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WCAP-3270

YANKEE ATOMIC ELECTRIC COMPANY
RESEARCH and DEVELOPMENT PROGRAM

NUCLEAR AND THERMAL CALCULATIONS FOR WCAP-4
IN-PILE LOOP EXPERIMENT

by

A. Bournia

W. Eich

J. J. Lombardo

For The Yankee Atomic Electric Company
Under Research and Development Subcontract
No. 1 of USAEC-YAEC Contract AT(30-3)-222

WESTINGHOUSE ELECTRIC CORPORATION
ATOMIC POWER DEPARTMENT

PITTSBURGH, 30

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Yankee Atomic Electric Company
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IN-PILE LOOP EXPERIMENT

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NUCLEAR AND THERMAL CALCULATIONS FOR WCAP-4 IN-PILE LOOP EXPERIMENT

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NUCLEAR AND THERMAL CALCULATIONS FOR WCAP-4 IN-PILE LOOP EXPERIMENT

INTRODUCTION

The purpose of this report is to provide a description of the nuclear and thermal analysis involved in the design of the WCAP-4 in-pile test. Prior to the detailed nuclear and thermal analysis by the authors of this report, thermal flux plots as a function of discrete positions with respect to the reflector top and specified reflector blocks during MTR cycle 93 were furnished by MTR personnel. These data made possible the numerical evaluation of "high" leg and "low" leg thermal fluxes. In another preliminary calculation, the computation of peak perturbed flux at a pellet-edge, it was necessary to make simplifying but reasonable assumptions regarding both material volume fractions and the nature and magnitude of the thermal neutron source. Other nuclear analytical computations were straight-forward. This analysis ultimately led to enrichment specifications for the UO_2 in the fuel rod samples such that the peak heat flux through the clad surface will be 4.5×10^5 Btu/ft² hr. The particular specifications follow:

	<u>"High Flux" Leg</u>	<u>"Low Flux" Leg</u>
Enrichment (%)	10	27

Figure 1 summarizes graphically the over-all results of the nuclear analysis. Section G defines all symbols in the order of their appearance. This section also specifies them numerically or as algebraic functions of enrichment.

Basic thermal flux data (furnished by MTR personnel, Figures 2 and 3) for cycle 93 enabled the computation of heat production as a function of neutron flux. It was also possible to calculate pertinent heat transfer data. In each case, sample calculations are given.

Figure 1. Maximum Clad Surface Heat Flux vs. Enrichment (λ) in In-Pile Specimens

Burn-out calculations reveal that no burnout conditions are expected at the operating heat fluxes. An analytically derived relationship was used to fix the central core temperature at 4137.5°F. The maximum heat output per unit length of specimen was found to be 2795 watts/in.

Various hot spot factor calculations for both non-local and local boiling conditions are given.

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NUCLEAR AND THERMAL CALCULATIONS FOR WCAP-4 IN-PILE LOOP EXPERIMENT

I NUCLEAR CALCULATIONS

A. Basic Data

MTR personnel provided graphs showing thermal flux values obtained during cycle 93 vs distance from the top of the reflector at several discrete positions in the A-13 and A-14 reflector blocks. These two blocks adjoin the B-1 block; the latter is to be replaced by a piece of aluminum of identical size and shape which will contain the U-shaped sample - holding section of the WCAP-4 test loop. These flux plots indicated no variation in an East-West line. Their maximum values were replotted versus distance along a North-South line; the flux increases with distance North, i.e., with distance decreasing from the core. From this plot were obtained the magnitudes of unperturbed flux whose positions on the North-South line coincided with the northermost possible location - one for each leg - of fuel rod edges. These magnitudes and locations are provided below:

Unperturbed Thermal Flux ($10^{13} \text{ cm}^{-2} \text{ sec}^{-1}$)

"High Leg: 4.35

"Low" Leg: 2.85

At respective locations (inches North from the South side of the B-1 block)

3-5/16

1-3/4

B. Qualitative Description of the Calculations

(a) Determination of the Peak Perturbed Thermal Flux Available at the Edge of a Fuel Pellet

A two-group two-region calculation of neutron diffusion in one dimensional cylindrical geometry was used in this phase of the calculation. The nuclear properties of the central region were obtained by homogenizing the representative materials within the hole containing each leg. The volume fractions of these materials were assumed to be the same as the

area fractions in a transverse slice through the middle of a fuel assembly. These fractions took into account the void around the pressurized pipe. This central region - capable of neutron multiplication - was assumed to be surrounded by an aluminum region containing a constant source of thermal neutrons. This source was assumed to equal in magnitude the macroscopic cross section of aluminum times the value of unperturbed flux listed above corresponding to the leg under consideration. Coupled two-group diffusion equations for each region were set up and solved in terms of four unknown quantities; since the geometry was cylindrical, the solutions involved Bessel functions having arguments equal to the appropriate inverse diffusion lengths times the radius. Equating fast and thermal fluxes and currents at the interface between the two regions led to the construction of a fourth-order determinant having as its elements the coefficients of the four unknown constants. Solution of the determinant provided numerical amplitudes for those "r" - dependent Bessel functions whose sum represents the variation of thermal flux in the inner region. Setting "r" equal to the distance from the axial centerline of the leg to a point on a pellet circumference most distant (in the Northerly direction) from this centerline allowed the numerical determination of the peak perturbed flux at a pellet edge.

(b) Determination of Peak Heat Flux at the Clad Surface

The heat flux at the clad surface was now determined in a straight-forward manner. The centerline of the fuel rod itself was considered to be the center of a one-dimensional cylindrical coordinate system. The flux within the pellet in this coordinate system varies as a modified Bessel function of the first kind having as its argument the

radius times the inverse diffusion length within the UO_2 itself. Integrating the product of the flux times the macroscopic fission cross section of the UO_2 over the cross-sectional area of the pellet provided the power production per cm of pellet height. Dividing by the circumference of the clad and normalizing to engineering units resulted in the peak heat flux at the clad surface in units of $\text{Btu/ft}^2 \text{ hr}$.

