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FIRST WALL THERMAL HYDRAULIC MODELS FOR FUSION BLANKETS*

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ABSTRACT

Subject to normal and off-normal reactor conditions, thermal hydraulic models of first walls, e.g., a thermal mass barrier, a tubular shield, and a radiating liner are reviewed. Under normal operation the plasma behaves as expected in a predicted way for transient and steady-state conditions. The most severe thermal loading on the first wall occurs when the plasma becomes unstable and dumps its energy on the wall in a very short period of time (milliseconds). Depending on the plasma dump time and area over which the energy is deposited may result in melting of the first wall surface, and if the temperature is high enough, vaporization.

NOMENCLATURE

- Bi Biot modulus, $h\ell/k$
- c Specific heat, Wsec/g^o
- c_p Specific heat at constant pressure, J/kgK
- h Heat transfer coefficient at cooled surface, W/cm^2 ^oC
- k Thermal conductivity, W/cm^{o}C
- ℓ Slab thickness, cm (Fig. 1)
- L_f Operator, $\kappa[\frac{1}{r}\frac{\partial}{\partial r}(rE_r\frac{\partial}{\partial r}) + \frac{1}{r^2}\frac{\partial}{\partial \phi}(E_\phi\frac{\partial}{\partial \phi})]$
- L_s Operator, $k_s[\frac{1}{r}\frac{\partial}{\partial r}(r\frac{\partial}{\partial r}) + \frac{1}{r^2}\frac{\partial^2}{\partial \phi^2}]$
- Q Average volumetric heating, W/m^3
- Q_o Applied surface heat flux, W/cm^2 (ig. 1)
- S_o Defined in Eq. (1), W/cm^3
- t Time, sec
- T_1 Period of applied heat flux Q_o (Eq. 3)
- T Temperature, ^{o}C
- x Cartesian thickness coordinate, cm (Fig. 1)
- γ Defined by exponential in Eq. (1), cm^{-1}
- κ Thermal diffusivity, cm^2/s
- ρ Density, g/cm^3
- τ Temperature variable for integration (Eqs. (4), sec

Subscripts

- f Fluid
- 0 Initial time
- s Solid

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INTRODUCTION

As a consequence of the thermonuclear reactions taking place in all fusion reactors using the deuterium-tritium (D-T) fuel cycle, a large fraction (~80%) of fusion energy is released as ~14-MeV neutrons as well as charged particles and radiation. The neutrons must be slowed down in a relatively thick structure, the blanket, surrounding the plasma and their kinetic energy converted to high temperature heat. As a consequence of the charged particles and radiation, the blanket surface interfacing the plasma is exposed to a high heat flux. The heating by neutrons and surface heat is continuously removed from the blanket by a coolant system. Finally, a portion of the heat in a power reactor is converted to electricity in a standard thermal cycle, i.e., a steam or gas turbine cycle. Since the thermodynamic efficiency of such a cycle is governed by the operating temperature of the heat source, the problems of heat removal from a fusion reactor are of considerable importance. The choice of the coolant and flow network impinges on such aspects as capital cost and power-plant efficiency, radioactivity, material and structural criteria, and reactor lifetime.

In addition to being a good moderator of neutrons with sufficiently good heat transfer characteristics for efficient heat removal, the blanket must breed tritium for commercial power reactors. For the D-T fuel cycle, it is necessary to have lithium present in the blanket to breed tritium to replace that consumed in the plasma. Consequently, tritium breeding impacts on coolant choice as well, e.g., liquid lithium or a solid breeder with tritium removed by a helium purge stream.

The material surface interfacing the plasma looms as the critical region of concern since all of the emissions from a reacting plasma may intersect this wall. These include ions and neutral particles, primary neutron, x-rays (Bremsstrahlung), and cyclotron radiation. In addition, scattered neutrons and gamma radiation generated in the blanket regions exterior to this first wall are also imposed on it. Finally, D-T gas surrounding the plasma may react chemically with the first wall materials. One result of these many interactions is the generation of appreciable heat which can be up to 20% of the plasma output; thus provision must be included for adequate cooling. In most analyses the above effects are usually lumped together as a radiant flux. While the incident fluxes are absorbed in a small depth of any first wall material, the usual assumption is to treat the lumped radiant flux as if it were deposited on the first wall surface. In heat transfer analyses, it is an applied heat flux boundary condition. The phenomena of sputtering and blistering, the formation of gaseous reaction products, and material vaporization processes from the first wall may represent the major sources of impurity in the plasma. Thus the first wall can be a limiting component in reactor power output due to a large power generation within it; and it may also limit plasma performance through impurity levels. The useful first-wall lifetimes in a power reactor may be severely limited through radiation damage and surface erosion. The attendant frequent replacement could unduly add to operating costs and require an excessive plant down-time for replacement. Thus, the design and material selection for this first wall is a vital element in the design of a fusion power reactor.

