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# TRITIUM PELLET INJECTOR FOR THE TOKAMAK FUSION TEST REACTOR*

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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) plasma phase. An existing deuterium pellet injector (DPI) was 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 for frozen pellets ranging in size from 3 to 4 mm in diameter in arbitrarily programmable firing sequences at tritium pellet 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 (PLC). The new pipe-gun injector assembly was installed in the modified DPI guard vacuum box, and modifications were also 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 testing program at ORNL are described. The TPI has been installed and operated on TFTR in support of the CY-92 deuterium plasma run period. In 1993, the tritium pellet injector will be retrofitted with a D-T fuel manifold and tritium gloveboxes and integrated into TFTR tritium processing systems to provide full tritium pellet capability.

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## 1. INTRODUCTION

The Tokamak Fusion Test Reactor (TFTR) at Princeton Plasma Physics Laboratory is the largest tokamak in the United States and has been in operation since 1982 with deuterium plasmas. The research program will be extended in 1993–94 to deuterium-tritium (D-T) plasmas, which will result in ~10–20 MW of fusion power owing to the larger nuclear fusion cross section of the D-T reaction relative to D-D. Three methods are used to fuel TFTR plasmas: room-temperature gas injection at the vacuum vessel wall, fueling by high-energy (~100-keV) neutral beams, and injection of frozen hydrogenic pellets. Gas injection is not very efficient in fueling the plasma center, and it is difficult to produce peaked density profiles with this method. Neutral beam injection is primarily used for plasma heating; it can provide limited central fueling capability, but this fuel source is at high energies per accelerated ion and significant power is required for reasonable plasma fueling rates. Hydrogenic pellet injection is attractive, especially for D-T plasmas, in that it can provide efficient core plasma fueling. The tritium pellet injector (TPI) is a cryogenic pellet injector to be used before and during the D-T phase of TFTR.[1] Using the TPI during 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 $n_e(0) = (1–5) \times 10^{20}$ m$^{-3}$. The injector is shown in perspective in Fig. 1; it has replaced the eight-shot deuterium pellet injector (DPI) at TFTR. While the DPI formed pellets by a cryogenic extrusion process, the TPI forms its four cylindrical pellets by the in situ condensation (pipe-gun) 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 is 1.25, but pellets can be formed with aspect ratios 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; the remaining three guns are conventional single-stage light gas guns using fast-acting electromagnetic propellant valves developed at Oak Ridge National Laboratory (ORNL).[2] In the configuration described here, the single-stage guns are capable of producing velocities approaching 1.7–1.8 km/s with deuterium pellets and 1.5 km/s with tritium pellets.[3]

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 (gloveboxes 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.

