PHOENIX MEMORIAL LABORATORY

MEMORANDUM REPORT NO. 1

Calculation of Maximum Fuel Cladding Temperatures for Two Megawatt Operation of the Ford Nuclear Reactor

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Introduction

Using an approach suggested by M.F. Sankovich of The Babcock and Wilcox Company,[1] a computer program for calculating the cladding temperature distribution in the hot channel of the FNR was written for the IBM-709, using the MAD language.

The assumptions made in the approach are:

(1) The power density distribution is a function of the radial and the axial length independently.

(2) The power density distribution may be treated as a "clipped" sine function (with appropriately chosen parameters) in both the axial and radial direction.

(3) Thermal conductivity, density and specific heat of water are constants.

(4) The viscosity of water as a function of temperature is given by Bingham's equation.[2]

(5) Nusselt number is determined by the Hausen equation.[3]

(6) Flow velocity through the fuel channels is constant for all channels.

(7) There is no pressure drop through the channels.

1) General Equations

Expressing the axial power density distribution as

$$P(x) = \mathrm{Sin}\,\pi\left(\frac{x + c}{L + 2c}\right),$$

the bulk coolant temperature rise in the hot channel may be written

$$Tb(x) = Ti + K \int_{o}^{x} \mathrm{Sin}\,\pi\left(\frac{x + c}{L + 2c}\right) dx \quad . \tag{1}$$

After integrating

$$Tb(x) = Ti - K\left(\frac{L + 2c}{\pi}\right)\left[\mathrm{Cos}\,\pi\left(\frac{x + c}{L + 2c}\right) - \mathrm{Cos}\left(\frac{\pi c}{L + 2c}\right)\right], \tag{2}$$

or for a channel length of L,

$$Tb(L) = Ti - K\left(\frac{L + 2c}{\pi}\right)\left[\mathrm{Cos}\,\pi\left(\frac{L + c}{L + 2c}\right) - \mathrm{Cos}\left(\frac{\pi c}{L + 2c}\right)\right]. \tag{3}$$

Since

$$\mathrm{Cos}\left[\pi\left(\frac{L + c}{L + 2c}\right)\right] = -\mathrm{Cos}\left(\frac{\pi c}{L + 2c}\right),$$

Equation (3) becomes

$$Tb(L) = Ti + 2K\left(\frac{L + 2c}{\pi}\right) \mathrm{Cos}\left(\frac{\pi c}{L + 2c}\right) \quad . \tag{4}$$

Since for the hot channel we also have

$$Tb(L) = Ti + \frac{g_{(mar)}\, P\, H_l}{Cp\, \delta} \tag{5}$$

where $g_{(mar)}$ is the ratio of maximum to average power distribution in the radial direction, P is the average power of the core and H_l is the local hot spot factor.

Equating (4) and (5)

$$K = \frac{g_{(max)} P H_1}{2\,C_p\,\dot{\omega}\,(\frac{L+2c}{\pi})\ \mathrm{Cos}\,(\frac{\pi c}{L+2c})} \quad . \tag{6}$$

Substituting (6) into (2) we get

$$Tb(x) = Ti + \frac{g_{(max)} P H_1}{2C_p\,\dot{\omega}\ \ \mathrm{Cos}\,(\frac{\pi}{L+2c})} \left[\mathrm{Cos}\,(\frac{\pi c}{L+2c}) - \mathrm{Cos}\,\pi\,(\frac{x+c}{L+2c}) \right] \quad . \tag{7}$$

The equation for the film drop is

$$\Delta T\ film\ (x) = \frac{g''_{max}}{h} \quad \mathrm{Sin}\,\pi\,(\frac{x+c}{L+2c}) \quad . \tag{8}$$

Here h is the film coefficient given by the Hausen equation

$$(\frac{hD}{k})_x = 0.166\,\eta \left[(Re)_{bx}^{2/3} - 125 \right] (Pr)_{bx}^{1/3} \left[1 + 1/3\ \ (\frac{D}{x})^{2/3} \right] (\frac{\mu b}{\mu w})_x^{0.14} \tag{9}$$

where the subscript x refers to conditions at position x from the inlet, b refers to the bulk water temperature, and μw refers to the viscosity of the water at the temperature of the wall or cladding.

Bingham's equation was used to calculate the viscosity of the water at each temperature of interest.

$$\mu = 242.0 \Big/ \left\{ 2.148 \left[(T - 32.0) \times .555 - 8.435 + \sqrt{8078.4 + \left[(T - 32.2) \times .555 - 8.435 \right]^2} \right] - 120.0 \right\} \tag{10}$$

where T is in $^{\circ}F$. and μ is in lbm/hr.ft.

