NUCLEAR SCIENCE AND ENGINEERING: **55**, 256-266 (1974)

A Comparative Study of Several Fusion Reactor Blanket Designs

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Received March 22, 1974

A study of the nuclear performance of several recently reported fusion reactor blanket designs is presented. In particular, the nuclear heating, the tritium breeding ratio, and the charged-particle production rates in the various systems are reported. It is found that the total nuclear heating can be overestimated by as much as 30%, that ~20 MeV per fusion is a typical value for the energy production capability of most blankets, and that 22.4 MeV per fusion is a more maximum than nominal value for blankets without fissile materials. The tritium breeding ratio in lithium blankets is high, and uncertainties in nuclear data are unlikely to prevent such systems from breeding. Flibe blankets are marginal in this regard, and uncertainties can prevent breeding in these systems. Hydrogen and helium production rates are fairly large in all systems; they are highest in sintered aluminum product and in the PE-16 alloy, and lowest in niobium, with stainless steel in between. However, much of the required nuclear data on charged-particle-producing reactions is unavailable, and the need for cross-section measurements in this area is discussed.

INTRODUCTION

The nuclear performance of blankets and shields will be important to future fusion reactor designs and is important now in assessing technological questions relevant to producing power from nuclear fusion. Among the important neutronic and photonic properties of these systems are the total energy deposition per fusion event, the spatial distribution of the nuclear heating, the tritium breeding ratio, and the gas production and atomic displacement rates in the structural material. Accurate determination of the total energy production per fusion reaction strongly affects the predicted economics of these systems since the power output is directly proportional to this energy production. The spatial distribution of the heating rate is the basic input data to heat transfer design. The gas production and atomic displacement rates are important in assessing radiation damage effects to the structural materials. This is most important since radiation damage appears as a major technological problem for fusion systems.

In this paper, we report a quantitative comparative study of the nuclear performance of several fusion reactor blanket designs.[1-6] These designs have been developed by groups at the University of Wisconsin[1] (UWMAK-I), the Oak Ridge National Laboratory[2,3] (ORNL), the Prince-

[1]B. BADGER et al., "UWMAK-I, A Wisconsin Toroidal Fusion Reactor Design," UWFDM-68, University of Wisconsin, Nuclear Engineering Department (1973).

[2]A. P. FRAAS, "Conceptual Design of the Blanket and Shield Region and Related Systems for a Full Scale Toroidal Fusion Reactor," ORNL-TM-3096, Oak Ridge National Laboratory (1973).

[3]D. STEINER, "The Nuclear Performance of Vanadium as a Structural Material in Fusion Reactor Blankets," ORNL-TM-4353, Oak Ridge National Laboratory (1973).

[4]W. G. PRICE, Jr., *Trans. Am. Nucl. Soc.*, **17**, 35 (1973); also, W. G. PRICE, Jr., Princeton Plasma Physics Laboratory, Personal Communication (1974).

[5]J. D. LEE, "Geometry and Heterogeneous Effects on the Neutronics Performance of a Yin Yang Mirror—Reactor Blanket," UCRL-75141, Lawrence Livermore Laboratory (1973); also, J. D. LEE, Lawrence Livermore Laboratory, Private Communication (1974).

ton Plasma Physics Laboratory[4] (PPPL), the Lawrence Livermore Laboratory[5] (LLL), and the Brookhaven National Laboratory[6] (BNL). A detailed description of these blanket designs is given in Table I. Several calculational methods have been used to obtain the results, and these are discussed.

COMPARISON OF BLANKET CHARACTERISTICS

Table II summarizes the main characteristics of the five blanket designs previously mentioned.[1-6] All designs are for fusion reactors operating on the deuterium-tritium (D-T) cycle. Except for the LLL design, which is for a mirror,[7] the reactors are based on the Tokamak confinement concept.[8]

[6]J. R. POWELL, F. T. MILES, A. ARONSON, and W. E. WINSCHE, "Studies of Fusion Reactor Blankets with Minimum Radioactive Inventory and with Tritium Breeding in Solid Lithium Compounds," BNL-18236, (Design #4A, p. 79), Brookhaven National Laboratory (1973).

[7]R. F. POST, *Ann. Rev. Nucl. Sci.*, **20**, 509 (1970).

[8]L. A. ARTSIMOVICH, *Nucl. Fusion*, **12**, 215 (1972).

