

EXTRUSION OF TRITIUM AND D-T PELLETS FOR ITER FUELING

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ABSTRACT

As part of the International Thermonuclear Engineering Reactor (ITER) plasma fueling development program, Oak Ridge National Laboratory (ORNL) has fabricated a pellet injection system to test the mechanical and thermal properties of extruded tritium. This repeating, single-stage, pneumatic injector, called the Tritium-Proof-of-Principle Phase II (TPOP-II) Pellet Injector, has a piston-driven mechanical extruder and is designed to extrude and accelerate hydrogenic pellets sized for the ITER device. The TPOP-II program has the following development goals: evaluate the feasibility of extruding tritium and deuterium-tritium (D-T) mixtures for use in future pellet injection systems; determine the mechanical and thermal properties of tritium and D-T extrusions; integrate, test, and evaluate the extruder in a repeating, single-stage light gas gun that is sized for the ITER application (pellet diameter ~ 7 to 8 mm); evaluate options for recycling propellant and extruder exhaust gas; evaluate operability and reliability of ITER prototypical fueling systems in an environment of significant tritium inventory that requires secondary and room containment systems.

In tests with deuterium feed at ORNL, up to 13 pellets have been extruded at rates up to 1 Hz and accelerated to speeds of 1.0 to 1.1 km/s, using hydrogen propellant gas at a supply pressure of 65 bar. Initially, deuterium pellets 7.5 mm in diameter and 11 mm in length were produced - the largest cryogenic pellets produced by the fusion program to date. These pellets represent about a 10% density perturbation to ITER. Subsequently, the extruder nozzle was modified to produce pellets which are nearly 7.5 mm right circular cylinders. Tritium and D-T pellets have been produced in experiments at the Los Alamos National Laboratory Tritium Systems Test Assembly (TSTA). Hydrogenic pellets will be used in ITER to sustain the fusion power in the plasma core and may be crucial in reducing first-wall tritium inventories by a process called isotopic fueling in which tritium-rich pellets fuel the burning plasma core and deuterium gas fuels the edge.

INTRODUCTION

An earlier ORNL tritium pellet injector experiment (1988-89)¹⁻³ operated at TSTA established the basic scientific feasibility of production and pneumatic acceleration of tritium pellets for fueling future fusion reactors. This earlier experiment, Tritium-Proof-of-Principle Phase I (TPOP-I), used a single-stage, light gas gun in which a single 4-

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mm diameter pellet (a cylindrical projectile of frozen hydrogenic gas at a temperature in the range 6-16 K) was frozen in-situ in the barrel and accelerated with high-pressure hydrogen gas. Over 100 kCi (~10 g) of tritium was processed through the experiment without incident during the entire lifetime of the project. In Phase II of this experiment, the pipe gun has been replaced with a repeating pneumatic pellet injector (RPI), which was developed by Combs, Milora, and Foust at ORNL.⁴ The specific embodiment of this gun is similar to the design of the injector used on the Joint European Torus (JET)^{5,6} and recently installed on the tokamak experiment at General Atomics (DIII-D).⁷ These extruder-based guns have been used to fuel fusion experiments with deuterium and hydrogen pellet streams ranging from 1.8-mm diameter at 10 Hz to 6-mm diameter at 1 Hz. The extrusion feed technique is quite general and has also been used in centrifugal pellet injectors. The TPOP-II gun is designed to produce 8-mm diameter pellets as a prototype for those that will be used to fuel the ITER device. Unlike TPOP-I, which was a single-shot device, the new gun is able to produce streams of more than ten pellets at frequencies up to 1 Hz. A TPOP-II run could require as much as 50 kCi (~5 g) of tritium for a single fill of the extruder.

