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ABSTRACT

The steady-state thermal-hydraulic safety margins and maximum allowed power were calculated using the PLTEMP/ANL code, for the HEU and LEU cores of a generic Miniature Neutron Source Reactor (MNSR) that operates by natural circulation flow through an array of fuel rods. Three global hot channel factors (HCFs) and 3 local random factors were used in this calculation to account for typical fuel fabrication tolerances and other thermal-hydraulic uncertainties. The local HCFs were estimated using equations relating them to the tolerances and uncertainties, which are derived and presented here. The local HCFs are different in natural circulation flow from those in forced flow, and different in rod geometry than in plate geometry. Typical values of power reactor fuel tolerances were used due to the unavailability of the tolerances specific to the fuel fabrication process for MNSRs. These HCF equations may be used for other research reactors that have rodded fuel and natural circulation flow without boiling.

1. Introduction

Six hot channel factors (defined below) are used in the PLTEMP/ANL V4.1 code to calculate research reactor safety margins. The hot channel factors for forced circulation over research reactor fuel plates have been formulated earlier[1,2]. However these factors are evaluated differently for reactors with natural circulation. The basic reason for this is that in natural circulation, the coolant flow is induced by the power produced in the pin (thus softening the effect of pin power on inlet-to-outlet coolant temperature rise) while in forced circulation, the pressure drop induces the coolant flow. The formulas for these factors are also different in pin geometry as compared to plate geometry.

System-wide or Global Hot Channel Factors:
FPOWER = a factor to account for the uncertainty in total reactor power
FFLOW = a factor to account for the uncertainty in total reactor flow
FNUSLT = a factor to account for the uncertainty in Nusselt number correlation

Local Hot Channel Factors:
FBULK = a hot channel factor for local bulk coolant temperature rise
FFILM = a hot channel factor for local temperature rise across the coolant film on cladding
FFLUX = a hot channel factor for local heat flux from cladding surface

2. Summary of Thermal-Hydraulic Calculations

The steady-state thermal-hydraulic safety margins and maximum allowed power were calculated for the HEU and LEU cores of a generic Miniature Neutron Source Reactor (MNSR). The calculations were done by the PLTEMP/ANL V4.1 code[1], using one-pin models of the core.

The reactor design data[3] used in the safety margin calculations are given in Table 1 and the power distribution in the HEU and LEU cores (Table 2) were calculated using the MCNP5 code[4]. The hydraulic resistance of the coolant flow circuit in the PLTEMP/ANL model was obtained by calibrating the model to reproduce an experimentally measured coolant temperature rise of 13 °C (from 24.5 °C to 37.5 °C) at a reactor power of 15 kW [Ref. 5, 6]. Using the calibrated model, the coolant inlet temperature was raised and adjusted to get an outlet temperature of 70 °C in steady-state at the nominal reactor power. The adjusted inlet temperature is given in Table 3. Using the adjusted inlet temperature, the allowed reactor power at the onset of nucleate boiling (ONBR = 1.0) on the peak power pin (without HCFs) was calculated to be 65.2 kW and 67.8 kW for the HEU and LEU cores.

Using the six hot channel factors shown in Table 1, the *true* maximum allowed reactor power at ONBR of 1.0 is found to be 51.2 kW and 53.0 kW for the HEU and LEU cores (see Table 3). These are *true* allowed power in the sense that there is no allowance in these values for any error in the power measuring instrument. The safety margins to flow instability and critical heat flux are also given in Table 3. The calculations were done using the Churchill-Chu heat transfer correlation[7].

The remainder of this paper presents the derivation of the equations relating the HCFs used in the above analysis to the manufacturing tolerances and other uncertainties for natural circulation over fuel pins. Table 4 shows the values and the sources of fuel fabrication tolerances and other uncertainties used, and the values of hot channel factors calculated for the HEU and LEU cores.

3. Method of Using the Hot Channel Factors in PLTEMP/ANL

The PLTEMP/ANL code obtains, for an input nominal reactor power P_{op}, a steady-state thermal-hydraulic solution using the three global hot channel factors FFLOW, FPOWER and FNUSLT. This calculation is done for a hot pin power of P_{op}*FPOWER*F_r/N (see nomenclature). Also, the channel flow rate is divided by FFLOW and the convective heat transfer coefficient found for laminar flow in the channel is divided by FNUSLT. The random hot channel factors FBULK, FFILM and FFLUX are applied to the coolant bulk temperature rise, coolant film temperature rise, and cladding wall heat flux obtained in the above solution.

