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# PNEUMATIC PELLET INJECTOR RESEARCH AT ORNL*

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## ABSTRACT

Advanced pneumatic-injector-based pellet fueling systems are under development at Oak Ridge National Laboratory (ORNL) for fueling magnetically confined plasmas. The general approach is that of producing and accelerating frozen hydrogen isotope pellets at speeds in the range from 1 to 2 km/s and higher. Recently, ORNL provided pneumatic-based pellet fueling systems for the Tokamak Fusion Test Reactor (TFTR) and the Joint European Torus (JET), and a new simplified eight-shot injector has been developed for use on the Princeton Beta Experiment (PBX) and the Advanced Toroidal Facility (ATF). These long-pulse devices operate reliably at up to 1.5 km/s with pellet sizes ranging between 1 and 6 mm. In addition to these activities, ORNL is pursuing advanced technologies such as the electrothermal gun and the two-stage light-gas gun to achieve pellet velocities significantly in excess of 2 km/s and is carrying out a tritium proof-of-principle (TPOP) experiment in which the fabrication and acceleration of tritium pellets to 1.4 km/s were recently demonstrated.

## 1. INTRODUCTION

Oak Ridge National Laboratory (ORNL) has been developing pellet injectors for several years [1–15]. These devices produce frozen hydrogen isotope pellets and then accelerate them to speeds in the range of 1 to 2 km/s by either pneumatic (light-gas gun) or mechanical (centrifugal force) techniques. The designs developed include single-shot guns [2, 4, 7, 11, 15], multiple-shot (four- and eight-pellet) guns [3, 8, 12], machine-gun (single- and multiple-barrel) types [5, 6, 9, 10], and centrifugal accelerators [14]. These injectors have been used to inject hydrogen and deuterium pellets into plasmas on numerous tokamak experiments [16–21]. Recently, ORNL provided pellet fueling systems for the Tokamak Fusion Test Reactor (TFTR) and the Joint European Torus (JET). The TFTR eight-shot pneumatic injector is described in Ref. [8]. The three-barrel repeating pneumatic injector [9, 10], which is briefly described here, is the central ingredient in the collaboration between the U.S. Department of Energy (DOE) and the European Atomic Energy Community (EURATOM) on plasma fueling. This injector, installed on JET in 1987, has been used in experiments during the last year. A new version of the centrifuge pellet injector for the Tore Supra tokamak is nearing completion. It will be featured in a collaboration with the Commissariat à l'Energie Atomique (CEA). In the ORNL-CEA collaboration, long-pulse, reactor-relevant tokamak discharges with simultaneous plasma fueling and exhaust capabilities will be studied. Here we describe the pneumatic injector research activities at ORNL. The status of the centrifuge injector and a unique ultrahigh-velocity concept based on an electron beam-driven thruster are described in a companion paper by C. A. Foster et al. [22].

## 2. CONVENTIONAL PNEUMATIC PELLET INJECTORS

### 2.1. Three-barrel repeating pneumatic injector for JET

For plasma fueling applications on JET, a pellet injector based on the prototype repeating pneumatic design [5, 6] was developed. The original repeating pneumatic injector used in the

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initial pellet fueling experiments on TFTR [20] is described in Ref. [23]. In this gun-like device, a cryogenic extruder supplies a continuous stream of deuterium ice to the gun section where individual pellets are repetitively formed, chambered, and accelerated. The new device (Fig. 1) [9, 10] consists of three independent machine-gun-like mechanisms in a common vacuum enclosure and features three nominal pellet sizes (2.7-, 4.0-, and 6.0-mm-diam) and repetitive operation (5, 2.5, and 1 Hz, respectively) for quasi-steady-state conditions (>10 s). The pulse length is limited only by the capacity of the solid hydrogen extruder. Pellet speeds are typically 1.2 to 1.5 km/s with deuterium pellets. An example of recent pellet injector performance on JET is shown in Fig. 2, where the line-averaged plasma density is plotted as a function of time for 3-MA discharges with 6 MW of ICRF heating and fueling sequences consisting of 4-mm pellets injected at 1 Hz and 2.7-mm pellets injected at 4 Hz.

