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A HIGH-FLUX FIRST-WALL DESIGN FOR A SMALL REVERSED-FIELD PINCH REACTOR

by

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ABSTRACT

To achieve the goal of a commercially economical fusion power reactor, small physical size and high power density should be combined with simplicity (minimized use of high-technology systems). The Reversed-Field Pinch (RFP) is a magnetic confinement device that promises to meet these requirements with power densities comparable to those in existing fission power plants. To establish feasibility of such an RFP reactor, a practical design for a first wall capable of withstanding high levels of cyclic neutron wall loadings is needed. Associated with the neutron flux in the proposed RFP reactor is a time-averaged heat flux of 4.5 MW/m^2 with a conservatively estimated transient peak approximately twice the average value.

We present the design for a modular first wall made from a high-strength copper alloy that will meet these requirements of cyclic thermal loading. The heat removal from the wall is by subcooled water flowing in straight tubes at high linear velocities. We combined a thermal analysis with a structural fatigue analysis to design the heat transfer module to last 10^6 cycles or one year at 80% duty for a 26-s power cycle. This fatigue life is compatible with a radiation damage life of 14 MW/yr/m^2.

INTRODUCTION

The Reversed-Field Pinch (RFP) is an attractive approach to magnetic confinement fusion. Recent experiments (1)[1] at the Los Alamos National Laboratory on the relatively small ZT-40M device have shown promising plasma confinement, stability, and RFP performance. Equally attractive is the prospect of a fusion reactor that has an engineering power density (total fusion power divided by total volume, including magnetic coils) that can be comparable to that of a conventional light-water fission reactor (2) without violating key physics or technology limits (for example, beta[2] limits or coil stresses). This potential of the RFP concept results from a combination of high plasma beta, direct ohmic heating, and confinement of thermonuclear plasma with low magnetic fields at the water-cooled copper coils. This high-density, "compact" approach to RFP reactors (CRFPR) differs considerably from the larger, more "conventional" RFP reactor (RFPR) designs (3) that have been proposed.

To establish the feasibility of such a reactor, a practical first wall must be designed that is capable of withstanding the neutron and thermal flux from the compact, but high-power-density, plasma. Most of the neutron flux passes through the first wall and is absorbed in a lithium-bearing blanket, but the thermal flux is entirely absorbed in the first wall. The first-wall thermal response, in fact, was judged early in the CRFPR study as the limiting engineering constraint for this newer approach, and the thermohydraulic work reported here was performed to provide key input to the CRFPR design point determination. In this paper, we present the design for a water-cooled first wall fabricated from a high-strength copper alloy. Because the CRFPR design has not progressed to where a definite burn cycle has been developed, this first-wall thermal-mechanical study has conservatively adopted the burn cycle that was developed for the earlier conventional RFPR (3). For this case, the wall is exposed to a time-averaged thermal flux of 4.5 MW/m^2 with a transient peak in the cycle of 9.2 MW/m^2. To put these projected CRFPR requirements into perspective, a compilation of heat fluxes normally encountered in science and industry is given for orientation in Fig. 1. The heat fluxes are higher in this CRFPR than in typical process equipment, but are approximately two orders of magnitude less than the highest rates reported in the literature. In a cyclic batch-burn mode of operation, the service life based on radiation damage limits in the 1[illegible] MW/m^2 neutron flux is projected to be on the order of one year. For the 26-s power cycle (3) assumed for this thermal-mechanical analysis and an 80% plant factor, this implies ~10^6 full-power cycles. It is emphasized that the actual CRFPR operation would be in a longer-pulsed, if not steady-state, mode.

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[1] Numbers in parenthesis designate references at end of paper.

[2] Beta is the ratio of the plasma pressure to the pressure exerted by the magnetic field. Beta is used to indicate the efficiency of a magnetically confined fusion device because the power density is generally proportional to the square of the plasma density and (for a given plasma temperature and magnetic field) is also proportional to the square of beta.

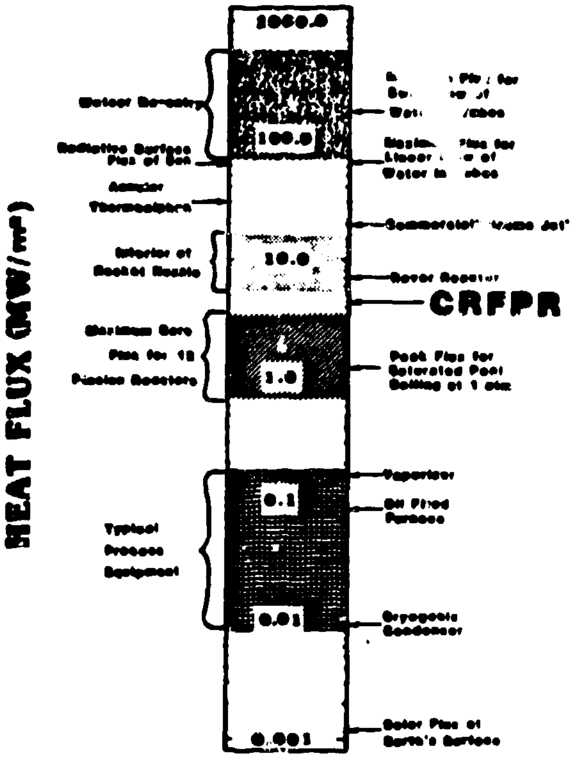

Fig.1 Comparison of heat fluxes. This figure extends a previous compilation (16) where the magnitude of the heat flux is that transferred to the coolant. The compilation does not consider the enormous transient heat fluxes that can be generated for brief periods, for example in shock tubes, but the heat is not transferred to a coolant.