4. Hot Channel Factors in Natural Circulation over Fuel Pins

4.1. Flow Rate in a Coolant Channel versus Power of a Fuel Pin

To find the hot channel factor for bulk coolant temperature rise in a channel (Fig. 1), first an analytical relationship is obtained for the natural circulation flow rate induced by the power of a fuel pin in a coolant channel (Fig. 2), and then an analytical relationship is derived for the bulk coolant temperature rise in the channel.

In the MNSR core, the pins are positioned in rings. Although the fuel pins are neither on a square lattice nor on a triangular lattice, the square lattice was assumed because the pin layout appears to be closer to a square lattice than to a triangular lattice. The pitch-to-pin diameter ratio in the square lattice is approximately 2.

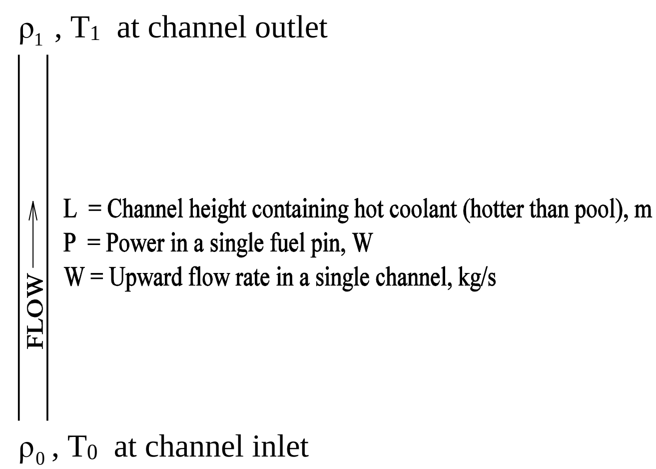

Fig. 1. Schematic of a single coolant channel heated by a fuel pin.

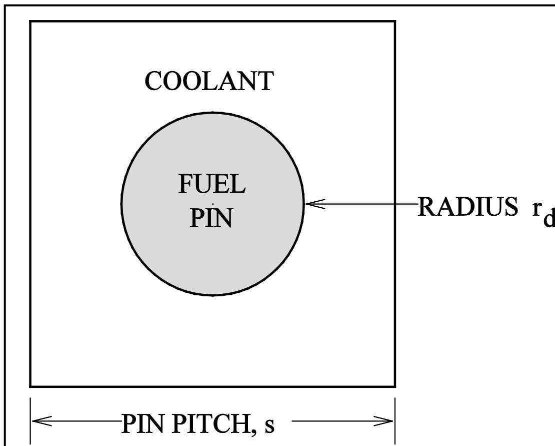

Fig. 2. Fuel Pin Lattice Assumed in Calculating Hot Channel Factors

The above schematics show a single coolant (water) channel heated by a fuel pin. The buoyancy force caused by the decrease in water density due to heating is given by Eq. (1). Over the limited temperature rise in the channel, the water density is given by Eq. (2), and the average coolant density can be approximated by Eq. (3). Equation (1) then reduces to Eq. (4). Equation (5) gives the coolant temperature rise ΔT in terms of the power P generated in a fuel pin. Using Eq. (5), Eq. (4) can be written in terms of the input power P, as shown by Eq. (6).

$$\text{Buoyancy}\,\Delta p = (\rho_0 - \bar{\rho})\, g\, L \tag{1}$$

$$\rho(T) = \rho_0 - \rho_0\, \beta\, (T - T_0) \tag{2}$$

$$\bar{\rho} = 0.5\,(\rho_0 + \rho_1) = \rho_0\,(1 - 0.5\beta\, \Delta T) \tag{3}$$

$$\text{Buoyancy}\,\Delta p = 0.5\rho_0\, \beta\, \Delta T\, g\, L \tag{4}$$

$$\Delta T = P/(W\, C_p) \tag{5}$$

$$\text{Buoyancy}\,\Delta p = \frac{\rho_0 \beta g L P}{2 W C_P} \qquad (6)$$

where

T_1	= Bulk water temperature at channel outlet, °C
ΔT	= T_1 - T_0 = Temperature rise in channel from inlet to outlet, °C
ρ_0	= Water density at channel inlet, i.e., the water density in the pool, kg/m^3
β	= Volumetric expansion coefficient of water, per °C
$\bar{\rho}$	= Average coolant density in the channel, kg/m^3
L	= Channel height that contains hotter coolant (hotter than pool), m.
g	= Acceleration due to gravity, 9.8 m/s^2