## 2. TPI SYSTEM DESIGN

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

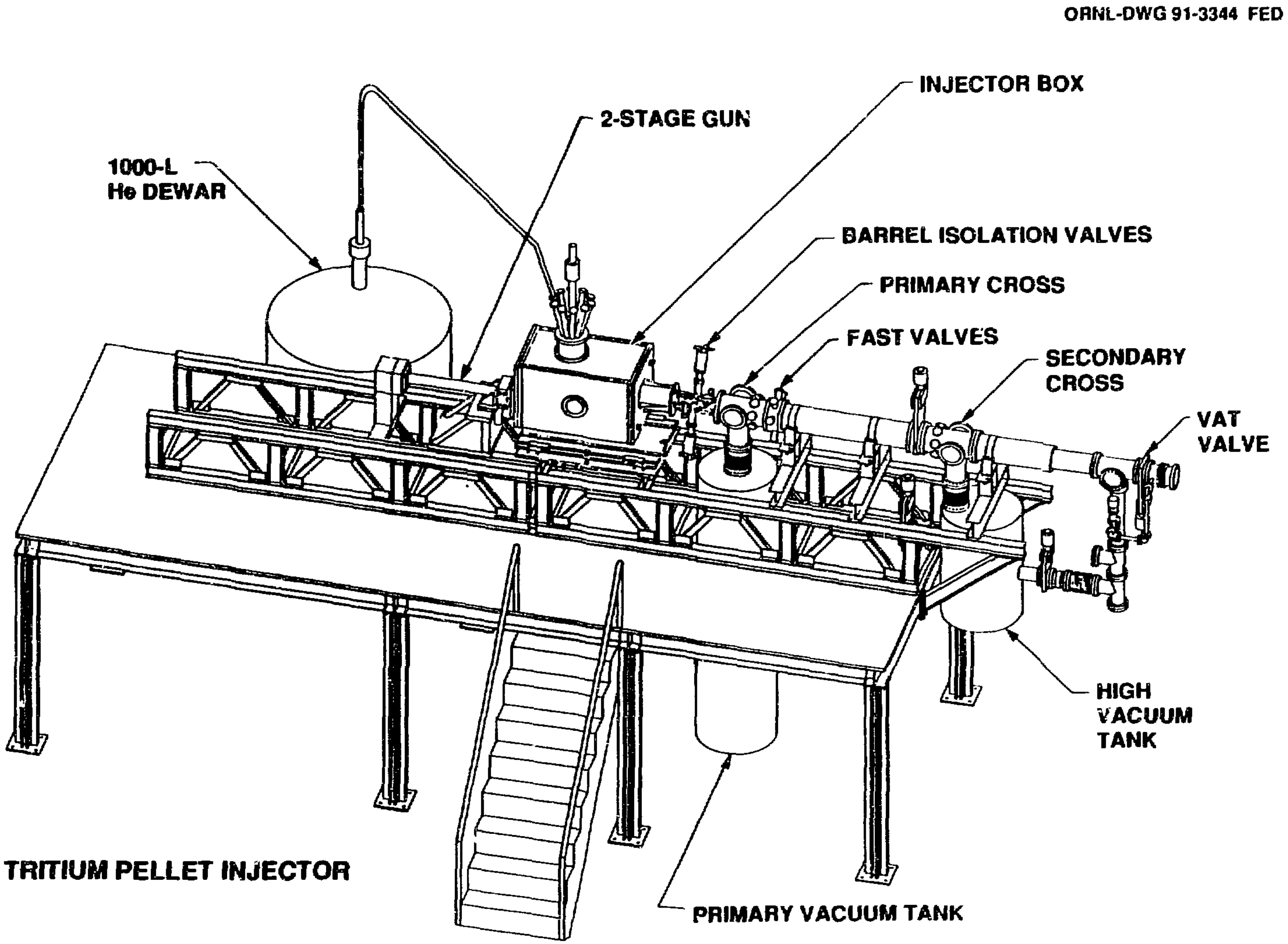


Fig. 1. Perspective view of the TPI installation on the TFTR.

