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TSR-II HEAT TRANSFER

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The temperature distribution in the fuel elements of the TSR-II has been calculated for a measured power distribution for the nominal operating conditions of a power level of 2 MW and a total cooling-water flow rate of 800 gpm. The distribution was also obtained for operation at a 3-MW power level and a total flow rate of 400 gpm. Under the latter conditions the maximum fuel plate temperature was 258°F, well below the saturation temperature of the water in the core, which is 283°F at the minimum core pressure of 36.5 psig.

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INTRODUCTION

The criterion for acceptable heat transfer in the TSR-II core (see Fig. 1) is that the surface temperature of the fuel plate be maintained below the saturation temperature of water at every point in the core. Initially, calculations based on the predicted thermal-flux distribution were performed^{1,2} to estimate the flow distributions required to suppress boiling at the plate walls, and a number of orifice plates were tested to determine the best design and location for obtaining the distributions in the various regions of the core.³ Later foil measurements were made of actual thermal-flux distribution in the core. Based on these measurements and on nuclear calculations of the final core geometry, the power distribution for each fuel plate in the core was obtained for clean-cold and end-of-life conditions⁴ (see Figs. 2 and 3). These new data have been used with the results of final coolant flow distribution tests⁵ to evaluate the heat transfer in the TSR-II.

The TSR-II core is divided into two major concentric regions (see Fig. 1). Coolant water flows at a total rate in excess of 800 gpm down through the central region and turns and makes a second pass upward through the outer region. The central first-pass region is divided into an upper section and a lower section, which are separated by a control mechanism housing. There are 41 principal channels for coolant flow in both the upper and lower sections of the first-pass region, and 33 principal channels in the second-pass region. These channels form parallel flow paths between plenums at the ends of the fuel elements, and in cross section they are high-aspect-ratio rectangles.

Fig. 1. Tower Shielding Reactor II (Vertical Section).

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Fig. 2. Power Generation Distribution in the Fuel Plates of a TSR-II Central Element as a Function of the Distance from the Inside Edge to the Fuel.

Fig. 3. Power Generation Distribution in the Fuel Plate of a TSR-II Annular Element as a Function of the Distance from the Horizontal Midplane to the Edge of the Fuel.

Since the factors affecting heat transfer are similar for the upper and lower regions of the first pass, only the calculations for the upper region are discussed in detail. The factors affecting heat transfer for the annular fuel elements, as well as those for the fuel-loaded cover plates on the control mechanism housing, differ from the heat-transfer factors for the upper and lower fuel regions and are therefore discussed separately.

ANNULAR FUEL ELEMENTS

The flow distribution in the annular fuel elements was measured in the reactor for a total cooling-water flow rate of 1000 gpm but without the first pass fuel in place and is shown as curve A in Fig. 4.

The temperature distribution in the annular fuel elements was calculated for a nominal power of 2 MW and a total cooling-water flow rate of 800 gpm which was distributed through the cooling channels as shown by curve B, which was obtained by proportionally reducing curve A (curve C was similarly obtained). Calculations were also performed for 3-MW operation of the reactor and a cooling-water flow rate of 400 gpm (see curve C), i.e., for a power of $1\frac{1}{2}$ times nominal and half the total cooling-water flow rate.

Early flow studies by the Engineering Research Group of the Reactor Projects Division indicated that the cooling-water flow in the annular fuel elements would be for the most part in the transition region. Tests by this same group on one channel of an annular element³ indicated that the transition from turbulent flow to laminar flow develops smoothly, as is shown in Fig. 5, a plot of the friction factor vs Reynolds number.

Fig. 4. Flow Through the Cooling Channels of a TSR-II Annular Fuel Element.

Fig. 5. Reynolds Modulus vs. Friction Factor.

Therefore operation in any regime is acceptable if the plate temperature is low enough.

Method of Calculation

To obtain the temperature of a point on the surface of an annular element, it was necessary to determine the temperature rise of the cooling water through the first-pass region and along the plate in question and then to calculate the temperature in the boundary region adjacent to the fuel plate. Since the flow regime in the annular elements may vary from laminar to turbulent, correlations that give satisfactory results in each flow regime were used.