Ignoring the minor losses at channel inlet and outlet, the frictional pressure drop in the channel is given by Eq. (9) where the laminar Moody friction factor f = C / R_e and C is a channel cross section-dependent constant [Ref. 8, Chapter 5], e.g., C depends on the pitch/diameter ratio for a square lattice of fuel pins.

$$\text{Frictional}\ \Delta p = \frac{\bar{\rho} f L_C V^2}{2D} = \frac{C \bar{\mu} L_C W}{2 \bar{\rho} A D^2} \qquad (9)$$

where

R_e	= Reynolds number in the channel = $\bar{\rho}\,VD/\bar{\mu}$
A	= Flow area of the channel cross section, m^2
D	= Equivalent hydraulic diameter of the channel cross section, m
L_C	= Total coolant channel length causing frictional pressure drop, m.
V	= Coolant velocity averaged over the channel cross section, m/s
W	= Coolant mass flow rate in the channel, kg/s
$\bar{\mu}$	= Axially averaged coolant dynamic viscosity in the channel, N-s/m^2
$\mu(T)$	= Temperature-dependent dynamic viscosity of water, N-s/m^2
μ_0	= $\mu(T_0)$ = Coolant dynamic viscosity at the channel inlet temperature T_0

The temperature-dependent dynamic viscosity of water over the range 47 °C ≤ T ≤ 87 °C (adequate for the treatment of hot channel factors in the MNSR) can be written as Eq. (10). The average viscosity used in Eq. (9) is estimated by evaluating Eq. (10) at the average coolant temperature (T_0+0.5ΔT) in the channel (see Eq. (11). Putting Eq. (11) into Eq. (9), the frictional Δp is given by Eq. (12). Equating this frictional Δp to the buoyancy Δp of Eq. (6), the steady-state coolant flow rate W in the channel is given by Eq. (13).

$$\mu(T) = \mu(T_0)\,(1+T-T_0)^{-\alpha} \ \text{where}\ \alpha = 0.13,\ T_0 = 47\ °C,\ \mu(T_0) = 0.577\times10^{-3}\ \text{N-s/m}^2 \qquad (10)$$

$$\bar{\mu} = \mu(T_0)\,(1+0.5\Delta T)^{-\alpha} \approx \mu(T_0)\,(0.5\Delta T)^{-\alpha}\ \text{for}\ \Delta T >> 2\ °C^{1} \qquad (11)$$

[1] For MNSR, the temperature rise ΔT is much greater than 2°C

$$\text{Frictional }\Delta p = \frac{C\mu_0 L_C W}{2^{1-\alpha}\bar{\rho}AD^2}\left(\frac{WC_P}{P}\right)^{\alpha} \quad (12)$$

$$W^{2+\alpha} = \frac{\rho_0\bar{\rho}AD^2\beta gLP^{1+\alpha}}{2^{\alpha}C\mu_0 L_C C_P^{1+\alpha}} \quad (13)$$

Equation (13) relates the channel flow rate to the pin power. At constant power, all parameters in this equation are constant except the parameter C of the laminar friction factor. Therefore, the flow rate W is related to the parameter C by Eq. (14).

$$W \propto \left(\frac{1}{C}\right)^{1/(2+\alpha)} \quad (14)$$

4.2. Hot Channel Factor for Bulk Coolant Temperature Rise FBULK

To obtain a relationship that relates pin power and channel dimensions to the bulk temperature rise, Equations (5) and (13) are combined to give Eq. (15) f. The second factor in Eq. (15) is sensitive to pin power and channel geometrical dimensions that usually have manufacturing tolerances and measurement uncertainties, and the first factor is insensitive to power and channel geometrical dimensions. The ratio of bulk coolant temperature rise in the hot channel to the temperature rise in the nominal channel, caused by the uncertainties in power and channel geometry, is given by Eq. (16).