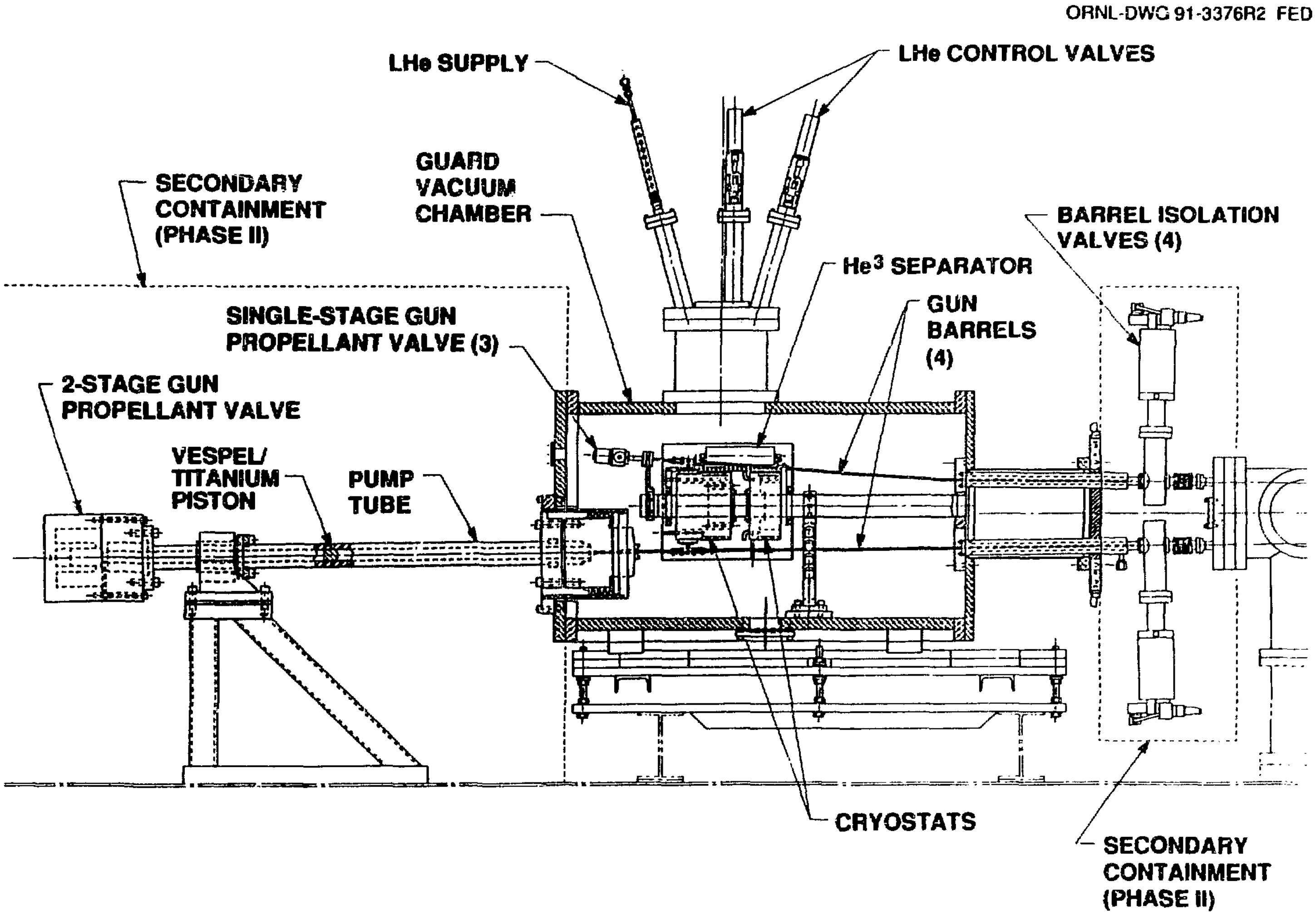


Fig. 2. The TPI injector and two-stage light gas gun assembly.