C. Mathematical Details of the Calculation

(a) Determination of the Peak Perturbed Thermal Flux

Region 1: Central Multiplying Region Fractional Volumes:

Steel	0.2565
UO ₂	0.1122
Water	0.3220
Void	0.3095

Region 2: Region containing constant source of thermal flux was composed of Al surrounded by Be and process water test holes. Since the Fermi age of aluminum is so large, it was considered more realistic to use Beryllium fast and aluminum thermal constants in region 2. As can be seen from the two tables in section D, the choice of fast constants in region 2 is not critical since the increment in the ambient perturbed thermal flux due to fissions within the samples themselves is so small.

Two-Group Equations:^{*}

$$\begin{aligned} \text{Region 1: } (D_{f1} \nabla^2 - \Sigma_{r1}) \phi_{f1} + k \Sigma_{a1} \phi_{s1} &= 0 \\ (D_{s1} \nabla^2 - \Sigma_{a1}) \phi_{s1} + \Sigma_{r1} \phi_{f1} &= 0 \end{aligned}$$

$$\begin{aligned} \text{Region 2: } (D_{f2} \nabla^2 - \Sigma_{r2}) \phi_{f2} &= 0 \\ (D_{s2} \nabla^2 - \Sigma_{a2}) \phi_{s2} + \Sigma_{r2} \phi_{f2} + s &= 0 \\ s &= \Sigma_{a2} \phi_o \end{aligned}$$

ϕ_o = unperturbed flux

^{*} cf. Glasstone and Edlund, "Elements of Nuclear Reactor Theory," Ch. 8 for an analogous exposition

Solutions of Equations:

$$\text{Region 1: } \varphi_{f1} = C J_0 (\kappa_1 r) + D I_0 (\kappa_2 r)$$

$$\varphi_{s1} = \Gamma_0 C J_0 (\kappa_1 r) + \Gamma_1 D I_0 (\kappa_2 r)$$

where

$$\Gamma_0 = \frac{D_{f1} \kappa_{f1}^2}{D_{s1}} \frac{1}{\kappa_{s1}^2 + \kappa_1^2}; \quad \kappa_{s1}^2 = \frac{1}{L_1^2} = \frac{\Sigma_{a1}}{D_{s1}}$$

$$\Gamma_1 = \frac{D_{f1} \kappa_{f1}^2}{D_{s1}} \frac{1}{\kappa_{s1}^2 - \kappa_2^2}; \quad \kappa_{f1}^2 = \frac{1}{L_1^2} = \frac{\Sigma_{r1}}{D_{f1}}$$

$$\text{Region 2: } \varphi_{f2} = A K_0 (\kappa_{f2} r)$$

$$\kappa_{f2} = \sqrt{\frac{\Sigma_{r2}}{D_{f2}}} = \frac{1}{\sqrt{\tau_2}}$$

$$\varphi_{s2} = \Gamma_2 A K_0 (\kappa_{f2} r) + B K_0 (\kappa_{s2} r) + \varphi_0$$

$$\kappa_{s2} = \frac{\Sigma_{a2}}{D_{s2}} = \frac{1}{L_2}; \quad \Gamma_2 = \frac{\Sigma_{r2}}{\Sigma_{a2} - D_{s2} \kappa_{f2}^2}$$

Upon equating fast and slow fluxes and currents at the interface between regions, the following four linear equations result:

$$\Gamma_0 C J_0 (\kappa_1 R_0) + \Gamma_1 D I_0 (\kappa_2 R_0) = \Gamma_2 A K_0 (\kappa_{f2} R_0) + B K_0 (\kappa_{s2} R_0) + \varphi_0$$

$$C J_0 (\kappa_1 R_0) + D I_0 (\kappa_2 R_0) = A K_0 (\kappa_{f2} R_0)$$

$$-D_{s1} \left[-\Gamma_0 C \kappa_1 J_1 (\kappa_1 R_0) + \Gamma_1 D \kappa_2 I_1 (\kappa_2 R_0) \right] =$$

$$-D_{s2} \left[-\Gamma_2 A \kappa_{f2} K_1 (\kappa_{f2} R_0) - B \kappa_{s2} K_1 (\kappa_{s2} R_0) \right]$$

$$-D_{f1} \left[-C \kappa_1 J_1 (\kappa_1 R_0) + D \kappa_2 I_1 (\kappa_2 R_0) \right] = -D_{f2} \left[-A \kappa_{f2} K_1 (\kappa_{f2} R_0) \right]$$

The matrix representation of these equations is provided below:

$$\begin{vmatrix}
 -\Gamma_2 K_o (\kappa_{f2} R_o) & -K_o (\kappa_{s2} R_o) & \Gamma_o J_o (\kappa_1 R_o) & \Gamma_1 I_o (\kappa_2 R_o) \\
 -K_o (\kappa_{f2} R_o) & 0 & +J_o^* (\kappa_1 R_o) & +I_o (\kappa_2 R_o) \\
 -D_{s2} \Gamma_2 \kappa_{f2} K_1 (\kappa_{f2} R_o) & -D_{s2} \kappa_{s2} K_1 (\kappa_{s2} R_o) & +D_{s1} \Gamma_o \kappa_1 J_1 (\kappa_1 R_o) & -D_{s1} \Gamma_1 \kappa_2 I_1 (\kappa_2 R_o) \\
 -D_{f2} \kappa_{f2} K_1 (\kappa_{f2} R_o) & 0 & +D_{f1} \kappa_1 J_1 (\kappa_1 R_o) & -D_{f1} \kappa_2 I_1 (\kappa_2 R_o)
 \end{vmatrix}
 \begin{vmatrix}
 A \\
 B \\
 C \\
 D
 \end{vmatrix}
 =
 \begin{vmatrix}
 \phi_o \\
 0 \\
 0 \\
 0
 \end{vmatrix}$$