It is also necessary to consider additional effects which the first wall could experience as well as potential scenarios, such as a plasma excursion and energy dump to the wall which could cause surface melting of the wall. Under normal operation, the first wall will be subjected to thermal cycling. This is not necessarily a problem in itself but rather the temperature excursions per pulse which the structure could be subjected to. What could occur are cracks in the first wall as a consequence of thermal stresses, the propagation of these cracks leading to the ultimate failure of the blanket. Consequently, knowledge of temperature behavior in the first wall/blanket is a prerequisite to not only efficient conversion of heat-to-electricity but also to the prediction of thermal stress and materials performance as well.

NORMAL AND OFF-NORMAL REACTOR OPERATION

In order to carry out a blanket or reactor heat transfer analysis, it is necessary to establish under what conditions the physical phenomena is time-dependent, and when steady state may be assumed. It is convenient to categorize the various operating regimes of a reactor as follows:

A. Normal Operation, i.e., the plasma behaves as expected within a predicted behavior. Under normal operation there are several scenarios of interest:

1. Reactor startup—This is associated with initial plasma fueling which results in the initial blanket and component transients.

2. Steady state—This assumes that the plasma burn is long enough so that the resulting physical phenomena (velocity, temperature, pressure, etc.) does not change with time.

3. Plasma shutdown—During the plasma off-condition, e.g., plasma pumpdown for removal of impurities or maintenance, there may be the need for thermal storage within the reactor complex.

B. Off-Normal Operation

1. Plasma dump—The most severe thermal loading on the first wall occurs when the plasma becomes unstable and dumps its energy on the first wall in a very short period of time. This could result in melting or vaporizing of the first wall.

2. Loss-of-coolant in the blanket—There could only be a fraction of the total blanket coolant lost during a disruption in the reactor system. Total loss-of-coolant could result in an "after-heat" problem.

Experimental reactor conditions will be characterized by short plasma burns, from a few seconds to possibly tens of seconds. Characteristic of short plasma burn times coupled with the plasma dwell time is a steady, periodic behavior in the temperature.

In subsequent sections, several first-wall options are reviewed, not only as examples of their heat removal capability but also as examples to identify heat transfer problems during normal and off-normal operation as well as for relevant physics.

THERMAL MASS BARRIER

The first-wall concept considered in this Section has a relatively thick, ~1 cm or so, structure facing the plasma. This structure is essentially a thermal mass with cooling tubes welded or brazed to the rear surface (away from the plasma). The two objectives for having the thick wall are: a) to protect the cooling tubes from off-normal energy dumps due to plasma distruptions or thermal transients; and b) for short pulse lengths, the thermal mass can significantly reduce the thermal fluctuations seen by the cooling tubes, reducing the alternating component of thermal stress, thereby giving a longer fatigue lifetime.

The first wall of a fusion blanket is approximated by a slab geometry (Figure 1), the surface interfacing the plasma subjected to an applied heat flux (Bremsstrahlung energy, etc.), while the rear surface is convectively cooled.

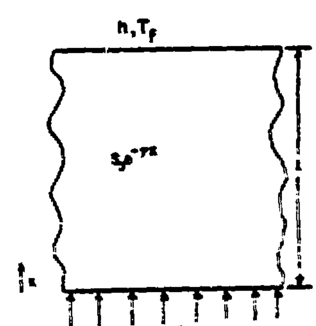

Fig.1 One-dimensional slab geometry.

Volumetric heating is due to neutron and gamma energy. While steady-state analyses yield the maximum temperatures, there are a wide range of time-dependent conditions which are anticipated. For example, in the case of steady-state commercial power reactors (long plasma burn), the dominant mode of temperature behavior will be steady state. In contrast, for experimental or near-term reactors, plasma burn times may only be tens of seconds, with dwell times the same order of magnitude or greater, so that a steady, periodic temperature behavior will persist.

