in Zones

The minimum value of NC for each zone is 4, since there must be two internal cells and two "ghost" cells at either end of the zone. The maximum value of NC for each zone is 100, since this is how the arrays are dimensioned. The NCs must be even. Choosing very small numbers of cells will result in poor resolution of flow features. On the other hand, choosing very large numbers of cells can result in excessive run times for the code. In general, we have had good results taking NC(1), the number of cells in the gunpowder/powder gas zone, to be 32. Likewise, we have had good results taking NC(2), the number of cells in the piston zone, to be 32. It is suggested to start with NC(1) = NC(2) = 32.

NC(3) is the number of cells in the gun working gas zone. Most recent (2018 - 2020) runs at Ames have been done with NC(3) = 40, and this is suggested as a starting point, since it provided a good balance between resolution of flow features and excessive run times. However, if the hydrogen zone becomes very much compressed during the CFD run, the time step can become extremely small and the code will essentially grind to a halt. The code does not usually crash under these circumstances, but a complete solution (up to projectile exiting the gun muzzle) is not obtained even after the recommended maximum number of timesteps (60,000). This is more likely to happen if one or more of the following apply:

(1) The initial pump tube hydrogen fill pressure is particularly low.
(2) The pump tube is particularly short.
(3) The projectile is particularly heavy.

In the period 2015 - 2018, many runs were made with NC(3) = 80. When we have failed to obtain a complete solution with NC(3) = 80, success has almost always been obtained if NC(3) is reduced to 40. [Runs with NC(3) = 60 might also be tried.] Even in such difficult cases, it is suggested that every attempt be made to keep NC(3) above 32, to allow reasonable resolution of flow features to be obtained.

7.2. Compilation and Execution of Code

Here, we discuss compilation and execution of the LGGUN code. The critical files include source, command, executable and COMMON files. All the original work at Ames was done on the UNIX operating system. The code is written in FORTRAN. The operation described in these two paragraphs is how the code is run at Ames and it is not expected that it can be done in exactly the same way at other sites. Some modifications in the following procedures will certainly be necessary.

All of the necessary files are contained in the directory "LGGUN_V1". This includes the three command files to be discussed below. There are four COMMON files, "COMMON1.inc", "COMMONA.inc", "COMMONB.inc" and "COMMOND.inc". The main program ONEDIM.f and all its subroutines can be compiled by invoking the command file "onedcomredO2". The executable file will be "a.out" and we usually rename it ONEDIM. To run the code, invoke the command "./ONEDIM". After a run is made, a number of output files will appear. Note that the names of the output (and input) files do not change. The useful output files are discussed in Appendices H and J. Note that in addition to the useful output files, the code produces a number of diagnostic files which were used to solve code problems in the past, but are no longer necessary. No attention need be paid to the content of these files, but they take up a lot of space. These files must be removed by invoking (on our machine) the command ./MMcl. This command removes the unnecessary diagnostic output files, but leaves the useful output files from the computer run just completed. After the output data which needs to be kept is transferred to another directory or computer, ALL the output files in the directory "LGGUN_V1" must be removed by invoking (on our machine) the command ./Mcl. The code will not run if its directory is not cleaned up this way.

The commands ./MMcl and ./Mcl mean, on our machine, "execute script MMcl" and "execute script Mcl", respectively. These two master scripts each call four sub scripts each of which contains a list of files to be removed using the Unix rm command. Each sub script, then, takes the form "rm FILE1 FILE2 ..... FILELN". All scripts and sub scripts are included in the LGGUN package. The user has only to execute script MMcl and script Mcl at the appropriate times.

8. Tuning of Code

8.1. Need for Tuning

One may ask: why can't the code calculate the solution directly from first principles? There are two main reasons, discussed in some detail in section 5.2 of Ref. 1. First, in the powder chamber of the gun, the powder burns at a considerably different rate than that

implied by the equation given by the powder maker. The usual burn rate tests are done in closed vessels, with no net flow of the powder gas. In a gun, the gas flows over the powder as the projectile accelerates and the resulting increase in convective heat transfer to the powder grains causes an increase in the burn rate over that measured in a closed vessel. Secondly, the burn rates given by the powder maker are power laws emphasizing the high chamber pressures characteristic of military guns - from 600 to 3000 bar. The pressures in the powder chambers of two-stage light gas guns are usually considerably less - 400 to 1000 bar and the powder burn rate equations given by the powder maker are frequently inaccurate at these lower chamber pressures. The upshot of this is that the powder burn rate in the two-stage gun in question has to be determined from actual two-stage gun data. This then requires "tuning" of the empirical constants in the burn rate equation given by the powder maker to data from the gun in question. Further, one should note that this tuning is unique for every powder/gun combination, unless, perhaps, one considers two powders or two guns which resemble each other rather closely.

The friction of the piston in the pump tube is also something which is very difficult to model from first principles. First, the piston land surfaces (see Fig. 6) may melt, reducing the friction coefficient below that used in the basic model. Second, the lands will wear away progressively, thereby reducing the land jam in the pump tube, over the course of the piston stroke. Both of these phenomena are very difficult to model. Third, there is considerable evidence (see section 5.7 of Ref. 1) that the high strain rate deflection and yielding behavior of the piston material is very different from that predicted using material parameters measured in low strain rate situations. These latter parameters are used in our model, lacking any data on high strain rate deflection and yielding behavior of the piston material. In general, the experimentally observed behavior of the piston indicates a substantially lower friction drag force than that which would be calculated applying our model directly, without modification. The result of this is that the parameters controlling the piston friction must be adjusted ("tuned") to reproduce the observed piston behavior and powder chamber pressure histories in the gun in question.

8.2. Parameters to Tune

To tune the powder burn rate, one adjusts the parameter BPOW(1) in the input file ONED1DE.DAT (see Appendix I, section on ONED1DE.DAT). For the two powders used in the 0.28" and 1.5" guns at the Ames Research Center, the BPOW(1) values taken directly from the powder makers' data had to be multiplied by ~1.6 and ~1.9, respectively, to produce CFD results matching the experimentally observed gun behavior. (See Ref. 1, section 5.2.) On the other hand, based on incomplete tuning attempts for other gun/gunpowder combinations, the burn rate of the powder concerned appeared to be much closer to that given by the powder manufacturer. Based on these observations, it is difficult to give a starting value for BPOW(1) for code "tuning" for a particular gun/powder combination. Various values must be tried to find the best match between the CFD burn rates and the actual experimental burn rates.

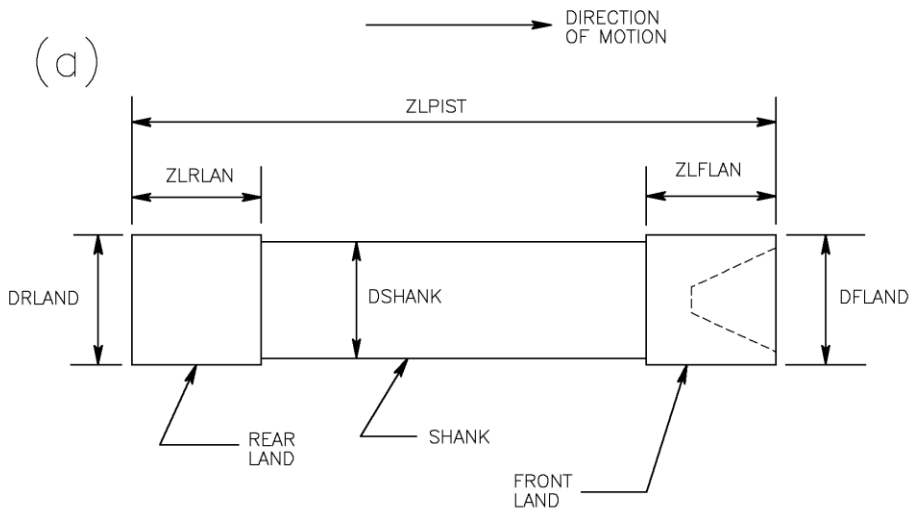

Fig. 8(a). Representative pump tube piston for two-stage light gas gun (not to scale). Actual piston is shown.

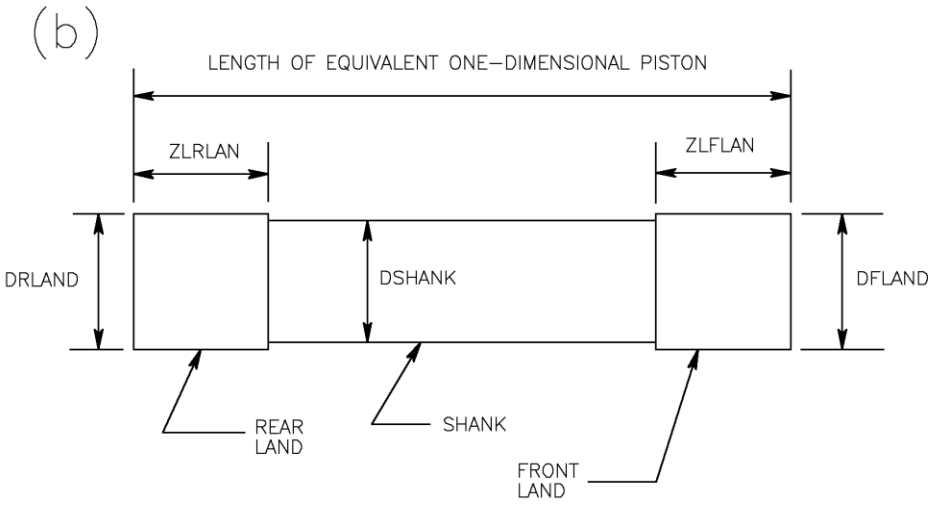

Fig. 8(b). Representative pump tube piston for two-stage light gas gun (not to scale). One-dimensional piston as modelled in CFD code is shown.

To tune the piston friction, one may:

(1) Change the CFD land diameters from the actual values to change the land jamming forces in the pump tube. The land diameters are DRLAND, DFLAND in Fig. 8.

(2) Remove the lands entirely, i.e., set DRLAND and DFLAND equal to DSHANK, the piston shank diameter in Fig. 8.

(3) Change the piston friction coefficients (dynamic and static) from those which would normally be used in the friction model. These coefficients are ADFCF(2) and ZMSCF(2) in the input file ONED1D.DAT (see Appendix I, section on ONED1D.DAT) and it is suggested that they be changed in proportion to each other.

All of these methods have been used in the past and it has not been obvious that any one of them is better than the others. Further, piston behavior has been found to be so unpredictable that it is difficult to give suggestions for how much these parameters should be adjusted to model a new powder/gun combination. One might reduce the land diameters to a value halfway between the actual land diameters and the shank diameter, and/or reduce the piston friction coefficients by half, and see what improvement this makes in the code predictions, as measured against actual gun data. This is only the crudest suggested starting point - one's actual gun data may well show that very different reductions in piston land diameter and friction coefficients would be required for good simulation of a given, new powder/gun combination. (Note that DRLAND, DFLAND and DSHANK are not read in directly in the input file ONED1D.DAT. Rather, these variables are determined from XB(2), XB(3), the NSRFCF values and the RPCFI values which are directly read in into the input file. The correspondence between the two sets of variables is given following the presentation of the variables NSRFCF and RPCFI in section 4.10.)

For the last series of CFD calculations (5/20), good results were obtained on a 0.28"/1.55" two stage light gas gun with polyethylene pistons with:

DRLAND = DFLAND = 1.552"
DSHANK = 1.5335"
Tube diameter = 1.550"
ADFCF = 0.4
ZMSCF = 0.0359

Some, but not all, of the CFD calculations were compared with data from actual gun firings. In those cases, the correspondence of the CFD and experimental results for piston and muzzle velocities was very good. The ADFCF and ZMSCF values given above may serve as a rough starting point for other polyethylene pistons.

8.3. Suggested Tuning Technique

One good, repeatable gun operating condition should be selected against which to tune the CFD code. Adequate powder chamber pressure history data and piston velocity data must be available. (Note that, for a given gun, if the powder is changed, the tuning process will likely have to be repeated.) The CFD code parameters discussed above will be tuned to reproduce the experimental powder chamber pressure histories and piston velocity data. In our experience, it is best to tune against a piston velocity near the maximum velocity

point in the pump tube. Tuning against velocities very close to the high pressure contraction section, where the piston is slowing down substantially, has proven to be less satisfactory. Several ways in which to characterize the powder chamber pressure histories (both experimental and theoretical) have been tried. These are:

(1) Maximum pressure.
(2) Average of maximum slope of pressure rise and (absolute value) of maximum slope of pressure fall.
(3) Width of pressure curve at a fixed pressure level about 1/2 of the observed, experimental maximum pressure.

The last of these three has proven to be very much superior to the other two and it is strongly recommended to use this parameter in code tuning for a new powder/gun configuration.

The tuning itself is a two-dimensional optimization problem; one runs several CFD solutions varying the powder burn rate and the piston friction and then one plots the CFD piston velocities and powder chamber pulse widths so obtained on a two-dimensional plot and tries to home in on the experimental values. Generally, it has been found that 10 to 12 well-chosen CFD runs should be sufficient to "tune" the code. When the code is very near being "tuned", it is good to run several CFD runs with slightly varying powder burn rates and piston friction and to make a final selection based on "eyeballing" the best match of the CFD and experimental powder chamber pressure histories (while maintaining, of course, a good CFD prediction of piston velocity).

Once the tuning is done against a good, reproducible benchmark gun operating condition, the powder burn rate variable and the piston friction are kept unchanged for all future predictions for that powder/gun combination.

9. Results

Appendix K gives sample input files for a run of the LGGUN code. Appendix L gives sample output files corresponding to the inputs given in Appendix K. All of the input variables in Appendix K are identified in Appendix I. Correspondingly, all of the output variables in Appendix L are identified in Appendix J. Appendix H provides a summary of the input and output files presented in Appendices I and J. As an example of examining the input/output variables, we consider the FINALOUTP output file. The numerical values of these output variables are given at the beginning of Appendix L. The identifications of and the units for these variables are given at the beginning of Appendix J. It can be seen that the muzzle velocity for this shot was 0.5796×10^6 cm/s = 5.796 km/s and the maximum projectile base pressure was 0.2717×10^{10} dynes/cm^2 = 39,400 psi. Code results are also presented in Refs. 1, 2, 20, 22, 23, 33 and 34.

10. Summary and Conclusions

We have presented a new code (LGGUN) for the calculation of the performance of two-stage light gas guns. The code is a quasi-one-dimensional Godunov code which is second order accurate in time and third order accurate in space, uses realistic equations of

state for all media, includes wall friction and heat transfer for all gas and dense media zones and includes a simple non-equilibrium model for gas phase turbulence. Gun tube wall heating, melting/ablation and the incorporation of melted wall material (taken to be fine droplets) into the (usually) hydrogen working gas is modelled. It has been extensively validated against analytical solutions and experimental data from the 0.22", 0.28", 0.50", 1.0" and 1.5" two stage guns at the NASA Ames and Marshall Research Centers operated over a wide range of operating conditions with muzzle velocities of 0.7 to 11.3 km/s. The code outputs piston and projectile velocities, maximum gas pressures and temperatures at selected locations and cells, piezometric ratios, snapshots of conditions at specific times and a number of time history files at various locations in the gun. Also given are the maximum gun tube wall and internal temperatures and the profile along the gun of the depth of eroded (melted) wall material during the shot.

The set up of the input files for the code was given in detail. This includes gun, piston and projectile dimensions and masses, equations of state for all working media, gunpowder properties, properties of gun steel (or rhenium or tantalum). Also, the powder load, working gas pressure and break valve (diaphragm) rupture pressure are input. Suggestions for operating the code were given and the compilation and execution of the code were outlined. The method of tuning of the code to match powder chamber pressures histories and piston velocities was presented. Results were given in the form of sample output files and attendant descriptions of variables Appendices H through L. Results presented in other reports were referenced.

Appendices A, B and B1 presented the equations of states used. The powder burn model was presented in Appendix C and the evaluation of the viscosities was presented in Appendix D. The arrangements and content of the subroutines was presented in Appendices E through G.

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Appendix A

Equations of State Used in Light Gas Gun Code

The equations of state (EOS) used are as follows. For the powder gas, the Abel volumetric equation of state (Eqn. 1) is used.

$$p(v - b) = \frac{R_u T}{m} \tag{1}$$

p is pressure, v, specific volume, b, molecular volume, R_u, the universal gas constant, T, temperature and m, molecular weight. The absolute enthalpy is determined assuming constant specific heat. The unburned powder is taken to be a constant density, constant internal energy solid at the initial (room temperature) conditions.

For the piston, the Zel'dovich and Raizer three term dense media EOS[4] with the third term neglected is used. From experimental shock Hugoniot data[5] for a given media, a good determination of the constants in this EOS can be made. [Shock Hugoniot data consists of a table (and graphs) of shock velocities, particle velocities, pressures and densities for shocks of different strengths in the media in question.] This method of constructing an EOS is described in Appendix B.

For the hydrogen gas, a two-dimensional tabulated EOS of the form T(ρ,e), p(ρ,e) can be used. For the LGGUN code, this EOS was constructed as follows. First, using Ref. 36, equilibrium calculations were made for point hydrogen molecules (and atoms) over the full required pressure and temperature ranges. Then, a molecular volume term was added which follows the Zel'dovich and Raizer[4] cold pressure-volume relation [Eqn. (2)] for dense media:

$$p = A\left[\left(\frac{\rho}{\rho_0}\right)^n - 1\right] \tag{2}$$

In Eqn. (2), ρ_o is a reference density and A and n are empirical constants for the medium in question. The constants in Eqn. (2) can be obtained using shock Hugoniot data for liquid hydrogen.[5] [Note that ρ in Eqn. (2) is the density of the hydrogen molecules (= 1/b, see Eqn. (1)) and not the overall density of the hydrogen.] It can be shown that this yields a EOS for hydrogen which compares rather well with the tabulated SESAME[7] EOS and is free of the "noise" problems of the latter. When melted wall material is mixed with the hydrogen, a mixture EOS is created, which is currently used for all two stage gun analyses.

A similar type of EOS was developed for He, N_2, Ar and H_2 gun working gases. Here, we use a version of Eqn. (1) in which the molecular volume term, b (=1/ρ_m) is compressible

according to Eqn. 2. In this case, v =1/ρ. Equations (1) and (2) then become Eqns. (3) and (4) below.

$$p\left(\frac{1}{\rho} - \frac{1}{\rho_m}\right) = \frac{R_u T}{m} \tag{3}$$

$$p = A\left[\left(\frac{\rho_m}{\rho_o}\right)^n - 1\right] \tag{4}$$

The constants A, ρ_0 and n in Eqn. (4) can be evaluated by fitting the EOS to shock Hugoniot data for the respective liquified gases. Equation (4) can be integrated to give the pdv work done on the molecules as they are cold compressed from zero pressure to a pressure p. The result is Eqn. (5) below, where e_c is the cold compression energy.

$$e_c = \frac{A}{\rho_0}\left\{\frac{1}{n-1}\left[\left(\frac{\rho_m}{\rho_0}\right)^{n-1} - 1\right] - \left[1 - \frac{\rho_0}{\rho_m}\right]\right\} \tag{5}$$

The total gas energy is $e = e_c + e_t$, where e_t is the thermal energy term, given by

$$e_t = \int C_v \, dT \tag{6}$$

where e_t is the thermal energy and C_v is the specific heat at constant volume. We invert Eqn. (6) to get

$$T = f(e_t) \tag{6a}$$

which we make available in tabular form for hydrogen. For the other working gases, Eqns. (6) and (6a) are replaced by the following equations:

$$e_t = \frac{R_u T}{m(\gamma - 1)} \tag{6b}$$

$$T = \frac{(\gamma - 1) m e_t}{R_u} \tag{6c}$$

The system of equations is solved by using the bisection method. Initial limiting values of ρ_m/ρ_o of 1.0 and 12.0 are chosen. Equation (5) is used to calculate e_c and then, using $e = e_c + e_t$ and Eqn. (6a) or (6b), T is found. Equation (3) can be rearranged to yield Eqn. (7) below.

$$\rho' = \frac{p}{\frac{R_u T}{m} + \frac{p}{\rho_m}} \tag{7}$$

ρ_m is then iterated until ρ' from Eqn. (7) is equal to the originally given ρ to one part in 10^6.

Generally, about 30 iterations are required to converge on the correct ρ. Using Eqns. (3) - (7), we can construct the EOSs for the pure gases He, N_2, H_2 and Ar. When melted wall material is mixed with the gun working gases, a mixture EOS is created, which is currently used for all two stage gun analyses.

Experimental shock Hugoniot data is available for liquid N_2 in Refs. 5 and 8 and for liquid Ar in Refs. 8 - 10. From this data, we can obtain after-shock pressures (p_2), densities (ρ_2) and internal energies (e_2). Using the EOS Eqns. (3) - (7) above, a second value for p_2, $p_2'(\rho_2,e_2)$ can be obtained for each data point. One may then compare the two values of p_2 for every data point. The parameters ρ_0 and n are then adjusted to produce the best overall fit between theory and experiment. The agreements are quite good up to pressures of 20 GPa (3000 ksi), but deteriorate progressively at higher pressures. However, for our present use, this does not pose a problem, since at 3000 ksi, we are already well above the maximum pressures which a two-stage gun could tolerate (perhaps ~300 ksi).

Experimental shock Hugoniot data is available for liquid He in Refs. 11 and 12. Pressure ranges for these two studies were 1.23 to 15.6 GPa and 51 to 118 GPa, respectively. In Ref. 13, room temperature static pressure-density data for He is presented at pressures of 0.1 to 1.0 GPa. Reference 14 presents this data of Ref. 13, together with the results of theoretical calculations at pressures of 1.0 to 12.0 GPa. Using Eqns. (3) - (6), the equation parameters were adjusted to provide the best fit to the combined experimental/theoretical data of Refs. 11, 13 and 14. This fit was very good, based on shock pressures up to 15.6 GPa. For the higher after-shock pressures of Ref. 12, the agreement between the theoretical EOS and experiment became progressively worse with increasing pressures, as was the case for N_2 and Ar.

Experimental shock Hugoniot data is available for liquid H_2 in Refs. 14a, 14b and 14c. Pressure ranges for these three studies were 1.7 to 6.5 GPa, 1.9 to 10 GPa and 25 to 55 GPa, respectively. Using Eqns. (3) - (6), the equation parameters were adjusted to provide the best fit to the experimental data of Refs. 14a, 14b and 14c. For all four gases, the beginning of the deterioration of agreement starts at ~30 GPa, with the experimental pressures trending lower than those using theoretical EOS fits. Table 1 shows the coefficients of the EOS fits for He, N_2, H_2 and Ar.

Table 1. Coefficients in EOSs for He, N_2, H_2 and Ar

GAS	A dyne/cm^2	n	ρ_0 g/cm^3	m	γ
He	1.601 x 10^7	4.7	0.1416	4.00	1.667
N_2	1.114 x 10^9	5.7	0.8200	28.0	1.35
H_2	6.12 x 10^8	4.5	0.073332	2.0	1.4
Ar	1.931 x 10^9	5.2	1.40	40.0	1.667

Appendix B

Zel'dovich-Raizer Equation of State Fit Used in Light Gas Gun Code

In these codes, use is made of an equation of state (EOS) for dense media (liquids and solids) taken from Ref. 37, pp. 697 – 711. This EOS is used for plastic pistons, metal weights for pistons and plastic matrix-metal shot pistons. It is also to construct the EOS for liquid hydrogen to obtain the cold molecular volume and energy data for compressible hydrogen molecules to be added to the Gordon-McBride (Ref. 36) point molecule volume and energy data to construct the EOS for hydrogen used in our code. Below is a description in some detail of how the EOS of Ref. 36 was modified and how the parameters of this EOS were fit to experimental data, including shock Hugoniot data.

The EOS considered here is for dense media (solids and liquids). The development and fit of the EOS starts with Eqns. 11.30 of p. 704, Ref. 37. The key equations are reproduced below.

$$e = e_c(V) + e_T + e_e \tag{1}$$

$$p = p_c(V) + p_T + p_e \tag{2}$$

$$e_c = \int_V^{V_{0c}} p_c\,(V)dV \tag{3}$$

$$e_T = 3\mathrm{Nk}(T - T_0) + e_0 \tag{4}$$

$$p_T = \Gamma(V)\frac{e_T}{V} \tag{5}$$

where:

e = energy/unit volume
p = pressure
V = specific volume (= 1/density)
T = temperature
k = Boltzmann's constant
N = number of molecules per unit mass
Γ (or G) = Gruneisen parameter = (thermal pressure)/ (thermal energy density)

and subscripts denote:

0 = reference state
c = cold compression terms
T = thermal terms
e = electronic terms

To proceed, we drop the electronic terms and keep the thermal energy term e_T in its general form. The form of the cold pressure term is taken from Eq. 11.38, p. 710 of Ref. 37:

$$p_c(V) = A\left[\left(\frac{V_0}{V}\right)^n - 1\right] \tag{6}$$

Originally, we had used one cold pressure term of type shown in Eq. (6). However, it has been found that a much better fit to the experimental shock Hugoniot data can be achieved if two terms of this type are used. We express p_c in this way and also change from using V, the specific volume to using ρ, the density. The resulting equation for the cold pressure is

$$p_c = A_1\left[\left(\frac{\rho}{\rho_o}\right)^n - 1\right] + A_2\left[\left(\frac{\rho}{\rho_o}\right)^m - 1\right] \tag{7}$$

p_c can be integrated to give the cold compression energy, as follows:

$$e_c = \frac{A_1}{\rho_o}\left\{\frac{1}{n-1}\left[\left(\frac{\rho}{\rho_o}\right)^{n-1} - 1\right] + \left[\frac{\rho}{\rho_o} - 1\right]\right\} + \frac{A_2}{\rho_o}\left\{\frac{1}{m-1}\left[\left(\frac{\rho}{\rho_o}\right)^{m-1} - 1\right] + \left[\frac{\rho}{\rho_o} - 1\right]\right\} \tag{8}$$

In the above 3 equations we have:

ρ = density
ρ_o = reference density, at zero pressure and temperature
A_1, A_2, n, m = parameters which can be tuned to match LASL shock Hugoniot[44] data

From Eqs. (1), (2) and (5) above, with the electronic terms dropped (EOS), we get the Gruneisen EOS in the following form:

$$p = p_c + \rho G(\rho)(e - e_c) \tag{9}$$

(The Gruneisen parameter is discussed in pp. 697 - 701 of Ref. 37.) The usual need in the code is to use the EOS to determine p and T after ρ and e are known from updating the conservation equations. With ρ known, p_c follows from Eq. (7) and e_c follows from Eq. (8). These values are then inserted into Eq. (9) and G(ρ) is taken as a linear function of ρ, $G(\rho) = G_1(\rho) + \rho G_2(\rho)$, fit to literature data. Thus, p can be determined.

The temperature is obtained from a fit to data $T = T(e_{thermal})$, where $e_{thermal} = e - e_c$. The fits take the form (in FORTRAN format):

If $e_{thermal}$ is less than or equal to T2CXN4, then

T = T2CXN1 x $(e_{thermal})^{.5}$

Else

T = T2CXN2 + $(e_{thermal})$/T2CXN3

Endif

Where T2CXN1 - T2CXN4 are constants

These fits are very simple; the specific heat is taken to rise linearly with temperature up to a break point and then to remain constant at higher temperatures. This follows very roughly the actual material behavior. The constants T2CXN1 - T2CXN4 are given for four piston materials in Table 1 below.

Table 1. Constants T2CXN1 - T2CXN4 for epoxy, polyethylene, aluminum and iron.

Material	T2CXN1	T2CXN2	T2CXN3	T2CXN4
Epoxy	6.324E-03	200	2.000E+07	4.000E+09
Poly-e	5.574E-03	180	2.317E+07	4.170E+09
Alum.	6.988E-03	120	9.837E+06	1.180E+09
Iron	9.649E-03	125	5.370E+06	6.710E+08

We can obtain the speed of sound as follows:

$$c^2 = \frac{dp}{d\rho}\Big]_s = \frac{dp}{d\rho}\Big]_e + \frac{p}{\rho^2}\frac{dp}{de}\Big]_\rho \qquad (10)$$

where s is the entropy. The derivatives can be found analytically (although complicated) or by evaluating p at, say, ρ and 1.001ρ and at e and 1.001e and taking the differences.

The EOS used has five parameters to fit to the experimental data. These are ρ_o, A_1, A_2, n and m. G(ρ) is generally taken from the literature values. (At times, a consensus is taken.). The parameters are fit by trial and error to experimental shock Hugoniot data from Ref. 5. The author has obtained good fits for Epon 828 epoxy, high density polyethylene, 2024 aluminum and iron. The fits obtained in this way were clearly superior to those obtained earlier using only one term of the form shown in Eq. (6). Table 2 shows the coefficients in EOSs for these four materials.

Table 2. Coefficients in EOSs for epoxy, polyethylene, aluminum and iron.

Material	ρ g/cm^3	ρ_o g/cm^3	A_1 dynes/cm^2	n	A_2 dynes/cm^2	m	G_1	G_2 cm^3/g
Epoxy	1.185	1.1875607	1.920E+10	3.6	3.840E+09	6	0.8	0
Poly-e	0.954	0.9578335	1.679E+10	3.6	3.360E+09	6	1.2	0
Alum.	2.784	2.830049	1.259E+11	3.6	2.520E+10	6	10.5	-2
Iron	7.856	7.9474191	2.646E+11	3.6	5.292E+10	6	2.613	-0.0625

From the table, we note that the same values of n and m (3.6 and 6) were found suitable for all four materials. Also, a ratio of $A_2/A_1 = 0.2$ was found to be suitable for all four materials. ρ is the material density under standard conditions. The ratio ρ/ρ_o was found to range from 1.002 to 1.004 for the plastics to 1.011 to 1.017 for the metals. The final values of ρ_o were obtained by tuning ρ_o until the piston material was at atmospheric pressure. before the gun dynamic cycle starts. It is suggested that Table 1 could be used as a guide if it were necessary to fit other materials with this form of EOS.

To perform such a fit, guesses are made for ρ_o, A_1, A_2, n and m, guided by Table 1. These guesses define a trial EOS. The trial EOS is then compared with experimental shock Hugoniot data from Ref. 5. For each data point, using the experimental after shock pressure and density data and the shock wave equations of mass, momentum and energy conservation, the energy per unit volume at the after shock condition is calculated. Then, using the trial EOS in the form p = p(ρ,e) - [Eqs. (7 - 9], a second pressure value is calculated. The two pressures will not, in general, match. From all of these "second" pressures (and the corresponding densities), a trial Hugoniot is constructed. The trial Hugoniot is then compared with the experimental data from Ref. 5. The guessed parameters are then iterated to improve the agreement of the trial Hugoniot and the experimental data. The final EOS parameters chosen are those which give the best overall agreement of the trial Hugoniot with the cloud of experimental data points. This judgement is currently made by eye. This procedure was used to construct the EOSs for the four piston materials shown in Table 1. A simplified version of the procedure, with only one term of the form shown in Eq. (6), was used to construct the EOS for shocked liquified gun working gases. The latter fits were used to obtain the cold molecular volume and energy data for compressible gun working gas molecules (see also Appendix A).

For a mixture, such as an epoxy matrix-steel shot piston, one can write the following equations

$$\frac{1}{\rho} = \frac{m_1}{\rho_1} + \frac{m_2}{\rho_2} \tag{11}$$

$$e = m_1 e_1 + m_2 e_2 \tag{12}$$

where:

unsubscripted variables refer to the effective mixture values
subscripts 1 and 2 refer to the 2 components
m = mass fraction
ρ = density
e = internal energy

At the end of each timestep for each cell, m_1, m_2, ρ and e are known. The latter two variables are known from the solution of the conservation equations. To proceed further, we must know the densities and thus, we iterate on ρ_1. For a chosen ρ_1, ρ_2 follows from Eq. (11). Evaluating Eqs. (7) and (8) for p and e of both components, values are found for

p_{c1}, p_{c2}, e_{c1} and e_{c2} (i.e., all the cold component values). Applying Eq. (9) to each component separately, we obtain the following two equations:

$$p = p_{c1} + \rho_1 G_1(\rho_1)(e_1 - e_{c1}) \quad (13)$$

$$p = p_{c2} + \rho_2 G_2(\rho_2)(e_2 - e_{c2}) \quad (14)$$

Setting the p values from Eqs. (13) and (14) equal to each other and using the relation $e = e_c + e_t$, where e_t denotes the thermal energy, for both components, we obtain

$$p_{c1} - p_{c2} + \rho_1 G_1(\rho_1) e_{t1} - \rho_2 G_2(\rho_2) e_{t2} = 0 \quad (15)$$

Expanding Eq. (12), we get

$$e = m_1 e_{c1} + m_1 e_{t1} + m_2 e_{c2} + m_2 e_{t2} \quad (16)$$

Equations (15) and (16) are two equations in two unknowns, e_{t1} and e_{t2}, which can therefore be solved for the unknowns. In general, the two temperatures, $T_1(e_{t1})$ and $T_2(e_{t2})$, will not be equal to each other, and ρ_1 must be iterated to make them equal. While this method of solution is straightforward, it involves an iteration, which would substantially slow down the code. However, for shot-loaded pistons, such as steel shot in an epoxy matrix or copper beads in a paraffin matrix, the stiffness of the shot loading is much greater than the stiffness of the matrix and we can consider the shot to be incompressible with resulting errors of the order of 0.5%. In this case, ρ_2 (considered to be ρ for the shot) can be taken as constant in Eq. (11) and e_2 can be taken as constant in Eq. (12). We take e_2 = zero, since there is no cold compressive work on the shot and we consider that there is not enough time for thermal heating of the shot. Equations (11) and (12) then transform to Eqs. (17) and (18) below:

$$\frac{1}{\rho} = \frac{m_1}{\rho_1} + \frac{m_2}{\rho_2(fixed)} \quad (17)$$

$$e = m_1 e_1 \quad (18)$$

Again, at the end of each timestep for each cell, m_1, m_2, ρ and e are known. In this case, we can go directly from ρ and e to ρ_1 and e_1, using Eqs. (17) and (18). p follows from Eq. (13), e_{t1} follows from $e_{t1} = e_1 - e_{c1}(\rho_1)$ and the temperature follows from $T_1 = T_1(e_{t1})$.

We now take the density differential, $d\rho$, of Eq. (11), divide by the corresponding pressure differential, dp and use the equation

$$c^2 = \frac{dp}{d\rho} \quad (19)$$

where c is the sound speed, to arrive at the equation

$$\frac{1}{\rho^2 c^2} = \frac{m_1}{\rho_1^2 c_1^2} + \frac{m_2}{\rho_2^2 c_2^2} \tag{20}$$

For our shot + matrix pistons, the m_2 term in Eq. (20) is of the order of 0.5% of the m_1 term and, hence, we drop the m_2 term. Solving the modified Eq. (20) for c, we get

$$c = \frac{\rho_1 c_1}{\rho \sqrt{m_1}} \tag{21}$$

Equations (17), (18) and (21), together with the EOS equations for the two components, are sufficient to deal with plastic matrix-metal shot pistons. Table 2 below gives the various EOSs used with various pistons.

Table 2. EOSs used with pistons.

