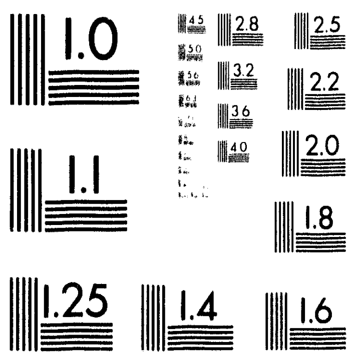
1.0
4.5
5.0
5.6
6.3
2.8
3.2
3.6
4.0
2.5
2.2
2.0
1.1
1.8
1.25
1.4
1.6

1 of 1

Ballistics Considerations for Small-Caliber, Low-Density Projectiles*

M. J. Gouge, L. R. Baylor, S. K. Combs, P. W. Fisher, C. A. Foster, C. R. Foust, S. L. Milora and A. L. Qualls

Oak Ridge National Laboratory
P.O. Box 2009
Oak Ridge, TN 37831-8071
USA

Presented at the
44th Aeroballistic Range Association Meeting
Munich, Germany

ABSTRACT

One major application for single- and two-stage light gas guns is for fueling magnetic fusion confinement devices. Powder guns are not a feasible alternative due to possible plasma contamination by residual powder gases and the eventual requirement of steady-state operation at ~ 1 Hz, which will dictate a closed gas handling system where propellant gases are recovered, processed and recompressed. Interior ballistic calculations for single-stage light gas guns, both analytical and numerical, are compared to an extensive data base for low density hydrogenic projectiles (pellets). Some innovative range diagnostics are described for determining the size and velocity of these small (several mm) size projectiles. A conceptual design of a closed cycle propellant gas system is presented including tradeoffs between different light propellant gases.

*Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

1. INTRODUCTION - BASIC PROJECTILE MATERIAL CONSIDERATIONS

All pellet acceleration concepts (light gas guns, centrifuges, railguns, coilguns) share common technological constraints associated with the unique material properties of the solid hydrogen isotopes [1]. The isotopes of hydrogen (H_2, D_2 and T_2) freeze in the temperature range of 14-20K which necessitates the use of liquid helium cooled components for the production of solid feed material. High vacuum and low heat loss techniques are important design considerations as well as the selection of suitable low temperature, high strength materials. The physical characteristics of hydrogen ice also play an important role especially with respect to acceleration to the projected 1-5 km/s range needed for future reactor grade plasmas [2]. The densities of the solid hydrogen isotopes are low (0.09, 0.20 and 0.32 gm/cc for H_2, D_2 and T_2 respectively) and this is certainly an advantage from the point of view of obtaining large projectile accelerations. For example, 6 mm diameter and length deuterium pellets weigh only about 34 mg and these can easily be accelerated to speeds in excess of 1.5 km/s in acceleration paths of order a meter long with single-stage light gas gun injectors operating at propellant gas breech pressures of ~60 bar (1 bar = 0.1 MPa = 14.5 psi). However, the yield strength of the solid is also small (~ several bar [1]) and this would be expected to place a rather low limit on tolerable acceleration forces. However, in single- and two-stage light gas guns, deuterium pellets have been subjected to accelerations of $5\text{-}9 \times 10^6$ m/s^2 which corresponds to an equivalent acceleration pressure of 60-100 bar. It is believed that the two-dimensional support provided by the gun barrel permits the larger stresses during the acceleration time which is of order 1 ms. Protective support structures called sabots could further increase acceleration limits while also eliminating the problem of pellet surface erosion observed at higher speeds.

2. SINGLE-STAGE LIGHT GAS GUN SYSTEMS

The basic single-stage light gas gun has been used with great success over the past decade in accelerating single and repetitive hydrogenic pellets of diameter from 1-6 mm. The simplest design variant (a single shot configuration) of this device is shown schematically in Fig. 1. A pellet forming or freezing cell is located at the center of a liquid helium cooled cryostat. In the example shown, the cavity is insulated thermally from the gun breech and barrel by polyimide inserts located between the cryostat and the flanged ends of the thin-wall (< 1 mm) stainless steel tubing sections that make up the breech and barrel. Heaters (optional) located close to the freezing cell are used to maintain the temperature of the breech and barrel sections adjacent to the pellet formation zone above the melting point of the hydrogen isotope. During normal operation with the cryostat at ~ 10 K, the gaseous hydrogen isotope is admitted to one or both ends of the freezing cell through the barrel/breech. Within a few minutes the gas condenses and solidifies in the cylindrical cavity. Pellet size is determined by the thickness of the freezing cell, the fill pressure, and the temperature gradients maintained between the freezing cell and the heated sections adjacent to it. The pellet is then discharged from the gun by opening a fast electromagnetic valve [3] that provides a short burst of up to several cm^3 of high pressure hydrogen propellant gas. The ORNL version of this valve develops full pressure within 300 μs and has operated with a supply pressure of up to 240 bar. Transient breech pressures are measured with a sub-miniature quartz piezoelectric pressure transducer (PCB® model 105B12) located in the breech section as shown in Fig. 1. A typical single-stage light gas gun sequence is shown in Fig. 2. The

