PELLET INJECTOR RESEARCH AND DEVELOPMENT AT ORNL*

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Oak Ridge National Laboratory (ORNL) has been developing pellet injectors for plasma fueling experiments on magnetic confinement devices for over fifteen years. Recently, ORNL has provided a tritium-compatible four-shot pneumatic injector for the Tokamak Fusion Test Reactor (TFTR); this injector, which is based on the *in situ* condensation technique for pellet formation, features three conventional single-stage gas guns and an advanced two-stage light gas gun driver. In addition, the international collaboration with the Commissariat à l'Energie Atomique (CEA), in which ORNL supplied a centrifuge pellet injector to the Tore Supra tokamak in 1989, continues with an objective of improving injector performance, including extending operation to longer pulse durations (from 100 to up to 400 pellets). In a new application, the three-barrel repeating pneumatic injector that operated on the Joint European Torus from 1987 to 1992 has been returned to ORNL and is being readied for installation on DIII-D; this device consists of three independent, machine-gun–like mechanisms (each can accommodate a different pellet size). In addition to these applications, ORNL is developing advanced technologies, including high-velocity pellet injectors, tritium injectors, and long-pulse pellet feed systems. Two acceleration techniques for achieving higher velocities under experimental investigation at ORNL are the two-stage light gas gun and the electron-beam–driven rocket; the objective of these studies is the development of reliable systems capable of providing pellets with higher speeds (2-10 km/s) than that available with conventional pneumatic or mechanical injectors. The tritium proof-of-principle (TPOP) experiment which operated in the period 1988-1989 demonstrated the basic scientific feasibility of the production and pneumatic acceleration of tritium pellets; these

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experiments also provided information on tritium properties. A new tritium-compatible, extruder-based repeating pneumatic injector (8-mm-diam) is being designed to replace the pipe gun in the TPOP experiment, and operation of this gun will explore issues related to the extrudability of tritium and acceleration of extruded pellets. The tritium experiments and development of long-pulse pellet feed systems are especially relevant to the International Tokamak Engineering Reactor (ITER). Recent research and development activities at ORNL are summarized in this paper.

1. INTRODUCTION

A variety of pellet injector designs have been developed at ORNL (REFS 1-3), including single-shot guns that inject one pellet, multiple-shot guns that inject four and eight pellets, machine gun-types (single- and multiple-barrel) that can inject up to >100 pellets, and centrifugal accelerators (mechanical devices that are inherently capable of high repetition rates and long-pulse operation). With these devices, macroscopic pellets (1-6 mm in diameter) composed of hydrogen isotopes are typically accelerated to speeds of ~1.0 to 2.0 km/s for injection into plasmas of experimental fusion devices. In the past few years, steady progress has been made at ORNL in the development and application of pellet injectors for fueling present-day and future fusion devices. In this paper , we briefly describe some research and development activities at ORNL, including: (1) two recent applications and a new one on large experimental fusion devices, (2) high-velocity pellet injector development, and (3) tritium injector research. A collaboration between ORNL and ENEA-Frascati in the development of a repeating two-stage light gas gun based on an extrusion-type pellet feed system is described by Frattolillo et al. in the paper "High-Speed Repetitive Pellet Injector Prototype for Magnetic Confinement Fusion Research."

2. DEVELOPMENT APPLICATIONS

TFTR Tritium-Compatible Four-Shot Pellet Injector

The original TFTR eight-shot pneumatic pellet injector (ref. 4) that operated on the tokamak from 1986 to 1991 was modified to provide a tritium-compatible, four-shot pipe-gun configuration with three single-stage guns and a two-stage light gas gun driver (Fig. 1). The pipe-gun (*in situ* condensation) design is ideal for tritium service because there are no moving parts inside the gun and because less tritium is required in the pellet production process. The upgraded injector (refs. 5-7) is equipped with 1-m-long gun barrels, two with a 3.4 mm ID and two with a 4.0 mm ID. The injector has gaseous-helium-cooled cryostats that provide cooling for pellet formation and, for DT pellets, cooling for cryogenic He^3 separation. The barrel assemblies are located symmetrically around the gun cryostat. Three of the barrel assemblies are coupled to ORNL-designed fast propellant valves (single-stage drivers). The remaining barrel assembly (4 mm) is connected to the two-stage driver. The advanced acceleration system provides the high-pressure, high-temperature driver gas required to accelerate pellets to the 2.5- to 3-km/s range. It is based on development of two-stage light gas guns at ORNL [refs. 8,9] and in Europe [refs. 10,11]. In the two-stage driver, moderate-pressure (20- to 60-bar) helium propellant gas initially in a 0.64-L first-stage reservoir accelerates a 25.4-mm-OD Vespel® or titanium piston (25-50 g) in a 0.9-m-long, thick-walled 4130 carbon steel pump tube. The reservoir is connected to the pump tube by a 1.9-cm-diam orifice, pneumatically actuated fast valve. The pump tube is visible in Fig. 1, which also shows the guard vacuum chamber interface. A bellows isolates the two-stage driver and the guard vacuum chamber. The high-pressure end of the pump tube is enclosed in a 4340 carbon steel head assembly. The accelerating piston compresses low-pressure, (initially 1- to 2-bar) room-temperature hydrogen propellant gas that becomes the driving gas for the cryogenic pellet.

In testing at ORNL with deuterium, the single-stage guns operated reliably at pellet speeds of up to 1.5-1.7 km/s, and the two-stage gun was qualified with intact pellets at speeds of up to 2.8 km/s. The size of individual pellets can be varied using techniques demonstrated in the TPOP experiment to freeze different amounts of ice. The nominal pellet aspect ratio (length/diameter) is 1.25, but pellets can be formed with aspect ratios in the range 1.0 to ≥1.5. The injector was recently installed on TFTR (Fig. 2) and used in some limited plasma fueling experiments, including the injection of 4-mm deuterium pellets at 2.2 km/s with the two-stage gun. This high-speed gun was designed for optimal performance with tritium, and speeds of up to 3 km/s or greater have been projected with the heavier and stronger material. However, phase II of the original experimental plan has been delayed; it called for the injector to be retrofitted with a D-T fuel manifold and secondary tritium containment systems and integrated into TFTR tritium processing systems to provide full tritium pellet capability. The present plan includes deuterium injection experiments in support of TFTR D-T experiments.

Tore Supra Centrifuge Injector

The centrifuge injector illustrated in Fig. 3 was developed at ORNL and has been operating on Tore Supra since 1989 (ref. 12). With the present configuration, the centrifuge has the capability of injecting up to 100 pellets into a single plasma discharge. Up to 10 pellets per second can be injected at speeds from 500 to 800 m/s, with sizes ranging from 3 to 10 torr•L per pellet [(2–7) × 10^{20} atoms per pellet]. The accelerator consists of a carbon fiber/epoxy filament-wound rotor attached to an aluminum hub. The 1.5 m diam rotor is a centrifugal catenary and spins continuously at a frequency of 60 to 90 Hz; pellets are captured by the rotor near the axis, accelerated to the periphery in a track, and ejected tangent to the rotor at twice the peripheral speed. The pellets leave the rotor at the same angular position and enter a guide tube that transports the pellets to the tokamak. A differential pumping system in the injection line effectively removes any gas formed during the pellet acceleration. Pellets are formed and injected into the centrifuge with the Zamboni-like pellet fabricator . Deuterium gas is first frozen onto the periphery of a rotating copper disk cooled with liquid helium. As the deuterium ice builds up on the disk, it is shaved into a triangular cross section. The process of forming a deuterium ice rim takes approximately 15 min. Once the ice rim is formed, up to 100 pellets can be cut from the rim at a rate approaching 10 pellets per second with a triangular punch that forms pellets in the shape of rounded tetrahedrons (similar to a taco). By varying the depth of the cut, pellets of different sizes can be formed. The punching and delivery of the pellets to the rotor are precisely controlled so that the pellets arrive at the rotor pickup point as it passes by.

The current experimental program that is under way combines repetitive pellet fueling with an ergodic divertor and pump limiters to establish and study long-pulse plasmas in which the pellet fuel source is in balance with the particle exhaust. With lower hybrid current drive, pulse lengths of up to 2 min might be achieved on Tore Supra. To accommodate these extended pulse lengths, Foster et al. (ref. 12) are developing an upgraded pellet fabrication apparatus (Fig. 4) capable of providing up to 400 pellets in a continuous pulse. In addition, the new feed system should improve the reliability of delivery of pellets to the plasma. In the new arrangement, the existing torque motor punch will be replaced with a four-axis brushless DC servo system. One axis is dedicated to cutting the pellets from an ice rim, and a separate axis is used for delivering the pellets into the rotor. To increase the number of pellets from 100 to 400, the single rim of ice in the original design will be replaced by a stack of four rims. The planned fueling experiments will provide an experimental basis that should be useful for determining refueling scenarios for ITER and for future steady-state fusion devices.

A similar system extended to steady-state pellet fabrication technology and designed for a radiation and tritium environment is a candidate for a fueling system for ITER. A centrifuge fueling system would have the capability of taking the D-T exhaust directly from the cryopumping systems, recondensing and purifying the fuel, and injecting the reconstituted pellets into the plasma, thereby minimizing the overall tritium inventory.

Three-Barrel Repeating Pneumatic Injector for DIII-D

The injector shown in Fig. 5 is a three-barrel, machine-gun-like device developed at ORNL and operated reliably on JET (refs. 13-16) from 1987 to 1992; it was used to inject ~3000 pellets into JET plasmas for fueling experiments. Three separate cryogenic extruders are used; each provides a continuous stream of frozen hydrogen isotope to its associated gun section, where individual pellets are repetitively formed, chambered, and accelerated. For the JET application, the device was equipped with gun barrel diameters of 2.7, 4.0, and 6.0 mm (nominally 9×10^{20}, 3×10^{21}, and 1×10^{22} atoms per pellet) and capable of repetitive operation (5, 2.5, and 1 Hz, respectively, for each pellet size) under quasi-steady-state conditions (>10 s). The injector has been returned to ORNL and is being readied for installation on DIII-D. Some of the individual gun hardware will be changed out to provide optimal pellet sizes; in the present scheme the 6-mm gun will be replaced by one with a 1.8 mm gun barrel and corresponding mechanisms. Since JET did not use a conventional delivery system with guide tubes and differential pumping, the injector will be equipped with such a system, including the pellet diagnostics required for measuring pellet parameters. The proposed installation on DIII-D is shown in Fig. 6.

