MASTER

CONF-760994--2

PREDEMONSTRATION FUSION DEVICES RESEARCH AND DEVELOPMENT NEEDS*

John F. Clarke

Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

ABSTRACT

In this concluding lecture, the criteria and reference design information for the PDFD will be examined with respect to the presently planned R&D programs, and the major research and development needs will be described. Emphasis will remain on the fusion core rather than the nuclear shell. Scaling, heating, fueling and other needs will be outlined. In the area of technology, magnet systems, and tritium handling compatible with PDFD operation will be discussed. Presently planned research and development programs will provide the information needed to support the TNS version of the PDFD by 1980.

Since the design of the PDFD must be based on our knowledge of present experiments and theoretical predictions, it is not surprising that the tokamak experimental program planned on the basis of this same knowledge and theory should be addressing itself to the key uncertainties in the physical requirements of the PDFD plasma. Table I outlines the key physical problems and the experiments which will provide answers to these questions. These experiments utilize neutral beams for plasma heating and with the exception of TFTR are hydrogen fueled by gas recycle. The exception, TFTR, has a DT handling system which

*Research sponsored by the US Energy Research and Development Administration under contract with Union Carbide Corporation.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

TABLE I

US EXPERIMENTS ADDRESSING KEY PDFD QUESTIONS

Problem	Experiment	Start
Impurity evolution and control	ISX	1977
	PDX	1978
Scaling	PLT	1976
	PLT + beams	1977
	ORMAK-Upgrade	1978
	Doublet-III	1978
	TFTR	1981
High beta equilibrium and stability	ORMAK-Upgrade	1978
Non-circular plasma operation	Doublet-III	1978
	PDX	1978
Neutral heating	PLT	1977
	ORMAK-Upgrade	1978
High field effects	Alcator	1978
D-T operation	TFTR	1981

is not designed to be extrapolated to a fusion reactor system. None of these devices are long pulse or operate with superconducting magnet systems. Since PDFD will have to address the ignition of a DT plasma and the maintenance of the ignited plasma for tens of seconds, it will require additional development in two areas not now receiving much support—fueling and tritium handling, and one area now being heavily supported because of its near-term impact—neutral injection.

In the latter area, the emphasis in development beyond that required for TFTR must be on efficiency. There may also be a need to raise the maximum beam energy, possibly as high as 300 keV which would require development beyond the TFTR beams. In this paper we will discuss these three technologies in the context of the requirements imposed by the TNS design.

Neutral Beams in TNS

Penetration of the injected fast neutrals must be adequate to heat the plasma core under all imaginable experimental operating conditions. If we examine the problem of adequate penetration in the high-density mode of operation ($\bar{n} = 2.10^{14}$ cm^{-3}) and allow some impurity accumulation during startup ($Z_{eff} = 1.5$) when charge exchange induced wall sputtering may be expected, a fast neutral energy of 300 keV results in slightly center-peaked deposition profile for ± 20° off-radial injection [1] into a 125 cm radius plasma. This injection scheme minimizes perturbation of the "normal" tokamak startup and operation physics, but requires a difficult technology to be developed.

Three alternative startup schemes which are presently being investigated theoretically, and which might lower the beam energy especially during the startup phase, are low density startup at full plasma radius, low radius startup at full density by programming the divertor separatrix, and injection of fast ions into ripple "windows" [2]. The possibly reduced complexity of neutral beam technology makes these schemes attractive, but further analysis of their effect on the tokamak physics is needed.

The requirement of 75 MW of power delivered to the plasma at energies up to 300 keV makes the problem of beam efficiency one of critical importance. Possible efficiencies range from about 12% in a $D^+ \rightarrow D^o$ "brute force" system to about 70% for a $D^- \rightarrow D^o$ system with an energy recovery system. The corresponding electric power required for the beam injectors would be about 625 MW and 107 MW, respectively. If we take a startup time for TNS of 4 seconds, after

which the α heating dominates and the beams may be turned off, the energy required for each TNS pulse in the two extremes above is 2500 MJ and 428 MJ, respectively. The former case raises large problems with respect to pulsed energy storage. The existing schemes for generating intense beams of negative ions, 1) direct extraction and acceleration of D^- ions from a D^- plasma generator and, 2) double charge exchange conversion of low-energy D^+ into a D^- beam followed by post-acceleration, may both have their inherently high neutralization efficiency further enhanced by the direct recovery of the unneutralized ions' energy. This may result in a net efficiency approaching 70%.

