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SUBJECT: Methods of Controlling Core-Wall Temperatures in
Aqueous Homogeneous Reactors

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ABSTRACT

The problem of controlling the surface temperatures of core vessels in two-region aqueous homogeneous reactors has been examined by analyzing several possible systems for cooling the wall: (1) direction of the inlet core fluid along the wall at a high velocity; (2) passage of heavy water through the wall of a double-wall core vessel; and (3) flow of cool blanket slurry past the wall.

If the required flow conditions can be achieved, method (1) will keep the surface temperature within 20°C of the inlet fuel temperature. Should use of that technique alone not be successful, method (2) could be used, with coolant temperatures probably in the range of 100 to 200°C. Use of the blanket slurry to lower the core-side temperature would require that the blanket be much cooler than the core.

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METHODS OF CONTROLLING CORE-WALL TEMPERATURES
IN AQUEOUS HOMOGENEOUS REACTORS*

INTRODUCTION

The release of gamma energy in the wall and fission energy in the fuel fluid near the surface can cause the core vessel of a two-region homogeneous reactor to be hotter than the fluid emerging from the core. The high wall temperature in turn may cause gross fuel deposition, with undesirable results.

Even if the fuel deposition problem did not exist, the effect of temperature on corrosion rate would make it desirable to keep the wall temperature low, and the temperature level which is acceptable with regard to corrosion may be below that at which fuel deposition occurs. In-pile corrosion studies have indicated that the corrosion rate of Zircaloy-2 will increase with increasing temperature. For example, Jenks et al.¹ found in experiments with uranyl-sulfate solution that under conditions of interest for power reactors, the attack rate more than doubles when the temperature is increased from 250 to 280°C. There is limited information concerning the temperature dependence of attack by urania-thoria slurries in a radiation field, but the corrosion rate of Zircaloy-2 does appear to be somewhat higher at higher temperatures.²

The temperature of the core wall could, of course, be limited by restricting the power of the reactor, but the economic penalty might be severe. In exploration of this problem, a computational study has been made of methods of controlling the wall temperature in large aqueous-homogeneous power reactors.

* This memorandum summarizes the results of a brief study to which a number of people contributed. They are: H. C. Claiborne, T. B. Fowler, P. R. Kasten, C. G. Lawson, M. P. Lietzke, F. N. Peebles, B. E. Prince, I. Spiewak, D. G. Thomas, and M. Tobias.

Three methods of removing heat from the vicinity of the wall were considered:

1. Passing the blanket slurry between the wall and a shroud at a sufficiently low temperature to remove heat at the rate required;
2. Using a double-wall core vessel and passing heavy water through it at the temperature and velocity required to accomplish the cooling needed;
3. Directing the entering stream of core fluid along the wall at a high velocity, so that the wall is in contact with the colder fluid, and the heat transfer conditions are good enough to keep the effect of the heat generation in the fluid from being important.

Another possible method of accomplishing the objective of a low corrosion rate is the use of a double wall system with porous walls. Heavy water emerging into the core by transpiration through the wall could reduce the fuel concentration near the surface and thus reduce the power density at the wall, while at the same time cooling the wall effectively. Use of this technique was not investigated.

In this study, computations were made of the application of the three methods numbered above, or combinations of them, to four core systems which are described in Table 1. The first two reactors have no thorium in the core region and thus are of the so-called "solution-core" type; the last two, which are larger, have thorium in the core and are of the "slurry-core" design. The cylindrical cores are approximately the reference designs used by the Fluid Fuel Reactors Task Force,³ and the spheres have diameters selected to give the same critical concentrations as the corresponding cylinders. For all of the reactors the blanket was 2-ft thick and contained 1000 g Th/l and 3 g U^{233} /kg Th.

Table 1. Core Systems Studied

Case	1	2	3	4
Core geometry	cylinder	sphere	cylinder	sphere
Core vessel dimensions,* ft	4 x 12	5.34	7 x 18	9.08
Core thorium concentration, g/l	0	0	200	200
Total power (heat), Mw	400	400	1000	1000
Mean core power density, kw/l	79	149	49	84

* Inside diameter and length of cylinders, inside diameter of spheres.

ENERGY SOURCES

There are three energy sources which can contribute significantly to raising the core-wall temperature above the mean fluid temperature: (1) fission energy generated in the fluid near the wall; (2) gamma energy released in the wall; and (3), energy from fissioning of uranium deposited on the wall surface.