The reactor cooling-water temperature at the entrance of the reactor was taken to be 125°F. The temperature rise through the first-pass region was calculated from

$$\Delta t = \frac{Q}{Gc} \text{ } ^\circ\text{F}, \quad (1)$$

where

Q = total heat generation rate in the first-pass fuel, Btu/hr,

G = total mass flow rate, lb/hr,

c = specific heat of water, Btu lb⁻¹(°F)⁻¹.

The first step in calculating the rise in the bulk-water temperature along a cooling channel in an annular element was to integrate graphically under the heat generation curves of Fig. 3 as follows:

$$q_z = b \int_0^z \frac{q}{A} dz \text{ Btu/hr}, \quad (2)$$

where

$\frac{q}{A}$ = local heat generation along the plate as given in Fig. 3,
Btu hr⁻¹ft⁻²,

b = width of heat-producing surface of the fuel plate, ft,

q_z = total heat transferred from the fuel plate from the
entrance to point z, Btu/hr.

The temperature rise of the cooling water in the channel to a point
z is

$$\Delta t = \frac{q_z}{Gc} \text{ } ^\circ\text{F}, \quad (3)$$

and the surface temperature (t_w) of the fuel element is

$$t_w = t_z + \frac{q}{2Ah} \text{ } ^\circ\text{F}, \quad (4)$$

where

t_z = mixed mean water temperature at point z, $^\circ\text{F}$,

$\frac{q}{2A}$ = heat flux that must be transferred across one surface
of the plate to the bulk water at point z, Btu hr⁻¹ft⁻²,

h = the heat transfer coefficient which satisfies the condi-
tions at point z, Btu hr⁻¹ft⁻²($^\circ\text{F}$)⁻¹.

Although the flow in most channels is in the transition flow regime, it may vary to the laminar or turbulent regime; therefore heat-transfer correlations for all three regimes were used to obtain values for the coefficient of heat transfer for the hottest channel for nominal conditions. The correlation used for the abnormal conditions was the one which gave the most conservative values for the nominal calculations.

For turbulent flow the Colburn j-factor analogy⁶ was used to obtain heat-transfer coefficients from the data of Fig. 5 and the relationship

$$j = \frac{h}{c_p \frac{G}{A}} N_{Pr}^{2/3} = f/2, \quad (5)$$

where

G = flow rate, lb/hr,

A = flow area, ft²,

c_p = specific heat of water at constant pressure, Btu lb⁻¹(°F)⁻¹,

N_{Pr} = Prandtl number, $\frac{c_p \mu}{k}$, at film temperature,

μ = viscosity of water, lb hr⁻¹ft⁻¹,

k = thermal conductivity, Btu hr⁻¹ft⁻²(°F/ft)⁻¹.

The j-factor analogy was used to determine the temperature at the midlength of annular fuel plates for the nominal condition of 2-MW operation and 800-gpm cooling-water flow rate, as shown in Fig. 6. Calculations of the surface temperature along the channel with the highest midpoint temperature were then made, and the surface temperature was plotted in Fig. 7. Similar calculations were made for 3-MW operation, and the effect on the midlength temperatures of reducing the cooling-water flow from 800 to 400 gpm is shown in Fig. 8.

The Nusselt number is related to the heat-transfer coefficient as follows:

$$h = N_{Nu} \frac{k}{D} \text{ Btu hr}^{-1}\text{ft}^{-2}(\text{°F})^{-1}, \quad (6)$$

Fig. 6. Fuel Plate Surface and Bulk Water Temperatures as a Function of Plate Number for a TSR-II Annular Fuel Element.

Fig. 7. Temperature Distribution Along TSR-II Annular Fuel Plate 53.

Fig. 8. Temperature Distribution Along TSR-II Annular Fuel Plate 45.

where D = equivalent diameter of channel, ft (2 times the channel width for high-aspect-ratio flat channels).

