ANL/RTR/TM-16/7 Rev. 1

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

Nuclear Science & Engineering Division

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ABSTRACT

STAT7 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 highly enriched uranium fuel to low-enriched 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 can be 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

STAT7 was written to perform analysis of the steady state thermal hydraulic safety basis for MITR-II [Ref. 1], the MIT research reactor, but the code also may be applicable to other reactors with plate fuel. The conversion of MITR-II from highly enriched uranium (HEU) to low-enriched uranium (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 STAT7. 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 (LSSS) 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 STAT software, development versions STAT5 and STAT6, has previously used the one interior channel approach, with additional features in each successive version including in STAT6 the ability to model an end channel. STAT7 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 RECOMMENDATIONS FOR APPLICATION

It has been noted that STAT7 cannot predict flow distribution correctly if the model involves both fins and bypass specifications. Therefore, the users must avoid this situation. Additionally, the users should consider the following points:

- The number of axial nodes should be large enough (ten or more) to make a valid ONB margin prediction.
- The output of Reynolds number should be used to check if the problem is within the applicable range of the thermal hydraulics correlations implemented in the software.
- The user should run the code using different seeds (isd1 and isd2) and different number of histories (nbatch and nsmpl) to confirm that the results obtained from run to run stay within expected tolerances.
- The fitted functions used to generate the coolant properties have only been checked for the temperature range of $10 < T < 95$ °C and pressure range of $0.9 < P < 1.5$ bar.
- For the input parameters that are not involved in the statistical sampling process, the users should evaluate the continuing applicability of the assumed values (e.g. flow distribution).

3 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 Figure 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.

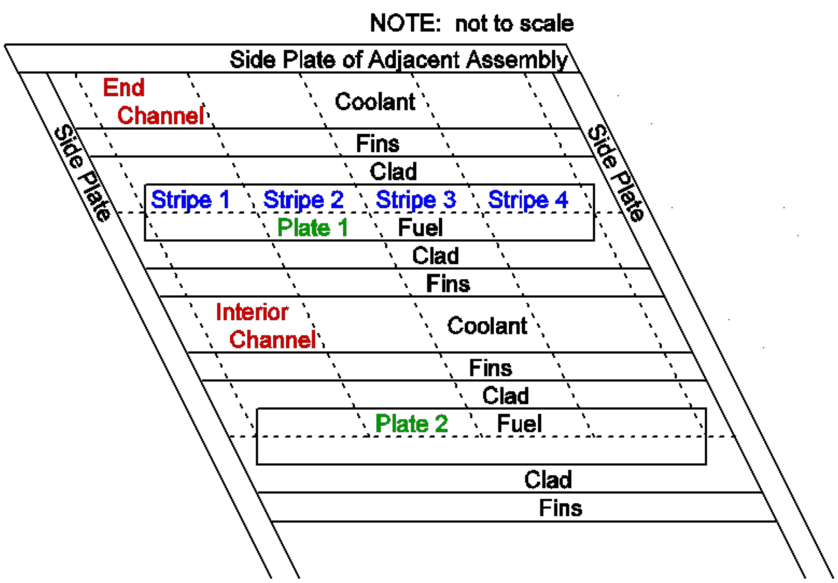

Figure 1. Channel Geometry for 4 Stripes

3.1 How Many Stripes are Necessary?

One of the issues that can be addressed by models implemented in this software 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 MITR-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 Figure 2, was set up using RELAP5-3D [Ref. 2]. 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.