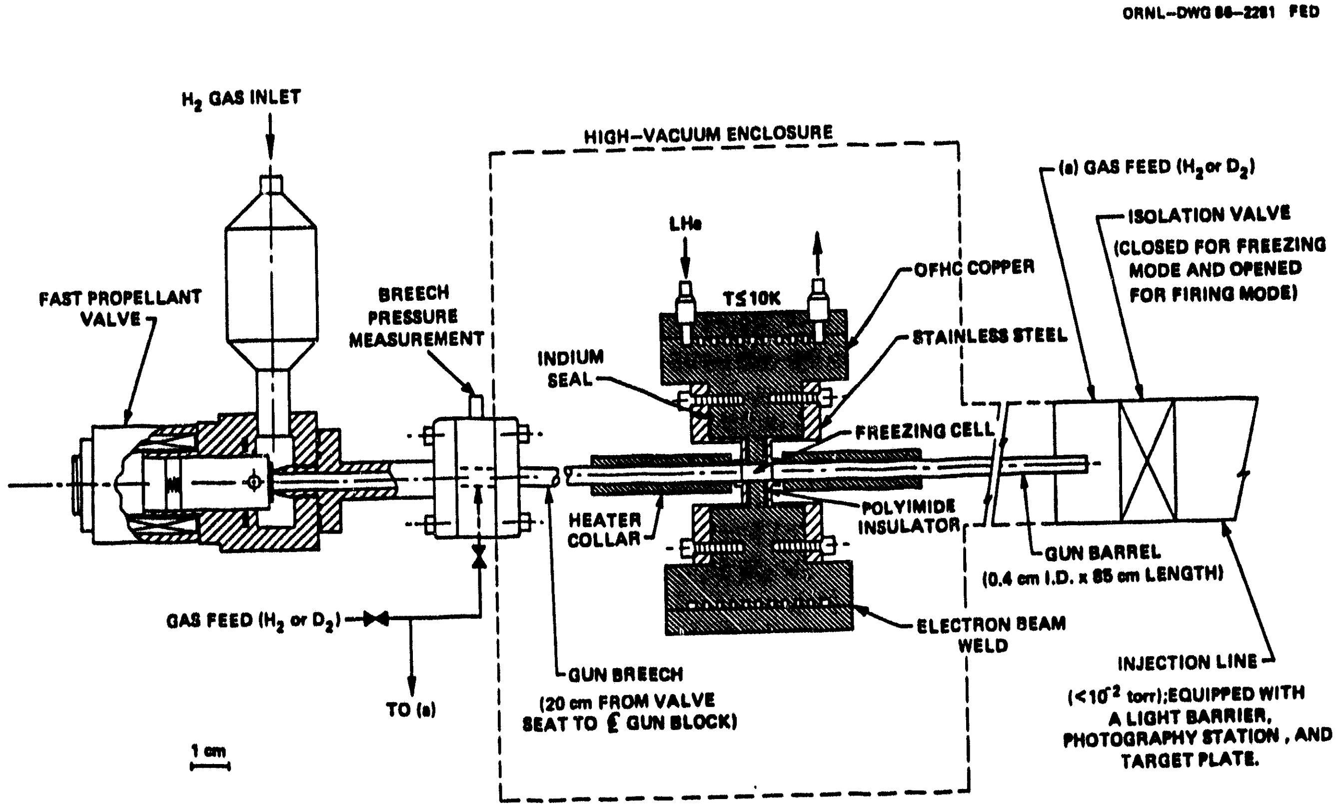

Fig. 1 Typical single-stage light gas gun pellet injector.

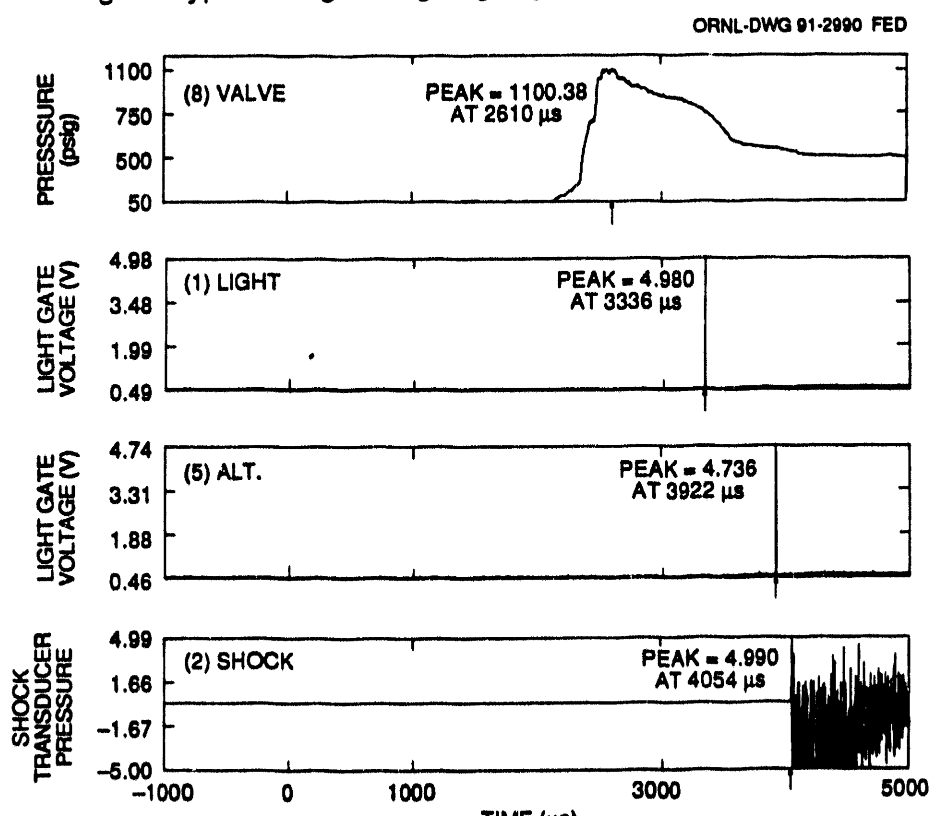

Fig. 2 Single-stage light gas gun shot sequence.

shot sequence is typically initiated with a manual or computer-generated trigger pulse to the fast valve power supply at 0 μs. The breech pressure (top curve) begins to rise about 2 ms after the trigger and reaches its peak about 0.5 ms later. The time between the trigger and the appearance of pressure in the breech is a function of both the amount of free travel in the solenoid-driven valve poppet and delays that can be set in the valve power supply. The power supply also controls the amount of time the valve is held open and the voltage that the solenoid receives. Generally, the peak breech pressure varies almost linearly with supply pressure and is 60% to 90% of the supply pressure for supply pressures from 138 bar to 34 bar. Breech pressure becomes a smaller fraction of supply pressure as the supply pressure is increased because the propellant gas pressure augments the closing force on the valve poppet. Typically before velocity scans are made, the power supply settings are raised until further increases do not increase breech pressure. At this point, breech pressure is limited by valve dynamics alone. However, power supply settings can not be made arbitrarily high because of limitations in the power supply. Therefore, some additional tailing off of velocities at higher supply pressure is unavoidable. However, the effect of power supply and valve dynamics on the results can be reduced by studying the behavior of velocity as a function of breech pressure. Any combination of valve and power supply with a similar time response that delivers the proper breech pressure should produce comparable results. Muzzle velocities are measured by a set of laser or light-emitting diode stations. The pellet crosses the light beam and blocks the normally high signal at a photo diode or transistor. Fig. 2 also shows typical diagnostic signals as the pellet passes the two light gates and strikes the end of the diagnostic line, where the shock is recorded with a quartz piezoelectric shock accelerometer (PCB® model 305A). Pellet velocities discussed in the next section were determined from these diagnostics. The three time signals (two light gates and a target shock) provide some redundancy in the pellet velocity measurement.