Solution of the preceding for the quantities, "C" and "D", allows the calculation of the peak flux available at a pellet edge:

$$\phi_{s1}(r_o) = \Gamma_o C J_o(\kappa_1 r_o) + \Gamma_1 D I_o(\kappa_2 r_o)$$

(b) Determination of the Peak Heat Flux

From elementary diffusion theory and with reference to a one-dimensional cylindrical coordinate system whose origin is at the axial centerline of the fuel pellet,

$$\phi(v) = \phi_{s1}(r_o) \times \frac{I_o(\kappa v)}{I_o(\kappa v_o)}$$

Consequently,

$$\text{Power} \left(\frac{\text{watts}}{\text{cm of pellet height}} \right) = \frac{\int_0^{v_o} \phi(v) \times \Sigma_f \times 2\pi v dv}{3.15 \times 10^{10}}$$

Finally,

$$Q/A \text{ (Btu/ft}^2\text{-hr)} = \frac{3.17 \times 10^3}{2\pi v'} \frac{\int_0^{v_o} \phi(v) \Sigma_f 2\pi v dv}{3.15 \times 10^{10}}$$

D. Over-all Results of the Calculation

The table following lists the particular enrichments considered in this analysis as well as the corresponding heat fluxes:

<u>Enrichment (%)</u>	<u>Q/A (10⁵ Btu/ft²-hr.)</u>	
	<u>"High" Leg</u>	<u>"Low" Leg</u>
6.8	3.38	2.21
8.5	4.03	2.64
9.3	4.30	2.81
10.3	4.61	3.02
11.8	5.07	3.32
13.3	5.41	3.55
30.0	7.06	4.62

The curves on figure 1 are based on the above data.

E. Effect of Neutron Regeneration

To illustrate the magnitude of the contribution to the heat flux due to neutron regeneration within the samples themselves, the next short table has been provided. It contains a set of data similar to the above but based on one-group diffusion theory in the same geometry:

<u>Enrichment (%)</u>	<u>Q/A (10⁵ Btu/ft²-hr.)</u>	
	<u>"High" Leg</u>	<u>"Low" Leg</u>
4	2.19	1.43
5.4	2.79	1.83
6.8	3.34	2.19
13.3	5.22	3.42

Comparison of the heat fluxes for the last two enrichments to the corresponding heat fluxes listed in the table of section D allows one to gauge the regeneration effect.

Further, since the thermal flux due to regeneration varies with radial distance as a descending exponential while the unperturbed thermal flux increases rapidly with lessened distance from the active part of the reactor, this incremental flux, negligible at the samples, is relatively nil at the core edge. This shows that there is no nuclear coupling of the experiment to the core of the MTR.

F. Slight Modifications of Pellet and Clad Diameters

Since this calculation was performed and the enrichments were specified, there has been a change in the diameter of the fuel pellet, and it has been decided to test another clad thickness. The table below summarizes these minor changes.

	Pellet Diameter (in.)	Clad Thickness (in.)	Clad O.D. (in.)
Preceding Calculation	.290	.021	.337
Actual Thin Clad Samples	.294	.015	.324
Actual Thick Clad Samples	.294	.021	.336

By simply scaling the transverse areas, it is seen that the total heat produced per unit height of pellet will be 2.8% greater for the new design. Then, by scaling the circumferences, it is seen that the following changes in the heat flux will be produced:

- a. The peak heat flux will be 3% greater than 4.5×10^{-5} Btu/ft²-hr. through the surface of the new 21 mil clad samples.

- b. The peak heat flux will be 7% greater than 4.5×10^5 Btu/ft²-hr. through the surface of the new 15 mil clad samples.

These changes in the calculated value of peak heat flux are insignificant in view of the range over which the unperturbed flux at any point will vary during a core cycle.

G. Table of Nomenclature and Numerical Values

D = Diffusion coefficient, cm

D_{f2} = 0.6333 cm.

D_{s2} = 3.838 cm.

D_{f1} = 1.718 cm.

D_{s1} = $\Sigma_{a1} / \kappa_{s1}^2$

Σ_r = Cross section for removal from fast group, cm⁻¹.

Σ_{r1} = 0.009455

Σ_{r2} = 0.006445

ϕ = Neutron flux, cm⁻² sec⁻¹; subscripts determine region and group.

k = Infinite multiplication constant.

= $2.08 \Sigma_{a1}^{25} / \Sigma_{a1}$

Σ_a = Thermal absorption cross section, cm⁻¹.

$\Sigma_a^{UO_2}$ = $0.1122 \times [13.54 \times \lambda + 0.05435 (1-\lambda)]$

Σ_{a1}^{25} = $0.1122 \times 13.54 \times \lambda$

Σ_{a1} = $0.0942 + \Sigma_a^{UO_2}$

Σ_{a2} = 0.01229

κ = Inverse diffusion length, cm⁻¹.

