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FUSION BLANKET HIGH-TEMPERATURE HEAT TRANSFER

J.A. Fillo
Department of Nuclear Energy
Brookhaven National Laboratory
Upton, New York 11973

ABSTRACT

Deep penetration of 14 MeV neutrons makes two-temperature region blankets feasible. A relatively low-temperature (~300°C) metallic structure is the vacuum/coolant pressure boundary, while the interior of the blanket, which is a simple packed bed of non-structural material, operates at very high temperatures (>1000°C). The water-cooled shell structure is thermally insulated from the steam-cooled interior. High-temperature steam can dramatically increase the efficiency of electric power generation, as well as produce hydrogen and oxygen-based synthetic fuels at high-efficiency.

NOMENCLATURE

A = Duct cross-sectional area, cm^2
B_i = Biot number, hR/k
C_p = Specific heat, W-sec/g°C
D = Duct diameter, cm
f = Fanning friction coefficient
h = Heat transfer coefficient, $W/cm^2 °C$
k = Thermal conductivity, W/cm°C
L = Duct length, cm
L^* = Operator, $k\left[\frac{1}{r}\frac{d}{dr}\left(r\frac{dT}{dr}\right)+\frac{d^2T}{dZ^2}\right]$
Pr = Prandtl number, $C_p\mu/k$
q_c = Heat transfer by convection, W
Q = Volumetric coolant flow rate, cc/s
$\bar{Q}$ = Average volumetric heating in bed, W/cc
Q_{fw} = Total power deposited in first wall, W
R = Radius of zirconia rod, cm
Re = Reynolds number, $\frac{uD\rho}{\mu}$
St = Stanton number, $h/C_p\rho u$
T_b = Bulk temperature, °C
T_w = Wall temperature, °C
u = Velocity, cm/s
ρ = Density, g/cc
μ = Dynamic viscosity, g/cms

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INTRODUCTION

The high-energy neutrons from Deuterium-Tritium (DT) fusion reactions can penetrate very deeply into materials before their kinetic energy is transformed to heat. The DT fusion reaction generates 17.58 MeV, of which 14.06 MeV is carried by a neutron that escapes from the confining magnetic field. This unique feature of fusion energy, and the fact that ~80% of the energy released per DT fusion reaction is carried by 14 MeV neutrons, can dramatically increase the efficiency of electric power generation, as well as produce hydrogen and hydrogen-based synthetic fuels at high-efficiency(1).

Brookhaven National Laboratory has been engaged in studies (hereafter referred to as HYFIRE)(2) investigating the potential merits of coupling a fusion reactor with a high-temperature blanket to a High-Temperature Electrolysis (HTE) process to produce hydrogen and oxygen. Westinghouse has assisted in these studies in the areas of system design integration, plasma engineering, balance-of-plant design, and electrolyzer technology. The electrolysis process selected is based on the high temperature, solid electrolyte fuel cell technology developed by Westinghouse.

The electrochemical decomposition of water into hydrogen and oxygen is an endothermic reaction requiring both heat and electricity. Figure 1 shows a simplified flow sheet for a HTE/fusion synthetic fuel plant. All electrical production goes to the HTE cells (and to operation of the fusion reactor) to make hydrogen for sale. Two blanket types are inferred; the first type heats steam to high temperatures (T>1000°C) for delivery to the HTE cells, while the second heats a working fluid for the thermal power cycle and conversion to electricity. The blanket system must also be capable of breeding tritium in sufficient amounts from lithium to replenish that burned in the plasma chamber. Since the heat input component for water decomposition is used directly at essentially 100% efficiency, there is a definite advantage to make the ratio of direct heat input to electrical energy input as large as possible. Circulating high-temperature steam through the blanket poses some engineering design problems, for example, transporting 1300°C steam in ceramic-lined

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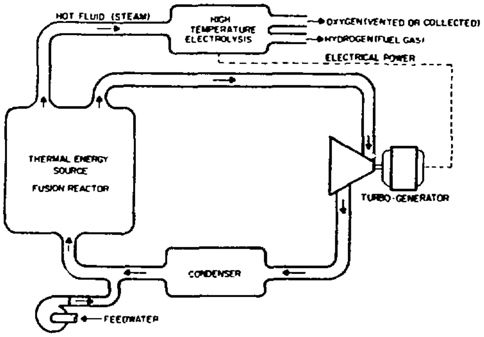


GENERAL HTE PROCESS WITH CONVENTIONAL POWER CYCLE

Figure 1

ducts. Similar problems arise in the transport of high temperature coolants in MHD systems and have been analyzed in greater detail(10) but have not been found to pose insurmountable problems.