Type of piston	Example	EOS
Plastic	Polyethylene, epoxy	1 Z-R
Metal	Steel, aluminum	1 Z-R†
Plastic matrix - metal shot	Epoxy + steel	1 Z-R + mixture
Plastic/metal 2 piece	Epoxy + steel	2 Z-R†

Z-R denotes Zeldovich-Raizer EOS

†Requires plastic sleeve over metal slug

Appendix B1

Solid Phase Friction and Heat Transfer

The method used is a variation of that presented in Ref. 37a. We begin by calculating the normal stress between the solid body (piston or projectile) and the tube wall (σ_n) using the following logic and equations. Equations (2 - 8) are written in the form of nested block IF FORTRAN statements.

$$\phi = \frac{E}{\sigma_y}\left[\frac{r_t}{r_p} - 1\right] \quad (1)$$

IF $\phi > 0$ THEN

$$p_{xo} = \frac{E}{\nu}\left[\frac{r_t}{r_p} - 1\right] \quad (2)$$

IF $p_{xo} > \sigma_y$ THEN

:

IF p > σ_y THEN

$$\sigma_n = p - \sigma_y \quad (3)$$

ELSE

$$\sigma_n = 0 \quad (4)$$

ENDIF

ELSE

IF $p > p_{xo}$ THEN

GO TO 100

ELSE

$$\sigma_n = 0 \quad (5)$$

ENDIF

ENDIF

ELSE

GO TO 100

ENDIF

100 CONTINUE

$$p_{xy} = \left[-E\left(\frac{r_t}{r_p} - 1\right) + (1-\nu)\sigma_y\right]/(1-2\nu) \qquad (6)$$

IF $p < p_{xy}$ THEN

$$\sigma_n = \left[-E\left(\frac{r_t}{r_p} - 1\right) + \nu p\right]/(1-\nu) \qquad (7)$$

ELSE

$$\sigma_n = p\ - \sigma_y \qquad (8)$$

ENDIF

where:

r_t = tube radius
r_p = unstressed initial radius of solid material (outside tube)
σ_y = yield stress of solid
E = Young's modulus of solid
m = Poisson's ratio of solid
p = axial pressure (from CFD code results)
σ_n = stress in solid normal to the x direction

In the above equations, since p is positive for pressures in the CFD code, we have taken σ_n to be positive for compression, which is the reverse of the usual strength of materials convention.

The above set of equations looks formidable but actually embodies a rather simple elastic-plastic model as follows. First, we determine whether the unpressurized piston material is jammed or free in the pump tube. (Of course, jammed is the normal operating procedure, but the code does allow for an initially free piston.) Then the pressure is applied and it is determined whether the piston under pressure expands enough to contact the pump tube wall or not. If it does, it is determined whether the contact pressure exceeds the piston yield strength or not. For each of the three cases (no contact, contact with no yielding and contact with yielding), σ_n, the bearing stress of the piston on the pump tube wall, can easily be calculated. If the piston is initially jammed in the tube (without applied pressure), when the pressure is applied, it is determined whether the piston plastic has yielded or not and the bearing stress can directly be calculated.

Again following Ref. 37a, the normal stress is limited as follows, so that it cannot become negative.

$$\sigma_n = \max(0, \sigma_n) \qquad (9)$$

A number of references (Refs. 37b, 45 - 48) have discussed high speed models for dynamic sliding friction. Reference 46 points out that the experimental data of Ref. 45 for nylon on steel up to about 0.7 km/sec can be fairly well fit with a curve of the form

$$\mu_d = Au^{-0.4} \qquad (10)$$

where u is the relative velocity, A is a constant and μ_d is the dynamic friction coefficient. Reference 46 used Eq. 10 for studies of model wear in a two-stage gas gun. Reference 48 used the same equation for friction modelling in an electromagnetic launcher. In reference 37b, Eq. 10 for the friction coefficient was generalized to the following expression for μ_f, at any velocity (including zero velocity)

$$\mu_f = min(\mu_s, Au^{-b}) \qquad (11)$$

where μ_s is the static friction coefficient. We have used Eq. (11) recommended by Ref. 37b and have reevaluated the coefficients A and b directly from the data of Ref. 45 for nylon on steel. We have obtained b = 0.4224 and A = 8.377 (if the velocity is in cm/sec). μ_s is estimated from Fig. 242 of Ref. 45 as 0.185. Lacking dynamic friction data for piston and projectile materials such as polyethylene and Lexan, we have simply scaled the A coefficient in Eq. (11), obtained from the data of Ref. 45 for nylon on steel, by the respective static friction coefficients to make first estimates for the dynamic friction coefficients for the other materials. From extensive comparisons between CFD results and experimental piston and muzzle velocities, to obtain good agreement it was found necessary to substantially reduce the A and μ_s values from those quoted above. Thus, we have:

Original values from Ref. 45:	A = 8.377	μ_s = 0.185
Tuned values for polyethylene piston:	A = 1.625	μ_s = 0.0359
Tuned values for Lexan projectile:	A = 2.264	μ_s = 0.05

The tuned values given above may be useful as starting points for modelling other guns.

With an estimate for the friction coefficient available, the wall shear stress, τ_w, is calculated from the following two equations

$$\tau_w = \mu_f \sigma_n \qquad (12)$$

$$\tau_w = min\left(\tau_w, \frac{\sigma_y}{\sqrt{3}}\right) \qquad (13)$$

Equation (12) is simply the basic friction relation and Eq. (13) limits the maximum possible wall shear stress to the shear yield stress, here taken to be $1/\sqrt{3}$ times the tensile yield stress, following Ref. 47.

The above procedure works for uniform plastic (e.g., polyethylene, epoxy) pistons and also for plastic matrix-steel shot pistons. (In this latter case, the value of E in Eqs. (1) - (7) must be adjusted to allow for the increased stiffness produced by the steel shot.). It would work for solid metal pistons if the piston metal were in direct contact with the pump tube wall. However, if we assume that the metal piston is inside a polyethylene casing, Eq. (13) would give a shear stress far above the correct value. Hence, in this case, we follow Eq. (13) with another such equation, but with σ_y taken as σ_y of the polyethylene. With τ_w

available, the wall friction force on the solid in a given cell can be found simply by multiplying τ_w by the area of the cell in contact with the wall. The heat flux rate to the solid, q_w, due to the solid friction work is simply taken to be one half the shear stress times the velocity, as follows.

$$q_w = -\frac{1}{2}|\tau_w u| \qquad (14)$$

This term, which appears as a source term in the energy equation, represents energy loss from the solid to the wall due to frictional heating occurring at the wall. The other half of the heat generated by the frictional work is assumed to flow to the solid and does not represent an energy loss from the cell and therefore should not be included in the energy equation. If a point mass projectile is assumed, the wall shear stress and heat flux source terms are calculated midway along the corresponding (equal mass) real-length projectile and multiplied by the proper wall-projectile contact area for the real-length projectile.

Appendix C

Powder Burn

One option for modelling the powder burn rate is to use the usual ballistics expression (see, for example, Ref. 15)

$$r = bp^n \tag{1}$$

where r is the linear surface regression rate of the powder grain, p is the pressure and b and n are constants given by the maker of the powder or by military testing laboratories.[16-19] [Note that b and n in Eqn. (1) are not the same as b and n used earlier in Eqns. (1) to (7) in Appendix A.]

The shapes of the powder grain are modelled as shown in Fig. 1. The grain is modelled as a cylinder of diameter D_0 and length L_0. There can be (or not) n cylindrical perforations of diameter d_0 parallel to the main cylinder axis. For the powders modelled to date, n has been 0, 1 or 7, as specified by the powder manufacturer. For spherical grains, a cylindrical model with length equal to diameter is used (Fig. 1b). Figure 2 shows a 7-perforation grain before burning starts (solid lines) and after burning has caused a retreat of $(w_0 g)/2$ of all surfaces (dashed lines). g is the fraction of the total burn distance burned. g = 0 before burning starts and g = 1 at all burnt. The

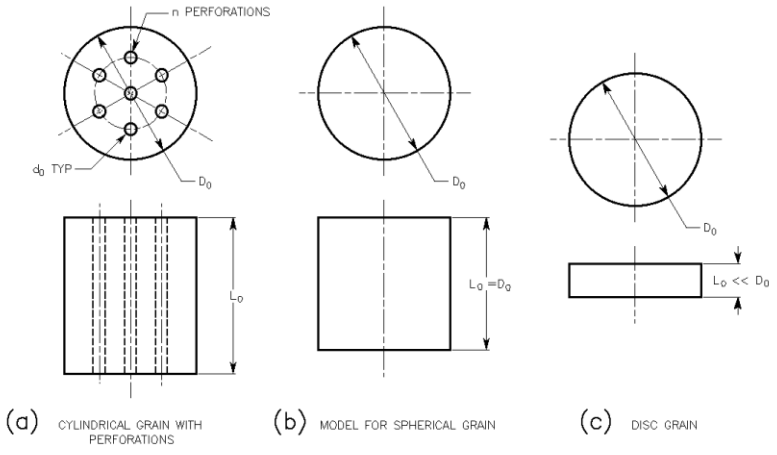

Fig. 1. Modelling of shapes of powder grains.

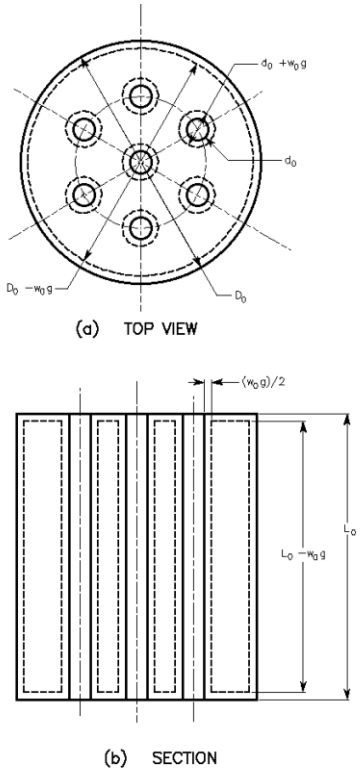

Figure 2. Seven-perforation grain before burning starts (solid lines) and after burning has caused a retreat of ($w_0 g$)/2 of all surfaces (dashed lines).

volume of the grain shown in Fig. 2 after the surface retreat ($w_0 g$)/2 is

$$Volume = \frac{\pi}{4}[(D_0 - w_0 g)^2 - n(d_0 + w_0 g)^2][L_0 - w_0 g] \tag{2}$$

At all burnt (g = 1), w_0 is determined from Eqn. (2) by setting either the first or second square bracket equal to zero. The two values of w_0 so obtained are

$$w_0 = \frac{D_0 - \sqrt{n} d_0}{1 + \sqrt{n}} \tag{3}$$

$$w_0 = L_0 \tag{4}$$

One must always choose the lower of the two values of w_0 to use in the calculations. At the beginning and ending of a burn time step in the code, the mass fractions of the unburned powder (m_1 and m_2, respectively) are related by

$$m_2 = m_1 \frac{[(D_0 - w_0 g_2)^2 - n(d_0 + w_0 g_2)^2][L_0 - w_0 g_2]}{[(D_0 - w_0 g_1)^2 - n(d_0 + w_0 g_1)^2][L_0 - w_0 g_1]} \tag{5}$$

where g_1 and g_2 are the values of g at the beginning and ending of a burn time step. g_2 can be calculated from g_1 using

$$g_2 = g_1 + dg = g_1 + \frac{2rdt}{w_0} \tag{6}$$

where r is the linear burn rate from Eqn. (1) and dt is the length of the burn timestep. Hence, given the mass fraction of unburned powder at the beginning of the timestep, m_1, using Eqns. (5) and (6), we can calculate m_2, the mass fraction of unburned powder at the end of the timestep. The modelling of the powder grain shape change during burn presented above is ideally correct for cylindrical grains with zero or one perforation(s). For grains with multiple perforations, the burn fronts from the perforations and the outer diameter will intersect at roughly 80% powder burn. Thereafter, the burn front area is essentially unknown and, for want of a model, we simply extend the model presented above until the powder grains are entirely consumed.

In the linear powder burn rate expression given previously, Eqn. (1), the burn rate depends only on the pressure and, in particular, does not depend on where the burn front is in the powder grain. If the grains are fabricated without deterrent and then coated with deterrent, the concentration of deterrent would be greatest at the grain surface and would be expected to decrease as one moves into the interior of the grain. In reference 19, powder burn rates were measured for fifteen different powder formulations (five tests of each powder). The reference gives the following expressions for the burn rate as a function of pressure and powder grain composition.

$$r = bp^n \tag{7}$$

$$log_e r = log_e b + n log_e p \tag{8}$$

$$log_e b = -6.61822 - 0.052882(\%DBP) + 0.015907(\%NG) \tag{9}$$

$$n = 0.80530 \tag{10}$$

where %DBP is the percent of dibutylphthalate (deterrent) and %NG is the percent of nitroglycerine. The balance of the powder is nitrocellulose (NC). The numbers in the above equations resulted from the seventy-five powder burn rates mentioned above. For the numbers given in Eqn. (9) the units are in/s for r and ksi for p. We consider St. Marks WC 886 powder with %DBP = 7 and %NG = 11.5. Inserting the %NG in Eqn. (9) and re-arranging, we get

$$r = 1.6039\ x\ 10^{-3}(0.94849)^{\%DBP} p^{0.8053} \tag{11}$$

We have no actual measurements of %DBP versus position in the grain, but a calculation of powder burn was made with an assumed gradated distribution of DBP. We take the surface %DBP to be 28 and also assume that the %DBP drops, linearly with g, to zero at the new surface when half the grain is consumed. With these assumptions, the %DBP is, as follows:

$$If\ g\ \leq\ 0.2937,\ \ \%DBP\ =\ 28(1-g/0.2937) \tag{12}$$

$$If\ g\ >\ 0.2937,\ \ \%DBP\ =\ 0. \tag{13}$$

Using Eqns. (7) - (13), the burn rates for a powder grain with a gradated distribution of deterrent can be calculated. For St. Marks WC 886 powder, a comparison was made between a particular gun shot with gradated deterrent as per Eqns. (7) – (13) and a corresponding shot with a uniform deterrent distribution (%DBP = 7). Both powder grains have the same total amount of deterrent. For the gradated deterrent grains, the piston velocities were ~3% lower and the muzzle velocities were about 4% lower. The maximum pressure at the projectile base was ~20% lower with gradated powder.

Appendix D

Viscosity Calculations in Light Gas Gun Code

There are six viscosity coefficients for the powder gas. We first list the coefficients and then discuss how they are obtained.

VIS(1,1) - First powder gas viscosity coefficient, prefactor in low pressure viscosity expression {g/cm/s/[K^VIS(1,2)]}.

VIS(1,2) - Second powder gas viscosity coefficient, temperature exponent in low pressure viscosity expression

VIS(1,3) - Third powder gas viscosity coefficient, prefactor in high pressure viscosity correction (g/cm/s).

VIS(1,4) - Fourth powder gas viscosity coefficient, reference density in high pressure viscosity correction (g/cm^3).

VIS(1,5) - Fifth powder gas viscosity coefficient, first exponent of density in high pressure viscosity correction.

VIS(1,6) - Sixth powder gas viscosity coefficient, second exponent of density in high pressure viscosity correction.

To calculate the viscosity of the powder gas, we must start with the viscosities of the individual components of the powder gas. The values for powder gas viscosities given in the originally provided input file ONED1D.DAT have been derived for Hercules HC-33FS powder. The powder gas composition[17] given by Hercules for this powder is (in mole percentages):

CO	34.1%
H_2O	15.1%
CO_2	20.2%
N_2	11.9%
H_2	18.6%

The method of calculating the individual gas viscosities starts with simple power law fits to experimental viscosity versus temperature data for low pressures. The data is taken from Ref. 38. The low pressure viscosity for component 1 is given by a curve fit in the form shown in Eq. (1)

$$\mu_{lpc1} = VIS(1,1)T^{VIS(1,2)} \quad (1)$$

where μ_{lpc1} is the viscosity at low pressure and T is the temperature. Similar expressions were obtained for the other components of the powder gas. The viscosity of the powder gas mixture at various temperatures was then found by adding up the individual viscosities from Ref. 38 multiplied by the respective mole fractions. Three other methods of calculating the viscosity of the gas mixture were also tried. These were Wilke's method[39], weighting by the square root of the molecular weight[39] and weighting by the square root of the product of the molecular weight and the critical temperature.[40] The differences between the mixture viscosities calculated by the four methods ranged from 2% up to 10%. Since the gun performance is very insensitive to the exact viscosity numbers, we have chosen to stay with the simplest viscosity averaging technique. The gas mixture data was then fit with a power law curve.

Golubev[41] gives density corrections for viscosity for H_2, N_2 CH_4, NH_3, CO_2. and D_2. The corrections, on a mole basis, for N_2 and CH_4 are very close to each other and the molecular weights of these gases (28 and 16) bracket the molecular weight of the powder gas (24.9). We have taken the average density correction of N_2 and CH_4 on a mole basis and changed to a density basis using the molecular weight of the powder gas. This correction as a function of density were fit with a sum of two terms with density ratios to two different powers and used to estimate a density correction for powder gas. The high pressure viscosity correction (for the powder gas mixture) is given in Eqn. (2).

$$\Delta\mu_{hp} = VIS(1,3)\left[\left(\frac{\rho}{VIS(1,4)}\right)^{VIS(1,5)} + \left(\frac{\rho}{VIS(1,4)}\right)^{VIS(1,6)}\right] \quad (2)$$

where $\Delta\mu_{hp}$ is the high pressure viscosity correction and ρ the gas density. The final powder gas viscosity, μ, is given by

$$\mu = \mu_{lp} + \Delta\mu_{hp} \quad (3)$$

The values for VIS(l,1) through VIS(l,6) given in the originally provided input file ONED1D.DAT have been derived for Hercules HC-33FS. Unless the composition of the user's powder gas is quite radically different from that from the Hercules powder, it is suggested the VIS(l,l) through VIS(l,6) values given in the originally provided input file could be used for the user's powder gas.

Viscosity equations of the form of Eqns. (1) - (3) above have been developed for H_2, He, N_2 and Ar gun working gases. Since there is only a single component gas in these

cases, the viscosity mixing step of the previously described method is unnecessary. For He and Ar, the high pressure viscosity correction was derived from data in Ref. 42. For the gun working gas, the viscosity coefficients are VIS(3,l) through VIS(3,6). The viscosity coefficients for the various gases are given in Table 1.

Table 1. Viscosity coefficients for the various gases.

GAS	VIS(NZ,1) g/cm/s/[K**VIS(NZ,2)]	VIS(NZ,2)	VIS(NZ,3) g/cm/s	VIS(NZ,4) g/cm**3	VIS(NZ,5)	VIS(NZ,6)
Helium	3.1940E-06	0.7175	1.2750E-03	1	2.0418	2.0418
Hydrogen	2.1130E-06	0.6593	7.1000E-06	0.0325	1.386	2.487
Nitrogen	4.0988E-06	0.66028	2.0409E-05	0.18331	0.98794	2.32143
Argon	4.0193E-06	0.70387	3.8587E-03	1	1.98758	1.98758
Powder gas	3.0450E-06	0.6898	4.1600E-05	0.248	1.3318	2.225

Appendix D1

Coding to Provide Profile Along the Gun of Maximum Pressures Reached

Introduction

The purpose of the coding described in this appendix is to provide a profile of the maximum pressures reached at all locations along the length of the gun. The first version of the LGGUN code did not have this capability, but rather, calculated the maximum pressures at only 5 x-positions along the gun. (x is measured along the gun axis starting from the blind end of the powder breech.)
The current version of the code can operate in the original manner (calculating only 5 maximum pressures) or can calculate these 5 maximum pressures plus a profile of maximum pressures along the length of the gun. This maximum pressure profile is accompanied by a profile of the calculated burst pressures of the gun tube. Both manners of operation of the code are described below.

Input files

The maximum pressures are denoted in Fortran as PMAXX(I). They are calculated in PLOTX.f and the first five values are written by the subroutine PLOTPROJ.f to the output file FINALOUTP by the statement

```
WRITE(45,400)PMAXX(1),PMAXX(2),PMAXX(3),PMAXX(4),PMAXX(5).
```

If the profile along the gun is to be taken, the remaining PMAXX values, along with the corresponding calculated gun tube burst pressures, are written to the output file PRESSVX by the statement:

```
      DO 602 J=6,NPLOTX
       ACONE=AR(XXPLOT(J))
             DCONE=1.1283*ACONE**.5
             PBURST=SIGCON*LOG(DOCONE/DCONE)
       WRITE(80,603)XXPLOT(J),PMAXX(J),PBURST,ACONE,
  1     DCONE
602    CONTINUE
```

The variables are:

ACONE = inside area of gun tube

DCONE = inside diameter of gun tube
DOCONE = outside diameter of gun tube
SIGCON = yield strength of gun tube material = 140 ksi for NASA Ames guns
PBURST = burst pressure of gun tube from equation of Ref. 43a.

The PBURST values are only valid in the HPC (where the highest pressures occur) since DOCONE is the outside diameter of the HPC. They are not valid for the pump tube or launch tube, for example.

The handling of the PMAXX files is controlled by a short section of the input file ONED1D.DAT. This section of ONED1D.DAT can have two configurations, one when only the basic five PMAXX files are calculated and the other, when, in addition, PMAXX and PBURST files are created along the length of the gun. The relevant section of ONED1D.DAT for the first case takes the following form (see also discussion of XXPLOT in Appendix I):

```
5                              NPLOTX

0 0 0 0 0                      IBLANK(NPLOTX)

10.0     1                     XXPLOT(NPLOTX),NVXPLT(NPLOTX)
371.0    1
384.0    1
387.0    1
391.00   1
```

NPLOTX is the number of PMAXX files - for the case without the maximum pressure profile along the length of the gun, it is recommended to keep NPLOTX at 5. The IBLANKS are set to 0 or 1, depending on whether one wants the pressure set to zero if solid piston material is passing over the specified x-location, where there could be a pressure transducer. The XXPLOTs are the x locations in cm along the gun where the maximum pressures are to be calculated. The NVXPLTs are not used in this version of the code, but it is recommended to set them all to unity.

For the second case (including the PMAXX and PBURST profiles along the length of the gun), the key section of ONED1D.DAT takes the following form:

```
328                    NPLOTX

0 0 0 0 0              IBLANK(NPLOTX)

10.0     1             XXPLOT(NPLOTX),NVXPLT(NPLOTX)
1000.0   1
1066.0   1             5 lines
1075.0   1
1082.0   1
```

```
0.400000E+02   1
0.500000E+02   1
0.600000E+02   1
0.700000E+02   1
      :        :        323 lines
      :        :
0.138400E+04   1
0.138700E+04   1
0.139000E+04   1
```

The difference between the two forms of the key section of ONED1D.DAT are:

NPLOTX is 5 for the first case and 328 for the second case
The total number of PMAXXs calculated and printed out follows NPLOTX and is likewise 5 for the first case and 328 for the second case.

The 323 x locations in the second grouping above can be chosen to cover the length of the gun from the blind end of the powder breech to the muzzle. If x locations outside this range are chosen the code may crash because a subroutine will be looking for data and won't find any. The x locations can also be chosen to focus in on the HPC, where the highest pressures occur. Then the maximum pressures calculated using LGGUN can be compared at high resolution with the HPC burst pressures. Note that NPLOTX was 328 for the current example, but values up to 468 have been successfully used.

Calculations, output files

The maximum pressures PMAXX are calculated in PLOTX.f and the first five values are written by the subroutine PLOTPROJ.f to the output file FINALOUTP. The format for the first five PMAXX values is given in Appendix J, FINALOUTP section. PLOTPROJ.f prints the second group of XXPLOTs (323 for the example case), along with the corresponding PMAXX, PBURST, ACONE and DCONE values in the output file PRESSVSX. A truncated version of this output file is shown below. (The captions are not normally included in the file, but were added for the present discussion.) This file is from the LGGUN CFD calculation for the gun firing condition defined by the files ONED1D.DAT and ONED1DE.DAT (see Appendix L).

```
  XXPLOT            PMAXX       PBURST      ACONE       DCONE

0.400000E+02  0.720076E+09  0.155432E+11  0.121737E+02  0.393673E+01
0.500000E+02  0.566469E+09  0.155432E+11  0.121737E+02  0.393673E+01
```

0.600000E+02	0.461755E+09	0.155432E+11	0.121737E+02	0.393673E+01
0.700000E+02	0.385587E+09	0.155432E+11	0.121737E+02	0.393673E+01
:	:	:	:	:
:	:	:	:	:
:	:	:	:	:
0.107600E+04	0.193692E+11	0.225305E+11	0.286389E+01	0.190942E+01
0.107625E+04	0.200577E+11	0.228092E+11	0.270328E+01	0.185511E+01
0.107650E+04	0.206882E+11	0.230962E+11	0.254730E+01	0.180080E+01
0.107675E+04	0.210313E+11	0.233919E+11	0.239596E+01	0.174648E+01
0.107700E+04	0.215185E+11	0.236970E+11	0.224926E+01	0.169217E+01
0.107725E+04	0.214655E+11	0.240121E+11	0.210718E+01	0.163786E+01
0.107750E+04	0.211459E+11	0.243377E+11	0.196975E+01	0.158354E+01
0.107775E+04	0.206732E+11	0.246748E+11	0.183695E+01	0.152923E+01
:	:	:	:	:
:	:	:	:	:
:	:	:	:	:
0.138100E+04	0.300142E+09	0.320686E+11	0.397260E+00	0.711151E+00
0.138400E+04	0.285466E+09	0.320686E+11	0.397260E+00	0.711151E+00
0.138700E+04	0.270791E+09	0.320686E+11	0.397260E+00	0.711151E+00
0.139000E+04	0.256115E+09	0.320686E+11	0.397260E+00	0.711151E+00

The middle cut-out section of the above table contains the highest calculated pressure in the HPC. Note very high pressures in the high pressure coupling (HPC) (up to ~310 ksi).

Example profiles of maximum pressures

Figures 1 and 2 below show example profiles of maximum shot pressures and burst pressures calculated for the Ames 0.28"/1.55" gun at the firing condition defined by files ONED1D.DAT and ONED1DE.DAT. Muzzle velocity was 5.80 km/s. Note that there is only a ~10% margin between the maximum calculated shot pressure and the corresponding burst pressure.

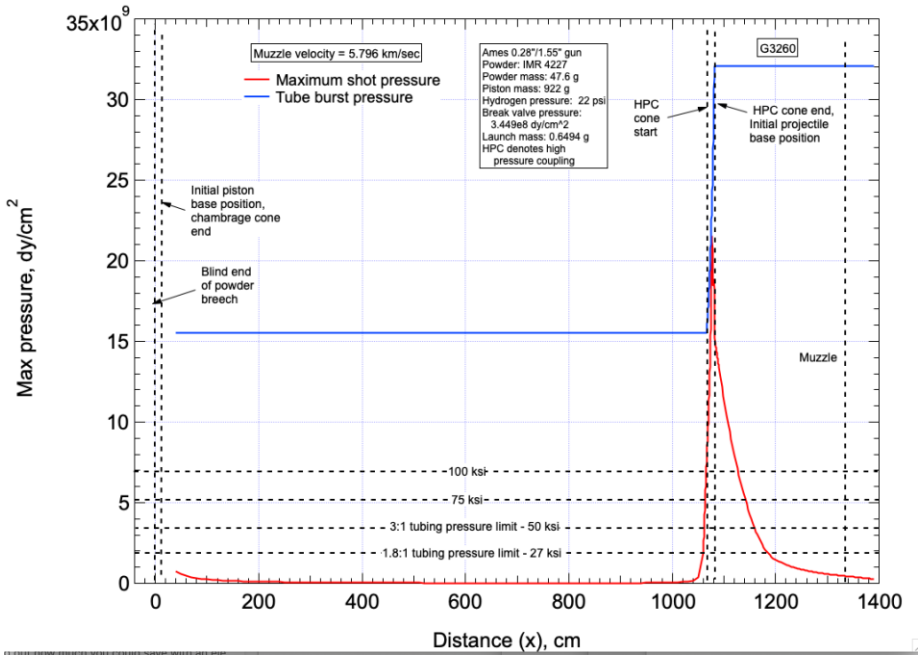

Figure 1. Profile of maximum shot pressures and burst pressures for example shot in the NASA Ames 0.28"/1.55" gun.

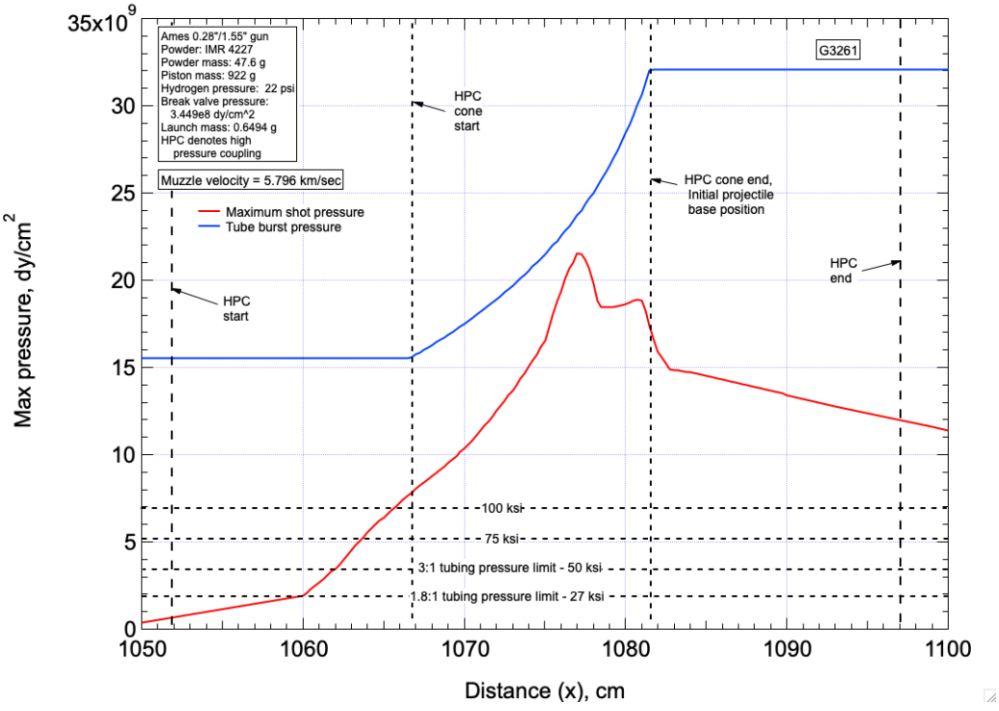

Figure 2. Expanded profile of maximum shot pressures and burst pressures for example shot in the NASA Ames 0.28"/1.55" gun.

Appendix E

Subroutines for Light Gas Gun Code

Note that the code uses a two-step predictor-corrector method to advance in time. Certain of the subroutines are invoked only on the corrector step.

AR.f

Calculates the gun tube area (perpendicular to the x axis) at any x position along the gun.

BCCHECK.f

Checks the consistency of the boundary conditions between zones, including those at the extreme ends of the package of 3 (or possibly 4) zones. (The zones are powder/powder gas, piston and gun working gas - usually hydrogen. The fourth zone would be a piston weight.)

BDYVF.f

Calculates the fluxes of mass, momentum, energy and species at the boundaries between zones, including those at the extreme ends of the package of 3 (or possibly 4) zones.

BDYVFC.f

Invoked after BDYVF.f only in the corrector step to complete the work of BDYVF.f.

BURN.f

Calculates the burning of the gunpowder grains. Many grains are cylindrical, with or without perforations parallel to the axis. Other grains are spherical or are thin discs. The BURN.f subroutine can model these cases. It can also model cases with a gradated deterrent - for example, with the deterrent decreasing in concentration as one moves inward from the grain surface. See also Appendix C.

CELLA.f

Calculates an effective cell area normal to the gun axis by using the cell volume and the length of the cell in the x-direction.

CELLFLUX.f

Calculates fluxes of mass, momentum, energy and species at internal boundaries of cells within zones.

CELLFLUXC.f

Invoked after CELLFLUX.f only in the corrector step to complete the work of CELLFLUX.f.

CELLV.f

Calculates velocity of moving cell. This is the cell ("grid") velocity, not the velocity of the material within the cell.

CELLVOL.f

Calculates the volume of a cell, given the x-coordinates of the two ends of the cell.

CELLX.f

Calculates the x-coordinates of all cells in all zones. As the solution proceeds, cells will squeeze in or expand out in accordion fashion as well as sliding along with the zones. Some zones (i.e., the piston zone) will have cells of the same size along the length of the zone. This size will change as the solution progresses, however. Other zones will have cells of increasing (or decreasing) size along the length of the zone (i.e. powder/powder gas zone and gun working gas zone). In this case, the ratio of the lengths of adjacent cells is kept the same throughout the zone. The total lengths of these zones will change as the solution progresses, however. In most cases, cell lengths are matched at junctions between two zones.

CHARX.f

Not used in this version of the code.

CONSERVQ.f

Not used in this version of the code.

CPRM.f, CPRM1.f to CPRM9.f, REPT.f, REPT1.f to REPT9.f,

Because these subroutines are very closely related to one another other, we break from our alphabetical ordering system and consider these subroutines as a group. **REPT1.f to REPT9.f** are nine different equation-of-state calculators that output pressure and

temperature from density and internal energy inputs. In some cases, the speed of sound is also calculated in the **REPTn.f** subroutine (n = 1 to 9) and passed on through to the corresponding **CPRMn.f** subroutine. In other cases the sound speed for the **REPTn.f** subroutine is calculated using the corresponding **CPRMn.f** subroutine. We note that, in the code, a call for **REPTn.f** (or **REPT.f)** is always followed by a call for the corresponding **CPRMn.f** (or **CPRM.f)** subroutine. **REPT.f** and **CPRM.f** are switching subroutines which choose among the various **REPTn.f** and **CPRMn.f** subroutines according to the number NTEOS for the zone in question read in from the input file ONED1DE.DAT. We now work our way through the various subroutines, noting that more detailed descriptions of the EOSs are given in Section 2.1 and the references therein.

REPT.f and **CPRM.f** are switching subroutines, as noted above.

REPTn.f and **CPRMn.f** subroutines with n = 2, 4 or 7 are not used.

REPT1.f and **CPRM1.f** subroutines are constructed using the Zel'dovich and Raizer three term dense media EOS[4] with the third term neglected. The sound speed is passed through from **REPT1.f** to **CPRM1.f.** These EOSs are used for the piston and the projectile.

REPT3.f and **CPRM3.f** subroutines assume a constant gamma, constant molecular weight gas with a compressible molecular volume term. These EOSs are used for pure He, N_2 and Ar gun working gases (normally in the third zone from the blind end of the powder breech). These EOSs should be quite good for He and Ar, but somewhat less good for N_2, on account of the variable specific heat of N_2. When melted wall material is mixed with the gun working gases, a mixture EOS is created, called for by subroutines **REPT5.f** and **CPRM5.f. REPT3.f** is embedded in **REPT5.f. CPRM3.f** is not embedded in **CPRM5.f** but, rather, the sound speed is passed through from **CPRM3.f** to **CPRM5.f**

REPT6.f and **CPRM6.f** subroutines are for pure hydrogen gas, for which a two-dimensional tabulated EOS of the form $T(\rho,e)$, $p(\rho,e)$ is used. To construct the table, equilibrium calculations for point molecules were first made. Then, a molecular volume term was added which follows the Zel'dovich and Raizer[4] cold pressure-volume relation for dense media. Interpolations for T and p are made using a 12 term expression including terms with up to cubic in ρ, and e. When melted wall material is mixed with the hydrogen, a mixture EOS is created, called for by subroutines **REPT9.f** and **CPRM9.f. REPT6.f** is embedded in **REPT9.f. CPRM6.f** is not embedded in **CPRM9.f** but, rather, the sound speed is passed through from **CPRM6.f** to **CPRM9.f.** This EOS is used with the hydrogen gun working gas.

REPT8.f and **CPRM8.f** subroutines are constructed using the Abel EOS (ideal gas EOS with a fixed molecular volume added) for the powder gas and a fixed density solid model for the unburned powder. This EOS is used for the powder breech.