No consensus exists today on the optimal concept for a magnetic confinement fusion reactor. Every potential design has its own special combination of unproven physics and engineering problems. Even the relatively well-understood Tokamak may have potential engineering difficulties related to its large size, the complexity of some of its subsystems, difficult maintenance procedure, and relatively low-power density (4). As discussed in Ref. 3, the compact RFPR promises to eliminate many of these problems, while presenting some new ones, including problems relating to the high-heat-flux first wall We have designed the high-performance first wall using a high-strength copper alloy with water cooling. The benefits of copper alloys for fusion reactor first walls were recently assessed (5). The heat-transfer, thermal fatigue, structural, and radiation damage considerations and evaluations that led to the choice of this copper-alloy and water-cooled system are discussed in the paper.

A transient two-dimensional heat-transfer and structural analysis of the wall serves as a basis for addressing the thermal fatigue problem. In the CRFPR design under consideration, this problem has been exacerbated by the assumed batch-burn mode of operation. We find that the copper-alloy wall is adequate for over 10^6 cycles, or about one year of operation, for the assumed burn conditions. A discussion of the analytical and numerical models and their results is found near the end of the paper. These results are generally applicable to other pulsed high-flux systems besides the CRFPR.

REACTOR OPERATION

For purposes of the engineering design of the first wall, we have elected to use the more conservative design conditions imposed by batch mode operation (3), although means can be proposed to induce a steady-state RFPR burn. Table I gives

TABLE I

CHARACTERISTICS OF CRFPR USED IN THIS STUDY[a]

Total thermal power (MW)	722
Power cycle duration (s)	
Time to ignition	0.1
Plasma burn period	21.6
Quench period	~4
Total	26
14.1 MeV neutron wall loading (MW/m²)	16.87[b]
Heat flux at first wall (MW/m²)	4.5[b]
Volumetric heating rate in copper	177.3[b]
Peak-to-average power during cycle	1.82
Plasma (and first-wall) minor radius (m)	0.2
Plasma (and first-wall) major radius (m)	3.8
Minor radius of system, including magnets (m)	1.03
First-wall and blanket module length (m)	0.3[c]

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[a] Parameters are a composite of those found in Refs. 2 and 3 and are used here only as a "worst-case" indication. The actual burn scenario for the CRFPR design has not been developed, but emphasis is being placed on long-pulsed and even steady-state operation.

[b] Time-averaged value.

[c] Length is somewhat arbitrary; 0.3 m is based on preliminary electrical resistance requirements (Ref. 2).

important characteristics of the CRFPR that were used as basic input to this first-wall design study.

FIRST-WALL MATERIALS AND DESIGN SELECTION

The important properties for candidate first-wall materials are compared first, and those for the material selected are then related to a specific configuration that minimizes the thermal stress and is feasible to build.

Materials Selection

The selection of the cooling medium and the structural material for the first wall is a critical step in the design. Many alternatives exist for withstanding high thermal and neutron fluxes and removing the associated heat (6-9). We selected subcooled water as the cooling medium and a high-strength, high-conductivity copper alloy as the structural material.[3]

As a heat-transfer fluid, water is unequaled. The use of subcooled water at 83 MPa (~1200 psia) provides an additional margin of safety before burnout conditions are reached. These factors, along with the design heat transfer coefficients and potential operational problems such as fouling and erosion, are discussed in the following section.

Additional complications are raised by radiation induced effects and interactions between the plasma and the first wall. For example, the transmutation of copper to nickel could reduce the thermal conductivity of the first wall. The copper alloys are reported to have high radiation activity at reactor shutdown. Within one year, however, it is believed that the activity of most copper alloys is reduced to the point where the long-term radwaste problem is not severe (5).

A part of the heat flux to the first wall will be attributable to energetic deuterium, tritium, or helium ions. The erosion associated with this plasma/wall interaction is a potentially serious problem. Both Hoffman (7) and Harling et al. (5) estimate that first walls 1 to 2 mm thick are capable of lifetimes of 10^6 cycles.