All of these three high-efficiency schemes have their own sets of difficult physics and technology problems, the solution of which requires an aggressive beam research and development program. Table II shows the possible schemes being explored to enhance high energy efficiency. All of these options will be examined in the next three years.

TABLE II

POSSIBLE APPROACHES TO EFFICIENT NEUTRAL BEAMS AT 300 keV

Approach	Efficiency
1. D^+ (300 keV) $\rightarrow D^o$ (300 keV)	12%
2. D^+ (300 keV) $\rightarrow D^o$ (300 keV) + direct recovery	35%
3. D^+ (1 keV) $\rightarrow D^-$ (1 keV) $\rightarrow D^-$ (300 keV) $\rightarrow D^o$ (300 keV)	50%
4. D^- (300 keV) $\rightarrow D^o$ (300 keV)	50%
5. Approach 3 or 4 + direct recovery	70%

Superconducting Magnets in TNS

The TNS machine is primarily aimed at achieving a deuterium-tritium fueled ignition. Plasma engineering studies on energy containment and ignition conditions indicate the need for a plasma major radius of about 5 m and minor radius of about 1 m with moderate elongation. This plus the requirement of the space for plasma shaping coils, magnetic ripple criteria [3], a divertor and shield dictates a TF coil bore of about 4 x 6 m.

The maximum field required for the machine is not completely fixed yet. A maximum field of 8 T will give an ignition plasma density at $\beta \approx 10\%$. Higher fields will allow operation at a lower value of β and improve the confinement. Therefore, there is still a good incentive for increased field. A 12 T or even higher field might be required as a fall-back position if high β cannot be achieved.

The ignited plasma is expected to deliver about 1500 MW of thermal power during the burn cycle. If a radiation shield (about 60 cm) capable of three-decade attenuation is used and we assume 1/3 of the radiation hits the TF coils, the peak radiation load on the TF coils would be about 500 kW. This is 30 times higher than the EPR design point. However, it is expected that the TNS machine will not have a duty cycle any higher than 10% so this load can be removed by the refrigeration system.

The poloidal field coil system of the TNS will have similar features to that used in the ORNL-EPR conceptual design study [4]. The EF coil inside the TF coil can serve to reduce the pulse field

on the TF coil. However, in the flux-conserving mode operation, the plasma current is raised from 4 MA to 8 MA in about 4 sec [5]. In this time period the shielding function of the EF coils may be degraded. Therefore, the average $\dot{B}$ on TF coil may be somewhat higher than 0.05 T/sec (the value used in the EPR study), but possibly lower than 0.5 T/sec (the value to be employed in the coil fabricating program).

The poloidal field coils required for the TNS consists of two types of coils: the Ohmic Heating (OH) coils and the Equilibrium Field (EF) coils. The main part of the OH coil will be inside the center column of about 4 m in diameter. It serves to supply a flux swing of about 80 V-sec for the plasma current start-up and burn period. The EF coils should be as close to the plasma surface as possible in order to shape the plasma. On the other hand, if the EF coils are placed inside the shield, the radiation load would be very high. If we assume 10% interception of the peak load, then the value is about 150 MW. This is probably too high even for a water-cooled copper coil and consequently optimization of the position and shielding of these coils is an important area of development.