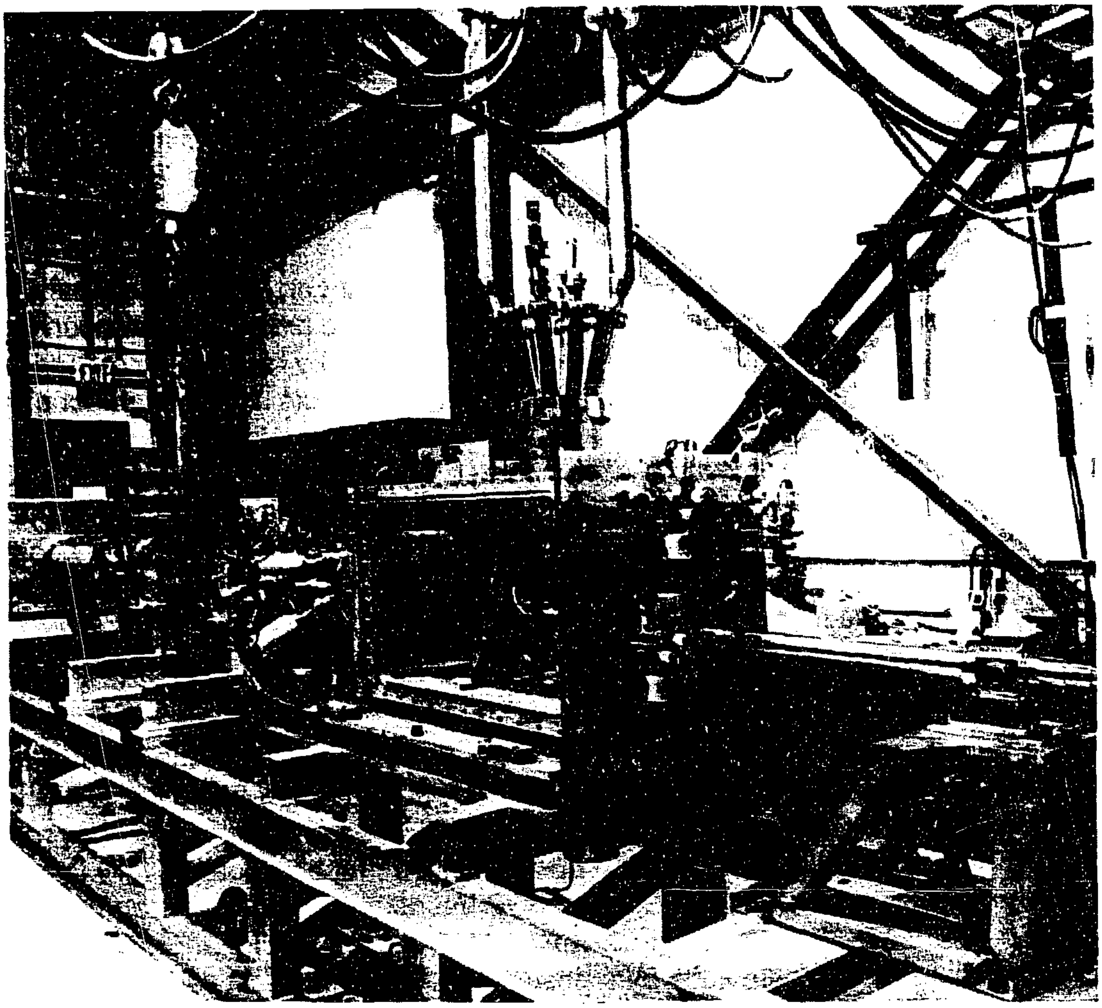

Fig. 3. Photograph of TPI during assembly at ORNL.

2.1 Injector

The injector has a gaseous-helium-cooled (~7 K) cryostat 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 at ~10 K by contact with a gaseous-helium-cooled copper block. Pellet length is controlled both by regulating the gas fill pressure magnitude and duration and, for the lower aspect ratio (AR ~ 1) pellets, by establishing temperature gradients along the barrel tube with auxiliary heating collars. 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 oxygen-free, high-conductivity (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[4] and the Princeton Beta Experiment. 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 in the Tritium Systems Test Assembly at Los Alamos National Laboratory using a prototype tritium pellet injector showed 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 (OHFC copper cryostat) that is also located in the guard vacuum enclosure adjacent 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.

## 2.2 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 near 2.5–3 km/s. It is based on development of two-stage light gas guns at ORNL[5–7] and in Europe.[8–10] In the two-stage driver, moderate-pressure (20- to 60-bar) helium propellant gas initially in a 0.64-L first-stage reservoir accelerates a 25.4-mm-OD Vespel™ or titanium piston to velocities in the range of 100–250 m/s in a thick-walled 4130 carbon steel pumptube. The reservoir is connected to the pumptube by a pneumatically actuated fast valve with a 2.2-cm-diam orifice. This 0.9-m-long, 2.54-cm-ID pumptube 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 pumptube is encased in a 4340 carbon steel head assembly. The accelerating piston compresses (nearly adiabatically) low-pressure, room-temperature hydrogen propellant gas initially at about 1–2 bar. This hydrogen gas becomes the driving gas for the cryogenic pellet. At the high pressures 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. The shear strength of the frozen pellet material also determines the breakaway pressure in the two-stage driver, which has a major influence on the realizable muzzle velocities.

2.3 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 part 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 collects most of the residual propellant gas used to accelerate the pellet which is not pumped by the primary vacuum system.

2.4 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 up to 70 bar (for first-stage propellant) 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.

2.5 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 and are always maintained at subatmospheric pressure, and (3) components that contain tritium and are maintained at pressures above atmospheric pressure. 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 (gloveboxes) 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, and the barrel isolation valves. The guard vacuum system is itself a secondary containment system. The TPI secondary containment systems (gloveboxes) are shown in Fig. 4.