Since

$$g''_{max} = \frac{P\, g_{(mar)}\, g_{(maa)}\, H_l}{A_H} \tag{11}$$

and

$$\Delta T\ film\,(x) = T_{clad}\,(x) - T_b(x) \quad . \tag{12}$$

Then from (11) and (12), (8) may be written

$$T_{clad}(x) = T_b(x) + \frac{P\, g_{(mar)}\, g_{(maa)}\, H_l}{A_H h}\, \mathrm{Sin}\, \pi \left(\frac{x+c}{L+2c}\right) \tag{13}$$

or using (7) for $T_b(x)$ and (9) for h, (13) becomes

$$T_{clad}(x) = Ti + \frac{g_{(mar)}\; P\; H_l \left[\mathrm{Cos}\left(\frac{\pi c}{L+2c}\right) - \mathrm{Cos}\,\pi\left(\frac{x+c}{L+2c}\right)\right]}{2\,C_p\;\dot{w}\;\mathrm{Cos}\left(\frac{\pi c}{L+2c}\right)} +$$

$$\frac{D\,P\,g_{(mar)}\,g_{(maa)}\,H_l\,\mathrm{Sin}\,\pi\left(\frac{x+c}{L+2c}\right)}{A_H\;.116\,\eta\;\;k\left[(Re)_{bx}^{2/3} - 125\right](Pr)_{bx}^{1/3}\left[1 + 1/3\left(\frac{D}{x}\right)^{2/3}\right]\left(\frac{\mu_b}{\mu_w}\right)^{0.14}} \tag{14}$$

Equation (14) may now be used to calculate the cladding temperature at any station x from the fuel channel inlet. Note however that Re, Pr and μ/μ_{clad} will be dependent on the water viscosity and Bingham's equation may be used at the appropriate temperature. In (14) all properties are evaluated at the bulk fluid temperature except for μ_w which must be evaluated at the cladding temperature. Thus a trial and error approach may be used until the solution converges. The digital computer is well suited for this type of calculation. In the MAD program listing, which is given in Appendix 1, it may be noted that the loop with entry label TRY is the trial and error calculation discussed above. [Note that the process continues until the error is less than 1%. If the number of trials at a given location exceeds 20.0, the program execution is terminated.]

This program uses the MESS simplified input-output format and all data cards were punched accordingly. The symbol definitions with units are given, following the program listing.

II Selection of Distribution Function Parameters

The proper selection of the parameter c in the clipped sine distribution function is very important. In an effort to get as realistic an estimate as possible, reference was made to the original power calibration data.(4) Using the power density calculations from the calibration report, a plot of power density data in the axial direction was made for the hot channel in the core loading 1-A. This data is shown in Figure 1 with the best-fit clipped sine function. The percent deviation of the data from the sine function is indicated at each data point. Since for a general clipped sine function of the form

$$F(x) = A \sin \pi \left(\frac{x + c}{L + 2c}\right)$$

the average is

$$\overline{F(x)} = \frac{\int_0^L A \ \mathrm{Sin}\, \pi \left(\frac{x+c}{L+2c}\right) \ dx}{\int_0^L dx}$$

and since the maximum of F(x) is A, it may be shown that the maximum to average (g_{maa}) for such a distribution is

$$g_{maa} = \frac{\pi L}{2(L+2c) \ \mathrm{Cos} \left(\frac{\pi c}{L+2c}\right)} \quad .$$

Thus g_{maa} for the axial data was calculated by (15) and is shown in Figure 1. To establish a value of $g_{(mar)}$, data taken at the mid-plane of the 1-A core extending from fuel element F-2 through fuel element F-11 was used. This profile was selected because it gives the largest value of $g_{(mar)}$ and hence the most conservative fuel cladding temperature calculation. The radial data is plotted in Figure 2 with the best-fit clipped sine function. Since the radial data inherently does not fit the sine function as accurately as the axial data, a reasonably conservative value of c was used to make $g_{(mar)}$ large. The data points shown in Figure 2 were taken from the core shown in Figure 1 of reference 4. If the same distribution is assumed in the north-south direction, i.e. from lattice position 43 through 47, the radial maximum-to-average may be calculated for the 4 x 5 array by

$$g_{(mar)} = \frac{A'}{\frac{A'}{L_1 L_2} \int_{-\frac{L_1}{2}}^{+\frac{L_1}{2}} \int_{-\frac{L_2}{2}}^{+\frac{L_2}{2}} \text{Cos}\left(\frac{\pi x}{L_1 + 2c}\right) \text{Cos}\left(\frac{\pi y}{L_2 + 2c}\right) dxdy} \tag{16}$$

where L_1 = 12 in. (4-fuel elements in x-direction)