REPT3.f and REPT6.f subroutines are not called directly but are called indirectly since the calls are embedded in REPT5.f and REPT9.f, respectively.

ERRG1.f

Calculates a number indicating the degree of convergence of an iteration performed in **GEO1.f**. The iteration is considered converged when the magnitude of the number decreases below 10^{-7}.

ERRG2.f

Calculates a number indicating the degree of convergence of an iteration performed in **GEO2.f**. The iteration is considered converged when the magnitude of the number decreases below 10^{-7}.

ERRHEEOS2.f

Calculates a number indicating the degree of convergence of an iteration performed in **REPT3.f**. The iteration is considered converged when the magnitude of the number decreases below 10^{-6}.

ERRPOWDER.f

A subroutine of **HALFPOWDER.f.** which calculates a parameter which measures the degree of convergence of the iteration of **HALFPOWDER.f.** The iteration is considered converged when the magnitude of the number decreases below 10^{-5}.

FLUXBLIND.f

Not called if IORFBL = 2, which is normally the case for the last 10 years or more.

FLUXBLIND2.f

Calculates the fluxes of mass, momentum, energy and species at a blind end of the gun tube - e.g., blind end of powder breech or at the diaphragm behind the projectile before the diaphragm breaks.

FLUXG1.f

Calculates the fluxes of mass, momentum, energy and species at a boundary between cells in the gun tube.

FLUXG1SHORT.f

Solves the Riemann problem at a boundary between zones in the gun tube.

FRICTION.f

Calculates the friction forces and heat transfer between the gun media and the gun tube. For the gas media, the reduction of heat transfer and friction forces due to blowing [flow of melted tube wall material (taken to be fine droplets) into the gases inside the gun tube] is taken into account. For the piston and projectile, a simple elastic-plastic model is used with the shear stress limited by the shear strengths of the plastics.

GEO1.f

Calculates the x-coordinates of all cells in a zone with cells increasing or decreasing in length with a constant ratio between adjacent cells as one moves along the length of the zone. Used when the zone in question has a blind end condition (velocity = zero) at one end and is in contact with a moving zone at the other end. At the boundary between the moving end of the zone in question and the adjacent zone, cell sizes are matched across the boundary.

GEO2.f

Calculates the x-coordinates of all cells in a zone with cells increasing or decreasing in length with a constant ratio between adjacent cells as one moves along the length of the zone. Used when the zone in question is in contact with two moving zones, one at either end of the zone in question. At one boundary between the moving end of the zone in question and the adjacent zone, cell sizes are matched across the boundary. At the other boundary, cell sizes are very roughly matched by varying the number of cells in the two abutting zones.

GHOST.f

We discuss **GHOST.f** together with **GHOST2.f, GHOST4.f, GHOST7.f, GHOST8.f** and **GHOST9.f.** Each of the zones (powder/powder gas, piston and gun working gas) of the CFD solution comprises NZ(I) cells, where I = 1, 2 and 3 for the three zones. In each zone the two end cells are not actual physical cells, but rather are virtual or "ghost" cells which aid in making the interpolations needed to obtain zone boundary conditions. At the beginning of each timestep, it is necessary to place the correct variable values in the ghost cells. For most variables, the blind end and projectile base condition, the cell number 2 or the cell number NZ - 1 variables are simply "reflected" off the blind end or projectile base. Thus, the cell number 1 variables are set equal to the cell number 2 variables and the cell number NZ variables are set equal to the cell number NZ - 1 variables. V(projectile) -V(NZ - 1). The subroutine **GHOST.f** performs these calculations. For a boundary between two zones, an extra Riemann solution is performed between the NZ - 1th cell of the first zone and the second cell of the second zone. This is performed by the subroutine **GHOST4.f.** The two inside regions of the solution of the Riemann problem provide the conditions for the NZth cell of the first zone and the first cell of the second

zone. The remaining subroutines **GHOST2.f, GHOST7.f, GHOST8.f** and **GHOST9.f** are not used in the current version of the code and relate to CFD solutions where there is inflow or outflow at the ends of the computational domain.

HALFPOWDER.f

A subroutine of **POWDGFLOW.f** which calls an error calculator subroutine **ERRPOWDER.f** which, in turn, calculates a parameter which measures the degree of convergence of the iteration of **HALFPOWDER.f.**

HTSTI.f

Provides the internal energy as a function of temperature for the gun wall material. Subroutine interpolates from a table of the data.

INITIAL.f

Initializes all variables in all cells. Includes mass fractions, densities, internal energies, material velocities, temperatures, pressures, speeds of sound, turbulent kinetic energies, powder grain burn factor, x-coordinates of cells, volumes of cells and cell (not material) velocities.

INTERP.f

Performs three point interpolations of various quantities between cell centers along the gun tube to obtain cell boundary values from which to calculate the fluxes. The order of the interpolation is reduced if the cell center values are non-monotonic or otherwise badly behaved.

INTERPNL.f

Performs three point interpolations of various quantities between cell centers along the gun tube to obtain cell boundary values from which to calculate the fluxes.

LIMIT1.f

Applies strong wave limiting factor ZETAC to cell boundary values - this reduces the effective order of the interpolations when strong waves are present.

NONEQTURB.f

Updates the turbulent kinetic energy (TKE) in each cell in each timestep. Allows for TKE flowing in and out of the ends of the cell and the relaxation of the TKE towards the mean flow kinetic energy.

ONEDIM.f

Master program. Calls, directly or indirectly, all subroutines. Initializes a few variables.

POWDGFLOW.f

Corrects the g parameter (a measure of the fraction of the powder grains burnt) for the grains flowing in or out of the ends of a cell.

PLOTH.f

Makes time history tables for (normally) 5 cells, chosen by zone number (NZ) and cell number (NC). For each cell, the table comprises 11 columns of data, including columns with the step number, the time and the dynamic and thermodynamic variables. To keep the size of the files reasonable, data from only every tenth step is included in the tables.

PLOTPROJ.f

Makes time history tables for x-position and velocity for the front and rear of the piston and for the projectile base. Also calculates and prints out whisker gauge piston velocities, muzzle velocities, maximum pressures for five chosen cells and for five x-positions along the gun tube and for the projectile base. Prints out times for the 3 snapshots and various piezometric ratios.

PLOTQ.f

At the 3 chosen snapshot times, makes tables for all cells along the gun tube. For each time, the table comprises 10 columns of data, including columns with the cell x-position, and the dynamic and thermodynamic variables.

PLOTX.f

Makes time history tables for (normally) five x-locations along the gun tube. For each x-location, the table comprises 3 columns of data, including columns with the step number, the time and the pressure.

PREPROW.f

Calculates coefficients for interpolations of temperatures used in the solution of the heat conduction problem into the gun tube wall (carried out in WALLH.f).

READEOS.f

Reads equation-of-state data for the media in all the gun zones. Also reads in gunpowder properties. All the data is read in from the input file ONED1DE.DAT, which variables are listed and explained in Appendix I, section on ONED1DE.DAT.

READW.f

Reads in properties of the gun wall material plus locations and sizes of the cells in the axial and radial directions. Reads from the file WAHE1D.DAT, which variables are listed and explained in Appendix I, section on WAHE1D.DAT.

READ1.f

Reads in a large number of quantities from the file ONED1D.DAT, which variables are listed and explained in Appendix I, section on ONED1D.DAT.

REIMPXT.f

Part of the Riemann problem solver of this Godunov code. The subroutine takes a completely defined condition at one pressure, expands or compresses it to another pressure and calculates all the parameters of the resulting new condition. This is done using a standard one-dimensional unsteady analysis. The wave system between the two conditions can be an expansion wave, a compression wave or a shock wave.

REIMPXU.f

Part of the Riemann problem solver of this Godunov code. The subroutine takes a completely defined condition at one pressure, expands or compresses it to another pressure and calculates the material velocity of the resulting new condition. This is done using a standard one-dimensional unsteady analysis. The wave system between the two conditions can be an expansion wave, a compression wave or a shock wave.

REIMUXT.f

Another part of the Riemann problem solver of this Godunov code. The subroutine takes a completely defined condition moving at one velocity, expands or compresses it so that it moves at another velocity and calculates all the parameters of the resulting new condition. This is again done using a standard one-dimensional unsteady analysis. The wave system between the two conditions can be an expansion wave, a compression wave or a shock wave.

SFRICADJ.f

Adjusts the skin friction used in the UPDATE.f solver. The UPDATE.f solver updates the cell variables based on the inflow and outflow at the ends of the cell and friction, heat transfer and mass flow from the gun tube wall.

SHOCKTERP.f

Part of a shock wave solver. Takes a fully defined (read in) condition before the shock wave, an after shock pressure and an assumed density ratio across the shock and calculates the after shock conditions using the conservation equations of mass, momentum and energy and the equation of state (EOS). An after shock pressure (not equal to the read-in after shock pressure) is calculated from the EOS. An error parameter measuring the mismatch of the two pressures is calculated and output.

SHOCKTERU.f

Part of a shock wave solver. Takes a fully defined (read in) condition before the shock wave, an after shock velocity and an assumed density ratio across the shock and calculates the after shock conditions using the conservation equations of mass, momentum and energy and the equation of state (EOS). One calculated after shock pressure follows directly from the conservation equations, not using the EOS. A second after shock pressure is calculated from the EOS. An error parameter measuring the mismatch of the two pressures is calculated and output.

SHOCKTRP.f

Part of a shock wave solver. Takes a fully defined (read in) condition before the shock wave and a given after shock pressure and calculates, by iteration, the full after shock conditions using the conservation equations of mass momentum and energy and the equation of state. The error parameter for convergence of the iteration is set at 0.005 but, also, no more than 12 iterations may be taken. SHOCKTERP.f is used within the iterations of SHOCKTRP.f

SHOCKTRU.f

Part of a shock wave solver. Takes a fully defined (read in) condition before the shock wave and an after shock velocity and calculates, by iteration, the full after shock conditions using the conservation equations of mass momentum and energy and the equation of state. The error parameter for convergence of the iteration is set at 0.005 but, also, no more than 12 iterations may be taken. SHOCKTERU.f is used within the iterations of SHOCKTRU.f

STEELH2.f

Taking the amount of gun tube wall material melted off per timestep from the results of WALLH.f, for each step, STEELH2.f updates each gun working gas cell for the amount of wall material incorporated into the gun working gas (which becomes a wall material/working gas mixture).

TAUWSF.f

Calculates the shear stress on the piston and the projectile surfaces. A simple elastic-plastic model is used, with the shear stress limited by the shear strengths of the plastics.

THREEONE.f

After a certain amount of calculations have been done within the timestep, the cell variables are in a "three level" (i.e., a key index of the variables is 3) state. In preparation for advancing to the next timestep, the "one level" variables of the next timestep are set equal to the "three level" variables of the current timestep.

THREEONEB.f

As for THREEONE.f above.

TIMESTEP.f

Calculates the minimum timestep for each of the the active cells in the gun tube. The overall minimum of these values is then taken. Also, calculates a minimum timestep for the radial heat conduction problem in the gun tube wall. The smaller of the two latter values is chosen for the timestep of the next step.

UPDATE.f

This solver updates the cell variables based on the inflow and outflow at the ends of the cell and friction, heat transfer and mass flow from the gun tube wall.

VIN.f

Calculates the volume of a "cell", given the x-coordinate of one end of the cell and taking the x-coordinate of the of the other end to be zero. This does not correspond to the volume of any real cell, but two VIN.f volumes can be subtracted in VOL.f to give the volume of a real cell.

VOL.f

Calculates the volume of a cell, given the x-coordinates of the two ends of the cell.

WALLH.f

Solves the one-dimensional unsteady heat transfer problem in the gun tube wall. The problem is very close to being one-dimensional and, for simplicity, we consider it to be so. When the surface temperature of the tube wall exceeds the melting point of the wall material, an energy balance is used to calculate the amount of wall material melted off.

WRITEWF.f

After the last timestep of the solution, writes temperatures at the tube wall surface and within the tube wall and wall retreat due to ablation all along the gun tube length. Also writes a radial profile of temperatures within the tube wall.

WRITEWFRUN.f

At selected timesteps of the solution, writes a radial profile of temperatures within the tube wall.

WRITE1.f

If special settings of variables are made, WRITE1.f can print snapshot profiles of all variables along the length of the gun. Normally, does not produce any output.

XBDY.f

Calculates the x positions of the zone boundaries at the end of a timestep.

ZCELLGEOCK.f

Checks the compatibility of types of cell distribution between the zones.

ZETACAL.f

Calculates the strong wave limiting factor ZETAC for each cell boundary.

ZKTSTI.f

Provides the thermal conductivity as a function of temperature for the gun wall material. Subroutine interpolates from a table of the data.

ZQQ.f

Interpolates, using cubic curve fits, pressure as a function of density and internal energy [$p(\rho,e)$] for hydrogen from a regular two dimensional array of data points.

ZTQQ.f

Interpolates, using cubic curve fits, temperature as a function of density and internal energy [$p(\rho,e)$] for hydrogen from a regular two dimensional array of data points.

ZXQQ.f

Interpolates, using cubic curve fits, the derivative of pressure with respect to density as a function of density and internal energy [$p_\rho(\rho,e)$] for hydrogen from a regular two dimensional array of data points.

ZYQQ.f

Interpolates, using cubic curve fits, the derivative of pressure with respect to internal energy as a function of density and internal energy [$p_e(\rho,e)$] for hydrogen from a regular two dimensional array of data points.

Appendix F

Subroutines Not Called in Light Gas Gun Code

These subroutines were used during development of the code but are not used in the final version of the code.

CHARX.f

CONSERVQ.f

ERRM.f

ERROBL.f

ERROR.f

ERRT1.f

ERRT3.f

ETEMP.f

ETEMPC.f

EXPT.f

EXPTS.f

FLUXBLIND.f - not called if IORFBL = 2, which generally been the case for the last ten years or more.

GHOST2.f

GHOST7.f

GHOST8.f

GHOST9.f

HALF.f

HALFT3.f

INTERSEC.f

OBLIQUE.f

PATHL.f

REIMP.f

REIMU.f

REIMUXP.f

SHOCKT.f

SHOCKTE.f

TEST1.f, TEST2.f, TEST3.f, TEST4.f - not called if ITEST = 0 which has been the case for the last ten years or more

Appendix G

Order in Which Major Subroutines Are Called by Main Program in Light Gas Gun Code (Flow Chart)

Note that in this appendix - the flow chart - the explanations of what the subroutines do are very short and telegraphic. For more details in this connection see Appendix E.

READ1.f Reads large number of quantities

READEOS.f Reads equation-of-state data

READW.f Reads gun wall data

PREPROW.f Calculates coefficients for interpolations of gun wall temperatures

BCCHECK.f Checks the consistency of the boundary conditions between zones

ZCELLGEOCK.f Checks the compatibility of types of cell distribution between the zones

INITIAL.f Initializes all variables in all cells

Return point of timestep loop

TIMESTEP.f Calculates the timestep for the next step

Return point of predictor - corrector loop

GHOST.f Calculates variables in "ghost" (or virtual) cells placed at both ends of each zone

ZETACAL.f Calculates the strong wave limiting factor for each cell boundary

BDYVF.f Calculates all fluxes at the boundaries between zones

BDYVFC.f - only called if on corrector step, in such case completes the work of BDYVF.f

XBDY.f Calculates the x positions of the zone boundaries

CELLX.f Calculates the x-coordinates of all cells in all zones

CELLV.f Calculates velocity of moving cell (not equal to the velocity of the material within the cell)

CELLVOL.f Calculates the volume of a cell

CELLA.f Calculates an effective cell area normal to the gun axis

CELLFLUX.f Calculates all fluxes at internal boundaries of cells within zones

CELLFLUXC.f - only called if on corrector step (calculates as for CELLFLUX.f)

FRICTION.f Calculates the friction forces and heat transfer between the gun media and the gun tube

UPDATE.f This solver updates the cell variables

End point of predictor - corrector loop

WALLH.f Solves the one-dimensional unsteady heat transfer problem in the gun tube wall

POWGFLOW.f Corrects the g parameter (a measure of the fraction of the powder grains burnt) for the grains flowing in or out of the ends of a cell.

NONEQTURB.f Updates the turbulent kinetic energy (TKE) in each cell in each timestep

WRITE1.f If special settings of variables are made, WRITE1.f can print snapshot profiles of all variables along the length of the gun. Normally, does not produce output.

PLOTX.f Makes time history tables for pressures at five x-locations along the gun tube

PLOTQ.f At the 3 chosen snapshot times, makes tables for all variables for all cells along the gun tube

PLOTPROJ.f Makes time history tables for x-position and velocity for the front and rear of the piston and for the projectile base.

THREEONEB.f Some of the variables currently at the end-of-step level (3 level) are written over the corresponding variables at the beginning-of-step level (1 level).*

BURN.f (1) Calculates the burning of the gunpowder grains (predictor)

BURN.f (2) Calculates the burning of the gunpowder grains (corrector)

PLOTH.f Makes time history tables of all variables for 5 cells, chosen by zone number and cell number

THREEONE.f A number of variables currently at the end-of-step level (3 level) are written over the corresponding variables at the beginning-of-step level (1 level). *

STEELH2.f Updates each gun working gas cell for the amount of wall material incorporated into the gun working gas

WRITEWFRUN.f At selected timesteps of the solution, writes a radial profile of temperatures within the tube wall

End point of timestep loop

WRITEWF.f At the end of the solution, writes temperatures within the gun tube wall and at the wall surface and wall retreat due to ablation along the length of the gun tube

End of program

*There are 3 levels for each variable. At the beginning of the timestep all variables are at level 1. The predictor calculations are made, using the variables in level 1 to start with and a new set of variables at level 2 are created. Then the corrector calculations are made, using the variables in levels 1 and 2 to start with and a new set of variables at level 3 are created. Before advancing to the next timestep, the new level 3 variables are written over the old level 1 variables.

Appendix H

Summary of Input and Output Files

Input Files

The code requires three input files, ONED1D.DAT, ONED1DE.DAT and WAHE1D.DAT. The main content of each of these three files is given below.

ONED1D.DAT:

- Gun shape variables, break valve rupture pressure
- Number of zones, number of cells for each zone
- Initial loading of cells - gunpowder, piston and projectile plastic, working gas (usually H_2)
- Projectile mass and length
- Viscosity coefficients of working gas - 6 terms including high pressure effects
- Piston and projectile moduli of elasticity, Poisson's ratios, coefficients of friction as a function of velocity
- Cell numbers and x positions at which history file will be printed out
- X-positions where maximum pressures will be calculated to construct maximum pressure and burst pressure profiles along the gun. Note that the burst pressure profile is only valid in the HPC.
- Step numbers at which snapshot files will be created

ONED1DE.DAT:

- Equation of state (EOS) choices for the various zones
- Coefficients for Zel'dovich-Raizer EOS with electron term dropped (for plastics)
- Coefficients for Abel-like EOS with compressible molecular volume term (for gases)
- Limiting negative pressures for stretched plastics
- Large array of coefficients for tabulated EOS of hydrogen
- Gunpowder grain sizes, energies, burn rates

WAHE1D.DAT:

- Heat of fusion and melting point of steel
- Enthalpy, thermal conductivity and density of steel as a function of temperature
- Temperature of steel as a function of enthalpy
- Cell thickness in the radial direction (r) inside the wall. This is defined by giving the cell thickness at the wall surface and the ratio of the adjacent cell

thicknesses as one moves into the wall
- Values of cell boundaries in the axial direction (x)
- Molecular weights of steel and hydrogen
- Wall blowing parameter as a function of wall blowing rate
- Internal energy of liquid steel at the melting point

(Note that WAHE1D.DAT files are available for gun steel, rhenium and tantalum.)

Output Files

The code has nine types of output files:

FINALOUTP
PLOT1, PLOT2 and PLOT3
PLOTPROJ1
PISTONXV
PLOTX1 to PLOTX5 (5 files)
PLOTH1 to PLOTH5 (5 files)
PRESSVSX
WAHE1OP
WAHE1OHA

The main content of each of these nine types of files is given below.

FINALOUTP

Piston velocities and projectile muzzle velocities
Maximum pressures at 5 selected cells and 5 selected x positions along the gun
Piezometric ratios based on the 10 maximum pressures given just previously

PLOT1, PLOT2 and PLOT3

These are snapshots, at three different step numbers, of working media conditions along the entire length of the gun

PLOTPROJ1

Time history of projectile location, velocity and base pressure

PISTONXV

Time history of piston and projectile locations and velocities

PLOTX1 to PLOTX5 (5 files)

Time histories of pressures at five different x positions along the gun

PLOTH1 to PLOTH5 (5 files)

Time histories of thermodynamic variables, velocity and burn status of powder grain at five different cells in the gun. Cells defined by zone number and cell number within the zone

PRESSVSX

Profile of maximum shot pressures and gun tube burst pressures along the length of the gun (presented as x, p_{max}, p_{burst}, ACONE, DCONE, where ACONE and DCONE are the inside area and inside diameter of the HPC at the corresponding x station). We note again that the burst pressures are only valid within the HPC.

WAHE1OP

Contains profiles in the x-direction along the gun at the time the projectile exits the muzzle. The variables profiled are the wall retreat (erosion), tube wall surface temperature, maximum (at any time) tube wall temperature and temperatures at two different cells (depths) within the metal of the gun tube.

WAHE1OHA

Three temperature versus depth in gun tube (from inside surface) profiles at three different step numbers (times). Each profile contains data at two different x cell numbers along the gun tube.

Note that in addition to the above listed useful output files, the code produces a number of diagnostic files which were used to solve code problems in the past, but are no longer necessary. No attention need be paid to these files. After a run is completed and the data which needs to be analyzed is transferred to another directory or computer, all the output files (including the diagnostic output files) should be removed by invoking (on our machine) the command ./Mcl. The code will not run if its directory is not cleaned up this way. The command ./Mcl is included in the code directory furnished to the user.

Appendix I

Details of Input Files

Below, we discuss all variables for the input files. (A complete set of the input files, ONED1D.DAT, ONED1DE.DAT and WAHE1D.DAT, is given in Appendix K.) The default difference between INTEGER and REAL variables is used; i.e., all variables starting with I, J, K, L, M and N are INTEGERS, all other variables are REAL. REAL variables can be written either in decimal (i.e., 0.00078) or in exponential (i.e., 7.8E-04) notational. The READ statements are all of the type READ(N,*); thus, location of variables in any given input file line is not critical, except that the first number in any line should start in the first space of that line. If there is more than one variable in a line, there must be at least one blank space between adjacent variables. The name of the variable(s) and the annotation to the right of the variables themselves are ignored by the reading subroutine after the required number of variables of the correct type(s) are read.

The variables which must be checked and may need to be changed are marked with the dagger (†). Variables that are not so marked should not be changed. If the dagger occurs at the start of a group of variables, it does not mean that all of these variables must be changed - changes are often needed only for some of the variables. See discussion following each group of variables. For many series of computational runs, only a very few of the input variables marked with the dagger need to be changed from run to run. For example, for a sweep through powder loads with other parameters constant, only the entries for the powder densities need to be changed between CFD runs.

ONED1D.DAT

The variables are given line by line. For each line (or group of lines where subscripted variables are involved) the variable names are given first and followed by representative values. This is followed by a discussion of each variable.

†NZ NS CFL DELIM

4 50001 0.70 0.050

NZ is the number of zones. We frequently use NZ = 3 for three zone calculations consisting of powder/powder gas, piston and hydrogen zones. However, to demonstrate the improved capabilities of the code, we have chosen a 4 zone case consisting of powder/powder gas, first piston zone (iron), second piston zone (epoxy matrix with steel shot) and hydrogen zones

NS is the maximum number of timesteps; we have used values ranging from 7000 to 80,000 for total numbers of computational cells ranging from ~50 to ~600, with NS being proportional to the number of cells. The code will stop shortly after the projectile exits the muzzle.

CFL is the CFL number. We have successfully used 0.70 for all of our calculations. It is recommended that this number **not** be changed.

DELIM governs limiting and interpolations in certain subroutines. Do not change this variable.

CFL1 CFL2 NCFL

0.70 0.70 2

These variables allowed for the possibility of gradually changing the CFL number during the course of the calculation. This was later found to be unnecessary. It is recommended that these variables **not** be changed.

We treat the next three lines grouped together.

ALPH1 ALPH2

1.00 0.50

ALPH1C ALPH2C NBZCRS

8.00 4.00 1

ZETAL1 ZETAL2 ZETAL3 ZETAL4

0.0125 0.0250 0.0005 0.0010

All of these variables are involved with limiting, changing between interpolation techniques and determining whether or not strong waves are present. They have all been determined through much trial and error and have been found to work very well for the last 10 years. It is recommended that these variables **not** be changed.

IVELEX IENEX NSKSWL

0 0 0

These variables not used in current version of code. It is recommended that these variables **not** be changed.

IORFBL IORIN ZEXIN

2 3 0.50

IORFBL = 2 calls second order blind end interpolations in the boundary value subroutine. IORIN = 3 calls third order interpolations in the interpolator. These values have been proven over years of service. ZEXIN is not used in the current version of the code. It is recommended that these variables **not** be changed.

NRITI

6

NRITI = 6 sets the maximum number of iterations in one of the Reimann solvers. The value of 6 has been proven over years of service. It is recommended that this variable **not** be changed.

We treat the next four lines grouped together.

ITEST UEXMIN UEXMAX TTEST1 TTEST2 IT2MOD

0 0.50E+05 0.90E+06 0.139547E-04 0.255217E-04 2

NTPRIN NTPRI2 NTPRI3

8 10 11

INOZCA ZHALF1 ZHALF6 R21HHI

0 2.80 2.80 50.00

AZTT(1,3,4,7,16,17,18) – subscripted variable, 7 variables

1464.300 729.600 1440.000 1459.300 45.603 6703.700 8000.000

These variables were used in diagnostic tests no longer needed. It is recommended that these variables **not** be changed.

† XMUZ(2) – subscripted variable, 2 variables

1336.744 1430.

XMUZ(1) is the x-position of the gun muzzle in cm. The code calculation is carried out to a distance somewhat farther downrange, XMUZ(2) (cm). The muzzle velocity results shown in FINALOUTP are interpolated between the two nearest timesteps between which the projectile base passes XMUZ(1). It is recommended that XMUZ(2) be roughly 10% larger than XMUZ(1). It is also recommended that the x-position of the blind end of the breech, XB(1), be set to 0.0 cm. This is only to reduce possible confusion and is not strictly obligatory.

† NXWG

5

Number of whisker gauge stations along the pump tube. Whisker gauges consist of a wire whisker maintained in the center of a circular hole in a fitting screwed into the wall of the pump tube. The whisker protrudes very slightly into the pump tube and when the piston arrives, the whisker is brought into contact with the side of the surrounding hole, thus completing a circuit which produces a timing pulse.

† XWG(NXWG) – subscripted variable, NXWG variables

267.09 273.09 323.715 359.715 395.715

The XWG(1) to XWG(NXWG) values are the x-positions of whisker gauges in the pump tube, in cm. All whisker gauges should be located downrange of initial position of the nose of piston, to avoid possible code confusion and failure. It is probably safer to set NXWG to 5 always to avoid possible I/O problems. There will then be 5 XWG values, from XWG(1) to XWG(5).

† UPISTW(3) – subscripted variable, 3 variables

55000.0 40000.0 1.0

If NPLSTE = 0 (This variable will be discussed later in this section.), when the piston is slowing down in the pump tube and the velocity of its nose passes UPISTW(1) and UPISTW(2) (cm/sec), snap-shots of the state of the materials in the gun will be taken and written to the output files PLOT1 and PLOT2. UPISTW(3) is a dummy variable and is not used in the current version of the code.

† DXPIST

3.3532

DXPIST, in cm, is the difference between the actual length of the piston (allowing for a possible cavity in the piston nose) and the length of the equivalent one-dimensional piston measured from the piston rear to the center of the most downrange piston cell. The latter length is **not** equal to the overall length of the equivalent one-dimensional piston. See also discussion of Ref. 1, pp. 19 – 20 (including Fig. 9). This length correction is applied to allow the most accurate whisker gauge piston velocities to be obtained for the actual pistons, which, at the Ames Research Center, can have a cavity in the piston nose. The four whisker gauge velocities given in FINALOUTP are calculated from the five times at which the nose of the piston, allowing for the correction distance DXPIST, passes the five whisker gauges in question. Since DXPIST is typically small, in recent (as of January, 2018) code runs, we have set DXPIST to zero.

† RDELTT

1.00

See also discussion of UPISTW(3) above. If NPLSTE = 0, two snapshots of the state of materials in the gun will be written to output files PLOT1 and PLOT2. These snapshots will be taken at times T1 and T2 as the piston nose is slowing down past velocities UPISTW(1) and UPISTW(2). A third snapshot will then be taken at time T3 = T2 + RDELTT x (T2 – T1) and written to output file PLOT3.

† NC(NZ) – subscripted variable, NZ variables; NZ = number of zones

32 12 22 40

NC(NZ) are the number of cells in each zone, There are two ghost cells, one at either end of each zone to aid in zone boundary condition calculations, thus the number of cells internal to each zone is NC(NZ) – 2. NC(1) is the number of cells in the powder/powder gas zone, NC(2) and NC(3) are the number of cells in the piston zones and NC(4) is the number of cells in the working gas zone. The minimum value of NC for each zone is 4, since there must be two internal cells and two "ghost" cells at either end of the zone. The maximum value of NC for each zone is 100, since this is how the arrays are dimensioned. Note (see also discussion of NZ above) that there can be either one or two piston zones and the corresponding NC values would be 3 or 4. We have chosen the NC = 4 case for the example in this manual.

† NCOM(NZ) – subscripted variable, NZ variables; NZ = number of zones

2 1 1 2

NCOM(NZ) are the number of components of the medium in each zone, For the powder/powder gas zone, NCOM(1) = 2, the two components of the medium being

unburned powder and powder gas. For the piston zones, NCOM(2) = 1 and NCOM(3) = 1 and for the hydrogen zone, NCOM(4) = 2, the two components of the medium being hydrogen and ablated steel droplets from the gun barrel wall.

† NTCG(NZ), CSRAT(NZ) – subscripted variables, 2 x NZ variables; NZ = number of zones

3 1.0 1 1.0 1 1.0 3 1.0

NTCG(NZ) and CSRAT(NZ) are to be entered in the form NTCG(1), CSRAT(1), NTCG(2), CSRAT(2), etc. NTCG determines the variation of the cell lengths within the zone in question. If NTCG = 1, all cells in the zone in question have the same length. For piston plastic zone, NTCG should be set to one, as above. If NTCG = 3, the cells in the zone in question increase in size by a fixed ratio from one end of the zone to the other. In this case, the cell at the internal end of the zone in question is made equal in length to the neighboring cell in the adjacent zone and the size ratio of the cells is chosen so that the cells will fill the zone. For the case above, this means that the last cell in zone 1 is the same size as the first cell (and all the other cells) in zone 2. Similarly, the first cell in zone 4 is the same size as the last cell (and all the other cells) in zone 3. One should use the values given above for 4 zone calculations, i.e., NTCG(1) = 3, NTCG(2) = NTCG(3) = 1, and NTCG(4) = 3. For a 4 zone calculation, it is strongly recommended that the zone lengths and the number of cells in zones 2 and 3 be chosen to make the cell sizes in zones 2 and 3 roughly equal to each other. For a 3 zone calculation, one would have NTCG(1) = 3, NTCG(2) = 1 and NTCG(3) = 3.

It is recommended that all CSRAT values be always kept at 1.0. CSRAT values are not used by the code unless NTCG = 2, which is an option that has never been checked out. If NTCG = 4, the cells in the zone in question increase in size by a fixed ratio from one end of the zone to the other. In this case, the cells at the ends of the zone in question are made equal in length to the neighboring cells in the adjacent zones and the size ratio of the cells is chosen so that the cells will fill the zone. This NTCG value has been successfully used for a 3 stage gun (with 5 zones) for the gas zone between the 2 pistons. In this case, NTCG(NZ) values are 3 1 4 1 3. Users are strongly discouraged against using other sets of NTCG(NZ) values than those given above. The code will not run for many other sets of NTCG(NZ) values.

†NTB(NZ,1) NTB(NZ,2) - subscripted variables, 2 x NZ variables; NZ = number of zones

1 4 4 4 4 4 4 1

NTB(NZ,1) and NTB(NZ,2) are to be entered in the form NTB(1,1), NTB(1,2), NTB(2,1), NTB(2,2), etc. NTB determines the type of boundary conditions at the two ends of each zone. If NTB = 1, the end of the zone in question rests against a blind, immovable wall. In

our gun calculations, NTB(1,1) is at the blind end of the powder breech and is always 1. NTB(4,2) is at the diaphragm behind the projectile and must initially be set to 1. Since the distance between the diaphragm and the projectile base and the diaphragm is very small for many guns, we usually set this distance to zero in the code. When the pressure at the diaphragm exceeds the diaphragm rupture pressure (PBKVAL – see also later discussion), the code will reset NTB(3,2) to 10, which defines the boundary condition with an accelerating projectile. At the moving boundary between two zones the two relevant boundary conditions must each be set to 4. At the boundary between the powder/powder gas zone and the first piston zone, we must have NTB(1,2) = NTB(2,1) = 4. At the boundary between the two piston zones, we must have NTB(2,2) = NTB(3,1) = 4. For the piston /hydrogen boundary, we must have NTB(3,2) = NTB(4,1) = 4. Thus, the NTB(NZ,1) NTB(NZ,2) values must set to 1 4 4 4 4 4 4 1.

†XB(NZ + 1) - subscripted variables, NZ + 1 variables; NZ = number of zones

0. 19.596 23.611 31.641 1081.514

XB(NZ + 1) are the initial positions of the zone boundaries, in cm. The piston comprises two parts. XB(1) is the position of the blind end of the powder breech, XB(2) is the initial position of the boundary between the powder/powder gas zone and the uprange part of the piston, XB(3) is the initial position of the boundary between the two parts of the piston, XB(4) is the initial position of the boundary between the downrange part of the piston and the gun working gas and XB(5) is the initial position of the diaphragm and the projectile base. It is suggested to set XB(1) to zero, but this is not obligatory. As the gun calculation proceeds, XB(1) and XB(5) (initially) will remain fixed while XB(2), XB(3) and XB(4) will move. When the diaphragm ruptures, XB(5) will start moving along with the projectile base.

Figure 1 shows a schematic sketch of a two-stage light gas gun (not to scale). Key dimensions are indicated. XB(1) to XB(4) have just been discussed; XMUZ(1) and XMUZ(2) have been discussed earlier. XD(1) to XD(6) and A(1,1), A(3,1) and A(5,1) will be discussed at a later point.

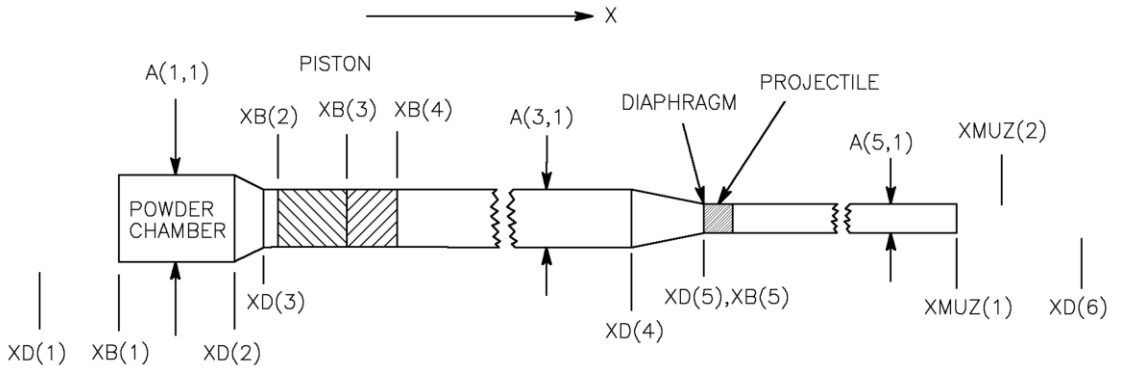

Figure 1. Schematic sketch of a two-stage light gas gun (not to scale). Key dimensions are indicated (see text for discussion).