### 2.2. Simplified eight-shot pneumatic pellet injector

A simplified eight-shot pneumatic pellet injector [12] developed at ORNL is the basis for plasma fueling systems for the Princeton Beta Experiment (PBX) and the Advanced Toroidal

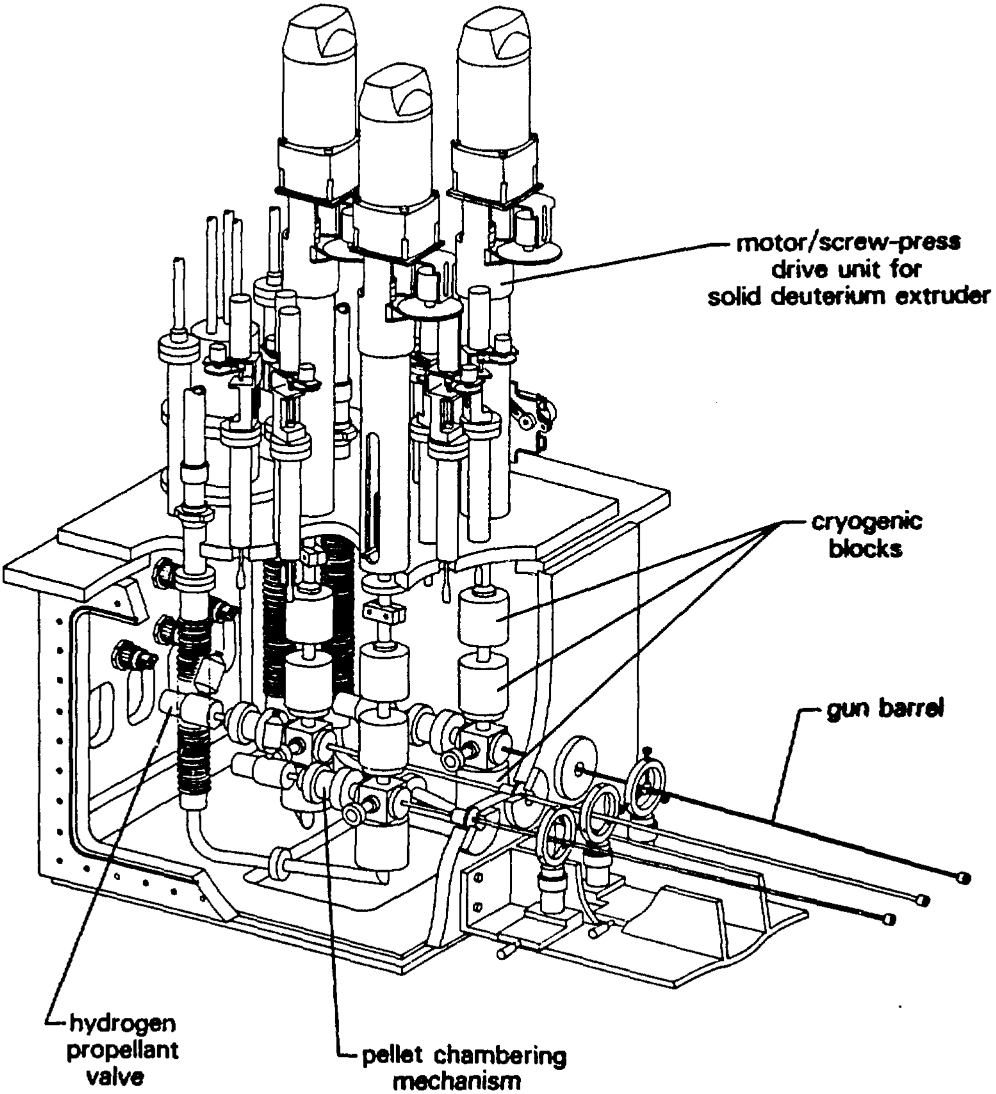

FIG. 1. Three-barrel repeating pneumatic pellet injector for JET.

