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REPEATING PNEUMATIC PELLET INJECTOR IN JAERI

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A repeating pneumatic pellet injector has been developed and constructed at Japan Atomic Energy Research Institute. This injector can provide repetitive pellet injection to fuel tokamak plasmas for an extended period of time, aiming at the improvement of plasma performance. The pellets with nearly identical speed and mass can be repeatedly injected with a repetition rate of 2-3.3 Hz and a speed of up to 1.7 km/s by controlling the temperature of the cryogenic system, the piston speed and the pressure of the propellant gas.

Keywords: Solid-hydrogen Pellet, Repeating Pneumatic Pellet Injector, Fueling, Plasma, Tokamak, Nuclear Fusion

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日本原子力研究所における高速多発ペレット入射装置

日本原子力研究所那珂研究所炉心プラズマ研究部

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繰り返して固体水素ペレットを射出できるニューマチック式ペレット入射装置を開発した。この入射装置はトカマクプラズマの特性を改善することを目的としている。冷却器の温度、ピストン速度、加速ガスの圧力を制御することにより、2-3.3Hz で速度と質量の揃ったペレットを繰り返し射出することができた。また最大1.7km/sの速度を得ることができた。

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Contents

1. Introduction	1
2. Description of Equipment	1
2.1 Injection System	1
2.2 Diagnostic System	4
3. Experimental Results	6
3.1 Cooling Tests	6
3.2 Production Tests of a Solid-hydrogen Filament	6
3.3 Extrusion Tests	8
3.4 Functional Tests of the Gun Assembly	9
3.5 Pellet Injection Tests	10
4. Discussion and Summary	13
Acknowledgments	14
References	15

目 次

1. はじめに	1
2. 装 置	1
2.1 入射システム	1
2.2 測定システム	4
3. 試験結果	6
3.1 冷却試験	6
3.2 棒状固体水素生成試験	6
3.3 棒状固体水素押出し試験	8
3.4 銃部の試験	9
3.5 ペレット発射試験	10
4. 議論とまとめ	13
謝 辞	14
参考文献	15

1. Introduction

High-speed injection of frozen macroscopic pellets of hydrogen-isotopes has become the leading technology to fuel magnetically confined plasmas for controlled thermonuclear fusion research. The technique of fueling by this approach has been demonstrated conclusively on numerous toroidal confinement devices⁽¹⁾. This method can provide modifications of the plasma density and/or temperature profiles in the bulk plasmas by the deposition of fuel particles inside the plasmas⁽¹⁾. It allows a central peaking of the plasma density profile and/or a reduction of ions by recycling in the plasma edge region. Peaking of the plasma density profile has been observed experimentally, when pellets are injected at a high speed in order to penetrate the plasma column and deposit fuel particles preferentially in the hot and dense core of the plasma. In order to realize a high repetition rate of pellet injection and high reliability for fusion research, it is necessary to develop a production technique of the solid hydrogen-isotope filament to form pellets and a pellet acceleration technique to achieve high-speed pellets.

2. Description of Equipment

The repeating pneumatic pellet injector has been developed in collaboration with Mitsubishi Heavy Industries, Ltd. The injector employs the basic design configurations developed at Oak Ridge National Laboratory in the U.S.⁽²⁾. The system consists of two main subsystems, i.e., an injection system and a diagnostic system.

2.1 Injection System⁽³⁾

The main parts of the injection system are schematically shown in Fig. 1. The injection system is composed of a cryogenic extruder and a gun assembly. The cryogenic extruder is capable of forming a frozen-hydrogen-isotope and extruding a frozen-hydrogen-isotope into the gun assembly as a filament. The gun assembly can form pellets from the extruded filament, chamber pellets, and inject them.

In this device, the cryogenic extruder consists of three copper-made coolers, which are convectively force-cooled by liquid helium flowing through cooling channels on the surface of each cooler, as shown in

Fig. 1. A brass cylinder is placed through the second and third coolers. Inside the cylinder, the frozen-hydrogen-isotope is formed, then extruded by a piston driven inside the cylinder. Liquid helium, supplied from a pressurized 250 l storage Dewar, is once stored in a gas/liquid helium phase separator and supplied to each cooler. The helium Dewar is pressurized to 30-50 kPa by the helium gas from a gas storage cylinder. A flow rate of liquid helium from the phase separator to each cooler is individually controlled by a liquid helium flow control valve (Model: V-6700E; Toko Laboratory Co., Ltd.). The pressure of the phase separator is controlled by a pressure control valve, and the quantity of liquid helium in the phase separator is controlled by a liquid helium gage. A manganese-wire heater (30 W) with a coated insulator is mounted on each cooler to control the temperature of each cooler by changing the supplied current to the heater. A digital controller (Model: DB1130-04B; Chino Co., Ltd.) with a temperature transmitter (Model: CST-901; Lake Shore Cryotronics Inc.) is used as a temperature controller for each cooler, together with a silicon-diode sensor (Model: DT-470-B0; Lake Shore Cryotronics Inc.) mounted on the surface of each cooler. The locations of the silicon-diode sensors are symbolized crosses, \times , in Fig. 1. The silicon-diode sensors are designed to detect the temperature with a range of 1.4 K to 325 K. The temperature of the coolers is independently controlled within a range of ± 0.1 K. Another kind of thermometer, AuFe-Cr, is also used to monitor the distribution of the temperature of the coolers and the other parts of the cryogenic extruder during the operations. Filled circles (\bullet) and triangles (\blacktriangle) in Fig. 1 show the locations of these thermometers.

The hydrogen-isotope is frozen inside the cylinder. The inventory of the frozen-hydrogen-isotope in the extruder is approximately 3 cm^3 , which is determined by the total inner volume of the cylinder and the extrusion nozzle. The piston extrudes the volume of nearly 2 cm^3 frozen-hydrogen-isotope, which is determined by the inside diameter of the cylinder (0.5 cm) and the effective travelling distance of the piston (10 cm). Four grooves are located both on the inner surface of the cylinder between the first cooler and the second cooler, and on the piston head, as shown in Fig. 2. When both sides of the grooves are matched, the gas/liquid hydrogen-isotope can flow downward to the bottom part of the cylinder, where the frozen-hydrogen-isotope is formed. The piston head, made of copper, can be driven at any speed in the range of 0 to 150 mm/s,

by a screw powered by a stepping motor. The piston speed or the extrusion speed of the frozen-hydrogen-isotope filament is controlled to meet with the required repetition rate of the pellet formation/injection. The extrusion force applied to the piston head is monitored by a load cell (Model: LM-200KS; Kyowa Electric Instruments Co., Ltd.) that is placed between the screw and the piston shaft. The third cooler is connected with a punch-type chambering mechanism, which has a gun barrel and a fast-opening magnetic valve. An extrusion nozzle is located between the second cooler and the third cooler to change the cylindrical frozen-hydrogen-isotope into a desired cross-sectional filament. In this experiment, two types of nozzles have been tested; one is an oval cross-section of 1.6 mm in width \times 3.2 mm in length, and the other one is a circular cross-section of 4 mm in diameter. When the frozen filament is extruded to the chambering mechanism, a punching tube is driven into the filament to punch out and chamber a pellet. Thus, the pellet size is established by the dimension of the cross-section of the extrusion nozzle and the inside diameter of the punching tube (1.5 mm and 3 mm).

A punch-type chambering mechanism has a stainless-steel punching tube with a knife-edge. The tube is mounted on a plunger and driven by a solenoid coil, as shown in Fig. 3. When the solenoid coil is excited, the knife-edge of the tube moves towards the extruded filament together with the plunger to punch out and to chamber a pellet inside the tube. After punching out a pellet, the punching tube is connected with a stainless steel gun barrel and stays there until the pellet is injected. The punching tube is aligned to the gun barrel. To prevent high-speed reciprocating parts from being connected together, due to frictional heat, the plunger is partially covered with two teflon rings, as seen in Fig. 3. The inner space of the punching mechanism is evacuated to the vacuum to exhaust the residual gas and the propellant gas leaked from the gun barrel during the pellet injection.

As shown in Fig. 4, two sets of fast-opening magnetic valves⁽⁴⁾ are used to eject the helium propellant gas to accelerate the pellets. The repetition rate of the valve operation is designed up to 10 Hz by operating these two valves reciprocally. In order to obtain high pellet velocity, this fast-opening magnetic valve can provide a short response time and propel high pressure and high temperature gas up to 10 MPa and up to 373 K, respectively. As seen in Fig. 4, the plunger is raised up to 4 mm by discharging electricity to the solenoid coil. When the plung-

er travels 2 mm in the sleeve, the polyimide disk (seat) is hit and lifted off the orifice by the travelling plunger, thereby, discharging the propellant gas through the valve. The valves are designed to develop full pressure (10 MPa) within 0.5 ms after they begin to open. The open/hold time is limited to 1 ms to restrict the propellant gas load (heat load) to the cryogenic extruder. The propellant gas is supplied from a 4 l main reservoir to each valve through a 135 cm³ supplemental reservoir, which is directly connected with the valve to keep the supplied gas pressure constant. To heat up the propellant gas, a 120 W electric heater and a 200 W electric heater are mounted on each valve and supplemental reservoir, respectively. The main reservoir has also a 4 kW electric heater. In this device, the temperature of the propellant gas is kept between room temperature to 373 K (100°C). Most of the parts described above (except the main reservoir) are covered with a super-insulation and installed in a vacuum vessel to reduce heat radiation to the cryogenic parts. The vacuum vessel is evacuated by a 500 l/s turbo-molecular pump (Model: TSU510; Pfeiffer Balzers).

The pellets, ejected from the gun barrel, are transported to the diagnostic vessel III (Volume=162 l) through the diagnostic vessel II (Volume=248 l) and a fast-shutter valve (Model: VACOA SOV-100-08FS; Vacuum Accessories Corp.), as shown in Fig. 5. The diagnostic vessel II, evacuated by a 500 m³/hr mechanical booster pump (Model: PMP006C; ULVAC), is connected to an expansion chamber (Volume=2.5 m³) to minimize the propellant gas flow into the diagnostic vessel III. A 2000 l/s compound turbo-molecular pump (Model: TG2200M; Osaka Vacuum Ltd.) is used to evacuate the diagnostic vessel III. The fast-shutter valve is opened to allow the path of the pellets, and closed to limit the propellant gas flow into the diagnostic vessel III.

2.2 Diagnostic System

Several kinds of diagnostics are used to characterize the performance of this injector.

(1) Temperature

Temperatures of the three coolers, the punch-type chambering mechanism, and the gun barrel are monitored during the operation of the system using silicon-diode sensors (×), AuFe-Cr thermocouples (▲, ●), and K-type thermocouples (■, ★) as shown in Fig. 1. The temperature of two

positions are measured on the gun barrel.

(2) Propellant Gas Pressure

The pressure of the helium propellant gas is detected by a pressure transducer (Model: 105B22; PCB Piezotronic Inc.) at a point around 10.5 cm downward from the fast-opening magnetic valves. The sensitivity of the sensor is 0.145 mV/kPa, and the rise time is 2 μ sec. The linearity between the output voltage and the pressure is designed to be less than 1%.

(3) Movement of Punch-Type Chambering Mechanism

An accelerometer (Model: 508ml01; Vibro-meter Corp.) is used to observe the movement of the punch-type chambering mechanism by detecting the impulse caused by hitting the stopper by the plunger.

(4) Frozen-Hydrogen-Isotope Filament

The frozen-hydrogen-isotope filament, extruded from the bottom of the third cooler, can be viewed in the diagnostic vessel I. A monitor camera (Model: Panasonic WV-CD1; Matsushita Electric Industrial Co., Ltd.) is set on this vessel to observe the characteristic of the extruded filament during the operations, as shown in Fig. 5. Figure 6(a) shows examples of the extruded hydrogen filament, which has an oval cross-section. This monitor camera can also observe the movement of the punching tube as seen in Fig. 6(b). When the punching tube is driven, the tube comes into view. When the chambering mechanism is not activated, the punching tube goes out of sight.

(5) Pellet Speed and Mass

The speed and mass of the injected pellets are measured by a time-of-flight method and a microwave-cavity calibration method, respectively. As shown in Fig. 5, two sets of photodiodes are set on the diagnostic vessel II with an interval of 4 cm between the two to measure the pellet speed, while two sets of microwave cavities are installed in the diagnostic vessels II and III to estimate the pellet mass. The resonance frequency of the cavities is 8.8 GHz. In addition, to acknowledge injected pellets and to detect the kinetic energy of the flying pellets, a shock sensor (impact sensor) is installed at the end of the pellet flying path.

(6) Pellet Shadowgraph⁽⁵⁾

The flying pellets are observed as shadowgraphs taken by a commercial video-camera (Model: Panasonic WV-CD1; Matsushita Electric Industrial Co., Ltd.) along with a pulse-lamp at two positions; one is about 3 cm downstream from the gun barrel and another is about 21 cm, as shown in Fig. 5. A flush-light from the pulse-lamp is polarized to be a parallel light using a collimator lens so that the size of the pellet is neither magnified nor reduced on the shadowgraphs.

3. Experimental Results

A series of experiments have been conducted to characterize the pellet injector and to search for the ideal conditions for freezing the hydrogen-isotope and repeating pellet injection.

3.1 Cooling Tests

Cooling tests have been performed to obtain the cooling characteristics of the cryogenic extruder. Temperatures of the three coolers and the other components are measured. The helium Dewar is pressurized to 30-50 kPa, while the pressure in the gas/liquid helium phase separator is kept at 20-50 kPa. A flow rate of liquid helium from the phase separator to each cooler is individually controlled by a liquid helium flow control valve. Figure 7 shows the time changes of the temperatures. Approximately 90 minutes is required to cool down the cryogenic extruder to the temperature level of 5-7 K, with a liquid helium consumption rate of 15 ℓ /hr. Although the flow rate of liquid helium to each cooler is not a measurable value, the flow rate of the exhaust helium gas evaporated after passing through each cooling channel is measured to be 80-100 N ℓ /min (200-300 ℓ /min).

3.2 Production Tests of a Solid-Hydrogen Filament

Hydrogen gas has been used as the fuel gas in the present experiments. The solid-hydrogen filament with a diameter of 4 mm, using the circular cross-sectional nozzle, is successfully formed under the following conditions. At the beginning of the production tests, prior to the supply of fuel gas, the temperatures are kept at 14-16 K for the first

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3.2 Production Tests of a Solid-Hydrogen Filament

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cooler, at 7-8 K for the second cooler, and at less than 7 K for the third cooler, respectively. The hydrogen gas is introduced into the cylinder with a flow rate of nearly 2 Nl/min (7 l/min). Under these conditions, the inner region of the extrusion nozzle is choked with a solid/frost hydrogen to prevent fuel gas/liquid/frost from draining through the nozzle to the diagnostic vessel I, where the fluttered frost is observed through the viewing port. Then, the solid-hydrogen is filled inside the region of the cylinder and the extrusion nozzle. After the solid-hydrogen is filled in the cylinder by monitoring the pressure rise of the hydrogen gas in the cylinder to 800-1400 Torr using a diaphragm-pressure gage (Model: Baratron 122AA-05000BB; MKS Instruments Inc.), the gas supply is stopped. The pressure inside the cylinder then decreases to less than a few hundred Torr. During these processes, if the temperature of the third cooler rises, the supplied hydrogen gas leaks through the extrusion nozzle, consequently, the pressure in the cylinder does not increase and the solid-hydrogen filament is not formed in the cylinder.

