Argonne NATIONAL LABORATORY

ANL/RERTR/TM-11-37
Revision 0

# Verification and Validation of the PLTEMP/ANL Code for Thermal-Hydraulic Analysis of Experimental and Test Reactors

*Revision 0*

**Nuclear Engineering Division**

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# Verification and Validation of the PLTEMP/ANL Code for Thermal-Hydraulic Analysis of Experimental and Test Reactors

*Revision 0*

by
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July 30, 2011

This work is sponsored by the
U.S. Department of Energy, National Nuclear Safety Administration NNSA,
Office of Global Threat Reduction (NA-21)

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## ABSTRACT

The document compiles in a single volume several verification and validation works done for the PLTEMP/ANL code during the years of its development and improvement. Some works that are available in the open literature are simply referenced at the outset, and are not included in the document. PLTEMP has been used in conversion safety analysis reports of several US and foreign research reactors that have been licensed and converted. A list of such reactors is given. Each chapter of the document deals with the verification or validation of a specific model. The model verification is usually done by comparing the code with hand calculation, Microsoft spreadsheet calculation, or *Mathematica* calculation. The model validation is done by comparing the code with experimental data or a more validated code like the RELAP5 code.

**Other Publications on PLTEMP/ANL Verification and Validation**

1. E. E. Feldman, "Comparison of the PLTEMP Code Flow Instability Predictions with Measurements Made with Electrically Heated Channels for the Advanced Test Reactor," ANL/RERTR/TM-11-23, Global Threat Reduction Initiative (GTRI) - Conversion Program, Nuclear Engineering Division, Argonne National Laboratory, Argonne, IL, USA (June 9, 2011).
2. M. Kalimullah, A. P. Olson, and E. E. Feldman, "Natural Circulation Flow Rate Calculation in PLTEMP/ANL Code," RERTR 2008 – 30th. International Meeting on Reduced Enrichment for Research and Test Reactors, Washington, D.C., USA (October 5-9, 2008).
3. M. Kalimullah, N. A. Hanan, E. E. Feldman, and A. P. Olson, "Implementation and Verification of Mishima's CHF Data at Low Flow and Atmospheric Pressure in the PLTEMP/ANL Code," RERTR 2009 – 31st. International Meeting on Reduced Enrichment for Resesarch and Test Reactors, Beijing, China (November 1-5, 2009).

**List of US Research Reactors Converted as Licensed by the U.S. Nuclear Regulatory Commission Based on Conversion Safety Analysis Reports in Which the PLTEMP Code was used:**

(1) University of Florida Training Reactor (UFTR)
(2) Purdue University Reactor (PUR-1)
(3) Georgia institute of Technology Research Reactor (GTRR)
(4) University of Massachusetts Lowell Research Reactor (UMLRR)
(5) University of Michigan Ford Nuclear Reactor (FNR)
(6) Rhode Island Nuclear Science Center (RINSC) Research Reactor
(7) University of Virginia Reactor (UVAR)
(8) University of Missouri-Rolla Nuclear Reactor (UMRR)

**List of Foreign Research Reactors Converted as Licensed by Other Regulatory Agencies Based on Conversion Safety Analysis Reports in Which the PLTEMP Code was used:**

(1) Portuguese research reactor (RPI) (reviewed by the International Atomic Energy Agency)

Research reactors of Russian design:
(2) Sophia research reactor in Bulgaria (IRT-200)
(3) Tajoura reactor in Libya (IRT-1)
(4) INP Tashkent in Uzbekistan (WWR-CM Tashkent)
(5) Dalat Nuclear Research Reactor in Vietnam (DNRR)

## 1. Verification Script for PLTEMP/ANL Code

(March 2006)

In order to routinely verify the PLTEMP/ANL code after a code modification, a UNIX script *verify.pltemp21.csh*, saved in directory */home/sol1a/kalimull/run_verif* has been developed that runs the new executable for a set of eight standard problems (whose accepted outputs from an older PLTEMP/ANL code executable are saved for comparison purposes) and compares each new output with the old, and saves the differences (using the program *differ.x* that finds the maximum temperature difference for each fuel plate) in a file for the code developer to examine.

The input data files of the eight standard problems used in the script, the output files obtained by version 2.14 of the code for these problems, and three other input files required for running the code are all saved in the directory */home/sol1a/kalimull/verify_problems*.

Before running the script one must reset (in the script) the filename of the executable that needs to be verified. The script writes the differences between the results of the old and new codes in the file *pltemp.verification.output*. A short summary of the differences is also written in the file. The input filenames with a brief description of the problem are:

<u>Sample Problem 1 Input File *input.A2.p3.c3r*</u>
This input file (shown in Table 1), provided by A. P. Olson, models one fuel subassembly of a single fuel type in radial geometry, with a power of 0.80811 MW. The subassembly has 6 fuel tubes and 7 coolant channels. The fueled length of 0.58 meter is divided into 11 axial nodes. The code is run in the flow-driven mode, i.e., using input fixed flow rates (1.943 kg/s, 1.577 kg/s, 1.542 kg/s, 1.411 kg/s, 1.168 kg/s, 1.151 kg/s and 0.914 kg/s) in coolant channels. One bypass channel is modeled. Hot channel factors are not used.