Correlations which define the average Nusselt number for transition and turbulent flow have been developed. An equation developed by Hausen from experimental data is reported to give satisfactory results for transition flow.⁷ His equation for the average Nusselt number is

$$\overline{N_{Nu}} = 0.116 \left(N_{Re}^{2/3} - 125 \right) N_{Pr}^{1/3} \left[1 + \left(\frac{D}{z} \right)^{2/3} \right] \left(\frac{\mu_b}{\mu_w} \right)^{0.14} z, \quad (7)$$

where

z = distance along the channel under consideration, ft,

N_{Re} = average Reynolds number over z , $\frac{DG}{\mu_a}$,

N_{Pr} = average Prandtl number over z , $\frac{c_p \mu}{k}$,

$\overline{N_{Nu}}$ = average Nusselt number over z , $\frac{hD}{k}$,

μ_b, μ_w = water viscosities at mixed mean water temperature and fuel plate surface temperature, respectively,

b = bulk (mixed mean) value,

w = fuel surface.

The local Nusselt number derived from the above is¹

$$N_{Nu} = 0.116 N_{Pr}^{1/3} \left(N_{Re}^{2/3} - 125 \right) \left[1 + \frac{1}{3} \left(\frac{D}{z} \right)^{2/3} \right], \quad (8)$$

where N_{Re} and N_{Pr} are average over the length z . The temperature distribution along the hottest channel for nominal conditions calculated from this equation would be slightly higher than those obtained from the j -factor analogy.

Gambill and Bundy have modified the above equation to correlate with HFTR data⁸ as follows:

$$N_{Nu_{bz}} = 0.105 \left[(N_{Re_{bz}})^{2/3} - 125 \right] (N_{Pr_{bz}})^{1/3} \left[1 + \frac{1}{3} \left(\frac{D}{z} \right)^{2/3} \right] \left(\frac{\mu_b}{\mu_w} \right)_z^{0.14}, \quad (9)$$

which gives a small increase in the maximum temperature as shown in Fig. 7.

The Hausen equation which is reported to account for thermal and hydrodynamic entrance effects under laminar flow conditions is⁹

$$\overline{N_{Nu}} = \left[3.65 + \frac{0.0668 \frac{D}{z} N_{Re} N_{Pr}}{1 + 0.04 \left(\frac{D}{z} \frac{N_{Re} N_{Pr}}{z} \right)^{2/3}} \right] \left(\frac{\mu_b}{\mu_w} \right)_z^{0.14}. \quad (10)$$

The value of 3.65 can be changed to 3.75¹⁰ for flat plate channels and the local Nusselt number derived as

$$N_{Nu} = \left(\frac{\mu_b}{\mu_w} \right)_z^{0.14} \left[\frac{2K_1 \frac{D}{z}}{1 + 0.04 K_2 \left(\frac{D}{z} \right)^{2/3}} - \frac{0.0267 K_1 K_2 \left(\frac{D}{z} \right)^{5/3}}{1 + 0.04 K_2 \left(\frac{D}{z} \right)^{2/3}} + 3.75 \right], \quad (11)$$

where $K_1 = 0.0668 N_{Re} N_{Pr}$, $K_2 = (N_{Re} N_{Pr})^{2/3}$, and N_{Re} and N_{Pr} are average moduli over the length z .

The results obtained with this equation for the temperature distribution in the hottest channel for the nominal case are shown as the highest

values on Fig. 7. This equation was also used to calculate for the abnormal conditions of 3-MW power level and 400-gpm total cooling-water flow rate the temperatures at the midlength of each fuel plate (see Fig. 8) and the temperature distribution along the hottest channel under these conditions (see Fig. 9).

UPPER FUEL REGION

For the studies presented here the reactor power was assumed to be 3 MW, with roughly one-third of the total reactor heat generated in the upper fuel and the same amount generated in the lower fuel. The average velocity of the cooling water in each channel of the first pass, assuming a total flow of 800 gpm, is 1.80 fps. When the total thermal power is 3 MW, the power generated in the upper section is 520 kW. Assuming that the temperature at the exit of a channel is the mixed mean for all channels, the Reynolds modulus for a nominal channel width of 0.120 in. is 5600 at the inlet to the upper section and about 5900 at the exit.

These values of the Reynolds modulus place the flow regime in the transition region³, where the modified Hausen equation for transition flow (9) can be used.

