

By acceptance of this article, the publisher or recipient acknowledges the U.S. Government's right to retain a nonexclusive, royalty-free license in and to any copyright covering the article.

DESIGN OF DEUTERIUM AND TRITIUM PELLET INJECTOR SYSTEMS FOR TOKAMAK FUSION TEST REACTOR*

R. B. Wysor, L. R. Baylor, W. E. Bryan, S. K. Combs, P. W. Fisher, R. V. Lunsford, B. S. Maxon, S. L. Milora, D. J. Webster Martin Marietta Energy Systems, Inc., Oak Ridge, Tennessee 37831 G. L. Schmidt, G. W. Labik Princeton Plasma Physics Laboratory, Princeton, New Jersey 08544

Abstract: Three pellet injector designs developed by the Oak Ridge National Laboratory (ORNL) are planned for the Tokamak Fusion Test Reactor (TFTR) to reach the goal of a tritium pellet injector by 1988. These are the Repeating Pneumatic Injector (RPI), the Deuterium Pellet Injector (DPI) and the Tritium Pellet Injector (TPI). Each of the pellet injector designs have similar performance characteristics in that they deliver up to 4-mm-diam pellets at velocities up to 1500 m/s with a design goal to 2000 m/s. Similar techniques are utilized to freeze and extrude the pellet material. The injector systems incorporate three gun concepts which differ in the number of gun barrels and the method of forming and chambering the pellets. The RPI, a single barrel repeating design, has been operational on TFTR since April 1985. Fabrication and assembly are essentially complete for DPI, and TPI is presently on hold after completing about 80% of the design. The TFTR pellet injector program is described, and each of the injector systems is described briefly. Design details are discussed in other papers at this symposium.

Introduction

Since 1976, pneumatic powered pellet injectors have been under development at ORNL for fueling plasma fusion devices. In early experiments, a single pellet pneumatic injector was used to demonstrate pellet fueling on the Impurity Study Experiment (ISX) and the Poloidal Divertor Experiment (PDX). The injector was gas driven and capable of injecting a single, solid hydrogen pellet nominally 1 mm in diameter at speeds in the 600-1000 m/s range. More recently, four-pellet pneumatic injectors have been used in experiments on ISX, PDX, and Alcator-C. These injectors feature four separate gun mechanisms and are capable of delivering all four pellets independently into a single plasma discharge. Pellet sizes and velocity ranges were similar to those for the original single-pellet injector. The formation of pellets in the single- and four-pellet injectors is a batch-type operation with a minimum cycle time of 1-2 min between firings.

During 1984, development was completed on a repeating pneumatic pellet injector that extends pneumatic injector operation to near steady-state operation. Design and performance details with references for the aforementioned developments have been presented by Combs [1]. Briefly, the Repeating Pneumatic Injector (RPI) demonstrated the firing of up to 12 consecutive pellets at a rate of 6 s^-1, the acceleration of larger pellets (nominally 2 to 4 mm in diameter) and muzzle velocities up to 1500 m/s with D2 or up to 1900 m/s with H2. These approach the performance parameters needed for fueling large present-day fusion devices such as the TFTR. The ORNL-RPI was modified and installed on TFTR [2] in April 1985 to conduct pellet injector experiments for the TFTR pellet injector program leading to a tritium pellet injector by 1988.

The TFTR Pellet Injector Program

The TFTR pellet injector program began in April 1983 with a conceptual design study for a tritium pellet injector. The results of this study, reported in October 1983, resulted in continued preliminary design efforts which were reported in May 1984. Detail design was authorized and continued through September. The goal was to install the TFTR TPI system in time to support Q = 1 experiments in 1986. During TPI detail design, it was recognized that early deuterium pellet injector experiments would be essential to verify performance requirements for TPI and at the same time to yield valuable TFTR operational experience. Also, it became apparent that the Q = 1 demonstration schedule would be delayed and would allow schedule time for these experiments. Thus, in September 1984 the program was redirected to include an RPI system to be installed in March 1985, and a DPI system, similar in design to the TPI, to be installed beginning May 1986. Current plans are to replace DPI with the TPI system in 1988. Supporting tritium gun technology experiments are planned for FY 1986 and 1987. Figure 1 illustrates the revised program schedule. The following sections briefly describe these systems.