3. HIGH-SPEED PELLET INJECTOR DEVELOPMENT

Two-stage light gas gun

Several small (4- and 6-mm-diam projectiles) two-stage guns have been constructed and tested in the laboratory (refs. 8-9, 17), and significant progress has been reported, including (i) pellet velocities approaching 3 km/s with deuterium pellets and over 5 km/s with plastic pellets and (ii) the demonstration of repetitive operation with surrogate plastic pellets at 1 Hz and 3 km/s. A two-stage driver/pipe gun configuration based on this technology was recently installed on the TFTR and is described in Sect. 2. A schematic of the ORNL repetitive two-stage light gas gun and key subsystems is shown in Fig. 7. The device comprises several components (and features) that must interact precisely to accomplish repetitive operation. The repetitive device consists of most of the standard components for two-stage light gas guns; in addition, special components were developed for repetitive operation, including a fast valve, mechanisms for automatic pellet loading, and a pneumatic clamping device for sealing the pump tube/gun barrel interface. Necessary techniques for rapid filling and evacuation of gases and control of pressure levels were also developed. The typical piston was ≈40 mm long (with a 45° taper on the front) and weighed 25–30 g; it was constructed of polyimide with 15% graphite filler by weight (supplied as Vespel® by E. I. du Pont de Nemours & Co., Inc.). Typically, a piston survived for up to hundreds of shots without excessive wear/damage or significant effects on gun performance.

Small plastic projectiles (4-mm nominal size) and helium gas have been used in the prototype device to demonstrate repetitive operation (up to 1 Hz) at relatively high pellet velocities (up to 3 km/s). Experimental data fot two 10-pellet test sequences with device operating at 1 Hz are listed in Table I. The equipment and experiments have been described thoroughly elsewhere (ref. 16). The highest experimental velocity is twice that available from conventional repeating single-stage pneumatic injectors that accelerate frozen pellets of hydrogen isotopes. Pellets composed of light hydrogen ice can quite easily be accelerated to 3 km/s (refs. 8-11); however, protective shells (or sabots) may be required to protect the relatively weak ice from high acceleration forces and temperatures in order to reliably achieve velocities approaching 5 km/s. Possible sabot/pellet configurations are being evaluated at ORNL in room temperature experiments with a larger two-stage gun equipped with a nominal 6-mm-diam rifled gun barrel bore.

The pellet test repetition rate of 1 Hz is relevant for fueling applications on future large fusion research devices. The next step in developing a functional high-speed repetitive hydrogen pellet injector is to combine the acceleration technology described here with the cryogenic extruder technology for supplying hydrogen ice previously developed at ORNL (see, e.g., ref. 18). The ORNL/Frascati collaboration referenced in Sect. 1 is an important part of that development. In this international effort, an ORNL continuous deuterium extruder (equipped with pellet chambering mechanism and gun barrel) and a small ENEA-Frascati two-stage gun will be combined to demonstrate and study repetitive operation with bare deuterium ice. For an alternative design, the key elements of the repetitive two-stage light gas gun described in this section can also be readily integrated into a pellet injection system, with or without sabot-handling capability.

Electron-beam-heated rocket

While the previous high-velocity technique has been applied in other others of research for many years, a new method of accelerating pellets to high velocity using a high-power, magnetically compressed electron beam is under development by Foster et. al. at ORNL (refs. 19-21). With this technique, intense electron beam heating is applied to a solid hydrogen surface to evaporate gas at elevated temperature and thus generate a net propulsive force. In one scheme, hydrogen ice propellant "sticks" (long pellets) are ablated and used to accelerate the payloads which could be deuterium, tritium, or D-T mixtures. Researchers have observed the "rocket effect" on pellets (asymmetric trajectories) injected into tokamaks since the first pellet fueling experiments. The neutral shielding model for pellet ablation in a plasma treats the plasma as an electron beam, and it has been adapted and employed as the physics model for the electron-beam-heated rocket.

A proof-of-principle apparatus (Fig. 8) with an effective 0.4-m acceleration path has been constructed and operated; cryogenic pellets of both hydrogen and deuterium (4-mm diam and up to 12-mm long, formed in a pipe gun) have been accelerated, with speeds of up to 580 m/s recorded with intact hydrogen pellets (using electron beam of 10 kV, 0.8 A, and 1 ms). For some selected data, the measured velocities as a function of e-beam current are compared with a theory adapted from the neutral gas shielding model (ref. 19) in Fig. 9. In the scan of beam current, the beam voltage increases systematically from from 4.5 kV to 14 kV as the current increases. Good agreement with the theory is obtained if it is assumed that 2/3 of the beam power is absorbed in the expanding gas and 1/3 of the exhaust gas velocity contributes to directional acceleration of the pellet. In the present experiments, the limits of the acceleration for hydrogenic pellets are found to correspond to an effective acceleration pressure of 0.2 MPA To overcome this limitation, a higher strength material such as lithium or lithium hydride has been proposed as the propellant material. A parametric analysis of systems capable of accelerating pellets to 10 km/s has been made. The accelerator characteristics are shown as a function of beam voltage in Fig. 10 for a constant perveance($I/V^{3/2}$) of 12 uP. The symbols Lo, Po and S correspond to initial pellet length, acceleration pressure and accelerator length respectively. Two design points are indicated (DP1, DP2) corresponding to acceleration lengths of 2 m and 12 m and beam currents of 100 A and 38 A respectively. The difference represents a tradeoff between accelerator length and acceleration pressure. Some initial tests with lithium and lithium hydride pellets are underway.

4. TRITIUM INJECTOR RESEARCH

The tritium proof-of-principle (TPOP) experiment was operated in the period 1988-1989 to demonstrate the basic scientific feasibility of production and pneumatic acceleration of tritium pellets for fueling future fusion reactors (refs. 22-23). The experiment was designed and built at ORNL and installed and operated by ORNL personnel in the Tritium Systems Test Assembly (TSTA) at Los Alamos National Laboratory. Hundreds of 4-mm-diam pellets composed of pure tritium and mixtures of deuterium and tritium (equilibrium D-T; $T_2 = D_2 = 25\%$ and D-T = 50% by volume) were made and accelerated in this device, with speeds of up to 1.4 km/s recorded; over 100 KCi of tritium was processed through the experiment without incident. The gun for this first phase of the TPOP program was based on the pneumatic pipe-gun concept in which pellets are formed *in situ* in the barrel and accelerated with high-pressure gas. This type of gun was ideal for initial tritium experiments because it has no moving parts and requires no excess tritium to produce pellets. Removal of ^{3}He from tritium is particularly important in this type of gun because it hinders the cryopumping action in the freezing zone of the barrel and prevents formation of complete pellets. These experiments have shown that ^{3}He levels below 0.005% are required to produce high-quality pellets. Some of the velocity data from this study are presented in Fig. 11, which also includes some data from repeating pneumatic injectors tested at ORNL. The effect of the mass (or density) for the different hydrogen isotopes on the pellet velocity is well illustrated in this plot.

Some parameters measured during the course of the experiment have been used to evaluate the physical properties of solid tritium. One parameter needed to model two-stage gun performance is the "breakaway pressure" of the pellet, which is the minimum propellant pressure required to shear the pellet from the barrel wall. Normally, this pressure cannot be found by evaluating the breech pressure data using the fast propellant valve because the breech pressure increases too rapidly. To observe the breakaway pressure, propellant gas flow was restricted by using an ordinary solenoid valve with a needle valve in series to launch the pellet. The propellant gas was helium, which does not condense and change the pellet size. In these experiments, the propellant pressure was slowly increased until the pellet broke away from the wall. The measured breakaway pressures are shown in Fig. 12 as a function of pellet length for various temperatures. The shear strength of the pellet can be calculated by setting the breakaway force exerted on the rear of the pellet equal to the shear force at the wall, $\sigma = (P_b D_p)/4L_p$, where P_b is the breakaway pressure, D_p is the pellet diameter, and L_p is the pellet length. Values of the shear strength inferred in this way are presented as a function of temperature in Fig. 13. Also shown are the ultimate tensile strengths of hydrogen (ref. 24) and deuterium (ref. 25). Strictly speaking, the shear strength and tensile strength of a material are not necessarily equal. However, the shear strength and tensile strength of deuterium have similar magnitudes and temperature dependencies. The shear strength for tritium is about twice that of deuterium at 8 K. This may seem like a large difference between isotopes; however, the tensile strengths of hydrogen and deuterium show similar large differences. Tritium pellets should be able to withstand higher accelerations (or pressures) than hydrogen or deuterium pellets without fracturing because of the greater strength. In principle, this makes tritium ice an attractive candidate for advanced acceleration techniques, such as the two-stage light gas gun.

A new 8-mm (ITER-relevant), tritium-compatible, extruder-based repeating pneumatic injector is being designed to replace the pipe-gun in the TPOP experiment. Operation of this gun will explore issues related to the extrudability of tritium and acceleration of extruded pellets. Tritium experiments with this gun are expected to begin at TSTA in 1994.