The cases calculated and the resulting peak wall temperatures are as follows:

1a. Nominal Case

First-pass inlet temperature	125°F
Average water velocity in channel	1.69 fps
Coolant channel width	0.12 in. (0.01 ft)
Equivalent diameter (D)	0.02 ft

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Fig. 9. Space Temperature at the Mid-Length of the Plates of a TSR-II Annular Element for Two Cooling Water Flow Rates.

Channel exit temperature	130°F
D/z for longest channel (channel 40)	0.0266
Heat flux (burnout case) at 3 MW	20,760 Btu hr ⁻¹ ft ⁻²
N _{Re} at exit	5900
N _{Nu_{bz}}	31.94 $\left(\frac{\mu_b}{\mu_w}\right)_z^{0.14}$
h	602 $\left(\frac{\mu_b}{\mu_w}\right)_z^{0.14}$ Btu hr ⁻¹ ft ⁻² (°F) ⁻¹
Δt	34.5°F
t _w	164.5°F

1b. Slow and Hot Channel

First-pass inlet temperature	125°F
Average water velocity in channel	0.80 fps
Coolant channel width	0.12 in. (0.01 ft)
Equivalent diameter	0.02 ft
Channel exit temperature	140°F
D/z for longest channel (channel 40)	0.0266
Heat flux (burnout case) at 3 MW	20,760 Btu hr ⁻¹ ft ⁻²
N _{Re}	3050
N _{Nu_{bz}}	13.55 $\left(\frac{\mu_b}{\mu_w}\right)_z^{0.14}$
h	258 $\left(\frac{\mu_b}{\mu_w}\right)_z^{0.14}$ Btu hr ⁻¹ ft ⁻² (°F) ⁻¹
Δt with $(\mu_b/\mu_w)_z^{0.14} = 1.045$	77°F
t _w with $(\mu_b/\mu_w)_z^{0.14} = 1.045$	217°F

1c. Constricted and Hot Channel

First-pass inlet temperature	125°F
Average water velocity in channel	1.18 fps
Coolant channel width	0.06 in. (0.005 ft)
Equivalent diameter	0.01 ft
Channel exit temperature	140°F
D/z for longest channel (channel 40)	0.0133
Heat flux (burnout case) at 3 MW	20,760 Btu hr ⁻¹ ft ⁻²
N _{Re}	2250
N _{Nu_{bz}} with $(\mu_b/\mu_w)_z^{0.14} = 1.045$	7.55
(both laminar and transition)	
h	$287 \left(\frac{\mu_b}{\mu_w}\right)_z^{0.14} \text{ Btu hr}^{-1}\text{ft}^{-2}(\text{°F})^{-1}$
Δt	72°F
t _w = 140 + 72	212°F

For cases 1b and 1c a viscosity correction of 1.045 was used, corresponding to a mixed mean water temperature of 140°F and a wall temperature of 170°F, which is a conservative correction.

In case 1c the flow regime borders on laminar. The local Nusselt number was therefore calculated both by the Hausen transition equation (8) and the Hausen laminar flow equation (11). The two values obtained were practically identical.

The consequences of water circulating within the channels of the first-pass region without sufficiently mixing with the cooler entering water were investigated.

One pass of water flowing at a velocity of 1.69 fps through channel 40, the channel with the greatest amount of heat generation in the first pass, produces a temperature rise of 6.57°F . A condition of the water temperature reaching 160°F , or five passes of the same volume of water without mixing, was investigated.

1d. Nominal Conditions Except for Number of Passes

First-pass inlet temperature	125°F
Average water velocity in channel	1.69 fps
Coolant channel width	0.12 in. (0.01 ft)
Equivalent diameter	0.02 ft
Channel exit temperature	160°F
D/z for longest channel (channel 40)	0.0266
Heat flux (burnout case) at 3 MW	$20,760 \text{ Btu hr}^{-1}\text{ft}^{-2}$
N_{Re}	7400
$N_{\text{Nu}_{\text{bz}}}$	38
h	$733 \left(\frac{\mu_b}{\mu_w} \right)^{0.14} \text{ Btu hr}^{-1}\text{ft}^{-2}(\text{F})^{-1}$
Δt without $\left(\frac{\mu_b}{\mu_w} \right)^{0.14}_z$ correction	28.4°F
t_w	188.4°F

