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TRITIUM SYSTEM DESIGN FOR THE MIRROR REACTORS FPD-I, FPD-II, AND FPD-III*

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TRITIUM SYSTEM DESIGN FOR THE MIRROR REACTORS FPD-I, FPD-II, and FPD-III

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ABSTRACT

The tritium system design for the Fusion Power Demonstration Reactor (FPD-I, II, and III) is described. The device operates at 25% availability. For FPD-II, an engineering mode using tritium neutral beams is part of the design.

I. INTRODUCTION

The Fusion Power Demonstration Device,¹ a deuterium-tritium burning device, is viewed in the tandem mirror program as the next logical step toward a power reactor after MFTF-B.² It was considered prudent therefore to explore both the physics and engineering options possible in the range of 100 to 500 MW of fusion power. Three options were considered. 1) FPD-I, a 360-MW device; 2) FPD-II, a 479-MW device; and 3) FPD-III, a 156-MW device. Two major assumptions were made: 1) 25% burn during a year and 2) self-sufficiency in tritium fuel. This paper describes and compares the tritium system design for each of these options.

II. REACTOR DESCRIPTION

The common features of tandem mirror reactors are: 1) a center of symmetry; 2) several central cell modules each composed of a vacuum space (~0.45 m in diameter) encircled by a cylindrical blanket/shield segment which is in turn encased in a cylindrical magnet; and 3) an end cell which contains the direct converter, the plugging magnets, halo scraper, etc. If an engineering test cell (termed an axicell) is present, it is located at the reactor's center of symmetry. A schematic of FPD-II, the only option with an engineering test cell is shown in Fig. 1. The design of FPD-I is quite similar to FPD-II's if one removes the axicell and a set of central cell modules. The FPD-III design which is the shortest reactor option, has no axicell, has the fewest central cell modules and also has a simpler set of plugging magnets in the end cell in an octupole configuration.³

The important differences between these options for tritium system design are the following: 1) For a given burn efficiency, the tritium and deuterium throughput is directly proportional to the fusion power. Therefore, since the fusion power increases from 150 MW for FPD-III to 360 MW for FPD-I to 479 MW for FPD-II, the mass flow rates increase proportionately. 2) Since the FPD options by definition are to be self-sufficient in tritium, i.e. breed all they need to replace that burnt, decayed or lost to waste, the higher the fusion power, the more tritium that must be bred. 3) As the fusion power increases, so too does the size of the reactor, the volume of the reactor vault and the volume of the building containing auxiliary tritium-contaminated systems. Since a similar plant layout was chosen for each option (Fig. 2), the volume of tritium contaminated air which must be treated increases as the fusion power increases. The important buildings to be considered are: the reactor vault, the hot cell, the tritium processing building, and the heat exchanger building. The relative volumes of these buildings are; $4.9 \times 10^4 \text{ m}^3$, $2.1 \times 10^4 \text{ m}^3$, $1.6 \times 10^4 \text{ m}^3$ and $3.2 \times 10^4 \text{ m}^3$ for FPD-I; $6.1 \times 10^4 \text{ m}^3$, $2.4 \times 10^4 \text{ m}^3$, $1.6 \times 10^4 \text{ m}^3$, and $4.3 \times 10^4 \text{ m}^3$ for FPD-II; $3.7 \times 10^4 \text{ m}^3$, $1.4 \times 10^4 \text{ m}^3$, $1.6 \times 10^4 \text{ m}^3$ and $1.4 \times 10^4 \text{ m}^3$ for FPD-III. 4) All three designs are assumed to have a 25% availability. The burn cycle consists of 100 h of continuous burn.

III. TRITIUM SYSTEM DESIGN

The types of tritium systems needed in a self-sufficient deuterium-tritium fusion reactor are of four types: 1) systems to supply and reprocess the fuel the reactor uses during a burn; 2) systems to process tritiated waste in the plant, this includes tritiated water; 3) systems to control tritium losses to the environment during maintenance or during an accident; and 4) systems needed to both recover tritium from the blanket and to control tritium losses to the environment from the blanket and the heat exchange system. The first two systems are usually grouped together.

FUSION POWER DEMONSTRATION (FPD)-II

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Fig. 1. Schematic of FPD-II.

Fig. 2. Layout of FPD-II.