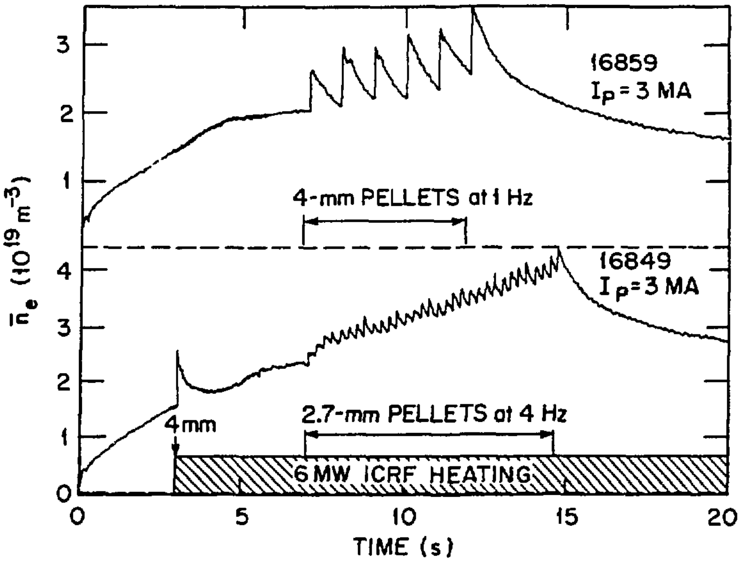

FIG. 2. Density evolution in 3-MA, 6-MW ICRF-heated JET discharges.

Facility (ATF). This injector is based on the so-called "pipe-gun" concept, in which deuterium and hydrogen pellets are formed by direct condensation in a one-piece, stainless steel gun barrel, a segment of which is held below the hydrogen triple-point temperature by contact with a liquid-helium-cooled block. Pellet length is controlled both by regulating the gas fill pressure and by establishing temperature gradients along the barrel tube with auxiliary heating collars. This injector (Fig. 3) features eight independent gun barrel assemblies (Fig. 4) mounted around the perimeter of a single cold block, each coupled to an ORNL-designed fast propellant valve [13]. The injector can inject up to eight pellets of sizes ranging from 1 to 3 mm in diameter in arbitrarily programmable firing sequences at speeds up to ≈1.3 km/s. Each gun is equipped with breech-side and muzzle-side deuterium fill valves. The entire pellet mass range from 1 to 30 torr·L is accessible merely by varying the fill conditions and the choice of pellet sizes.

## 3. HIGH-VELOCITY PNEUMATIC PELLET INJECTOR RESEARCH

### 3.1. Hydrogen electrothermal accelerator

A prototype accelerator [24], consisting of a vortex-stabilized arc discharge plasma generator coupled to the breech tube of a "pipe-gun" pneumatic pellet injector, has been developed and operated. The arc chamber is designed for arc initiation at pressures of 1 to 4 bar. Electrical power is supplied to the arc from a capacitor bank supply and from an LC-line pulse transformer supply, which can produce 1-ms pulses at 5-kA currents into 0.1-Ω loads. The arc is triggered as hydrogen gas is admitted into the arc chamber; the Ohmic dissipation increases the rate of rise of the gun breech pressure from 30 bar/ms to > 100 bar/ms. Muzzle velocities increase from 1.3 to 2.0 km/s for 10-mg hydrogen pellets; these increases represent a 5 to 10% conversion of electrically dissipated energy to projectile kinetic energy. The electrothermal gun performance agrees with an ideal gas gun code calculation that assumes a propellant gas temperature of 2000 K. This suggests that substantial propellant heating has resulted in the desired increase in propellant sound speed.

