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

Nuclear Science & Engineering Division
The STAT7 Code for Statistical Propagation of Uncertainties In Steady-State Thermal Hydraulics Analysis of Plate-Fueled Reactors

prepared by
Se Ro Yang¹, Dhongik S. Yoon¹, Lin-wen Hu², and Erik H. Wilson¹

¹Nuclear Science & Engineering Division, Argonne National Laboratory
²Massachusetts Institute of Technology Nuclear Reactor Laboratory

January 2023
ABSTRACT

The STAT7 software was developed to perform steady-state thermal hydraulic analyses. Application of the software is for non-power research and test reactors, including conversion to low-enriched uranium fuel of U.S. High-Performance Research Reactors such as MITR-II. Since it can be necessary to repeat analysis during fuel reloading, STAT7 accommodates flexibility in analyzing many realistic aspects of reactor fuel management. STAT7 uses a Monte Carlo approach to model common fabrication parameters and other key reactor analysis uncertainties required for research and test reactor thermal hydraulic analyses. 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 lateral 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 onset of nucleate boiling and onset of flow instability for each axial node of each stripe of each plate of each element in the core.
## Table of Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>i</td>
</tr>
<tr>
<td>Table of Contents</td>
<td>ii</td>
</tr>
<tr>
<td>List of Figures</td>
<td>iii</td>
</tr>
<tr>
<td>List of Tables</td>
<td>iv</td>
</tr>
<tr>
<td>1 INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>2 RECOMMENDATIONS FOR APPLICATION</td>
<td>2</td>
</tr>
<tr>
<td>3 CHANNEL TREATMENT</td>
<td>3</td>
</tr>
<tr>
<td>3.1 Channel Geometry</td>
<td>3</td>
</tr>
<tr>
<td>3.2 How Many Stripes are Necessary?</td>
<td>4</td>
</tr>
<tr>
<td>4 TREATMENT OF UNCERTAINTIES USING STATISTICAL APPROACH</td>
<td>7</td>
</tr>
<tr>
<td>5 CODE IMPLEMENTATION</td>
<td>9</td>
</tr>
<tr>
<td>5.1 Thermal Hydraulics Calculations for a History</td>
<td>9</td>
</tr>
<tr>
<td>5.2 Carnavos Friction Factor for Fins</td>
<td>13</td>
</tr>
<tr>
<td>5.3 Statistical Sampling</td>
<td>14</td>
</tr>
<tr>
<td>5.4 Comparison with Oracle-Crystal Ball Results</td>
<td>16</td>
</tr>
<tr>
<td>6 THE STAT7 CODE</td>
<td>17</td>
</tr>
<tr>
<td>6.1 Power Splits</td>
<td>17</td>
</tr>
<tr>
<td>6.2 STAT7 Thermal Hydraulic Solution for a History</td>
<td>17</td>
</tr>
<tr>
<td>6.3 Comparison of STAT7 Results with RELAP5 Results</td>
<td>24</td>
</tr>
<tr>
<td>7 PLATE-FUELED REACTOR APPLICATIONS</td>
<td>28</td>
</tr>
<tr>
<td>8 INPUT DESCRIPTION</td>
<td>29</td>
</tr>
<tr>
<td>8.1 Input Formats</td>
<td>29</td>
</tr>
<tr>
<td>8.2 Input Description and Sample Values</td>
<td>29</td>
</tr>
<tr>
<td>9 OUTPUT VARIABLES</td>
<td>35</td>
</tr>
<tr>
<td>10 SAMPLE INPUT</td>
<td>37</td>
</tr>
<tr>
<td>11 REPRESENTATIVE PARTS OF A SAMPLE OUTPUT</td>
<td>40</td>
</tr>
<tr>
<td>12 FORTRAN CODING</td>
<td>43</td>
</tr>
<tr>
<td>13 EXECUTING THE CODE</td>
<td>43</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>45</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>46</td>
</tr>
<tr>
<td>APPENDIX A: COMMENTS ON FINS</td>
<td>48</td>
</tr>
</tbody>
</table>

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

Figure 1. Schematics of the discretized MITR LEU element in the STAT7 model .................................................. 4
Figure 2. Multi-stripe RELAP5-3D Model .................................................................................................................. 5
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. .................. 6
Figure 4. Comparison of STAT7 and Oracle-Crystal Ball Results .............................................................................. 16
Figure 5. Comparison of STAT7 and RELAP5 End Channel and Interior Channel Flow Rates .................. 24
Figure 6. Comparison Between STAT7 and RELAP5 Coolant Temperatures for an End Channel and the First Two Interior Channels ........................................................................................................... 25
Figure 7. Comparison Between STAT7 and RELAP5 Clad Surface Temperatures for an End Plate and the First Interior Plate ..................................................................................................................... 26
Figure 8. Comparison Between STAT7 and RELAP5 Peak Fuel Temperatures for an End Plate and the first Interior Plate ........................................................................................................................................ 27
Figure 9. Comparison Between STAT7 and RELAP5 for Power Splits in an End Plate and the First Interior Plate .......................................................................................................................................... 27
List of Tables

Table 1. Parameters and Uncertainties for MITR.................................................................7
Table 2. Geometry parameters in Carnavos correlation and derived values for an inner channel of an LEU fuel element .................................................................................................................................13

Table A.1. STAT7 Results for Various Fin Treatment Options..............................................49
1 INTRODUCTION

STAT7 is a steady-state, single-phase thermal hydraulics (TH) software for plate fueled research and test reactors that supports statistical propagation of uncertainties of fabrication tolerances and other key reactor parameters using Monte Carlo method. Application of the software includes the reactor conversion from highly enriched to low-enriched uranium fuel of U.S. High Performance Research Reactors (USHPRR) such as MITR-II. STAT7 can calculate multiple histories of datasets that includes flow rate of coolant and bypass channels and temperature distribution of the coolant and fuel plate with or without fins. Furthermore, it can predict operational safety margins for the onset of nucleate boiling (ONB) or onset of flow instability (OFI), including statistical uncertainties. The statistical sampling and TH capabilities of STAT7 have been validated and verified against hand calculations, other codes, and experimental data. STAT7 has been actively employed in various TH analyses to support MITR-II low-enriched uranium (LEU) conversion from highly enriched uranium (HEU), such as TH impact assessment of fuel specification and LEU transitional cores and fuel cycle analysis [1, 2, 3, 4].

Reactor conversions from HEU to LEU would involve significant changes to the core including key operational parameters such as steady state power and mass flow rate, and new TH safety analyses are required consequently. The number of required new safety analysis cases may be quite large. In addition to the safety analyses, optimization of the new fuel element design requires analysis of many design options. Furthermore, considering the future 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 purpose of STAT7 software is to provide a standardized and automated tool for the steady-state TH safety analysis with the statistical uncertainty propagation that involves multiple calculations.

According to NUREG-1537, Part II, Guidelines for Preparing and Reviewing Applications for the Licensing of Non-Power Reactors [5], the acceptance criteria for the TH design in research and test reactor with a forced-convection cooling system include avoiding departure from nucleate boiling (DNB) or critical heat flux (CHF) and avoiding flow instability in any fuel channel. In some reactor analyses, including MITR-II, limits – such as limiting safety system settings (LSSS) – are based on avoiding onset of nucleate boiling (ONB) to provide additional margin because ONB will occur before either OFI or DNB. In STAT7 v1.1, ONB and OFI power search capabilities are available.

The STAT7 Version 1.1 (v1.1) is the first major update from its predecessor, STAT7 v1.0 [6]. It should be noted that the STAT7 v1.1 is backward compatible with the STAT7 v1.0. In the STAT7 v1.1 update, a new capability of calculating the onset of flow instability (OFI) using the Whittle and Forgan correlation with a bubble detachment parameter $\eta$ [7-10] has been implemented. Several bug fixes were made for (1) bypass flow calculation with finned fuel, (2) double precision handling for all the floating points, (3) several invalid input parameters are now disabled via a fatal error, and (4) correction of typographical errors. Now with the new OFI calculation capability, the steady-state thermal hydraulics calculations have been automated in the STAT7 v1.1 to the point that the current practice is to make multiple runs to calculate the margin to ONB or OFI for each axial node of each stripe of each plate and each coolant channel including the end channels of a single element in the core.
2 RECOMMENDATIONS FOR APPLICATION

The users should consider the following recommendations for applying STAT7 to reactor analysis:

- 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 (see Section 5.1), 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 $10^\circ\text{C} < T < 95^\circ\text{C}$ 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). The user will need to determine the appropriate stripe discretization (i.e., stripe dimension), of stripes needed to adequately model the reactor being analyzed. This will require the use of an analysis that models heat conduction in multiple dimensions, usually in the lateral direction along the width of the plate transverse to the flow direction. Many software tools are capable of this type of analysis if the user has not already obtained a solution prior to use of STAT7.
3 CHANNEL TREATMENT

3.1 Channel Geometry

Figure 1 illustrates a cross section of the channel geometry used for thermal hydraulics calculations of a typical Materials Test Reactor (MTR)-type fuel element. A number of axial nodes are modeled in this manner in the vertical direction [12].

