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TRITIUM PROJECTILES FOR FUELING MAGNETIC FUSION PLASMAS

P. W. Fisher and M. J. Gouge
Oak Ridge National Laboratory
P.O. Box 2009
Oak Ridge, TN 37831-8071

ABSTRACT

As part of the International Thermonuclear Engineering Reactor (ITER) plasma fueling development program, Oak Ridge National Laboratory (ORNL) has fabricated a pellet (cylindrical projectile of frozen hydrogenic gas at a temperature in the range 6-16 K) injection system to test the mechanical and thermal properties of extruded tritium, a radioactive isotope of hydrogen. 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 initial 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. The pellets, typically 7.4 mm in diameter and up to 11 mm in length, are the <u>largest cryogenic pellets produced by the fusion program to date</u>. These pellets represent about a 11% density perturbation to ITER. 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 Oak Ridge National Laboratory (ORNL) tritium pellet injector experiment (1988–89)[1–3] at the Tritium Systems Test Assembly (TSTA) at Los Alamos National Laboratory 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-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 will be 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

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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 will be 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 tailoring.[8] In this concept, pellets of high-tritium concentration would be delivered beyond the diverter 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 the tritium inventory in the wall, which could approach 10 kg without tailoring. Therefore, pellets with a broad range of tritium concentration will be evaluated in these experiments. Fueling requirements for ITER have not been fully established at this time, but early concepts[9] 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 11% 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 will be 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 simply 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 highly successful RPI technology with few changes to get a direct comparison of tritium with the extensive deuterium 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 form the RPI gun. The gun is housed in a guard vacuum enclosure that provides a vacuum environment for insulation of the cryogenic systems. A cryogenic ^{3}He 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 the 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 will be used to support the TPOP-II experiment. The new glovebox shown in Fig. 1 has been added above one end of the TPOP-1 glovebox to accommodate the extruder drive, which is too tall to fit in the original glovebox. This extension plus the weight of the extruder and guard vacuum box surrounding the RPI required the strengthening of the TPOP glovebox support structure. 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). All interfaces between the glovebox and TSTA (tritium, deuterium, nitrogen, helium, electrical, control, vacuum connections, etc.) are through panels in the top of the glovebox as can be seen in Fig. 2, which is a photograph of the original TPOP-I apparatus. Cajon VCR fittings are used for all external gas connections in these panels. Operation of the entire experiment is controlled remotely from the console at the right in Fig. 2. High-speed data acquisition for pellet diagnostics is accomplished through a MicroVAX II computer (not shown) and CAMAC interfaces located at the back of the control console. Descriptions of the TPOP-I system[1–3] and RPI gun[4,5] are given elsewhere.

At TSTA, tritium will be supplied to the experiment from a product container (PC) mounted in the load-in/load-out (LIO) glovebox. It is anticipated that several pure tritium extruder fills can be obtained from a single PC. Exhaust gas from the experiment will be returned to another PC in the LIO glovebox using an all-metal scroll pump and bellows pump located in the transfer pump glovebox (TP1). Much larger tritium throughputs are anticipated for TPOP-II than were required in the earlier TPOP-I experiments; therefore, the baseline approach will include 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 extrudate, which could equal up to 75% of the gas fed to the extruder, will be 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 or slightly less than the mass of the pellets. It is planned to use deuterium propellant gas at TSTA that will mix with the pellet gas in the injection line as the pellets are fired. This gas will be collected in the 600-L vacuum ballast volume located under the glovebox. Pressure in this tank will increase about 10-20 mbar during a sequence of shots from a single extrudate. After each run, some of this gas will be 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 will be measured by Raman spectroscopy. Recycling these exhaust streams will facilitate generation of the maximum amount of experimental data for pellets of varying D-T composition for each batch of tritium received from a PC.

