CONF-821111--26

CONF-821111--26

DE84 004690

SOLID DEUTERIUM CENTRIFUGE PELLET INJECTOR*

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ABSTRACT

Pellet injectors are needed to fuel long pulse tokamak plasmas and other magnetic confinement devices. For this purpose, an apparatus has been developed that forms 1.3-mm-diam pellets of frozen deuterium at a rate of 40 pellets per second and accelerates them to a speed of 1 km/s. Pellets are formed by extruding a billet of solidified deuterium through a 1.3-mm-diam nozzle at a speed of 5 cm/s. The extruding deuterium is chopped with a razor knife, forming 1.3-mm right circular cylinders of solid deuterium. The pellets are accelerated by synchronously injecting them into a high speed rotating arbor containing a guide track, which carries them from a point near the center of rotation to the periphery. The pellets leave the wheel after 150° of rotation at double the tip speed. The centrifuge is formed in the shape of a centrifugal catenary and is constructed of high strength KEVLAR/epoxy composite. This arbor has been spin-tested to a tip speed of 1 km/s.

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*Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under contract W-7405-eng-26 with the Union Carbide Corporation.

I. INTRODUCTION

Pellet injection systems[1] to fuel present and future tokamak-type plasma machines are being developed. Past experiments[2-5] that injected single pellets into the Oak Ridge Tokamak (ORMAK) and the Impurity Study Experiment (ISX) and the ablation theory developed from these experiments[6-8] indicate that tokamak fusion reactors[9] could be continuously fueled with 4-mm-diam frozen pellets of D_2,T_2 injected at speeds of 2 km/s at a rate of 20 pellets per second.

A high speed centrifuge[10] was proposed as a potential means to repetitively accelerate frozen D_2 pellets to these speeds. A small demonstration device[1,11] built at Oak Ridge National Laboratory (ORNL) successfully produced and accelerated 0.8-mm-diam pellets to a speed of 300 m/s at a rate of 150 pellets per second. This device was used to inject a burst of four pellets into ISX-B.[12] This paper reports on an upgraded version designed to accelerate 1.4-mm-diam D_2 pellets to a speed of 2 km/s at a rate of 40 pellets per second. This equipment has been operated with pellets up to a speed of 1 km/s, and the accelerator alone has been tested to speeds which should give 2-km/s pellets.

II. THE CENTRIFUGE CONCEPT

Solid pellets of D_2, like most cryogenic materials, will "float" with very little friction when placed on a room temperature surface.

This effect, while basically transient, can last for the order of seconds before the pellets completely evaporate; the acceleration of pellets to speeds of 1 km/s over a 1-m path takes only a few milliseconds. Frozen D_2 pellets can be accelerated by injecting them into a track on a high speed rotating wheel and allowing them to spin off.

Consider a pellet constrained to move without friction along a rotating track. The pellet is stationary when entering the track at point $a(r_o,\theta_o,\phi_o)$ and leaves the track at point $b(R,\theta,\phi)$, where ϕ_o is the angle between the track entrance and the direction perpendicular to a radial line and ϕ is the angle of the track exit.

The work done on the pellet is the path integral of the Coriolis force, so that the speed of the pellet in the rotating reference frame is

$$\frac{1}{2}\,mv^2 = \frac{1}{2}\,mv_o^2 + \int_a^b m\omega^2 \sin\,\phi\;d\ell$$

$$= \frac{1}{2}\,m\omega^2 r_o^2 + \int_{r_o}^{R} m\omega^2 r\;dr = \frac{1}{2}\,m\omega^2 R^2 \qquad (1)$$

or

$$|\vec{v}| = \omega R\ . \qquad (2)$$

Vectorially adding the tip speed of the track, we obtain the reference frame exit velocity,

$$v = 2v_{tip}\cos\frac{\phi}{2}\ . \qquad (3)$$

The pellet resides on the rotating tract through an angle

$$\Delta\theta = \omega t = \omega \int_a^b \frac{d\ell}{v} = \omega \int_a^b \frac{d\ell}{\omega r} , \tag{4}$$

so that the residence angle is independent of the pellet mass and the rotating frequency of the track. Also, since the integral diverges if the track passes through the center of rotation, the track should originate far from the center. It is also advisable to make $\phi_o = 0$ so that the pellet can smoothly enter the track and to make $\phi \approx 0°$ for maximum pellet velocity.

For a tangential exit track, a simple derivation for the speed of a pellet starting from rest and interacting with a rotating object can also be made by conserving angular momentum and energy, giving

$$v_{eff} = \frac{2v_{tip}}{1 + \frac{1}{2}\frac{mR^2}{I}} , \tag{5}$$

where m is the mass of the pellet ejected at radius R on a wheel having a moment of inertia I.

To achieve high pellet velocities with this method, it is apparent that very high rotating peripheral speeds are required. The practical limit on the peripheral speeds of rotating objects is the possible fracture of the rotating member due to inertial stresses. The maximum stress built up at the center of a simple bar is

$$\sigma = \frac{1}{2} \rho R^2 \omega^2 = \frac{1}{2} \rho v_{tip}^2 \quad . \tag{6}$$

Similarly, it can be shown for any rotating object that the peak stress is proportional to the density, the square of the tip speed, and a geometrical factor.

Since the stress is proportional to the density of the rotor, strong lightweight materials are desirable. The relatively new composite materials offer great advantages since they are both lightweight and strong. The aramid fiber KEVLAR 49 produces the composites with the highest strength-to-density ratio, 1 MPa·m^3/kg, three times that of high strength titanium alloys.

