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Design Considerations for Single-Stage and Two-Stage Pneumatic Pellet Injectors

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ABSTRACT

Performance of single-stage pneumatic pellet injectors is compared with several models for one-dimensional, compressible fluid flow. Agreement is quite good for models that reflect actual breech chamber geometry and incorporate nonideal effects such as gas friction. Several methods of improving the performance of single-stage pneumatic pellet injectors in the near term are outlined. The design and performance of two-stage pneumatic pellet injectors are discussed, and initial data from the two-stage pneumatic pellet injector test facility at Oak Ridge National Laboratory are presented. Finally, a concept for a repeating two-stage pneumatic pellet injector is described.

INTRODUCTION

Oak Ridge National Laboratory (ORNL) has been developing pneumatic pellet injectors for about ten years to supply hydrogenic fuel for magnetic confinement devices.[1–11] All previous designs have been based on single-stage pneumatic injectors that use high-pressure hydrogen gas (50–120 bar) to accelerate frozen hydrogen and deuterium pellets with masses in the milligram range to velocities of 800–1800 m/s. Higher velocities are desired to provide deeper penetration into high-temperature plasmas. Several development programs are in place for providing pellet velocities in the range of 2–5 km/s (electrothermal guns,[12] two-stage pneumatic guns) and 5–10 km/s (electron-beam accelerator pellet injector[13]). This paper concentrates on simple improvements to single-stage pneumatic guns to achieve moderate gains in velocity and on the design of a two-stage pneumatic system for large gains in pellet terminal velocity. One of the goals of the high-velocity pellet injector development program is to determine, given the strength of solid hydrogenic pellets, the limits on peak acceleration and, therefore, terminal velocity for a finite barrel length (accelerator path) on the order of 1–2 m.

I. IMPROVEMENTS OF SINGLE-STAGE PNEUMATIC GUNS

A. Background

There is a large body of data on the performance of pneumatic single-stage pellet injectors. Performance is usually specified by plotting pellet terminal velocity vs supply or breech pressure of hydrogen gas supplied to the back end of the pellet via a fast (1- to 2-ms), high-pressure valve. Factors determining performance include the accelerating gas type (usually hydrogen), accelerating gas pressure and temperature, pellet specific gravity, pellet length, and barrel length. Perhaps the largest data base is for the repeating pneumatic injector (RPI),[5] developed at ORNL in 1982–1985 for use on the Tokamak Fusion Test Reactor (TFTR). Figure 1 shows results for 3.4-mm-diam by 4-mm-long deuterium pellets with a 0.785-m barrel. A simple analytic theory[14] based on the similarity principle can be used to predict performance scaling of single-stage pneumatic guns. The theory assumes nonsteady, isentropic, one-dimensional (1-D) gas flow in an infinite pipe of constant radius accelerating a projectile of mass m. At time $t = 0$, a supply pressure, p_0, is applied to one side of

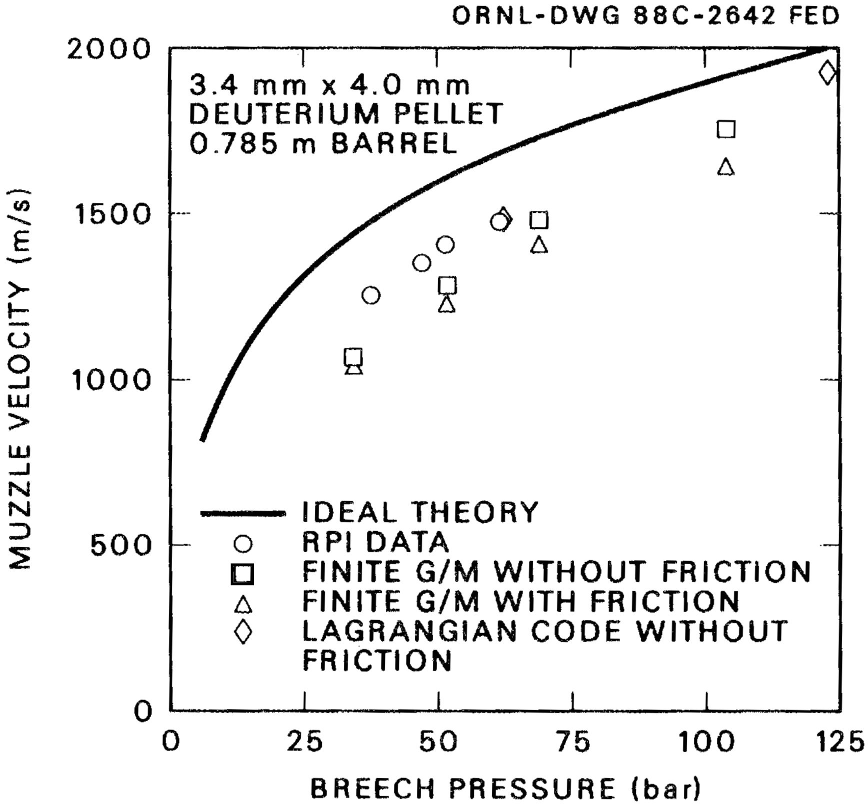

Fig. 1. RPI data.

the projectile (breech side), which has a vacuum on the other (muzzle) side. The equation of motion of the projectile is[14]

$$m\frac{du_p}{dt} = p_0\left[1 - \frac{1}{2}\frac{(\gamma - 1)u}{c_0}\right]^{2\gamma/(\gamma-1)} , \tag{1}$$

where u_p is the projectile (pellet) velocity, c_0 is the initial sound velocity, and γ is the ratio of specific heats.