$$\Delta T = \left(\frac{2^{\alpha}C\mu_0 L_C}{C_P\,\rho_0\,\bar{\rho}\,\beta\,g\,L}\right)^{\frac{1}{2+\alpha}}\left(\frac{P}{AD^2}\right)^{\frac{1}{2+\alpha}} \quad (15)$$

$$\frac{\Delta T_{hc}}{\Delta T_{nc}} = \left(\frac{P_{hc}}{P_{nc}}\right)^{\frac{1}{2+\alpha}}\left[\frac{(AD^2)_{nc}}{(AD^2)_{hc}}\right]^{\frac{1}{2+\alpha}} \quad (16)$$

In order to evaluate the hot channel factor on bulk coolant temperature rise, it is necessary to evaluate the uncertainties on channel dimensions and pin power. This implies evaluating the uncertainties on (1) D, (2) AD^2, (3) r_c^2/r_d , and (4) U-235 mass per fuel pellet.

(1) The uncertainty in channel hydraulic diameter D is related to the uncertainties in pin radius and pitch by writing Eq. (17) based on Fig. 2, and getting the total differential of D, as given by Eq. (18). If the uncertainties of pin radius and pitch are combined statistically, the uncertainty $\delta D/D$ is given by Eq. (19).

$$D = \frac{4A}{P_w} = 2\left(\frac{s^2}{\pi\,r_d} - r_d\right) \quad (17)$$

$$\frac{\delta D}{D} = \frac{4s^2}{\pi\,r_d D}\frac{|\delta s|}{s} + \left(\frac{2s^2}{\pi\,r_d D} + \frac{2r_d}{D}\right)\frac{|\delta r_d|}{r_d} \quad (18)$$

$$u_{5d} = \frac{\delta D}{D} = \sqrt{\left(\frac{4 s^2}{\pi\, r_d D}\right)^2 u_{13}^2 + \left(\frac{2\, s^2}{\pi\, r_d D} + \frac{2\, r_d}{D}\right)^2 u_{12}^2} \tag{19}$$

(2) Similarly, the uncertainty in the quantity AD^2 is related to the uncertainties in pin radius and pitch by Eqs. (20) and (21). If the uncertainties of pin radius and pitch are combined statistically, the uncertainty in the quantity AD^2 is given by Eq. (22). The ratio of the nominal value of AD^2 to its value in hot channel, i.e., the ratio required in Eq. (16) is given by Eq. (23).

$$AD^2 = \frac{16 A^3}{P_w^2} = \frac{4}{\pi^2\, r_d^2}\left(s^2 - \pi\, r_d^2\right)^3 \tag{20}$$

$$\frac{\delta(AD^2)}{(AD^2)_{nc}} = \frac{8 A}{\pi\, r_d\, D^2}\left[\frac{3\, s^2}{\pi\, r_d}\frac{|\delta s|}{s} + \left(\frac{A}{\pi\, r_d} + 3\, r_d\right)\frac{|\delta r_d|}{r_d}\right] \tag{21}$$

$$u_{5a} = \frac{\delta(AD^2)}{(AD^2)_{nc}} = \frac{8 A}{\pi\, r_d\, D^2}\sqrt{\left(\frac{3\, s^2}{\pi\, r_d}\right)^2 u_{13}^2 + \left(\frac{A}{\pi\, r_d} + 3\, r_d\right)^2 u_{12}^2} \tag{22}$$

$$\frac{(AD^2)_{nc}}{(AD^2)_{hc}} = \frac{1}{1 - \dfrac{\delta(AD^2)}{(AD^2)_{nc}}} = \frac{1}{1 - u_{5a}} \tag{23}$$

(3) The uncertainty in the quantity r_c^2/r_d is given by Eq. (24) with the assumption that the cladding thickness remains unchanged, i.e., a change δr_c in the meat radius is accompanied by an equal change δr_d in the cladding outer radius r_d.

$$f = \frac{r_c^2}{r_d}, \qquad \frac{\delta f}{f} = (2 - r_c/r_d)\, u_3 \tag{24}$$