TABLE I

Description of Various Blanket Designs*

Zone	Outer Radius (cm)	Composition[a]	Outer Radius (cm)	Composition[a]
	UWMAK-I (Cylindrical Geometry) (Ref. 1)		ORNL (Cylindrical Geometry) (Refs. 2 and 3)	
1	500	plasma	280	plasma
2	550	vacuum	350	vacuum
3	550.4	stainless steel[b]	350.25	niobium
4	567.4	95% Li + 5% (SS)	380.25	99% Li + 1% Nb
5	584.4	95% Li + 5% (SS)	380.5	niobium
6	601.4	95% Li + 5% (SS)	420.5	graphite
7	616.4	stainless steel	420.75	niobium
8	621.4	95% Li + 5% (SS)	450.75	99% Li + 1% Nb
9	623.4	stainless steel	451.0	niobium
	PPPL (Cylindrical Geometry) (Ref. 4)		LLL (Spherical Geometry)[c] (Ref. 5)	
1	290	plasma	320	plasma
2	360	vacuum	480	vacuum
3	366	16.4% PE-16	480.1	stainless steel[b]
4	376	0.731% flibe + 5.7 PE-16	481	lithium
5	376.36	PE-16	490	85% Li + 5% SS
6	388.36	78.8% flibe + 4.5% PE-16	510	85% Li + 5% SS
7	388.72	PE-16	510.9	lithium
8	408.72	82.0% flibe + 3.8% PE-16	511	stainless steel
9	409.09	PE-16	512	graphite
10	439.64	91.2% flibe + 3.8% PE-16	540	40% Li + 40% C + 10% SS
11	440.0	PE-16	580	40% Li + 40% C + 10% SS
		BNL (Cylindrical Geometry)[c] (Ref. 6)		
1	250	plasma		
2	300	vacuum		
3	302	sintered aluminum product (SAP)		
4	332	17% SAP + 11% Al_2O_3 + 10% Li Al + 45% Be + 17% He		
5	357	20% SAP + 11% Al_2O_3 + 10% Li Al + 42% C + 17% He		
6	382	20% SAP + 11% Al_2O_3 + 10% Li Al + 42% C + 17% He		
7	462	(shield) 20% SAP + 11% Al_2O_3 + 52% $TiH_{1.5}$ + 17% He		

*All these blankets were followed by shields. While these shields were included in our calculations, their description is not given here as they do not significantly affect the results.

[a]All composition percentages are by volume.

[b]In the UWMAK-I design, the composition of stainless steel was taken as 0.06, 0.014, and 0.009×10^{24} at./cm^3 of iron, chromium, and nickel, respectively. In the LLL design, the atomic densities per cubic centimeter were taken as 0.0672×10^{24} for iron and 0.0168×10^{24} for chromium plus nickel.

[c]The UWMAK-I, ORNL, and PPPL designs utilize natural lithium (7.56% ^{6}Li). In the LLL design the lithium is depleted to 4.0% ^{6}Li, and in the BNL design lithium is enriched to 90% ^{6}Li.

TABLE II

Comparison of Characteristics of the Various Designs

Design	First Wall and Structure	Form of Breeding Material	Lithium Enrichment	Reflector Material	Shield Composition	Blanket Coolant	Neutron Wall Loading (MW/m^2)	Is Beryllium Used?
UWMAK-I (Ref. 1)	stainless steel	lithium	natural (7.56 at.% ^6Li)	stainless steel	lead + B_4C + structural steel	lithium	1.25	no
ORNL (Refs. 2 and 3)	niobium	lithium	natural (7.56 at.% ^6Li)	graphite	graphite + lead	lithium	0.69	no
PPPL (Ref. 4)	PE-16	flibe	natural (7.56 at.% ^6Li)	none	heavy concrete + Type 304 stainless steel	helium	1.76	yes (in flibe)
LLL (Ref. 5)	stainless steel	lithium	depleted (4 at.% ^6Li)	graphite	lead + kerosene	lithium	1.63	no
BNL (Ref. 6)	SAP	LiAl (solid)	enriched (90 at.% ^6Li)	none	SAP + Al_2O_3 $TiH_{1.5}$	helium	1.0	yes

The UWMAK-I and LLL designs employ stainless steel as the first wall and blanket structure. The maximum operating temperature in these designs is limited to ~550°C. The PE-16 alloy used in the PPPL blanket is ~43 wt% nickel, 39 wt% iron, and 18 wt% chromium. The ORNL blanket uses niobium, a refractory metal, and is designed for operation at much higher temperatures than either the stainless steel, PE-16, or sintered aluminum product (SAP) blankets. The BNL design utilizes SAP, a material in which pure aluminum is strengthened by the addition of 5 to 10 wt% Al_2O_3 finely dispersed throughout the aluminum matrix; SAP was first proposed for use in fusion blankets by Powell et al.[6] on the basis of its low long-term activation.

Liquid lithium is used in the UWMAK-I, ORNL, and LLL blankets for tritium breeding, neutron slowing down, and heat removal. The PPPL blanket incorporates flibe ($LiF \cdot BeF_2$) for tritium breeding and slowing down. Helium is used as the coolant. In the SAP blanket of BNL, the breeding material is limited to a solid lithium alloy or compound because of corrosion problems between liquid lithium and SAP. The lithium used in the UWMAK-I, ORNL, and PPPL blankets is natural lithium, i.e., 7.56 at.% ^6Li and 92.44 at.% ^7Li. The lithium in the LLL blanket is depleted to 4 at.% ^6Li to lower the tritium breeding ratio, while the lithium in the BNL design is enriched to 90 at.% ^6Li to increase tritium production.

NUCLEAR HEATING

The $T(d,n)He$ fusion reaction releases 17.6 MeV, divided between a 14.1-MeV neutron and a 3.5-MeV alpha particle. The neutron escapes the plasma zone without colliding and enters the surrounding blanket region where it slows down through collisions. We denote by E_H the total energy deposited per fusion reaction in the blanket by neutron interactions and the absorption of any resulting gamma rays. The total recoverable energy, E_f, per fusion reaction is the sum of E_H and the 3.5-MeV kinetic energy of the alpha particle. The E_H may be smaller or larger than 14.1 MeV since the neutron induces both exothermic and endothermic reactions.

