The STAT7 Code for Statistical Propagation of Uncertainties In Steady-State Thermal Hydraulics Analysis of Plate-Fueled Reactors

Nuclear Engineering Division

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The STAT7 Code for Statistical Propagation of Uncertainties In Steady-State Thermal Hydraulics Analysis of Plate-Fueled Reactors

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ABSTRACT

The STAT code was written to automate many of the steady-state thermal hydraulic safety calculations for the MIT research reactor, both for conversion of the reactor from high enrichment uranium fuel to low enrichment uranium fuel and for future fuel re-loads after the conversion. A Monte-Carlo statistical propagation approach is used to treat uncertainties in important parameters in the analysis. These safety calculations are ultimately intended to protect against high fuel plate temperatures due to critical heat flux or departure from nucleate boiling or onset of flow instability; but additional margin is obtained by basing the limiting safety settings on avoiding onset of nucleate boiling. STAT7 can simultaneously analyze all of the axial nodes of all of the fuel plates and all of the coolant channels for one stripe of a fuel element. The stripes run the length of the fuel, from the bottom to the top. Power splits are calculated for each axial node of each plate to determine how much of the power goes out each face of the plate. By running STAT7 multiple times, full core analysis has been performed by analyzing the margin to ONB for each axial node of each stripe of each plate of each element in the core.

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1 INTRODUCTION

The STAT code was written to perform analysis of the steady state thermal hydraulic safety basis for MITR-II, the MIT research reactor, but the code also may be applicable to other reactors with plate fuel. The conversion of MITR-II from HEU to LEU will involve a number of significant changes to the core, so a new steady-state and transient thermal hydraulic safety analyses is required. The number of required new safety analysis cases may be quite large. Optimization of the new fuel element design requires analysis of a large number of design options. Also, since there is great flexibility in MITR-II reactor fuel shuffling and reloading, it may be necessary to repeat at least part of the safety analysis in the future for every fuel reloading. The main goal is to provide a standardized and automated procedure and tool for the safety analysis. The work described in this report only addresses steady-state analysis as codified in the STAT program. Transient analysis of accidents is also required, but the transient analysis is not within the scope of this code.

For steady-state operation safety limits analysis is performed in order to protect against critical heat flux (CHF) or departure from nucleate boiling (DNB). Since onset of flow instability (OFI) can lead to DNB, OFI is also to be avoided. In order to provide additional margin, the limiting safety system settings are based on avoiding onset of nucleate boiling (ONB). ONB will occur before either OFI or DNB.

The original thermal hydraulics approach was to calculate the margin to ONB for an interior channel at each axial node of the limiting fuel plate stripe in the core. The stripes run the length of the fuel, from the bottom of the fuel to the top of the fuel. For nominal dimensions before accounting for uncertainties, usually the stripe with the maximum stripe power will be the most limiting; but it may also be necessary to analyze the stripe containing the peak spot power to determine which stripe is limiting. Also, an end channel may be more limiting than the most limiting interior channel. The original STAT code and versions STAT1 to STAT6 used the one interior channel approach, with additional features in each successive version. The STAT7 code added the capability to analyze one stripe for each plate and each coolant channel of one element, including the end channels. With STAT7, the steady-state thermal hydraulics calculations have been automated to the point that the current practice is to make multiple STAT7 runs to calculate the margin to ONB for each axial node of each stripe of each plate of each element in the core.

2 CHANNEL TREATMENT

Figure 1 illustrates a cross section of the channel geometry used for thermal hydraulics calculations. A number of axial nodes are modeled in this manner in the vertical direction.

Both interior channels and end channels must be considered. A simple interior ‘half-channel’ models the middle of the fuel to the middle of the adjacent interior coolant channel. There are a number of possible end channel geometries. An end channel models the region from the middle of the fuel of an end plate, including the whole end coolant channel, to the surface of the side plate of an adjacent assembly. This effectively models a coolant channel heated on one side but with wall friction on both sides. Variations on this type of end channel include end coolant channels that face the core housing, the inner hex or an arm. Qualitatively these situations are similar, but the end coolant gap size depends on what the end channel is facing. Another possibility is that the end coolant channel of one element could face the end coolant channel of another element, creating one larger coolant channel heated on both sides.

Originally the calculations done for this work included only half of one fuel plate and half of an adjacent coolant channel for an interior channel or an end channel heated on both sides. The entire adjacent coolant channel was used for an end channel facing an unheated surface. Only a minor modification to the computational procedure was required to add the option to treat a coolant channel heated on both sides. With this option an interior channel was modeled from the middle of plate 1 to the middle of plate 2, as shown in Fig. 1. Also, an end channel heated on both sides can be treated more accurately. The treatment has been extended to simultaneously treat every plate and every coolant channel in one stripe of an element.

In this channel treatment, the width of a sub-channel is equal to the width of a single stripe in the fuel. The non-fueled sides of the plate and the coolant in contact with the non-fueled sides are ignored. Lateral coolant mixing between stripes is ignored. Also lateral conduction between stripes in the fuel and clad is ignored.

Figure 1. Channel Geometry for 4 Stripes

2.1 How Many Stripes are Necessary?

One of the issues addressed by this work is the question of how many lateral stripes are necessary to obtain an accurate or conservative evaluation of peak clad temperatures. The plate power profiles for MTR-II are peaked fairly sharply at the sides of the fuel near the side plate since beyond the edges of the fuel there is less fuel self-shielding of the thermal neutron flux, which causes most of the fissions. Absorption and fission in the fuel reduces the thermal neutron flux in the fuel. The fuel is a source for high energy fission neutrons but a sink for thermal neutrons.

Lateral thermal conduction in the fuel and the clad can reduce the peaking in lateral temperature profiles. To investigate this situation a multi-stripe model, as shown in Fig. 2, was set up for the RELAP5-3D code¹. Eighteen channels were used to model the region from the middle of the end plate fuel to the surface of the side plate of the adjacent assembly. Channels 1 to 16 model 16 stripes in the fueled part of the plate. Channels 0 and 17 model the plate and coolant between the sides of the fuel foil and the side plates. Axial power profiles for a peak power LEU case were obtained with the MCNP code for each of the 16 fueled stripes. A number of variations on this model were run, with and without lateral conduction between adjacent channels or axial conduction in the plate. Also, adjacent fueled channels were combined to make 4 channels or 8 channels in the fuel for additional cases. In all cases coolant mixing or direct lateral heat transfer between coolant channels was ignored.

RELAP5-3D is mainly a transient code. It does not provide a direct steady-state solution for this type of case. Therefore, a null transient, starting from uniform temperatures everywhere, was run. For the null transient the power levels, coolant inlet temperature, and total coolant flow rate were held constant; and the transient was run until the temperatures reached steady-state.

Figure 2. Multi-stripe RELAP5-3D Model

Results from these RELAP5-3D multi-stripe runs are shown in Fig. 3. Axial conduction makes no significant change in the peak clad temperatures, so no axial conduction cases are shown in this figure. With no lateral conduction the peak clad temperature rise from the inlet temperature is proportional to the stripe power, so the no lateral conduction results indicate the lateral power peaking. Lateral conduction significantly reduces the peak clad temperature. The peak clad temperature for 4 stripes and no lateral conduction is higher than that for 8 or 16 stripes and with lateral conduction. Therefore, 4 stripes are conservative for a multi-stripe steady-state calculation with no lateral conduction.

Figure 3. Peak Clad Temperature results from RELAP5-3D for various stripe discretization of the fuel plate and the coolant channel, both with and without lateral heat conduction in the plate.

3 TREATMENT OF UNCERTAINTIES USING STATISTICAL APPROACH

For the thermal hydraulics calculations to support the LSSS settings, uncertainties in important parameters are treated with a Monte-Carlo statistical propagation approach. The statistical propagation approach for MITR-II was initially implemented by L-W Hu and K-Y Chang² using the Oracle spreadsheet program with the Crystal Ball plug-in. For a given nominal (measured) value of the total reactor power, a large number of histories are run. For each history the values of important parameters are set based on random sampling from the uncertainty distributions for respective parameters. Then a steady-state thermal hydraulics calculation is done for the channel. If the clad surface temperature exceeds the ONB limit at any axial node, then the ONB count is increased by one. Note that for a given history the result used in the statistical analysis is either a 0 (no ONB anywhere) or a 1 (ONB at one or more axial nodes of one or more plates). The amount by which ONB is exceeded in a history is not used. The ONB probability

for the specified nominal operating parameters is then given by the ratio of the number of ONB histories to the total number of histories. An iteration process is used to repeat the calculations for additional nominal reactor powers until the power at which a specific probability of ONB occurring is predicted. During the reactor power iteration the nominal values of all other parameters are held constant. Currently the specified probability of ONB occurring is 0.00135, which corresponds to a 3-sigma confidence level of 99.865%.

The parameters whose uncertainties are treated with the statistical propagation approach are listed in Table 1. The uncertainty values in this table are examples that have been used or that are currently being used. The uncertainties listed in this table are treated as 3-sigma values, and normal distributions are assumed for the uncertainties.

Table 1. Parameters and Uncertainties

Parameter	3-sigma Uncertainty (%)
Reactor power	5
Local power	14.1
Pump flow	5
Fin-to-fin interior channel coolant gap size	6.9
Film heat transfer coefficient	20

4 CODE IMPLEMENTATION, THE STAT6 CODE

A small FORTRAN program, the Stat code, was written to implement and automate the thermal hydraulics calculations for the statistical propagation method for MITR-II. The Stat code is not integrated with neutronics. One neutronic calculation for each core configuration of interest must be made to generate for the whole core stripe powers and axial power shapes used in the Stat thermal hydraulic analysis.

A Stat6 case calculates the nominal reactor power level at which a specified ONB probability occurs for one channel representing a stripe in one element. The input for a Stat6 case includes design information, plus axial fuel plate power shapes for a stripe in one or two plates and the fraction of the total reactor power in the stripe for the plate or plates, plus the standard deviations in the probability distributions for the parameters listed in Table 1. Also inputs are the ONB probability level, the number of Monte-Carlo histories for each reactor power iteration, and the first value of the nominal power for the power iteration.

The output from a Stat6 case is mainly the nominal reactor power level at which the specified ONB probability occurs. Also output is some statistical information on the standard deviation of the ONB probability for the final power iteration. Thermal hydraulics results for some samples can also be outputted.

4.1 Thermal Hydraulics Calculations for a History

At the start of the thermal hydraulics calculations for a history, the nominal reactor power, P_r , is known from the power iteration. The coolant outlet temperature, T_x , and the nominal pump flow are set by the input. After some initialization, the calculations for a history go through the following steps in order. Note that there is no over-all iteration in the thermal hydraulics calculations for a history, although there are two-step iterations within some individual steps to make temperature-dependent coolant properties consistent with the coolant temperatures.

Nominal Stripe Power and Flow

The nominal hot stripe power, P_s , is calculated as:

$$P_s = P_r f_c f_s / (N_e N_p N_s) \quad (1)$$

Where

P_r = nominal core power

f_c = the fraction of the fission power deposited in the core region (calculated value = 0.965)

f_s = hot stripe power/core average stripe power

N_e = number of elements

N_p = number of plates per element

N_s = number of stripes/plate

If the 2-plate option is used, then the nominal stripe 2 power, P_{s2} , is calculated the same way using f_{s2} , the stripe 2 power/core average power, instead of f_s .