(4) The mass of U-235 per fuel pellet is given by Eq. (25), and its fractional uncertainty u_4 is given by Eq. (26). The uncertainty u_4 is a local uncertainty which exits in addition to the uncertainty in the mass of U-235 per pin.

$$m = \pi\, r_c^2\, L_p\, \rho\, f_U\, e \tag{25}$$

$$\frac{\delta m}{m} = u_4 = 2\frac{\delta\, r_c}{r_c} + \frac{\delta \rho}{\rho} + \frac{\delta\, e}{e}, \quad \text{or } \sqrt{4\, u_3^2 + u_{11}^2 + u_{10}^2} \text{ when combined statistically} \tag{26}$$

where

e	= Enrichment of U in a fuel pellet, weight fraction
f_U	= Mass fraction U in the UO_2 mass in a fuel pellet
L_p	= Axial length of fuel pellet, m
r_c	= Nominal fuel pellet or meat radius, m
ρ	= Density of fuel (UO_2) in a pellet, kg/m^3
u_4	= Fractional uncertainty of U-235 local homogeneity

In Eq. (16), the ratio of the power generated in the hot pin to its nominal power, caused by the uncertainties in neutronics-computed power and in U-235 mass per pin, can be written as Eq. (27). Using Eqs. (23) and (27), Eq. (16) is written as Eq. (28). In Eq. (28), the local random uncertainties (u_1, u_2 and u_{5a}) are combined multiplicatively. If they are combined statistically, Eq. (28) simplifies to Eq. (29). The uncertainty in flow per fuel pin due to flow redistribution is assumed to reduce the channel flow to (1- u_6) times the flow without this uncertainty, and therefore the bulk coolant temperature rise is increased by the factor (1+ u_6). This uncertainty in bulk coolant temperature rise is statistically combined with that given by Eq. (29) to obtain Eq. (30) for the hot channel factor FBULK.

$$\frac{P_{hc}}{P_{nc}} = (1+u_1)(1+u_2) \tag{27}$$

$$\frac{\Delta T_{hc}}{\Delta T_{nc}} = \left[\frac{(1+u_1)(1+u_2)}{1-u_{5a}}\right]^{\frac{1}{2+\alpha}} \tag{28}$$

$$\frac{\Delta T_{hc}}{\Delta T_{nc}} = 1 + \frac{\sqrt{u_1^2+u_2^2+u_{5a}^2}}{2+\alpha} \tag{29}$$

$$\text{FBULK} = 1 + \sqrt{\frac{u_1^2+u_2^2+u_{5a}^2}{(2+\alpha)^2} + u_6^{\,2}} \tag{30}$$

<u>4.3. Hot Channel Factors for Temperature Drop Across Coolant Film FFILM</u>:

The temperature drop across coolant film on the cladding surface at an axial location is given by Eq. (31). The cladding surface heat flux q’’ (W/m^2) is replaced here by r_c^2 q’’’/(2 r_d) in terms of the volumetric power density q’’’ (W/m^3) in the fuel meat.

$$\Delta T_{film} = \frac{q''}{h} = \frac{r_c^2 q'''}{2\, r_d h} \tag{31}$$

The convective heat transfer coefficient h (W/m^2-C) is given by Eq. (32). In natural circulation or in developing laminar flow in the entrance length of a coolant channel in MNSR, Nu = C_1 Ra^b where Ra is Rayleigh number and the exponent b = 1/4 to 1/3. The Rayleigh number is directly proportional to ΔT_{film} and therefore, Nu = C_2 $(\Delta T_{film})^b$. In fully-developed laminar flow, the Nusselt number Nu is independent of flow rate; the main variation of heat transfer coefficient is due to the hydraulic diameter D in the denominator of Eq. (32); and b = 0. Using Eq. (32), Eq. (31) becomes Eq. (33). Taking the natural logarithm of Eq. (33) and writing the differential of the resulting equation, the fractional uncertainty of ΔT_{film} is given by Eq. (34) (ignoring the variation of coolant thermal conductivity K_{cool}).