The E_H is usually calculated by integrating the spatial distribution of the nuclear heating over the system volume. The spatial distribution of the total nuclear heating, $H_t(\boldsymbol{r})$, is normally divided into neutron, $H_n(\boldsymbol{r})$, and gamma-ray, $H_\gamma(\boldsymbol{r})$, heating, where[9]

$$H_t(\boldsymbol{r}) = H_n(\boldsymbol{r}) + H_\gamma(\boldsymbol{r}) \tag{1}$$

$$H_n(\boldsymbol{r}) = \sum_j N_j(\boldsymbol{r}) \int \phi_n(\boldsymbol{r}, E_n)\, k_{nj}(E_n) dE_n \tag{2}$$

$$H_\gamma(\boldsymbol{r}) = \sum_j N_j(\boldsymbol{r}) \int \phi_\gamma(\boldsymbol{r}, E_\gamma)\, k_{\gamma j}(E_\gamma) dE_\gamma \quad , \tag{3}$$

and where

$\boldsymbol{r}$ = spatial variables

$k_{nj}(E_n)$ = neutron kerma[10] factor in element j for an incident neutron energy, E_n

[9] M. A. ABDOU, "Calculational Methods for Nuclear Heating and Neutronics and Photonics Design for CTR Blankets and Shields," PhD Thesis, University Microfilms Inc., 74-8981; also issued as Reports UWFDM-66 and UWFDM-67, University of Wisconsin, Nuclear Engineering Department (1973).

[10] "Kerma" is an acronym standing for Kinetic Energy Released in Materials.

$k_{\gamma j}(E_\gamma)$ = gamma-ray kerma factor in element j for a photon energy, E_γ

$\phi_n(E_n)$ = neutron flux for neutrons of energy E_n.

The gamma-ray flux, ϕ_γ, is obtained by solving the transport equation with a secondary photon production source,

$$S_\gamma(\mathbf{r}, E_\gamma) = \sum_j N_j(\mathbf{r}) \int \phi_n(\mathbf{r}, E_n)\, \sigma_p^j(E_n, E_\gamma) dE_n \quad , \quad (4)$$

where σ_p^j is the photon production cross section in element j for neutrons of energy E_n and photons of energy E_γ. The summation over j includes all elements in the mixture present in the system.

This procedure has been used to calculate the nuclear heating in the five designs previously discussed,[1-6] using two sets of kerma factors. The first set of neutron kerma factors was derived with the recently developed MACK program[11,12] using ENDF/B Version-III data.[13,14] The second set was obtained from the work of Ritts, Solomito, and Steiner.[15] The spatial distribution of neutron and gamma-ray heating obtained in both cases has been integrated over the blanket volume to obtain E_H. We have also calculated E_H using an integral energy balance method developed in Ref. 9 and outlined in the following equations.

For a finite segment of any nuclear system, define

$$H_{nv} = \int_{\text{volume}} H_n(\mathbf{r}) d\mathbf{r} \quad (5)$$

$$H_{\gamma v} = \int_{\text{volume}} H_\gamma(\mathbf{r}) d\mathbf{r} \quad . \quad (6)$$

Then, the sum, H_{tv}, is

$$H_{tv} = H_{nv} + H_{\gamma v} = -(L_{nE} + L_{\gamma E}) + \sum_j \sum_i R_{ij}\, Q_{ij} + \sum_j \sum_{i'} R_{i'j}\, E_{Di'j} \quad , \quad (7)$$

where

L_{nE} = net neutron energy transported out of the segment

$L_{\gamma E}$ = net gamma-ray energy transported out of the segment

R_{ij} = reaction rate (integrated over the segment volume) for reaction i in element j, where reaction i is a reaction in which conversion of kinetic energy into mass (or vice versa) occurs

Q_{ij} = Q value for reaction i in element j

$E_{Di'j}$ = energy deposited per reaction i' in element j from radioactive decay of the residual nucleus.

The E_H is equal to H_{tv} if the latter is normalized to one fusion neutron. Although the integral energy balance method is quite accurate in predicting the total energy deposition in any system, it does not provide the spatial distribution of the heating.

The neutron and gamma-ray fluxes were calculated by solving the discrete ordinates form of the transport equation[16] using the ANISN program[17] in the S_8-P_3 approximation. All neutron and gamma-ray multigroup cross sections were processed using SUPERTOG (Ref. 18) and MUG (Ref. 19) from ENDF/B-III (Refs. 13 and 14) except for fluorine. The neutron cross sections for fluorine were obtained from the GAM-II library.[20] The photon production cross sections [see Eq. (4)] were processed from ENDF/B-III (Ref. 13) with LAPHANGAS (Ref. 21) [a modified version of LAPHANO (Ref. 22)], except for ^{6}Li, ^{7}Li, carbon, and niobium, which come from Ref. 15, and for fluorine, which is discussed later.

[11] M. A. ABDOU, C. M. MAYNARD, and R. Q. WRIGHT, "MACK: A Computer Program to Calculate Neutron Energy Release Parameters (Fluence-to-Kerma Factors) and Multigroup Neutron Reaction Cross Sections from Nuclear Data in ENDF Format," UWFDM-37, University of Wisconsin (1973); also issued as ORNL-TM-3994, Oak Ridge National Laboratory (1973).

[12] M. A. ABDOU and C. W. MAYNARD, *Trans. Am. Nucl. Soc.*, **16**, 129 (1973).

