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APAE MEMO NO. 157

**THERMAL DESIGN CRITERIA
FOR
APPR PRESSURIZED WATER REACTORS**

AEC Contract #AT(30-3)-326

Issued November 26, 1958

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TABLE OF CONTENTS

	Page No.
1.0 HEAT TRANSFER COEFFICIENT	1
2.0 POWER DISTRIBUTION UTILIZATION	1
3.0 HOT CHANNEL FACTORS	2
4.0 LATTICE REQUIREMENTS	3
5.0 INSTRUMENTATION TOLERANCES	3
6.0 CALCULATIONS	3
6.1 Hot Channel Factors	3
6.1.1 Plate Spacing Deviation Factors	6
6.1.2 Uranium Content Deviation	9
6.1.3 Active Core Length Deviation	10
6.1.4 Clad Thickness Deviation Factors	11
6.1.5 Orifice Sizing Factors	18
6.1.6 Inlet Box Effect on Flow Distribution	19
6.2 Lattice Requirement Determination	20
6.3 Heat Release Distribution	22
REFERENCES	24

TABLES

Table No.	Page No.
3.1 Hot Channel Factors	2
6.1 Specification Tolerances and Expected Deviations	3

THERMAL DESIGN CRITERIA
FOR
APPR PRESSURIZED WATER REACTORS

The following criteria have been established for thermal design of APPR pressurized-water reactors:

1.0 HEAT TRANSFER COEFFICIENT

The heat transfer coefficient is to be calculated by use of the Dittus-Boelter equation with a constant coefficient of 0.021:

$$h = 0.021 \frac{k}{D} \left(\frac{\rho V D}{\mu} \right)^{0.8} (Pr)^{0.4}$$

where:

h = heat transfer coefficient, Btu/ft²hr⁰F

k = thermal conductivity, Btu/ft hr⁰F

D = equivalent diameter of channel, ft

ρ = density of coolant, lb/ft³

V = velocity of coolant, ft/hr

μ = viscosity of coolant, lb/ft-hr

Pr = Prandtl number of coolant

The coefficient 0.021 was established subsequent to a survey of the literature on experimental heat transfer data, and is felt to be conservative, but not extremely so. Papers reviewed are referenced at the end of this section.

2.0 POWER DISTRIBUTION UTILIZATION

A calculated axial power distribution is to be used for the analysis. Values from a calculated radial power distribution are combined with a side plate flux peaking factor and other existing peaking factors to

establish individual nuclear radial factors for the various elements or groups of similar elements. Methods for the establishment of these factors are outlined by B. Byrne in paper entitled, "Thermal Design Basis for APPR Type Elements". In addition a nuclear uncertainty factor is applied to both the bulk coolant temperature rise and the film temperature gradient to account for uncertainties in the calculation of power distributions. In the heat transfer analysis the assumption is made that 95% of the heat released in the core is released in the active fuel elements. The basis for this assumption is explained in Section 6.3.

3.0 HOT CHANNEL FACTORS

Manufacturing, orifice sizing, and inlet box effect hot channel factors are derived in Section 6.1 for APPR-1 elements and are listed below. Elements with other dimensions should be treated similarly.

Average factors are those which apply to the bulk coolant temperature rise, and local factors, those which apply to the film temperature gradient.

TABLE 3.1 HOT CHANNEL FACTORS

<u>Item</u>	<u>Factor</u>	
	<u>Average</u>	<u>Local</u>
Plate spacing deviation	1.0706	1.1623
Uranium content deviation*	1.0050	1.0250
Length deviation	1.0357	1.0357
Clad thickness deviation	1.0064	1.0128
Orifice sizing	1.0417	1.0332
Inlet box effect:		
Fuel element	1.0309	1.0247
Control rod	1.0638	1.0507
Combined factor (Product of individual factors):		
Fuel element	1.2044	1.3230
Control rod	1.2428	1.3566

* This factor includes uranium content of the whole element along with homogeneity within the element.

4.0 LATTICE REQUIREMENTS

Since it is not possible to tailor lattice flow as is done with the internal flow, the entire lattice flow must be based on the maximum fuel element requirement. Calculations (see Section 6.2) indicate that the larger tolerances on lattice channel dimensions constitute an additional hot channel factor of 1.033. It is therefore felt that the lattice flow should be established on the basis of an average lattice velocity 5% greater than the highest stationary fuel element velocity.