After the first production of the solid-hydrogen filament and the extrusion of it, the temperature of the third cooler is set up at 9-9.5 K by adjusting the liquid helium flow control valve and the current to the electric heater. The temperatures of the first and second coolers are controlled at 14-16 K and 9-9.5 K, respectively. Then, the fuel gas is introduced into the cylinder without leaking through the nozzle, because the solid-hydrogen at the bottom of the cylinder remains after the first extrusion of the filament. It requires 2-3 minutes for the new solid-hydrogen filament to be formed from the hydrogen gas.

The extrusion process is resumed by moving a piston driven by a screw. The piston moves with a stroke of 10 cm. When coming to the most-bottom position, the piston is stopped, then the piston moves back to the top position. If the fuel gas is continuously supplied into the cylinder, with a low flow rate of around 0.8 Nl/min (3 l/min) during the extrusion process, the hydrogen gas is liquefied in the cylinder above the piston head, mainly in the first cooler. When the piston head goes back to the top position, the grooves on both the piston head and the inner surface of the cylinder are matched to allow the liquefied hydrogen to flow down to the bottom region of the cylinder through the grooves. These conditions allow the continuous filament extrusion by moving the piston down and up. 4-5 hours of experiments can be conducted using a 250 l liquid helium Dewar.

3.3 Extrusion Tests

The extrusion tests of the hydrogen filaments have been conducted to investigate the dependence of the temperatures of the three coolers, the condensation pressure, the extrusion speed (piston speed), and the shape of the extrusion nozzle, upon the extrusion pressure (extrusion force). The following results are obtained for the case of the circular cross-sectional filaments.

The movement of the piston and the extrusion force, monitored by an encoder and a load cell, are shown in Fig. 8. The piston speed is set at 10 mm/s in this case, and the temperatures are about 14.5 K for the first cooler, and 9.1 K for the second and third coolers, respectively. Although a small amplitude of the fluctuation is detected on the traces of the extrusion pressure just after the extrusion begins, the extrusion pressure stays constant and is reproducible throughout the tests. The clear solid-hydrogen filaments are observed by the monitor camera for these tests. In case that the temperatures of the second and third coolers are set at lower than those of the tests in Fig. 8, the spikes (sudden increases) of the extrusion pressure are detected. In addition, even if the temperature of the cryogenic system is the same as that in Fig. 8, the spikes are observed when the extrusion speed is set at a higher value as shown in Fig. 9. When these spikes are observed, the pellets are not delivered successfully.

Figures 10 to 12 summarize the experimental results showing the dependence of the temperatures of the coolers and the piston speed upon the extrusion pressure. The relations between the piston speed and the extrusion pressure are shown in Fig. 10. The successful extrusions of the solid-hydrogen filaments are symbolized as solid circles (●) and solid triangles (▲), while the unsatisfied results (i.e., muddy white filaments) and the failed results (i.e., filaments broken into pieces) are symbolized as crosses (×) and plus signs (+), respectively. It is found that as the piston speed increases, the extrusion pressure gradually increases up to the upper limit of the extrusion pressure (4 MPa). Figure 11 shows the relation between the temperature of the second cooler and the extrusion pressure. The extrusion pressure indicates a linear-dependence of the temperature of the second cooler. A similar tendency is also found for the temperature of the third cooler. In case that the extrusion pressure exceeds 4 MPa, good quality solid-hydrogen filaments are not extruded. Good quality solid-hydrogen filaments are obtained

for the piston speed of 10 to 30 mm/s, if the temperatures of the second and third coolers are met with the ideal values; 10-11 K for the second cooler and 8-9 K for the third cooler, as shown in Fig. 12.

3.4 Functional Tests of the Gun Assembly

Functional tests of the gun assembly have been conducted to examine the functions of the punch-type chambering mechanism and the fast-opening magnetic valves under the actual operation conditions. After cooled down to 8.5-9.5 K, the chambering mechanism is operated with the repetition rate of up to 12.5 Hz⁽³⁾. A timing control of the sequence should be optimized to minimize the propellant gas load (heat load) to the cryogenic extruder and to the inner region of the chambering mechanism. Figure 13 shows an example of the control sequence diagrams together with the measured supplied current to the chambering mechanism and the magnetic valve, and the measured signals from the accelerometer on the chambering mechanism and the pressure sensor. The supplied current to the chambering mechanism is increased gradually, saturated after around 10 ms, and held for 40 ms, as shown in Fig. 13. Then, the magnetic valve is triggered at 10 ms after the chambering mechanism is excited. These timings are changeable values and determined by a pulse controller. The supplied electric powers to the chambering mechanism and the magnetic valves are also controllable by changing the supplied voltages to the capacitors, which store the electric energy and discharge it to each solenoid coil. The signal of the accelerometer shows that the chambering mechanism completes to move the punching tube within 6.5 ms after it is excited and pulls back the punching tube at about 16 ms after the trigger pulse is switched off. The open/hold time of the fast-opening magnetic valves is limited within 1 ms to restrict the propellant gas load (heat load) to the cryogenic extruder. This time is determined by the time-width of the supplied current by the pulse controller. The signal of the pressure sensor indicates that the propellant gas is developed to the full pressure within 3 ms after the valves obtain the trigger signals, the pressure decreases rapidly to less than half within 1 ms, and slowly decays, due to a small gas-conductance of the gun barrel. This effect will be one of the key issues to achieve higher repetition rates of pellet injections.

3.5 Pellet Injection Tests

Pellet injection tests have been performed using hydrogen pellets. Firstly, the repetition rate is set from 1 to 2 Hz, i.e., low repetition rate. Figure 14 shows the time-evolution of the temperatures measured on the three coolers and the barrel. After a pre-cooling process, hydrogen gas is supplied with a flow rate of 7 ℓ /min until the pressure inside the cylinder reaches 800 Torr. During the process of the fuel gas supply, the temperature of the first cooler increases from 14 K to 15-16 K, while the temperatures of other coolers are relatively constant, as shown in Fig. 14. After the fuel gas is supplied, approximately 3 minutes are required to fill up the cylinder with solid-hydrogen. Then, the piston is driven with a speed of 10 mm/s to extrude the filament, and the pellets are chambered and injected. When the propellant gas is ejected from the fast-opening magnetic valves, the temperatures of the second and the third coolers increase. Especially, the temperatures measured at the positions close to the chambering mechanism increase rapidly. For the position at the top of the third cooler, temperature is raised by 3 K. The temperatures of the gun barrel are monitored at the two points. When the propellant gas is ejected, the temperature near the outlet of the gun barrel is observed to decrease by about 5 K, while the temperature near the chambering mechanism increases by around 5 K. This temperature decrease is considered to be caused by adiabatic expansion of the propellant gas. Figure 15 shows the time-evolutions of the extrusion pressure (solid line), the piston position (dashed line) detected by an encoder, and the pressure of the diagnostic vessel II (dotted line). The helium propellant gas is ejected in a time interval of 500 ms to inject four pellets. The pressure signal in the diagnostic vessel II in Fig. 15 has the synchronized step signals showing these four pellets injection. A series of the pellet injection tests have been conducted under the same conditions. The observed velocities and mass of the injected pellets are summarized in Fig. 16, showing that these quantities are reproducible. The injected pellets have small deviations to the average values of their velocities and mass; i.e., around 10% and 20% deviations for the velocities and the mass, respectively. Figure 17(b) shows the time-evolutions of the signals from the photodiodes used to measure the pellet speed and from the microwave cavity used to measure the mass of the flying pellets. The shadowgraphs of the flying pellets are also taken and presented in Fig. 17(a) and (c). The pellet speeds are around 1.1 km/s for those

cases. The shadowgraphs of Fig. 17(a) are the pellets just after ejection from the gun barrel, while Fig. 17(c) shows the shadowgraphs of the pellets after flying some distance. The pellets just after ejection from the gun barrel look to be covered by a cloud, while the pellets travelling a distance give clear shadows of the pellets. This may be caused by a sublimation gas from the solid-hydrogen pellets, because the pellet is sublimated by large amount of the propellant gas near the muzzle. Once the sublimation gas is ejected to the vacuum in the diagnostic vessel II, it immediately scatters away. Thus, this sublimation gas is only observed in the shadowgraphs taken near the gun barrel. In addition, the positions of the pellets in the shadowgraphs are different for the pellets travelling a distance (Fig. 17(c)), while the positions of the pellets are nearly the same for the pellets just after ejection from the gun barrel (Fig. 17(a)). This fact may be attributed to the existence of the guide tube between the second set of the photodiode sensor and the second set of the video-camera, as shown in Fig. 5. During a free flight of the pellets, the pellets may touch the inside wall of the teflon guide tube which changes the positions of the pellets.

In the next experiments, the repetition rate is increased to 3.3 Hz, which allows the pellet injections with a time interval of 300 ms. Eight pellets are ejected successively. The piston speed for the filament extrusion is set at 10 mm/s. The temperatures of the three coolers are controlled similarly to the previous experimental case. Figure 18 shows the time-evolutions of the signals from the photodiodes measuring the pellet speed and from the microwave cavity measuring the mass of the flying pellets. The deviations of the pellet velocities and the pellet mass to those of the average values are found to be slightly larger than those in the previous case, i.e., 10-14% for the pellet velocities and 20-30% for the pellet mass. The shadowgraphs of the eight flying pellets, taken at the outlet of the gun barrel, are shown in Fig. 19. All of the ejected pellets have nearly an identical cylindrical shape, whose dimensions are close to those designed. However, it is sometimes observed that the edges of the pellets are slightly chipped. An effect of the temperature rise due to the repetitive propellant gas loads is found to be insignificant for the cases of the pellet injections with pellet speeds of 1 km/s and a repetition rate of 2-3.3 Hz. When good quality solid-hydrogen filaments are formed, the pellets are reliably delivered for those pellet injections without any failure.

The repetition rate is then raised to 5 Hz (200 ms of a time interval). To achieve this repetition rate, the piston speed is set up at 15 mm/s to extrude the solid-hydrogen filament more rapidly. Ten pellets are delivered in this case. Propellant gas pressure is measured to be around 1.6 MPa by the pressure transducer. Figure 20 shows the time-evolutions of the extrusion pressure, the piston position, the pressure of the diagnostic vessel II, and the temperatures of the three coolers and the gun barrel. The temperature of the third cooler is set at 7-9 K, which is slightly lower than that in the previous tests with repetition rates of 2-3.3 Hz. The temperature profiles of the coolers show oscillations, which may be caused by the instability of the liquid helium flow. It is considered that liquid helium and helium gas flow reciprocally through the cooling channels to cause this instability. Since the liquid helium does not flow smoothly, due to this instability, the cooling ability is lowered. It is shown that the difference of temperature distribution on each cooler, i.e., temperature difference between the solid and dashed lines in Fig. 20, is slightly larger than that of the previous case as shown in Fig. 14. Under these conditions, the pellet injection test is conducted. The signals from the photodiodes and from the microwave cavity are shown in Fig. 21. From the first to the fourth pellets show the similar pellet speed and mass, while the other pellets are largely deviated in terms of these quantities. Especially, the mass of the pellets decreases for the latter injected pellets. This can be seen in the shadowgraphs of the flying pellet in Fig. 22. As the repetition rate is increased, it requires the higher extrusion speed to increase the frictional heat between the piston head and the cylinder. Thus, the temperatures observed on the coolers are slightly larger than those obtained for the cases of lower repetition rates.

The observed pellet velocities are plotted in Fig. 23, as a function of the propellant gas pressure. These experimental data are obtained for the cases of the repetition rate of 2-3.3 Hz. The results for the large pellets ($3 \text{ mm}\phi \times 3.5 \text{ mmL}$) are symbolized as triangles (\triangle) and double circled (\odot), while the small pellets ($1.5 \text{ mm}\phi \times 1.6 \text{ mmL}$) are symbolized as open (\circ) and solid circles (\bullet). Theoretical curve for the large pellet based on the ideal gun theory⁽⁶⁾ is also shown in Fig. 23. The pellet velocities range from 0.9 to 1.7 km/s for the propellant gas pressure of 2-10 MPa and the room temperature of the gas. The maximum pellet velocities up to 1.7 km/s and 1.55 km/s are observed for the large pel-

lets and the small pellets, respectively. The measured velocities are about 80-90% of the ideal theory.

4. Discussion and Summary

A repeating pneumatic pellet injector has been developed and constructed to investigate the ideal conditions for forming the solid-hydrogen filaments, extruding the filaments, and repeating pellet injection. The pellets with nearly identical speed and mass can be repeatedly injected with a repetition rate of 2-3.3 Hz and a speed of up to 1.7 km/s. In order to achieve reliable pellet injections, it is necessary to form good quality solid-hydrogen filaments. In the present device, excessive heat flows into the cryogenic extruder as a result of the thermal transfer mainly through the piston shaft, the thermal radiation, the propellant gas load (heat load), and the heat generated by friction mainly between the piston head and the cylinder. For the 2-3.3 Hz repetitive pellet injections, the temperature rise of the second and third coolers is 2-3 K. Then, this excessive heat restricts the upper repetition rate of the pellet injections. Lower thermal conductive material, such as teflon or polyimide, can be replaced to the copper piston head. An additional cooling channel can be placed along the extrusion nozzle to take away the frictional heat. In addition, the fast-opening magnetic valve should be upgraded to reduce the propellant gas load. Higher response for a valve to open and close should be achieved.

In this device, the taper-angle of the extrusion nozzles are selected to be small (0.44 degree). Therefore, the plastic deformation is small and the heat generated by the plastic deformation is also small during the extrusion process⁽⁷⁾. However, the total frictional heat generated between the extruded filament and the inner surface of the extrusion nozzle, because the surface area, where the extruded filament is sliding, is large. Furthermore, as the extrusion speed increases, more frictional heat will be generated. This frictional heat is also considered to be one of the main causes to soften and even melt the solid-hydrogen filament. In order to improve the pellet injection rate, it is necessary to increase the extrusion speed of the solid-hydrogen filament. Generally, if material deformation speed is fast or material temperature is low, the deformation stress (yield stress) increases.

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Namely, the relation of the strain speed $\dot{\epsilon}$ and the yield stress Y is given by the following equation.

$$Y = f |\dot{\epsilon}|^m$$

From this relation, it is not always that the extrusion force decreases as the taper-angle of the nozzle increases. As the taper-angle increases, the local strain speed becomes faster and reversely the total extrusion force becomes higher. If the strain speed is faster than the critical value, the material can no longer be continuously extruded, i.e., the material becomes to be intermitted. If the temperature is too low, similar phenomenon can be considered since the material becomes brittle. Therefore, it is necessary to survey further optimum conditions, i.e., taper-angle, extrusion speed and cryogenic temperature, in order to extrude good solid-hydrogen filaments with faster speeds.

So far, it is found that the present type of extruder can provide appropriate solid-hydrogen filament for a short time under certain conditions of temperature and extrusion speed. In order to extend the operation time of extrusion, it is necessary to do further investigation, including the modification of the extruder and/or the application of a screw-press technique instead of a piston-press technique.

The results of the present performance tests are summarized as follows.

- (1) The long and high quality solid-hydrogen filament can be extruded by the optimization of the temperature of the cryogenic extruder and extrusion speed.
- (2) Multi-pellets with high quality can be ejected with the repetition rate of 2-3.3 Hz.
- (3) The obtained maximum speed of the pellets is about 1.55 km/s for large pellets and about 1.7 km/s for small pellets.

