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TRITIUM PELLET INJECTOR FOR TFTR*

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ABSTRACT

The tritium pellet injector (TPI) for the Tokamak Fusion Test Reactor (TFTR) will provide a tritium pellet fueling capability with pellet speeds in the 1- to 3-km/s range for the TFTR deuterium-tritium (D-T) phase. The existing TFTR deuterium pellet injector (DPI) has been modified at Oak Ridge National Laboratory (ORNL) to provide a four-shot, tritium-compatible, pipe-gun configuration with three upgraded single-stage pneumatic guns and a two-stage light gas gun driver. The TPI was designed to provide pellets ranging from 3.3 to 4.5 mm in diameter in arbitrarily programmable firing sequences at speeds up to approximately 1.5 km/s for the three single-stage drivers and 2.5 to 3 km/s for the two-stage driver. Injector operation is controlled by a programmable logic controller. The new pipe-gun injector assembly was installed in the modified DPI guard vacuum box, and modifications were made to the internals of the DPI vacuum injection line, including a new pellet diagnostics package. Assembly of these modified parts with existing DPI components was then completed, and the TPI was tested at ORNL with deuterium pellets. Results of the limited testing program at ORNL are described. The TPI is being installed on TFTR to support the D-D run period in 1992. In 1993, the tritium pellet injector will be retrofitted with a D-T fuel manifold and secondary tritium containment systems and integrated into TFTR tritium processing systems to provide full tritium pellet capability.

I. INTRODUCTION

The tritium pellet injector (TPI) is a cryogenic pellet injector to be used prior to and during the deuterium-tritium (D-T) phase of operations on the Tokamak Fusion Test Reactor (TFTR). The injector is shown in perspective in Fig. 1; it has replaced the eight-shot deuterium pellet injector[1] (DPI) at TFTR Bay T. While the DPI formed pellets by an cryogenic extrusion process, the TPI forms its four cylindrical pellets by the in situ condensation process. Two of these pellets have diameters of 3.4 mm (guns 1 and 2); the other two, diameters of 4.0 mm (guns 3 and 4). The nominal pellet aspect ratio (AR) is 1.25, but pellets can be formed with ARs in the range from 1.0 to ≥1.5. One of the 4.0-mm guns (gun 4) is equipped with a two-stage light gas gun driver, while the other three guns operate with a conventional single-stage light gas gun driver using fast-acting electromagnetic propellant valves developed at Oak Ridge National Laboratory (ORNL).[2] In the configuration described here, the single-stage guns can produce velocities approaching 1.7–1.8 km/s for deuterium pellets and 1.5 km/s for tritium.[3] Performance specifications for the TPI are given in Table I.

Using the TPI during the TFTR D-T phase will permit access to both a regime suitable for initial alpha particle physics studies and a regime suitable for studies of particle and energy confinement in high-density D-T plasmas with $n_e(0) = (1\text{–}5) \times 10^{20}\ m^{-3}$. The TPI will provide the capability for extending the supershot regime to densities suitable for high-Q operation and provide access to both the peaked-density-profile, pellet-fueled PEP regime[4] and a regime of sustained high-density operation using multiple tritium pellets and ion cyclotron range of frequencies (ICRF) heating. The project is divided into two phases. Phase I activities allow the deuterium fueling capability to be used during 1992 operations, while the Phase II activities incorporate systems required for tritium operation (secondary containment and a D-T fuel manifold) and include an extended period of testing at the TFTR site, ending with the formation and acceleration of tritium pellets in 1993.

II. TPI SYSTEM DESIGN

The TPI consists of several systems, which are shown in Figs. 1–3 and described below.