TABLE 1. TRITIUM AND DEUTERIUM MASS FLOW RATES (g/h) FOR FPD-I, II AND III¹

	FPD-I		FPD-II		FPD-II(E) ²		FPD-III	
	T	D	T	D	T	D	T	D
Total Feed ⁴	8.8	11.9	9.2	20.0	19.3	32.5	3.8 ³	9.8
Pellet Feed ⁵	4.4	5.9	(4.6)	(6.3)	----	----	1.9	2.6
Pellet Waste ⁵	4.4	5.9	4.6	6.3	----	----	1.9	2.6
(-) Beam Feed ⁶	---	0.3	---	0.7	----	0.7	---	0.5
(-) Beam Waste ⁶	---	2.3	---	(6.7)	----	6.7	---	4.1
(+) Beam Feed ⁷	---	---	---	---	5.8	7.9	---	---
(+) Beam Waste ⁷	---	---	---	---	13.5	18.2	---	---
Reactor Exhaust	2.1	4.8	(1.5)	(5.0)	2.7	5.6	0.9	2.4
Total Exhaust	6.5	13.0	6.1	18.0	15.2	30.5	2.8	9.1
Burn	2.3	1.5	3.1	2.0	3.1	2.0	1.0	0.7
Breed	2.4	---	3.1	---	(3.1)	---	1.0	---

¹ Tritium is designated T. Deuterium is designated D. A ratio of 2:1 deuterium/tritium is assumed.

² The engineering mode is designated (E).

³ If a 1:1 ratio is assumed, this design would require 5.8 g/h (T) and 6.1 g/h (D).

⁴ The total needed current is 0.235 A for FPD-I; 0.249 A for FPD-II; 0.311 A for FPD-II(E); and 0.102 A for FPD-III. The improved performance for FPD-II and FPD-III versus FPD-I is due to improved plasma physics in these latter designs.

⁵ An efficiency of 50% is assumed.

⁶ An efficiency of 10% is assumed.

⁷ An efficiency of 30% is assumed.

The design of each of these systems is dependent somewhat on the options chosen in designing the reactor. These options will now be described.

A. Fuel Processing

The reference method of fueling in the FPD designs is by pellet fueling. (The use of lasers was being examined for FPD-III.) The wastage expected using a pellet fueler is equal to the input rate. For FPD-II, both tritium and deuterium neutral beams are used during the engineering mode. Since the overall delivery efficiency of positive neutral beams is 30%, the wastage in the engineering mode is equal to 2.3 times the input rate. Besides the main fuel system, all three options use deuterium negative (-) neutral beams in the end cells to assist in plugging the plasma. These beams have a delivery efficiency of 10%. The wastage is 10 times the input rate.

To design the fuel processing system, the number and relative magnitude of the reactor inlet and outlet streams needs to be determined. A summary of the mass flow rates for each design is found in Table 1. An example is shown in the circled items under FPD-II, i.e. 4.6 g of tritium arises from pellet

wastage, 13 g of deuterium from pellet and negative neutral beam wastage and 6.5 g of a deuterium/tritium mixture from the end cell exhaust each hour. Thus for each design, there are three exhaust streams and three inlet streams (tritium pellet, deuterium pellet, deuterium (-) beam). The function of the fuel processing system is to remove impurities and to provide the desired isotopic ratio (2:1 D/T). The two basic units needed are a fuel cleanup unit and an isotopic separation unit. Several systems are grouped with these two units. They include a tritium receiving station, shipping containers, storage systems, analytical systems, secondary confinement systems, tritium monitors, control systems, and last, systems for handling gas, solid and water waste. In total these systems enable the reactor to burn tritium. A detailed description of these systems has been given.^{4,5} The capital cost for the fuel processing system is shown in Table 2 for the three designs.

B. Tritiated Water Waste

A tritiated water recovery unit (CECE) is used in a tritium facility in several ways. First, it is an effective means of reducing water waste both during plant operation and during decommissioning. Second, it is a

TABLE 2. COMPARISON OF THE TRITIUM SYSTEM CAPITAL COSTS (\$M) FOR FPD-I, II, III

System/Design	I	II	III
Fuel processing ¹	28	28	26
ATR ²	29	33	23
Blanket recovery	58	75	27
Total	115	136	76

¹ A tritiated water recovery system is included in this cost.

² A five day cleanup is assumed for the atmospheric tritium recovery system.

system which can be used to control the tritium concentration in water coolants or heat exchange systems. There are three areas in the FPD designs where implantation of tritium is a potential problem. These are: 1) the beam dumps for the positive tritium beams; 2) the halo scraper in the end cells; and 3) the outer and inner collectors of the direct converter also in the end cells. The first area is a problem only for FPD-II(E). The tritium inventory in the beam dumps and in the coolant was estimated.⁶ For copper beam dumps, the tritium inventory in the dump is < 1 g. In the water coolant it is $\sim 1 \times 10^3$ Ci after 3 years, $\sim 5 \times 10^3$ Ci after 6 years, and 2.2×10^4 Ci after 8 years if no processing is done. In a system containing $10^4 - 10^5$ L, this corresponds to a concentration range of .01 Ci/L to 2.2 Ci/L.