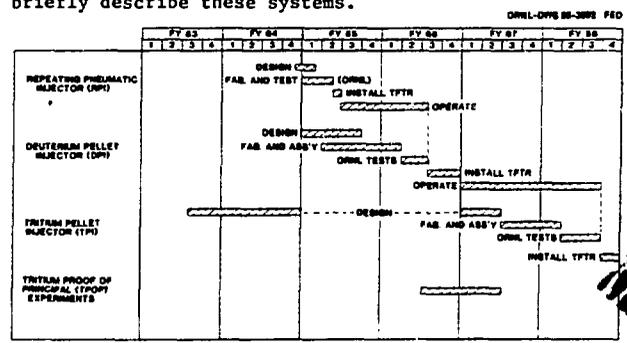


Fig.1. TFTR pellet injector program; overall plan and schedule.

Injector Gun Concepts

Figures 2, 3, and 4 illustrate the three injector gun concepts utilized in the RPI, DPI, and TPI systems, respectively. Operating principles are common in that each concept operates on a pneumatic principle in which compressed gas provides the driving force to accelerate a frozen pellet confined laterally in a tube. Each uses a cryogenic extruder to supply a continuous stream of frozen hydrogen isotope to the gun section where individual pellets are formed, chambered, and accelerated. Each extruder and gun assembly is housed in a high-vacuum enclosure to provide thermal isolation. Figure 2 best illustrates the two-stage freezing process extrusion prior to pellet forming. Each of the concepts uses a fast or propellant valve to release the high-pressure hydrogen (=1500 psig) for accelerating the pellet.

In principle, the three concepts differ primarily in the method used to form and chamber the pellet for firing. In the RPI concept, Fig. 2, the gun assembly utilizes a punch-type chambering mechanism in which a stainless steel gun barrel is brazed directly to a solenoid plunger. When the solenoid is activated, the

Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under Contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

Received by OSTI

NOV 26 1985

90

knife-edge end of the barrel is driven into the extrusion, forming and chambering a pellet. While the punch mechanism is engaged, the hydrogen pellet is admitted to the gun breech by a fast-opening magnetic valve. The valve is connected directly to a 10-cm³ storage reservoir that is connected to a regulated high-pressure hydrogen system. Note that although the RPI concept is a single-barrel concept, it has a proven firing rate of six pellets per second.

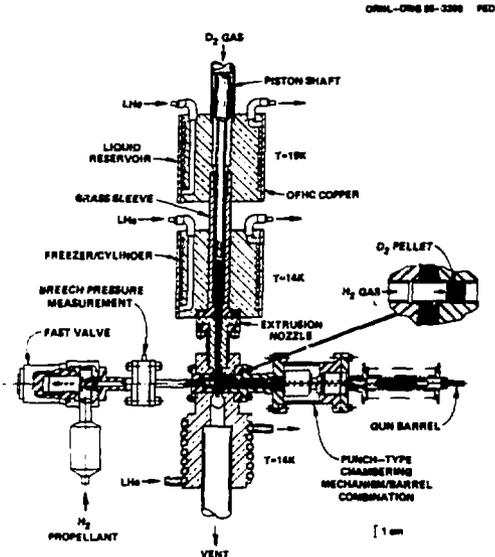


Fig. 2. RPI injector gun.

The DPI gun concept, Fig. 3, utilizes an eight-vane pellet wheel in which the pellet is extruded into each of the pellet vanes sequentially from the extruder. The pellet wheel is then aligned with each of eight gun barrels for firing at a programmed rate. The pellet wheel is driven and aligned with a precision motor-encoder servo system. Each gun barrel is equipped with a solenoid-driven barrel clamp for sealing the barrel against the pellet wheel during pellet firing. Lunsford [3] describes this more completely.