Acknowledgments

The authors are acknowledged to Dr. H. Maeda for useful discussion and continuous encouragements of this development and research. Also, we are grateful to the members of the Experimental Plasma Physics Laboratory and JFT-2M Facility Division for their encouragements.

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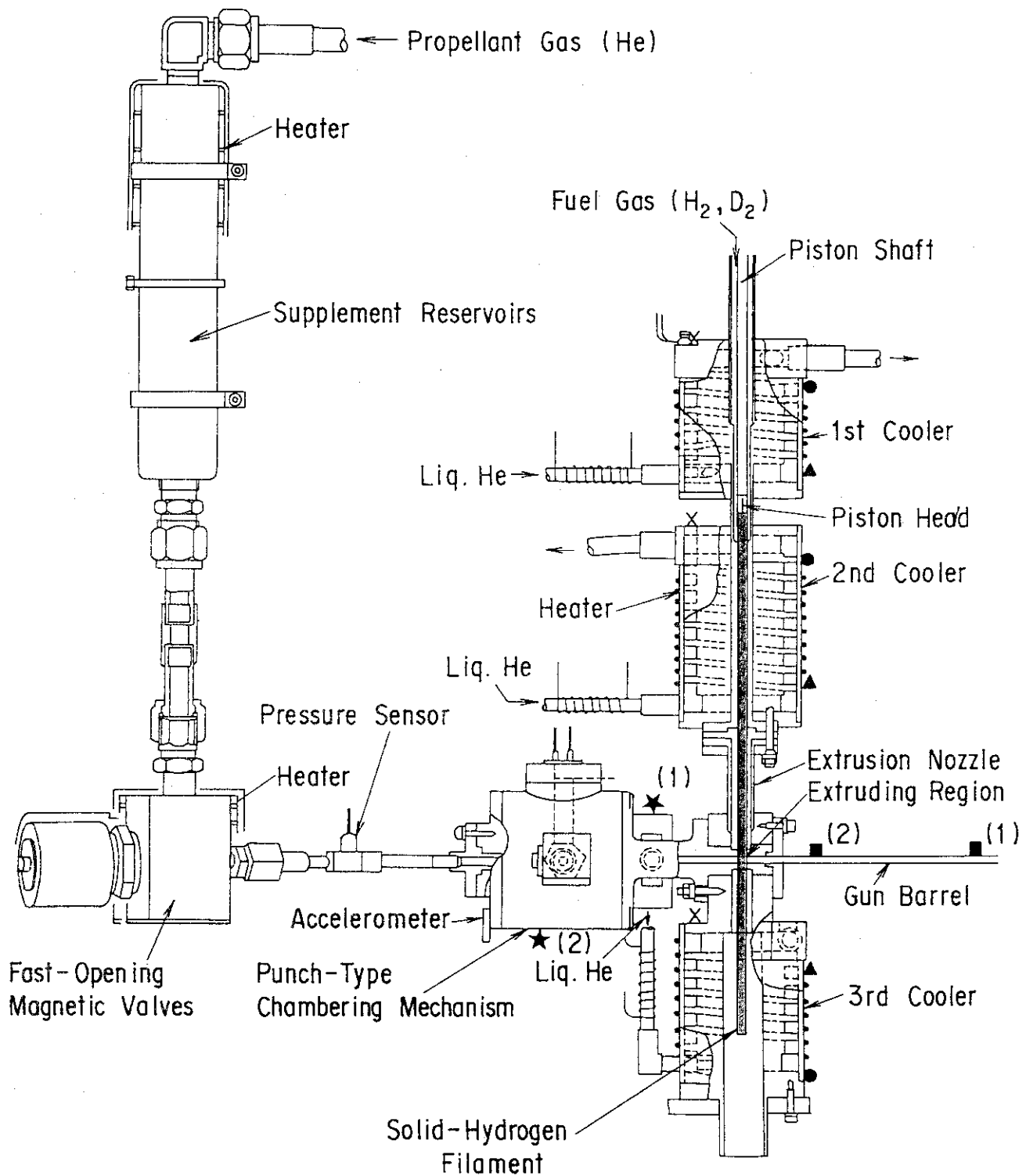


Fig. 1 Main assembly of the repeating pneumatic-pellet injector developed at JAERI and MHI.

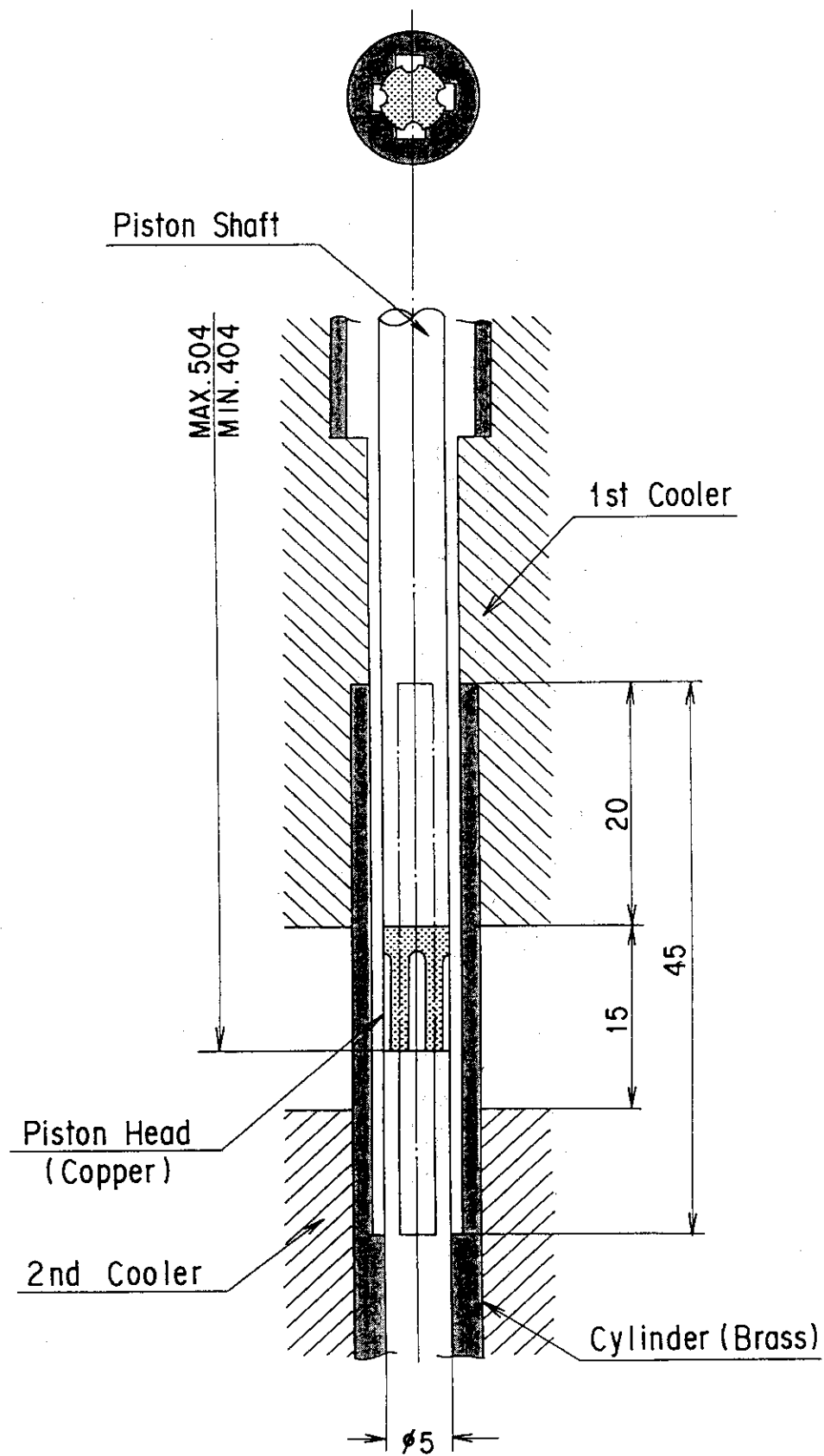


Fig. 2 Cross-section of the cylinder including a piston.

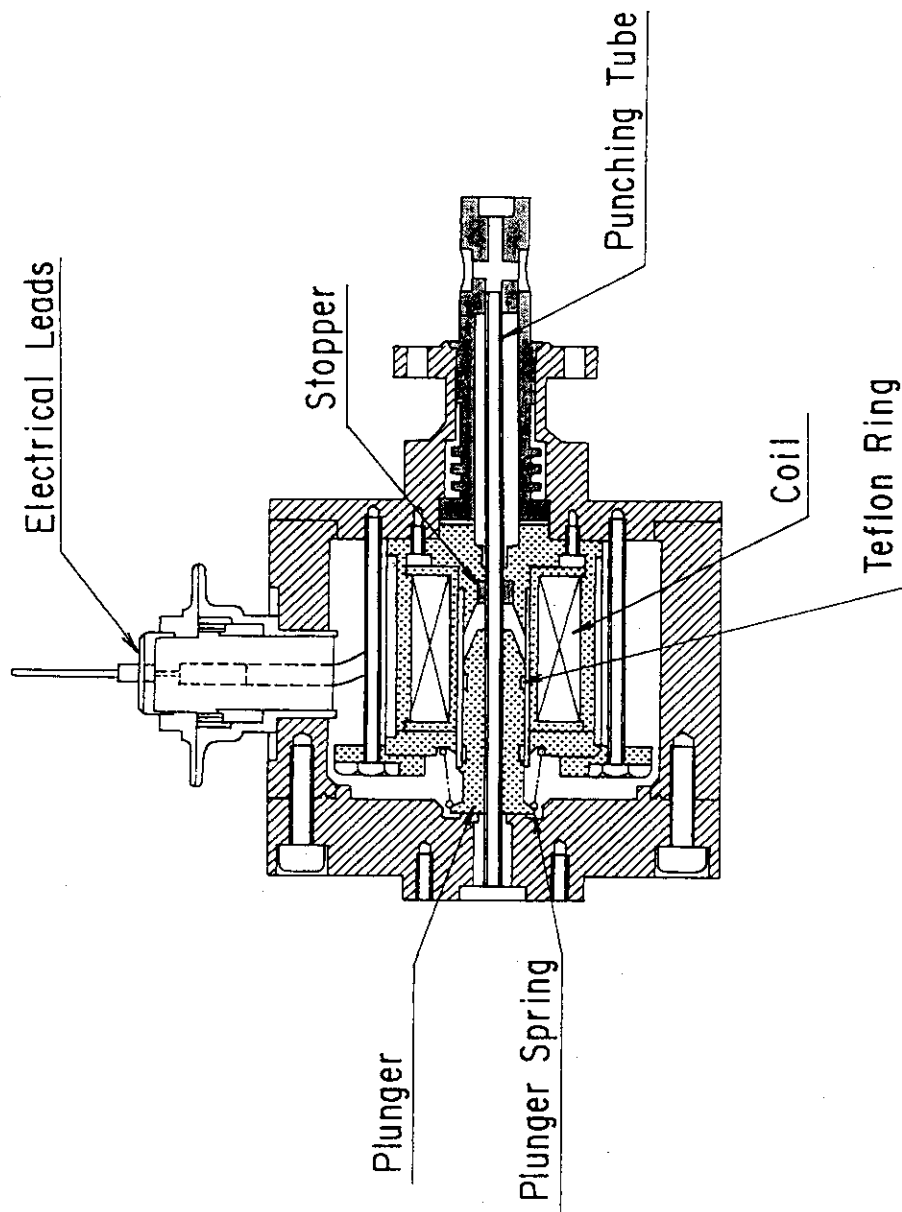


Fig. 3 Cross-section of the punch-type chambering mechanism.

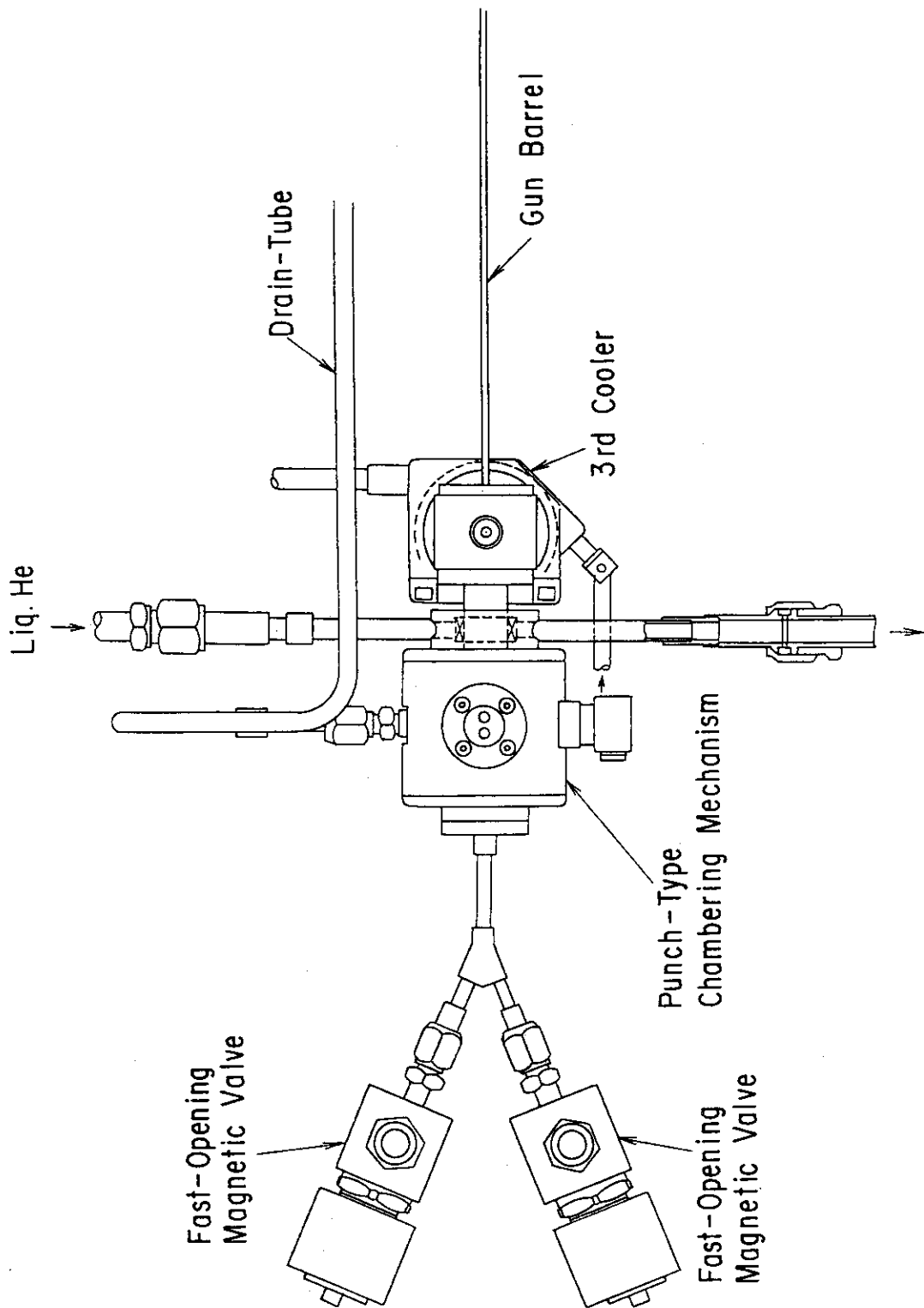


Fig. 4(a) Top view of fast-opening magnetic valves connected to the punch-type chambering mechanism.