In addition to the requirement for tritium self-sufficiency, an important ground rule for the studies was that hydrogen would be the only product produced for sale. Thus, the electrical generation equipment and the overall power conversion process are sized to exactly provide the electrical energy required to operate the fusion reactor, e.g., a Tokamak, electrolysis plant, and balance-of-plant systems.

A HTE process should generate H_2 from water at an overall efficiency of ~50 to 55% depending on temperature and power conversion design. Since H_2 production cost by electrolysis is primarily determined by electric power cost, the fact that high-temperature process blanket steam is used for directly decomposing water to H_2 and that high overall efficiency (~50% compared with 30 to 35% by conventional electrolysis) can be achieved, implies significant potential economic advantages of a fusion-HTE system.

The key technology development required for the consideration of fusion as a heat source for H_2 production is a high-temperature blanket. The deep penetration of the primary neutrons make two-temperature region blankets feasible(3,4) to achieve the necessary high temperatures. In this concept, a relatively low-temperature metallic structure is the vacuum/coolant pressure boundary, while the interior of the blanket, which is a simple packed bed of nonstructural material, operates at very high temperatures. Separate coolant circuits are required for the two-temperature regions, as well as a thermal insulator between them.

Materials for the hot interior, e.g., ZrO_2 and Al_2O_3, are capable of much higher temperatures than HTGR-type conditions (800°C). Further, the coolant for the hot interior need not be He, but can be a process fluid such as steam or CO_2. This direct heating feature eliminates the transfer of high-temperature heat across a metallic primary heat exchanger, which could severely limit the maximum temperature and choice of coolant. Direct neutron heating of refractory oxides which then transfers its energy to raise steam appears practical and is the mode of generating process heat in the fusion/high-temperature electrolysis process for producing H_2.

For a blanket design consisting of rods in the high-temperature interior, a heat transfer analysis is performed to elucidate the heat transfer mechanisms for high-temperature systems. An estimate of the peak-temperatures in the metallic structure and rods is carried out so as to determine potential problems. Calculations are performed for a conceptual design of a fusion/high-temperature electrolysis plant.

FUSION BLANKETS FOR HIGH-TEMPERATURE ELECTROLYSIS PROCESS

The HYFIRE blanket must perform three functions: 1) provide high-temperature (>1000°C) process steam at moderate pressures (in the range of 10 to 30 atm) to the high-temperature electrolysis units; 2) provide high-temperature (~700° to 800°C) heat to a thermal power cycle for generation of electricity to the HTE units and fusion reactor; and 3) breed enough tritium to sustain the DT fuel cycle.

Since natural sources of tritium are negligible, new tritium must be bred to make up for that burned in the reactor plasma. Setting the requirement that the global breeding ratio equal 1.1 to allow for doubling time requirements, perturbations, etc., for HYFIRE, places a premium on space, i.e., it is necessary to breed tritium in regions adjacent to the process steam blanket modules. The tritium deficit must be made up from surplus tritium produced by other modules in the same reactor, or by surplus tritium shipped from other fusion reactors. The HTE fusion synfuel process allows this make-up tritium to be supplied in a very efficient manner. Part of the blanket in each reactor is used to generate thermal energy for an electric power cycle, with the generated electricity being consumed by the HTE process units. Tritium from the power cycle part of the blanket must make up the tritium deficiency. In other words, HYFIRE employs a dual blanket system.

The two-temperature zone blanket approach is mandatory for the process steam portion of the energy supply. The modules will have relatively cool shells (~300°C) with thermal insulation between the shell and the high-temperature (~1300°C) interior. The two-temperature design concept is also carried over for the tritium breeding/power cycle modules. While there are two blanket types, it is the former, the steam-cooled blanket, which is subjected to thermal-hydraulic analysis since the most severe thermal conditions occur for this blanket.