ITER requires pellet fueling to replenish burned-up fuel in the plasma, to control plasma density and burn rate, to establish a flow of hydrogenic ions in the scrape-off layer to reduce impurities and helium ash concentrations in the core of the plasma, and to control gas composition in the plasma edge. This latter point is important to the development of the concept of isotopic fueling.⁸ In this concept, pellets of high-tritium concentration would be delivered beyond the scrape-off layer for plasma fueling, and gas of high-deuterium concentration would be delivered into the scrape-off layer to control the density and composition of the diverter region. The high concentration of deuterium next to the wall would translate into lower tritium concentration in the wall and would significantly reduce (~50%) the tritium inventory in the wall, which could approach several kgs. Therefore, pellets with a broad range of tritium concentration are being evaluated in these experiments. Fueling requirements for ITER have not been fully established at this time, but early concepts⁹ called for the use of up to 8-mm diameter D-T pellets at a rate of 1 Hz. These pellets would represent about a 10% perturbation in the plasma density if the entire mass is deposited in the core. More recent estimates of fueling requirements call for smaller pellets at higher repetition rates. Nevertheless, a conservative approach has been adopted here; the largest anticipated pellets are being produced so that issues related to volumetric heat generation due to decay heat from tritium in both the extruder and pellets can be evaluated.

Physical properties of solid tritium that would facilitate the design and operation of an extruder for tritium are not known. In the course of TPOP-I experiments,¹⁰ data from break-away pressure measurements of deuterium and tritium pellets indicate that the shear strength for tritium may be about twice that of deuterium around 10 K. These numbers indicate that one might expect to encounter about twice the extrusion forces for tritium as are encountered for deuterium. The actual behavior of tritium during the extrusion, punching, and acceleration processes must be tested to gain any confidence in the use of extruder-based pellet injectors for ITER. Because of this lack of information, it was decided to utilize the successful RPI technology with few changes to get a direct comparison of tritium with the extensive deuterium extruder database. The goals of the TPOP-II program are to determine the feasibility and conditions under

which tritium and D-T mixtures can be extruded, to determine the mechanical and thermal properties of tritium and D-T extrusions, to extrude and accelerate ITER relevant pellets in a repeating mode, to evaluate options for recycling extruder and pellet exhaust, and to evaluate the RPI design in an environment having significant tritium inventory, secondary containment, and interfaces with other tritium processing systems.

EXPERIMENT

Figure 1 is a layout of the TPOP-II experiment as it is installed at TSTA. The tritium extruder, extruder drive, 8-mm gun mechanism, and propellant valve are based on the RPI gun design. The gun is housed in a guard vacuum enclosure that provides a vacuum environment for thermal insulation of the cryogenic systems. A cryogenic ^3He separator is also housed in this enclosure. Liquid helium coolant is supplied from portable dewars to the glovebox, and coolant exhaust gas is exhausted from the glovebox to the stack at TSTA. Flow rate of coolant to the various cryostats is controlled by four helium flow control valves. The injection line contains light gates and photographic stations to record the velocities and integrity of the pellets. The three-bay glovebox shown in Fig. 1 is the same glovebox as was used in the original TPOP-I experiment. With the exception of the gun, essentially all of the original equipment from the TPOP-I experiment has been used to support the TPOP-II experiment. A new glovebox extension shown in Fig. 1 has been added above one end of the TPOP-I glovebox to accommodate the extruder drive, which is too tall to fit in the original glovebox. Shown below the glovebox is a secondarily contained, 600-L ballast volume to maintain pressure in the injection line below about 50 mbar (38 torr) during pellet production runs. With very few exceptions, tritium-wetted surfaces are all metal (usually stainless steel). Operation of the entire experiment is controlled remotely from the console. High-speed data acquisition for the pellet diagnostics is accomplished through a MicroVAX II computer and CAMAC interfaces. Descriptions of the TPOP-I system¹⁻³ and RPI gun^{4,5} are given elsewhere.

At TSTA, tritium is supplied to the experiment from a product container (PC) mounted in the load-in/load-out (LIO) glovebox. Several pure tritium extruder fills can be obtained from a single PC. Exhaust gas from the experiment is returned to a holding tank and is later transferred to a uranium bed (UTB) using an all-metal scroll pump and bellows pump located in the transfer pump glovebox (TP1). Much larger tritium throughputs are required for TPOP-II than were required in the earlier TPOP-I experiments; therefore, the standard operating procedure includes recycling of extruder and injection line exhaust gas streams within the TPOP manifold system to maximize experimental output within TSTA constraints of tritium supply and tritiated gas storage. Unused extrusion, which could equal up to 75% of the gas fed to the extruder, is recycled directly into the TPOP storage reservoirs for reuse. Typically the mass of high pressure propellant gas used to accelerate the pellets is about equal to the mass of the pellets. Deuterium propellant gas is used at TSTA; this mixes with the pellet gas in the injection line as the pellets are fired. This gas is collected in the 600-L vacuum ballast volume located under the glovebox. Pressure in this tank increases about 10-20 mbar during a sequence of shots from a single extrusion. After each run, some of this gas is mixed back with the gas that has been recycled directly from the extruder to produce a leaner (in tritium) mixture of D-T feed. Composition of the feed gas is measured by Raman or mass spectroscopy. Recycling these exhaust streams facilitates generation of the maxi-