$$h = \frac{Nu\, K_{cool}}{D} = \frac{C_2\,(\Delta T_{film})^b\, K_{cool}}{D} \tag{32}$$

$$(\Delta T_{film})^{1+b} = \frac{q'''D}{2\, C_2\, K_{cool}} \frac{r_c^2}{r_d} \tag{33}$$

$$\frac{\delta(\Delta T_{film})}{\Delta T_{film}} = \frac{1}{1+b}\left[\left|\frac{\delta q'''}{q'''}\right| + \left|\frac{\delta D}{D}\right| + \left|\frac{\delta f}{f}\right|\right] \qquad \text{where } f = \frac{r_c^2}{r_d} \tag{34}$$

Equation (34) states that the uncertainty of ΔT_{film} consists of 3 parts: (i) the hydraulic diameter D uncertainty u_{5d} given by Eq. (19), (ii) the uncertainty in the quantity r_c^2/r_d given by Eq. (24), and (iii) the uncertainty in meat power density q'''. The uncertainty in q''' is in turn caused by three uncertainties, u_1, u_2 and u_4. Statistically combining these five uncertainties gives the following formula for the hot channel factor FFILM. The uncertainty in the heat flux at the cladding surface is included in this formula. For conservative calculations, the parameter b is set to zero in this work, thus getting a little higher value of FFILM.

$$\mathrm{FFILM} = 1 + \frac{\sqrt{u_1{}^2 + u_2{}^2 + (2 - r_c/r_d)^2\, u_3{}^2 + u_4{}^2 + u_{5d}{}^2}}{1 + b} \tag{35}$$

4.4. Hot Channel Factors for Heat Flux FFLUX

A hot channel factor FFLUX for the heat flux is found from Eq. (36) for heat flux in terms of the power density q''' in the fuel meat. The fractional uncertainty in heat flux is given by Eq. (37), i.e., the statistical sum of fractional uncertainties in power density and in the quantity r_c^2/r_d. The uncertainty in power density is caused by three uncertainties, that is, u_1, u_2 and u_4. Statistically combining the four uncertainties of Eq. (37), the formula for the hot channel factor FFLUX is given by Eq. (38).

$$q'' = \frac{q'''\, r_c^2}{2\, r_d} \tag{36}$$

$$\frac{\delta q''}{q''} = \frac{\delta q'''}{q'''} + \frac{\delta(r_c^2/r_d)}{(r_c^2/r_d)} = \frac{\delta q'''}{q'''} + \left(2 - \frac{r_c}{r_d}\right) u_3 \tag{37}$$

$$\mathrm{FFLUX} = 1 + \sqrt{u_1{}^2 + u_2{}^2 + (2 - r_c/r_d)^2\, u_3{}^2 + u_4{}^2} \tag{38}$$

4.5. Global Hot Channel Factors FPOWER, FFLOW and FNUSLT

The six hot channel factors (three global/system-wide and three local/random) are obtained from 11 manufacturing tolerances and measurement (fractional) uncertainties u_1, u_2, u_3, and u_6 to u_{13} that are defined in Table 1. Of these 11 uncertainties, those affecting a particular hot channel factor are indicated in Table 4. The system-wide hot channel factors are given by Eqs. (39) to (41).

$$\mathrm{FPOWER} = 1 + u_7 \tag{39}$$
$$\mathrm{FFLOW} = 1 + u_8 \tag{40}$$
$$\mathrm{FNUSLT} = 1 + u_9 \tag{41}$$

5. Conclusions

Equations (30), (35), and (38) to (41) for estimating 3 local and 3 global hot channel factors for a test reactor using rodded fuel cooled by natural circulation are derived and used in the steady-state thermal-hydraulics code PLTEMP/ANL to calculate the maximum allowed reactor power at the onset of nucleate boiling and other safety margins of a generic MNSR.

