NUCLEAR DESIGN AND ANALYSIS OF THE FUSION TRANSMUTATION OF WASTE REACTOR

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The nuclear design and safety analyses for the Fusion Transmutation of Waste Reactor (FTWR) are described. The advantages of sub-critical operation for nuclear stability and safety are illustrated.

KEYWORDS: *fusion transmutation, sub-critical reactor*

I. INTRODUCTION

We are developing the concept of a Fusion Transmutation of Waste Reactor (FTWR)—a sub-critical, metal fuel, liquid metal cooled fast reactor driven by a tokamak DT fusion neutron source. The emphasis in our work is on using nuclear, separation/processing and fusion technologies that either exist or are at an advanced state of development and using plasma physics parameters that are supported by the existing database. We have previously discussed the general capabilities of DT tokamak neutron sources for driving transmutation reactors[1] and developed a design concept for a FTWR.[2] The purpose of this paper is to describe the nuclear design and analysis for the FTWR concept.

II. CORE DESIGN

The reactor core approximates an annular ring of inner radius 405 cm, thickness 40 cm and height 230 cm surrounding the toroidal plasma chamber on the outboard side. The layout of the FTWR is shown in Figure 1. This annulus consists of 360 vertical hexagonal assemblies and 180 half-assemblies of the type used in the IFR and ATWR designs,[3] with a 16.1 cm pitch. The assemblies are grouped into 90 core segments surrounded by a steel coolant channel. The core segments are aligned with the 90 flat plates used to form the outboard first-wall that surrounds the toroidal plasma (see fig. 2).

There are 210 fuel pins and 7 structural pins per assembly (117 fuel / 5 structural pins per half assembly) with a 6.35 mm O.D. and 1.08 cm triangular pitch. The fuel is a transuranic zirconium alloy (TRU-10Zr) dispersed in a zirconium matrix and clad with a ferritic steel (HT-9), with a maximum transuranic loading of 45 v/o. Each assembly is cooled by Li17Pb83 eutectic or PbBi eutectic. Steel clad B_4C control rods are inserted vertically between segments. The toroidal plasma and reactor core are surrounded (top, bottom, inboard and outboard) first by a neutron reflector (15% HT-9, 85% coolant) and then by a shield (24% HT-9, 18.4% coolant, 44.8% 20% enriched B_4C). In the PbBi 'solid breeder' design, a row of assemblies containing Li_2O is located just outboard of the core annulus for the purpose of tritium breeding.

The thermal power is maintained at a constant 3000 MW_{th} by compensating for fuel burnup by increasing the fusion neutron source strength. Most of the thermal power is from fission, but the fusion neutrons and other minor reactions contribute up to 120 MW by the end of cycle. The conditions were evaluated for the equilibrium fuel cycle for a 5 batch core with 99.9% of the actinides recycled and a transuranic feed consistent with the current inventory of spent nuclear fuel. The cycle length is 564 full power days for the liquid breeder design and 540 full power days for the solid breeder design.

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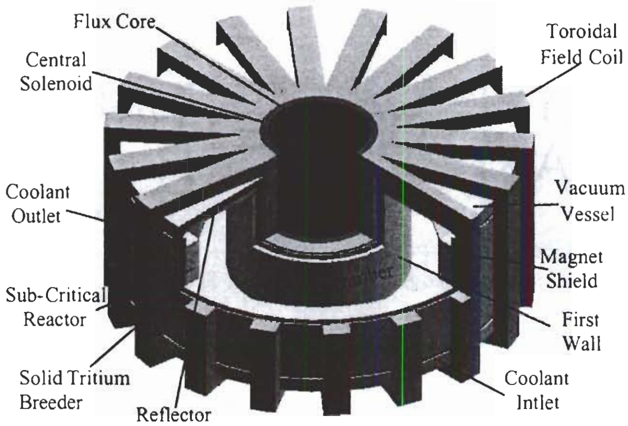

Fig. 1. Fusion Transmutation of Reactor Layout. Major Radius – 3.10 m, Minor Radius – 0.89 m, Magnet Radius – 1.81 m.