5.0 INSTRUMENTATION TOLERANCES

Instrumentation tolerances for pressurized water reactors have been estimated by C. J. Fredericks in memo of 10/23/58, and verified by G. W. Knighton, to be as follows:

system pressure	$\pm 20\#$ at 1200 psia to $\pm 40\#$ at 2400 psia
core power	$\pm 3.5\%$
inlet temperature	$\pm 4^{\circ}\text{F}$ at 415-465 $^{\circ}\text{F}$ $\pm 5^{\circ}\text{F}$ at 465-515 $^{\circ}\text{F}$ $\pm 6^{\circ}\text{F}$ at 515-570 $^{\circ}\text{F}$

The above values are conservative and it is feasible to improve same with more accurate, and more costly instrumentation.

6.0 CALCULATIONS

6.1 Hot Channel Factors

The hot channel factors, as listed in Table 3.1 were calculated on the basis of the following maximum deviations:

TABLE 6.1

SPECIFICATION TOLERANCES AND EXPECTED DEVIATIONS

<u>Item</u>	<u>Nominal</u>	<u>Max. Deviation</u>
Internal plate spacing	.133"	$\pm .006$ avg $\pm .0133$ local

TABLE 6.1 (continued)

<u>Item</u>	<u>Nominal</u>	<u>Max. Deviation</u>
Uranium Content		$\pm 0.5\%$ average $\pm 2.5\%$ local
Length	21.75"	± 0.75 "
Clad thickness	.005"	$\pm .0005$ avg $\pm .001$ local
Relative Channel Flow as Governed by Orifice Diameter	1.00	$\pm 4\%$ avg. and local
Effect of inlet box on flow distribution:		
Fuel element		3%
Control rod		6%

SYMBOLS AND NOMENCLATURE

- Max. negative average deviation of plate spacing, in.
- A - Channel flow area, in.²
- b - Max. positive local deviation of plate spacing, in.
- c - Specific heat of water, Btu/lb.-°F
- C - Flow coefficient
- d - Nominal plate spacing, in.
- D - Hydraulic diameter of channel, in.
- f - Channel friction factor
- F - Hot channel factor
- h - Water film heat transfer coefficient, Btu/in.²-°F.-sec.

SYMBOLS AND NOMENCLATURE (CONT.)

k - Thermal conductivity, Btu-in./in.²-°F.-sec.

L - Channel length, in.

p - Perimeter of channel, in.

ΔP - Pressure drop across channel, in. of water

q - Heat flow rate, Btu/in.²-°F.-sec.

Q - Volumetric heat generation rate in meat, Btu/in.³-sec.

t - Thickness of meat or clad in fuel element, in.

T - Temperature, °F.

TR - Bulk temperature rise of channel flow, °F.

μ - Water viscosity, lb./in.-sec.

V - Water velocity in channel, in./sec.

w - Width of channel, in.

W - Relative weight of uranium per plate

X - Distance to point inside meat, measured from hot channel side perpendicular to plate, in.

ϕ - Thermal neutron flux

ρ - Water density, lb/in.³

Subscripts

a - Average conditions along length of channel

avg. - Average conditions across width of fuel plate meat

c - Clad

C - Contraction flow on entering channel

E - Expansion flow on leaving channel

SYMBOLS AND NOMENCLATURE (CONT.)

Subscripts (Cont.)

- f - Water film
- h - Hot channel conditions
- l - Local conditions along length of channel
- m - Meat of fuel element
- n - Nominal conditions
- o - Outside channel (adjacent to hot channel)
- p - Peak meat temperature
- ΔT - Temperature gradient across water film
- TR - Bulk temperature rise of channel flow
- w - Water

6.1.1 Plate Spacing Deviation Factors

(a) Average Hot Channel Factor

A flow passage may be restricted by plate bowing or sagging in the center, or by deviations in the plate edge spacing, the latter case being the most severe, thermally.