### 3.2. Two-stage light-gas gun

ORNL is developing a two-stage light-gas gun [25] to accelerate pellets to high speeds. Two other research groups [26, 27] are also developing this technique. In the initial configuration of the two-stage device (Fig. 5), a 2.2-L volume (pressure ≤ 55 bar) provides the gas to accelerate a 25.4-mm-diam piston in a 1-m-long pump tube; a burst disk or a fast valve initiates

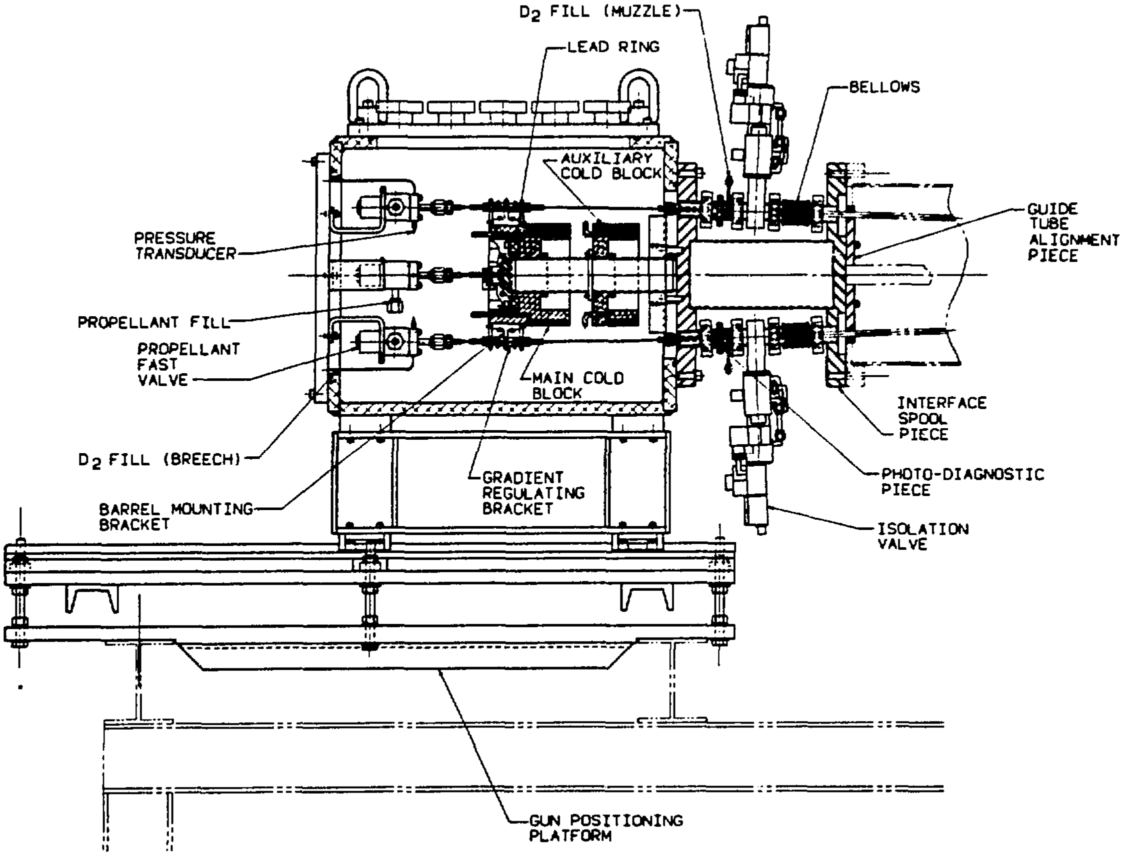

FIG. 3. Schematic of PBX eight-shot pipe-gun injector.