Although copper alloys have not often been considered as structural materials for fusion reactors, they have attracted recent attention (3,5,8) as a tendency toward achieving higher power density continues. The criteria for selecting first-wall materials have been summarized by Conn (6). These criteria include, in order of priority, resistance to radiation damage and surface effects, compatibility with coolant and with hydrogen isotopes, desirable mechanical and thermal properties (especially in the irradiated condition), and miscellaneous factors generally related to resource availability and cost. A commonly accepted method of applying all of these criteria in a consistent manner to the selection process does not exist, although several attempts have been made (8,9). Reactor system definition, design criteria, and materials requirements are mutually dependent on each other and will be subject to change as the science and technology of fusion power systems evolves. High thermal conductivity is important for the CRFPR and other high-power-density systems, to minimize the temperature gradients at high heat flux levels and thus lead to reduced thermal cycle fatigue. High strength at operating temperature and resistance to creep deformation are also important.

Although design criteria related to plasma/wall interactions and to radiation-induced effects can be identified, the relevant data are very sparse. It is not possible, therefore, to reach informed judgments concerning the relative irradiation performance of copper alloys with respect to other candidate materials.[4] However, there is nothing in the available data base summarized in Refs. 3 and 5 to preclude copper alloy as a structural/heat-transfer material in fusion systems. The MZC copper alloy demonstrates all of the desired qualities and is further recommended because it is commercially produced in quantity, is easily fabricated into the desired shapes, and is relatively low cost. The latter items are favorable in light of the probable need for frequent replacement of fusion reactor first walls, no matter what the material. Copper alloys should be about as compatible with water, helium, and hydrogen as austenitic stainless steel (5,8). The following discussion makes a quantitative comparison of MZC copper alloy with some of the other metals to substantiate this material choice for the high-heat-flux CRFPR first wall.

The maximum temperature in the wall occurs at the surface facing the plasma. If the maximum temperature in the metal is assumed to not exceed one-half the melting temperature (an optimistic criterion selected only for purposes of comparison), then the maximum heat flux for the assumed conditions is only a function of the wall thickness, δ. The results of this analysis for several representative metals are shown in Fig. 2. The MZC alloy, when compared on this basis, is superior to most common engineering metals and alloys, reflecting a favorable combination of thermal conductivity and melting point. Molybdenum and titanium alloys are also superior by this measure, but they are more costly; molybdenum is difficult to fabricate, and titanium is subject to hydrogen embrittlement.

A measure of the ability to withstand thermal stress can be defined as the thermal stress parameter, M (6).

$$M = \frac{2\sigma_y k(1-\nu)}{\alpha E} = \frac{\sigma_y}{\sigma_{th}} q''\delta \quad ,$$

where σ_y is the yield strength, k is the thermal conductivity, ν is Poisson's ratio, α is the coefficient of thermal expansion, E is Young's modulus, σ_{th} is the thermal stress, q" is the surface heat flux, and δ is the tube-wall thickness. The parameter M(W/m) is most applicable to high heat fluxes applied to thin-walled tubes.

Under these conditions, the ratio (σ_y/σ_{th}) represents a structural safety factor. If the same safety factor and the same tube-wall thickness is used for all materials, then M is directly proportional to the maximum heat flux that the material

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[3] The copper alloy (10) designated MZC is a high-strength copper alloy with 0.06% magnesium, 0.15% zirconium, and 0.4% chromium by weight.

[4] These include stainless steel, vanadium, niobium, molybdenum, titanium, aluminum, and various alloys of these metals. For near-term experimental reactors, the importance of radiation damage is diminished with respect to the other criteria (6).

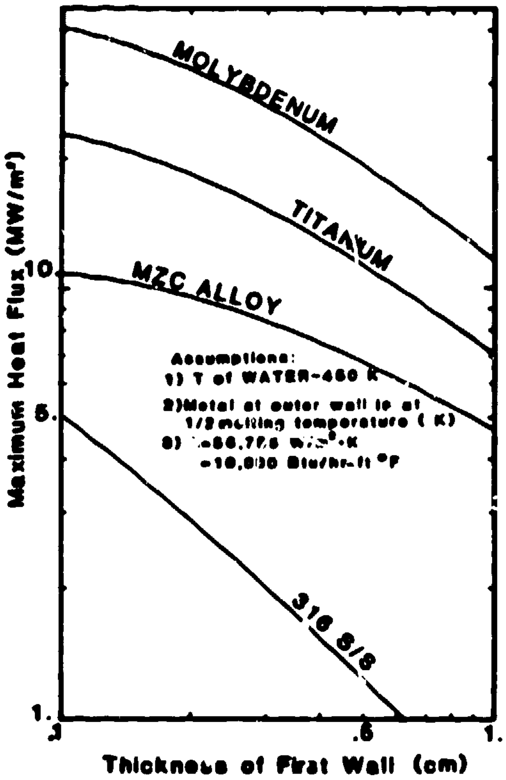

Fig.2 For a heat flux applied at the outer wall of a water-filled coolant tube (representing a section of the first wall), the maximum temperature in the metal depends on the magnitude of the heat flux, the thermal conductivity of the metal, the thickness of the metal, the water temperature, and the effectiveness of the water cooling (expressed as the film heat-transfer coefficient, h). We have assumed that the upper limit for the metal's working temperature is one-half the melting temperature (K) for all metals. We also assume that the water temperature is 450 K (350°F) and its film heat transfer coefficient is 56.8 kW/m^2 (10^4 Btu/hr-ft°F).

