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for the Tokamak Experimental
Power Reactor**

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OAK RIDGE NATIONAL LABORATORY

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Neutron Physics Division

NEUTRONICS AND PHOTONICS CALCULATIONS FOR THE
TOKAMAK EXPERIMENTAL POWER REACTOR*

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Abstract

The results of one-dimensional neutronic and photonic calculations that compare the nuclear performance of blanket and shield designs proposed for use in the Tokamak Experimental Power Reactor are presented. The nuclear analysis was carried out for both nonbreeding and tritium-breeding blanket modules to compare the spatial variations of the radiation flux and energy distributions, nuclear heating, radiation damage, and tritium breeding. Nonbreeding blanket modules that contain potassium plus SS-316 or potassium only as the energy-absorbing medium and breeding blankets that use natural lithium as the fertile material were evaluated as a function of the first-wall cooling scheme.

I. INTRODUCTION

To design a D-T burning thermonuclear power reactor requires a collaborative effort involving plasma, mechanical, electromagnetic, materials, and nuclear research. The nuclear-research effort provides much of the basic data to the other research areas that are essential for selecting suitable materials and for optimizing the blanket and shield design, as well as other components in the reactor. This paper summarizes the results of one-dimensional neutronics and photonics calculations that were carried out in support of the conceptual design of the Tokamak Experimental Power Reactor (EPR) being undertaken at the Oak Ridge National Laboratory.

The blanket and shield designs compared in this paper and proposed for use in the EPR evolved, in part, from the results of a scoping study^{1,2} wherein several blanket and shield concepts were evaluated in terms of the EPR design objectives.³ The design criteria specified that the blanket and shield in the EPR have the capabilities of (1) recovering > 90% of the kinetic energy of the fusion neutrons in the blanket and converting this energy, along with that of secondary gamma rays produced by the neutrons, into heat at useful temperatures; (2) reducing the intensity of the plasma neutrons and providing sufficient radiation shielding to minimize the nuclear heating and radiation damage in the superconducting toroidal field (TF) coils; and (3) demonstrating in a few experimental blanket modules tritium breeding. A blanket and shield design that resulted from the scoping study was incorporated into the EPR Reference Design.^{4,5} However, in the continuing research effort on the EPR, several changes were made in important reactor components, including the blanket.

For completeness, a detailed nuclear analysis was carried out for the blanket and shield design described in Refs. 4 and 5. Calculations, in which stainless steel 316 (SS-316) was used as the structural material and in which a more accurate representation for the TF coils was incorporated, were made for both nonbreeding and tritium-breeding blanket modules. The results of these more detailed calculations, along with mechanical, thermodynamic, and hydraulic analyses, revealed that the blanket could not be adequately cooled if the neutron loading on the first wall exceeded $\sim 0.2 \text{ MW/m}^2$. The design was subsequently modified to include water-filled cooling channels adjacent to the first wall. The water-cooling channels reduce the heat loads and temperature gradients in the first wall to manageable levels where the neutron wall loading is extended to 1 MW/m^2 . Some calculated results are also given for another blanket concept using sodium hydroxide as an alternative to the water coolant. The water-cooled design is currently preferred so most of the calculated results are given for this concept, and the nuclear performance of the older reference design and that of the blanket cooled by sodium hydroxide are compared relative to this design.

The nuclear performances of the EPR when each type of blanket design was used for both the nonbreeding and the tritium breeding configurations are compared in terms of (1) the spatial variations in the omnidirectional neutron and gamma-ray fluxes and energy distributions throughout the reactor assembly; (2) the spatial distributions and integrals of the nuclear heating, particularly in the blanket and TF coil windings; (3) the neutron-induced radiation damage in the reactor structural materials, particularly the first structural wall and the conductors and insulators in the TF coil; and (4) the tritium breeding in the experimental blanket modules.

A description of the reactor model and the details of the calculations are given in sect. II. The results are presented and discussed in sect. III.

II. THE REACTOR MODEL AND DETAILS OF THE CALCULATIONS

Reactor Configuration and Composition of Materials

A schematic representation of the EPR used in carrying out the one-dimensional neutronics and photonics calculations is shown in Fig. 1. The reactor is represented in a cylindrical geometry about the plasma centerline. The plasma has a nominal radius of 223.7 cm and is surrounded by a 0.3-cm-thick graphite curtain.⁶ Beyond this liner at an inner radius of 225 cm is the 51.5-cm-thick blanket, which is followed by a 30-cm-thick void region and surrounded by a 48.5-cm-thick TF coil shield. The blanket and shield, excluding the void that separates them, have a combined thickness of 100 cm. The TF coils that surround the blanket and shield are 62.2-cm-thick and are separated from the outer surface of the shield by a 10-cm-thick gap. Detailed representations of these reactor components and discussions of the philosophy of their design are found elsewhere,^{4,7,8} so only the salient features of the blanket, shield, and TF coils necessary for interpreting the nuclear calculations are included here.

The graphite curtain⁶ that separates the plasma from the first wall of the blanket protects the wall from the damaging effects of low-energy photons, X-rays, and charged particles that are emitted from the plasma. Simultaneously, the graphite curtain prevents metallic atoms and chunks of wall material that are knocked loose from the first wall from entering the plasma. The validity of using a low-Z material for the curtain has not been fully resolved, and further research is required to define the composition, thickness, and location relative to the first wall of impurity

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Fig. 1 Schematic diagram of the EPR Blanket-Shield and TF Coil.

control materials. The graphite curtain is included in the calculational model to obtain approximate results of its inclusion on the nuclear performance of the blanket.

The blanket consists of 60 autonomous segments that form the torus. Each blanket segment is composed of three compartments: an energy absorber (and breeding section when lithium is used), a reflector, and a gamma-ray shield. The blanket superstructure, including the first wall, is SS-316, and in the calculations the composition of SS-316 was taken to be 63.6% Fe, 18% Cr, 13% Ni, 2.6% Mo, 1.9% Mn, and 0.9% Si, Ti, and C.

The choice of SS-316 as the structural and first-wall material was based on its economy, availability, and suitability for use in the EPR without limiting project goals, performance, and schedules. It is also compatible with both potassium and lithium, the energy absorbing and fertile materials chosen for use in the nonbreeding and tritium-breeding blanket modules, respectively. The alloy can also endure, within certain restrictions, the radiation and temperature environments in the reactor. It is not within the scope of this paper to argue the merits and demerits of using SS-316. Arguments for its selection for use in the EPR may be found in Ref. 4. Comparative studies of different iron alloys, as well as other materials, for CTR application may be found elsewhere.⁹⁻¹²

The energy-absorbing compartment in the blanket is 25 cm thick and is followed by a 10-cm-thick graphite neutron reflector. The gamma-ray shield at the rear of the blanket assembly consists of alternating layers of stainless steel and coolant. The dimensions and compositions of the three blanket designs are compared in Table I. The configuration labeled "Reference Design" corresponds to that described in Refs. 4 and 5. Note that in the