Equation (1) can be integrated to give

$$u_p(t) = \frac{2c_0}{\gamma - 1}\left\{1 - \left[1 + \frac{(\gamma + 1)p_0 t}{2mc_0}\right]^{-[(\gamma-1)/(\gamma+1)]}\right\} . \tag{2}$$

For a given barrel length L, a muzzle velocity can be computed if p_0, c_0, γ, and m are known. This has been done in Fig. 1 where the ideal theory predicts consistently higher muzzle velocities than those observed experimentally. For this particular pneumatic injector, a good fit to the empirical data is obtained by decreasing the ideal performance by about 15%. It is believed that the 15% reduction is due to some or all of the following factors:

1. Friction and heat transfer effects in the barrel, which make the process non-isentropic.
2. Finite time to cycle the high-pressure propellant valve (on the order of 1 ms).
3. Reflection of the rarefaction wave from the fast valve to the pellet while the pellet is still in the barrel, which reduces the pressure behind the pellet.
4. Finite volume of accelerating gas behind the pellet (the ideal theory assumes an infinite volume).

The purpose of the present study is to determine if the ideal theory can be modified to give better agreement with the experimental data through increased understanding of these nonideal effects. A second objective is to identify simple modifications to single-stage pneumatic injectors that would improve performance by 10–30% in the near term.

B. Effects of finite chamber and barrel length

Relevant geometry is shown in Fig. 2. The chamber is defined as the region between the fast propellant valve and the pellet. Initially, we assume that the chamber diameter D_C equals the barrel diameter D. This is the case for the RPI and is usually the case except with very small pellets.

If the chamber length is finite, then the mass of the accelerating gas is finite and Eq. (1) is no longer strictly valid. In particular, the rarefaction wave is reflected

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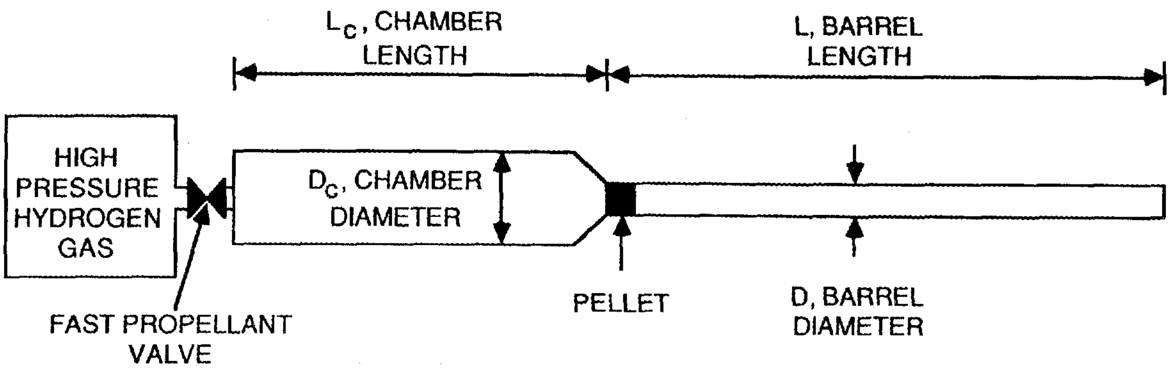

Fig. 2. Simplified pneumatic injector geometry.

from the breech end and, when it reaches the area behind the projectile, lowers the pressure of the gas and reduces projectile velocity relative to the ideal case of infinite chamber length. A convenient parameter to reflect the finite chamber effect is the dimensionless coefficient G/M, which is the ratio of the mass of propellant gas (now finite due to the finite chamber length, L_C) to the mass of the projectile[15]:

$$\frac{G}{M} = \frac{\gamma p_B A(L_C)}{m c_0^2} , \tag{3}$$

where m is the pellet mass and A the cross-sectional area of the chamber. For the conditions of Fig. 1 [$\gamma = 1.4$, $c_0 = 1309$ m/s, $A = \pi(1.7 \times 10^{-3}$ m$)^2$, $L_C = 0.12$ m, $m = 7.26 \times 10^{-3}$ g], the dimensionless value G/M is shown vs p_0 in Table I for the RPI gun. In Table I, X_B is the dimensionless barrel length,

$$X_B = \frac{p_B \pi D^2 L}{4 m c_0^2} , \tag{4}$$

where L is the physical barrel length and D is the barrel diameter.

In Eqs. (3) and (4), p_B is the breech pressure, which is defined as the maximum pressure developed in the chamber due to cycling of the fast propellant valve. The design and performance of the fast propellant valve are described in Ref. 16. Typically, the breech pressure is 50–75% of the supply pressure of the propellant gas. Figure 3 shows pellet release pressure as a function of pellet length. These data are from experiments on the Tritium Proof-of-Principle (TPOP) injector[17] at ORNL with helium propellant gas and a commercial solenoid valve. Typical release

Table I. Results from RPI gun.

p_B (bar)	G/M	X_B	u_p/c_0
34.5	0.42	1.97	0.82
51.7	0.63	2.96	0.98
69.0	0.84	3.95	1.13
89.7	1.10	5.13	1.26
103.4	1.27	5.92	1.34
117.2	1.44	6.71	1.40
131.0	1.61	7.50	1.44
144.8	1.77	8.29	1.48