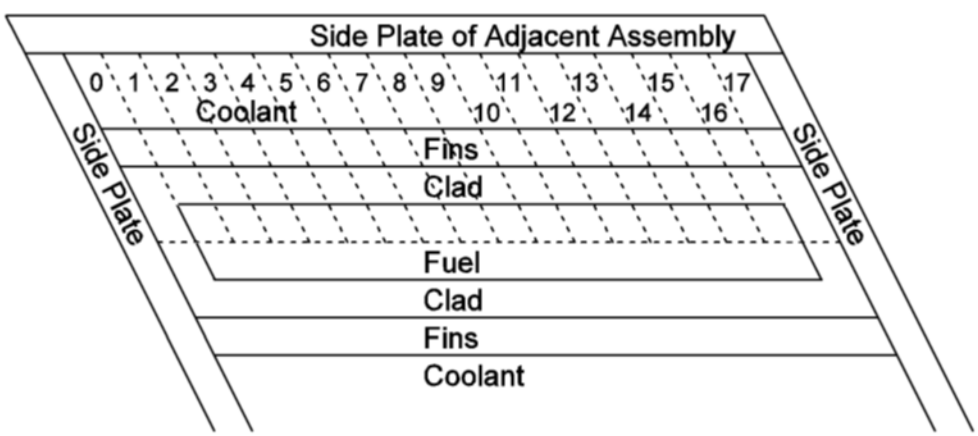

Figure 2. Multi-stripe RELAP5-3D Model

Results from these RELAP5-3D multi-stripe runs are shown in Figure 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, in the case of MITR fuel plates, 4 stripes are conservative for a multi-stripe steady-state calculation with no lateral conduction.

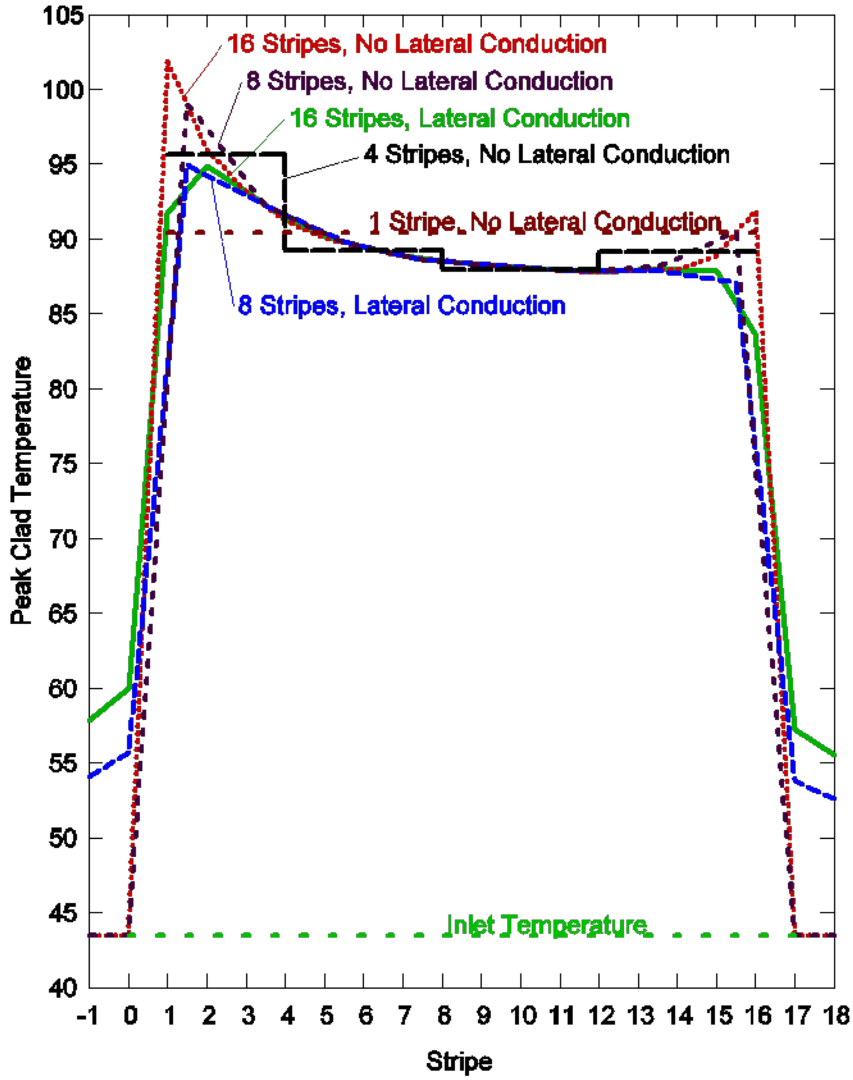

Figure 3. Peak Clad Temperature results from RELAP5-3D for various stripe discretization of the fuel plate and the coolant channel, both with and without lateral heat conduction in the plate.

4 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 Chang [Ref. 3] 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

5 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 neutronics 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.