RESULTS

The TPOP-II injector has been fabricated and operated at ORNL over a period of several months prior to shipment to TSTA in March 1995. During this period it has been used to produce deuterium pellets that have been accelerated with hydrogen propellant. Figure 3 shows one of the early deuterium pellets produced by the gun. After acceleration these pellets were typically 7 mm in diameter by 11 mm long and traveled at speeds of 1.1 km/s. These pellets would represent about a 11% density perturbation to ITER. Subsequently, the extruder nozzle was modified to produce a pellet with an accelerated aspect ratio of about one. Figure 4 shows a sequence of these pellets, which 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 extrudate 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. In limited testing at TSTA in August 1995 following several months of installation activity, 7 x 8 mm 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.

PROGRAM STATUS

An extruder-based tritium pellet injector has been fabricated and tested with deuterium at ORNL and has produced the largest cryogenic pellets made to date. The injector has been installed in a glovebox at TSTA and operated with deuterium propellant and deuterium pellets. Operation with tritium at TSTA is expected to commence in September 1995. This technology will provide design information for a fusion-reactor-scale, flexible fueling system that can provide the required D-T fuel mixture to the interior of burning plasmas, while deuterium-rich gas is used to replenish the edge to optimize edge conditions set by diverter performance and impurity flushing requirements.

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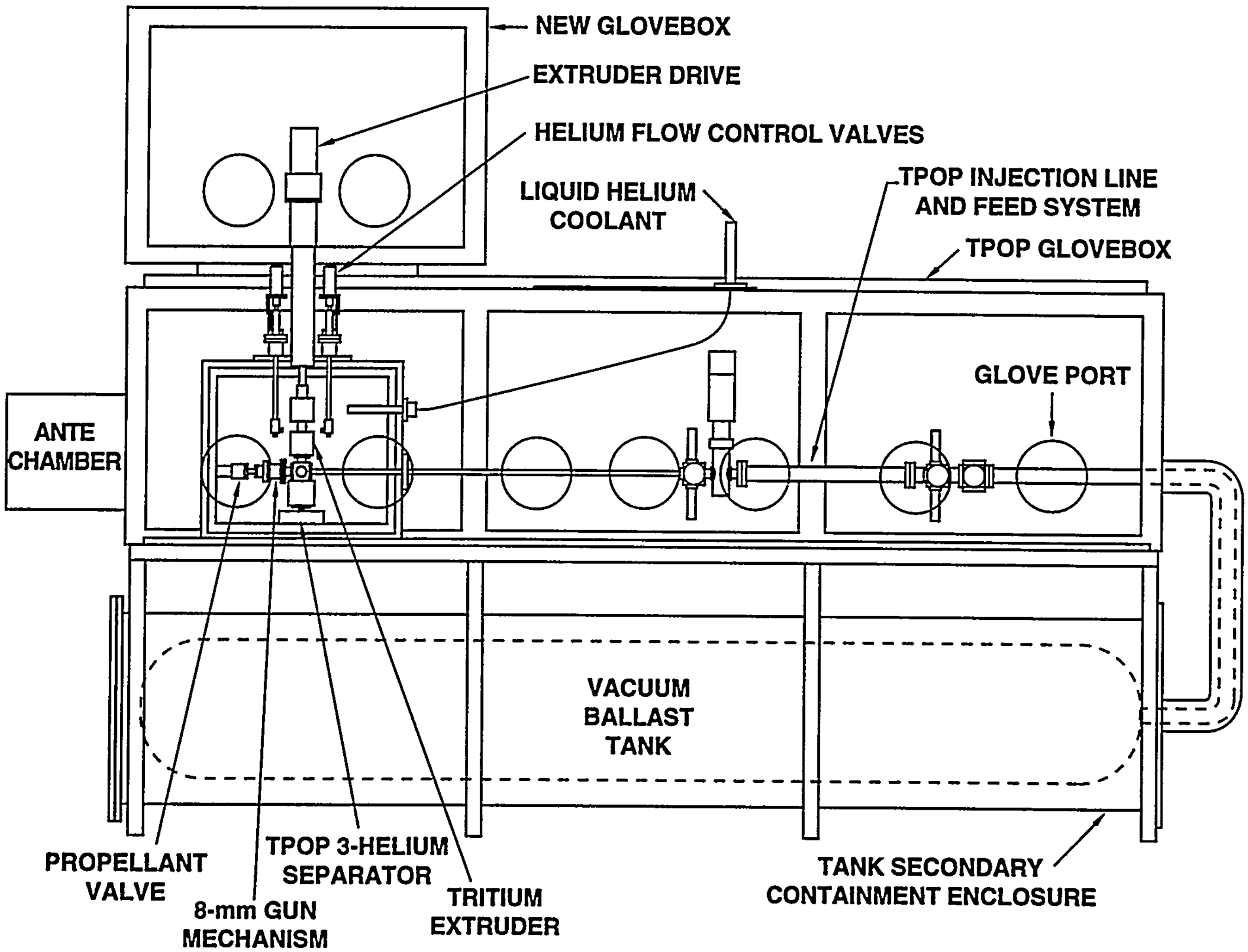