3. SINGLE-STAGE LIGHT GAS GUN INTERIOR BALLISTICS

Over the years, substantial data has been generated with single-stage light gas gun systems over a wide range of pellet densities (from hydrogen at 0.09 g/cc to tritium at 0.32 g/cc) and supply/breech pressures. Fig. 3 shows some results from an extensive database for the three pure isotopes of hydrogen plus deuterium-tritium (DT, at a density of 0.25 gm/cc) which have been used as solid projectiles. The performance variation with almost a factor of four variation in projectile density from hydrogen to tritium pellets is apparent. The performance with deuterium is reduced by about 15% relative to the lighter hydrogen pellets. Recent experiments with tritium pellets show a similar reduction relative to the deuterium data.

Several interior ballistics calculation methods have been used to compare data with theory:

- (1) a simple analytical theory based on unsteady, one-dimensional gas dynamics with an infinite barrel and breech section as an implicit assumption [4],
- (2) a more complicated and accurate analytical theory, which takes into account the finite mass of the propellant gas and the finite length of the barrel but ignores reflections of the rarefaction wave at the breech and projectile [5,6],

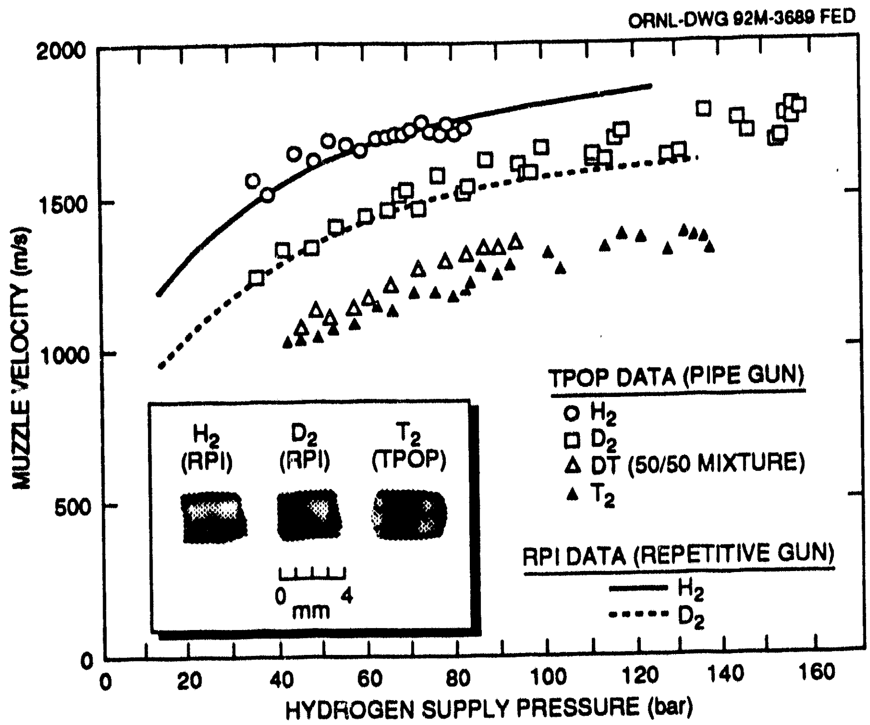

Fig. 3 Performance of single-stage light gas guns with different isotopes of hydrogen

- (3) one-dimensional computer calculations based on the method-of-characteristics which take into account the effects of finite propellant gas mass, actual breech and barrel lengths and all wave reflections [7],
- (4) one-dimensional computer calculations based on the method of finite differences which take into account all of the above effects plus gas friction due to viscosity-related losses [8].

In method (1), the basic single-stage light gas gun can be modeled analytically by assuming that the pellet accelerates in an infinite tube of constant cross section (i.e. infinite breech and barrel). The motion of the pellet is then governed by the propagation of simple rarefaction waves into the high pressure medium. Neglecting non-ideal effects such as friction at the projectile-tube interface, heat transfer, and viscosity, the pellet velocity U(t) at time t after the sudden application of the propellant gas at pressure P_o is given by:

$$U(t) = \frac{2C_o}{\gamma - 1}\left\{1 - \left[1 + \frac{(\gamma+1)\,A_p}{2M_p\,C_o}\,P_o\,t\right]^{-(\gamma-1)/(\gamma+1)}\right\}$$

where C_o is the (assumed constant) propellant gas sound speed at room temperature, γ is the ratio of specific heats, M_p is the projectile mass, and A_p is the projectile base area. This result illustrates several important points concerning the acceleration of the hydrogen isotopes. First, high performance is possible with relatively low forces (pressures) since the projectile mass is small. Secondly, a high sound speed is required for high speed operation and this favors low molecular weight gases and high temperature. The relative effect on performance due to different light propellant (H_2, D_2, He) gases as predicted by equation (1) is shown in Fig. 4. This is useful information as there may be safety or technical considerations related to gas separation which would lead to a consideration of other propellant gases than hydrogen, which is obviously the best choice based on interior ballistics considerations alone. In Fig. 5 experimental data from the Tritium-Proof-of-Principle (TPOP) injector [9] with solid deuterium pellets is shown as well as results from the ideal unsteady gas calculations of method (1); it can be seen that this simple theory generally over predicts measured performance by about 15%. Note that the horizontal axis is not breech pressure, but rather G/M_p, the ratio of propellant gas mass to projectile mass. In all cases presented in Fig. 5, both experimental data and modeling, the breech length was 0.19 m, the barrel length was 1.0 m and hydrogen propellant gas was used. Although the ideal theory itself does not give an accurate prediction of the muzzle velocity, it does give a good representation of the shape of the curve. The saturation in velocity shown in Figs 4 and 5, which occurs at about 1.5-2 km/s is due to the fact that the pellet is traveling at speeds greater than the local sound speed. At velocities above ~ 1.5 C_o, pressure pulses emanating from the breech of the gun can not propagate quickly enough in the cold gas that fills the barrel and consequently the pressure at the base of the pellet which is responsible for the acceleration is reduced substantially below the breech pressure P_o.