Nominal Channel

Average Hot Condition

The reduction in flow area = aw

$$A_n = dw$$

$$A_{ha} = dw - aw = (d-a) w$$

$$D_n = \frac{4 A_n}{P_n} = \frac{4 dw}{2(d+w)} = \frac{2dw}{d+w}$$

$$D_{ha} = \frac{4 A_{ha}}{P_{ha}} = \frac{4(d-a)w}{2(w+d-a)}$$

As the pressure drop ΔP across each channel of the same element is essentially equal and as contraction and expansion coefficients for the channels are negligible, velocity variation is only a function of the average hydraulic diameter deviation.

$$P = \frac{V^2}{12(2g)} \left[C_c + f \frac{L}{D} + C_E \right]$$

where C_c and C_E are essentially zero.

$$\frac{V_n^2}{V_{ha}^2} = \frac{D_n}{D_{ha}} = \frac{d}{(d+w)} \times \frac{(w+d-a)}{(d-a)}$$

$$\frac{V_n}{V_{ha}} = \sqrt{\frac{d(w+d-a)}{(d+w)(d-a)}}$$

$$F_{TR} = \frac{(TR)_{ha}}{(TR)_n} = \frac{A_n}{A_{ha}} \frac{V_n}{V_{ha}}$$

$$F_{TR} = \left(\frac{d}{d-a} \right)^{3/2} \left(\frac{d+w-a}{d+w} \right)^{1/2}$$

Substituting the numerical values applicable for previous
APPR elements:

$$d = .133''$$

$$a = .006'' \text{ (min. average deviation)}$$

$$w = 2.733''$$

$$F_{TR} = 1.0706$$

(b) Local Hot Channel Factor

In defining the worst possible channel, thermally, the conservative approach is taken of considering that the average deviation could be the negative observed limit, while a local deviation could simultaneously be at the positive observed limit in the same channel.

$$A_n = dw$$

$$A_{hl} = (d + b)w$$

$$\frac{D_{hl}}{D_n} = \frac{A_{hl}}{A_n} = \frac{d + b}{d}$$

The local deviation is assumed to be sufficiently gradual to permit complete diffusion.

$$\frac{V_n}{V_{hl}} = \frac{V_n}{V_{ha}} \times \frac{V_{ha}}{V_{hl}} = \frac{(d + b)}{(d - a)^{3/2}} \sqrt{\frac{d(d + w - a)}{(d + w)}}$$

The film coefficient is reduced not only by the drop in coolant velocity but also by the increase in hydraulic diameter:

$$h = .021 \frac{K}{D} \left(\frac{\rho VD}{\mu} \right)^{0.8} \left(\frac{C_p \mu}{K} \right)^{0.4}$$

$$\begin{aligned} F_{\Delta T} &= \frac{\Delta T_{hl}}{\Delta T_h} = \frac{h_n}{h_{hl}} \\ &= \left(\frac{V_n}{V_{hl}} \right)^{0.8} \left(\frac{D_{hl}}{D_n} \right)^{0.2} \\ &= \frac{(d+b)^{0.8}}{(d-a)^{1.2}} \left[\frac{d(d+w-a)}{(d+w)} \right]^{0.4} \left(\frac{d+b}{d} \right)^{0.2} \\ F_{\Delta T} &= d^{0.2} \frac{(d+b)}{(d-a)^{1.2}} \left(\frac{d+w-a}{d+w} \right)^{0.4} \end{aligned}$$

Substituting values for previous APPR elements:

$$b = .0133''$$

$$F_{\Delta T} = 1.1623$$

6.1.2 Uranium Content Deviation

(a) Average Hot Channel Factor

Both fuel elements forming the hot channel are assumed to contain the maximum allowable uranium content per plate.

$$F_{TR} = \frac{TR_{ha}}{TR_n} = \frac{W_{ha}}{W_n}$$

The maximum allowable positive deviation of uranium content per plate has been 0.5%.

$$F_{TR} = \frac{W_n (1 + .005)}{W_n} = 1.0050$$

(b) Local Hot Channel Factor

$$F_{\Delta T} = \frac{\Delta T_h}{\Delta T_n} = \frac{W_{hl}}{W_n}$$

In addition to the 0.5% uranium content deviation per plate, there has been a maximum allowable non-homogeneity within a plate of 2%. Assuming, conservatively, that the maximum positive deviation per plate and the maximum positive non-homogeneity deviation occur simultaneously, the maximum local uranium content deviation is 2.5%.