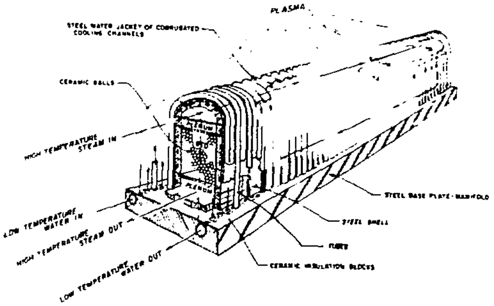
Vacuum/Pressure Boundary for Steam Coolant

The steam coolant must be prevented from leaking to the plasma chamber by some type of vacuum/coolant structural pressure boundary. Currently, the only practical materials for this purpose appear to be metals whose working temperature is in the range of ~300° to 500°C, depending on material, wall thickness, blanket module size, and internal pressure. Because of the temperature limitation, the metal structure must be cooled by a separate coolant circuit (e.g., water) which operates at a considerably lower temperature than the high-temperature steam-cooled interior.

Blanket designs of this type were first proposed in connection with studies on minimum activity blankets using an aluminum structure(3). More recent designs(4,5) have developed the low-temperature structure/hot interior concept in greater detail. A conceptual design approach is shown in Fig. 2.

Thermal Insulator Between Hot Interior and Cool Structure

A good thermal insulator is required between the hot interior and cool structure in either the process heat or tritium breeding blanket module. This material must be compatible with both the steam or gas coolant



HTE PROCESS MODULE
5000 MW REACTOR

Figure 2

and the refractory interior. In addition to low thermal conductivity, the insulating material should have high resistance to radiation damage, should maintain its structural integrity in the coolant/radiation environment, and should have low density to minimize total internal heat generation within it. The most promising insulator option is to use the same material as used in the interior, but in a low-density form, i.e., as a fibrous layer.

Table 1 summarizes the results of the materials tested(6) at BNL in air, argon, and helium in a nonradiation environment. Helium is a candidate coolant for the tritium breeding/power blanket modules; air and argon are treated as standards against which helium is to be compared. The thermal conductivity tests in helium were limited to temperatures on the order of 800°C due to the power requirements of the heater, so that the data shown at 1000°C are extrapolated values. At this temperature, little difference exists between the five insulators tested. The zirconia felt is the lowest at 0.40 W/mK and the alumina-silica mat the highest at 0.54 W/mK.

TABLE 1

SUMMARY OF MATERIALS TESTED
Thermal Conductivity of Insulators in the Temperature Range of 300° to 1000°C

Watts/m- K

	Air		Argon		Helium	
	300°C	1000°C	300°C	1000°C	300°C	1000°C
Alumina-silica mat, 8 lb/ft^3	.06	.22	.07	.28	.24	.54
Carbon felt, 5 lb/ft^3	---	NA	.11	.29	.24	.51
Graphite felt, 4 lb/ft^3	---	NA	.11	.27	.26	.51
Zirconia fibrous board, 24 lb/ft^3	.07	.14	.07	.14	.15	.49
Zirconia felt, 14 lb/ft^3	.08	.17	.08	.17	.18	.40

In summary, the zirconia felt has the lowest thermal conductivity at 1000°C but its density is three times that of the carbon felt and two times the alumina-silica mat density. The graphite felt would give equal insulating properties in helium to the zirconia felt with 25% more thickness, and the increase in weight would still make it one of the lightest of the insulators; therefore, at this point, graphite felt would be the preferred insulator. Of the materials tested, all have approximately the same thermal conductivity values in the temperature range of interest and would be acceptable for the blanket applications.

Table 2 summarizes the results of the materials tested in steam in a nonradioactive environment. The thermal conductivity tests in steam were again limited by equipment to temperatures on the order of 1000°C. The choice is not so clear for insulating the steam-cooled modules. Graphite, tested in steam at ~900°C appears satisfactory up to this temperature; however, it does not appear likely that it would be suitable all the way up to 1400°C. The best insulator from the standpoint of compatibility with ZrO_2 hot interiors would be ZrO_2 felt or fiber board. The design question is how one fabricates an insulator liner to keep it in place in the blanket module. This might be done by placing a thin material support ring around the loose insulator, e.g., zirconia felt or insertion of the zirconia fibrous board as a sleeve insert.