Toroidal Field Coils

Superconducting, resistive, and hybrid magnet designs were all considered for the TF magnet system. At first thought, one might assume that a smaller TF coil would suffice if it is resistive. One needs less shielding for high temperature resistive coils operating at 350-600 K than for superconducting coils at 4 K. However, because of

the need for space for the EF coils and some shield and the consideration of field ripple, the size of resistive coils would not be less than superconducting ones. The minimum space between the plasma edge and the TF coil necessary to meet the field ripple and access requirements might just be enough for shielding the superconducting coils. Furthermore, a resistive coil should be operated in pulsed mode. The capital cost of a resistive system and the operating costs (power consumption) are both probably higher than a comparable superconducting coil and the latter allows dc operation. The pulse nature also introduces a serious mechanical fatigue problem. An all resistive TF magnet is most probably not scaleable to the larger devices such as an EPR. The technique of using resistive insert coils in a superconducting coil (hybrid design) for the size and environment required in TNS is still uncertain. A much closer look at this approach both from a mechanical and thermal point of view is necessary. The TNS design employs superconducting TF coils because they are feasible and can be applicable to larger machines. However, their design is not fixed and the options are many. A direct conclusion of the design project to date is the requirement of fields in excess of 80 kg at the coil to provide a margin for ignition in the presence of uncertain plasma behavior.

To select the best set of design choices, the US has a research, development, and demonstration program for superconducting toroidal magnets centered at ORNL. The program includes both in-house research, industrial design and fabrication and international cooperation. The industrial and international cooperation is centered

around the Large Coil Project (LCP). This project will let industrial subcontracts for building 6 coils with 2.5 x 3.5 m bore covering the range of viable possibilities above. These coils will be assembled in a compact torus which will allow full field testing by 1979. Co-operation with the International Energy Agency (IEA) on LCP will result in 1 to 3 coils being contributed to the compact torus demonstration by the IEA members.

Fueling Requirements for TNS

The principal problem to be addressed in fueling a TNS-like plasma is that of injecting D-T material deeply into the central portion of a hot, dense plasma against the confining effects of the magnetic fields. It is generally acknowledged that fueling by neutral beams would require prohibitively large power expenditures and that the most practical method of introducing fuel into such a device is by injection of solid D-T pellets accelerated to hypervelocities. The work of Gralnick [6] suggests that millimeter size pellets moving into the plasma at speeds of the order of 10^4 m/sec would be required to refuel a reactor grade plasma. Velocities of this magnitude have been reached in the laboratory using ballistic techniques, but the technology for accelerating hydrogen ice to hypervelocities has not been developed. In recent experiments, small frozen hydrogen pellets (about 0.1 mm) were successfully formed and injected into ORMAK [7] but only at velocities of 100 m/sec. Acceleration was accomplished by gas dynamic drag and it is believed that this technique can be extended with relative ease to reach velocities of about 1000 m/sec. The magnitude of the problem associated with attaining higher speed is

made clear by recognizing that at 10^4 m/sec each molecule in the pellet acquires about 1 eV of directed kinetic energy. Since the binding energy of the solid hydrogen phase is only about 0.01 eV, it is apparent that any acceleration scheme must be highly efficient in the sense that only a very small fraction of the energy involved could be permitted to appear as internal energy or heat. This criterion alone would ostensibly eliminate many of the known hypervelocity techniques that rely on strong impulsive loading of the pellet for acceleration.

Pellet Ablation Scaling Law

In addition to the work of Gralnick, a recent pellet ablation theory was proposed by Parks, Foster and Turnbull [8] to explain the observed behavior of pellets injected into the research tokamak, ORMAK [7]. The model accurately predicts the observed pellet lifetimes under the conditions investigated (ORMAK edge plasma parameters). The essential difference between this latest theory and that proposed by Gralnick is in the treatment of the interaction of the hot plasma with the pellet surface. Gralnick assumes that the incident plasma electrons evaporate ion pairs from the surface and that the resultant warm plasma cloud partially shields the pellet from the hot plasma by Coulomb collisions. The energy input required for the solid-to-plasma phase transition at the surface is the 32 eV corresponding to dissociative ionization of molecular hudrogen. In the model of Parks, et al., the assumption is made that a cold neutral gas ic created at the surface and that the expanding neutral cloud shields the pellet by providing a dense medium for inelastic collisions with incoming

electrons. The energy requirement for this neutral ablation process is the 0.01 eV corresponding to the latent heat of evaporation of hydrogen. The key elements of the two theories differ widely but the predictions agree surprisingly well for a plasma representative of TNS. The neutral ablation model lends itself more easily to numerical calculations and a pellet lifetime scaling law can be extracted from it easily.