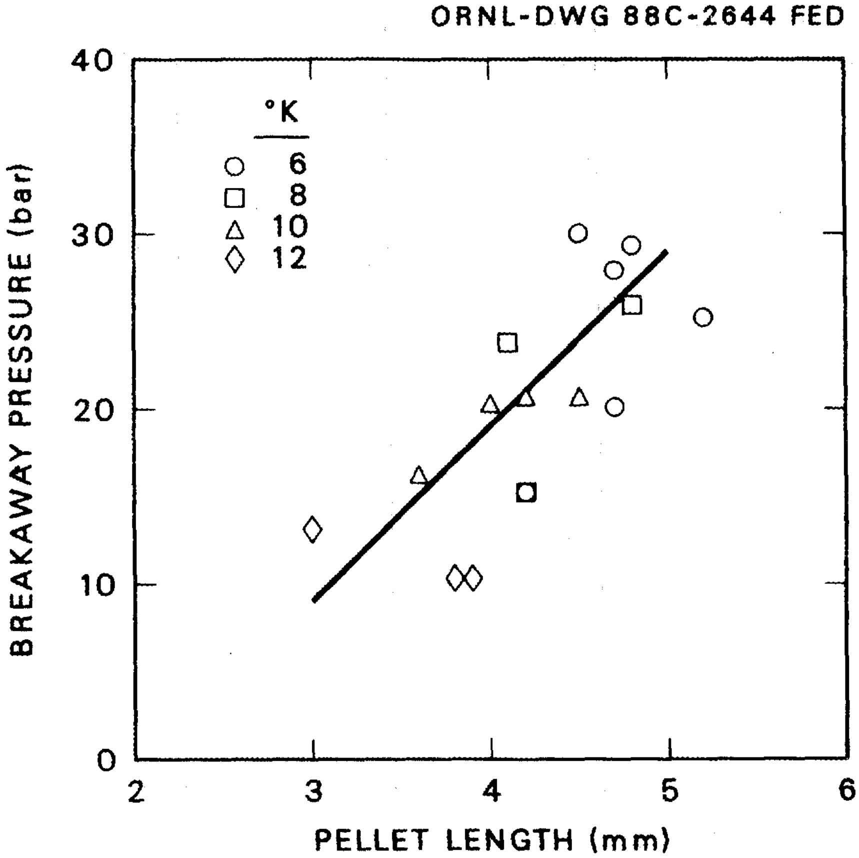

Fig. 3. Pellet release pressure vs pellet length.

pressures are 15–30 bar for deuterium pellets with a nominal length of 4 mm. Since the pellet release pressure is much lower than typical breech pressures (50–100 bar), the pressure pulse from the fast valve shears the frozen pellet and starts it in motion before the peak breech pressure is realized. This incremental volume growth with time and transient choke flow effects through the fast valve account for the lower breech pressure relative to supply pressure.

This calculation assumes that the volume between the fast valve and the pellet determines the mass of the propellant gas. Calculations of the performance of single-stage light gas guns with finite chamber length require numerical solutions because of the multiple reflections from the back chamber wall, which, in the present case, is the vertical fast valve surface. Results based on generic numerical calculations by Seigel[15] are shown in Fig. 1 for a barrel length of 0.785 m. Shown also are the same data corrected for effects of gas friction and heat transfer on the basis of experimental work done at the U.S. Naval Ordnance Laboratory,[18] which is summarized in Fig. 4. Figure 4 shows that friction/heat transfer effects become important for $\gamma u_p/c_0 \geq 1.5$. For pneumatic pellet injectors working with room-temperature hydrogen gas, the friction/heat transfer loss is typically 3% at 1000 m/s, 6% at 1500 m/s, and 9% at 2000 m/s. A review of Fig. 1 indicates that the numerical calculations with finite chamber volume and gas friction/heat transfer effects are within 5–8% of the RPI data.

Also shown in Fig. 1 are two points for the RPI that were calculated with the finite difference Lagrangian ballistics code[19] described in Sec. III. This code models the actual RPI geometry effects, such as finite chamber volume and barrel length, and can also incorporate heat transfer, gas friction, and effects due to shocks. Again, agreement with the RPI data is excellent. It can be seen that, to achieve

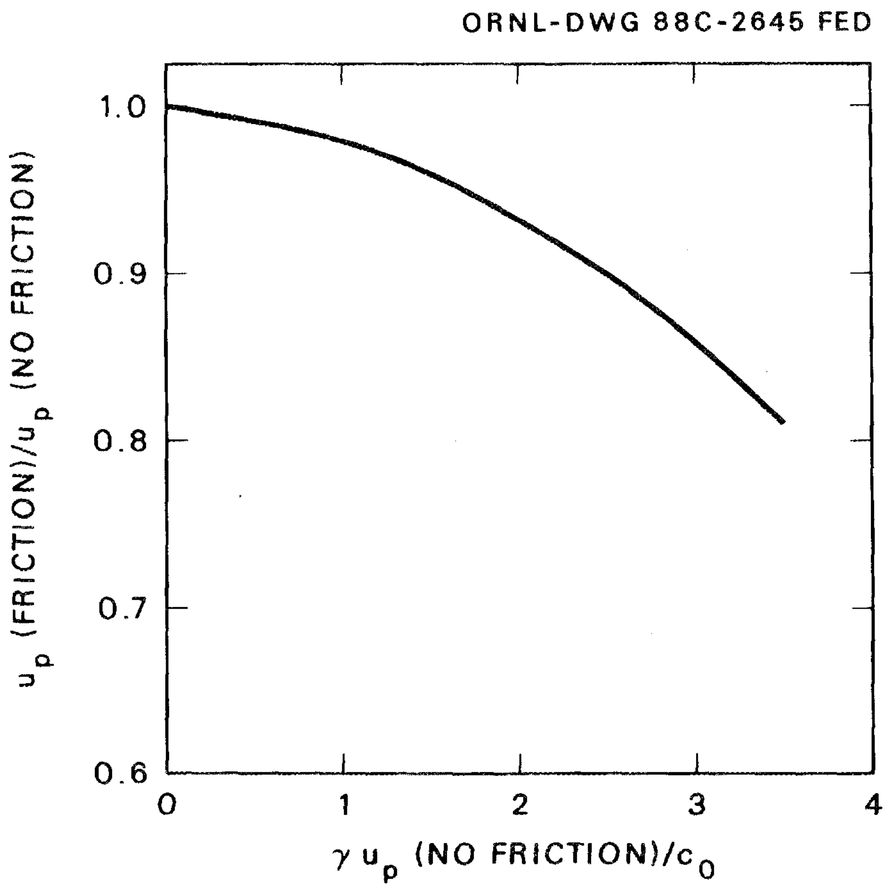

Fig. 4. Empirical friction factors for light gas guns.

pellet velocities on the order of 2000 m/s, a breech pressure of about 150 bar is required for the RPI.