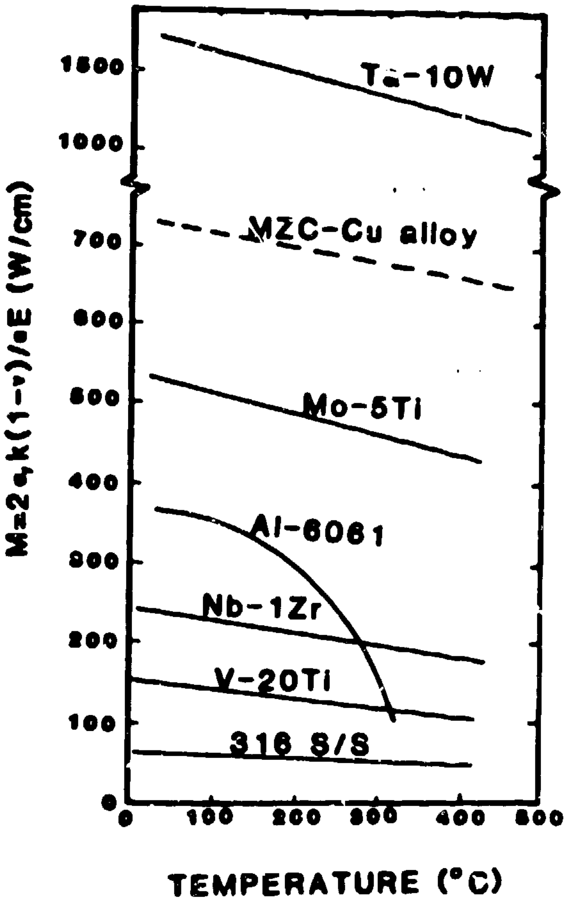

Fig.3 The figure has been reproduced from Ref. 6 except that the dotted curve for MZC copper alloy has been added, based on properties reported in Ref. 10. Although this is by no means a complete analysis, it is clear that because of its high strength and thermal conductivity the copper alloy is a good candidate for the high-flux first wall. The figure was originally published in 1974 in Lawrence Livermore National Laboratory report UCRL-75622 by M. A. Hoffman and R. W. Werner.

can tolerate. Figure 3 shows that the MZC copper alloy compares quite favorably with other commonly employed materials. The tantalum-tungsten alloy was rejected because of cost, fabrication, neutronics, and corrosion problems. The satisfactory ranking of the MZC copper alloy in the above generic evaluation, along with low cost and ease of fabrication when compared with more exotic competitors, led to its adoption as the first-wall material for the CRFPR.

Design

The criteria used for materials selection so far has not been design specific. To carry this design further, we discuss in this section the selection of the principal design variables: the coolant channel dimensions, the wall thickness, and the configuration of a heat transfer module for the torus. The normalized tensile hoop stress, σ_θ, in a thin-walled tube subjected to internal pressure, P, is given by

$$\frac{\sigma_\theta}{P} = \frac{R^2+1}{R^2-1} ,$$

where R is the ratio $d_o/d_i = 1 + 2\delta/d_i$ of outer tube diameter, d_o, to inner tube diameter, d_i. Small values of R lead to high tensile hoop stress, but low thermal stress; the reverse is true for large R with thick walls. A "knee" in the curve of σ_θ/P vs R occurs for R = 1.3. For δ = 1-mm wall thickness (to maximize the heat flux, see Fig. 2) and R = 1.33, d_i = 12 mm. Combining the thermal and tensile hoop stress for the thin-wall tube leads to

$$\sigma = \sigma_\theta + \sigma_{th} = \frac{Pd_i}{2\delta} + \frac{\alpha E q'' \delta}{2k(1-\nu)} .$$

For internal pressure P = 8.3 MPa[5] (1200 psia), the nominal wall stress in the 12-mm-diam MZC copper alloy tube is given as a function of wall thickness and heat flux in Fig. 4.

To minimize the stress, an optimum wall thickness of 1-3 mm is needed. For walls of this thickness range, the nominal stress is 100 MPa (Fig. 4) and is about a factor of four less than the reported (10) tensile strength for the copper alloy at 673 K (750°F).

These preliminary structural considerations do not constitute a complete failure analysis and must be refined to account for nonuniformity of heat flux, axial loading, cyclic fatigue, and radiation damage effects. We have, however, arrived at an acceptable configuration, a 12-mm-diam copper alloy tube with 2-mm-thick wall, that promises to achieve the desired performance.

Fabrication Techniques

The copper-alloy tubes envisaged for the CRFPR first wall must be assembled in a heat-transfer module. When assembled, as shown in Fig. 5, the modules will cover the entire inner surface area of the torus and will ultimately include the first wall, the tritium-breeding blanket, and the magnets.