†VB(NZ + 1) - subscripted variables, NZ + 1 variables; NZ = number of zones

0.0 0.0 0.0 0.0 0.0

VB(NZ + 1) are the initial velocities of the zone boundaries, in cm/sec. For gun calculations, all VBs must be set to zero. (The option to have non-zero VBs is historical, relating to when to code was used for impact calculations.)

We treat the next 14 lines grouped together.

QQGP QQGREX

0.0001 0.01

ROLIM(NZ) ALPH(NZ)

9.55 0.117 2.2 1.2 9.00 0.125

ALPHHI(NZ) ALPHLO(NZ)

10.0 0.05 10.0 0.05 10.0 0.05

IALPEX

1

GRUN(NZ)

4.0 4.0 4.0

NITGRU IREIMS IPRECS IRMG2S NG256 NG2VBY

6 5 1 2 5 5

IPRECE

0

IPPRCS ZPPRCS IPRUPS

0 0.5 0

NPKLUG ZPKLUG ZPKLG4

1 1.1 1

IPWAPA

0

ERRSH RRSHLO RRSHHI NITRS(NZ)

0.005 1.005 9.800 12
0.005 1.005 4.000 12
0.005 1.005 9.400 12

These variables are used in connection with the Riemann solvers of the Godunov method, the calculation of fluxes and the detection of strong waves. (See discussion of Ref. 1, pp. 8 – 15.) Some of the values are limiting ratios of various quantities. Some variables are no longer used in the current version of the code. IPWAPA is used to choose the method of calculating the wall pressure force. All these parameters have been optimized and proven through many years of use. It is advised not to change any of these variables.

†ND

5

ND is the number of break points of the gun shape, including powder breech, pump tube, high pressure contraction section and launch tube. Currently, one should restrict oneself to the use of cylindrical sections and conic frustums. (Higher order shapes for sections of the gun exist, but have never been tested.) It is strongly recommended to make up the gun shape of these two elements. Whenever there is a change from cylinder to cone or vice versa or a change between cones of two different slopes, there must be a break point. The current maximum value of ND is 10. If there are many break points very close together, the code can fail if more than 4 break points occur within one cell. The current cell volume calculation routine (VOL.f) will work only for up to and including 4 break points within one cell.

†XD(ND+1), subscripted variables, ND + 1 variables

-200. 15.151 17.691 1066.667 1081.514 10000.

XD(ND + 1) are the locations of the break points of the gun shape, in cm, along the gun. The first and last “break points” must be beyond the two extremities of the gun, the blind end of the powder breech and XMUZ(2) (discussed previously), respectively.

†NTD(ND), subscripted variables, ND variables

1 2 1 2 1

NTD(ND) denotes the shape of the gun element. NTD = 1 is a cylinder and NTD = 2 is a conic frustum. For example, NTD(1) = 1 denotes that the gun shape is a cylinder between x = -200.0 and x = 15.151 cm and NTD(2) = 2 denotes that the gun shape is a conic frustum between x = 15.151 and x = 17.691 cm.

†A(ND,1) A(ND,2) A(ND,3), subscripted variables, ND rows of three variables per row

5.08 0. 0.
-0.45 11.89795 0.
3.9370 0. 0.
-.152138848 165.251494 0.
0.7112 0. 0.

A(ND,1) A(ND,2) A(ND,3) determine the gun shape between any two break points. For a cylindrical section, with NTD(ND) = 1, A(ND,1) is the gun diameter, in cm, and A(ND,2) = A(ND,3) = 0. For a conic frustum, with NTD(ND) = 2, the gun diameter at any point along the section is A(ND,1)*x + A(ND,2) and A(ND,3) = 0, where x is the distance along the gun, in cm. For the conic frustum case, a negative A(ND,1) means a contraction section and a positive A(ND,1) means an expansion section. A(ND,3) was to have been used for higher order shapes for the sections of the gun. It is recommended to set all A(ND,3) values equal to zero. Note that A(1,1) is the diameter of the powder breech, A(3,1) is the diameter of the pump tube and A(5,1) is the barrel diameter.

†NINIB(NZ), subscripted variables, NZ variables on NZ lines

4
2
2
2

NINIB(NZ) are the number of regions of different initial conditions within each zone. These variables cannot be less than 2. The only purpose of this option would be to model ullage regions in the powder/powder gas zone. This option would serve no purpose for the remaining zones in the gun. For example, one could have the first group of cells in the powder/powder gas zone filled with a powder/powder gas mix and the second group of cells with a small amount of powder/powder gas mix. This would provide the option of having a (near) ullage region in the second part of the powder chamber. In the powder/powder gas regions, a small amount (typically 1%) of the powder is assumed to already be combusted, in order to get the remaining powder burning. Otherwise, there will

be zero pressure in the powder/powder gas regions and powder burning will not start. The option of having different initial conditions within the powder/powder gas zone has been used to model powder loads with ullage spaces. The difference between the performance of the gun with the ullage region and with the same powder load uniformly distributed in the powder chamber was found to be very small. Thus, for many years now, we have mostly assumed the powder to be uniformly loaded throughout the powder chamber. This type of calculation has always agreed very well with experiment. Hence, in the current code practice, the initial conditions in the two regions of powder/powder gas zone have nearly always been set equal to each other.

†RII(NZ,NINIB(NZ)), UII(NZ,NINIB(NZ)), EII(NZ,NINIB(NZ)), GPOWI(NZ,NINIB)), INIB(NZ,NINIB(NZ)), doubly subscripted variables, NINIB(1) + NINIB(2) + …. + NINIB(NZ) lines with 5 variables on each line

First version of table (with powder region and ullage region):

```
.758510    0.   3.5247E9   .00785700    -200
.758510    0.   3.5247E9   .00785700      4
.005210    0.   3.5247E9   .00785700      5
.005210    0.   3.5247E9   .00785700    200
7.8516 0. 9.12900E8 1.00 -200
7.8516 0. 9.12900E8 1.00 200
5.500  0. 1.61600E8 1.00 -200
5.500  0. 1.61600E8 1.00 200
1.2374E-4 0. 2.956E10 1.00 -200
1.2374E-4 0. 2.956E10 1.00 200
```

Second version of table (with one region of uniformly distributed powder):

```
.128290  0. 3.5247E9 .00785700  -200
.128290  0. 3.5247E9 .00785700    4
.128290  0. 3.5247E9 .00785700    5
.128290  0. 3.5247E9 .00785700  200
7.8516 0. 9.12900E8 1.00 -200
7.8516 0. 9.12900E8 1.00 200
5.500  0. 1.61600E8 1.00 -200
5.500  0. 1.61600E8 1.00 200
1.2374E-4 0. 2.956E10 1.00 -200
1.2374E-4 0. 2.956E10 1.00 200
```

We start the discussion dealing with the first version of the table. RII(NZ,NINIB(NZ)) are the initial densities in the various zones, in gm/cm^3. UII(NZ,NINIB(NZ)) are the initial velocities in the various zones, in cm/sec. For gun performance problems, all UII should be set to zero. The option for non-zero initial velocities is a hold-over from when the code was used to model plate slap problems. EII(NZ,NINIB(NZ)) are the initial internal energies

in the various zones, in erg/gm. GPOWI(NZ,NINIB)) only have meaning for the powder/powder gas zone. GPOWI(NZ,NINIB)) are the fractions of the web of the powder grains (WPOW) burned at the initial condition. In the case given GPOWI(1,1) = GPOWI(1,2) = GPOWI(1,3) = GPOWI(1,4) = 0.007857 corresponds to 1% of the powder burned for the initial condition for the powder grains in question. This can be calculated by taking Eq. (5) in Appendix C, setting g_1 to 0.0, setting m_2 to $0.99*m_1$ and solving for g_2 which will be the desired GPOW(1,n) value. See also further discussion of WPOW in the ONED1DE.DAT section following. INIB(NZ,NINIB(NZ)) are the cell numbers of the break points of regions of different initial conditions within the zone in question. For example, the initial conditions given in lines one and two would be inserted in any cell in zone one with a cell number from -200 and to 4. The initial conditions given in lines 3 and 4 would be inserted in any cell in zone one with a cell number from 5 to 200. The cell numbers -200 and 200 were simply chosen to be guaranteed to be outside the region of calculation. Thus, for the conditions of the table of numbers just given previously, we have the majority of the powder in cells 2 to 4 and "ullage" for cells 5 to 31 (NC(1) = 32). (The powder/powder gas density in the ullage zone was taken to be 0.006868 times that in the main powder containing zone - this number is arbitrary, but of the order of 1%.) The second version of the table assumes that the powder is uniformly distributed in all the cells of the powder chamber.

We now go through the method for selecting the initial conditions, RII and EII for the various zones. We assume that zone 1 comprises the main powder containing sub-zone and the ullage sub-zone described above. From the powder breech geometry, the volumes of these two sub-zones are calculated by the user. Then, assuming that the powder density ratio between the two sub-zones of zone 1 is chosen (e.g., 0.006868, as given above) and that the total mass of the powder charge is known, the two values of RII for zone 1 can be calculated. If the powder is assumed to be uniformly distributed in the powder breech, RII is simply (powder mass)/(powder breech volume). EII is the initial internal energy of the powder/powder gas combination, which is calculated as the initial energy of the unburned powder, E1SOL(1) plus the fraction of the powder assumed to be burned at the beginning of the calculation (typically 0.01) times the energy of combustion of the powder ECPOW(1) i.e.,

$$EII = E1SOL(1) + 0.01*ECPOW(1)$$

E1SOL(1) is taken as an average specific heat of nitroguanidine (NQ) multiplied by the assumed (room) temperature of the powder charge, 294.4 K (70° F). The energy of combustion of the (Du Pont IMR) powder is taken as the heat of explosion of IMR powder given in Ref. 24. For other powders, other appropriate heats of explosion would have to be used. (Further discussion of E1SOL(1) and ECPOW(1) is presented in Appendix I, in the section which deals with the file ONED1DE.DAT.)

For the case given as an example here, zone 2 is the rear portion of the piston, taken to be an iron slug within a thin polyethylene sleeve. (The shear stress between the iron slug and the tube wall is taken to be limited by the strength of the polyethylene sleeve - see Appendix B1.) For the iron, a version of Zel'dovich and Raizer's equation of state is used that has two cold compression terms of the type shown in Eq. (2), Appendix A. Generally, one knows the initial pressure and temperature of the piston, but one needs to have the

density (RII) and internal energy (EII) to load into the initial condition input files. The variables defining the Zel'dovich-Raizer (ZR) equation of state (EOS) for zone 2 are ROZZX(2), ZNZZX(2), ZMZZX(2), AA1ZZX(2), AA2ZZX(2), T2CXN1(2) to T2CXN4(2), GRZZ1X(2) and GRZZ2X(2).

For the example case, zone 3 is the front portion of the piston, taken to be an epoxy matrix loaded with steel shot. For the epoxy, another Zel'dovich and Raizer equation of state, similar to the one used for the iron is used. The variables defining the equation of state (EOS) for zone 3 are ROZZX(3), ZNZZX(3), ZMZZX(3), AA1ZZX(3), AA2ZZX(3), T2CXN1(3) to T2CXN4(3), GRZZ1X(3) and GRZZ2X(3). The variables defining the EOSs for zones 2 and 3 are read into input file ONED1DE.DAT (See Appendix I - the section which deals with the file ONED1DE.DAT.) For zone 3, the steel shot loading is taken to be incompressible compared to the epoxy (It has a compressibility of about 0.5% of that of the epoxy.) This allows the relation between the properties of epoxy-shot mixture to be related to those of the pure epoxy by very simple equations - see Appendix B. The constants controlling this relation are ZM1PIS(3), ZM2PIS(3) and ZR2PIS(3) in line 20 of ONED1DE.DAT. These are the mass fractions of the matrix and the steel shot and the density of the steel shot, respectively. We note that ZM1PIS(NZ), ZM2PIS(NZ) and ZR2PIS(NZ) also exist for NZ = 1, 2 and 4. For NZ = 1 and 4, these are dummy variables. For NZ = 2, the values of these three variables indicate that there is no shot loading of the iron "matrix" and the "matrix" becomes a solid iron slug. It is suggested to set up separate small programs for the ZR EOS and iterate the density and internal energy values until the required pressures and temperatures are obtained. With a little practice, good values can be found in 5 or 6 iterations.

The fourth zone is the working gas (often hydrogen) zone and the required initial density (RII) and internal energy (EII) values are again chosen to produce the known initial temperature and pressure values. (Note that the working gas can be Ar, N_2 and He as well as H_2.) Using the JANAF tables,[32] the internal energy of the working gas necessary to produce the required working gas temperature can be found. The density of the working gas necessary can then be found using the ideal gas equation of state. Some care must be used in selecting the initial conditions in order to avoid the production of spurious waves at the beginning of the gun calculations. In particular, if the conditions for zones 2 and/or 3 are slightly in error, there will be initial pressure differences in these zones which will give rise to spurious pressure waves. We usually choose the initial conditions in zones 2 and 3 to produce temperatures within ~1 K of room temperature and pressures between 0.5×10^6 and 2.0×10^6 dynes/cm^2. This limits the strengths of the spurious pressure waves to small enough values to be unimportant. One way to check the accuracy of the initial conditions is to run the code a small number of timesteps and then to check the output files PLOTH1, PLOTH2, ….. , PLOTH5 (see Appendix J) to see what initial values of pressure and temperature are produced by the EOS routines of the code for the chosen values of the RIIs and EIIs for each zone. To sample at least one cell from each zone, the variables IWHHZ and IWHHC (to be discussed later in this section) would have to be correctly set. If undesirable spurious waves were then seen, the initial values of the RIIs and the EIIs could be further adjusted to minimize these waves.

†ZMII(NZ,1,NINIB(NZ)), ZMII(NZ,2,NINIB(NZ)), ZMII(NZ,3,NINIB(NZ)), ZMII(NZ,4,NINIB(NZ)), ZMII(NZ,5,NINIB(NZ)), ZMII(NZ,6,NINIB(NZ)), ZMII(NZ,7,NINIB(NZ)), ZMII(NZ,8,NINIB(NZ)), ZMII(NZ,9,NINIB(NZ)), ZMII(NZ,10,NINIB(NZ)), triply subscripted variables, NINIB(1) + NINIB(2) + …. + NINIB(NZ) lines with 10 variables on each line

.99 .01 0. 0. 0. 0. 0. 0. 0. 0.
.99 .01 0. 0. 0. 0. 0. 0. 0. 0.
.99 .01 0. 0. 0. 0. 0. 0. 0. 0.
.99 .01 0. 0. 0. 0. 0. 0. 0. 0.
1. 0. 0. 0. 0. 0. 0. 0. 0. 0.
1. 0. 0. 0. 0. 0. 0. 0. 0. 0.
1. 0. 0. 0. 0. 0. 0. 0. 0. 0.
1. 0. 0. 0. 0. 0. 0. 0. 0. 0.
1. 0. 0. 0. 0. 0. 0. 0. 0. 0.
1. 0. 0. 0. 0. 0. 0. 0. 0. 0.

ZMII(NZ,1,NINIB(NZ)), ZMII(NZ,2,NINIB(NZ)), etc. are the initial mass fractions of the components in the various regions. The arrangements of the regions within each zone is the same as for the previous variables, RII(NZ,NINIB(NZ)), UII(NZ,NINIB(NZ)), etc. For lines one to four, for the powder/powder gas zone, only the first two entries in each line are used. The first entry in each line is the mass fraction of the unburned powder and the second entry of each line is the mass fraction of the powder gas. As mentioned earlier, we have typically set these two variables to 0.99 and 0.01 with good success. For lines 5 to 8, for the piston zones, only the first entry of each line is used, since this zone always has a mass fraction of 1.00 of the plastic. For lines 9 and 10, for the gun working gas, only the first two entries of each line are used. The first entry is the mass fraction of the gun working gas, which would be 1.00 initially for all normal gun performance calculations. The second entry is the mass fraction of ablated steel gun barrel material mixed in with the hydrogen. This will, of course, normally be zero at the beginning of the calculations. Later on in the gun code calculations, for severe gun operating conditions, the mass fraction of hydrogen can decrease below 1.00 and the mass fraction of ablated steel gun barrel material can increase above zero. It is recommended that these variables **not** be changed, even though many of them are of historical interest only and are not used. The code had been proven to work with these variables as given above.

†IPIST NZPIST NCPIST

0 3 21

If IPIST = 1, the nose of the piston will stop when its velocity decreases to zero. This simulates the frictional stopping (jamming) of the piston nose in the high pressure coupling. If IPIST = 0, the piston nose does not stop upon reaching zero velocity but will rebound back towards the breech of the gun, in general. We have had good correspondence between experimental and computational results by forcing the piston nose to stop when its velocity decreases to zero. (See Ref. 1, p. 26.) NZPIST is the number of the zone which contains

the piston nose. NZPIST would normally be 2 for a three zone calculation. NCPIST is the number of the last internal cell at the piston nose. NCPIST should always be equal to NC(NZPIST) – 1, but this is not checked by the code. To determine the time at which the piston nose stops, the velocity U(NZPIST,1,NCPIST) is tracked until it decreases past zero and then the piston nose is stopped. The three indexes of U are, in order, the zone number, the predictor/corrector indicator, indicating the stage of the timestep and the cell number.

†PBKVAL NZBKPR NCBKPR NBCCH1 NBCCH2 IBKVAL

3.4490E08 4 39 4 4 0

PBKVAL is the rupture pressure of the diaphragm behind the projectile, in dynes/cm^2. NZBKPR is the zone number of the hydrogen zone. NCBKPR is the cell number of the last internal cell in the hydrogen zone just adjacent to the diaphragm. The pressure in this cell is monitored and when it exceeds PBKVAL, the boundary condition at the end of the hydrogen zone is changed from that for a blind end of the tube to that for an accelerating projectile. NBCCH1 and NBCCH2 are not used at this time, but were used in earlier shock tube applications of the gun code. It is suggested that these variables be left unchanged. IBKVAL must initially be set to zero for the rupturing of the break valve to be modelled.

†NPROJ ZMPROJ VPROJI ZLPROJ

1 .6494 0. 1.362

NPROJ must be set to 1. ZMPROJ is the mass of the projectile, in g. VPROJI is the initial velocity of the projectile and must be set to zero for gun performance calculations. ZLPROJ is the length of the projectile, in cm. The projectile is treated as a simple cylindrical slug and ZLPROJ is used in the calculation of the frictional drag force on the projectile.

TWALL RATRE ERATRE NRATRE

300.0 0.50 0.50 1

TWALL is the wall temperature of the gun and is no longer used since the wall heating and erosion calculations were instituted. RATRE, ERATRE and NRATRE are involved in limiting the amount that the density and internal energy of a cell can drop in one time step. These latter three values have been proven by years of service. It is strongly recommended that none of these variables be changed.

†ITWALL TWMELT FRACQW

2 1673.0 0.50

ITWALL must be set to 2 to invoke the correct initial gun wall temperature. TWMELT and FRACQW are no longer used in the current version of the code. It is recommended that neither of the latter two variables be changed, however (just in case!).

GFFUDG(NZ), subscripted variables, NZ variables

1.0 1.0 1.0 1.0

The GFFUDG(NZ) are fudge factors that were, early in the code development, set not equal to unity and used in the wall friction calculations. Improvements in the friction modelling made it unnecessary to use non-unity fudge factors. All the GFFUDG values should now always be set to unity as they are above.

NSTWTE NXTWAL ITWALX

10 6 1

These variables are no longer used; however, it is recommended not to change them.

XTWALL(NXTWAL) FRACQW(NXTWAL), subscripted variables, NXTWAL lines with 2 variables in each line

-1000.000 1.000
1057.651 1.000
1068.923 1.000
1143.673 1.000
1330.363 1.000
10000.000 1.000

These variables are no longer used; however, it is recommended not to change them.

†RLTKE ITETKE NTETKE IDTKEI

3.27 0 1000 1

RLTKE is the relaxation length for turbulent kinetic energy (TKE) as a number of tube diameters. (See Ref. 1, p. 39.) This is a variable used in the code, proven through years of service and should be left unchanged. If ITETKE = 1, it turns on TKE diagnostic print-outs which are not needed at the present time; it is recommended to keep ITETKE = 0. NTETKE is a step number at which TKE diagnostics are printed out; it is not used if ITETKE = 0.

IDTKEI must be set to 1 to properly invoke the TKE calculations in the code.

NTTKE1 NTTKE2 NTTKE3

6721 18397 6723

These three variables are step numbers at which TKE diagnostics are printed out if ITETKE = 1; they are not used if ITETKE = 0. These diagnostics are not needed at the present time. (See also preceding paragraph.)

†IDTKE(NZ), subscripted variables, NZ variables

1 0 0 1

For a four zone calculation, these variables must be set to 1 0 0 1, as above, to properly invoke the TKE calculations.

†VIS(NZ,1) VIS(NZ,2) FPR(NZ) NFR(NZ), doubly and singly subscripted variables, NZ lines with four variables per line

3.045E-6 .6898 .002 0
2.3615E-6 .75 .002 1
2.3615E-6 .75 .002 1
2.113E-6 .6593 .002 0

VIS(1,1), VIS(1,2), VIS(4,1) and VIS(4,2) are the low pressure viscosity coefficients for the powder gas and the gun working gas. (See discussion in Appendix D.) These values are used in the code calculations. For zones 2 and 3, VIS(NZ,1) and VIS(NZ,2) are merely space fillers for the read statement and are not used in the code. FPR(NZ) are not used in the current version of the code. NFR(NZ) switches between the friction calculations for gas (or gas/powder) and dense media zones and must be as given above. For calculations with hydrogen working gas, it is recommended not to change any of the above variables. For calculations with other working gases, VIS(4,1) and VIS(4,2) must be changed.

†VIS(NZ,3) VIS(NZ,4) VIS(NZ,5) VIS(NZ,6), doubly subscripted variables, NZ lines with four variables per line

4.16E-5 .248 1.3318 2.225
4.16E-5 .248 1.3318 2.225
4.16E-5 .248 1.3318 2.225
7.1E-6 .0325 1.386 2.487

VIS(1,3), VIS(1,4), VIS(1,5), VIS(1,6) VIS(4,3), VIS(4,4), VIS(4,5) and VIS(4,6) are the coefficients of the high pressure corrections for the viscosity for the powder gas and the hydrogen. (See discussion in Appendix D.) These values are used in the code calculations. For zones 2 and 3, VIS(NZ,3), VIS(NZ,4), VIS(NZ,5) and VIS(NZ,6) are space fillers for the read statement and are not used in the code. For calculations with hydrogen working gas, it is recommended not to change any of the above variables. For calculations with other working gases, VIS(4,3), VIS(4,4), VIS(4,5) and VIS(4,6) must be changed. Table 1 shows the viscosity coefficients for various gases.

Table 1. Viscosity coefficients for various gases.

GAS	VIS(NZ,1) g/cm/s/[K**VIS(NZ,2)]	VIS(NZ,2)	VIS(NZ,3) g/cm/s	VIS(NZ,4) g/cm**3	VIS(NZ,5)	VIS(NZ,6)
Helium	3.1940E-06	0.7175	1.2750E-03	1	2.0418	2.0418
Hydrogen	2.1130E-06	0.6593	7.1000E-06	0.0325	1.386	2.487
Nitrogen	4.0988E-06	0.66028	2.0409E-05	0.18331	0.98794	2.32143
Argon	4.0193E-06	0.70387	3.8587E-03	1	1.98758	1.98758
Powder gas	3.0450E-06	0.6898	4.1600E-05	0.248	1.3318	2.225

The method of calculating the gas viscosities is discussed in some detail in Appendix D and is reviewed briefly here for the case of the powder gas. To get the viscosity of the gas mixture, the individual low pressure experimental gas viscosities are weighted by mole fractions and summed. We use a simple power law fit to this mixture viscosity versus temperature data. The data is taken from Ref. 38. The low pressure viscosity is given in Eqn. (1)

$$\mu_{lp} = \mathrm{VIS}(1,1)T^{VIS(1,2)} \tag{1}$$

where μ_{lp} is the viscosity at low pressure and T is the temperature. The high pressure correction to the viscosity is fit to experimental data as the sum of two different power law variations with gas density. The data is taken from Refs. 41 and 42. The high pressure viscosity correction is given in Eqn. (2).

$$\Delta\mu_{hp} = VIS(1,3)\left[\left(\frac{\rho}{VIS(1,4)}\right)^{VIS(1,5)} + \left(\frac{\rho}{VIS(1,4)}\right)^{VIS(1,6)}\right] \tag{2}$$

where $\Delta\mu_{hp}$ is the high pressure viscosity correction and ρ is the gas density. The final gas viscosity, μ, is given by

$$\mu = \mu_{lp} + \Delta\mu_{hp} \tag{3}$$

The values for VIS(1,1) through VIS(1,6) have been derived for Hercules HC-33FS powder as described in Appendix D. The powder gas composition given by Hercules for the HC-33FS powder is (in mole percentages):

CO 34.1%

H_2O 15.1%
CO_2 20.2%
N_2 11.9%
H_2 18.6%

Unless the composition of the user's powder gas is quite radically different from that given above, it is suggested the VIS(1,1) through VIS(1,6) values given in Table 1 could be used for the different powder and that this would result in only very minor errors.

†ECF(NZ+1) SYCF(NZ+1) RTCF(NZ+1), subscripted variables, NZ + 1 lines with three variables per line

8.6224E9 2.1E8 1.96850
2.069E12 3.449E9 1.96850
6.76510 3.135E8 1.96850
8.6224E9 2.1E8 1.96850
2.2935E10 3.02E8 0.35560

For these variables, the first four lines are for the four zones of the calculation and the last line is for the projectile. The ECFs are the moduli of elasticity (in dynes/cm^2) of the materials of the zones in question and of the projectile. The SYCFs are the yield strengths (in dynes/cm^2) of the materials of the zones in question and of the projectile. For the piston zones (zones 2 and 3) and the projectile (last line), the values given are used in the calculations. For zones 1 and 4, the ECFs and SYCFs are merely space fillers for the read statement and are not used in the code. RTCF(NZ+1) (in cm) must be set equal to the radius of the launch tube in cm. The remaining RTCF values are not used in the code. The values for ECF and SYCF given above in lines 2, 3 and 5 are for iron, epoxy matrix/steel shot and polycarbonate, respectively. If different materials for the piston or the projectile are used, the corresponding different values for ECF and SYCF must be used in place of those given above.

†NRPCF(NZ+1), subscripted variables, NZ + 1 variables

1 5 5 1 1

NRPCF(NZ+1) are the number of cells where the initial radius of the piston or projectile (RPCFI – see next group of variables) changes. If NRPCF = 1, the piston or projectile initial radius is the same for all cells. Values are given for the four zones in the present calculation followed by the value for the projectile. It is suggested that the NRPCFs for the powder/powder gas zone, the gun working gas zone and the projectile all be set to unity. The necessary values for NRPCF for the piston zones will be explained in the discussion of the next group of variables.

†NSRFCF(NZ+1,NRPCF(NZ+1)), RPCFI(NZ+1,NRPCF(NZ+1)), doubly subscripted

variables, NRPCF(1) + NRPCF(2) + … + NRPCF(NZ+1) rows with two variables per row

```
1   1.5      POW BR
1   1.9685   PIS 1
2   1.9685  PIS 1
3   1.9685   PIS 1
4   1.9685   PIS 1
9   1.9685   PIS 1
1   1.97100  PIS 2
6   1.95830  PIS 2
7   1.94750  PIS 2
18  1.95680  PIS 2
19  1.97100  PIS 2
1   1.5      H2GAS
1   .355600  BARR
```

These variables are used in the friction calculations for the piston and projectile. (The notations "POW BR", "PIS 1", etc., are to aid the data preparer and are not read by the READ1.f reading subroutine.) (See also earlier piston discussion in Sec. 4.10) Hence, the values of NSRFCF and RPCFI in line 1 (for zone 1 – powder/powder gas) and line 12 (for zone 4 – gun working gas) are merely space fillers for the read statement and are not used in the code. The remaining variables are used in the code calculations. The RPCFI values are in cm. For each zone of the piston, the initial piston radius is RPCFI(NZ,I) starting at cell number NSRFCF(NZ,I) and going up to cell number NSRFCF(NZ,I+1) - 1. This applies up to cell number NSRFCF(NZ,NRPCF(NZ)-1). Cells with numbers NSRFCF(NZ,NRPCF(NZ)) and upwards all have initial piston radii of RPCFI(NZ,NRPCF(NZ)). Thus, in the second (epoxy matrix/steel shot) piston zone (NZ = 3), five initial piston radii are given. The five values will apply in order, to cell numbers 2 – 5, 6, 7 – 17, 18 and 19 – 21. With these five values, we are simulating a piston section with larger diameter lands at either end and a smaller diameter shank between the lands. In the first (iron slug) piston zone, all the initial piston radii are the same. Thus, the piston in this zone is a simple cylinder without lands. The piston diameter in this zone is taken to be equal to the gun tube diameter. There is only one initial radius for the projectile. (The projectile is not divided into zones.) This value is given by RPCFI(NZ+1,NRPCF(NZ+1)). It is suggested that the NSRFCFs for the powder/powder gas zone, the gun working gas zone and the projectile all be set to unity.

It is very important to realize that the RPCFI values are only used for the calculation of the wall friction (and heat transfer) for the piston and the projectile. For the main Godunov CFD calculations, the piston weight and piston plastic always completely fill the gun bore. If the piston radius is not equal to the tube radius it may either be larger or smaller than the tube radius. Having the piston radius larger than the tube radius can be achieved by cooling the piston or projectile, slipping it into the corresponding tube and allowing it to warm up to room temperature and jam in the tube. The projectile can also simply be hammered into the launch tube. With the piston radius larger than the corresponding tube diameter, the code will model the increase in wall friction above that for the case where the piston radius is equal to the corresponding tube diameter (as discussed in Appendix

B1). This can be important in tending to restrain the initial motion of the piston and thus allowing higher powder gas pressures to be obtained with a corresponding more rapid burning of the powder.

The most important case where RPCFI can be less than corresponding tube diameter is the case, mentioned earlier, of a piston with two lands at either end which have initial radii equal to or greater than the corresponding tube diameter and a shank between the lands which has an initial diameter less than the corresponding tube diameter. The values of the NRPCFs, NSRFCFs and RPCFIs given in the previous table are for a case where the second piston component is of this type while the first piston component has a constant diameter of 2 x 1.9685 cm. For this case, the NC values are 32 12 22 40 for the four zones and the tube radii for the pump tube and the launch tube are 1.9685 and 0.3556 cm, respectively. Cells 2 to 5 are completely on the rear land of piston component 2, cell 6 covers part of the rear land and part of the shank, cells 7 to 17 are completely in the shank region, cell 18 covers part of the shank and part of the front land and cells 19 to 21 are completely on the front land. (Cells 1 and 22 are ghost cells.) The radii for the cells which straddle the shank and one of the lands are simply calculated proportionally to the fraction of the length of the cell which is occupied by the shank and the land. Thus, in this case, the lands are jammed into the pump tube, while the shank rides initially free of the pump tube, thus reducing the piston component 2 friction. Note that if the pressure in the piston component 2 shank becomes sufficiently high, the shank can deflect outwards to contact the tube wall and produce piston component 2 friction. Also, when piston component 2 is compressed into the high pressure coupling (HPC), in general, the shank of piston component 2 will contact the HPC wall and friction will occur. If piston component 2 is significantly deformed axially, the distributions of the initial diameters with the cells given above will no longer be correct. The main purpose of being able to model the lands and shank of piston component 2 is for the friction calculations during the long passage of the piston down the pump tube at relatively low pressures, which is modelled as described above. During this passage, the distributions of the initial piston component 2 radii given by the NRPCFs, NSRFCFs and RPCFIs are very nearly correct since the piston is only slightly distorted. Once piston component 2 is compressed into the high pressure coupling and/or reaches pressures above the yield strength of the plastic, piston component 2 has yielded and the initial piston component 2 diameters are no longer important. The values of the NRPCFs, NSRFCFs and RPCFIs discussed above are for certain piston radii, land and shank lengths, projectile radii, and piston zone cell counts. For different piston and projectile dimensions and cell counts, the variables must be changed accordingly.

In general, we have found that modelling plastic piston components as constant diameter slugs (that is, not modelling the lands and shank) was found to give very nearly as good results as modelling the piston lands and shank. Since it is somewhat easier to set up the constant diameter slug, this is what we have done most of the time in recent years. The discussion of the lands and shank given here was provided for the sake of completeness.

†DELRTP

.003

In the previously discussed friction calculations, if the initial piston diameter is less than (1-DELTRP) x (tube diameter), the piston friction is set to zero. It is strongly advised to keep DELTRP set to 0.003, this being a well proven value for this variable.

†POICF(NZ+1) ADFCF(NZ+1) ZMSCF(NZ+1), subscripted variables, NZ + 1 variables

.4 5.886 .130
.4000 1.625 0.0359
.4000 1.625 0.0359
.4 5.886 .130
.403 2.264 .050

These variables are used in the friction calculations for the piston and projectile. Hence, the values in line 1 (for zone 1 – powder/powder gas) and line 4 (for zone 4 – working gas) are merely space fillers for the read statement and are not used in the code. The remaining variables are used in the code. The POICFs are the Poisson's ratios for the materials in question. The values given above in lines 2, 3 and 5 are for polyethylene/epoxy and polycarbonate for the piston plastics and the projectile, respectively. Using the equations of Ref. 43, it can be shown that Poisson's ratio (ν) can be obtained from the longitudinal and shear sound speeds in the media in question (c_l and c_s, respectively). The relation is

$$\nu = \frac{(0.5c_l^2 - c_s^2)}{(c_l^2 - c_s^2)} \tag{4}$$

The required speeds of sound are given in Ref. 44, pp. 442 and 432 for polyethylene and polycarbonate, respectively.

The ADFCFs are the coefficients of the dynamic (varying with velocity) coefficient of friction for the material in question. The ZMSCFs are the static (and low velocity) coefficient of friction for the material in question. The static coefficient of friction is μ_s (= ZMSCF) and is a constant. The dynamic coefficient of friction is μ_d and is taken to vary as μ_d = ADFCF x $u^{-.4224}$, where u is the absolute velocity (in cm/sec) of the piston or projectile. From zero velocity up to the critical cross-over velocity between μ_s and μ_d, μ_s is used. At higher velocities where μ_d is less than μ_s, μ_d is used. Reference 45 gives friction coefficients for Nylon versus steel between velocities of 40 and 670 m/sec. Reference 46 has fit this data with a curve of the form μ_d = Const. x $u^{-.4}$ and scaled up the constant by the ratio of the static friction coefficients of Lexan and Nylon to produce, for Lexan, the

expression $\mu_d = 4.0 \times u^{-.4}$, where u is in ft/sec. With u in cm/sec, this expression becomes $\mu_d = 15.69 \times u^{-.4}$. We have performed our own fit to the data of Ref. 45 and obtained, for Nylon, $\mu_d = 8.377 \times u^{-.4224}$. We have chosen μ_s (Nylon) = 0.185, based on a number of values from handbooks and suppliers of Nylon. This value is lower than the value of μ_d from Ref. 45 at the lowest velocity. Thus, this one data point of Ref. 45 is cut off in our friction model for Nylon.

