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Linear Plasma-Based Tritium Production Facility

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Concept

A schematic diagram of a 5 kg/yr tritium breeder is shown in Figure 1. The system is simply a long fully ionized dense tritium plasma column confined radially by a linear magnetic field. An intense flux of 14-MeV neutrons is produced by transverse injection of 150-keV deuterons into the tritium plasma, which is sufficiently dense to essentially stop all of the beams. The trapped deuterium ions collide with tritium target ions maintaining the D-T fusion reaction rate. The energetic ions are confined radially by the magnetic field and longitudinally by magnetic mirrors. Through collisions the hot ions lose their energy to the plasma electrons, which in turn ionize and heat the tritium component and thus maintain the plasma target. All injected power is transported by electron thermal conduction along a solenoidal guide field to end regions where it is absorbed in neutral tritium gas at high pressure. The high-density tritium serves two functions: it is the source of tritium for the plasma column, and it prevents the erosion of the end walls by the hot plasma column. Ions entering the end chambers are cooled and either recombined with electrons or reach the walls with energies below the thresholds for sputtering. Power loading at the walls is reduced to values that can be handled by conventional cooling technology. In principle part of the energy can be recovered to reduce power consumption and thus lower operating costs. This option has not been evaluated and is not included in the estimates given below.

The concept presented here is an adaptation of a recently completed conceptual design[1] of a compact high-fluence D-T neutron source for accelerated end-of-life testing of fusion reactor materials. Although this preliminary assessment serves to illustrate the main features of a linear plasma-based tritium breeder, it is not necessarily an optimized design. We

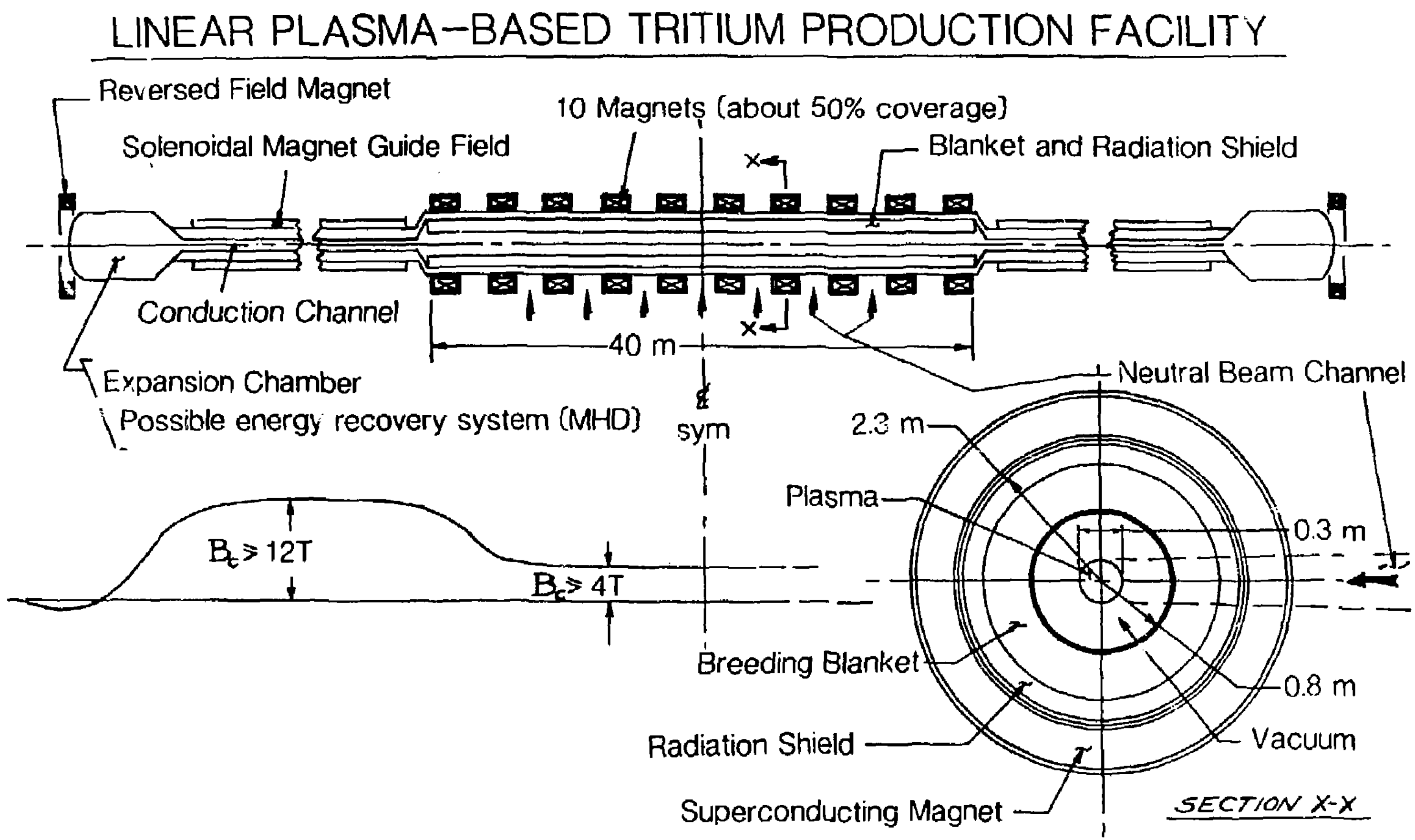
LINEAR PLASMA–BASED TRITIUM PRODUCTION FACILITY
Reversed Field Magnet
Solenoidal Magnet Guide Field
10 Magnets (about 50% coverage)
Blanket and Radiation Shield
X
Conduction Channel
40 m
Expansion Chamber
Possible energy recovery system (MHD)
sym
Neutral Beam Channel
2.3 m
Plasma
0.3 m
$B_t \geq 12T$
$B_c \geq 4T$
Breeding Blanket
0.8 m
Radiation Shield
Vacuum
Superconducting Magnet
SECTION X-X