[13] M. K. DRAKE, Ed., "Data Formats and Procedures for the ENDF Neutron Cross Section Library," BNL-50279, Brookhaven National Laboratory (1970).

[14] O. OZER and D. GARBER, "ENDF/B Summary Documentation," BNL-17541 and ENDF-201, Brookhaven National Laboratory (1973).

[15] J. J. RITTS, M. SOLOMITO, and D. STEINER, "Kerma Factors and Secondary Gamma-Ray Sources for Some Elements of Interest in Thermonuclear Blanket Assemblies," ORNL-TM-2564, Oak Ridge National Laboratory (1970).

[16] G. I. BELL and S. GLASSTONE, *Nuclear Reactor Theory*, Chap. 5, Van Nostrand-Reinhold, New York (1970).

[17] W. W. ENGLE, Jr., "A User's Manual for ANISN," K-1693, Oak Ridge Gaseous Diffusion Plant (1967).

[18] R. Q. WRIGHT et al., "SUPERTOG: A Program to Generate Fine Group Constants and P_n Scattering Matrices from ENDF/B," ORNL-TM-2679, Oak Ridge National Laboratory (1969).

[19] J. R. KNIGHT and F. R. MYNATT, "MUG: A Program for Generating Multigroup Photon Cross Sections," CTC-17, Oak Ridge Computer Technology Center (1970).

[20] GAM-II Cross Section Library; these data are available from the Radiation Shielding Information Center, Oak Ridge National Laboratory.

[21] W. E. FORD III, Oak Ridge National Laboratory, Private Communication (1972).

[22] D. J. DUDZIAK et al., "LAPHANO: A P_0 Multigroup Photon-Production Matrix and Source Code for ENDF," LA-4750-MS, Los Alamos Scientific Laboratory (1972); see also, ENDF-156.

The energy group structure used in all cases consists of 46 neutron groups and 43 gamma-ray groups.[9]

Table III shows the results for neutron, gamma-ray, and total nuclear heating in the five designs[1-6] outlined in Table I, using the three calculational procedures outlined above. From these results, the following observations can be drawn:

1. The total nuclear heating derived with neutron kerma factors from the MACK program[11] agrees with the results obtained from the integral energy balance to within 2%. This relatively small difference can be readily accounted for by the inconsistency of the basic neutron interaction and gamma-ray production data[23] from which the neutron kerma factors and gamma-ray production cross sections are derived, and the error in the energy balance which results from using the multigroup approximation. This requires the use of an effective energy for each neutron and gamma-ray group.[9] In this work, the middle point energy for the group was used. Therefore, we conclude that the neutron kerma factors processed with the MACK program are reliable. For completeness, the detailed reaction rates, the Q values, and the decay energies from which the results of the integral energy balance for the UWMAK-I design were obtained are given in Table IV.

2. The use of neutron kerma factors from Ritts, Solomito, and Steiner[15] overestimates the neutron heating by 15 to 25% in all designs. Dudziak[24] came to a similar conclusion in a study of the reference theta pinch reactor (RTPR) design.

3. Fluorine in flibe affects the spectrum substantially in the PPPL design. This is unfortunate since the nuclear data for fluorine are not well known. Information is lacking, and the uncertainty in the available data is greater than for any other material used in the five designs under consideration. There are no evaluated data for fluorine in ENDF/B-III (Refs. 13 and 14). The United Kingdom Atomic Energy Authority evaluation[25] lacks much of the necessary information on partial cross sections, secondary neutron energy, and angular distributions. For these reasons, an accurate prediction of the spatial distribution of nuclear heating in the PPPL design is not possible. This is also true for the quantities E_H and E_f if the approach of neutron kerma factors and gamma-ray production cross sections is to be used. Thus, the integral energy balance method is the only method available to calculate E_H with reasonable accuracy. In the transport calculations for the PPPL design reported here, the neutron multigroup cross sections of the GAM-II library were used. (These same data were also used by the Princeton group.) All data for the other materials are from ENDF/B-III (Refs. 13 and 14), as mentioned previously. The sum of the last two terms of Eq. (7), for all materials except fluorine, was calculated to be 3.017 MeV (normalized to one

[23]M. A. ABDOU and C. W. MAYNARD, *Trans. Am. Nucl. Soc.*, **17**, 33 (1973).

[24]D. J. DUDZIAK, *Trans. Am. Nucl. Soc.*, **17**, 36 (1973).

[25]K. PARKER, "The Aldermaster Nuclear Data Library as of May 1963," AWRE 0-70163, U.K. Atomic Weapons Establishment, Aldermaston (1963).

TABLE III

Neutron, Gamma-Ray, and Total Heating for Various Designs in MeV per D-T Neutron as Calculated by Various Methods

Design	Neutron Heating		Gamma-Ray Heating	Total (Neutron + Gamma Ray) Heating				Total (neutron + gamma-ray + 3.52-MeV alpha particle) Energy Deposition
	MACK (Ref. 11) (A)	Ritts et al. (Ref. 15) (B)	LAPHANO and others (C)	MACK (Ref. 11) (A + C)	Ritts et al. (Ref. 15) (B + C)	Integral Energy Balance	Values Previously Reported	
UWMAK-I	12.43	15.09	4.13	16.56	19.22	16.40	16.56 (Ref. 1)	20.1 ± 0.1
ORNL	12.95	15.65	2.73	15.68	18.38	15.31	18.38 (Refs. 2 and 3)	19.0 ± 0.2
PPPL	12.88	16.12	4.99	17.87	21.12	17.87	23.10 (Ref. 4)	21.4 ± 0.5
LLL	12.18	14.10	3.61	15.79	17.71	15.53	15.82 (Ref. 5)	19.2 ± 0.2
BNL	15.23	19.25	4.04	19.28	23.30	19.01	18.87[a] (Ref. 6)	22.6 ± 0.2

[a]This value was calculated using the S_4-P_0 approximations, while our results were derived using S_8-P_3 in all methods.