L_2 = 15 in. (5-fuel elements in y-direction)

c = 3.8 in. (graphical determination)

after integrating (16), the equation for $g_{(mar)}$ becomes

$$g_{(mar)} = \frac{L_1 L_2 \pi^2}{(L_1 + 2c) \ \text{Sin}\left(\frac{\pi L_1/2}{L_1 + 2c}\right)\left[(L_2 + 2c) \ \text{Sin}\left(\frac{\pi L_2/2}{L_2 + 2c}\right)\right]} \tag{17}$$

which gives

$$g_{(mar)} = 1.47.$$

The original power density data may also be used to get the volumetric maximum-to-average power density, $g_{(mav)}$. This value was determined by summing all the quarter element power cells and dividing by the total number of cells to get the average and then taking the ratio of maximum to average. This calculation gives

$$g_{(mav)} = 1.63 \ .$$

Alternatively, a $g_{(mav)}$ may be determined as:

$$g_{(mav)} = g_{(mar)} \times g_{(maa)} \tag{18}$$

using the values of $g_{(mar)}$ and $g_{(maa)}$ determined from the distributions in Figures 1 and 2, equation (18) gives

$$g_{(mav)} = 1.47 \times 1.11 = 1.63 .$$

The agreement between the two methods suggest that the distributions shown in Figures 1 and 2 may be used to calculate the temperature profiles in the hot channel with a high degree of reliability.

In summary, the parameters for the power density distribution function are given by

$g_{(maa)} = 1.11$ axial (max to av)

$g_{(mar)} = 1.47$ av. radial max/av (midplane)

$g_{(mav)} = 1.63$

$c = 11.8$ (for use in equation 14) .

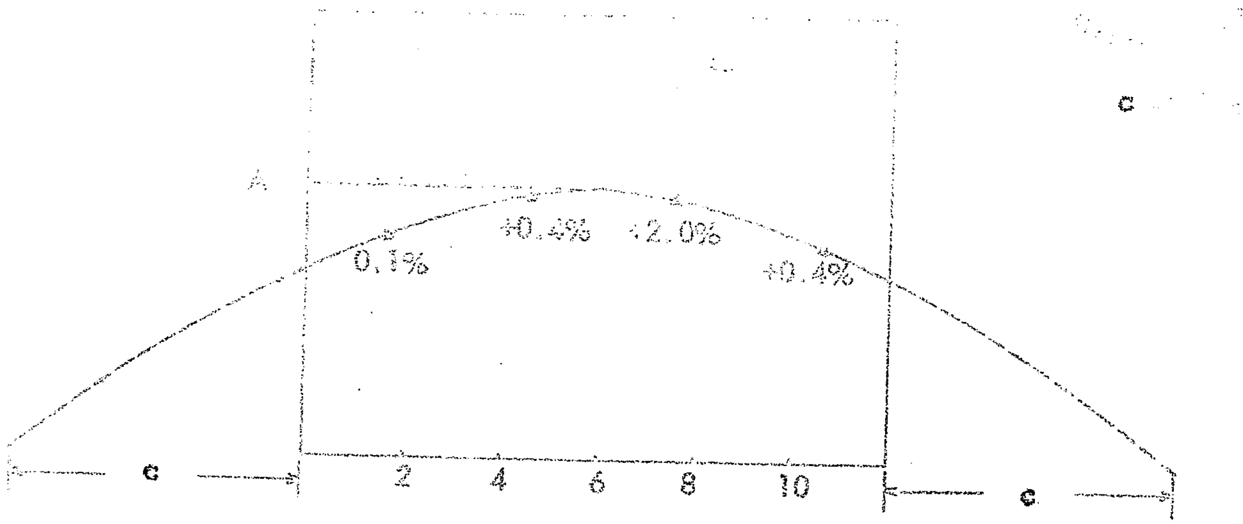
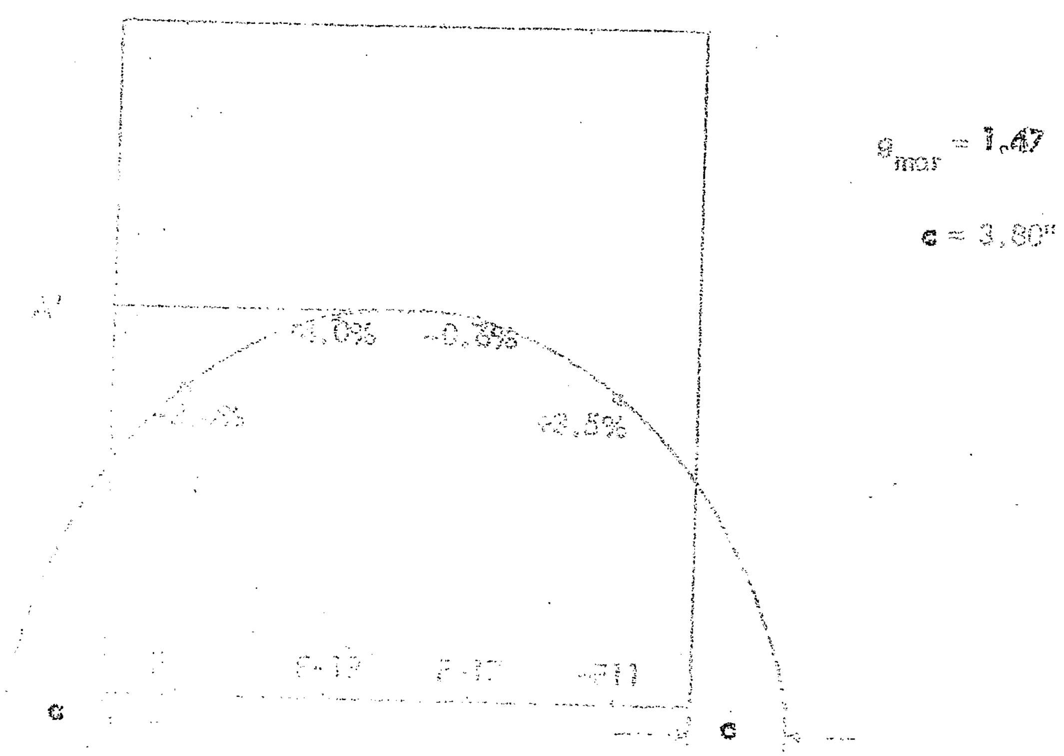