5. SUMMARY

In this paper, we report on the recent progress and status of pellet injection research and development activites at ORNL, including applications of recent injection systems on present large experimental fusion devices. With ITER becoming an important part of the fusion program in the United States and worldwide, a large part of future ORNL development will be directed in support of the large international fusion device. The present high-velocity pellet injector development and tritium research are particularly relevant to ITER and any future experimental fusion devices or reactors. Also, applications such as ITER will require long-pulse fueling, and reliable steady-state operation of pellet injection systems is a major objective of the ORNL program. A straight forward technique in which multiple extruder units of identical design operate in tandem to provide a continuous source of hydrogen ice for steady-state operation may be a solution; this approach makes use of a reliable ORNL technoloy . Also, the capability of the zamboni-type feed system used on the Tore Supra centrifuge injector can possibly be extended to steady-state pellet fabrication technology. Development of these techniques are planned, and such feed systems combined with reliable acceleration systems can form the basis for a steady-state pellet fueling system for ITER and fusion reactors.

REFERENCES

1. S. L. Milora, *J. Fusion Energy* **1**, 15 (1981).

2. S. L. Milora, *J. Fusion Energy* **1**, 15 (1981).

3. S. K. Combs, "Pellet Injection Technology," in press, Rev. Sci. Instrum. (August 1993).

4. S. K. Combs, S. L. Milora, C. R. Foust, et al., *Rev. Sci. Instrum.* **58**, 1195 (1987).

5. S. L. Milora, M J. Gouge, G. L. Schmidt et. al.," Design of a Tritium Pellet Injector TFTR,"*Proceedings of the 14th Symposium on Fusion Engineering*," **II**, 716, IEEE (1992).

6. M J. Gouge, G. L. Schmidt et. al., " *Fusion Technology*, **21**, No. 3, Part 2A, 1665 (1992).

7. G. W. Barnes, M. J. Gouge et. al., "The TFTR Tritium Pellet Injection Facility Mechanical Design, " *Fusion Technology*, **21**, No. 3, Part 2A, 1662 (1992).

8. S. K. Combs, S. L. Milora, C. R. Foust, M. J. Gouge, D. T. Fehling and D. O. Sparks, *J. Vac Technol. A* **7**, 963 (1989).

9.S. K. Combs, C. R. Foust, M. J. Gouge, and S. L. Milora, *J. Vac. Sci. Technol. A***8** **(3)** , (1990).

10. F. Scaramuzzi, A Frattolillo, A. Reggiori, et al., *Proc. 16th Symp. on Fusion Tech.*,**1**, 747 (199

11. P. Kupschus, K. Sonnenberg et al., *Proc. 16th Symp. on Fusion Tech.*, **1**, 268 (1991).

12.C. A. Foster, W. A. Houlberg, M. J. Gouge, M. J. Grapperhaus, S. L. Milora, H. Dr A. Geraud, M. Chatelier, and G. Gros, ORNL centrifuge pellet fueling system, presented at the Symposium on Fusion Technology, Rome, September 14–18, 1992 (proceedings to be published).

13. S. L. Milora, S. K. Combs, L. R. Baylor, C. R. Foust, F. E. Gethers, and D. O. Sparks, in *Proceedings of the 12th Symposium on Fusion Engineering,* Monterey, 1987 (IEEE, New York, 1987), pp. 784–786.

14. P. Kupschus, W. Bailey, M. Gadeberg, L. Hedley, P. Twynam, T. Szabo, and D. Evans, in *Proceedings of the 12th Symposium on Fusion Engineering,* Monterey, 1987 (IEEE, New York, 1987), pp. 780–783.

15. S. K. Combs, S. L. Milora, L. R. Baylor, C. R. Foust, F. E. Gethers, and D. O. Sparks, *J. Vac Technol. A* **6**, 1901 (1988).

17. S. K. Combs, C. R. Foust, D. T. Fehling, M. G. Gouge, and S. L. Milora, *Rev. Sci. Instru* **(8)**, 1978 (1991).

16. S. K. Combs, T. C. Jernigan, L. R. Baylor, S. L. Milora, C. R. Foust, P. Kupschus, M. Gadeberg, and W. Bailey, *Rev. Sci. Instrum.* **60(8)**, 2697 (1989).

18. S. K. Combs, S. L. Milora, C. R. Foust, C. A. Foster, and D. D. Schuresko, *Rev. Sci. Ins* **56(6)**, 1173 (1985).

19. C. A. Foster, C. C. Tsai, D. E. Schechter, M. J. Gouge, S. L. Milora, S. K. Combs, F. E. Ge D. W. Simmons, C. W. Sohns, B. E. Argo, and G. C. Barber, in *Proceedings of the IAEA Tech Meeting on Pellet Injection and Toroidal Confinement,* Gut Ising, 1988, IAEA-TECDOC-534 (Interna Atomic Energy Agency, 1989), p. 275.

20. C. C. Tsai, C. A. Foster, S. L. Milora, and D. E. Schechter, in *Proceedings of the 14th Symposium on Fusion Engineering*, San Diego, 1991 (IEEE, New York, 1992), Vol. 2, p. 724.

21. C. C. Tsai, C. A. Foster, S. L. Milora, D. E. Schechter, and J. H. Whealton, "Electron-beam rocket acceleration of hydrogen pellets," *J. Vac. Sci. Technol. A*, accepted for publication.

22. P. W. Fisher, Tritium Proof-of-Principle Pellet Injector, Oak Ridge National Laboratory Report ORNL/TM-11781, July 1991. Available from the National Technical Information Service, Springfield, VA 22161.

23. P. W. Fisher, *Fusion Technol.* **21**, 794 (1992).

24. L. A. Alekseeva, O. V. Litvin, and I. N. Krupskii, *Sov. J. Low Temp. Phys.* **8**, 158 (1982).

25. D. N. Bolshutkin, Y. E. Stetsenko, and L. A. Alekseeva, *Sov. Phys. Solid State* **12**, 119 (1970).

Table I. Experimental data for two 10-pellet test sequences with repetitive two-stage light gas gun operating at 1 Hz

	Transient timing data[a] (s)			
Pellet number	Gun muzzle light gate	Target plate accelerometer	Flight time[b] (µs)	Pellet velocity (m/s)
		Test sequence 1056		
First-stage pressure: 62 bar		Piston mass: 25 g	Pellet material: acetal	
Second-stage pressure: 0.8 bar		Pellet mass: 0.055 g	Pellet shape: solid cylinders	
		Pellet size: 4.0 mm diam × 3.5 mm long		
1	0.071106	0.071811	705	2130
2	1.0737659	1.0745409	775	1935
3	2.0740361	2.074781	745	2015
4	3.074631	3.075371	740	2030
5	4.075336	4.0760708	735	2040
6	5.0758257	5.076561	735	2040
7	6.076481	6.077211	730	2055
8	7.0688057	7.069541	735	2040
9	8.077776	8.078511	735	2040
10	9.070187	9.070921	734	2045
				Avg = 2040
		Test sequence 1109		
First-stage pressure: 100 bar		Piston mass: 30 g	Pellet material: polypropylene	
Second-stage pressure: 0.8 bar		Pellet mass: 0.029 g	Pellet shape: solid spheres	
		Pellet size: 4.0 mm diam		
1	0.051846	0.052321	475	3160
2	1.0476309	1.0481009	470	3190
3	2.0481758	2.048681	505	2970
4	3.0510309	3.0515509	520	2885
5	4.048901	4.0494113	510	2940
6	5.049611	5.0501113	500	3000
7	6.0423713	6.042881	520	2885
8	7.0497513	7.050221	470	3190
9	8.050951	8.05148	529	2835
10	9.051056	9.051620	564	2660
				Avg = 2970

[a] Taken as time of abrupt change in instrument signals as determined by software code that analyzes raw transient data.

[b]Separation distance of 1.5 m between muzzle light gate and target plate.

FIGURES

Fig. 1. TFTR tritium-compatible four-shot pellet injector
(ORNL-DWG 91-3376R2 FED)

Fig. 2 Schematic of thetritium-compatible four-shot injector installation on TFTR
(ORNL-DWG 91-3344 FED)

Fig. 3. Pellet fabrication device and high-speed rotating arbor for the Tore Supra centrifuge injector
(ORNL-DWG 88-3397 FED)

Fig. 4. Feed system upgrade for Tore Supra centrifuge injector
(ORNL-DWG92-3459 fed)

Fig. 5. Three-barrel repeating pneumatic pellet injector
(ORNL-DWG 87-2148 FED)

Fig. 6. Planned installation of three-barrel repeating pneumatic pellet injector on DIII-D
(ORNL-DWG 93 M 2899 FED)

Fig. 7 Schematic of repetitive two-stage light gas gun
(ORNL-DWG 91-2345 FED)

Fig. 8. Schematic of electron-beam rocket pellet accelerator, consisting of a pipe-gun-type pellet source, an electron gun, a pellet accelerator with guide rails and electromagnets, and diagnostics
(ORNL-DWG 88-3555A3R2 FED)

Fig. 9. Proof-of-principle electron-beam rocket accelerator performance
(ORNL-DWG 92M-2825R FED)

Fig. 10. Projected 10 km/s electron-beam rocket accelerator parameters for Li pellets and beam perveance =12 μP
(ORNL-DWG 92M-2824AR FED)

Fig. 11. Experimental muzzle velocities of nominal 4 mm diam pellets accelerated in ORNL single-stage light gas guns. Data are from the tritium proof-of-principle (TPOP) and repeating pneumatic injector (RPI) experiments, with 1 m long and 0.8 m long gun barrels, respectively
(ORNL-DWG 92M-3689 FED)