The "slow channel" cases (1b and 1c) were also calculated for an exit temperature of 160°F and the following results were obtained:

1e. Slow and Hot Channel

N_{Re}	3515
$N_{\text{Nu}_{\text{bz}}}$	15.70

h	$320 \left(\frac{\mu_b}{\mu_w} \right)_z^{0.14} \text{ Btu hr}^{-1} \text{ ft}^{-2} (\text{°F})^{-1}$
Δt with $\left(\frac{\mu_b}{\mu_w} \right)_z^{0.14} = 1.07$	65°F
t_w	225°F
<u>1f. Constricted and Hot Channel</u>	
N_{Re}	2600
N_{Nu}	$9.4 \left(\frac{\mu_b}{\mu_w} \right)_z^{0.14}$
h with $\left(\frac{\mu_b}{\mu_w} \right)_z^{0.14} = 1.07$	$386 \text{ Btu hr}^{-1} \text{ ft}^{-2} (\text{°F})^{-1}$
Δt	54°F
t_w	214°F

For cases 1e and 1f the exit temperature of 160°F represents about three passes through channel 40.

All the values of the wall temperature obtained under these conditions are well below saturation of 283°F at the minimum reactor core pressure of some 36.5 psi when the reactor is operating at its maximum altitude.

From the heat-transfer standpoint the upper and lower fuel regions are analogous, and the several cases studied for the upper fuel are applicable to the lower region.

CONTROL MECHANISM HOUSING COVER PLATES

The four cover plates of the control mechanism housing are fuel-loaded, and generate heat at a uniform rate over the spherical surface. The plates are $1/8$ in. thick and contain a layer of uranium-aluminum alloy 0.034 in. thick, enclosed between two faces of 1100 aluminum, each 0.046 in. thick. The peak heat generation in the cover plates will be $60,600 \text{ Btu hr}^{-1} \text{ ft}^{-2}$ at 3 MW.⁴

The water that passes through the upper section of the first-pass region is directed downward directly at the surface of the cover plates. Over the upper hemisphere of the control mechanism housing, therefore, a highly turbulent stream of water flows. The velocity of this water increases as outer channels add more water, until it reaches a maximum value at the equator (see Fig. 1).

For the upper hemisphere the fuel region begins under channel 4 of the upper fuel elements. The velocity of the cooling water was taken as 2.36 fps, the average in the 1/4-in. passage between the cover shells and the fuel elements, and the Reynolds number was calculated to be 17,300. Equation 8, which provides reasonable agreement for both transition and turbulent flow, was used to obtain the local Nusselt number, with the D/z term taken as 1 because each point on the upper hemisphere is essentially an entrance point. The results of the heat transfer and temperature calculations are as follows:

$$\begin{array}{ll}
 N_{Nu} & 125 \left(\frac{\mu_b}{\mu_w} \right)^{0.14}_z \\
 h & 1130 \left(\frac{\mu_b}{\mu_w} \right)^{0.14}_z \text{ Btu hr}^{-1}\text{ft}^{-2}(\text{°F}) \\
 \Delta t \text{ (without viscosity correction)} & 54^{\circ}\text{F} \\
 t = 130 + 54 & 180^{\circ}\text{F}
 \end{array}$$

It is clear that at this point on the ball surface the temperature of the inside surface, from which no heat transfer was assumed, will remain within saturation. This follows after assuming a plane source of heat at the center of the fuel layer (actual half thickness, L_1 , of 0.017 in. which has a thermal conductivity, k_1 , of $97 \text{ Btu hr}^{-1}\text{ft}^{-2}(\text{°F/ft})^{-1}$)

and calculating the temperature along this plane required to drive the entire heat generation through the 0.046-in. cladding, L_2 , which has a thermal conductivity, k_2 , of $128 \text{ Btu hr}^{-1} \text{ ft}^{-2} (\text{°F/ft})^{-1}$.

$$Q = \frac{\Delta t}{\frac{L_1}{k_1} + \frac{L_2}{k_2}} = 60,600 \text{ Btu hr}^{-1} \text{ ft}^{-2}$$

This suggests that even the center of the fuel-bearing layer will be at a temperature below 187°F .