TABLE I
EPR Reference Design Blanket Assemblies

Zone	Reference Design, Water Cooled			Reference Design ^a			Reference Design, NaOH Cooled		
	Material Composition	Outer Radius (cm)	Thickness (cm)	Material Composition	Outer Radius (cm)	Thickness (cm)	Material Composition	Outer Radius (cm)	Thickness (cm)
1	Plasma	224.07	224.07	Plasma	223.70	223.70	Plasma	223.70	223.70
2	Carbon	224.37	0.30	Carbon	224.00	0.30	Carbon	224.00	0.30
3	Water	225.00	0.63	Void	225.00	1.00	NaOH	224.64	0.64
4	SS-316	226.11	1.11	SS-316	226.11	1.11	SS-316	225.28	0.64
5	Absorber	251.11	25.00	Absorber	251.11	25.00	Absorber	227.78	2.50
6	SS-316	252.11	1.00	SS-316	252.11	1.00	SS-316	227.82	0.04
7	Carbon	262.11	10.00	Carbon	262.11	10.00	NaOH	227.92	0.10
8	SS-316	263.38	1.27	SS-316	263.38	1.27	SS-316	227.96	0.04
9	Coolant	265.88	2.50	Coolant	265.88	2.50	Absorber	247.96	20.00
10	SS-316	268.38	3.00	SS-316	268.38	3.00	SS-316	248.00	0.04
11	Coolant	268.88	0.50	Coolant	268.88	0.50	NaOH	248.10	0.10
12	SS-316	271.38	2.50	SS-316	271.38	2.50	SS-316	248.14	0.04
13	Coolant	271.88	0.50	Coolant	271.88	0.50	Absorber	250.64	2.50
14	SS-316	274.38	2.50	SS-316	274.38	2.50	SS-316	251.64	1.00
15	Coolant	274.83	0.50	Coolant	274.88	0.50	Carbon	261.64	10.00
16	SS-316	276.50	1.62	SS-316	276.50	1.62	SS-316	262.64	1.00
17	-	-	-	-	-	-	Absorber	266.64	4.00
18	-	-	-	-	-	-	SS-316	266.68	0.04
19	-	-	-	-	-	-	NaOH	266.78	0.10
20	-	-	-	-	-	-	SS-316	266.82	0.04
21	-	-	-	-	-	-	Coolant	268.00	1.18
22	-	-	-	-	-	-	SS-316	270.50	2.50
23	-	-	-	-	-	-	Coolant	271.00	0.50
24	-	-	-	-	-	-	SS-316	273.50	2.50
25	-	-	-	-	-	-	Coolant	274.00	0.50
26	-	-	-	-	-	-	SS-316	276.50	2.50
27	-	-	-	-	-	-	Coolant	277.00	0.50
28	-	-	-	-	-	-	SS-316	278.16	1.16

a. See Refs. 4 and 5.

water-cooled reference design the dimension of the plasma radius is slightly larger (by 0.37 cm) than in the design without water cooling. Also note that the blanket thickness in the sodium-hydroxide-cooled blanket is slightly larger (53.52 cm) than in the other designs and the first-wall inner radius is 225.28 cm. The dimensional differences among the three blanket designs are small and have no significant influence on the calculated results and comparisons.

The compositions of the absorber and coolant materials used in blankets in the nonbreeding and breeding modules are given in Table II. In the nonbreeding modules, both potassium and potassium plus stainless steel in the form of spheres were considered. Natural lithium was the fertile material used in the breeding modules. Potassium and lithium are both easily cooled and have thermal conductivity properties that permit satisfactory exchange of heat between the first wall and blanket-cooling tubes (not shown in Fig. 1) that are interspersed in the blanket.⁴

Neutronic and photonic analyses were also carried out for blankets using sodium rather than potassium as the absorber. The nuclear performance of the reactor using sodium as the blanket was found to be similar to that using potassium. However, the use of sodium as the energy absorbing material was rejected principally because the energetic gamma radiation from sodium isotopes produced in the neutron environment would unduly complicate the shielding and remote maintenance of the blanket assembly.

The graphite reflector is used primarily to enhance the tritium breeding by reflecting neutrons back into the thick energy-absorbing compartment in the blanket when lithium is used to breed tritium. Graphite is not essential in the nonbreeding modules, but it is retained in the design to maintain symmetry.

TABLE II
Blanket Absorber and Gamma-Ray Shield Coolant Materials

Blanket Type	Absorber ^a	Coolant ^b
Nonbreeding	Potassium (35 v/o) SS-316 (65 v/o)	Potassium
	Potassium	Potassium
Tritium Breeding	Lithium ^c	Lithium ^c

- a. In the breeding-type blanket module, the absorber compartment has the dual function of recovering the kinetic energy of the fusion neutrons and breeding tritium.
- b. The cooling material for the blanket gamma-ray shield compartment.
- c. Natural lithium (7.42% ^6Li + 92.58% ^7Li).

Because the blanket does not sufficiently attenuate the neutrons and secondary gamma rays and provide adequate protection for the superconducting TF coils against nuclear heating and radiation damage and because a thermal barrier is required between the high-temperature blanket and the cryogenic coils, the 48.5-cm-thick shield must surround the blanket in the space between the coils and the blanket. The shield is comprised of a 32-cm-thick compartment filled with borated water (35 v/o) and SS-316 spheres (65 v/o) surrounded by a 6.5-cm-thick lead liner. The shield is supported by a 5-cm-thick SS-316 structural layer on both the inner and outer radial surfaces.

Surrounding the blanket and shield are the superconducting TF coils. The coil windings are 52.2 cm thick and are supported by 5-cm-thick stainless-steel supports on the radial surfaces. The coil-winding assemblies were approximated in the calculations by alternating stainless steel and conducting material layers 1.62 and 1.28 cm thick, respectively. The composition of the conductor is given in the insert in Fig. 1. In the calculations, the materials in the conductor were homogenized. Modeling the coil in this manner accounts for, in an approximate way, the conductors and their supports. Additional details concerning the TF coils and other electromagnetic systems may be found in Ref. 4.

Methods of Calculation

All of the neutronics and photonics calculations were carried out using the one-dimensional discrete ordinates code ANISN,¹³ a P_3 scattering expansion, and an S_{12} angular quadrature. The transport cross sections were taken from the coupled 100 n-21 γ cross-section library prepared for EPR calculations^{14,15} that were compiled from the latest available ENDF/B-IV data. The GAM-II¹⁶ 99 epithermal and fast groups, plus a thermal group,

comprise the neutron energy group structure. The neutron- and photon-production cross sections were weighted with an E^{-1} function for neutrons with energies > 5 kT and with a Maxwellian distribution peaked at 800°K for neutrons with energies ≤ 5 kT. All resonance nuclides were treated as infinitely dilute. The photon-interaction cross sections were flat-weighted.

Energy deposition in the reactor blanket, shield, and TF coils was estimated with neutron kerma factors obtained from MACK¹⁷ and MACKLIB¹⁸ and photon kerma factors generated by SMUG.¹⁹ Radiation damage was calculated with the newly developed data base RECOIL²⁰ that generates atomic-displacement and gas-production cross sections in multigroup format from ENDF/B-IV point cross-section data.