5.1 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, W_p 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:

$$P_s = P_r f_c f_s/(N_e N_p N_s) \tag{1}$$

Where
- P_r = nominal core power
- f_c = the fraction of the fission power deposited in the core region
- 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

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

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

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

where f_c is the fraction of the power deposited in the core region. C_p is the heat capacity of the water. T_x is the outlet temperature. Note that all coolant properties are calculated by fitted functions which were established using NIST fluid database [Ref. 4].

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 Equation 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 for the hot stripe gap size, $[G]$, 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

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

Typically a_{fr} = 0.184, and bfr = -0.2 [Ref. 5], 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

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

Where
A_0 = nominal interior channel stripe flow area
D_{h0} = nominal interior channel stripe hydraulic diameter

Note that although Equation (2) applies to the nominal interior channel, Equation (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 Equation 4, 0.667 is replaced by D_{hrat} given by

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

Hot Stripe Axial Node Power Uncertainties

The statistical sampling value for the axial node plate power in the stripe, $[p_j]_j$, 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 uj 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

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

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 occurs [Ref. 6].

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

Where

$T_{clad,\,ONB}$ = fuel clad temperature (°C) at which ONB occurs,
T_{sat} = saturation temperature (°C),
q" = local heat flux (W/m2), and
p = pressure (bar).

Carnavos Fin Heat Transfer Coefficients and Clad Surface Temperatures

The fin heat transfer coefficients are calculated using the Carnavos correlation [Ref. 7]. 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 applicable for 10000<Re<100000 and is given as:

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

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 5.4 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%.

The clad surface temperatures are calculated from the coolant temperatures, the heat transfer coefficients and the clad heat fluxes. Additional discussion on fins is provided in Appendix A.

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

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

5.2 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:

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

where

f = friction factor
Re = actual Reynolds number
$F^* = (A_{fa} / A_{fn})^{0.5} (Sec[\alpha])^{0.75}$
A_{fa} = actual free flow area, mm^2
A_{fn} = nominal flow area based on tube ID as if the fin structure were not present, mm^2
$Sec[\alpha] = 1.0$ 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, ws, calculated by Eqn. 4, is then multiplied by a fin flow multiplier, fwm, 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

5.3 Statistical Sampling

The statistical sampling method is taken from a mathematical handbook [Ref. 8]. 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

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

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

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

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

$$r = I_p(x) \tag{11}$$

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

$$r = I_q(x) \tag{12}$$

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

for $r \le 0.5$

$$x(r) = v - (c_0 + c_1 v + c_2 v^2)/(1 + d_1 v + d_2 v^2) + \varepsilon(r) \tag{13}$$

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

c_0 = 2.515517 d_1 = 1.432788
c_1 = 0.802853 d_2 = 0.189269
c_2 = 0.010328 d_3 = 0.001308

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

for r > 0.5

$$x(r) = -x(1 - r) \tag{14}$$

5.4 Comparison with Oracle-Crystal Ball Results

A consistent series of cases for various coolant outlet temperatures was run with the Oracle Crystal Ball approach [Ref. 9] and with the STAT6 code. Figure 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 Figure 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.

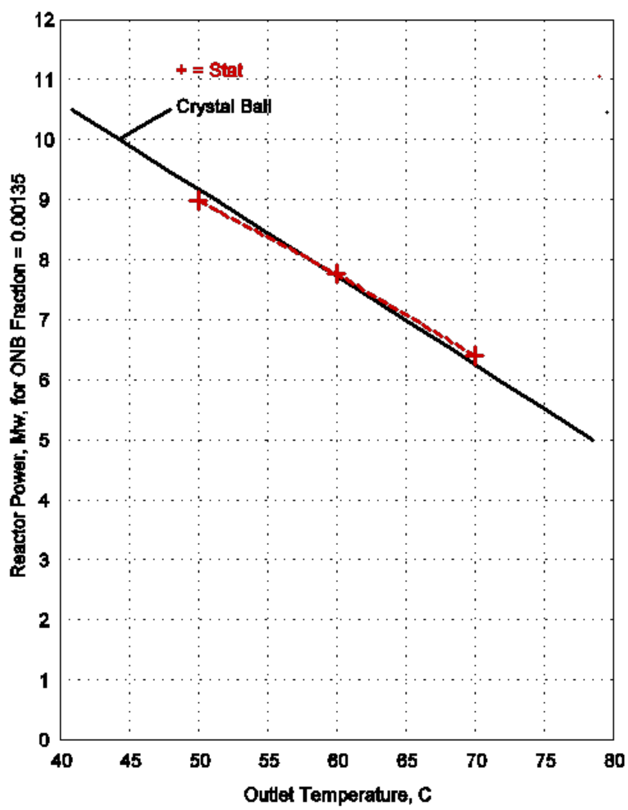

Figure 4. Comparison of STAT and Oracle-Crystal Ball Results

There are three advantages to the STAT6 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.