imum amount of experimental data for pellets of varying D-T composition for each batch of pure tritium received from a PC.

RESULTS

The TPOP-II injector was fabricated and operated at ORNL in 1994-1995 and shipped to TSTA in March 1995. During this period it was used to produce deuterium pellets that were accelerated with hydrogen propellant. Figure 2 shows one of the early deuterium pellets produced by the gun. After acceleration these pellets were typically 7.5 mm in diameter by 11 mm long and traveled at speeds of 1.1 km/s. These pellets would represent about a 10% density perturbation to ITER. Subsequently, the extruder nozzle was modified to produce a pellet with an accelerated aspect ratio of about one. Figure 3 shows a sequence of these pellets. Each of these pellets would represent about a 7% density perturbation in ITER. During commissioning with deuterium feed at ORNL, the extruder and injection line diagnostics were optimized for proper operation, and the CAMAC-based data acquisition and fast control system was developed and tested for operation at pellet frequencies up to 1 Hz. Strings of up to 13 pellets have been extruded, punched at rates up to 1 Hz, and accelerated to speeds of 1.0 to 1.1 km/s, using hydrogen propellant gas at a supply pressure of 65 bar. The quality of the extrusion and accelerated pellets was evaluated as a function of extrusion speed, repetition rates, feed pressure, cryostat temperatures, and timing sequence between the punch and propellant valve.

Initial testing at TSTA began in August 1995 following several months of installation activity. Deuterium pellets were successfully extruded at rates up to 0.3 Hz and accelerated to speeds in the 600-800 m/s range with deuterium propellant gas. Following this, the system was prepared for tritium service. Following successful completion of tritium leak checking, the first tritium and D-T pellets were produced in Sept. 1995. This was followed with another successful run period in April 1996.

Tritium received from a PC generally contains several percent of helium-3. During TPOP-I experiments it was found that levels on the order of 0.005% were required for production of pipe-gun pellets³. It was anticipated that this high purity standard would not have to be maintained for extruded pellets because the extruder itself acts as a separator. Helium-3 separations were carried out as described in Ref. 3, however, because of the limited size of the separator (which was designed for TPOP-I), a purity level of only ~1% helium-3 was reached. Nevertheless, both good extrusions and pellets were produced under these conditions. Figure 4 shows an extrusion of pure tritium and a pure tritium pellet. The extrusion has a rectangular cross-section 5.5 mm wide and 9.5 mm thick. This photograph is of fresh extrusion which appears transparent, however, if allowed to age the extrusion becomes opaque in a short time (~10s); an effect probably associated with beta decay. The extrusion was produced with the top extruder cryostat at 23K and the bottom two cryostats at 13K. The time required for the beta decay heat to melt an isolated piece of tritium extrusion is given by

$$\Delta t = (C_s \Delta T + \Delta H_f) / dH/dt \quad (1)$$

where C_s is the heat capacity of the solid, ΔH_f is the heat of fusion of the solid, and dH/dt is the decay heat output of tritium. Using values from Sauers¹¹ ($C_s \sim 11 \text{ J/mole-K}$, $\Delta H_f = 233 \text{ J/mole}$, and $dH/dt = 1.95 \text{ W/mole}$), one would expect the 13K extrusion to persist about 2.7 min in vacuum. It has been observed that the extrusion persists even longer periods of time than this and heating of the lower block well above the melting point ($\sim 30 \text{ K}$) is required to flush the solid out of the cryostat for recycling. The peak force observed during these extrusion runs was 200psi for pure tritium (higher pressures were observed when the cryostats were operated at lower temperatures). When the pellet is cut from the extruded ribbon its diameter is reduced from 9.5 mm to 8 mm in the barrel, thus increasing its length to about 8 mm also. Some material is lost by erosion during the acceleration process producing the 7.5 mm diam. by 7.5 mm long pellet shown in Fig. 4. This pellet is traveling 605 m/s and was accelerated with deuterium propellant at a supply pressure of 66 bar. Both pure tritium and D-T extrusions have now been produced and pellets have been accelerated to velocities in the range of 600-900 m/s.