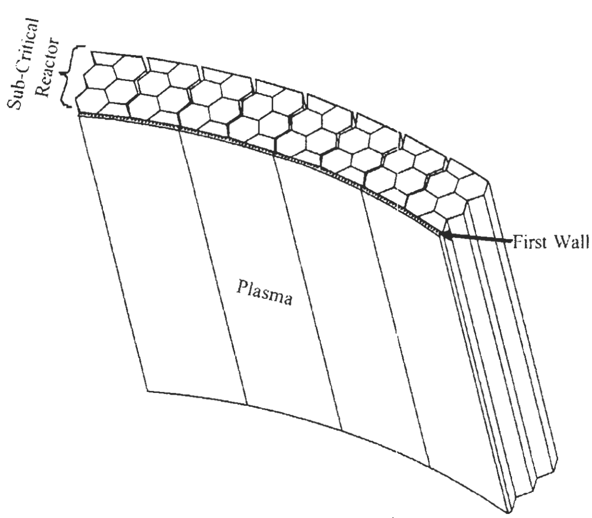

Fig. 2. Reactor Core.

III. NUCLEAR ANALYSIS

III.A. Neutronics Model

The FTWR was modeled in toroidally symmetric R-Z geometry that represented the plasma neutron source, core, reflector, shield, first-wall, magnets, etc. explicitly. A 2D, 34-group, S8 discrete ordinates neutronics calculation using the DANT[4] code with material-dependent multi-group cross section libraries was used. The material-dependent multi-group libraries were based on the ENDF/B-V.2 nuclear data library processed using the MCC-2 and SDX codes[5,6] for each of the reactor design concepts. The reactor core was divided into five radial regions of equal thicknesses and fuel volumes (varying fuel volume fractions).

The 2D RZ neutronics models and cross section libraries were verified by comparison with 3D continuous energy Monte Carlo calculations which modeled the core in explicit detail (i.e. at the pin level) using MCNP[7]. The tritium production rate, sub-critical multiplication, fission rate, and other parameters driving the design of the FTWR were verified. Comparisons were made using uniform fuel loadings where the TRU/Zr ratio was adjusted to obtain a range of multiplication factors. Table I shows the results for two comparisons for each design. The results implied that the complex geometry of the sub-critical reactors was adequately modeled in the TWODANT models. In general, most parameters showed good agreement with a tendency for the DANT model to under predict the tritium production and therefore over estimate the ^{6}Li enrichment required for tritium self-sufficiency.

TABLE I

RZ Model Verification Results

		Liquid Breeder		Solid Breeder	
Case	Parameter	MCNP	TWODANT	MCNP	TWODANT
1	Source Multiplication	16.6	15.7	16.1	13.7
	k_{sub}	0.940	0.936	0.938	0.927
	Tritium Breeding Ratio	2.06	1.87	1.77	1.36
	Fission per Fusion	4.79	4.71	4.65	4.05
2	Source Multiplication	7.84	7.77	6.73	6.20
	k_{sub}	0.872	0.871	0.851	0.839
	Tritium Breeding Ratio	1.00	0.994	0.640	0.573
	Fission per Fusion	1.88	2.07	1.54	1.57

III.B. Sub-critical Multiplication

The beginning of cycle (BOC)/end of cycle (EOC) values of the sub-critical multiplication constant, k_{sub}, were 0.925/0.836 for the LiPb 'liquid breeder' design and 0.913/0.836 for the PbBi+Li_2O 'solid breeder' design. The fusion power was adjusted over the cycle to compensate for the fuel burnup. The resulting BOC/EOC fusion power (MW) is 62/150 for the LiPb 'liquid breeder' design and 73/148 for the PbBi+Li_2O 'solid breeder' design.

III.C. Tritium Inventory

Time-dependent tritium inventory calculations including non-radioactive process losses[8] were performed to ensure that the design requirement for tritium self-sufficiency was met. The BOC tritium inventory must be sufficient to allow for the tritium produced in situ to be processed and made available. One month supply of tritium was assumed to be required at the BOC for the liquid breeder. The supply for the entire cycle is required for the solid breeder. In order to achieve tritium self-sufficiency, the EOC tritium inventory needs to be slightly higher than the BOC tritium inventory to account for radioactive decay and processing losses, which were modeled explicitly. The BOC/EOC tritium inventories (kg) are 0.18/0.59 for the LiPb 'liquid breeder' design and 11.02/12.09 for the Li_2O 'solid breeder' design. Both of these designs are producing more tritium than is required.