6 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 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.

6.1 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.

6.2 STAT7 Thermal Hydraulic Solution for a History

Nomenclature:

i = coolant channel number
Ni = number of coolant channels in the model = nchan (input value)
Ne = number of elements in the core = nelm (input)
Np = number of plates in the model = Ni + 1
Npe = number of plates per element
Ns = number of stripes/plate
Nz = 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 = (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
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 5.3.

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

$$Tin = Tx - Pr\, fc/(WpCp) \quad (16)$$

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 unfueled 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 head losses. Orifice pressure losses are also small compared to friction. The friction pressure drop, Δp(i), for a channel is:

$$\Delta p(i) = [fr\ L/Dh(i)]\ \ [Ws(i) / Ac(i)]^2 /(2\ \rho) \qquad (18)$$

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

$$fr = af\ Re^{bf} \qquad (19)$$

where

$$Re = \text{Reynolds number} = Dh(i)\ Ws(i)/[\mu\ Ac(i)] \qquad (20)$$

af, bf are correlation coefficients

μ = average viscosity

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

$$Ws(i) = C\ Ac(i)\ Dh(i)^{c2} \mu(i)^{c3} \qquad (21)$$

where

C is a constant

$$c2 = (1 - bf)/(2 + bf) = 0.714 \text{ if } bf = -0.25 \text{ or } .667 \text{ if } bf = -0.2 \qquad (22)$$

and

$$c3 = bf / (2 + bf) = -0.143 \text{ if } bf = -0.25 \text{ or } -0.111 \text{ if } bf = -0.2 \qquad (23)$$

The reference flow is calculated as

$$Woi = Wpo\ ff\ df\ fin\ fsf / (Ne\ Np\ Ns) \qquad (24)$$

where

Woi = average nominal interior channel stripe flow times df (flow disparity factor)

The reference flow is calculated once and used for all histories. Also, Aco and Dho, 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

$$Ws(i) = Woi\ [Ac(i) / Aco\ ]\ [Dh(i) / Dho]^{c2} \qquad (24a)$$

If the bypass option is used, flow fraction ff needs to be calculated as

$$ff = wtotel/(wtotel + wbyp) \quad (24b)$$

where wtotel is total core flow calculated by

$$wtotel = Sum(Ws(i)) * Ne * Ns / (df * fsf) \quad (24c)$$

and wbyp is bypass flow rate calculated by

$$wbyp = Woi\ [acbyp / Aco\ ]\ [dhbyp / Dho]^{c2} \quad (24d)$$

An iteration is performed with the equations from 24 to 24d to obtain channel and bypass flowrates.

If the viscosity effect on flow is taken into account, the equation (24a) for channel flowrates becomes

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

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 μ(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. Also, the equation (24d) for bypass flowrate becomes

$$wbyp = Woi\ [acbyp / Aco\ ]\ [dhbyp / Dho]^{c2}\ [\ \mu byp / \mu_o]^{c3} \quad (25b)$$

Carnavos Fin Factor

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

Power Plate 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,

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

Then the average coolant temperature for the axial node is:

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

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

$$Tps(k,1,j) = Twa(k\text{-}1,j) + Flxs(k,1,j) / Hw(k,1,j) \qquad (28a)$$

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

where

Hw(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:

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

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

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

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

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

where

Ct and Kc are clad thickness and conductivity, respectively.

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

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

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

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

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

Where
Ft = fuel thickness.