Method (2) was the result of intense analytical effort in the 1920s and 1930s to solve the long-standing Lagrange ballistics problem by R. P. Pidduck [5] and, later, R. H. Kent [6]. Fig. 5 has two curves based on their work, one that is built on an expansion in G/M_p terms that is only valid for $G/M_p \ll 1$ and the other based on a polynomial fit to an implicit equation in G/M_p, which was done over the range $0.4 < G/M_p < 6$. As can be seen the former curve fits the data well through G/M_p values up to 0.7-0.8 as expected. The latter

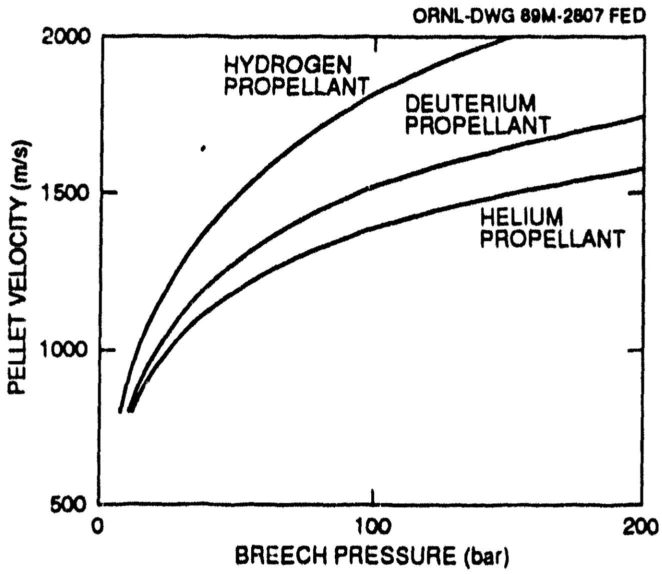

Fig. 4 Relative performance of single-stage light gas guns with different propellant gases.

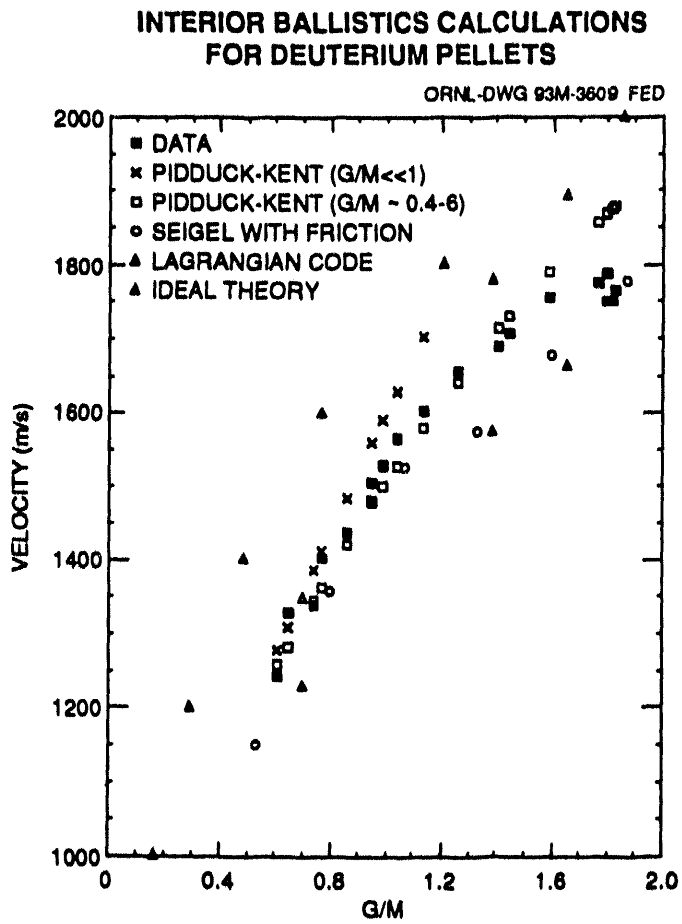

Fig. 5 Comparison of the performance of single-stage light gas guns with theory.

curve fits the data over a broader range; there begins to be disparity for velocities above 1.7 km/s due to the practical effect of approaching the performance limit of the propellant valve power supply. One assumption in the theory is an initial negative gradient in the breech pressure and density which is not the true initial condition; nevertheless, at large enough projectile travel down the barrel, the observed pressure gradient from the breech to the base of the projectile is well represented by this analytic theory. The fundamental value of this theory has decreased as modern numerical methods and computer capability permit rapid calculations with more realistic initial conditions and loss terms but this method can be easily programmed into a hand-held calculator to allow real time evaluation of range data.

Method (3) is based on the extensive calculations of A. E. Seigel [7] who made generic numerical calculations of muzzle velocity using the basic assumptions of an ideal gas model with the amount of propellant gas being limited by the length of the breech tube behind the pellet. The calculations represent the actual geometry of the single-stage light gas gun, including finite barrel and breech chamber lengths as well as the option for an increase of breech chamber diameter over barrel diameter which is not used in this present analysis. The generic, dimensionless curves presented by Seigel were developed using both the method-of-characteristics and an early Lagrangian code with no losses. Results are presented in plots of dimensionless velocity (U/C_0) vs. dimensionless length of travel $\{(P_0A_pL/(M_pC_0^2)\}$ for various values of the parameter G/M_p, where G is the mass of propellant gas in the breech of the gun and L is the length of the barrel. To estimate the effect of finite G/M_p in the present experiments it was assumed that G could be calculated from the volume of propellant trapped between a pellet in the freezing zone of the cryostat and the face of the poppet of the fast valve and the measured peak breech pressure. The effect of friction was estimated from an empirical relationship developed at the U.S. Naval Ordnance Laboratory [7], in which the ratio of the actual velocity to the predicted frictionless velocity is a function of the dimensionless frictionless velocity. Velocity predictions based on this correlation, shown in Fig. 5, are in good agreement with the data.