Power Density in Fluid

The power densities in the blanket and core fluids at the wall were obtained from two-group neutron diffusion calculations and the values obtained are plotted in Figs. 1 and 2 (the values for the cylinders are those at the mid-plane). The computations were performed for isothermal reactors and are applicable to cores in which the flow pattern results in a fairly uniform core temperature, or in which one dimension is not appreciably greater than the other. However, for long cylinders with an axial temperature gradient

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Fig. 1. Power Densities in Fluids at Inner and Outer Surfaces of Core Vessel.

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Fig. 2. Power Densities in Fluids at Inner and Outer Surfaces of Core Vessel.

(and thus varying nuclear properties), the flux distribution can be significantly distorted from the symmetrical pattern which would exist in an isothermal system, the point of maximum flux being shifted towards the cold end of the core. As a consequence, for the same core power the maximum wall power density is higher than it would be with a uniform temperature core.

This effect has been investigated⁴ by an MIT Practice School group using WANDA, a numerical two-group neutron diffusion program for the IBM-704. The program was operated to have the iteration routine terminate on convergence of the multiplication constant. However, with this criterion the flux distribution has not necessarily converged when the computation is completed (point flux conversion is possible but the computation time was deemed excessive). As a consequence, there is scatter in the computed values of the maximum wall power density. The scatter is seen in the points of Fig. 3, where the ratio of maximum power density with axially varying temperature to that with uniform temperature ("asymmetry factor") is plotted.

M. Tobias⁴ has computed the asymmetry factor for the 4 x 12 core of Case 1 using the two-space-variable PDQ code, with an axial temperature rise of 50°C. He found the factor to be 1.08. He also computed the factor for the Case 1 and 3 reactors with "swirling" flow (discussed later) in which the core fluid enters near the wall at one end and emerges in the center at the same end. The factor was found to be 1.05 for Case 1 and 1.02 for Case 3 when the axial velocity component in the annular region was 10 ft/sec.

In the results presented in this memo the maximum wall power densities are for uniform temperature cores. Allowance for the asymmetry correction would not significantly affect the results for the reactor sizes treated. However, with axial flow through longer cores, the effect would be appreciable.

Fig. 3. Ratio of Maximum Power Density at Wall of Cylinder with Axially Varying Nuclear Properties to that with Uniform Properties.

The heavy water present in an internally-cooled wall would act as a neutron reflector and moderator and would increase the power density in the fuel at the core side of the wall. B. E. Prince has estimated what the effect would be in the 4 x 12 cylinder of Case 1 if the wall were formed of two 1/4-in. thicknesses of Zircaloy-2 separated by D₂O gaps of various width. For the same total power, he obtained the following ratios of power density with the double wall to that with a single 1/2-in.-thick core vessel.

Table 2. Effect of Heavy-Water Coolant on Power Density at Fuel Side of Core Wall

Coolant Gap Thickness	Power Density with Coolant Power Density without Coolant
0	1.0
1/2	1.07
1	1.14
1-1/2	1.21
2	1.27

Gamma Heating of Core Wall

The gamma heating rate in the spherical core vessels was estimated by H. C. Claiborne and T. B. Fowler using an Oracle routine which allows for the various gamma sources in two-region homogeneous reactors.⁵ (The technique used in their routine was checked for a different geometry against experiments in the Bulk Shielding Reactor with three materials, and the disagreement was 15% in the worst case.⁶) The maximum gamma heating in the walls of cylinders was approximated by adjustment of the sphere results. However, one value was checked by a direct calculation and the agreement was good. The results for spheres and cylinders

are plotted in Fig. 4 on the basis of total heat generation in a 1/2-in.-thick Zircaloy-2 wall per square foot of wall area, and the right-hand scale shows the values in watts per milliliter. The cylinder values were computed with the neutron flux distribution for an isothermal system.

Uranium Deposited on Surface

The effect of uranium on the wall surface has been neglected in this study. However, some values of the heat generation rate per unit surface which would result from deposited U^{233} are given in Table 3, as well as the maximum flux of thermal neutrons at the wall.

Table 3. Heat Generation Rate from 1.0 mg U^{233}/cm^2 on Core Wall

Case	1	2	3	4
Max. core-wall neutron flux	8.9×10^{14}	9.5×10^{14}	1.4×10^{14}	1.4×10^{14}
Heat generation rate (Btu/hr-ft ²)	72,000	77,000	14,000	14,000

In in-pile loop experience¹ with uranyl-sulfate solution, the uranium found on the surface of Zircaloy-2 corrosion specimens has never exceeded 1/10 mg/cm² and generally has been less than 1/40 mg/cm². At the higher value the energy contributed would still be small compared to the gamma heat in the wall. Of course, if there were gross deposition of uranium, the situation would be completely altered.

