CONF-900918--4

DE90 017024

PELLET INJECTOR DEVELOPMENT AT ORNL*

M. J. Gouge, B. E. Argo, L. R. Baylor, S. K. Combs, D. T. Fehling, P. W. Fisher, C. A. Foster, C. R. Foust, S. L. Milora, A. L. Qualls, D. E. Schechter, D. W. Simmons, D. O. Sparks, and C. C. Tsai

Oak Ridge National Laboratory, P.O. Box 2009, Oak Ridge, Tennessee, 37831-8071, United States of America

Advanced plasma fueling systems for magnetic confinement experiments are under development at Oak Ridge National Laboratory (ORNL). The general approach is that of producing and accelerating frozen hydrogenic pellets to speeds in the kilometer-per-second range by either pneumatic (light-gas gun) or mechanical (centrifugal force) techniques. ORNL has recently provided a centrifugal pellet injector for the Tore Supra tokamak and a new, simplified, eight-shot pneumatic injector for the Advanced Toroidal Facility stellarator at ORNL. Hundreds of tritium and DT pellets were accelerated at the Tritium Systems Test Assembly facility at Los Alamos in 1988–89. These experiments, done in a single-shot pipe-gun system, demonstrated the feasibility of forming and accelerating tritium pellets at low ^{3}He levels. A new, tritium-compatible extruder mechanism is being designed for longer-pulse DT applications. Two-stage light-gas guns and electron beam rocket accelerators for speeds of the order of 2–10 km/s are also under development. Recently, a repeating, two-stage light-gas gun accelerated 10 surrogate pellets at a 1-Hz repetition rate to speeds in the range of 2–3 km/s; and the electron beam rocket accelerator completed initial feasibility and scaling experiments. ORNL has also developed conceptual designs of advanced plasma fueling systems for the Compact Ignition Tokamak and the International Thermonuclear Experimental Reactor.

1. INTRODUCTION AND PELLET INJECTOR APPLICATIONS

Oak Ridge National Laboratory (ORNL) has been developing hydrogenic pellet injectors for more than a decade.[1,2] These devices produce frozen hydrogen isotope pellets and then accelerate these projectiles to speeds in the kilometer-per-second range by either pneumatic (light-gas gun) or mechanical (centrifugal force) techniques. ORNL has provided pellet fueling systems for three major, large tokamak experiments: the Tokamak Fusion Test Reactor (TFTR), the Joint European Torus (JET), and the Tore Supra tokamak. The TFTR eight-shot pneumatic injector[3] was installed in 1986 and has operated reliably since that time. The JET three-barrel repeating pneumatic injector[4–6] is the central part of a major collaboration between the United States and the European Community on plasma fueling and transport physics in the high-plasma-density regime. The injector was installed on JET in 1987 and has operated at high reliability.[6] ORNL has recently installed and operated a centrifuge pellet injector[7,8] on the Tore Supra tokamak as part of an extensive particle control experimental program. The objective of this ORNL–Commissariat à L'Energie Atomique collaboration is to study long-pulse, reactor-relevant tokamak discharges with simultaneous plasma fueling and exhaust capabilities. A simplified eight-shot pneumatic pellet injector design[9,10] has been developed at ORNL based on the so-called "pipe-gun" concept in which deuterium and hydrogen 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 liquid-helium-cooled block. Plasma fueling systems based on this design were supplied to the Princeton Beta Experiment (PBX) in October 1988 and to the Advanced Toroidal Facility (ATF) in May 1989.

2. HIGH-VELOCITY PELLET DEVELOPMENT

Higher pellet velocities (>2 km/s) are desirable for plasma fueling applications because the faster pellets can penetrate more deeply into large, hot plasmas to deposit atoms of fuel directly in a greater fraction of plasma volume. Two techniques for achieving higher speeds are being evaluated experimentally at ORNL.