III.D. Stability

The stability of the reactor core against nuclear excursions was evaluated, using standard methods of nuclear reactor analysis.[9] Both designs had very similar heat removal properties. The heat removal time constants for the fuel elements and the flowing coolant were calculated to be approximately 0.5 s and 1.2 s, respectively. The stability was evaluated at a large number of points over a wide range of coolant (CTC) and fuel (FTC) temperature coefficients. The line of stability appeared to be linear. Figure 3 shows a least squares fit of the line of stability for the liquid breeder design for a critical and three sub-critical systems. This figure shows that for the critical system one or both temperature coefficients must be negative for a critical system to be stable. As expected, the more sub-critical a system, the larger the magnitude of the positive temperature coefficients that can exist and still maintain a stable system. For both the 'liquid breeder' and 'solid breeder' designs, the sub-critical FTWR was stable against power excursions even with large positive CTCs and FTCs of reactivity; by contrast, a critical reactor would be unstable under most conditions when both reactivity coefficients are positive.

The CTC was calculated taking into account only the temperature and density effects for the coolant. The thermal expansion of the structural material was not evaluated, but would be expected to provide a significant negative temperature feedback. With natural Li, the 'liquid breeder' design had a positive CTC of reactivity. Even though this preliminary design was stable, it may experience power excursions unless actively controlled, because of the positive CTC arising from the ^6Li in the fuel region coolant. The design was modified to have de-enriched Li (0.5%) in the core coolant and highly enriched Li (65%) in the coolant in the reflector/shield regions. The BOC/EOC CTC of reactivity (pcm/K) were –0.25/+0.13, which is still slightly positive at the end of cycle. For the solid breeder design the BOC/EOC CTC of reactivity (pcm/K) was -1.37/-1.11. The BOC/EOC Doppler FTC of reactivity (pcm/K) were -0.01/-0.03 for the liquid breeder design and -0.03/-0.02 for the solid breeder design.

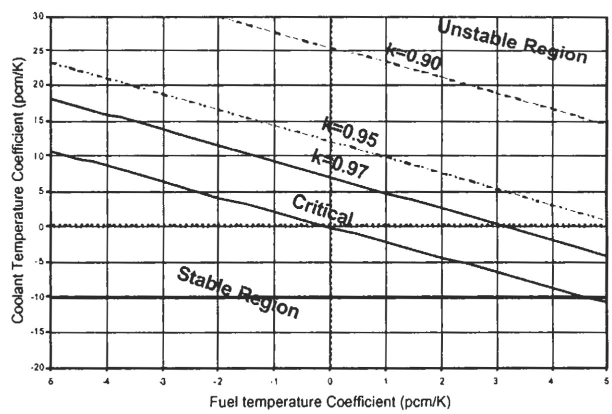

Fig. 3. Line of Stability. Two-temperature feedback model parameters: τ_F = 0.5 s; τ_M = 1.2 s; a = 1.8×10^{-7} K/J; b = 0.7 s^{-1}

III.E. Accidental Criticality

The criticality at the most reactive BOC condition was calculated for a number of 'off-normal' conditions—plasma chamber flooded, core coolant voided, both of the preceding, reflector coolant voided, etc. In these analyses, it was assumed that the fusion source was shut off (eigenvalue calculations) and the control rods were inserted. The 'liquid breeder' design remained sub-critical for all conditions considered, but the 'solid breeder' design had k = 1.001 for the plasma chamber flooded. Very conservative assumptions were made about the design and number of control rods. Most significant was the assumption that control rods would not be placed beneath the magnets, which eliminates approximately 50% of the available control rod locations. Some increase in the number of control rods should be possible, but this still indicates that further design modification maybe needed for the solid breeder design. Table II shows the eigenvalue (k_{eff}) for nominal conditions, control rods inserted, and with the plasma chamber flooded.

TABLE II

Criticality Safety Calculations at Beginning of Cycle

	Liquid Breeder	Solid Breeder
Nominal Conditions - Source On (k_{sub})	0.925	0.913
Nominal Conditions - Source Off (k_{eff})	0.951	0.937
Control Rods In (k_{eff})	0.896	0.895
+ Plasma Chamber Flooded (k_{eff})	0.932	1.001

Note: There are two values for the neutron multiplication factor. k_{sub} is based on the sub-critical source multiplication. k_{eff} is the conventional eigenvalue calculation.

IV. CONCLUSIONS

A FTWR design was developed based on technologies that either exist or are at an advanced stage of development. The simplified RZ model used for design analysis was shown to adequately represent the complex 3-D geometry. The FTWR would operate with a significant sub-criticality margin, which would result in a very stable reactor even with large positive reactivity coefficients. By operating with the liquid breeder design with two separate coolant systems, it is possible to design a system that is tritium self-sufficient and has negative reactivity coefficients. Accidental criticality is a concern for the very high leakage design of the FTWR. Preliminary calculations suggest that this will not be a prohibitive design limitation, but certainly needs to be evaluated further.

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