Since the volumetric internal heat generation can be closely approximated by a decaying exponential function, the one-dimensional, time-dependent heat conduction equation may be written as:

$$\kappa \frac{\partial^2 T}{\partial x^2} - \frac{\partial T}{\partial t} = - \frac{S_o}{\rho c} e^{-\gamma x} \phi(t) \qquad (1)$$

subject to the following boundary and initial conditions,

$$-k \frac{\partial T}{\partial x} = Q_o \phi(t),\ x=0; \ -k \frac{\partial T}{\partial x} = h(T-T_f),\ x=\ell \qquad (2a)$$

and

$$T = T_o,\ t=0 \quad . \qquad (2b)$$

Here, T is the temperature while S and γ are parameters dependent on plasma conditions as well as blanket structural material and are derived from the results of a neutronics analysis. Q_o is the incident flux to the first wall and is assumed to be a certain percentage of the plasma output, usually of the order of 20%. The heat transfer coefficient, h and mean fluid temperature, T_f, are assumed known, in addition to continuous cooling during the plasma "off" period. Taking into account an "on" and "off" cooling behavior is straightforward. We assume the blanket structure is at some uniform temperature, T_o at time t=0.

For definiteness, we consider only the case of an applied rectangular wave form but other cases such as a r[illegible] [illegible]wed by a constant flux and heat source (in time) [illegible]ated in the same way. In the calculation [illegible] the periodic flux and heat source to be a[illegible] for t>0. Thus, the applied heat flux and source may be represented by the function,

$$\phi(t) = 0,\ t<0 \quad ,$$

$$\phi(t) = 1,\ n\tau<t<n\tau+\tau_1,\ n=0,\ 1,\ \ldots \qquad (3)$$

$$\phi(t) = 0,\ n\tau + \tau_1<t<(n+1)\tau,\ n=0,\ 1,\ \ldots \quad .$$

In other words, the applied flux, $Q_o\phi(t)$, represents a flux Q_o which is "on" for time τ_1 and "off" for time $\tau-\tau_1$ and so on, with period τ.

The general solution to Eq. (1), subject to Eqs. (2a-2b), is:[1]

$$T-T_f = (T_o - T_f) \sum_{n=1}^{\infty} 2\mathrm{Bi} \frac{\cos\alpha_n}{\alpha_n^2} \frac{\alpha_n^2 + \mathrm{Bi}^2}{\alpha_n^2 + \mathrm{Bi}^2 + \mathrm{Bi}} \left[\cos\left(\frac{\alpha_n x}{l}\right)\right] e^{-(\kappa\alpha_n^2 t/l^2)}$$

$$+ \sum_{n=1}^{\infty} \left\{ \frac{2}{\rho C} \frac{1}{\alpha_n^2 + B^2} \left[\mathrm{Bi}\, e^{-B}\left(1 - \frac{B}{\mathrm{Bi}}\right)\cos\alpha_n + B\right] \int_0^t S_0(\tau)\, e^{-[\kappa\alpha_n^2(t-\tau)/l^2]}\, d\tau \right.$$

$$\left. + \frac{2}{\rho C l} \int_0^t Q_0(\tau)\, e^{-[\kappa\alpha_n^2(t-\tau)/l^2]}\, d\tau \right\} \frac{\alpha_n^2 + \mathrm{Bi}^2}{\alpha_n^2 + \mathrm{Bi}^2 + \mathrm{Bi}} \left[\cos\left(\frac{\alpha_n x}{l}\right)\right] \qquad (4)$$

where $\kappa = k/\rho c$ is the thermal diffusivity, $B = \gamma\ell$, and the α's = eigenvalues, determined by $\tan\alpha_n = B_i/\alpha_n$. Additional details of the solution to Eq. (1) for various plasma conditions may be found in ref. 1.

From the standpoint of thermal cycling and the resultant temperature changes over a cycle, it is advantageous to consider high-thermal conductivity materials to minimize temperature changes across the first wall and thermal fatigue. Representative temperature profiles are shown in Figure 2, for water-cooled,

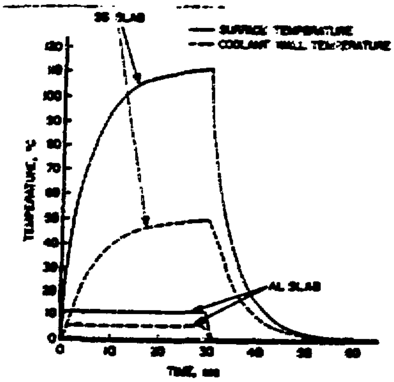

Fig.2 Steady, Periodic Temperature Histories

aluminum and stainless steel first walls. The walls are assumed to be 1/2 cm in thickness and the plasma on- and off-conditions are 30 s for each period. In either first wall case, steady state is reached by the end of the plasma "on" period, steady state being reached within a few seconds for the high-conductivity aluminum slab. It is clear, from Figure 2, that for shorter plasma "on" times for stainless steel, steady state would not be reached. From a thermal standpoint, aluminum appears to be a viable first wall candidate.