$$\kappa_1^2 = \frac{1}{2} \left[-(\kappa_{f1}^2 + \kappa_{s1}^2) + \sqrt{(\kappa_{f1}^2 + \kappa_{s1}^2) + 4\kappa_{f1}^2 \kappa_{s1}^2 (k-1)} \right]$$

$$\kappa_2^2 = \frac{1}{2} \left[+(\kappa_{f1}^2 + \kappa_{s1}^2) + \sqrt{(\kappa_{f1}^2 + \kappa_{s1}^2) + 4\kappa_{f1}^2 \kappa_{s1}^2 (k-1)} \right]$$

$$\kappa_{f1} = 0.07419 \text{ cm}^{-1}.$$

$$\kappa_{s1}^2 = 3 \Sigma_{al} \Sigma \left[1 - 0.8 \frac{\Sigma_{al}}{\Sigma} + \frac{4}{175} \left\{ \left(\frac{\Sigma_{al}}{\Sigma} \right)^2 + \left(\frac{\Sigma_{al}}{\Sigma} \right)^3 \right\} \right]$$

$$\Sigma = \Sigma_{al} + \Sigma_{tr}$$

$$\Sigma_{tr} = \text{Macroscopic transport cross section, cm}^{-1}.$$

$$\Sigma_{tr} = 0.7286 \text{ cm}^{-1}.$$

$$\kappa_{s2} = 0.05659 \text{ cm}^{-1}.$$

$$\kappa_{f2} = 0.1009 \text{ cm}^{-1}$$

$$\Gamma = \text{Coupling coefficient}$$

$$\Gamma_0 = 0.02241 \times \frac{1}{\kappa_{s1}^2 + \kappa_1^2}$$

$$\Gamma_1 = 0.02241 \times \frac{1}{\kappa_{s1}^2 - \kappa_2^2}$$

$$\Gamma_2 = -0.01719$$

$$r_0 = \text{Distance from leg centerline to most distant point on a pellet edge, cm.}$$

$$r_0 = 1.03 \text{ cm.}$$

$$v = \text{Radial distance measured from fuel rod centerline, cm.}$$

$$v_0 = \text{Fuel pellet radius, cm.}$$

$$v_0 = 0.3683 \text{ cm.}$$

$$\Sigma_f = \text{Fission cross section of pellet, cm}^{-1}$$

$$\Sigma_f = 13.54 \times \lambda \times \frac{2.07}{2.47}$$

$$v' = \text{Outside radius of clad, cm.}$$

$$v' = 0.428 \text{ cm.}$$

II THERMAL CALCULATIONS

A. Basic Data

Graphs of neutron flux as a function of the distance from top of reflector through the core for the A-14 NW and NE and SE positions were furnished by MTR personnel as basic data for the thermal heat output and other calculations that follow. For each type calculation presented, a sample computation is given.

From heat transfer test data, information will be obtained as to how fuel pins will withstand the high heat flux of 450,000 Btu/hr ft², pressure of 2000 psia, and temperature of 500 to 600°F. These conditions are anticipated in the Yankee reactor.

Figure 2

SECOND LEG

A-14 NW & NE POSITION
40MW FLUX RUN - UNPERTURBED
NORMALIZED FOR CYCLE 93
9/18/57

Figure 3

TABLE I

Basic Heat-Neutron Flux Data

No.	$\Phi \times 10^{13}$ n/cm ² -sec	Q/A $\times 10^5$ Btu/hr-ft ²	Length of Pin in Flux, in.	Heat Given Off at Increment Q $\times 10^5$ Btu/hr	Total Heat Given Off Q $\times 10^5$ Btu/hr
1	1.100	2.48	1	0.0526	0.0526
2	1.195	2.69	1	0.0571	0.1097
3	1.290	2.90	1	0.0615	0.1712
4	1.382	3.11	1	0.0660	0.2372
5	1.492	3.36	1	0.0713	0.3085
6	1.590	3.58	1	0.0759	0.3844
7	1.705	3.84	1	0.0814	0.4658
8	1.820	4.10	1	0.0870	0.5528
9	1.916	4.31	1	0.0914	0.6442
10	1.980	4.46	1	0.0946	0.7388
11	2.000	4.50	1	0.0954	0.8342
12	1.995	4.49	1	0.0952	0.9294
13	1.950	4.39	1	0.0931	1.0225
14	1.890	4.25	1	0.0901	1.1126
15	1.825	4.11	1	0.0872	1.1998
16	1.740	3.92	1	0.0831	1.2829
17	1.645	3.70	1	0.0785	1.3614
18	1.540	3.47	1	0.0736	1.4350
19	1.405	3.16	1	0.0670	1.5020
20	1.265	2.85	1	0.0604	1.5624
21	1.100	2.48	0.8	0.0421	1.6045
22	1.23	1.38	1	0.0304	1.6349
23	1.45	1.63	1	0.0360	1.6707
24	1.68	1.89	1	0.0417	1.7126
25	1.90	2.14	1	0.0472	1.7598
26	2.10	2.36	1	0.0521	1.8119
27	2.31	2.60	1	0.0574	1.8693
28	2.50	2.81	1	0.0620	1.9313
29	2.74	3.08	1	0.0679	1.9992
30	2.92	3.24	1	0.0726	2.0718
31	3.12	3.51	1	0.0774	2.1492
32	3.30	3.71	1	0.0818	2.2310
33	3.50	3.94	1	0.0869	2.3179
34	3.70	4.16	1	0.0918	2.4097
35	3.88	4.37	1	0.0964	2.5061
36	3.96	4.46	1	0.0984	2.6045
37	4.0	4.5	1	0.0993	2.7038
38	4.0	4.5	1	0.0993	2.8031
39	4.0	4.5	1	0.0993	2.9024
40	4.0	4.5	1	0.0993	3.0017
41	4.0	4.5	1	0.0993	3.1010
42	4.0	4.5	1	0.0993	3.2003
43	4.0	4.5	1	0.0993	3.2996
44	3.95	4.44	1	0.0979	3.3975
45	3.85	4.33	1	0.0995	3.4930
46	3.73	4.20	1	0.0927	3.5851
47	3.53	3.97	1	0.0876	3.6733
48	3.35	3.77	1	0.0832	3.7565
49	3.10	3.49	1	0.0770	3.8335
50	2.85	3.21	0.8	0.0566	3.8901