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 channel coolant gap thickness 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.
3.2 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[13]. 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.

![Multi-stripe RELAP5-3D Model](image)

**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 predicted lateral temperature profile trend follows the profile of the lateral power profile. Accounting for 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 OFUNCERTAINTIES 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 measurement and
calculation uncertainties of the input parameters of STAT7 code including reactor power, primary
coolant flow rates (pump flow), interior coolant channel gap thickness, and film heat transfer
coefficient are set to follow the normal distributions within the 99.7% confidence level (or 3-
• deviation). The statistical propagation approach for MITR-II was initially implemented by L.-W. Hu
and K.-Y. Chang [14] 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 (when the input parameter ioptn(7)=0 or 2. See section 8.2 for further
details). Likewise, if the coolant exit temperature exceeds the OFI limit at any channel, then the OFI
count is increased by one (when the input parameter ioptn(7)=1 or 2. See section 8.2 for further
details). Note that for a given history the result used in the statistical analysis is either a 0 (no ONB or
OFI anywhere) or a 1 (ONB or OFI at one or more axial nodes of one or more plates). It should be
noted that the ONB and OFI counts are managed independently. The amount by which ONB or OFI is
exceeded in a history is not used. The ONB or OFI probability for the specified nominal operating
parameters is then given by the ratio of the number of ONB or OFI 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 or OFI occurring is predicted. During
the reactor power iteration, the nominal values of all other parameters are held constant.
For the evaluation of reactor safety margins, it is recommended to specify the probability of ONB occurring
as 0.135%, which corresponds to a 3-sigma confidence level of 99.865%. Similarly, the specified
probability of OFI occurring can be input as 0.135%, which corresponds to a 3-sigma confidence level
of 99.865%.

The parameters whose uncertainties are treated with the statistical propagation approach for the
case of MITR 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>
<thead>
<tr>
<th>Parameter</th>
<th>3-sigma Uncertaintya (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor power</td>
<td>5.00</td>
</tr>
<tr>
<td>Local powerb</td>
<td>14.1</td>
</tr>
<tr>
<td>Pump flow</td>
<td>5.00</td>
</tr>
<tr>
<td>Interior coolant channel gap thickness (axial average)c</td>
<td>6.17</td>
</tr>
<tr>
<td>Film heat transfer coefficient</td>
<td>20.0</td>
</tr>
</tbody>
</table>

a Values are rounded to have three significant digits.
b Based on an RMS combination of 10% each on flux distribution and local fuel
loading inspection criteria.
c As in this example, for a reference coolant channel gap thickness of 0.00746 inch,
the minimum trace fabrication limit (average) is 0.0070 inch.

The STAT7 Code for Statistical Propagation of Uncertainties In
Steady-State Thermal Hydraulics Analysis of Plate-Fueled Reactors 7
5 CODE IMPLEMENTATION

The STAT7 code is written to implement and automate the steady-state thermal hydraulics calculations for the statistical propagation method for research and test reactors with plate type fuels. The STAT7 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 STAT7 thermal hydraulic analysis.

5.1 Thermal Hydraulics Calculations for a History

A STAT7 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 STAT7 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 STAT7 case is mainly the nominal reactor power level at which the specified ONB probability occurs. Additional output includes 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.

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, $T_o$, 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. There is no overall 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.

Initializing the Nominal Stripe Power and Flow

Prior to starting the first history of a reactor power iteration, the nominal hot stripe power, $P_s$, and the nominal interior channel stripe coolant flow, $W_i$, must be initialized from user-input data. The initial hot stripe power for an interior channel is evaluated as:

$$P_s = \frac{P_r f_c f_s}{N_e N_p N_s}$$

where

- $P_r$ = nominal core power [MW]
- $f_c$ = 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

The nominal interior channel stripe coolant flow, $W_i$, is calculated as
\[ W_i = \frac{W_p \cdot f_f \cdot d_f \cdot f_{in} \cdot f_{sf}}{N_e \cdot N_p \cdot N_s} \] (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.

The above initialization is performed only 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 its standard deviation. Also, the sample value, \([W_p]\), for the pump flow is randomly sampled from the nominal value, \(W_p\), and its standard deviation.

**Coolant Inlet Temperature**

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

\[ T_{in} = T_x - \frac{[P_r] \cdot f_c}{[W_p] \cdot C_p} \] (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. All coolant properties, including \( C_p \), are calculated by fitted functions which were established using NIST fluid database [15].

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 Thickness, Coolant Flow Area, and Hydraulic Diameter**

The statistical sampling value for the hot stripe gap thickness, \([G]\), is obtained from the nominal value, \( G \), and its standard deviation. The coolant flow area, \( A_{ga} \) and hydraulic diameter, \( D_{ha} \), for this, gap thicknesses are then calculated.

**Hot Stripe Coolant Flow Rate**

The coolant channel friction factor, \( f \), is obtained from \( f = a_f \cdot Re^{b_f} r \). Typically, \( a_f = 0.184 \), and \( b_f = -0.2 \) [16], 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 \( b_f \) power,
then a channel flow rate will be proportional to the flow area times the hydraulic diameter to the power \((1-b_{fr})/(2+b_{fr})\). Thus, the hot stripe coolant flow rate, \(W_s\), is obtained from

\[
W_s = W_i \left( \frac{[W_p]}{W_p} \right) \left( \frac{A_G}{A_0} \right)^{D_{hrat}} \left( \frac{D_{h0}}{D_{h0}} \right)^{D_{hrat}}
\]  

(4)

where

- \(A_0\) = nominal interior channel stripe flow area
- \(D_{h0}\) = nominal interior channel stripe hydraulic diameter
- \(D_{hrat} = (1-b_{fr})/(2+b_{fr})\)

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 \(D_{h0}\).

**Hot Stripe Axial Node Power Uncertainties**

The statistical sampling value for the plate power in the stripe, \([p]_j\), for axial node \(j\) is obtained from

\[
[p]_j = \theta_j [u_j] P_s
\]  

(5)

where

- \(\theta_j\) = 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

\[
T_{wj, j+1} = T_{wj, j} - \frac{p_{wj}}{W_s C_p}
\]  

(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 [17].

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

(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).

**Channel OFI temperatures**

The Whittle and Forgan correlation with a bubble detachment parameter \( \eta \) can predict the coolant exit temperature at which OFI occurs [7-10].

\[ T_{OFI,exit} = \frac{T_{sat,exit} - T_{in}}{1 + \eta D_h/L_f} + T_{in} \]  

(8)

where

- \( T_{OFI,exit} \) = coolant exit temperature (°C) at which ONB occurs,
- \( T_{sat,exit} \) = coolant saturation temperature (°C) at the outlet,
- \( T_{in} \) = coolant inlet temperature (°C),
- \( \eta \) = bubble detachment parameter,
- \( D_h \) = equivalent heated diameter (m) of the channel, and
- \( L_f \) = heated length (m) of the channel.