TABLE IV

Detailed Reaction Rates (in reactions per D-T neutron), Q-Values, and Decay Energies Used in Carrying Out the Integral Energy Balance for UWMAK-I Design (Ref. 1)

Material/ Reaction	R (Reactions/ D-T Neutron)	Q-Value (MeV)
Lithium-6		
$(n,2n)\alpha$	5.9433 (-3)	-3.696
$(n,n')d$	7.5197 (-2)	-1.471
(n,γ)	3.4970 (-5)	+7.252
(n,p)	1.6437 (-3)	-2.733
$(n,\alpha)t$	8.8348 (-1)	+4.786
Lithium-7		
$(n,2n)$	2.5044 (-2)	-7.252
$(n,2n)\alpha$	3.1302 (-2)	-8.723
$(n,n')t$	6.0371 (-1)	-2.466
(n,γ)	4.8513 (-4)	+2.032
(n,d)	1.00 (-2)	-7.760
Iron		
$(n,2n)$	5.2190 (-2)	-11.200
(n,γ)	5.7986 (-2)	+7.803
(n,p)	2.4091 (-2)	-2.731
(n,α)	1.2990 (-2)	+0.3926
Nickel		
$(n,2n)$	3.9243 (-4)	-12.19
$(n,n'p)$	8.1219 (-3)	-8.1776
(n,γ)	1.4614 (-2)	+8.602
(n,p)	1.4272 (-2)	-0.5034
(n,α)	1.3353 (-3)	+2.317
Chromium		
$(n,2n)$	6.2578 (-3)	-12.03
$(n,n'p)$	4.6568 (-4)	-11.00
(n,γ)	2.5372 (-2)	+8.127
(n,p)	4.7566 (-3)	-3.088
(n,α)	2.6074 (-3)	-8.657

Material/ Reaction	R (Reactions/ D-T Neutron)	Decay Energy (MeV)
^{6}Li (n,p)	1.6437 (-3)	1.56
^{7}Li (n,γ)	4.8513 (-4)	9.31
^{7}Li (n,d)	1.0000 (-2)	1.56
Fe (n,p)	2.4091 (-2)	0.731
Ni $(n,2n)$	3.9243 (-4)	0.26
Cr $(n,2n)$	6.2578 (-3)	0.026
Cr (n,p)	4.7566 (-3)	0.998

D-T neutron). The sum of $-L_{nE}$ and $-L_{\gamma E}$ is equal to (and cannot exceed) 14.06 MeV. The E_H is then equal to 17.077 MeV plus a quantity, C, defined by

$$C = \sum_i R_i Q_i + \sum_{i'} R_{i'} E_{Di'} \quad , \qquad (8)$$

where i is a converting reaction and i' is a reaction followed by radioactive decay in fluorine; R, Q, and E_D are as defined in conjunction with Eq. (7). The only neutron-induced *exothermic* reaction in fluorine is radiative capture, which has a Q value of 6.597 MeV and is followed by a β^- decay with E_D = 2.49 MeV. The $\sigma_F(n,\gamma)$ is not well known at high energies, but for energies below 40 keV where it is known to a resonable accuracy $\sigma_F(n,\gamma)$ is <10 mb except for a weak resonance with a minimum value of ~20 mb, as reported by Stehn et al.[26] The parasitic absorption [sum of (n,γ), (n,α), (n,p), (n,d), (n,t) $(n,2\alpha)$, etc.] is more accurately known. The total reaction rate for parasitic absorption in the PPPL blanket is calculated to be 0.159 per D-T neutron. Clearly, the (n,γ) reaction rate is much lower than this value. However, if this value is used for radiative capture, then $R(Q + E_D)$ is 1.45 MeV. Hence, an upper limit on the total nuclear heating per D-T neutron in the PPPL design is 18.5 MeV. When the actual (n,γ) cross sections are considered and the endothermic reactions are taken into account, we calculate E_H as 17.87 MeV. The remaining neutron and gamma-ray heating rates given in Table III for the PPPL design were derived as described previously, except for the gamma-ray production for fluorine. This was normalized such that the sum of the neutron and gamma-ray heating agrees with the value obtained from the integral energy balance method. Note that when the neutron kerma factors and gamma-ray production cross sections of Ref. 15 were used, the neutron heating is 16.12 MeV, and gamma-ray heating is 15.41 MeV, of which 11.92 MeV come from gamma-ray production in fluorine. Thus, E_H is 31.5 MeV which, from the above analysis, is clearly too high. Values of E_H previously reported for the LLL (Ref. 5) and BNL

[26]JOHN R. STEHN et al., "Neutron Cross Sections," BNL-325, Vol. I, Suppl. 2, Brookhaven National Laboratory (1964).