<u>Sample Problem 2 Input File *input.12assemblies*</u>
This input file (shown in Table 2) models 12 fuel subassemblies of a single fuel type in slab geometry, with a total power of 1.0 MW. Each subassembly has 4 fuel plates (made of 1.0 mm thick fuel meat with 0.5 mm thick cladding on both sides) and 5 coolant channels (each 3.0 mm thick and 20.0 cm wide). The fueled length of 0.75 meter is divided into 10 equal-length axial nodes. The code is run in the flow-driven mode, i.e., using input fixed flow rates in coolant channels. Bypass channel or hot channel factors are not used.

<u>Sample Problem 3 Input File *input.2assemblies*</u>
This input file (shown in Table 3) models 2 fuel subassemblies of a single fuel type in slab geometry, with a total power of 1.0 MW. Each subassembly has 4 fuel plates (made of 1.0 mm thick fuel meat with 0.5 mm thick cladding on both sides) and 5 coolant channels (each 3.0 mm thick and 20.0 cm wide). The fuel plates have an un-fueled length of 0.15 meter above (minor loss factor 8.0) and an un-fueled length of 0.15 meter below (minor loss factor 8.0) the fueled length of 0.75 meter which is divided into 10 equal-length axial nodes. The code is run in the pressure-driven mode with a pressure drop of 0.10 MPa and an inlet pressure of 1.4 MPa. Bypass channel or hot channel factors are not used.

Sample Problem 4 Input File *input.2subassTypes*

This input file (shown in Table 4) models 4 fuel subassemblies, with 2 subassemblies of one type and 2 of another type, in slab geometry, with a total power of 2.0 MW. Each subassembly has 4 fuel plates (made of 1.0 mm thick fuel meat with 0.5 mm thick cladding on both sides) and 5 coolant channels (each 3.0 mm thick and 20.0 cm wide). The fuel plates have an un-fueled length of 0.15 meter above (minor loss factor 8.0) and an un-fueled length of 0.15 meter below (minor loss factor 8.0) the fueled length of 0.75 meter which is divided into 10 equal-length axial nodes. The code is run in the pressure-driven mode with a pressure drop of 0.10 MPa and an inlet pressure of 1.4 MPa. Bypass channel or hot channel factors are not used.

Sample Problem 5 Input File *input.DeltaPloop_Powerloop*

This input file (shown in Table 5) models 2 fuel subassemblies of a single fuel type in slab geometry. It runs the code in pressure-driven mode. It exercises the power loop and the pressure drop loop features of the code. In a single run, the code does 45 steady-state calculations by increasing the total power from 1.0 MW to 3.8 MW in steps of 0.2 MW (thus assuming 15 values of total power), and by assuming 3 values of pressure drop (0.10 MPa, 0.14 MPa and 0.18 MPa) for each value of total power. The pressure drop is increased in steps of 0.04 MPa, starting from 0.10 MPa, the inlet pressure always being 1.4 MPa. The total power and pressure drop loops are set up using the input data on card type 0600. Each subassembly has 4 fuel plates (made of 1.0 mm thick fuel meat with 0.5 mm thick cladding on both sides) and 5 coolant channels (each 3.0 mm thick and 20.0 cm wide). The fuel plates have an un-fueled length of 0.15 meter above and an un-fueled length of 0.15 meter below the fueled length of 0.75 meter which is divided into 10 axial nodes. Bypass channel or hot channel factors are not used. The total number of tables (of coolant, cladding and fuel temperatures) in its output is 360 (2 x 4 x 45).

Sample Problem 6 Input File *input.fixedflows*

This input file (shown in Table 6) models 2 fuel subassemblies of a single fuel type in slab geometry, with a total power of 1.0 MW. Each subassembly has 4 fuel plates (made of 1.0 mm thick fuel meat with 0.5 mm thick cladding on both sides) and 5 coolant channels (each 3.0 mm thick and 20.0 cm wide). The fuel plates have an un-fueled length of 0.15 meter above and an un-fueled length of 0.15 meter below the fueled length of 0.75 meter which is divided into 10 axial nodes. The code is run in flow-driven mode, i.e., using an input fixed flow rate of 0.50 kg/s in each coolant channel. Bypass channel or hot channel factors are not used.

Sample Problem 7 Input File *input.Powerloop*

This input file (shown in Table 7) models 2 fuel subassemblies of a single fuel type in slab geometry. It exercises the code's power loop feature using the input data on card type 0600. In a single run, the code does 11 steady-state calculations by increasing the total power from 1.0 MW to 3.0 MW in steps of 0.2 MW (i.e., using the values 1.0 MW, 1.2 MW, 1.4 MW … 2.8 MW and 3.0 MW). The code is run in pressure-driven mode using a pressure drop of 0.1 MPa and an inlet pressure of 1.4 MPa. Each subassembly has 4 fuel plates (made of 1.0 mm thick fuel meat with 0.5 mm thick cladding on both sides) and 5 coolant channels (each 3.0 mm thick and 20.0 cm wide). The fuel plates have an un-fueled length of 0.15 meter above and an un-fueled length of

0.15 meter below the fueled length of 0.75 meter which is divided into 10 axial nodes. Bypass channel or hot channel factors are not used.