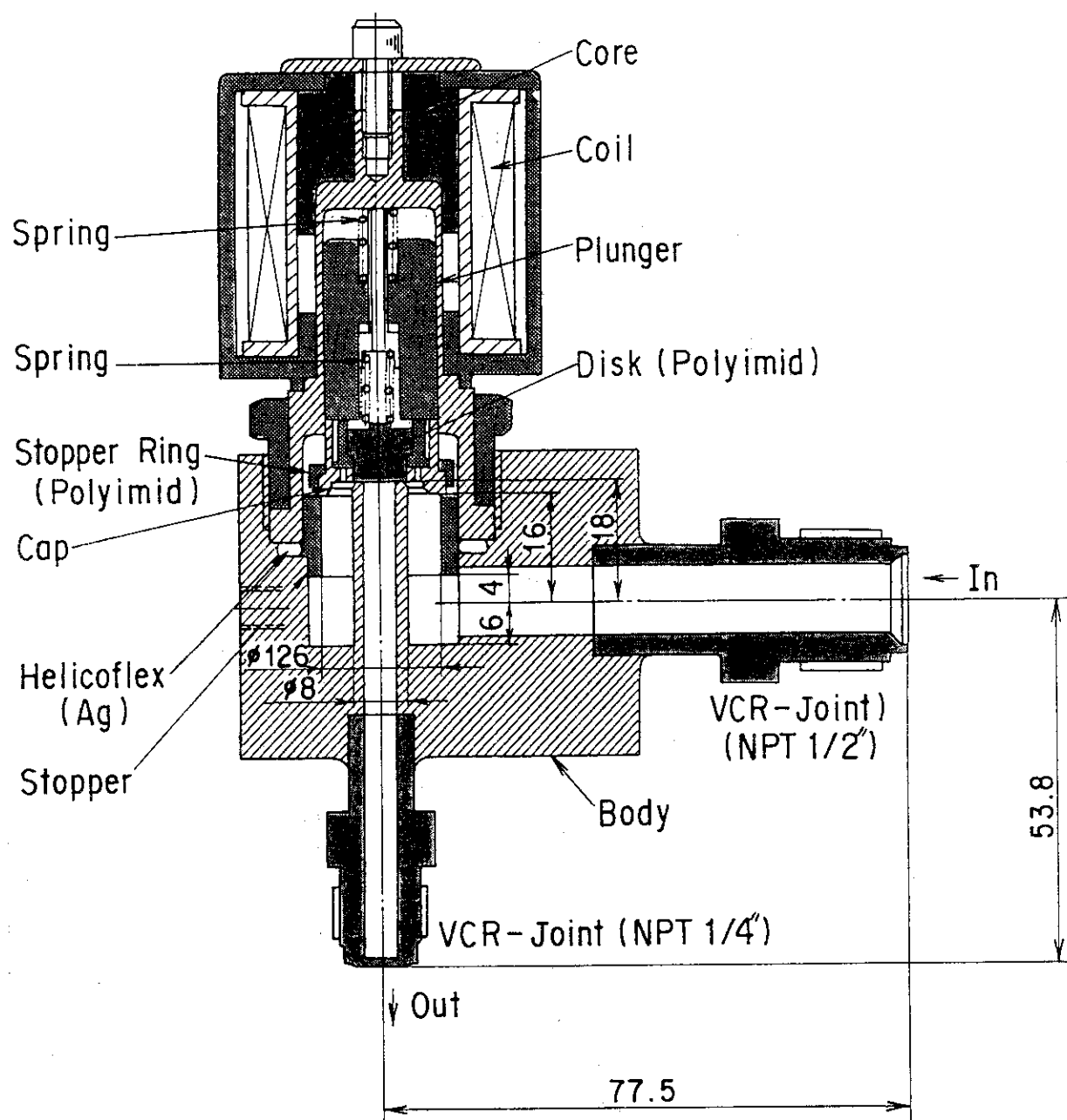
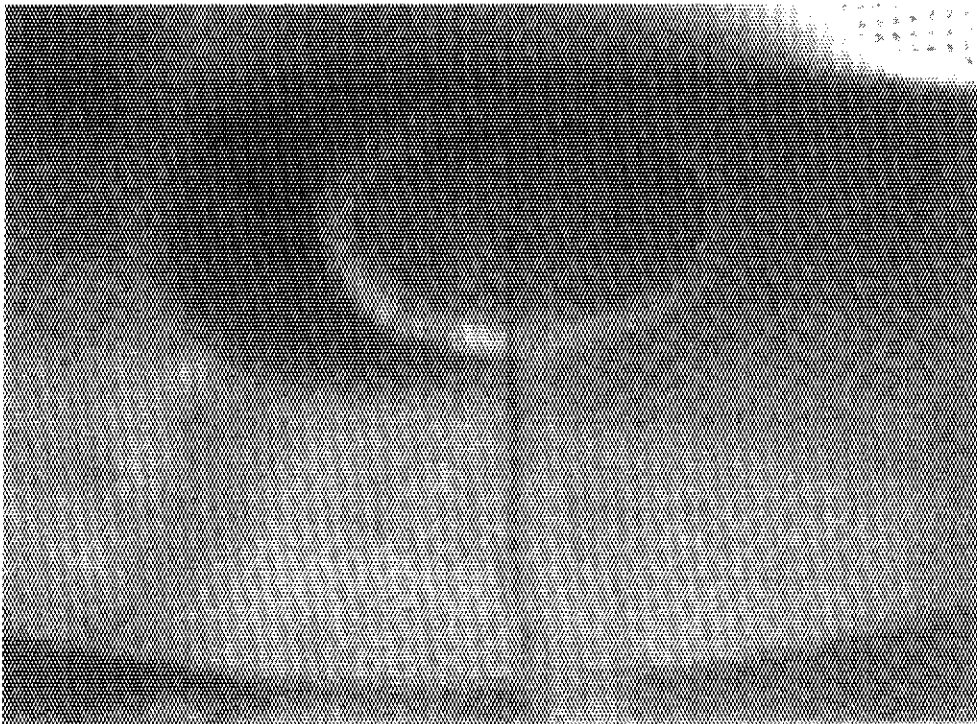


Fig. 4(b) Cross-sectional view of the fast-opening magnetic valve. A diameter of the orifice is 4.5 mm.



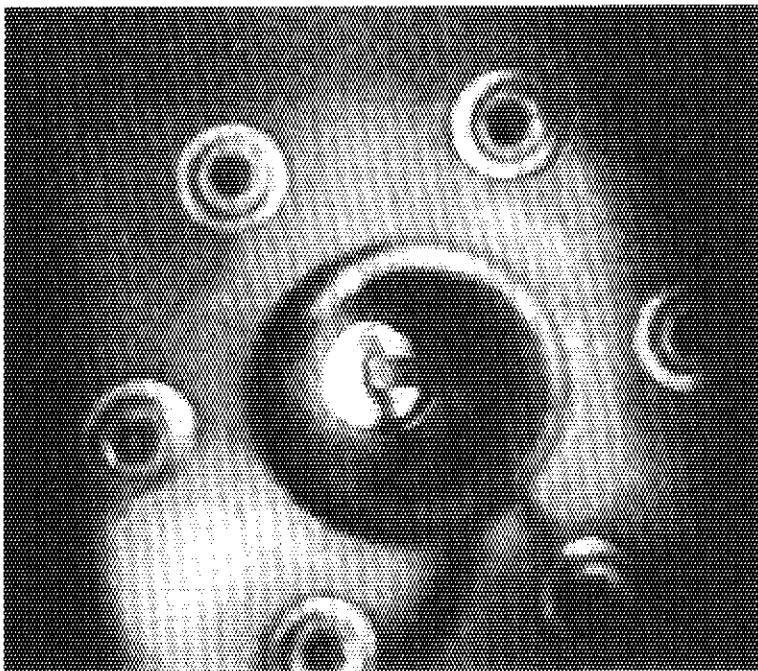
Fig. 5 Schematic of the repeating pneumatic pellet injector and diagnostic system.

Extruded Solid-Hydrogen Filament



Side-View

1989/5/17/#19

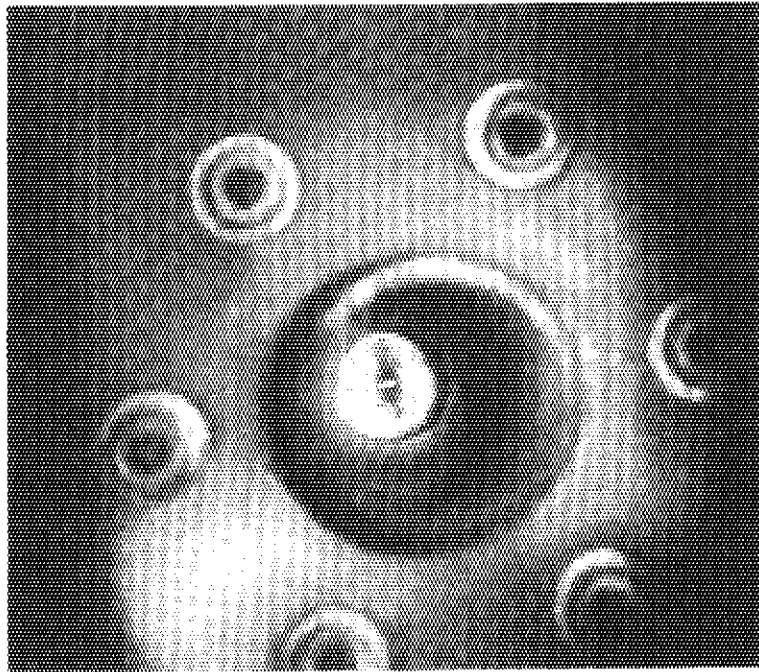


Bottom-View

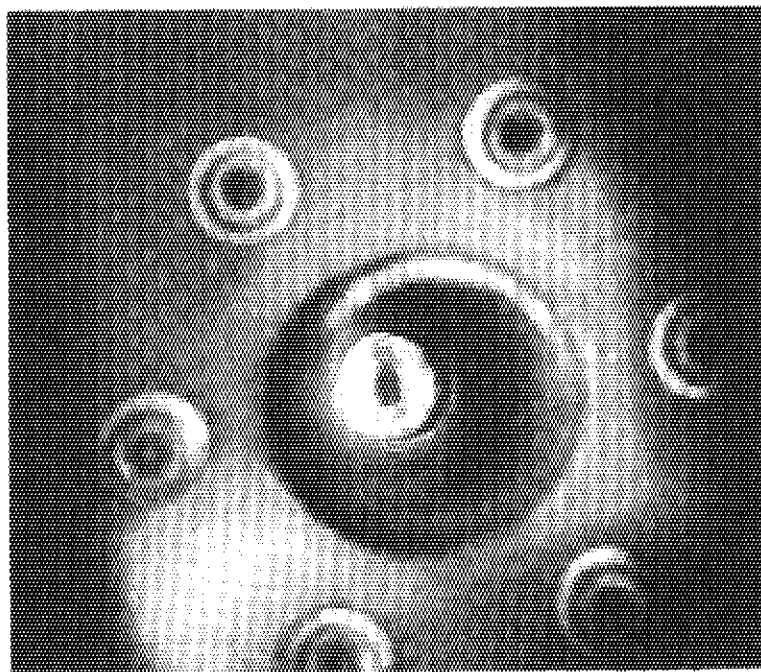
1989/9/1/#10

Fig. 6(a) Photographs of extruded hydrogen filament; upper picture is a view from the side and lower picture is view from the bottom.

Movement of Punch-Type Chambering Mechanism



When the punching tube is driven,
the tube comes into view.



When the chambering mechanism is not activated,
the punching tube goes out of sight.

Fig. 6(b) Movement of the punching-tube; the punching-tube is driven (upper picture) and the chambering mechanism is not activated (lower picture) (taken by a video-camera from outside of the viewing port in Fig. 5).

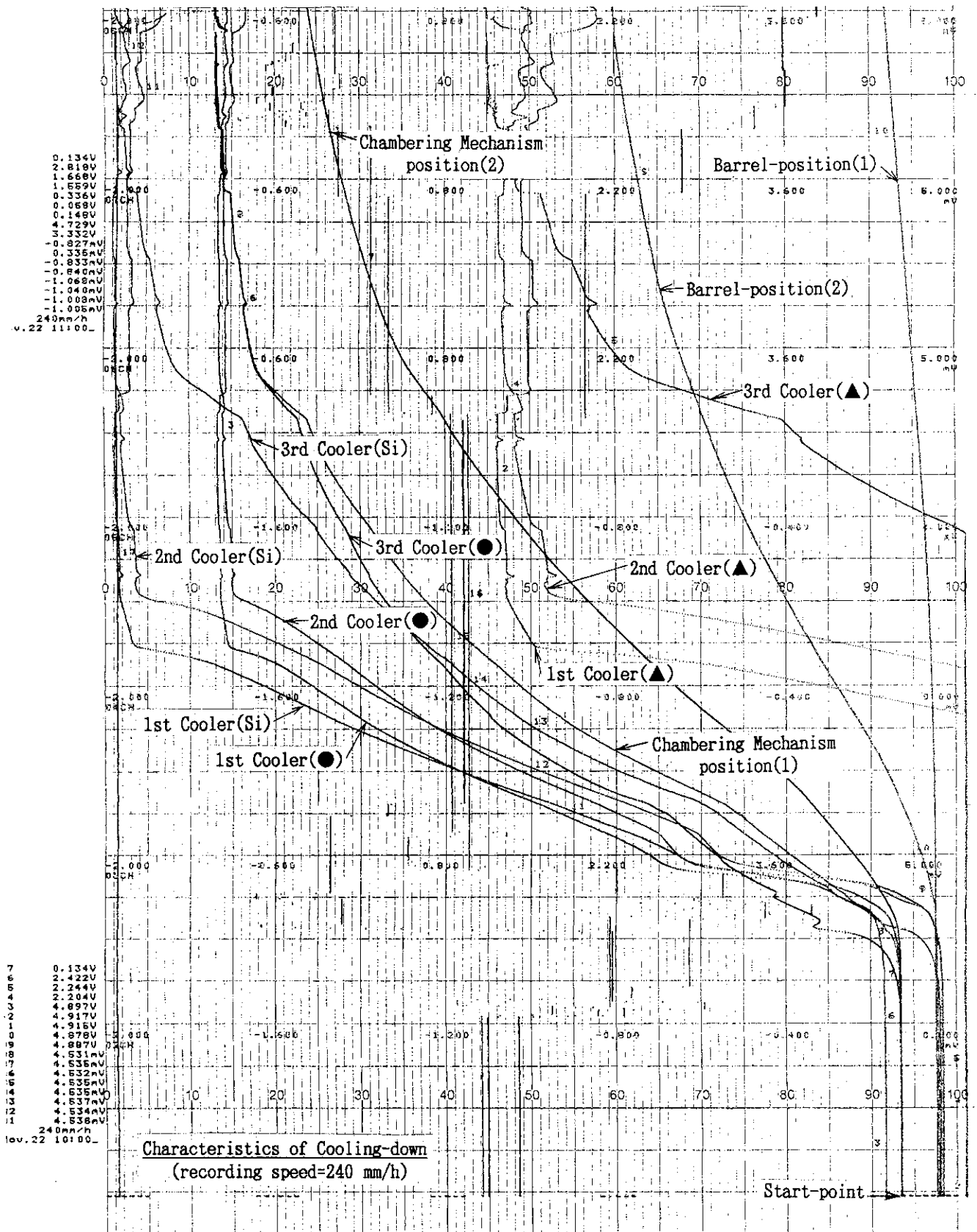


Fig. 7 Characteristics of cooling-down of the cryogenic system.