**Carnavos Fin Heat Transfer Coefficients and Clad Surface Temperatures**

The fin heat transfer coefficients are calculated using the Carnavos correlation [18]. 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:

\[ Nu = 0.023 \cdot Re_a^{0.8} \cdot Pr_f^{0.4} \cdot \left( \frac{A_f a}{A_f c} \right)^{0.1} \cdot \left( \frac{A_f}{A_f} \right)^{0.5} \cdot \sec^3 \alpha \]  

(9)
where \( \text{Nu} = \frac{h \cdot D_h}{k} \), \( h \) is heat transfer coefficient, \( D_h \) is hydraulic diameter, \( k \) is fluid thermal conductivity, \( \text{Nu}, \text{Re} \) and \( \text{Pr} \) 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 STAT7 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>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
<th>Counterpart in MITR element</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A_{fa} )</td>
<td>Actual free flow area</td>
<td>Stripe Width \times (water gap' + 2\times fin height) - 2 \times \text{number of fins per stripe} \times \text{single fin area}</td>
</tr>
<tr>
<td>( A_{fc} )</td>
<td>Open core free flow area, fin tip-fin tip</td>
<td>Stripe width \times \text{water gap'}</td>
</tr>
<tr>
<td>( A_n )</td>
<td>Nominal heat transfer area based on tube inner diameter as if fins were not present</td>
<td>Nominal heated perimeter \times \text{fuel length}</td>
</tr>
<tr>
<td>( A_a )</td>
<td>Actual heat transfer area Actual heat transfer area</td>
<td>Actual heated perimeter \times \text{fuel length}</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>Helix angle in finned tube</td>
<td>0</td>
</tr>
<tr>
<td>( D_{ha} )</td>
<td>Actual hydraulic diameters</td>
<td>( \frac{4 \times \text{actual flow area}}{\text{(actual wetted perimeter)}} )</td>
</tr>
</tbody>
</table>

* 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:

\[
f = \frac{0.184}{Re^{0.2} (F^*)}
\]

(10)

Where

\( f \) = friction factor
\( Re \) = actual Reynolds number
The STAT7 Code for Statistical Propagation of Uncertainties In Steady-State Thermal Hydraulics Analysis of Plate-Fueled Reactors

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

- \(A_{fa}\) = 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

\[
F_{fn} = 1/F = \text{friction factor multiplier for fins}
\]

- \(g\) = 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
- \(ffrat\) = \(-\frac{1}{2 + b_{fr}}\)

if \(b_{fr} = -0.2\), then \(ffrat = -0.5556\)

### 5.3 Statistical Sampling

The statistical sampling method is taken from a mathematical handbook [19]. A random variable \(Y\) is said to be normally distributed with mean \(m\) and standard deviation \(\sigma\) if the probability, \(I_p\), that \(Y\) is less than or equal to \(y\) is given by

\[
I_p (Y \leq y) = \frac{1}{\sigma \sqrt{2\pi}} \int_{-\infty}^{y} e^{-\frac{(t-m)^2}{2\sigma^2}} dt
\]  \hspace{1cm} (11a)

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

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
- \(ffrat\) = \(-\frac{1}{2 + b_{fr}}\)

if \(b_{fr} = -0.2\), then \(ffrat = -0.5556\)

### 5.3 Statistical Sampling

The statistical sampling method is taken from a mathematical handbook [19]. A random variable \(Y\) is said to be normally distributed with mean \(m\) and standard deviation \(\sigma\) if the probability, \(I_p\), that \(Y\) is less than or equal to \(y\) is given by

\[
I_p (Y \leq y) = \frac{1}{\sigma \sqrt{2\pi}} \int_{-\infty}^{y} e^{-\frac{(t-m)^2}{2\sigma^2}} dt
\]  \hspace{1cm} (11a)

or if \(x = (y - m) / \sigma\), then
\[ I_p(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{x} e^{-\frac{t^2}{2}} dt \quad (11b) \]

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

\[ r = I_p(x) \quad (12) \]

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

\[ r = I_q(x) \quad (13) \]

Reference [15] gives a rational approximation for \( x(r) \) where \( r = I_q(x) \)

for \( r \leq 0.5 \),

\[ x(r) = \nu - \frac{c_0 + c_1 \nu + c_2 \nu^2}{1 + d_1 \nu + d_2 \nu^2} + \varepsilon(r) \quad (14) \]

\[ \nu = \sqrt{\ln\left(\frac{1}{r^2}\right)} \]

\[ c_0 = 2.515517 \quad d_1 = 1.432788 \]
\[ c_1 = 0.802853 \quad d_2 = 0.189269 \]
\[ c_2 = 0.010328 \quad d_3 = 0.001308 \]

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

for \( r > 0.5 \)

\[ x(r) = -x(1 - r) \quad (15) \]
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 [20] and with the STAT7 code. Figure 4 shows the results. For an outlet temperature of 60°C, the results are almost identical, indicating that both approaches are equivalent.

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 STAT7 calculates temperature-dependent water properties using the axial node temperatures for each history.

![Figure 4. Comparison of STAT7 and Oracle-Crystal Ball Results](image-url)
6 THE STAT7 CODE
The STAT7 code treats $N_{ch}$ coolant channels and $N_{pl} = (N_{ch} + 1)$ plates. This code can model one stripe of each 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 two 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:

- $A_c(i)$ = coolant flow area
- $C_p$ = Heat capacity of the coolant (water)
- $D_h(i)$ = hydraulic diameter
- $d_f$ = flow disparity factor = df (input), accounts for element-to-element flow variation
- $f_c$ = the fraction of the fission power deposited in the core region = fcore (input)
- $f_f$ = coolant core flow fraction = flwfac(input), this accounts for bypass flow
- $f_in$ = 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.
- $f_s(k)$ = current plate stripe power/core average power = fstrp(k) (input)
- $f_{sf}$ = 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.
- Gap$(i)$ = gap thickness
- $i$ = coolant channel number
The STAT7 Code for Statistical Propagation of Uncertainties In
Steady-State Thermal Hydraulics Analysis of Plate-Fueled Reactors

### $j = \text{axial node index}$

### $k = \text{plate number. Plate } k \text{ is in contact with coolant channels } (k - 1) \text{ and } k$

### $l = \text{plate surface number. Surface } 1 \text{ is in contact with channel } (k - 1). \text{ Surface } 2 \text{ is in contact with channel } k$

### $Ni = \text{number of coolant channels in the model} = \text{nchan (input value)}$

### $Ne = \text{number of elements in the core} = \text{nelm (input)}$

### $Np = \text{number of plates in the model} = Ni + 1$

### $Npe = \text{number of plates per element}$

### $Ns = \text{number of stripes/plate}$

### $Nz = \text{number of axial nodes} = nz (input)$

### $P_p(k,j) = \text{plate power for the sample}$

### $P_{ro} = \text{nominal reactor power}$

### $P_r = \text{reactor power for the history}$

### $P_s(k) = \text{nominal plate power}$

### $T_{av} = \text{average coolant temperature}$

### $T_j(k,l,j) = \text{peak fuel temperature, calculated from face l}$

### $T_p(k,l,j) = \text{fuel-clad interface temperature}$

### $T_p(k,l,j) = \text{plate surface temperature}$

### $T_w(i,j) = \text{coolant temperature at bottom of node } j$

### $T_x = \text{average coolant outlet temperature} = \text{tout (input)}$

### $T_{in} = \text{coolant inlet temperature}$

### $W_{oi} = \text{reference interior channel flow, accounting for element-to-element flow variation}$

### $W_{po} = \text{nominal pump mass flow}$

### $W_p = \text{pump flow for the history}$

### $W_s(i) = \text{stripe flow for the history}$

### Statistical Sampling

The statistical sampling value, $[Y]$, for a variable $y$ with a fractional standard deviation of $\sigma$ is obtained by multiplying the mean value, $Y_o$, by a statistical multiplier, $F_y$, given by

$$F_y = 1 + x\sigma \quad (16)$$

The method used to obtain $x$ is described in Section 5.3.

### Reactor Power, Pump Flow, and Inlet Temperature

The average coolant outlet temperature, $T_x$, the nominal (measured) reactor power, and the nominal pump flow are supplied by the user in the input. The reactor power for the history, $P_r$, and the pump mass flow for the history, $W_p$, are obtained by statistical sampling process described in Section 5.3. Then the inlet coolant temperature, $T_{in}$, is obtained from

$$T_{in} = T_x - f_c \frac{P_r}{W_p C_p} \quad (17)$$

Where the coolant heat capacity $C_p$ is evaluated at a temperature $T_{av}$ given by

$$T_{av} = 0.5 \left( T_{in} + T_x \right) \quad (18)$$
A two-step iteration between Equations (17) and (18) is used to obtain consistency between $T_{av}$ and $C_p$.

**Gap Thickness, Coolant Flow Area, Hydraulic Diameter**

The gap thickness, Gap($i$), is obtained for each coolant channel by statistical sampling. Then the coolant flow area, $A_c(i)$, and hydraulic diameter, $D_h(i)$ are calculated. 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, $\Delta p(i)$, for a channel is:

$$\Delta p(i) = f_r \frac{L}{D_h(i)} \frac{1}{2\rho} \left( \frac{W_s(i)}{A_c(i)} \right)^2$$  \hspace{1cm} (19)

where $\rho$ is the density of water, $L$ is the channel length, and $f_r$ is the friction factor given by

$$f_r = a_{fr} Re^{b_{fr}} F_{fin}$$  \hspace{1cm} (20)

where

- $Re = \text{Reynolds number} = D_h(i) W_s(i) / [\mu A_c(i)]$
- $a_{fr}, b_{fr}$ are correlation coefficients
- $\mu = \text{average viscosity}$
- $F_{fin} = (A_{fin} / A_{fr})^{0.5} (\cos[\alpha])^{0.75}$
- $A_{fin} = \text{actual free flow area, mm}^2$
- $A_{fr} = \text{nominal flow area based on tube ID as if the fin structure were not present, mm}^2$
- $\cos[\alpha] = 1.0$ for fins parallel to the flow ($\alpha = 0$)
- If there is no fin, $F_{fin} = 1.0$.