TABLE 2
SUMMARY OF MATERIALS TESTED
Thermal Conductivity of Insulators in Steam
in the Temperature Range of 500°C to 1000°C

	Watts/m- K	
	500°C	1000°C
Carbon felt, lb/ft^3	0.11	0.25
Graphite felt, 4 lb/ft^3	0.25	0.45
Zirconia fibrous board, 24 lb/ft^3	0.14	0.16
Zirconia felt, 14 lb/ft^3	0.07	0.26

Compatibility of Blanket Interior with High-Temperature Steam/Steam Hydrogen Mixtures

The major requirement of a material to be used in the high-temperature region of a fusion reactor is the maintenance of structural integrity in an environment hostile to most materials of construction, e.g., high-radiation flux and high temperature. In addition, when blanket functions such as heat removal and tritium breeding are considered, a flowing fluid must be accommodated.

For the HTE modules, the refractory oxides (ZrO_2 and Al_2O_3) in the high-temperature region of the blanket must be stable under exposure to the steam or steam/hydrogen process stream under radiation and thermal cycling conditions. Such materials will fill the interior of the blanket as solid rods or balls and will also be used as a low-density solid block or fibrous thermal insulation between the high-temperature interior and the structural shell. Materials compatibility tests(7) in steam and steam/hydrogen indicate that ZrO_2 and Al_2O_3 are suitable for long-term service up to ~1500°C (the present testing limit at BNL). Tests with SiC and MgO indicate these materials are restricted to somewhat lower temperatures, as shown in Fig. 3.

Minimum Activity of High-Temperature Steam and H_2/O_2 Products

Neutron activation of the blanket interior will occur, but prevention of this activation from seriously contaminating the high-temperature steam circuit and the H_2/O_2 product gases from the HTE process is imperative. Use of minimum activity materials like MgO, Al_2O_3, SiC, etc., could minimize this problem.

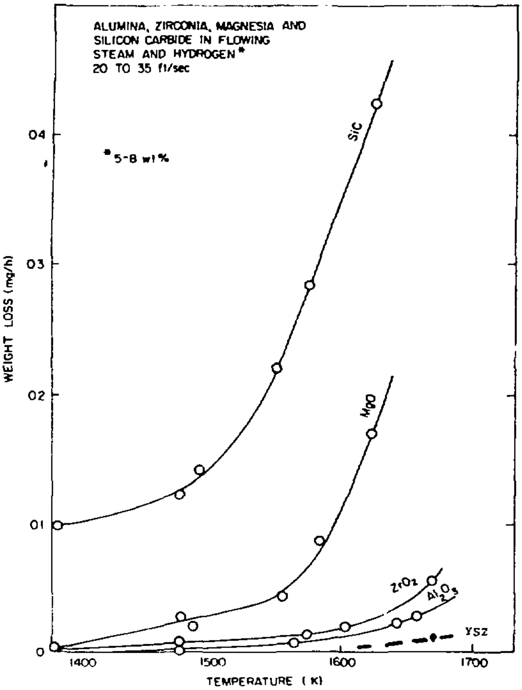


Figure 3

Considerable ^{24}Na activation (15 hour half-life) will be produced in MgO and Al_2O_3 but will decay to negligible levels in a few days. Activation of impurities should be negligible, since the impurity levels in these blanket materials will be in the ppm range.

HTE BLANKET DESIGN

While there are two types of blanket modules, this paper is only concerned with the steam-cooled (or HTE) blanket. Figures 4 through 6 show the HTE blanket design. Three cylindrical blanket modules are attached to a common backing plate. The center cylinder is allowed to butt up against the outer two cylinders for support.