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Fig. 4. Heat Generation Rate in Zircaloy-2 Core-Vessel Wall.

RESULTS OF COOLING ANALYSES

Cooling with Blanket Slurry

D. G. Thomas has examined the possibility of reducing the temperature at the inner surface of the core vessel by cooling the wall with slurry flowing in the blanket. The entering fluid would be directed along the wall by a shroud. Use of educators to entrain fluid at the shroud inlet would reduce the amount of slurry to be circulated outside the blanket for a specified shroud throughput.

The blanket fluid was assumed to have a yield stress of 0.1 lb/sq ft and a coefficient of rigidity of 1.0 cp. At a Reynold's number several times greater than the critical value (associated with the onset of turbulence), the heat transfer behavior of this material can be estimated satisfactorily using the relationships for Newtonian fluids.⁷ For a Bingham plastic having the assumed properties, the critical velocity through a 3-in. gap would be 3.4 ft per second. If the flow rate through the shroud were selected to make the velocity equal to 4 times the critical velocity, the heat transfer coefficient would be 4000 Btu/hr-sq ft-°F.

Values are given in Table 4 for the conditions which would exist at the point of maximum wall power density if all of the heat generated in a 1/2-in.-thick Zircaloy wall were removed by the blanket fluid. The " ΔT across core wall" in Table 4 is the temperature difference between the inner and outer surfaces of the core vessel. The " ΔT wall-to-slurry for wall gamma heat" is the difference which would exist between the outer wall surface and the bulk slurry if there were no volume heat source in the slurry. Conversely, " ΔT for volume heat in slurry" is the difference which would exist between the

Table 4. Results for Wall Cooling by Blanket Slurry

Case	1	2	3	4
Max. heat generation rate in core wall, watts/ml	19	30	6	9
Max. power density in blanket slurry at core wall, kw/liter	59	63	9	9
Shroud flow rate, gpm	19,000	25,000	34,000	43,000
ΔT across core wall, $^{\circ}C$	89	138	29	44
ΔT wall-to-slurry for wall gamma heat, $^{\circ}C$	5	8	3	5
ΔT for volume heat in slurry	<u>0.8</u>	<u>0.9</u>	<u>0.2</u>	<u>0.3</u>
ΔT core-side of wall to blanket fluid, $^{\circ}C$	95	147	32	49

outer surface and slurry if there were no heat transfer from the wall (computed from volume heat source solutions for flow between parallel plates).⁸ These separately computed quantities are additive, and they were summed to obtain the values in the last row.

The temperature difference in the last row, when subtracted from a specified inner-surface temperature, indicates at what temperature level the blanket would have to be operated to have all of the wall heat removed on that side. If some of the wall heat were removed by the core fluid, the blanket temperature could be higher. On the other hand, if some of the heat generated in the core fluid had to be removed through the wall, the blanket temperature would have to be lower.

For example, transfer of 25,000 Btu/hr-sq ft from the core would add 60°C to the temperature drop between the inner core-vessel surface and the blanket slurry.

Cooling with Directed Core Fluid

Two core flow systems were examined --- one applicable to spheres and the other to cylinders --- in which the entering fuel fluid is made to flow past the core-vessel surface at a high velocity. These systems have two advantages: the entering fluid is at the lowest temperature in the core; and the high flow rate creates favorable heat transfer conditions for removing wall heat and for reducing the effect of the volume heat source in the fluid. The temperatures which would occur in such systems, if the proposed flow conditions can be achieved, have been estimated.

Annular Inlet Spheres --- I. Spiewak and C. G. Lawson have proposed that the wall of a sphere could be cooled by directing part of the entering core fluid tangent to the wall from an annular inlet. The liquid would flow symmetrically from one pole at sufficient velocity to carry it to the opposite pole, where it would either be removed or entrained in a polar stream. The remainder of the fluid would enter and be removed at the poles. In experimental studies of annular inlet systems with some fluid being removed at the pole opposite to the inlet, the directed stream maintained its identity to the point of take-off. The flow behavior indicated that some fluid was transferred from the wall layer to the main body as it passed around the sphere. If there is no mixing of the hotter core liquid with the wall layer, the directed stream will not increase appreciably in temperature.