Method (4) is based on a more recent Lagrangian finite-difference code [8] has the following capabilities for modeling either single-stage or two-stage light-gas guns:

- Lagrangian formulation of the finite difference representation of the one-dimensional differential equations of continuity, motion, and energy.
- Shocks that form in the pump tube and barrel are treated by the artificial viscosity method of von Neumann and Richtmyer, which spreads out shocks due to dissipative effects such as viscosity and heat conduction.
- The code can model either real (variable specific heat) or ideal gases.
- Non-ideal effects can be included:
  - piston friction and plastic deformation,
  - heat transfer from gas to wall, and
  - smooth wall or constant factor gas friction.

When the code was used in the single-stage light gas gun mode to model TPOP injector data, the best agreement was obtained using the ideal gas equation-of-state with smooth wall gas friction (see Fig. 5). The actual experimental data, for a given G/M_p, is in between the code results for runs with and without gas friction losses.

Overall, Methods (2), (3) and (4) provided fairly good fits to the experimental data. It is of interest to calculate where the projectile is located in the barrel at the point when the first rarefaction wave reflected from the breech reaches the base of the projectile. A simple analytical approximation to calculate this is in reference [7] :

$$\frac{L_{p1st}}{L_o} \approx 2.5\,\frac{P_0A_pL_o}{M_pC_0^2} \approx 2.5\,\frac{G}{M_p\gamma}$$

where L_o is the breech length (0.19 m for all cases in Fig. 5) and L_{p1st} is the location of the projectile relative to its starting position when the first rarefaction wave reaches it. In Fig. 5, $L_{p1st} \approx 0.2$ m for the lower values of $G/M_p \sim 0.4$ and increases to $L_{p1st} \approx 0.6$ m for the highest values of $G/M_p \sim 1.8$. Thus, in all cases in Fig. 5, the ratio of barrel to breech length is sufficiently large that the projectile feels the 1st reflected rarefaction wave. For the higher values of G/M this is not a major constraint as the projectile is already going faster than the sound speed at the position of L_{p1st}.

4. RANGE MASS DIAGNOSTICS FOR SMALL PROJECTILES

The most common methods of determining final (accelerated) pellet mass are direct photography and microwave cavity perturbation. In the first method, a short-pulse (several ns) light source (for example, a nitrogen-dye laser) illuminates the pellet to produce a CCD or CID camera image on a single video frame. The light source is triggered by a circuit that detects the pellets as they interrupt a light gate. This method is usually reliable close to the gun muzzle, but triggering becomes more difficult farther downrange because of inherent dispersion in the pellet trajectory. Dispersion also complicates precise size determination because image size is a function of distance from the camera. The second method of measuring relative mass is based on the perturbation caused by the dielectric pellet to a tuned microwave cavity [10]. This measurement, based on a volume dielectric perturbation by the pellet, gives no information on the shape or orientation of the accelerated pellet. A potential problem with the method (depending on the cavity mode used) is that the perturbation can be a nonlinear function of the distance of the center of mass of the pellet from the cavity axis. As an example, for a cavity tuned for the TM_{010} mode with the axis perpendicular to the pellet's path, the microwave power density varies as the square of a first-order Bessel function argument of the pellet's radial position relative to the cavity axis.

To eliminate some of these problems and take advantage of the inherent strengths of each method, a combined microwave cavity/photographic diagnostic station was developed and tested with high-speed cryogenic deuterium and plastic projectiles. Earlier microwave cavities for hydrogenic pellets had been in the 5- to 10-GHz range, and the resulting small cavity dimensions (cavity diameter 2–4 cm) made the addition of windows for photography impractical. In this particular application, the high-speed projectile passes through a 3.5-cm-i.d. guidetube which extends over 1.6 m from the gun muzzle. A cylindrical cavity was designed (cavity diameter of 7.12 cm and height of 6.98 cm) with pass-through ports for the pellet equal to the diameter of the guidetube. The cavity frequency was 3.219 GHz (wavelength 9.313 cm) based on excitation of the TM_{010} cavity mode. This rather large cavity permitted the addition of 2.5-cm-diameter windows perpendicular to the pellet flight path so that pellets could be photographed while traversing the cavity. Fig. 6 is an elevation view of the assembled cavity that indicates general details of the design. The cavity is made of stainless steel, because Conflat seals are used for connection to the pellet injection line, which is operated in a vacuum. The cavity was copper plated to enhance the Q factor by reducing the skin depth of the cavity surface material. The perturbation caused by the shift in cavity frequency due to entry of the pellet is detected by the microwave crystal detector and used to trigger a pulsed laser, which illuminates the pellet. The laser light is transmitted via fiber optics to a window and lens arrangement on a port at the end of the cylindrical cavity; the camera viewing port is at the opposite end. In principle, the cavity response can be calibrated with the physical pellet dimensions from the photograph to obtain an absolute mass measurement. The photograph can also eliminate ambiguity caused by the actual location of the pellet in the cavity. This could also be eliminated by using smaller pellet pass-through ports where feasible.