$$F_{\Delta T} = \frac{W_n (1 + .025)}{W_n} = 1.0250$$

6.1.3 Active Core Length Deviation

For a given volume of meat per plate, a negative deviation in active length increases the amount of meat per unit length and therefore per unit heat transfer area. This affects both the bulk coolant temperature rise and the film gradient. Based on the conservative approach that decreased length increases only meat thickness and not active width:

$$F_{TR} = F_{\Delta T} = \frac{L_n}{L_{min}}$$

for APPR fuel elements:

$$L_n = 21.75''$$

$$L_{min} = 21''$$

$$F_{TR} = F_{\Delta T} = \frac{21.75}{21} = 1.0357$$

It may be noticed that since the nominal meat width is also the minimum meat width, a corresponding calculation is not necessary for active width deviation.

6.1.4 Clad Thickness Deviation Factors

Derivation of General Equations

If the two clad thicknesses of a fuel plate are unequal, a greater portion of the total heat generated in the meat will pass out through the thinner clad because of lower thermal resistance. A hot channel is, therefore, defined as being composed of two fuel plates whose inner and outer clad thicknesses are at the minimum and maximum observed values respectively. Both the average and local hot channel factors are then equal to the proportional increase in the heat transmitted through the inner sides.

A cross section of the hot channel fuel plate is shown in the diagram below. The water temperatures are conservatively assumed equal.

The determination of hot channel factors is derived in the following steps.

- a) Determine the general differential equation for the temperature distribution through the meat as a volume heat source.
- b) Determine the general solution for step (a). Substituting boundary conditions, solve for the general constants of integration.

- c) Determine the location of the temperature peak by setting slope of temperature curve equal to zero. Portion the heat flow through two clads accordingly, in terms of meat boundary conditions.
- d) Determine the temperature gradient through each clad and water film combination, using the results of step (c). The meat boundary conditions are then defined in terms of physical dimensions and properties.
- e) Substitute the meat boundary conditions as determined by step (d) into the expressions for proportioning of heat flow as determined in step (c). The hot channel factor is then simply the ratio of the hot channel side flow to the average or nominal flow.
- (a) The general differential equation for temperature distribution through a volume heat source is determined as follows:

$$q_{in} = -K_m \left(\frac{dt_m}{dx} \right)_x$$

$$q_{out} = -K_m \left(\frac{dt_m}{dx} \right)_{x+dx}$$

$$q_{out} - q_{in} = Q dx$$

$$\left(\frac{dt_m}{dx} \right)_{x+dx} = \left(\frac{dt_m}{dx} \right)_x + \left(\frac{d^2 t_m}{dx^2} \right) dx$$

By proper substitution and simplification:

$$q_{out} - q_{in} = -K_m \left(\frac{dt_m}{dx} \right)_{x+dx} + K_m \left(\frac{dt_m}{dx} \right)_x$$

$$Q dx = -K_m \left[\left(\frac{dt_m}{dx} \right)_x + \left(\frac{d^2 t_m}{dx^2} \right) dx \right] + K_m \left(\frac{dt_m}{dx} \right)_x$$

$$Q dx = -K_m \left(\frac{d^2 t_m}{dx^2} \right) dx$$

$$\frac{d^2 t_m}{dx^2} = - \frac{Q}{K_m}$$

(b) The differential equation is solved by the reduction of order method:

$$\text{Let } \frac{dt_m}{dx} = y; \quad \text{Then } \frac{dy}{dx} = -\frac{Q}{K_m}$$

$$\int dy = -\frac{Q}{K_m} \int dx$$

$$\frac{dt_m}{dx} = -\frac{Q}{K_m} x + C_1$$

$$\int dt_m = -\frac{Q}{K_m} x dx + C_1 \int dx$$

$$t_m = -\frac{Q}{2K_m} x^2 + C_1 x + C_2$$

Boundary conditions (see Figure):

$$x = 0 ; \quad T_m = T_2$$

$$x = t_m ; \quad T_m = T_3$$

By substitution of boundary conditions into the general solution:

$$T_2 = c_2$$

$$T_3 = -\frac{Q}{2K_m} t_m^2 + c_1 t_m = T_2$$

$$c_1 = \frac{T_3 - T_2}{t_m} + \frac{Qt_m}{2K_m}$$

Substituting these results to obtain the specific solution:

$$T_m = -\frac{Q}{2K_m} x^2 + \left[\frac{T_3 - T_2}{t_m} + \frac{Qt_m}{2K_m} \right] x + T_2$$