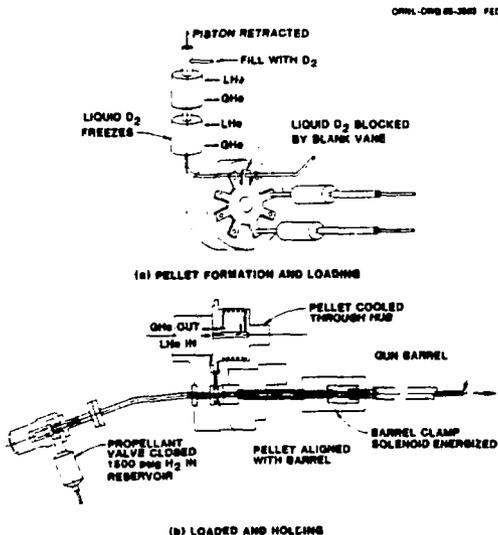


Fig. 3. DPI injector gun.

The TPI injector gun, Fig. 4, is configured differently but uses the same operating principles as the DPI concept. Like the DPI, it utilizes eight guns and gun barrels but forms and chambers the pellet with a different mechanism. The pellet is formed in a central magazine block and transported to the gun block using a pellet slide. Note the horizontal orientation of the extruder mechanism. The main advantage of this configuration is that it minimizes the tritium inventory (≈ 3000 Ci). It is described more fully by Fisher [4].

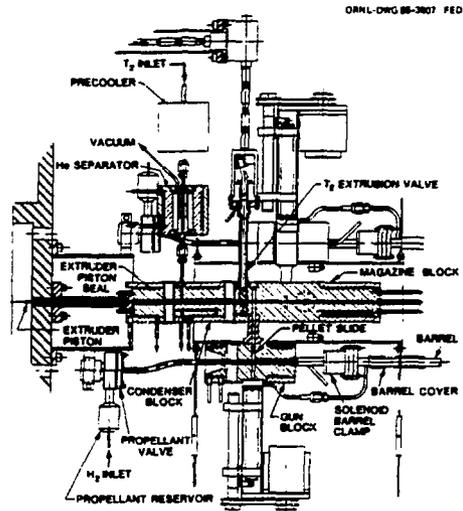


Fig. 4. TPI injector gun.

The RPI System

The RPI installation on TFTR is shown in Figs. 5 and 6. The injector gun (Fig. 2) is housed in an aluminum vacuum box denoted as pellet injector. The gun barrel connects to an injection line that interfaces with the TFTR vacuum vessel (Fig. 5). The injector centerline is 3.1 m above the test cell floor, and the gun center is approximately 8.9 m from the machine center. The pellets are transported in the injection line that was designed to minimize problems associated with the handling of high-pressure gaseous propellants and with angular dispersion in the pellet trajectory.

After exiting the gun muzzle, the pellet passes through a diagnostic station equipped with a light

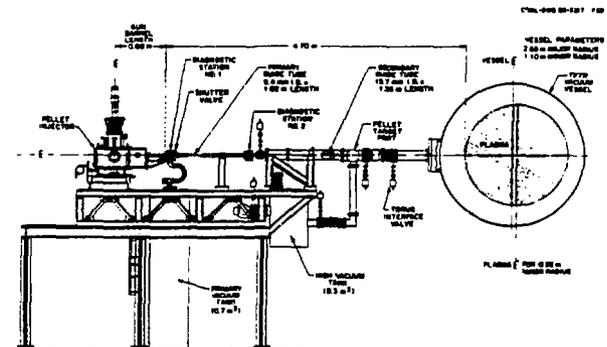


Fig. 5. RPI installation on TFTR.

barrier (for velocity measurement) and a fast-shutter valve. The valve is opened to allow passage of the pellet; valve closure is synchronized with the pellet exit to limit gas throughput (total cycle time of valve ≈ 25 ms). Upon exiting the shutter valve, the pellet enters the first guide tube (9.4 mm ID by 1.0 m long). At the outlet of the guide tube, the pellet crosses another light barrier located inside the second diagnostic station.