Usually, $a_{fr} = 0.316$ and $b_{fr} = -0.25$ for $3,000 < Re < 20,000$. For the higher range, $20,000 < Re < 200,000$, $a_{fr} = 0.184$ and $b_{fr} = -0.2$. Combining Equations (19) – (21) gives:

$$W_s(i) = C A_c(i) D_h(i)^2 \mu(i)^{c3} F_{fin}^{1.5}$$  \hspace{1cm} (21)

where

- $C$ is a constant
- $c2 = \frac{1 - b_{fr}}{2 + b_{fr}} = 0.714$ if $b_{fr} = -0.25$, or $c2 = 0.667$ if $b_{fr} = -0.2$  \hspace{1cm} (22)
The STAT7 Code for Statistical Propagation of Uncertainties In Steady-State Thermal Hydraulics Analysis of Plate-Fueled Reactors

\[ c_3 = \frac{b_{fr}}{2 + b_{fr}} = -0.143 \text{ if } b_{fr} = -0.25, \text{ or } c_3 = 0.111 \text{ if } b_{fr} = -0.2 \]  

and

\[ ff_{rat} = -\frac{1}{2 + b_{fr}} = -0.5714 \text{ if } b_{fr} = -0.25, \text{ or } ff_{rat} = -0.5556 \text{ if } b_{fr} = -0.2 \]  

The reference flow in a channel, \( W_{oi} \), is and is calculated by:

\[ W_{oi} = \frac{W_{po} f_f df fin f_{sf}}{Ne Np Ns} \]  

By including the flow disparity factor, \( df \), this reference channel flow accounts for element-to-element variation in the inlet flow rate. The reference flow is calculated once at the beginning of the STAT7 calculation 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 thickness; and \( \mu_o \), the nominal average viscosity is calculated for the nominal average coolant temperature. Then for a given history the channel flow rates are first approximated without the temperature effect as

\[ W_{s,approx}(i) = W_{oi} \left( \frac{A_c(i)}{A_{co}} \right) \left( \frac{D_h(i)}{D_{ho}} \right)^c_2 \left( \frac{F_{fin}}{F_{fin0}} \right)^{ff_{rat}} \]  

If the bypass option is used, flow fraction \( f_f \) needs to be calculated as

\[ f_f = \frac{w_{total}}{w_{total} + w_{byp}} \]  

where \( w_{total} \) is the total core flow rate calculated by

\[ w_{total} = \sum_i W_s(i) Ne Ns df f_{sf} \]  

and \( w_{byp} \) is bypass flow rate calculated by

\[ w_{byp} = W_{oi} \left( \frac{A_{c,byp}}{A_{co}} \right) \left( \frac{D_{h,byp}}{D_{ho}} \right)^c_2 \left( \frac{1}{F_{fin0}} \right)^{ff_{rat}} \]  

An iteration is performed with the Equations from (25) to (26d) to obtain channel and bypass flowrates.

Once the channel heat transfer is calculated, the viscosity effect due to the temperature change on flow is taken into account, the equation (26a) for channel flowrates becomes

\[ W_s(i) = W_{oi} \left( \frac{A_c(i)}{A_{co}} \right) \left( \frac{D_h(i)}{D_{ho}} \right)^c_2 \left( \frac{F_{fin}}{F_{fin0}} \right)^{ff_{rat}} \left( \frac{\mu(i)}{\mu_o} \right)^c_3 \]  

The viscosity term in equation (27a) addresses the viscosity effect only 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. Also, the equation (26d) for bypass flowrate becomes

\[ w_{byp} = W_{ol} \left( \frac{A_{c,byp}}{A_{co}} \right) \left( \frac{D_{h,byp}}{D_{ho}} \right)^{c2} \left( \frac{1}{f_{frat}} \right) \left( \frac{\mu_{byp}}{\mu_o} \right)^{c3} \]  

(27b)

Carnavos Fin Factor

The Carnavos fin heat transfer factor is calculated using Equation (10).

Power Plate Profiles

The plate power for 1 stripe for each node of each plate, \( P_p(k,j) \), 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, \( F_{ps1}(k,j) \) for axial 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, \( T_f(k,l,j) \), calculated from surface \( l=1 \) equals that calculated from surface \( l=2 \).

At the beginning of the calculations for channel \( i \), the coolant temperature, \( T_w \), at the bottom axial node \((j=1)\) is known from the inlet boundary condition. Then the axial coolant temperature in the next axial node \( j+1 \) is computed from the conditions at node \( j \) using the power splits between adjacent plates \( k=i \) and \( k=i+1 \) as follows:

\[ T_w(i,j+1) = T_w(i,j) + \frac{(1 - F_{ps1}(i,j)) P_p(i,j) + F_{ps1}(i+1,j) P_p(i+1,j)}{W_s(i) C_p} \]  

(28)

Then the average coolant temperature for the axial node is:

\[ T_{wa}(i,j) = 0.5 \left( T_w(i,j) + T_w(i,j+1) \right) \]  

(29)

The plate surface temperatures, \( T_{ps}(k,l,j) \), are obtained from:

\[ T_{ps}(k,1,j) = T_{wa}(k-1,j) + \frac{F_{ixs}(k,1,j)}{H_w(k,1,j)} \]  

(30a)
The steady-state thermal-hydraulic analysis of plate-fueled reactors involves calculating the temperature distribution in the fuel and cladding. The fuel surface heat flux, $\phi_{fsx}(k, l, j)$, is given by:

$$
\phi_{fsx}(k, l, j) = F_{ps1}(k, j) P_p(k, j) F_{pf} / S_{o}(k)
$$

where $S_{o}(k)$ is the plate surface area of 1 stripe of 1 node, not including fins.

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

$$
T_c(k, 1, j) = T_{fs}(k, 1, j) + \phi_{fsx}(k, 1, j) \delta_c / K_c
$$

$$
T_c(k, 2, j) = T_{fs}(k, 2, j) + \phi_{fsx}(k, 2, j) \delta_c / K_c
$$

where $\delta_c$ and $K_c$ are clad thickness and conductivity, respectively.

The peak fuel temperature, $T_f(k, l, j)$, is calculated from the surface temperature, $T_{fs}(k, l, j)$, as:

$$
T_f(k, 1, j) = T_{fs}(k, 1, j) + \frac{F_{ps1}(k, j)^2 P_p(k, j) F_{pf} \delta_f}{2S_{o}(k)K_f}
$$

$$
T_f(k, 2, j) = T_{fs}(k, 2, j) + \frac{(1 - F_{ps1}(k, j))^2 P_p(k, j) F_{pf} \delta_f}{2S_{o}(k)K_f}
$$

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

The plate surface heat flux, $\phi_{ps}(k, l, j)$, is:

$$
\phi_{ps}(k, l, j) = F_{ps1}(k, j) P_p(k, j) F_{pf}
$$

where $S_{o}(k)$ is the plate surface area of 1 stripe of 1 node, including fins, and $F_{pf}$ is the fraction of the power deposited in the fuel = $f_{fuel}$ (input).

The power deposited in the clad is not accounted for separately; it should be included in $F_{pf}$.
\( \delta_f \) and \( K_f \) are fuel thickness and conductivity, respectively.