B. Calculated Data

(a) Sample Calculations for Table of Heat Transfer Data

$$\begin{aligned} \left(\frac{Q}{A}\right)_x &= \frac{450,000}{\Phi_m} \quad \Phi_x & (1) \\ &= \frac{450,000}{2} \quad 1.1 \\ &= 2.48 \times 10^5 \text{ Btu/hr ft}^2 \end{aligned}$$

For the first leg,

$$\frac{\text{surface area of 3 pins}}{\text{length}} = \frac{3 (0.324) (1)}{144} = 0.02121 \text{ ft}^2/\text{in}$$

$$\begin{aligned} Q_x &= (2.48 \times 10^5) (0.0212) (1) \\ &= 0.0526 \times 10^5 \text{ Btu/hr} \end{aligned}$$

Since the outlet temperature, total heat output, and velocity through the specimens of the loop is set, the inlet temperature can be calculated.

$$\text{Velocity} = 10.3 \text{ ft. per sec}$$

$$Q = 3.8901 \times 10^5 \text{ Btu/lb}$$

$$\text{Assume } T_{\text{avg}} = 560^\circ\text{F}$$

$$Q = W\Delta H \quad (2)$$

$$\Delta H = \frac{(3.8901 \times 10^5)(144)(0.02173)}{(0.303)(10.3)(3600)}$$

$$= 108.3 \text{ Btu/lb}$$

$$H_{\text{in}} = 614.5 + 108.3 = 506.2 \text{ Btu/lb } 516^\circ\text{F}$$

$$H_{\text{avg}} = 506.2 + \frac{108.3}{2} = 506.4 \text{ Btu/lb } 560^\circ\text{F}$$

$$\text{at } T_{\text{avg}} = 560^\circ\text{F } c_p = 1.278 \text{ Btu/lb } ^\circ\text{F } k = 0.3256 \text{ Btu/hr ft } ^\circ\text{F } \mu = 0.231 \text{ lb/hr ft}$$

$$v = 0.02173 \text{ ft}^3/\text{lb } D_e = 0.01651 \text{ ft.}$$

Because both the total heat output and the heat flux along the specimens is known, the surface temperature can be determined, see Table II and following calculations:

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$$\begin{aligned}
 h &= \frac{(0.023) K}{D_e} \left[\frac{D_e \rho S}{\mu} \right]^{0.8} \left[\frac{c_p \mu}{K} \right]^{0.4} \quad (3) \\
 &= \frac{(0.023)(0.3256)}{0.01651} \left[\frac{(0.01651)(10.3)(3600)}{(0.231)(0.02173)} \right]^{0.8} \left[\frac{(1.278)(0.231)}{0.3256} \right]^{0.4} \\
 &= 5252
 \end{aligned}$$

$$Q/A = h \Delta t \quad (4)$$

$$\begin{aligned}
 \Delta t &= \frac{2.48 \times 10^5}{5252} \\
 &= 47.2^\circ \text{F}
 \end{aligned}$$

$$\begin{aligned}
 T_s &= T_w + \Delta t \quad (5) \\
 &= 517.2 + 47.2 \\
 &= 564.4^\circ \text{F}
 \end{aligned}$$

To determine whether local boiling exists at any point across the rods, the Jens and Lottes equation is used:

$$T_s - T_{\text{sat}} = \frac{60 \left[Q/A / 10^6 \right]^{0.25} \star}{e P / 500} \quad (6)$$

$$\begin{aligned}
 T_s - 635.8 &= \frac{(60)(0.248)^{0.25}}{e \frac{2000}{900}} \\
 &= \frac{(60)(0.7057)}{9.2276}
 \end{aligned}$$

$$T_s - 638.5 = 4.6$$

$$T_s = 640.4^\circ \text{F}$$

Hence, local boiling exists at a point when the surface temperature determined by the Jens and Lottes equation (6) is less than the surface temperature determined by Newton's equation (4). From the calculations, it is indicated that approximately 35% of the surface will be in local boiling and will only occur in the second leg of the loop, see Figure 4.

^{*} Jens, W. H. and Lottes, P. A., "Analysis of Heat Transfer, Burnout, Pressure and Density Data for High Pressure Water," ANL-4627, May 1951.

Figure 4

Figure 5

Figure 6

Figure 7

(b)