The nuclear performance of the EPR was estimated using the parameters summarized in Table III. Except for the physical dimensions of the reactor, all other values were obtained for an assumed neutron wall loading of 1 MW/m² and an average neutron energy of 14.1 MeV per D-T fusion.

All of the comparisons are based on the parameters given in Table III. As noted above, the reference design without water cooling for the first wall is not suitable for use in an operating reactor at this neutron wall loading. However, the results, in general, can be scaled as a function of neutron wall loading, so the results are compared in this manner only for convenience.

TABLE III
EPR Reference Design Parameters

<u>Plasma Dimensions</u>	
Major radius (m)	6.75
Minor radius (m)	2.237
Plasma volume (cm ³)	6.67×10^8
Plasma surface area (cm ²)	5.96×10^6
Toroidal length (cm)	4.24×10^3
<u>Reactor Power Parameters</u>	
Neutron wall loading (MW/m ²)	1.0
Wall loading (n/cm ² /sec)	4.42×10^{13}
Neutrons per sec per cm ^a	6.21×10^{16}
Reactor power (MW) ^b	595

a. The one-dimensional calculations were normalized to one neutron per sec per cm.

b. The reactor power was inferred from the neutron wall loading and the reactor dimensions.

III. DISCUSSION OF RESULTS

Detailed one-dimensional nuclear analyses were carried out for each of the EPR configurations summarized in Table I. The reference-design reactor with water cooling adjacent to the first structural wall was generally accepted to be the preferred design. The two remaining reactor models each have features which, under appropriate conditions, would also make them desirable for the EPR. In terms of the neutronics analyses, the designs are quite similar, so, in general, the detailed results of the calculations reported here will pertain to the water-cooled design and, when relevant, the differences in the nuclear performances in the other designs will be noted.

Flux and Energy Distributions

The spatial distributions of the integral neutron, secondary gamma-ray, and total (neutron plus gamma ray) fluxes as a function of the radial position in the blanket and shield in the reference-design reactor (water cooled) are shown in Fig. 2 when potassium plus SS-316, lithium, and potassium only are used as the energy-absorbing materials in the blanket assembly. These data were obtained by integrating the neutron and secondary gamma-ray omnidirectional fluxes per unit energy over the appropriate particle energy range at each radial interval used in the radiation-transport calculation. The curves have been hand-smoothed to more clearly illuminate the spatial variation in the integral flux for the two radiation modes.

A more rapid attenuation of the integral neutron flux takes place in the energy-absorbing compartment of the blanket containing potassium plus SS-316 than in the blankets containing lithium or potassium. The large concentration of stainless steel (65 v/o) in this compartment effectively

Fig. 2 Spatial Distributions of the Integral Particle Fluxes in the Blanket and Shield of the Water-Cooled Reference Design Reactor When Potassium plus SS-316, Lithium, and Potassium Only are Used as the Energy Absorber.

attenuates the neutrons emitted from the plasma. In each blanket, the integral neutron flux decreases in the graphite reflector followed by a fairly rapid decrease in the gamma-ray shield of the blanket. This rapid decrease again is due to the large amount of stainless steel in the shield.

The rapid decrease in the integral gamma-ray flux in the potassium plus SS-316 blanket is due to the presence of the stainless steel. The higher effective Z value of the material in this blanket compared to the lithium- or potassium-filled assembly leads to the more rapid attenuation in the gamma-ray flux. The abrupt changes in the slopes of the integral gamma-ray fluxes in the lithium- and potassium-laden assemblies at a radius of ~ 265 cm are due to the passage of the photons through the SS-316 layers in the gamma-ray shield.

The shield composition and thickness are the same for the three cases shown in Fig. 2. In each case, the neutron and gamma-ray fluxes are reduced by ~ 3 orders of magnitude through the shield. The differences in the slopes of the curves, as well as the magnitude at the inner surface of the shield, are due to the differences in the average energy of the neutrons or gamma rays incident on the shield.

The blanket assembly has the principal function of recovering the energy of the fusion neutrons and secondary gamma rays in the form of usable heat. In the case of the lithium blanket, tritium breeding is also a requirement. However, of equal importance is the effectiveness of the blanket and shield in minimizing the radiation flux incident on the TF coils within the constraints of specified thickness, heat-recovery capability, and, if necessary, tritium breeding. The radiation-attenuating effectiveness of the blanket-shield cases shown in Fig. 2 is given in Table IV as a function

Table IV

Radiation Attenuating Capability of the Blanket and Shield
as a Function of Absorber Material in the
Reference Design Reactor (Water-Cooled)

Location	Absorber Material		
	K + SS-316	Li	K
	Fraction of the Total Flux		
First structural wall	1.00	1.00	1.00
Rear of the blanket	3.74×10^{-2}	9.36×10^{-2}	1.23×10^{-1}
Rear of the shield	1.88×10^{-5}	1.52×10^{-4}	2.10×10^{-4}
Attenuating effectiveness ^a	1.00	0.12	0.09

a. Relative to the blanket with K + SS-316 as the absorber material.

of the energy-absorbing material. The values given in the table are the fractions of the total flux relative to the flux at the first structural wall. The blanket containing potassium plus SS-316 is 2.5 times more effective in attenuating the radiation than the blanket containing lithium and 3.3 times more effective than the one containing potassium. The combined radiation attenuating effectiveness of the three designs are compared in the last row of the table. When lithium is used as the energy absorber, the blanket and shield are only 12% as effective as the assembly containing potassium plus SS-316, and when potassium only is used in the energy-absorbing compartment, the radiation-attenuating effectiveness is reduced to 9%.

The spatial distributions of the integral neutron and gamma-ray fluxes as a function of radial position in the blanket and shield of the reference-design reactor (without water cooling) are essentially the same as those shown in Fig. 2 for the same blanket absorber materials. The differences in the flux distributions between the two designs are due primarily to the variations in the neutron and gamma-ray spectra that result from the presence of the 0.63-cm-thick water-cooling channel that differentiates the two reactor designs. The radiation attenuating effectiveness of the blanket and shield as a function of blanket absorber material without water cooling is very nearly the same as that given in Table IV.

The spatial distributions of the flux were also obtained for the reference design with sodium hydroxide as the cooling material, but only when lithium was used as the energy-absorbing material. The flux distributions and the radiation attenuating capability for this reactor were also essentially the same as those obtained for the lithium-laden blankets in the two reactor designs cited above.

The space and energy dependences of the neutron scalar flux in the reference-design reactor (water cooled) when potassium plus SS-316 and lithium are used as the energy-absorbing material in the blanket are shown in Fig. 3 (a) and (b), respectively.²¹ The radial dimensions of the reactor are plotted in equal intervals corresponding to the number of radial mesh intervals used in the ANISN code¹³ to define the blanket, shield, and TF coils. This results in a compression of the radial extent of the reactor. The energy scale is plotted in lethargy intervals obtained with the relation $u = \ln(E_u/E_l)$ evaluated at the upper (E_u) and lower (E_l) energy bounds of each neutron group.^{14,15} The neutron flux in each spatial interval has been normalized to unity. This normalization removes effects of the spatial attenuation of the flux and magnifies its energy dependence.