A similar comparison is shown in Fig. 5 for recent deuterium pellet experiments with the TPOP injector. In this case the pellets are 4 mm by 4 mm, the barrel length is 1.0 m, and the breech pressure was scanned over a larger range than in the earlier RPI experiments. Again, actual velocities are 80–90% of ideal values, and both the Seigel generic numerical calculations based on finite propellant gas volume and empirical friction effects and the Lagrangian finite difference code with smooth-wall gas friction give reasonable agreement with the data.

Given that the models reasonably reproduce the experimental data, the next question to address is geometry changes in the chamber and barrel to improve performance.

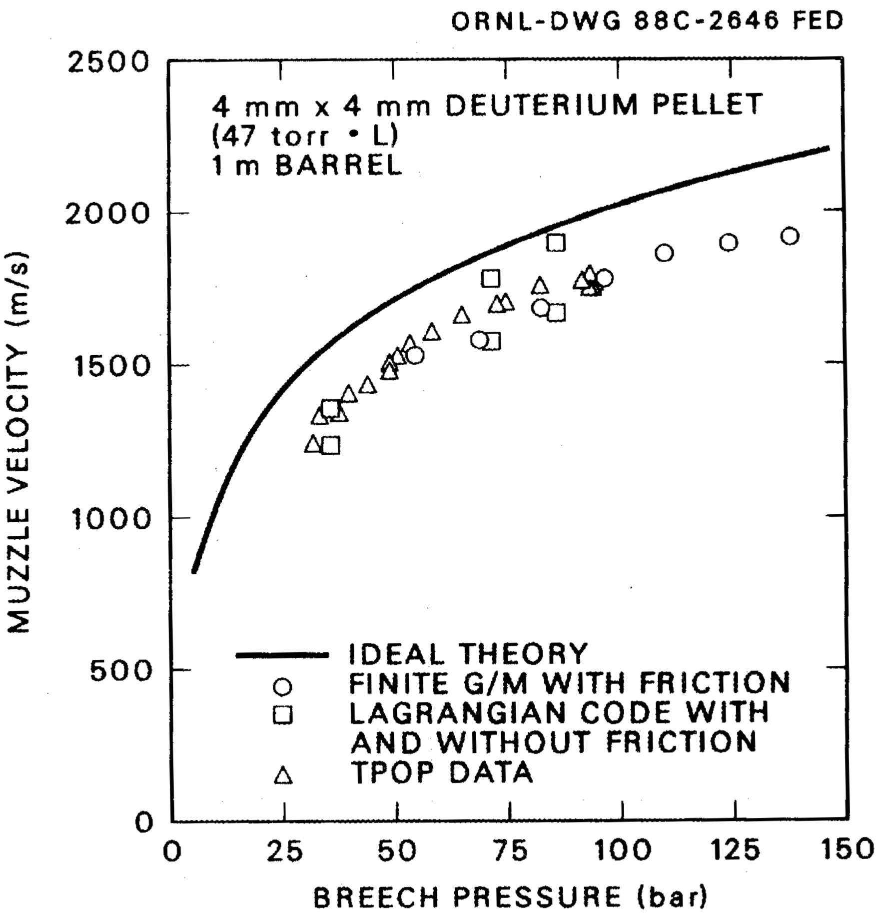

Fig. 5. TPOP data.

C. Improving single-stage pneumatic pellet injectors

The following options exist for improving the performance (muzzle velocity) of single-stage pneumatic injectors:

(1) Increase the ratio of propellant gas mass to pellet mass G/M [given in Eq. (3)].

(2) Increase the normalized barrel length X_B [given in Eq. (4)].

An obvious way of increasing the pellet velocity u_p is by decreasing the pellet mass m, since this increases both G/M and X_B. In practice, this is not usually possible, because the pellet mass is set by the refueling requirements of the magnetic confinement device to which the pellet injector is attached. A schematic diagram showing performance curves as a function of G/M and X_B is given in Fig. 6.

Increasing the breech pressure p_B will increase both G/M and X_B and will improve muzzle velocity. Before 1988, the technology for fast valves set a limit of about 140 bar on p_B. Increasing L_C, D_C, L, and D will also improve performance. It is not feasible to increase D for a constant pellet mass m, since this would lead to unreasonably short pellets. What is feasible is increasing D_C, L_C, and L. However,