CONCLUSIONS

The TPOP-II experiment has been made fully operational for production and acceleration of ITER relevant pellets. Extrusions of pure tritium have been produced with helium-3 concentrations of $\sim 1\%$. Decay heating of tritium does not seem to adversely affect extruder performance, neither excessive force is required nor do extrusions melt on a timescale which would pose a problem for use of extruders to produce pellets for centrifugal injectors like those proposed for ITER. Good quality ITER relevant tritium and D-T pellets have been produced and accelerated with deuterium propellant.

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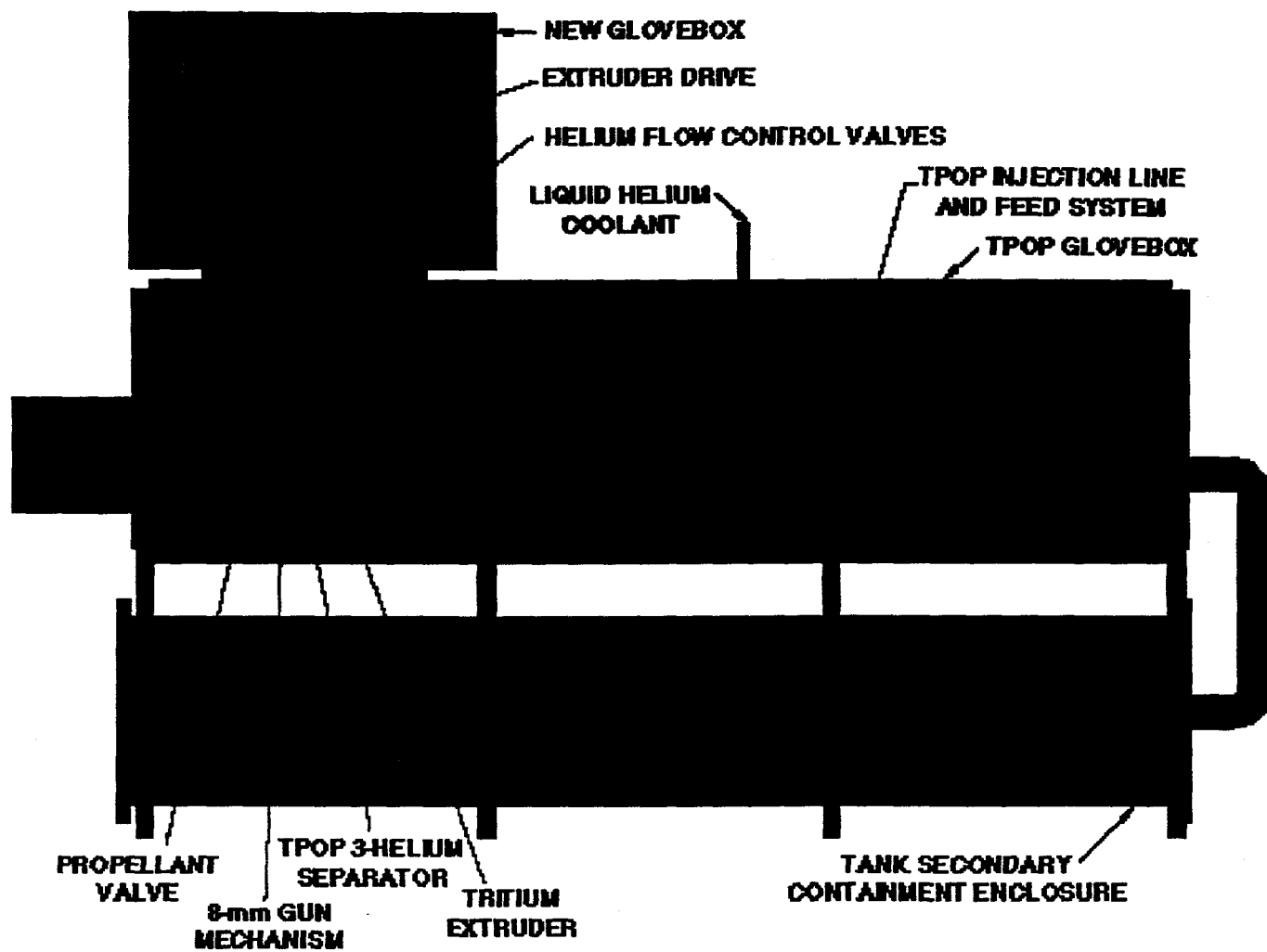