Composite materials are anisotropic; that is, they have high strength only along the fiber axis. Objects that have stresses in more than one direction must be fabricated by laying the fibers in various directions at a sacrifice to the strength of the whole. Objects that have unidirectional stresses are therefore desirable for making full use of the high strength properties of the composite. A spinning bar and a hoop are two shapes having unidirectional stress. These are members of a more general classification of unidirectionally stressed shapes referred to as centrifugal catenaries. These are the shapes that a flexible string or chain with a constant mass-to-length ratio of length L would take if pinned to one place at distance a from the axis and confined to the plane of rotation. For example, the hoop is the case in which a = $L/2\pi$, and the bar is the shape for $L \gg a$. For values in between these two extremes the chain assumes a teardrop shape. If a counterweight is placed at the pin point, the chain can be balanced. This geometry has the advantage of providing a tangential track exit for the pellet.

III. DEVICE DESIGN

A. The KEVLAR Hoop Accelerator

The rotor shown in Fig. 1 was designed and fabricated in the shape of a centrifugal catenary. A computer code[13] was written to solve for the shapes and to do finite element analyses of the stresses in the design. A design with a major-to-minor radius aspect ratio of 3 was chosen. At this value the minor radius is small enough to allow a relatively low stress metal hub or arbor to support the hoop, but it still has a relatively large radius of curvature passing through the apogee to reduce the stresses on the pellet, which should be kept on the order of 0.1-0.4 MPa, the tensile strength of D_2.[14] The peak stress on the pellet in this design is 0.3 MPa at a pellet speed of 1 km/s. The equivalent acceleration path of the pellet at constant peak stress would be 12 cm.

The KEVLAR 49 hoop has a peak stress near the minor radius of 900 MPa for a peripheral speed of 1 km/s. Since KEVLAR 49/epoxy filament-wound composites have ultimate strengths over 1400 MPa, the hoop operates at 60% of ultimate, a reasonable value for long life. The finite element analysis including the KEVLAR cloth layers indicated that there would be no problems with interlaminar shear except in the region of the counterweight. To reduce this stress, the catenary shape near the counterweight was replaced with a semicircular shape that distributes the counterweight forces over a large region and was designed to maintain this shape under load.

The cross section of the hoop shown in Fig. 1 was made to form a track for the pellet. Two layers of KEVLAR 49 cloth were used to form the track, tying two hoop bands together. A hole molded through the cloth layers near the apogee terminates the track, allowing for a near-tangential exit of the pellet.

The hoop-counterweight combination spinning about its axis is in balance and retains its shape under inertial loading. However, during high speed operation the hoop will stretch because of the finite modulus of the KEVLAR. Since the design is asymmetric, this could cause the mass center to shift; to prevent this the code was used to determine the point of attachment at which the stretching fore and aft cancels. This point turned out to be conveniently near but slightly behind the perigee of the hoop.

The hoop was fabricated by the filament winding technique. A mold or mandrel was machined in the computer-generated centrifugal catenary shape by numerical milling techniques. The mold, made in several pieces, can be disassembled and removed from the cured hoop. The mold was hand-polished along the region containing the pellet track. Pins at the attachment points were placed in the mold, and a section of groove for the track exit hole was epoxied to the mold. Two layers of cloth were stretched over the mandrel, each overlapping at the counterbalance end. Low twist KEVLAR 49 thread saturated with epoxy was then wound over the cloth. The part was wound for 2 h until the proper depth of composite was achieved. Note that the pins and the track extension protrude through the cloth, and the fibers go around them during winding. The finished part was cured at room temperature for 24 h and then oven-cured for 12 h before the mold was removed. Since voids were found in the cloth, an overcoat of filled epoxy was used to smooth the track, followed by several coats of epoxy paint, until a polished finish was obtained.

The hub was machined from 7075T6 aluminum using numerical milling techniques to duplicate the hoop contours along the hoop-hub attachment region. Because the hub is only moderately stressed (the hoop applies no forces to it), it was designed using hand calculation techniques at points of suspected high stress; because it is asymmetric, the hub was made with a sacrificial surface that could be machined to achieve balance. The hub holds the hoop in position and provides the beginning of the pellet track. This section of the track is a simple semicircle, which blends into the hoop track 50 mm forward of the perigee point. The entrance of the track is tangential to the rotation and is located 115 mm from the center. The hub was balanced and spin-tested at the

ORNL Flywheel Test Center to 22,000 rpm (10% over the operating design speed) before it was mounted.

The hoop is affixed to the aluminum hub by a band of KEVLAR thread hand-wrapped around a semicircular magnesium block and is preloaded to 200 MPa by wedges placed between the block and the hoop. Pins placed under the block are used to position the hoop and block on the hub. The hub-hoop interface was filled with epoxy, which was allowed to bond only around a 6-mm region of the pins; a Teflon mold release was applied to the rest of the interface. This ensures that the hoop, which has large strains, is free to move along the interface. The counterweight is fitted by pinning and epoxy adhesive only, since the groove forming the track holds it in place. Again, mold release was used on this interface except for a region around the pins.

After the hoop was attached, the assembly was balanced by removing mass from the counterweight. The balance method found most useful was simply to roll the assembly on horizontal parallels. Sophisticated spin balance machines proved useless, since the large asymmetric hoop generated large windage forces.

The completed hoop was successfully spin-tested to its design speed of 20,000 rpm at the Flywheel Test Center. This facility uses a flexible-shaft, air turbine drive system in which the rotor revolves about its own mass center, a system that is very forgiving in balancing. At 20,000 rpm the peripheral speed of the hoop is 1 km/s. Since the track exit is tangential, pellets should be accelerated to a speed of 2 km/s.