Figure 7 shows an amplified cavity response signal from an approximately 3.4 × 4.3-mm (mass ~7–8 mg) deuterium pellet traveling at 1.4 km/s and a photograph of the actual pellet taken through the cavity window. The circular (25-mm-diam) window can be seen in the photograph; the pellet is traveling horizontally from left to right. The horizontal axis is a time signal relative to a trigger generated when the pellet interrupted a photo diode signal near the muzzle of the barrel. This can be related to

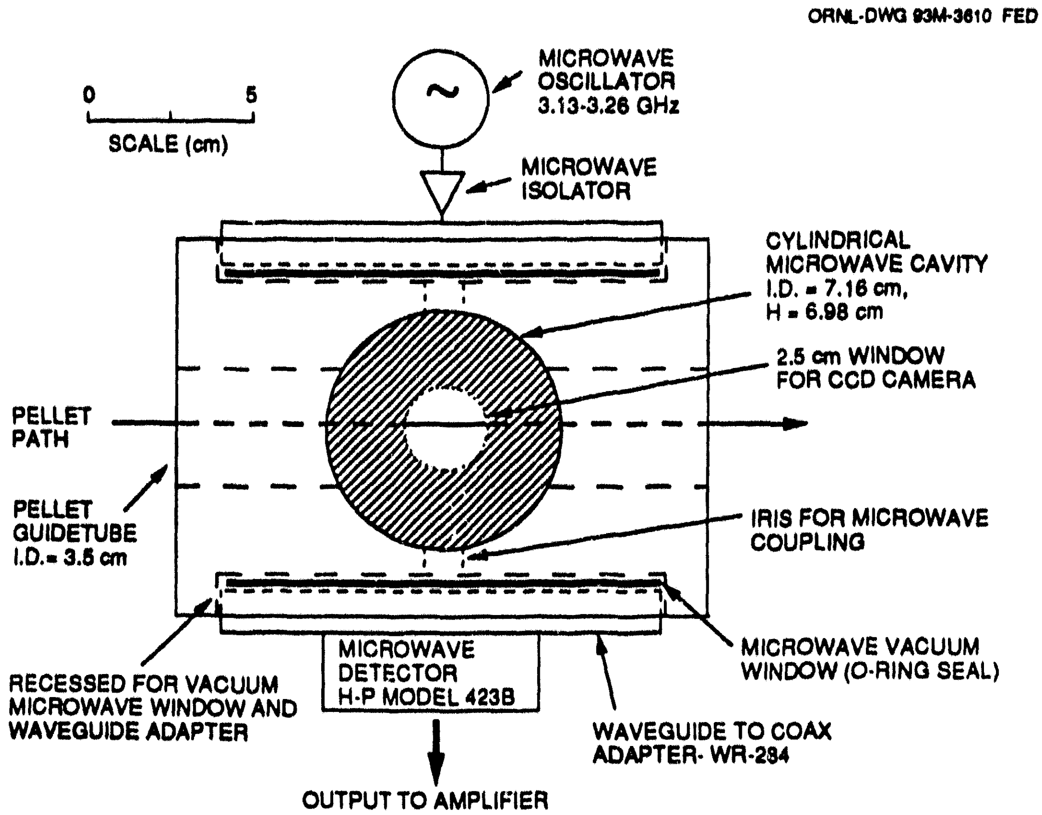

Fig. 6 Elevation view of the microwave cavity

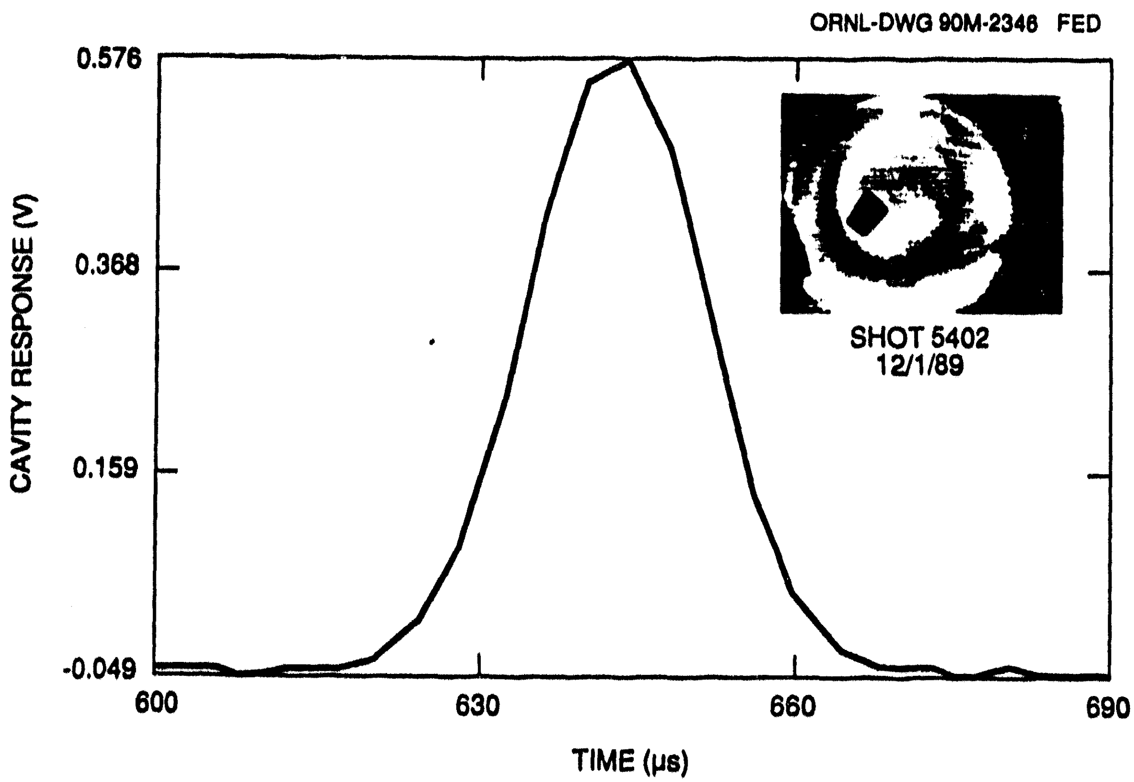

Fig. 7 Measured response of the microwave cavity to the 1.4 km/s deuterium pellet shown in the inset photograph

distance from the muzzle trigger by multiplying the time signal by the pellet velocity. The signal strength is measured in volts from the microwave detector and amplifier circuit. The signal maximum in Fig. 7 corresponds to the pellet traversing the center of the cavity. The change in the voltage signal is related to the frequency shift of the cavity caused by the dielectric pellet volume perturbation of the cavity. For this shot, the pellet perturbation resulted in a measured (unamplified) voltage change of 0.061 V. This is consistent with a calculated value of 0.057–0.066 V for the cavity response [10] based on the pellet size (mass) range of 7–8 mg and orientation in the cavity obtained from the photograph. For these calculations, a relative dielectric constant of 1.33 for deuterium was used.