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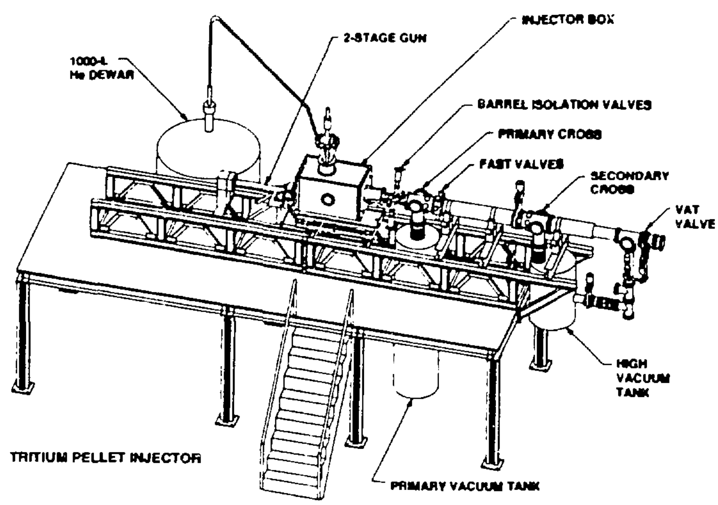

Fig. 1. Perspective view of the TPI installation on the TFTR.

II.A. Injector

The injector has a cryostat cooled with gaseous helium (GHe) that provides cooling for cryogenic pellet formation. The injector is located within the guard vacuum system, and its design is based on the so-called "pipe-gun" concept, in which hydrogenic (H, D, T) pellets are formed by direct condensation in the gun barrel, a segment of which is held below the hydrogen triple-point temperature by contact with a GHe-cooled, oxygen-free high-conductivity (OFHC) copper block. Pellet length is controlled both by regulating the gas fill pressure magnitude and duration and, for pellets with AR ~ 1, by establishing temperature gradients along the barrel tube with auxiliary heating collars.[3] This design is ideal for tritium service because there are no moving parts inside the gun and because little excess tritium is required in the pellet production process. The injector uses four independent 1-m-long gun barrel assemblies mounted around the perimeter of two OFHC copper cryostats; the rear cryostat provides conduction cooling for the four barrel pellet freezing zones, and the front cryostat provides conduction cooling for the four barrel collars. The cryostats shown in Fig. 2 are based on designs used for pipe-gun injectors built for the Advanced Toroidal Facility and the Princeton Beta Experiment.[5,6] Three of the barrel assemblies are coupled to an ORNL-designed fast propellant valve (single-stage driver). This valve develops full pressure within 300 µs and has operated with a supply pressure of up to 138 bar (2000 psi) using upgraded power supplies. The remaining barrel assembly is connected to the two-stage driver.

Experiments at the Tritium Systems Test Assembly (TSTA) using a prototype TPI have shown that the presence of noncondensible helium-3 at levels above 0.005% prevents pellet formation by blocking the condensation of tritium in the pipe-gun freezing cell.[3] Since helium-3 occurs as a by-product of tritium decay, specific removal of residual helium-3 from the tritium feed gas to this level of purity is required. This removal is accomplished using a cryogenic separator (OFHC copper cryostat) that is also located in the guard vacuum enclosure next to the main cryostats. The tritium is purified by circulating the fuel charge through the separator, which freezes only the hydrogenic isotopes and leaves the noncondensible helium-3 to be removed from the loop by a mechanical vacuum pump.

II.B. Two-Stage Driver

The two-stage driver system shown in Figs. 2 and 3 provides the high-pressure, high-temperature drive gas required to accelerate pellets to 2.5–3 km/s. It is based on development of two-stage light gas guns at ORNL[7–9] and in Europe.[10–12] In the two-stage driver, moderate-pressure (20- to 50-bar) helium propellant gas in a 0.64-L first-stage reservoir accelerates a 25- to 50-g titanium piston to velocities in the range of 100–150 m/s in a thick-walled 4130 carbon steel pump tube. The reservoir is connected to the pump tube by a pneumatically actuated fast valve with a 2.2-cm-diam orifice. This 0.9-m-long, 2.54-cm-ID pump tube is visible in Fig. 3, which also shows the guard vacuum chamber interface. A bellows isolates the two-stage driver and the guard vacuum chamber. The high-pressure end of the pump tube is encased in a heat-treated (Rockwell C hardness 42), 4340 carbon steel head assembly. The accelerating piston compresses (nearly adiabatically) low-pressure, room-temperature hydrogen