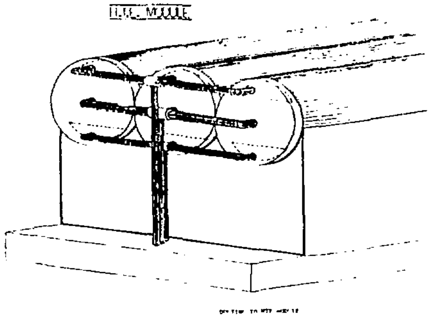


Figure 4

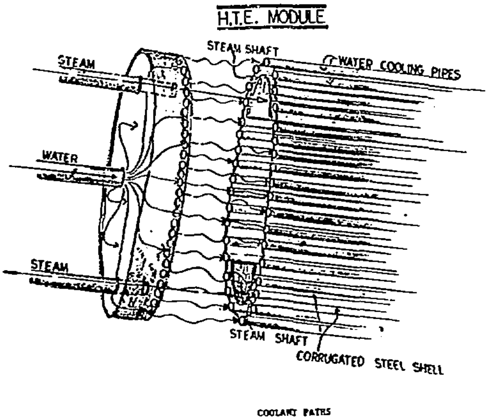


Figure 5

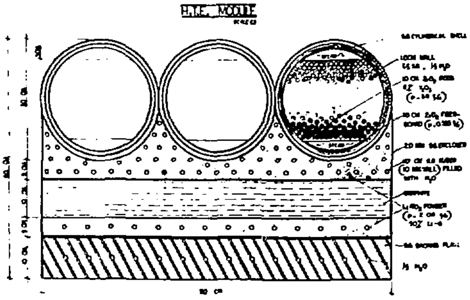


Figure 6

Since the outer structural shell is subjected to neutron/gamma heating as well as radiation, water cooling tubes, integral with the shell, are attached with water flowing axially along the cylinder to remove the energy. Water is fed to the end cap of the cylinder through a series of finger tubes. In addition to the water cooling tubes, the first wall is made up of a series of ribbed channels through which water also flows. Outlet ducts, not shown in Fig. 5, at the base of the module distribute the heated water to a common header for the three blanket cylinders.

The ceramic-lined ZrO_2 steam inlet duct distributes steam to the three modules through plenums at the top of the blanket module. In this case flow is crosswise, the steam picking up heat as it flows across the rod bed. It is collected at the bottom of the module whereby it is directly sent through ceramic-lined ducts to the electrolyzers.

Immediately in back of the high-temperature steam zone is a separate tritium breeding mop-up region. This zone is necessary so as to achieve a net overall breeding ratio of 1.1 for the system. The design of this region is a packed bed of $LiAlO_2$ with a helium purge gas stream to remove the bred tritium.

THERMAL HYDRAULIC ANALYSIS

First Wall/Insulation Coupling

In the design of the HYFIRE blanket, the first wall is the critical region. Emissions from a reacting plasma which may intersect this wall include ions and neutral particles, primary neutrons, x-rays (Bremsstrahlung) and cyclotron radiation. In addition, scattered neutrons and gamma radiation generated in the blanket region's exterior to the first wall can also be imposed on it. Finally, deuterium-tritium 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. In most analyses these effects are lumped into a radiant flux incident on the first wall, i.e., an applied surface heat flux. In the current design, a limiter fronts the first wall (in selected regions) and takes up part of the 20% applied heat load. Nevertheless, there is a significant surface heat flux which is taken to be 85 W/cm^2 on the average for a neutron wall loading of 3.6 MW(th) /m^2. Low-Z coatings, e.g., Be, for the first wall have been proposed(8) to mitigate impurities deposited in the plasma due to sputtering. The current first wall design will allow for coatings if they are deemed viable, but will not be included in the thermal hydraulic analysis.

For either the HTE or power blanket, the first wall design is basically a tubular structure. In order to have some idea of the first wall heat removal characteristics, we consider an overall energy balance. The average coolant velocity, u, is related to the total volumetric coolant flow rate, Q, by:

$$u = Q/A \quad , \tag{1}$$

where A is the total duct flow area. The total volumetric coolant flow rate, Q, is related in turn to the total heat Q_{fw}, (surface heat flux + volumetric heating), deposited in the first wall by an overall energy balance:

$$Q = \frac{Q_{fw}}{\rho C_p \Delta T_b} \quad , \tag{2}$$

where ρ and C_p are the density and heat capacity of the coolant; while ΔT_b is the average coolant temperature rise for single-phase flow, or difference in bulk temperature between cross sections in question. Knowing the average coolant velocity, u, the Reynolds number (Re) can be determined to establish whether the flow is laminar or turbulent.