Figure 1

believe that proper design choices for the breeder application will certainly reduce costs, perhaps as much as a factor of two. We also point out that Q (the ratio of fusion power produced to power input to the plasma) increases with system length and that the cost per kg of tritium decreases for longer systems with higher output (see Table 1). In earlier studies of linear two-component plasma systems, Q values as high as three were predicted. At this level of performance and with energy recovery, operating power requirements of the breeder could approach zero.

Similar values of Q are obtained in recent Soviet studies of long linear mirror system. They discuss development of these systems for production of fissile fuel and tritium.

Physics and Technical Basis

The physics and technology data base for the breeder design has been developed in the magnetic fusion program over a considerable time span and has extensive verification. This data base was summarized by Molvik[2]. The breeder plasma design closely resembles that of the 2XIIB experiment, which was operated at LLNL from October 1973 to October 1978 and demonstrated stable operation of a two-component plasma.[3] Notable among the achievements in that experiment was the demonstration of stable confinement of high-β plasmas, which are needed for economic operation of the breeder. β is the ratio of plasma energy density to magnetic field energy density. Also 2XIIB experiments confirmed the theoretically derived conditions for control of high-frequency fluctuations (i.e., mirror mode microinstabilities). Recent work on MHD stability in axisymmetric systems is reported by Molvik et al.[4] Much of this work was carried out in a US/USSR collaborative effort on the Soviet Gas Dynamic Trap experiment at the Institute for Nuclear Physics, Novosibirsk, USSR.

All technologies needed for the tritium breeder are within the state of the art. The 150-keV neutral beams will be demonstrated on JET in the spring of 1989 for a duration of 10-20 sec. All components are essentially at steady state. A longer lived cathode is desirable since present filaments are estimated to have a 2-week lifetime in steady state operation. Superconducting magnets of 12-T fields were demonstrated during MFTF acceptance tests. The blanket technology is based on existing designs.

Development

We believe that a tritium breeder based on a linear plasma system could be an alternative for a production facility, and we recommend a serious design effort be initiated at this time. To make the transition from the existing physics and technology facilities to a safe, reliable, continuously operating production facility as soon as possible, a test section of a full-sized breeder could be initiated following the design study. This test section would first be run using hydrogen to avoid neutron radiation and activation problems during development of continuous operation of neutral-beam systems, power removal and/or energy recovery, and remote-controlled operation and maintenance. All safety aspects of the facility would also be perfected and demonstrated in the hydrogen operation phases. Once reliability and safety are demonstrated, the test section would be operated as a tritium breeder to perfect blanket technology and tritium extraction. Based on our cost analysis of the intense neutron source, we estimate the construction cost of a 200-MW test section to be approximately $250 M.

In a more conservative approach to develop the breeder, the integrated physics design and power handling techniques could be verified first, using lower energy beams at lower power. Based on previous estimates, a pulsed 20-MW test facility could be constructed at LLNL using existing equipment for approximately $10 M in about 1 year.

Table 1. Performance Parameters

	System & Length	
	2000 m	40 m
Unit size (kg T/yr)	18.0	5.0
Capital costs (1×10^9 $)	2.5	1.6*
Power required (MWe)	2000.0	1400.0
Operating and maintenance costs (1×10^6 $)	550.0	350.0
Number of units to produce 5 kg T/yr	0.28	1.0
Q	0.7	0.3

*Blanket and tritium recovery system not included.

Cost Basis

To estimate construction and operating costs, we note that the size of the system is essentially proportional to the required power, which is estimated as outlined below. Costs are then obtained by scaling our estimates for the intense neutron source. For the 5-kg/yr facility, the estimated construction cost is $1.6 billion without tritium breeding blankets or extraction facilities. Opereting costs are strongly dependent on power costs and energy recovery.

As stated above, the dominate heat loss is the electron thermal conduction from the hot plasma core to the gas target in each end cell. For a cylindrical plasma column, this power flow is given by

$$\text{Flow power} = (4\Pi a^2/l_c) \int K dT_e$$

where $K = 9.3 \times 10^{13}(T_e)^{5/2}$ W/m-keV with T_e expressed in keV. The coefficient of thermal conductivity was derived by Spitzer and Harm.[5] For a gaussian radial profile, the fusion power is

$$\text{Fusion power} = n_h n_w \langle\sigma v\rangle E e \Pi a^2 l_h/2$$

where n_h and n_w are the peak densities of the hot and warm plasma, respectively; l_h is the length of the plasma column occupied by the hot ions; and a is the radial e-folding length of the plasma. Q is defined as

$$Q = \text{fusion power/flow power} = 1.47 \times 10^{-24} \langle\sigma v\rangle n_w n_h (l_c l_h R)/(T_e)^{7/2}$$

for cgs units except T_e is expressed in keV. For a neutral-beam efficiency of 30%, the tritium production rate becomes

$$M_t/E = 12.7 \text{ Q kg/GW-yr}$$

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