TABLE I
Tritium Pellet Injector Performance Requirements

Parameter	Requirement
Injector type	Pipe gun, condensing type
Number of barrels	4 (3 single-stage guns, 1 two-stage gun)
Pellet material	H_2, D_2, T_2, D-T[a]
Plasma fueling	(2–4) × 10^{21} atoms per pellet
Pellet size capability (mm)	
Diameter	3.3–4.5 (all four guns)
Length	Diameter × 5/4
Nominal pellet size, Phase 1 (mm)	
Diameter	
Single-stage guns	3.43 (two guns), 4.0 (one gun)
Two-stage gun	4.0
Length	Diameter × 5/4
Pellet speed (m/s)	
Single-stage guns	
With T_2 pellet	1500[b]
Range	800–1500
Two-stage gun with T_2 pellet	2500–3000[c]
Propellant gas	
Single-stage guns	H_2 at <150 bar
Two-stage gun	
First stage	He at <70 bar
Second stage	H_2 at <50 bar
Propellant gas consumption pepellet (bar•L)	
Single-stage guns (H_2)	<1.33
Two-stage gun	
First stage (He)	<20
Second stage (H_2)	<0.5
Tritium inventory per tokamak pulse (Ci)	<900
Tritium efficiency (T to plasma/T supplied)	
Single-stage guns	0.8
Two-stage gun	0.7
LHe consumption (L/h)	
Specification	<20 at operating temperature
Design goal	10
Design radiation dose to Bay T of vacuum vessel (rad)	10^6
Cycle time (min)	
D pellets	<10
T pellets	<40
Delay between pellets (ms)	Variable, 0–2500
Lifetime (cycles)	
Total	5000
Two-stage gun[d]	500

[a]Small doping levels of H_2 (up to 10%) permitted in D_2 feed gas.
[b]Expected conditions for 4- × 4-mm T_2 pellet with propellant at 138 bar.
[c]Upper end of range depends on strength of T_2 pellet.
[d]Cycles between piston replacement.