The MZC copper alloy obtains its properties by rapid water quenching from solutioning[6] temperatures. Although it can be cold-worked, this is not required to attain the desired strength, which is obtained by age hardening. For the CRFPR, cold working will be avoided because of the tendency to cause overaging at operating temperature and to accelerate grain growth and creep. Loss of strength by overaging will occur at temperatures above 694 K (790°F); but with no cold work, negligible overaging should occur at normal operating temperatures.

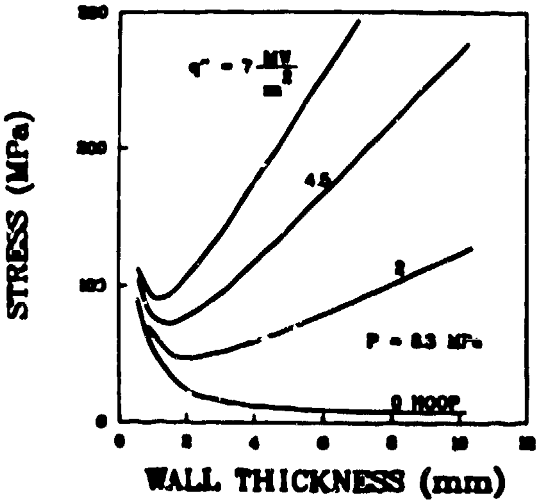

Fig.4. Stress in 12-mm diam MZC copper tube with 8.3 MPa internal pressure and surface heat flux given by q". The minimums in the curves indicate an optimum design for wall thickness between 1 and 3 mm.

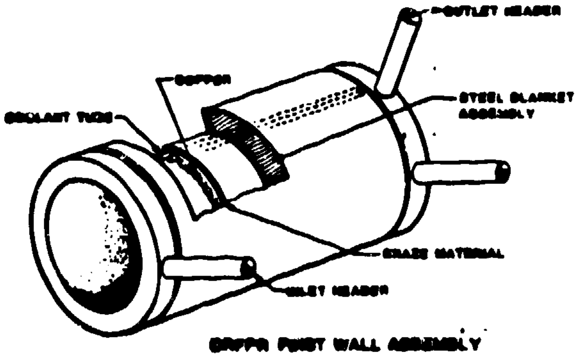

Fig.5 Conceptual design of heat transfer module. When connected together these modules will eventually cover the entire surface area of the torus. The individual tubes are 12-mm i.d., 2-mm thick, and 0.3-m long.

The tube bundle will probably be furnace-brazed at ~1300 K (~1875°F) and cooled in a normal fashion. Then the assembly will be reheated to the lowest possible solutioning temperature, 1183 K (1670°F), and rapidly quenched to obtain the desired properties that have been published. Various quenching techniques are possible that can achieve the desired quench rate with minimum distortion of the assembly. Connecting plena, manifolds, and piping (also fabricated of copper) can be brazed or welded in place (Fig. 5). Successful welding only requires the exclusion of oxygen, similar to OFHC copper. It is desirable to fabricate the complete first-wall coolant flow circuit of copper to minimize the possibility of fouling on the heat-transfer surfaces.

HEAT-TRANSFER ANALYSIS

For the conditions assumed for this first-wall design exercise, which are expected to be more stringent than for a long-pulsed or steady-state CRFPR, the water heat-transfer system must be capable of safely removing 8.2 MW/m² (peak) from the plasma side of the first wall plus the volumetric heating associated with neutron and gamma radiation throughout the copper amounting to 367.6 MW/m³ (peak). To achieve the desired heat transfer rates in the straight tubes, it was necessary to have high-purity water moving at high linear velocities (~9 m/s). These high velocities also aid in minimizing the fouling and maximizing the burnout flux. Additional increases in the burnout flux were obtained by operating the system near the optimum pressure for maximum pool boiling. Many of the important heat transfer and fluid flow parameters are listed in Table II.

Convective Heat-Transfer Coefficient

The convective heat-transfer coefficient for the flow of subcooled water in a 12-mm-diam coolant channel is based on the well-known Dittius-Boelter correlation for fully developed flow in a circular tube. To achieve the water heat-transfer coefficient of 56.8 kW/m² K, the corresponding Nusselt number is 1006 and the Dittius-Poelter correlation gives a Reynolds number of 6.3 x 10^5 based on the tube diameter.

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[5] The pressure was chosen on the basis of thermodynamic considerations, see the next section.

[6] This is the temperature at which the alloying elements are in their lowest energy states on the atomic scale.