Larger pellet radii contribute to longer lifetimes and this effect tends to relieve the requirements for high injection velocities. However, pellets cannot be made arbitrarily large, but must be limited to sizes that contain no more than a small fraction of the total plasma ion content. In terms of this fractional value f and the plasma volume V, the expression for the pellet lifetime τ reduces to

$$\tau \propto 7.1 \times 10^{-3} \, (fV)^{5/9} \, n_e^{2/9} \, T_e^{-11/6} \qquad (1)$$

One important result is that pellet lifetimes are <u>increased</u> with plasma density and volume. This is due to the fact that large dense plasmas will accommodate bigger pellets which provide a more effective gas dynamic shield. High β operation affords a slight but definite advantage in this respect.

The most important parameter in this scaling law is the plasma energy and it is this fact that may make hotter plasmas difficult to fuel. To demonstrate this we take as typical average parameters for TNS the values $n_e = 2 \times 10^{20}/m^3$, $T_e = 13$ keV, $V = 250\ m^3$. Assuming that pellets contain 10% of the plasma ion content ($f = 0.1$) a characteristic lifetime of 40 μsec results. If the pellet must

penetrate 0.60 m to the center of the TNS shifted plasma, characteristic velocities in the 10^4 m/sec range are required. Non-circular shifted plasmas might offer significant advantages with respect to injection velocity requirements since pellets can be injected along the plasma minor axis from the outer wall which is closest to the plasma center. Because of the projected high velocity requirements, perpendicular injections seems wise.

Calculated fueling parameters for various experimental tokamaks are presented in Table Table III based upon the complete neutral ablation model and accounting for the variation of plasma parameters along the pellet trajectory. Pellet radii were limited to values that would contribute only 10% of the plasma ion content. It is clear that velocity requirements become more demanding as plasma parameters progress toward breakeven values. The 6000 m/sec velocity projected for TNS is high but as will be shown in the following section, at least one acceleration scheme appears to be capable of providing this performance.

It should be noted that none of the various pellet ablation models have had sufficient experimental verification and, in view of this, the results presented here should be viewed only as approximate guidelines for future hardware development programs.

Pellet Acceleration Methods

Some of the methods that may be applicable to acceleration of the needed millimeter size D-T pellets to hypervelocities are listed in Table IV, along with estimates of velocity capabilities. Other schemes will undoubtedly be proposed in the future and so this

TABLE III

ESTIMATES OF EXPERIMENTAL PELLET FUELING REQUIREMENTS

For Pellets Containing 10% of Device Total Ion Content and for Perpendicular Injection. Parameters are Plasma Center Values.

Device	Device Characteristics a(m)	Te(keV)	ne(m^{-3})	Pellet Radius (10^{-6}m)	Velocity (m/sec)
ORMAK	0.23	1.0	7×10^{19}	220	2000
ISX	0.25	1.0	7×10^{19}	240	2000
ORMAK	0.30	0.9	1×10^{20}	300	1500
Upgrade		3.0+	1×10^{20}	300	5000
PDX	0.47/0.57	1.0	3×10^{19}	300	1500
		3.0+	1×10^{20}	475	3000
PLT	0.45	1.7	5×10^{19}	360	3000
		4.0+	1×10^{20}	450	6000
TNS+	1.25/2.0	20.0+	3×10^{20}	3000	6000

+with neutral beams.

+parameters chosen to preserve line average values.

TABLE IV

CATALOGUE OF ACCELERATING DEVICES FOR 1 mm RADIUS D-T PELLETS

Device	Speed (m/sec)	Comments
Gas dynamic Light gas gun	1000	Requires moderate working pressures and temperatures.
Electrostatic	600	Charging limit requires acceleration voltage = 13×10^6 V.
Laser rocket	500	Requires higher performance.
Electron beam rocket	2000	90% of pellet mass consumed as propellant.
Mechanical centrifuge	2500	Aluminum rotor.
	5400	Fiber composite rotor.

discussion is not intended to exhaust all possibilities.