In the examples treated, the boundary fluid was assumed to enter at 40 ft/sec velocity and to slow down to 20 ft/sec at the exit. To obtain the wall temperature near the exit, Poppendiek's treatment⁸ of fully developed flow between

parallel plates was assumed to apply. The fictitious plate spacing was taken as 6 in. The blanket temperature was chosen to be that which would make half of the core-wall heat go in each direction. Otherwise, the blanket system was that previously described. The results obtained are given in Table 5.

Table 5. Results for Annular Inlet Flow in Spheres

Case	2	4
Inlet fuel temperature, °C	250	250
Axial temperature rise in boundary fluid, °C	3.6	3.3
ΔT wall-to-fluid for wall gamma heat, °C	6.3	1.9
ΔT for volume heat in fuel, °C	<u>2.4</u>	<u>1.6</u>
ΔT wall to mean core boundary fluid, °C	8.7	3.5
Maximum wall-surface temperature, °C	262	257
Blanket-fluid temperature, °C	253	254
Pressure drop across core, psi	14	17

The possibility of attaining the flow conditions postulated in the model is being checked experimentally.

Swirling Flow in Cylinders --- F. N. Peebles has examined the possibility of using swirling flow in cylindrical cores. In the systems considered, the cold fluid would enter at one end of the core with both axial and tangential velocity components and spiral down along the wall to the bottom, then reverse its axial direction and swirl back up the center. The velocity profile would be fairly uniform at the fuel inlet, but a retarded boundary layer would develop

at the wall and grow thicker as the fluid progressed down the core. For a given flow rate, specification of the axial velocity component in the outer ("annular") core region determines the flow pattern in the core.

The flow pattern of the bulk fluid has been analyzed with techniques which have been verified in experimental studies of swirling flow in other geometries, but have not been checked in models of the reactors being considered. Unfortunately, no solution of the heat transfer problem with volume heat sources in a boundary layer is available. The upper limit of the adiabatic wall temperature was therefore obtained by using the fully-developed-flow solution for parallel plates,⁸ as was done with spheres (however, taking the fictitious plate spacing as twice the annular region width). Assuming the heat from the wall goes evenly to core and blanket, the results in Table 6 were obtained for the point of maximum wall power density. In the cases analyzed, the flow rate of core fluid was that which would result in an average temperature rise of 50°C.

Internal Wall Cooling

The conditions which would exist if the wall were cooled internally were studied for two 1/4-in. thicknesses of Zircaloy-2 separated by a 1/2-in.-gap through which heavy water is passed. This design was investigated with both axial and swirling flow of fuel through the core; in both cases, fuel fluid enters the core at 250°C and leaves at 300°C. The coolant was assumed to be directed about the cylinder in a spiral path so that its velocity is always 10 ft/sec, and its temperature rise was taken as 50°C. For both flow patterns, the coolant temperatures at the point of maximum wall power density that would be required to reduce the wall temperature either to 250 or 275°C were computed.

Table 6. Results for Swirling Flow in Cylinders

Case	1		3	
Inlet fuel temperature, °C	250		250	
Axial velocity component in annular region, ft/sec	10	20	10	20
Axial temperature rise in annular region to mid-plane, °C	4.6	2.3	3.0	1.5
ΔT wall-to-fluid for wall gamma heat, °C	4.8	3.2	4.4	2.9
ΔT for volume heat in fuel fluid, °C	<u>4.6</u>	<u>1.4</u>	<u>3.6</u>	<u>1.1</u>
ΔT wall to mean annular region temperature, °C	9.4	4.6	8.0	4.0
Wall-surface temperature at mid-plane, °C	264	257	261	256
Blanket-fluid temperature, °C	256	249	256	252
Pressure drop across core, psi	9	14	24	38

In the case of axial fuel flow, the velocity profile of the fuel was assumed to be fully developed at the mid-plane, permitting use of the heat transfer solution⁹ for volume heat sources in pipe flow. The total heat removed by the coolant was obtained by an approximate integration along the length of the core, with the coolant flow direction being counter to that of the fuel. The heat removal from the blanket was computed assuming the blanket slurry to be at 280°C. The heat transfer results for axial flow are given in Table 7.