Then, setting

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

gives

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

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

$$Fsp1(k,j)^2\ Pp(k,j)\ Fpf\ Ft\ /\ [\ 2\ So(k)\ Kf] =$$

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

$$[\ 1 - Fps1(k,j)]\ Pp(k,j)\ Fpf\ /\ [\ Sf(k)\ \ Hw(k,2,j)\ ] + (1 - Fps1(k,j))\ Pp(k,j)\ Fpf\ Ct\ /[\ So(k)\ Kc\ ] +$$

$$[\ 1 - Fps1(k,j)\ ]^2\ Pp(k,j)\ Fpf\ Ft\ /\ [\ 2\ So(k)\ Kf] \quad (34)$$

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:

$$Fps1(k,j) = Fps1o(k,j) + [\ Fs1(k,j) - Fps1o(k,j) \quad (35)$$

where Fps1o is an initial guess for Fs1 or the computed value from the last iteration. Then:

$$Fps1(k,j)^2 \sim Fps1o(k,j)^2 + 2\ [Fps1(k,j) - Fps1o(k,j)\ ]\ Fps1o(k,j) =$$

$$2\ Fps1(k,j)\ Fps1o(k,j) - Fps1o(k,j)^2$$

Similarly:

$$(1 - Fps1\ ) = (1 - Fps1o) + [\ (1 - Fps1) - (1 - Fps1o\ )\ ] = (\ 1 - Fps1o) + (Fps1o - Fps1)$$

$$(1 - Fps1)^2 \sim (1 - Fps1o)^2 + 2\ [\ (\ 1 - Fps1o)\ (\ Fps1o - Fps1)] = 1 - Fps1o^2 - 2\ Fps1\ (\ 1 - Fps1o)$$

The linearized version of Equation 34 has the form:

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

Equation 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.

6.3 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 × 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.

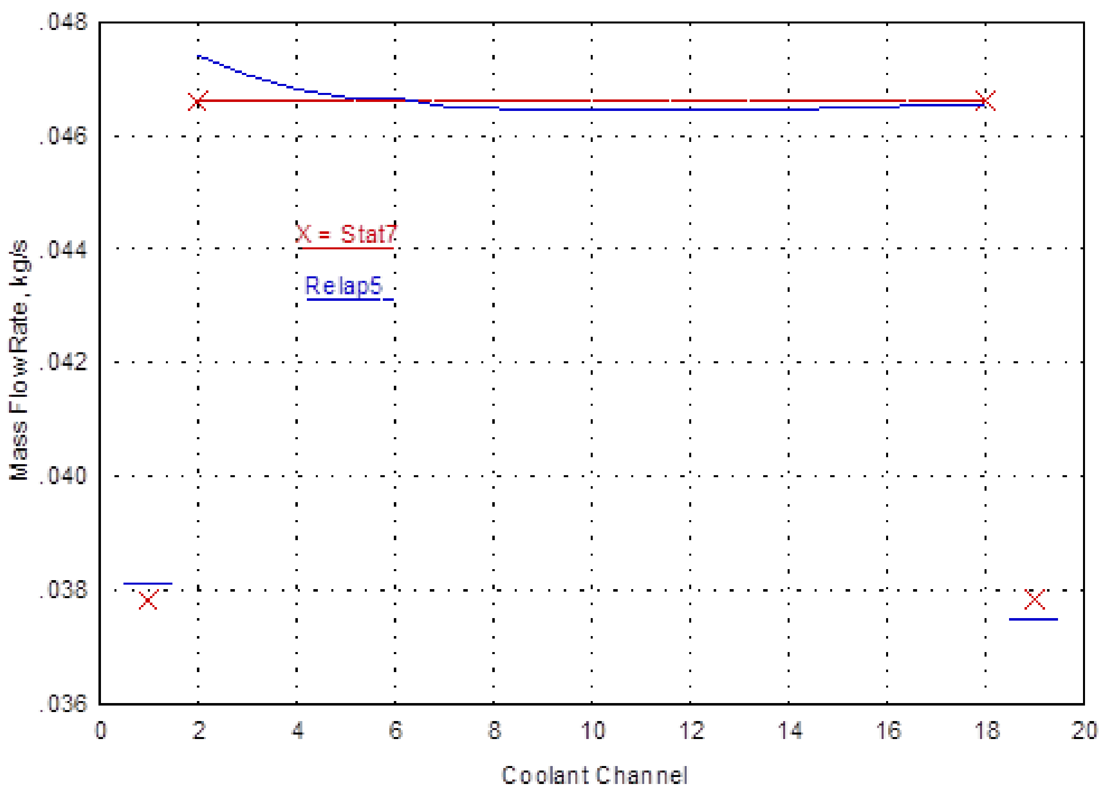

Figure 5. Comparison of STAT7 and RELAP5 End Channel and Interior Channel Flow Rates

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.