B. The Spin Tank Drive System

Several potential drive systems were investigated to spin the hoop at an operating speed of 10,000-20,000 rpm. The flexible shaft system was rejected because it is prone to oil leakage at the oil damper shaft seal. Furthermore, since it was originally planned to use the direct pellet feed technique, in which an extruder nozzle must ride a fraction of a millimeter over the entrance of the track, rigid bearing mounts were specified. The oil-lubricated vacuum motor from a Sergeant Welch 1500-L/s turbomolecular pump and its electronic controller formed the basis of the drive system. The upper and lower bearing mounts, which are normally resiliently mounted, were replaced with solid mounts. The upper bearing, designed for 50,000-rpm operation, was replaced with a pair of heavier precision angular contact bearings rated at 25,000 rpm. The upper bearings were solidly located and the lower bearing was axially spring-loaded. To accommodate operation on a near-horizontal axis, the oil drain holes were aligned along the bottom and the oil pump and reservoir were mounted separately. The turbocontroller was slightly modified to perform better at the lower speed. First, the clock frequency was made to operate at the lower ranges by changing a capacitor, and the speed-to-torque ratio was adjusted so that the motor was at full torque at 20,000 rpm rather than 50,000 rpm. This drive has been very reliable and, under normal vacuum operation, free from oil.

The vacuum spin tank shown in Fig. 2 is fabricated from aluminum plates. Again, to accommodate the direct pellet feed option, a very rigid tank cover was required to hold the extruder close to the hub. For this reason the tank cover was made 3 in. thick, which is much thicker than would normally be required. The tank cover plate was designed with a 36-bolt pattern so that the pellet feed mechanism could be indexed to align the accelerated pellets with the exit port, which is horizontal.

The spin tank is lined with a steel ring that serves two safety purposes. First, it acts to prevent fragments from penetrating the tank in case the rotor fails; second, it is free to spin so that it reduces the potential torque loading on the tank in case of rotor failure. The ballistic penetration was determined using NASA data,[15] which indicate that a 0.125-in. steel plate would contain the counterweight, the most energetic fragment in this design. (The problems associated with containment of large metal fragments were part of the reason for choosing the lightweight composite arbor over a metal system. When composites fail they tend to disintegrate by shredding into small objects that are easily contained. Large metal wheels can contain several megajoules of stored mechanical energy and tend to fracture into three large pieces, which can create a significant containment problem.) The torque containment ring was made of 1-in.-thick stainless steel, which is a very conservative design. The frame was also made strong enough to absorb a complete rotor and torque ring lockup. Resilient nylon pads mounted under the feet act as shock absorbers to absorb this energy.

The spin tank is pumped using a Leybold-Heraeus 1000 Roots blower that has a speed of 300 L/s. This relatively large pump is required because during normal operation, pellets are fed into the system at a rate of 60 Torr•L/s. The spin tank pressure equilibrates at 0.2 Torr of evaporated D_2 during pellet feeding. At this pressure, the drag on the hoop causes only a slight current rise in the motor.

C. The Pellet Feed Mechanism

In the demonstration device, pellets were fed into the centrifuge accelerating tube by a direct feed mechanism. An extruder was placed a fraction of a millimeter over the knife-edged entrance tube that would, on each revolution, shear a pellet off a continuously extruding filament. Since the accelerator was operating at 150 Hz this required a rather rapid extrusion rate, which was difficult to achieve due to an instability that occurs at high extrusion rates. To alleviate this problem and to decouple the pellet production rate from the rotating speed of the accelerator, a system was developed that can synchronously inject a pellet into the entrance of the accelerator. Two such feed mechanisms were tested. The first was a razor knife mounted on a separate chopper wheel that was run subsynchronously to the accelerator wheel using a phase-locked loop circuit; the second was an electromagnetically operated punch mechanism. The second system proved the most versatile and is the apparatus discussed in this paper. The pellet-forming systems are based on a screw-press-driven piston extruder developed for the demonstration device. The apparatus is shown in a cross-sectional schematic in Fig. 3. The extruder forms a quasi-continuous filament of solid D_2 extruding through a 1.3-mm nozzle at a speed of 5 cm/s. Cylindrical pellets are then punched from the filament at a rate of 40/s. The extrusion is accomplished by an extruder piston (1)* made from PPS plastic filled with graphite and Teflon fibers, which forces a billet of solid deuterium from a brass cylinder (2) through the nozzle (3). The piston, sealed by bellows (4), is connected to the screw press with a 0.5-in.-OD, 0.465-in.-ID stainless steel tube (16), driven at a constant speed by a screw press (5) powered by a 0.25-hp, 0- to 42-rpm gear motor (6). To produce solid D_2, deuterium gas from a 10-ft^3 storage cylinder (45) is reduced to 25 psig by a regulator (46) and metered by a valve (47) before passing through a tube (7) into a heat exchanger (8) held at 19 K where the gas is liquefied. A 50-psig relief valve (25) protects the system from thermal pressure excursions. The liquid D_2 feeds into the cylinder (2) through ports (9) in the top of the cylinder, which are open when the piston is fully retracted. The billet of D_2 freezes and cools to 14.6 K, the temperature of the second heat exchanger (10). The extrudate flows through the third heat exchanger (11), which is held at 14.6 K, and reaches its final diameter passing

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*Numbers in parentheses refer to the schematic in Fig. 3.