For other materials, such as polyethylene and Lexan, we have followed the lead of Ref. 45 and scaled the friction coefficients of nylon either upwards or downwards. For polyethylene, we have scaled the friction coefficients using $\mu_s = 0.10$ from Ref. 47. Thus, for polyethylene, we have started with $\mu_s = 0.100$ and $\mu_d = 4.528 \times u^{-.4224}$. After a number of tuning sequences, we finally arrived at lower values for polyethylene, $\mu_s = 0.0359$ and $\mu_d = 1.625 \times u^{-.4224}$. We have found that the friction coefficients for polyethylene also work well for epoxy. For Lexan, there are a number of choices for μ_s. Reference 48 gives μ_s(Lexan) = 0.23. One handbook gives $\mu_s = 0.31$. A simple sliding test made on the office desk gives $\mu_s = 0.34$. We had initially chosen a somewhat higher value, $\mu_s = 0.40$. When the dynamic coefficient of friction is scaled to $\mu_s = 0.40$, this gives $\mu_d = 18.11 \times u^{-.4224}$. These values were found to produce maximum projectile base pressures which were, in some cases, 2 to 3 times larger than those measured experimentally using a microwave technique (Ref. 37c). Large reductions in the friction coefficients (to $\mu_s = 0.050$ and $\mu_d = 2.264 \times u^{-.4224}$) were necessary to produce good agreement between the CFD and experimental maximum projectile base pressures. With the optimized friction coefficients, for 27 pairs of data points, 2/3 of the differences were within ±20%. A first suggestion would be to start with the values for polyethylene and Lexan given in this paragraph, but there certainly is a considerable degree of freedom for the user as to which static coefficients of friction to use to scale the dynamic friction coefficients. Should new data at higher velocities than those of the experiments of Ref. 45 become available, a new correlation of friction coefficient versus velocity should likely be developed.

"Tuning" of the code to match the powder pressure history and the piston velocity involves adjusting the piston friction coefficients and the powder burn rate to achieve a good match between CFD and experiment. Tuning is discussed further in Sec. 8 and in Ref. 1, pp. 21-23. If projectile maximum base pressures are available, the projectile friction coefficients can be tuned to match these pressures between theory and experiment. Otherwise, tuning of the projectile friction coefficients can be done with muzzle velocity. Tuning of the friction coefficients and the powder burn rate should be done for a well established, repeatable gun operating condition. Once this is done, it should not be necessary to "re-tune" the code for other firing conditions as long as the same powder and same piston material is used. If one is using a polyethylene or epoxy piston, for a new gun, it is suggested to start working with the code with $\mu_s = 0.0359$ and $\mu_d = 1.625 \times u^{-.4224}$ for polyethylene/epoxy. If one is using a Lexan projectile, it is suggested to start working with the code with $\mu_s = 0.050$ and $\mu_d = 2.264 \times u^{-.4224}$ for Lexan. For other piston and/or projectile materials, the user must develop their own friction coefficients.

TAUYCG(NZ+1), NTAUYG(NZ+1), subscripted variables, NZ + 1 variables

0. 0
1.809E8 1
0. 0
0. 0
0. 0

There are five pairs of values, four for the four zones and one for the projectile. The 0. 0 pairs of values are dummy variables and only the remaining pair of values is active. These (active) variables are only used for the case of a metal slug piston section which is surrounded by a plastic sleeve, which is the case for zone 2 in the above example. For this zone, 1.809E8 dynes/cm^2 is the maximum shear stress of the sleeve and "1" indicates that to calculate the friction drag on the sleeved part of the piston, this value is to be used instead of the maximum shear stress of the underlying metal slug. See also Appendix B1.

We treat the next four lines of variables together.

MPIFD NZPIFD NCPIFD MPRFD

5250 2 12 10991

TW1 TW2 TW3 NWS NWM NWNO

1000.00 1000.00 1000.00 1 0 0

NW1 NW2 NW3 NW4 NW5 NW6 NWN NWSKIP IPRWNT

761 1711 2000 2000 2000 2000 2 1300 3

†IWH IWHZ IWHC

1 1 11

All of these variables are associated with the printing out of diagnostics that are no longer needed. The diagnostics will continue to be printed out, however, in the output files ONED1OW, ONED1OH and PISFRICDIAGS. It is highly recommended not to change any of these variables. One of these variables, IWH, must be set to unity to enable the print out of diagnostics which should be useful to the user and will be discussed in connection with the following next two lines of variables.

†IWHH

5

IWHH is the number of cells for which history files will be created. There are enough output files created so that IWHH can be set up to 10.

†IWHHZ(IWHH) IWHHC(IWHH)), subscripted variables, IWHH lines with 2 variables per line

1 2
1 31
2 11
4 2
4 39

The IWHHZs and IWHHCs are the zone numbers and cell numbers, respectively, of the cells for which history files will be created. The names of the history files are PLOTH1, PLOTH2, etc. up to PLOTH10 if IWHH = 10. Entries will be made into the history files once every 10 timesteps. The values entered are the values for the timestep in question after both the predictor and corrector calculations of the CFD method have been made. For the IWHHZ and IWHHC values given above, the first history file will be file PLOTH1 and will be for zone 1 (powder/powder gas zone), cell 31. Similarly, the last history file will be file PLOTH5 and will be for zone 4 (hydrogen zone), cell 39. It is up to the user to choose the number of history files and the zones and cells of interest. The variables read to the history files and their units are discussed in Appendix J.

†NPL1 NPL2 NPL3 NPRDIA NPLSTE

18151 18221 18271 3 1

NPRDIA is no longer used in the code, but it is recommended to keep it set to 3 as a safety measure. The remaining four variables are used in connection with creating the 3 snapshot files of the solution. If NPLSTE = 0, the snapshot files are created in connection with particular velocities which the piston passes as it slows down. In this connection, see the earlier discussion of the variables UPISTW and RDELTT. If NPLSTE = 1, this method is not used to determine when the snapshots are taken; rather the snapshots are taken at steps NPL1, NPL2 and NPL3. The snapshot files are PLOT1, PLOT2 and PLOT3. It is up to the user to choose the method of creating the snapshots files and what piston velocities and time intervals to choose or, for the NPLSTE = 1 case, at what timesteps to create the snapshot files. The variables read to the snapshot files and their units are discussed in Appendix J.

†NPLOTX

328

NPLOTX is the number of pressure history files to be processed at fixed locations in the gun. The first five of these are directly used to make pressure history files. The remaining pressure history profiles (numbers six to NPLOTX) are processed to create profiles of maximum shot pressures and gun tube burst pressures. The maximum shot pressure profile is valid along the entire length of the gun, but the gun tube burst pressure profile is only valid in the HPC.

†IBLANK(5), subscripted variable, 5 variables

0 0 0 0 0

The IBLANKs are used in connection with the comparison of the CFD pressure histories with experimental values. It is assumed that the pressure transducer diaphragm is recessed, at least slightly, so that if the piston passes over the transducer, it would not see the pressure in the plastic of the piston. In this case, it is assumed that the pressure transducer would read zero pressure. Hence, we have options in creating the pressure histories to set all pressures at times when the dense media zones are passing over the x-position (i.e. position along the gun) in question to zero. If IBLANK for the pressure history file in question is set to 1, the pressure under these conditions in the history file will be set to zero if, also, NPLAST (see discussion below) for the dense media zones are set to zero.

†XXPLOT(NPLOTX) NVXPLT(NPLOTX), subscripted variables, NPLOTX lines with two variables per line

```
10.0     1
1000.0   1
1066.0   1
1075.0   1
1082.0   1
 0.400000E+01     1
 0.750000E+01     1
 0.110000E+02     1
      ..          ..
      ..          ..
      ..          ..
 0.138400E+04     1
 0.138700E+04     1
 0.139000E+04     1    (NPLOTX lines total)
```

The first five XXPLOTs are the positions along the gun, in cm, where the pressure history files will be created. The remaining XXPLOTs are the x-locations at which maximum pressures are calculated in order to construct a profile of maximum pressures along the

length of the gun. Along with the maximum pressures are calculated the gun tube burst pressures, which are, however only valid within the HPC. The NVXPLTs are not used in the current version of the code, but it is recommended to keep them all set to unity as a safety measure. The pressure history files are PLOTX1, PLOTX2, … up to PLOTX5. It is up to the user to choose the locations of these files along the gun and which x-locations will be used to construct the maximum shot pressure and the gun tube burst pressure profiles. For the latter, in the case given above, 323 x-locations were chosen as follows

x = 40 to 1060 cm at a spacing of 10 cm
x = 1060 to 1090 cm at a spacing of 0.25 cm
x = 1090 to 1390 cm at a spacing of 3 cm

The variables read to the history files and their units are discussed in Appendix J. The maximum pressure profile, PRESSVSX, is in the form of a table XXPLOT, PMAXX, PBURST, ACONE, DCONE where:

XXPLOT are the x-positions along the gun
PMAXX are the maximum pressures
PBURST are the gun tube burst pressures
ACONE are the inside gun tube areas
DCONE are the gun tube inside diameters

†NPLAST(NZ), subscripted variable, NZ variables

0 1 1 0

NPLAST should be set to 1 for the dense media (piston plastic) zone and to zero for the powder/powder gas and hydrogen zones. Then, if IBLANK for the pressure history in question is equal to 1, the pressures at the x-position in question will be set to zero when the dense media zone passes over that x-position. If it is wished to examine a pressure history without setting the pressures to zero for the passage of the dense media zone, one simply sets the IBLANK value for the history in question to zero.

We discuss the next two lines of variables together.

NSFRI1 NSFRI2 NSFRI3 NSFRI4

41 401 4001 11881

NZFRI1 NCFRI1 NZFRI2 NCFRI2

1 8 3 27

All of these variables are associated with the printing out of diagnostics that are no longer needed. The diagnostics will continue to be printed out, however, in the output file FRICDIAGS. It is highly recommended not to change any of these variables.

ONED1DE.DAT

†RU DTECTA NTABR IE4TTT NTABRS

0.83144E+08 100.0 0 1 1

RU is the universal gas constant in erg/g-mole/K. DTECTA is the temperature interval, in K, in certain of the internal energy tables for certain media. DTECTA is not used in the current version of the code, but is suggested to leave it set to 100.0 to avoid the risk of code failure. NTABR controls the reading in of certain equation of state (EOS) data and must be set to zero. IE4TTT controls the limiting of the minimum negative pressure for the dense media (e.g. , for the piston plastic and the projectile) and must be set to 1. The minimum negative pressure is set to the negative of the yield strength of the media in question. This point will be discussed further at a later point in connection with the variables PLIMOO and PLIMO2. NTABRS controls the reading in of certain EOS data and must be set to 1.

†NTEOS(NZ) AA(NZ) RO(NZ) ZN(NZ), subscripted variables, NZ rows with 4 variables per row

8 .248935E+11 1.10731 4.31827
1 3.697E10 1.02613 3.30346
1 3.697E10 1.02613 3.30346
9 6.12E8 0.073332 4.5

NTEOS(I) determines the type of equation of state to be used for the media of zone I. If zone 1 is a powder/powder gas zone (as it is in the majority of the cases studied), NTEOS(1) must be set to 8. If zone 1 is a H_2, He, Ar or N_2 zone, NTEOS(1) must be set to 9 (for H_2) or 5 (for the remaining gases). For the dense media piston zone(s), NTEOS must be set to 1. In the present version of the code, which allows for the ablation of the steel wall material and the incorporation of the ablated wall material into the working gas, NTEOS(working gas zone) must be set to 9 if the working gas is hydrogen and to 5 if the working gas is helium, nitrogen or argon. For zones with NTEOS = 5, AA, RO and ZN are constants in the Zel'dovich-Raizer equation of state (see Appendix A) used for the gas zones. Otherwise, the values of AA, RO and ZN listed above are place holders for the read statement and are not used in the code. It is suggested to leave these variables as given above, however, to avoid the chance of code failure. AA, RO and ZN for the various media are given in section 2.1, Table 1.

The next three blocks of four lines each are treated together.

ROZZX(NZ) ZNZZX(NZ) ZMZZX(NZ) AA1ZZX(NZ) AA2ZZX(NZ), subscripted variables, NZ rows with 5 variables per row

0.0 0.0 0.0 0.0 0.0
7.9474 3.6 6.0 2.646E11 5.292E10
1.1876 3.6 6.0 1.920E10 3.84E9
0.0 0.0 0.0 0.0 0.0

Corresponding Appendix B variables: ρ_o, n, m, A_1,A_2

T2CXN1(NZ) TO T2CXN4(NZ), subscripted variables, NZ rows with 4 variables per row

0.0 0.0 0.0 0.0
9.649E-3 125. 5.370E6 6.71E8
6.320E-3 200. 2.000E7 4.00E9
0.0 0.0 0.0 0.0

Corresponding Appendix B variables: T2CXN1, T2CXN2, T2CXN3, T2CXN4

GRZZ1X(NZ) GRZZ2X(NZ), subscripted variables, NZ rows with 2 variables per row

0.0 0.0
2.613 -.0625
0.8 0.0
0.0 0.0

Corresponding Appendix B variables: G_1, G_2

These are constants in the version of the dense media Zeldovich-Raizer (ZR) equation of state used for piston materials (see Appendix B). Hence, the values given in lines 1 and 4 of each block are merely dummy variable place holders. For lines 2 and 3 of each block, the values given above are the actual constants in the ZR EOS fits to the iron slug and epoxy matrix materials of the two parts of the piston. The constants for 4 different piston materials are given in Tables 1 and 2 in Appendix B.

ZM1PIS(NZ), ZM2PIS(NZ), ZR2PIS(NZ), subscripted variables, NZ rows with 3 variables per row

0.0 0.0 0.0
1.0 0.0 1.0
.074275 .925725 7.856
0.0 0.0 0.0

These constants are used for piston materials which consist of a plastic matrix loaded with metal shot. Hence, the values given in lines 1 and 4 of this block are merely dummy variable place holders. For line 3 of this block, the values given above are:

ZM1PIS(3) - mass fraction of matrix
ZM2PIS(3) - mass fraction of metal shot
ZR2PIS(3) - density of metal shot

For line 2 of this block, the values given above are for a piston section which consists of a "matrix" of solid iron with no shot loading.

We treat the next two lines of variables together.

RADJ, EADJ, NFINE, MMMX

.0 .0 16000 1

CKLUE4

1.250

These variables are no longer used in the program. It is strongly suggested to leave the values unchanged.

†ZMW(NZ,NCOM(NZ)) G(NZ,NCOM(NZ)) BCO(NZ,NCOM(NZ)) BCOJ(NZ,NCOM(NZ)) NTABE(NZ,NCOM(NZ)), doubly subscripted variables, NCOM(1) + NCOM(2) + …. + NCOM(NZ) lines, 5 variables per line.

```
23.788     1.24560  0.96432  0.0  1
23.788     1.24560  0.96432  0.0  1
13.13310   1.20000  0.90000  0.0  1
13.13310   1.20000  0.90000  0.0   1
2.0        1.40000  0.90000  0.0  1
2.0        1.40000  0.90000  0.0  1
```

There are two lines of entries for the first zone because there are two components (powder and powder gas) in the first zone. For the second and third zones, there is only one line of entries per zone, since there is only one component per zone. For the fourth zone, there are again two lines of entries because there are two components (gun working gas and ablated metal from the tube wall) in this zone. The doubling of the lines for zones one and four is historical and is not really necessary at this point, but must be kept in place because of the formulation of the relevant variables and the read statement.

The ZMW values are molecular weights in grams/gram mole. For the powder/powder gas zone, these are active variables in the code. For the piston zones, the ZMW values are

merely space fillers and are not used in the code. For the gun working gas zone (zone 4) , ZMW is an active variable for H_2, He, N_2 and Ar working gases, except when the working gas is H_2 and NTEOS = 9 for the working gas zone. The ZMWs for the working gas zones are just equal to the molecular weights of the gases in these zones. The ZMW for the powder/powder gas zone (zone 1) is taken from Ref. 25 for IMR/Dupont gunpowder gas.

The G values are specific heat ratios of the gases in question. The Gs for zone 1 are taken from Ref. 25 for IMR/Dupont gunpowder gas. The G values for zones 2 and 3 are again space fillers needed to accommodate the read statement and are not used in the current version of the code. For the gun working gas zone (zone 4), G is an active variable for H_2, He, N_2 and Ar working gases, except when the working gas is H_2 and NTEOS = 9 for the working gas zone.

The BCO values are the molecular volumes in cm^3/g. The BCOs for zone 1 are taken from Ref. 26 for IMR/Dupont gunpowder gas. The remaining BCO values are again space fillers needed to accommodate the read statement and are not used in the current version of the code. It is suggested, however, that the BCO values for these remaining zones not be changed. The BCOJ and NTABE variables are not used in the current version of the code. It is suggested, however, that these variables also not be changed. The values of ZMW, G and BCO in the first two lines given above are for IMR/DuPont gunpowder. For other gunpowders, different values of these variables would have to be inserted.

†PLIBBB(NZ) PLIMOO(NZ) TOBBB(NZ) DEBBB(NZ) R1SOL(NZ) E1SOL(NZ) TNSSS(NZ), subscripted variables, NZ lines with 7 variables per line

```
0.0  0.0000E+00  0.0  0.0   1.580  .3148E+10  1.0
0.0  -.3449E+10  0.0  0.0   1.000  .1000E+01  1.0
0.0  -.3140E+09  0.0  0.0   1.000  .1000E+01  1.0
0.0  0.0000E+00  0.0  0.0   6.963  .1000E+01  1.0
```

The PLIBBB values are not used in the current version of the code. The PLIMOO variable are limiting negative pressures for the dense media piston zones (zones 2 and 3). For these zones, PLIMOO is a live variable in the code. The PLIMOO values for the first and fourth zones are merely place holders for the read statement and are not used in the current version of the code. The PLIMOO variables for zones 2 and 3 are set to the negatives of the respective yield strengths (in $dynes/cm^2$) for the materials in question. Thus PLIMOO(2) = -SYCF(2) and PLIMOO(3) = -SYCF(3) where the SYCF values have been discussed in a previous section. The TOBBB and DEBBB variables are not used for zones 1 and 3 and are merely place holders for the read statement. For the piston zone, these variables do exist in the relevant equations of state, but must be set to zero for the current version of the code.

The R1SOL variables are live variables for zones 1 and 4, but merely place holders for zones 2 and 3. The units of the R1SOLs are g/cm^3. For the powder/powder gas zone, R1SOL is the density of an unburned gunpowder grain (not equal to the powder loading density). The density shown above (R1SOL(1)) is for IMR/DuPont powder and was taken to be equal to that for the Navy M6+2 powder,[16] since these two powders have very similar

compositions. The value of R1SOL for zone 4 is set to the density of molten gun tube wall material (usually steel) just above the melting point. This value is used as an approximate steel density to allow the calculation of approximate working gas densities solely to judge whether strong waves are present or not. The strong wave detection scheme for density variations is very similar to that described for other variables in Ref. 1, pp. 8 – 15. For the actual code CFD flux calculations, the correct value of the steel density is always used. The value of molten steel density used for R1SOL(1) is the value of RWSTE in the wall erosion data file WAHE1D.DAT just above the steel melting point. This value is 6.963 gm/cm^3. E1SOL for zone 1 (powder/powder gas zone) is the internal energy of the unburned powder (in erg/gm). The remaining E1SOL values are merely place holders for the read statement. The value of E1SOL for gunpowder was estimated from the average specific heat of nitroguanidine of 0.2555 calories/gm/K. Assuming that the powder is loaded at room temperature = 70 degrees F = 294.4 K, the internal energy of the unburned powder is estimated to be equal to 0.2555 x 4.186 x 10^7 x 294.4 = 0.3144 x 10^{10} erg/gm. This is a rough estimate.

The TNSSS value for zone 4 is a live code variable and must be set to 1.0. The remaining TNSSS values are merely place holders for the read statement. It is suggested to keep the values of any of the variables in PLIBBB – TNSSS set discussed above (or anywhere else in this manual) which are not used in the current version of the code (or are merely place holders) equal to the values given herein. The values of R1SOL(1) given above is estimated for IMR/DuPont gunpowder. If another powder is used, a different value for R1SOL(1) would have to be used. As mentioned previously, E1SOL(1) was estimated for the gunpowder from specific heat data for nitroguanidine. The code user may be able to come up with a better value for E1SOL(1) for his gunpowder. The PLIMOO(2) and PLIMOO(3) values given above is for iron and epoxy. If different materials are used for the piston, different values would have to be inserted for these variables.

†PLIBB2(NZ) PLIMO2(NZ) C2LIMO(NZ) C2LIM2(NZ) subscripted variables, NZ lines with 4 variables per line

```
0.0  0.0000E+00  0.2250E+11  0.2475E+11
0.0  -2.759E+09   1.7540E+11  1.9290E+11
0.0  -2.512E+08   0.2250E+11  0.2475E+11
0.0  0.0000E+00   0.2250E+11  0.2475E+11
```

The PLIBB2 values are not used in the current version of the code. The PLIMO2 variables are limiting negative pressure for the piston zones (zones 2 and 3). For these zones, these variables are live variables in the code. The PLIMO2 values for the first and fourth zones are merely place holders for the read statement and are not used in the current version of the code. The PLIMO2 variables for zones 2 and 3 are set to 0.8 times the negatives of the yield strengths (in dynes/cm^2) for the materials in question. Thus PLIMO2(2) = -0.8 x SYCF(2), and likewise for PLIMO2(3), where the SYCF values have been discussed in a previous section. For a dense media zone, the use of PLIMOO = -SYCF and PLIMO2 = -0.8 x SYCF assures a smooth, blended change from a decreasing negative pressure to a constant, limiting negative pressure in the "plastic" regime. For other piston materials, it is suggested to use PLIMOO = -SYCF and PLIMO2 = -0.8 x SYCF also.

The C2LIMO and C2LIM2 variables are limiting values for the speed of sound squared (in cm^2/sec^2) for the piston zones 2 and 3. For these zones, these variables are live variables in the code. The C2LIMO and C2LIM2 values for the first and fourth zones are merely place holders for the read statement and are not used in the current version of the code. C2LIMO and C2LIM2 are used for the piston zones, to prevent the sound speed from the equation of state from dropping to extremely low values as the dense media is highly extended with large strains in the "plastic" zone. The use of C2LIMO and C2LIM2 is a "fix" which has been found to be highly effective in controlling code instabilities in regions of highly extended materials. C2LIMO is the absolute minimum allowed value of the speed of sound squared and C2LIM2 has been set to 1.1 x C2LIMO by extensive testing to allow a smooth blend between the region of the equation of state where the speed of sound is limited and the region of the equation of state where the speed of sound is calculated by the normal means. C2LIMO corresponds to a sound speed of 4.18 km/s.

The formulas which we are about to present are given in or can be obtained from formulas given in Ref. 49. The sound speed which we use for dense media is the sound speed based on the bulk modulus, K, and is given by

$$c_0^2 = \frac{K}{\rho} \tag{5}$$

where c_o is the "bulk modulus" speed of sound and ρ is the density. The bulk modulus can be obtained from the Young's modulus of elasticity, E, using the following equation

$$K = \frac{E}{3(1-2\nu)} \tag{6}$$

where ν is Poisson's ratio. The "bulk modulus" speed of sound can be related to the longitudinal wave speed of sound (c_l) and the shear wave speed of sound (c_s) as follows.

$$c_0^2 = c_l^2 - \frac{4}{3}c_s^2 \tag{7}$$

From Ref. 44, p. 442, for high density polyethylene, c_l = 2.46 km/sec and c_s = 1.01 km/sec. From Eqn. (7), this leads to c_0^2 = 4.6914 x 10^{10} cm^2/sec^2, which is <u>not</u> the value used for C2LIMO(2) above. The value of ν corresponding to these values of c_l and c_s is, from Eqns. (5) - (7) above, equal to 0.3986. Two other values for c_0^2 were obtained as follows. From Ref. 50, for UHMW polyethylene, the Young's modulus (E) is given as 100 – 150 ksi (kilopounds per square inch). Taking a mean value for E of 125 ksi = 0.8622 x 10^{10} dynes/cm, assuming the density given in Ref. 44, p. 442, and taking ν = 0.40, yields c_0^2 = 1.5063 x 10^{10} cm^2/sec^2. For high speed (~700 m/sec) calculations of a polyethylene piston motion, Ref. 47 used an E value of 1.500 x 10^{10} $dynes/cm^2$. Assuming the density value given in Ref. 47, 0.95 gr/cm^3, and taking ν = 0.40, yields c_0^2 = 2.6315 x 10^{10} cm^2/sec^2. For C2LIMO(2), we have chosen a value of 2.2500 x 10^{10} cm^2/sec^2, between the two latter values calculated, but considerably less than the value calculated from the data of Ref. 44, p. 442. Obviously, there is some freedom of choice for the value of C2LIMO(2).

The values discussed above for C2LIMO and C2LIM2 have worked very well for a

polyethylene piston. If this material is unchanged, one may continue to use the values given above. If other materials are used for the piston, different values for these variables must be inserted in the ONED1DE.DAT input file. Table 1 shows the values of C2LIMO (= c_0^2) for three different piston materials. For the iron and the polycarbonate, values in the third column are used. For the epoxy, which is shot loaded in the example case, the value in the fourth column is used. If the epoxy were not shot loaded, the value in the third column would be used.

Table 1. Values of C2LIMO (= c_0^2) for three different piston materials.

Material	c_o^2 from LASL shock velocities $(km/s)^2$	c_o^2 from modulus (E) and density $(km/s)^2$	c_o^2 from modulus (E) and density with shot correction $(km/s)^2$
Epon 828 epoxy	5.123×10^{10}	3.305×10^{10}	2.306×10^{10}
Iron	21.1×10^{10}	22.0×10^{10}	----
Polycarbonate	3.72×10^{10}	3.33×10^{10}	----

Variables for fits to hydrogen equation of state

```
0.130000E-04     0.279999E+01     0.150000E+11     0.199999E+13     0.135935E+01
0.113012E+01   41   41

 0.170485E+04   0.606330E-13
-0.814907E-09   0.000000E+00
 0.252359E+05  -0.606330E-13
 0.749532E+05   0.138666E+03
 0.283560E+03   0.121266E-12
-0.698492E-09   0.000000E+00
 0.405228E+04  -0.121266E-12

  **********      **********

 0.513800E+10   0.416380E+02
-0.796820E+11  -0.354166E+03
-0.171267E+10  -0.138793E+02
```

The first 8 variables are limiting values for certain variables and the ranges of the indexes for the following data to be read. (Note that in the computer input file, the first eight variables are all side by side, but on the paper here, three of these variables are "wrapped".) The following data comprises a two column set of values with roughly 19,000 lines of data. These are the coefficients of the fits to the hydrogen equation of state (EOS) data and must not be changed as long as one wants to continue to use the hydrogen EOS provided with the code. The formulation of the equation of state for pure hydrogen is discussed in Ref.

1, pp. 5 – 6. For the present version of the code, ablation of the wall material and incorporation of the ablated material (as molten or solidified metal droplets) into the hydrogen gas is modelled. With both hydrogen and metal in the "hydrogen" zone, the hydrogen EOS is taken to be that just discussed and an equation for solid and liquid metal was developed. This two phase EOS matches the pressure and temperature of the hydrogen and the ablated metal. Note that, as mentioned previously, the code can work with He, N_2 or Ar working gases, as well as with H_2 working gas.

†DDPOW(1) DPOW(1) ZNPOW(1) ECPOW(1), subscripted variables, but only the values for zone 1 are read in

0.06096 0.01524 1.0 .37674E+11

These variables characterize, in part, the gunpowder used in zone one. Most gunpowder grains are short circular cylinders with or without circular perforations parallel to the cylinder axis. Gunpowder grains exist with 0, 1, 7, 19 (and possibly more) perforations. DDPOW is the outside diameter of the powder grain, in cm. DPOW is the diameter of the perforation(s), in cm. ZNPOW is the number of perforations. These data were taken from Ref. 25 for IMR/DuPont IMR-4227 powder. ECPOW is the energy of combustion of the powder. This value is taken as the heat of explosion of IMR powder, given to be 3.7674 $x10^{10}$ erg/g in Ref. 24. The values of the variables DDPOW, DPOW, ZNPOW and ECPOW above are for IMR/DuPont IMR-4227 gunpowder. If other gunpowders are used, different values of the variables DDPOW, DPOW, ZNPOW and ECPOW would have to be used.

†APOW(1) BPOW(1) ZNXPOW(1) WPOW(1) ZLPOW(1), subscripted variables, but only the values for zone 1 are read in

0.00000E+00 0.60204E-06 0.80000 0.02286 0.05334

These variables also characterize, in part, the gunpowder used in zone one. The burning rate of many gunpowders is given as

$$r = a + bp^n, \tag{8}$$

where r is the burning rate, p is the pressure and a, b and n are constants. The burning rate constants a and b for powders are given in the original data sheets in various units, but we have converted them so that the final unit system is as follows. r and a are in cm/sec, p is in dynes/cm^2 and b is in (cm/sec)/[(dynes/cm^2)^n]. Values for a, b and n for IMR/DuPont powder are taken from Ref. 25. In Ref. 25, a is given to be zero, b is given as 0.27 (in/sec)/[(kilopounds/in^2)^n] and n is given as 0.8. Hence, for the input variables now being

discussed, we have taken APOW = a = 0, BPOW = b = 0.43324E-06 (cm/sec)/[(dynes/cm^2)^n] (making the necessary change of units) and ZNXPOW = n = 0.8. WPOW is the "web" of the powder grains. For a single perforation powder grain, the web is the initial distance between the external and internal burning surfaces (in cm). Thus, for the IMR/DuPont IMR-4227 powder, WPOW = (DDPOW – DPOW)/2 = 0.0090 in = 0.02286 cm. This value for the web is also given in Ref. 25. ZLPOW is the initial length of the powder grain, in cm. Reference 25 gives the length of the grains of the IMR/DuPont IMR-4227 powder as 0.021 in = 0.05334 cm. Note that the BPOW value in the input file is about 1.4 times that calculated directly from the data of Ref. 25. It is known from much experimental data that the powder burn rates in two stage light gas guns are different from those observed in more conventional military gun systems. The higher BPOW value in the input file resulted from "tuning" of the code to match the observed powder breech pressure histories. Tuning is discussed further in section 8.

Note that the value of WPOW initially read into the code is never actually used for powder burn calculations. In the initialization subroutines, WPOW is overwritten with a new value, calculated from the smaller of the two values given in Eqns. (9) and (10) below.

$$WPOW = \frac{DDPOW - ZNPOW^{.5}DPOW}{1 + ZNPOW^{.5}}, \tag{9}$$

$$WPOW = ZLPOW \tag{10}$$

†GLIM ZMAXDT BPOW2 EFFDET(NZ) The last variable is subscripted, but only the value for zone 1 is read in.

0.2937224 28. 5.1787E-7 .94849

These variables have to do with a gradated deterrent applied to the powder grain. (See section 2.3 and Appendix C for more details.) There, we have introduced the variable g, the fraction of the total burn distance (WPOW) burned. g = 0 before burning starts and g = 1 at all burnt. The above variables in the input file ONED1DE.DAT are for a calculation of powder burn made with an assumed gradated distribution of dibutylphthalate (DBP) deterrent. We take the surface %DBP to be 28 and also assume that the %DBP drops, linearly with g, to zero at the new surface when half the grain is consumed. With these assumptions, the %DBP is, as follows:

$$If\ g \le GLIM,\ \ \%DBP = ZMAXDT(1 - g/GLIM) \tag{11}$$

$$If\ g > GLIM,\ \ \%DBP = 0. \tag{12}$$

From the %DBP, the burn rate (r, in cm/s), can be calculated, following the analysis of Appendix C, as

$$r = 1.6039\ x\ 10^{-3}(EFFDET)^{\%DBP}p^{ZNXPOW} \tag{13}$$

Equations (11) - (13) here correspond to Eqns. (11) - (13) in Appendix C.

†NLDSW NGRSW(NZ) The last variable is subscripted, but only the value for zone 1 is read in.

0 0

These are two switches associated with the powder burn. NLDSW has to do with the two values of WPOW given by Eqns. (9) and (10). If WPOW from Eqn. (9) is the smaller of the two WPOW values, NLDSW must be set to 0. If not, NLDSW must be set to 1. If NGRSW = 0, the deterrent is assumed to be uniformly distributed in the powder grain, GLIM, ZMAXDT, BPOW2 EFFDET(NZ) are not used and the prefactor, b, in the burn rate equation [Eqn. (8)] is given by BPOW. If NGRSW = 1, the gradated deterrent analysis presented above is used.

NSPOW NZPOW NCPOW NPCPOW(NZ)

4500 1 10 1

These variables are not used in the current version of the code.

WAHE1D.DAT

Note that this file is for gun steel (e.g. 4340 steel). Files exist for rhenium (WAHE1DRERE.DAT) and tantalum (WAHE1DTATA.DAT), which have much higher thermal properties than steel. With the refractory metals, gun erosion is much reduced and the consequent loading down of the gun working gas with eroded gun metal is also much reduced. This results in CFD-predicted muzzle velocity increases of up to 2 to 4 km/s. Tantalum has better ductility and a lower Young's modulus than rhenium - these properties are very important when the refractory metals are used as coatings over a gun steel back up tube. See Refs. 22 and 23 for discussions of rhenium and tantalum liners.

†RSTEEL QWSTEE ITESST

7.8 0.178E+12 1

RSTEEL is the barrel wall density at room temperature, g/cm^3
QWSTEE and ITESST are dummy variables

†TSMELT

1723.

TSMELT is the melting point of the barrel wall material, K

†HMELT

2.8932E9

HMELT is the heat of fusion of the barrel wall material, erg/g

†TSTEEL ZKSTEE HSTEEL - subscripted variables, 38 lines, N = 1 to 38

0.000000E+00 0.262000E+07 0.000000E+00
0.500000E+02 0.262000E+07 0.240650E+09
****** ******* *******
****** ******* *******
0.185000E+04 0.313000E+07 0.117848E+11

TSTEEL(N) is the temperature of the barrel wall material, K
ZKSTEE(N) is the thermal conductivity of the barrel wall material at TSTEEL(N), erg/cm/s/K
HSTEEL(N) is the internal energy of the barrel wall material at TSTEEL(N), erg/g

†HRSTEE TRSTEE - subscripted variables, 59 lines, N = 1 to 59

0.000000E+00 0.000000E+00
0.250000E+09 0.519427E+02
****** *******
****** *******
0.145000E+11 0.227193E+04

HRSTEE(N) is the internal energy of the barrel wall material, erg/g
TRSTEE(N) is the temperature of the barrel wall material at HRSTEE(N), K

†TSTEEI NXSTEE NYSTEE DYSTE1 RDYSTE

300. 400 18 .001170 1.10

TSTEEI is the barrel wall initial temperature, K
NXSTEE is the number of x positions along the barrel for which erosion is calculated
NYSTEE is the number of cells in the (y-) direction normal into the barrel wall, for the

purpose of unsteady heat conduction calculations

DYSTE1 is the y-direction depth of the first barrel wall cell, cm

RDYSTE is the ratio of the depths of successive cells in the y-direction = $\Delta y3/\Delta y2 = \Delta y4/\Delta y3$, etc.

N. B: the cell with a y-number of 1 is a "ghost" cell, which has no physical significance; the first real cell within the metal of the barrel wall has a y-number of 2.