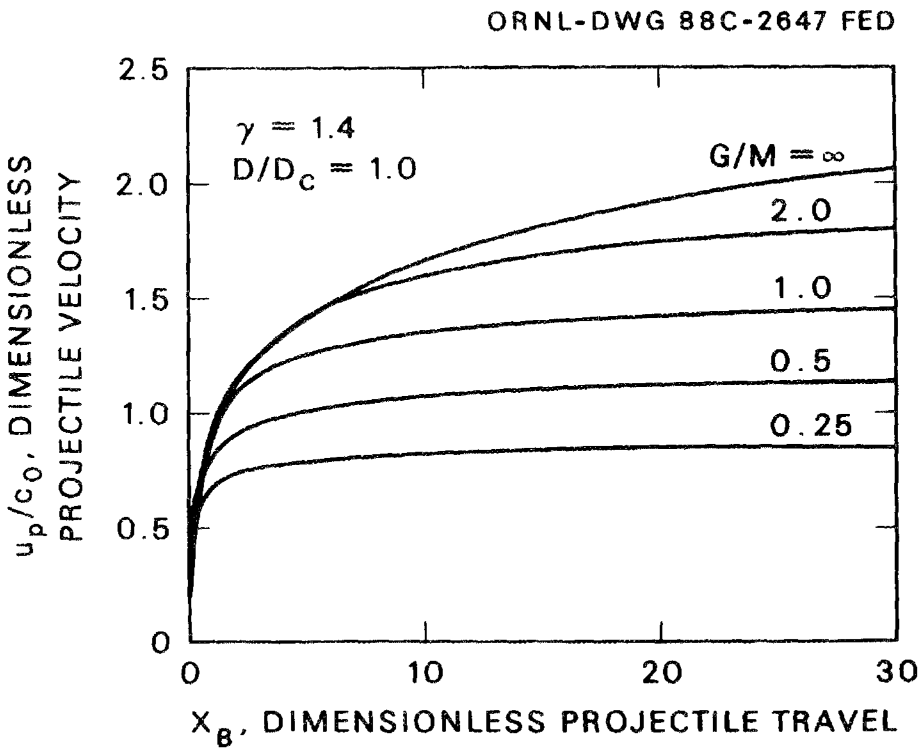

Fig. 6. Generic G/M curves for single-stage guns.

L and L_C cannot be changed independently, as there is a maximum ratio of L/L_C to avoid reflections of the rarefaction wave off the fast valve vertical surface before the pellet exits the barrel. This ratio depends on a number of factors such as p_B and m, but a rough rule of thumb is that reflections are avoided if $L \leq 6L_C$.

At this point a numerical example is helpful. To accelerate a 3.4- by 4-mm deuterium pellet into a 1.25-m barrel, the rule of thumb indicates $L_C \geq 21$ cm. Let $D_C = 2D = 6.8$ mm and let p_B vary from 35 to 140 bar. Table II summarizes the results of this calculation for $L_C = 25$ cm.

Table II. Acceleration of a 3.4- by 4-mm deuterium pellet with $\gamma = 1.4$, $L = 1.25$ m, $L_c = 25$ cm, $D = 3.4$ mm, and $D_C = 6.8$ mm. For this calculation, $c_0 = 1309$ m/s ($T = 295$ K).

p_B (bar)	G/M	X_B	u_p/c_0	Friction correction	u_p (m/s)
34.5	3.5	3.14	1.35	0.94	1661
51.7	5.25	4.72	1.58	0.92	1903
69.0	7.0	6.29	1.65	0.915	1976
103.4	10.5	9.43	1.8	0.90	2121
137.9	14.0	12.57	1.9	0.885	2201

Recall from Fig. 1 that a similar deuterium pellet was accelerated to about 1400 m/s with 51.3-bar breech pressure in the RPI. Thus, these simple changes in L_C ($\times 2$), L ($\times 1.6$), and D_C ($\times 2$) resulted in about a 35% (500-m/s) improvement in muzzle velocity. Further increases in G/M (breech pressure) do not increase muzzle velocity significantly. Modest improvements to pneumatic pellet injectors are possible if fast valve technology can be developed to permit high breech pressures with the larger chamber volumes. Recent modifications to the fast propellant valves and power supplies developed at ORNL have resulted in peak supply pressures on the order of 240 bar.

II. TWO-STAGE PNEUMATIC INJECTOR DESIGN

As shown in Sec. II, it will be difficult to accelerate hydrogenic pellets with a mass on the order of 10 mg to speeds above 2.0–2.5 km/s with single-stage pneumatic guns that use room-temperature propellant. To achieve muzzle velocities in the range of 2–5 km/s requires raising the temperature (sound speed) of the propellant gas at significant pressure levels. A straightforward way of doing this is to use two-stage pneumatic light gas guns. This concept was developed in the late 1940s by W. D. Crozier.[20] It was refined over the next 25 years and is today the major method for hypervelocity research at the major defense and aerospace facilities. The main reason for the concept's longevity is its basic simplicity, as shown in Fig. 7. Moderate-pressure propellant gas (5–50 bar) accelerates a piston to velocities of several hundred meters per second in a high-pressure, thick-walled pump tube. The low-pressure gas (H or He) on the other side of the piston is initially at room temperature; it is compressed to high temperature and pressure (>1000 K and >500 bar) and becomes the driving gas for the projectile. At this higher pressure, the mechanical strength of the hydrogenic pellet becomes a design constraint, and the peak pellet acceleration must be controlled. Single-stage pneumatic guns typically have peak pellet acceleration values in the range of (1–10) $\times$ 10^6 m/s^2 for barrel lengths of 0.5–1.0 m. By carefully controlling the pellet formation process and temperature, it is possible to accelerate consistently intact pellets in this acceleration range. Initial experiments to accelerate hydrogenic pellets with two-stage light gas guns are described in Refs. 21 and 22. These experiments report peak acceleration levels of 5–6 $\times$ 10^6 m/s^2 without pellet breakup. This is somewhat