Then, setting

\[ T_f(k, 1, j) = T_f(k, 2, j) \]

(35)
gives

\[
T_w(k - 1, j) + \frac{\left( 1 - F_{ps1}(k - 1, j) \right) P_p(k - 1, j) + F_{ps1}(k, j) P_p(k, j)}{2W_s(k - 1)C_p} + \frac{F_{ps1}(k, j) P_p(k, j)F_{pf}}{S_f(k)H_w(k, 1, j)} + \frac{F_{ps1}(k, j) P_p(k, j) F_{pf} \delta_c}{S_o(k)K_c} + \frac{F_{ps1}(k, j)^2 P_p(k, j) F_{pf} \delta_f}{2S_o(k)K_f} = T_w(k, j) + \frac{\left( 1 - F_{ps1}(k, j) \right) P_p(k, j) + F_{ps1}(k + 1, j) P_p(k + 1, j)}{2W_s(k)C_p} + \frac{\left( 1 - F_{ps1}(k, j) \right) P_p(k, j)F_{pf}}{S_f(k)H_w(k, 2, j)} + \frac{\left( 1 - F_{ps1}(k, j) \right) P_p(k, j) F_{pf} \delta_c}{S_o(k)K_c} + \frac{\left( 1 - F_{ps1}(k, j) \right)^2 P_p(k, j) F_{pf} \delta_f}{2S_o(k)K_f}
\]

(36)

Equation (36) involves \( F_{ps1}(k-1,j), F_{ps1}(k,j) \), and \( F_{ps1}(k+1,j) \). When combined with \( F_{ps1}(1,j) = F_{ps1}(Np,j) = 0.5 \) it leads to a series of \( N \) equations in \( N \) unknowns where \( N \) is a natural number. Because the equations include \( F_{ps1}(k,j)^2 \) and \( [1 - F_{ps1}(k,j)]^2 \) the equations are not completely linear, and iteration is used to solve them. First, the squares are linearized using:

\[
F_{ps1}(k, j) = F_{ps10}(k, j) + \{F_{ps1}(k, j) - F_{ps10}(k, j)\}
\]

(37)

where \( F_{ps10} \) is an initial guess for \( F_{ps1} \) or the computed value from the last iteration. Then:

\[
F_{ps1}(k, j)^2 \approx F_{ps10}(k, j)^2 + 2F_{ps10}(k, j)\{F_{ps1}(k, j) - F_{ps10}(k, j)\} = 2F_{ps1}(k, j)F_{ps10}(k, j) - F_{ps10}(k, j)^2
\]

Similarly:

\[
1 - F_{ps1}(k, j) = 1 - F_{ps10}(k, j) + \{F_{ps10}(k, j) - F_{ps1}(k, j)\}
\]

\[
(1 - F_{ps1}(k, j))^2 \approx (1 - F_{ps10}(k, j))^2 + 2 \left( 1 - F_{ps10}(k, j) \right) \{F_{ps10}(k, j) - F_{ps1}(k, j)\} = 1 - F_{ps10}(k, j)^2 - 2F_{ps1}(k, j) \left( 1 - F_{ps10}(k, j) \right)
\]

The linearized version of Equation (36) has the form:
\[ a(k, j)F_{ps1}(k - 1, j) + b(k, j)F_{ps1}(k, j) + c(k, j)F_{ps1}(k + 1, j) = d(k, j) \]  

(38)

Equation (38) 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 and a RELAP5 model of one stripe of an 18 fuel plate element with fins. The fins are 8 mil high, 10 mil wide and 10 mil 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. 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 thickness, and all interior channels had a second same gap thickness.

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 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 PLATE-FUELED REACTOR APPLICATIONS

STAT7 can calculate important thermal-hydraulic safety criteria in plate-fueled reactor design such as ONB or OFI power with statistical uncertainty propagation using a Monte Carlo method. The uncertainties for reactor power, pump flow, heat transfer coefficient, and coolant channel gap thickness as important core system parameters are considered statistically with probability distributions of the random samples. STAT7 can be particularly useful in HEU-to-LEU reactor core conversion application to provide the statistical calculation basis to assess the impact of the engineering uncertainties such as fuel manufacturing tolerances for coolant channel gap thickness, which directly impacts the system thermal-hydraulics.

For example, the LSSS power for the MISTR-II preliminary LEU design 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 \( P_{\text{ONB}} \) is found to occur with a 3-sigma confidence level of 99.865%. The margin between the HEU-licensed power and the 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 \( P_{\text{ONB}} \). 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, \( P_{\text{ONB}} \), 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.

For research and test reactors with a forced-convection cooling, NUREG-1537, Part II, Guidelines for Preparing and Reviewing Applications for the Licensing of Non-Power Reactors [5] requires that the departure from nucleate boiling ratio (DNBR) must be greater than 2.0 and flow instability must be avoided in any fuel channel. The probabilistic OFI power can be predicted using STAT7 program.
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—resulting in input values that are orders of magnitude different than what the user intended. Lines beginning with an exclamation mark (!) are ignored by STAT7 for commenting purposes. Inline comments are not supported. 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.

Floating-point format 9f10.5 used in the input indicates 9 numbers using 10 spaces per number. Please note that the first and last integer (9, 5 in this example) may vary throughout the input deck depending on the variable. 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, nsrtp, nz, nbatch, nsmpl, isd1, isd2, iprt, idbstt (10i8)
nelm = number of elements (24 for the MITR-II)
nplt = number of plates/element (19 for an LEU element)
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 stripes/plate (4 for the MITR-II)
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, max = 100

nsmpl = number of sampling calculations in each batch = 10000

isd1, isd2 = 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 plcsel 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 plcsel

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 nplt (last plate) option, same as for iend1

ivsc = 0, calculate viscosity and film heat trans coefficient (k) at bulk coolant temperature.

= 1, calculate viscosity and film heat trans coefficient (k) at the clad surface temperature.

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 (25a4)
ipwshp, ifat1, iflwnc, idf, itrprt, inom, ipronb, ibypas, ivsclf, ioptn, ofieta, iprofi (9i8,8i1,i8,i11)

ipwshp = not yet implemented

ifat1 = 0, stop only on fatal input errors, not on comments about questionable input (e.g., 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 = npit + 1, modeling 1 complete element.
= 1, use input value for flwinc

df
= 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.

inom
> 0, for each nominal reactor power, the calculation starts with history 0, which has nominal values for everything (no uncertainties accounted for the history 0).
≤ 0, for each nominal reactor power, the calculation starts with history 1, which accounts for the uncertainty values from the sampling (no nominal calculation is included in the iteration).

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. It also prints 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 groove depth grvdml is > 0
> 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
= 0, calculate power splits

ioptn(3) = 0, use the STAT7 version of the Carnavos friction factor multiplier for fins
= 1, Carnavos friction factor multiplier for fins = 1.0
= 2, use the PLTEMP version of the Carnavos friction factor multiplier for fins. See PLTEMP/ANL manual [8].

ioptn(4-6) reserved for future use.

ioptn(7) = 0, STAT7 only searches for ONB power. No OFI calculation will be performed. The power search iteration will be started from the nominal power input specified in the input deck and terminated at the ONB power. The output file will be the same as the previous version.
= 1, STAT7 only searches for OFI power. OFI temperatures will be reported in each coolant channel. The power search iteration will be started from the nominal power input specified in the input deck and terminated at the OFI power. Corresponding ONB calculations and statistics will be reported at each OFI power iteration, but ONB power search will not be performed.

= 2, STAT7 searches for both ONB and OFI powers. First, STAT7 will search for ONB power. This step will return the same results as ioptn(7) = 0. The power search iteration will be started from the nominal power input specified in the input deck and terminated at the ONB power. When the STAT7 obtained the ONB power, OFI power search iteration will be initiated from the searched ONB power and terminated at the OFI power. Both ONB and OFI limiting power will be reported at the end of the output file.
ioptn(8)  Developer option flag. Not yet implemented.
Note: For ioptn(3), the STAT7 and PLTEMP end channel 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.

iprofi = 1, Print the first iprofi histories where OFI occurs. (Default = 0)