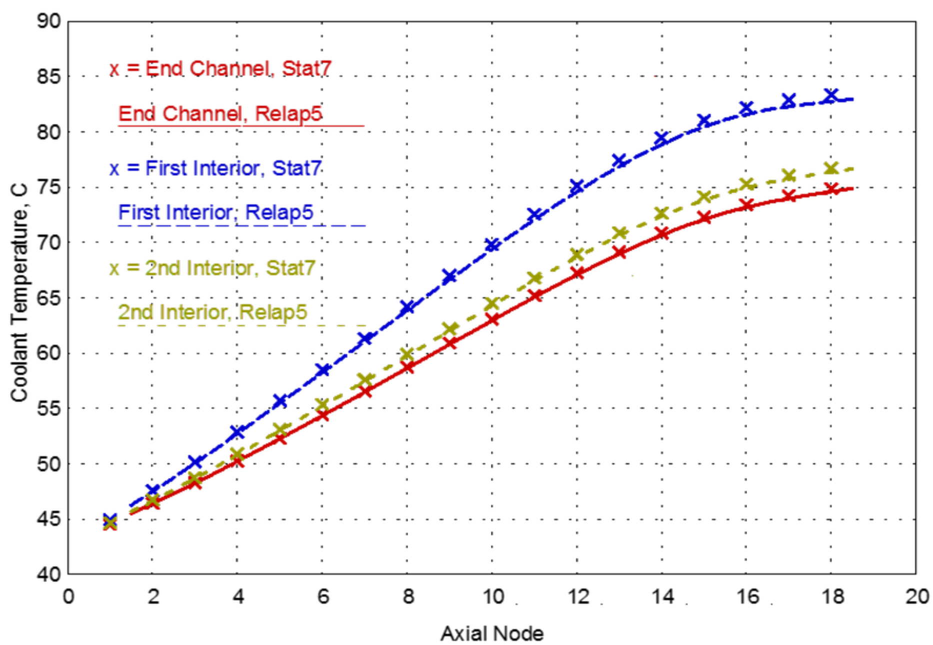

Figure 6. Comparison Between STAT7 and RELAP5 Coolant Temperatures for an End Channel and the First Two Interior Channels

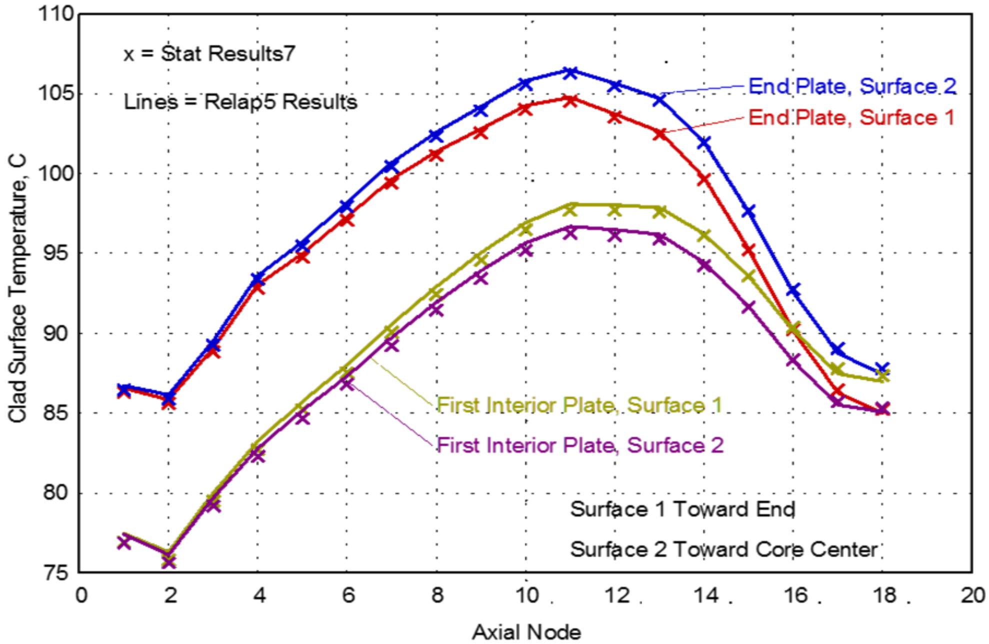

Figure 7. Comparison Between STAT7 and RELAP5 Clad Surface Temperatures for an End Plate and the First Interior Plate

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 5.4 between STAT6 and Oracle-Crystal Ball results show that the statistical methods are equivalent.