Upon exiting the last diagnostic station, the pellet enters the secondary guide tube (15.7 mm ID by 1.4 m long). After traversing the second guide tube, the pellet is in free flight for the remainder (1.4 m) of the trip to the torus. In total, the pellet travels 4.7 m from the gun barrel outlet to the outer plasma edge.

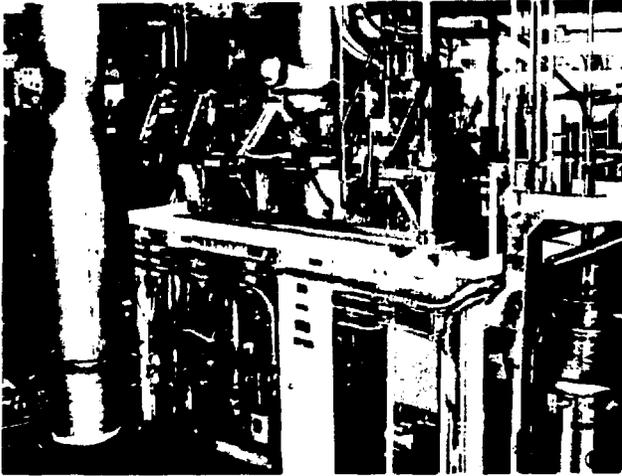


Fig. 6. RPI installation pictorial.

The injection-line vacuum system is divided into two sections - the primary vacuum and the high vacuum. The primary side includes a large vacuum tank (0.7 m³) that handles both the extruder vent and the gun barrel exhaust. The pressure runs at a few hundred millitorr (function of solid deuterium temperature) except during a pellet shot when it increases to about 1 torr with each burst of propellant gas. The high vacuum is isolated from the primary vacuum by the valve at the second diagnostic section (Fig. 5); this valve and the other two injection line valves are only opened during pellet injection. The large volume of the high-vacuum tank (0.3 m³), along with the low conductance of the secondary guide tube, reduces the amount of gas that accompanies a pellet into the torus.

The injector and the injection line up through the isolation valve were provided by ORNL. The Princeton Plasma Physics Laboratory (PPPL) provided the supporting structure, the secondary injection line portion, and the vacuum pumping systems (primary and high-vacuum). The aluminum support structure is a bolted design with electrical isolation at all joints including the floor. Adjustable supports are provided for the gun box and the injector line. A commercial ceramic-to-metal adaptor in the injection line electrically isolates the TFTR vacuum vessel from the injector system. Also, a welded metal bellows is provided for motion isolation.

The first phase of pellet fueling experiments on TFTR using the ORNL repeating pneumatic injector has been concluded. Two separate experiments were performed using 4- and 2.7-mm deuterium pellets. Pellet speed ranged from 1.0 to 1.5 km/s. Single 4-mm deuterium pellets injected into 1.4-MA ohmic plasmas

yielded the best performance results. A line-averaged density of 8.1×10^{13} cm⁻³, a near-triangular shape, and a central density of $1.6-1.8 \times 10^{14}$ cm⁻³ were obtained. Operation of TFTR with 4-mm pellets at the plasma parameters then available was extremely difficult during this series of experiments due to the occurrence of major disruptions. Thus, the pellet size was changed, which involved replacing the gun barrel and the extruder nozzle (Fig. 2).

After conversion to the 2.7-mm pellets, the pellet injector was operated in the repeating mode to gradually increase the plasma density. Up to five pellets were injected into a plasma on a single machine pulse. This operation is shown in Fig. 7; five pellets were injected at 0.25-s intervals into a staggered beam, giving a line-averaged density of 1×10^{14} cm⁻³.