through the nozzle (3). The extruding filament (33) is guided through a tube (12) to the razor-knife hammer punch (13) driven by a solenoid (14). Two razors attached to the punch simultaneously cut both the front and rear of the pellet and eject the pellet (57) at 3 m/s into the entrance of the accelerator track. The unused D_2 filament continues through the tube (15) where it evaporates and is pumped by a rotary pump. The three heat exchangers (8,10,11) are cooled by liquid helium metered through valves (20-22) fed with liquid helium from the phase separator (23), which is supplied from a pressurized 100-L storage dewar (24) through a flexible transfer line (34). The helium dewar is pressurized to 1250 Torr by the gas from the storage cylinder (26) through a pressure regulator (27) The exhaust gas from the phase separator (23) is metered by a needle valve (28) and can be shut off by a solenoid valve (29). The exhausts of the three heat exchangers can similarly be shut off by solenoid valves (30-32) that vent into the atmosphere. The three heat exchangers are temperature regulated using Lake Shore Cryotronics temperature controllers with silicon diode thermometers (36-38) screwed to the heat exchangers and 60-Ω Nichrome heater wires (39-41) epoxied to the heat exchangers. The helium flow through each heat exchanger can be set using servomotors that remotely control the needle valves (20-22). To thermally insulate the heat exchangers, they are wrapped with Mylar superinsulation and are housed in a gold-plated high vacuum jacket (48) pumped by a diffusion pump. The high vacuum jacket is sealed on the cold end by a bellows assembly (50). The exhaust gas from the phase separator and the heat exchangers is used to intercept heat flowing into the heat exchangers (at points 51, 52, 53, and 54). The heat exchanger (11) is mechanically mounted to the vacuum jacket (48) by a spider mechanism (55). A high pressure electroformed bellows (56) connects heat exchangers (10,11) and takes up the thermal contraction of the upper heat exchanger assembly, allowing the nozzle to remain fixed in location. The nozzle, made of aluminum, tapers at 20°, reducing the D_2 extrudate from 4.5 mm to its final value of 1.3 mm. The nozzle screws into the copper heat exchanger and can be replaced if different-sized pellets are desired.

IV. OPERATION AND STARTUP

A typical run begins with a complete evacuation of the D_2 gas lines using the rotary pump (35) and a helium gas purge through the helium lines. The transfer tube is inserted and the helium dewar is pressurized to 1250 torr. The solenoid valves (29-32) are open and the metering valves (20-22) are adjusted for even cooldown of the three heat exchangers. Approximately 1 h is required to reach operating temperatures. The deuterium gas is introduced by opening the metering valve (47) while the temperatures of the three heat exchangers are 19, <9, and <9 K. The gas flow rate is reduced if the latter temperatures rise. In this manner the bottom heat exchangers become filled with D_2 frost, which prevents D_2 liquid from flowing through the nozzle (3) into the spin tank. After several minutes the system fills with D_2 and the pressure of the D_2 above the first heat exchanger (8) rises to 2000 Torr, as monitored by a Bourdon vacuum gage (63). The temperatures of the heat exchangers (8,10,11) are increased to 19, 14.6, and 14.6 K by adjusting metering valves (20,21,22) so that 7 W of feedback power is required to regulate the temperature. The screw press gear motor (6) is turned on, initiating the extrusion, which continues for ∿2 min, depending on the extrusion rate chosen. At the bottom of the screw press stroke, a limit switch shuts off the motor, which is then reversed. As the piston approaches the top of the cylinder it passes the liquid inlet ports, allowing liquid D_2 from the first heat exchanger (8) to fill the cylinder bore. The solid D_2 that remains in the bottom heat exchangers (10,11) prevents the liquid from entering the spin tank. After allowing several seconds for the fresh D_2 billet to freeze in the cylinder, the extrusion process is resumed by turning on the screw press. The first two batches of D_2 are extruded at a slower rate while monitoring the force applied to the piston, apparently because the solid D_2 formed directly from the gas phase as frost is stronger than the solid formed by freezing the liquid. After this, the extruder can recycle continuously until the liquid helium from the storage dewar runs out, which is ∿7 h of operation for a 100-L dewar.

The force applied to the piston is monitored by a force washer (17). The extrusion pressure is dependent on both the extrusion rate and the temperature and geometry of the nozzle. A typical pressure is 30 MPa at 14.6 K. The extrusion rate is limited at a given temperature by an instability in the flow, characterized by a sudden dumping of solid D_2. As the extrusion rate increases, the work done on the solid becomes enough to start melting the solid, thereby lowering the impedance of the nozzle, which further raises the extrusion rate. Thus, the D_2 dumps out at a high rate until the strain energy in the billet is relieved. The extrusion then ceases while the mechanical press recompresses the billet, at which point the extrusion begins again. This instability occurs at 13 K for a 5-cm/s extrusion rate through a 1.3-mm-diam nozzle at a pressure of 50 MPa.

V. PELLET DIAGNOSTICS

Direct observation of the extruding filament and the pellets being formed is possible. Viewing the punch mechanism with synchronously triggered strobe lamps makes the pellets, punch, and entrance aperture of the accelerating track appear stationary. The strobe and punch are triggered by time-delayed trigger pulses generated from a LED phototransistor pickup viewing a mirror surface on the accelerator. A standard black-and-white television camera, a video monitor, and a stop-action video tape recorder are used to remotely observe the operation and allow frame-by-frame viewing of individual pellets. Figure 4 shows a D_2 pellet being launched into the entrance of the accelerator from the punch.

In order to detect the accelerated pellets, it has been found useful to detect their impact on a plate using a shock transducer. To experimentally determine the residence angle of the pellets in the accelerator, a metal band equipped with a shock transducer (shown in Fig. 2) was placed around the periphery of the spin tank. By knowing the position of the accelerator when the pellets hit the band, the pellet residence angle was determined to be 150° ± 4° during initial tests. This compares exactly with the calculated angle, assuming no friction. Oscillographs of the pellets hitting the metal band and of the encoder signals are shown in Fig. 5. Once the pellet residence angle was experimentally determined, the tank cover was rotated so that the pellets would exit into the exhaust port of the tank, where they are detected in-flight by the shadow they make passing between a lamp and a PIN diode photodetector. Pellets entering the accelerator track are photographed, as shown in Fig. 4, using a strobe light and television camera.