Figure 1 - Axial Power Density Distribution



III By-Pass Flow

The FNR uses modified MTR-type curved plate fuel elements. The 1st and 18th fuel plate of each fuel element have the same fuel loading as the interior fuel plates; hence, in addition to the interior flow analysis, consideration must be given to the by-pass flow outside (around) the fuel elements. The FNR core-matrix plate has been provided with 63- 7/8" diameter coolant flow passages to insure coolant flow between adjacent fuel and/or reflector elements. Since the flow geometry outside the fuel is approximately the same as the interior channels, it will be assumed that the flow will separate in proportion to the flow area provided by the respective flow channel dimensions. A larger by-pass flow will result in lower coolant velocity inside the fuel elements; hence, to obtain a conservative estimate the largest estimate for by-pass flow will be used. The largest possible by-pass flow area is limited by the space between the bottom of the element and the grid plate while the smallest possible flow area for each fuel element is fixed by the cylindrical end piece having a 2.0" diameter opening. A core containing 19 fuel elements (including 4 partial elements) represents the smallest fuel loading of operational interest, so

$$\text{fuel flow area} = 19\pi = 59.6 \text{ in.}^2$$

To determine the by-pass flow fraction, consideration was given to determining the minimum flow area presented to the by-pass coolant. The results of this study indicate the critical dimensions to be the space between the bottom of each element and the top of the matrix plate. Using the mean tolerance of all the pertinent dimensions results in an average element-to-grid gap of 0.109 inches. This gives a by-pass flow area of

$$\text{by-pass flow area} = 0.109 \times 7/8 \times \pi + 0.050 \times 7/8 = 0.343 \text{ in.}^2 \text{ per } 7/8 \text{ in. hole.}$$

So the total by-pass area for a 19 element core is

$$\text{total by-pass flow area} = \underbrace{63}_{\text{No. of holes in matrix}} \times 0.343 = 20.6 \text{ in.}^2$$

Hence   No. of holes in matrix   Each hole = 0.6 in^2

$$\text{\% of total flow which is by-pass flow} = \frac{20.6}{59.6 + 20.6} = 25.7 \quad .$$

Consideration of the ratio of minimum to average flow area for both the by-pass and fuel element flow channels, indicates that the average velocity in the by-pass channels will be larger than the velocity inside the elements. Hence, to give the most conservative estimates temperature calculations will be based on the conditions inside the fuel channels.

all matrix holes need not be open.
special plugs are provided.

