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SURFACE EFFECTS AT THE FIRST-WALL OF THE REFERENCE THETA-PINCH REACTOR (RTPR)

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Summary

The fundamental operating principles and parameters inherent to the Reference Theta-Pinch Reactor (RTPR) are described herein. An emphasis is placed on those engineering aspects of the RTPR design which bear directly on the thermal, hydraulic, and radiation response of the first wall. The major portion of the data presented is calculational, and further experimental and theoretical results are needed to assess accurately anticipated material problems and to forecast appropriate solutions. Material problems envisioned for the RTPR first wall are discussed briefly in the context of the particular RTPR design described.

Description of RTPR Power Plant

The Argonne National Laboratory and the Los Alamos Scientific Laboratory have recently completed an engineering design of a fusion reactor which uses the theta-pinch principle of plasma confinement.(1-3) The RTPR operates in a pulsed mode, and during the 10.0-sec duty cycle the following sequence of events occurs: (i) implosion heating of the preionized DT plasma to ~ 2 keV (0.000-0.010 sec), (ii) adiabatic compression of the plasma to ignition at ~ 6 keV (0.010-0.030 sec), (iii) thermonuclear burn of the ($\beta \sim 1$.) plasma at constant magnetic field (0.030-0.110 sec), (iv) quench of the burning (~ 15 keV) plasma by a programmed relaxation of the magnetic field (0.110-0.130 sec), (v) transfer of the plasma internal energy by conduction through a neutral gas layer (4) to the blanket (0.130-1.130 sec), and (vi) removal of excess blanket enthalpy by flowing lithium metal, ash removal, refueling, and preionization for the next power pulse (1.130-10.0 sec).

Figure 1 illustrates schematically the essential elements of the staged theta-pinch concept. A low-energy magnetic field, (~ 1.4 T), implodes a fully ionized, low-temperature plasma. The implosion field is driven by a large azimuthal electric field

FIG. 1

Plasma heating, thermonuclear burn, and direct conversion in a staged theta-pinch reactor.

(~ 2 kV/cm) which is derived from a capacitive discharge and must have a risetime of a few tenths of a microsecond to be effective in heating the plasma without a significant decrease in plasma radius. The implosion stage is followed by a slowly rising ($\sim$ tens of milliseconds) compression field (~ 11.0 T) which is generated by massive, room-temperature coils that are energized by an external, superconducting magnetic energy store. The energy contained by the compression field is significant (178 MJ/m) and must be efficiently recovered. The shaded regions of Figure 1 represent a magnetic field perpendicular to the plane of the figure. The arrows indicate the flow of energy into and out of the system. As the plasma is reduced in radius, the density and temperature increase isentropically. Shortly before the maximum compression field is attained, the plasma ignites and the thermonuclear burning accelerates at a constant compression field. The energetic alpha particles (a DT cycle is being considered) thermalize in the dense plasma and the internal energy of the plasma increases proportionately. The plasma, therefore, expands against the constant magnetic field, doing useful (direct conversion) work in the process. After the burn the compression field is reduced (to ~ 3.2 T), the density and temperature decrease, and the thermonuclear burn is quenched. The plasma internal energy, which is still significant following the quench (~ 4.1 MJ/m), is conducted through a neutral gas layer to the first wall of the reactor; the neutral DT gas layer is introduced during or immediately after the adiabatic compression. Once the plasma internal energy has been slowly transferred to the lithium primary coolant, the

burn ash is removed, new fuel is injected and ionized, and the system is readied for the next power cycle. The total duty time is governed by the desire to derive a maximum of useful energy per cycle, the need to restrict the radiation, thermal, and stress levels to which the first vacuum wall will be exposed, and the need to evacuate and refuel the plasma chamber. The unoptimized choice of 10-sec for the RTPR duty cycle is based on the latter considerations.

Table I summarizes important design parameters for the RTPR power plant, which is schematically depicted in Figure 2. A total of 36 GJ (101 MJ/m) of recoverable neutron, gamma and bremsstrahlung energy is deposited into the RTPR blanket every 10.0 sec. The detailed energy and radiation damage distribution throughout the 0.4 m thick blanket has been presented elsewhere, (1, 5) and only the calculational results that have pertinence to the first wall are presented in Table II. The first-wall loading corresponds to 2.01 MW/m^2 based on the 14.1 MeV neutron current or 2.9 MW/m^2 based on total thermal power generation by neutrons (3.3 MW/m^2 based on total thermal power generation). The ratio of instantaneous-to-average neutron flux is ~ 100 , and continuous, full-power operation is assumed. Table II also summarizes the calculated thermal excursions, thermal stresses, dpa and transmutation rates, and H/He production rates. This summary of neutronic and thermal numerical results serves as a basis for the discussion and evaluation of material requirements which are specific to this particular RTPR "point design." In certain instances the conditions (neutron fluence, instantaneous neutron flux, gas generation rate, transmutation rate, etc.) under which the first-wall materials are expected to function have never before been experienced. Extrapolation of existing fission-reactor and accelerator irradiation data, however, forecasts potential troubles. The goal of the following discussion is to define major problem areas and where possible to identify quantitatively the kinds of design changes which will alleviate these problems.