TABLE II

SUMMARY OF COOLANT-FLOW PARAMETERS

Channel parameters	
Number per module	90
Length (m)	0.3
Diameter (mm)	12
Wall thickness (mm)	2
Flow parameters	
Inlet pressure (MPa/psia)	8.273/1200.
Pressure drop, including headers (MPa/psi)	0.4674/6.8
Mass flow rate per tube (kg/s)	0.9274
Velocity (m/s)	9.1
Reynolds number	6.3×10^5
Pumping power per module (kW_e)	4.9
Temperatures (K)	
Coolant inlet	442
Coolant outlet	450
Design maximum local wall temperature	675
Cyclic temperature change at apex, max-min	236
Water subcooling $\Delta T_{sat} = T_{sat} - T_{out}$	120.7
Wall superheat, $T_w - T_{sat}$, at power peak	16
Heat flux (MW/m^2)	
Time-averaged local maximum	4.5
Time and area averaged for channel	2.76
Local Peak	8.2
Heat flux for incipient boiling	7.09
Critical heat flux for subcooled flow boiling	
Tong correlation	12[a]
Griffel correlation	9.77
Heat transfer coefficient (kW/m^2-K)	56.8
Thermal energy absorbed by first wall (MW)	
Per coolant tube	0.03
Per module	2.56
Total	205
Per cent of reactor output	28

[a] The correlation actually predicted 20 MW/m^2, but 12 MW/m^2 was the limit substantiated by experimental data.

The choices of coolant pressure and outlet temperature were made deliberately to give a large subcooling, $\Delta T_{sat} = 120.7$ K. As a result, the critical heat flux for subcooled flow boiling evaluated at the tube exit is also large (Table II). The two correlations listed, Tong's (11) and Griffel's (7), are based on steady-state conditions with uniform circumferential heat flux in a circular channel. Their use is conservative (12) in this application because the peak heat flux is transient and occurs only on one side of the tube.

The adequacy of the margin between the local peak and the critical heat flux is a matter of judgment that we would like to be able to base on a more refined analysis, and (we hope) some experimentation at high transient heat fluxes. The design concept is not yet advanced to the point where heat transfer in the inlet and outlet headers has been considered. Careful attention to the area where the flow turns from radial to axial will be needed to prevent the critical heat flux from being exceeded.

The Dittius-Boelter correlation predicts conservative heat-transfer coefficients for the first-wall coolant. It is valid for fully developed velocity and thermal boundary layers in uniformly heated tubes at steady state. The flow in the 0.3-m-long coolant tubes is not fully developed at the exit. The peak heat flux at the tube wall next to the plasma is about 16% greater than the heat flux for incipient nucleate boiling. For about 10 s, the wall is above the water saturation temperature and the convective heat transfer will be improved by the addition of the boiling. Also, because the heat flux is nonuniform around the tube, the Nusselt number will vary circumferentially. According to the analysis by Reynolds (13), which includes effects of circumferential wall heat conduction, the Nusselt number locally at the apex of the tube may be significantly less than used in our design.[7] Swirling flow (see next section) would greatly alleviate this problem.

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[7] A more detailed analysis by Fillo and Powell (14), including both radial and circumferential conduction, shows that, for our conditions, the neglect of radial conduction is not important and supports the decrease in heat transfer at the apex. In the same paper, they caution, based on experiments by Chan et al. (15) that the circumferential variation in the local heat transfer coefficient is less pronounced than theoretical analyses predict and the decrease in heat transfer mentioned above may be too severe a penalty.

We are not able to pursue these subjects with the thorough attention that they deserve in this brief paper, but we point out that two of the three lead to conservatism in our analysis. Superposition of these effects on heat transfer is not necessarily justified, and thorough experimentation will be required to resolve these questions.

Enhancement of Heat Transfer

If the first-wall heat-transfer rates should require additional augmentation, there are at least two methods by which they can be improved with acceptable penalty in pressure drop. Extended surfaces ("fins") can be considered established technology. The same is true for swirl-flow devices, including twisted tape inserts, first used in the year 1896.[8] A fine spiral groove on the inner tube surface achieves both swirl and extended-surface benefits. Other variations are possible and are commercially available. Their precise benefit in this high-Reynolds-number, nonuniform, transient, high-flux application must be the subject of experimentation, but a factor of 2 reduction in film ΔT does not seem unreasonable. It is of interest that some of the highest steady-state heat fluxes to flowing water (173 MW/m^2) ever measured (16) were obtained with swirl flow in short smooth tubes.

Fouling, Corrosion, and Erosion

Fouling of the surface at the tube/water interface will lead to reduced heat-transfer efficiency and higher copper temperatures. Many variables affect fouling and we note that among these are time in service, tube surface material, temperatures of the tube surface and the water, and the water velocity. Finally and most importantly, careful control of water chemistry (by polishing, for example) can greatly reduce the effects of fouling. For the CRFPR, all of the above are in a parameter range where fouling is low, and so no fouling resistance has been incorporated into the heat-transfer calculations.

At high flow velocities, the possibility of fluid erosion of the copper coolant passages must be considered. This effect is distinct from the wall erosion that occurs at the plasma/copper interface by sputtering. For pure water, with low solids content and no cavitation, erosion should not be a problem. The flow passage geometry must carefully avoid low-pressure regions that can lead to cavitation. Corrosion of the copper wall by the water coolant in the one-year design life should be <0.1 mm (5).