## 2.6 Control System

The TPI is controlled by a programmable logic controller (PLC, Allen Bradley PLC 5/40) located in the TFTR mezzanine beneath the injector. The operator controls 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 with a color mimic display/terminal interfaced to the existing pellet injector MicroVAX, which has a communications link to the PLC. To the operator, the PLC appears 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 performs 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 for the two-stage light gas gun are controlled by the TFTR fire sequencer, which is programmable through the MicroVAX. In addition to the automated operation of the TPI, the injector can be operated manually by controlling individual valves and changing individual set points.

## 2.7 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-emitting diode 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 used to backlight pellets in the pellet photography system. A fiber-optic beam splitter enables a single laser to backlight 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 neutron and gamma radiation 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 using elastomer O-rings, which also provide the fiber-optic or camera interface. A microwave cavity[11] 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

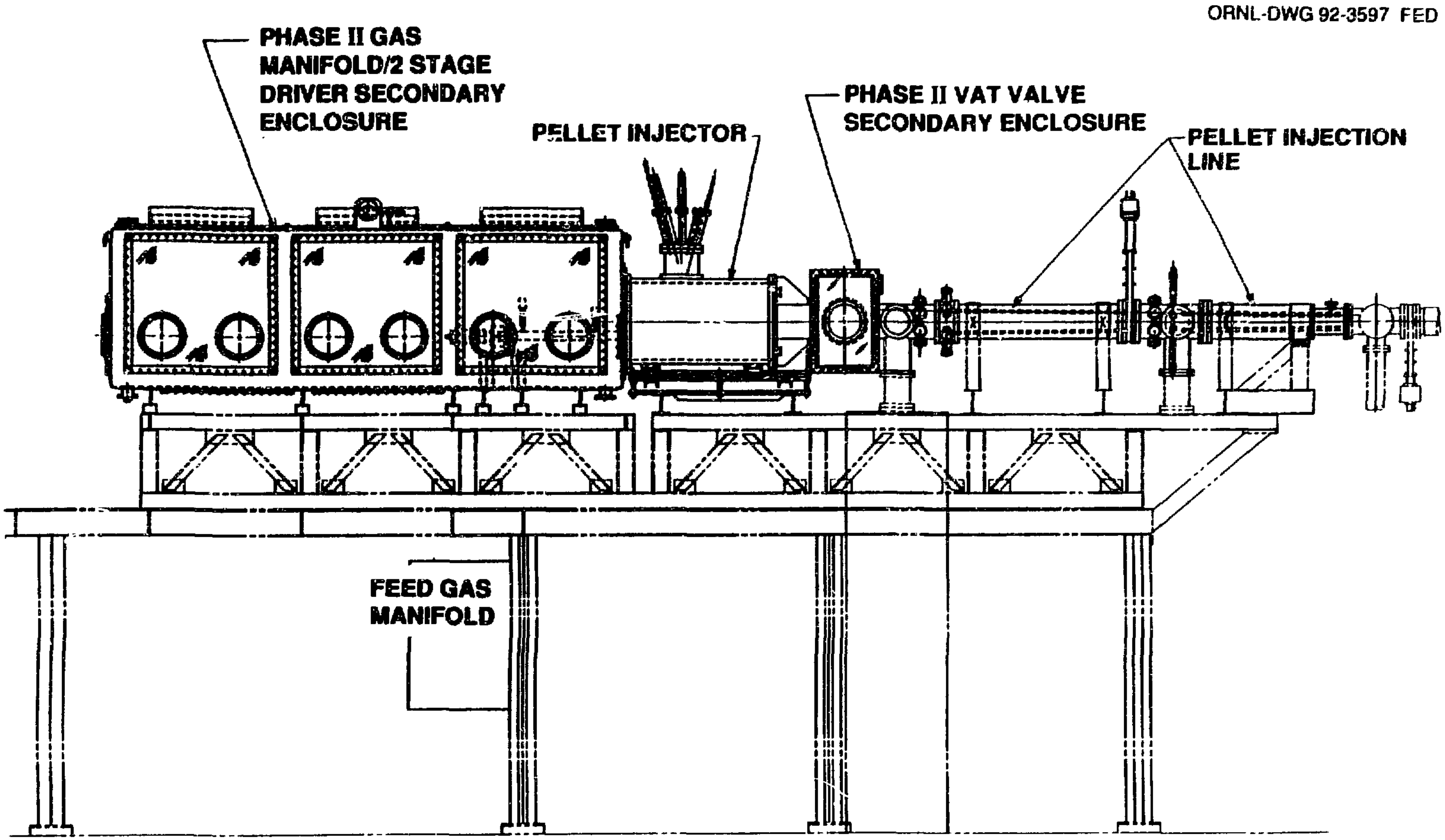


Fig. 4. The TPI secondary containment system for operation with tritium pellets.