IV Discussion of Calculations and Results

Using equation (14) and the constants shown in Table 1, heat transfer calculations were made on the IBM-709 at the University of Michigan for reactor power levels of 1, 2 and 3 MW, with inlet water temperatures of 85, 110 and 120°F. A sample hand calculation is shown in Appendix II for the 2 MW case with 110°F. inlet water temperature. In all the calculations η was selected as 75%, which corresponds to reducing the film coefficient predicted by the Hausen equation by 25%. A 25% reduction in the Hausen equation gives a correlation which includes 99% of the data points by Gambill and Bundy.[3]

The maximum-to-average factors for the distribution functions were obtained from data taken on a core containing seventeen standard 18-plate fuel elements and were treated as constants in the calculations for both the 19-element core and the 28-element core. Both core loadings considered were assumed to have four partial 9-plate elements in addition to the standard elements.

The results of fuel cladding temperature calculations are plotted in Figure 3 as maximum cladding temperature vs. inlet water temperature. It may be noted that maximum plate temperature does not change drastically with size of the core loading. This behaviour is due primarily to the assumptions that the power density distribution is the same for the two cases and the primary coolant flow rate remains constant for both cases. Both of the above assumptions are considered to be conservative because they predict higher cladding temperatures for the larger core.

The local boiling point corresponds to the saturated water temperature at the operating pressure of the core. It is assumed that microscopic, very local, sub-cooled boiling will occur whenever the fuel element wall temperature becomes equal to or greater than the saturation temperature of the water.