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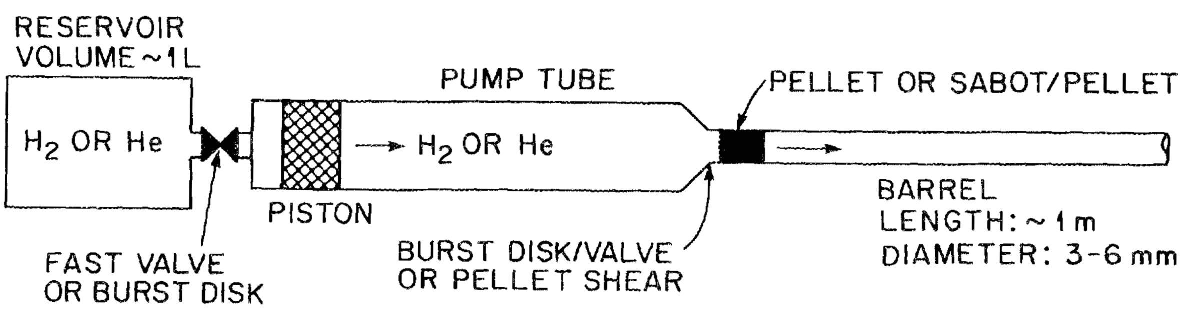

Fig. 7. Two-stage pneumatic gun.

lower than pellet acceleration values inferred from the best pellet performance in single-stage guns. The TPOP data presented in Fig. 5 had inferred peak acceleration values for deuterium pellets near 10^7 m/s^2 at the higher breech pressures; this agrees well with peak acceleration computed by the Lagrangian code with smooth wall gas friction. In designing a two-stage gun it will be necessary to limit the peak pellet acceleration to levels around $(6\text{–}10) \times 10^6$ m/s^2. Higher acceleration levels would be feasible with sabots, and Ref. 22 reports initial efforts with unoptimized plastic sabots encasing deuterium pellets that were accelerated to muzzle velocities of 3400 m/s. The sabots also limit the erosion of the pellet that becomes an issue at higher velocities. A complication introduced by sabots is the separation of the sabot from the pellet and the sabot impact on a suitable target material. These become more critical for a repeating injector, as needed for the steady-state operation desired for reactor-scale fusion devices.

To maximize performance of a two-stage gun, it is necessary to maintain the pellet acceleration as close as possible to the pellet fracture limit throughout the travel through the gun barrel. This is essentially the constant base pressure approach discussed by Seigel.[15] This concept has recently been advocated for single-stage pellet injectors.[23] The two-stage concept is potentially attractive for maintaining constant base pressure because it provides the added flexibility of choosing an operational envelope relative to single-stage guns. This results from the ability to control pump tube conditions by varying first-stage pressure input, initial pressure in the second stage, and piston mass density.

The Lagrangian code was used in designing a simple two-stage pellet injector test facility at ORNL. This two-stage code has the following capabilities:

- It provides a Lagrangian formulation of the finite difference representation of the 1-D differential equations of continuity, motion, and energy.
- It treats shocks that form in the pump tube and barrel with the artificial viscosity method of von Neumann and Richtmyer,[24] which spreads out shocks due to dissipative effects such as viscosity and heat conduction.
- It can model either real (variable specific heat) or ideal gases.
- It can model nonideal effects, including 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 pneumatic mode to model RPI and TPOP injector data, the best agreement was obtained using the ideal gas equation of state with smooth-wall gas friction. Runs made with the two-stage version of the code show that gas friction is the dominant nonideal effect, with heat transfer and piston friction accounting for only 10% of the energy loss due to smooth wall gas friction. This conclusion agrees with recent theoretical work at the Risø Laboratory in Denmark.[25]

The design process was constrained by several factors:

(1) The initial prototype facility should be of modest dimensions to allow rapid turnaround for piston replacement and pump tube modifications.

(2) Peak pump tube pressures should be limited to 600–3000 bar for safety reasons and to limit the peak stress on the pellet, which will be initially tested without a sabot.

(3) Moderate piston kinetic energy is desired for piston lifetime and eventual operation in a repeating mode.

These factors led to a 1.0-m-long pump tube with an inner diameter of 2.54 cm and a 1.0-m-long barrel with an inner diameter of 4 mm. Piston masses of 10–22 g were considered in the design phase with projectile masses in the range of 10–35 mg. By varying the piston mass, initial pump tube pressure, and first-stage pressure, it is possible to optimize pellet acceleration values to achieve the highest possible muzzle velocities. Typical results are shown in Fig. 8, where pellet speed and acceleration are plotted as a function of projectile position in the barrel. Input and output data are summarized in Table III. The muzzle velocity of the 35-mg (4-mm nylon pellet) projectile is about 4.3 km/s. This case is for helium propellant gas.

For initial experiments with the ORNL two-stage pneumatic gun facility, helium propellant gas was used because of safety considerations. Pistons with masses of approximately 20 g and nylon projectiles with masses of 10–35 mg have been used in this facility, with typical first-stage helium supply gas pressures of 10–60 bar. This results in maximum piston velocities in the range from 200 to 400 m/s with projectile speeds to date of up to 3.8 km/s with helium propellant gas. These speeds are somewhat lower than those predicted by the code, and the discrepancy is now being investigated.