- (c) To find the point of temperature peaking, and therefore the point of direction change in heat transfer, determine t_p where $\frac{dT_m}{dx} = 0$:

$$\frac{dT_m}{dx} = -\frac{Q}{K_m} t_p + \frac{T_3 - T_2}{t_m} + \frac{Qt_m}{2K_m} = 0$$

$$t_p = \frac{t_m}{2} + \frac{K_m}{Qt_m} (T_3 - T_2)$$

It is seen from this expression for t_p that the peak temperature normally occurs in the center of the meat, but that a correction is necessary with unequal sink temperatures. This is, of course, as expected. As heat generation per unit volume is uniform, the fraction of the total heat flow that is leaving the fuel plate on the hot channel side is equal to t_p/t_m . Therefore:

$$\begin{aligned} q_h &= Q t_p \\ &= \frac{Qt_m}{2} + \frac{K_m}{t_m} (T_3 - T_2) \end{aligned}$$

$$\begin{aligned} q_o &= Q (t_m - t_p) \\ &= \frac{Qt_m}{2} - \frac{K_m}{t_m} (T_3 - T_2) \end{aligned}$$

- (d) Since an expression is available for the heat flow rate through the clad and water film on either side, the corresponding temperature gradients can be determined:

$$T_2 - T_w = q_h \left(\frac{1}{h_{ch}} + \frac{1}{h_f} \right)$$

$$= q_h \left(\frac{t_{ch}}{K_c} + \frac{1}{h_f} \right)$$

Similarly for the other plate side:

$$T_3 - T_w = q_o \left(\frac{t_c}{K_c} + \frac{1}{h_f} \right)$$

By subtraction and substitution for q_o :

$$T_3 - T_2 = q_h \left[\frac{t_{co}}{k_c} + \frac{1}{h_f} \right] - q_h \left[\frac{t_{ch}}{k_c} + \frac{1}{h_f} \right]$$

$$T_3 - T_2 = \left[Qt_m - q_h \right] \left[\frac{t_{co}}{k_c} + \frac{1}{h_f} \right] - q_h \left[\frac{t_{ch}}{k_c} + \frac{1}{h_f} \right]$$

$$T_3 - T_2 = Qt_m \left[\frac{t_{co}}{k_c} + \frac{1}{h_f} \right] - q_h \left[\frac{t_{ch}}{k_c} + \frac{2}{h_f} + \frac{t_{co}}{k_c} \right]$$

For convenience in handling, this latter expression will be written as:

$$T_3 - T_2 = Qt_m \alpha - q_h \beta ; \quad \alpha = \frac{t_{co}}{k_c} + \frac{1}{h_f}$$

$$\beta = \frac{t_{co}}{k_c} + \frac{t_{ch}}{k_c} + \frac{2}{h_f}$$

- (e) The final expression for q_h can now be determined by substituting this final relationship in paragraph (d) for $T_3 - T_2$ into the equation for q_h in paragraph (c):

$$\begin{aligned} q_h &= \frac{Qt_m}{2} + \frac{K_m}{t_m} (T_3 - T_2) \\ &= \frac{Qt_m}{2} + \frac{K_m}{t_m} (QL_m \alpha - q_h \beta) \\ &= \frac{\frac{Qt_m}{2} + QK_m \alpha}{\frac{K_m}{t_m} \beta + 1} \end{aligned}$$

The hot channel factor is now determined by dividing the maximum by the nominal heat flux

$$F = \frac{q_h}{q_n} = \frac{\frac{\frac{Qt_m}{2} + QK_m \alpha}{\frac{K_m}{t_m} \beta + 1}}{\frac{Qt_m}{2}}$$

$$F = \frac{Qt_m + 2QK_m}{2} \cdot \frac{t_m}{K_m \beta + t_m} \cdot \frac{2}{Qt_m}$$

$$F = \frac{t_m + 2K_m \alpha}{t_m + K_m \beta} ; \quad \alpha = \frac{t_{co}}{k_c} + \frac{1}{h_f}$$

$$\beta = \frac{t_{co}}{k_c} + \frac{t_{ch}}{k_c} + \frac{2}{h_f}$$

It is seen that when the two clad thicknesses t_{co} and t_{ch} are equal, then $\beta = 2\alpha$, and $F = 1$ as expected.