The nominal interior channel stripe coolant flow, W_i , is calculated as

$$W_i = W_p f_f d_f f_{in} f_{sf} / (N_e N_p N_s) \quad (2)$$

Where

W_p = Nominal pump flow

f_f = Coolant core flow fraction. This accounts for bypass flow.

d_f = Plenum flow disparity factor; accounts for element to element flow variation

f_{in} = Ratio of the average interior channel flow to the average channel flow. This accounts for the average end channel flow being different from the average interior channel flow.

f_{sf} = Fraction of the coolant channel flow in the stripe region. This accounts for neglecting the flow between the side plate and the edge of the fuel foil.

This section is skipped except for the first history of each reactor power iteration, since the results are the same for later histories.

Reactor Power and Pump Flow

The statistical sampling value, $[P_r]$, for the reactor power is randomly sampled from the nominal value, P_r , and the standard deviation. Also, the sample value, $[W_p]$, for the pump flow is randomly sampled from the nominal value and the standard deviation.

Coolant Inlet Temperature

The coolant inlet temperature, T_{in} , is obtained from

$$T_{in} = T_x - [P_r]f_c / ([W_p]C_p) \quad (3)$$

where f_c is the fraction of the power deposited in the core region (value assumed conservatively to be 0.965 and is to be reevaluated for final design). C_p is the heat capacity of the water. T_x is the outlet temperature. A two-step iteration is used to obtain some consistency between the temperature-dependent value of C_p and the average core coolant temperature. In the first step, C_p is calculated using T_x as the coolant temperature. In the second step Eq. 3 is repeated with the temperature used for C_p based on the average of T_x and the first step value for T_{in} .

Hot Stripe Gap Size, Coolant Flow Area and Hydraulic Diameter

The statistical sampling value, $[G]$, for the hot stripe gap size is obtained from the nominal value, G , and the standard deviation. The coolant flow area, A_G , and hydraulic diameter, D_{hG} , for this gap size are then calculated.

Hot Stripe Coolant Flow Rate

The coolant channel friction factor, f , is obtained from

$$f = a_{fr} R_e^{bfr}$$

Typically $a_{fr} = .184$, and $bfr = -0.2$, but the user can specify different values. If the core channel pressure drop is mainly due to friction with a turbulent friction factor proportional to the Reynolds number raised to the -0.20 power, then a channel flow rate will be proportional to the flow area times the hydraulic diameter to the 0.667 power. Thus, the hot stripe coolant flow rate, W_s , is obtained from

$$W_s = W_i ([W_p]/W_p)(A_G/A_0)(D_{hG}/D_{h0})^{0.667} \quad (4)$$

Where

A_0 = nominal interior channel stripe flow area

D_{h0} = nominal interior channel stripe hydraulic diameter

Note that although Eq. (2) applies to the nominal interior channel, Eq. (4) can be used for either an interior channel or an end channel if the appropriate values are used for A_G and D_{hG} . Also note that if bfr is not equal to -0.20, then in Eq. 4, 0.667 is replaced by D_{hrat} given by

$$D_{hrat} = (1 - bfr)/(2 + bfr)$$

Hot Stripe Axial Node Power Uncertainties

The axial node plate power in the stripe, $[p_j]$, for axial node j is obtained from

$$[p_j] = \theta_j [u_j] P_s \quad (5)$$

where

θ_j = input axial power shape, normalized to sum to 1.0

$[u_j]$ = local power uncertainty factor, obtained by statistical sampling from the local power distribution.

The code has options to obtain a separate value for u_j for each axial node or to use the same value for all nodes in a plate.

Axial Node Coolant Temperatures

The axial node coolant temperature, T_{wj} , at the bottom of node j is obtained by starting with the inlet temperature for node 1 and then using

$$T_{wj+1} = T_{wj} + p_{wj} / (W_s C_p) \quad (6)$$

where the value of p_{wj} , the power in the coolant, depends on the options being used. For an interior channel for the single plate option and a full coolant channel, p_{wj} is equal to $[p_j]$. For an interior channel with the two plate option, p_{wj} is the average of the $[p_j]$ for the two plates. For an end channel facing an unheated surface, p_{wj} is half of $[p_j]$.

A two-step iteration is used for each axial node to make the temperature-dependent value of C_p consistent with the calculated coolant temperatures.

Axial Node Coolant Pressures and Saturation Temperatures

The coolant pressure at the top of the core is calculated, based on the height of the water above the core and the coolant outlet temperature. Then the pressure drop in each axial node is calculated, based on friction and gravity head. The saturation temperature at each node is obtained after the pressures are calculated.

Axial Node ONB Temperatures

The Bergles-Rohsenow correlation predicts the fuel clad temperature at which ONB occurs³.

$$T_{clad, ONB} = T_{sat} + 0.556 \left[\frac{q''}{1082 \cdot p^{1.156}} \right]^{0.463 \cdot p^{0.0234}} \quad (7)$$

Where

$T_{clad, ONB}$ is the fuel clad temperature (°C) at which ONB occurs,

T_{sat} is the saturation temperature (°C),

q'' is the local heat flux (W/m²), and

p is the pressure (bar).

Carnavos Fin Heat Transfer Coefficients and Clad Surface Temperatures

The fin heat transfer coefficients are calculated using the Carnavos correlation⁴. The Carnavos correlation is an empirical correlation based on 11 finned tubes of different number of fins, fin height,

fin helix angles and tube diameters. The fins were on the inside surface of the tubes. Carnavos fitted experimental data from these tests to obtain this correlation within 10% error. The correlation is given as:

$$Nu = 0.023 \cdot Re_a^{0.8} \cdot Pr^{0.4} \cdot \left(\frac{A_{fa}}{A_{fc}} \right)^{0.1} \cdot \left(\frac{A_n}{A_a} \right)^{0.5} \cdot \sec^3 \alpha \quad (8)$$

where $Nu = h D_{ha} / k$

Nu , Re and Pr are Nusselt, Reynolds and Prandtl Number, respectively. Other terms in the Carnavos correlation and their counterparts in MITR-II are summarized in Table 2.

It should be noted that the definition of the A_{fc} term is somewhat ambiguous in the Carnavos paper: the term is mentioned in the paper but not defined in the Nomenclature section where the other terms are defined, so it is necessary to infer the meaning from other information in the paper. An initial guess for the meaning was used for the Oracle-Crystal Ball calculations described in Section 4.3 and for STAT6 and earlier versions of the STAT code. A careful examination of the paper showed that a different interpretation given in Table 2 is correct. This corrected interpretation corresponds exactly to the values given in the paper for the “open core free flow area” for experiments used to derive the Carnavos correlation. The corrected interpretation is used in STAT7. For typical MIT cases the difference in the heat transfer coefficient due to the error in A_{fc} is only about 2%, but STAT6 results will agree better with Oracle-Crystal Ball results than STAT7 results will.

The clad surface temperatures are calculated from the coolant temperatures, the heat transfer coefficients and the clad heat fluxes.

Table 2. Geometry parameters in Carnavos correlation and derived values for an inner channel of an LEU fuel element

Symbol	Meaning	Counterpart in MITR element
A_{fa}	Actual free flow area	Stripe Width $\times$ (water gap* + 2 $\times$ fin height) – 2 $\times$ number of fins per stripe $\times$ single fin area
A_{fc}	Open core free flow area, fin tip-fin tip	Stripe width $\times$ water gap*
A_n	Nominal heat transfer area based on tube inner diameter as if fins were not present	Nominal heated perimeter $\times$ fuel length
A_a	Actual heat transfer area Actual heat transfer area	Actual heated perimeter $\times$ fuel length
α	Helic angle in finned tube	0
D_{ha}	Actual hydraulic diameters	(4 $\times$ actual flow area)/(actual wetted perimeter)

* water gap refers to the fin-tip to fin-tip distance

4.2 Carnavos Friction Factor for Fins

In addition to the heat transfer coefficients for finned surfaces mentioned above, Carnavos also measured friction factors for finned tubes. The data was fit by:

$$f = 0.184 / [R_e^{0.2} (F^*)] \quad (9)$$

where

f = friction factor

R_e = actual Reynolds number

$$F^* = (A_{fa} / A_{fn})^{0.5} (\sec \alpha)^{0.75}$$

A_{fa} = actual free flow area, mm²

A_{fn} = nominal flow area based on tube ID as if the fin structure were not present, mm²

$\sec \alpha = 1.0$ for fins parallel to the flow

Use

$f_{fin} = 1 / F^*$ = friction factor multiplier for fins

g = gap (fin-tip to fin-tip for an interior channel, fin-tip to end of channel for an end channel)

d_g = groove depth = fin height

w_g = groove width

w_f = fin width

W_{stripe} = width of stripe

G_{rf} = average groove gap factor = $w_g / (w_g + w_f)$

Interior Channel, fins on both sides

$$A_{fa} = W_{stripe} (g + 2d_g G_{rf})$$

$$A_{fn} = W_{stripe} (g + 2d_g)$$

$$f_{fin} = [(g + 2d_g) / (g + 2d_g G_{rf})]^{0.5}$$

End Channel, fins on one side

$$A_{fa} = W_{stripe} (g + d_g G_{rf})$$

$$A_{fn} = W_{stripe} (g + d_g)$$

$$f_{fin} = [(g + d_g) / (g + d_g G_{rf})]^{0.5}$$

The hot stripe coolant flow rate, w_s , calculated by Eqn. 4, is then multiplied by a fin flow multiplier, f_{wm} , given by

$$f_{wm} = (f_{fin} / f_{fin0})^{ffrat}$$

where

f_{fin0} = value for a nominal interior channel, and

$$ffrat = -1 / (2 + bfr)$$

if $bfr = -0.2$, then $ffrat = -0.5556$

4.3 Statistical Sampling

The statistical sampling method is taken from a mathematical handbook⁵. A random variable Y is said to be normally distributed with mean m and standard deviation σ if the probability, I_p , that Y is less than or equal to y is given by

$$I_p(Y \leq y) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^y e^{\frac{-(t-m)^2}{2\sigma^2}} dt \quad (10a)$$

or if $x = (y - m)/\sigma$, then

$$I_p(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^x e^{-(t^2/2)} dt \quad (10b)$$

Define $I_q(x) = 1 - I_p(x)$

Then if a random number, r , evenly distributed from 0 to 1 is obtained from a random number generator, then sampling from a normal distribution is obtained by obtaining the value of x for which

$$r = I_p(x) \quad (11)$$

Alternatively, one can obtain random sampling from a normal distribution by using

$$r = I_q(x) \quad (12)$$

Reference 4 gives a rational approximation for $x(r)$ where $r = I_q(x)$

for $r \leq 0.5$

$$x(r) = v - (c_0 + c_1v + c_2v^2)/(1 + d_1v + d_2v^2) + \varepsilon(r) \quad (13)$$

$$v = \sqrt{\ln \frac{1}{r^2}}$$

$$c_0 = 2.515517 \quad d_1 = 1.432788$$

$$c_1 = 0.802853 \quad d_2 = 0.189269$$

$$c_2 = 0.010328 \quad d_3 = 0.001308$$

$$|\varepsilon(r)| < 4.5 \times 10^{-4}$$

for $r > 0.5$

$$x(r) = -x(1 - r) \quad (14)$$

4.4 Comparison with Oracle-Crystal Ball Results

A consistent series of cases for various coolant outlet temperatures was run with the Oracle Crystal Ball approach and with the Stat code. Fig. 4 shows the results. For an outlet temperature of 60°C, the results are almost identical, indicating that both approaches are equivalent.