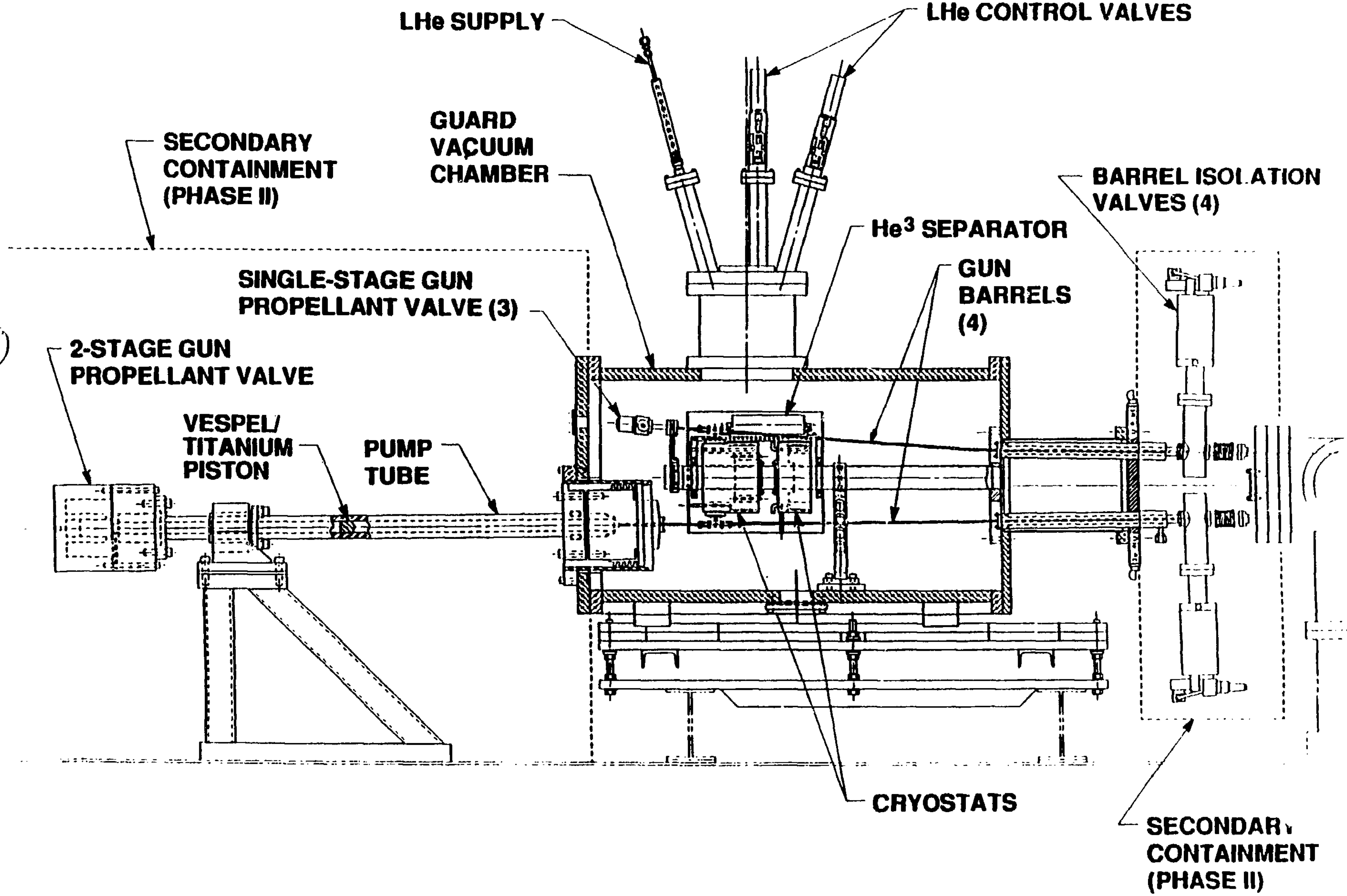
Fig. 12. Breakaway pressures for deuterium and tritium pellets of various temperatures and lengths
(ORNL-DWG 92M-4106 FED)

Fig. 13. Shear strengths of deuterium and tritium ice estimated from breakaway pressure data. (Lines represent