The rate of heat transfer by convection between a surface and a fluid may be computed by the relation:

$$\dot{q}_c = hA\Delta T \quad , \tag{3}$$

where q_c = rate of heat transfer by convection;

A = heat transfer area;

ΔT = difference between the coolant surface temperature T_w and the bulk temperature, T_b, of the fluid;

h = average convective heat transfer coefficient

The use of the fluid bulk temperature as the reference temperature in Eq. (3) allows us to readily make heat balances because in the steady state the difference in the average bulk temperature between two sections of a conduit is a direct measure of the rate of heat transfer, i.e.,

$$q_c = \rho Q_p C_b \Delta T \quad , \tag{4}$$

where $q_c = Q_{fw}$.

To calculate the heat transfer coefficient, it is more convenient for engineering purposes to use a semi-empirical equation. For fluids having Prandtl numbers in the range from 0.5 to 100 (which is the case for the current applications), Colburn recommends(9), on the basis of experimental data, that the Stanton number,

$$\frac{h}{C_p \rho u} \quad ,$$

be given by:

$$St = 0.023\ Re^{-0.2}Pr^{-2/3} \quad , \tag{5}$$

or

$$h = 0.023\ Re^{-0.2}Pr^{-2/3}C_p\rho u \quad ; \tag{6}$$

where Pr = Prandtl number = $C_p\ \mu/k$.

According to experimental data for fluids flowing in smooth tubes in the range of Reynolds numbers from 10,000 to 120,000, the friction coefficient, f(9), is given by the empirical relation:

$$f = 0.184\ Re^{-0.2} \quad . \tag{7}$$

Knowing the friction coefficient and mean velocity, u, the pressure drop in a duct between cross-sections is simply:

$$\Delta P = f\ \frac{L}{D}\ \frac{\rho u^2}{2g_c} \quad . \tag{8}$$

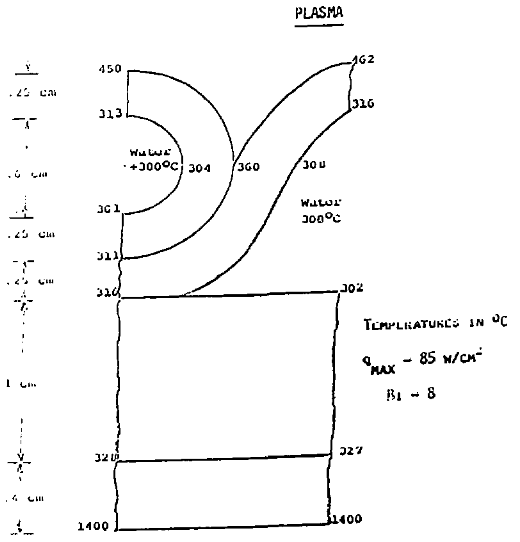
For the conditions shown in Table 3, the velocity, Reynolds number, heat transfer coefficient, pressure drop, and maximum surface temperature are shown as a function of fixed surface heat flux. The remainder (80%) of the energy in the form of neutrons is deposited in the first wall/blanket structure. Depending on design and application the deposition of this energy can be tailored, the goal, in general, being to minimize the amount of neutron energy deposited in the first wall/blanket structural material. In other words, it is to be made available for useful work, and not simply to heat structural elements to be wasted. In the current design, the energy deposited in the first wall is removed by the pressurized water and circulated through a steam generator to raise saturated steam on the secondary side.

TABLE 3
THERMAL HYDRAULIC PARAMETERS
Surface Heat Flux=85W/cm^2, Volume Heating Rate=40W/c

Maximum velocity, m/s	3.5
Reynolds number	12.5x10
Pressure drop, atm	1/2
Maximum surface temperature, °C	460

For an applied surface heat flux with cosine circumferential variation at the outer tube wall, as well as neutron/gamma heating of the structure, the temperature distribution in the tube wall is determined by the classical Fourier heat conduction equation. Both radial and circumferential temperature variations are permitted. The energy equations for the tube wall and fluid are uncoupled so that the boundary condition at the inner tube wall is specified by a heat transfer coefficient.