Table 7. Internally-Coolant Cylinder Wall with Axial Core Flow

Case	1		3	
Mean fuel temp. at mid-plane, °C	275		275	
Max. power density in fuel fluid at core wall, kw/liter	48		26	
Adiabatic wall* AT, °C	37		65	
Max. core wall temp. at mid-plane, °C	250	275	250	275
q/A removed from core fluid, Btu/hr-sq ft	109,000	67,000	88,000	63,000
Required coolant temp. at mid- plane, °C	60	143	119	178
Total heat removed by coolant, Mw	9	5	21	14
Coolant flow rate, gpm	690	390	1900	1200
Coolant pressure drop, psi	4.6	8.1	2.7	4.2

* Wall temperature minus mean fuel temperature (from volume heat source in fluid) if there were no heat transfer across surface.

If the power were 200 Mw instead of 400 Mw in the two examples of Case 1 (Table 7), the coolant temperatures required at the mid-plane would be 157 and 216°C.

The swirling-flow system was treated in a manner similar to the axial-flow case except that the core-side heat transfer was based on the parallel-plate model. The results are given in Table 8.

In none of the examples of internal wall cooling would increasing the coolant velocity have much effect on the required coolant temperature, since most of the temperature drop takes place across the Zircaloy wall.

Table 8. Internally-Cooled Cylinder Wall with Swirling Core Flow

Case	1		3	
Axial velocity component in annular region, ft/sec	10	20	10	20
Mean annular region temperature at mid-plane, °C	254.6	252.3	253.0	251.5
Adiabatic wall* ΔT, °C	4.6	1.4	3.6	1.1
Max. core-wall temperature at mid-plane	250	250	250	250
q/A removed from core fluid, Btu/hr-sq ft	36,000	16,000	21,000	10,000
Required coolant temperature at mid-plane, °C	170	197	200	216

* Wall temperature minus mean fuel temperature (from volume heat source in fluid) if there were no heat transfer across surface.

The increase in power density in the fuel which results from neutron reflection by the wall coolant was neglected in obtaining the preceding results. As shown in Table 2 for the Case 1 reactor, the 1/2-in. thickness of heavy water would have increased the power density on the core side of the wall by 7%. A more exact treatment of the wall cooling problem would require inclusion of this effect. However, for the coolant gap considered only a small change in temperatures would result.

SUMMARY OF RESULTS

If the postulated flow conditions can be achieved, direction of the entering fuel fluid along the core wall will keep the surface temperature from being over 20°C above the inlet temperature (for the cases studied). However, should use of that technique not be successful, energy may have to be transferred through the Zircaloy vessel and be removed in either the blanket fluid or a coolant which flows through the wall.

The use of blanket slurry to remove heat from the core could require fairly large temperature differences between core and blanket. For example, to remove just the gamma heat generated in the 1/2-in.-thick wall of the Case 1 reactor, the blanket slurry would have to be 95°C below the temperature at the inner surface of the core vessel; and over 90% of that temperature drop would be across the wall itself. Transfer of energy from the core fluid to the blanket at significant rates would appreciably increase the temperature difference.

Smaller temperature potentials would be required to remove heat at the same rate with an internally-cooled wall. Assuming that each section of a double-wall vessel would be half the thickness of a single wall, the resistance of the wall between core and coolant would be half that normally existing between core and blanket, and in each wall section only half as much gamma energy would be liberated. As a result, removal of the heat generated in the wall can be done with much smaller temperature differences than those computed for blanket cooling. Nevertheless, the heat transfer resistance between the core fluid and the coolant would still be appreciable, and in the cases studied the coolant temperatures were generally in the range of from 100 to 200°C.

The required rate of heat removal from the core is a strong function of both the core flow system used and the temperature limit established for the wall surface. In the worst example considered, maintaining the surface at 250°C with axial flow of the core fluid would require that the coolant be at 60°C . In the same system, the coolant temperature would need to be only 143°C if the wall were allowed to reach 275°C . Use of the directed-core-flow technique along with internal wall cooling would let the coolant be at 170°C for a 250°C wall temperature.

Thus the difficulty of meeting a specified temperature restriction depends to a large degree on whether a flow pattern can be achieved in which the inlet fluid moves along the wall at a high velocity, and under conditions such that there is little mixing of the hotter fluid near the center of the core with the cooler wall stream. The problem also depends, of course, on the power density in the wall and in the fuel fluid at its surface. In the particular examples considered, it was easier to limit the wall temperature in the Case 3 and 4 reactors because their power densities were generally lower than those in the other two systems. However, the advantages of a lower power density obtained by enlarging the core or altering its shape must be balanced against changes in breeding ratio, fuel inventory, and other economic considerations.

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