reported ultimate tensile strengths of hydrogen and deuterium.)

(ORNL-DWG 92M-4107 FED)

ORNL-DWG 91-3376R2 FED

(5)



ORNL-DWG 91-3344 FED

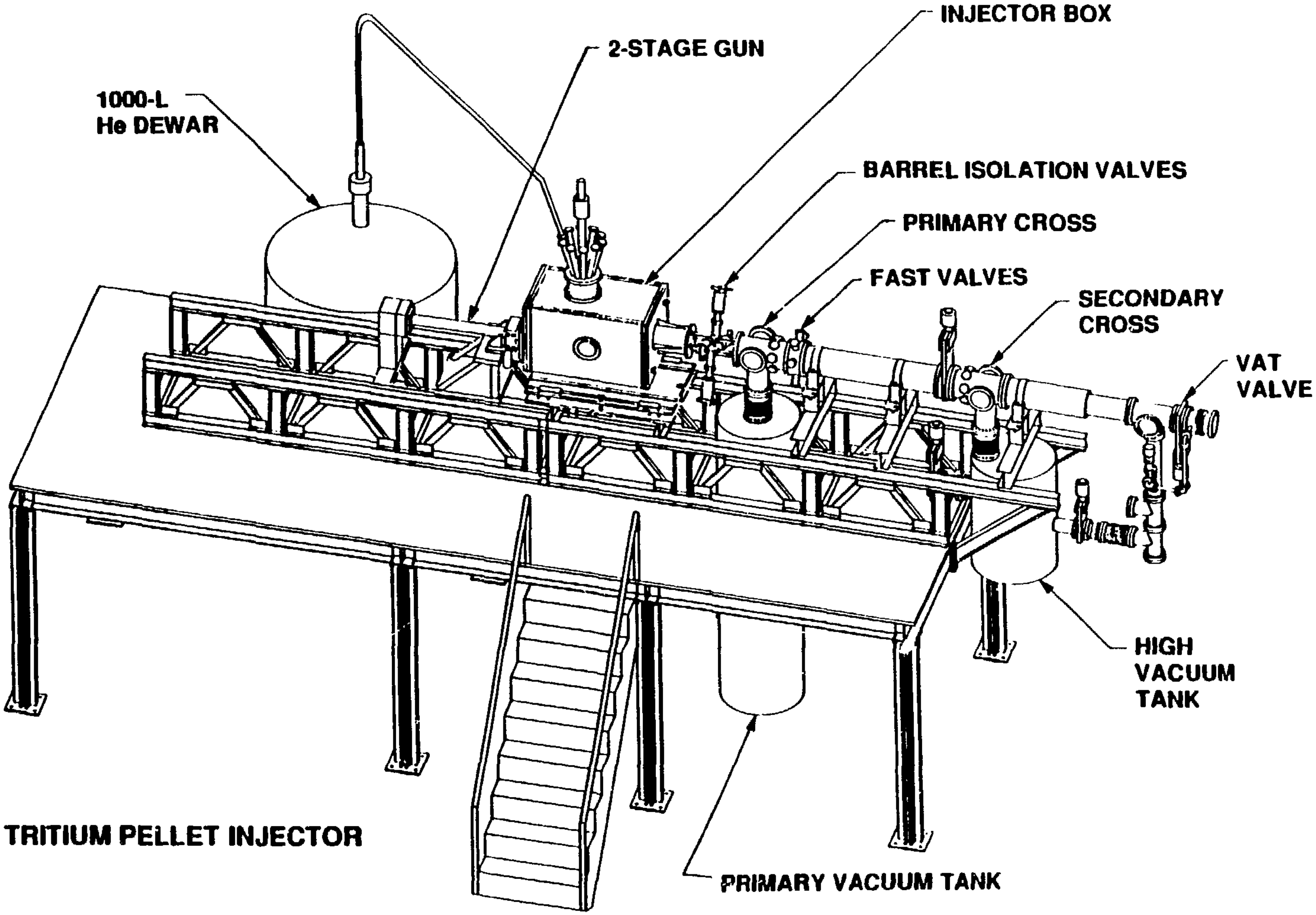
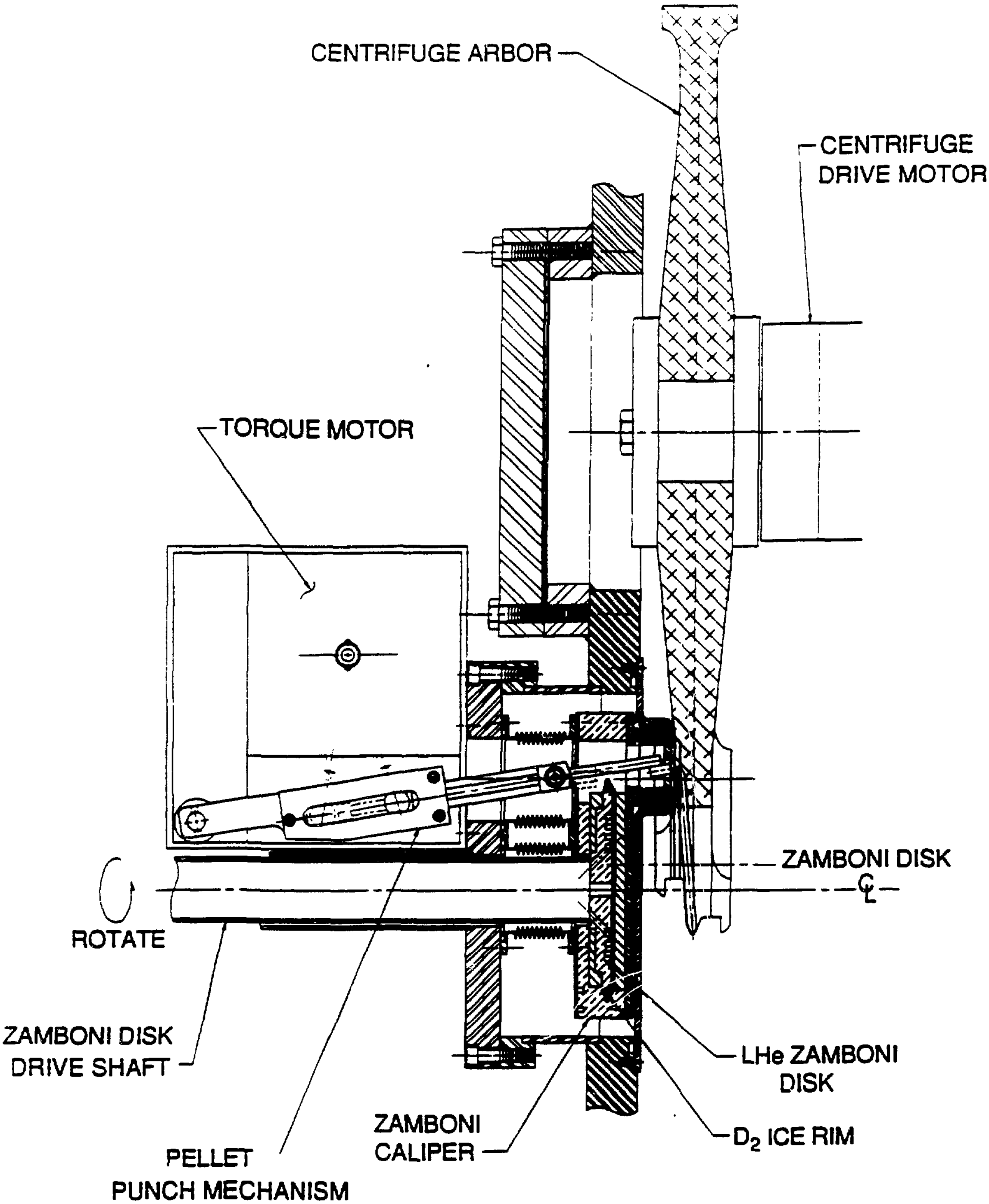
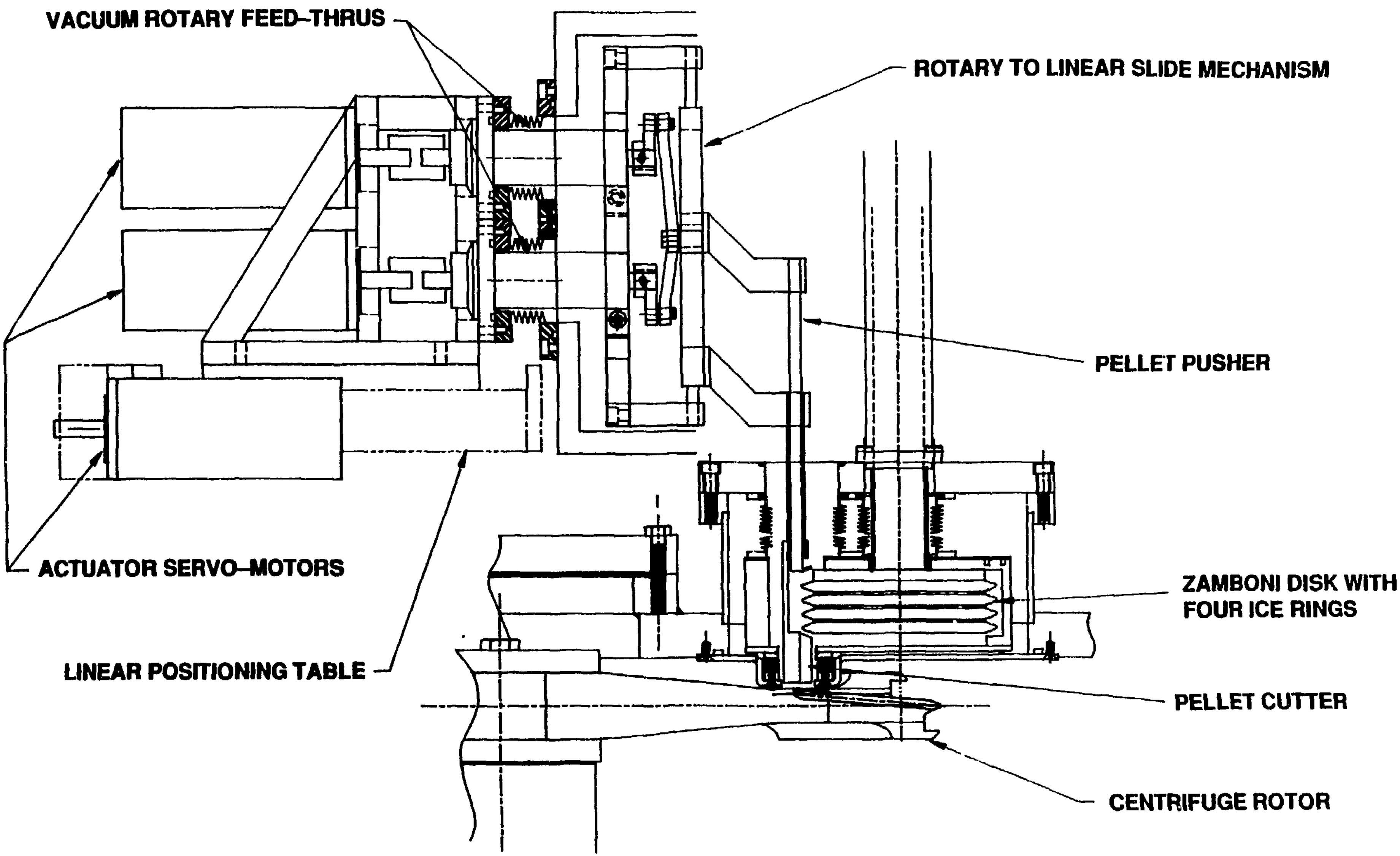