Nucleate boiling is defined by

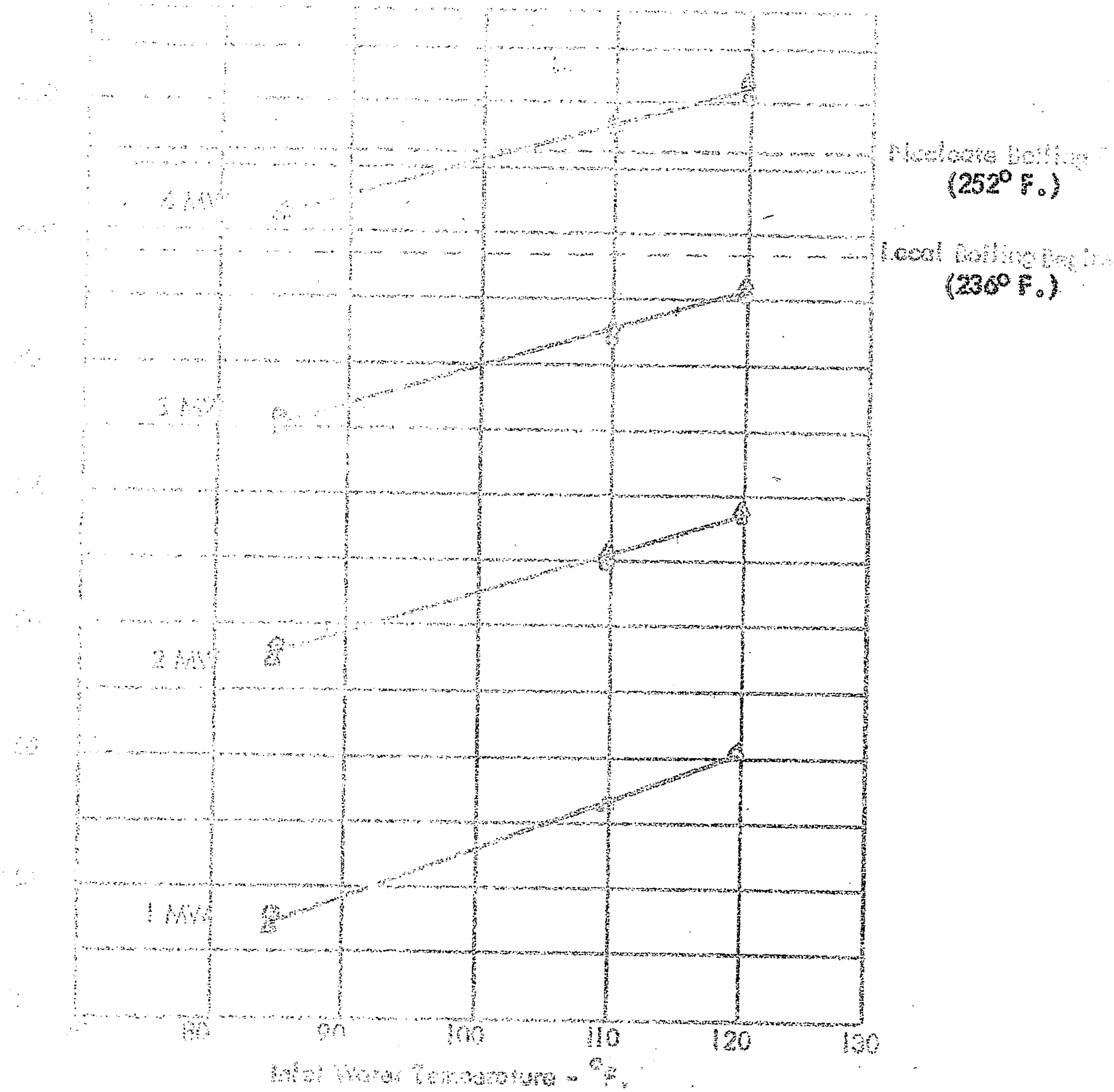
$$T_{bulk} = T_{sat} .$$

The cladding temperature which results in nucleate boiling was calculated by the film temperature drop predicted by the Jens-Lottes equation.[5] The film-drop predicted by the Jens-Lottes equation was reduced by 50% for a conservative estimate.

Based on the results shown in Figure 3, it is concluded that the FNR may be operated at power levels up to 3 MW with no local boiling if the inlet water temperature is restricted to less than 120°F.

J.B. Bullock
Reactor Supervisor

6 June, 1962.



Δ [illegible] - 18 plate elements ○ 24 - 18 plate elements

Figure [illegible] - MAXIMUM CLADDING TEMPERATURE
vs. WATER INLET TEMPERATURE

TABLE I

Constants Used in the Calculations

C	=	11.8 in.
Cp	=	1.0 btu/lbm/°F.
D	=	.212 in.
$g_{(max)}$	=	1.11
$g_{(nor)}$	=	1.47
H_1	=	1.3
K	=	.36 btu/ft.^{2}/°F/hr.
L	=	24.0 in.
η	=	.75
$\dot{w}$	=	3.74×10^5 lbm/hr. *
DEN	=	61.5 lbm/ft.^{3}

* This value of mass flow rate corresponds to a primary flow rate of 1020 gpm and a by-pass flow of 25.7%.

DEFINITION OF SYMBOLS IN TEXT

A_H	Heat transfer surface area
c	A parameter of the clipped sine function, sometimes called the reflector savings (see Figure 1)
C_p	Specific heat of coolant.
D	Hydraulic diameter of coolant channel
$\theta_{(max)}$	Ratio of maximum to average power density in the axial direction.
$\theta_{(mar)}$	Ratio of maximum to average power density in the radial direction.
$\theta_{(mav)}$	Ratio of maximum to average power density for the total volume.
q''_{max}	Maximum heat flux.
h	Local heat transfer coefficient.
H_l	Local maximum to average power density.
K	Thermal conductivity of coolant.
L	Length of fuel channel.
P	Average reactor power.
$(Pr)_{bx}$	Local Prandtl number based on bulk coolant temperature.
$(Re)_{bx}$	Local Reynolds number based on bulk coolant temperature and hydraulic diameter.
t	Bulk (mixed mean) coolant temperature.
$t_{b(x)}$	Bulk (mixed mean) coolant temperature at position x.
t_i	Mixed mean coolant temperature at the channel inlet
	Axial length coordinate measured from inlet of fuel channel.

DEFINITION OF SYMBOLS IN TEXT (Contd.)

GREEK SYMBOLS

η	Factor on Hausen correlation to set confidence level.
μ_b	Viscosity of coolant at bulk temperature.
μ_w	Viscosity of coolant at wall temperature.
δ	Mass flow rate of coolant in fuel channel.

REFERENCES

(1) Sankovich, M.F. Babcock and Wilcox Co. Private communication.

(2) Perry, John H., Ph.D., ed. Chemical Engineers' Handbook. 3rd ed McGraw-Hill Book Company, Inc.; New York, 1950. p. 374.

(3) Gambill, W.R. and Bundy, R.D., HFIR Heat-Transfer Studies in Turbulent Water Flow in Thin Retangular Channels. ORNL-3079. Oak Ridge National Laboratory; Oak Ridge, Tennessee, 1961.

(4) Shapiro, J.L., et al. Calibration of the Ford Nuclear Reactor MMPP-110-1. Michigan Memorial Phoenix Project, University of Michigan; Ann Arbor, Michigan, 1958.

(5) Lottes, Paul A., Nuclear Reactor Heat Transfer. Argonne National Laboratory; Argonne, Illinois, 1961. p. 82. ANL-6469.