A guide tube[16,17] will be used to transport the pellets from the spin tank to the tokamak. By allowing the pellets to skip through a polished tube, a much smaller injection line can be used and the pellet injector can be located a greater distance from the tokamak. This also allows for a convenient vacuum isolation between the spin tank, which operates at 0.2 Torr, and the high vacuum tokamak.

VI. CONCLUSIONS

A high speed centrifuge D_2 pellet injector has been tested to a pellet speed of 1 km/s. At this speed, the interaction between the pellets and the centrifuge can be described with frictionless Newtonian mechanics. The pellets reside in the track through a rotation of 150° ± 4° of the accelerator. Future tests of this apparatus will focus first on 1-km/s operation for potential tokamak experiments and then on demonstration of 2-km/s operation.

ACKNOWLEDGMENTS

I would like to thank the following persons for their support and help: my colleague Stan Milora, the finite element analyst Charles Knight, mechanical engineer Ted Sanderson, and machinists-mechanics Glenn Monger and Lynn Rutherford.

This research was sponsored by the Office of Fusion Energy, U.S. Department of Energy, under contract W-7405-eng-26 with the Union Carbide Corporation.

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FIGURE CAPTIONS

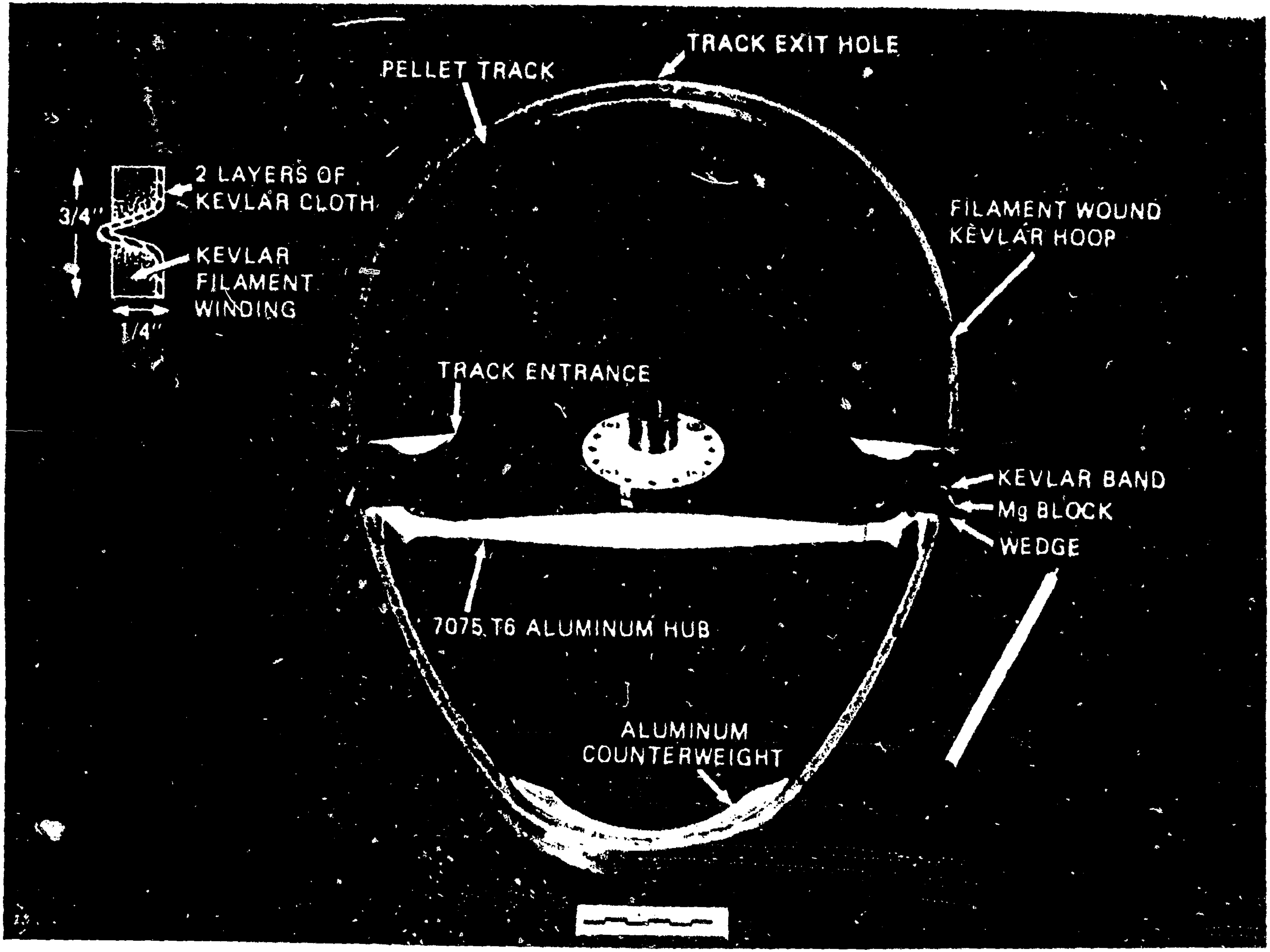
Fig. 1. The KEVLAR hoop accelerator.

Fig. 2. The vacuum spin tank.