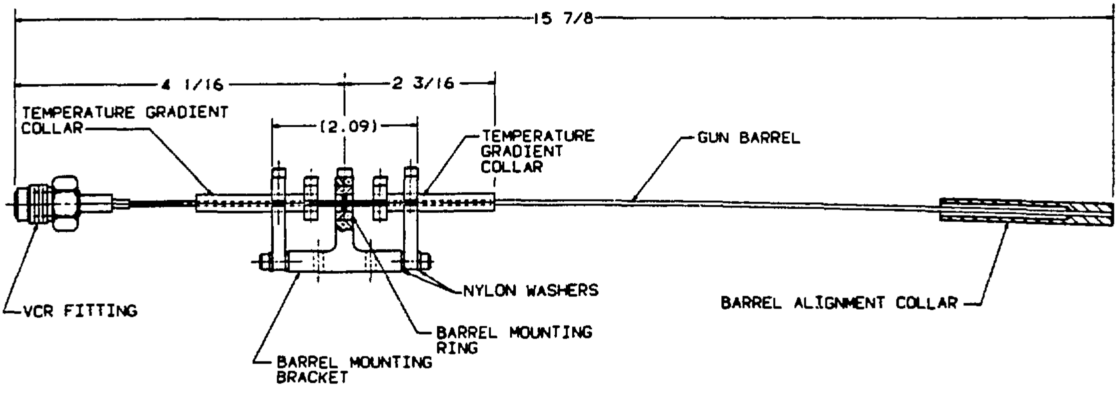

FIG. 4. Gun barrel assembly details for the PBX eight-shot pipe-gun injector.

the acceleration process in the first stage. As the piston travels the length of the pump tube, the downstream gas (initially at < 1 bar) is compressed adiabatically. The typical pressure pulse shown in Fig. 6 was obtained with a peak piston speed near 400 m/s. Temperatures above 7000 K are inferred from an isentropic compression calculation. The increased sound speed resulting from the high temperature provides an effective way to overcome the basic limitation of the single-stage light-gas gun. In preliminary tests that used helium as the driver in both stages,

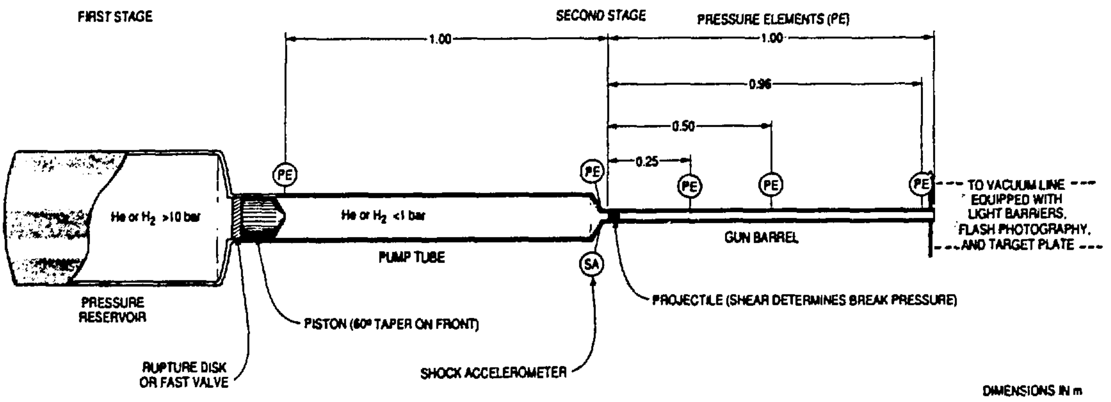

FIG. 5. Schematic of ORNL two-stage light-gas gun.