Note that for this comparison the local power uncertainty used was 10% (3-sigma). The slight difference in slopes in Fig. 4 is probably due to differences in the treatment of the temperature dependence of water properties where Stat calculates temperature-dependent water properties using the axial node temperatures for each history.

Figure 4. Comparison of Stat and Oracle-Crystal Ball Results

There are three advantages to the Stat code over the Oracle-Crystal Ball approach. The first advantage is that setting up the Stat input and running the code is much simpler and less time consuming. Oracle-Crystal Ball requires hand iteration to obtain a consistent solution. All iteration in Stat is done internally by the code. Another advantage is that the Stat code can be easily expanded and integrated into a 3-D fuel management program. The third advantage is computing speed. The Stat calculations for one outlet temperature for 250,000 histories and ONB tests at all 18 axial nodes run in seconds. The Oracle-Crystal Ball computer time is substantially longer because it is a general purpose software with a spreadsheet interface.

5 THE STAT7 CODE

The Stat7 code is an expansion of the Stat6 code to treat N_{ch} coolant channels and $N_{pl} = N_{ch} + 1$ plates. This code can model one stripe of all of the plates and coolant channels in an element, from end channel through the internal channels to the other end channel. When modeling an element containing N_{fp} fuel plates there are $N_{fp} - 1$ internal channels and 2 end channels. Also, an extra plate is added before the first end channel and another after the last end channel to account for whatever is beyond the end channels. If the end channel butts up against the end channel of an adjacent element, then the extra plate can model half of the end fuel plate of the adjacent element, with a zero heat flux boundary condition at the middle of the plate. If the end channel butts up against an unheated side plate of an adjacent element or against an unheated structural wall, then the only impact of the extra plate is to contribute to the wetted perimeter used in computing the hydraulic diameter of the end channel.

Even though the Stat7 code was produced to model one stripe of all of the plates and coolant channels in an element, it can model other cases. If the end channel of one element butts up against the end channel of an adjacent element, then the code can model one stripe of both elements. Another option is to model only part of an element to determine the sensitivity of the results to how much of the element is modeled.

5.1 Power Splits

When calculating steady-state temperatures for a series of plates separated by coolant channels, zero heat flux boundary conditions at the centers of the plates cannot be assumed. Instead, a power split must be calculated for each axial node of each plate. The power split for a plate surface is defined as the ratio of the heat flux from the surface to the sum of the heat fluxes from both surfaces. The approach taken in Stat7 for calculating power splits involves assuming that the plate power density is uniform across the thickness of the fuel. Then a zero heat flux boundary condition occurs a fraction f_{ps} of the way across the thickness of the fuel. The value of the flow split is set so that the peak fuel temperature calculated starting from the bulk coolant temperature on one side of the plate equals the peak fuel temperature calculated starting from the other side. For the extra plates at the ends, the power split is assumed to be 0.5 at all axial nodes.

5.2 Stat7 Thermal Hydraulic Solution for a History

Nomenclature:

i = coolant channel number

N_i = number of coolant channels in the model = $nchan$ (input value)

N_e = number of elements in the core = $nelm$ (input)

N_p = number of plates in the model = $N_i + 1$

N_{pe} = number of plates per element

N_s = number of stripes/plate

N_z = number of axial nodes = nz (input)

j = axial node

k = plate number. Plate k is in contact with coolant channels $k - 1$ and k

l = plate surface number. Surface 1 is in contact with channel $k - 1$. Surface 2 is in contact with channel k

$Ac(i)$ = coolant flow area

$Dh(i)$ = hydraulic diameter

df = flow disparity factor = df (input), accounts for element to element flow variation
 ff = coolant core flow fraction = $flwfac$ (input), this accounts for bypass flow
 fin = ratio of the average interior channel flow to the average channel flow = $flwinc$ (input), this accounts for the average end channel flow being different from half of the average interior channel flow.
 fsf = fraction of the coolant channel flow in the stripe region = $flstrf$ (input), this accounts for neglecting the flow between the side plate and the edge of the fuel foil.
 fc = the fraction of the fission power deposited in the core region = $fcore$ (input)
 $fs(k)$ = current plate stripe power/core average power = $fstrp(k)$ (input)
 $Gap(i)$ = gap size
 $Pp(k,j)$ = plate power for the sample
 $Tw(i,j)$ = coolant temperature at bottom of node j
 $Tps(k,l,j)$ = plate surface temperature
 $Tfc(k,l,j)$ = fuel-clad interface temperature
 $Tf(k,l,j)$ = peak fuel temperature, calculated from face l
 Tx = average coolant outlet temperature = $tout$ (input)
 Tin = coolant inlet temperature
 Pro = nominal reactor power =
 Pr = reactor power for the history
 $Pso(k)$ = nominal plate power
 Wpo = nominal pump mass flow (kg/s)
 Wp = pump flow for the history
 Tin = coolant inlet temperature
 $Ws(i)$ = stripe flow for the history
 Woi = average nominal interior channel stripe flow times df (flow disparity factor)

Statistical Sampling

The statistical sampling value, $[Y]$, for a variable y with a fractional standard deviation of σ is obtained by multiplying the mean value, Yo , by a statistical multiplier, Fy , given by

$$Fy = 1 + x\sigma \quad (15)$$

The method used to obtain x is described in Section 4.2.

Reactor Power, Pump Flow, and Inlet Temperature

The average coolant outlet temperature, Tx , the nominal (measured) reactor power and the nominal pump flow are supplied by the user in the input. The reactor power for the history, Pr , and the pump mass flow for the history, Wp , are obtained by statistical sampling. Then the inlet coolant temperature, Tin , is obtained from

$$Tin = Tx - Pr fc / (Wp Cp) \quad (16)$$

Where the coolant heat capacity Cp is evaluated at a temperature Tav given by

$$Tav = (Tin + Tx) \quad (17)$$

A two-step iteration between equations 16 and 17 is used to obtain consistency between Tav and Cp .

Gap Size, Coolant Flow Area, Hydraulic Diameter

The gap size, Gap(i), is obtained for each coolant channel by statistical sampling. Then the coolant flow area, Ac(i), and hydraulic diameter, Dh(i) are calculated. Note that the unfuelled sides of the plate are neglected in the calculations for flow area, hydraulic diameter and coolant flow rate.

Coolant Channel Mass Flow Rates

The channel flow rate splits are calculated based on obtaining the same friction pressure drop in all channels. At normal pump flow rates gravity heads are insignificant compared to friction. Orifice pressure losses are also small compared to friction. The friction pressure drop, $\Delta p(i)$, for a channel is:

$$\Delta p(i) = [f_r L / D_h(i)] [W_s(i) / A_c(i)]^2 / (2 \rho) \quad (18)$$

where ρ is the density, L is the channel length, and f_r is the friction factor given by

$$f_r = a_f Re^{b_f} \quad (19)$$

where

$$Re = \text{Reynolds number} = D_h(i) W_s(i) / [\mu A_c(i)] \quad (20)$$

a_f, b_f are correlation coefficients
 μ = average viscosity

Usually $a_f = 0.316$ and $b_f = -0.25$ if Re is less than 20,000. For higher Re, $a_f = 0.184$ and $b_f = -0.2$. Combining equations 18 – 20 gives:

$$W_s(i) = C A_c(i) D_h(i)^{c_2} \mu(i)^{c_3} \quad (21)$$

where

C is a constant

$$c_2 = (1 - b_f) / (2 + b_f) = 0.714 \text{ if } b_f = -0.25 \text{ or } .667 \text{ if } b_f = -0.2 \quad (22)$$

and

$$c_3 = b_f / (2 + b_f) = -0.143 \text{ if } b_f = -0.25 \text{ or } -0.111 \text{ if } b_f = -0.2 \quad (23)$$

The reference flow is calculated as

$$W_{oi} = W_{po} f_f d_f f_{in} f_{sf} / (N_e N_p N_s) \quad (24)$$

where

W_{oi} = average nominal interior channel stripe flow times d_f (flow disparity factor)

The reference flow is calculated once and used for all histories. Also, A_{co} and D_{ho} , the nominal interior channel flow area and hydraulic diameter, are calculated for the nominal interior gap size; and μ_o , the nominal average viscosity is calculated for the nominal average coolant temperature. Then for a given history the channel flow rates are calculated as

$$Ws(i) = Woi [Ac(i) / Aco] [Dh(i) / Dho]^{c2} [\mu(i) / \mu_o]^{c3} \quad (25)$$

The viscosity effect in Equation 25 is only calculated approximately. The coolant channel flow rates are calculated before the fuel plate power splits, so power splits of 0.5 everywhere are used for the calculation of the average coolant temperature to use for $\mu(i)$. The accuracy of the viscosity effect could be improved by iterating between the power split calculation and the flow calculation, but the viscosity effect is fairly small, and a moderate improvement in the effect would make little difference in the plate surface temperatures.

Carniavos Fin Factor

The Carnavos fin heat transfer factor is calculated using Equation 8.

Plate Power Profiles

The plate power for 1 stripe for each node of each plate, $Pp(k,j)$, is obtained by statistical sampling.

Coolant Heat Transfer Coefficient Statistical Multiplier

A coolant heat transfer multiplier is obtained by statistical sampling. For each sample only one heat transfer multiplier is used for all nodes of all plate surfaces. This may be excessively conservative, but it is likely that the heat transfer coefficient uncertainties are systematic, and applying to all nodes of all surfaces, rather than random, and differing from node to node and from surface to surface.

Power Splits

The power split calculation requires solving for the splits for all plates at a given axial node simultaneously, starting from the inlet node and working up one node at a time. The power split, $Fps1(k,j)$ for node j of plate k is defined as the ratio of the flux at surface 1 to the sum of the fluxes at both surfaces. Surface 1 is in contact with coolant channel $k - 1$, and surface 2 is in contact with coolant channel k . The power splits are calculated so that the peak fuel temperature, $Tf(k,l,j)$, calculated from surface 1 equals that calculated from surface 2.

At the beginning of the calculations for node j , the coolant temperatures, $Tw(i,j)$, at the bottom of the node for all channels are known. Then,

$$Tw(i,j+1) = Tw(i,j) + \{ [1 - Fps1(i,j)] Pp(i,j) + Fps1(i+1,j) Pp(i+1,j) \} / [Ws(i) Cp] \quad (26)$$

Then the average coolant temperature for the axial node is:

$$Twa(i,j) = [Tw(i,j) + Tw(i,j+1)] / 2 \quad (27)$$

The plate surface temperatures, $Tps(k,l,j)$, are obtained from:

$$Tps(k,1,j) = Twa(k-1,j) + Flxs(k,1,j) / Hw(k,1,j) \quad (28a)$$

$$Tps(k,2,j) = Twa(k,j) + Flxs(k,2,j) / Hw(k,2,j) \quad (28b)$$

where

$H_w(k,l,j)$ = coolant heat transfer coefficient, including the Carnavos fin factor and the coolant heat transfer statistical multiplier.

and the plate surface heat flux, $Flxs(k,l,j)$ is:

$$Flxs(k,1,j) = Fps1(k,j) Pp(k,j) Fpf / Sf(k) \quad (29a)$$

$$Flxs(k,2,j) = [1 - Fps1(k,j)] Pp(k,j) Fpf / Sf(k) \quad (29b)$$

where

$Sf(k)$ = plate surface area of 1 stripe of 1 node, including fins, and

Fpf = fraction of the power deposited in the fuel = $ffuel$ (input)

Note that the power deposited in the clad is not accounted for separately; it should be included in Fpf .