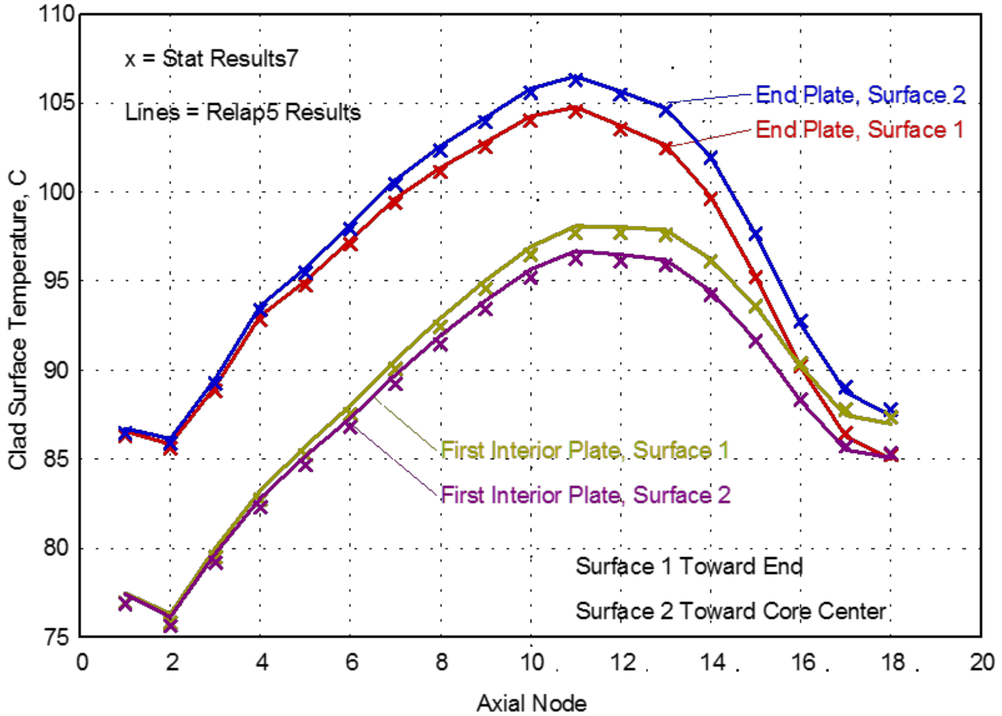

Figure 8. Comparison Between STAT7 and RELAP5 Peak Fuel Temperatures for an End Plate and the first Interior Plate