	^{6}Li	^{7}Li	Fe	Ni	Cr	Sum for all Materials[a]
$\sum_i R_i Q_i$	4.0915	-2.0200	-0.1928	+0.0504	+0.0886	+2.2962
$\sum_i R_i E_{Di}$	0.0026	0.0201	0.0176	0.0001	0.0049	+0.0453

[a]Other materials in the shield regions are included.

(Ref. 6) designs are in reasonable agreement with those obtained from MACK and the integral energy balance method.

4. The BNL design has the highest energy multiplication for two reasons:

a. The lithium used is enriched to 90 at.% ^{6}Li. The ^{6}Li$(n,\alpha)t$ reaction has a large low-energy cross section and is exothermic with a Q value of 4.786 MeV.

b. Beryllium of 45 vol% is used in the high-energy region (zone 4; see Table I). The use of beryllium significantly increases the energy production in fusion blankets.[27] The Q value of the $(n,2n)$ reaction in beryllium is only -1.66 MeV. In addition to neutron multiplication, the Be$(n,2n)$ increases the energy production by reducing the number of high-energy endothermic reactions with other materials present in the blanket. Note, however, that using lithium enriched in ^{6}Li does not increase the energy multiplication compared with natural lithium unless beryllium is used with the enriched lithium.

5. The last column in Table III gives the total recoverable energy, E_f, per fusion reaction; E_f is the sum of E_H and the 3.5-MeV kinetic energy of the alpha particle. It is clear from these results that E_f is on the order of 20 MeV or less in blankets not utilizing beryllium. Although enriching lithium is expensive, as is beryllium metal, the increases of $\sim$2 MeV in E_f is an approximately 10% increase in the plant power output. This appears to more than offset the enriching and beryllium costs by lowering the cost per unit power.

TRITIUM PRODUCTION

Tritium production by neutron reactions in ^{6}Li and ^{7}Li and the tritium breeding ratio (number of tritium atoms produced in the blanket per fusion reaction) are given in Table V. The tritium breeding ratio, T, is $\sim$1.5 in the UWMAK-I, ORNL, and BNL blankets, $\sim$1.4 in the LLL design, and 1.07 in the PPPL design.

Vogelsang[28] has shown that a tritium breeding ratio of $\sim$1.02 is adequate for a doubling time of less than seven years. However, allowing for roughly 10% uncertainty in nuclear data and 5 to 10% uncertainty due to loss in access regions (feed pipes, divertors, etc.) and processing, it appears that a breeding ratio of $\sim$1.2 is a reasonable value for design considerations. Yet to minimize tritium hazards,[1] it is necessary to avoid producing more tritium than is required. As such, we conclude that the tritium breeding ratio in all designs except that of PPPL is higher than necessary to meet a doubling time of about seven years. On the other hand, a tritium breeding ratio of $\sim$1.07 may not allow enough margin for both uncertainty in nuclear data and unavoidable losses under practical operating conditions.

TABLE V

Comparison of Tritium Production Rate per D-T Neutron

	^{6}Li $(n,\alpha)t$ (T_6)	^{7}Li $(n,n'\alpha)t$ (T_7)	Breeding Ratio $(T = T_6 + T_7)$
UWMAK-I (Ref. 1)	0.8835	0.6037	1.4872
ORNL (Refs. 2 and 3)	0.8474	0.5931	1.4405
PPPL (Ref. 4)	0.9350	0.1342	1.0692
LLL (Ref. 5)	0.8619	0.5024	1.3643
BNL (Ref. 6)	1.4825	0.0023	1.4848

CHARGED-PARTICLE PRODUCTION AND ATOMIC DISPLACEMENT RATES

Accurate calculation of hydrogen, deuterium, and helium production in the first wall and structural material of controlled thermonuclear reactor (CTR) blankets is important for radiation damage problems. Tables VI.a through VI.e tabulate the production rate of the hydrogen isotopes and of helium in the first wall of the five designs considered in this paper. A comparison of total gas production rates in the first wall of the various designs[1-6] is given in Table VII in units of (appm/yr) per (MW/m^2). The production rate of hydrogen isotopes is the sum of the reaction rates for (n,p), $(n,n'p)$, (n,d), and (n,t). The helium production rate is obtained by summing the (n,α) and $(n,n'\alpha)$ reaction rates. Reaction rates for which the phrase "no data" is indicated in Tables VI.a through VI.e are taken as zero. This must be considered in comparing the systems on a gas production basis. The cross sections for charged-particle-producing reactions were taken from the ENDF/B-III evaluations.[13,14] The "no data" phrase in the tables means that no data are given in the

[27] M. A. ABDOU and C. W. MAYNARD, "Neutronics and Photonics Study of Fusion Reactor Blankets," *Proc. 1st Top. Mtg. Technology of Controlled Nuclear Fusion*, CONF-740402, U.S. Atomic Energy Commission (1974).

[28] W. F. VOGELSANG, *Nucl. Technol.*, **15**, 470 (1972).

TABLE VI.a

Charged-Particle Production in the Stainless-Steel First Wall of UWMAK-I

		(n,α)	$(n,n'\alpha)$	(n,p)	$(n,n'p)$	(n,d)
(Reactions/cm^3) per (n/cm^2)	Ni	1.066 (-3)	no data[a]	8.359 (-3)	7.204 (-3)	no data[a]
	Cr	1.991 (-3)	no data	3.637 (-3)	4.295 (-4)	no data
	Fe	1.066 (-2)	no data	1.702 (-2)	no data	no data
(Sum/cm^3) per (n/cm^2)		1.3717 (-2)	---	2.901 (-2)	7.633 (-3)	---
Sum, in (appm/yr) per (MW/m^2)		228.78	---	483.89	127.32	---

[a]"No data" in Tables VI.a through VI.e refers to ENDF/B-III.