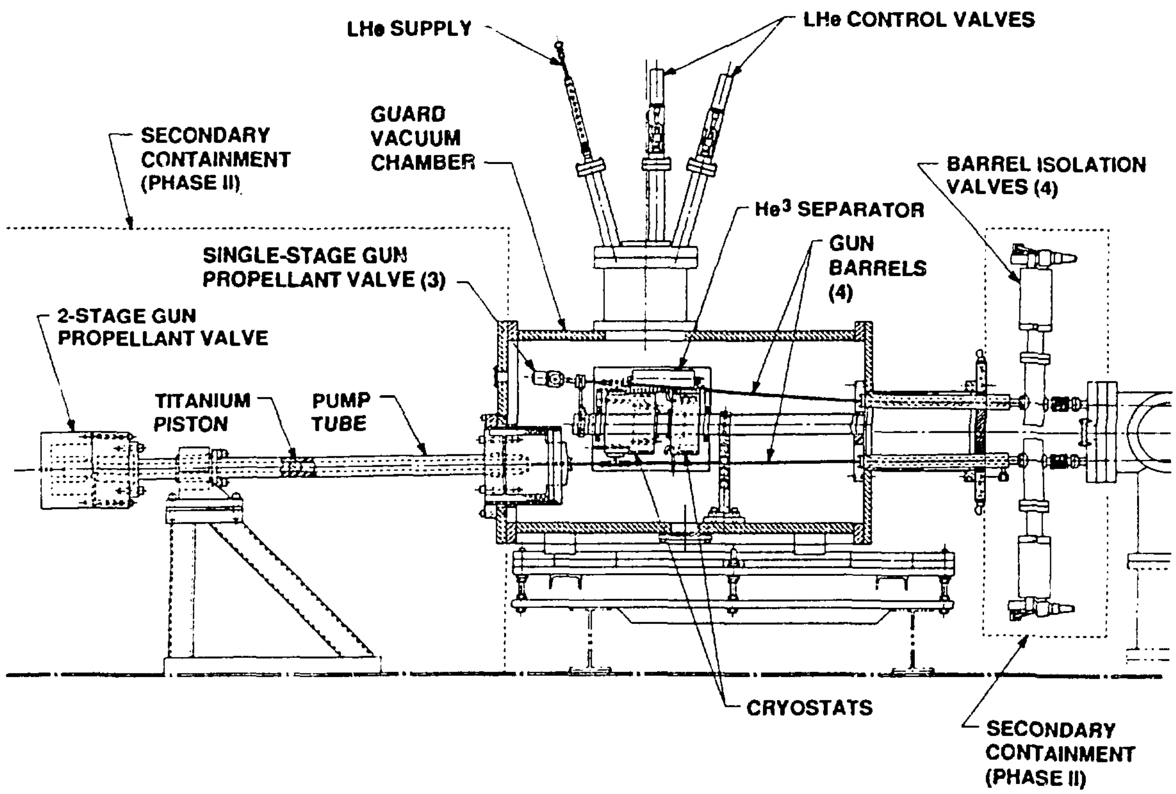

Fig. 2. The TPI injector and two-stage light gas gun assembly.