Figure 1. Diagram of TPOP-II experiment as configured at TSTA.

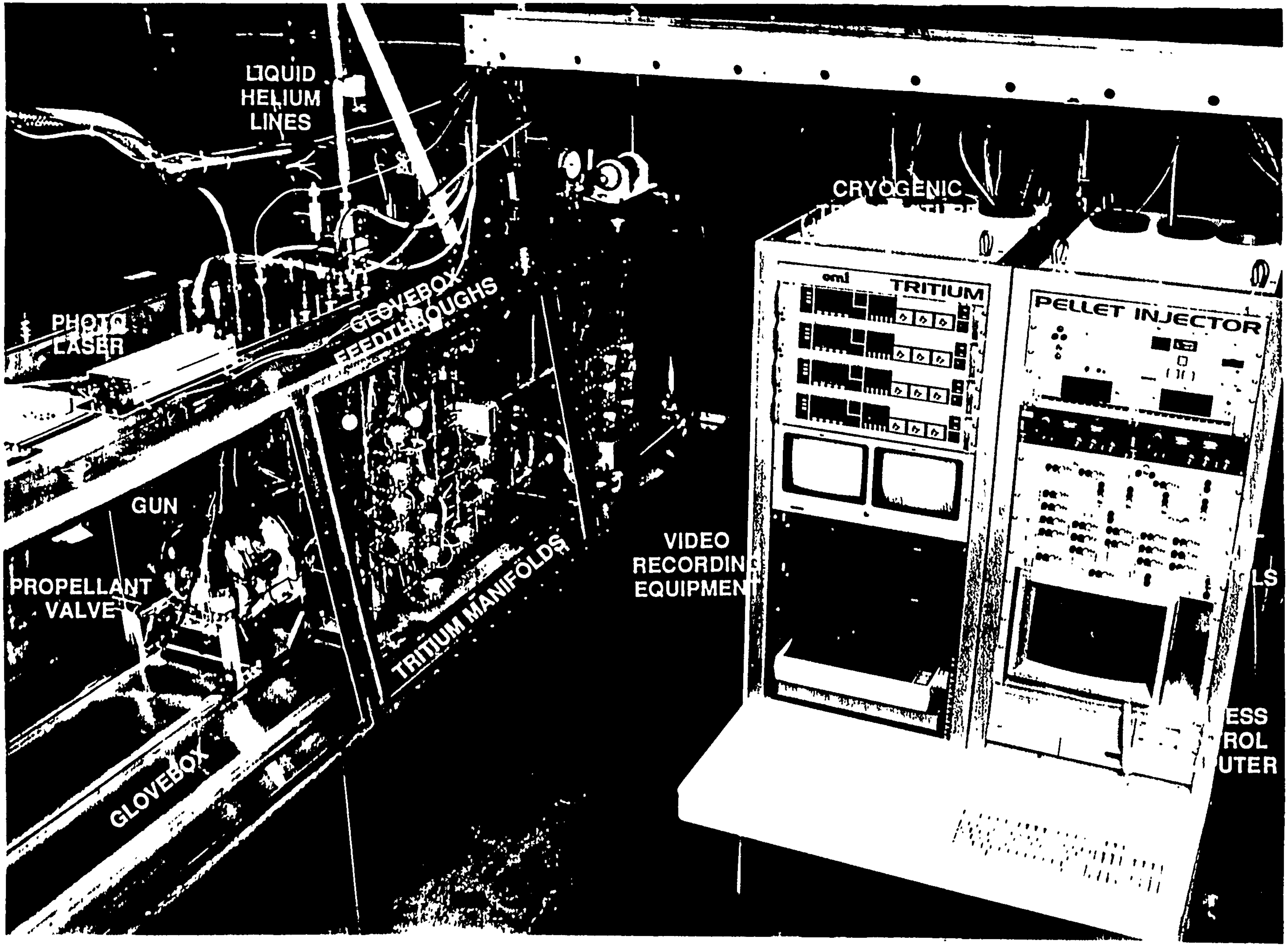

Figure 2. Photograph of TPOP-I experimental apparatus.

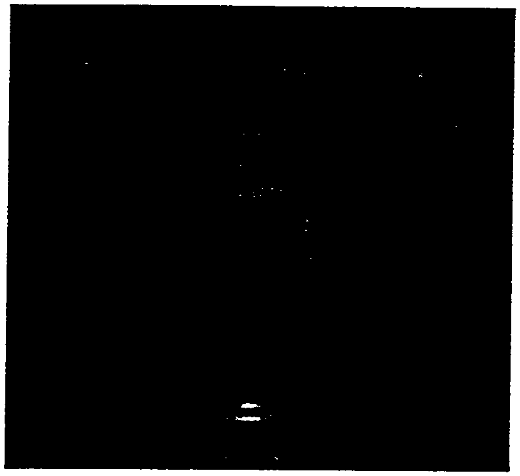

Figure 3. Photograph of TPOP-II deuterium