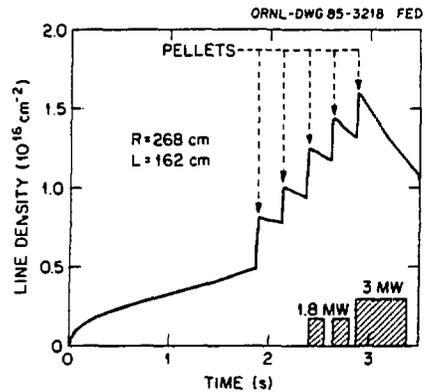


Fig. 7. Density evolution for five 2.7-mm deuterium pellets injected into 2.2-MA TFTR plasma with staggered neutral beam operation (from [2]).

The DPI System

The DPI system is an eight-shot injector gun concept designed to fire batches of eight pellets at a cycle time of approximately five minutes. Firing intervals for each of the eight pellets may be from 2 ms to 1.5 s. The gun accommodates a mix of pellet sizes which are 3.0- to 4.0-mm-diam and 3.5-mm long. Design pellet speed is 800 to 1500 m/s, with a 2000 m/s design goal. The gun concept, Fig. 3, is described in detail by Lunsford [3]. The injector gun assembly installed on TFTR is shown in Fig. 8.

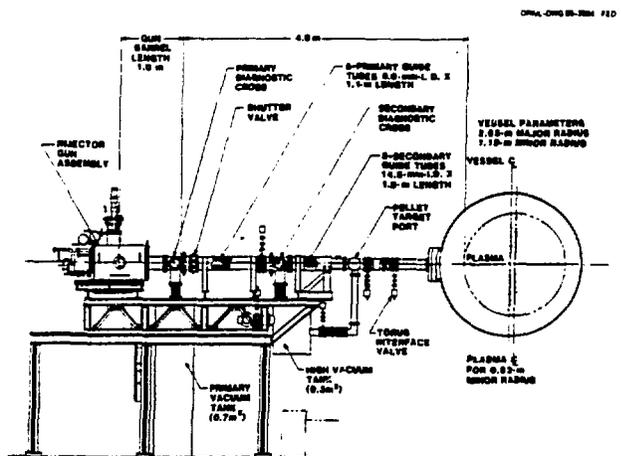


Fig. 8. DPI installation on TFTR.

The gun assembly is connected to the TFTR vessel through an injection line as shown. The injection line contains guide tubes for each of the eight gun barrels to control the propellant gases and pellet trajectory as described earlier for the RPI system. In comparison, the RPI and DPI injection line elements are essentially the same except the DPI injection line is more complex because of the eight gun barrels. The DPI system utilizes the same basic support structure and vacuum pumping system (See Figs. 5 and 8). The pellet target port and vacuum line connecting to the TFTR vacuum vessel are common for the RPI and DPI systems.

The assembled injection line and gun housing are shown in Fig. 9. Final assembly is essentially complete. Performance tests will be performed at ORNL prior to delivery to the TFTR facility by May 1986.

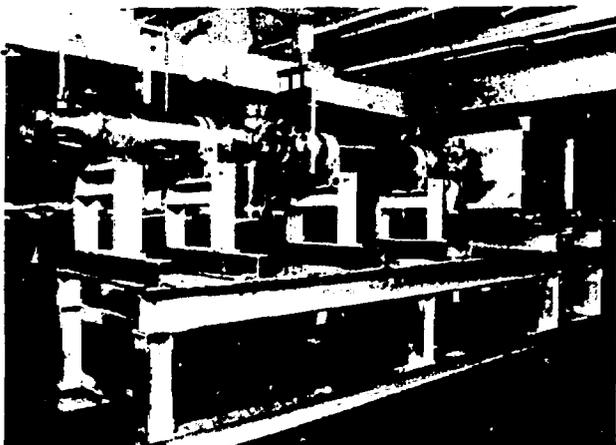


Fig. 9. DPI injection line and gun housing.

