UCRL-94037
PREPRINT

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This Paper Was Prepared For Submittal To The
7th Topical Meeting on the Technology of
Fusion Energy, MGM Grand Hotel, Reno, NV;
American Nuclear Society; June 15-19, 1986

June 5, 1986

Lawrence
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NUCLEAR PERFORMANCE OPTIMIZATION OF THE MOLTEN-SALT FUSION BREEDER*

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UCRL--94037

DE86 013897

ABSTRACT

Improved nuclear analysis, including the treatment of resonance and spatial self-shielding, coupled with an optimization procedure, has resulted in an improved performance estimate for the molten salt blanket. Net U-233 breeding ratio ranges between 0.58 and 0.63, and blanket energy multiplication ranges between 1.8 and 1.9.

INTRODUCTION

The principal activity of the Fusion Breeder Project is the conceptual design and analysis of fissile-fuel-producing blankets for fusion reactors. In FY84, we developed and analyzed a conceptual design of a blanket containing Be pebbles for neutron multiplication, molten salt (MS) (70 mol% LiF + 18 mol% ThF₄ + 12 mol% BeF₂) in steel tubes for tritium and U-233 breeding, and helium for cooling (Ref. 1). Molten salt is an attractive fuel form, because it allows online refueling and low-cost processing, and it requires no fuel fabrication. Figure 1 is an artist's drawing of this blanket.

In this study, our objective was to maximize specific U-233 breeding (atoms/MeV) in the helium-cooled molten-salt blanket, while including the effects of resonance self-shielding and the heterogeneous makeup of the

blanket. The U-233/Th-232 ratio in the salt was set at 0.0011, while the Li-6/Li ratio was varied to maintain a tritium-breeding ratio of 1.06. The U/Th ratio of 0.0011 was recommended by Grimes at Oak Ridge National Laboratory (ORNL) and is supported by Hine et al. (Ref. 2). We also examined performance sensitivity to structural fraction and protactinium (Pa) in the MS.

METHODS AND RESULTS

The one-dimensional discrete ordinates code ANISM (Ref. 3) and the ENDF-B5-based VITAMIN-E (Ref. 4) cross-section library (a 174-neutron-group, 38-gamma-group library, distributed by ORNL), were used for the neutron transport calculations. The MACKLIB-IV (Ref. 5) KERMA-factor library from Argonne National Laboratory (ANL) was used to calculate energy deposition.

To perform the neutronic optimization of this blanket, we used ANISM in conjunction with a gradient-ascent optimization scheme to maximize the neutronic figure of merit P_{net}/M (the net production of fissile material divided by the net blanket energy multiplication) by raising or lowering the blanket salt-volume fraction at the expense of the blanket Be-volume fraction. During this optimization, we maintained a constant tritium-breeding ratio by varying the Li-6 enrichment in the molten salt.

*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

†Work supported by the Nuclear Engineering, Health Physics, and Radioactive Waste Management Fellowship program administered by Oak Ridge Associated Universities for the U.S. Department of Energy.

To make the calculations more economical, the 174-neutron-group and 38-gamma-group structure of the raw VITAMIN-E library was collapsed to a smaller structure. A series of preliminary 174N-38G calculations were performed to obtain representative neutron and gamma spectra over which to collapse the VITAMIN-E group structure. We used a full blanket cylindrical model, similar to Fig. 1, to obtain the spectra. The cross section

Fig. 1. One module of a helium-cooled molten-salt blanket.

were disadvantage-factor weighted by separate one-dimensional cylindrical-cell calculations. Modules of the ORNL cross-section preparation system AMPX-III (Ref. 6) were used to prepare the 174N-38G VITAMIN-E cross sections for use in the unit-cell calculations. First, we employed the BOMAMI-2 module to resonance self-shield each of the unit-cell cross sections, using the one-dimensional cylindrical molten-salt unit cell (Fig. 3). Next, we used the NITAWL, ALPO, and GIP modules to obtain separate 174N-38G group, independent ANISN libraries for each unit cell. Two P3-S8 ANISN 174N-38G unit cells were then run to obtain disadvantage-factor-weighted cross sections for use in the P3-S8 ANISN full-blanket spectral calculation. Both the neutron and gamma spectra were plotted at 20 positions in the blanket. We chose three representative neutron and gamma spectra for use in collapsing the 174N-38G library to a smaller group structure. The materials making up the first wall and the Be-containing zones were then collapsed to a 70N-15G group structure over the chosen spectrum in each of the zones. The collapsing spectrum in the Be zone is shown in Fig. 4. We chose the 70N-15G group structure by examining plots of the

macroscopic total cross section in each of the three blanket materials and plots of various

Fig. 2. Model of Fe - 5% smeared-material full blanket.

microscopic reaction cross sections of special importance, [e.g., Be (n,2n), Th-232 (n, γ), U-233 (n, γ), U-233 (n,fission)]. Group boundaries were chosen at energies where a large change in any of the above-mentioned cross sections were observed.