TABLE VI.b

Charged-Particle Production in the Niobium First Wall of the ORNL Design

	(n,α)	$(n,n'\alpha)$	(n,p)	$(n,n'p)$	(n,d)
(Reactions/cm^3) per (n/cm^2)	1.071 (-3)	no data	3.684 (-3)	no data	no data
Production Rate in (appm/yr) per (MW/m^2)	26.80	---	92.18	---	---

TABLE VI.c

Charged-Particle Production in the PE-16 First Wall of the PPPL Design*

		(n,α)	$(n,n'\alpha)$	(n,p)	$(n,n'p)$	(n,d)
(Reactions/cm^2) per (n/cm^2)	Ni	4.065 (-3)	no data	2.916 (-2)	2.789 (-2)	no data
	Cr	2.294 (-3)	no data	4.189 (-3)	5.029 (-4)	no data
	Fe	5.930 (-3)	no data	9.134 (-3)	no data	no data
(Sum/cm^3) per (n/cm^2)		1.229 (-2)	---	4.248 (-2)	2.839 (-2)	---
Sum in (appm/yr) per (MW/m^2)		199.15	---	688.46	460.15	---

*The first wall in PPPL design is 16.4 vol% PE-16 (the remainder being helium); the results in this table are per cubic centimeter and per atom of PE-16.

ENDF files. In particular, no data are provided for the $(n,n'\alpha)$, $(n,n'p)$, and (n,d) reactions in iron and niobium, or for the $(n,n'\alpha)$ and (n,d) reactions in nickel and chromium. Values are provided for the relevant gas-producing reactions in aluminum and oxygen. We have not included the contributions from minor but necessary alloying constituents, such as carbon and silicon in stainless steel, to the gas production rates. These can typically contribute ~5%.

The absence of data for some reactions from ENDF/B evaluations does not imply that these reactions are unimportant in CTR work. The (n,d) cross section in niobium, for example, was calculated by Pearlstein[29] to be about 50% larger than the (n,α) cross section. The results in Table VI.e for SAP indicate that the $(n,n'p)$ reaction rate in the BNL design is about twice as

[29]S. PEARLSTEIN, *J. Nucl. Energy*, **27**, 81 (1973).

TABLE VI.d

Charged-Particle Production in the Stainless-Steel First Wall of the LLL Design

		(n,α)	$(n,n'\alpha)$	(n,p)	$(n,n'p)$	(n,d)
(Reactions/cm^3) per (n/cm^2)	Ni	5.546 (-4)	no data	4.694 (-3)	3.699 (-3)	no data
	Cr	1.017 (-3)	no data	1.856 (-3)	2.162 (-4)	no data
	Fe	8.511 (-3)	no data	1.400 (-2)	no data	no data
(Sum/cm^3) per (n/cm^2)		1.008 (-2)	---	2.055 (-2)	3.915 (-3)	---
Sum in (appm/yr) per (MW/m^2)		166.95	---	340.35	64.84	---

TABLE VI.e

Charged-Particle Production in SAP First Wall of the BNL Design

		(n,α)	$(n,n'\alpha)$	(n,p)	$(n,n'p)$	(n,d)	(n,t)
(Reactions/ cm^3) per (n/ cm^2)	Al	1.500 (-2)	1.129 (-4)	1.090 (-2)	2.122 (-2)	3.040 (-3)	1.449 (-5)
	O	1.471 (-3)	2.224 (-3)	4.145 (-4)	6.984 (-5)	1.423 (-4)	---
(Sum/ cm^3) per (n/ cm^2)		1.647 (-2)	2.337 (-3)	1.131 (-2)	2.129 (-2)	3.183 (-3)	1.449 (-5)
Sum, in (appm/ yr) per (MW/m^2)		358.31	50.82	246.03	463.13	69.23	0.315

TABLE VII

Comparison of Gas Production [in (appm/yr) per (MW/m^2)] and Atomic Displacements [(in displacements per atom per year) per (MW/m^2)] in the First Wall for the Various Designs

Design First-wall Material	UWMAK-I Stainless Steel	ORNL Niobium	PPPL PE-16	LLL Stainless Steel	BNL SAP
Hydrogen isotopes	611.2	92.2	1148.6	405.2	778.6
Helium	228.8	26.8	199.1	167.0	409.1
Displacements	18	14	---	15	---

large as the (n,p) reaction rate and that the $(n,n'\alpha)$ contribution to helium production is significant. For iron, Pearlstein's calculations yield cross sections at 14 MeV for the $(n,n'p)$ and (n,d) reactions of $\sim$20 mb each. If such cross sections had been included, the hydrogen isotope production rate in the stainless-steel systems would have increased by as much as 30%. In addition, it is often the case that even when charged-particle-producing reaction cross sections are provided, they may be estimated from calculations or be based on one or a few experiments at a single energy. For example, the (n,d) cross section for aluminum is based on a single measurement of Grover and Weigold.[30] In addition, as in the case of the aluminum (n,d) reaction, the experiments are sometimes performed for purposes other than measuring the cross section, such as fitting the angular distribution to obtain nuclear level data. In the paper of Grover and Weigold,[30] the cross sections reported were only incidentally deduced