The 14-MeV neutrons produced in the plasma are attenuated rapidly as they pass through the reactor, as shown by the rapidly decreasing amplitude of the peaks along the left edges of both (a) and (b) of Fig. 3. These neutrons lose energy in the blanket containing potassium plus SS-316 as the energy absorber primarily through inelastic collisions with the absorber nuclei, particularly iron. The peaks in the distributions occur at cross-section minima and show the energy intervals through which the neutrons stream, suffering the least number of reactions. The valleys, or depressions, indicate the energy intervals in which neutron interactions are greatest. The sharply defined valleys occur at cross-section resonances. The two large peaks arising along the inner spatial intervals are due to neutron streaming in the 24- and 80-keV cross-section minima in iron. Other cross-section minima and resonances in iron are apparent but are less accentuated because of compensating neutron interactions taking place in the potassium or with other nuclei that comprise stainless steel.

Fig. 3 Space and Energy Dependences of the Neutron Scalar Flux in the Water-Cooled Reference Design Reactor When Potassium Plus SS-316 and Lithium are Used as the Energy Absorber.

In the energy-absorbing compartment of the blanket containing lithium, there is considerably less structure in the flux distributions. The energy dependence follows that predicted by the total neutron cross section of natural lithium. The depression in the curves between 100 keV and 1 MeV is due to ${}^6\text{Li}(n,\alpha)$ reactions taking place in the large resonance about 240 keV that is characteristic of this reaction.

The neutrons that leak through the energy-absorbing compartment of each blanket in Fig. 3 are moderated in the graphite reflector. The space and energy dependences of the flux in the graphite follow the energy dependence of the neutron cross section for this material. The thermal-neutron flux in the graphite in Fig. 3 (a) is larger than that in Fig. 3 (b) and is due to the difference in the average energy of the neutrons incident on the reflector in each case.

The structure in the flux distributions in the blanket gamma-ray shield and in the stainless-steel support at the inner surface of the shield shows the cross-section minima and resonances in stainless steel. The neutrons leak into the borated-water and stainless-steel section of the shield, mainly through the 24- and 80-keV cross-section minima in iron. However, these neutrons are rapidly moderated and thermalized by the borated water, giving rise to the large flux distributions in the thermal-energy group in each design. Again, the difference in the magnitude of the flux in each case is due to the differences in the energy distribution of the neutrons incident on this section of the shield.

The flux distributions in the rear of the shield and through the TF coil section show the characteristics of neutron transport in stainless steel. The structure in the curves below 10 keV is due to neutron transport in the

coil-conductor material, particularly through the 7.5-, 9.1-, and 9.5-keV cross-section minima in copper.

The space and energy dependences of the secondary gamma-ray flux per unit energy in the two reactor configurations are shown in Fig. 4 (a) and (b), respectively.²¹ These data are plotted using the same spatial mesh as in Fig. 3 but with the energy scale plotted in intervals spaced in proportion to the widths of the gamma-ray energy group structure.^{14,15} The gamma-ray spectra are normalized to unity in each spatial interval to remove the effects of attenuation, and these data are plotted at the midpoint of each energy group.

The distributions in Fig. 4 show the production of gamma radiation throughout the reactor. The peaks at 7 MeV that occur in the energy-absorbing compartment of the blanket containing potassium plus SS-316 show the photon production from thermal-neutron-capture reactions in the iron nuclei in the stainless steel. Note that these gamma-rays are not produced in the blanket containing lithium as the energy absorber. The large peaks rising in the low-energy intervals at and below 1.25 MeV show the gamma radiation through (n,n') reactions. The peaks in the spectra in the energy interval about 1.25 MeV are due to inelastic neutron reactions in chromium (1.44 MeV) and in nickel (1.33 MeV), and the larger peaks in the spectra in the interval about 0.7 MeV correspond to 0.85-MeV gamma-rays from inelastic neutron reactions with iron nuclei. These photon-producing reactions occur throughout the potassium-plus-SS-316-filled compartment. These photons also appear in the lithium absorber, but in this case they are produced elsewhere in the reactor and leak into the lithium. The large amplitude peaks in the lithium absorber in the energy interval about 0.3 MeV are the

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Fig. 4 Space and Energy Dependences of the Secondary Gamma-Ray Flux per Unit Energy in the Water-Cooled Reference Design Reactor When Potassium Plus SS-316 and Lithium are Used as the Energy Absorber.

0.48-MeV gamma-rays from (n,n') reaction in ${}^7\text{Li}$.

The secondary gamma-ray spectra throughout the remaining sections of both reactor configurations in Fig. 4. are very similar in shape. The 4.43-MeV gamma-ray production in the graphite reflector following the lithium absorber is greater than in the graphite following the potassium-plus-SS-316 absorber because the lithium is less effective in reducing the energetic incident neutron flux that leads to the production of these photons. The large peak at low energy in the graphite reflector is due to photons produced elsewhere in the reactor that pass through the graphite and are slowed down in the reflector. Throughout the shield, the gamma-ray spectra are characterized by the production of 7-MeV gamma rays from thermal-neutron-capture reactions by iron and by the production of 1.44-, 1.33-, and 0.85-MeV photons from inelastic neutron reactions with chromium, nickel, and iron nuclei in the stainless steel. In the lead liner at the rear of the shield, photon production occurs via neutron reactions leading to the excited states from 3.0 MeV down to 0.3 MeV. The large hole in the spectral distributions in the lead at low photon energies shows the absorption of photons by the lead through Compton and photoelectric reactions.

The gamma-ray production in the TF coil shows similar behavior to that in the blanket and is due to low-energy neutron inelastic reactions with the conductor materials and the stainless-steel structure. The 7-MeV photons are those produced from thermal neutron capture in iron and to a lesser extent in the copper and aluminum of the conductor. The low-energy photons are produced by neutrons having energies > 850 keV leading to inelastic neutron scattering in iron, aluminum, and copper.

Nuclear Heating

The spatial distributions of the nuclear heating rates in the reference-design reactor (water cooled) are shown in Fig.5 when potassium plus SS-316, lithium, and potassium only are used as the energy-absorbing materials in the blanket assembly (see Table II). The solid curves show the total heating rates (neutrons plus secondary gamma rays) and the curves bearing tick marks show the heating rates from neutrons only. Note that the ordinate has been broken in order to display the results for the three cases in the same figure.

The peak heating rate occurs in the first SS-316 structural wall in each of the cases shown in the figure. At a neutron wall loading of 1 MW/m^2 , the peak heating rates are 11.7, 10.4, and 12.0 W/cm^3 for the potassium plus SS-316, the lithium, and the potassium configurations, respectively. In the blanket assembly containing potassium plus SS-316, the nuclear heating rate decreases by approximately three orders of magnitude through the blanket. The large concentration of stainless steel (65 v/o) in the energy-absorbing compartment is effective in moderating the energetic neutrons emitted from the plasma. The gamma rays produced in inelastic neutron reactions with the nuclei of stainless steel, particularly iron, are absorbed by the stainless steel and potassium, giving rise to the large gamma-ray contribution to the nuclear heating in the energy-absorbing compartment. In the lithium-laden blanket assembly, the nuclear heating is dominated by the ${}^7\text{Li}(n,n',\alpha)\text{T}$ reaction at high energy and by the ${}^6\text{Li}(n,\alpha)\text{T}$ reaction which is characterized by a large $1/v$ cross section at low energy. In the blanket assembly containing potassium as the energy absorber, the neutrons and gamma rays contribute approximately equally to the nuclear heating.