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[illegible] PROFILE
[illegible]
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[illegible] USING THE FOLLOWING PARAMETERS ;
[illegible], POW, IMAX, RRATIO, LRATIO, RS, I, PRFLO,
[illegible], NOSL, NP, NPS, DEN, A, T, K, CP, ATA, ARATIO, PIE
[illegible] NOSL*(NP-1.0) +NOSL*NPS)
[illegible] PRFLO * DEN
[illegible] 2.0 *A+ 2.0 * T)
[illegible] BYP) * TWDOT
[illegible] 0.0208 * PRFLC / AFLO * (1.0 - BYP)
[illegible] A * L * NP*NOSL +NPS*NOSL)
* POW*0.4[illegible] * RRATIO * LRATIO * ARATIO/ AH
[illegible]
[illegible] = COS( PI* RS/(L + 2.0 *RS))
[illegible] RRATIO * LRATIO / (2.0 * CF * WDOT * (COSPHI)
[illegible] = 0, 1, 1, . G. IMAX
* PIE * [illegible] IMAX + 0.0) + RS) / (L + 2.0 * RS)
[illegible] * (COSPHI - COS (THETA))
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[illegible]
[illegible]
[illegible] TRANSFER TO OUT
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[illegible]
[illegible] 0.4666 - 175.0) * (RE [illegible] 0.5333)* (1.0 + 0.350
[illegible] 0.4666)*(MU/MUAL) [illegible] 0.140 )
[illegible] (IMAX + 0.0) + RS)/ (L + 2.0 * RS)) / H
[illegible]
[illegible]
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[illegible]

[illegible] AREA OF SURFACE AREA [illegible] ^{2}

[illegible] DIAMETER (ft.)

[illegible] TEMPERATURE DROP ($^\circ$F)

[illegible] - FILM COEFFICIENT (Btu/ft ^{2}/$^\circ$F)

[illegible] - VISCOSITY OF WATER AT TEM (lbm/hr./ft.)

[illegible] - VISCOSITY OF WATER AT TEMAL (lbm/hr./ft.)

[illegible] - NUSSELT NUMBER

[illegible] - PRANDTL NUMBER

[illegible] - MAXIMUM HEAT FLUX (Btu/ft. ^{2}/hr.)

[illegible] - REYNOLDS NUMBER

[illegible] - BULK WATER TEMPERATURE AT GIVE I ($^\circ$F)

[illegible] - TEMPERATURE OF ALUMINUM CLADDING ($^\circ$F)

[illegible] - TOTAL MASS FLOW RATE IN PRIMARY (lb./hr.)

[illegible] - VELOCITY OF FLOW IN FUEL ELEMENTS (ft./hr.)

[illegible] - MASS FLOW RATE IN FUEL ELEMENTS (lb./hr.)

DEFINITION OF DATA SYMBOLS

DATA SYMBOLS

A	WIDTH OF FUEL PLATE (ft.)
ARATIO	AXIAL RATIO OF MAXIMUM TO AVERAGE POWER DENSITY
ATA	FACTOR ON HAUSEN CORRELATION TO SET CONFIDENCE LEVEL
BYP	BY PASS FLOW (fraction of primary)
CP	SPECIFIC HEAT OF H_2O (Btu/lb./ °F)
DEN	DENSITY OF H_2O (lb./ft.^{3})
IMAX	MAXIMUM NUMBER OF DIVISIONS OF FLOW CHANNEL
INTEM	CORE INLET TEMPERATURE (°F)
K	THERMAL CONDUCTIVITY OF H_2O (Btu/ft.^{2}/hr./ °F)
L	LENGTH OF FUEL PLATE (ft.)
LRATIO	LOCAL, MAXIMUM TO AVERAGE POWER DENSITY RATIO
NORL	NUMBER OF REGULAR FUEL ELEMENTS
NOSE	NUMBER OF PARTIAL FUEL ELEMENTS
NP	NUMBER OF FUEL PLATES PER REGULAR FUEL ELEMENT
NPS	NUMBER OF FUEL PLATES PER PARTIAL FUEL ELEMENT
PIE	CONSTANT = 3.14159
POW	REACTOR POWER LEVEL (MW)
RFLO	PRIMARY LOOP FLOW RATE (gal./min/)
RRATIO	RADIAL RATIO OF MAXIMUM TO AVERAGE POWER DENSITY
RS	REFLECTOR SAVINGS (ft.)
T	WATER GAP THICKNESS (ft.)