[30]R. N. GROVER and E. WEIGOLD, *Nucl. Phys.*, 24 630 (1961).

from such data and may not be reliable.[31] The lack of complete data in ENDF/B-III is also relevant for the nuclear heating calculations. It has been shown that the charged-particle contribution to neutron heating is more than 50% in most of CTR materials.[9]

In light of the above discussion, we draw only tentative conclusions from the results in Table VII. A niobium first wall has the lowest hydrogen and helium production rates. The PE-16 has the largest hydrogen production rates, 1149 (appm/yr) per (MW/m^2), due mainly to the high nickel content. This number would increase with the availability of (n,d) data. The SAP first walls have high hydrogen production rates and the highest helium production rate, due to the aluminum. The stainless-steel systems have helium production rates of ~200 (appm/yr) per (MW/m^2) and hydrogen production rates of 400 to 600 (appm/yr) per (MW/m^2). We note again that when $(n,n'p)$ and (n,d) data become available for the elements in stainless steel, the hydrogen production rate will increase.

Note that both the UWMAK-I and LLL designs employ stainless steel for the first wall, but charged-particle production rates are lower in the LLL design. This is primarily caused by two effects: (a) the use of lithium depleted in ^{6}Li in the LLL design and, (b) the fact that the LLL group approximated the chromium cross sections by those of nickel. In the calculations reported here, the same approximation was employed so that meaningful comparisons of nuclear heating rates and breeding ratios could be made. However, when we calculated charged-particle reaction rates, we used the actual cross sections for chromium and nickel with the approximated neutron spectrum.

The atomic displacement rates in displacements per atom per year per (MW/m^2) neutron wall loading are also given in Table VII, based on displacement cross sections given in Ref. 1. The atomic displacement cross sections for PE-16 and SAP materials are not available at present. Comparing the results for the UWMAK-I and ORNL designs, one finds that the displacement rate in stainless steel is roughly 20% higher than that in niobium.

CONCLUSIONS

A comparative study of several recently discussed fusion reactor blanket designs[1-6] has been presented. The total energy per fusion in these systems is nominally ~20 MeV per fusion reaction rather than the commonly assumed value of 22.4 MeV. In fact, 22.4 MeV per fusion appears to be a more maximum than nominal value. Only the BNL design, which employed both beryllium and ^{6}Li-enriched lithium to produce 22.6 MeV per fusion, came close to this value. In addition, the neutron kerma factors derived from the MACK program[11] reliably determined the total nuclear heating, E_H, whereas the data derived by Ritts, Solomito, and Steiner[15] can severely overestimate this quantity. Reliability has been determined by comparing results with those from the integral energy balance method and by examining the self-consistency of the results. Most importantly, the power output varies directly with the value of the total energy per fusion. The total nuclear heating in the ORNL and PPPL designs are overestimated by ~17 and 29%, respectively. The total thermal output of these designs will therefore be overestimated by 15 and 25%, respectively.

The tritium breeding ratio in lithium blankets is high, and uncertainties in nuclear data are unlikely to prevent such systems from breeding. Flibe blankets, on the other hand, appear marginal in this regard, and data uncertainties and/or access region losses can prevent breeding in such systems.

A^{t}om displacement rates per (MW/m^2) in both stainless steel and niobium are ~15. No displacement rate data for PE-16 or SAP are available.

The gas production in the first wall has been calculated for the various blankets.[1-6] Also included are the individual reactions in each isotope which contribute to the total hydrogen and helium production. The hydrogen production rate is highest in the first wall of PE-16 [~1150 (appm/yr) per (MW/m^2)] and high in stainless steel and SAP first walls [400 to 800 (appm/yr) per (MW/m^2)]. Helium production is highest in SAP [~400 (appm/yr) per (MW/m^2)] and about the same in stainless steel and PE-16 first walls [~200 (appm/yr) per (MW/m^2)]. The niobium system has the lowest first-wall production rates of both hydrogen and helium.

Perhaps the most relevant point regarding gas production rate calculations in CTR first walls is the paucity of gas-producing reaction cross sections themselves. When the reaction leads to a radioactive product nucleus, some data are usually available, particularly at 14 MeV. Otherwise, there are few experimental data.[31,32] For several elements considered in this paper, no data are

[31]The authors thank Prof. H. H. Barschall for pointing this out.

[32]H. H. BARSCHALL, "Production of Hydrogen and Helium by 14-MeV Neutrons," University of Wisconsin Fusion Design Memo FDM-84, University of Wisconsin, Nuclear Engineering Department (1974).

available in ENDF/B-III (Ref. 13) for the (n, d), $(n, n'p)$, and $(n, n'\alpha)$ reactions. Indications are that these cross sections are significant.[29,32] In part, this situation reflects the fact that such cross sections in the 14-MeV range are not of great importance to fission reactor problems. For CTR systems based on the D-T fuel cycle, the situation is quite different. In view of the apparent magnitude of the gas production rates, as indicated in Table VII, and given the relevance of such information to radiation damage[33] and nuclear heating[9] in fusion systems, experiments to obtain these data are required.

[33]G. L. KULCINSKI, R. G. BROWN, R. G. LOTT, and P. A. SANGER, *Nucl. Technol.*, **22**, 20 (1974).