NOMENCLATURE

C **=** Channel cross section-dependent constant in laminar friction factor $f = C / R_e$
F_r = Radial power factor of the fuel pin cooled by the channel
N = Number of fuel pins in the core
P_w = Wetted perimeter of the nominal channel, m
P_{nc} = Power generated in a fuel pin, without applying manufacturing tolerances, W
P_{hc} = Power generated in a fuel pin, after applying manufacturing tolerances, W
u_1 = Fractional uncertainty of local power density in a fuel pin
u_2 = Fractional uncertainty of U-235 mass per pin
u_3 = Fractional uncertainty of local (at an axial position) fuel meat radius = $\delta r_c/r_c$
u_6 = Fractional uncertainty of channel flow due to flow redistribution among channels.
u_7 = Fractional uncertainty in reactor power measurement
u_8 = Fractional uncertainty in channel flow due to uncertainty in friction factor
u_9 = Fractional uncertainty in the Nu number correlation
u_{10} = Fractional uncertainty of U enrichment in a pellet
u_{11} = Fractional uncertainty of density of fuel (UO_2) in a pellet
u_{12} = Fractional uncertainty of fuel pin radius = $\delta r_d/r_d$
u_{13} = Fractional uncertainty of pitch or spacing between fuel pins
$_{nc}$ = Subscript for the nominal value of a parameter
$_{hc}$ = Subscript for the minimum or maximum value of the parameter in hot channel

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Table 1. Thermal-Hydraulics Data Used for Steady-State Analysis of a Generic MNSR

	Generic MNSR	
Thermal Hydraulics Data	**HEU**	**LEU**
Nominal Reactor Power, kW	30	34
Number of Fuel Pins in Reactor	345	348
Peak Pin Power, W	99.66	113.19
Average Pin Power, W	86.96	97.70
Peak Pin/Average Pin Power Ratio	1.1461 ±0.3% (3σ)	1.1586 ±0.3% (3σ)
Fuel Meat	U-Al alloy	UO_2
Uranium enrichment	90.2 %	12.5
U wt % in Fuel Meat	27.5	
Cladding Material	Al alloy	Zircaloy-4
Gas in Meat-Cladding Gap	-	He
Meat Radius, mm	2.15	2.15
Gas Gap Thickness, mm	-	0.05
Cladding Thickness, mm	0.6	0.6
Fueled Length, m	0.230	0.230
Gap Thermal Resistance, m^2-C/W	-	~ 0.000283
Depth of Water Above Core Top, m	4.7	4.7
Pressure at Core Top, MPa	0.1468	0.1468
Adjusted Inlet Temperature, °C	53.78	52.28
(1) Global HCF: FPOWER [1]	1.150	1.162
(2) Global HCF: FFLOW	1.039	1.039
(3) Global HCF: FNUSLT	1.130	1.130
(4) Local HCF: FBULK	1.081	1.081
(5) Local HCF: FFILM	1.109	1.115
(6) Local HCF: FFLUX	1.109	1.115

1. FPOWER = Uncertainty in **true power** = (Peak pin-to-average pin power ratio) x (1.003 representing 3-sigma uncertainty, 0.3 % , in MCNP statistics for the calculated peak pin power).

Table 2. Axial Power Profiles of the Peak and Average Power Pins in HEU and LEU Cores

Axial Segment	Peak Pin		Average Pin	
	LEU348 @ 34 kW	HEU345 @ 30 kW	LEU348 @ 34 kW	HEU345 @ 30 kW
-10.35	11.55	10.03	9.66	8.59
-8.05	11.39	10.11	9.62	8.56
-5.75	12.21	10.84	10.34	9.20
-3.45	12.95	11.24	10.85	9.64
-1.15	12.90	11.20	10.98	9.76
1.15	12.29	10.77	10.73	9.55
3.45	11.46	10.15	10.10	9.00
5.75	10.33	9.18	9.15	8.15
8.05	8.99	7.99	8.06	7.18
10.35	9.11	8.14	8.22	7.33
Pin Total, W	113.19	99.66	97.70	86.95

Table 3. Results of the Steady-State Analysis of a Generic MNSR at $ONBR_{min}$ of 1.0 with All HCFs

	Generic MNSR	
	HEU	**LEU**
Reactor Power at Min. ONBR=1 with All HCF	51.2	53.0
Location of Min. ONBR	Node 10	Node 10
ONB Temp. at the Location of Min. ONBR	112.7	112.7
Flow Instability Power Ratio	2.02	2.00
CHFR Minimum	8.9	8.5
Critical Heat Flux, MW/m^2	0.48	0.48
Flow Rate in Hot Channel, kg/s	0.00157	0.00157
Coolant Velocity in Hot Channel, m/s	0.0160	0.0160
Channel Outlet Temperature, °C	81.7	81.2
Max. Cladding Surface Temp., °C	112.7	112.7
Max. Fuel Centerline Temp., °C	113.9	145.2