1991/9/12

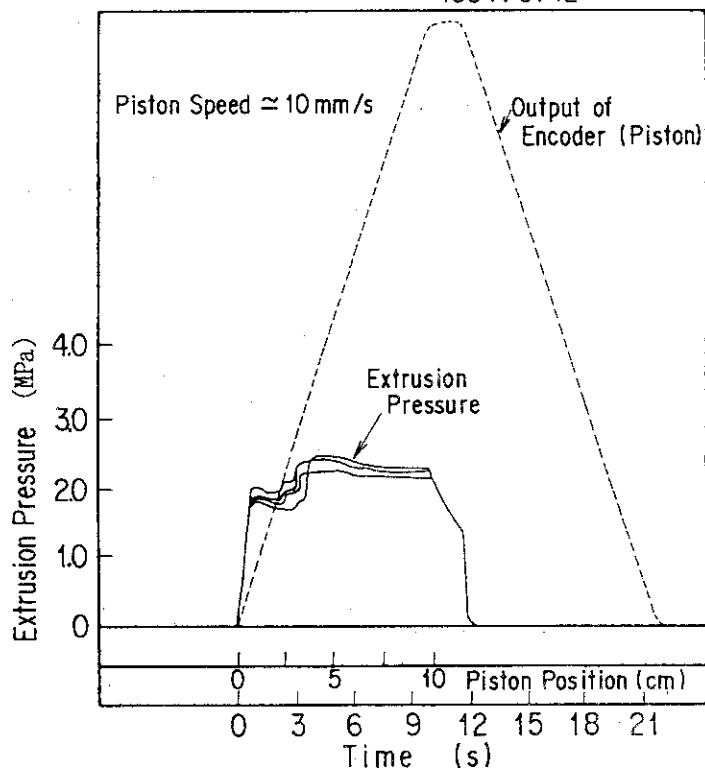


Fig. 8 Time-evolutions of extrusion pressure (solid-line) acted on the piston head, which is measured by a load cell, and the output of an encoder indicating the position of the piston head (dashed-line). The piston speed is 10 mm/s.

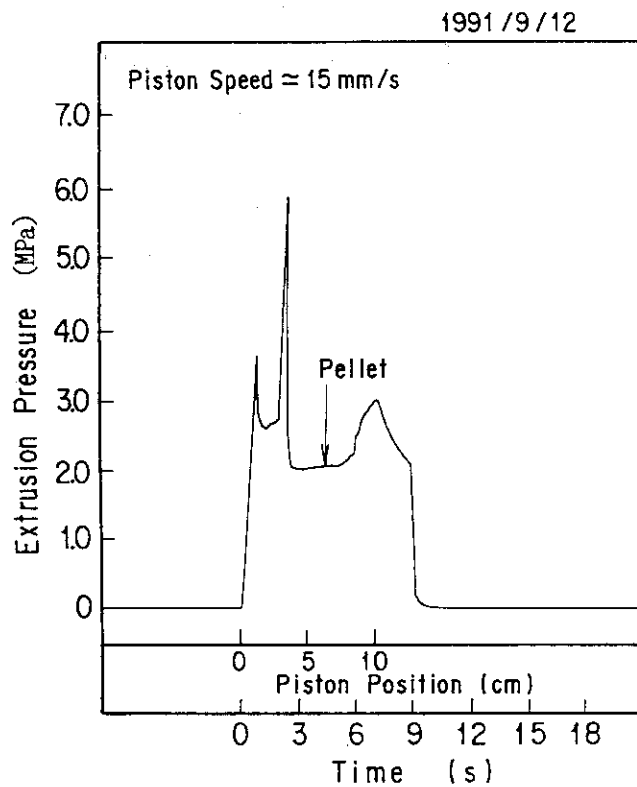


Fig. 9 Time-evolution of the extrusion pressure. Piston speed is 15 mm/s.

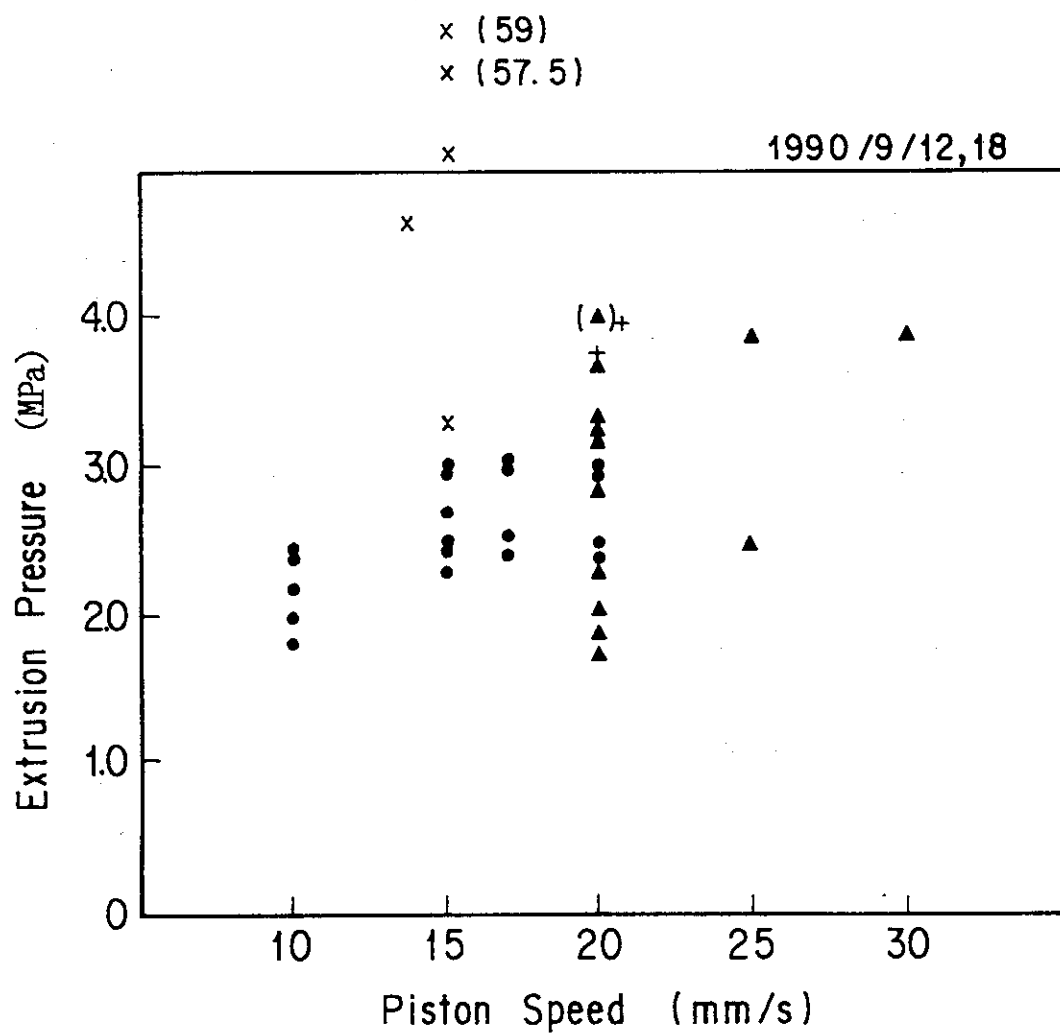


Fig. 10 Dependence of the extrusion pressure on the piston speed. Unsatisfied extrusion results are symbolized by a cross sign (x) and plus sign (+).

1990/9/18

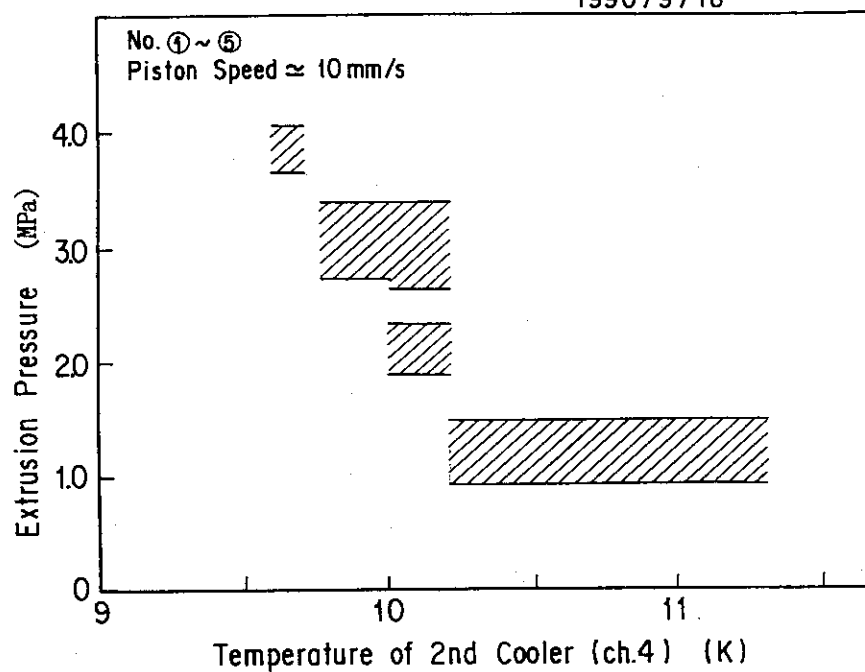


Fig. 11 Dependence of the extrusion pressure on the temperature of the 2nd cooler. Piston speed is 10 mm/s.

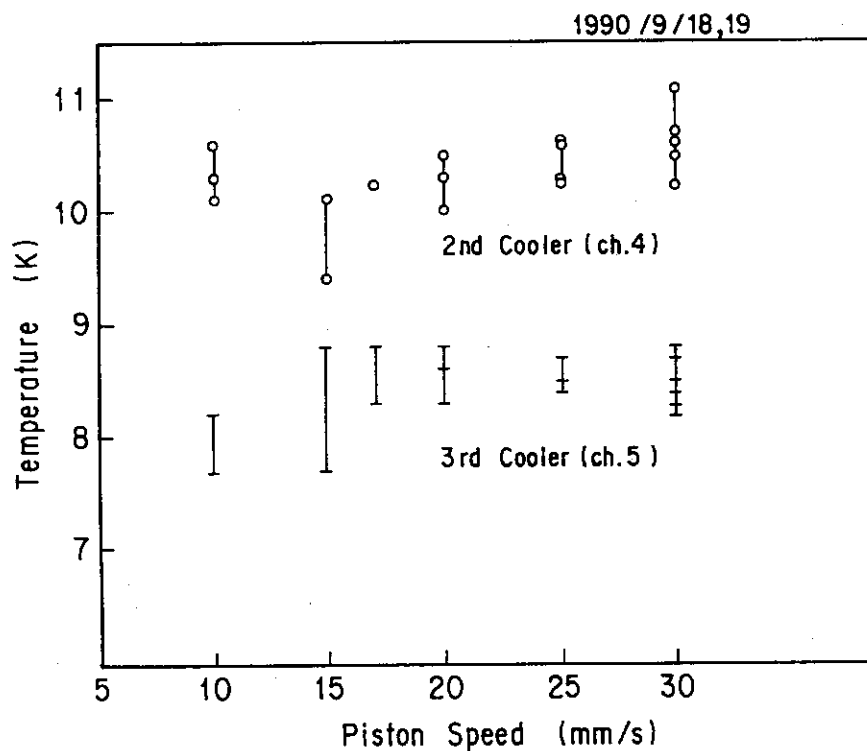


Fig. 12 Temperatures of the 2nd and 3rd coolers versus piston speed.

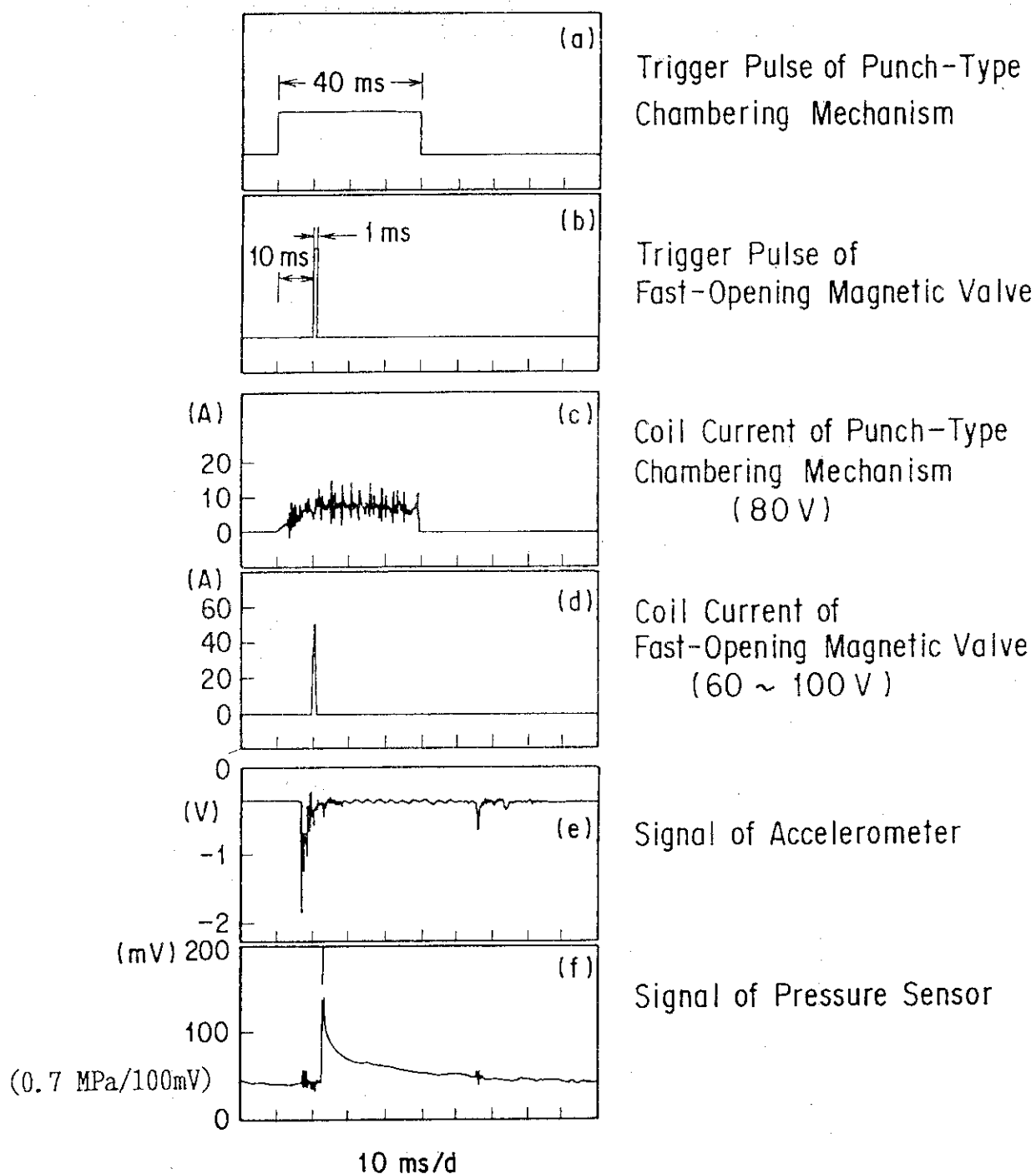


Fig. 13 (a) Trigger-pulse of the punch-type chambering mechanism,
 (b) Trigger-pulse of the fast-opening magnetic valve,
 (c) Coil current of the punch-type chambering mechanism,
 (d) Coil current of the fast-opening magnetic valve,
 (e) Time evolution of the signal of the accelerometer mounted on the chambering mechanism,
 (f) time evolution of the signal of the pressure sensor mounted on the middle position between the fast-opening magnetic valve and chambering mechanism.