TABLE II
Table of Heat Transfer Data

No.	ΔH Btu/lb	H Btu/lb	T_w °F	Δt °F	T_s °F	Local Boiling Surface Temperature, °F	(Q/A) B.O. $\times 10^6$ Btu/hr ft ²
		506.2	516				
1	1.5	507.7	517.2	47.2	564.4	640.4	1.358
2	3.1	509.3	518.5	51.2	569.7		1.339
3	4.8	511.0	520	55.2	575.2		1.320
4	6.6	512.8	521.5	59.2	580.7		1.301
5	8.6	514.8	523.2	64.0	587.2		1.281
6	10.7	516.9	524.9	68.2	593.1		1.260
7	13.0	519.2	526.8	73.1	599.9		1.238
8	15.4	521.6	528.8	78.1	606.9		1.217
9	17.9	524.1	530.9	82.1	613.0		1.195
10	20.6	526.8	533.1	84.9	618.0		1.174
11	23.2	529.4	535.3	85.7	621.0		1.151
12	25.9	432.1	537.5	85.5	623.0		1.129
13	28.5	534.7	539.7	83.6	623.3	641.1	1.110
14	31.0	537.2	541.6	80.9	622.5		1.089
15	33.4	539.6	543.6	78.3	621.9		1.071
16	35.7	541.9	545.3	74.6	619.9		1.054
17	37.9	544.1	547.0	70.5	617.5		1.037
18	40.0	546.2	548.8	66.1	614.1		1.019
19	41.8	548.0	550.2	60.2	610.4		1.007
20	43.5	549.7	551.7	54.3	606.0		0.993
21	44.7	550.9	552.7	47.2	599.9		0.983
22	45.5	551.7	553.2	26.3	579.5		1.104
23	46.5	552.7	554.0	31.0	585.0		1.092
24	47.7	553.9	555.0	36.0	591.0		1.080
25	59.0	555.2	555.9	40.7	596.6		1.065
26	50.5	556.7	557.1	44.9	602.0		1.054
27	52.1	558.3	558.3	49.5	607.8		1.039
28	53.8	560.0	559.8	53.5	613.3		1.025
29	55.7	561.9	561.1	58.6	619.7		1.010
30	57.7	563.9	653.7	62.6	625.3		0.996
31	59.9	566.1	564.2	66.8	631.0		0.980
32	62.1	568.3	566.0	70.6	636.6	640.9	0.964
33	64.6	570.8	568.0	75.0	643.0	641.0	0.949
34	57.1	573.3	570.0	79.2	649.2	641.0	0.932
35	69.8	576.0	572.0	83.2	644.2	641.1	0.916
36	72.5	578.7	574.0	84.9	658.9	641.1	0.900
37	75.3	581.5	576.1	85.7	661.8	641.1	0.883
38	78.1	584.3	578.2	85.7	663.9	641.1	0.867
39	80.8	587.0	580.1	85.7	665.8	641.1	0.853
40	83.6	587.8	582.2	85.7	667.9	641.1	0.838
41	86.4	592.6	584.4	85.7	670.1	641.1	0.823
42	89.1	595.3	586.2	85.7	671.9	641.1	0.908
43	91.9	598.1	588.3	85.7	674.0	641.1	0.794
44	94.6	600.8	590.2	84.5	675.0	641.1	0.780
45	97.3	603.5	592.3	82.4	674.7	641.1	0.767
46	99.9	606.1	594.0	80.0	674.0	641.0	0.754
47	102.3	608.5	595.9	75.6	671.5	641.0	0.742
48	104.6	610.8	597.5	71.8	669.3	640.9	0.731
49	106.8	613.0	599.0	66.5	665.5	640.8	0.720
50	108.3	614.5	600.0	61.1	661.1	640.7	0.712

(c) Burnout Calculations

To calculate the burnout heat flux, the following correlation was used:

$$\left(\frac{Q}{A}\right)_{B.O.} = 0.28 \left[\frac{H_{B.O.}}{10^3} \right]^{-2.5} \left[1 + \frac{G}{10^7} \right]^2 e^{-0.0012 L/D_e} 10^6 \quad (7)$$

Since there was a spread of plus or minus 35 per cent in the data which determined the correlation, a factor of two-thirds was used to take this into account. Therefore, the operating heat fluxes are such that no burnout conditions are expected since the minimum ratio of calculated burnout heat flux to actual heat flux is 1.76, see Figures 5, 6, and 7.

(d) Determination of Central Core Temperature

To determine the central core temperature the following equation was analytically derived:

$$t_c = T_s + \frac{Q}{A} \left[\frac{r_{od}}{K_{ss}} \ln \frac{r_{od}}{r_{id}} + \frac{r_{od} \Delta x}{r_{id} K_g} + \frac{r_{od}}{K_{UO_2} \kappa r_f} \left\{ \frac{I_o(\kappa r_f) - 1}{I_1(\kappa r_f)} \right\} \right] \quad (8)$$

where the first term is the surface temperature, second term is the temperature drop across the cladding, third term is temperature drop across the gas gap and fourth term is the temperature drop across the UO_2 . Since the maximum fuel temperature for both legs occurs at the same maximum heat flux, the difference in the center fuel temperature is due to the surface temperature and the inverse diffusion length κ . The following are the conditions for each leg;

$$\begin{aligned} \text{enrichment} &= 0.27 & r_{od} &= 0.162 \text{ in.} & \Delta x &= 0.0002 \text{ in.} \\ \kappa &= 4.115 \text{ 1/cm} & r_{id} &= 0.147 \text{ in.} & K_{ss} &= 11 \text{ Btu/hr ft } ^\circ\text{F} \\ & & & & K_g &= 0.0102 \text{ Btu/hr ft } ^\circ\text{F} \\ & & & & K_{UO_2} &= 1 \text{ Btu/hr ft } ^\circ\text{F} \end{aligned}$$

* Green, S. J., "Heat Transfer Burnout at High Pressure," WAPD-T-845

$$\begin{aligned}
t_s &= 621 + 4.5 \times 10^5 \left[\frac{0.162}{(12)(11)} \ln \frac{0.162}{0.147} + \frac{(0.162)(0.0002)}{(0.147)(12)(0.0102)} + \frac{0.162}{(12)(1.5361)} \right. \\
&\quad \left. \left\{ \frac{I_o(1.5361)-1}{I_1(1.5361)} \right\} \right] \\
&= 621 + 4.5 \times 10^5 \left[\frac{(0.162)(0.09712)}{(12)(11)} + 18.0072 \times 10^{-4} + \frac{(0.162)(0.11612)}{(12)(1.5361)(1.01783)} \right] \\
&= 621 + 4.5 \times 10^5 [1.1919 \times 10^{-4} + 18.0072 \times 10^{-4} + 58.9459 \times 10^{-4}] \\
&= 621 + 53.6 + 810.3 + 2652.6 \\
&= 4137.5 ^\circ\text{F}
\end{aligned}$$