The fuel – clad interface temperature, $Tfc(k,l,j)$, is calculated as

$$Tfc(k,1,j) = Tps(k,1,j) + Flxo(k,1,j) Ct / Kc \quad (30a)$$

$$Tfc(k,2,j) = Tps(k,2,j) + Flxo(k,2,j) Ct / Kc \quad (30b)$$

where

$$Flxo(k,1,j) = Fps1(k,j) Pp(k,j) Fpf / So(k) \quad (31a)$$

$$Flxo(k,2,j) = [1 - Fps1(k,j)] Pp(k,j) Fpf / So(k) \quad (31b)$$

$So(k)$ = plate surface area of 1 stripe of 1 node, not including fins

Based on the analytic temperature solution for a uniformly heated slab with a zero heat flux boundary on one side, the peak fuel temperature calculated from surface l , $Tf(k,l,j)$, is

$$Tf(k,1,j) = Tfc(k,1,j) + Fsp1(k,j)^2 Pp(k,j) Fpf Ft / [2 So(k)Kf] \quad (32a)$$

$$Tf(k,2,j) = Tfc(k,2,j) + [1 - Fsp1(k,j)]^2 Pp(k,j) Fpf Ft / [2 So(k)Kf] \quad (32b)$$

Then, setting

$$Tf(k,1,j) = Tf(k,2,j) \quad (33)$$

gives

$$Tw(k-1,j) + \{ [1 - Fps1(k-1,j)] Pp(k-1,j) + Fps1(k,j) Pp(k,j) \} / [2 Ws(k-1) Cp] +$$

$$Fps1(k,j) Pp(k,j) Fpf / [Sf(k) Hw(k,1,j)] + Fps1(k,j) Pp(k,j) Fpf Ct / [So(k) Kc] +$$

$$\begin{aligned}
& Fsp1(k,j)^2 Pp(k,j) Fpf Ft / [2 So(k) Kf] = \\
& Tw(k,j) + \{ [1 - Fps1(k,j)] Pp(k,j) + Fps1(k+1,j) Pp(k+1,j) \} / [2 Ws(k) Cp] + \\
& [1 - Fps1(k,j)] Pp(k,j) Fpf / [Sf(k) Hw(k,2,j)] + (1 - Fps1(k,j)) Pp(k,j) Fpf Ct / [So(k) Kc] + \\
& [1 - Fps1(k,j)]^2 Pp(k,j) Fpf Ft / [2 So(k) Kf]
\end{aligned} \tag{34}$$

Equation 34 involves $Fsp1(k-1,j)$, $Fsp1(k,j)$, and $Fsp1(k+1,j)$. When combined with $Fsp1(1,j) = Fsp1(Np,j) = 0.5$ it leads to a series of N equations in N unknowns. Because the equations include $Fsp(k,j)^2$ and $[1 - Fsp1(k,j)]^2$ the equations are not completely linear, and iteration is used to solve them. First, the squares are linearized using:

$$Fps1(k,j) = Fps1o(k,j) + [Fps1(k,j) - Fps1o(k,j)] \tag{35}$$

where $Fps1o$ is an initial guess for $Fps1$ or the computed value from the last iteration. Then:

$$\begin{aligned}
& Fps1(k,j)^2 \sim Fps1o(k,j)^2 + 2 [Fps1(k,j) - Fps1o(k,j)] Fps1o(k,j) = \\
& 2 Fps1(k,j) Fps1o(k,j) - Fps1o(k,j)^2
\end{aligned}$$

Similarly:

$$\begin{aligned}
& (1 - Fps1) = (1 - Fps1o) + [(1 - Fps1) - (1 - Fps1o)] = (1 - Fps1o) + (Fps1o - Fps1) \\
& (1 - Fps1)^2 \sim (1 - Fps1o)^2 + 2 [(1 - Fps1o) (Fps1o - Fps1)] = 1 - Fps1o^2 - 2 Fps1 (1 - Fps1o)
\end{aligned}$$

The linearized version of Eq. 34 has the form:

$$aa(k,j) Fpsl(k-1,j) + bb(k,j) Fps1(k,j) + cc(k,j) Fps1(k+1,j) = dd(k,j) \tag{36}$$

Eq. 36 is solved by Gaussian elimination.

The power split iteration for an axial node for all of the plates in an element converges very rapidly. Two iterations are enough to produce an accurate result.

5.3 Comparison of Stat7 Results with RELAP5 Results

For verification of the Stat7 thermal hydraulic calculations, a comparison was made of the results from a Stat7 case and from a RELAP5 case that was set up to be equivalent to the Stat7 case. One stripe of an 18 fuel plate element with fins was modeled in both codes. The fins are 8 mils high, 10 mils wide and 10 mils apart, giving a surface area of 1.8 times as high as a no-fins case. Stat7 uses a Carnavos film heat transfer fin factor of 0.75 for this case. RELAP5 does not have a fin treatment, but fin heat transfer effects were accounted for by multiplying the plate surface area by $1.8 \times 0.75 = 1.35$. In order to obtain the correct temperatures in the plates, the clad and fuel thermal conductivities used in RELAP5 were divided by 1.35.

Stat7 calculates steady-state coolant flow rates and temperatures. RELAP5 does not have a steady-state solver, so the RELAP5 case was run as a null transient with powers, total element flow, and the coolant

inlet temperature held constant at the Stat7 values for 300 seconds. The RELAP5 transient results settled down to steady-state values well before 300 seconds.

Figure 5 shows the coolant mass flow rates by channel. For this case the end channels both had the same gap size, and all interior channels had a second same gap size. The small differences between the Stat7 results and the RELAP5 results are probably mainly due to the change in water viscosity with temperature: an effect that is not included in the Stat7 coolant channel flow rate calculation.

Figure 5. Comparison of Stat7 and RELAP5 End Channel and Interior Channel Flow Rates

Figure 6 shows the coolant temperatures for the end channel and for the first two interior channels. One slight complication is that RELAP5 prints axial node coolant temperatures at the outlet (upper boundary) of the node and uses these node boundary coolant temperatures in the calculations for the axial node plate temperatures. Stat7 uses coolant temperatures at the middle of the axial node in the calculations for the axial node plate temperatures. The Stat7 temperatures in Figure 6 are mid-node temperatures and are plotted at the middles of the nodes. The RELAP5 temperatures in this figure are node boundary values plotted at the node boundaries. Thus the coolant temperatures in Figure 6 are plotted consistently. On the other hand, the axial node plate temperatures calculated by RELAP5 are based on node boundary coolant temperatures but node average heat fluxes. In the following figures for plate temperatures, the axial node plate temperatures for both Stat7 and RELAP5 are plotted at the middle of the node. For RELAP5, the bulk coolant temperature rise in a full axial node, based on the node-average heat flux, is larger than the Stat7 bulk coolant temperature rise in half of an axial node.

Figure 7 and Figure 8 show the comparisons for the clad surface temperatures and the peak fuel temperatures. Figure 9 shows the comparisons for the plate power splits at each axial node.

Figure 6. Comparison Between Stat7 and RELAP5 Coolant Temperatures for an End Channel and the First Two Interior Channels

Figure 7. Comparison Between Stat7 and RELAP5 Clad Surface Temperatures for an End Plate and the First Interior Plate

The comparisons between Stat7 results and RELAP5 results for this family of channels verified, that the thermal hydraulic calculations in Stat7 have been implemented correctly. Also, the method used to

account for fins in RELAP5 is consistent with the Carnavos treatment in Stat7. Also, the comparisons in Section 4.3 between Stat6 and Oracle-Crystal Ball results show that the statistical methods are equivalent.

Figure 8. Comparison Between Stat7 and RELAP5 Peak Fuel Temperatures for an End Plate and the first Interior Plate

Figure 9. Comparison Between Stat7 and RELAP5 for Power Splits in an End Plate and the First Interior Plate

6 DETERMINATION OF LSSS

In summary, the Limiting Safety System Settings (LSSS) are based on Onset of Nucleate Boiling (ONB) in the core. Uncertainties are accounted for in the analysis by using Monte Carlo uncertainty propagation of the parameters influencing ONB, as discussed above. The requirement is that the measured total reactor power should have at least 20% margin to the power at which the ONB (P_{ONB}) is found to occur with a 3-sigma confidence level of 99.865%. The margin between HEU licensed power and LSSS power is 20%, and so this should be maintained in the LEU case in order to provide an equivalent margin.

Using a 3-sigma confidence level of 99.865%, the probability of ONB occurring in the most limiting element is 0.135% at P_{ONB} . As is the case in the HEU core, it is proposed that the total core reactor power, P_r , should have an additional 20% margin to the ONB power, P_{ONB} , such that $P_r = P_{\text{ONB}} / 1.2$. All channels of an element are analyzed, and each element is analyzed in this manner so that a whole core analysis may identify the most limiting locations for each core configuration considered.

7 INPUT DESCRIPTION

7.1 Input Formats

The Stat code input is read by fixed format FORTRAN read statements, so spacing matters. Integers must be right-justified within the allotted spaces: otherwise zeroes will be added to the right to fill out the allotted spaces. Floating point numbers need to be within the allotted spaces. It is best to type the decimal point in a floating point number: otherwise the decimal point will be inserted at the location indicated by the format.

As an aid to the user, title lines are included in the input. As indicated in the sample input in Section 9, the title lines can be used to list the variables being read and to indicate the spacing for the input. Each title line has a 20a4 format: 20 words, each 4 characters long, for a total of 80 spaces. "a" format indicates character data. If less than 80 characters are entered, the rest will be filled with blanks. In the Stat code the title lines are read and then printed out as read. The code does not make any use of the information on a title line other than to print it out.

Much of the integer input uses 10i8 format. This indicates 10 integers, each 8 spaces long. Leading blanks are ignored. Trailing blanks are filled with zeroes. If there is no value supplied (blank or the line end precedes this input) the value is interpreted as zero.

Much of the floating point input uses 8f10.5 format. This indicates 8 numbers using 10 spaces per number. If no decimal point is typed, the decimal point will be added so that there are 5 numbers to the right of the decimal point. If the decimal point is typed, then it will be used where typed. Again leading blanks are ignored and trailing blanks are filled with zeroes. If there is no value supplied (blank or the line end precedes this input) the value is interpreted as zero.

7.2 Input Description and Sample Values

Block 1: Case Title

title (20a4)

Note: title = 80 columns of title or comment information used for the case, or in subsequent lines as a comment text for names and alignment of input variables.