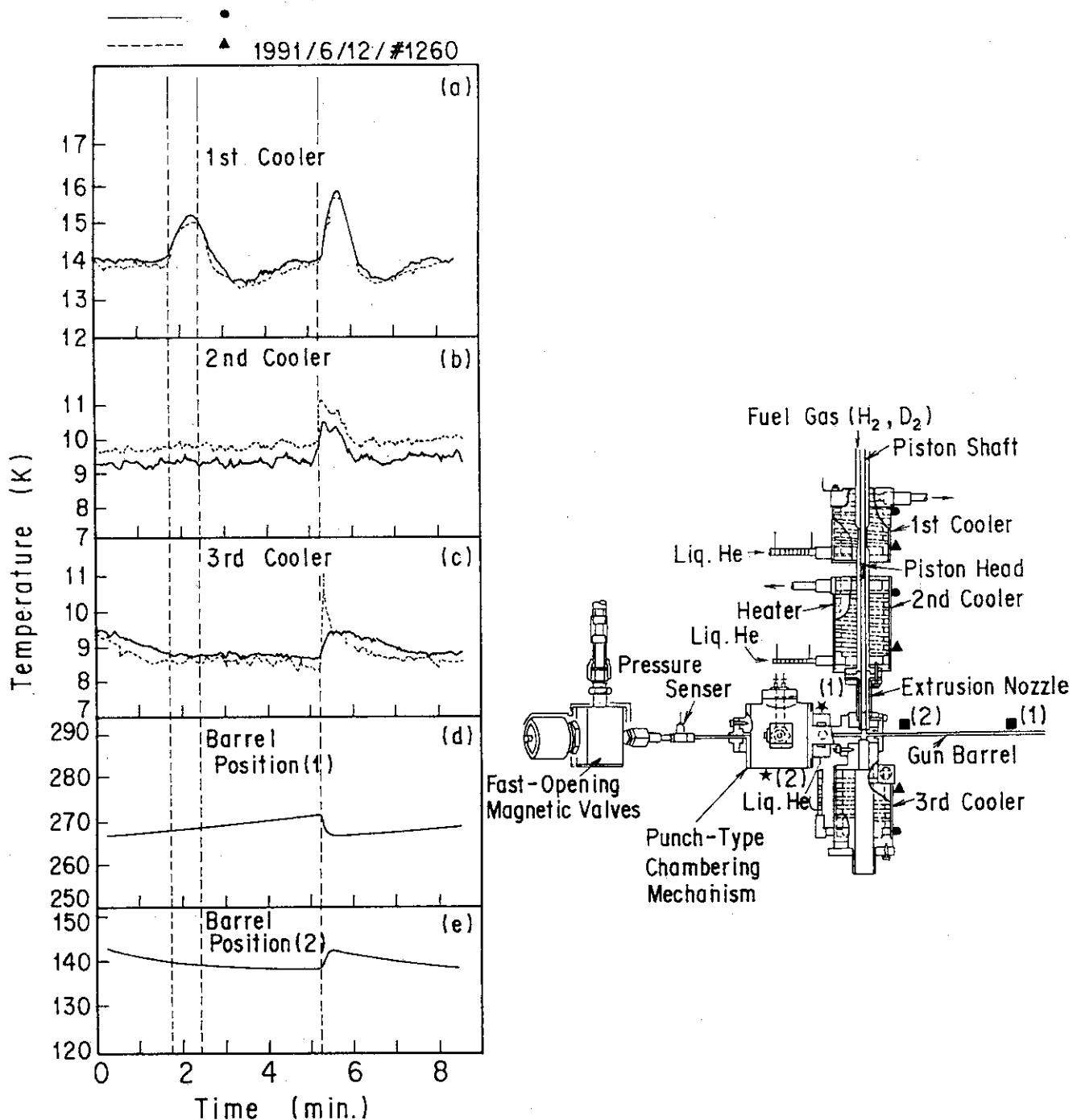


Fig. 14 Time evolutions of the temperatures of the 1st, 2nd and 3rd coolers, and of the gun barrel at the positions of (1) and (2) for the 2 Hz repeating injection of 4 pellets. Solid lines and dotted lines are the temperatures of the coolers monitored by the sensors symbolized by closed-circles (●) and closed triangles (▲) on the picture, respectively. First vertical dashed-line from the left indicates the start-time of the H_2 fuel supply and second one the stop-time, and 3rd one represents when the pellet is injected. Piston speed is 10 mm/s.

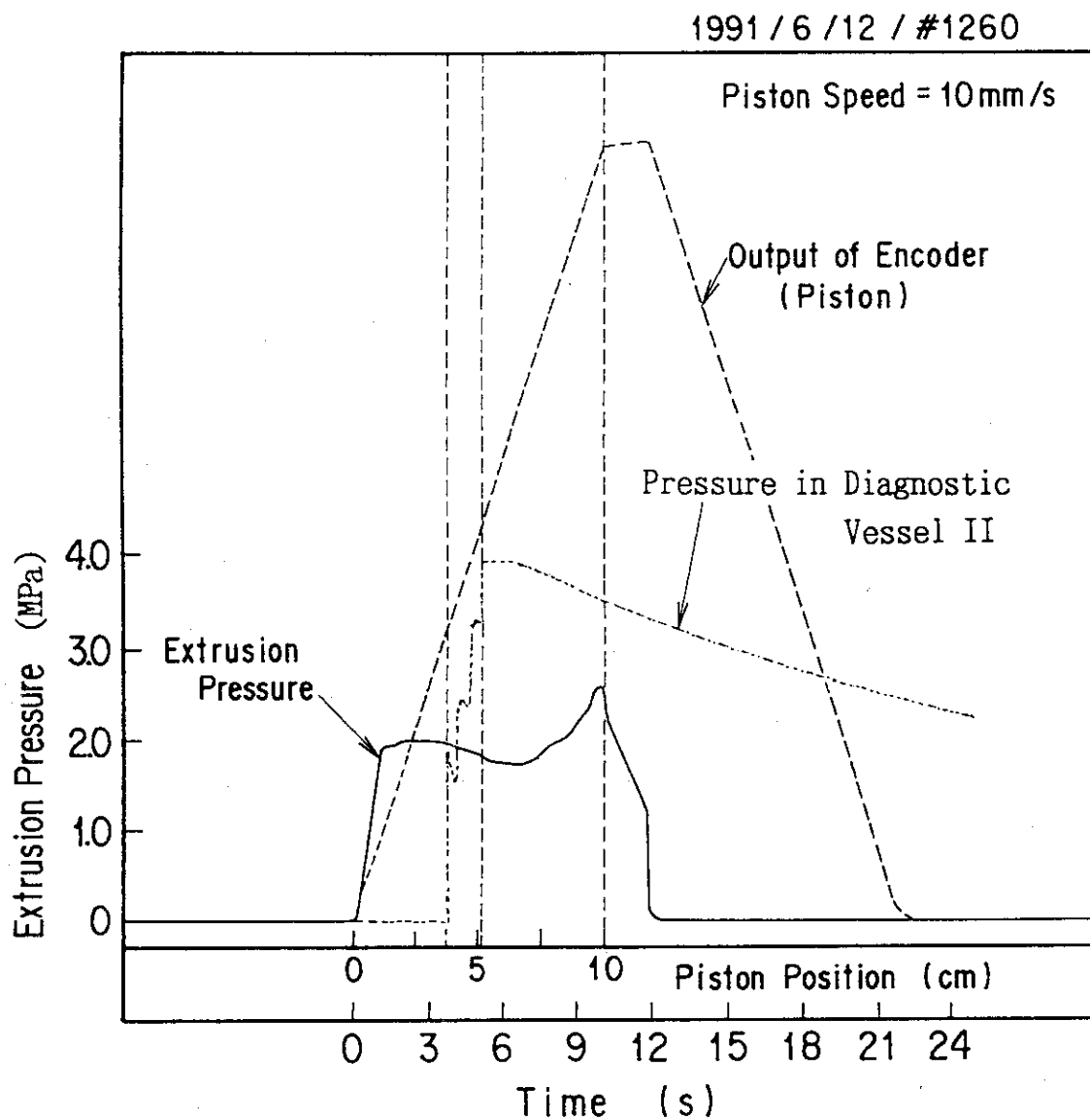


Fig. 15 Time evolutions of the extrusion pressure and the pressure in the diagnostic vessel II, and the position of the piston for the 2 Hz repeating injection of 4 pellets. Piston speed is 10 mm/s and the temperature condition is the same as that in Fig. 13.

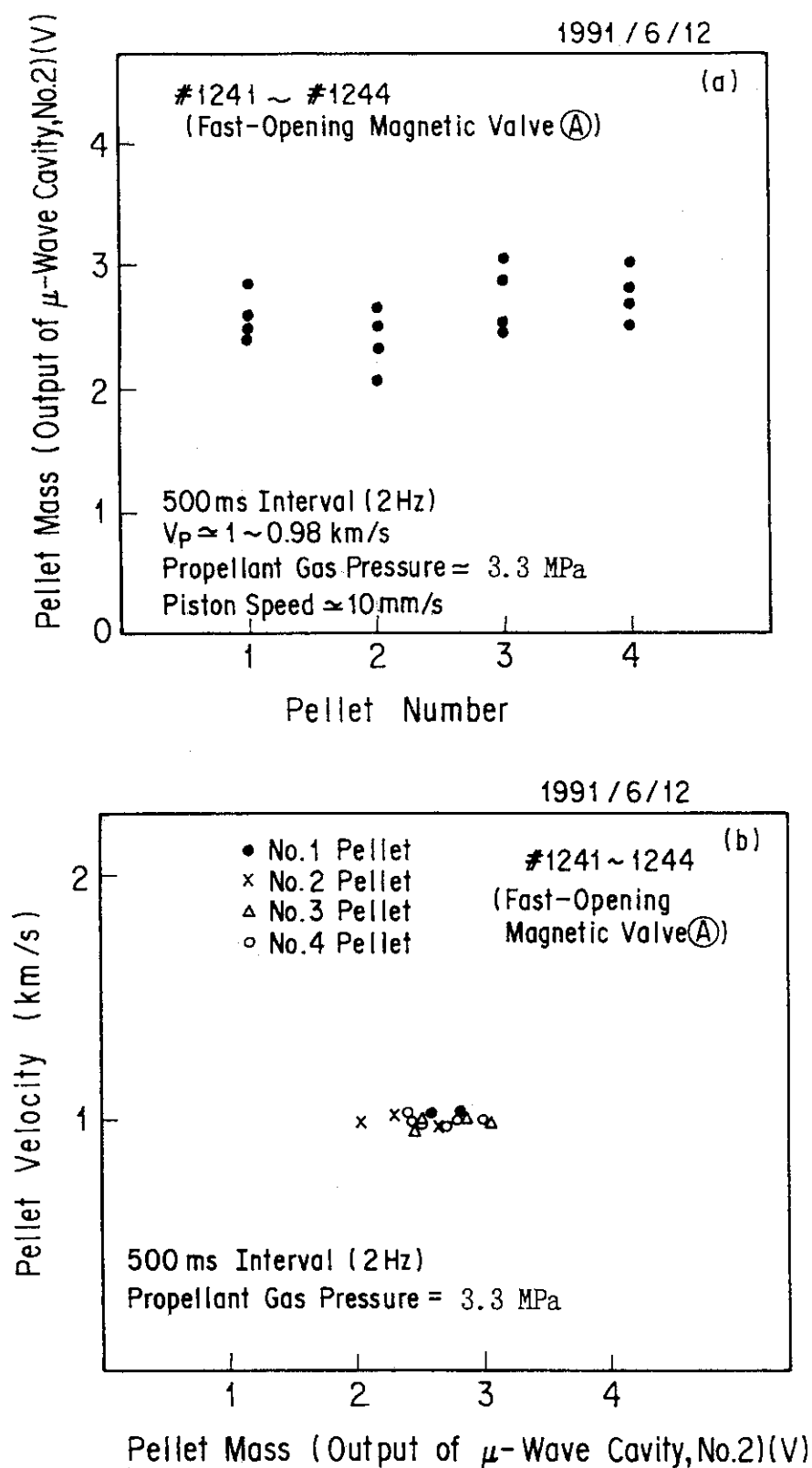


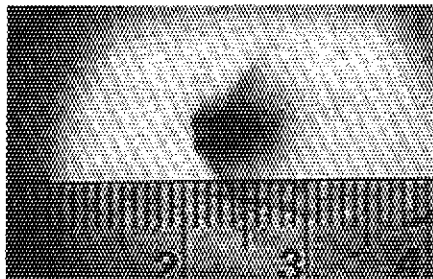
Fig. 16 (a) Reproducibility of injected pellet mass (output from the No.2 micro-wave cavity) for the 1st, 2nd, 3rd and 4th pellets.
 (b) Pellet velocity versus pellet mass for each pellet. Operation conditions are the 2 Hz repeating injection, piston speed is 10 mm/s and the propellant gas pressure is about 3.3 MPa.

Hydrogen Pellets (1991/ 6/12/#1241)

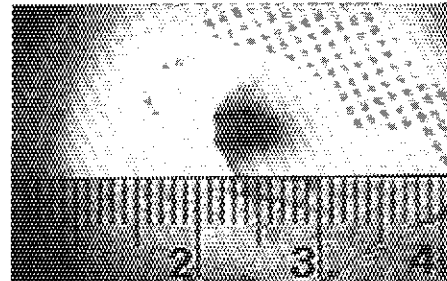
Repeat Time = 500 ms (4 pellets)
 Piston Speed = 10 mm/s
 Material of Pellet = H₂

Pellet No.1

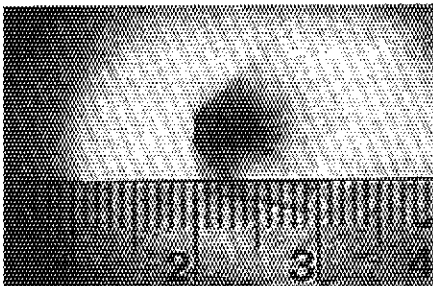
Speed= 1.0
 km/s
 $\Delta V = 2.4 \text{ V}$

Pellet No.2

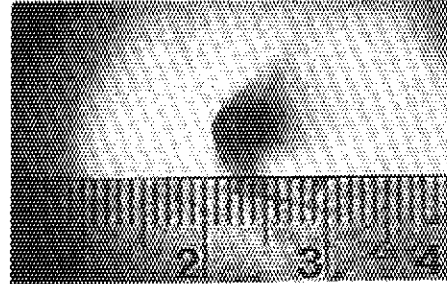
Speed= 1.0
 km/s
 $\Delta V = 2.4 \text{ V}$

Pellet No.3

Speed= 0.98
 km/s
 $\Delta V = 2.5 \text{ V}$

Pellet No.4

Speed= 1.0
 km/s
 $\Delta V = 2.8 \text{ V}$



Pellet → → → →

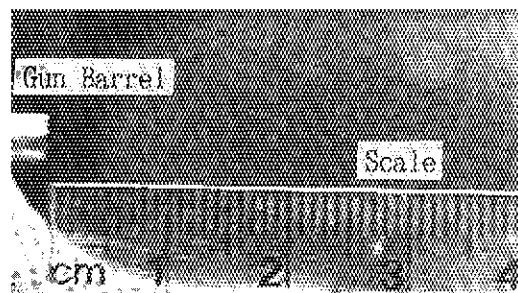
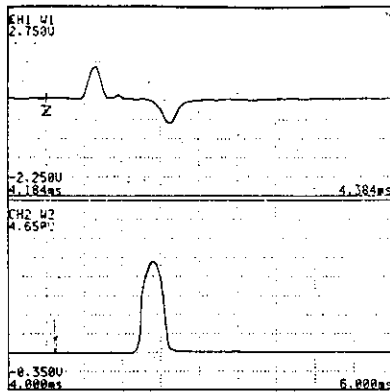


Fig. 17(a) Shadowgraphs of 4 pellets, taken at the first position, near the gun barrel under the 2 Hz repeating injection.