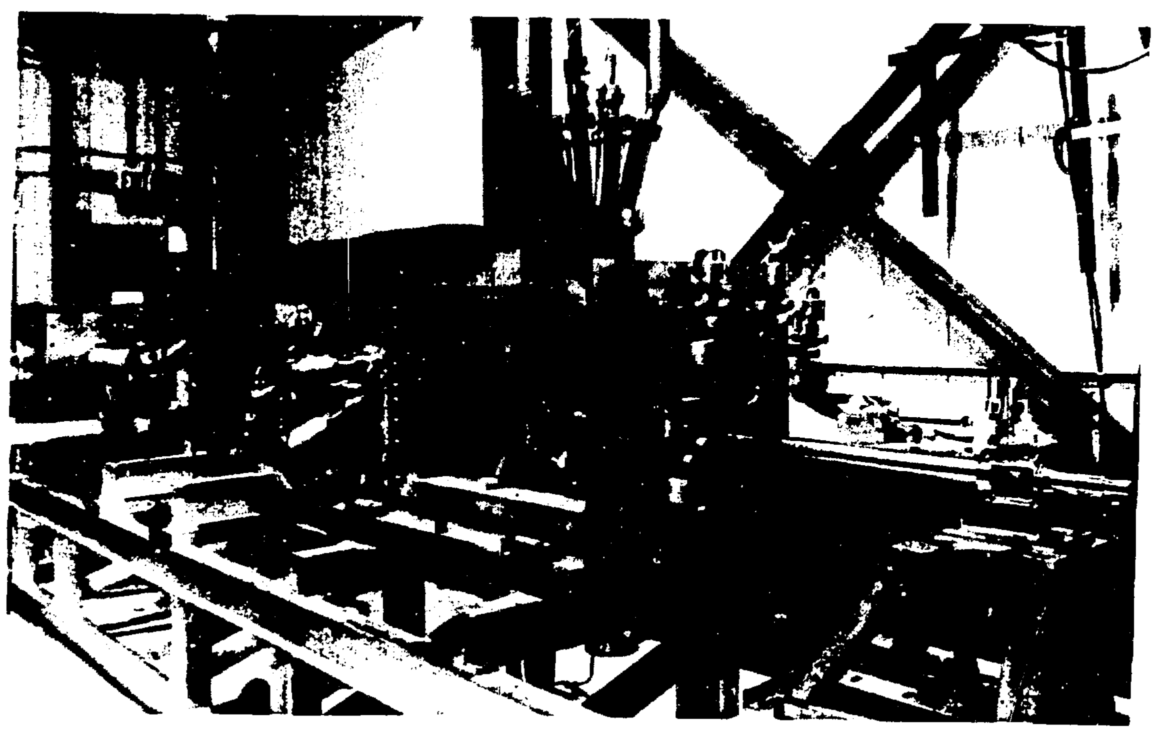

Fig. 3. Photograph of TPI during assembly.

propellant gas initially at about 1 bar. This hydrogen gas becomes the driving gas for the cryogenic pellet. At the high pressure reached following near-adiabatic compression, the mechanical strength of the hydrogenic pellet becomes a design constraint and determines the maximum muzzle velocity, which is estimated to be of order 2.5–3 km/s.

II.C. Pellet Injection Line

The barrel isolation valve system links the injector with the primary vacuum subsystem. It consists of four vacuum isolation valves and four double-wall bellows units, one assembly per barrel. The valves, when closed, isolate the injector from the primary vacuum system. The injection line primary vacuum system links the injector with the high-vacuum system. It consists of a stainless steel injection line containing an array of four 8.0-mm-ID, 1.1-m-long pellet guide tubes, four fast-acting (~25-ms cycle time) conductance-limiting valves, a pellet diagnostic station, an isolation valve at the connection to the high-vacuum system, and a 0.71-m^3 stainless steel chamber. When pellets are fired, the primary vacuum system absorbs virtually all of the propellant gas used to accelerate the pellet. The injection line high-vacuum system links the primary vacuum system to the TFTR vacuum vessel through a region of high vacuum. The high-vacuum system consists of a stainless steel injection line containing four 14.8-mm-ID, 1.0-m-long pellet guide tubes, a pellet diagnostic station for photography and pellet mass measurements, a system isolation valve and bellows, and a ceramic break. This portion of the system ends with a connection to the pellet injector torus interface valve. The system also contains a 0.265-m^3 stainless steel chamber that absorbs most of the residual propellant gas that is not pumped by the primary vacuum system.

II.D. Gas Supply and Manifold

All nontritium working gases required for operation of the TPI will be supplied from a gas bottle farm located in the TFTR test cell basement. The gas supply system will provide deuterium at ~3 bar, hydrogen at pressures up to 138 bar, and helium at 50 bar and 8 bar (for pneumatic valve actuation). Tritium at ~2.5 bar will be supplied from the tritium gas delivery system using a connection in the test cell near the pellet injector location. The tritium delivery lines will be doubly contained. The gas manifold system consists of separate pellet fuel gas (initially deuterium feed gas and, later, D-T feed gas) and propellant gas feed systems. A diaphragm pump and a scroll pump are incorporated into the feed system for Phase II to facilitate transfer of tritium to and from the injector. The gas manifold system will be located immediately behind the injector guard vacuum box.

II.E. Secondary Containment and Tritium System Connections

The TPI consists of three classes of components: (1) components that are never exposed to tritium, (2) components that are exposed to tritium but are passive in nature and are always maintained at subatmospheric pressure, and (3) components that contain tritium and either are maintained at pressures above atmospheric pressure or are expected to require maintenance (e.g., vacuum pumps). Containment of these three classes of components/systems will differ. Components/systems in class 1 will not use secondary containment and will not be linked directly to the tritium cleanup systems. Components in class 2 will not use secondary containment but will be linked to the tritium cleanup systems. Components in class 3 will use secondary containment and will be linked to the tritium cleanup systems. The TPI components that will require secondary containment structures include the gas manifold, the two-stage driver, the injector, the barrel isolation valves, and the vacuum pumping system. The guard vacuum system is itself a secondary containment system.