The signal can also be used for a projectile speed measurement. Even though the signal is extended in time because of the cavity dimensions (see Fig. 7), it has been confirmed that the signal peak is at the center of the cavity, which is geometrically well defined. Speeds calculated from the peak cavity signal and a second time point agree within a few percent with other independent speed measurements made using light gates and target time signals from a shock transducer.

5. STEADY-STATE PROPELLANT GAS PROCESSING SYSTEM

All pneumatic injectors, whether single- or two-stage, use a light propellant gas to accelerate the pellets and a consideration for fusion reactor design is ensuring that only a small amount of this hydrogen or helium propellant gas is introduced into the plasma vacuum vessel (≤ 0.1-1.0 mbar-l/s). If one uses deuterium as a propellant gas, the leakage rate to the torus can be much higher (≤1-10 mbar-l/s) since the propellant gas is also the fuel gas for the DT fusion reaction. This simplifies the design of the vacuum pumping system. For pneumatic injectors, there are three potential light gases for pellet acceleration: hydrogen, deuterium and helium. The sound speed C_o and what is called in interior ballistics theory the "escape velocity" U_e are defined below:

$$C_o = \sqrt{\frac{\gamma R T}{M}} \qquad U_e = \frac{2 C_o}{\gamma - 1}$$

where γ is the ratio of specific heats, T is the gas temperature (room temperature for the single-stage light gas guns), M is the gas molecular weight and R is the universal gas constant. The escape velocity, which is never realized in practice, is that velocity attained by a projectile undergoing an ideal isentropic acceleration in a semi-infinite tube when the gas pressure behind the projectile decreases to zero. Both of these parameters are figures of merit for the choice of gas in pneumatic injectors. Hydrogen gas has the highest sound speed and escape velocity with values of 1310 m/s and 6550 m/s, respectively. For this reason hydrogen is normally used for the propellant gas in contemporary light gas guns. Helium is also used to avoid safety complications of designing exhaust systems for hydrogenic gases. The relative pellet muzzle velocity at a given propellant gas pressure for hydrogen, deuterium and helium is shown in Fig. 4. The muzzle velocities on the vertical axis are from ideal gun theory and in practice higher breech pressures would be required for a given muzzle velocity.

As stated above, hydrogen propellant gas leakage criteria into the fusion vacuum vessel is of order 0.1-1.0 mbar-l/s as this gas is an impurity for deuterium or DT plasmas. This value is much smaller than the propellant gas load used to accelerate the pellet. For a fusion plant at ~ 1 GW thermal power level, a refueling rate of about 1.2×10^{22} DT molecules/s is required [2]. With an pellet erosion mass loss of 30%, this requires injection of ~ 8 x 8 mm cylindrical DT pellets at a rate of ~ 1 Hz (if pellets provide all the fueling). This requires of order 1300 mbar-l/s of hydrogen propellant gas for a single stage light gas gun accelerating these ~ 100 mg pellets to speeds of 1.4-1.5 km/s. The design propellant gas load for the vacuum pumping system is set at 2500 mbar-l/s to provide capability for higher repetition rates for transients or operation at higher plasma densities. Fig. 8 shows a schematic of a differentially-pumped vacuum injection line which would use tritium-compatible vacuum pumps and limits hydrogen propellant gas leakage to the vacuum vessel to less than 0.1 mbar-l/s. To accomplish this goal, the pneumatic pellet injector(s) are isolated from the torus by a series of three separately-pumped vacuum chambers (volumes of ≤ 1 m^3) connected by conductance-limiting pellet guide tubes and flow-limiting fast-acting valves.

From the exhaust of the various vacuum pumps the propellant gas (H_2, D_2 or He) and fuel gas (D_2, T_2) from pellet erosion losses in the barrel has to be separated and then, in the case of the propellant gas, recompressed to ~100-200 bar. Hydrogen propellant gas separation from the DT fuel gas requires substantial cryogenic isotope separation columns for real time reprocessing. A simpler approach is to accept the modest velocity reduction with helium propellant gas (see Fig. 4); this allows the simpler task of separating the DT erosion gases from the He propellant stream. The He propellant is separated from the pellet erosion DT gas by a real time process such as Pressure Swing Absorption (PSA) which has been proposed for fusion breeder blanket gas processing. The helium would have to removed to high purity levels in the recycled DT feed gas as helium is noncondensible and leads to very poor quality hydrogenic solids due to the presence of voids in the cryogenic pellets. Fig. 9 shows a schematic of a closed cycle helium propellant system for a repetitive single-stage light gas gun for continuous fusion reactor refueling. Another option is to employ lower velocity (~1 km/s) centrifuge injectors for edge fueling which do not require propellant gas.