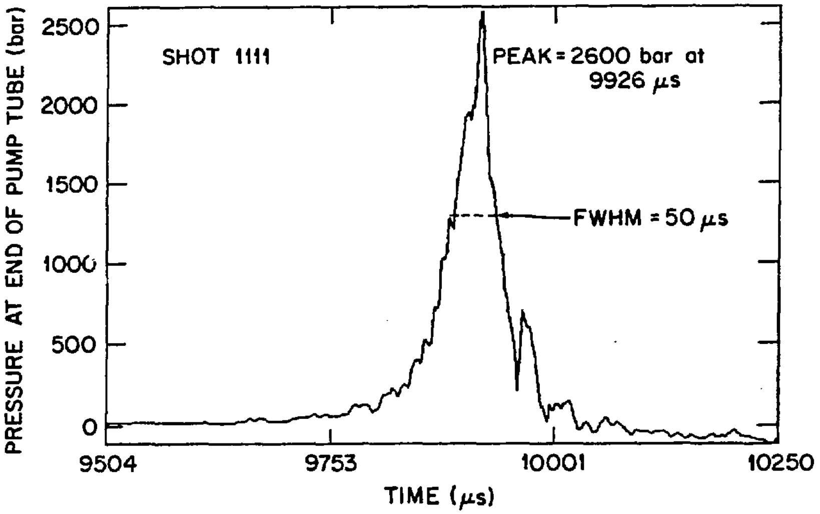

FIG. 6. Pressure pulse developed by the apparatus shown in Fig. 5. Piston diameter = 2.54 cm, piston mass = 22 g, first-stage pressure = 55 bar, second-stage initial pressure = 0.8 bar.

35-mg plastic pellets were accelerated to speeds as high as 4.5 km/s in a 1-m-long gun barrel. As soon as the gun design and operating parameters are optimized, projectiles composed of hydrogen ice with masses in the range of 5 to 20 mg ($\rho \approx 0.087$, 0.20, and 0.32 g/cm$^3$ for frozen hydrogen isotopes) will be accelerated. The hardware is being designed to accommodate repetitive operation as a natural extension of the repeating pneumatic injector technology already developed at ORNL.

A Lagrangian two-stage ballistics code was obtained from the Arnold Engineering Development Center and modified to model both single- and two-stage gas guns. The code can model either real (variable specific heat) or ideal gases and includes parasitic losses such as piston friction, heat transfer, and smooth-wall or constant-friction factor viscous losses.

When the code was used in the single-stage pneumatic mode to model single-stage injector data, the best agreement was obtained with the ideal gas equation of state and smooth-wall gas friction. With the two-stage version of the code, gas friction is the dominant nonideal effect; heat transfer and piston friction accounting for only 10% of the energy loss due to smooth-wall gas friction. The results of initial modeling of the two-stage experiments using both 25.4-mm-diam and 51-mm-diam pump tubes agree with the measured data within 10 to 15%. This agreement was obtained with a model using ideal helium gas, Reynold's analogy heat transfer losses, piston friction, and gas friction based on actual surface roughness measurements of the 4-mm-diam barrel. The code is particularly useful in predicting the effect of parameter changes on gun performance.

## 4. TRITIUM PELLET INJECTOR EXPERIMENT

The properties of tritium, especially its radioactive decay, are quite different from those of the other hydrogen isotopes. Decay heating, the production of $^3$He and its effect on the physical properties of solid tritium, the need for tritium-compatible materials of construction, and use of double containment to prevent tritium release are all problems unique to tritium.

A fully instrumented and automated pipe-gun-based injector has been developed for the tritium proof-of-principle (TPOP) experiment (Fig. 7) [11, 15]. The objective of the TPOP is to demonstrate the feasibility of forming and accelerating 4-mm $T_2$ and DT pellets to speeds of 1.5 km/s. The pipe gun is ideal for tritium service because there are no moving parts inside the gun and no excess tritium is required in the pellet production process. A schematic of the TPOP cryostat is shown in Fig. 8. A cryogenic separator inside the vacuum housing removes $^3$He from tritium to prevent blocking of the cryopuming action by the noncondensible gas. In tests at ORNL, the device accelerated unity-aspect-ratio 4-mm $D_2$ pellets (47 torr·L) to 1.85 km/s; it has since been installed and operated with tritium in the Tritium Systems Test Assembly at Los Alamos National Laboratory. Although this experiment is still in its preliminary stages, we have already shown that $T_2$ and equilibrium DT ($T_2 = D_2 = 25\%$, $DT = 50\%$) pellets can be formed and accelerated to 1.4 km/s. Figure 9 is a photograph of a $T_2$ pellet at the muzzle of the gun; Fig. 10 shows velocities for both deuterium and tritium pellets as a function of propellant gas pressure. The tritium velocities are lower because of the higher mass density of tritium ice.