target plate in a known volume tank. A photograph of a 3.4- by 4.3-mm pellet at a speed of ~1.4 km/s and the corresponding microwave cavity signal are shown in Fig. 5. The TPI single-stage light gas guns (guns 1–3) have a fast 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 pumptube 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.

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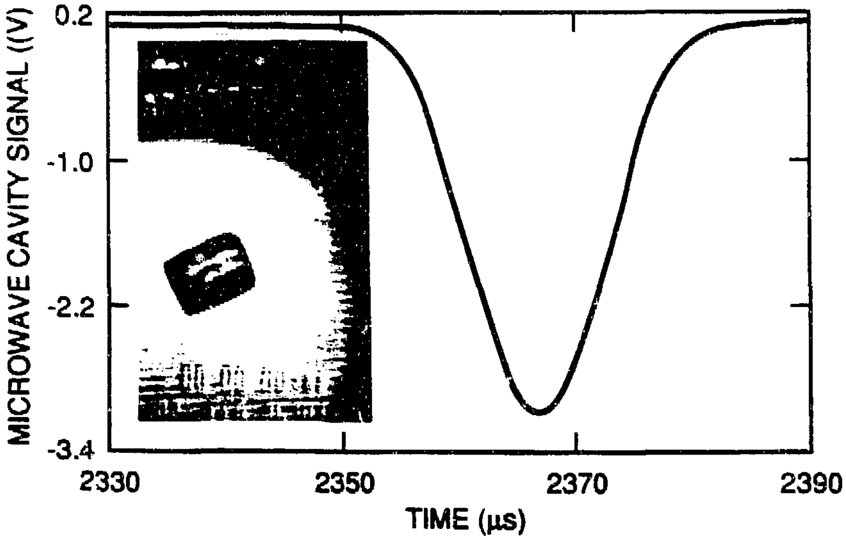


Fig. 5. Microwave cavity signal and photograph of a 3.4- by 4.3-mm pellet at 1.4 km/s.

## 3. TPI TESTING WITH DEUTERIUM PELLETS

TPI components were tested at ORNL in 1992 prior to delivery to TFTR. This testing emphasized initial operation of the three single-stage light gas guns (guns 1–3) 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 helium gas cooling circuit had a sufficiently low pressure drop at operating temperatures to allow operation at TFTR with a closed cryogenic helium system developed for the TFTR neutral beam injectors. It was found at ORNL and in later testing at TFTR that the gun copper cooling cryostat could be maintained at temperatures as low as 8 K with a system pressure drop of ~0.1 bar. 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 an 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-diam and 4-mm-diam 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 69–138 bar, and deuterium pellet muzzle velocities over 1.7 km/s were achieved. 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 6 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.[5,12]