II.F. Control System

The TPI will be controlled by a programmable logic controller (PLC, Allen Bradley PLC 5/40) located in the TFTR mezzanine beneath the injector. The operator will control the injector through a touch panel color mimic screen provided with the PLC (one primary unit in the control room and a second unit in the mezzanine for checkout) or through a color mimic display/terminal interfaced to the existing pellet injector MicroVAX, which will have a communications link to the PLC. To the operator, the PLC will appear as a finite-state engine in which the injector will be in one of several defined states or modes. In each of these states, the PLC will perform a series of operations (a procedure to enable the injector to go to the next state). The operator controls the system by setting the state to which the PLC is to go. All set points for temperatures and pressures within the injector are set automatically within the procedures by the PLC but can be modified by changing the preset values in the PLC, either through the touch panel via a pop-up keypad or through the MicroVAX interface. Firing of the propellant valves and timing of hydrogen propellant prefill and pump tube vacuum exhaust for the two-stage light gas gun are controlled by the TFTR fire sequencer, which is programmable through the MicroVAX. The injector can also be operated manually by controlling individual valves and changing individual set points.

II.G. Pellet Diagnostics

The TPI has two light gate stations separated by 1.41 m to provide timing signals for pellet speed measurement. The pellet interupts a continuous light beam to provide the timing pulse. This system also provides a pellet-speed-dependent trigger pulse for the two 3-ns pulsed nitrogen dye lasers in the pellet photography system. A fiber-optic beam splitter enables a single laser to photograph pellets in two separate barrels within the constraints of the 20-Hz laser repetition rate. The photography system for the ORNL testing period used both a CID camera (guns 2 and 3) and a CCD camera (guns 1 and 4). The system for the TFTR D-T operations will use only CID cameras designed to function at integrated doses estimated for the D-T phase. Windows used for pellet speed measurement and photography were kept at minimum size and tested at 2.5 atm to provide a reliable tritium barrier for the D-T phase. All windows also have a simple secondary containment structure using elastomer O-ring seals, which also provides the fiber-optic or camera interface. A microwave cavity system was also implemented for the TPI. It operates at a nominal resonant frequency of 4.21 GHz and provides a relative measure of pellet mass. It was initially calibrated at ORNL by measuring the fast pressure rise due to a pellet striking a target plate in a tank of known volume. A photograph of a 3.4- × 4.3-mm pellet at a speed of ~1.4 km/s and the corresponding microwave cavity signal are shown in Fig. 4. The TPI single-stage light gas guns (guns 1, 2, and 3) have a piezoelectric pressure transducer in the breech area between the hydrogen propellant valve and the pellet freezing zone. The two-stage driver has a piezoelectric pressure transducer on the pneumatically actuated fast valve and at the other end of the pump tube in the high-pressure section. There are also piezoelectric shock transducers on each of the four fast-acting conductance-limiting valves in the injection line and on the high-pressure section of the two-stage driver.

III. TPI TESTING WITH DEUTERIUM PELLETS

The TPI was initially tested at ORNL over a three-week period. This testing emphasized initial operation of the three-single stage light gas guns (guns 1, 2, and 3) and the two-stage driver (gun 4) and integration of gun mechanical systems into the PLC-based control system. One major goal was to verify that the pressure drop in the helium gas cooling circuit was low enough at operating temperatures to allow operation at TFTR with a closed cryogenic helium system developed for the TFTR neutral beam injectors. It was found that the gun copper cooling