Reference 2 considers this first wall design in more detail. For example, to relieve thermal stress for low conductivity materials, grooves are cut in the surface. Thermal stress analyses for the grooved and non-grooved slab geometry are considered in refs. 2 and 3.

TUBULAR SHIELD

A possible configuration for a fusion reactor first wall is an array of tubes or tube-bank forming a first wall shield. They could be welded or brazed together to form a vacuum boundary as proposed in some designs,[4] or the coolant tubes could serve as a radiation shield for a thicker structural wall behind them as in the original Princeton Reference Design.[5]

The attendant heat transfer problem for single-phase fluids is that of turbulent heat transfer in a circular tube with variable circumferential heat flux, volumetric neutron-gamma heat generation in the tube wall, and a coolant such as water. Theoretical work allowing for a nonuniform heat flux distribution around the circumference of a circular tube for both fully-developed laminar and turbulent flow has been considered by Reynolds,[6-8] Sparrow and Lin,[9] Rapier,[10] Gartner et al.,[11] and most recently by Fillo and Powell.[12,13]

A. Coupled Conduction-Convection Equations

For the case of single-phase fluids in a circular duct, we consider hydrodynamically, fully-developed turbulent flow. Thermal properties of the fluid are taken to be constant. The fluid temperature field is also assumed to be fully developed. Anisotropy of turbulent energy transport has been taken into account employing theoretical results,[11] for eddy diffusivity in the radial and circumferential directions. For an applied heat flux with arbitrary circumferential variation at the outer tube wall (see Figure 3), but invariant in the flow direction, the

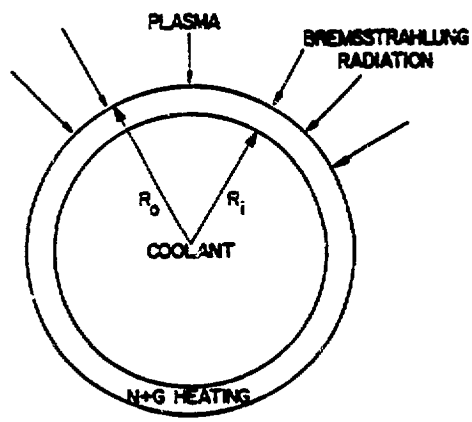

Fig.3 Tubular First Wall to Remove Heat From the Plasma

temperature distributions in the tube wall and fluid are to be determined. Both radial and circumferential temperature variations are permitted. The energy equations for the temperatures in the tube wall and fluid are solved simultaneously, subject to continuity conditions in heat flux and temperature at the interface. Internal heat generation is permitted in the tube wall, but it is assumed constant, i.e., averaged over the tube thickness. Likewise, internal heat generation in the coolant is allowed but assumed constant and averaged over the inner tube diameter. The governing conduction equation for the tube is:

$$L_s(T_s) + Q_s = 0 \ , \qquad (5)$$

subject to the boundary conditions:

$$k_s \left.\frac{\partial T_s}{\partial r}\right)_{R_o} = \dot{q}(\phi) \qquad (6a)$$

$$-k_s \left.\frac{\partial T_s}{\partial r}\right)_{R_i} = -k_f \left.\frac{\partial T_f}{\partial r}\right)_{R_i} ; \ T_s(R_i,\phi) = T_f(R_i,x,\phi), \qquad (6b,c)$$

in addition to:

$$T_s(r,\phi) = T_s(r,\phi+2\pi) ; \ \frac{1}{r}\frac{\partial T_s}{\partial \phi}(r,\phi) = \frac{1}{r}\frac{\partial T_s}{\partial \phi}(r,\phi+2\pi) \ . \qquad (7)$$

The first boundary condition, Eq. (6a), is the applied heat flux and is prescribed to vary in an arbitrary manner at the outer wall of the tube. It is represented by:

$$q(\phi) = q_o + F(\phi) \ ; \text{ where } \int_0^{2\pi} F(\phi)d\phi = 0 \ . \qquad (8)$$

Equation (6b) matches the heat flux at the boundary between solid and fluid and allows for the coupling between the governing equations in the tube wall and fluid. Equations (6c) assumes continuity of temperatures at the interface; Eq. (7) satisfies the condition that the temperature in the tube will be single valued.