APPENDIX II

Sample Calculation

A hand calculation is given for the case of constant water viscosity and a core containing 24 regular fuel elements and 4 special fuel elements operating at 2 MW. In addition to the constants given in Table 1 the following are required:

$$P = 6.825 \times 10^6 \text{ BTU/hr. (2 MW)}$$

$$Ti = 110^\circ F$$

$$A_H = 428.7 \text{ ft.}^2$$

Flow Area Within Elements

$$A_{flo} = 24 \times 17 \times \frac{.110 \times 2.75}{144} + \frac{4 \times 9 \times .110 \times 2.75}{144}$$

$$A_{flo} = .856 + .076 = .932 \text{ ft.}^2$$

Average Coolant Velocity

Since

$$\dot{\omega} = 3.74 \times 10^5 \text{ lbm/hr.}$$

$$DEN = 61.5 \text{ lbm/ft.}^3$$

$$Vel = \frac{\dot{\omega}}{DEN \times A_{flo}} = \frac{3.74 \times 10^5}{61.5 \times .932} = 6520 \text{ ft./hr.}$$

or

$$Vel = 1.81 \text{ ft./sec.}$$

Bulk Coolant Temperature Rise

Using equation (7) for the bulk coolant temperature rise through the core gives

$$\frac{g_{(max)} P H_i}{2 C_p \dot{\omega} \cos\left(\frac{\pi c}{L + 2c}\right)} = \frac{1.47 \times 6.825 \times 10^6 \times 1.3}{2.0 \times 1.0 \times 3.74 \times 10^5 \cos(.778)} = 24.6^\circ F$$

So

$$T_{b(x)} = Ti + 24.6 \left[\text{Cos} \left(\frac{\pi c}{L + 2c}\right) - \text{Cos}\, \pi \left(\frac{x + c}{L + 2c}\right) \right]$$

TABLE 1A

x	$x + c$	$\Theta = \frac{\pi(x + c)}{L + 2c}$	$\text{Cos}\,\Theta$	$\text{Cos}\frac{\pi c}{L + 2c} - \text{Cos}\,\Theta$	$\Delta T_{coolant}$	T_{wx}
0	11.8	.779	.711	0	0	110.0°F
4	15.8	1.042	.503	.208	5.1	115.1
8	19.8	1.308	.260	.451	11.1	121.1
12	23.8	1.572	-.002	.703	17.3	127.3
16	27.8	1.832	-.227	.938	23.0	133.0
20	31.8	2.100	-.508	1.219	29.95	140.0
24	35.8	2.370	-.713	1.424	35.0	145.0

Fuel Plate Cladding Temperature

Using equation (8) for the film drop

$$\Delta T_f(x) = \frac{g''_{max}}{h} \; \text{Sin} \left(\frac{x + c}{L + 2c}\right)$$

where the maximum heat flux is

$$g''_{max} = \frac{P \; g_{(mar)} \; g_{(maa)} \; H_I}{A_H}$$

or

2.12

$$g''_{max} = \frac{6.825 \times 10^6 \times 1.47 \times 1.11 \times 1.3}{428.7} = 3.38 \times 10^4 \text{ BTU/ft.}^2\text{-hr.}$$

1.63

Since the viscosity is to be assumed constant, the parameters will be evaluated at a bulk water temperature of 120° F.

Hence $\mu = 1.35$ lb/hr.-ft.

So $Pr = \frac{1.35}{.36} = 3.75$

and $Re = \frac{61.5 \times 6520 \;\; .212}{1.35 \times 12} = 5260$ ok

The film coefficient may now be determined from equation (9), where $\eta = .75$.

Assuming a film drop of 55°F, the viscosity of the water (μw) should be evaluated at 175°F.

So $\mu w \approx .88$

Hence

see page 3 (Equation 4)

$$\frac{hD}{K} = .116 \times .75 \left[(5260)^{2/3} - 125\right] \times (3.75)^{1/3}\left[1 + 1/3\left(\frac{.212}{17}\right)^{2/3}\right]\left(\frac{1.35}{.88}\right)^{.14}$$

$$\frac{hD}{K} = .087\,(300 - 125) \times 1.554 \left[1 + \frac{.0583}{3}\right] \times 1.062$$

K = 0.36 BTU/ft²/hr/°F

$$\frac{hD}{K} = 25.6$$

or

$$h = \frac{25.6 \times \overset{K}{.36} \times 12}{.212 \text{ in.}} = 522.0 \text{ BTU/hr.-ft.}^2\text{-}^\circ\text{F}$$

From Table 2-A, it may be noted that the maximum cladding temperature is 196.1°F, which is in reasonable agreement with the more exact value of 190°F as calculated by the computer program.

TABLE 2A

x	$\sin \frac{\pi(x + c)}{L + 2c}$	$\frac{q''_{max}}{h} \sin \Theta = \Delta R_f$	$\Delta T_f + Tw = T_{clad}$
0	.702	45.4	155.4
4	.864	55.3	170.4
8	.965	62.5	183.6
12	1.000	64.8	192.1
16	.974	63.1	196.1
20	.861	55.7	195.7
24	.701	46.1	191.1