Second leg:

$$\begin{aligned}
\text{enrichment} &= 0.10 & r_{od} &= 0.1685 \text{ in.} & \Delta x &= 0.0002 \text{ in.} \\
\kappa &= 1.80 \text{ l/cm} & r_{id} &= 0.1475 \text{ in.} & K_{ss} &= 11 \text{ Btu/hr ft } ^\circ\text{F} \\
& & & & K_g &= 0.0105 \text{ Btu/hr ft } ^\circ\text{F} \\
& & & & K_{UO_2} &= 1 \text{ Btu/hr ft } ^\circ\text{F}
\end{aligned}$$

$$\begin{aligned}
t_s &= 641.1 + 4.5 \times 10^5 \left[\frac{0.1685}{(12)(11)} \ln \frac{0.1685}{0.1475} + \frac{(0.1685)(0.0002)}{(0.1475)(12)(0.0105)} + \frac{0.1685}{(12)(0.672)} \right. \\
&\quad \left. \left\{ \frac{I_o(0.672)-1}{I_1(0.672)} \right\} \right] \\
&= 641.1 + 4.5 \times 10^5 \left[\frac{(0.1685)(0.13313)}{(12)(11)} + 18.1946 \times 10^{-4} + \frac{(0.1685)(0.11612)}{(12)(0.672)(0.35533)} \right] \\
&= 641.1 + 4.5 \times 10^5 [1.6994 \times 10^{-4} + 18.1946 \times 10^{-4} + 68.2849 \times 10^{-4}] \\
&= 641.1 + 76.5 + 818.8 + 3072.8 \\
&= 4069.2 ^\circ\text{F}
\end{aligned}$$

(e) Determination of the Maximum Heat Output per Unit Length of Specimen

$$\begin{aligned}\frac{\text{watts}}{\text{in}} &= \left[450,000 \text{ Btu/hr ft}^2 \right] \left[0.02121 \text{ ft}^2/\text{in} \right] \left[\frac{\text{kw-hr}}{3415 \text{ Btu}} \right] \left[\frac{1000 \text{ watts}}{\text{kw}} \right] \\ &= 2795\end{aligned}$$

C. Nomenclature

(a) List of Symbols

A	- Surface area, ft^2
c_p	- Specific heat at constant pressure, $\text{Btu/lb } ^\circ\text{F}$
D_e	- Equivalent diameter, feet
G	- Mass velocity lbs/hr ft^2
H	- Enthalpy, Btu/lb
ΔH	- Enthalpy change, Btu/lb
h	- Heat transfer coefficient, $\text{Btu/hr ft}^2 ^\circ\text{F}$
K	- Thermal conductivity, $\text{Btu/hr ft } ^\circ\text{F}$
L	- Length, feet
P	- Pressure, lbs/in^2
Q	- Thermal heat output, Btu/hr
r	- Radius, ft.
S	- Velocity, ft/sec
T, t	- Temperature, $^\circ\text{F}$
Δt	- Film temperature drop, $^\circ\text{F}$
V	- Volume, ft^3
v	- Specific volume, ft^3/lb
W	- Mass rate of flow lbs/hr
κ	- Inverse diffusion length, cm^{-1}
μ	- Viscosity, lb/hr ft
Φ	- Thermal neutron flux, $\text{neutrons/cm}^2 \text{ sec}$

(b) Subscripts

avg	- Average conditions
B.O.	- Thermal burnout conditions
c	- Pertaining to center
f	- Pertaining to fuel
g	- Pertaining to gas
id	- Inside diameter
in	- Inlet conditions
m	- Maximum point
o	- Outlet conditions
od	- Outside diameter
s	- Pertaining to the surface
sat	- Pertaining to the saturation temperature
ss	- Pertaining to stainless steel
UO ₂	- Pertaining to uranium oxide
w	- Pertaining to water
x	- Distance from leading edge

D. Hot Spot Factor Calculations

Since the Heat Transfer Subcommittee of the Phillips Reactor Safeguard Committee requires that an analysis of hot spot and hot channel factors is a prerequisite for an MTR experiment, the following calculations are performed as prescribed by document IDO-16343. Also, Table I of that document was followed. Because our computations are for a small diameter loop, an analysis for the hot channel is not required. Also since the design criteria of the loop allows for local boiling even the hot spot analysis is somewhat superfluous.

(a) Mechanical Tolerances (Hydraulic Effects)

The flow that was used in the analysis was obtained experimentally with the loop; therefore, no hot spot factor is required since the actual mechanical configuration was used to obtain the data.

(b) Mechanical Distortion

Similar to A, no correction factor is required. As far as the radiation damage is concerned, the In-process specimens, WCAP-2, shows that no radiation damage is anticipated.

(c) Correlation Equations of h

Dittus-Boelter Equation: (3)

$$h = 5252 \text{ Btu/hr ft } ^\circ\text{F}$$

Modified Colburn: (9) at 635.8 $^\circ\text{F}$ and 2000 psia

$$\begin{aligned} c_p &= 1.816 \text{ Btu/lb } ^\circ\text{F} & K &= 0.26 \text{ Btu/hr ft } ^\circ\text{F} & \mu &= 0.191 \text{ lb/hr ft} \\ v &= 0.0257 \text{ ft}^3/\text{lb} & D_e &= 0.01651 \text{ ft} \end{aligned}$$

$$\frac{h D_e}{k_f} = 0.023 \left[\frac{D_e \rho_f S}{\mu_f} \right]^{0.8} \left[\frac{c_p \mu}{k} \right]_f^{0.4} \quad (9)$$

$$h = 0.023 \frac{k_f^{0.6} c_{pf}^{0.4}}{\mu_f^{0.4}} \frac{1}{D_e^{0.2}} \left[\frac{S}{v} \right]^{0.8}$$

$$= 0.023 \frac{(0.26)^{0.6} (1.816)^{0.4}}{(0.191)^{0.4} (0.01651)^{0.2}} \frac{10^1}{(10.3)} \frac{10^3}{(3.600)}^{0.8}$$

$$= 4806 \text{ Btu/hr ft}^2 \text{ } ^\circ\text{F}$$

$$h_{\text{corrected}} = (4806)(0.8) = 3845$$

$$\frac{5252}{3845} = 1.37$$

$$F_h = 1.37$$

(d) Determination of Critical Parameters

1. Flow Measurements

The error in the flow meter reading is plus or minus one per cent.

$$\text{Therefore } F_h = 1.01$$

$$\Delta T = 84 \text{ } ^\circ\text{F}$$

$$\text{Therefore } \Delta T_{\text{add}} = 0.8 \text{ } ^\circ\text{F}$$

2. Pressure Measurements

The error in pressure gage reading is plus or minus one-half per cent.