The mean-thermal energy equation governing the fluid is:

$$L_f(T_f) - u\frac{\partial T_f}{\partial x} + \frac{Q_f}{\rho c} = 0 \ , \qquad (9)$$

Since the temperature, T_f, appears only as the first power in Eq. (9), superposition of solutions to a linear equation is applied. In particular, we separate the general problem into the following two problems: (1) a fluid with no internal heat generation (Q_f=0) flowing in a duct with heat transfer at the tube wall; and (2) a fluid with internal heat generation, Q_f, flowing in a duct with insulated walls. As a consequence of splitting the fluid temperature into two superposable solutions and coupling of the tube wall and fluid temperatures through the interface boundary conditions, the temperature for the solid (since the conduction Eq. (5) is linear) is likewise split into two superposable solutions. Solutions to the resulting equations are found by the method of separation-of-variables.[12,13]

B. Summary of Results

As indicated, detailed solutions and results may be found in refs. 12 and 13. Space does not permit detailed analyses and results so that major conclusions are summarized.

1. Neglecting radial conduction but allowing circumferential conduction results in underestimating the wall temperature for relatively thin-walled structures. Results differ approximately in proportion to the ratio of outer-to-inner (R_o/R_i) tube radii so that multiplying the inner wall temperature by R_o/R_i brings the two results together.

2. A comparison of the dimensionless tube wall temperature equation derived from the coupled analysis with that based on a constant heat transfer coefficient indicates that the two analyses are in good agreement for Prandtl numbers $\sim$1, while for low Prandtl numbers fluids, in the liquid-metal range, the results are markedly different.

3. The maximum temperature difference across the tube wall can be correlated with $\chi\delta/k_s$, i.e.,

$$\Delta T_s = 0.12 \ \chi\delta/k_s \ ,$$

where χ is the wall loading, δ is the wall thickness, and k_s is the thermal conductivity. This implies that the temperature difference across the tube wall is independent of the coolant. The maximum and minimum temperatures, though, are coolant dependent.

4. The effect of neutron plus gamma heating of the coolant on the inside wall temperature is negligible. The volumetric heating of the coolant would have to be several orders of magnitude greater than

currently envisaged fusion reactor designs and/or the flows operate in a much lower Reynolds number regime (laminar) before it would have an appreciable affect on the inside tube wall temperature. The contribution to the overall bulk or mean temperature is a few degrees. The affect is more noticeable for the low Prandtl number fluids as well.

5. For a given maximum outlet temperature, the maximum surface and inner tube wall temperatures for stainless steel are greater than that of aluminum for either a helium or water coolant. For the same maximum outlet temperature, the water-cooled first wall operates at lower temperatures than a He-cooled wall for either material. In general, a water-cooled wall offers a higher wall loading capability. Representative temperature profiles for a water-cooled wall are shown in Figure 4.

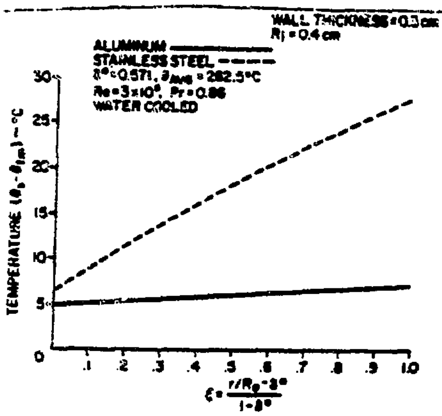

Fig.4 Radial Temperature Distribution in Tube Wall

PLASMA ENERGY DUMP

The most severe thermal loading on the first wall occurs when the plasma becomes unstable or at the end of a discharge when the plasma is dumped on the wall in a very short period of time. Assuming a sufficiently high heating rate to melt the first-wall surface, and if the temperature increases to cause vaporization, a phase-change problem arises. If the melted material is sloughed off the surface as it is formed, the moving boundary becomes the receding surface of the wall. If the melted material stays in place and reaches the vaporization temperatue, a moving face where vaporization occurs becomes a boundary in addition to the moving internal boundary between the liquid and the solid. Because of the moving boundaries and the difference between the properties of the liquid and solid states of the same material, the temperature distribution is, of course, nonlinear.

There is another possible scenario in which phase phase change would not occur as a consequence of a plasma dump. Because the rate of energy input during thermonuclear processes is sometimes extremely rapid, it is to be expected that there may sometimes be insufficient time for the phase change to occur during the period of the energy burst, and often the phase change would not occur under equilibrium circumstances. In the extreme case of rapid energy deposition, it is assumed that the material remains a superheated solid, with no latent heat of phase change being involved. For this case, a standard one-dimensional analytical solution is available for the temperature distribution in a thick wall.