†XSTEEL - subscripted variable, 400 lines, N = 1, 400

-0.100000E+03
-0.960000E+02
-0.920000E+02
******
******
0.149200E+04
0.149600E+04

XSTEEL(N) are the x-positions along the barrel at which heat conduction and erosion calculations are done, cm

Note that the range of the XSTEEL values here is -100 to 1496 cm. This range MUST exceed the range of x-positions along the barrel within which the gun tube CFD is being performed. If not, the x-position interpellator will not work correctly. For our example CFD run, the latter range is from XB(1) = 0 cm to XMUZ(2) = 1430 cm, so we are OK.

†NCXST1 NCXST2 NCYST1 NCYST2

115 136 2 6

NCXST1 and NCXST2 are the x-position cell numbers (i.e., the indices I in XSTEEL(I)) at which profiles of temperature versus y-position (cm) are printed out in WAHE1OHA. (These temperatures are in the second and third columns of WAHE1OHA)

NCYST1 and NCYST2 are the y-position cell numbers at which profiles of temperature versus x-position (cm) are printed out in WAHE1OP. (These temperatures are in the fifth and sixth columns of WAHE1OP.) Note that the cell with NCYST1 (or NCYST2) equal to 1 would be "ghost" cell; to obtain information at the first real cell inside the barrel wall, one must set NCYST1 (or NCYST2) equal to 2.

†ZMWHYD ZMWSTE

2. 55.85

ZMWHYD is the molecular weight of the gun working gas, g/g-mole
ZMWSTE is the molecular weight of the barrel wall material, g/g-mole

†PHIBLT GBLOWT - subscripted variables, 116 lines, N = 1 to 116

0.000000E-01 0.100000E+01
0.200000E-01 0.101601E+01
****** *******
****** *******
0.230000E+01 0.198467E+00

PHIBLT(N) is the wall blowing parameter, but is not used, is a dummy variable
GBLOWT(N) is a ratio used in the calculation of the reduction of skin friction due to wall blowing; is used in the "FRICTION.f" subroutine

†TSTEEL HWSTE - subscripted variables, 71 lines, N = 1 to 71

0.000000E+00 0.000000E+00
0.500000E+02 0.240650E+09
****** *******
****** *******
0.350000E+04 0.252957E+11

TSTEEL(N) is the temperature of the barrel wall material, but is not read in at this location in the input file and thus, is a dummy variable here
HWSTE(N) is the internal energy of the barrel wall material at TSTEEL(N), erg/g; this value of internal energy is different from HSTEEL(N) in that it includes data for the barrel wall material in both the solid and liquid state and is used in the two-component (hydrogen, barrel wall material) equation of state.

†TST RWSTE BWSTE - subscripted variables, 71 lines, N = 1 to 71

0.000000E+00 0.788214E+01 0.000000E+00
0.500000E+02 0.788190E+01 0.601166E-05
****** ******* *******
****** ******* *******
0.350000E+04 0.618995E+01 0.660082E-04

TST(N) is the temperature of the barrel wall material, but is not read in at this location in the input file and thus, is a dummy variable here
RWSTE(N) is the density of the barrel wall material at TST(N), g/cm^3; these density values vary with temperature and include data for solid and liquid barrel wall material used in the two-component (gun working gas, barrel wall material) equation of state.
BWSTE(N) is a dummy variable

†ESTLIQ ISTH2

0.138607E11 1

ESTLIQ in the internal energy of the just-melted barrel wall material, erg/g
ISTH2 must always be kept at 1 if the correct gun working gas-barrel wall material equation of state is to be invoked. The code will not work if this variable is not 1.

†INOHEA

0

If set to 1, will print out WALLH.f diagnostics which are not needed, suggest leave at 0.

Special Discussion of Selection of Equations of State (EOS)

Which equation of state (EOS) is invoked for each zone is controlled by the value of NTEOS for that zone. The EOSs are as follows:

NTEOS = 1. A Zeldovich-Raizer EOS for dense media, can be modified for a plastic matrix/steel shot piston or a metal piston inside a thin plastic sleeve.

NTEOS = 5. An Abel-type EOS with a compressible molecular volume - used for gases other than hydrogen.

NTEOS = 8. An Abel EOS for powder gas with incompressible unburned powder.

NTEOS = 9. A tabulated EOS for hydrogen with a compressible molecular volume combined with point molecule equilibrium calculations.

The various EOSs are described in sections 2.1 and 4.12 and Appendices A and B. Below are listed various options for EOSs that can be used for four zone and three zone gun modelling. Explanations are given regarding the modifications to the basic NTEOS = 1 EOS used to model a thin plastic sleeve around a metal slug piston and a plastic matrix/steel shot piston.

Four zone case

Zone 1 - Abel - NTEOS = 8
- H_2 - NTEOS = 9
- He, Ar, N_2 - NTEOS = 5

Zone 2 - Iron, Aluminum - NTEOS = 1†
Zone 3 - Polyethylene, Epoxy - NTEOS = 1
Zone 4 - H_2 - NTEOS = 9
- He, Ar, N_2 - NTEOS = 5

Three zone case

Zone 1 - Abel - NTEOS = 8
- H_2 - NTEOS = 9
- He, Ar, N_2 - NTEOS = 5

Zone 2 - Iron, Aluminum - NTEOS = 1†
- Polyethylene, Epoxy - NTEOS = 1
- Polyethylene/Steel shot, Epoxy/Steel shot - NTEOS = 1*

Zone 3 - H_2 - NTEOS = 9
- He, Ar, N_2 - NTEOS = 5

†Taken to be a metal slug surrounded by a thin polyethylene sleeve. For this zone, TAUYCG in ONED1DE.DAT must be set to 1.809E8 (for polyethylene) and NTAUYG in ONED1DE.DAT must be set to 1 to model the sleeve friction correctly.

* ZM1PIS(NZ), ZM2PIS(NZ) and ZR2PIS(NZ) in ONED1D.DAT for zone NZ must be correctly set to model the matrix plus shot piston correctly. For the example given in Appendix I, we have, for NZ = 3

ZM1PIS(3) - mass fraction of matrix = 0.074275
ZM2PIS(3) - mass fraction of metal shot = 0.925725
ZR2PIS(3) - density of metal shot = 7.856 (g/cm^3)

The user must insert the values for his own pistons. Note that these three variables can appear for a zone which is a solid plastic or metal piston. In such a case, they must be set, in order, to 1.0, 0.0 and 1.0. Such a piston consists of a "matrix" of solid metal or plastic with zero shot loading.

Most of the time, NTEOS for zone one is 8 (gunpowder plus powder gas). However,

by changing this NTEOS from 8 to 9 (for H_2) or from 8 to 5 (for He, Ar or N_2) one can operate the two-stage gun with a cold (or heated) gas first stage. Heating the first stage gas is accomplished by simply specifying an elevated initial temperature for the first stage gas instead of room temperature.

Appendix J

Details of Output Files

Below, we discuss all variables for all the useful output files. Appendix M contains at least one file of each type for the CFD run with the gun operating condition defined by the input files contained in Appendix L. The time history and snapshot files presented are necessarily truncated to show data at only 10 - 50 timesteps or 10 - 50 positions along the gun. The files are presented below in the order in which they occur in Appendix M and the variables in each file are presented below in the order in which they appear in the sample output files of Appendix M. It will be assumed in the following discussion that histories have been requested at the maximum number (5) of positions along the gun and for the maximum number (5) of cells. Also, it will be assumed that the maximum number of whisker gauge positions (5) has been specified. Also, it will be assumed that a profile of maximum pressures along the gun (PRESSVSX) has been requested, consisting of NPLOTX maximum pressures at locations XXPLOT along the gun. (See also earlier discussion of NPLOTX and XXPLOT and later discussion of PRESSVSX.)

FINALOUTP

This is the master or summary output file for the gun operating condition in question. The first line of output variables are:

Velocity, WG1-2 (cm/s)	Velocity, WG2-3 (cm/s)	Velocity, WG3-4 (cm/s)	Velocity, WG4-5 (cm/s)
x.xxxxxxxE+xx	x.xxxxxxxE+xx	x.xxxxxxxE+xx	x.xxxxxxxE+xx

These are the piston velocities calculated between whisker gauges 1 and 2, 2 and 3, etc., in cm/s. The whisker gauge locations are the input variables XWG in the input file ONED1D.DAT. x.xxxxxxxE+xx represents the actual numbers. Note that the actual output files do not have the labels as shown above, but rather only the numbers. The next line of output variables are:

Velocity, WG1-2 (ft/s)	Velocity, WG2-3 (ft/s)	Velocity, WG3-4 (ft/s)	Velocity, WG4-5 (ft/s)
x.xxxxxxxE+xx	x.xxxxxxxE+xx	x.xxxxxxxE+xx	x.xxxxxxxE+xx

These are exactly the same piston velocities, but now given in ft/s.

The next output variable is:

Muzzle velocity
(cm/s)

X.XXXXXXE+XX

This is the projectile muzzle velocity in cm/s. It is followed by:

Muzzle velocity
(ft/s)

X.XXXXXXE+XX

This is the muzzle velocity in ft/s.

The next line of output variables is:

Maximum pressure Zone n, Cell n ($dyne/cm^2$)	Maximum pressure Zone n, Cell n ($dyne/cm^2$)	Maximum pressure Zone n, Cell n ($dyne/cm^2$)	Maximum pressure Zone n, Cell n ($dyne/cm^2$)	Maximum pressure Zone n, Cell n ($dyne/cm^2$)
X.XXXXXXE+XX	X.XXXXXXE+XX	X.XXXXXXE+XX	X.XXXXXXE+XX	X.XXXXXXE+XX

These are the maximum pressures recorded during the gun launch cycle at the five selected cells. The ns represent the zone numbers (Zone n) and cell numbers (Cell n) of the cells selected The zone and cell numbers of the cells are selected by setting the variables IWHHZ and IWHHC in the input file ONED1D.DAT.

The next line of output variables is:

Maximum pressure at X=XXPLOT(1) ($dyne/cm^2$)	Maximum pressure at X=XXPLOT(2) ($dyne/cm^2$)	Maximum pressure at X=XXPLOT(3) ($dyne/cm^2$)	Maximum pressure at X=XXPLOT(4) ($dyne/cm^2$)	Maximum pressure at X=XXPLOT(5) ($dyne/cm^2$)
X.XXXXXXE+XX	X.XXXXXXE+XX	X.XXXXXXE+XX	X.XXXXXXE+XX	X.XXXXXXE+XX

These are the maximum pressures recorded during the gun launch cycle at the five selected positions along the gun. The positions are selected by setting the variables XXPLOT in the input file ONED1D.DAT.

The next output variable is:

Maximum pressure
at projectile base
($dyne/cm^2$)

X.XXXXXXE+XX

This is the maximum projectile base pressure recorded during the gun launch cycle.

The next line of output variables is:

TIME OF SNAPSHOT 1 (S)	TIME OF SNAPSHOT 2 (S)	TIME OF SNAPSHOT 3 (S)
X.XXXXXXE+XX	X.XXXXXXE+XX	X.XXXXXXE+XX

These are the times at which the three snapshots of the gun launch cycle are taken. The snapshot data appears in the files PLOT1, PLOT2 and PLOT3. The times at which the snapshots are taken can be changed by adjusting the variables UPISTW(1), UPISTW(2) and RDELTT in the input file ONED1D.DAT (see also discussion in Appendix I, section on ONED1D.DAT).

The next line of output variables is:

Piezometric ratio Zone n, Cell n	Piezometric ratio Zone n, Cell n	Piezometric ratio Zone n, Cell n	Piezometric ratio Zone n, Cell n	Piezometric ratio Zone n, Cell n
X.XXXXXXE+XX	X.XXXXXXE+XX	X.XXXXXXE+XX	X.XXXXXXE+XX	X.XXXXXXE+XX

These are the piezometric ratios recorded during the gun launch cycle at the five selected cells. They are for the same cells for which the maximum pressures were output above. The piezometric ratios are constructed with an average effective barrel pressure defined by Eqns. (1) and (2) below.

$$\overline{p_b} A_b l_b = \frac{1}{2} m_{proj} u_{muz}^2 \tag{1}$$

$$\overline{p_b} = \frac{m_{proj} u_{muz}^2}{2 A_b l_b} \tag{2}$$

where

$\overline{p_b}$ = average effective barrel pressure
A_b = barrel area
l_b = barrel length
m_{proj} = projectile mass
u_{muz} = projectile muzzle velocity

The piezometric ratios are then defined by Eqn. (3) below

$$PIEZOMETRIC\ RATIO = \frac{p_{max}}{\overline{p_b}} \tag{3}$$

where

p_{max} = maximum pressure at location or cell in question

The piezometric ratio is usually defined by ballisticians as that obtained from Eqn. (3) when p_{max} is the maximum projectile base pressure. We have extended this definition to include ratios calculated from Eqn. (3) when p_{max} is the maximum pressure at any of the selected locations or cells. The first set of piezometric ratios, presented above, is obtained using the maximum pressures at each of the five selected cells mentioned earlier.

The next line of output variables is:

Piezometric ratio at X=XXPLOT(1)	Piezometric ratio at X=XXPLOT(2)	Piezometric ratio at X=XXPLOT(3)	Piezometric ratio at X=XXPLOT(4)	Piezometric ratio at X=XXPLOT(5)
X.XXXXXXE+XX	X.XXXXXXE+XX	X.XXXXXXE+XX	X.XXXXXXE+XX	X.XXXXXXE+XX

These are the piezometric ratios based on the maximum pressures at the five selected positions along the gun.

The last line of output variables is:

Piezometric ratio at projectile base	Effective average barrel pressure (dyne/cm^2)
X.XXXXXXE+XX	X.XXXXXXE+XX

The first of these two variables is the usual ballistician's piezometric ratio, based on the maximum pressure at the projectile base. The second variable is the effective average barrel pressure (dy/cm^2), as defined in Eqns. (1) and (2).

PRESSVSX

This file consists of five columns of data

X-location along the gun (cm) = XXPLOT	PMAXX, maximum pressure (dyne/cm^2) at X = XXPLOT	PBURST, tube burst pressure (dyne/cm^2) at X = XXPLOT	ACONE, HPC inside area (cm^2) at X = XXPLOT	DCONE, HPC inside dia. (cm) at X = XXPLOT
X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX
X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX
X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX
:	:	:	:	:
:	:	:	:	:
X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX
X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX

The first 3 columns comprise the profiles of maximum shot pressures along the length of the gun and gun tube burst pressures in the HPC. The burst pressures are only valid in the HPC. The last two columns give the inside area and the inside diameter of the HPC.

PLOT1-PLOT3

There are three of these output files, named PLOT1, PLOT2 and PLOT3. They are the snapshot files at the times which are determined from the values of the variables UPISTW(1), UPISTW(2) and RDELTT in the input file ONED1D.DAT. (See also discussion in Appendix I, section on ONED1D.DAT). These times are given in the FINALOUTP file. (See also Appendix J, section on FINALOUTP). The variables are listed in columns for all internal (real) cells of all four zones [gunpowder/powder gas, piston (2 zones) and hydrogen] for the time of the snapshot in question. The variables appear in the following form:

Distance (cm)	Area (cm^2)	Density (g/cm^3)	Internal energy (erg/g)	Pressure ($dynes/cm^2$)
X	A	R	E	P
X.XXXXXXE+XX	X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX
X.XXXXXXE+XX	X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX
X.XXXXXXE+XX	X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX

Velocity (cm/s)	Temperature (K)	(TKE NEQ)/ (TKE EQ)	Mass fraction (1)	Mach number
U	T	RTKE	ZM1	M
X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX
X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX
X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX

Note that the ten variables are all side by side in the computer output (see Appendix L), but here are split into two blocks of five variables each because of page size limitations. We now discuss each variable.

Distance (cm)	Location of cell center in axial direction.
Area (cm^2)	Gun tube cross-section area for cell in question.
Density (g/cm^3)	Average density in cell.
Internal energy	Internal energy for cell in

(erg/g)	question.
Pressure (dynes/cm^2)	Pressure in cell.
Velocity (cm/s)	Mass averaged cell velocity.
Temperature (K)	Temperature in cell.
(TKE NEQ)/ (TKE EQ)	Non-equilibrium turbulence kinetic energy divided by equilibrium value. (See discussion in Appendix B of Ref. 1 for more information.)
Mass fraction (1)	Mass fraction of first component (unburned gunpowder in powder zone).
Mach number	Mach number for cell in question.

PLOTPROJ1

This output file is the history file of projectile base and piston front conditions. The variables appear in the following form:

Step number	Time (s)	Boundary velocity (cm/s)	Projectile position (cm)	Projectile pressure (dynes/cm^2)
nnnnn	X.XXXXXXE+XX	X.XXXXXXE+XX	X.XXXXXXE+XX	X.XXXXXXE+XX
nnnnn	X.XXXXXXE+XX	X.XXXXXXE+XX	X.XXXXXXE+XX	X.XXXXXXE+XX
nnnnn	X.XXXXXXE+XX	X.XXXXXXE+XX	X.XXXXXXE+XX	X.XXXXXXE+XX

Projectile velocity (cm/s)	Piston position (cm)	Hydrogen volume (cm^3)
X.XXXXXXE+XX	X.XXXXXXE+XX	X.XXXXXXE+XX
X.XXXXXXE+XX	X.XXXXXXE+XX	X.XXXXXXE+XX
X.XXXXXXE+XX	X.XXXXXXE+XX	X.XXXXXXE+XX

Note that the eight variables are all side by side in the computer output (see Appendix L), but here are split into two blocks of five and three variables because of page size

limitations. The columns contain data from every 10th step only in order to limit the files to manageable sizes. Thus, for a run with a representative number of time steps, say, 8000, the columns would each have 800 entries. To plot these variables, a plotting utility such as IGOR can be used. We now discuss each variable.

Step number	Number of the time step for the following row of data.
Time (s)	Time for the time step in question.
Boundary velocity (cm/s)	Velocity of zone boundary at projectile base. Appears only for historical reasons. It is suggested that this velocity be ignored in favor of Projectile velocity, in column 6.
Projectile position (cm)	Position of projectile base.
Projectile pressure (dynes/cm^2)	Projectile base pressure.
Projectile velocity (cm/s)	Projectile velocity.
Piston position (cm)	Position of front of piston.
Hydrogen volume (cm^3)	Volume of hydrogen (or other working gas) in pump tube

A plot of the hydrogen (or other working gas) volume versus time or projectile position is useful is assessing whether the motion of the front of the piston (the "pump rate") is well matched to the acceleration of the projectile.

PISTONXV

This output file is the history file of the piston rear, joint and front positions and velocities. (The piston joint is the joint between the two piston components.) The variables appear in the following form:

Step number	Time (s)	Piston rear axial position (cm)	Piston rear velocity (cm/s)	Piston joint axial position (cm)
nnnnn	X.XXXXXXE+XX	X.XXXXXXE+XX	X.XXXXXXE+XX	X.XXXXXXE+XX
nnnnn	X.XXXXXXE+XX	X.XXXXXXE+XX	X.XXXXXXE+XX	X.XXXXXXE+XX
nnnnn	X.XXXXXXE+XX	X.XXXXXXE+XX	X.XXXXXXE+XX	X.XXXXXXE+XX

Piston joint velocity (cm/s)	Piston front axial position (cm)	Piston front velocity (cm/s)
X.XXXXXXE+XX	X.XXXXXXE+XX	X.XXXXXXE+XX
X.XXXXXXE+XX	X.XXXXXXE+XX	X.XXXXXXE+XX
X.XXXXXXE+XX	X.XXXXXXE+XX	X.XXXXXXE+XX

Note that the eight variables are all side by side in the computer output (see Appendix L), but here are split into two blocks of five and three variables because of page size limitations. Also note that, as the piston extrudes, the velocities of the rear, the joint and the front of the piston can differ. We now discuss each variable.

Step number	Number of the time step for the following row of data.
Time (s)	Time for the time step in question.
Piston rear axial (x) position (cm)	Self-explanatory
Piston rear velocity (cm/s)	Self-explanatory
Piston joint axial (x) position (cm)	Self-explanatory
Piston joint velocity (cm/s)	Self-explanatory
Piston front axial	Self-explanatory

(x) position (cm)	
Piston front velocity (cm/s)	Self-explanatory

Note that if there are only three zones instead of the four zones in the above example, the outputs labelled "joint" will become the outputs for the piston front and outputs labelled "front" will be zero.

PLOTX1-PLOTX5

There are five of these output files, named PLOTX1, PLOTX2, ... , up to PLOTX5. They are the pressure history files at the positions selected by setting the variables XXPLOT in the input file ONED1D.DAT. The variables appear in the following form:

Step number	Time (s)	Pressure (dynes/cm^2)
nnnnn	X.XXXXXXE+XX	X.XXXXXXE+XX
nnnnn	X.XXXXXXE+XX	X.XXXXXXE+XX
nnnnn	X.XXXXXXE+XX	X.XXXXXXE+XX

We now discuss each variable.

Step number	Number of the time step for the following row of data.
Time (s)	Time for the time step in question (sec).
Pressure (dynes/cm^2)	Pressure at position of history in question.

PLOTH1-PLOTH5

There are five of these output files, named PLOTH1, PLOTH2, ... , up to PLOTH5. They are the history files of the cells selected by setting the variables IWHHZ and IWHHC in the input file ONED1D.DAT. IWHHZ(1) and IWHHC(1) are the zone and cell numbers for which data is given in PLOTH1. Likewise, IWHHZ(2) and IWHHC(2) are the zone and cell numbers for which data is given in PLOTH2 and so on, for the files PLOTH3, PLOTH4 and PLOTH5. The variables appear in the following form:

Step number	Time (s)	Distance (cm)	Density (g/cm^3)	(TKE NEQ)/ (TKE EQ)
nnnnn	X.XXXXXE+XX	X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX
nnnnn	X.XXXXXE+XX	X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX
nnnnn	X.XXXXXE+XX	X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX

Velocity (cm/s)	Pressure ($dynes/cm^2$)	Temperature (K)	Sound speed (cm/s)	Mass fraction (1)
X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX
X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX
X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX	X.XXXXE+XX

Powder web fraction burned
X.XXXXE+XX
X.XXXXE+XX
X.XXXXE+XX

Note that the eleven variables are all side by side in the computer output (see Appendix L), but here are split into three blocks of five, five and one variables because of page size limitations. We now discuss each variable.

Step number	Number of the time step for the following row of data.
Time (s)	Time for the time step in question.
Distance (cm)	Location of cell center in axial direction.
Density (g/cm^3)	Average density in cell.
(TKE NEQ)/ (TKE EQ)	Non-equilibrium turbulence kinetic energy divided by equilibrium value. (See discussion in Appendix B of Ref. 1 for more information.)
Velocity (cm/s)	Mass averaged cell velocity.

Pressure (dynes/cm^2)	Pressure in cell.
Temperature (K)	Temperature in cell.
Sound speed (cm/s)	Sound speed in cell.
Mass fraction (1)	Mass fraction of first component (unburned gunpowder in powder zone).
Powder web fraction burned	Fraction of web thickness of powder grain burned. (This is zero at start of burn and 1 at end of burn.)

WAHE1OP

This output file consists of a single dummy variable of no interest followed by NXSTEE rows of data arranged in six columns (for which see Appendix L, section on WAHE1OP). Each row of data is for one of the NXSTEE x-positions for which erosion calculations were made. The data in this file is calculated just after the projectile passes the x-coordinate XMUZ(2). For our example case, the actual muzzle exit x-coordinate XMUZ(1) is 1336.744 cm, whereas XMUZ(2) is 1430 cm. There should be very little difference between the temperature profiles at the times that the projectile passes XMUZ(1) and XMUZ(2). The six columns give the following data:

Column 1: x-position along gun (cm)

Column 2: Total wall erosion (cm)

Column 3: Wall temperature as projectile passes XMUZ(2) (K)

Column 4: Maximum wall temperature at any time up to the time that the projectile passes XMUZ(2) (K)

Column 5: Temperature at the center of the cell inside the metal of the gun barrel indicated by the y cell number NCYST1 at the time that the projectile passes XMUZ(2) (K)

Column 6: Temperature at the center of the cell inside the metal of the gun barrel

indicated by the y cell number NCYST2 at the time that the projectile passes XMUZ(2) (K)

Note that the numbers of the y cells where data is printed out in WAHE1OP in columns 5 and 6 were read in in the input file WAHE1D.DAT. The y-distances of these cell centers from the barrel wall surface are given by the corresponding entries in the first column of the output file WAHE1OHA. If NCYST1 (or NCYST2) is equal to 2, 3, etc., the corresponding y distance would be the 2nd, 3rd, etc., entry in column 1 of WAHE1OHA. Note that the cell with NCYST1 (or NCYST2) equal to 1 would be a "ghost" cell, not a real cell within the metal of the gun barrel. The first entry in column 1 of WAHE1OHA is always zero and corresponds to the surface of the barrel wall, not to the "ghost" cell conditions.

WAHE1OHA

This output file ideally consists of one block of output with three columns of data giving two temperature profiles into the metal of the barrel wall at x-position numbers NCXST1 and NCXST2 along the barrel. The first column is the distance from the barrel wall surface into the metal of the barrel (cm). The second and third columns are the barrel wall temperatures at these locations (K). The first row gives conditions at the barrel wall surface. The 2nd, 3rd, etc., rows give conditions at the center of cells with y-numbers of 2, 3, etc. within the barrel wall metal. (As mentioned earlier, the cells with y-numbers of 1 are "ghost" cells and do not contain real data.) The x-positions (cm) at which these two profiles are given can be determined from the WAHE1D.DAT file as XSTEEL(NCXST1) and XSTEEL(NCXST2). The data in this file is calculated at the same time as the data of the WAHE1OP file.

N.B: If NTTKE1, NTTKE2 and NTTKE3 (read in in main input file ONED1D.DAT) are less than the final step number where the projectile passes XMUZ(2) and the code stops, there will be 3 additional blocks of data in WAHE1OHA before the data set of interest referred to above. These three data blocks will each be 18 lines long. Should this happen, it is suggested to ignore the first three sets of data and use only the last set of data. The three earlier sets of data do give barrel temperature profiles at the times corresponding to time steps NTTKE1, NTTKE2 and NTTKE3, however.

Appendix K

Gun Configurations Which Can Be Modelled

The gun configuration example modelled herein comprises four zones, as follows:

Zone 1 - powder/powder gas
Zone 2 - iron slug (in thin walled polyethylene sleeve)
Zone 3 - epoxy matrix/steel shot slug
Zone 4 - hydrogen working gas plus finely divided droplets (liquid or solid) of melted off tube wall material (usually gun steel)

We note that there are two weighted pistons joined together. This most likely is not a practical arrangement; it was chosen to illustrate the code capabilities and furnish a "universal" data block which could easily be converted into practical configurations. Table 1 below lists some of these configurations.

Table 1. Light gas gun configurations.

Configuration	Zone 1	Zone 2	Zone 3	†Zone 4
1 (example)	Powder/powder gas	Iron slug	Epoxy + steel shot	H_2
2	Powder/powder gas	Iron slug	Epoxy slug	H_2
3	Powder/powder gas	Iron slug	Polyethylene slug	H_2
4	Powder/powder gas	Metal* slug	H_2	-------
5	Powder/powder gas	Epoxy + steel shot	H_2	-------
6	Powder/powder gas	Paraffin + Cu beads	H_2	-------
7	Powder/powder gas	Paraffin + Pb powder	H_2	-------
8	Powder/powder gas	Epoxy slug	H_2	-------
9	Powder/powder gas	Polyethylene slug	H_2	-------

†All working gases include melted off wall material
*Could be iron, aluminum or brass or other metal

Configuration 2 is constructed from the example case by removing the steel shot from the epoxy matrix of zone 3. Case 3 is constructed by replacing the epoxy of Case 2 by polyethylene. Case 2 and 3 can be altered by replacing the iron slug by aluminum or brass (or other metal) slugs. Equation of state parameters for aluminum are given in this report (see Appendix B), but those for brass are not. Shock Hugoniot data for free-machining leaded brass are available in Ref. 44. Case 4 is constructed by removing the epoxy plus steel shot zone of Case 1 and replacing the iron slug by a generic metal slug. Case 5 is constructed by removing the iron slug zone of Case 1. Other workers have used lead powder[51] or copper beads in a paraffin wax matrix for a three zone configuration as shown

for cases 6 and 7. We have noted (see Appendix B) that with a dense shot loading in a light matrix, such as epoxy or paraffin, that only the density of the shot loading is required for the two component equation of state (EOS), since the compressibility of the shot loading can be taken as zero. Thus, the construction of the EOS for zone 2 in cases 5 to 7 is very simple once the EOS of the matrix is known. Cases 8 and 9 in Table 1 are for unweighted pistons and are obtained from cases 2 and 3 by removing the iron slug zone.

All of the cases (configurations) in Table 1 are shown with hydrogen working gas. In this case the NTEOS for the working gas zone must be 9 (see Sec. 4.12). EOS parameters and viscosities are also available for He, N_2 and Ar working gases (again see Sec. 4.12). If one of these alternate working gases is chosen, the EOS parameters and viscosities must be changed out from those for hydrogen to those for the gas of choice. The initial conditions in file ONED1D.DAT must also be changed to reflect the change of the working gas. In the case of "non-hydrogen" working gas, NTEOS for the working gas zone must be 5.

All of the cases (configurations) in Table 1 are shown with powder/powder gas in zone 1. In this case the NTEOS for zone 1 must be 8 (see Sec. 4.12). The code can also be run with cold (or heated) gas in zone 1. EOS parameters and viscosities are available for H_2, He, N_2 and Ar (again see Sec. 4.12). If one of these gases is chosen for zone 1, instead of powder/powder gas, the EOS parameters and viscosities must be changed out from those for powder/powder gas to those for the gas of choice. The initial conditions in file ONED1D.DAT must also be changed to reflect the change of the gas in zone 1. NTEOS for zone 1 must be 9 for hydrogen and 5 for the three remaining gases. It is noted that air in zone 1 would be very closely simulated by our data for nitrogen. Heated gases are simulated by calculating the initial RII and EII values in zone 1 at the chosen temperature.

Appendix L

Sample Input Files for Light Gas Gun Code

ONED1D.DAT

```
4 90001  .70 .05                          NZ NS CFL DELIM
.70  .70  2                               CFL1,CFL2,NCFL
1.  .5                                    ALPH1,ALPH2 (FOR FLUXBLIND2)
8.  4.  1                                 ALPH1C,ALPH2C,NBZCRS (FOR INTERP)
.0125 .025 .0005 .001                     ZETAL1,ZETAL2,ZETAL3,ZETAL4
0  0  0                                   IVELEX,IENEX,NSKSWL
2  3  .5                                  IORFBL,IORIN,ZEXIN
6                                         NRITI
0 .5E5 9.E5 .139547E-4 .255217E-4 2    ITEST,UEXMIN,UEXMAX,TTEST1,TTEST2,IT2MOD
8  10  11                                 NTPRIN,NTPRI2,NTPRI3
0  2.8  2.8  50.                          INOZCA,ZHALF1,ZHALF6,R21HHI
1464.3 729.6 1440. 1459.3 45.603 6703.7 8000.   AZTT(1,3,4,7,16,17,18)
1336.744  1430.                           XMUZ(2)
5                                         NXWG
267.09 273.09 323.715 900.0 950.0         XWG(NXWG)
55000. 40000.    1.                       UPISTW(3)
0.0                                       DXPIST
1.0                                       RDELTT
32  12  22  40                            NC(NZ)
2  1  1  2                               NCOM(NZ)
3 1. 1 1. 1 1. 3 1.                       NTCG(NZ) CSRAT(NZ)
1 4 4 4 4 4 4 1                           NTB(NZ,1) NTB(NZ,2)
0. 19.596 23.611 31.641 1081.514          XB(NZ+1)
0.  0.  0.  0.  0.                          VB(NZ+1)
.0001  .01                                QQGP QQGREX
9.55 .117 2.2 1.2 2.2 1.2 9. .125         ROLIM(NZ),ALPH(NZ)
10. .05 10. .05 10. .05  10. .05          ALPHHI(NZ),ALPHLO(NZ)
```

ONED1D.DAT

```
1                                       IALPEX

4.  4.  4.  4.                          GRUN(NZ)

6  5  1  2  5  5        NITGRU,IREIMS,IPRECS,IRMG2S,NG256,NG2VBY

0                                       IPRECE

0 .5 0                                  IPPRCS,ZPPRCS,IPRUPS

1  1.1  1                              NPKLUG,ZPKLUG,ZPKLG4

0                                       IPWAPA

.005 1.005 9.8 12
.005 1.005 4.  12
.005 1.005 4.  12
.005 1.005 9.4 12                       ERRSH,RRSHLO,RRSHHI,NITRS(NZ)

5                                       ND

-200. 15.151 17.691 1066.667 1081.514   10000.  XD(ND+1)

1 2 1 2 1                               NTD(ND)

5.08   0. 0.
-0.45 11.89795    0.
3.9370 0. 0.
-.217269    235.691      0.
0.7112 0. 0.                             A(ND,1) A(ND,2) A(ND,3)

4
2
2
2                                        NINIB(NZ)

.128290  0. 3.5247E9 .00785700  -200  RII,UII,EII,GPOWI,INIB(NZ,NINIB(NZ))
.128290  0. 3.5247E9 .00785700    4
.128290  0. 3.5247E9 .00785700    5
.128290  0. 3.5247E9 .00785700  200
7.8516 0. 9.12900E8 1.00 -200
7.8516 0. 9.12900E8 1.00 200
5.500  0. 1.61600E8 1.00 -200
5.500  0. 1.61600E8 1.00 200
1.2374E-4 0. 2.956E10 1.00 -200
1.2374E-4 0. 2.956E10 1.00 200

.99 .01 0. 0. 0. 0. 0. 0. 0. 0.  ZMII(NZ,1-10,1-3)
.99 .01 0. 0. 0. 0. 0. 0. 0. 0.
.99 .01 0. 0. 0. 0. 0. 0. 0. 0.
.99 .01 0. 0. 0. 0. 0. 0. 0. 0.
1. 0. 0. 0. 0. 0. 0. 0. 0. 0.
1. 0. 0. 0. 0. 0. 0. 0. 0. 0.
1. 0. 0. 0. 0. 0. 0. 0. 0. 0.
1. 0. 0. 0. 0. 0. 0. 0. 0. 0.
1. 0. 0. 0. 0. 0. 0. 0. 0. 0.
1. 0. 0. 0. 0. 0. 0. 0. 0. 0.

0  3   9                         IPIST,NZPIST,NCPIST

3.4490E08  4 39 4 4 0   PBKVAL,NZBKPR,NCBKPR,NBCCH1,NBCCH2,IBKVAL
```