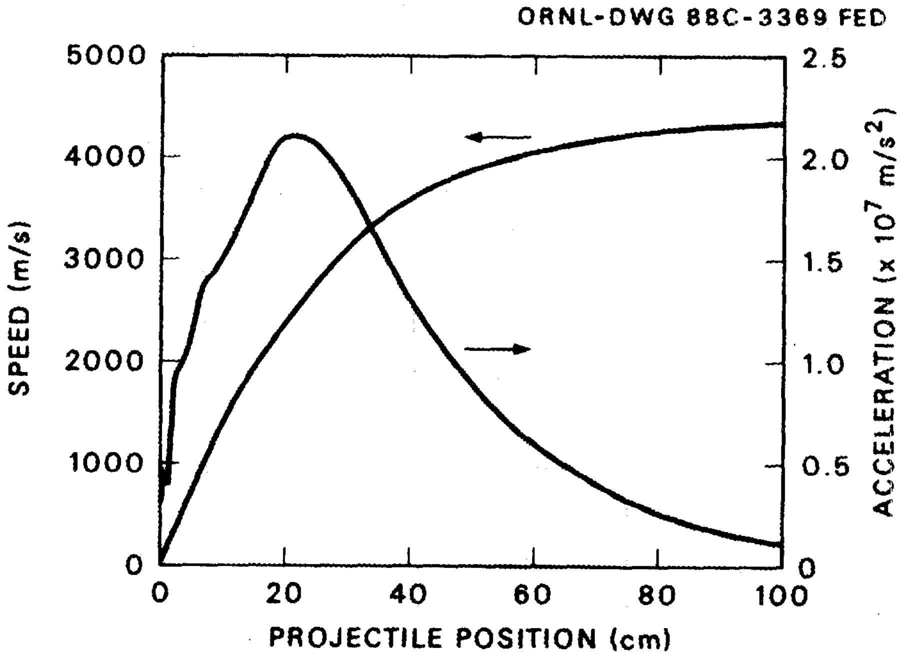

Fig. 8. Lagrangian code predictions for ORNL two-stage pneumatic gun.

Table III. Code input and output.

Input	
Pump tube length, m	1.0
Pump tube diameter, cm	2.54
Barrel length, m	1.0
Barrel diameter, mm	4
Projectile breakaway pressure, bar	70.0
Piston mass, g	20.5
Propellant gas	Helium
First-stage initial pressure, bar	33.0
Second-stage initial pressure, bar	0.8
Projectile mass, mg	35.0
Gas friction (smooth wall)	
Piston friction	
Output	
Muzzle velocity, m/s	4326
Maximum piston velocity, m/s	299
Maximum pump tube pressure, bar	1463
Peak projectile acceleration, m/s^2	2.2×10^7

III. TWO-STAGE REPEATING PELLET INJECTOR

Future fusion engineering test facilities and power reactors will need long-pulse to steady-state plasma fueling systems that can deliver the equivalent of 20- to 200-mg deuterium-tritium pellets to the interior of a hot (ion temperatures of 10–30 keV) fusion plasma. With the long particle confinement time in these large devices, which will be much longer than in present experiments, it is estimated that pellets with diameters of 4 to 8 mm and repetition rates of 1 to 3 Hz will be required.[26] Thus, a repetitive, two-stage pneumatic pellet injector has been considered. This concept was previously studied, on a larger scale, by the U.S. Air Force Armament Laboratory.[27] That study, which concluded that the concept was feasible, identified two areas requiring further development: (1) piston and pump tube wear and (2) high-pressure, fast-response propellant gas and exhaust valves. For cryogenic repeating pellet injectors, the same issues exist; however, they are less severe because of the much lower piston and projectile weights and lower pump tube pressures.

With these factors in mind, the basic two-stage pneumatic pellet injector described in Sec. III will be modified in a straightforward fashion for operation with multiple pellets. The first-stage propellant gas supply valve and second-stage gas supply and exhaust valves are solenoid operated and can cycle several times per second. This hardware will be merged with the basic single-stage RPI[5] used on TFTR and the Joint European Torus (JET) to form a prototype two-stage RPI. Initially, the intrinsic pellet breakaway pressure (Fig. 3) will be used to prevent pellet motion until the latter stages of piston forward motion. Since the initial pump tube pressures are in the range of 1–3 bar, this will allow pellet breakway when the piston is at 80 to 90% of the pump tube length. If necessary, a modified gas propellant valve can be placed between the second stage and the pellet to allow higher breakaway pressures for better (higher) muzzle velocities, with a penalty of higher initial pellet acceleration. Eventually, sabots may be needed to mitigate pellet stress and erosion problems.[22] The issue of piston and pump tube wear will be studied initially in the single-shot version of the two-stage gun, described in Sec. III. By carefully controlling maximum piston velocity and initial pressures in the pump tube, it has been possible to use a single piston for 10 to 20 separate single-shot experiments. To date, nylon pistons have performed best, and, when piston failure did occur, it appeared to be caused by a gas leakage in the second stage, which resulted in severe impact shock when the piston hit the front end of the pump tube. Use of a more robust (all-metal) sealing system in the pump tube and careful control of operating pressures, combined with further optimization of piston material, should produce a long-life piston design. Another factor in piston degradation is the high temperatures (1000 to 5000 K) reached in the second stage during peak compression. These peak temperatures have damaged piston materials such as Vespel. Switching from helium to hydrogen propellant gas will lower the peak temperatures by a factor of $(V_i/V_f)^{\gamma_{He}-\gamma_{H_2}}$, where V_i and V_f are the initial and final (minimum) gas volumes in the second stage and γ is the ratio of specific heats.

In summary, the present single-shot, two-stage pneumatic injector facility has been designed with the inherent capability for multiple pellets, and a development program is under way with a goal of providing a repeating, high-velocity, pneumatic pellet injector for future magnetic fusion devices.

IV. CONCLUSIONS

For single-stage pneumatic pellet injectors, there is good agreement between actual performance data and the various models discussed in Sec. II. The effects of gun geometry and loss terms on ideal performance have been quantified and suggestions made for moderate improvement in single-stage pneumatic injectors in the near term. Changing the breech chamber geometry and upgrading the gas propellant valves for high-pressure operation will produce velocities of 2.0 to 2.5 km/s.