Fig. 1. Perspective view of the TPI installation on the TFTR.


CENTRIFUGE ARBOR
CENTRIFUGE DRIVE MOTOR
TORQUE MOTOR
ZAMBONI DISK
ROTATE
ZAMBONI DISK DRIVE SHAFT
LHe ZAMBONI DISK
D_2 ICE RIM
ZAMBONI CALIPER
PELLET PUNCH MECHANISM

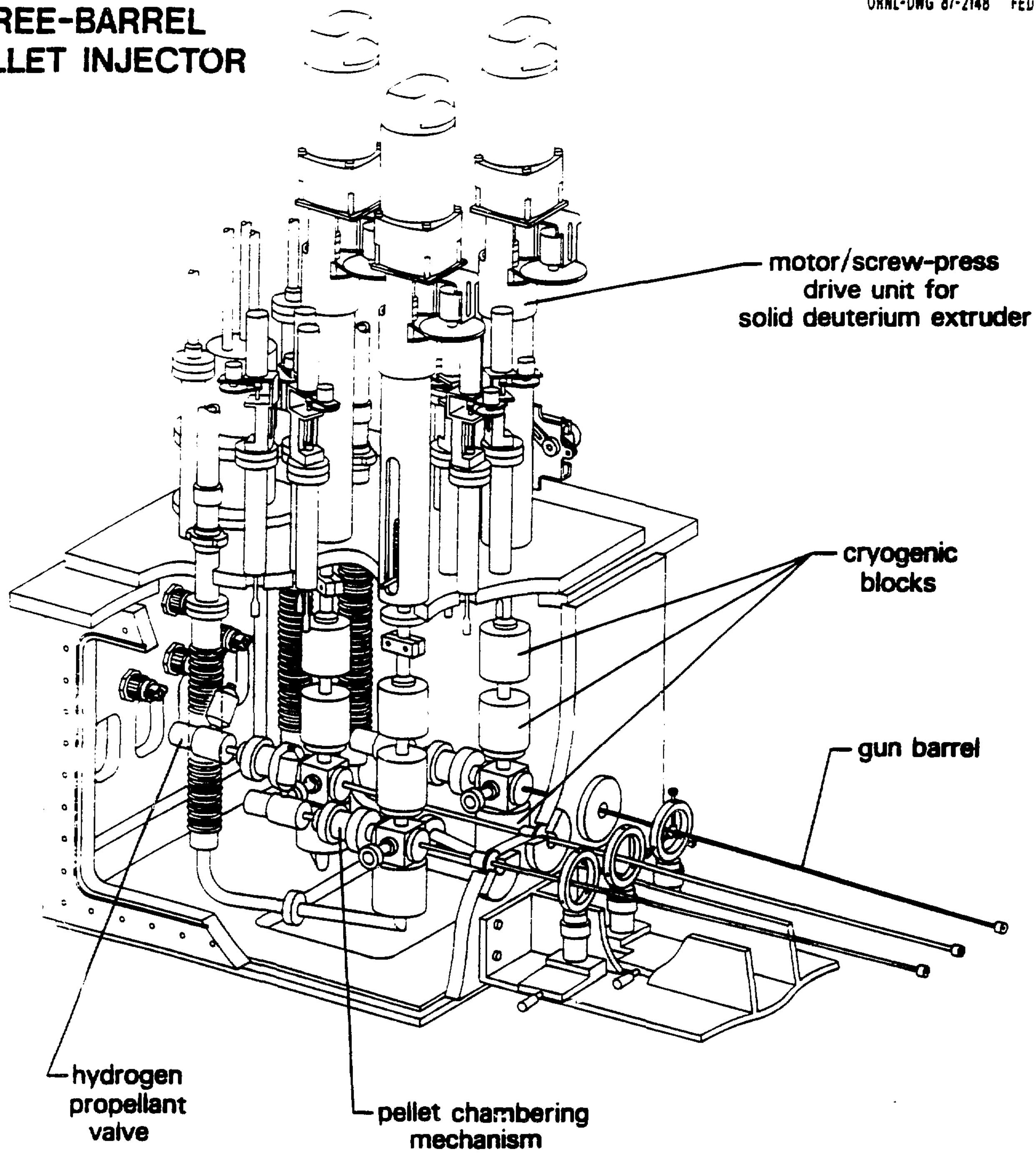
ORNL-DWG 92-3459 FED

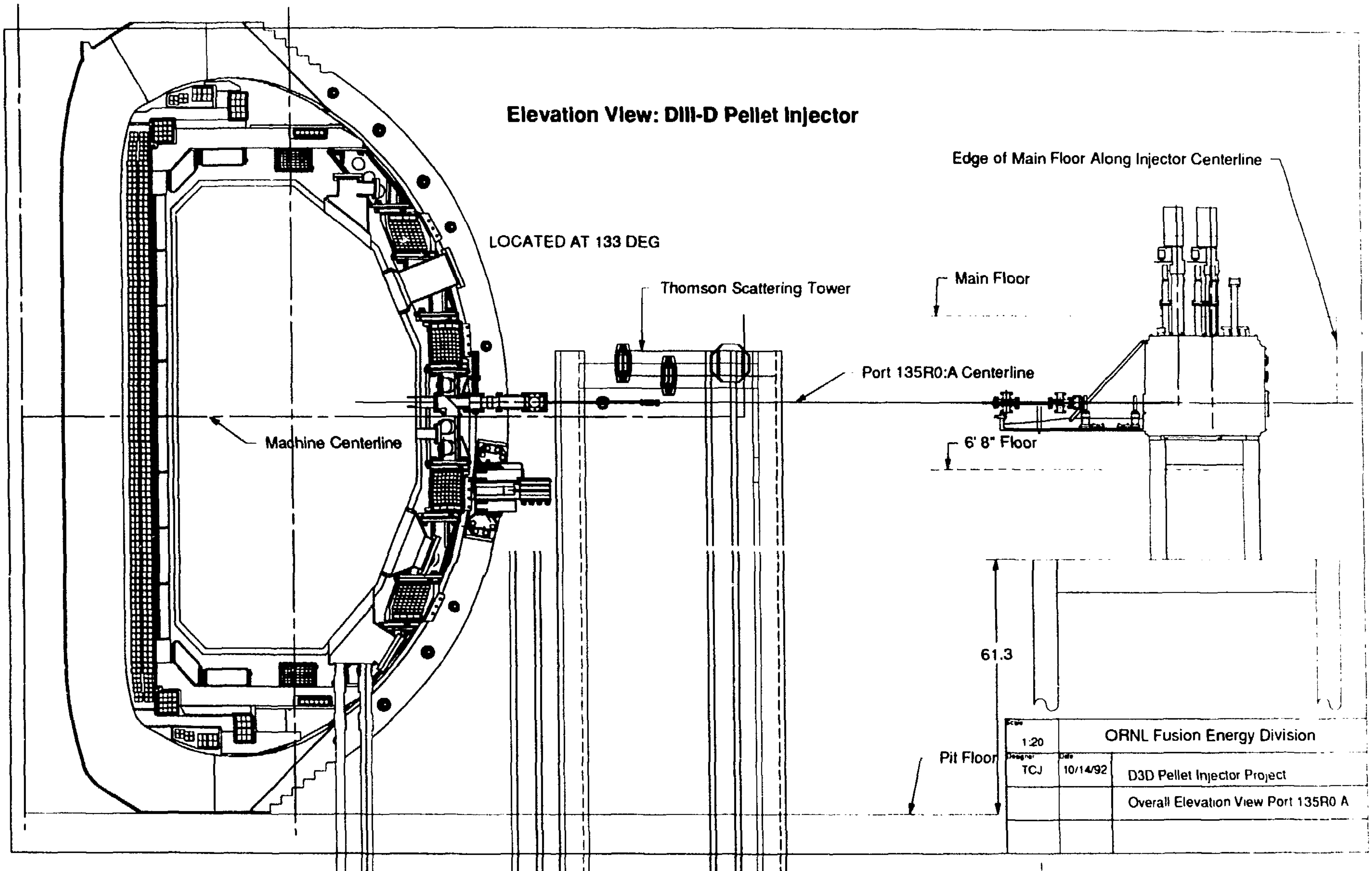


Tore Supra Pellet Injector Punch Upgrade

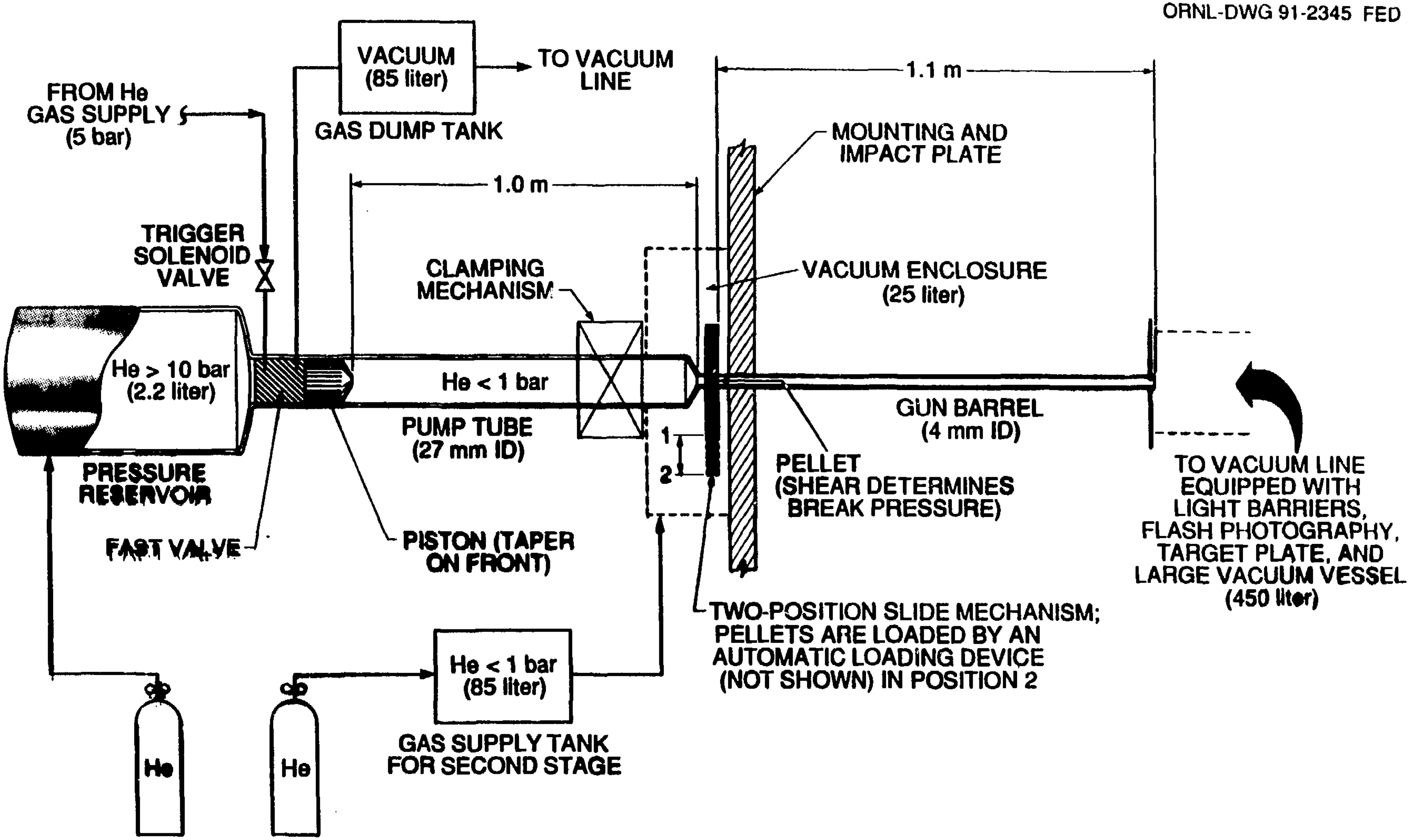
REPEATING THREE-BARREL PELLET INJECTOR

ORNL-DWG 87-2148 FED

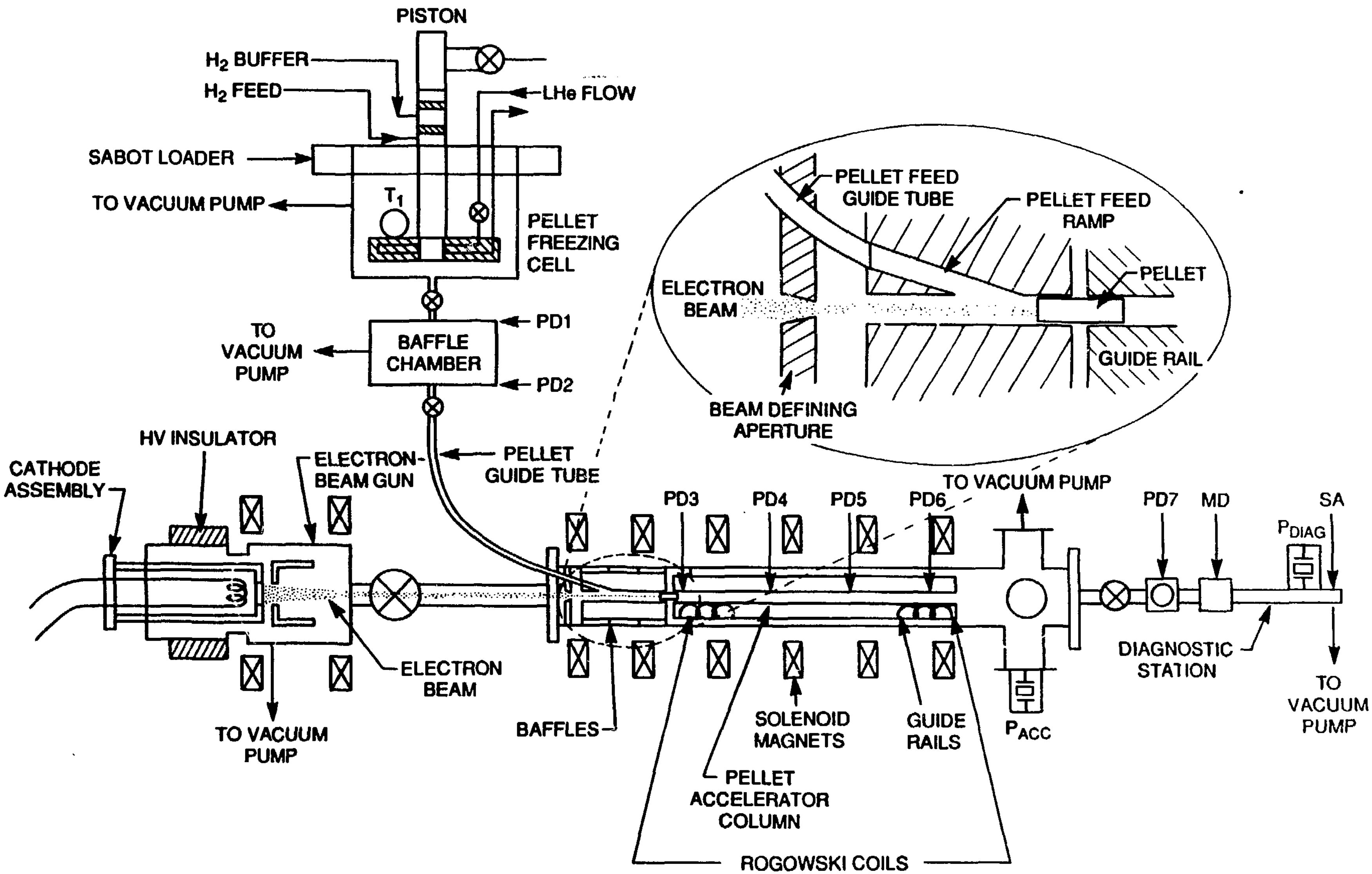




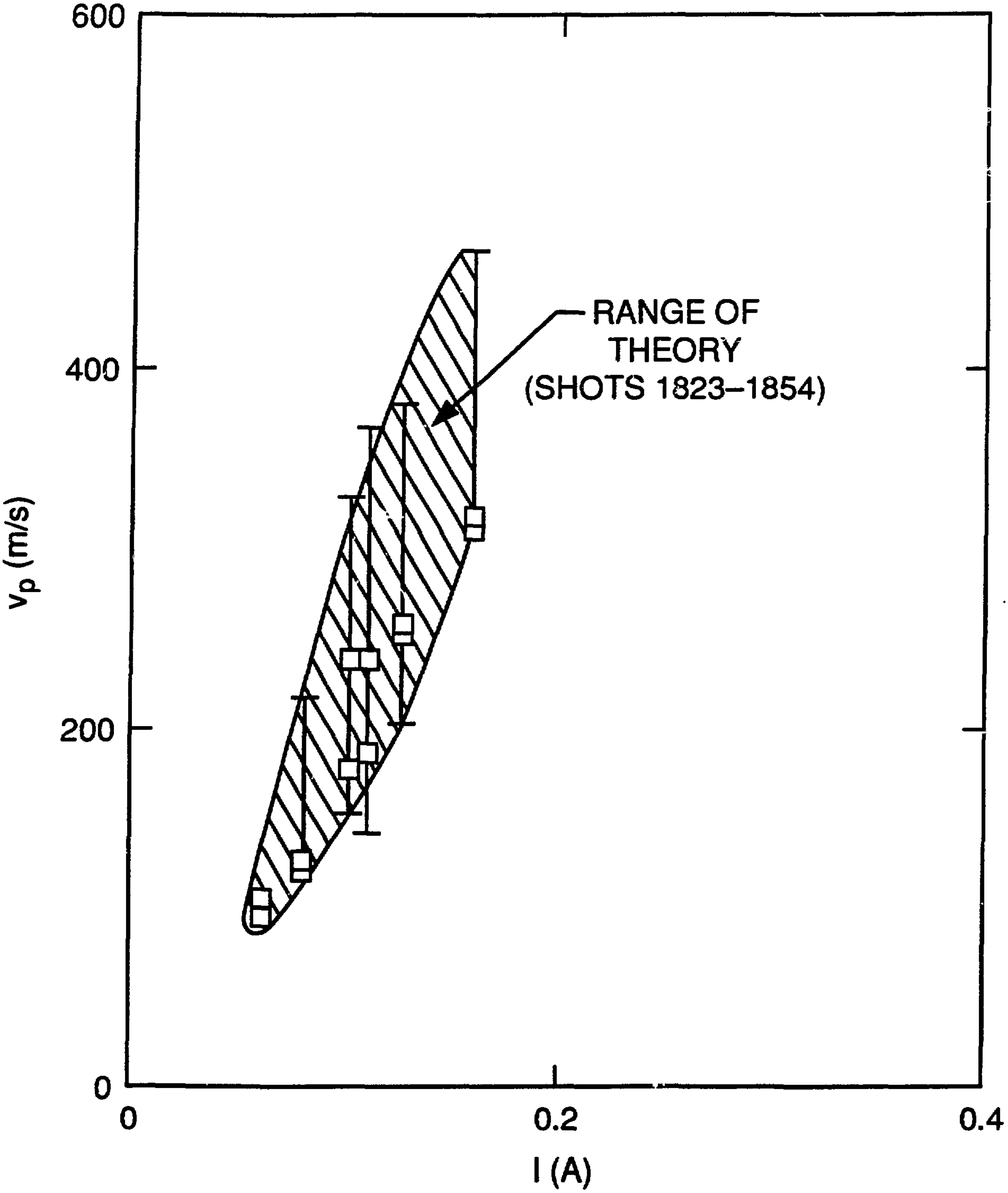
Elevation View: DIII-D Pellet Injector
Edge of Main Floor Along Injector Centerline
LOCATED AT 133 DEG
Main Floor
Thomson Scattering Tower
Port 135R0:A Centerline
Machine Centerline
6' 8" Floor
61.3
Pit Floor