The other two areas are problems for all three designs. An estimate⁷ was made of the magnitude of the problem for FPD-II. Using copper at low temperatures ($< 125^\circ\text{C}$), the total tritium inventory in the copper halo scrapers and collectors is ~ 2.5 g. Tritium is expected to reach the coolant at a rate of ~ 38 Ci/d at steady state if clean surfaces are assumed. This influx corresponds to a tritium inventory in the coolant of 0.34 g (~ 0.03 to 0.3 Ci/L) in the first year after steady state rates are attained. This may occur in ~ 5 years. Thus in the latter years of operation, the worker hazard due to tritiated water increases significantly. Therefore, it is considered prudent to include in the reference design of each of these systems, a tritiated water recovery unit capable of processing ~ 100 L/D. The capital cost of this unit is \$6 M. It is included in the capital cost of the fuel processing system (Table 2).

G. Atmospheric Tritium Recovery Systems

The design of atmospheric tritium recovery systems in recent years has assumed that ventilation efficiencies are 100%. In the chemical industry,⁸ the best efficiency is 33% with some systems being as poor as 10%. This

efficiency has a significant effect on the effectiveness of the planned performance of the atmospheric tritium recovery systems. A summary of the effect of ventilation efficiency on the ATR for the FPD-III design is shown in Fig. 3.

Fig. 3. The total capital cost of the atmospheric tritium recovery system for FPD-III, sized for a 10 g tritium release. (No surface effects are assumed.)

Case 1, the system recommended has a 0.5 vol%/min cleanup rate. This system would achieve cleanup of a 10 g tritium release in a given FPD-III area to $50 \mu\text{Ci}/\text{m}^3$ in 5 days if the ventilation system was 33% efficient, the optimum efficiency. This assumes that adsorption and subsequent release of tritium on surfaces is not a problem. This same system would also provide cleanup to $50 \mu\text{Ci}/\text{m}^3$ in ~ 10 days if the efficiency was 20% or in ~ 20 days if the efficiency was 10%, the worst case.

Case 2 is currently assumed in most designs, i.e. $E = 1.0$. This results in a 10 M\$ system being the reference design. However, since the optimum ventilation efficiency is ~ 0.33 , it would take the system in Case 2 ~ 20 days to achieve cleanup to $50 \mu\text{Ci}/\text{m}^3$ or 60 days if E was 0.1. For FPD-I and FPD-II, similar analyses were done to determine equivalent design points for $E = 0.33$. The capital

costs are shown in Table 2.

D. Blanket Tritium Recovery System

The tritium needed to replace that burnt, that lost to radioactive decay and that lost to waste is shown in Table 3 for FPD-II. The value of the tritium bred (6.8 kg/yr) is ~70 M\$/yr. For a 10 yr operating life, this amounts to 700 M\$. The value of including a blanket and a blanket tritium recovery system in the FPD designs is driven by this cost consideration.

TABLE 3. MINIMUM TRITIUM BREEDING RATIO FOR SELF SUFFICIENT FPD-II¹

Breeding Ratio	1.01	1.02	1.03	1.05	1.07
Tritium bred (g)	6750	6817	6885 ²	7018	7152
Tritium burn (g)	6684	6684	6684 ²	6684	6684
Tritium decay (g)	~ 20	~ 20	~ 20	~ 20	~ 20
Tritium waste (g)	46	113	181	314	448
Z	0.1	0.2	0.3	0.5	0.9

¹ Assuming 25% availability.

² The corresponding numbers for FPD-I and FPD-II are 5173/5023 and 2242/2176.

The blanket material chosen for FPD is ¹⁷Li83Pb; the structure is ferritic steel. The blanket tritium recovery system consists of several components. They include: 1) a tritium removal system for the ¹⁷Li83Pb, A; 2) an impurity removal system for the recovered tritium, B; 3) a tritium removal system in the heat exchanger, C; 4) an impurity removal system for ¹⁷Li83Pb, D; and 5) a dump tank for the ¹⁷Li83Pb, E. The estimated unit cost for each of these systems for the FPD-II design was estimated at \$15 M, \$15 M, \$20 M, and \$20 M for a total of \$75 M. See Ref. 9 for a discussion of the costing methodology. The volume which this system would occupy is estimated at ~800 m³. A schematic of these systems is shown in Fig. 4.

