TRITIUM PROOF-OF-PRINCIPLE PELLET INJECTOR RESULTS*

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ABSTRACT

The tritium proof-of-principle (TPOP) experiment was built by Oak Ridge National Laboratory (ORNL) to demonstrate the feasibility of forming solid tritium pellets and accelerating them to high velocities for fueling future fusion reactors. TPOP used a pneumatic pipe-gun with a 4-mm-i.d. by 1-m-long barrel. Nearly 1500 pellets were fired by the gun during the course of the experiment; about a third of these were tritium or mixtures of deuterium and tritium. The system also contained a cryogenic ^3He separator that reduced the ^3He level to $<0.005\%$. Pure tritium pellets were accelerated to 1400 m/s. Experiments evaluated the effect of cryostat temperature and fill pressure on pellet size, the production of pellets from mixtures of tritium and deuterium, and the effect of aging on pellet integrity. The tritium phase of these experiments was performed at the Tritium Systems Test Assembly (TSTA) at Los Alamos National Laboratory. About 100 kCi of tritium was processed through the apparatus without incident.

INTRODUCTION

Injection of high-velocity frozen hydrogen and deuterium pellets has become the leading method of fueling magnetic fusion experiments [1]. Future fusion reactors, such as the Compact Ignition Tokamak (CIT) [2] and the International Thermonuclear Experimental Reactor (ITER) [3], will be heavily dependent on tritium pellet fueling for their success. The TPOP experiment was conceived to begin the study of tritium pellet fueling by demonstrating the basic feasibility of tritium pellet production and acceleration. Very little information is available on the properties (especially the mechanical properties) of solid tritium [4]—certainly not enough to evaluate the probability of success for direct application of, or extrapolation from, present pellet injector technology to a successful tritium pellet injector. Radioactive decay of tritium produces both heat and ^3He within the solid. The magnitude of decay heat is small compared to other thermal parameters and should not be a problem. However, ^3He has a known detrimental effect on cryopumping of tritium [4]. Furthermore, ^3He production may affect other

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critical properties such as thermal conductivity and mechanical strength. Therefore, the behavior of tritium in a pellet injector may be quite different from that of other hydrogen isotopes.

The initial phase of the TPOP program involved design and testing of a pneumatic pipe-gun-type pellet injector. This gun uses *in situ* condensation [5] to form pellets directly in the breech of the barrel, where they are ready for acceleration by high-pressure propellant gas. This concept is ideal for this phase of the work because it requires very little excess tritium to produce the pellets. In addition, the gun itself is very simple; there are no moving parts inside the gun where tritium compatibility and maintenance might be a problem. A cryogenic ^3He separator was included as part of the apparatus to meet the anticipated need for very high purity tritium. This paper describes the results of tritium experiments. The design of the system, its integration into the TSTA facility, and the results of deuterium tests have been described in previous papers [6,7].

TPOP APPARATUS

Figure 1 is a schematic diagram of the TPOP experiment. The gun, gun line with pellet diagnostics, and gas handling system are housed in a glovebox for secondary tritium containment. Equipment is arranged in the glovebox to allow maximum space for gun maintenance and addition of future gun designs. Pellet diagnostics include fiber-optic light gates for velocity measurement and photography timing, pulsed laser-illuminated video photography, shock measurement when the pellet strikes the end of the pellet line, and a rotatable target plate to observe pellet impact. A Normetex all-metal spiral pump, backed by a metal diaphragm pump (not shown), is used to pump vacuum and transfer gas within the TPOP system. The propellant valve is the standard high-speed, high-pressure design developed by Milora, Combs, and Foust [8]. Hydrogen was used as the propellant gas in all experiments.

Figure 2 shows the overall TPOP system, including the control console. All interfaces from the experiment to the controls, to the TSTA systems, and to the liquid helium supply are through two demountable panels on top of the glovebox. A third panel exists for addition of future experiments. The system can be controlled either from the manual control panel or from the process control computer. All routine process control was performed automatically by a program named "THE FIX" from Intellution. Not visible are the CAMAC crate (located in the bottom of the control rack)

and the MicroVAX computer used for high-speed data acquisition.

Figure 3 shows the gun assembly in the glovebox. Visible are the 1-m-long gun barrel, the guard vacuum enclosure and vacuum pump, and the propellant valve. The pellet gas valve at the propellant valve admits tritium to the breech of the gun during pellet formation. A similar feed valve is located at the exit from the barrel. Liquid helium enters and is exhausted from the gun through vacuum-jacketed lines. Figure 4 shows the gun with the guard vacuum enclosure removed. The gun cryostat and ^3He separator, along with all of their associated feedthroughs, are mounted on the front flange of the guard vacuum chamber to facilitate easy access to these components with minimal disassembly. Liquid helium coolant flows first through the gun cryostat and then through the ^3He separator. Cryostat temperatures are controlled by resistance heaters. The collar heaters shown in the figure were not used in these experiments. Instead, a thermal short to the 300 K flange was made to the barrel 10 cm in front of the cryostat. The gun cryostat contacts and cools the barrel over 4 mm of the barrel's length in the work presented here. More complete descriptions of the apparatus are given in Refs. [6] and [7].