(a) Average Hot Channel Factor

The following numerical values are applicable for previous APPR elements:

$$t_m = .0200 \text{ in. (nominal)}$$

$$t_{ch} = .0045 \text{ in. (minimum average)}$$

$$t_{co} = .0055 \text{ in. (maximum average)}$$

$$k_m = .000205 \text{ Btu/in. } ^\circ\text{F sec (at } 600^\circ\text{F)}$$

$$k_c = .000274 \text{ Btu/in. } ^\circ\text{F sec (at } 600^\circ\text{F)}$$

$$h_f^* = .00459 \text{ Btu/in.}^2 \text{ } ^\circ\text{F sec}$$

By computation:

$$\alpha = 237.94 \text{ in.}^2 - ^\circ\text{F} - \text{sec/Btu}$$

$$\beta = 472.23 \text{ in.}^2 - ^\circ\text{F} - \text{sec/Btu}$$

Substituting into the expression for hot channel factors developed in section (a):

$$F_{TR} = \frac{TR_h}{TR_n} \frac{q_h}{q_n} \frac{t_m + 2 k_m \alpha}{t_m + k_m \beta}$$

$$F_{TR} = 1.0064$$

- * To be precisely correct, h_f would have to be re-evaluated for each new core and for each element within the core. However, as even a large change in h_f has an insignificant effect on required flow, an average value is used.

(b) Local Hot Channel Factor

The following numerical values are applicable for the local factor:

$$t_{ch} = .0040 \text{ in. (minimum local)}$$

$$t_{co} = .0060 \text{ in. (maximum local)}$$

By computation:

$$\alpha = 239.76 \text{ in.}^2 - ^\circ\text{F} - \text{sec/Btu}$$

$$\beta = 472.23 \text{ in.}^2 - ^\circ\text{F} - \text{sec/Btu}$$

Substituting into the expression for hot channel factors:

$$F_{\Delta T} = \frac{\Delta T_h}{\Delta T_n} = \frac{q_h}{q_n} = \frac{t_m + 2 K_m \alpha}{t_m + K_m \beta}$$

$$F = 1.0128$$

6.1.5 Orifice Sizing Factors

The orifice diameter required to yield a given flow rate for a particular fuel element will be determined by a flow test rig. Some flow deviation allowance must be made for instrument error and experimental accuracy. As the calculated value of the proper orifice diameter is expressed to the nearest 1/64" for machining purposes, an additional deviation allowance must be introduced. Experience with the APPR-1 demonstrates that a combined maximum deviation of $\pm 4\%$ is sufficient for both stationary element and control rod flow.

The hot channel factors associated with a 4% reduction in flow from an undersized orifice are determined in a manner similar to that used for the factors associated with plate spacing deviation with the exception that no change in the channel flow area is considered.

(a) Average Hot Channel Factor

$$F_{TR} = \frac{TR_h}{TR_n} = \frac{V_n}{V_h}$$

$$F_{TR} = \frac{V_n}{V_n (1 - .04)} = 1.0417$$

(b) Local Hot Channel Factor

$$F_{\Delta T} = \frac{\Delta T_h}{\Delta T_n} = \frac{h_n}{h_h} = \left(\frac{V_n}{V_h} \right)^{0.8}$$

$$F_{\Delta T} = \left[\frac{V_n}{V_n (1 - .04)} \right]^{0.8} = 1.0332$$

6.1.6 Inlet Box Effect on Flow Distribution

An allowance is made for uneven flow distribution on leaving the fuel element inlet boxes. For stationary elements, the outer channel flow was assumed to be 3% below average. For control rods the outer channel flow was assumed to be 6% below average. Further investigation of this subject is intended.