The presence of $^3$He in the $T_2$ fuel has proven to be the largest obstacle to the production of pellets of good consistency. The condensation process in the pipe gun is generally inhibited at $^3$He

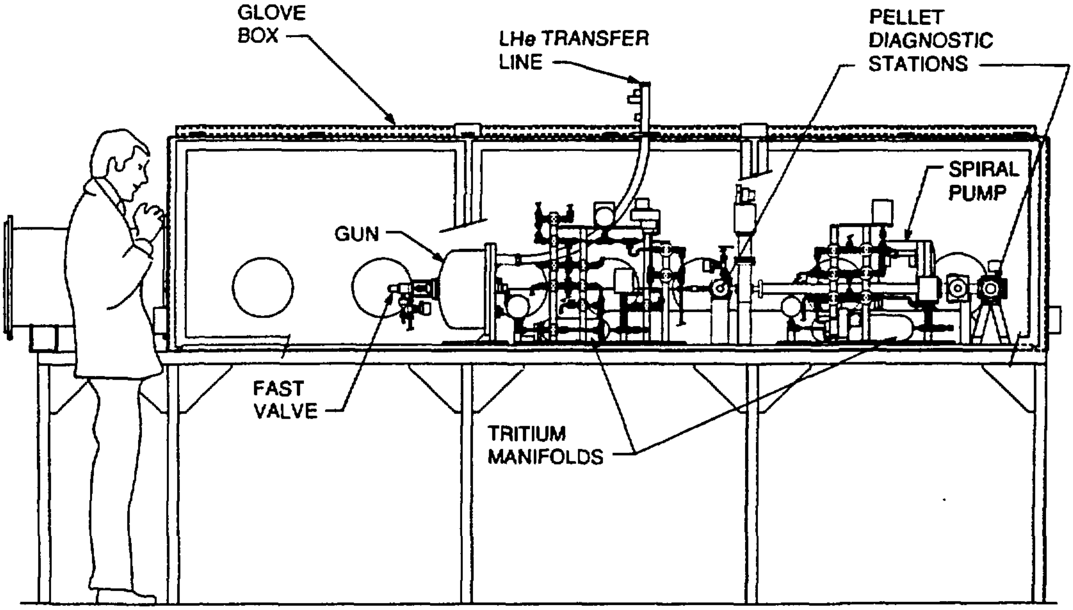

FIG. 7. Schematic of the tritium proof-of-principle (TPOP) injector.

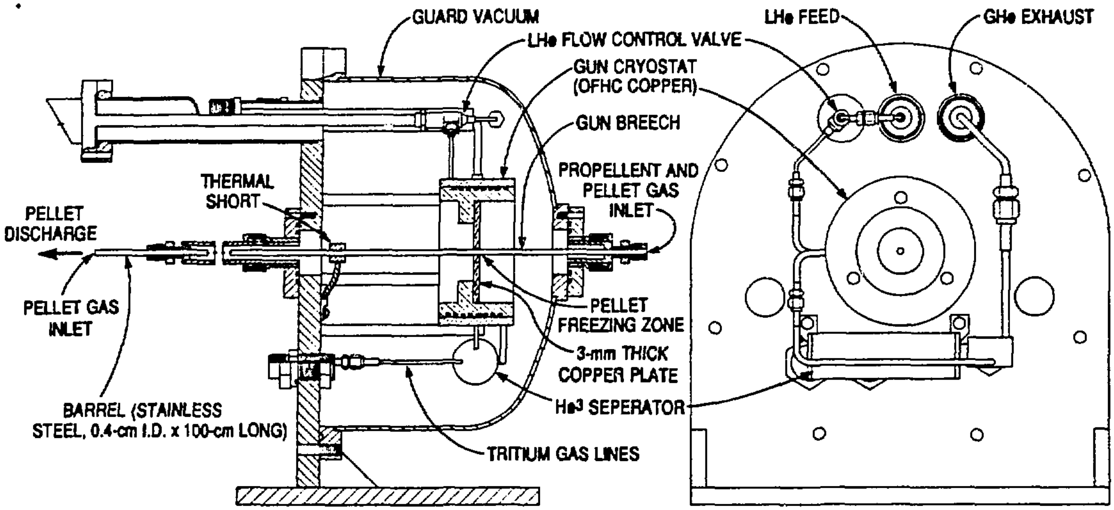

FIG. 8. TPOP cryostat details.