To achieve pellet velocities of 2 to 5 km/s, two-stage light gas gun technology offers the potential for reliable, single-shot pellet injectors and the eventual capability for a repeating, two-stage pneumatic injector. This technology allows operation at near-constant base pressure through careful control of system pressures and piston masses. This will permit maximum muzzle velocity for a given barrel length. Initial results from the ORNL two-stage pneumatic gun facility are encouraging, with muzzle velocities of 2.5–3.0 km/s with 10- to 30-mg, room-temperature, polystyrene pellets and helium propellant gas. The ultimate system capability has not yet been approached, and near-term improvements are expected to result from the use of hydrogen as the propellant gas and from upgrades of the soft vacuum seals now used in the 1.0-m-long pump tube.

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REFERENCES

1. S. L. Milora, J. Fusion Energy **1**, 15 (1981).
2. S. L. Milora and C. A. Foster, Rev. Sci. Instrum. **50**, 482 (1979).
3. S. K. Combs, S. L. Milora, C. A. Foster, D. D. Schuresko, and J. T. Hogan, Nucl. Technol./Fusion **4**, 666 (1983).
4. D. D. Schuresko, S. L. Milora, J. T. Hogan, C. A. Foster, and S. K. Combs, J. Vac. Sci. Technol. A **1**, 959 (1983).
5. S. K. Combs, S. L. Milora, C. R. Foust, C. A. Foster, and D. D. Schuresko, Rev. Sci. Instrum. **56**, 1173 (1985).
6. S. K. Combs, S. L. Milora, C. R. Foust, G. L. Schmidt, and T. P. McBride, J. Vac. Sci. Technol. A **4**, 1113 (1986).
7. S. K. Combs, S. L. Milora, and C. R. Foust, Rev. Sci. Instrum. **57**, 2636 (1986).
8. S. K. Combs, S. L. Milora, C. R. Foust, L. R. Baylor, G. C. Barber, R. D. Burris, P. W. Fisher, C. A. Foster, R. V. Lunsford, G. L. Schmidt, D. D. Schuresko, T. Senko, R. C. Shanlever, W. D. Shipley, D. O. Sparks, K. A. Stewart, and R. B. Wysor, Rev. Sci. Instrum. **58**, 1195 (1987).
9. S. K. Combs, S. L. Milora, L. R. Baylor, G. R. Foust, F. E. Gethers, and D. O. Sparks, J. Vac. Sci. Technol. A **6** (3), 1901 (1988).
10. P. W. Fisher, S. L. Milora, S. K. Combs, R. V. Carlson, and D. O. Coffin, presented at the Third Topical Meeting on Tritium Technology in Fission, Fusion, and Isotopic Applications, Toronto, Canada, May 1–6, 1988 [proceedings to be published in Fusion Technol. (September 1988)].
11. D. D. Schuresko, M. J. Cole, P. W. Fisher, R. B. Wysor, M. L. Bauer, D. J. Webster, B. E. Argo, P. Lickliter, S. K. Combs, S. L. Milora, C. A. Foster, C. R. Foust, H. Takahashi, and T. Kozub, presented at the 35th Annual Symposium of the American Vacuum Society, Atlanta, Ga. (October 1988).
12. D. D. Schuresko, S. L. Milora, S. K. Combs, C. R. Foust, B. E. Argo, G. C. Barber, C. A. Foster, and N. S. Ponte, J. Vac. Sci. Technol. A **5** (4), 2194 (1987).
13. S. K. Combs, S. L. Milora, C. A. Foster, D. D. Schuresko, C. R. Foust, D. W. Simmons, and D. S. Beard, in Fusion Technology 1986 (Proc. 12th Symposium, Avignon, France, September 8–12, 1986), Vol. 1, p. 355.
14. L. D. Landau and E. M. Lifshitz, *Fluid Mechanics* (Addison-Wesley, Reading, Mass., 1959).
15. A. E. Seigel, *The Theory of High Speed Guns*, AGARDograph-91, May 1965.

16. S. L. Milora, S. K. Combs, and C. R. Foust, Rev. Sci. Instrum. **57**, 2356 (1986).
17. P. W. Fisher et al., "Tritium Pellet Fueling for Fusion Reactors," paper PS-ThM6 presented at the 34th National Symposium of the American Vacuum Society, Anaheim, Calif. (1987).
18. A. E. Seigel, op. cit., Section 40.
19. J. W. DeWitt, Arnold Engineering Development Center, private communication.
20. W. D. Crozier and W. Hume, J. Appl. Phys. **28**, 892 (1957).
21. A. Reggiori and F. Scaramuzzi, "Development of a Two-Stage Injector for Solid H_2 Pellets," *Fusion Technology 1986* (Pergamon Press, Oxford, 1986), Vol. 2, p. 1381.
22. K. Sonnenberg et al., "High Speed Pellet Development," in *Proceedings of the 12th Symposium on Fusion Engineering, Monterey, CA, October 1987*, Vol. 2, p. 1207.
23. Ming-Lun Xue, *Comparisons Among Various Possible Ways to Accelerate High-Speed Pellets under Constant Base Pressure*, Risø Report M-2662, September 1987.
24. J. von Neumann and R. D. Richtmyer, J. Appl. Phys. **21**, 232 (1950).
25. Ming-Lun Xue, *Considerations of Several Real Effects in Pneumatic Pellet Injection Processes*, Risø Report M-2663, October 1987.
26. L. L. Lengyel, Fusion Technol. **10**, 354 (1986).
27. L. M. Jenke, *Conceptual Design of an Automatic Light Gas Gun Weapon*, Air Force Armament Laboratory Report AFATL-TR-82-59, September 1982 (limited distribution).

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