No distinction is made between low pressure gas dynamic acceleration and the light gas gun because hydrogen pellets are not expected to survive the extremely high pressure atmosphere at which present design gas guns operate. The limit of 10^3 m/sec corresponds to the approximate speed of sound of hydrogen gas at ordinary working pressures and temperatures. Because of the proven performance of light gas guns, this device should not be excluded from consideration. Its exact capabilities with hydrogen pellets should be determined experimentally.

Electrostatic acceleration techniques are limited by the inability to attain sufficiently large charge-to-mass ratios on pellets above 1 μ size. The low tensile strength of solid hydrogen limits the amount of charge that a 1 mm pellet can accommodate (surface space charge fields $< 2.5 \times 10^8$ V/m).

It has been suggested that a giant laser pulse could be used to ablate a small amount of material from one side of a pellet to provide a large impulse fo acceleration. The strong shock wave that is transmitted to the pellet bulk imparts half of its energy as directed kinetic energy with the remaining half appearing as internal heat. The low binding energy of the condensed phase limits the strength of the shock wave and hence the velocity. A limit of about 500 m/sec has been estimated for this concept; but it is recognized that it needs to be explored. The use of a focused electron beam to provide an ablation driven acceleration is also possible. In a properly designed device, the velocity of the expanding material would not be

as high as that for the laser ablation concept and the impulse would be less severe.

The final acceleration concept considered is a purely mechanical device that would utilize centrifugal forces to accelerate pellets outward along the arms of a rotating arbor designed for optimum peripheral, or tip, speeds. In the present concept, pellets would be introduced at the arbor hub after being cut from a continuously extruded filament of solid hydrogen and would be guided by channels formed in the arbor arms to the tip where they leave with equal components of radial and tangential velocity. Present designs attain tip speeds of 1800 m/sec using high strength aluminum alloys as the material of construction in the arbor. This should provide pellet velocities of the order of 2500 m/sec. For this device, performance varies as the square root of the strength-to-weight ratio of the material used. Several fiber composite materials exhibit strength-to-weight ratios several times larger than that of aluminum. Highest performance would result from a choice of either Kevlar 49 or Thornel 300 fibers embedded in an epoxy resin matrix. Pellet velocities as high as 5400 m/sec are indicated with 1 m diameter rotors operating at 1000 Hz rotational speed. Development of this device might lead to a slight increase in performance, but velocities higher than 10,000 m/sec do not seem possible.

Of the concepts considered here, the centrifugal accelerator appears to be the most practical solution for a TNS fueling device with 6000 m/sec capabilities. The gas gun is a likely back-up device although it has not been proven with hydrogen pellets. If the

theoretical predictions probe to be correct, it is clear that the most advanced type of accelerator will need to be developed.

Tritium Recycle in TNS

The tritium recycle system for TNS will remove unburned fuel, ash (helium), and impurities from the divertor chamber; purify the unburned fuel by removing helium and other impurities; separate high purity deuterium for recycle to the neutral beam injectors; prepare a small hydrogen purge stream for discharge; supply suitable fuel surge and storage capacity; and provide containment sufficient to hold tritium exposures and releases to acceptable levels. The ORNL design for a TNS tritium recycle system is expected to resemble that proposed for EPR. This would be a system with essentially the same process components expected to be used in EPR, and they could be easily applied to even larger devices.

Removal of fuel from the divertor chamber will require a vacuum pump with high pumping speeds, complete containment of tritium, complete recovery of fuel, minimum probability for adding contaminants to the plasma, and ability to operate under the space restrictions, radiation fields, and magnetic fields around the torus. A compound cryosorption pump is recommended with separate sorption panels for pumping the unburned D-T fuel and the helium ash. The fuel can be pumped by a molecular sieve panel cooled to approximately 15°K; helium can be pumped by a similar panel cooled to 4.2°K (liquid helium temperature). The 4.2°K panel would be located "behind" the 15°K panel so only a minimum amount of fuel would reach the helium pump. The most likely alternative to this would be substitution of

a 4.2°K cryocondensation panel for the 15°K cryosorption panel in the fuel pump. All other pump systems considered failed to meet one or more of the TNS requirements.