Figure 1. Diagram of TPOP-II experiment as configured at TSTA.

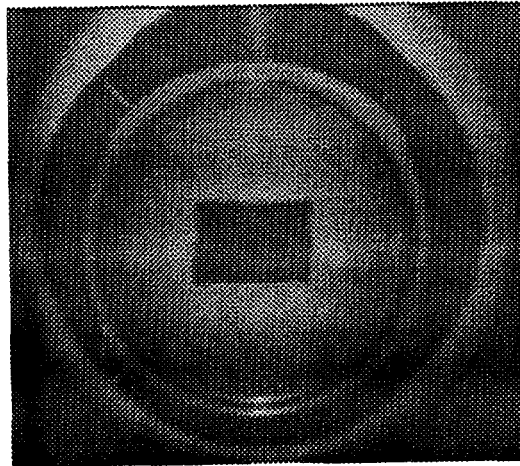
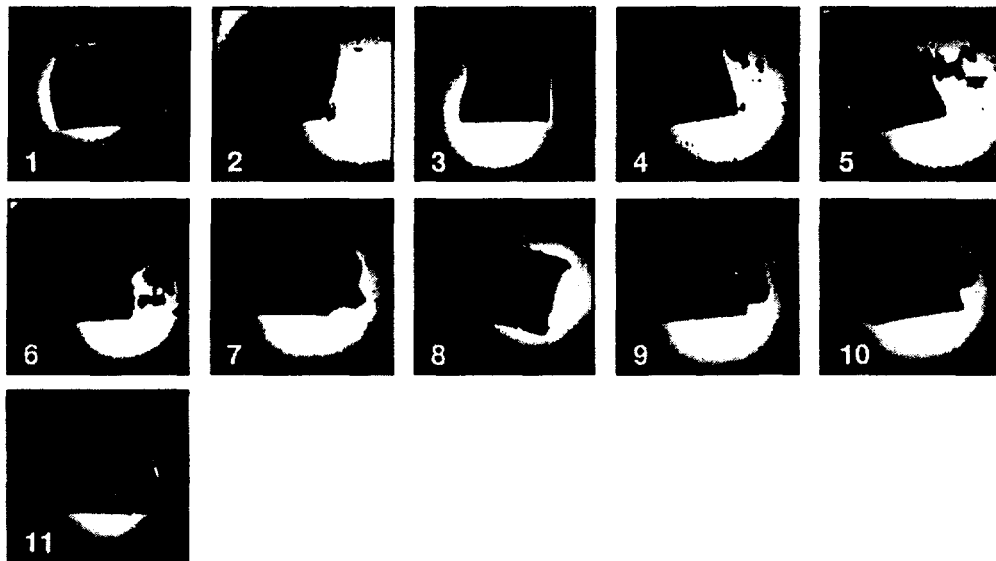


Figure 2. Photograph of TPOP-II deuterium pellet measuring 7 mm in diameter by 11 mm long and traveling at 1 km/s.



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Figure 3. Photograph of a sequence of TPOP-II deuterium pellets at a repetition rate of 0.5 Hz and traveling at 1.1 km/s.

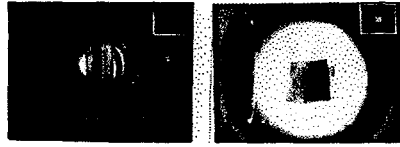


Figure 4. Photograph of an extrusion of pure tritium (left) and a pure tritium pellet in flight at the second photo station (right).