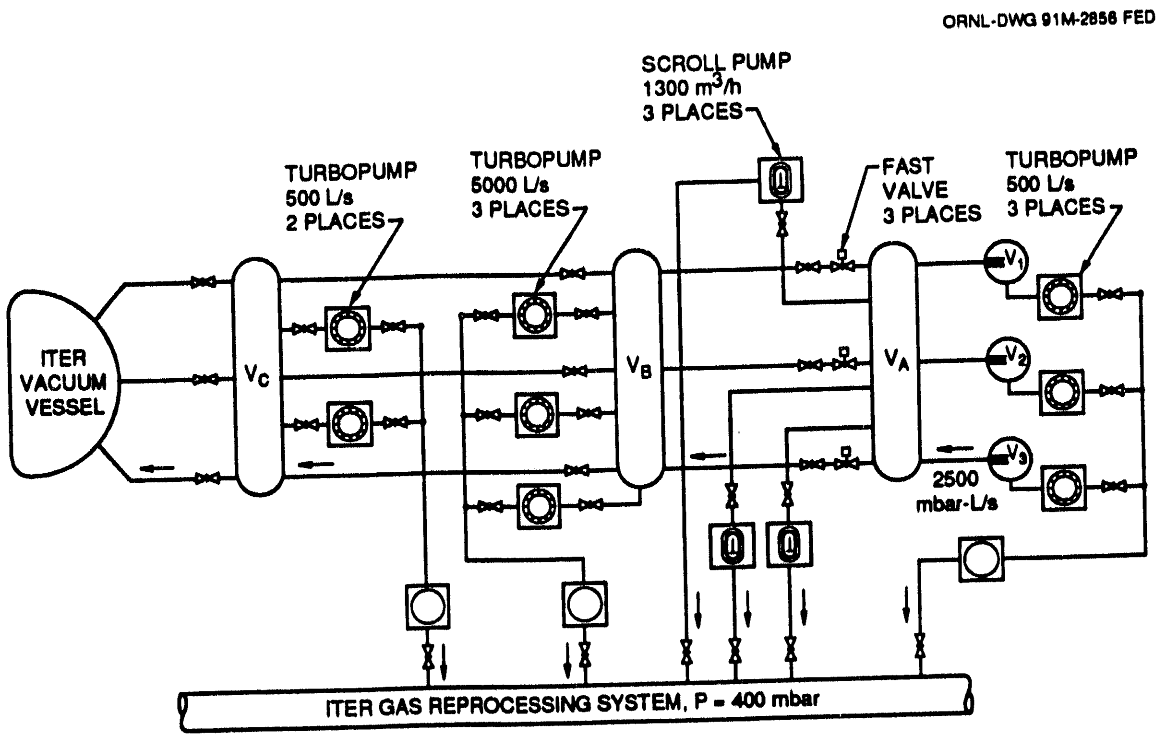

Fig. 8 Conceptual sketch of a differentially pumped pellet injection line

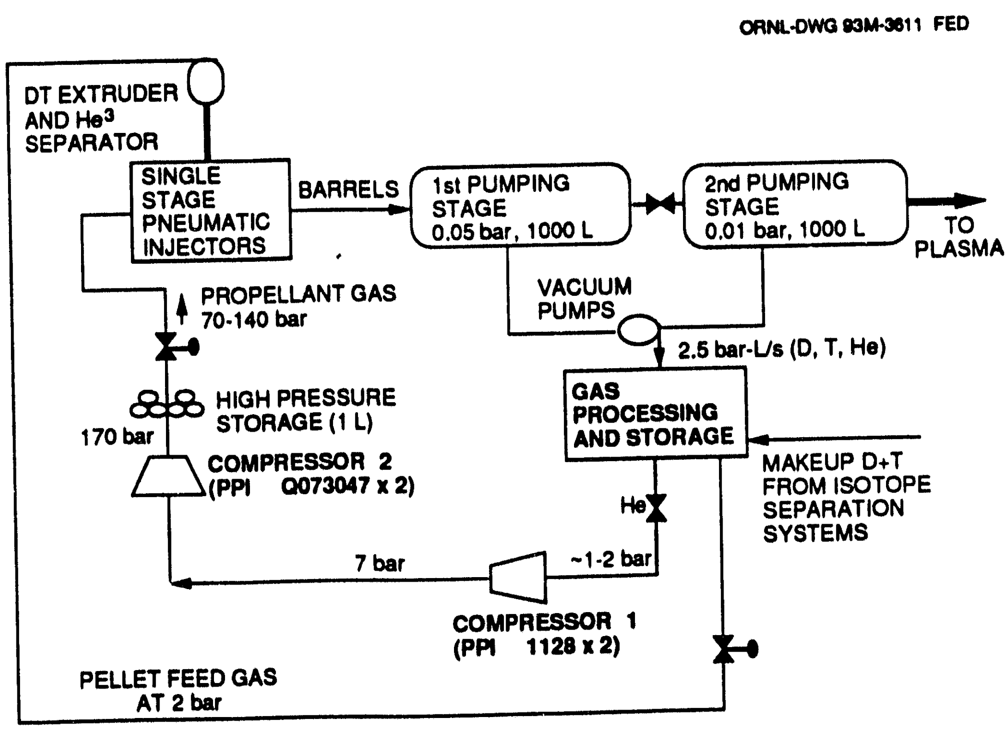

Fig. 9 Conceptual sketch of closed loop propellant gas reprocessing system

REFERENCES

[1] P. C. Souers, *Hydrogen Properties for Fusion Energy*, University of California Press, Berkeley, 1986.

[2] M. J. Gouge, K. D. St. Onge, S. L. Milora, P. W. Fisher and S. K. Combs, "Pellet Fueling System for ITER," *Fusion Engineering and Design* **19** (1), p. 53, (1992).

[3] S. L. Milora, S. K. Combs, and C. R. Foust, "Fast-Opening Magnetic Valve for High Pressure Gas Injection and Applications to Hydrogen Pellet Fueling Systems," *Rev. Sci. Instrum.* **57**, 2356 (1986).

[4] L. D. Landau and E. M. Lifshitz, *Fluid Mechanics*, Pergamon Press, London, 1959.

[5] A. E. H. Love and R. P. Pidduck , *Phil. Trans. Royal Soc.* **A222**, 167 (1921).

[6] R. H. Kent, "Some Special Solutions for the Motion of the Powder Gas," *Physics* **7**, 319 (1936).

[7] A. E. Seigel, *The Theory of High Speed Guns,* AGARDograph-91, NATO AGARD Fluid Dynamics Panel (May 1965).

[8] M. J. Gouge, S. K. Combs, P. W. Fisher, and S. L. Milora, "Design Considerations for Single-Stage and Two-Stage Pneumatic Pellet Injectors," *Rev. Sci. Instrum.* **60**, 570 (1989).

[9] P. W. Fisher, "Tritium Proof-of-Principle Pellet Injector," Oak Ridge National Laboratory Technical Report ORNL/TM 11781 (1991).

[10] M. J. Gouge, S. K. Combs, and S. L. Milora, "A Combined Microwave Cavity and Photographic Diagnostic for High Speed Projectiles," *Rev. Sci. Instrum.* **61**, 2102 (1990).

DATE

FILMED

12/30/93

END