We used this collapsed 70N-15G VITAMIN-E-based cross-section set for P4-S12 cylindrical unit-cell calculations at the Fe = 3% and Fe = 5% Fnet optima, determined by an intermediate set of unit-cell-optimization calculations. An example of this unit cell is shown in Fig. 3. The 70N-15G cross sections used in these calculations were resonance self-shielded with the BONAMI-2 module, using the LWR pin-cell configuration. In addition, neutron and gamma KERMA factors for each element in the unit cell were obtained from MACKLIB-IV. The results of these unit-cell calculations can be seen in Table 1.

Fig. 3. Model of cylindrical unit cell for Fe = 5% structure case.

These two 70N-15G ANISN unit-cell calculations were then used to disadvantage-factor weight the cross sections for use in two P4-S8 full-blanket homogenized-material calculations. The results of these latter calculations appear in Table 2.

Next, we optimized the complete blankets for maximum Fnet/M at a tritium-breeding ratio of 1.06. Because direct use of the 70N-15G group structure in the optimization procedure is too costly, the two previously described Fe = 5% and Fe = 3% ANISN full-blanket calculations were used to zone collapse the 70N-15G group structure to a more compact 9N-1G format. Table 3 shows summaries of the Fnet/M optimizations for the Fe = 5% and Fe = 3% full blankets.

Fig. 4. Representative neutron spectrum in beryllium blanket zone.

Additional 70N-15G ANISN calculations were then performed at the Fnet/M optima obtained with the 9N-1G libraries (see Table 4 for the results). A comparison of these results with those obtained with the 9N-1G library shows very little difference in most reaction rates. The value of β in both 70N-15G calculations dropped by about 5%, while Fnet increased by approximately the same amount. This tradeoff is the result of collapsing the 9N-1G libraries using ANISN calculations containing blanket constituents different from the optimal Fnet/M mixtures. The importance of optimization can be seen by a comparison of these new optimized results with those obtained with the same 70N-15G libraries before optimization, which shows at least a 40% increase in Fnet/M, combined with the required value of tritium breeding (1.06). This better blanket performance takes place in spite of a 20% decrease in Be (n,2n) reactions and an almost 50% increase in thorium fission, uranium (n,gammas) and uranium fission reactions.

Lastly, we ran a 70N-15G calculation to determine the effect of placing Pa-233 in the blanket in a state of radioactive decay equilibrium, with its production by Th-232 (n,gamma) reactions, a state that would exist when Pa-233 is not removed from the blanket during reprocessing. The equilibrium Pa-233 concentration was derived from the Th-232 (n,gamma) reaction rate in our 70N-15G, Fe = 5% optimum full-blanket calculation, assuming a blanket-neutron wall loading of 2 MW/m². This concentration of Pa-233 was first self-shielded and disadvantage-factor weighted, then placed in the 70N-15G Fe = 5% optimum full-blanket ANISN calculation, with no other changes. The results of this new calculation can be seen in Table 4 under the title "Fe = 5% with Pa-233." As shown, the addition of

Table 1. Reactions per fusion neutron for Fe = 3% and 5% structure molten-salt unit cells. (Note: $F_{net}^* = T + F_{net} - 1.5$.)

Fe (%)	Tube OR	$\frac{Li-6}{Li}$	T	F	F_{net}	$T+F_{net}$	Th(n,f)	U(n, γ)	U(n,f)	M	$\frac{F_{net}^*}{M}$	F-19 Capt.	Be (n,2n)	Fe Capt.
3	1.618	0.0286	1.42	0.504	0.485	1.90	0.0109	0.00257	0.0160	1.95	0.207	0.0293	1.13	0.200
5	1.794	0.0685	1.41	0.463	0.452	1.86	0.0125	0.00161	0.00971	1.83	0.198	0.0323	0.974	0.136

R_{OR} = Outer radius.

*Capt. = Neutron capture reaction

Table 2. Reactions per fusion neutron for Fe = 3% and 5% structure full-blanket models at respective unit cell F_{net} optimum. (Note: $F_{net}^* = T + F_{net} - 1.06$.)

Fe (%)	T	F	F_{net}	$T+F_{net}$	Th(n,f)	U(n, γ)	U(n,f)	M	$\frac{F_{net}^*}{M}$	First wall Capt.	Struct. Fe capt.	F-19 Capt.	Be (n,2n)	Fe Capt.
3	1.29	0.468	0.451	1.75	0.00971	0.00238	0.0147	1.88	0.365	0.0639	0.182	0.261	1.00	0.0190
5	1.32	0.435	0.425	1.74	0.0111	0.00151	0.00909	1.77	0.385	0.0395	0.125	0.289	0.866	0.0122

Pa-233 causes the blanket net fissile production to drop by about 2% and lowers the other reactions by less than 1%. Therefore, the addition of Pa-233 to the calculation causes no significant variation in any of the neutronic results, implying that all conclusions made from the previous calculations without Pa-233 remain valid.

SUMMARY

Results of this work are encouraging. The deleterious effects of using the intermediate thorium-density molten salt (18 vs 27 mol% ThF₄), adding additional structure to the blanket, and using a more rigorous method to treat spatial self-shielding were

Table 3. Summary of ANISM 9N-1G F_{net}/M optimization of Fe = 3% and 5% structure full-blanket model.