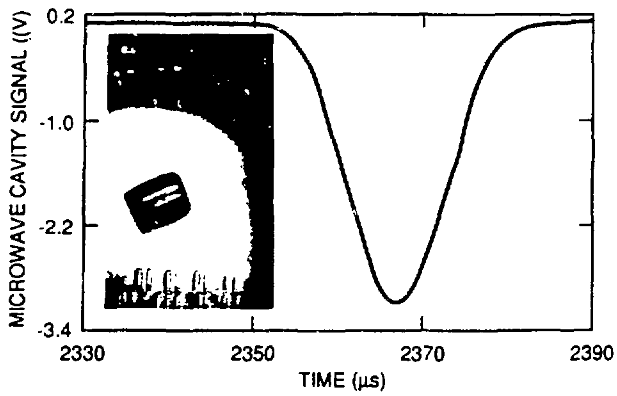

Fig. 4. Microwave cavity signal and photograph of a 3.4- × 4.3-mm pellet at 1.4 km/s.

cryostat could be maintained at the temperatures of 9–12 K needed for deuterium pellet fabrication with a dewar pressure of 3–4 psi. Cold helium gas at 5–6 K was used for gun cooling; this gas was generated by immersion of a 50-Ω electrical heater into a 500-L liquid helium (LHe) dewar. Steady-state heater currents of 0.3–0.4 A indicated LHe consumption of 8–12 L/h, meeting a TPI design goal.

Testing of the three single-stage light gas guns verified the ability to make 3.4-mm and 4-mm deuterium pellets at aspect ratios of 1, 1.25, and 1.5. Each single-stage light gas gun was tested at various hydrogen propellant supply pressures in the range from 69 to 138 bar. In particular, it was verified that the upgraded propellant power supplies could open the electromagnetic propellant valves at the design pressure of 138 bar. Figure 5 shows a scan of pellet speed as a function of breech propellant gas pressure for gun 1. Also shown are predicted values from interior ballistics theory.[7,13]

Initial testing of the two-stage light gas gun was conducted to quantify operating valve response and gas dynamics time scales for initially prefilling the pump tube with hydrogen propellant gas, accelerating the piston with helium gas from the first stage reservoir, and evacuating the pump tube and reseating the piston after a shot. The results of these initial timing runs were used to program the fire sequencer and PLC to provide consistent performance from the two-stage light gas gun. Pellet speeds in this initial phase were in the range 1.5–2.2 km/s and were limited by a leak in the pump tube's high-pressure head metal O-ring seal (with an internal spring), which developed as high pressures (up to 1100 bar) were reached during the shot. This small, transient leak limited pellet speed performance and caused occasional lockup of the titanium piston in the pump tube. A new seal configuration is being developed at ORNL and will be retrofitted on the TPI at TFTR.

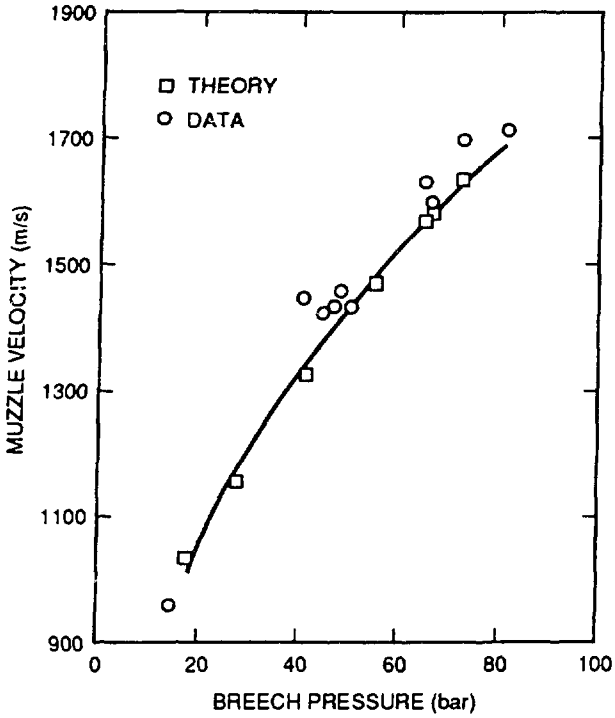

Fig. 5. Pellet speed vs breech pressure for gun 1.

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