In determining the cost of the tritium extraction and the tritium control system, a cost tradeoff is needed since an extraction system which did not reduce the tritium partial pressure in the ¹⁷Li83Pb would require a larger tritium control system in the heat exchanger. This tradeoff is shown in Fig. 5 for a 400 MW fusion plant using ¹⁷Li83Pb as a blanket.

An algorithm was derived using the individual costs of the subsystems, A through E, to predict the total capital cost of the blanket recovery systems needed for each of the FPD designs. The algorithm is:

Fig. 4. Blanket tritium removal system for self-cooled ¹⁷Li83Pb (FPD-II).

Fig. 5. Minimization of total capital cost for tritium recovery from ¹⁷Li83Pb (~400 MW plant).

$$\text{Cost } (\$M) = \frac{5 \times 10^4 (\text{TPPD})^{0.9}}{\text{ppm}^{0.5} + 0.001} \quad (1)$$

where TPD is the tritium bred per day and ppm is the weight part per million tritium in $^{171}\text{Li}^{83}\text{Pb}$, the given blanket for FPD. The capital cost derived from this algorithm for each FPD design is shown in Table 2.

E. Tritium Inventories

The major areas in which tritium is found are in the reactor proper, the blanket and the associated processing system and in the tritium fuel processing building. The amount present in various systems is often contingent upon the assumptions that are made for the design. For the FPD design, some important assumptions are these. 1) For each tritium system design, there is in reserve storage 2 hours of tritium input. This is 18, 18, and 8 g for the respective designs. 2) For each system the tritium inventory in the blanket recovery system is equal to one day's breeding. This is 57, 75, and 25 g, respectively for FPD-I, II, and III. 3) The pellet feed (reference fueling system) contains a base inventory of 10 g plus one hour's fueling needs, i.e. 19, 19 and 14 g. (This ensures minimal problems in the 100 h burns assumed.) 4) The structures category includes not just the beam dumps, direct converters, etc. but also all piping and structural components throughout the fusion plant. (This number is a gross estimate since the FPD designs are preconceptual designs.) A summary of the inventory for all three designs is shown in Table 4.

IV. COMPARISONS

For each of the designs, capital costs were determined. The total is equal to the sum of the cost of the fuel processing system, a blanket recovery system, and the atmospheric tritium recovery systems. The total costs for FPD-I, II and III are shown in Table 2. As seen the capital costs are essentially the same ~\$30 M for the basic fuel processing units which include all secondary systems for containment of tritium. The atmospheric tritium recovery system (ATR) costs increase from \$23 M for FPD-III, the design with the smallest building volumes (test cell, tritium building, hot cell, heat exchanger building) to \$33 M for FPD-II, the design with the largest building volumes. The volume range is $8.1 \times 10^4 \text{ m}^3$ to $1.4 \times 10^5 \text{ m}^3$.

A comparison of the tritium system parameters for FPD-I, II, and III is summarized in Table 5. The main conclusions that can be made are these.

1) For a fusion device run at 25% availability at the power levels suggested for FPD (150 to 500 MW), the same basic tritium fuel processing system could be used for either pellet fueling or neutral beam fueling. The base tritium inventory for this processing system would range from 140 to 150 g of tritium.

TABLE 4. COMPARISON OF THE TRITIUM INVENTORIES (g) FOR FPD-I, II, III

System/Design	I	II	III
Structures	30	30	30
Pellet feed	19	19	14
Fuel cleanup	42	42	41
Isotope separation	52	52	51
Reserve storage	18	18	8
Blanket recovery	57	75	25
Blanket	1	1	1
Total	219	237	170

¹ Includes all structural components in the fusion plant in contact with tritium.

TABLE 5. COMPARISON OF THE TRITIUM SYSTEM PARAMETERS FOR FPD-I, II, III AT 25% AVAILABILITY

	I	II	III
Fusion power (MW)	360	479	156
Burn (kg/y)	5	7	2
Minimum input ¹ (g/h)	13 ²	14 ³	6
Minimum inventory (g)	219	237	170
Estimated cost ⁴ (\$M)	115	136	76

¹ Pellet fueling is assumed.

² FPD-I had a lower fractional burn than -II and -III.

³ Use of tritium neutral beams for the engineering test cell requires ~30 g/h as minimum input.

⁴ Building and reactor size increased as II > I > III.

2) The minimum tritium input is attained with pellet fueling at the lowest fusion power (FPD-III).

3) FPD-III could be designed without a blanket since tritium needs are 2 kg/yr which could be supplied from outside sources. This action would reduce capital costs by \$27 M but would increase operating costs by \$21 M/yr (\$1.10 per Curie for tritium).

4) The cost of the tritium systems is dominated by blanket and ATR costs as the fusion power is increased to 479 MW.

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