Basis for Analytical Studies

In order to obtain some estimate of the temperature rise of the first wall due to a plasma excursion which comes in contact with the wall, we consider the following assumptions and analysis.

We assume a semi-infinite slab exposed to a burst of radiant energy, Q, deposited on a unit area of the surface during a time interval, τ. The instantaneous rate is dQ/dt. Initially the slab is assumed to be at a constant temperature, T_o. The assumption that the slab temperature is uniform at time equal to zero seems reasonable for small x.

For rapid heating, either the slab is superheated with no latent heat of phase change being involved or part of the slab is heated to temperatures above the melting point, T_m, and the heated face to the vaporization temperature, T_v, if the melted material is not sloughed off.

In either the region of melted material or in the solid, the temperature distribution is adequately described by the heat conduction equation, Eq. (1), with appropriate constant local values for the thermal conductivity, specific heat, and density. Actually, the neutron and gamma heating source term is a second order effect since surface heating dominates, and has been neglected in plasma dump analyses.

Case A: Melting of a solid with complete removal of melt (ablation).

In the general problem of melting there exists a temperature distribution in both the liquid and solid phase. If the melting liquid is completely removed as it is formed, as in the process of ablation, the surface recedes with time, the surface temperature remains constant at the phase-change temperature, and a temperature distribution exists only in the remaining solid, Figure 5.

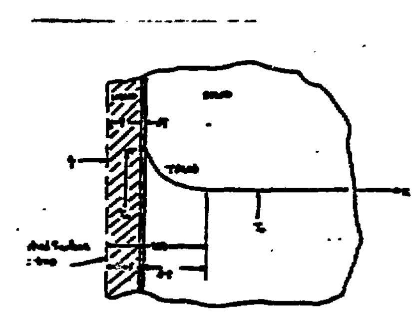

Fig.5 Melting solid with complete removal of melt.

To analyze this problem, we assume that the semi-infinite solid is heated by sudden application of a constant heat flux, q, to the surface x=0. At time, t=0, the surface temperature has risen to the melting temperature, and the phase change ensues. The melted material is removed; thus, the boundary of the solid and the melt time are identical and located at $x=\xi(t)$. The temperature distribution in the solid penetrates to a depth $\delta(t)$. The temperature for $x>\delta(t)$ is the constant T_o.

The heat balance at the melting face is:

$$q+k\frac{\partial T}{\partial x}=\rho L_m\frac{d\xi}{dt}\ ,\quad x=\xi(t)\ ,\quad (t>0)\ , \qquad (10)$$

where L_m is the latent heat of melting, all properties are referred to the liquid state. The constant flux, $q=Q/\tau A$, represents the heat flow into the solid with total energy Q dumped on an area A in time, τ.

The general solution to Eq. (1) subject to Eq. (10) has been treated by the approximate integral method,[14] and more recently, as a particular case in ref. 15. Application to the fusion energy dump problem does not seem to have been reported.

Case B: Melting and vaporization of a solid.

In this case, the melt stays in place and the temperature of one heated surface reaches the vaporization temperature. As a result of the heating process, a moving boundary is formed between the liquid and solid regions and the receding face of the slab is at the vaporization temperature. In the general problem of melting and vaporization there exists a temperature distrubution in both the liquid and solid phases.

To analyze this problem, as in the previous case, we assume that the semi-infinite solid is heated by the sudden application of a constant heat flux, q, to the surface x=0. At time, t=0, the surface temperature has risen to the melting temperature, and the phase change ensues. The melted material remains in place until it reaches the vaporization temperature, at which point it leaves the surface. The boundary between the liquid region and the solid region moves at a rate designated by $d\xi/dt$. The conditions at the melt line interface, x=b, are designated by:

$$T_l(b,t) = T_s(b,t) \tag{11}$$

and

$$-k_l \frac{\partial T_l}{\partial x}\Big|_b + k_s \frac{\partial T_s}{\partial x}\Big|_s = L_m \rho \frac{d\xi}{dt} \quad . \tag{12}$$

When vaporization occurs at the surface x=0, which is moving at a position x=a, the boundary condition is:

$$q + k_l \frac{\partial T_l}{\partial x}\Big|_a = L_v \rho \frac{dn}{dt} \quad , \tag{13}$$

where dn/dt is the velocity with which the surface is receding as it vaporizes. We assume the far boundary insulated so that:

$$\frac{\partial T_s}{\partial x} = 0, \quad \text{as } x\to\infty \tag{14}$$

The heat conduction Eq. (1), must be solved in each region, liquid and solid. Numerical results for a plasma dump may be found in ref. 16.