General Evaluation of Material Requirements for the RTPR First Wall

The first wall of the RTPR is a composite structure composed of an insulator on a metal backing. The 1.0-m-diam first-wall metal must be electrically insulated against the emf which develops the implosion heating. This insulator is thin (0.3 mm) and is supported by a metallic backing (1.0 mm thick). During the thermonuclear burn and plasma cooling stages of the RTPR power cycle, energy will be deposited in both the insulator and the metal backing. Molten lithium will cool the first wall and will be in direct contact with the refractory metal surface. Both the insulator and the refractory metal will sustain neutron radiation damage. The composite first wall will experience a temperature spike driven primarily by bremsstrahlung ($0.5\text{-}1.0 \text{ \AA}$) radiation during the plasma burning and cooling stages. Thermal stresses will be induced by (cyclic) temperature gradients, because of constraints internal to the first-wall structure and

TABLE I
Summary of RTPR Power Plant Characteristics^a

Minor diameter (first wall)	1.0	m
Major diameter	112.	m
Number of 2-m-long modules	176.	
Blanket thickness	0.4	m
Blanket construction material	Al ₂ O ₃ , Nb-1%Zr, Be, C	
Duty cycle ^b	10.0	sec
Burn time	~ 0.080	sec
Uncollided (14.1 MeV) neutron current averaged over the power cycle	8.91×10^{13}	n/cm ² -sec
Total instantaneous neutron flux averaged over the ~ 0.08-sec burn period	1.13×10^{17}	n/cm ² -sec
Total neutron flux averaged over the power cycle	9.03×10^{14}	n/cm ² -sec
Annual fluence of uncollided 14.1-MeV neutrons (2.0 MW/m ²)	2.8×10^{21}	n/cm ² -yr
Annual fluence of 14.1-MeV neutrons	5.4×10^{21}	n/cm ² -yr
Annual fluence of neutrons with E > 10 MeV	6.6×10^{21}	n/cm ² -yr
Annual fluence of all neutrons	2.6×10^{22}	n/cm ² -yr
Bremsstrahlung energy flux at the first wall	71.62	J/cm ² -pulse
Total power density in Al ₂ O ₃ ^c	1652.2	J/cm ³ -pulse
Total power density in Nb ^d	493.4	J/cm ³ -pulse
Burnup/pulse	4.8	%
Breeding ratio	1.11	
Ratio thermal power to recirculating power	16.1 (14.2) ^e	
Gross thermal output	3,600.	MWt
Thermal conversion efficiency	40. (56.4)	%
Recirculating power fraction	0.16 (0.13)	
Gross electrical output	1,440. (2030.)	MWe
Net electrical output	1,210. (1770.)	MWe

^a based on a sodium/steam power conversion system. Plant characteristics for a power conversion system which uses a potassium topping cycle are summarized in Ref. 1. Flux, fluence, and energy values are evaluated at the first wall.

^b The duty cycle is limited to a lower value of 3.0 sec by first-wall heat transfer and fuel/ash pumpout time constants.

^c 86.6% bremsstrahlung, 3.9% gamma, 9.5% neutron.

^d 58.0% bremsstrahlung, 37.2% gamma, 4.8% neutron.

^e Numerical values in parenthesis refer to a power conversion system which uses a high-temperature potassium topping cycle.

FIG. 2

Cutaway view of RTPR power plant.

TABLE II
Summary of First-Wall Responses to RTPR Power Cycle
 (Burn Time ~0.080 sec, Plasma Cooling Time ~1.0 sec, Duty Cycle ~10.0 sec)