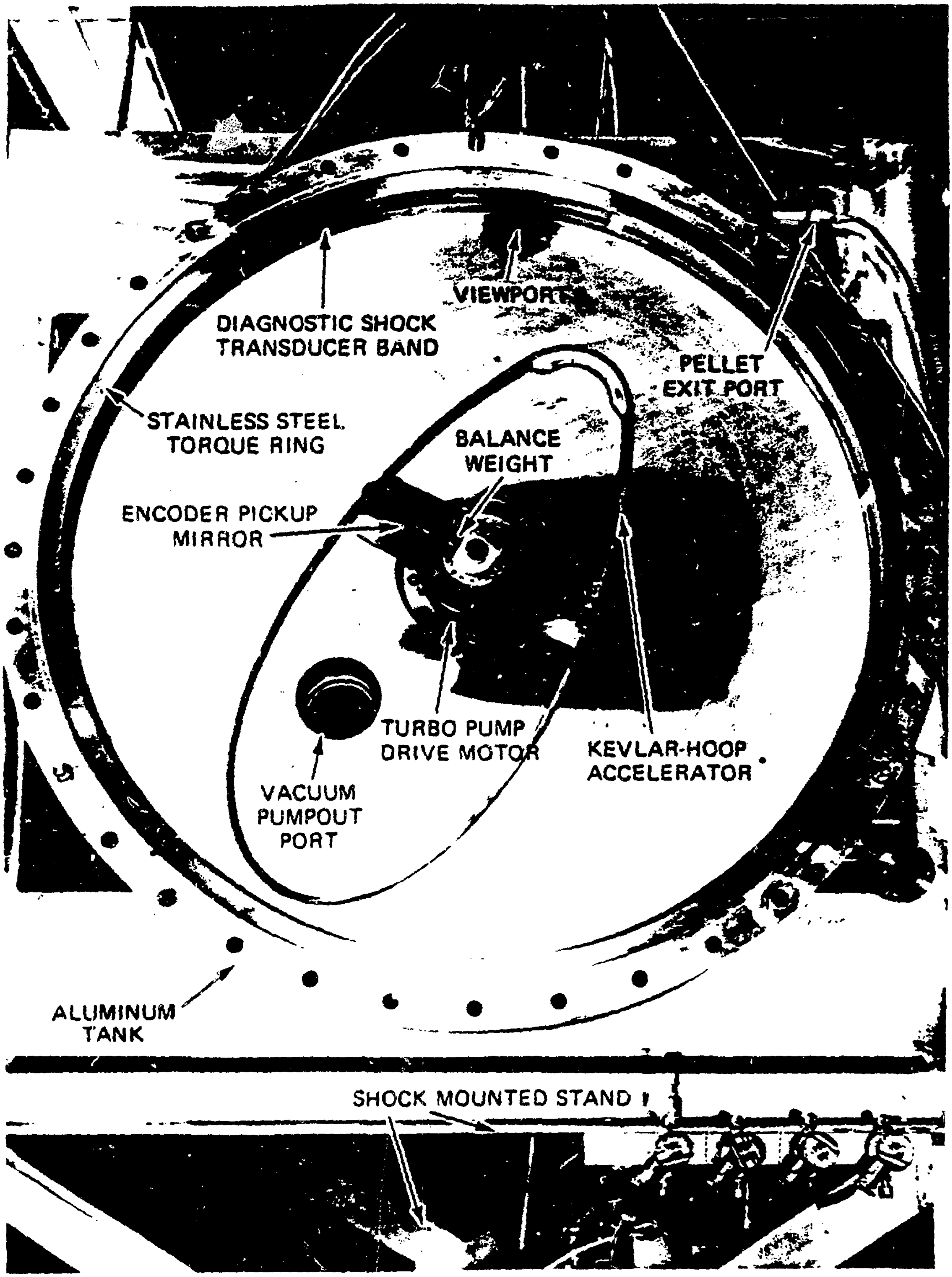
Fig. 3. Schematic of the pellet feed mechanism. (1) Extruder piston. (2) Brass cylinder. (3) 1.3-mm-diam nozzle. (4) Bellows. (5) Screw press. (6) Motor. (7) Deuterium gas inlet tube. (8) First heat exchanger. (9) Deuterium gas inlet ports. (10) Second heat exchanger. (11) Third heat exchanger. (12) Filament guide tube. (13) Razor-knife hammer punch. (14) Solenoid. (15) Filament removal tube. (16) Stainless steel tube. (17) Force washer. (20)-(22) Needle valves. (23) Phase separator. (24) Helium storage dewar. (25) Relief valve. (26) Helium storage cylinder. (27) Pressure regulator. (28) Needle valve. (29) Solenoid shutoff valve for exhaust gas from (23). (30)-(32) Solenoid shutoff valves for exhaust gas from heat exchangers. (33) Extruded filament. (34) Flexible transfer line. (35) Rotary pump. (36)-(38) Silicon diode thermometers. (39)-(41) Nichrome heater wires. (45) Deuterium storage cylinder. (46) Regulator. (47) Deuterium metering valve. (48) Vacuum jacket. (50) Bellows assembly. (51)-(54) Points where exhaust gas intercepts heat. (55) Spider mechanism. (56) Electroformed bellows. (57) Pellet. (63) Bourdon vacuum gage.

Fig. 4. A 1.3-mm D_2 pellet being launched into the accelerator from the punch.