(a) Average Hot Channel Factor

$$F_{TR} = \frac{TR_h}{TR_n} = \frac{V_n}{V_h}$$

$$(F_{TR})_{F.E.} = \frac{V_n}{V_n (1 - .03)} = 1.0309$$

$$(F_{TR})_{C.R.} = \frac{V_n}{V_n (1 - .06)} = 1.0638$$

(b) Local Hot Channel Factor

$$F_{\Delta T} = \frac{\Delta T_h}{\Delta T_n} = \frac{h_n}{h_h} = \left(\frac{V_n}{V_h} \right)^{0.8}$$

$$(F_{\Delta T})_{F.E.} = \left[\frac{V_n}{V_n (1 - .03)} \right]^{0.8} = 1.0247$$

$$(F_{\Delta T})_{C.R.} = \left[\frac{V_n}{V_n (1 - .06)} \right]^{0.8} = 1.0507$$

6.2 Lattice Requirement Determination

The manufacturing tolerances for the lattice passages are, by necessity broader than those for the internal passages.

Since the larger lattice tolerances are a result of misalignment of entire elements rather than warping of individual plates, it is not possible for the average and local deviations to be in opposite directions. As the pressure drops across the various lattice channels are essentially equal, velocity variation is a function only of average hydraulic diameter deviation.

$$\frac{V_n^2}{V_h^2} = \frac{D_n}{D_h}$$

Since the effect on required flow of increased bulk coolant temperature rise hot channel factors is insignificant in comparison with the effect of increased film gradient hot channel factors, only the latter will be derived here.

$$h = .021 \frac{K}{D} \left(\frac{\rho V D}{\mu} \right)^{0.8} \left(\frac{C_p \mu}{K} \right)^{0.4}$$

$$F_{\Delta T} = \frac{\Delta T_h}{\Delta T_n} = \frac{h_n}{h_h} = \left(\frac{V_n}{V_h} \right)^{0.8} \times \left(\frac{D_h}{D_n} \right)^{0.2}$$

$$= \left(\frac{D_n}{D_h} \right)^{0.4} \times \left(\frac{D_h}{D_n} \right)^{0.2}$$

$$F_{\Delta T} = \left(\frac{D_n}{D_h} \right)^{0.2}$$

Nominal Channel

Hot Channel

$$A_n = dw$$

$$; F_{\Delta T} = \left(\frac{d}{d-a} \right) \left(\frac{d+w-a}{d+w} \right)$$

$$A_h = (d-a)w$$

$$D_n = 4 A_n / p_n = \frac{2dw}{(d+w)}$$

$$D_h = 4 A_h / p_h = \frac{2(d-a)w}{d+w-a}$$

Between two fuel elements:

$$F_{\Delta T} = 1.033$$

Between fuel element and control rod basket

$$F_{\Delta T} = 1.019$$

It is therefore considered conservative to base the lattice flow on an average velocity 5% greater than the largest internal fuel element velocity.

6.3 Heat Release Distribution

The direct fission energy has the following distribution (Proceedings of the Symposium on the Physics of Fission held at Chalk River, Ontario, May 14-18, 1956. Session C, CRP-642-A (July 1956).

<u>Source</u>	CRP-642A
<u>Energy</u>	1956
KE of Fission Fragments	167.1 $\pm$ 2 Mev
KE of Fast Neutrons	5 $\pm$ 0.5 Mev
Prompt Gamma Rays	7 $\rightarrow$ 12 Mev
Fission Product Gamma Rays	7.5 Mev
Beta Decay Energy	5.5 Mev
	} $\pm$ 2 Mev
Totals	192.1 + 9.5 - 4.5 Mev

It may be expected that most of the energy of the fast neutrons (5 Mev fissions) is released in the water moderator. Also a large fraction of the prompt gamma rays will be released in the fuel element side plates, end boxes, thermal shield, etc. In addition, there is a net energy gain in the n, γ reactions in materials other than the fuel plates. Calculation for the MTR (An Estimate of the Heat

Generation and Distribution in the MTR, R. A. Gremesey, IDO-16443) indicates that only 90% of the heat generated is released in the fuel elements. Until detail heat generation and distribution are available for a particular design, a heat generation rate of 0.95 times the maximum expected shall be used as a basis for thermal design.

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