Therefore a conservative assumption is:

$$F_h = 1.005$$

4. Temperature Measurements

The error in the measurement of coolant temperature is plus or minus one per cent.

$$\text{Therefore } T_{\text{out}} = 600 \text{ } ^\circ\text{F}$$

$$\Delta T_{\text{add}} = 6 \text{ } ^\circ\text{F}$$

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(e) Flow Distribution Effects

2. Edge Effects

Assumes 10%

$$\text{Therefore } F_h = 1.1$$

(f) Heat Flux Over Element Surface

1. Fuel Homogeneity

The enrichment in one leg will vary from 26.8% to 27.2% and in the second leg from 9.8% to 10.2%. The nominal enrichments are 27% and 10%.

$$\frac{27.2}{27} = 1.0074 \qquad \frac{10.2}{10} = 1.02$$

Therefore

$$F_h = 1.01$$

2. Mechanical Effects - Clad Thickness

A tolerance of 0.005 inch on the clad thickness.

$$\frac{0.025}{0.02} = 1.25 \qquad \frac{0.020}{0.015} = 1.333$$

Therefore

$$F_h = 1.333$$

A tolerance of 0.0005 on the UO_2 pellet

$$\frac{0.2945}{0.294} = 1.0017$$

The total hot spot is

$$F_h = 1.34$$

(g) Table of Hot Channel Factors with Local Boiling

	F_h	ΔT_{add}
Mechanical Tolerance (Hydraulic Effects) (a)		
1. Effect on mass flow-external effects end boxes, etc.	1.0	0
2. Effect on mass flow-entrance and exit effects	1.0	0
3. Effect on mass flow-channel effects	1.0	0
4. Effect of D variation	1.0	0
Mechanical Distortion (b)		
1. Effect on mass flow-external effects end boxes, etc.	1.0	0
2. Effect on mass flow-entrance effect	1.0	0
3. Effect on mass flow-channel effect	1.0	0
4. Effect on D variation	1.0	0
Correlation Equation of h (c)	1.37	0
Determination of Critical Parameters (d)		
1. Flow measurements	1.01	0.8 °F
2. Temperature measurements (metal)	1.0	0
3. Pressure measurements	1.005	0
4. Temperature measurements (coolant)	1.00	6.0 °F
Flow Distribution Effects (e)		
1. Plenum effects	1.0	0
2. Edge effects	1.1	0
Neutron and Gamma Flux Distribution		
1. Vertical distribution	1.0	0
2. Horizontal distribution	1.0	0
3. Internal distribution	1.0	0
Neutron and Gamma Flux Uncertainty		
1. Unperturbed flux source	1.2	0
2. Average depression	1.0	0
3. Internal distribution	1.0	0
4. Experimental power generation variation timewise	1.0	0
Heat Flux over Element Surface (f)		
1. Fuel homogeneity	1.02	0
2. Mechanical effects clad thickness	1.34	0
Effects Peculiar to Experiment	1.00	0
Total	2.51	6.8 °F

() Small case letters refer to discussion of this topic in report

(h) Sample Hot Spot Temperature Calculations for Non-Local Boiling

The maximum surface temperature under convective conditions will therefore be:

$$\text{First leg: } (2.51) (83.6) = 209.8^{\circ}\text{F}$$

$$T_s = 209.8 + 539.7$$

$$= 749.5^{\circ}\text{F}$$

$$\text{Second leg: } (2.51) (84.5) = 212.1^{\circ}\text{F}$$

$$T_s = 212.1 + 590.2$$

$$= 802.3^{\circ}\text{F}$$

Although these are somewhat high surface temperatures, the mechanism of local boiling which is a design criteria for the loop is not depended on the same factors used to obtain the hot spot factor. For the hot spot determination under local boiling conditions, only those factors which will affect the heat flux and pressure should be considered:

Therefore:

(i) Table of Hot Channel Factors with Local Boiling

	F_Q	F_p
A. Mechanical Tolerance (Hydraulic Effects) (a)	1.0	
B. Mechanical Distortion (b)	1.0	
C. Correlation Equation of h (c)	1.0	
D. Determination of Critical Parameters (d)		
3. Pressure measurements		1.005
E. Flow Distribution Effects (e)	1.0	
F. Neutron and Gamma Flux Distribution	1.0	
G. Neutron and Gamma Flux Uncertainty		
1. Unperturbed flux source	1.2	
H. Heat Flux over Element Surface		
1. Fuel homogeneity	1.02	
2. Mechanical effects clad thickness	1.34	
I. Effects Peculiar to Experiment	1.00	
Total	1.64	1.005

() Small case letters refer to discussions of this topic in reports

(j) Sample Hot Spot Temperature Calculations for Local Boiling

$$T_s - T_{sat} = 60 \frac{[(1.64 (Q/A/10^6)]^{0.25}}{e^{(1.005) P/900}}$$

$$= 60 \frac{[(1.64) (0.45)]^{0.25}}{e^{2010/900}}$$

$$T_s - 636.5 = \frac{60 (0.738)^{0.25}}{e^{2.2333}}$$

$$= \frac{(60) (0.9268)}{9.33061}$$

$$T_s - 636.5 = 6.0$$

$$T_s = 642.5 ^\circ\text{F}$$