Hydrogen Pellets (1991/ 6/12/#1260)

Repeat Time = 500 ms (4 pellets) Piston Speed = 10 mm/s
 Propellant Gas Pressure = 3.3 MPa (He, $\sim 30^\circ\text{C}$)

NO. 1



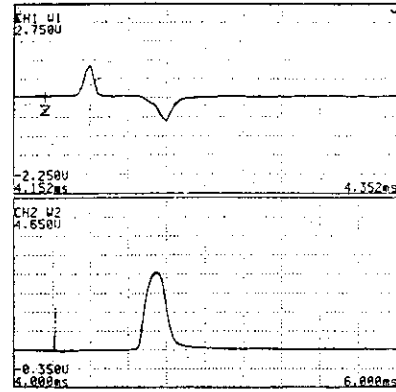
500mV/d

 $20 \mu\text{s/d}$

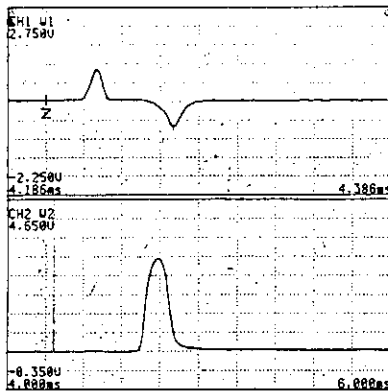
500mV/d

 $200 \mu\text{s/d}$ $V_s = 1.0 \text{ km/s}$ $M_p = 2.4 \text{ V}$

NO. 2

 $V_s = 1.0 \text{ km/s}$ $M_p = 2.4 \text{ V}$

NO. 3



500mV/d

 $20 \mu\text{s/d}$

500mV/d

 $200 \mu\text{s/d}$ $V_s = 0.98 \text{ km/s}$ $M_p = 2.5 \text{ V}$

NO. 4

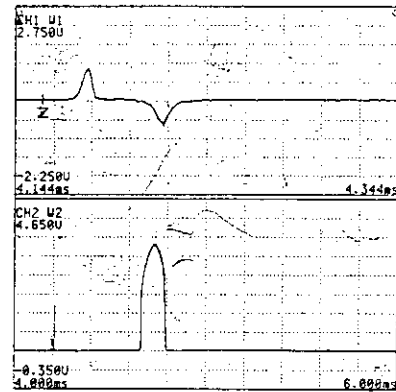
 $V_s = 1.0 \text{ km/s}$ $M_p = 2.8 \text{ V}$

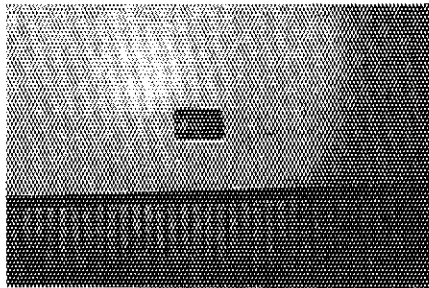
Fig. 17(b) Time evolutions of the output signals of the photo-diode and the micro-wave cavity (No.2), which are used to calculate the pellet velocity and mass, respectively.

Hydrogen Pellets (1991/ 6/12/#1260)

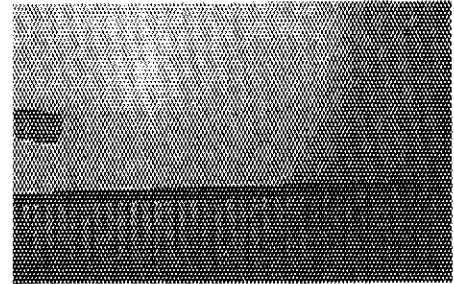
Repeat Time = 500 ms (4 pellets)
 Piston Speed = 10 mm/s
 Material of Pellet = H₂

Pellet No.1

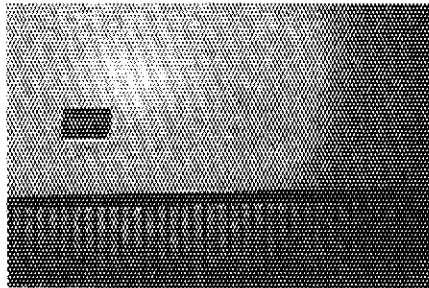
Speed= 1.1
 km/s
 $\Delta V = 2.6 \text{ V}$

Pellet No.2

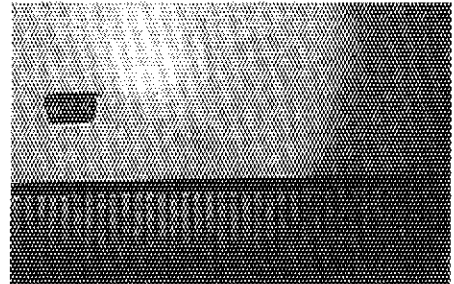
Speed= 1.1
 km/s
 $\Delta V = 2.6 \text{ V}$

Pellet No.3

Speed= 1.1
 km/s
 $\Delta V = 2.1 \text{ V}$

Pellet No.4

Speed= 1.1
 km/s
 $\Delta V = 2.3 \text{ V}$



Pellet → → → →

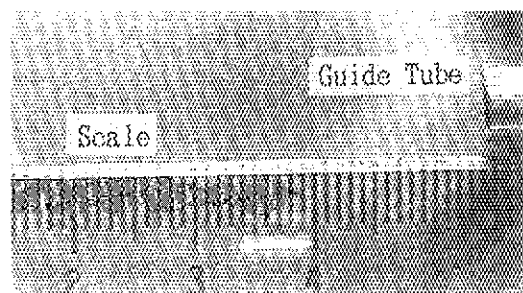


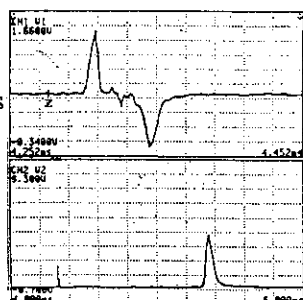
Fig. 17(c) Shadowgraphs of 4 pellets, taken at the 2nd position, near the No.2 cavity.

Hydrogen Pellets (1991/ 2/14/#22)

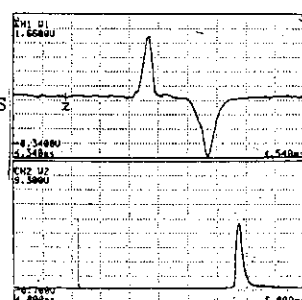
Repeat Time = 300 ms (8 pellets)
 Propellant Gas Pressure = 2.1 MPa (He, $\sim 29^{\circ}\text{C}$)
 Piston Speed = 10 mm/s

Pellet No.1

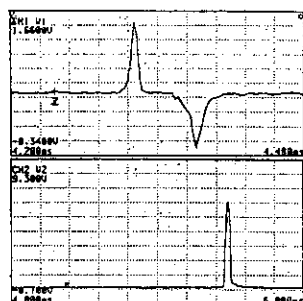
Speed= 1.1 km/s

 $\Delta V = 3.7 \text{ V}$ Pellet No.2

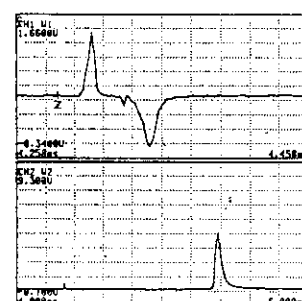
Speed= 0.98km/s

 $\Delta V = 4.7 \text{ V}$ Pellet No.3

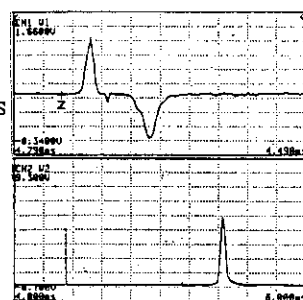
Speed=0.93km/s

 $\Delta V = 5.9 \text{ V}$ Pellet No.4

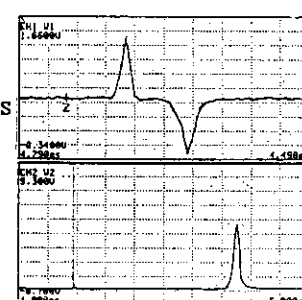
Speed=1.0 km/s

 $\Delta V = 4.0 \text{ V}$ Pellet No.5

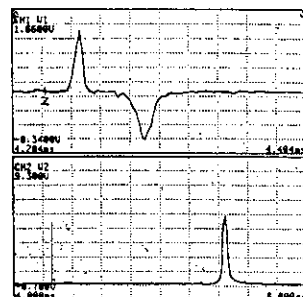
Speed= 0.98km/s

 $\Delta V = 4.8 \text{ V}$ Pellet No.6

Speed= 0.95km/s

 $\Delta V = 4.6 \text{ V}$ Pellet No.7

Speed=0.91km/s

 $\Delta V = 4.6 \text{ V}$ Pellet No.8

Speed=0.87km/s

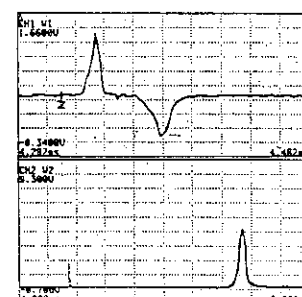
 $\Delta V = 4.1 \text{ V}$ 

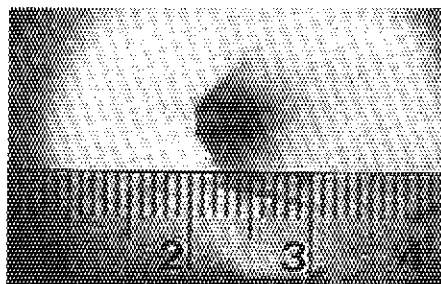
Fig. 18 Time evolutions of the output signals of the photo-diodes and the No.3 micro-wave cavity under the 3.3 Hz repeating injection of 8 pellets. Piston speed is 10 mm/s and propellant gas pressure is about 2.1 MPa.

Hydrogen Pellets (1991/ 2/14/#22)

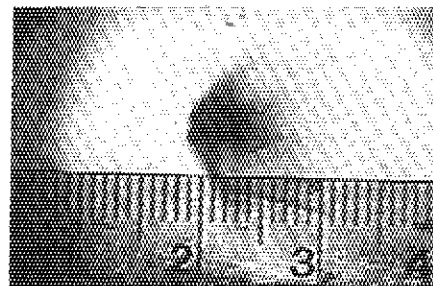
Repeat Time = 300 ms (8 pellets)
 Piston Speed = 10 mm/s
 Material of Pellet = H₂

Pellet No.1

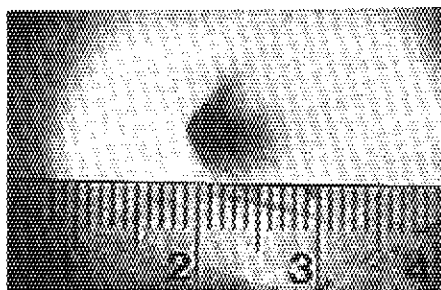
Speed= 1.1
 km/s
 $\Delta V = 3.7$ V

Pellet No.2

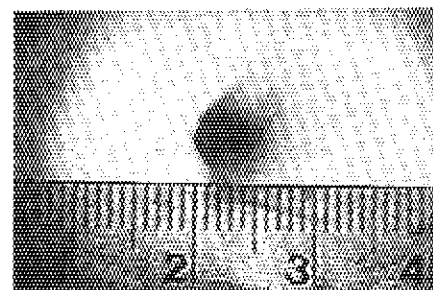
Speed= 0.98
 km/s
 $\Delta V = 4.7$ V

Pellet No.3

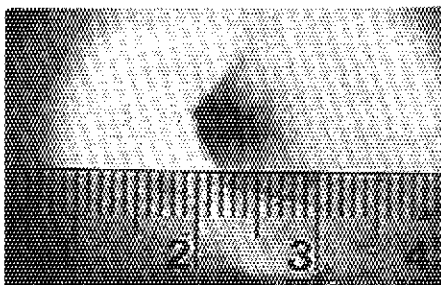
Speed= 0.93
 km/s
 $\Delta V = 5.9$ V

Pellet No.4

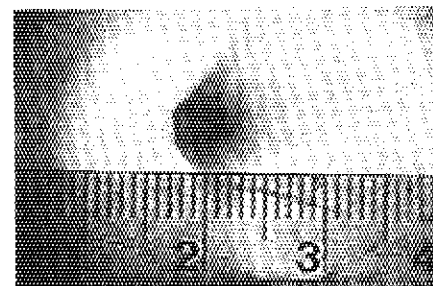
Speed= 1.0
 km/s
 $\Delta V = 4.0$ V

Pellet No.5

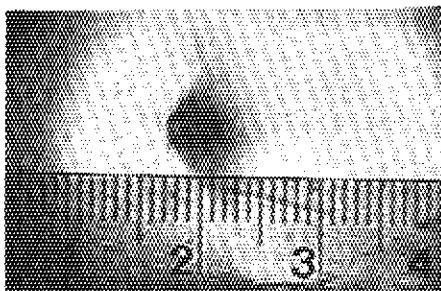
Speed= 0.98
 km/s
 $\Delta V = 4.8$ V

Pellet No.6

Speed= 0.95
 km/s
 $\Delta V = 4.6$ V

Pellet No.7

Speed= 0.91
 km/s
 $\Delta V = 4.6$ V

Pellet No.8

Speed= 0.87
 km/s
 $\Delta V = 4.1$ V

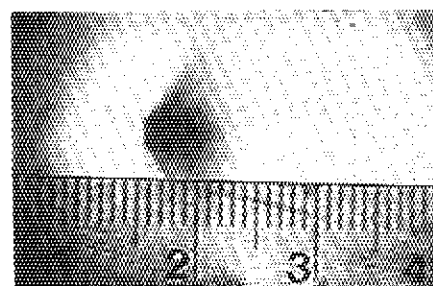


Fig. 19 Shadowgraphs of hydrogen pellets under the 3.3 Hz repeating injection of 8 pellets. Pellet speed and mass are the same as those in Fig. 18.