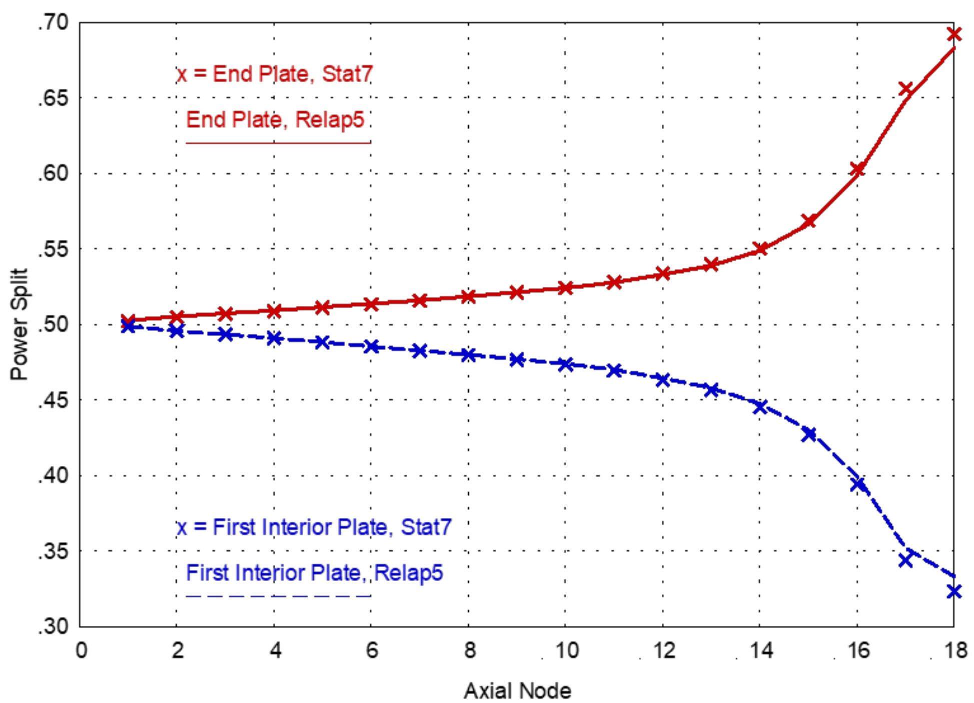

Figure 9. Comparison Between STAT7 and RELAP5 for Power Splits in an End Plate and the First Interior Plate

7 APPLICATION IN DETERMINATION OF MITR LSSS

In summary, the LSSS are based on 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 $P_r = P_{ONB} / 1.2$. 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.

8 INPUT DESCRIPTION

8.1 Input Formats

STAT7 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 10, 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. The "a" format indicates character data. If less than 80 characters are entered, the rest will be filled with blanks. In STAT7 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.

Most 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.

Most 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.

8.2 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, nstrp, 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 and isd2 are values used to calculate random number seed as 2**isd1 + 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. Variables "iend1" and "iendn" determine the nature of the extra plates. . 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 = epsonb
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 < iprt
ioptn = options, 8 one–character integers

Note: ioptn is an array containing 8 integers, 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 grove depth grvdml is > 0

ioptn(1) > 0 for user-specified Carnavos heat transfer fin factor, if the finned grove 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 (Fcore)
ffuel = fuel deposition factor (Ffuel)
flwfac = coolant flow factor acounts for bypass flow (Ff)
df = plenum flow disparity factor (df)
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 = Np /(Np - 1 + 2 x (We/Wi))
Np = number of plates, We = end channel mass flow rate
Wi = 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 layer (Zr) between the fuel surface and cladding (mil)
    xkzr = thermal conductivity of the layer (Zr) between the fuel surface and cladding [w/(m-K)]

title (20a4)
grvdml, grvwml, grvtml, gapml, gapsg, grvfav, htcsgm, epsonb, 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
        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
    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 (W/m-K)
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), gapsgi(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
gapsgi(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 Lines

Standard 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 x pow0 x fcore x fstrp(ipl) x axpow(j,ipl)/(nelm x nplt x nstrp)

Limits on number of regions

Note that the following maximum number of regions apply:

axial nodes: 40
coolant channels: 50
plates: 51

9 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*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
fflwt = 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 pn 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

10 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 | iflwnc|  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
 grvdml  | grvwml  | grvtml  | gapml   | gapsg   | fdumy3  | htcsgm  | 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
```

11 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
grvdml  | grvwml  | grvtml  | gapml   | gapsg   | fdumy3  | htcsgm  | 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   0.05594   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 Tfmax1 Tfmax2 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 occured in at least one axail 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
```

12 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.

13 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*

ACKNOWLEDGEMENTS

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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 Sections 5.1 and 5.2.

There are two issues with using the Carnavos fin correlations for RERTR applications. The first is that the Carnavos measurements were made in circular geometry tubes, whereas the coolant channels we are interested in are rectangular. The second issue is that the measurements were made in 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 x the flow area/the wetted perimeter, suggests that the measurement geometry issues mentioned above can be overcome. 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 experiments are the best available results that 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 A.1. STAT7 Results for Various Fin Treatment Options

	Limiting power (MW)	Coolant flow (kg/s)		friction factor multiplier		heat transfer multiplier		Pressure drop (kPa)	D_h (cm)	
channel		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 ±10% from the correlations, so 1% differences are well within the accuracy of the correlations.

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