Fusion neutron (14.1 MeV) current	8.91 x 10 ¹⁴	n/cm ² /pulse	Metal (Nb)			
Total neutron flux	9.03 x 10 ¹⁵	n/cm ² /pulse	isothermal (300-800 K)	0.80 x 10 ⁸ ^a	Pa	
Bremsstrahlung flux (0.5-1.0 Å)	71.62	J/cm ² /pulse	during burn	0.80 x 10 ⁸	Pa	
			during plasma cooling	0.60 x 10 ⁸	Pa	
			pumping differential	0.20 x 10 ⁸	Pa	
<u>Average energy density in</u>						
<u>Insulator</u>						
neutron	156.3	J/cm ³ /pulse	Average atom displacement			
gamma	63.5	J/cm ³ /pulse	Al ₂ O ₃	~ 30 ^b	dpa/yr	
bremsstrahlung	1432.4	J/cm ³ /pulse	Nb	36	dpa/yr	
total	1652.2	J/cm ³ /pulse	Average helium production			
			Al ₂ O ₃	.17	at.%/yr	
<u>Metal</u>			Nb (maximum)	59	ppm/yr	
neutron	23.6	J/cm ³ /pulse	Hydrogen production			
gamma	183.4	J/cm ³ /pulse	Al ₂ O ₃	0.10	at.%/yr	
bremsstrahlung	286.4	J/cm ³ /pulse	Nb	204	ppm/yr	
total	493.4	J/cm ³ /pulse	Neutron transmutation			
			Al ₂ O ₃	0.24 0	at.%/yr	
<u>Temperature transients in</u>						
<u>Insulator</u>						
	<u>Inside</u>	<u>Outside</u>		0.22 Al	at.%/yr	
during burn	310	250	K	Nb	0.29	at.%/yr
during plasma cooling	75	60	K			
total	385	310	K			
average	350		K			
<u>Metal</u>						
during burn	250	220	K			
during plasma cooling	40	30	K			
total	290	250	K			
average	270		K			
<u>Stresses induced in</u>						
<u>Insulator (Al₂O₃)</u>						
isothermal (300-800 K)	-2.57 x 10 ⁸ ^a	Pa				
during burn	-2.00 x 10 ⁸	Pa				
during plasma cooling	-1.20 x 10 ⁸	Pa				
			<u>Product</u>	<u>Production (ppm/yr)</u>		
			H	975		
			He	1,685		
			C	1,340		
			N	66		
			Na	9		
			Mg	830		
			Si	23		

^aThese stresses arise because of the analytic assumption that the composite structure is stressfree at room temperature. In view of current techniques used to apply ceramic layers to metal backings, the stressfree (or reference) state will be closer to RTPR operating temperatures and the stresses listed above for the 300-800 K transition are expected to be near zero.

^bEstimated by extrapolation of neutron spectral results calculated for other materials.

differential thermal expansion of the insulator relative to the metal backing. The thermal and stress response of the first wall have been estimated quantitatively in Table II. A detailed materials evaluation of the first-wall composite has been made in References 1 and 5 and only a summary of anticipated first-wall material problems is given below.

The RTPR design specifies alumina (Al_2O_3) as the electrically insulating liner of the first wall. This choice was made because alumina is a well-characterized, high-temperature dielectric, with thermal, mechanical and electrical properties typical of most ceramic insulators. Alumina in a form used for other reactor applications (thermionics) is not a good choice for the first wall, however, because of documented(6) poor structural behavior under neutron irradiation, and other materials are under consideration. The insulator should generally (i) have good thermal and electrical properties at high temperatures, (ii) tolerate irradiation without unacceptable degradation of these properties, (iii) not undergo large dimensional changes as a result of irradiation and the buildup of transmutation products, and (iv) resist chemical attack at elevated temperatures by hydrogen isotopes. The insulator must also be chemically and mechanically compatible with the metal substrate. The major task of the first-wall insulator is to prevent electrical breakdown between the plasma and blanket segments during the 0.1- μsec implosion heating stage. Once the plasma is compressed and ignited, the radiation intensity at the first wall may be sufficient to increase significantly electrical conduction. The insulator, however, is not required to operate under voltage after the implosion heating. The design dielectric properties of the insulator must be regained, however, ~9 sec after the plasma has cooled. Reestablishment of these properties after periodic intense irradiation represents a major, short-term materials question for the RTPR. Insulators which anneal rapidly could prove relatively insensitive to pulsed reactor radiation damage insofar as electrical properties are concerned. An experiment is planned at LASL to evaluate the recovery kinetics of insulating properties after pulsed ion irradiation. Information obtained in this study may allow the adjustment of material parameters so as to accelerate recovery of dielectric properties.

The first-wall structural metal selected in the RTPR design is Nb-1Zr. The function of the first-wall structure in any fusion reactor is to provide a vacuum barrier between the plasma and the surrounding blanket. In addition, the first-wall metal in the RTPR must support the electrical insulation which is crucial for the successful operation of the plasma implosion heating. Economic operation of the reactor demands that the first-wall metal maintain structural integrity under the influence of energetic and intense neutron fluxes and bremsstrahlung/gamma irradiation. Table II summarizes the thermal, neutronic, and stress environment to which the first-wall metal will be subjected. In addition to cyclic thermal stresses, the first wall will be subjected to steady-state

lithium pumping pressure differentials ($\sim 10^5$ Pa leading to hoop stresses on the order of 0.2×10^8 Pa) as well as pressure surges resulting from lithium flow transients. Additionally, forces generated by liquid-metal/magnetic field interactions as well as the short impulse which is generated by the implosion field must be sustained by the first-wall metal. (1)

High temperature fatigue in the presence of an intense radiation field undoubtedly represents a major concern for the first-wall metal; this problem is unique to pulsed fusion reactors. The major radiation effects are (i) loss of ductility (embrittlement) resulting from void formation, helium generation and/or hydrogen production and (ii) dimensional changes resulting from the creation of voids and/or bubbles. Hydrogen embrittlement per se and liquid-metal corrosion represent lower-order problems.