---

*Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

2.1 Two-Stage Light-Gas Gun Development

Recently, ORNL began developing a two-stage light-gas gun[11–13] to accelerate pellets to high speeds. The basic single-stage light-gas gun is limited in performance by the sound speed of the room temperature propellant gas to about 2 km/s. To overcome this limitation, the two-stage gun relies on a piston moving at high speeds (100–400 m/s) in a cylinder (pump tube) to adiabatically compress the propellant gas (He or H) to high pressure and temperature in a chamber located at the gun breech. In the current configuration of the two-stage device, a 2.2-L volume (pressure, <120 bar) provides the gas to accelerate a 25.4-mm-diam plastic piston in a 1-m-long pump tube; a specially designed pneumatically operated fast valve initiates the acceleration process in the first stage. As the piston travels the length of the pump tube, the downstream gas (initially at <1 bar) is compressed (to pressures >2500 bar) and thus is driven to high temperatures (approximately 5,000–10,000 K). This provides the driving force for acceleration of a 4-mm pellet in a 1-m-long gun barrel. In earlier tests that used helium gas as the driver in both stages and a burst disk between the two stages, 35-mg plastic pellets were accelerated to speeds as high as 4.5 km/s. More recently, bare deuterium pellets formed in a pipe-gun geometry have been accelerated to speeds near 2.9 km/s using the pneumatic valve between the first and second stages. Theoretical modeling[12] of these experiments with a one-dimensional Lagrangian hydrodynamics code has identified gas friction in the pump tube and small-diameter barrel to be the dominant loss mechanism.

The use of sabots to encase and protect the cryogenic pellets from the high peak pressures (accelerations) will be required to realize speeds above about 3 km/s; speeds above 4 km/s have been achieved by encasing the pellet in a sabot.[14] The speeds of bare hydrogenic pellets have also been limited by a progressive reduction in the pellet diameter thought to be due to erosion by the gun barrel wall; this occurrence becomes important at speeds of 2 km/s and above.[14,15] With sabots, the pellet is also protected from the effects of erosion. Sabots that separate from the pellet after it exits the muzzle are being developed at ORNL and in Europe. At ORNL, this technology is being developed for long-pulse to continuous fueling of such devices as the Compact Ignition Tokamak (CIT) and the International Thermonuclear Experimental Reactor (ITER). Piston lifetimes have exceeded several hundred experimental shots, and the two-stage light-gas gun has recently been operated in a repetitive mode. A repeating pneumatically operated valve between the first and second stages and a magazine-type plastic pellet loading mechanism were used in these initial multishot experiments. A pressure/vacuum ballasting system was implemented for recharging the 0.5-L second stage between shots, and a programmable logic controller-based control system linked to a Camac-based data acquisition system was developed. The two-stage injector has been operated in bursts of several to 10 pellets at repetition rates in the range of 0.7 to 1 Hz and at pellet speeds of 2–3 km/s. Figure 1 shows a data sequence of 10 pellets at 1 Hz and a velocity of 2 km/s. The upper plot shows initial pressure behind the piston. The uniformity of this pressure resulted in nearly identical velocities for pellets 2–10. The lower plot shows an impact signal on the target from a shock transducer.

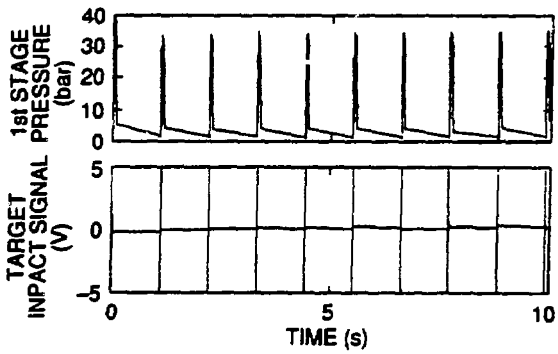

FIGURE 1

Data from repeating two-stage pneumatic injector (10 pellets at 1 Hz)