Block 2: Integer Variable Input Lines

title (20a4)

nelm, nplt, nsrtp, nz, nbatch, nsmpl, isd1, isd2, iprt, idbstt (10i8)

nelm = number of elements = 24

nplt = number of plates/element = 18 (LEU)

Note: nplt is the number of real fuel plates/element. An element contains nplt – 1 interior coolant channels plus 2 end channels.

For a description of the differences between a real element and the computational model see “nchan” below.

nsrtp = number of strips/plate = 4

nz = number of axial nodes in the stripe, max = 40

nbatch = number of statistical sampling batches for a given nominal power and nominal pump flow combination = 25, max = 100

nsmpl = number of sampling calculations in each batch = 10000

isd1 the random number seed = 2**isd1 + isd2

isd2 default: isd1 = 21, isd2 = 3

iprt print detailed results for the first iprt samples

idbstt print statistical treatment debug prints if idbstt > 0

title (20a4)

nchan, iaxpow, irndmn, ipow, iterpw, iend1, iendn, ivsc, niter, ilocp (10i8)

nchan = number of coolant channels in the case

Note: For the computational model an extra plate is added to each end to account for what is just beyond the element. :”iend1” and “iendn” determine the nature of the extra plates. nplate = number of plates in the case = nchan + 1. If nchan = nplt + 1, then the case models one stripe of the whole element. Smaller values of nchan can be used to model one stripe of part of an element. If an end channel butts up to an end channel of an adjacent element, larger values of nchan can be used to model one stripe of one whole element plus part or all of the adjacent element.

iaxpow = 0, all axial nodes use the same plocsg sample for local

power statistical uncertainties

= 1, each axial node uses a separate sample for local power statistical uncertainties

irndmn > 0, use extra random number calls so that all iplat2 and

iaxpow options use the same random numbers

ipow = 0, local power uncertainties are independent of overall power uncertainties

1, the total power uncertainty factor, using powsgm, multiplies the local value, using plocsg

iterpw 0, no power iteration

>0, iterate on power until ONB fraction = eponb

pow0 is used for the first iteration

2 add extra iteration prints

<0, same as >0, but add 1 more iteration after convergence
iend1 plate 1 option
0 no plate, zero heat flux boundary, no friction at the boundary
1 plate with no power, no fins. For side plate or core barrel
2 fuel plate with power and fins -- not currently implemented.
iendn plate nplate (last plate) option, same as for iend1
ivsc =0, calculate viscosity and k for film heat trans coef at bulk coolant temp. =1, use clad surface T.
niter number of iterations to get the plate power splits for an axial node consistent with the node temperatures
ilocp = 0, each plate uses a separate random local power factor
= 1, all plates use the same random local power factor multiplier

title (20a4)

ipwshp, ifatl, iflwnc, idf, itrprt, inom, ipronb, ibypas, ivscfl, ioptn (9i8,8i1)
ipwshp > 0, read power shapes for plates 2 - nplate-1 from unit ipwshp -- not yet implemented
ifatl = 0, stop on fatal input errors. not on comments about questionable input (repeated values for the same channel or plate)
= 1, stop on fatal errors or comments
iflwnc = 0, calculate flwinc on basis of gapmla(ich), only accurate if nchan = nplt + 1, modeling 1 complete element.
1, use input value for flwinc
idf = 0, use flow disparity factor = df as the same for all elements
= 1, treat df statistically by element: average = 1.0, sigma = (1.0 - df)/3
itrprt print plate power split iteration information from the first itrprt histories.
if inom > 0, for each nominal reactor power start with history 0, nominal values for everything.
ipronb print the first ipronb histories where onb occurs
ibypas = 1, code calculates bypass flow and flwfac using acbyp and dhbyp
= 0, use input value for flwfac
ivscfl = 0, no viscosity effect in channel flow calculation
+N include viscosity effects, iterate up to N times
-N also print iteration results if history < ipt
ioptn = options, 8 one-character integers

Note: ioptn is an array containing 8 numbers, read in using 8i1 for a format. Thus one space is used for each number.

ioptn(1) = 0 Stat7 calculates the Carnavos heat transfer fin factor, if the finned groove depth grvdml is > 0

ioptn(1) > 0 for user-specified Carnavos heat transfer fin factor, if the finned groove depth grvdml is > 0

Note: If grvdml = 0, then there are no fins; and the Carnavos heat transfer fin factor = 1.0.

ioptn(2) > 0 use equal power splits (0.5) for all nodes of all plates

ioptn(2) = 0, calculate power splits

ioptn(3) = 0, use the Stat7 version of the Carnavos friction factor multiplier for fins
 ioptn(3) = 1, Carnavos friction factor multiplier for fins = 1.0
 ioptn(3) = 2, use the PLTEMP version of the Carnavos friction factor multiplier for fins
 ioptn(4-8) reserved for future use.

Note: For ioptn(3) the Stat7 and PLTEMP treatments are the same except for in the case where there is an end channel with fins on one side and an unfinned plate on the other side.

Block 2: Floating Point Variable Input Lines

title (20a4)

thdbug, fcore, ffuel, flwfac, df, flwinc, pow0, powsgm, cnveps (9f10.5)

thdbug = turn on thermal hydraulic debug prints if thdbug > 0.

fcore = fraction of the fission power deposited in the core region (F_{core})

ffuel = fuel deposition factor (F_{fuel})

flwfac = coolant flow factor accounts for bypass flow (F_f)

df = plenum flow disparity factor (d_f)

flwinc = ratio of the average interior channel flow to the average channel

flow. Accounts for end channel flow being different from half of interior channel flow. If all interior channels are nominally the same, then

$$flwinc = N_p / (N_p - 1 + 2 \times (W_e/W_i))$$

N_p = number of plates, W_e = end channel mass flow rate

W_i = interior channel mass flow rate

pow0 Total power, Mw. nominal value = 7.0

powsgm = 1 sigma fractional total power uncertainty.

cnveps = ONB power iteration convergence criterion, default = 0.05

title (20a4)

plocsg, sigmax, tout, wp0, wpsgm, coolht, fl, fw, thzrml, xkzr (10f10.5)

plocsg = 1 sigma fractional local power uncertainty

sigmax random values limited to the range -sigmax to +sigmax, default = 5

tout = coolant outlet temperature (C) = 60

wp0 = nominal (measured) pump flow (kg/s) = 112.1 kg/s

wpsgm = 1 sigma fractional pump flow uncertainty.

coolht = coolant height above the top of the fuel plates (m)

fl = fuel length in the plate, (m)

fw = fuel width in the plate, (m)

thzrml = thickness of the the layer (Z_r) between the fuel surface and cladding (mil)

xkzr = thermal conductivity of the layer (Z_r) between the fuel surface and cladding [$w/(m-K)$]

title (20a4)

grvdml, grvwml, grvtml, gapml, gapsg, grvfav, htcsgrm, eponb, thkoxm, xkox (10f10.5)

grvdml = groove depth (mil) = 10. currently

grvwml = groove width (mil) = 10. currently

grvtml = width of groove tip (mil) = 10. currently

gapml = fin-tip-to-fin-tip gap (mil) = 72. for LEU

default value, used only if gapmli(ich) = 0. for

ich = 2 ... nchan - 1

gapsg = nominal gap fractional sigma, gap = gapml(1 + x*gapsg)

x = random sampling for (val - mean)/sigma

default value, used only if gapsgi(ich) = 0. for

ich = 2 ... nchan - 1

Note: Section 4.6.4 gives 3 sigma channel flow uncertainty = 13%

Note: Section 4.6.3.2 gives channel flow proportional to

(effective gap)**1.714

nominal effective gap = 72 + 10 = 82 mil

if gapsg = .0854/3 and x = 3, then gap = 1.0854*72 = 78.05 mil

(78.05 + 10)/(72 + 10) = 1.074 1.074**1.714 = 1.13 = 13%

therefore gapsg = .0854/3 = .0285 results in a 3 sigma flow uncertainty = 13%

alternatively, gapsg can be set based on min gap = nominal gap - 4 mil

grvfav = average groove gap factor = average groove width/groove width + fin width.

grvfav corresponds to grvwml/(grvwml + grvtml) for the av ch

htcsgm = 1 sigma fractional heat transfer coef.uncertainty

Section 4.6.4 value = .20/3

epsonb = iterate on power until ONB fraction = epsonb, only used if iterpw = 1

thkoxm = thickness (mil) of the oxide layer on the plate surface

xkox = thermal conductivity (w/m-K) of the oxide

title (20a4)

gapml0, flstrf, acbyp, dhbyp, afrv, xke, bfrv, xkf, fcarff (9f10.5)

gapml0 = nominal interior gap size, default = same as gapml

flstrf = fraction of channel flow in the fuel (stripe) region, .902

acbyp = bypass flow area

dhbyp = bypass hydraulic diameter

afrv friction factor = afr x Re**bfr. If bfrv less than 0. then

afr = afrv, bfr = bfrv. Otherwise afr = .316, bfr = -.25

thke = effective clad thickness for conduction, one side of plate (mil)

xke = clad thermal conductivity

bfrv = see afrv above

thkf = fuel thickness, total (mil)

xkf = fuel thermal conductivity (w/m-K)

fcarff = user-specified Carnavos heat transfer fin factor

Block 3: Coolant Channel Gap Variable Input Lines

Standard input format:

title (20a4)

ich, gapmli(ich), gapsg(ich), gapmla(ich) (i8,2x,f10.2,f10.5,f10.2)

ich = coolant channel

gapmli(ich) = nominal fin tip-to-fin tip gap (mil) for this element

gapsg(ich) = fractional standard deviation

gapmla(ich) = average fin tip-to-fin tip gap (mil),

average over whole core

repeat for ich = 1 to nchan

Alternate input format:

ich1, ich2, gapmli(ich), gapsgi(ich), gapmla(ich) (2i4,2x,f10.2,f10.5,f10.2)
 sets values for ich = ich1 to ich2

The two input formats can be mixed as long as all channels are included.

The default for gapmla(ich) is gapmli(ich)

Block 4: Fuel and Cladding Thickness Variable Input LinesStandard input format:

title (20a4)
 ich, thkf(ipl), thke(ipl) (i8,2x,f10.2,f10.5)

ipl = plate
 thkf = fuel thickness (mil)
 thke = clad thickness (mil)
 repeat for ipl = 1 to nplate
 nplate = nchan + 1

Note: nplate includes the two extra end plates, as described under “nchan” above.

Alternate input format:

ip1, ip2, thkf(ipl), thke(ipl) (2i4,f10.2,f10.5)
 sets values for ipl = ip1 to ip2

The two input formats can be mixed as long as all plates are included.

Block 5: Plate Power Distribution Variable Input Lines

title (20a4)
 ipl, fstrp(ipl) (i8,2x,f10.2,f10.5)
 ipl = plate
 fstrp = stripe power / core average stripe power

(axpow(j,ipl), j=1,nz) (8f10.5)
 j = axial node
 axpow = axial power shape

repeat title /ipl, fstrp(ipl) / and axpow(j,ipl) for all nplate plates

Note: axpow(j,ipl) will be renormalized by the code so that for each plate the sum of axpow over all axial nodes = 1.0. Then the nominal power (watts) in the stripe for axial node j of plate ipl will be
 $1.0e+6 \times \text{pow0} \times \text{fcore} \times \text{fstrp(ipl)} \times \text{axpow(j,ipl)} / (\text{nelm} \times \text{nplt} \times \text{nstrp})$

Limits on number of regions

Note that the following maximum number of regions apply:

axial nodes: 40
 coolant channels: 50
 plates: 51

8 OUTPUT VARIABLES

Initial flwinc iteration

flwinc = ratio of the average interior channel flow to the average channel flow.