Fig. 5 Energy Deposition Rate as a Function of Reactor Radius in the Water-Cooled Reference Design Reactor When Potassium Plus SS-316, Lithium, and Potassium Only are Used as the Energy Absorber.

The graphite reflector in each blanket extracts the kinetic energy of the neutrons that leak from the energy-absorbing compartment. The neutrons are moderated by the graphite and recovered in the form of heat via (n,α) reactions. The gamma-ray heating is due mainly to the absorption of photons produced by neutron reactions in the graphite as well as those photons that leak from the energy-absorbing compartment. In the gamma-ray shield of the blanket, the structure in the curves shown in Fig. 5 indicates the heating rates in the alternating stainless-steel plates and coolant channels. The large gamma-ray heating in the plates is due to the absorption of gamma rays by the stainless steel.

The shield composition and dimensions are the same for the three blanket configurations. The peak heating rate occurs at the inner edge of each shield. For a neutron wall loading of 1 MW/m^2 , the peak total heating rates are 0.31, 0.43, and 0.75 W/cm^3 for the potassium plus SS-316, lithium, and potassium configurations, respectively. The differences in these values are due to the relative radiation shielding effectiveness of the blanket assembly in each reactor configuration. The neutron energy leaking from the blanket is moderated by the 5-cm-thick stainless-steel structural member at the inner surface of the shield. The large difference between the total and neutron heating rates in this structure is due to the absorption of gamma radiation leaking from the blanket assembly along with that produced in inelastic and neutron-capture reactions that occur in the stainless steel. The abrupt change in the neutron heating rate at the inner surface of that portion of the shield containing stainless steel (65 v/o) and borated water (35 v/o) is due to the absorption of low-energy neutrons by the boron leading to the exothermic $^{10}\text{B}(n,\alpha)$ reaction. These reactions take place throughout

this portion of the shield as the stainless steel further moderates the neutrons and the water thermalizes them. The large gamma-ray heating rate is due mainly to the absorption of gamma rays by the stainless steel. The heating rate in the lead liner that surrounds the shield is due almost entirely to gamma-ray absorption.

The shapes of the heating-rate curves in the TF coils are essentially the same for each configuration but differ in magnitude according to the relative shielding effectiveness of the blanket-shield combination. The peak heating rates in the TF coils for the potassium plus SS-316, lithium, and potassium only configurations correspond to 1.1×10^{-4} , 5.4×10^{-4} , and 9.3×10^{-4} W/cm³, respectively, for a neutron wall loading of 1 MW/m².

The volume-integrated neutron, gamma-ray, and total heating rates in the various components of the reactor, as well as the fractional total heating rate in the reactor components, are given in Table V as a function of the blanket-absorber material. The total heating rate in the reactor containing potassium plus SS-316 is 1.16 times greater than that in the configuration containing lithium and 1.12 times greater than that in the assembly containing potassium only. The larger value is due primarily to the large number of exothermic (n, γ) reactions that take place in the stainless steel in the energy-absorbing compartment. For a power-producing reactor, the larger value results in a net increase in the system power output.

For all of the configurations, $\geq 90\%$ of the fusion energy is recovered in the form of heat in the blanket modules. The blanket modules are defined here to include all of the components of the reactor except the shield and the TF coil assemblies. In the reactor containing potassium plus SS-316, $\sim 97\%$ of the available neutron and secondary gamma-ray energy is recovered

Table V. Volume-integrated neutron and gamma-ray contributions to the nuclear heating rate in the water-cooled reference design reactor as a function of blanket absorber material

Reactor components	Absorber material											
	K + SS-316				Li				K			
	Neutron heating rate	Gamma-ray heating rate	Total heating rate	Fractional heating rate	Neutron heating rate	Gamma-ray heating rate	Total heating rate	Fractional heating rate	Neutron heating rate	Gamma-ray heating rate	Total heating rate	Fractional heating rate
	(w/n/sec)	(w/n/sec)	(w/n/sec)	(%)	(w/n/sec)	(w/n/sec)	(w/n/sec)	(%)	(w/n/sec)	(w/n/sec)	(w/n/sec)	(%)
Graphite curtain	3.56×10^{-14}	9.30×10^{-15}	4.49×10^{-14}	1.41	3.41×10^{-14}	8.22×10^{-15}	4.23×10^{-14}	1.55	3.35×10^{-14}	1.21×10^{-14}	4.56×10^{-14}	1.61
Water coolant	1.48×10^{-13}	2.12×10^{-14}	1.69×10^{-13}	5.31	1.40×10^{-13}	1.07×10^{-14}	1.51×10^{-13}	5.52	1.33×10^{-13}	1.70×10^{-14}	1.50×10^{-13}	5.30
Blanket												
First structural wall	9.28×10^{-14}	2.85×10^{-13}	3.78×10^{-13}	11.88	9.49×10^{-14}	1.43×10^{-13}	2.38×10^{-13}	8.72	9.17×10^{-14}	2.13×10^{-13}	3.05×10^{-13}	10.78
Absorber compartment	4.12×10^{-13}	1.69×10^{-12}	2.10×10^{-12}	66.02	1.24×10^{-12}	1.14×10^{-13}	1.35×10^{-12}	49.59	4.69×10^{-13}	4.02×10^{-13}	8.71×10^{-13}	30.79
Reflector ^a	4.99×10^{-14}	1.48×10^{-13}	1.98×10^{-13}	6.22	1.92×10^{-13}	2.37×10^{-13}	4.29×10^{-13}	15.72	2.96×10^{-13}	4.07×10^{-13}	7.03×10^{-13}	24.84
Gamma-ray shield	6.80×10^{-15}	1.85×10^{-13}	1.92×10^{-13}	6.04	1.23×10^{-13}	2.12×10^{-13}	3.35×10^{-13}	12.27	6.00×10^{-14}	4.09×10^{-13}	4.69×10^{-13}	16.56
Shield	1.44×10^{-14}	8.47×10^{-14}	9.91×10^{-14}	3.12	3.64×10^{-14}	1.44×10^{-13}	1.80×10^{-13}	6.61	5.69×10^{-14}	2.27×10^{-13}	2.84×10^{-13}	10.03
TF coil												
SS-316 structure	1.62×10^{-18}	1.71×10^{-17}	1.87×10^{-17}	5.8×10^{-4}	8.43×10^{-18}	8.36×10^{-17}	9.20×10^{-17}	3.3×10^{-3}	1.51×10^{-17}	1.46×10^{-16}	1.61×10^{-16}	5.7×10^{-3}
TF coil windings	2.29×10^{-18}	2.59×10^{-17}	2.82×10^{-17}	8.9×10^{-4}	1.20×10^{-17}	1.33×10^{-16}	1.45×10^{-16}	5.3×10^{-3}	2.07×10^{-17}	2.26×10^{-16}	2.46×10^{-16}	8.7×10^{-3}
SS-316 structure	7.55×10^{-21}	3.26×10^{-19}	3.34×10^{-19}	1.0×10^{-5}	3.99×10^{-20}	1.72×10^{-18}	1.76×10^{-18}	6.45×10^{-5}	6.12×10^{-20}	2.20×10^{-18}	2.26×10^{-18}	8.0×10^{-5}
Total heating rate	7.60×10^{-13}	2.42×10^{-12}	3.18×10^{-12}		1.86×10^{-12}	8.65×10^{-13}	2.73×10^{-12}		8.15×10^{-12}	1.68×10^{-12}	2.83×10^{-12}	
Mev per neutron	4.74	15.10	19.84		11.67	5.37	17.04		7.18	10.48	17.66	