2.2 Electron Beam Rocket Accelerator

Another method under development at ORNL for accelerating deuterium and/or tritium pellets to higher speeds is based on an electron-beam-driven rocket.[8,16] The method uses an intense electron beam to evaporate a hydrogen propellant "ice stick" and to heat the exhaust cryogenic hydrogen gas to high velocity and, subsequently, to accomplish rocket-like acceleration of the hydrogenic pellets. Unlike other pellet injection concepts using impulsed acceleration, this method uses continuous acceleration through a long acceleration path. A proof-of-principle device has been designed, fabricated, assembled, and operated to demonstrate electron beam acceleration of pellets to speeds above the sound velocity of ablated cryogenic gases (about 300 m/s). The device is being operated to evaluate pellet ablation velocity, exhaust gas velocity, and final speed of hydrogen propellant pellets as a function of beam parameters such as voltage, current, and pulse duration. The device consists of a pipe-gun-type pellet fabricator, an electron gun, a set of acceleration guide rails, and diagnostics for measuring beam and pellet parameters. Cryogenic, cylindrical (4-mm-diam) pellets of frozen hydrogen (12 mm long) and of frozen deuterium (18 mm long) were reliably injected through a baffle chamber and guide tube into the acceleration guide rails. The speed of the pellet is detected by using light trip monitors installed along the pellet path and the shock accelerometer at the end of the diagnostic chamber. The size of the accelerated pellets is measured by a capacitive pressure gage in the diagnostic chamber. The image of the accelerated pellet is obtained from a laser-illuminated shadowgraph and then recorded. Experimental data were taken by accelerating hydrogen pellets with intense and pulsed electron beams at various beam voltages, beam currents, and pulse lengths. The maximum speed of 575 m/s was measured for a hydrogen pellet that was accelerated by an electron beam of 14 keV, 0.4 A for 1.11 ms. For this case, 2.65 J is used to evaporate the solid hydrogen, and 0.27 J is the kinetic energy of the accelerated pellet (which has about 23% of the original pellet mass). At the moment, the pellet speed is limited by the relatively short acceleration path of about 0.4 m. The theoretical burn velocity (v_b in meters per second) is obtained from the following equation, which is derived with assumptions that the thermal evaporation energy is negligible and the neutral gas shielding ablation model is valid for slowing down beam electrons and dissipating the beam power.[8]

$$v_b = (v_s E^2 m)/(2a\rho r_p) ,$$

where v_s is the sound velocity of cryogenic hydrogen gas (about 300 m/s); E is the beam voltage in volts; m is $3.? \times 10^{-27}$ kg, the mass of molecular hydrogen; a is about 2×10^{-16} V^2m^2, a constant electron energy loss function in hydrogen gas; ρ is 88 kg/m^3, the solid density of the hydrogen pellet; and r_p is the radius of the pellet. For E = 10 kV and r_p = 0.002 m, the value of v_b is 1.43 m/s. Figure 2 shows experimental and calculated burn velocities of hydrogen pellets ablated by electron beams with different beam voltages. Qualitatively, the measured burn velocity increases with the square of beam voltage, as the model predicts. Quantitatively, there are differences between the measured and theoretical values. The discrepancy could be due to fluctuations in initial pellet sizes and integrity of the pellet during acceleration. In addition, the model may need to include the effect of beam current, as published elsewhere.[2] The exhaust gas velocity and acceleration efficiency associated with the electron beam rocket pellet acceleration are being studied in the ongoing experiments.

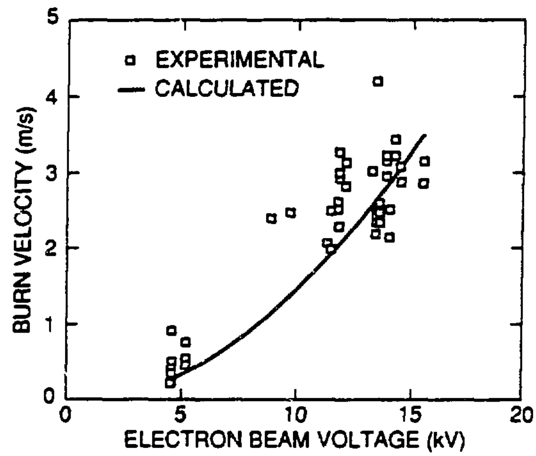

FIGURE 2
Pellet burn velocity vs electron beam voltage

3. TRITIUM PELLET EXPERIMENTS

The tritium proof-of-principle (TPOP) experiment[17–19] was initiated to demonstrate the basic scientific feasibility of production and pneumatic acceleration of tritium pellets for fueling future fusion reactors. The experiment was designed and built at ORNL and installed and operated by ORNL personnel in the Tritium Systems Test Assembly at Los