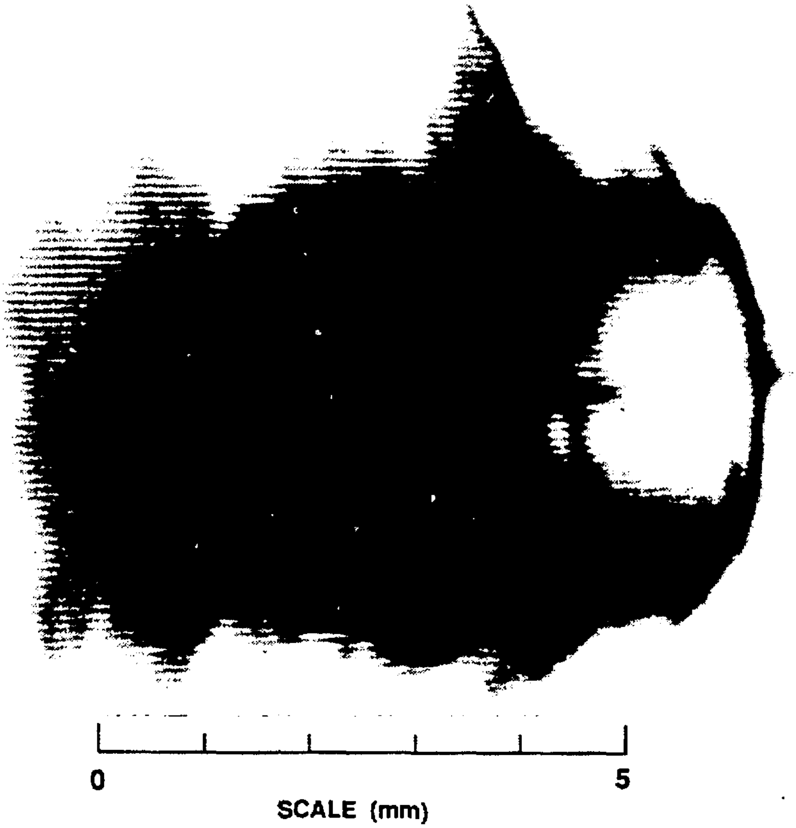

FIG. 9. Photograph of tritium pellet.

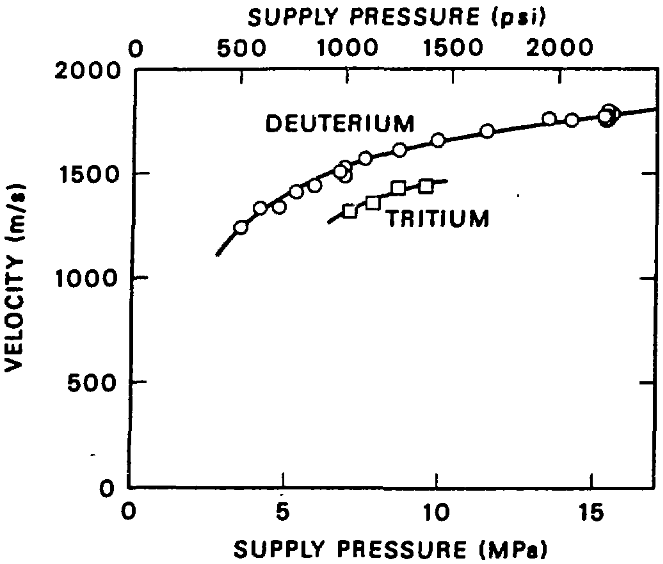

FIG. 10. Measured velocities in deuterium and tritium from the TPOP experiment.

concentrations above 0.05%. Also, a higher fill pressure (60 torr versus 20 torr) is required to form $T_2$ pellets of the same size as the $D_2$ pellets for the same cryostat temperature (10 K). This may result from internal decay heating (1 W/cm$^3$) or from a lower-than-expected thermal conductivity of the $T_2$ ice.

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