^aIncludes SS-316 on the inner and outer radial surfaces.

as heat in the blanket assembly compared to $\sim 93\%$ for the configuration containing potassium. In each reactor design, the shield recovers nearly all of the remaining neutron and secondary gamma-ray energy in the form of heat. The small fraction of the remaining energy that leaks from the shield is deposited in the TF coils. It is interesting to note that the ratio of the volume-integrated gamma-ray heating rate to the volume-integrated neutron-heating rate in the TF coil windings is essentially the same ($\sim 11:1$) in each configuration. The fractional heating rate in the TF coil windings in the reactor containing potassium plus SS-316 of $8.9 \times 10^{-4}\%$ is a factor of six lower than the fractional heating rate in the TF coils in the reactor containing lithium and a factor of ~ 10 smaller than in the TF coils in the reactor containing potassium as the energy absorber.

The nuclear heating rates as a function of radius in the reference-design reactor without water cooling of the first structural wall (see Table I) exhibit essentially the same behavior as the heating rates as shown in Fig. 5. The spatial distributions of the nuclear heating were calculated for the reactor configurations when potassium plus SS-316 and lithium were used as the energy-absorbing material in the blanket assembly. The heating rate in the SS-316 first structural wall for a neutron wall loading of 1 MW/m^2 is 12.4 W/cm^3 for the configuration containing potassium plus SS-316 and 9.5 W/cm^3 when lithium is the energy-absorbing material. The differences between these heating rates and those given above for the same energy-absorbing material can be ascribed to the exclusion of the water-filled cooling channel. The presence of the water leads to a reduction in energy of the plasma neutrons as a result of neutron collisions with the hydrogen nuclei in the water.

The peak heating rates at the inner surfaces of the shield and the TF coil assembly are 0.43 and 1.2×10^{-4} W/cm³, respectively, for the potassium plus SS-316 case and 0.48 and 5.7×10^{-4} W/cm³, respectively, in the reactor configuration containing lithium. All of these values are higher than those obtained at the same locations in the water-cooled reference-design reactor. The shift in the energy distribution of the neutrons as a result of the inclusion of the water leads to lower peak heating rates, particularly in the cryogenic TF coil assembly where temperature increases due to nuclear heating are costly to overcome. It is generally asserted that ~ 500 W of refrigeration power are required to overcome the temperature rise for an energy deposition rate of 1 W.

The volume-integrated neutron, gamma-ray, and total heating rates, and the fractional total heating rates are summarized in Table VI as a function of the energy-absorbing material for the reference-design reactor (without water cooling). In both configurations $> 90\%$ of the energy is recovered in the form of heat in the blanket assembly. The shield recovers all but a small fraction of the remaining energy. The integral rate in the TF coil windings is a factor of ~ 6 smaller in the potassium plus SS-316 case than in the lithium case.

The nuclear heating rate as a function of reactor radius in the reference reactor with sodium hydroxide as the first wall and blanket coolant is shown in Fig. 6 when lithium is used as the energy-absorbing material in the blanket assembly. The solid curves show the total heating rate and the curves bearing tick marks show the heating rate due to neutrons only. The peak heating rates in the sodium-hydroxide-filled cooling channel adjacent to the first SS-316 structural wall and in the wall itself for a

Table VI. Volume-integrated neutron and gamma-ray contributions to the heating rate in the reference design reactor as a function of absorber material

Reactor components	Absorber material							
	K + SS-316				Li			
	Neutron heating rate	Gamma-ray heating rate	Total heating rate	Fractional heating rate	Neutron heating rate	Gamma-ray heating rate	Total heating rate	Fractional heating rate
	(w/n/sec)	(w/n/sec)	(w/n/sec)	(%)	(w/n/sec)	(w/n/sec)	(w/n/sec)	(%)
Graphite curtain	3.82×10^{-14}	1.16×10^{-14}	4.98×10^{-14}	1.56	3.58×10^{-14}	1.90×10^{-15}	4.37×10^{-14}	1.61
Blanket								
First structural wall	1.05×10^{-13}	2.09×10^{-13}	3.14×10^{-13}	9.81	1.06×10^{-13}	1.52×10^{-13}	2.38×10^{-13}	8.78
Absorber compartment	4.57×10^{-13}	1.70×10^{-12}	2.16×10^{-12}	67.5	1.28×10^{-12}	1.20×10^{-13}	1.40×10^{-12}	51.66
Reflector ^a	5.89×10^{-14}	2.11×10^{-13}	2.70×10^{-13}	8.44	2.08×10^{-13}	2.42×10^{-13}	4.50×10^{-13}	16.61
Gamma-ray shield	2.21×10^{-15}	2.73×10^{-13}	2.75×10^{-13}	8.59	1.55×10^{-13}	2.26×10^{-13}	3.81×10^{-13}	14.06
Shield	1.75×10^{-14}	1.13×10^{-13}	1.31×10^{-13}	4.09	3.97×10^{-14}	1.59×10^{-13}	1.99×10^{-13}	7.34
TF Coil								
SS-316 structure	1.72×10^{-18}	1.84×10^{-17}	2.01×10^{-17}	6.3×10^{-4}	8.97×10^{-18}	8.88×10^{-17}	9.78×10^{-17}	3.6×10^{-3}
TF Coil windings	2.44×10^{-18}	2.78×10^{-17}	3.02×10^{-17}	9.4×10^{-4}	1.28×10^{-17}	1.41×10^{-16}	1.54×10^{-16}	5.7×10^{-3}
SS-316 structure	8.00×10^{-21}	3.47×10^{-19}	3.55×10^{-19}	1.1×10^{-5}	4.24×10^{-20}	1.82×10^{-18}	1.86×10^{-18}	6.9×10^{-5}
Total heating rate	6.79×10^{-13}	2.52×10^{-12}	3.20×10^{-12}		1.82×10^{-12}	8.87×10^{-13}	2.71×10^{-12}	
MeV per neutron	4.24	15.72	19.96		11.36	5.54	16.90	

^aIncludes SS-316 on the inner and outer radial surfaces.