ONED1D.DAT

```
1  .6494  0.  1.362    NPROJ,ZMPROJ,VPROJI,ZLPROJ

300.  .5  .5   1               TWALL,RATRE,ERATRE,NRATRE

2  1673.  .50                  ITWALL,TWMELT,FRACQW

1.  1.  1.  1.                 GFFUDG(NZ)

10  6  1                       NSTWTE,NXTWAL,ITWALX

-1000.  1.0                    XTWALL(NXTWAL),FRACQV(NXTWAL)
1057.651  1.0
1068.923  1.0
1143.673  1.0
1330.363  1.0
10000.  1.

3.27  1  1000  1               RLTKE,ITETKE,NTETKE,IDTKEI

6721  18397  6723              NTTKE1,NTTKE2,NTTKE3

1  0  0  1                    IDTKE(NZ)

3.045E-6  .6898 .002 0
2.3615E-6  .75  .002 1
2.3615E-6  .75  .002 1
2.113E-6  .6593 .002 0                 VIS(NZ,1) VIS(NZ,2) FPR(NZ) NFR(NZ)

4.16E-5  .248  1.3318  2.225
4.16E-5  .248  1.3318  2.225
4.16E-5  .248  1.3318  2.225
7.1E-6  .0325  1.386  2.487            VIS(NZ,3),VIS(NZ,4),VIS(NZ,5),VIS(NZ,6)

8.6224E9  2.1E8  1.96850
2.069E12  3.449E9  1.96850
6.76510   3.135E8  1.96850
8.6224E9  2.1E8  1.96850
2.2935E10 3.02E8 0.35560               ECF,SYCF,RTCF(NZ+1)

1  5  5  1  1                         NRPCF(NZ+1)

1   1.5      POW BR
1   1.9685   PIS 1
2   1.96850  PIS 1
3   1.9685   PIS 1
4   1.9685   PIS 1
9   1.9685   PIS 1
1   1.97100  PIS 2
6   1.95830  PIS 2
7   1.94750  PIS 2
18  1.95680  PIS 2
19  1.97100  PIS 2
1   1.5      H2GAS
1   .355600  BARR                      NSRFCF,RPCFI(NZ+1,NRPCF(NZ+1))

.003                                   DELTRP

.4  5.886 .130
.4000 1.625 0.0359
.4000 1.625 0.0359
.4  5.886  .130
.403  2.264  .050              POICF,ADFCF,ZMSCF(NZ+1)
```

ONED1D.DAT

```
0.  0
1.809E8  1
0.  0
0.  0
0.  0                          TAUYCG(NZ+1),NTAUYG(NZ+1)

9.6571E9  19.685               SIGCON,DOCONE

24251 2  12 10991                      MPIFD,NZPIFD,NCPIFD,MPRFD

3  10                                  NCSTEP,NCCOUN

1000. 1000. 1000. 1  0  0              TW1,TW2,TW3,NWS,NWM,NWNO

761 1711 2000 2000 2000 2000 2 1300 3 NW1,NW2,NW3,NW4,NW5,NW6,NWN,NWSKIP,IPRWNT

1  1  11                              IWH,IWHZ,IWHC

5                                      IWHH

4  2
4  3
3  21
4  5
4  6                            IWHHZ(IWHH),IWHHC(IWHH)

45831 45821 45811         3  1           NPL1,NPL2,NPL3,NPRDIA,NPLSTE

328                      NPLOTX

0 0 0 0 0                              IBLANK(5)

10.0     1                     XXPLOT(NPLOTX),NVXPLT(NPLOTX)
1000.0   1
1066.0    1
1075.0    1
1082.0    1
  0.400000E+02         1
  0.500000E+02         1
  0.600000E+02         1
  0.700000E+02         1
  0.800000E+02         1
  0.900000E+02         1
```

328 lines total

```
  0.138400E+04         1
  0.138700E+04         1
  0.139000E+04         1

0  1  1  0                                   NPLAST(NZ)

41  401  4001  11881                    NSFRI1,2,3,4

1  8  3  27                              NZFRI1,NCFRI1,NZFRI2,NCFRI2
```

ONED1DE.DAT

```
.83144E+08 100.0 0 1 1   RU DTECTA NTABR IE4TTT NTABRS

8 .248935E+11 1.10731 4.31827
1 3.697E10 1.02613   3.30346
1 3.697E10 1.02613   3.30346
9  6.12E8     0.073332  4.5    NTEOS(NZ) AA(NZ,1) RO(NZ,1) ZN(NZ,1)

0.0   0.0  0.0  0.0 0.0
7.9474   3.6 6.0 2.646E11 5.292E10
1.1876   3.6 6.0 1.920E10 3.84E9
0.0   0.0  0.0  0.0 0.0 ROZZX(NZ) ZNZZX(NZ) ZMZZX(NZ) AA1ZZX(NZ) AA2ZZX(NZ)

0.0  0.0 0.0 0.0
9.649E-3 125. 5.370E6 6.71E8
6.320E-3 200. 2.000E7 4.00E9
0.0 0.0 0.0 0.0  T2CXN1(NZ) TO T2CXN4(NZ)

0.0  0.0
2.613 -.0625
0.8 0.0
0.0 0.0  GRZZ1X(NZ) GRZZ2X(NZ)

0.0  0.0  0.0
1.0 0.0 1.0
.074275  .925725  7.856
0.0 0.0 0.0             ZM1PIS(NZ),ZM2PIS(NZ),ZR2PIS(NZ)

.0   .0   16000    1  RADJ,EADJ,NFINE,MMMX

1.250  CKLUE4

23.788    1.24560  0.96432 0.0 1
23.788    1.24560  0.96432 0.0 1
13.13310  1.20000  0.90000 0.0 1
13.13310  1.20000  0.90000 0.0 1
2.0       1.40000  0.90000 0.0 1
2.0       1.40000  0.90000 0.0 1  ZMW G BCO BCOJ NTABE(NZ,NCOM(NZ))

0.0 0.0000E+00 0.0 0.0  1.580 .3148E+10 1.0
0.0 -.3449E+10 0.0 0.0  1.000 .1000E+01 1.0
0.0 -.3140E+09 0.0 0.0  1.000 .1000E+01 1.0
0.0 0.0000E+00 0.0 0.0  6.963 .1000E+01 1.0  PLIBBB PLIMOO TOBBB DEBBB R1SOL E1SOL TNSSS

0.0 0.0000E+00 0.2250E+11 0.2475E+11
0.0 -2.759E+09 2.1950E+11 2.4150E+11
0.0 -2.512E+08 0.2036E+11 0.2240E+11
0.0 0.0000E+00 0.2250E+11 0.2475E+11  PLIBB2 PLIMO2 C2LIMO C2LIM2(NZ)

 0.130000E-04 0.279999E+01 0.150000E+11 0.199999E+13 0.135935E+01 0.113012E+01  41  41

  0.170485E+04  0.606330E-13
 -0.814907E-09  0.000000E+00
  0.252359E+05 -0.606330E-13
  0.749532E+05  0.138666E+03
```

~19,000 lines total below

ONED1DE.DAT

~19,000 lines total above

```
 0.239046E+12  0.106250E+04
 0.513800E+10  0.416380E+02
-0.796820E+11 -0.354166E+03
-0.171267E+10 -0.138793E+02

.06096 .01524  1.0 3.7674E+10  DDPOW DPOW ZNPOW ECPOW(NZ)

0.00000E+00 6.0204E-7 .8000 .022860 .05334 APOW BPOW ZNXPOW WPOW ZLPOW(NZ)

0.2937224 28. 5.1787E-7 .94849  GLIM ZMAXDT BPOW2 EFFDET(NZ)

0   0                          NLDSW NGRSW(NZ)

4500  1  10  1                 NSPOW NZPOW NCPOW NPCPOW(NZ)
```

```
7.8 0.178E+12 1                          RSTEEL,QWSTEE,ITESST

1723.                                    TSMELT

2.8932E9                                 HMELT

  0.000000E+00  0.262000E+07  0.000000E+00  TSTEEL,ZKSTEE,HSTEEL(38)
  0.500000E+02  0.262000E+07  0.240650E+09
  0.100000E+03  0.262000E+07  0.481300E+09
  0.150000E+03  0.282904E+07  0.721950E+09
  0.200000E+03  0.313864E+07  0.962600E+09
  0.250000E+03  0.337864E+07  0.120325E+10
  0.300000E+03  0.355700E+07  0.144390E+10
  0.350000E+03  0.368200E+07  0.168476E+10
  0.400000E+03  0.375876E+07  0.193104E+10
  0.450000E+03  0.379376E+07  0.218668E+10
  0.500000E+03  0.379660E+07  0.245016E+10
  0.550000E+03  0.377160E+07  0.272161E+10
  0.600000E+03  0.372248E+07  0.300358E+10
  0.650000E+03  0.365248E+07  0.329807E+10
  0.700000E+03  0.357712E+07  0.360425E+10
  0.750000E+03  0.349712E+07  0.392636E+10
  0.800000E+03  0.341980E+07  0.426996E+10
  0.850000E+03  0.335707E+07  0.463606E+10
  0.900000E+03  0.328980E+07  0.502560E+10
  0.950000E+03  0.321480E+07  0.546776E+10
  0.100000E+04  0.313980E+07  0.611008E+10
  0.105000E+04  0.306480E+07  0.669931E+10
  0.110000E+04  0.303000E+07  0.703735E+10
  0.115000E+04  0.303000E+07  0.734080E+10
  0.120000E+04  0.303000E+07  0.764924E+10
  0.125000E+04  0.303000E+07  0.795899E+10
  0.130000E+04  0.304340E+07  0.826900E+10
  0.135000E+04  0.306840E+07  0.858032E+10
  0.140000E+04  0.309340E+07  0.889452E+10
  0.145000E+04  0.311840E+07  0.921211E+10
  0.150000E+04  0.313000E+07  0.953257E+10
  0.155000E+04  0.313000E+07  0.985435E+10
  0.160000E+04  0.313000E+07  0.101761E+11
  0.165000E+04  0.313000E+07  0.104978E+11
  0.170000E+04  0.313000E+07  0.108195E+11
  0.175000E+04  0.313000E+07  0.111413E+11
  0.180000E+04  0.313000E+07  0.114630E+11
  0.185000E+04  0.313000E+07  0.117848E+11

  0.000000E+00  0.000000E+00   HRSTEE,TRSTEE(59)
  0.250000E+09  0.519427E+02
  0.500000E+09  0.103885E+03
  0.750000E+09  0.155828E+03
  0.100000E+10  0.207771E+03
  0.125000E+10  0.259713E+03
  0.150000E+10  0.311656E+03
  0.175000E+10  0.363266E+03
  0.200000E+10  0.413505E+03
  0.225000E+10  0.462031E+03
  0.250000E+10  0.509194E+03
  0.275000E+10  0.555043E+03
  0.300000E+10  0.599390E+03
  0.325000E+10  0.641904E+03
```

```
  0.350000E+10  0.683044E+03
  0.375000E+10  0.722685E+03
  0.400000E+10  0.760745E+03
  0.425000E+10  0.797220E+03
  0.450000E+10  0.831495E+03
  0.475000E+10  0.864695E+03
  0.500000E+10  0.896936E+03
  0.525000E+10  0.925868E+03
  0.550000E+10  0.952502E+03
  0.575000E+10  0.971909E+03
  0.600000E+10  0.991316E+03
  0.625000E+10  0.101167E+04
  0.650000E+10  0.103251E+04
  0.675000E+10  0.105746E+04
  0.700000E+10  0.109428E+04
  0.725000E+10  0.113522E+04
  0.750000E+10  0.117591E+04
  0.775000E+10  0.121627E+04
  0.800000E+10  0.125662E+04
  0.825000E+10  0.129694E+04
  0.850000E+10  0.133714E+04
  0.875000E+10  0.137713E+04
  0.900000E+10  0.141669E+04
  0.925000E+10  0.145594E+04
  0.950000E+10  0.149494E+04
  0.975000E+10  0.153379E+04
  0.100000E+11  0.157263E+04
  0.102500E+11  0.161148E+04
  0.105000E+11  0.165033E+04
  0.107500E+11  0.168918E+04
  0.110000E+11  0.172803E+04
  0.112500E+11  0.176688E+04
  0.115000E+11  0.180573E+04
  0.117500E+11  0.184458E+04
  0.120000E+11  0.188343E+04
  0.122500E+11  0.192228E+04
  0.125000E+11  0.196113E+04
  0.127500E+11  0.199998E+04
  0.130000E+11  0.203883E+04
  0.132500E+11  0.207768E+04
  0.135000E+11  0.211653E+04
  0.137500E+11  0.215538E+04
  0.140000E+11  0.219423E+04
  0.142500E+11  0.223308E+04
  0.145000E+11  0.227193E+04

300.   400   18   .001170 1.10      TSTEEI,NXSTEE,NYSTEE,DYSTE1,RDYSTE

 -0.100000E+03           XSTEEL(NXSTEE)
 -0.960000E+02
 -0.920000E+02
 -0.880000E+02
 -0.840000E+02
 -0.800000E+02
 -0.760000E+02
 -0.720000E+02
 -0.680000E+02
 -0.640000E+02
 -0.600000E+02
```

```
-0.560000E+02
-0.520000E+02
-0.480000E+02
-0.440000E+02
-0.400000E+02
-0.360000E+02
-0.320000E+02
-0.280000E+02
-0.240000E+02
-0.200000E+02
-0.160000E+02
-0.120000E+02
-0.800000E+01
-0.400000E+01
 0.000000E+00
 0.400000E+01
 0.800000E+01
 0.120000E+02
 0.160000E+02
 0.200000E+02
 0.240000E+02
 0.280000E+02
 0.320000E+02
 0.360000E+02
 0.400000E+02
 0.440000E+02
 0.480000E+02
 0.520000E+02
 0.560000E+02
 0.600000E+02
 0.640000E+02
 0.680000E+02
 0.720000E+02
 0.760000E+02
 0.800000E+02
 0.840000E+02
 0.880000E+02
 0.920000E+02
 0.960000E+02
 0.100000E+03
 0.104000E+03
 0.108000E+03
 0.112000E+03
 0.116000E+03
 0.120000E+03
 0.124000E+03
 0.128000E+03
 0.132000E+03
 0.136000E+03
 0.140000E+03
 0.144000E+03
 0.148000E+03
 0.152000E+03
 0.156000E+03
 0.160000E+03
 0.164000E+03
 0.168000E+03
 0.172000E+03
 0.176000E+03
```

```
 0.180000E+03
 0.184000E+03
 0.188000E+03
 0.192000E+03
 0.196000E+03
 0.200000E+03
 0.204000E+03
 0.208000E+03
 0.212000E+03
 0.216000E+03
 0.220000E+03
 0.224000E+03
 0.228000E+03
 0.232000E+03
 0.236000E+03
 0.240000E+03
 0.244000E+03
 0.248000E+03
 0.252000E+03
 0.256000E+03
 0.260000E+03
 0.264000E+03
 0.268000E+03
 0.272000E+03
 0.276000E+03
 0.280000E+03
 0.284000E+03
 0.288000E+03
 0.292000E+03
 0.296000E+03
 0.300000E+03
 0.304000E+03
 0.308000E+03
 0.312000E+03
 0.316000E+03
 0.320000E+03
 0.324000E+03
 0.328000E+03
 0.332000E+03
 0.336000E+03
 0.340000E+03
 0.344000E+03
 0.348000E+03
 0.352000E+03
 0.356000E+03
 0.360000E+03
 0.364000E+03
 0.368000E+03
 0.372000E+03
 0.376000E+03
 0.380000E+03
 0.384000E+03
 0.388000E+03
 0.392000E+03
 0.396000E+03
 0.400000E+03
 0.404000E+03
 0.408000E+03
 0.412000E+03
```

```
 0.416000E+03
 0.420000E+03
 0.424000E+03
 0.428000E+03
 0.432000E+03
 0.436000E+03
 0.440000E+03
 0.444000E+03
 0.448000E+03
 0.452000E+03
 0.456000E+03
 0.460000E+03
 0.464000E+03
 0.468000E+03
 0.472000E+03
 0.476000E+03
 0.480000E+03
 0.484000E+03
 0.488000E+03
 0.492000E+03
 0.496000E+03
 0.500000E+03
 0.504000E+03
 0.508000E+03
 0.512000E+03
 0.516000E+03
 0.520000E+03
 0.524000E+03
 0.528000E+03
 0.532000E+03
 0.536000E+03
 0.540000E+03
 0.544000E+03
 0.548000E+03
 0.552000E+03
 0.556000E+03
 0.560000E+03
 0.564000E+03
 0.568000E+03
 0.572000E+03
 0.576000E+03
 0.580000E+03
 0.584000E+03
 0.588000E+03
 0.592000E+03
 0.596000E+03
 0.600000E+03
 0.604000E+03
 0.608000E+03
 0.612000E+03
 0.616000E+03
 0.620000E+03
 0.624000E+03
 0.628000E+03
 0.632000E+03
 0.636000E+03
 0.640000E+03
 0.644000E+03
 0.648000E+03
```

```
 0.652000E+03
 0.656000E+03
 0.660000E+03
 0.664000E+03
 0.668000E+03
 0.672000E+03
 0.676000E+03
 0.680000E+03
 0.684000E+03
 0.688000E+03
 0.692000E+03
 0.696000E+03
 0.700000E+03
 0.704000E+03
 0.708000E+03
 0.712000E+03
 0.716000E+03
 0.720000E+03
 0.724000E+03
 0.728000E+03
 0.732000E+03
 0.736000E+03
 0.740000E+03
 0.744000E+03
 0.748000E+03
 0.752000E+03
 0.756000E+03
 0.760000E+03
 0.764000E+03
 0.768000E+03
 0.772000E+03
 0.776000E+03
 0.780000E+03
 0.784000E+03
 0.788000E+03
 0.792000E+03
 0.796000E+03
 0.800000E+03
 0.804000E+03
 0.808000E+03
 0.812000E+03
 0.816000E+03
 0.820000E+03
 0.824000E+03
 0.828000E+03
 0.832000E+03
 0.836000E+03
 0.840000E+03
 0.844000E+03
 0.848000E+03
 0.852000E+03
 0.856000E+03
 0.860000E+03
 0.864000E+03
 0.868000E+03
 0.872000E+03
 0.876000E+03
 0.880000E+03
 0.884000E+03
```

```
 0.888000E+03
 0.892000E+03
 0.896000E+03
 0.900000E+03
 0.904000E+03
 0.908000E+03
 0.912000E+03
 0.916000E+03
 0.920000E+03
 0.924000E+03
 0.928000E+03
 0.932000E+03
 0.936000E+03
 0.940000E+03
 0.944000E+03
 0.948000E+03
 0.952000E+03
 0.956000E+03
 0.960000E+03
 0.964000E+03
 0.968000E+03
 0.972000E+03
 0.976000E+03
 0.980000E+03
 0.984000E+03
 0.988000E+03
 0.992000E+03
 0.996000E+03
 0.100000E+04
 0.100400E+04
 0.100800E+04
 0.101200E+04
 0.101600E+04
 0.102000E+04
 0.102400E+04
 0.102800E+04
 0.103200E+04
 0.103600E+04
 0.104000E+04
 0.104400E+04
 0.104800E+04
 0.105200E+04
 0.105600E+04
 0.106000E+04
 0.106400E+04
 0.106800E+04
 0.107200E+04
 0.107600E+04
 0.108000E+04
 0.108400E+04
 0.108800E+04
 0.109200E+04
 0.109600E+04
 0.110000E+04
 0.110400E+04
 0.110800E+04
 0.111200E+04
 0.111600E+04
 0.112000E+04
```

```
 0.112400E+04
 0.112800E+04
 0.113200E+04
 0.113600E+04
 0.114000E+04
 0.114400E+04
 0.114800E+04
 0.115200E+04
 0.115600E+04
 0.116000E+04
 0.116400E+04
 0.116800E+04
 0.117200E+04
 0.117600E+04
 0.118000E+04
 0.118400E+04
 0.118800E+04
 0.119200E+04
 0.119600E+04
 0.120000E+04
 0.120400E+04
 0.120800E+04
 0.121200E+04
 0.121600E+04
 0.122000E+04
 0.122400E+04
 0.122800E+04
 0.123200E+04
 0.123600E+04
 0.124000E+04
 0.124400E+04
 0.124800E+04
 0.125200E+04
 0.125600E+04
 0.126000E+04
 0.126400E+04
 0.126800E+04
 0.127200E+04
 0.127600E+04
 0.128000E+04
 0.128400E+04
 0.128800E+04
 0.129200E+04
 0.129600E+04
 0.130000E+04
 0.130400E+04
 0.130800E+04
 0.131200E+04
 0.131600E+04
 0.132000E+04
 0.132400E+04
 0.132800E+04
 0.133200E+04
 0.133600E+04
 0.134000E+04
 0.134400E+04
 0.134800E+04
 0.135200E+04
 0.135600E+04
```

```
  0.136000E+04
  0.136400E+04
  0.136800E+04
  0.137200E+04
  0.137600E+04
  0.138000E+04
  0.138400E+04
  0.138800E+04
  0.139200E+04
  0.139600E+04
  0.140000E+04
  0.140400E+04
  0.140800E+04
  0.141200E+04
  0.141600E+04
  0.142000E+04
  0.142400E+04
  0.142800E+04
  0.143200E+04
  0.143600E+04
  0.144000E+04
  0.144400E+04
  0.144800E+04
  0.145200E+04
  0.145600E+04
  0.146000E+04
  0.146400E+04
  0.146800E+04
  0.147200E+04
  0.147600E+04
  0.148000E+04
  0.148400E+04
  0.148800E+04
  0.149200E+04
  0.149600E+04

115 136 2  6            NCXST1,NCXST2,NCYST1,NCYST2

2.  55.85               ZMWHYD,ZMWSTE

  0.000000E-01  0.100000E+01    PHIBLT(116),GBLOWT(116)
  0.200000E-01  0.101601E+01
  0.400000E-01  0.103165E+01
  0.600000E-01  0.104689E+01
  0.800000E-01  0.106169E+01
  0.100000E+00  0.107602E+01
  0.120000E+00  0.108985E+01
  0.140000E+00  0.110314E+01
  0.160000E+00  0.111587E+01
  0.180000E+00  0.112801E+01
  0.200000E+00  0.113951E+01
  0.220000E+00  0.115036E+01
  0.240000E+00  0.116053E+01
  0.260000E+00  0.116997E+01
  0.280000E+00  0.117868E+01
  0.300000E+00  0.118662E+01
  0.320000E+00  0.119378E+01
  0.340000E+00  0.120012E+01
  0.360000E+00  0.120563E+01
```

0.380000E+00	0.121028E+01
0.400000E+00	0.121407E+01
0.420000E+00	0.121698E+01
0.440000E+00	0.121900E+01
0.460000E+00	0.122011E+01
0.480000E+00	0.122032E+01
0.500000E+00	0.121961E+01
0.520000E+00	0.121798E+01
0.540000E+00	0.121544E+01
0.560000E+00	0.121198E+01
0.580000E+00	0.120762E+01
0.600000E+00	0.120235E+01
0.620000E+00	0.119621E+01
0.640000E+00	0.118918E+01
0.660000E+00	0.118131E+01
0.680000E+00	0.117259E+01
0.700000E+00	0.116306E+01
0.720000E+00	0.115274E+01
0.740000E+00	0.114166E+01
0.760000E+00	0.112984E+01
0.780000E+00	0.111732E+01
0.800000E+00	0.110412E+01
0.820000E+00	0.109029E+01
0.840000E+00	0.107585E+01
0.860000E+00	0.106086E+01
0.880000E+00	0.104534E+01
0.900000E+00	0.102933E+01
0.920000E+00	0.101288E+01
0.940000E+00	0.996026E+00
0.960000E+00	0.978812E+00
0.980000E+00	0.961278E+00
0.100000E+01	0.943466E+00
0.102000E+01	0.925417E+00
0.104000E+01	0.907174E+00
0.106000E+01	0.888777E+00
0.108000E+01	0.870265E+00
0.110000E+01	0.851677E+00
0.112000E+01	0.833050E+00
0.114000E+01	0.814423E+00
0.116000E+01	0.795829E+00
0.118000E+01	0.777302E+00
0.120000E+01	0.758874E+00
0.122000E+01	0.740576E+00
0.124000E+01	0.722435E+00
0.126000E+01	0.704480E+00
0.128000E+01	0.686734E+00
0.130000E+01	0.669221E+00
0.132000E+01	0.651962E+00
0.134000E+01	0.634976E+00
0.136000E+01	0.618281E+00
0.138000E+01	0.601892E+00
0.140000E+01	0.585822E+00
0.142000E+01	0.570085E+00
0.144000E+01	0.554689E+00
0.146000E+01	0.539645E+00
0.148000E+01	0.524957E+00
0.150000E+01	0.510634E+00
0.152000E+01	0.496677E+00
0.154000E+01	0.483091E+00

```
 0.156000E+01  0.469877E+00
 0.158000E+01  0.457035E+00
 0.160000E+01  0.444565E+00
 0.162000E+01  0.432464E+00
 0.164000E+01  0.420731E+00
 0.166000E+01  0.409362E+00
 0.168000E+01  0.398352E+00
 0.170000E+01  0.387698E+00
 0.172000E+01  0.377393E+00
 0.174000E+01  0.367433E+00
 0.176000E+01  0.357809E+00
 0.178000E+01  0.348517E+00
 0.180000E+01  0.339548E+00
 0.182000E+01  0.330895E+00
 0.184000E+01  0.322552E+00
 0.186000E+01  0.314510E+00
 0.188000E+01  0.306761E+00
 0.190000E+01  0.299298E+00
 0.192000E+01  0.292113E+00
 0.194000E+01  0.285198E+00
 0.196000E+01  0.278545E+00
 0.198000E+01  0.272146E+00
 0.200000E+01  0.265994E+00
 0.202000E+01  0.260080E+00
 0.204000E+01  0.254399E+00
 0.206000E+01  0.248941E+00
 0.208000E+01  0.243700E+00
 0.210000E+01  0.238668E+00
 0.212000E+01  0.233840E+00
 0.214000E+01  0.229208E+00
 0.216000E+01  0.224765E+00
 0.218000E+01  0.220506E+00
 0.220000E+01  0.216423E+00
 0.222000E+01  0.212512E+00
 0.224000E+01  0.208767E+00
 0.226000E+01  0.205181E+00
 0.228000E+01  0.201749E+00
 0.230000E+01  0.198467E+00

 0.000000E+00  0.000000E+00                    TSTEEL(71),HWSTE(71)
 0.500000E+02  0.240650E+09
 0.100000E+03  0.481300E+09
 0.150000E+03  0.721950E+09
 0.200000E+03  0.962600E+09
 0.250000E+03  0.120325E+10
 0.300000E+03  0.144390E+10
 0.350000E+03  0.168476E+10
 0.400000E+03  0.193104E+10
 0.450000E+03  0.218668E+10
 0.500000E+03  0.245016E+10
 0.550000E+03  0.272161E+10
 0.600000E+03  0.300358E+10
 0.650000E+03  0.329807E+10
 0.700000E+03  0.360425E+10
 0.750000E+03  0.392636E+10
 0.800000E+03  0.426996E+10
 0.850000E+03  0.463606E+10
 0.900000E+03  0.502560E+10
 0.950000E+03  0.546776E+10
```

```
 0.100000E+04  0.611008E+10
 0.105000E+04  0.669931E+10
 0.110000E+04  0.703735E+10
 0.115000E+04  0.734080E+10
 0.120000E+04  0.764924E+10
 0.125000E+04  0.795899E+10
 0.130000E+04  0.826900E+10
 0.135000E+04  0.858032E+10
 0.140000E+04  0.889452E+10
 0.145000E+04  0.921211E+10
 0.150000E+04  0.953257E+10
 0.155000E+04  0.985435E+10
 0.160000E+04  0.101761E+11
 0.165000E+04  0.104978E+11
 0.170000E+04  0.108195E+11
 0.175000E+04  0.140345E+11
 0.180000E+04  0.143562E+11
 0.185000E+04  0.146780E+11
 0.190000E+04  0.149997E+11
 0.195000E+04  0.153215E+11
 0.200000E+04  0.156432E+11
 0.205000E+04  0.159650E+11
 0.210000E+04  0.162867E+11
 0.215000E+04  0.166085E+11
 0.220000E+04  0.169302E+11
 0.225000E+04  0.172520E+11
 0.230000E+04  0.175737E+11
 0.235000E+04  0.178955E+11
 0.240000E+04  0.182172E+11
 0.245000E+04  0.185390E+11
 0.250000E+04  0.188607E+11
 0.255000E+04  0.191825E+11
 0.260000E+04  0.195042E+11
 0.265000E+04  0.198260E+11
 0.270000E+04  0.201477E+11
 0.275000E+04  0.204695E+11
 0.280000E+04  0.207912E+11
 0.285000E+04  0.211130E+11
 0.290000E+04  0.214347E+11
 0.295000E+04  0.217565E+11
 0.300000E+04  0.220782E+11
 0.305000E+04  0.224000E+11
 0.310000E+04  0.227217E+11
 0.315000E+04  0.230435E+11
 0.320000E+04  0.233652E+11
 0.325000E+04  0.236870E+11
 0.330000E+04  0.240087E+11
 0.335000E+04  0.243305E+11
 0.340000E+04  0.246522E+11
 0.345000E+04  0.249740E+11
 0.350000E+04  0.252957E+11

 0.000000E+00  0.788214E+01  0.000000E+00      TST(71),RWSTE(71),BWSTE(71)
 0.500000E+02  0.788190E+01  0.601166E-05
 0.100000E+03  0.787740E+01  0.168295E-04
 0.150000E+03  0.786865E+01  0.246352E-04
 0.200000E+03  0.785802E+01  0.291287E-04
 0.250000E+03  0.784576E+01  0.330155E-04
 0.300000E+03  0.783212E+01  0.359964E-04
```

0.350000E+03	0.781757E+01	0.377732E-04
0.400000E+03	0.780259E+01	0.401450E-04
0.450000E+03	0.778625E+01	0.419145E-04
0.500000E+03	0.776996E+01	0.427821E-04
0.550000E+03	0.775301E+01	0.439473E-04
0.600000E+03	0.773588E+01	0.448109E-04
0.650000E+03	0.771835E+01	0.459711E-04
0.700000E+03	0.770040E+01	0.471285E-04
0.750000E+03	0.768206E+01	0.476876E-04
0.800000E+03	0.766377E+01	0.482449E-04
0.850000E+03	0.764508E+01	0.488013E-04
0.900000E+03	0.762646E+01	0.490587E-04
0.950000E+03	0.760767E+01	0.493157E-04
0.100000E+04	0.758894E+01	0.489786E-04
0.105000E+04	0.757050E+01	0.489384E-04
0.110000E+04	0.755189E+01	0.491949E-04
0.115000E+04	0.753335E+01	-0.667534E-04
0.120000E+04	0.760247E+01	-0.560168E-04
0.125000E+04	0.757567E+01	0.709027E-04
0.130000E+04	0.754876E+01	0.708193E-04
0.135000E+04	0.752221E+01	0.707355E-04
0.140000E+04	0.749555E+01	0.706525E-04
0.145000E+04	0.746925E+01	0.705691E-04
0.150000E+04	0.744284E+01	0.704865E-04
0.155000E+04	0.741678E+01	0.704035E-04
0.160000E+04	0.739063E+01	0.703213E-04
0.165000E+04	0.736481E+01	0.121564E-03
0.170000E+04	0.730133E+01	0.559799E-03
0.175000E+04	0.696379E+01	0.507534E-03
0.180000E+04	0.693995E+01	0.685734E-04
0.185000E+04	0.691621E+01	0.684951E-04
0.190000E+04	0.689257E+01	0.684170E-04
0.195000E+04	0.686905E+01	0.683391E-04
0.200000E+04	0.684563E+01	0.682613E-04
0.205000E+04	0.682232E+01	0.681837E-04
0.210000E+04	0.679911E+01	0.681063E-04
0.215000E+04	0.677601E+01	0.680291E-04
0.220000E+04	0.675302E+01	0.679521E-04
0.225000E+04	0.673012E+01	0.678752E-04
0.230000E+04	0.670733E+01	0.677985E-04
0.235000E+04	0.668465E+01	0.677220E-04
0.240000E+04	0.666206E+01	0.676456E-04
0.245000E+04	0.663958E+01	0.675695E-04
0.250000E+04	0.661720E+01	0.674934E-04
0.255000E+04	0.659492E+01	0.674176E-04
0.260000E+04	0.657274E+01	0.673419E-04
0.265000E+04	0.655066E+01	0.672664E-04
0.270000E+04	0.652868E+01	0.671911E-04
0.275000E+04	0.650679E+01	0.671160E-04
0.280000E+04	0.648500E+01	0.670410E-04
0.285000E+04	0.646331E+01	0.669661E-04
0.290000E+04	0.644172E+01	0.668915E-04
0.295000E+04	0.642023E+01	0.668170E-04
0.300000E+04	0.639882E+01	0.667427E-04
0.305000E+04	0.637752E+01	0.666685E-04
0.310000E+04	0.635631E+01	0.665945E-04
0.315000E+04	0.633519E+01	0.665207E-04
0.320000E+04	0.631416E+01	0.664470E-04
0.325000E+04	0.629323E+01	0.663735E-04

```
  0.330000E+04  0.627239E+01  0.663002E-04
  0.335000E+04  0.625165E+01  0.662270E-04
  0.340000E+04  0.623099E+01  0.661540E-04
  0.345000E+04  0.621042E+01  0.660811E-04
  0.350000E+04  0.618995E+01  0.660082E-04

.138607E11  1                           ESTLIQ,ISTH2

0                                       INOHEA
```

Appendix M

Sample Output Files for Light Gas Gun Code

FINALOUTP

```
 0.385166E+05  0.390512E+05  0.413337E+05  0.415487E+05
 0.126367E+04  0.128121E+04  0.135609E+04  0.136314E+04
 0.579621E+06
 0.190164E+05


 0.185908E+11  0.184642E+11  0.218206E+11  0.186786E+11  0.189775E+11
 0.107413E+10  0.556729E+08  0.721034E+10  0.165668E+11  0.158992E+11
 0.271737E+10


 0.296561E-01  0.264195E-01  0.296561E-01


 0.578699E-01  0.582667E-01  0.493044E-01  0.575979E-01  0.566908E-01
 0.100160E+01  0.193245E+02  0.149209E+00  0.649400E-01  0.676670E-01
 0.395916E+00  0.107585E+10
~
```