In the compound pump system just proposed, considerable separation of helium from the fuel will be accomplished in the vacuum pump itself. The final purification step would take place in beds of hydride-forming materials, probably uranium. These beds can be operated to remove all likely impurities (He, oxygen, carbon, nitrogen, etc.), and they will serve other purposes as well. They will provide necessary surge capacity at low pressures and fuel accumulation capacity in the event that the pumps or other portions of the fuel recycle system loses refrigeration. Other purification systems have been considered, particularly permeable Pd membranes, but these require compressors, or at least transfer pumps, which are undesirable and do not appear to be necessary.

To supply a high purity deuterium stream for the injectors, an isotope separation system will be required. The most promising isotope separation technique for TNS (and later fusion devices) is cryogenic distillation. This is a well established technique, and it appears to be clearly the most economic technique, principally because of the low tritium inventory and energy costs. One column would produce the high purity deuterium stream, and a second smaller column would process a portion of the deuterium to produce a hydrogen stream for discharge.

Tritium containment is usually associated with the fuel recycle system partly because most of the TNS tritium inventory (hazard) will

be associated with the recycle system. Since tems of millions of curies of tritium will be used and stored in TNS, a most effective and reliable containment system will be required. We suggest a multi-level containment system with active atmosphere process systems to remove tritium at each level. The fuel recycle system will be constructed as compactly as possible once allowances are made for convenient maintenance of all components. All portions containing large quantities of tritium or significant probabilities for tritium release will be contained in a tight enclosure with continuous processing of the atmosphere to hold the tritium concentration low enough to prevent unacceptable releases of tritium from diffusion and leaks through the enclosure and from the necessary exhaust to the atmosphere. In addition, an emergency tritium cleanup system is required for the much larger reactor room.

Although the tritium recycle system may not be either the most expensive system to build or the most difficult system to develop for TNS, it certainly will be one of the most critical systems because of the crucial role it plays in containing the relatively hazardous tritium containing fuel and preventing excessive contamination of either the TNS equipment or the environment. The TNS can serve as a test stand for many components of tokamak fusion reactors, but it will be necessary to have a high reliability tritium system for TNS. Most of the development and testing of the tritium system should precede TNS, and we have proposed a relatively rapid development and testing program to assure that the components we have selected can fit into a working tritium recycle system. This assurance will be

needed by the time the design for TNS is finalized, perhaps as early as 1980. This requires detailed design of a major tritium test facility to begin almost immediately, and construction should begin within a year.

Conclusion

The physical uncertainties in the TNS version of the PDFD will be addressed by an array of experiments over the next five years. The beams and superconducting magnets are also under development on a large scale. These programs expect to have minimally acceptable products for TNS by 1980. The pellet fueling and the tritium handling systems require the largest increase in effort in the immediate future but promising techniques exist in both areas. We conclude that with a reasonably aggressive development program, firm answers to the questions existing in the TNS design can be obtained by 1980. This would allow this PDFD to be in operation by 1987.

REFERENCES

1 CALLEN, J. D, CLARKE, J. F., ROME, J. A., "Theory of Neutral Injection into Tokamaks, Paper E14, Third Internation Symp. on Toroidal Plasma Confinement, Garching (1973).

2

3. UCKAN, N. W., TSANG, K. T., CALLEN, J. D., "Effects of the Poloidal Variation of the Magnetic Field Ripple on Enhanced Heat Transport in Tokamaks", ORNL/TM-5438, Oak Ridge (1976).

4 ROBERTS, M., Ed. "Oak Ridge Tokamak, EPR Study", ORNL/TM-5572-77, Oak Ridge (1976).

5. CLARKE, J. F., "High Beta Flux Conserving Tokamsks", ORNL/TM-5429, Oak Ridge (1976).

6 GRANLICK, S. L., Nuclear Fusion 13 (1973) 703.

7 FOSTER, C. A., et al., Bull. Am. Phys. Soc. 10 (1975) 1300.