For a 2.5-mm-thick wall, the first wall steady-state temperature profile is shown in Fig. 7. The difference in the maximum surface temperature is due to the asymmetry in the corrugated and straight tubular ducts. While the temperature gradient through the structure is significant, steady state plasma operation



FIRST WALL TEMPERATURE PROFILE

SCALE 6:1

Figure 7

should help insofar as the thermal stress problem is concerned. That is, while there will be transient thermal stresses associated with start-up and shut down of the reactor, the repetitive stresses as in a pulsed mode will not be present. The maximum thermal stress can be kept to values compatible with the allowable stress for stainless steel.

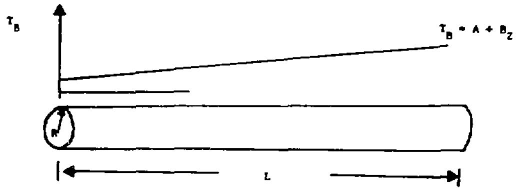
The temperature profile through the insulator/stainless steel structure is also given. Based on heat conduction through the insulator, heat leakage from the hot interior to the coolant shell is minimized using zirconia fiberboard. For example, the heat leakage is ~1 to 1-1/2% of the total energy deposition.

Heating of Zirconia Rods

To arrive at some estimate of the maximum heating in the zirconia rods, the following steady-state heat transfer analysis is considered to assess if there are heat transfer problems associated with the steam-cooled rods. While the rods are closely spaced, a simple rod, (Fig. 8), is analyzed assuming steam flow past it. Heat transfer through the rod is governed by Fourier heat conduction equation:

$$L^*(T) + \bar{Q} = 0 \quad . \tag{9}$$

Symmetry is assumed while radial and axial conduction are allowed. The bulk or volumetric heating is specified by $\bar{Q}$ which is assumed constant, i.e., averaged over the rod thickness. The bulk steam temperature, T_B, is assumed to vary linearly between the inlet and outlet of the module, e.g., T_B=A+Bz. That is, the flow and heat transfer are fully developed.



HEAT TRANSFER FROM ZIRCONIA RODS

Figure 8

The boundary conditions are specified in terms of the inlet and outlet temperatures of the steam as well as convective heat transfer to the steam by the following equations:

$$T(r,0) = T_o \quad ; \quad T(r,L) = T_L \quad . \tag{10a}$$

(Note that T_o=A and T_L=A+BL.)

$$T(0,Z) = \text{finite} \quad , \tag{10b}$$

$$-k\frac{\partial T}{\partial r}\Big)_R = h\left(T-T_B\right) \quad . \tag{10c}$$

The solution to Eq. (9) subject to Eqs. (10a-c) is found by superposition of two solutions, i.e.,

$$T(r,z) = \theta_1(r)+\theta_2(r,z) \tag{11}$$

where

$$L^* \theta_1 + \bar{Q} = 0 \quad , \tag{12}$$

subject to:

$$\theta_1(o) = \text{finite} \quad , \tag{13a}$$

$$-k \frac{\partial\theta_1}{\partial r}\Big)_R = h \left(\theta_1-A\right) \quad . \tag{13b}$$

In addition,

$$L^* \theta_2 = 0 \quad , \tag{14}$$

subject to:

$$\theta_2(r,o) = T_o-\theta_1(r) \quad , \tag{15a}$$

$$\theta_2(r,L) = T_L-\theta_1(r) \quad , \tag{15b}$$

and

$$-k \frac{\partial\theta_2}{\partial r}\Big)_R = h \left(\theta_2-Bz\right) \quad . \tag{15c}$$