**Block 2: Floating Point Variable Input Lines**

<table>
<thead>
<tr>
<th>Title</th>
<th>20a4</th>
</tr>
</thead>
<tbody>
<tr>
<td>thdbug, fcore, ffuel, flwfac, df, flwinc, pow0, powsgm, cnveps, ofieta (10f10.5)</td>
<td></td>
</tr>
<tr>
<td>thdbug</td>
<td>= turn on thermal hydraulic debug prints if thdbug &gt; 0.</td>
</tr>
<tr>
<td>fcore</td>
<td>= fraction of the fission power deposited in the core region</td>
</tr>
<tr>
<td>ffuel</td>
<td>= fuel deposition factor</td>
</tr>
<tr>
<td>flwfac</td>
<td>= coolant flow factor accounts for bypass flow</td>
</tr>
<tr>
<td>df</td>
<td>= plenum flow disparity factor</td>
</tr>
<tr>
<td>flwinc</td>
<td>= 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 × (We/Wi)), where Np = number of plates, We = end channel mass flow rate, and Wi = interior channel mass flow rate</td>
</tr>
<tr>
<td>pow0</td>
<td>= total power, MW. Nominal value = 7.0</td>
</tr>
<tr>
<td>powsgm</td>
<td>= one-sigma fractional standard deviation for expressing the uncertainty in the total power (one-sigma fractional total power uncertainty).</td>
</tr>
<tr>
<td>cnveps</td>
<td>= ONB power iteration convergence criterion, default = 0.05</td>
</tr>
<tr>
<td>ofieta</td>
<td>= 0.0, Use default value of bubble detachment parameter χ = 32.5 for OFI calculation [8, 9].</td>
</tr>
<tr>
<td>&gt;0, Use the user input value of bubble detachment parameter χ = ofieta</td>
<td></td>
</tr>
<tr>
<td>Note: ofieta is a floating-point number with a Format specifier f10.5, all other inputs on this line are integer.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Title</th>
<th>25a4</th>
</tr>
</thead>
<tbody>
<tr>
<td>ploscg, sigmax, tout, wp0, wpsgm, coolht, fl, thzrml, xkzr (10f10.5)</td>
<td></td>
</tr>
<tr>
<td>ploscg</td>
<td>= one-sigma fractional local power uncertainty</td>
</tr>
<tr>
<td>sigmax</td>
<td>= random values (see Equation 14) are limited to the range -sigmax to +sigmax, such that, -sigmax &lt; x(r) &lt; +sigmax. default = 5</td>
</tr>
<tr>
<td>tout</td>
<td>= coolant outlet temperature (°C)</td>
</tr>
<tr>
<td>wp0</td>
<td>= nominal (measured) pump flow (kg/s) wpsgm = one-sigma fractional pump flow uncertainty</td>
</tr>
<tr>
<td>coolht</td>
<td>= coolant height above the top of the fuel plates (m)</td>
</tr>
<tr>
<td>fl</td>
<td>= fuel length in the plate, (m)</td>
</tr>
<tr>
<td>fw</td>
<td>= fuel width in the plate, (m)</td>
</tr>
<tr>
<td>thzrml</td>
<td>= thickness of the layer (Zr) between the fuel surface and cladding (mil)</td>
</tr>
<tr>
<td>xkzr</td>
<td>= thermal conductivity of the layer (Zr) between the fuel surface and cladding [W/(m-K)]</td>
</tr>
</tbody>
</table>

The STAT7 Code for Statistical Propagation of Uncertainties In Steady-State Thermal Hydraulics Analysis of Plate-Fueled Reactors
\text{grvdml}^1 = \text{groove depth (mil)}
\text{grvwml}^1 = \text{groove width (mil)}
\text{grvttml}^1 = \text{width of groove tip (mil)}
\text{gapml} = \text{Nominal gap thickness (mil). If grooves are specified, this declares nominal fin-tip-to-fin-tip gap thickness (mil). This variable is going to be a default value for gapml(i), ich = 2 to (nchan - 1), only if, gapml(i) = 0.0 in Block 3.}
\text{gapsg} = \text{one-sigma fractional nominal gap uncertainty. This variable is going to be a default value for gapsgi(i), ich = 2 to (nchan - 1), only if, gapsgi(i) = 0.0 in Block 3. The gapsg is directly related to the uncertainty of the coolant channel flow distribution [20]. To be specific, the three-sigma (3\sigma) uncertainty of the coolant channel flow distribution is proportional to } \{(1+3\times\text{gapsg})^{1.714} - 1\}. \text{ For example, if gapsg = 0.075/3, three-sigma uncertainty of the coolant channel flow is } \{(1+0.075)^{1.714} - 1\} = 0.1319 \approx 13.2\%. \text{ Alternatively, gapsg can be set based on min gap = nominal gap - 4 (mil).}
\text{grvfav} = \text{average groove gap factor = average groove width/groove width + fin width. grvfav corresponds to grvwml/(grvwml + grvttml) for the average channel.}
\text{htcsgm} = \text{one-sigma fractional heat transfer coef. uncertainty}
\text{epsonb} = \text{iterate on power until ONB fraction = epsonb, only used if iterpw = 1}
\text{thkoxm} = \text{thickness (mil) of the oxide layer on the plate surface}
\text{xkox} = \text{thermal conductivity (W/m\cdot T) of the oxide layer}
\text{epsofi} = \text{iterate on power until OFI fraction = epsofi, only used if iterpw = 1}

\text{title (20a4)}
\text{gapml0, flstrf, acbyp, dhbyp, afrv, xke, bfrv, xkf, fcarff (9f10.5)}
\text{gapml0} = \text{nominal interior gap thickness, default = same as gapml}
\text{flstrf} = \text{fraction of channel flow in the fuel (stripe) region, .902}
\text{acbyp} = \text{bypass flow area (m$^2$)}
\text{dhbyp} = \text{bypass hydraulic diameter (m)}
\text{afrv} = \text{friction factor coefficient. Friction factor = afr \times Re$^{bfr}$. If bfrv less than 0, then afr = afrv, bfr = bfrv. Otherwise afr = 0.316, bfr = -0.25}
\text{xke} = \text{clad thermal conductivity (W/m\cdot T)}
\text{bfrv} = \text{see afrv above}
\text{xkf} = \text{fuel thermal conductivity (W/m\cdot T)}
\text{fcarff} = \text{user specified Carnavos heat transfer fin factor}

\textbf{Block 3: Coolant Channel Gap Variable Input Lines}
\text{title (20a4)}
\text{Standard input format:}
\text{ich, gapmli(i), gapsgi(i), gapmla(i) (i8,2x,f10.2,f10.5,f10.2)}
\text{i = coolant channel number}
\text{gapmli(i) = nominal fin tip-to-fin tip gap (mil) for this element}
\text{gapsgi(i) = fractional standard deviation}

\footnote{If grvdml = 0.0 (no fin/no groove) then grvwml or grvttml must be specified as a non-zero value to avoid the solver to diverge. When grvdml = 0, grvwml or grvttml value do not affect the calculation results because there is no groove presented. Violation of this rule will result in a fatal error at runtime.}

\textbf{The STAT7 Code for Statistical Propagation of Uncertainties In Steady-State Thermal Hydraulics Analysis of Plate-Fueled Reactors}
**The STAT7 Code for Statistical Propagation of Uncertainties In Steady-State Thermal Hydraulics Analysis of Plate-Fueled Reactors**

**Block 4: Fuel and Cladding Thickness Variable Input Lines**

- **Title:** (20a4)
- **Standard input format:**
  - `ipl, thkf(ipl), thke(ipl)`
  - `ipl` = plate number
  - `thkf` = fuel thickness (mil)
  - `thke` = clad thickness (mil), one side of plate, repeat for `ipl = 1 to nplate`, where `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)`
  - 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)
- **Input format:**
  - `ipl, fstrp(ipl)`
  - `ipl` = plate number
  - `fstrp` = stripe power / core average stripe power
  - `(axpow(j,ipl), j=1,nz)`
    - `axpow` = axial power shape
    - `j` = axial node number

  - **Note:** `axpow(j,ipl)` will be renormalized by the code so that for each plate the sum of `axpow` overall axial nodes = 1.0. Then the nominal power (Watts) in the stripe for axial node `j` of plate `ipl` will be:
    - `pow0 \times 10^6 \times fcore \times fstrp(ipl) \times axpow(j,ipl)/(nelm \times nplt \times 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 flowinc 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 (m²)
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 the node
reya = Reynolds number, middle of the node
vsc = viscosity (Pa-s), middle of the node
rhocol = coolant density (kg/m³), bottom of the node
rhocla = coolant density, node average
pcool = coolant pressure (Pa) at bottom of the node
pcoola = coolant pressure, node average
cpa = coolant isobaric specific heat (J/kg-°C)

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
fp1 = 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 (W/m-°C) of the film on face 1 or 2
prp4p1, prp4p2 = (Prandtl number)^{0.4} for the film on face 1 or 2
hcool1, hcool2 = film heat transfer coefficient (W/m²°C), face 1 or 2
qc1, qc2 = surface heat flux, (W/cm²)
10 SAMPLE INPUT