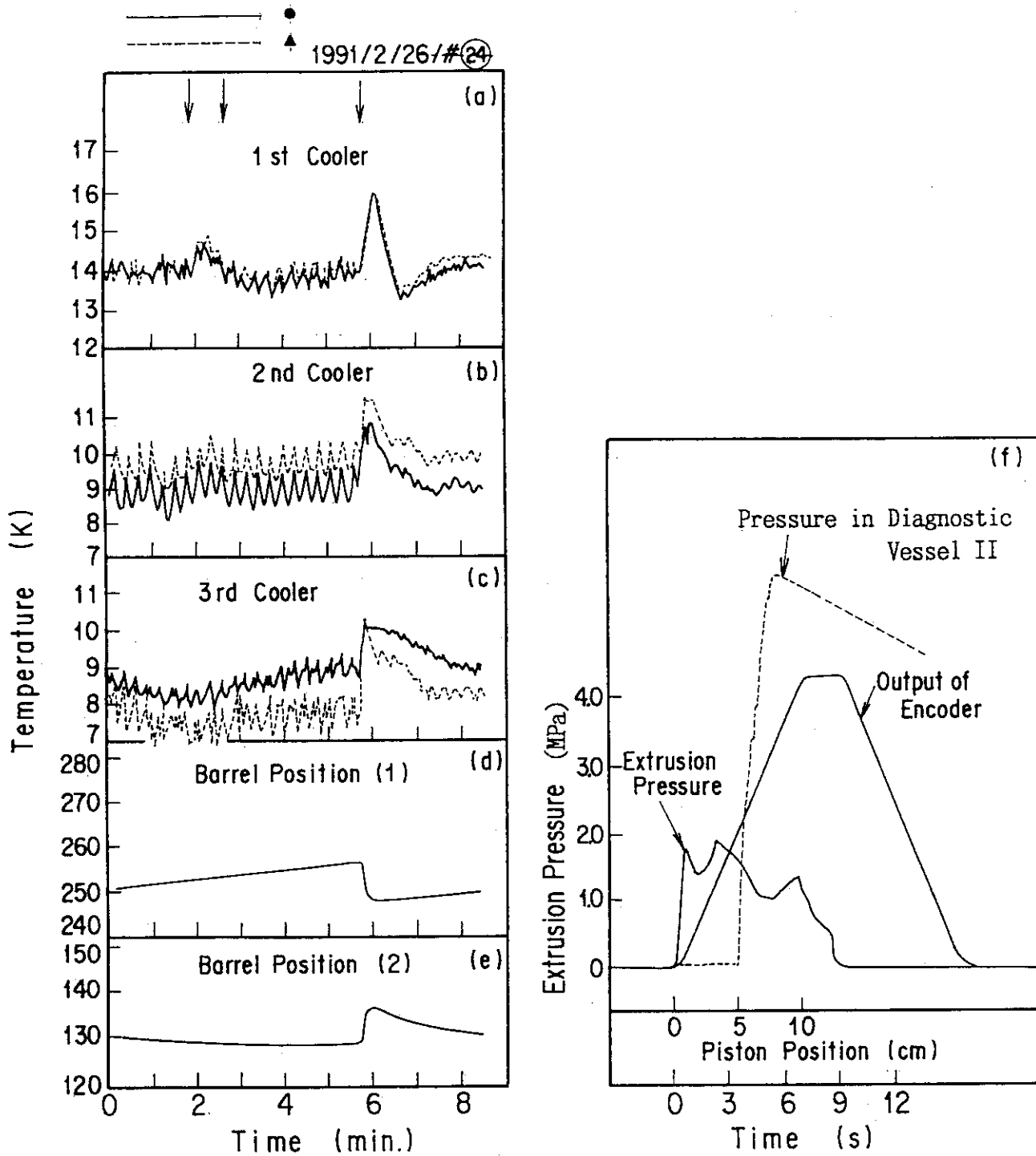


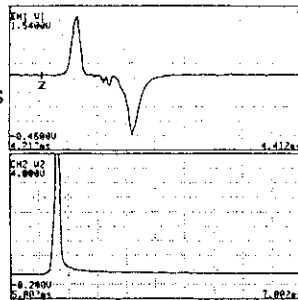
Fig. 20 (a-e) Time evolutions of the temperatures of the 1st, 2nd and 3rd coolers, and of the gun barrel at the positions of (1) and (2) for the 5 Hz repeating injection of 10 pellets.
 (f) Time evolutions of the extrusion pressure of the piston, the pressure in the diagnostic vessel II, and the piston position (output of the encoder). Piston speed is 15 mm/s.

Hydrogen Pellets (1991/ 2/26/#24)

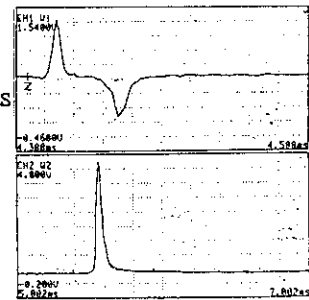
Repeat Time = 200 ms (10 pellets)
 Propellant Gas Pressure = 1.7 MPa (He, $\sim 29^{\circ}\text{C}$)
 Piston Speed = 15 mm/s

Pellet No.1

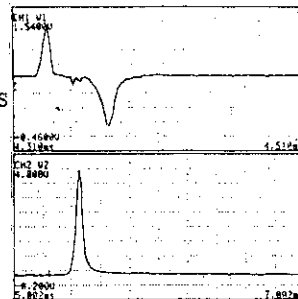
Speed= 1.05km/s

 $\Delta V = 8.2 \text{ V}$ Pellet No.2

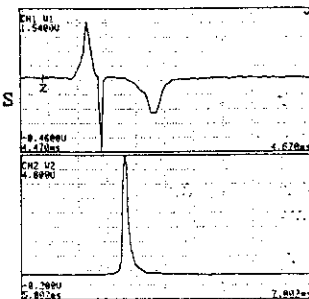
Speed= 0.93km/s

 $\Delta V = 7.8 \text{ V}$ Pellet No.3

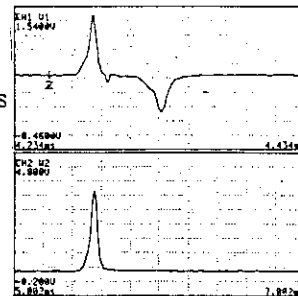
Speed= 0.95km/s

 $\Delta V = 7.3 \text{ V}$ Pellet No.4

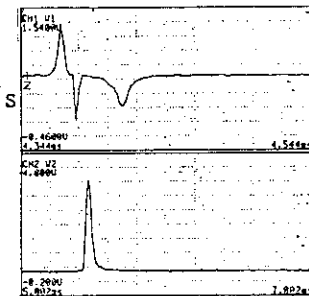
Speed= 0.87km/s

 $\Delta V = 8.4 \text{ V}$ Pellet No.5

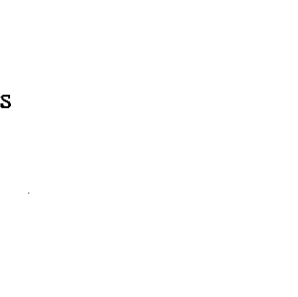
Speed= 0.83km/s

 $\Delta V = 5.7 \text{ V}$ Pellet No.6

Speed= 0.95km/s

 $\Delta V = 6.3 \text{ V}$ Pellet No.7

Speed= km/s

 $\Delta V = \text{V}$ Pellet No.8

Speed= 0.74km/s

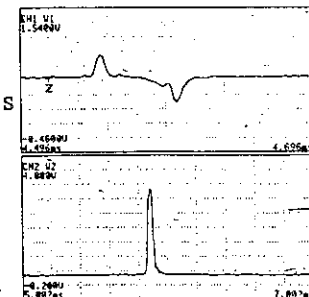
 $\Delta V = 6.0 \text{ V}$ 

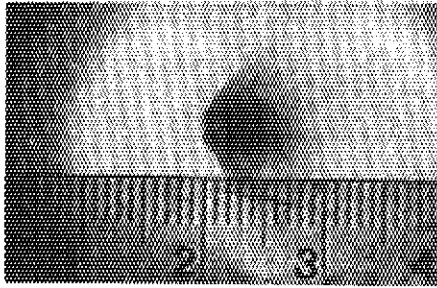
Fig. 21 Time evolutions of the output signals of the photo-diode and the micro-wave cavity (No.3) under the same condition as that in Fig. 20. The propellant gas pressure is 1.7 MPa.

Hydrogen Pellets (1991/ 2/26/#24)

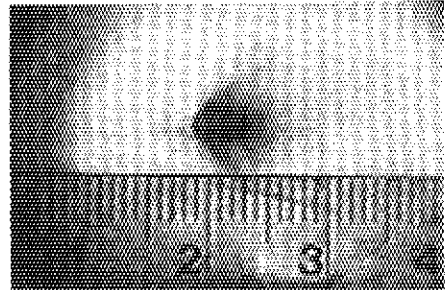
Repeat Time = 200 ms (10 pellets)
 Piston Speed = 15 mm/s
 Material of Pellet = H₂

Pellet No.1

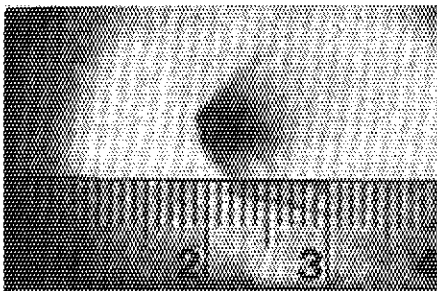
Speed= 1.05
 km/s
 $\Delta V = 8.2$ V

Pellet No.2

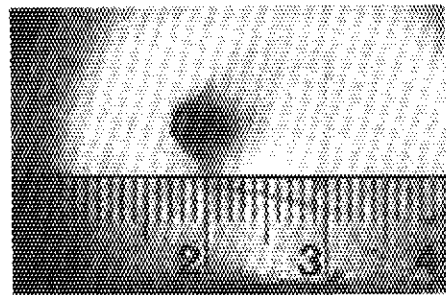
Speed= 0.93
 km/s
 $\Delta V = 7.8$ V

Pellet No.3

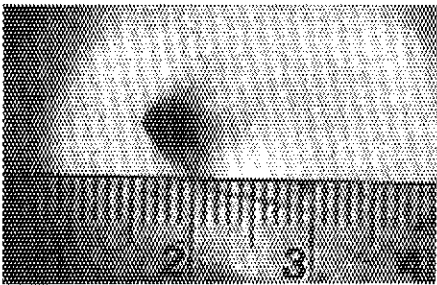
Speed= 0.95
 km/s
 $\Delta V = 7.3$ V

Pellet No.4

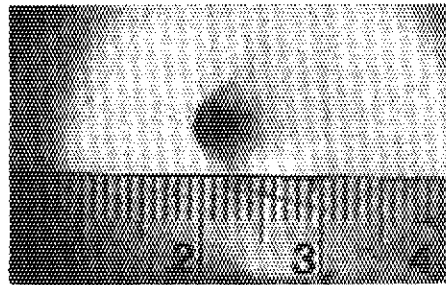
Speed= 0.87
 km/s
 $\Delta V = 8.4$ V

Pellet No.5

Speed= 0.83
 km/s
 $\Delta V = 5.7$ V

Pellet No.6

Speed= 0.95
 km/s
 $\Delta V = 6.3$ V

Pellet No.7

Speed=
 km/s
 $\Delta V =$ V

Pellet No.8

Speed= 0.74
 km/s
 $\Delta V = 6.0$ V

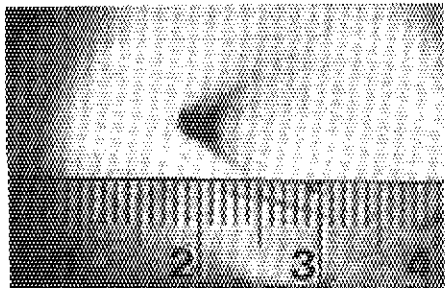


Fig. 22 Shadowgraphs of the hydrogen pellets under the same condition as that in Fig. 20, which are obtained near the gun barrel.

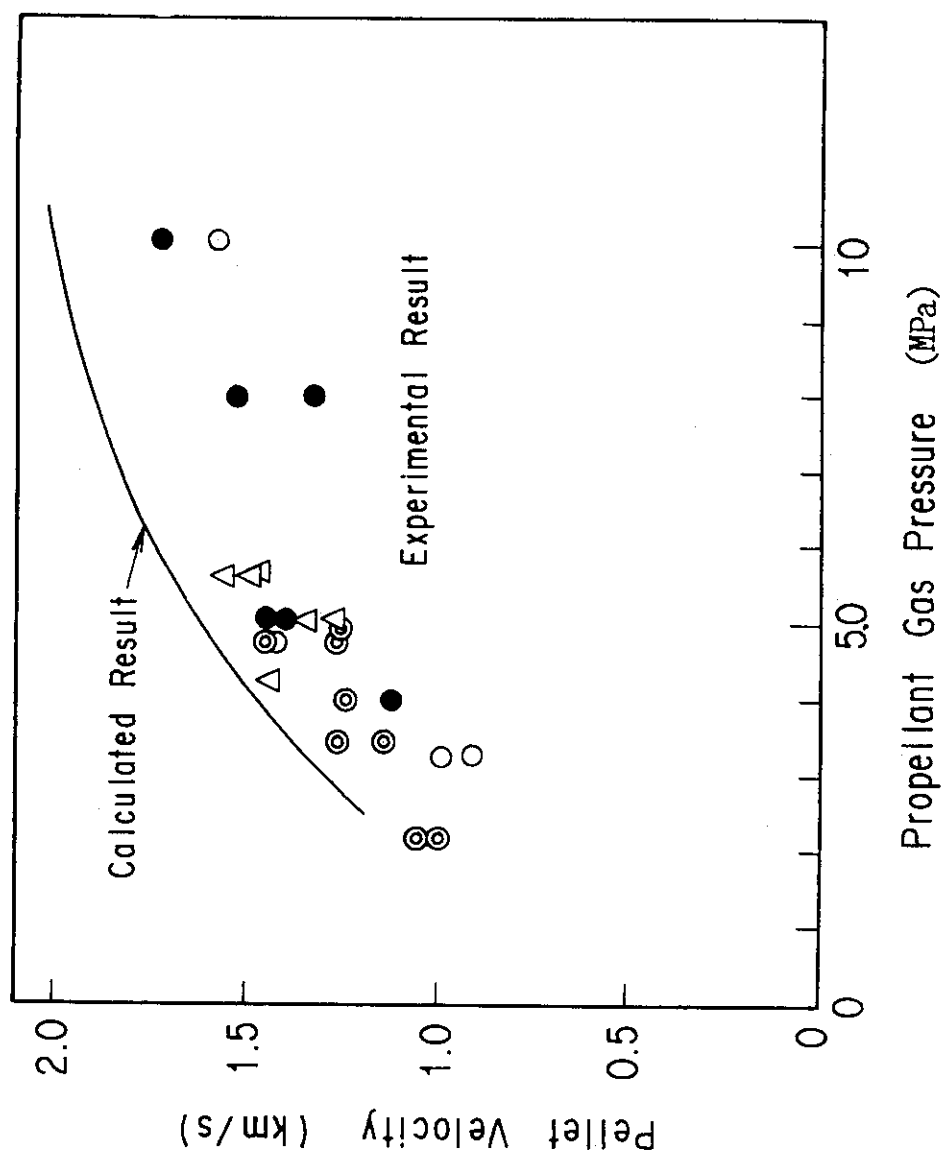


Fig. 23 Pellet velocity versus propellant-gas pressure under the repeating injection rate of 2-3.3 Hz (●, ⊙, △) for large pellets, and under the single-pellet injection (●, ○) for small pellets.