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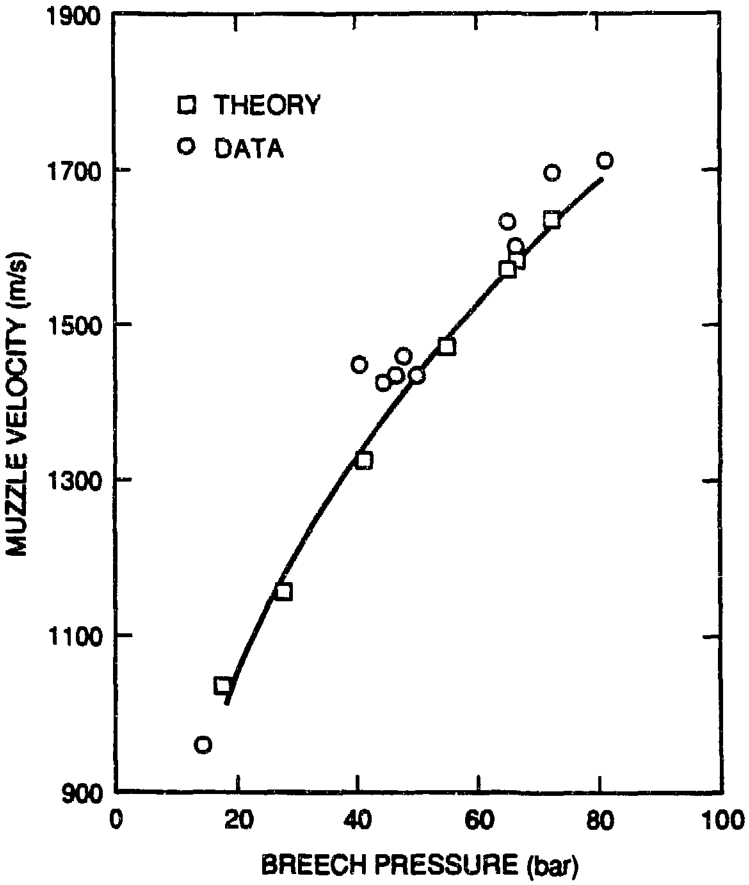


Fig. 6. Pellet speed vs breech pressure for gun 1.

Testing of the two-stage light gas gun was conducted to quantify operating valve response and time scales for initial prefilling of the pumptube with hydrogen propellant gas, acceleration of the piston with helium gas from the first stage reservoir, and evacuation of the pumptube and reseating of 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 were initially in the range 1.5–2.2 km/s and were limited by leaks in the metal O-ring seals (with an internal spring) between the pumptube and the high-pressure head and between the barrel and the high-pressure head, which developed as high pressures (up to 1100 bar) were generated during the shot. This small, transient leak limited pellet speed performance and caused occasional lockup of the titanium piston in the pumptube. A new seal configuration was developed at ORNL using Vespel seals, which are tritium-compatible. With this new seal, the TPI two-stage driver has accelerated deuterium pellets to 2.8 km/s with a 25-g Vespel piston. Peak head pressures are estimated at ~1000 bar based on a pressure measurement made about 1 cm into the 4-mm-diam bored section of the high-pressure head. Data from a 2.8-km/s shot are shown in Fig. 7. The results of modeling this shot are provided in Table 1. Three different ballistics codes were used: a 1-D Lagrangian code,[5] a 0-D/1-D PC-based code, QUICKGUN,[13] and a 0-D/1-D code, TRUCCO, developed in Italy[9] and run on a UNIX workstation. The agreement between the codes and the data is good, especially for the TRUCCO and Lagrangian codes. The inferred pellet breakaway pressure (34.5 bar) is consistent with data presented in ref. 5 for single-stage light gas gun experiments with 5-mm-long deuterium pellets and helium propellant.