PLOT1

X	A	R	E	P	U	T	RTKE	ZM1	C
0.871406E+02	0.1622E+02	0.3243E-02	0.1434E+11	0.1146E+08	0.4412E+04	0.1008E+04	0.9703E+00	0.1591E-07	0.6645E+05
0.245456E+03	0.1217E+02	0.3731E-02	0.1235E+11	0.1135E+08	0.1223E+05	0.8676E+03	0.1003E+01	0.3613E-07	0.6168E+05
0.374765E+03	0.1217E+02	0.4087E-02	0.1108E+11	0.1116E+08	0.1766E+05	0.7782E+03	0.1006E+01	0.6224E-07	0.5844E+05
0.480381E+03	0.1217E+02	0.4310E-02	0.1027E+11	0.1091E+08	0.2188E+05	0.7214E+03	0.1006E+01	0.7090E-07	0.5627E+05
0.566647E+03	0.1217E+02	0.4446E-02	0.9704E+10	0.1064E+08	0.2528E+05	0.6819E+03	0.1006E+01	0.6246E-07	0.5472E+05
0.637107E+03	0.1217E+02	0.4521E-02	0.9296E+10	0.1037E+08	0.2806E+05	0.6532E+03	0.1005E+01	0.5224E-07	0.5356E+05
0.694658E+03	0.1217E+02	0.4555E-02	0.8990E+10	0.1010E+08	0.3036E+05	0.6317E+03	0.1005E+01	0.5246E-07	0.5267E+05
0.741664E+03	0.1217E+02	0.4563E-02	0.8755E+10	0.9855E+07	0.3227E+05	0.6152E+03	0.1005E+01	0.5818E-07	0.5198E+05
0.780057E+03	0.1217E+02	0.4554E-02	0.8572E+10	0.9631E+07	0.3388E+05	0.6024E+03	0.1004E+01	0.6164E-07	0.5144E+05
0.811416E+03	0.1217E+02	0.4536E-02	0.8429E+10	0.9432E+07	0.3521E+05	0.5923E+03	0.1004E+01	0.6070E-07	0.5100E+05
0.837030E+03	0.1217E+02	0.4515E-02	0.8315E+10	0.9260E+07	0.3631E+05	0.5843E+03	0.1004E+01	0.5738E-07	0.5066E+05
0.857950E+03	0.1217E+02	0.4493E-02	0.8224E+10	0.9115E+07	0.3722E+05	0.5779E+03	0.1004E+01	0.5485E-07	0.5038E+05
0.875038E+03	0.1217E+02	0.4472E-02	0.8152E+10	0.8993E+07	0.3797E+05	0.5728E+03	0.1004E+01	0.5507E-07	0.5016E+05
0.888995E+03	0.1217E+02	0.4452E-02	0.8094E+10	0.8890E+07	0.3859E+05	0.5688E+03	0.1004E+01	0.5754E-07	0.4998E+05
0.900394E+03	0.1217E+02	0.4435E-02	0.8048E+10	0.8804E+07	0.3910E+05	0.5655E+03	0.1004E+01	0.6012E-07	0.4983E+05
0.909705E+03	0.1217E+02	0.4419E-02	0.8012E+10	0.8733E+07	0.3952E+05	0.5630E+03	0.1004E+01	0.6086E-07	0.4972E+05
0.917310E+03	0.1217E+02	0.4405E-02	0.7982E+10	0.8673E+07	0.3987E+05	0.5609E+03	0.1004E+01	0.5905E-07	0.4963E+05
0.923522E+03	0.1217E+02	0.4393E-02	0.7959E+10	0.8623E+07	0.4016E+05	0.5593E+03	0.1004E+01	0.5505E-07	0.4955E+05
0.928595E+03	0.1217E+02	0.4382E-02	0.7942E+10	0.8583E+07	0.4039E+05	0.5580E+03	0.1004E+01	0.4967E-07	0.4950E+05
0.932739E+03	0.1217E+02	0.4373E-02	0.7928E+10	0.8551E+07	0.4058E+05	0.5571E+03	0.1004E+01	0.4366E-07	0.4946E+05
0.936124E+03	0.1217E+02	0.4364E-02	0.7919E+10	0.8524E+07	0.4073E+05	0.5565E+03	0.1004E+01	0.3756E-07	0.4943E+05
0.938889E+03	0.1217E+02	0.4357E-02	0.7913E+10	0.8503E+07	0.4086E+05	0.5560E+03	0.1004E+01	0.3167E-07	0.4941E+05
0.941147E+03	0.1217E+02	0.4350E-02	0.7910E+10	0.8486E+07	0.4095E+05	0.5558E+03	0.1005E+01	0.2614E-07	0.4940E+05
0.942991E+03	0.1217E+02	0.4343E-02	0.7910E+10	0.8472E+07	0.4104E+05	0.5558E+03	0.1005E+01	0.2105E-07	0.4940E+05
0.944497E+03	0.1217E+02	0.4336E-02	0.7912E+10	0.8460E+07	0.4110E+05	0.5559E+03	0.1005E+01	0.1642E-07	0.4940E+05
0.945728E+03	0.1217E+02	0.4329E-02	0.7916E+10	0.8451E+07	0.4116E+05	0.5562E+03	0.1005E+01	0.1226E-07	0.4942E+05
0.946733E+03	0.1217E+02	0.4322E-02	0.7920E+10	0.8443E+07	0.4121E+05	0.5565E+03	0.1005E+01	0.8556E-08	0.4943E+05
0.947554E+03	0.1217E+02	0.4317E-02	0.7924E+10	0.8436E+07	0.4125E+05	0.5568E+03	0.1005E+01	0.5298E-08	0.4944E+05
0.948224E+03	0.1217E+02	0.4313E-02	0.7927E+10	0.8432E+07	0.4127E+05	0.5570E+03	0.1005E+01	0.2457E-08	0.4945E+05
0.948772E+03	0.1217E+02	0.4311E-02	0.7928E+10	0.8428E+07	0.4130E+05	0.5571E+03	0.1005E+01	0.6849E-16	0.4945E+05
0.949219E+03	0.1217E+02	0.7837E+01	0.1052E+10	0.8777E+07	0.4131E+05	0.3180E+03	0.1005E+01	0.1000E+01	0.4801E+06
0.949621E+03	0.1217E+02	0.7837E+01	0.1049E+10	0.1187E+08	0.4132E+05	0.3175E+03	0.1005E+01	0.1000E+01	0.4801E+06
0.950023E+03	0.1217E+02	0.7838E+01	0.1046E+10	0.1485E+08	0.4132E+05	0.3170E+03	0.1005E+01	0.1000E+01	0.4801E+06
0.950425E+03	0.1217E+02	0.7838E+01	0.1043E+10	0.1552E+08	0.4132E+05	0.3165E+03	0.1005E+01	0.1000E+01	0.4801E+06
0.950827E+03	0.1217E+02	0.7838E+01	0.1040E+10	0.1543E+08	0.4132E+05	0.3159E+03	0.1005E+01	0.1000E+01	0.4801E+06
0.951230E+03	0.1217E+02	0.7839E+01	0.1037E+10	0.1680E+08	0.4132E+05	0.3153E+03	0.1005E+01	0.1000E+01	0.4801E+06
0.951632E+03	0.1217E+02	0.7839E+01	0.1033E+10	0.1864E+08	0.4132E+05	0.3147E+03	0.1005E+01	0.1000E+01	0.4801E+06
0.952034E+03	0.1217E+02	0.7839E+01	0.1030E+10	0.1886E+08	0.4132E+05	0.3141E+03	0.1005E+01	0.1000E+01	0.4801E+06
0.952436E+03	0.1217E+02	0.7840E+01	0.1027E+10	0.1783E+08	0.4132E+05	0.3134E+03	0.1005E+01	0.1000E+01	0.4801E+06
0.952838E+03	0.1217E+02	0.7840E+01	0.1023E+10	0.1827E+08	0.4131E+05	0.3127E+03	0.1005E+01	0.1000E+01	0.4801E+06
0.953240E+03	0.1217E+02	0.5483E+01	0.2233E+09	0.1677E+08	0.4131E+05	0.3444E+03	0.1005E+01	0.1000E+01	0.2729E+06

Snapshot PLOT1 taken at 0.026853 seconds after code start. Note density changes at passage from powder/powder gas zone to first piston zone to second piston zone. Note that PLOT2 and PLOT3 have the same variable arrangement as PLOT1.

PLOTPROJ1

49471	0.28987E-01	0.00000E+00	0.10815E+04	0.00000E+00	0.00000E+00	0.10397E+04	0.97868E+02
49481	0.28993E-01	0.00000E+00	0.10815E+04	0.00000E+00	0.00000E+00	0.10399E+04	0.97870E+02
49491	0.28999E-01	0.00000E+00	0.10815E+04	0.00000E+00	0.00000E+00	0.10401E+04	0.97874E+02
49501	0.29005E-01	0.00000E+00	0.10815E+04	0.00000E+00	0.00000E+00	0.10404E+04	0.97878E+02
49511	0.29011E-01	0.00000E+00	0.10815E+04	0.00000E+00	0.00000E+00	0.10406E+04	0.97882E+02
49521	0.29017E-01	0.00000E+00	0.10815E+04	0.00000E+00	0.00000E+00	0.10408E+04	0.97886E+02
49531	0.29022E-01	0.00000E+00	0.10815E+04	0.00000E+00	0.00000E+00	0.10410E+04	0.97889E+02
49541	0.29028E-01	0.00000E+00	0.10815E+04	0.00000E+00	0.00000E+00	0.10413E+04	0.97893E+02
49551	0.29034E-01	0.00000E+00	0.10815E+04	0.00000E+00	0.00000E+00	0.10415E+04	0.97895E+02
49561	0.29040E-01	0.00000E+00	0.10815E+04	0.00000E+00	0.00000E+00	0.10417E+04	0.97897E+02
49571	0.29046E-01	0.00000E+00	0.10815E+04	0.00000E+00	0.00000E+00	0.10419E+04	0.97897E+02
49581	0.29052E-01	0.00000E+00	0.10815E+04	0.00000E+00	0.00000E+00	0.10422E+04	0.97895E+02
49591	0.29058E-01	0.00000E+00	0.10815E+04	0.00000E+00	0.00000E+00	0.10424E+04	0.97892E+02
49601	0.29063E-01	0.00000E+00	0.10815E+04	0.00000E+00	0.00000E+00	0.10426E+04	0.97886E+02
49611	0.29069E-01	0.11734E+04	0.10815E+04	0.44479E+09	0.12420E+04	0.10429E+04	0.97880E+02
49621	0.29075E-01	0.26847E+04	0.10815E+04	0.51651E+09	0.27651E+04	0.10431E+04	0.97874E+02
49631	0.29081E-01	0.42477E+04	0.10816E+04	0.47180E+09	0.43219E+04	0.10433E+04	0.97868E+02
49641	0.29087E-01	0.56095E+04	0.10816E+04	0.39293E+09	0.56714E+04	0.10435E+04	0.97864E+02
49651	0.29093E-01	0.67414E+04	0.10816E+04	0.32952E+09	0.67932E+04	0.10438E+04	0.97861E+02
49661	0.29099E-01	0.77037E+04	0.10817E+04	0.28565E+09	0.77485E+04	0.10440E+04	0.97859E+02
49671	0.29105E-01	0.85529E+04	0.10817E+04	0.25797E+09	0.85934E+04	0.10442E+04	0.97858E+02
49681	0.29110E-01	0.93334E+04	0.10818E+04	0.23903E+09	0.93711E+04	0.10444E+04	0.97859E+02
49691	0.29116E-01	0.10065E+05	0.10818E+04	0.22514E+09	0.10100E+05	0.10447E+04	0.97860E+02
49701	0.29122E-01	0.10772E+05	0.10819E+04	0.22514E+09	0.10808E+05	0.10449E+04	0.97861E+02
49711	0.29128E-01	0.11499E+05	0.10819E+04	0.23377E+09	0.11536E+05	0.10451E+04	0.97863E+02
49721	0.29134E-01	0.12255E+05	0.10820E+04	0.24149E+09	0.12293E+05	0.10454E+04	0.97864E+02
49731	0.29140E-01	0.13040E+05	0.10821E+04	0.25446E+09	0.13080E+05	0.10456E+04	0.97864E+02
49741	0.29146E-01	0.13952E+05	0.10822E+04	0.33339E+09	0.14005E+05	0.10458E+04	0.97862E+02
49751	0.29151E-01	0.15185E+05	0.10823E+04	0.43759E+09	0.15255E+05	0.10460E+04	0.97858E+02
49761	0.29157E-01	0.16671E+05	0.10823E+04	0.46593E+09	0.16747E+05	0.10463E+04	0.97853E+02
49771	0.29163E-01	0.18163E+05	0.10824E+04	0.43911E+09	0.18234E+05	0.10465E+04	0.97846E+02
49781	0.29169E-01	0.19528E+05	0.10826E+04	0.39628E+09	0.19593E+05	0.10467E+04	0.97838E+02
49791	0.29175E-01	0.20774E+05	0.10827E+04	0.36591E+09	0.20834E+05	0.10469E+04	0.97832E+02
49801	0.29181E-01	0.21940E+05	0.10828E+04	0.34524E+09	0.21997E+05	0.10471E+04	0.97828E+02

Projectile variables from step 49471 to step 49801. Note diaphragm rupture and start of projectile motion just after step 49601.

PISTONXV

49471	0.28987E-01	0.10356E+04	0.39051E+05	0.10397E+04	0.39051E+05	0.10477E+04	0.39076E+05
49481	0.28993E-01	0.10359E+04	0.39031E+05	0.10399E+04	0.39026E+05	0.10479E+04	0.39066E+05
49491	0.28999E-01	0.10361E+04	0.39005E+05	0.10401E+04	0.38997E+05	0.10482E+04	0.39051E+05
49501	0.29005E-01	0.10363E+04	0.38973E+05	0.10404E+04	0.38974E+05	0.10484E+04	0.39031E+05
49511	0.29011E-01	0.10366E+04	0.38941E+05	0.10406E+04	0.38951E+05	0.10486E+04	0.39008E+05
49521	0.29017E-01	0.10368E+04	0.38918E+05	0.10408E+04	0.38928E+05	0.10488E+04	0.38981E+05
49531	0.29022E-01	0.10370E+04	0.38900E+05	0.10410E+04	0.38906E+05	0.10491E+04	0.38955E+05
49541	0.29028E-01	0.10372E+04	0.38887E+05	0.10413E+04	0.38890E+05	0.10493E+04	0.38933E+05
49551	0.29034E-01	0.10375E+04	0.38876E+05	0.10415E+04	0.38878E+05	0.10495E+04	0.38909E+05
49561	0.29040E-01	0.10377E+04	0.38866E+05	0.10417E+04	0.38865E+05	0.10498E+04	0.38879E+05
49571	0.29046E-01	0.10379E+04	0.38855E+05	0.10419E+04	0.38851E+05	0.10500E+04	0.38840E+05
49581	0.29052E-01	0.10382E+04	0.38842E+05	0.10422E+04	0.38838E+05	0.10502E+04	0.38799E+05
49591	0.29058E-01	0.10384E+04	0.38827E+05	0.10424E+04	0.38824E+05	0.10504E+04	0.38760E+05
49601	0.29063E-01	0.10386E+04	0.38809E+05	0.10426E+04	0.38807E+05	0.10507E+04	0.38726E+05
49611	0.29069E-01	0.10388E+04	0.38791E+05	0.10429E+04	0.38789E+05	0.10509E+04	0.38700E+05
49621	0.29075E-01	0.10391E+04	0.38770E+05	0.10431E+04	0.38765E+05	0.10511E+04	0.38680E+05
49631	0.29081E-01	0.10393E+04	0.38745E+05	0.10433E+04	0.38738E+05	0.10514E+04	0.38666E+05
49641	0.29087E-01	0.10395E+04	0.38713E+05	0.10435E+04	0.38709E+05	0.10516E+04	0.38656E+05
49651	0.29093E-01	0.10397E+04	0.38680E+05	0.10438E+04	0.38678E+05	0.10518E+04	0.38644E+05
49661	0.29099E-01	0.10400E+04	0.38643E+05	0.10440E+04	0.38643E+05	0.10520E+04	0.38626E+05
49671	0.29105E-01	0.10402E+04	0.38607E+05	0.10442E+04	0.38610E+05	0.10523E+04	0.38607E+05
49681	0.29110E-01	0.10404E+04	0.38574E+05	0.10444E+04	0.38578E+05	0.10525E+04	0.38588E+05
49691	0.29116E-01	0.10407E+04	0.38543E+05	0.10447E+04	0.38549E+05	0.10527E+04	0.38567E+05
49701	0.29122E-01	0.10409E+04	0.38516E+05	0.10449E+04	0.38522E+05	0.10529E+04	0.38546E+05
49711	0.29128E-01	0.10411E+04	0.38492E+05	0.10451E+04	0.38494E+05	0.10532E+04	0.38518E+05
49721	0.29134E-01	0.10413E+04	0.38470E+05	0.10454E+04	0.38469E+05	0.10534E+04	0.38480E+05
49731	0.29140E-01	0.10416E+04	0.38446E+05	0.10456E+04	0.38445E+05	0.10536E+04	0.38424E+05
49741	0.29146E-01	0.10418E+04	0.38421E+05	0.10458E+04	0.38420E+05	0.10538E+04	0.38377E+05
49751	0.29151E-01	0.10420E+04	0.38395E+05	0.10460E+04	0.38394E+05	0.10541E+04	0.38335E+05
49761	0.29157E-01	0.10422E+04	0.38368E+05	0.10463E+04	0.38367E+05	0.10543E+04	0.38277E+05
49771	0.29163E-01	0.10425E+04	0.38341E+05	0.10465E+04	0.38337E+05	0.10545E+04	0.38227E+05
49781	0.29169E-01	0.10427E+04	0.38310E+05	0.10467E+04	0.38304E+05	0.10547E+04	0.38202E+05
49791	0.29175E-01	0.10429E+04	0.38277E+05	0.10469E+04	0.38265E+05	0.10550E+04	0.38192E+05
49801	0.29181E-01	0.10431E+04	0.38233E+05	0.10471E+04	0.38225E+05	0.10552E+04	0.38186E+05

Piston variables from step 49471 to step 49801 (same step range as for PLOTPROJ1). Note that piston is slowing down. Piston reverses direction at step 50821 at 0.029778 seconds after code start.

PLOTX5

50651	0.296789E-01	0.948472E+10
50661	0.296848E-01	0.972310E+10
50671	0.296906E-01	0.111050E+11
50681	0.296965E-01	0.113377E+11
50691	0.297023E-01	0.128351E+11
50701	0.297082E-01	0.131328E+11
50711	0.297140E-01	0.141346E+11
50721	0.297199E-01	0.149088E+11
50731	0.297257E-01	0.147599E+11
50741	0.297316E-01	0.158279E+11
50751	0.297374E-01	0.158553E+11
50761	0.297433E-01	0.156075E+11
50771	0.297492E-01	0.158992E+11
50781	0.297550E-01	0.153225E+11
50791	0.297609E-01	0.145288E+11
50801	0.297667E-01	0.142451E+11
50811	0.297726E-01	0.135636E+11
50821	0.297784E-01	0.125058E+11
50831	0.297843E-01	0.115449E+11
50841	0.297901E-01	0.109456E+11
50851	0.297960E-01	0.101960E+11
50861	0.298019E-01	0.934618E+10
50871	0.298077E-01	0.862644E+10
50881	0.298136E-01	0.796268E+10

Pressure at x = 1082.0 cm from step 50651 to step 50881. (Small end of high pressure coupling cone is at 1081.514 cm.) The time range of the above table includes the maximum pressure of 0.158553 x 10^{11} dynes/cm^2 = 230,000 psi. Note that PLOTX1 through PLOTX4 have the same variable arrangement as PLOTX5.

PLOTH3

50651	0.29679E-01	0.1074E+04	0.3962E+01	0.5666E+01	0.5901E+09	0.4731E+05	0.1466E+11	0.5889E+03	0.3121E+06	0.1000E+01
50661	0.29685E-01	0.1075E+04	0.3744E+01	0.5675E+01	0.6246E+09	0.4714E+05	0.1575E+11	0.6107E+03	0.3146E+06	0.1000E+01
50671	0.29691E-01	0.1075E+04	0.3533E+01	0.5681E+01	0.6604E+09	0.4673E+05	0.1664E+11	0.6338E+03	0.3164E+06	0.1000E+01
50681	0.29696E-01	0.1075E+04	0.3331E+01	0.5688E+01	0.6988E+09	0.4599E+05	0.1767E+11	0.6585E+03	0.3186E+06	0.1000E+01
50691	0.29702E-01	0.1076E+04	0.3136E+01	0.5693E+01	0.7376E+09	0.4540E+05	0.1853E+11	0.6838E+03	0.3202E+06	0.1000E+01
50701	0.29708E-01	0.1076E+04	0.2950E+01	0.5699E+01	0.7793E+09	0.4444E+05	0.1955E+11	0.7107E+03	0.3222E+06	0.1000E+01
50711	0.29714E-01	0.1076E+04	0.2773E+01	0.5700E+01	0.8201E+09	0.4343E+05	0.2019E+11	0.7380E+03	0.3231E+06	0.1000E+01
50721	0.29720E-01	0.1076E+04	0.2605E+01	0.5704E+01	0.8633E+09	0.4231E+05	0.2106E+11	0.7664E+03	0.3246E+06	0.1000E+01
50731	0.29726E-01	0.1077E+04	0.2446E+01	0.5700E+01	0.9039E+09	0.4116E+05	0.2135E+11	0.7944E+03	0.3245E+06	0.1000E+01
50741	0.29732E-01	0.1077E+04	0.2296E+01	0.5699E+01	0.9465E+09	0.3969E+05	0.2182E+11	0.8235E+03	0.3248E+06	0.1000E+01
50751	0.29737E-01	0.1077E+04	0.2155E+01	0.5691E+01	0.9858E+09	0.3836E+05	0.2179E+11	0.8513E+03	0.3238E+06	0.1000E+01
50761	0.29743E-01	0.1077E+04	0.2024E+01	0.5679E+01	0.1024E+10	0.3665E+05	0.2153E+11	0.8789E+03	0.3222E+06	0.1000E+01
50771	0.29749E-01	0.1078E+04	0.1901E+01	0.5667E+01	0.1060E+10	0.3508E+05	0.2115E+11	0.9054E+03	0.3204E+06	0.1000E+01
50781	0.29755E-01	0.1078E+04	0.1787E+01	0.5650E+01	0.1093E+10	0.3357E+05	0.2042E+11	0.9299E+03	0.3176E+06	0.1000E+01
50791	0.29761E-01	0.1078E+04	0.1682E+01	0.5631E+01	0.1125E+10	0.3190E+05	0.1961E+11	0.9534E+03	0.3146E+06	0.1000E+01
50801	0.29767E-01	0.1078E+04	0.1584E+01	0.5609E+01	0.1156E+10	0.3013E+05	0.1865E+11	0.9757E+03	0.3112E+06	0.1000E+01
50811	0.29773E-01	0.1078E+04	0.1494E+01	0.5584E+01	0.1183E+10	0.2811E+05	0.1747E+11	0.9957E+03	0.3073E+06	0.1000E+01
50821	0.29778E-01	0.1079E+04	0.1413E+01	0.5556E+01	0.1208E+10	0.2586E+05	0.1615E+11	0.1013E+04	0.3030E+06	0.1000E+01
50831	0.29784E-01	0.1079E+04	0.1341E+01	0.5530E+01	0.1230E+10	0.2381E+05	0.1499E+11	0.1028E+04	0.2993E+06	0.1000E+01
50841	0.29790E-01	0.1079E+04	0.1276E+01	0.5502E+01	0.1249E+10	0.2170E+05	0.1371E+11	0.1040E+04	0.2953E+06	0.1000E+01
50851	0.29796E-01	0.1079E+04	0.1219E+01	0.5473E+01	0.1267E+10	0.1931E+05	0.1246E+11	0.1050E+04	0.2914E+06	0.1000E+01
50861	0.29802E-01	0.1079E+04	0.1170E+01	0.5447E+01	0.1281E+10	0.1687E+05	0.1135E+11	0.1058E+04	0.2879E+06	0.1000E+01
50871	0.29808E-01	0.1079E+04	0.1128E+01	0.5420E+01	0.1293E+10	0.1422E+05	0.1022E+11	0.1063E+04	0.2844E+06	0.1000E+01
50881	0.29814E-01	0.1079E+04	0.1095E+01	0.5394E+01	0.1301E+10	0.1118E+05	0.9127E+10	0.1065E+04	0.2812E+06	0.1000E+01

Variables at zone 3 (piston), cell 21 (last internal cell of piston) from step 50651 to step 50881 (same step range as for PLOTX5). The time range of the above table includes the maximum pressure of 0.2181 x 10^{11} dynes/cm^2 = 316,000 psi. Note that PLOTH1, PLOTH2, PLOTH4 and PLOTH5 have the same variable arrangement as PLOTH3.

PRESSVSX

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0.107400E+04  0.150385E+11  0.205506E+11  0.431560E+01  0.234393E+01
0.107425E+04  0.153626E+11  0.207770E+11  0.411791E+01  0.228962E+01
0.107450E+04  0.157212E+11  0.210088E+11  0.392486E+01  0.223531E+01
0.107475E+04  0.161666E+11  0.212464E+11  0.373645E+01  0.218099E+01
0.107500E+04  0.165668E+11  0.214899E+11  0.355267E+01  0.212668E+01
0.107525E+04  0.173117E+11  0.217397E+11  0.337352E+01  0.207236E+01
0.107550E+04  0.180162E+11  0.219962E+11  0.319901E+01  0.201805E+01
0.107575E+04  0.188171E+11  0.222597E+11  0.302913E+01  0.196374E+01
0.107600E+04  0.193692E+11  0.225305E+11  0.286389E+01  0.190942E+01
0.107625E+04  0.200577E+11  0.228092E+11  0.270328E+01  0.185511E+01
0.107650E+04  0.206882E+11  0.230962E+11  0.254730E+01  0.180080E+01
0.107675E+04  0.210313E+11  0.233919E+11  0.239596E+01  0.174648E+01
0.107700E+04  0.215185E+11  0.236970E+11  0.224926E+01  0.169217E+01
0.107725E+04  0.214655E+11  0.240121E+11  0.210718E+01  0.163786E+01
0.107750E+04  0.211459E+11  0.243377E+11  0.196975E+01  0.158354E+01
0.107775E+04  0.206732E+11  0.246748E+11  0.183695E+01  0.152923E+01
0.107800E+04  0.198099E+11  0.250240E+11  0.170878E+01  0.147492E+01
0.107825E+04  0.188529E+11  0.253863E+11  0.158524E+01  0.142060E+01
0.107850E+04  0.184550E+11  0.257628E+11  0.146634E+01  0.136629E+01
0.107875E+04  0.184436E+11  0.261545E+11  0.135208E+01  0.131198E+01
0.107900E+04  0.184322E+11  0.265628E+11  0.124245E+01  0.125766E+01
0.107925E+04  0.184592E+11  0.269892E+11  0.113745E+01  0.120335E+01
0.107950E+04  0.184940E+11  0.274352E+11  0.103709E+01  0.114904E+01
0.107975E+04  0.185672E+11  0.279028E+11  0.941366E+00  0.109472E+01
0.108000E+04  0.186403E+11  0.283942E+11  0.850273E+00  0.104041E+01
```

Section of profile of maximum shot pressure plus other variables along the length of the gun. First column is x distance in cm, second column is maximum shot pressure in dynes/cm^2, third column is gun tube burst pressure in dynes/cm^2, fourth column is inside gun tube area in cm^2 and fifth column is inside gun tube diameter in cm. Note that the last three columns are valid only in the HPC. For the above case, the maximum pressure was 0.215185E+11 dy/cm^2 = 312 ksi at x = 1077 cm.

The x-distances used above for PRESSVSX were chosen to allow the maximum pressure along the entire gun to be examined from the point of view of required tube wall thicknesses, but focusing on the HPC where the highest pressures occur. In the case given above, 323 x-locations were chosen as follows:

x = 40 to 1060 cm at a spacing of 10 cm
x = 1060 to 1090 cm at a spacing of 0.25 cm
x = 1090 to 1390 cm at a spacing of 3 cm

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0.105600E+04	0.000000E+00	0.373055E+03	0.501402E+03	0.372937E+03	0.365218E+03
0.106000E+04	0.000000E+00	0.480310E+03	0.785959E+03	0.479567E+03	0.453082E+03
0.106400E+04	0.171159E-04	0.845934E+03	0.172311E+04	0.844084E+03	0.718292E+03
0.106800E+04	0.107071E-02	0.844849E+03	0.172313E+04	0.840806E+03	0.702208E+03
0.107200E+04	0.155044E-02	0.882026E+03	0.172300E+04	0.867571E+03	0.682042E+03
0.107600E+04	0.102703E-02	0.972657E+03	0.172297E+04	0.960404E+03	0.716873E+03
0.108000E+04	0.000000E+00	0.985012E+03	0.171173E+04	0.972644E+03	0.757473E+03
0.108400E+04	0.344236E-02	0.958630E+03	0.172298E+04	0.942753E+03	0.711366E+03
0.108800E+04	0.396415E-02	0.931838E+03	0.172297E+04	0.917347E+03	0.698053E+03
0.109200E+04	0.394237E-02	0.918046E+03	0.172300E+04	0.904768E+03	0.693138E+03
0.109600E+04	0.391357E-02	0.908649E+03	0.172296E+04	0.896480E+03	0.690465E+03
0.110000E+04	0.389096E-02	0.903795E+03	0.172336E+04	0.892890E+03	0.690149E+03
0.110400E+04	0.383428E-02	0.902225E+03	0.172447E+04	0.893041E+03	0.691393E+03
0.110800E+04	0.378245E-02	0.906081E+03	0.172461E+04	0.898814E+03	0.694478E+03
0.111200E+04	0.372920E-02	0.917460E+03	0.172470E+04	0.911133E+03	0.698517E+03
0.111600E+04	0.365647E-02	0.940512E+03	0.172475E+04	0.932901E+03	0.703288E+03
0.112000E+04	0.358091E-02	0.974881E+03	0.172483E+04	0.963869E+03	0.709208E+03
0.112400E+04	0.347745E-02	0.100165E+04	0.172488E+04	0.991356E+03	0.715798E+03
0.112800E+04	0.335113E-02	0.103151E+04	0.172499E+04	0.101942E+04	0.723584E+03
0.113200E+04	0.321442E-02	0.106110E+04	0.172510E+04	0.104891E+04	0.732210E+03
0.113600E+04	0.304023E-02	0.110222E+04	0.172515E+04	0.108683E+04	0.741697E+03
0.114000E+04	0.285426E-02	0.115126E+04	0.172520E+04	0.112864E+04	0.747871E+03
0.114400E+04	0.266367E-02	0.120325E+04	0.172520E+04	0.117511E+04	0.753836E+03
0.114800E+04	0.244217E-02	0.125068E+04	0.172512E+04	0.121778E+04	0.757933E+03
0.115200E+04	0.221266E-02	0.129524E+04	0.172495E+04	0.125745E+04	0.760682E+03
0.115600E+04	0.195657E-02	0.134346E+04	0.172473E+04	0.130077E+04	0.764420E+03
0.116000E+04	0.169930E-02	0.140143E+04	0.172440E+04	0.135278E+04	0.768019E+03
0.116400E+04	0.144723E-02	0.145944E+04	0.172413E+04	0.140303E+04	0.769382E+03
0.116800E+04	0.120507E-02	0.151227E+04	0.172389E+04	0.144833E+04	0.770196E+03
0.117200E+04	0.956312E-03	0.156488E+04	0.172371E+04	0.149264E+04	0.770328E+03
0.117600E+04	0.711106E-03	0.161349E+04	0.172357E+04	0.153273E+04	0.770780E+03
0.118000E+04	0.493894E-03	0.165176E+04	0.172338E+04	0.156254E+04	0.769819E+03
0.118400E+04	0.313111E-03	0.167841E+04	0.172323E+04	0.158162E+04	0.766377E+03
0.118800E+04	0.160424E-03	0.169893E+04	0.172311E+04	0.159477E+04	0.760885E+03
0.119200E+04	0.269562E-04	0.171312E+04	0.172302E+04	0.160167E+04	0.752986E+03
0.119600E+04	0.000000E+00	0.168656E+04	0.168770E+04	0.157014E+04	0.735877E+03
0.120000E+04	0.000000E+00	0.164604E+04	0.164608E+04	0.152871E+04	0.718494E+03
0.120400E+04	0.000000E+00	0.160955E+04	0.160955E+04	0.149158E+04	0.702616E+03

Variables at x-distances along gun from 1056 to 1204 cm at time projectile passes XMUZ(2) (see section 4.2). Small end of high pressure coupling cell is at x = 1081.514 cm. The x-distances in the table cover the range where there is predicted to be barrel erosion (1064 to 1192 cm). The maximum predicted wall retreat per shot is 0.003964 cm at x = 1088 cm. Note that where there been erosion, the maximum wall temperature reached is 1723 K, the melting point of the gun steel.

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0.000000E+00	0.299999E+03	0.300000E+03
0.585000E-03	0.300000E+03	0.300000E+03
0.181350E-02	0.300000E+03	0.300000E+03
0.316485E-02	0.300000E+03	0.300000E+03
0.465134E-02	0.300000E+03	0.300000E+03
0.628647E-02	0.300000E+03	0.300000E+03
0.808512E-02	0.300000E+03	0.300000E+03
0.100636E-01	0.300000E+03	0.300000E+03
0.122400E-01	0.300000E+03	0.300000E+03
0.146340E-01	0.300000E+03	0.300000E+03
0.172674E-01	0.300000E+03	0.300000E+03
0.201641E-01	0.300000E+03	0.300000E+03
0.233505E-01	0.300000E+03	0.300000E+03
0.268556E-01	0.300000E+03	0.300000E+03
0.307112E-01	0.300000E+03	0.300000E+03
0.349523E-01	0.300000E+03	0.300000E+03
0.396175E-01	0.300000E+03	0.300000E+03
0.447492E-01	0.300000E+03	0.300000E+03

0.000000E+00	0.299999E+03	0.300000E+03
0.585000E-03	0.300000E+03	0.300000E+03
0.181350E-02	0.300000E+03	0.300000E+03
0.316485E-02	0.300000E+03	0.300000E+03
0.465134E-02	0.300000E+03	0.300000E+03
0.628647E-02	0.300000E+03	0.300000E+03
0.808512E-02	0.300000E+03	0.300000E+03
0.100636E-01	0.300000E+03	0.300000E+03
0.122400E-01	0.300000E+03	0.300000E+03
0.146340E-01	0.300000E+03	0.300000E+03
0.172674E-01	0.300000E+03	0.300000E+03
0.201641E-01	0.300000E+03	0.300000E+03
0.233505E-01	0.300000E+03	0.300000E+03
0.268556E-01	0.300000E+03	0.300000E+03
0.307112E-01	0.300000E+03	0.300000E+03
0.349523E-01	0.300000E+03	0.300000E+03
0.396175E-01	0.300000E+03	0.300000E+03
0.447492E-01	0.300000E+03	0.300000E+03

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```
0.000000E+00  0.300331E+03  0.300287E+03
0.585000E-03  0.300321E+03  0.300279E+03
0.181350E-02  0.300302E+03  0.300261E+03
0.316485E-02  0.300282E+03  0.300243E+03
0.465134E-02  0.300262E+03  0.300224E+03
0.628647E-02  0.300240E+03  0.300205E+03
0.808512E-02  0.300219E+03  0.300185E+03
0.100636E-01  0.300197E+03  0.300166E+03
0.122400E-01  0.300175E+03  0.300146E+03
0.146340E-01  0.300153E+03  0.300127E+03
0.172674E-01  0.300132E+03  0.300108E+03
0.201641E-01  0.300113E+03  0.300091E+03
0.233505E-01  0.300094E+03  0.300075E+03
0.268556E-01  0.300078E+03  0.300061E+03
0.307112E-01  0.300065E+03  0.300050E+03
0.349523E-01  0.300055E+03  0.300041E+03
0.396175E-01  0.300050E+03  0.300036E+03
0.447492E-01  0.300050E+03  0.300036E+03


0.000000E+00  0.333448E+03  0.326920E+03
0.585000E-03  0.333344E+03  0.326805E+03
0.181350E-02  0.333128E+03  0.326567E+03
0.316485E-02  0.332892E+03  0.326308E+03
0.465134E-02  0.332636E+03  0.326026E+03
0.628647E-02  0.332359E+03  0.325722E+03
0.808512E-02  0.332061E+03  0.325394E+03
0.100636E-01  0.331743E+03  0.325044E+03
0.122400E-01  0.331406E+03  0.324673E+03
0.146340E-01  0.331053E+03  0.324284E+03
0.172674E-01  0.330689E+03  0.323884E+03
0.201641E-01  0.330321E+03  0.323478E+03
0.233505E-01  0.329960E+03  0.323080E+03
0.268556E-01  0.329619E+03  0.322705E+03
0.307112E-01  0.329319E+03  0.322374E+03
0.349523E-01  0.329085E+03  0.322117E+03
0.396175E-01  0.328951E+03  0.321969E+03
0.447492E-01  0.328951E+03  0.321969E+03
```

There can be 4 blocks of data (as above) or only one block of data. If there are 4 blocks of data, it is recommended to ignore the first three blocks and focus on the fourth block. If there is only one block of data, it will correspond to the fourth block when there are four blocks. The last (or only) data block gives two temperature profiles into the metal of the barrel wall at x-position numbers NCXST1 and NCXST2 along the barrel. The first column is the distance from the barrel wall surface into the metal of the barrel (cm). The second and third columns are the barrel wall temperatures at these locations (K). The first row gives conditions at the barrel wall surface. See also discussion of Appendix J, section on WAHE1OHA. This data is taken at the same time as the data of WAHE1OP

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