A sample STAT7 input deck is provided for user's reference. The input deck describes a hypothetical MITR-II core configuration with 22 fuel elements that have 18 finned fuel plates and primary coolant flow rate of 138.8 kg/s (2200 gpm). Other details of the input deck configuration can be cross-referenced with the input description provided in Section 8.

```
s7n189b iend1, iendm = 1, run in stat7_v1.1

! Sample input deck of hot stripe in MITR-II LEU core
! Please note that this input deck is provided as an example and may have different
! settings from the actual core. Lines starting with an exclamation mark (!) indicate comments.
! In comments, information in parenthesis indicates parameters used in the input deck.

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 | iloc p |
19 | 0 | 0 | 1 | 2 | 1 | 0 | 2 | 1

! General Descriptions: 22 LEU Element configuration (nelm = 22).
! Each element has 18 Fuel Plates (nplt = 18) and 19 Coolant Channels (nchan = 19).
! This input deck simulates a quarter stripe of a single element (nstrp = 4).
! The element has two end plates that do not have power and fins (iend1 = iendm = 1).
! It has 18 axial nodes for each fuel plate (nz = 18).

ipwshp | ifatl | iflwnc | idf | itrprt | inom | ipronb | ibypas | ivscfl | ioptn | ofieta | iprofi |
0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 2 | 1

thdbug | fcore | ffuel | flwfac | df | flwinc | pow0 | powsgm | cnveps |
0.471 | .965 | .94 | .921 | .93 | .964 | 8.00 | .01667

! Statistical Sampling: This input deck shall calculate 25 sampling batches, and each batch shall run 4000
! samples for all the thermal hydraulic calculations. Each sample shall generate random
! numbers with 1-sigma fractional uncertainties of total power (powsgm), local power
! (plocsg), pump flow (wpsgm), coolant channel gap thickness (gaps[i]), and heat transfer
! coefficient (htcsgm) based on the random number seed of 2**(isd1) + (isd2).
! The output file shall print detailed calculation results from the first 2 sample per
! iteration (iprt = 2) in addition to extra iteration prints (iterpw = 2).

plocsg | sigmax | tout | wp0 | wpsgm | coolht | fl | fw | thzrml | xkzr |
.0471 | 8.0 | 60. | 138.8 | .01667 | 3.048 | .568 | .0529

gvrdm1 | grvwml | grvtml | gapml | gapsg | grvfav | htcsgm | epsonb | thkoxm | xkox | epsofi |
10. | 10. | 10. | 10. | .01878 | .0667 | .00135

! Core TH Settings: This input deck shall search for the ONB power (iterpw > 0) iteratively until ONB
! fraction = 0.135% (epsonb = .00135). Initial power iteration shall be started
! from 8.00 MW (pow0) with the fission power deposition in the core of 96.5%
! (fcore = .965, for the total volume of the core).
! Fuel plate power split shall be calculated with two iterations (niter = 2) based
! on 94% of the power deposited in the fuel region (ffuel = .94, for the surface area
! of the fuel). Nodal coolant viscosity and the heat transfer coefficient shall be calculated
! based on the bulk coolant temperature (ivsc = 0). Inlet Mass Flow Rate is fixed at
! 2200.02 gpm (wp0 = 138.8 kg/s). Initial outlet temperature boundary condition is imposed
! as 60 °C (tout = 6). Fuel width is .0529 m (fw), and fuel height is .568 m (fl)

gapml0 | flstrf | achbyp | dhbyp | afrv | xke | bfrv | xkfr | fcarff |
72.0 | .91 | .184 | 160. | 1.0 | 14.

! Fuel plate thickness is 50 mil with the fuel core thicknesses of 20 mil (thkfr) and the
! cladding thickness of 15 mil (thke, one side). Interior coolant channel gap thickness is
! 72.0 mil

and end channel gap thickness is 58.5 mil. The following ich | gapml | gapsgi specify
! coolant channel number, coolant gap thickness, and coolant gap 1-sigma uncertainty.

ich | gapml | 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

```
The following iplate | thkf | thke specify fuel plate number, fuel core thickness, and fuel cladding thickness (one side):

<table>
<thead>
<tr>
<th>iplate</th>
<th>thkf</th>
<th>thke</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>17.0</td>
<td>17.5</td>
</tr>
<tr>
<td>2</td>
<td>20.00</td>
<td>15.00</td>
</tr>
<tr>
<td>3</td>
<td>20.00</td>
<td>15.00</td>
</tr>
<tr>
<td>4</td>
<td>20.00</td>
<td>15.00</td>
</tr>
<tr>
<td>5</td>
<td>20.00</td>
<td>15.00</td>
</tr>
<tr>
<td>6</td>
<td>20.00</td>
<td>15.00</td>
</tr>
<tr>
<td>7</td>
<td>20.00</td>
<td>15.00</td>
</tr>
<tr>
<td>8</td>
<td>20.00</td>
<td>15.00</td>
</tr>
<tr>
<td>9</td>
<td>20.00</td>
<td>15.00</td>
</tr>
<tr>
<td>10</td>
<td>20.00</td>
<td>15.00</td>
</tr>
<tr>
<td>11</td>
<td>20.00</td>
<td>15.00</td>
</tr>
<tr>
<td>12</td>
<td>20.00</td>
<td>15.00</td>
</tr>
<tr>
<td>13</td>
<td>20.00</td>
<td>15.00</td>
</tr>
<tr>
<td>14</td>
<td>20.00</td>
<td>15.00</td>
</tr>
<tr>
<td>15</td>
<td>20.00</td>
<td>15.00</td>
</tr>
<tr>
<td>16</td>
<td>20.00</td>
<td>15.00</td>
</tr>
<tr>
<td>17</td>
<td>20.00</td>
<td>15.00</td>
</tr>
</tbody>
</table>

The following iplate | fstrp | axpow specify the fuel plate number, stripe power factor, and axial power distribution (18 axial nodes):

<table>
<thead>
<tr>
<th>iplate</th>
<th>fstrp</th>
<th>axpow</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.</td>
<td>64.764</td>
</tr>
<tr>
<td></td>
<td>70.952</td>
<td>71.630</td>
</tr>
<tr>
<td>20.451</td>
<td>15.700</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2.140</td>
<td></td>
</tr>
<tr>
<td>49.319</td>
<td>44.677</td>
<td>47.762</td>
</tr>
<tr>
<td>52.859</td>
<td>53.686</td>
<td>51.999</td>
</tr>
<tr>
<td>15.990</td>
<td>13.474</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1.105</td>
<td></td>
</tr>
<tr>
<td>40.868</td>
<td>36.151</td>
<td>39.150</td>
</tr>
<tr>
<td>42.843</td>
<td>43.149</td>
<td>42.369</td>
</tr>
<tr>
<td>14.274</td>
<td>12.159</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1.145</td>
<td></td>
</tr>
<tr>
<td>36.208</td>
<td>31.947</td>
<td>34.117</td>
</tr>
<tr>
<td>36.801</td>
<td>37.270</td>
<td>36.840</td>
</tr>
<tr>
<td>13.117</td>
<td>12.100</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1.048</td>
<td></td>
</tr>
<tr>
<td>33.385</td>
<td>28.014</td>
<td>31.144</td>
</tr>
<tr>
<td>33.723</td>
<td>34.853</td>
<td>32.674</td>
</tr>
<tr>
<td>12.759</td>
<td>12.172</td>
<td></td>
</tr>
<tr>
<td>iplate</td>
<td>fstrp</td>
<td>axpow</td>
</tr>
<tr>
<td>--------</td>
<td>-------</td>
<td>-------</td>
</tr>
<tr>
<td>7</td>
<td>0.985</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>0.652</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.946</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.927</td>
<td></td>
</tr>
<tr>
<td>29.668</td>
<td>30.197</td>
<td>29.547</td>
</tr>
<tr>
<td>10</td>
<td>0.920</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>0.916</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>0.903</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>0.919</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>1.255</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>0.956</td>
<td></td>
</tr>
<tr>
<td>30.995</td>
<td>29.744</td>
<td>29.878</td>
</tr>
<tr>
<td>16</td>
<td>0.963</td>
<td></td>
</tr>
<tr>
<td>30.893</td>
<td>30.851</td>
<td>29.832</td>
</tr>
<tr>
<td>17</td>
<td>0.986</td>
<td></td>
</tr>
<tr>
<td>30.572</td>
<td>29.897</td>
<td>28.830</td>
</tr>
<tr>
<td>18</td>
<td>0.956</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>1.021</td>
<td></td>
</tr>
<tr>
<td>31.012</td>
<td>27.404</td>
<td>27.990</td>
</tr>
<tr>
<td>20</td>
<td>1.059</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>1.059</td>
<td></td>
</tr>
</tbody>
</table>
## 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.