Accounts for end channel flow being different from interior channel flow.

afr, bfr: friction factor = $afr \cdot Re^{**}bfr$

Plate power split iteration

ip = plate number

plate surface 1 faces coolant channel ip – 1

plate surface 2 faces coolant channel ip

fp1 = power split = flux at surface 1/(flux at surface 1 + flux at surface 2)

Tfuel1 = peak fuel temperature calculated from surface 1

Tfuel2 = peak fuel temperature calculated from surface 2

Coolant channel results for a sample

fpowt = reactor power statistical multiplier

fllwt = pump flow multiplier

ich = coolant channel

whs = coolant mass flow rate (kg/s)

gap = fin-tip to fin tip gap (mil)

acc = coolant flow area (sq m)

dh = hydraulic diameter (m)

fcar = Carnavos fin heat transfer multiplier

jz = axial node

tcool = coolant temperature (C) at bottom of the node

tcoola = average coolant temperature at middle of the node

tsata = saturation temperature, middle of node

reya = Reynolds number, middle of node

vsca = viscosity, middle of node

rhocol = coolant density, bottom of node

rhocla = coolant density, node average

pcool = coolant pressure (bar) at bottom of node

pcoola = coolant pressure, node average

Plate results

aclad = clad surface area on the 2 surfaces

tsurf1, tsurf2 = clad surface temperatures on faces 1 and 2

tonb1, tonb2 = ONB temperature on face 1 or 2

fpl1 = power split = face 1 flux / (face 1 flux + face 2 flux)

powplt = axial node plate power

hcool1, hcool2 = film heat transfer coefficient, face 1 or face 2

fstrpw = statistical multiplier for the stripe power

tfuel1, tfuel2 = peak fuel temperature calculated starting from face 1 or 2

reyp1, reyp2 = Re for film on face 1 or 2

vscp1, vscp2 = viscosity of film on face 1 or 2

xkcp1, xkcp2 = thermal conductivity of the film on face 1 or 2

prp4p1, prp4p2 = (Prandtl number)**0.4 for the film on face 1 or 2

9 SAMPLE INPUT

s7n189b iend1, iendn = 1, run in stat7n

```

nelm | nplt | nstrp | nz | nbatch | nsmpl | isd1 | isd2 | iprt | idbstt |
22 18 4 18 25 4000 21 3 2 1
nchan | iaxpow | irndmn | ipow | iterpw | iend1 | iendn | ivsc | niter | ilocp |
19 0 0 1 2 1 1 0 2 1
ipwshp | ifatl | iflwn | idf | itprt | inom | ipronb | ibypas | ivscfl | ioptn |
0 0 0 0 1 1
thdbug | fcore | ffuel | flwfac | df | flwinc | pow0 | powsgm |
0. .965 .94 .921 .93 .964 8.00 .01667
plocsg | sigmax | tout | wp0 | wpsgm | coolht | fl | fw |
.0471 8.0 60. 138.8 .01667 3.048 .568 .0529
grvdm1 | grvwml | grvtm1 | gapml | gapsg | fdumy3 | htcsgrm | epsonb |
10. 10. 10. 72.0 .01878 0.0 .0667 .00135
gapml0 | flstrf | fuelthnu | fuelk nu | afrv | xke | bfrv | xkf |
72.0 .91 .184 160. -.2 14.
ich | gapmli | gapsgi |
1 50.5 0.1122
2 72.0 0.0185
3 72.0 0.0185
4 72.0 0.0185
5 72.0 0.0185
6 72.0 0.0185
7 72.0 0.0185
8 72.0 0.0185
9 72.0 0.0185
10 72.0 0.0185
11 72.0 0.0185
12 72.0 0.0185
13 72.0 0.0185
14 72.0 0.0185
15 72.0 0.0185
16 72.0 0.0185
17 72.0 0.0185
18 72.0 0.0185
19 50.5 0.1122
iplate | thkf | thke |
1 17. 17.5
2 20.00 15.00
3 20.00 15.00
4 20.00 15.00
5 20.00 15.00
6 20.00 15.00
7 20.00 15.00
8 20.00 15.00
9 20.00 15.00
10 20.00 15.00
11 20.00 15.00
12 20.00 15.00
13 20.00 15.00
14 20.00 15.00
15 20.00 15.00

```

```

16 20.00 15.00
17 20.00 15.00
18 20.00 15.00
19 20.00 15.00
20 17. 17.5
iplate| fstrp | axpow
1 0.
64.764 61.337 64.866 67.677 68.455 70.141 71.184 70.775
70.952 71.630 68.597 64.352 59.538 53.110 42.929 31.686
20.451 15.700
iplate| fstrp | axpow
2 2.140
64.764 61.337 64.866 67.677 68.455 70.141 71.184 70.775
70.952 71.630 68.597 64.352 59.538 53.110 42.929 31.686
20.451 15.700
iplate| fstrp | axpow
3 1.605
49.319 44.677 47.762 51.364 51.294 51.859 52.941 53.319
52.859 53.686 51.999 48.065 44.330 39.241 32.614 24.066
15.990 13.474
iplate| fstrp | axpow
4 1.313
40.868 36.151 39.150 41.729 41.249 41.948 42.409 42.939
42.843 43.149 42.369 39.597 36.819 32.096 27.125 20.256
14.274 12.159
iplate| fstrp | axpow
5 1.145
36.208 31.947 34.117 35.856 34.873 35.968 36.548 37.090
36.801 37.270 36.840 34.483 32.279 28.170 24.006 18.099
13.117 12.100
iplate| fstrp | axpow
6 1.048
33.305 28.014 31.144 32.145 32.132 32.865 33.104 34.330
33.723 34.053 32.674 31.243 29.651 25.474 22.454 17.171
12.759 12.172
iplate| fstrp | axpow
7 0.985
31.531 26.358 28.464 30.783 30.050 30.324 31.118 32.071
31.698 31.295 31.300 29.373 26.869 24.564 20.720 16.500
12.253 12.652
iplate| fstrp | axpow
8 0.946
30.056 24.639 27.133 28.886 28.556 29.194 30.004 29.876
29.960 30.419 29.818 28.210 26.145 23.843 20.729 16.163
12.360 12.947
iplate| fstrp | axpow
9 0.927
29.668 24.435 26.518 28.547 27.229 28.214 29.096 29.324
29.294 29.887 29.376 27.634 25.566 23.237 20.143 16.225
12.400 12.935
iplate| fstrp | axpow
10 0.920
29.610 23.521 25.991 28.231 27.165 27.812 28.385 28.592
28.934 29.044 28.746 27.413 26.166 23.613 19.846 16.904

```

```

12.870 13.550
iplate| fstrp | axpow
11 0.916
29.716 24.399 26.069 27.813 27.368 27.314 27.946 28.603
28.837 28.515 28.748 27.061 25.412 23.445 19.584 16.381
12.903 14.255
iplate| fstrp | axpow
12 0.919
30.617 23.981 25.963 28.086 27.047 27.498 28.250 28.022
29.009 28.232 29.280 27.438 25.419 23.431 20.055 16.021
13.041 14.669
iplate| fstrp | axpow
13 0.928
30.814 24.073 26.522 27.895 27.362 27.447 28.191 28.216
28.657 28.550 29.312 26.746 25.880 23.908 20.763 16.835
13.757 15.200
iplate| fstrp | axpow
14 0.942
31.070 24.672 26.883 28.393 27.643 28.227 28.769 28.954
29.527 28.861 29.298 27.177 26.392 23.697 20.660 17.341
13.792 15.640
iplate| fstrp | axpow
15 0.956
30.995 25.603 27.022 28.934 28.027 28.286 29.027 29.489
29.744 29.078 29.777 27.791 26.473 23.744 21.080 17.717
14.692 16.317
iplate| fstrp | axpow
16 0.963
30.893 25.358 27.209 29.397 28.348 28.290 29.591 29.381
29.601 29.382 29.786 28.830 27.146 23.715 21.382 18.199
14.567 16.237
iplate| fstrp | axpow
17 0.986
31.214 25.502 28.150 29.599 28.922 29.021 29.901 30.497
30.703 30.033 30.561 29.292 27.441 24.938 21.590 18.600
15.074 17.463
iplate| fstrp | axpow
18 1.021
32.697 26.494 29.400 30.608 29.957 30.253 30.782 31.323
31.725 30.993 31.351 30.244 28.519 25.927 22.462 19.168
15.662 17.991
iplate| fstrp | axpow
19 1.059
33.722 26.584 29.897 31.919 30.527 30.815 32.015 32.056
32.850 32.831 32.863 31.960 29.587 26.674 23.939 20.139
16.388 18.935
iplate| fstrp | axpow
20 0.
33.722 26.584 29.897 31.919 30.527 30.815 32.015 32.056
32.850 32.831 32.863 31.960 29.587 26.674 23.939 20.139
16.388 18.935

```

10 REPRESENTATIVE PARTS OF A SAMPLE OUTPUT

The output from a STAT7 run can be rather large, depending on the print options, and there is a lot of repetition for different plates, channels, histories and power iterations. Shown below are representative parts of the output from the above sample input case.

```

Stat7_1.0
s7n189b iend1, iendn = 1, run in stat7n
nelm | nplt | nstrp | nz | nbatch | nsmpl | isd1 | isd2 | iprt | idbstt |
  22  18   4  18  25  4000  21   3   2   1
nchan | iaxpow | irndmn | ipow | iterpw | iend1 | iendn | ivsc | niter | ilocp |
  19   0   0   1   2   1   1   0   2   1
ipwshp | ifatl | iflwnc | idf | itprt | inom | ipronb | ibypas | ivscfl | ioptn |
   0   0   0   0   1   1   0   0   000000000
thdbug | fcore | ffuel | flwfac | df | flwinc | pow0 | powsgm |
  0.00000 0.96500 0.94000 0.92100 0.93000 0.96400 8.00000 0.01667 0.00000
plocsg | sigmax | tout | wp0 | wpsgm | coolht | fl | fw |
  0.04710 8.00000 60.00000 138.80000 0.01667 3.04800 0.56800 0.05290 0.00000 0.00000
grvdm1 | grvwml | grvtml | gapml | gapsg | fdumy3 | htcsgr | epsonb |
  10.00000 10.00000 10.00000 72.00000 0.01878 0.00000 0.06670 0.00135 0.00000 0.00000
gapml0 | flstrf | fuelthnu | fuelk nu | afrv | xke | bfrv | xkf |
  72.00000 0.91000 0.00000 0.00000 0.18400 160.00000 -0.20000 14.00000 0.00000
ich | gapmli | gapsgi |
0 1  50.50 0.11220 0.00
0 2  72.00 0.01850 0.00
0 3  72.00 0.01850 0.00
0 4  72.00 0.01850 0.00
0 5  72.00 0.01850 0.00
0 6  72.00 0.01850 0.00
0 7  72.00 0.01850 0.00
0 8  72.00 0.01850 0.00
0 9  72.00 0.01850 0.00
0 10 72.00 0.01850 0.00
0 11 72.00 0.01850 0.00
0 12 72.00 0.01850 0.00
0 13 72.00 0.01850 0.00
0 14 72.00 0.01850 0.00
0 15 72.00 0.01850 0.00
0 16 72.00 0.01850 0.00
0 17 72.00 0.01850 0.00
0 18 72.00 0.01850 0.00
0 19 50.50 0.11220 0.00
after processing gapsgi and gapmli values
ich | gapmli | gapsgi |
1  50.50 0.11220 50.50
2  72.00 0.01850 72.00
3  72.00 0.01850 72.00
4  72.00 0.01850 72.00
5  72.00 0.01850 72.00
6  72.00 0.01850 72.00
7  72.00 0.01850 72.00
8  72.00 0.01850 72.00
9  72.00 0.01850 72.00
10 72.00 0.01850 72.00
11 72.00 0.01850 72.00
12 72.00 0.01850 72.00
13 72.00 0.01850 72.00

iplate | fstrp | axpow
1  0.0000
64.76400 61.33700 64.86600 67.67700 68.45500 70.14100 71.18400 70.77500
70.95200 71.63000 68.59700 64.35200 59.53800 53.11000 42.92900 31.68600
20.45100 15.70000