Several conditions are different for the lower hemisphere. The fuel extends closer to the vertical center line of the reactor but a higher velocity of cooling water (4.6 fps) passes the fuel, giving a Reynolds number of 33,700. The flow of water is directed away from the spherical surface but because of the high pressure drop across the lower baffle plate (about 8 psi at 750 gpm) and the apparent uniform velocity in all channels of the lower fuel elements, it is unlikely that there can be any flow separation from the lower ball surface. The D/z term is taken to be zero, which is equivalent to having established flow in long channels, or no benefit from entrance turbulence. The calculation of the heat transfer at the edge of the fuel region yielded the following:

temperature rise of water past spherical surface	0.7°F
N_{Nu}	$158 \left(\frac{\mu_b}{\mu_w} \right)^{0.14} z$

It is obvious that the heat transfer on this basis is even more favorable than at the upper edge of the spherical fuel.

The velocity for the lower hemisphere was calculated on the same basis as in the case of the upper hemisphere. An indication of the actual velocities was also obtained by the conductivity probe method. This confirmed an apparent positive flow downward around the ball at a radius corresponding to the innermost channels of the lower element and the outer channel of the centered cylindrical element.

In addition, the water that flows continuously through the five control mechanisms, amounting to about 10 gpm, is all directed downward within the control mechanism housing, which should provide some cooling within the ball.

SUMMARY OF RESULTS

The objectives of the study were to provide operating conditions which would insure that the fuel element surface temperatures everywhere were below the saturation temperature of the cooling water. Since the minimum pressure in the core is always greater than 36.5 psig during normal operation, the design saturation temperature was established as 283°F.

The maximum surface temperature of the fuel-loaded cover plates on the control mechanism housing for operation of the reactor at a 3-MW power level and a cooling-water flow rate of 800 gpm is 184°F. The maximum surface temperature of a TSR-II upper fuel element for various operating conditions is shown in Table 1 and of a TSR-II annular element in Table 2.

CONCLUSIONS

The values of fuel element surface temperature which were calculated from a measured power distribution for operation of the reactor at a power level of 3 MW and a cooling-water flow rate of 400 gpm are below 258°F,

TABLE 1. Maximum Surface Temperature of a TSR-II Upper Fuel Element for Operation of the Reactor at a Power Level of 3 MW for Various Flow Conditions

Case No.	Bulk-Water Temperature and Flow	Fuel Plate Temperature ($^{\circ}\text{F}$)
1a	Nominal velocity, 1.69 fps; exit temp., 130 $^{\circ}\text{F}$	164.5
1b	Slow and hot velocity, 80 fps; exit temp., 140 $^{\circ}\text{F}$	217
1c	Constricted and hot channel velocity, 1.18 fps; exit temp., 140 $^{\circ}\text{F}$	212
1d	Nominal conditions except water makes five passes through channel	188.4
1e	Slow and hot channel with water making approximately three passes through channel	225
1f	Constricted and hot channel with water making approximately three passes through channel	214

TABLE 2. Maximum Fuel Plate Surface Temperature for a TSR-II
Annular Element for Two Operating Conditions

Method of Calculation	Operating Conditions	
	2 MW, 800 gpm	3 MW, 400 gpm
Colburn j-factors (turbulent flow)	171°F	
Hausen equation for transition flow	173.4°F	
Modified Hausen equation for transition flow	174.6°F	
Hausen equation for entrance effects in laminar flow	195.0°F	258°F

which is the saturation temperature of water at 19.5 psig. With the reactor suspended at its maximum altitude above the ground level of 185 ft and the reactor cooling system operating normally, the minimum pressure in the core is 36.5 psig. For the indicated flow distribution in the core at a total cooling-water flow rate of 800 gpm, operation of the reactor at a power level of 5 MW would be possible from the heat-transfer standpoint if the reactor were operated at ground level, where the minimum core pressure is 60 psig. It seems clear, therefore, that from the heat-transfer standpoint operation of the reactor at a power level of 2 MW and a cooling-water flow rate of 800 gpm should be satisfactory up to 185 ft.

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