1:20
ORNL Fusion Energy Division
TCJ
10/14/92
D3D Pellet Injector Project
Overall Elevation View Port 135R0 A


ORNL-DWG 91-2345 FED
VACUUM
(85 liter)
TO VACUUM LINE
GAS DUMP TANK
FROM He GAS SUPPLY (5 bar)
1.1 m
MOUNTING AND IMPACT PLATE
1.0 m
TRIGGER SOLENOID VALVE
CLAMPING MECHANISM
VACUUM ENCLOSURE (25 liter)
He > 10 bar (2.2 liter)
He < 1 bar
GUN BARREL (4 mm ID)
PUMP TUBE (27 mm ID)
PRESSURE RESERVOIR
1
2
PELLET (SHEAR DETERMINES BREAK PRESSURE)
TO VACUUM LINE EQUIPPED WITH LIGHT BARRIERS, FLASH PHOTOGRAPHY, TARGET PLATE, AND LARGE VACUUM VESSEL (450 liter)
FAST VALVE
PISTON (TAPER ON FRONT)
TWO-POSITION SLIDE MECHANISM; PELLETS ARE LOADED BY AN AUTOMATIC LOADING DEVICE (NOT SHOWN) IN POSITION 2
He < 1 bar (85 liter)
GAS SUPPLY TANK FOR SECOND STAGE
He
He