Anticipated Surface Effects

This section discusses specific, deleterious surface effects expected or anticipated during the operation of the RTPR. These effects can be generally categorized as surface sputtering (by ions or neutrons), chemical (reduction) erosion, corrosion, blistering, and evaporation. In addition to the free surface defined by the vacuum/insulator boundary, the bond interface between the insulator and the metallic first-wall structure represents a "closed" surface and in a sense is unique to the theta-pinch reactor.

Ion sputtering of the insulator surface is to be minimized by the use of a protective neutral gas blanket, which is interposed between the plasma and the first wall shortly after ignition. (1,4) This protective gas blanket in conjunction with the high beta plasma should ameliorate problems associated with bombardment of the first-wall surface by energetic alpha particles and attendant blistering phenomena. Neutron sputtering could pose a problem, although calculations indicate that the sputtering yield for atom-atom ejection should be only $\sim 10^{-5}$ ($\sim 0.1 \mu\text{m}/\text{yr}$).

The rate of chemical erosion of the oxide insulator by hydrogen has been estimated within thermodynamic constraints. (7) If the hydrogen gas is appreciably dissociated, these calculations indicate potentially high erosion rates, although a process occurring in the neutral gas blanket which could sustain such high, nonequilibrium concentrations of atomic hydrogen is difficult to envision. Additionally, these thermodynamic calculations cannot account for rate limiting reaction sequences and chemical kinetics of the reduction reaction.

Desorption from the first wall of gaseous impurities is not expected to present a major problem because of the high operating temperature (~ 1000 K). Photodecomposition

of either adsorbed impurities or the oxide insulator (in the presence of hydrogen), which is driven by the intense bremsstrahlung flux ($71.6 \text{ J/cm}^2/\text{pulse}$), represents a possibility; laboratory investigation must ultimately resolve the importance of this effect. The bremsstrahlung radiation which impinges upon the first wall during the thermonuclear burn is a contributor to the thermal spike ($\Delta T \sim 300 \text{ K}$), although thermal evaporation of the insulator into the plasma chamber is not expected to be significant.

The thermal and hydrostatic stresses at the insulator/metal interface can be maintained at a level which precludes short-term structural failure. Long-term fatigue stresses, however, may cause interfacial roughening via intrusion/extrusion mechanisms. Experiments are underway at LASL to evaluate this potential problem. The internal surface at the insulator/metal interface will also experience stresses resulting from differential, radiation-induced swelling. Recent studies of this phenomenon(8) suggest that radiation-induced swelling can be controlled to some extent by adjustment of the material microstructure. Additionally, plastic flow of the weaker of the two first-wall materials (presumably the metal) can partially relieve these interfacial stresses.(6) Pore deposition at the insulator/metal interface represents an additional concern, although evidence for this process in other systems is not conclusive.(9,10) Another process which may portend problems at the insulator/metal interface is the transport of anions from the insulator, through the metal, and into the lithium coolant; this process has been observed to occur in vanadium and its alloys.(11)

Concluding Remarks

As is the case for all fusion concepts, the outstanding materials problems focus on the long-term response of the first wall. Because of the electrical insulator required for a theta-pinch reactor, the first-wall requirement for the RTPR assumes a unique character. An insulator research program, active for the past year, has been organized to attack these crucial problems. This program has already established the desirable pulsed-breakdown characteristics of alumina and is working toward a realistic assessment of the use of glassy materials as the first-wall insulator. The rate of recovery of electrical properties after intense neutron and bremsstrahlung irradiation is also being studied. In addition, the fatigue strength of first-wall metals and insulator/metal composites is presently being determined without radiation, and similar tests performed under high-energy neutron irradiation are scheduled within a year. Although just beginning, this kind of directed experimental research program will eventually yield results on which sound design decisions can be made. More importantly, this approach will pro-

vide a means to relate the existing strong capability to predict primary effects (i.e., dpa, He and H production, etc.) to the capability of assessing materials behavior. This kind of iterative feedback between materials research and reactor design has been highly successful in the past (e.g., fission reactors, space nuclear systems) and has often resulted in the successful "reengineering" of materials to provide enhanced performance and lifetime, as well as redesigning of reactor systems to conform to realistic materials constraints.

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