### Stat7.1.1

```
s7n189b iend1, iendn + 1, run in stat7_v1.1
nelm | nplt | nstrp | nz | nbatch | nsmpl | isd1 | isd2 | iprt | idbstt |
-----|------|-------|----|--------|-------|------|------|------|--------|
   22 |   18 |    4  | 18 |   25000 |   25 |      |      |      |        |

nchan | iaxpow | irndmn | ipow | iterpw | iend1 | iendn | ivsc | niter | ilocp |
------|--------|--------|-----|--------|-------|-------|-----|-------|-------|
   19  |      0  |       0 |    1|        2 |      1 |       1 |     1 |       0 |       2 |       1

ipwshp | ifatl | iflwnc | idf | itrprt | inom | ipronb | ibypas | ivscfl | ioptn | ofieta | iprofi |
------|-------|--------|----|--------|-----|--------|-------|--------|------|-------|-------|
     0 |       0 |       0 |    0|        0 |     1 |       1 |      0 |       0 |    0 |       0 |       0 |       0
```

### thdbug | fcore | ffuel | flwfac | df | flwinc | pow0 | powsgm | cnveps |
---------|-------|-------|-------|---|-------|------|-------|-------|
 0.00000 | 0.96500 | 0.94000 | 0.92100 | 0.93000 | 0.96400 | 8.00000 | 0.01667 | 0.00000 |

### plocsg | sigm | tout | wp0 | wpsgm | coolht | flw | fw | thzrml | xkzr |
---------|-----|-----|-----|-------|-------|-----|-----|-------|-----|
 0.04710 |     |    |    |      |       |     |     |       |     |

### grvdml | grvwml | grvtml | gapml | gapsg | grvfav | htcsgm | epsonb | thkoxm | xkox | epsofi |
---------|-------|-------|-------|-------|--------|-------|-------|-------|-----|-------|

### ich | gapmli | gapsgi |
------|-------|-------|
 0 1 50.50 0.11220 0.00
 2 72.00 0.01850 0.00

```
 0 18 72.00 0.01850 0.00
 0 19 50.50 0.11220 0.00
```

### recap of thkf, thke

```
 0 19 20.00 15.00000
 0 20 17.00 17.50000
```

### fstrp | axpow |
------|------|
 1 64.76400 60.00000 64.86600 67.67700 68.45500 67.01400 67.18400 67.77500 70.95000 71.01600 68.57000 64.35200 59.53000 59.11000 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
```

```
iplate| fstrp | axpow |
------|------|------|
 2 64.76400 60.00000 64.86600 67.67700 68.45500 67.01400 67.18400 67.77500 70.95000 71.01600 68.57000 64.35200 59.53000 59.11000 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
```

```
### *** Output Variables ***

Initial flowinc 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`
- `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

#### Plate results

- `aclad` = clad surface area on the 2 surfaces
- `Tcool` = coolant temperature (°C) at the middle of the node
- `Tcool2` = same for face 2
- `Tsat` = saturation temperature
- `Tomb` = ONB temperature
- `Tsurf1, Tsurf2` = plate surface temperatures
- `Tox-cld` = temperature at the oxide-clad boundary
- `Tcd-zr` = temperature at the clad-zirconium boundary
- `Tmax, Tfuel2` = maximum fuel temperature, calculated from surface 1 or 2
- `fp1` = power split = face 1 flux / (face 1 flux + face 2 flux)
- `reyp1, reyp2` = Re for film on face 1 or 2
- `xkcp1, xkcp2` = thermal conductivity (W/m-°C) of the film on face 1 or 2
- `prp4p1, prp4p2` = (Prandtl number)**0.4 for the film on face 1 or 2
- `hcool1, hcool2` = film heat transfer coefficient (W/m²-°C), face 1 or 2
- `qc1, qc2` = surface heat flux, (w/cm²)

### *** BEGINNING OF STAT7 CALCULATION ***

- After 2 iterations `flwinc = 0.98531`, previous val= 0.98531
- `afr, bfr= 0.3100 -0.2500`
- `flwfac = 0.92100 previous val= 0.92100`

- plate power split iteration step 1 for axial node 9
The STAT7 Code for Statistical Propagation of Uncertainties In
Steady-State Thermal Hydraulics Analysis of Plate-Fueled Reactors

42
The STAT7 Code for Statistical Propagation of Uncertainties In Steady-State Thermal Hydraulics Analysis of Plate-Fueled Reactors

nominal power = 9.17248
peak ONBR at node 13 on surface 1 of plate 2
ONBR = 1.300E+03

computer time for thermal hydraulics and sampling = 1.778E+01 seconds
computer time for statistical analysis = 6.866E-05

number of ONB cases in plates* 1 to 5

<table>
<thead>
<tr>
<th>plate 1</th>
<th>plate 2</th>
<th>plate 3</th>
<th>plate 4</th>
<th>plate 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>jz surf1 surf2 surf1 surf2 surf1 surf2 surf1 surf2 surf1 surf2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 0 0 7 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 0 0 39 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11 0 0 77 3 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12 0 0 101 4 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13 0 0 130 3 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14 0 0 117 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 3 3 57 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16 3 3 17 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17 6 6 5 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18 6 6 5 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>all 18 18 555 13 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*please note that the plate numbering may include UNFUELED plate depending on the iend1 and iendn input.

limiting surface is surface 1 of plate 2, peak node = 13.

iteration power ONB fraction sigma ONB fraction - criterion
1 8.0000 6.000E-05 2.135E-05 -0.373E+00
2 9.0000 9.300E-04 7.813E-05 -0.373E+00
3 10.0000 8.070E-03 2.296E-04 0.179E+01
4 9.1725 1.320E-03 9.436E-05 -0.225E+01

ilow= 2, valow=-3.727E-01, ihigh= 3, valgh= 1.788E+00

power converged at iteration 4, power = 9.1725, ONB fraction = 1.320E-03, sigma = 9.436E-05
limiting: power = 9.1725 MW, surface 1, fuel plate* 1, axial node 13

*please note that the plate numbering here only accounts for the FUELED plates

*** END OF STAT7 CALCULATION ***

12 FORTRAN CODING

The STAT7 code is written using the FORTRAN 90 (Formal name: Fortran ISO/IEC 1539:1991), standard (X3.198-1992) of the American National Standards Institute (ANSI) [21].

13 EXECUTING THE CODE

The executable binary file of STAT7, stat7.x, is included in Linux_Executable directory in the official STAT7 production package. If the path to stat7.x is in the user’s PATH environmental variable, then the command used to execute the code in Linux environments is:

    stat7.x < input
The above command will print the calculation results on the terminal prompt. If a user wants to redirect the output to an ASCII text file while the calculation results are printing on the terminal prompt, one may execute the STAT7 using:

```
stat7.x < input | tee output
```

If a user wants to run the STAT7 calculation on the background, one may use:

```
stat7.x < input > output &
```

The output file can be monitored with a tail command as follows:

```
tail -f output
```
ACKNOWLEDGEMENTS

The authors express their gratitude to the staff of the MIT Nuclear Reactor Laboratory with whom this code was conceived. In particular, the Master's degree work of Keng-Yen Chiang provided the initial methodology to begin this effort which was continued in a collaboration between MIT and Argonne staff. Floyd Dunn, who originally authored this software, and Son Pham who originally completed the STAT7 V&V referred to in this work are gratefully acknowledged.

This work was sponsored by the U.S. Department of Energy, Office of Material Management and Minimization in the U.S. National Nuclear Security Administration Office of Defense Nuclear Nonproliferation under Contract DE-AC02-06CH11357.
REFERENCES


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 [A1]. The fins are 10 mil high, 10 mil wide, and they are 10 mil 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, \( D_h = 4 \times \) 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 [A2]. 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

\[
 f_{\text{avg}} = \left( f_{\text{fin}} W_{\text{fin}} + f_{\text{nofin}} W_{\text{nofin}} \right) / \left( W_{\text{fin}} + W_{\text{nofin}} \right)
\]

where \( f_{\text{fin}} \) and \( f_{\text{nofin}} \) are the finned and no-fin friction factors, and \( W_{\text{fin}} \) and \( W_{\text{nofin}} \) 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 the reference [A3] 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

<table>
<thead>
<tr>
<th>Channel</th>
<th>Limiting power (MW)</th>
<th>Coolant flow (kg/s)</th>
<th>Friction factor multiplier</th>
<th>Heat transfer multiplier</th>
<th>Pressure drop (kPa)</th>
<th>Dₜ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>No fins</td>
<td>5.9307</td>
<td>0.03555</td>
<td>0.06813</td>
<td>---</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Fins, friction factor multiplier= 1.0</td>
<td>9.2786</td>
<td>0.04255</td>
<td>0.06731</td>
<td>1.0</td>
<td>0.714</td>
<td>0.716</td>
</tr>
<tr>
<td>Fins, STAT7 friction factor multiplier</td>
<td>9.2834</td>
<td>0.04286</td>
<td>0.06727</td>
<td>1.044</td>
<td>1.059</td>
<td>0.714</td>
</tr>
<tr>
<td>Fins, PLTEMP friction factor multiplier</td>
<td>9.3410</td>
<td>0.04318</td>
<td>0.06724</td>
<td>1.029</td>
<td>1.059</td>
<td>0.714</td>
</tr>
</tbody>
</table>

a The channel gap thickness 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 0.714 – 0.716 reduces the overall improvement in the clad-to-coolant heat transfer. Also, the heat transfer coefficient is proportional to 1/Dₜ⁰.², 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.
REFERENCES