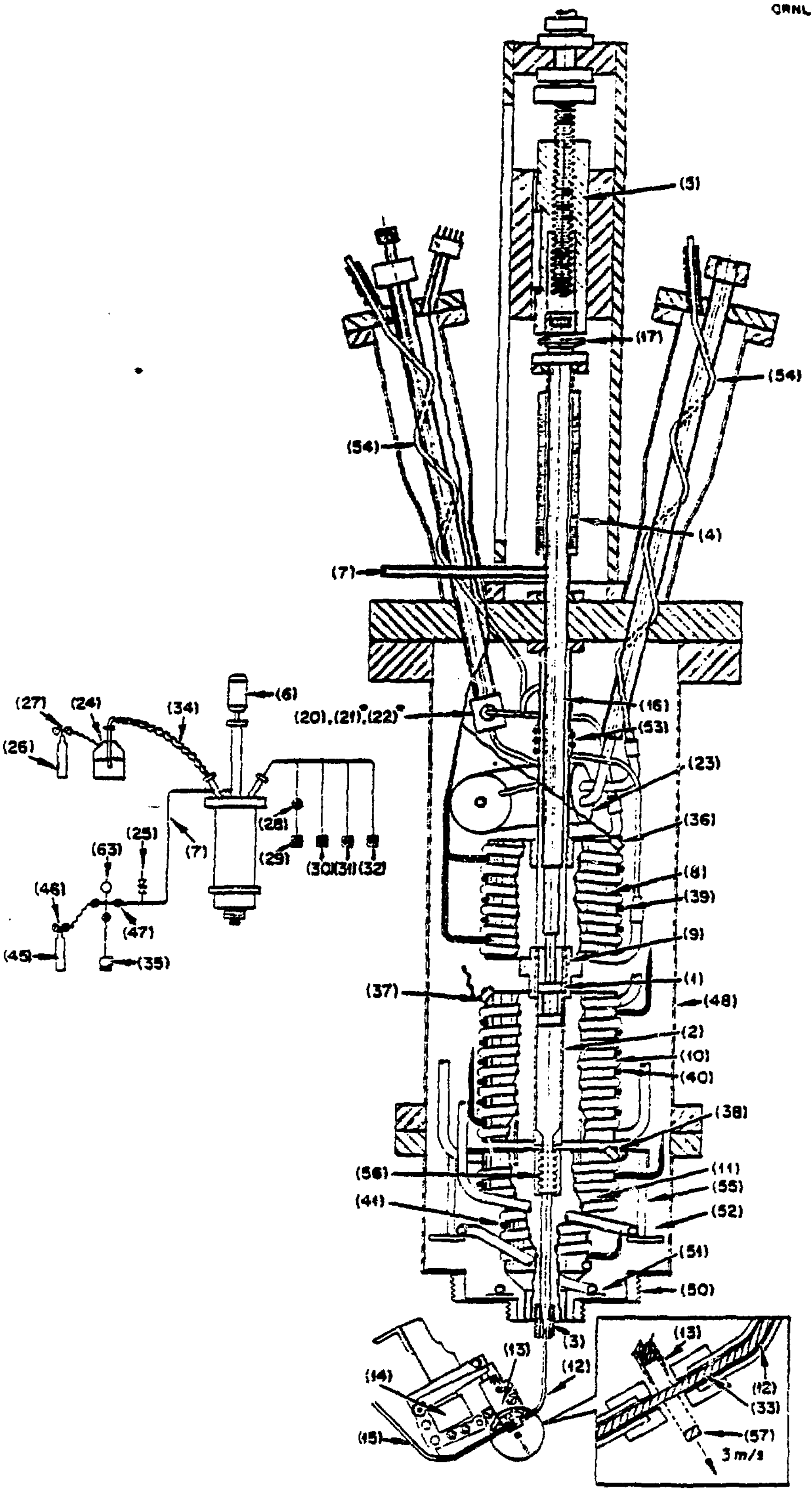
Fig. 5. Oscillographs of pellets hitting the diagnostic shock transducer band and the resulting encoder signals.