The solutions to Eqs. (12 - 15) are found by superposition of solutions and the method of separation of variables, and are given by:

$$\theta_1(r) = A + \frac{\bar{Q}R^2}{4k} \left[\frac{2}{Bi} + 1 - \left(\frac{r}{R}\right)^2\right] \quad , \tag{16}$$

and

$$\Theta_2(r,Z) = BZ + \sum_{n=1}^{\infty}\left(a_n \sinh \lambda_n(L-z) + b_n \sinh \lambda_n z\right)J_o\left(\lambda_n r\right) \tag{17}$$

where

$$a_n = \frac{1}{\sinh \lambda_n L}\left\{\frac{2\left[T_o - \left(A + \frac{\bar{Q}R^2}{2kB_1}\right)\right]B_1 J_o \lambda_n R - \frac{\bar{Q}R^2}{k} J_2\left(\lambda_n R\right)}{\left[\left(\lambda_n R\right)^2 + B_1^{\,2}\right] J_o\left(\lambda_n R\right)}\right\}$$

$$b_n = \frac{1}{\sinh \lambda_n L}\left\{\frac{2\left[T_L - BL - \left(A + \frac{\bar{Q}R^2}{2kB_1}\right)\right]B_1 J_o \lambda_n R - \frac{\bar{Q}R^2}{k} J_2 \lambda_n R}{\left[\left(\lambda_n R\right)^2 + B_1^{\,2}\right] J_o\left(\lambda_n F\right)}\right\}$$

The eigenvalues are given by

$$\left(\lambda_n R\right)J_1\left(\lambda_n R\right) - B_1 J_o\left(\lambda_n R\right) = 0 \quad , \tag{18}$$

where J_i (i=0,1,2) are Bessel functions.

A representative temperature profile is shown in Fig. 9. The inlet steam temperature is 1000°C while the outlet is ~1300°C. The zirconia rods are 1 cm in diameter, 5 m long. The rod would not be continuous, but rather made-up of short segments, 0.5 m long, with spacers in between. Spacing between rods is 3 mm. The volumetric heating rate is taken to be 10 W/cc. Of course, there is a radial heating rate distribution from top to bottom across the high temperature bed interior which decreases exponentially. The heating rate chosen is the maximum in the bed. The maximum temperature rise in the rod is ~25°C with only a slight variation from inlet to outlet. Thermal stress across the rod is small. Basically, the shape of the temperature profile across the bed is parabolic. Maximum temperatures meet design specification. From the point of view of heat transfer, the design does not appear to pose problems.

TEMPERATURE PROFILES ALONG ZIRCONIA ROD IN STEAM COOLED CYLINDRICAL MODULE

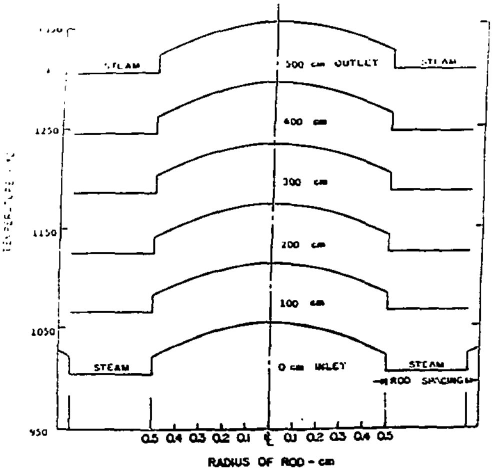


Figure 9

DISCUSSION

Conduction and convective heat transfer are the dominant modes of heat transfer for the system analyzed. With the temperature levels reached in the rods, as well as steam temperatures, thermal radiation may be significant and needs to be examined. Depending on the materials chosen for the high-temperature rods, e.g., Al_2O_3 or ZrO_2, mass transfer may be small since tests in steam and steam/hydrogen mixtures indicate very little mass loss with Al_2O_3 and no detectable mass loss with yttria stablized ZrO_2. Analyzing a single rod in the steam flow is an approximation to the true configuration which is a bed of rods from which heat is extracted by steam. Flow and thermal boundary layer interaction between boundary layers developing on the rods needs to be studied. Alternate flow configurations for extracting heat also need study, e.g., cross flow across the rods to minimize pressure drop.

Critical to the successful operation of the two-temperature zone blanket concept is the integrity of the insulation in contact with high temperature steam. Thermal conductivity increases with increasing steam temperature, and needs to be quantified at higher temperatures when the insulation is in contact with flowing steam. The results reported in Table 2 are for static steam conditions, that is, insulation in contact with steam in a box.

First wall studies of tubular structures have been reported elsewhere(11-13) and are not repeated here except for the results of a specific case to provide the reader with some idea of potential thermal problems.

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