Table 4. Uncertainties Included in the Six Hot Channel Factors
(X implies that an uncertainty affects a hot channel factor)

	Uncertainty Type	Fractional Value	FPOWER	FFLOW	FNUSLT	FBULK	FFILM	FFLUX
LOCAL OR RANDOM UNCERTAINTIES								
1	Neutronics calculation of power density in a pin, u_1	0.10 [1]				X	X	X
2	U-235 mass per pin, u_2	0.03 [2]				X	X	X
3	UO_2 pellet radius, u_3	0.003 [3]					X	X
4	U enrichment in a pellet, u_{10}	0.016 [3]					X	X
5	UO_2 pellet density, u_{11}	0.044 [3]					X	X
6	Fuel pin radius, u_{12}	0.003 [3]				X	X	X
7	Fuel pin pitch, u_{13}	0.003 [4]				X	X	
8	Flow redistribution among channels, u_6	0.064 [5]				X		
SYSTEM-WIDE UNCERTAINTIES								
9	Reactor power measurement uncertainty, u_7	0.003 [6]	X					
10	Flow uncertainty due to uncertainty in friction factor, u_8	0.0385 [7]		X				
11	Heat transfer coefficient uncertainty due to uncertainty in Nu number correlation, u_9	0.13 [8]			X			

1. J. G. Stevens of ANL has an engineering judgment that MCNP-calculated *local* power density is within 10 % of the actual power density. This value has been used in past conversion analyses at ANL, and is reported in the User's Guide to the PLTEMP/ANL Code.
2. Typical value given in Appendix V of Ref. 1 (PLTEMP/ANL Users Guide). Typical fuel fabrication tolerance (given in Appendix V of Ref. 1) is used because specific tolerances for MNSR fuel rod fabrication are not available.
3. The typical value for early light water reactors given in Ref. 9 by N. E. Todreas and M. S. Kazimi of M.I.T.
4. It is assumed to be equal to the uncertainty in pin radius.
5. In natural circulation, each channel's flow is induced by the power of the single fuel pin in the channel. However, the hot channel's flow is dragged down by the neighboring channel's flow that is colder and hence moving slower. To estimate this flow reduction, it is assumed that the hot pin is surrounded by average pins which have 8 % less flow (because the average pin has 16 % less power. Flow varies nearly as $(\text{Power})^{0.5}$ in natural circulation, see Eq. 13.) One colder neighboring channel acting on the hot channel would reduce the hot channel's flow by 4 % (the colder channel's flow itself getting dragged up by 4 %). However, all four neighboring channels could be colder. Four colder neighboring channels would reduce the hot channel's flow by 6.4 % while each colder channel's flow itself gets dragged up by 1.6 %.
6. u_7 = (Peak pin-to-average pin power ratio) x 1.003 – 1.0 where 1.003 represents the 3-sigma uncertainty, 0.3 % , in MCNP statistics for the calculated peak pin power.
7. $u_8 = 0.5/13 = 0.0385$. This uncertainty in flow rate is due to the uncertainties in the coolant channel friction factor and hydraulic loss factors. The flow rate uncertainty equals the uncertainty in the measured coolant temperature rise of 13 °C in the thermal-hydraulic test at 15 kW because the PLTEMP/ANL hydraulic model is calibrated to this test. An uncertainty of 0.5 °C is assumed in the measured coolant temperature rise of 13 °C in the reactor. A fractional uncertainty of 0.5/13 in ΔT implies an equal uncertainty in the flow rate.
8. The Churchill-Chu Nusselt number (Nu) correlation developed for natural circulation on a vertical flat plate is used in this thermal hydraulic analysis for a vertical circular rod. The natural circulation Nu on a rod's vertical surface (convex surface) is greater than that on a flat vertical surface which is in turn greater than that on the inner surface of a tube (concave surface). The rod-to-plate Nu ratio was estimated using Eq. (4-44) of Ref. 8 to be about $\zeta / \ln(1 + \zeta) = 0.15/\ln(1.15) = 1.073$ where $\zeta = 1.8\,(L/D)/(Nu,plate) = 1.8(0.23/0.0055)/(\approx 500) = 0.15$. Hence, this uncertainty is lowered from the typical 20 % to 13 % in this analysis.