Fig. 6 Energy Deposition Rate Versus Reactor Radius in the Sodium Hydroxide-Cooled Reference Design Reactor with Lithium as the Energy Absorbing Material.

neutron wall loading of 1 MW/m^2 are 8.5 and 8.7 W/cm^3 , respectively. The peak heating rates at the inner surface of the shield and the first conductor layer in the TF coil assembly are 0.53 and $2.8 \times 10^{-4} \text{ W/cm}^3$, respectively.

The volume-integrated neutron, gamma-ray, and total heating rates in the components of the reactor along with the fractional heating rates are summarized in Table VII. The blanket assembly recovers $> 90\%$ of the fusion energy in the form of heat. The total heating rate in the TF coil windings is slightly higher in this design than in the two previous designs when lithium is the absorbing material.

Radiation Damage

The radiation damage induced in the SS-316 structural materials at various locations throughout the reference-design reactors (see Table I) are summarized in Tables VIII, IX, and X as a function of the energy-absorbing material used in the blanket. These data have been normalized to a neutron wall loading of 1 MW/m^2 . The radiation damage is compared in terms of the atomic displacement rate in displacements per atom per year in Table VIII and in terms of the hydrogen and helium gas production rates in atom parts per million per year in Tables IX and X, respectively. The gas-production rates take into account the hydrogen production from the (n,p) and $(n,n')p$ reactions and the helium production from the (n,α) and $(n,n')\alpha$ reactions that take place in the stainless steel.

Of particular interest in fusion-reactor design is the radiation damage that occurs in the first structural wall in the reactor. This structure is nearest to the harsh neutron environment of the plasma, and the maintenance schedule and related problems are based on the damage rate to this component

Table VII. Volume-integrated neutron and gamma-ray heating rates in the sodium-hydroxide-cooled reference design reactor

Reactor components	Absorber material = lithium			
	Neutron heating rate	Gamma-ray heating rate	Total heating rate	Fractional heating rate
		(w/n/sec)		(%)
Graphite curtain	3.50×10^{-14}	6.80×10^{-15}	4.18×10^{-14}	1.57
Blanket				
Sodium hydroxide coolant	1.05×10^{-13}	1.80×10^{-14}	1.23×10^{-13}	4.61
First structural wall	5.76×10^{-14}	6.84×10^{-14}	1.26×10^{-13}	4.72
Absorber compartment	1.30×10^{-12}	1.20×10^{-13}	1.42×10^{-12}	53.2
Reflector ^a	1.94×10^{-13}	2.03×10^{-13}	3.97×10^{-13}	14.9
Gamma-ray shield	1.73×10^{-13}	1.80×10^{-13}	3.53×10^{-13}	13.20
Shield	4.53×10^{-14}	1.76×10^{-13}	2.21×10^{-13}	8.28
TF coil				
SS-316 structure	1.67×10^{-17}	1.63×10^{-16}	1.30×10^{-16}	6.7×10^{-3}
TF coil windings	2.32×10^{-17}	1.97×10^{-16}	2.21×10^{-16}	8.3×10^{-3}
SS-316 structure	6.92×10^{-20}	2.52×10^{-18}	2.59×10^{-18}	9.7×10^{-5}
Total heating rate	1.90×10^{-12}	7.73×10^{-13}	2.57×10^{-12}	
MeV per nucleon	11.86	4.82	16.68	

^aIncludes SS-316 structure on the inner and outer radial surfaces.

Table VIII. Spatial dependences of the displacements per atom per year in the SS-316 structure at various locations in the reference reactor designs^a

(Neutron wall loading = 1.0 MW/M²)

Location	Reference reactor design					
	Water cooled			Without cooling		NaOH cooled
	Absorber material					
	K + SS-316	Li	K	K + SS-316	Li	Li
First structural wall	10.9	10.7	10.1	13.5	12.2	11.3
Rear of absorber	1.2	3.3	4.7	1.5	3.8	4.1
Rear of reflector	0.39	1.3	2.0	0.46	1.5	1.4
Rear of blanket	0.13	0.38	0.58	0.15	0.42	0.31
Front of shield	0.08	0.23	0.38	0.09	0.26	0.25
Rear of shield	1.2×10^{-4}	6.1×10^{-4}	1.1×10^{-3}	1.3×10^{-4}	6.8×10^{-4}	1.0×10^{-3}
Front of TF coil	7.3×10^{-5}	3.6×10^{-4}	4.6×10^{-4}	7.7×10^{-5}	6.8×10^{-4}	7.3×10^{-4}
Center of TF coil	9.5×10^{-6}	5.1×10^{-5}	5.5×10^{-5}	1.0×10^{-5}	6.7×10^{-5}	1.1×10^{-4}
Rear of TF coil	5.4×10^{-7}	2.3×10^{-6}	4.0×10^{-6}	5.7×10^{-7}	3.0×10^{-6}	4.7×10^{-6}

^aBased on an effective displacement energy of 40 eV.

Table IX. Spatial dependences of the hydrogen gas production rate (appm/year) in the SS-316 structure at various locations in the reference reactor designs
(Neutron wall loading = 1.0 MW/M²)

Location	Reference reactor design					
	Water cooled			Without cooling		NaOH cooled
	Absorber material					
	K + SS-316	Li	K	K + SS-316	Li	Li
First structural wall	423	452	421	464	497	476
Rear of absorber	14.0	103	153	14.7	110	134
Rear of reflector	5.0	34	51	5.3	36	43
Rear of blanket	0.98	5.8	8.9	1.1	6.2	6.1
Front of shield	0.53	3.1	6.9	0.55	3.3	4.9
Rear of shield	1.5×10^{-3}	7.8×10^{-3}	1.4×10^{-2}	1.5×10^{-3}	8.3×10^{-3}	1.6×10^{-2}
Front of TF coil	5.9×10^{-4}	3.1×10^{-3}	5.6×10^{-3}	6.0×10^{-4}	3.3×10^{-3}	6.3×10^{-3}
Center of TF coil	1.73×10^{-5}	8.9×10^{-5}	7.2×10^{-4}	2.2×10^{-5}	9.4×10^{-5}	3.3×10^{-4}
Rear of TF coil	3.7×10^{-7}	1.9×10^{-6}	3.6×10^{-6}	3.8×10^{-7}	1.9×10^{-6}	3.7×10^{-6}

Table X. Spatial dependences of the helium gas-production rate (appm/year) in the SS-316 structure at various locations in the reference reactor designs
(Neutron wall loading = 1.0 MW/M²)