Transient Heat-Transfer Analysis

A transient numerical analysis of the first wall was carried out with the finite-element heat transfer code, AYER (17). The purpose of this modeling was to determine the highest temperature experienced by the first wall during the cycle and to determine the temperature profile as a function of time for the thermal fatigue analysis. The dimensions and configuration for the first wall are shown in Fig. 6. A typical symmetry section includes the region between the centerline of a tube and the line dividing two adjacent tubes. Because the heat flux is assumed to be uniform (both poloidally and toroidally, an optimistic assumption) at the plasma-first wall interface, these lines represent adiabatic boundaries for the model. The surface of the model opposite the plasma (bottom and right in Fig. 6) is assumed to be insulated, although a relatively small heat flux could exist in either direction, depending on blanket temperatures and construction details. The tube wall thickness, δ, was varied parametrically over the range 1-2 mm. A ~5-mm-thick copper backing plate is included in the model for interfacing between the tube array and the structure surrounding the reactor blanket. The coolant film heat-transfer coefficient, 56.8 kW/m^{2}K, was assumed to be uniform around the circumference of the circular tube and constant with time. The former assumption is optimistic and the latter is pessimistic.

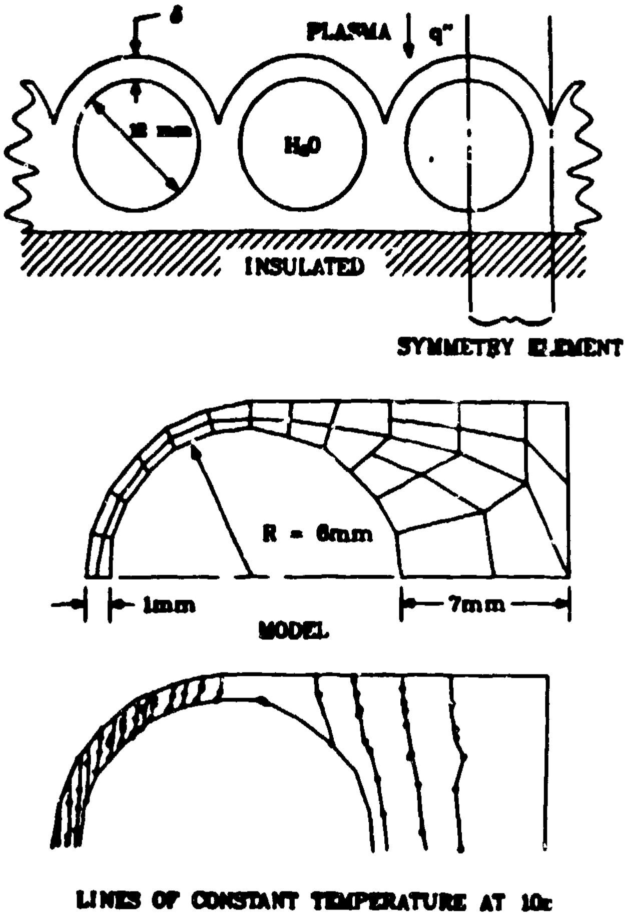

Fig.6 Heat-transfer analysis model.

Some of the parameters used as input to the model are summarized in Tables I and II. The heat flux at the plasma/copper interface, the volumetric heat flux, and the coolant temperature[9] all cycle with a 26-s period according to the plasma burn profile (3) adopted for this first-wall design exercise. The plasma heat flux normal to the tube

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[8] Presented orally by A. E. Bergles in a talk at the 6th International Heat Transfer Conference, Toronto, Canada, August 1978.

[9] The water transit time from end-to-end of the tube is $\approx$0.03 s, so the response of the water temperature to cyclic changes in input power is very fast.

surface is assumed to vary with the cosine of the angle from the apex. The finite-element mesh is shown in Fig. 6, and the calculated isotherms are illustrated for the time into the burn (10 s) when temperatures reach their peak.

The copper temperatures during the power cycle are shown in Fig. 7. The maximum temperature at the apex varies by 236 K during the cycle, and the volume average temperature varies by 124.5 K. The structural fatigue analysis, based on these temperatures and temperature profiles, is presented in the next section.

STRUCTURAL ANALYSIS

A preliminary thermal-cycle fatigue calculation was performed for the proposed reactor first-wall design and assumed operating conditions. A one-year operating life can be expected for the heat-transfer module. The modular array of side-by-side coolant tubes is subjected to a multiaxial, multicomponent state of stress in the first wall. The tubes are free to expand axially, but are not allowed to bend. The model is based on a single tube with an externally applied heat flux on one side. Both the tube inner and outer walls were analyzed as the critical locations.