```

renormalized axial power

0.06238 0.05908 0.06248 0.06519 0.06594 0.06756 0.06857 0.06817
 0.06835 0.06900 0.06608 0.06199 0.05735 0.05116 0.04135 0.03052
 0.01970 0.01512
 iplate| fstrp | axpow
 2 2.1400
 64.76400 61.33700 64.86600 67.67700 68.45500 70.14100 71.18400 70.77500
 70.95200 71.63000 68.59700 64.35200 59.53800 53.11000 42.92900 31.68600
 20.45100 15.70000

renormalized axial power
 0.06238 0.05908 0.06248 0.06519 0.06594 0.06756 0.06857 0.06817
 0.06835 0.06900 0.06608 0.06199 0.05735 0.05116 0.04135 0.03052
 0.01970 0.01512

thermal hydraulic results for sample 0
 pow0 = 8.0000 fpowt= 1.0000, fflwt= 1.0000 ONB occurred at 0 places

ich= 1 whs= 4.286E-02. gap= 5.050E+01 acc= 1.864E-05 dh= 1.880E-03
 fcar= 0.714, Carnavos friction factor multiplier 1.044
 jz tcool tcoola tsata reya vsca rhocol rhocla pcool pcoola cpa
 1 46.70 47.60 113.37 7.590E+03 5.694E-04 9.895E+02 9.892E+02 1.611E+05 1.603E+05 4.180E+03
 2 48.50 49.35 113.04 7.820E+03 5.526E-04 9.888E+02 9.884E+02 1.594E+05 1.585E+05 4.180E+03
 3 50.21 51.11 112.71 8.054E+03 5.366E-04 9.880E+02 9.876E+02 1.576E+05 1.568E+05 4.181E+03
 4 52.01 52.96 112.37 8.302E+03 5.205E-04 9.872E+02 9.867E+02 1.559E+05 1.550E+05 4.182E+03
 5 53.90 54.86 112.03 8.560E+03 5.048E-04 9.863E+02 9.858E+02 1.542E+05 1.533E+05 4.182E+03
 6 55.82 56.80 111.69 8.825E+03 4.897E-04 9.854E+02 9.849E+02 1.524E+05 1.516E+05 4.183E+03
 7 57.78 58.78 111.35 9.099E+03 4.749E-04 9.844E+02 9.839E+02 1.507E+05 1.499E+05 4.184E+03
 8 59.78 60.77 111.01 9.377E+03 4.609E-04 9.834E+02 9.828E+02 1.490E+05 1.482E+05 4.185E+03
 9 61.76 62.76 110.67 9.658E+03 4.475E-04 9.823E+02 9.818E+02 1.473E+05 1.465E+05 4.186E+03
 10 63.76 64.77 110.32 9.943E+03 4.346E-04 9.813E+02 9.807E+02 1.456E+05 1.448E+05 4.187E+03
 11 65.78 66.75 109.97 1.023E+04 4.226E-04 9.802E+02 9.796E+02 1.439E+05 1.431E+05 4.188E+03
 12 67.72 68.63 109.62 1.050E+04 4.117E-04 9.791E+02 9.786E+02 1.423E+05 1.414E+05 4.189E+03
 13 69.54 70.38 109.27 1.075E+04 4.019E-04 9.781E+02 9.776E+02 1.406E+05 1.397E+05 4.190E+03
 14 71.23 71.99 108.91 1.099E+04 3.933E-04 9.771E+02 9.767E+02 1.389E+05 1.381E+05 4.191E+03
 15 72.74 73.36 108.55 1.119E+04 3.861E-04 9.762E+02 9.758E+02 1.372E+05 1.364E+05 4.192E+03
 16 73.98 74.44 108.19 1.135E+04 3.807E-04 9.755E+02 9.752E+02 1.356E+05 1.348E+05 4.193E+03
 17 74.90 75.21 107.83 1.147E+04 3.769E-04 9.749E+02 9.747E+02 1.339E+05 1.331E+05 4.193E+03
 18 75.52 75.76 107.46 1.155E+04 3.742E-04 9.746E+02 9.744E+02 1.323E+05 1.315E+05 4.194E+03
 19 76.00 9.743E+02 1.306E+05

ich= 2 whs= 6.727E-02. gap= 7.200E+01 acc= 2.755E-05 dh= 2.083E-03
 fcar= 0.716, Carnavos friction factor multiplier 1.059
 jz tcool tcoola tsata reya vsca rhocol rhocla pcool pcoola cpa
 1 46.70 47.72 113.36 8.953E+03 5.682E-04 9.895E+02 9.891E+02 1.611E+05 1.602E+05 4.180E+03
 2 48.75 49.69 113.03 9.259E+03 5.494E-04 9.887E+02 9.882E+02 1.593E+05 1.584E+05 4.181E+03
 3 50.64 51.64 112.69 9.565E+03 5.318E-04 9.878E+02 9.873E+02 1.576E+05 1.567E+05 4.181E+03
 4 52.64 53.70 112.36 9.891E+03 5.143E-04 9.869E+02 9.864E+02 1.558E+05 1.550E+05 4.182E+03
 5 54.76 55.82 112.02 1.023E+04 4.972E-04 9.859E+02 9.853E+02 1.541E+05 1.532E+05 4.183E+03
 6 56.88 57.95 111.68 1.058E+04 4.810E-04 9.848E+02 9.843E+02 1.524E+05 1.515E+05 4.184E+03
 7 59.03 60.11 111.34 1.093E+04 4.654E-04 9.837E+02 9.832E+02 1.507E+05 1.498E+05 4.185E+03
 8 61.20 62.29 111.00 1.129E+04 4.506E-04 9.826E+02 9.820E+02 1.490E+05 1.481E+05 4.186E+03
 9 63.37 64.45 110.65 1.165E+04 4.366E-04 9.815E+02 9.809E+02 1.473E+05 1.464E+05 4.187E+03
 10 65.53 66.62 110.31 1.202E+04 4.233E-04 9.803E+02 9.797E+02 1.456E+05 1.447E+05 4.188E+03
 11 67.71 68.75 109.96 1.238E+04 4.110E-04 9.791E+02 9.785E+02 1.439E+05 1.431E+05 4.189E+03
 12 69.79 70.75 109.61 1.272E+04 3.999E-04 9.779E+02 9.774E+02 1.422E+05 1.414E+05 4.190E+03
 13 71.71 72.60 109.26 1.304E+04 3.901E-04 9.768E+02 9.763E+02 1.405E+05 1.397E+05 4.192E+03
 14 73.48 74.26 108.91 1.333E+04 3.816E-04 9.758E+02 9.753E+02 1.389E+05 1.381E+05 4.193E+03
 15 75.03 75.65 108.55 1.358E+04 3.747E-04 9.749E+02 9.745E+02 1.372E+05 1.364E+05 4.194E+03
 16 76.28 76.72 108.19 1.376E+04 3.696E-04 9.741E+02 9.738E+02 1.356E+05 1.347E+05 4.194E+03
 17 77.16 77.43 107.83 1.389E+04 3.663E-04 9.736E+02 9.734E+02 1.339E+05 1.331E+05 4.195E+03
 18 77.70 77.91 107.46 1.397E+04 3.641E-04 9.732E+02 9.731E+02 1.323E+05 1.315E+05 4.195E+03
 19 78.11 9.730E+02 1.306E+05