Location	Reference reactor design					
	Water cooled			Without cooling		NaOH cooled
	Absorber material					
	K + SS-316	Li	K	K + SS-316	Li	Li
First structural wall	129	134	129	142	148	141
Rear of absorber	3.7	28	41	3.9	29.5	36
Rear of reflector	1.3	8.8	13	1.4	9.3	9.4
Rear of blanket	0.25	1.5	2.4	0.27	1.6	1.5
Front of shield	0.13	0.8	1.3	0.14	0.82	1.2
Rear of shield	3.7×10^{-4}	1.9×10^{-3}	3.5×10^{-3}	3.7×10^{-4}	2.1×10^{-3}	3.8×10^{-3}
Front of TF coil	1.5×10^{-4}	7.5×10^{-4}	1.4×10^{-3}	1.5×10^{-4}	7.9×10^{-4}	1.5×10^{-3}
Center of TF coil	4.2×10^{-6}	2.0×10^{-5}	4.1×10^{-5}	4.4×10^{-6}	2.1×10^{-5}	7.5×10^{-5}
Rear of TF coil	8.9×10^{-8}	4.3×10^{-7}	8.7×10^{-7}	9.12×10^{-8}	4.6×10^{-7}	8.4×10^{-7}

of the reactor. In general, less damage is incurred in the first wall of the reactor design with water cooling than in the design without water cooling or when sodium hydroxide is used as the coolant. The neutrons emitted from the plasma are degraded in energy as they pass through the 0.64-cm-thick water-cooling channel as the result of scattering from hydrogen nuclei. The atomic displacement and gas-production cross sections are each peaked at high (~ 14 MeV) neutron energy, and the reduction in the intensity of energetic neutrons resulting from these collisions leads

As shown in Table VII, the atomic-displacement rate in the first-wall in the reactor design using potassium plus SS-316 as the absorber material is $\sim 20\%$ smaller in the water-cooled design than in the configuration without water cooling. When lithium is used as the absorber, the atomic-displacement rate is $\sim 12\%$ lower in the water-cooled design than in the design without water cooling and $\sim 5\%$ lower than in the design using sodium hydroxide as the coolant.

The hydrogen and helium gas-production rates in the first wall follow essentially the same trend as the atomic-displacement rate as shown in Tables IX and X. The differences in the data in each design may be attributed to the degradation of the high-energy neutron intensity due to the presence of the water- or sodium-hydroxide-cooling channels.

For a given design, some of the differences in the first-wall radiation damage as a function of the absorber material can be attributed to neutrons backscattered from the absorber material. These differences may be noted in the water-cooled design and in the design without cooling when potassium plus SS-316 and lithium are used as the absorber.

The radiation damage induced in the SS-316 structural components elsewhere in the reference-design reactor assemblies is also summarized in Tables VIII, IX, and X. The extent of the damage induced in these components depends strongly on the energy-absorbing material in the blanket. The atomic-displacement and gas-production rates in the stainless steel behind the potassium-plus SS-316-filled blanket are considerably smaller than in the structure behind the lithium- and potassium-filled blankets. The stainless steel in this blanket moderates the neutrons in energy more rapidly than in the other absorber materials. The small differences in the damage values in the structure behind the potassium plus SS-316 or lithium-filled absorber compartments compared as a function of the first-wall cooling scheme are due to the differences in the neutron spectra that result from the presence or exclusion of coolant.

The spatial distributions of the atomic displacement, and the hydrogen and helium gas production rates in the aluminum, copper, and niobium in the conductors in the TF coil are shown in Figs. 7, 8, and 9, respectively. These results were obtained for the water-cooled reference reactor and are compared as a function of the energy absorbing material used in the blanket. The data are normalized to a neutron wall loading of 1 MW/m^2 .

The results in each figure exhibit the same behavior as a function of the energy absorber. The radiation damage to the coil in the configuration containing potassium plus SS-316 is smaller than in the configurations that use potassium only or lithium as the absorber.

Fig. 7 Atomic Displacement Rate as a Function of Depth in the TF Coil and of Absorber Material in the Water-Cooled Reference Design Reactor.

Fig. 8 Hydrogen Gas Production Rate as a Function of Depth in the TF Coil and of Absorber Material in the Water-Cooled Reference Design Reactor.

Fig. 9 Helium Gas Production Rate as a Function of Depth in the TF Coil and of Absorber Material in the Water-Cooled Reference Design Reactor.

Tritium Breeding

The design criteria for the EPR specified that tritium breeding be demonstrated in a few experimental blanket modules. The calculations to determine tritium breeding in the various reference designs were carried out using natural lithium as the fertile material with breeding being accomplished via the ${}^6\text{Li}(n,\alpha)\text{T}$ and the ${}^7\text{Li}(n,n'\alpha)\text{T}$ reactions. The ${}^6\text{Li}$ reaction is exothermic and is characterized by a large thermal cross section (~ 950 b) that varies as $1/v$ and by a large resonance at ~ 0.25 MeV. The ${}^7\text{Li}$ reaction has a threshold at ~ 2.5 MeV and peaks to ~ 425 mb at 8 MeV.

The tritium breeding ratios in the three reactor designs described above are compared in Table XI. Successful breeding (> 1) is achieved in each design with $\sim 85\%$ of the total tritium production taking place in the primary lithium region (i.e., the energy absorbing compartment) in the blanket. Neutron reactions in ${}^6\text{Li}$ account for $\sim 60\%$ of the breeding. In the water-cooled design, the number of tritium nuclei per incident neutron produced in the ${}^6\text{Li}$ in the primary lithium region (0.623) is larger than in the design with no cooling (0.603) or when sodium hydroxide is the first-wall coolant (0.607). The difference is due to the presence of the water which reduces the energy of the neutrons incident on the lithium from the plasma and also thermalizes low-energy neutrons that backscatter from the lithium. The total breeding in the primary lithium compartment is, however, essentially the same in each blanket and is due to the compensating neutron reactions in ${}^7\text{Li}$.

Table XI. Tritium breeding in the EPR reference reactor designs

Reference design zone	Thickness (cm)	Water-cooled			No cooling			Zone	Thickness (cm)	Sodium-hydroxide cooled		
		^6Li	^7Li	$^6\text{Li} + ^7\text{Li}$	^6Li	^7Li	$^6\text{Li} + ^7\text{Li}$			^6Li	^7Li	$^6\text{Li} + ^7\text{Li}$
		(Tritium nuclei/incident neutron)								(Tritium nuclei/incident neutron)		
Primary lithium region	25	0.623	0.409	1.032	0.603	0.437	1.040	Primary lithium region	2.5	0.099	0.069	0.168
									20.0	0.426	0.342	0.768
Lithium behind graphite reflector	2.5	8.4×10^{-2}	6.4×10^{-3}	0.090	0.105	0.007	0.112		2.5	0.082	0.025	0.107
Lithium coolant in gamma shield	0.5	1.1×10^{-2}	7.5×10^{-4}	0.012	1.4×10^{-2}	7.9×10^{-4}	0.015	Lithium behind graphite reflector	4.0	0.104	0.011	0.115
	0.5	8.3×10^{-3}	4.7×10^{-4}	0.009	1.0×10^{-2}	5.0×10^{-4}	0.010					
	0.5	7.0×10^{-3}	3.0×10^{-4}	0.007	8.4×10^{-3}	3.2×10^{-4}	0.009					
								Lithium coolant in gamma shield	1.18	2.6×10^{-2}	2.8×10^{-3}	0.029
									0.5	7.9×10^{-3}	7.0×10^{-4}	0.009
									0.5	5.4×10^{-3}	4.5×10^{-4}	0.006
									0.5	3.1×10^{-3}	2.9×10^{-4}	0.003
Total		0.733	0.417	1.150	0.740	0.445	1.186			0.754	0.448	1.205

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