Variants of this scenario and simplification to the general problem may be envisaged. For example, the solid is assumed to be at the melting temperature and the vapor is immediately removed. Thus, a temperature distribution exists only in the liquid phase.[14] In ref. 17, it is assumed that the plasma energy deposition time is short enough (milliseconds) and the depth of the affected region is so small (tens of micrometers) that only vaporization of the steel is important. Significant transport of metal in the liquid phase is not considered for the thin regions and short dump times of interest.

Case C: No phase change.

At the heated face, if no phase change occurs, the slope of the temperature matches the energy input according to:

$$-k\frac{\partial T}{\partial x} = q = \frac{Q}{\tau A} \quad , \quad x=0 \quad , \tag{15a}$$

as well as:

$$T\to T_o, \quad x\to\infty \ , \ \text{and } T = T_o, \quad t=0 \quad . \tag{15b}$$

As noted previously, Eq. (1) subject to boundary conditions, Eqs. (15a,b), admits to a closed-form solution. The maximum temperature increase of the surface of the solid due to an energy dump, Q, per area, A, in time, τ, is:

$$T_{s_{max}} - T_o = \frac{2Q}{Ak}\sqrt{\frac{\alpha}{\pi\tau}} \quad . \tag{16}$$

Figure 6, based on Eq. (16), shows the temperature increase of a surface for different materials due

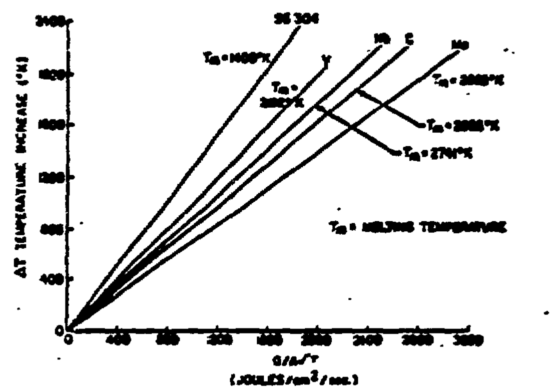

Fig.6 Temperature Increase of Surface

to sudden heating. While some materials seem superior from the standpoint of higher melting temperatures, choices as to first-wall material on the basis of surface temperature rise during a plasma dump seem arbitrary since one does not have, at this point in time, a realistic idea as to the surface area or time scale that will be involved. Plausible scenarios can always be constructed so that portions of the wall will be melted no matter what material is used. If plasma dumps are a problem because of sudden unexpected instabilities, it probably will be necessary to line the first metallic wall with a protective layer-like graphite or silicon carbide that can ablate when the dump occurs.

RADIATING LINER

To minimize plasma energy losses from wall-derived plasma impurities, low atomic number materials are attractive since calculations of plasma energy loss by impurity ions[18] show a high sensitivity to the atomic number of the impurity ion. Hopkins[19] suggested the employment of low atomic number materials such as graphite for first-wall structures as a way of coping with this problem.

As a means of protecting the blanket from erosion as well as providing an ablation layer, the concept of a radiating graphite liner was introduced. A thermally radiating first wall liner transmits energy by radiation from a relatively thick, eroding, sacrifical wall to a thin, noneroding wall of the blanket (Fig. 7). The conduction of heat through the liner first wall

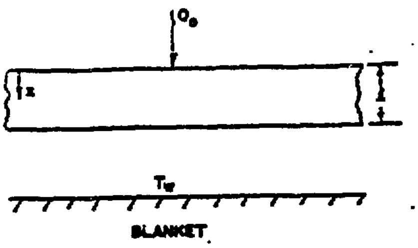

Fig.7 Graphite Radiating Liner

creates thermal gradients which can cause thermal stresses that limit the design wall loading. In a rigidly-supported liner, any thermal gradient causes thermal stresses; in a freely-supported liner, only nonlinear gradients are caused by transient energy fluxes, such as at the beginning and end of a burn, and by internal nuclear heating. Convectively-cooled liners have also been considered.[20]

For a given first-wall lifetime, the maximum wall loading and liner thickness are coupled through the liner erosion rate during operation. Also, the maximum heat flux and therefore, the maximum wall loading is set by the temperature at the liner back surface, which in turn depends on the allowable front surface temperature and the liner thermal conductivity and thickness. Liners which are cooled by convection rather than radiation are capable of much higher charged particle and photon surface loadings, and therefore, can be used in reactors with higher power density or, in reactors with low-power density, need only cover a fraction of the wall area. This feature partially compensates for the increased complexity of the liner panels and plumbing.