Step	OR _{Tube}	Salt vol.	$\frac{Li6}{Li}$	T	F	F_{net}	M	F_{net}/M
(cm) fraction								
(3 vol% Fe case)								
1	1.00	0.0578	0.0178	1.06	0.280	0.265	1.89	0.141
9	2.24	0.307	0.0268	1.06	0.654	0.636	1.93	0.330
10	2.32	0.331	0.0310	1.06	0.649	0.632	1.91	0.331
11	2.39	0.350	0.0349	1.06	0.643	0.627	1.90	0.330
19	3.50	0.763	0.181	1.06	0.378	0.374	1.80	0.208
(5 vol% Fe case)								
1	1.00	0.0578	0.0396	1.06	0.234	0.225	1.79	0.126
8	2.16	0.286	0.0386	1.06	0.602	0.587	1.83	0.220
9	2.28	0.319	0.0447	1.06	0.601	0.588	1.82	0.322
10	2.39	0.351	0.0517	1.06	0.593	0.581	1.81	0.320
19	3.50	0.763	0.204	1.06	0.353	0.349	1.75	0.199

Table 4. Reactions per fission neutron for Fe = 3% and 5% structure full-blanket models at respective full-blanket F_{net}/M optimums. (Note: $F_{net} = T \cdot F_{eff} \cdot M = 1.06$.) Fe = 5%: salt tube OM = 2.282 cm, salt volume (%) = 31.5, Li-6/Li = 0.0447, F_{net} = 3%: salt tube OM = 2.322 cm, salt volume (%) = 33.7, Li-6/Li = 0.0310.

(%)	T	F	F_{net}	$T \cdot F_{net}$	$M(n,f)$	$U(n,v)$	$U(n,f)$	M	F_{net}/M	First wall capt.	Struct. Fe capt.	P-19 capt.	Be(n,2n)	n leak	Fe-213(n,v)
Fe-3	1.0	0.712	0.636	1.7	0.0177	0.00284	0.0147	1.91	0.332	0.0356	0.0723	0.0455	0.693	0.00901	
Fe-5	1.04	0.627	0.591	1.65	0.0166	0.00187	0.0115	1.84	0.321	0.0338	0.0958	0.0422	0.663	0.00773	
Fe-5 with PA-233	1.03	0.626	0.575	1.64	0.0166	0.00186	0.0114	1.84	0.313	0.0337	0.0953	0.0422	0.663	0.00771	0.00834

mostly negated by optimization. With a 3-vol% Fe structure in addition to the salt tubes, specific breeding maximized at 33-vol% salt with a net fissile breeding (F_{net}) of 0.63 (T breeding is 1.06) and a blanket energy multiplication (M) of 1.91. The initial estimate for this blanket concept was $F_{net} = 0.6$ and $M = 1.6$ (Ref. 1).

Optimization of nuclear performance proved to be important. As seen in Fig. 5, F_{net} climbs dramatically from the starting point of 5-vol% salt, more than doubling at 30-vol% salt. Because M is dropping at this point with the increasing salt-volume fraction, the figure of merit, F_{net}/M , maximizes at a salt fraction of 33 vol%.

Fig. 5. Blanket performance vs salt volume fraction.

To determine the sensitivity of this blanket to structure, the blanket was re-optimized with a structure-volume fraction of 5 vol%, resulting in an F_{net} of 0.59 and an M of 1.84. Thus, increasing structure from 3 to 5 vol% results in a 3.3% decrease in F_{net}/M .

We also used the optimized 5-vol% Fe structure case to see how the presence of Pa

in the salt affects performance. This is of interest because the preferred salt-processing method, fluorination only, does not remove Pa. Our appraisal was performed by adding Pa to the salt in such quantities as to be in secular equilibrium with its production rate, assuming a neutron wall loading of 2 MW/m^2 ; as a result, F_{net} dropped 2.7% to 0.58, while M did not change.

With this study, we made good progress in the analysis and optimization of this blanket. Our results show that this blanket has good breeding promise, and the methodology developed will allow us to take the next step—a combined nuclear/economic optimization in which the production cost of U-233 is minimized by optimizing nuclear and cost sensitive parameters together. Parameters to be optimized include Be-multiplier zone thickness, moderator zone thickness, salt-volume fractions in each of these zones, Li6/Li ratio in the salt to maintain tritium-breeding ratio (T) at 1.06, and shield thickness. The trade-off between Be and SiC zone thicknesses is a trade-off between more neutron multiplication and less high-cost Be. The trade-off between blanket and shield thickness and total blanket and shield thickness is a trade-off between higher blanket performance and smaller bore, lower cost magnets, as well as blanket and shield costs. This optimization should be done while keeping total nuclear power constant and/or not exceeding a maximum capital cost. In addition, wall loading will not be allowed to exceed a predetermined upper bound, such as 2 MW/m^2 , to reflect heat transfer limitations. Future work should also include three-dimensional analysis of the full blanket to benchmark the one-dimensional methods developed here. We look forward to doing this future work.

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