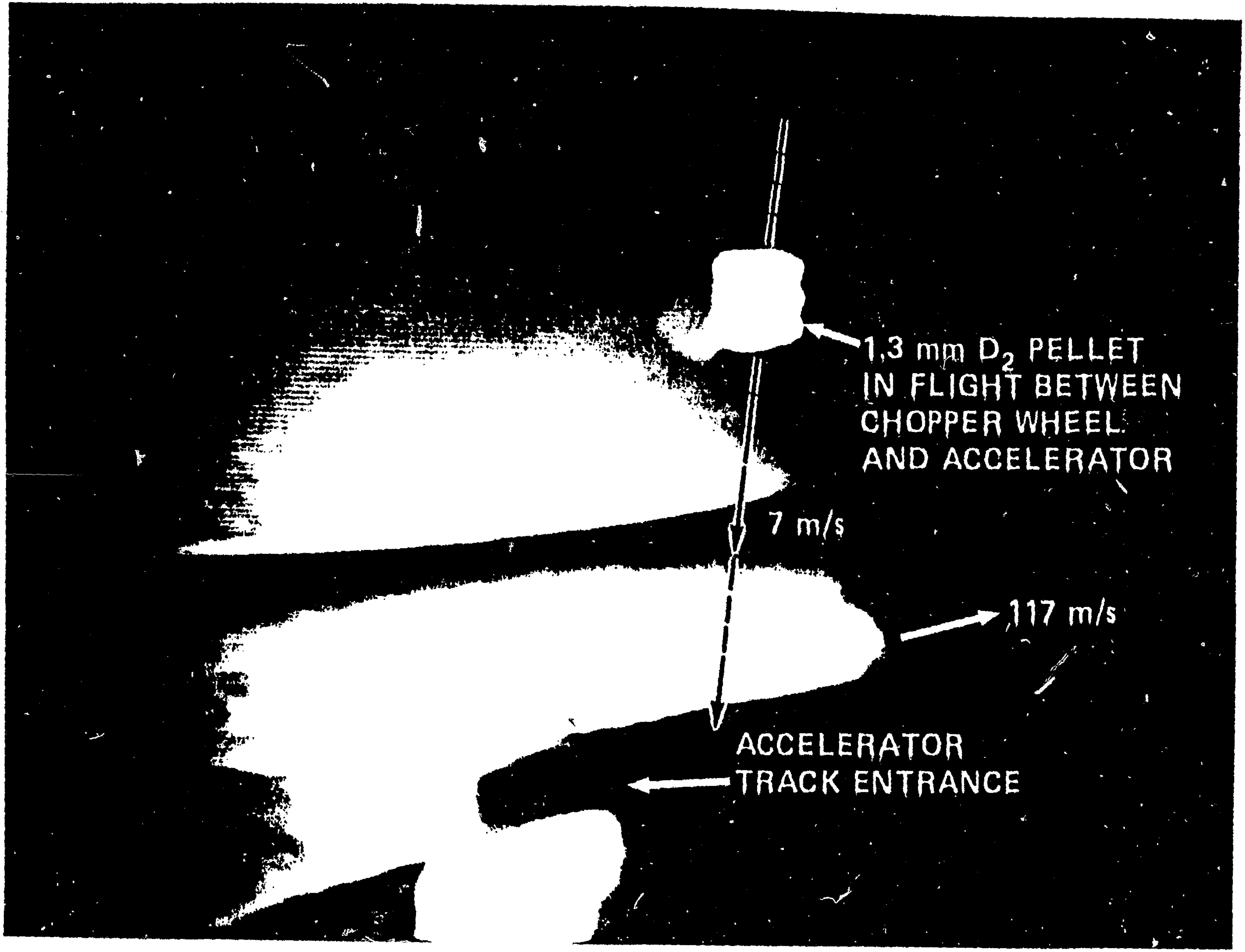
TRACK EXIT HOLE
PELLET TRACK
2 LAYERS OF KEVLAR CLOTH
3/4"
KEVLAR FILAMENT WINDING
1/4"
FILAMENT WOUND KEVLAR HOOP
TRACK ENTRANCE
KEVLAR BAND
Mg BLOCK
WEDGE
7075 T6 ALUMINUM HUB
ALUMINUM COUNTERWEIGHT


VIEWPORT
DIAGNOSTIC SHOCK TRANSDUCER BAND
PELLET EXIT PORT
STAINLESS STEEL TORQUE RING
BALANCE WEIGHT
ENCODER PICKUP MIRROR
TURBO PUMP DRIVE MOTOR
KEVLAR-HOOP ACCELERATOR
VACUUM PUMPOUT PORT
ALUMINUM TANK
SHOCK MOUNTED STAND

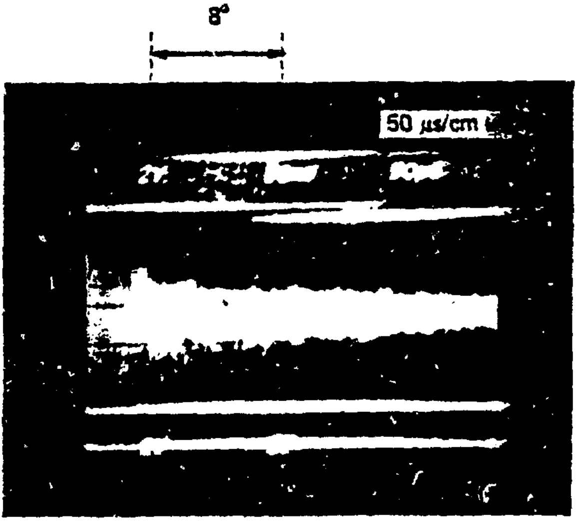
ORNL-DWG 82-5232 FED



* (21), (22) NOT SHOWN FOR CLARITY


1,3 mm D_2 PELLET
IN FLIGHT BETWEEN
CHOPPER WHEEL
AND ACCELERATOR
7 m/s
117 m/s
ACCELERATOR
TRACK ENTRANCE

ORNL-PHOTO 3803-82 FED



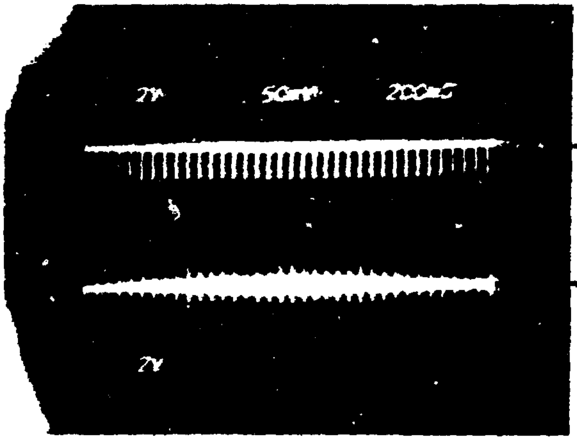
ACCELERATOR
ENCODER
SIGNAL

SHOCK TRANSDUCER
SIGNAL (TRIGGERS SCOPE)
~ 20 TRACES

150°
PELLET RESIDENCE
IN THE ACCELERATOR
9600 RPM
6.25 ms/rev

(a) ↑ FAST SWEEP
(MULTIPLE TRACE)

(b) ↓ SLOW SWEEP
(SINGLE TRACE)



FREQUENCY DIVIDED
ACCELERATOR ENCODER
SIGNAL
160 Hz/9

PELLET-SHOCK
TRANSDUCER

2 SECOND TRACE
36 PELLETS