pellet measuring 7 mm in diameter by 11 mm long and traveling at 1 km/s.

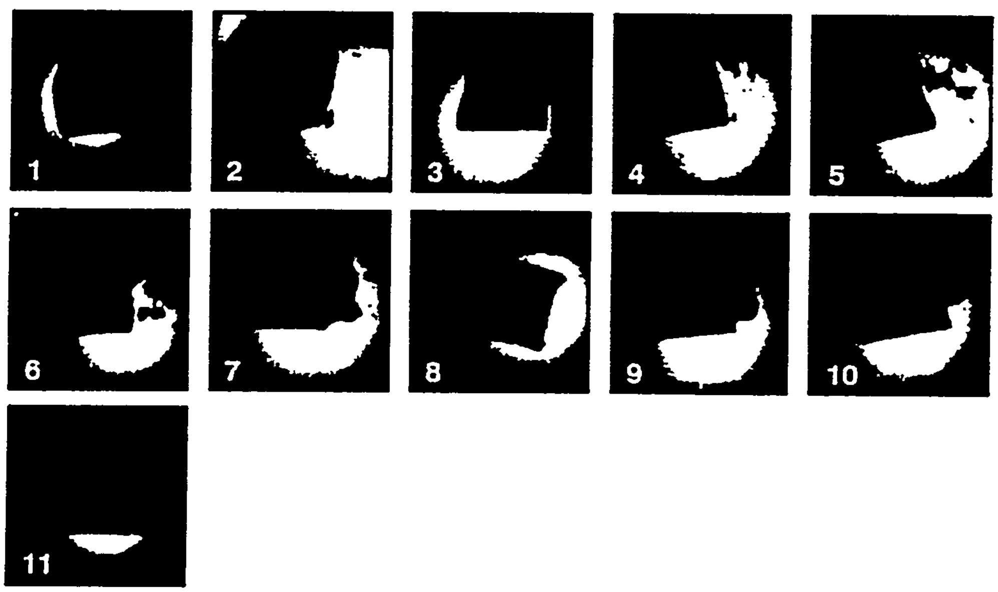

Figure 4. Photograph of a sequence of TPOP-II deuterium pellets at a repetition rate of 0.5 Hz and traveling at 1.1 km/s.