The loading applied to the tube comes from three sources: the internal water pressure, the temperature gradient in the tube wall, and the temperature difference across the tube because the heat flux is applied on one side only. The primary loading under equilibrium conditions is from the 8.27-MPa internal pressure, with small additions from the thermal loading. In steady state, the inner wall is in tension both circumferentially and longitudinally. The outer wall is in circumferential tension and slight longitudinal compression.

The alternating stresses from thermal cycling are compressive everywhere except for the tensile circumferential stress at the inner wall. Because cyclic plasticity is important for fatigue, the maximum shearing stress at the critical planes (the inner and outer walls) was used for the fatigue evaluation. The stresses are summarized in Table III. The critical surface is the inner wall because of the proportionally higher tensile stress in the circumferential direction that can propagate a crack initiated from cyclic plasticity.

The maximum shear stresses obtained from a Mohr's circle were plotted on a modified Goodman diagram with the material strength reduced[10] to account for the shearing stresses by a distortion energy criterion (Hencky-von Mises). The modified Goodman diagram given in Fig. 8 shows that operating points for both inner and outer walls lie well on the safe side of the line with 10^6 operating cycles.

If future developments permit increased burn duration, the number of operating cycles will be reduced and probably the magnitude of the alternating stress will decrease because of the more uniform heat flux. In this case, high-temperature creep would probably become the governing failure mechanism.

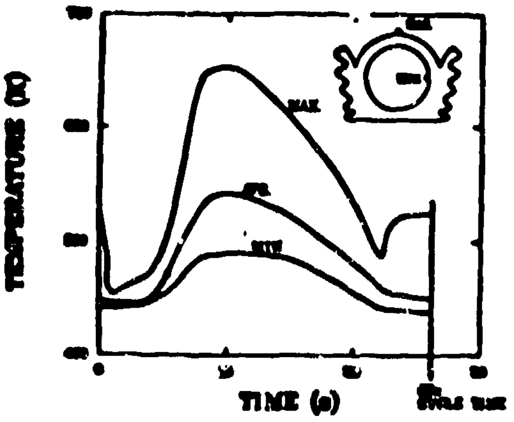

Fig.7 Copper temperature during power cycle.

TABLE III

STRESSES IN 2-MM-THICK MZC COPPER TUBE

	(MPa/ksi)[a] Steady	Alternating
Inner Wall		
Circumferential	37/5.4	127/18.4
Longitudinal	8.3/1.2	-4.1/-0.6
Outer Wall		
Circumferential	23/3.4	-105/-15.2
Longitudinal	-5.5/-0.8	-2[illegible]/-34.2

[a] Negative values are compressive.

SUMMARY

This paper describes the preliminary design for the first-wall heat-transfer system in a high-power-density compact RFPR. The MZC copper alloy selected as the structural material has a very high thermal conductivity with excellent strength and ductility at operating temperature in comparison with other candidate metals and alloys. It is the high conductivity and strength of the copper that are primarily responsible for the increased heat flux capacity of this design over previous first-wall studies of fusion reactors (6,7). These characteristics aid in minimizing thermal stress and fatigue for the conservative operating cycle assumed. The copper first wall is cooled to safe operating temperatures by subcooled water flowing at high linear velocities in 12-mm-diam tubes. By the use of extended surfaces or swirl-flow promoters in the tubes, the maximum safe heat flux through the first wall, and hence the system power density or the first-wall design margin, could conceivably be increased even further.

The first-wall design in this paper is based on a batch-burn operating cycle with 10^6 power transients in the one-year service life. A less rigorous operating cycle leading to improved performance or increased life may result from future developments in understanding of the RFP physics and reactor potential. Improved reactor technology would permit longer pulses and more optimally shaped power transients leading to steady-state operation where the alternating thermal stress would be reduced.

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[10] Tensile strength was multiplied by 0.577.

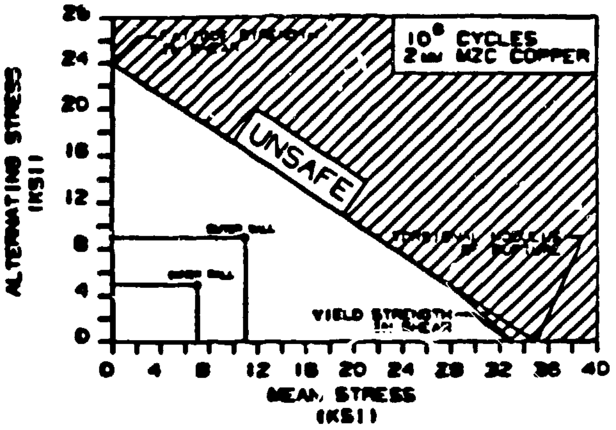

Fig.8 Modified Goodman diagram.

Although the first-wall design appears feasible as a concept, important questions remain that are related to bulk radiation effects and surface damage for the copper alloy. Little data are available to determine irradiation performance, and copper alloys have not been developed that are optimized for the fusion reactor's environment (5). We do not, however, foresee any insurmountable engineering problems in the way of development of a prototype for the RFP fusion reactor.

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