The TPI System

The TPI system is planned to replace the DPI system in order to provide deuterium and tritium fueling for the TFTR machine. Performance parameters for TPI are essentially the same as those described for the DPI system. The gun concept, Fig. 4, is enclosed in a vacuum box and connected to the TFTR vacuum vessel through an injection line like the DPI system. The TPI injection line is essentially the same design as DPI except that it is about 1 m longer to enable packaging the entire system inside a glove box as shown in Fig. 10. The 500-ft³ stainless steel glove box completely encloses the injector gun, a major portion of the injection line, and the vacuum pumping system. The latter is designed especially for pumping tritium. Detail design of the TPI, which is about 80% complete, is described by Fisher [4]. The project is presently on hold until FY 1987. Some development efforts are planned in FY 1986-1987 in support of tritium gun technology.

Control and Data Acquisition System

A stand-alone control and data acquisition system developed by ORNL was used for injector and vacuum system operation on the RPI system. A similar system is planned for DPI and TPI. A Model 2/30 Allen-Bradley programmable logic controller (PLC) performs all of the control functions and is interfaced via CAMAC to a VAX 11/730 minicomputer for remote operation. Local operation of the injector is provided by an intelligent panel system with a keypad and pushbutton module programmed from the PLC. The VAX has a CAMAC serial highway interface which is used for color graphics

status and mimic displays, data acquisition from transient recorders, the communications link with the PLC and a fire control sequencer that triggers the chambering mechanism, the propellant valve, and the fast shutter valve (in the injection line) at the predetermined times. The CAMAC interface also allows for interconnection to the timing and control systems of TFTR. The system is operated remotely through a combination of track-ball and keyboard commands. Data archives are maintained for both transient data from pellet shots and trend data acquired from the PLC during operation of the pellet injector. Details of the hardware and software design and operation of the system are presented by Baylor [5].

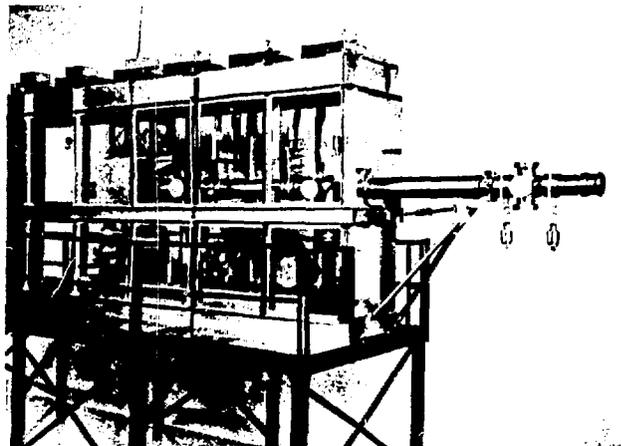


Fig. 10. Tritium pellet injector (TPI) assembly, 1/8 scale model.

Summary

The TFTR pellet injector program is well under way, with the RPI system successfully installed and operated. Results are very encouraging. Assembly of the DPI system is nearing completion with the tested unit planned for May 1986. The TPI system design is almost complete and is in a hold mode until FY 1987.

References

- [1]. S. K. Combs et al., "Repeating pneumatic hydrogen pellet injector for plasma fueling," *Rev. Sci. Instrum.* vol. 56, part 6, p. 1173, (1985).
- [2]. S. K. Combs et al., "Operation of repeating pneumatic injector on TFTR," presented at the 32nd Annual National Symposium of the American Vacuum Society, Houston, Texas, November 18-22, 1985.
- [3]. R. V. Lunsford et al., "Deuterium Pellet Injector gun design," these proceedings.
- [4]. P. F. Fisher et al., "Tritium Pellet Injector design for Tokamak Fusion Test Reactor," these proceedings.
- [5]. L. R. Baylor et al., "Design and Implementation of a control and data acquisition system for pellet injectors," these proceedings.