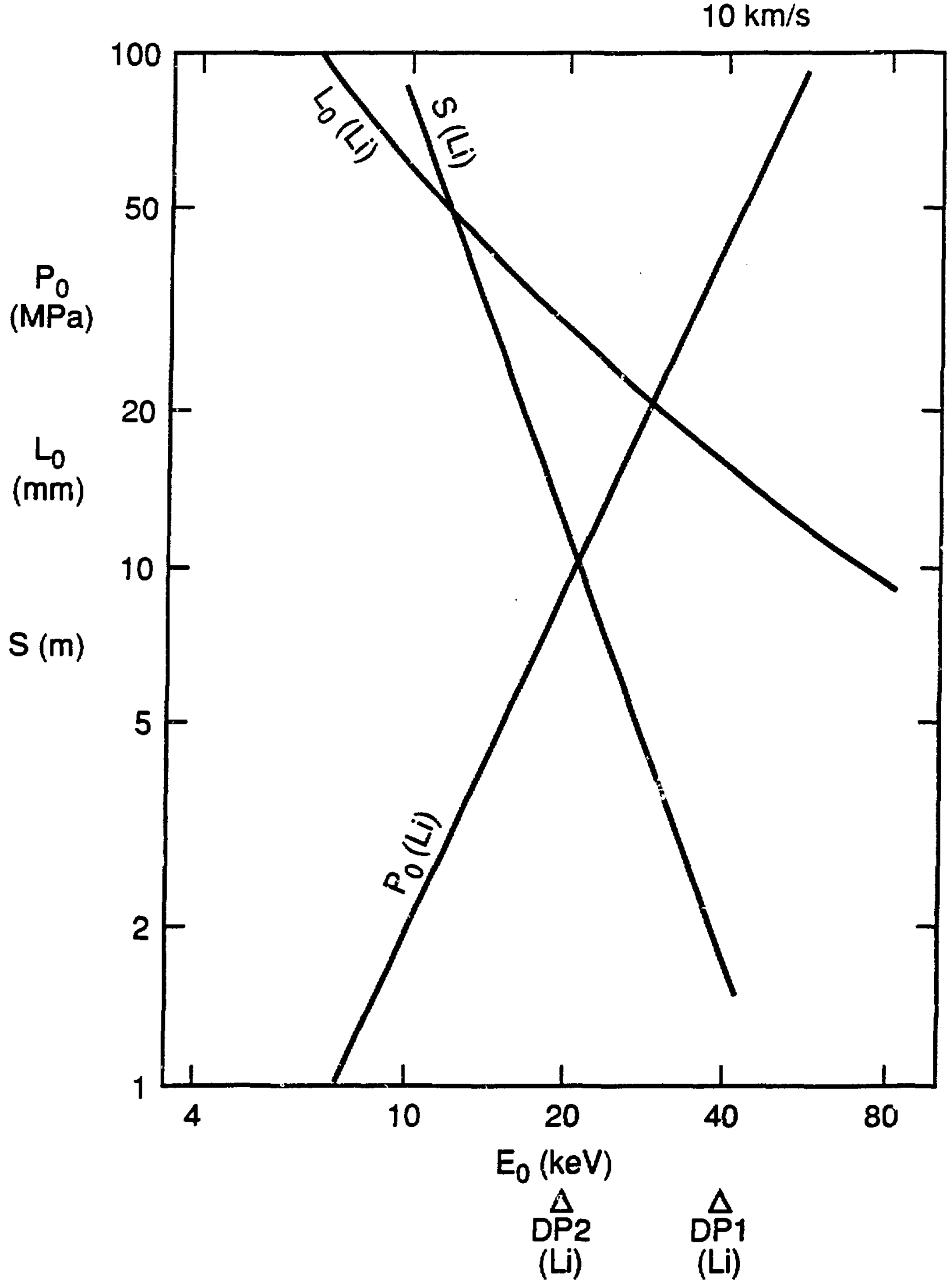
ORNL-DWG 88-3555A3R2 FED



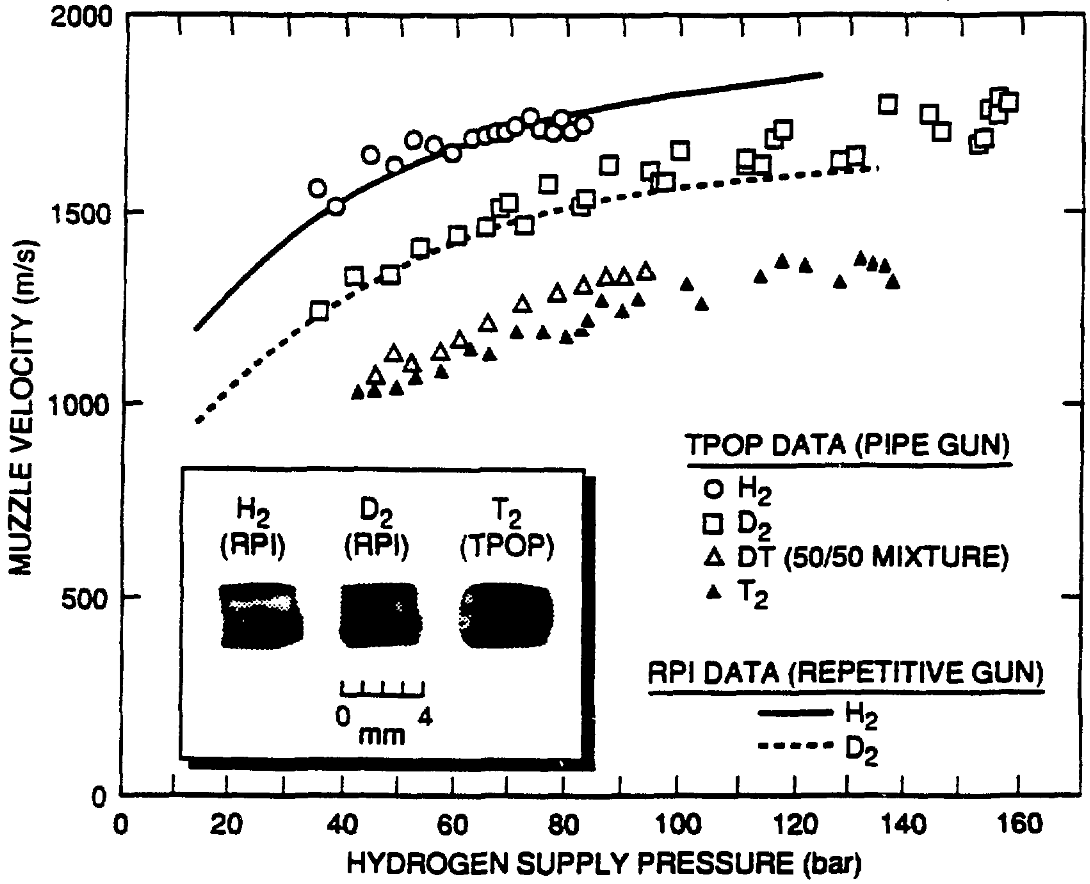
ORNL-DWG 92M- 2825R FED



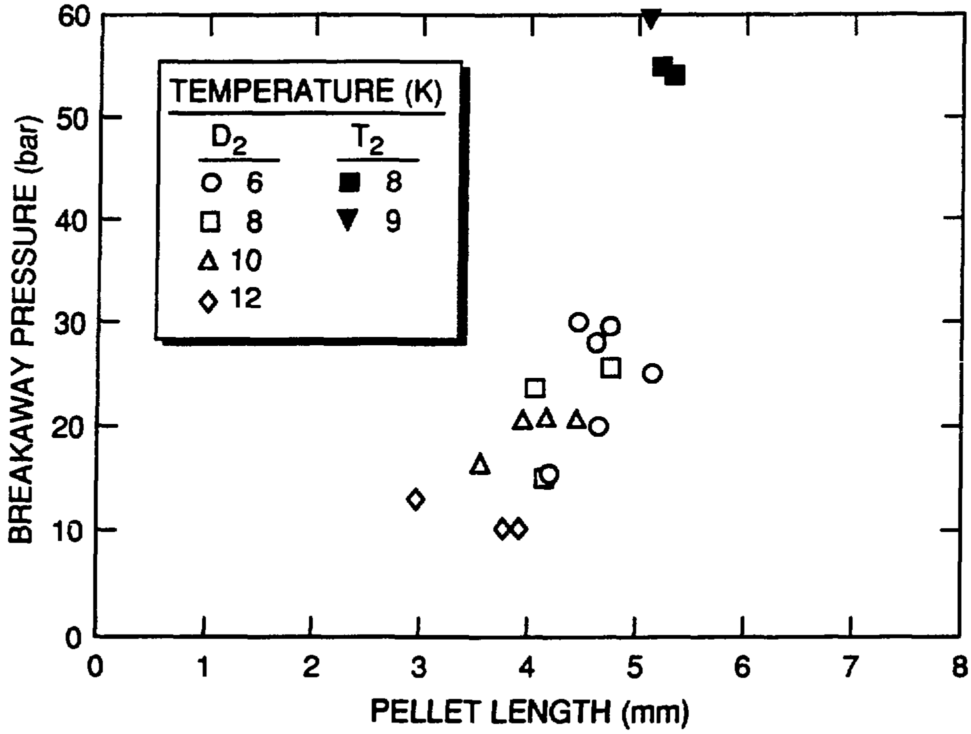
ORNL-DWG 92M-2824AR FED

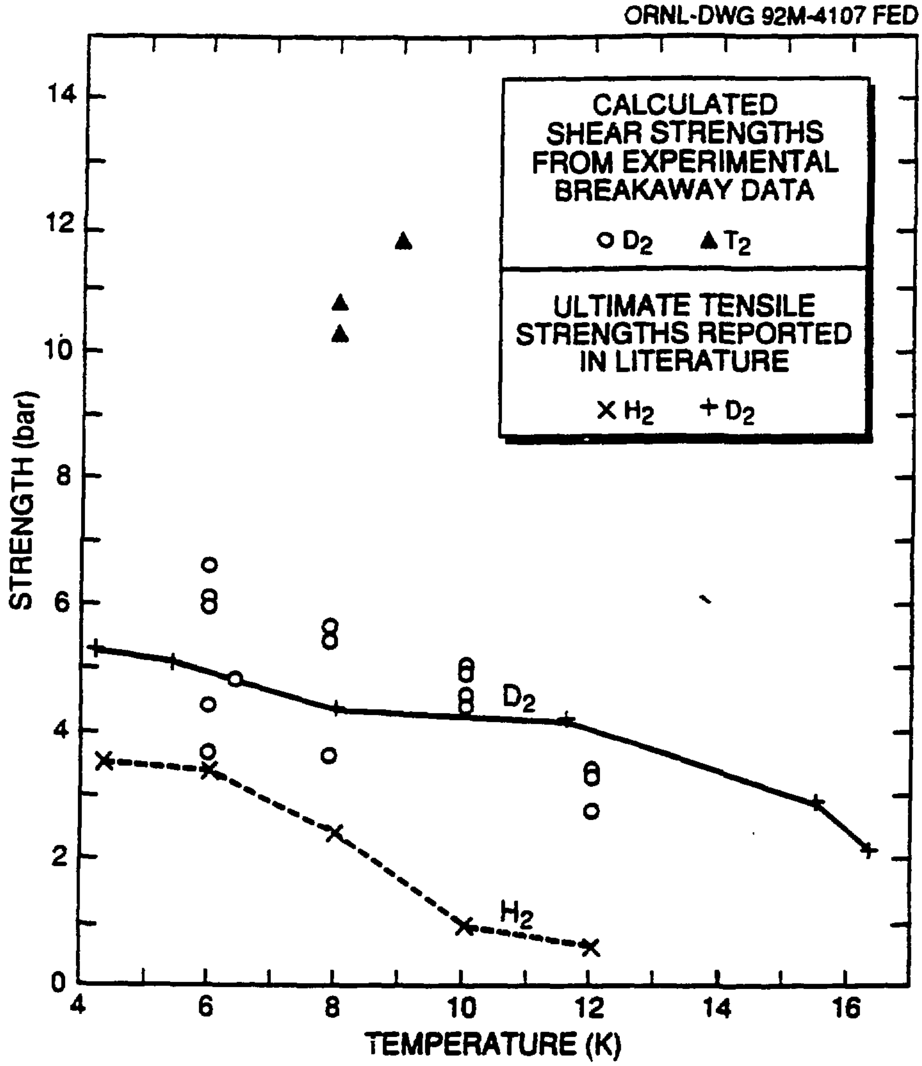


ORNL-DWG 92M-3689 FED



ORNL-DWG 92M-4106 FED





ORNL-DWG 92M-4107 FED
CALCULATED SHEAR STRENGTHS FROM EXPERIMENTAL BREAKAWAY DATA
O D2
▲ T2
ULTIMATE TENSILE STRENGTHS REPORTED IN LITERATURE
X H2
+ D2
D2
H2
STRENGTH (bar)
TEMPERATURE (K)
0
2
4
6
8
10
12
14
4
6
8
10
12
14
16