RESULTS

The key to making good tritium pellets in a pipe-gun such as that used in the present experiments is to produce tritium with very low ^3He levels. Helium-3 levels on the order of 0.1% had serious detrimental effects on pellet size and strength. A pellet usually breaks approximately in half along its axis, and very few unfractured pellets emerged at propellant pressures above 6.9 MPa (1000 psi). Levels on the order of 0.01% made better pellets, some of which could actually hold 6.2 MPa (900 psi) of pressure for a period of time without being dislodged from the barrel. Many of these pellets, however, appeared to undergo brittle fracture as they passed through the pellet line. Good-quality pellets that could be accelerated without fracture to velocities of nearly 1400 m/s (Fig. 5) had ^3He concentrations of <0.005%. Helium-3 compositions were determined by mass spectroscopy, which had a limit of detectability of about 0.005%. Measurement of the residual pressure in the ^3He separator cooled to a point where the tritium vapor pressure was well below the residual pressure showed about 0.002% ^3He in these latter samples.

Each time fresh tritium was received from TSTA, or whenever a long period of time had passed without purification, a ^3He separation was performed. Tritium obtained from TSTA ranged from 3% to 13% ^3He .

About 100 kCi of tritium was processed through the TPOP system without incident during the course of tritium operations. Separations were initiated by cryopumping the tritium (usually on the order of 7000 Ci) into the separator, which was initially at <12 K. The temperature of the separator rose significantly (to >20 K) during the initial condensation. After the temperature dropped below 12 K, the separator was opened to vacuum for a period of time (1 min) to remove the ^3He cover gas. This "burping" restored the pressure gradient to the separator and enabled additional tritium condensation. The separator was then evacuated for a period of 4 min at a temperature of 15 K. The higher temperature produced a small flow of tritium (vapor pressure = 4 torr at 15 K), which swept the ^3He along with it. When the separator was operated at much below this temperature, ^3He levels reached only about 0.1% because of either the large flow restriction from the separator or cryotrapping in the solid. After evacuation of the separator was complete, the balance of the system was carefully rinsed with pure deuterium to remove all traces of residual ^3He . Helium-3 grows into tritium at a rate of 0.0006%/h, so that only one separation was required per 8-h shift.

Figure 6 shows the operating curve for production of tritium pellets. These pellets were produced with a 4-mm-long cooled section of barrel, with thermal shorts to 300 K located 10 cm from each side of the cryostat, and with $<0.005\%$ ^3He in the tritium. Pellets were formed by admitting gas to the barrel from the breech end only. Previous work with deuterium [7] showed that condensation from this direction produced pellets with the least tendency to fracture during acceleration due to trapping of high-pressure gas in voids in the rear of the pellet. Pellets can be produced over a wide range of sizes by varying the cryostat temperature and fill pressure. Pellets formed at 16 K, however, could not be fired at that temperature because they left the barrel under the force of their own vapor pressure. Although 4-mm-long deuterium pellets behaved quite well [8], 5-mm-long tritium pellets appeared to give better results than their 4-mm-long counterparts. With low ^3He levels, forming and firing at a constant temperature of 10 K or below works well. If ^3He levels are on the order of 0.1%, formation at high temperatures followed by cooling to below 8 K seems to produce stronger pellets (but not as good as the low- ^3He pellets). Pellets held in the barrel up to 30 min after formation showed no detrimental effects due to aging.

Figure 7 shows the velocity of 4-mm-diam, 5-mm-long tritium pellets, which were formed and fired at 10 K, as a function of propellant supply pressure. These results were obtained using the standard ORNL fast

propellant valve and power supply [8]. Higher-powered supplies or alternative acceleration concepts (e.g., two-stage light gas guns) should be capable of taking them to higher velocities. Velocities of 4-mm-diam, 4-mm-long deuterium pellets are shown for comparison. Tritium speeds are on the order of 75% of deuterium speeds at a given supply pressure. About 1500 pellets were produced and fired with this gun; of these, about a third contained tritium. Pellets produced with 50%, 10%, 1%, and 0.1% tritium presented no additional problems.

CONCLUSIONS

In over a year of tritium operation at TSTA, the pellet injector was operated safely with the support of TSTA systems and personnel. The off-gas produced by the injector was purified and separated into its constituents for recycle by the TSTA system. This shows that pneumatic pellet injectors can be readily integrated into future reactor fueling systems. No failures or detrimental effects were observed in the TPOP hardware because of tritium, or any other operational parameter, during the life of the experiment. During the course of the work, the gun received several modifications (e.g., removing the collar heaters and lengthening the cooled section of barrel). These operations were performed on the contaminated system through the gloves. Maintenance of future tritium pellet injectors should be possible using similar techniques. Although tritium pellets can be routinely produced in a pipe-gun with properly prepared tritium, continuous injectors will be required for future reactors [3]. TPOP has clearly demonstrated the feasibility of producing and accelerating tritium pellets. However, the properties of tritium appear to be different enough from those of deuterium that any continuous injector design should probably undergo a prototype test with tritium before it is adopted for fueling a fusion reactor. Injectors with extruders may not require as low a ^3He level as the pipe-gun. However, the extrudability of tritium and the design of continuous tritium-compatible extruders should be addressed in future phases of the TPOP experiment.

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Fig. 1. Schematic diagram of the TPOP experiment.

Fig. 2. The overall TPOP system.

Fig. 3. The gun assembly in the glovebox.

Fig. 4. The gun with the guard vacuum enclosure removed.

Fig. 5. 1400-m/s pellets formed by the TPOP injector.

Fig. 6. Operating curves for tritium pellet production.

Fig. 7. Pellet velocity as a function of supply pressure.

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FLIGHT DIRECTION
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SCALE (mm)

SECOND PHOTO
STATION

SCALE (mm)

FIRST PHOTO
STATION