Alamos National Laboratory. More than 100 kCi of tritium was processed through the experiment without incident. The gun for this first phase of the TPOP program was based on the pneumatic pipe-gun concept, described above, in which pellets are formed in situ in the barrel and accelerated with high-pressure gas. This gun was ideal for initial tritium experiments because it has no moving parts and it requires no excess tritium to produce pellets. Removal of ^{3}He from tritium is particularly important in this type of gun because it hinders the cryopumping action in the freezing zone of the barrel and prevents formation of complete pellets. These experiments have shown that ^{3}He levels below 0.005% are required to produce high-quality pellets. The ^{3}He separator employed to reach these levels was a simple cryogenic condenser that had a large volume for ^{3}He disengagement. Tritium was cryopumped into the separator at <12 K. The separator was then heated to 15 K and evacuated for several minutes to remove the ^{3}He. Low ^{3}He levels could not be reached with the separator at lower temperatures. Formation of tritium pellets was found to require a longer freezing zone than deuterium pellets (3 mm for deuterium and 4 mm for tritium). Integrity of tritium pellets after acceleration also improved when the aspect ratio was increased. Deuterium pellets 4 mm long by 4 mm in diameter worked well, but tritium pellets 5 mm long were better than their 4-mm-long counterparts. These effects appear to be a result of the internal heat generation from the radioactive decay of tritium. Tritium pellet velocities on the order of 1400 m/s were reached, and higher velocities may be possible with a different driver system. Pellets made from mixtures of deuterium and tritium with concentrations from 0.1 to 50 vol % were also produced and accelerated without difficulty. Some pellets were held in the barrel for 30 min after formation and fired without any deleterious effects from aging being observed. The pressure required to just overcome the shear strength of the pellets was measured as a function of temperature for deuterium pellets. These data were found to agree with strengths reported for deuterium by other workers. Shear strengths for tritium were not systematically measured, but minimum values could be inferred from data for several pellets that did not dislodge when fired. From these data, it appears that tritium has about twice the shear strength of deuterium at 8 K (5 bar for deuterium and 10 bar for tritium). The initial phase of the TPOP experiment has clearly demonstrated the feasibility of producing high-speed tritium pellets. However, the physical properties of tritium (shear strength, internal heating, etc.) are quite different from those of deuterium. Since repeating injectors used for continuous fueling all have extruders, the next phase of the TPOP program will concentrate on studying acceleration of extruded tritium pellets.

4. CONCEPTUAL DESIGN OF PLASMA FUELING SYSTEMS FOR CIT AND ITER

The proposed CIT pellet injection system will have short-pulse single- and two-stage repeating pneumatic injectors; details of the CIT system are provided in reference 20. The ITER will use an advanced, high-velocity pellet injection system to achieve and maintain ignited plasmas. Three pellet injectors are proposed. For rampup to ignition, a highly reliable, moderate-velocity (1- to 1.5-km/s) single-stage pneumatic injector and a high-velocity (1.5- to 5-km/s) two-stage pneumatic pellet injector using frozen hydrogenic pellets encased in sabots will be used. For the steady-state burn phase, a continuous, single-stage pneumatic injector is proposed which will provide a flexible fueling source beyond the edge region to aid in decoupling the edge region (constrained by divertor requirements) from the high-temperature burning plasma. All three pellet injectors are designed for operation with a variable ratio of tritium and deuterium feed gases. A plan view of the pellet injector installation is shown in Figure 3. The moderate-velocity injectors (items 1) are on either side of the two-stage pneumatic injector (item 2) such that the centerlines of the three injectors converge in the midplane at the ITER major radius of 6.0 m. The pellet injector bay is shielded by the structural shielding wall, by a rotating eccentrically bored shielding drum in each injection line (to limit line-of-sight exposure of the injectors), and by modular shielding (item 3) around the high-vacuum isolation chamber. The bay also serves as a redundant containment boundary and is sealed by bellows (item 4) at the shielding wall and by an airlock (item 5) at the entrance. The walls, floor, and ceiling of the bay have a metal liner, which acts as a tritium