plate 2, aclad= 8.346E-04 8.346E-04

```

jz Tcoola Tsata Tonb Tsurf1 Tox-cd Tcd-zr Tzr-f Tfm1 Tfm2 Tf-zr Tzr-cd Tcd-ox Tsurf2 Tonb Tsata Tcoola2 fp1
1 47.60 113.37 119.96 77.81 77.81 79.54 79.54 86.06 86.06 79.29 79.29 77.53 77.53 120.00 113.36 47.72 0.495
2 49.35 113.04 119.50 77.63 77.63 79.27 79.27 85.48 85.48 79.09 79.09 77.43 77.43 119.53 113.03 49.69 0.496
3 51.11 112.71 119.38 80.66 80.66 82.39 82.39 88.98 88.98 82.24 82.24 80.48 80.48 119.40 112.69 51.64 0.497
4 52.96 112.37 119.22 83.40 83.40 85.22 85.22 92.11 92.11 85.11 85.11 83.28 83.28 119.23 112.36 53.70 0.498
5 54.86 112.03 118.96 85.28 85.28 87.12 87.12 94.11 94.11 87.06 87.06 85.21 85.21 118.96 112.02 55.82 0.499
6 56.80 111.69 118.74 87.57 87.57 89.46 89.46 96.65 96.65 89.45 89.45 87.56 87.56 118.73 111.68 57.95 0.500
7 58.78 111.35 118.49 89.62 89.62 91.54 91.54 98.86 98.86 91.57 91.57 89.66 89.66 118.48 111.34 60.11 0.501
8 60.77 111.01 118.18 91.07 91.07 92.98 92.98 100.29 100.29 93.07 93.07 91.17 91.17 118.15 111.00 62.29 0.502
9 62.76 110.67 117.89 92.77 92.77 94.69 94.69 102.05 102.05 94.83 94.83 92.93 92.93 117.84 110.65 64.45 0.502
10 64.77 110.32 117.62 94.70 94.70 96.65 96.65 104.09 104.09 96.83 96.83 94.92 94.92 117.57 110.31 66.62 0.503
11 66.75 109.97 117.17 95.12 95.12 96.98 96.98 104.15 104.15 97.23 97.23 95.40 95.40 117.10 109.96 68.75 0.504
12 68.63 109.62 116.66 95.00 95.00 96.76 96.76 103.52 103.52 97.08 97.08 95.36 95.36 116.57 109.61 70.75 0.506
13 70.38 109.27 116.11 94.60 94.60 96.23 96.23 102.53 102.53 96.61 96.61 95.03 95.03 116.00 109.26 72.60 0.508
14 71.99 108.91 115.45 93.47 93.47 94.93 94.93 100.61 100.61 95.37 95.37 93.97 93.97 115.32 108.91 74.26 0.510
15 73.36 108.55 114.53 90.73 90.73 91.92 91.92 96.59 96.59 92.44 92.44 91.31 91.31 114.37 108.55 75.65 0.515
16 74.44 108.19 113.45 87.37 87.37 88.26 88.26 91.81 91.81 88.84 88.84 88.02 88.02 113.23 108.19 76.72 0.522
17 75.21 107.83 112.20 83.76 83.76 84.35 84.35 86.77 86.77 84.98 84.98 84.47 84.47 111.90 107.83 77.43 0.537
18 75.76 107.46 111.39 82.44 82.44 82.90 82.90 84.85 84.85 83.54 83.54 83.16 83.16 111.05 107.46 77.91 0.549
jz reyp1 reyp2 vscp1 vscp2 xkcp1 xkcp2 prp4p1 prp4p2 hcool1 hcool2 qc1 qc2
1 7.590E+03 8.953E+03 5.694E-04 5.682E-04 6.405E-01 6.406E-01 1.689E+00 1.688E+00 1.201E+04 1.241E+04 36.29 36.98
2 7.821E+03 9.259E+03 5.526E-04 5.494E-04 6.426E-01 6.430E-01 1.667E+00 1.663E+00 1.218E+04 1.260E+04 34.45 34.95
3 8.054E+03 9.565E+03 5.365E-04 5.318E-04 6.447E-01 6.453E-01 1.645E+00 1.639E+00 1.235E+04 1.280E+04 36.49 36.91
4 8.302E+03 9.891E+03 5.205E-04 5.143E-04 6.468E-01 6.476E-01 1.623E+00 1.615E+00 1.253E+04 1.300E+04 38.13 38.44
5 8.560E+03 1.023E+04 5.048E-04 4.972E-04 6.489E-01 6.499E-01 1.602E+00 1.591E+00 1.271E+04 1.320E+04 38.65 38.81
6 8.825E+03 1.058E+04 4.897E-04 4.810E-04 6.510E-01 6.521E-01 1.580E+00 1.568E+00 1.289E+04 1.341E+04 39.66 39.70
7 9.099E+03 1.093E+04 4.749E-04 4.654E-04 6.530E-01 6.543E-01 1.560E+00 1.546E+00 1.307E+04 1.362E+04 40.32 40.23
8 9.377E+03 1.129E+04 4.609E-04 4.506E-04 6.550E-01 6.564E-01 1.539E+00 1.524E+00 1.326E+04 1.382E+04 40.16 39.92
9 9.658E+03 1.165E+04 4.475E-04 4.366E-04 6.568E-01 6.584E-01 1.520E+00 1.504E+00 1.344E+04 1.403E+04 40.33 39.95
10 9.943E+03 1.202E+04 4.346E-04 4.233E-04 6.587E-01 6.603E-01 1.501E+00 1.484E+00 1.362E+04 1.423E+04 40.78 40.27
11 1.023E+04 1.238E+04 4.226E-04 4.110E-04 6.604E-01 6.621E-01 1.483E+00 1.465E+00 1.380E+04 1.443E+04 39.16 38.46
12 1.050E+04 1.272E+04 4.117E-04 3.999E-04 6.620E-01 6.637E-01 1.466E+00 1.448E+00 1.397E+04 1.461E+04 36.85 35.96
13 1.075E+04 1.304E+04 4.019E-04 3.901E-04 6.634E-01 6.651E-01 1.452E+00 1.433E+00 1.413E+04 1.478E+04 34.21 33.16
14 1.099E+04 1.333E+04 3.933E-04 3.816E-04 6.646E-01 6.663E-01 1.438E+00 1.420E+00 1.427E+04 1.493E+04 30.66 29.44
15 1.119E+04 1.358E+04 3.861E-04 3.747E-04 6.656E-01 6.673E-01 1.427E+00 1.409E+00 1.439E+04 1.506E+04 25.00 23.58
16 1.135E+04 1.376E+04 3.807E-04 3.696E-04 6.664E-01 6.680E-01 1.419E+00 1.401E+00 1.448E+04 1.515E+04 18.72 17.13
17 1.147E+04 1.389E+04 3.769E-04 3.663E-04 6.669E-01 6.685E-01 1.413E+00 1.396E+00 1.455E+04 1.521E+04 12.44 10.70
18 1.155E+04 1.397E+04 3.742E-04 3.641E-04 6.673E-01 6.688E-01 1.408E+00 1.392E+00 1.460E+04 1.526E+04 9.75 8.01

```

Results for 25 batches with 4000 samples per batch
 ONB occurred in at least one axial node in 136 samples,
 giving an ONB fraction = 1.360E-03
 sigma = 9.704E-05 for sqrt(variance), or sigma = 1.166E-04 for sqrt(N)
 nominal power = 9.28340
 peak ONBR at node 13 on surface 1 of plate 2
 ONBR = 1.320E-03

computer time for thermal hydraulics and sampling = 1.187E+01 seconds
 computer time for statistical analysis = 6.104E-05

power iteration table
 iteration power ONB fraction sigma ONB fraction - criterion
 1 8.0000 5.000E-05 2.000E-05 -3.296E+00
 2 9.0000 8.000E-04 6.633E-05 -5.232E-01
 3 10.0000 6.740E-03 2.012E-04 1.608E+00
 4 9.2455 1.240E-03 9.642E-05 -8.499E-02
 5 9.2834 1.360E-03 9.704E-05 7.380E-03
 ilow= 4, vallow=-8.499E-02, ihigh= 3, valhgh= 1.608E+00

power converged at iteration 5, power = 9.2834, ONB fraction = 1.360E-03, sigma = 9.704E-05
 limiting: power = 9.2834 Mw, surface 1, fuel plate 1, axial node 13

11 FORTRAN CODING

With one exception the Stat code is written using the FORTRAN 77 standard (X3.9-1978) of the American National Standards Institute (ANSI), which is a subset of FORTRAN 90. The one exception is that the Stat code is written with lower case letters, which is allowed in FORTRAN 90. The FORTRAN 77 standard calls for upper case letters for all coding.

12 COMPILING AND EXECUTING THE CODE

The command used to compile the Stat7 code with the ifort compiler is:

```
ifort source.f  
mv a.out executable
```

The command used to execute the code in Unix or Linux is:

```
executable < input > output
```

or

```
./ executable < input > output
```

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APPENDIX A, COMMENTS ON FINS

Fins can be used to improve the heat transfer performance of a device by increasing the heat transfer area. The current MITR HEU core uses fins on the fuel plates. The fins are 10 mils high, 10 mils wide, and they are 10 mils apart. These fins double the heat transfer area of the fuel plates. The fins also increase the friction pressure drop in the fuel elements.

The Carnavos treatment is used in Stat7 to account for fins. Carnavos made pressure drop measurements and heat transfer coefficient measurements involving coolant flow inside circular tubes, with fins on the inside of the tube wall. The results of the measurements are correlated in terms of ratios of surface areas and flow areas. The implementation of these correlations in Stat7 is described in Section 4.1.

There are two problems with using the Carnavos fin correlations for RERTR applications. The first problem is that the Carnavos measurements were made on circular geometry, whereas the coolant channels we are interested in are rectangular. The second problem is that the measurements were made on a geometry with fins all of the way around the outside of the coolant channels, which may be similar to an interior rectangular channel with fins on both long sides; but we are also interested in end channels with fins on only one side. Carnavos did not make any measurements with fins only part way around the tubes. The analogy with the use of the hydraulic diameter, $D_h = 4 \times \text{the flow area/the wetted perimeter}$, suggests that the measurement geometry problems mentioned above may not be too bad. For turbulent flow, the hydraulic diameter can be used to calculate reasonably accurate pressure drops for almost any geometry. A similar situation may exist for the use by Carnavos of the ratio of the actual free flow area to the nominal flow area without the fins to correlate a fin friction factor multiplier. The Carnavos results are probably all we have got to address the fin effects.

The Carnavos fin treatment is also used in the PLTEMP code^{A1}. The PLTEMP fin treatment is the same as that in Stat7, except for the friction factor multiplier for an end channel with fins on one side and no fins on the other side. For this case, Stat7 uses a straight-forward application of the Carnavos correlation, whereas PLTEMP uses a weighted average of a finned friction factor and a no-fin friction factor. PLTEMP uses

$$f_{avg} = (f_{fin} w_{fin} + f_{nofin} w_{nofin}) / (w_{fin} + w_{nofin})$$

where f_{fin} and f_{nofin} are the finned and no-fin friction factors, and w_{fin} and w_{nofin} are the wetted perimeters of the finned and no-fin surfaces. There is no experimental data to determine whether the Stat7 treatment or the PLTEMP treatment is more accurate for an end channel with fins on one side. There is an option in Stat7 to use either the Stat7 fin treatment or the PLTEMP treatment, so for a particular case it is possible to find out how much difference it makes.

In order to determine the impact of the fin treatment for a case of interest, Stat7 runs were made for case 189 from Reference A2 using various fin treatment options. This case is a LEU case with fins the same as the fins in current HEU core: 10 mil wide x 10 mil high x 10 mil between fins. In this case channel 1 is the limiting channel. Channel 1 is an end channel, and channel 2 is the first interior channel. The results of these runs are listed in Table A1.

Table A1, Stat7 Results for Various Fin Treatment Options

channel	Limiting power (Mw)	Coolant flow (kg/s)		friction factor multiplier		heat transfer multiplier		Pressure drop (kPa)	D _h (cm)	
		1	2	1	2	1	2		1	2
No fins ^a	5.9307	.03555	.06813	---	---	1.0	1.0	16.0	.2819	.4166
Fins, friction factor multiplier = 1.0	9.2786	.04255	.06731	1.0	1.0	.714	.716	29.1	.1880	.2083
Fins, Stat7 friction factor multiplier	9.2834	.04286	.06727	1.044	1.059	.714	.716	30.5	.1880	.2083
Fins, PLTEMP friction factor multiplier	9.3410	.04318	.06724	1.029	1.059	.714	.716	30.4	.1880	.2083

a) The channel gap sizes in the no-fins case were adjusted to give the same coolant flow areas as in the cases with fins.

The impact of the Carnavos fin treatment is mainly due to the heat transfer multiplier rather than the friction factor multiplier. For this case, the heat transfer multiplier has about a 30% impact on the heat transfer, whereas the friction factor multiplier has a 3 – 6% impact on the friction factor and less than 1% on the limiting power.

For this case the fins double the heat transfer surface area, although the Carnavos heat transfer multiplier of .714 – .716 reduces the overall improvement in the clad-to-coolant heat transfer. Also, the heat transfer coefficient is proportional to $1/D_h^{0.2}$, and this improves the heat transfer coefficient by 8–15%. The net heat transfer is improved by a factor of about 1.5 by adding the fins.

The impact on the pressure drop caused by adding fins is mostly caused by the change in hydraulic diameter due to the change in wetted perimeter. The friction factor multiplier is a small shape factor correction to account for effects not captured by the change in wetted perimeter.

The differences in limiting power or pressure drop between using the Stat7 friction factor multiplier and using the PLTEMP friction factor multiplier are less than 1%. Carnavos states that his measured data points for pressure drop and for temperature drop from the clad surface to the bulk liquid fall between $\pm 10\%$ from the correlations, so 1% differences are well within the accuracy of the correlations.

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