To gain some estimate of the thermal performance of a radiating liner (see Figure 7), the temperature equation is determined by Eq. (1). The incident flux to the first wall is governed by Eq. (2a). At the liner back surface, $x=\ell$, the boundary condition is:

$$-k \frac{\partial T}{\partial x} = \sigma H \left(T^4 - T_w^4\right), \quad x=\ell \quad , \tag{17}$$

where σ is the Stefan-Boltzmann constant, $H = (\epsilon_\ell^{-1}+\epsilon_w^{-1}-1)^{-1}$, accounts for the liner and wall emissivities, and T_w is the blanket wall temperature, assumed constant.

As a consequence of the nonlinear back-surface boundary condition, Eq. (1) does not admit to a simple analytical solution. To solve Eq. (1) and attendant boundary conditions, we resort to numerical means, in particular, an explicit finite difference scheme.[3]

Since steady state is also of interest, Eq. (1), with the time derivative suppressed, is solved analytically.

$$T = (-)\frac{S_o}{k\gamma^2} e^{-\gamma x} + \frac{Q_o+S_o/\gamma}{k}(\ell-x) + \left[T_w^4 + \frac{Q_o+S_o/\gamma}{\sigma H}\right]^{1/4} \tag{18}$$

Discussion of Results

Temperature distributions at selected times from the start of a plasma burn to steady state for a 1-cm graphite slab is shown in Figure 8.

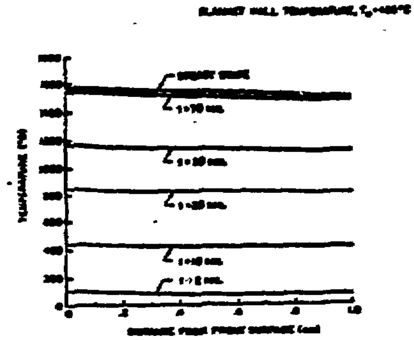

Fig.8 Transient Temperature Through Liner

Because of the high specific heat of graphite, about 1.5 minutes are required to reach steady state (within 2%) in the first pulse. For short intervals between burns less time would be required in subsequent pulses because the liner would not radiatively cool to room temperature. For the first 10 to 20 sec, backside temperatures are so low that little heat is radiated. Because of the high-thermal conductivity of graphite, this interval displays a quasi-steady-state gradient since heat is added but none is removed and the rate of temperature rise is about the same for all points in the liner. After about 30 sec, the backside temperature becomes high enough to radiate heat and the temperature gradients steepen from that time on. The first wall temperature is less than 2000 C, the temperature at which surface evaporation could occur.

The effect of short plasma burns, i.e., pulses which are less than that required to reach steady-state blanket temperatures, is found in Figure 9.

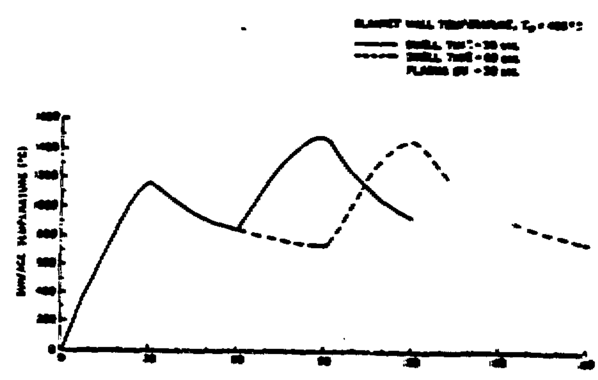

Fig.9 Surface Temperature vs. Time for Radiating Liner

The results indicate that steady, periodic temperatures are reached within three periods with lower temperatures at the end of the longer dwell times as well as peak surface temperatures.

SUMMARY

There are, of course, a number of additional trade-offs which must be made before selecting a first-wall concept. This has been an attempt to summarize some of the main thermal issues for several proposed first walls. The relative advantages and disadvantages of the various concepts are: a) liner concepts intercept charged particles but do not alleviate the thermal load on the blanket wall; b) the tubular wall intercepts charged particles and the blanket wall heat load is considerably reduced; c) the main advantage of the tubular configuration is the increased wall loading capability due to convective cooling; and d) the stress problem in tubular walls is intensified compared with the liner; thermal stresses are not alleviated by deflections and additional mechanical stresses are caused by coolant pressure.

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