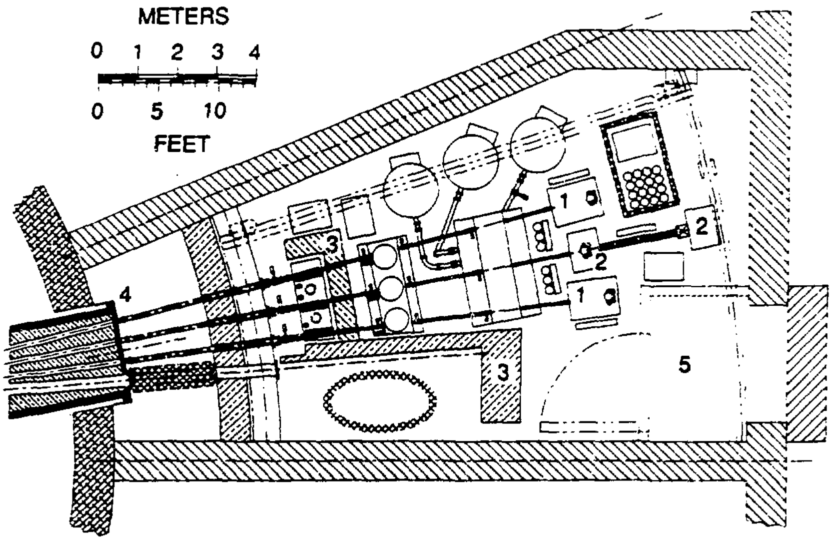

FIGURE 3
Layout of ITER pellet injection system

boundary. In principle, activation of injector components can be low because of the small-diameter (a few centimeters) guide tubes used for pellet transport in the vacuum injection line. A design goal is to maintain the capability of limited hands-on maintenance for all components beyond the modular shielding wall (item 3, Figure 3).

REFERENCES

1. S.L. Milora, *J. Fusion Energy* 1 (1981) 15.
2. S. L. Milora. *J. Vac. Sci. Technol. A* 7 (1989) 925.
3. S.K. Combs et al., *Rev. Sci. Instrum.* **58** (1987) 1195.
4. S.L. Milora et al., in: *Proceedings of the 12th Symposium on Fusion Engineering, Monterey, California, October 1987*, Vol. 2, p. 784.
5. S.K. Combs et al., *J. Vac. Sci. Technol. A* **6** (1988) 1901.
6. S. K. Combs, T. C. Jernigan, L. R. Baylor, et. al., *Rev. Sci. Instrum.* **60** (1989) 2697.
7. S.K. Combs et al., in: *Fusion Technology 1988 (Proc. 15th Symp. Utrecht, The Netherlands, Sept. 19-23, 1988)*, Vol. 1, p. 709.
8. C.A. Foster, C. C. Tsai, D. E. Schecter, et al., in: *Proceedings of the IAEA Technical Committee Meeting on Pellet Injection and Toroidal Confinement, Gut Ising, Federal Republic of Germany*, IAEA-TECDOC-534 (1989) 275.
9. D. D. Schuresko, M. J. Cole, P. W. Fisher, et. al., *J. Vac. Sci. Technol. A* 7 (1989) 949.
10. A. L. Qualls et al., in: *Proceedings of the IEEE 13th Symposium on Fusion Engineering, Knoxville, Tennessee, October 2-6, 1989*, Vol. 2, p. 1244.
11. S. K. Combs, C. R. Foust, M. J. Gouge, and S. L. Milora, *J. Vac. Sci. Technol. A* 7 (1989) 963.
12. M. J. Gouge, S. K. Combs, P. W. Fisher, and S. L. Milora, *Rev. Sci. Instrum.* **60** (1989) 570.
13. S. K. Combs, C. R. Foust, M. J. Gouge, and S. L. Milora, *J. Vac. Sci. Technol. A* 8 (1990) 1814.
14. K. Sonneberg et al., in: *Proceedings of the 12th Symposium on Fusion Engineering, Monterey, California, October 1987*, Vol. 2, p. 1207.
15. A. Reggiori, G. Riva, G. Daminelli, A. Frattolillo, L. Martinis, and F. Scaramuzzi, *J. Vac. Sci. Technol. A* 7 (1989) 959.
16. C. C. Tsai, C. A. Foster et. al., in: *Proceedings of the IEEE 13th Symposium on Fusion Engineering, Knoxville, Tennessee, October 2-6, 1989*, Vol. 2, p. 1230.
17. P.W. Fisher et al., *Fusion Technol.* 14 (1988) 977.
18. P. W. Fisher, M. L. Bauer, L. R. Baylor, et. al., *J. Vac. Sci. Technol. A* 7 (1989) 938.
19. P. W. Fisher, D. T. Fehling, M. J. Gouge, and S. L. Milora, in: *Proceedings of the IEEE 13th Symposium on Fusion Engineering, Knoxville, Tennessee, October 2-6, 1989*, Vol. 2, p. 1236.
20. M. J. Gouge, S. K. Combs, P. W. Fisher, and S. L. Milora, in: *Proceedings of the IEEE 13th Symposium on Fusion Engineering, Knoxville, Tennessee, October 2-6, 1989*, Vol. 2, p. 1240.

DISCLAIMER