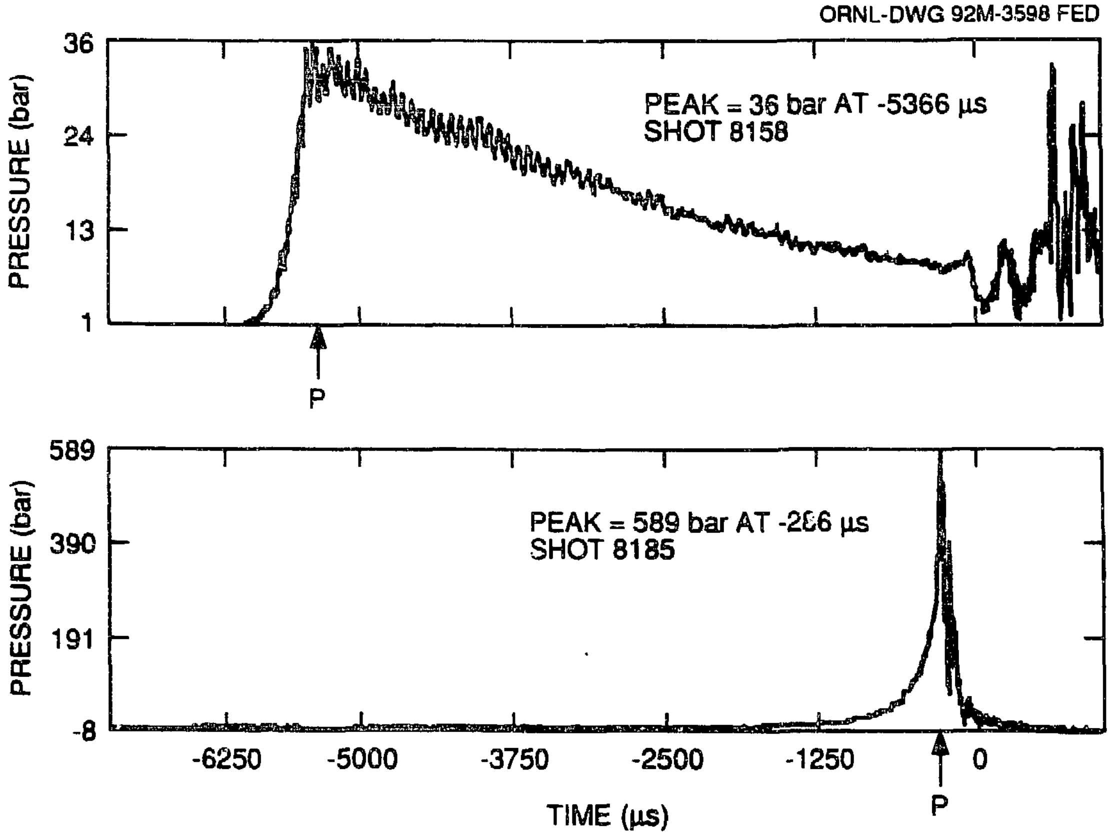


Fig. 7. Data from a 2.8 km/s deuterium pellet shot (gun 4). Upper plot is pressure in breech end of pumptube and lower plot is pressure in the two-stage driver high pressure head.

Table 1. Measured and calculated values for two-stage driver

| | Data | Model | | |
|---|---|---|---|---|
| | | Lagrangian code | QUICKGUN | TRUCCO |
| **Inputs** | | | | |
| First stage pressure, bar | 60 (He) | 41.3[a] | 60 | 43.5[a,b] |
| Second stage pressure, bar | 1.93 ($H_2$) | 1.93 | 1.93 | 1.93[b] |
| Pellet mass, mg | ~12.5 | 12.6 | 12.6 | 12.6 |
| Piston mass, g | 24.8 | 24.8 | 24.8 | 24.8 |
| Breakaway pressure, bar | — | 34.5 | 34.5 | 34.5 |
| **Outputs** | | | | |
| Second stage pressure, bar | 590[c] | 1000 | 1630 | 1150 |
| Piston travel time, ms | 5.6 | 5.7 | 5.7 | 5.7 |
| Maximum piston velocity, m/s | — | 255 | 299 | 275 |
| Pellet velocity, km/s | 2.8 | 3.0 | 3.2 | 2.8 |

[a] Lagrangian and TRUCCO codes have a burst disk between first and second stage; therefore model with lower pressure than on upstream side of propellant valve to match measured piston travel time.
[b] TRUCCO code must use same gas ($H_2$) in both stages.
[c] Pressure is measured in high-pressure head about 1 cm into 4-mm-bore section and is beyond point where peak pressure occurs.

## 4. CONCLUSION

The TPI system, as installed on TFTR for the 1992 deuterium experimental run, is fully tritium compatible and radiation hardened for the 1993–94 TFTR D-T operations. Ongoing design and fabrication activities will provide a D-T gas manifold and two secondary containment glovebox structures, shown in Fig. 4. These components, when retrofitted on TPI in 1993, will provide for full tritium pellet capability. The present TFTR D-T plan calls for extensive use of the TPI.

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