Sample Problem 8 Input File *input.pressuredriven*

This input file (shown in Table 8) models 2 fuel subassemblies of a single fuel type in slab geometry. It is identical to the input file for Sample Problem 3 except for more skewed radial power factors now input on card type 0309.

### Table 1. Input Filename *input.A2.p3.c3r* Used as Standard Problem 1 in PLTEMP/ANL Verification Script

```
IRT-3M 36% Enr FA; 6 Tubes 0.58 m Height - ASTRA2 P3 true->plate
! input.A2.p3.c3r
! Notes by Kalim, Jan 12, 2006
! NFTYP=1,   Only one type of subassembly in the problem
! NELF(1)=1, A single subassembly in type 1
   4   2   2   1   1   0   1   0   1   1                                       Card(1)0200
   1   3  0.0        1.00        1.000       1.00                              Card(1)0300
   7   7  1.000                                                                Card(1)0301
   1   2   1                                                                   Card(1)0302
 1.3135                                                                        Card(1)0303
 0.0043433  0.038540    0.10        0.5                                        Card(3)0304
 0.0        0.0         0.580       0.0                                        Card(3)0304
 0.0043433  0.038540    0.035       1.0                                        Card(3)0304
 0.316      0.250                                                              Card(1)0305
   7  0 0.0         0.580         0.450E-03  170.        0.500E-03  100.       Card(1)0306
  6.0524E-04 4.46024E-03  0.27139    0.27139                                   Card(7)0307
  5.2931E-04 4.17778E-03  0.50679    0.50679                                   Card(7)0307
  4.7273E-04 4.18729E-03  0.45159    0.45159                                   Card(7)0307
  4.1615E-04 4.19944E-03  0.39639    0.39639                                   Card(7)0307
  3.5957E-04 4.21553E-03  0.34119    0.34119                                   Card(7)0307
  3.0299E-04 4.23783E-03  0.28599    0.28599                                   Card(7)0307
  2.4641E-04 4.27080E-03  0.23079    0.23079                                   Card(7)0307
 0.267193   0.239593    0.211993    0.184393    0.156793    0.129193           Card(1)0308
  .0340      .03055      .02710      .02365      .02020      .01675
 1.1696     1.0901      1.0234      0.9579      0.90175     0.85731            Card(1)0309
1.94282     1.57675     1.54174     1.41065     1.16807     1.15058
0.91358
   1   1         1.0
  1.1545E-04    3.00E-03    0.680           1.4
       0.316    0.25
 .100633     .0005        .12540     0.80811      45.0        .135             Card(1)0500
 100 1.00000E-04   25.0        0.0000        0.80811
 -12
0.00000      0.025       0.52323
0.05000      0.100       0.62029
0.15         0.20        0.85886
0.25         0.30        1.06336
0.35         0.40        1.24058
0.45         0.50        1.34964
0.55         0.60        1.36328
0.65         0.70        1.27466
0.75         0.80        1.09062
0.85         0.90        0.85886
0.95         0.975       0.75662
1.00000
   0
```

## Table 2. Input Filename *input.12assemblies* Used as Standard Problem 2 in PLTEMP/ANL Verification Script

```
Test Problem: 12 subassemblies (of identical geometry) producing 1 MWt
! Each subassembly has 4 fuel plates and 5 coolant channels
! H2O coolant, Flow = 6.0 kg/s, All hot channel factors = 1.0
! No bypass flow, NCTYP=0
! 10 axial heat transfer nodes in the heated length of fuel plates
!  1   2   3   4   5   6   7   8   9  10  11  12  13                  Card 0200 indeces
   0   0   0   1   0   1   1   1   0   0   0   0   0                  Card(1)0200
  12   3 0.00       1.00        1.00        1.00           3          Card(1)0300
! Using pressure driven mode
! 12   3 0.45       1.00        1.00        1.00           3          Card(1)0300
   1  20 1.00                                                         Card(1)0301
   1   1   1                                                          Card(1)0302
1.20        1.20        1.20        1.20        1.20        1.20      Card(2)0303
1.20        1.20        1.20        1.20        1.20        1.20      Card(2)0303
30.0E-04    0.02955665  0.15        1.0                               Card(3)0304
30.0E-04    0.02955665  0.15        1.0                               Card(3)0304
30.0E-04    0.02955665  0.15        1.0                               Card(3)0304
! Use code's correlation for friction factor
0.00        0.00        0.00                                          Card(1)0305
   5   3 0.00       0.75        0.50E-03    0.00        1.00E-03   100.00      Card(1)0306
6.00E-04    5.91133E-03 0.4060      0.20        0.20        3.00E-03  Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03  Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03  Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03  Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.20        0.20        3.00E-03  Card(5)0307
0.20        0.20        0.20        0.20                              Card(1)0308
! Card 0308a not required
! Radial power peaking factor data by fuel plate for each subassembly. Input flow data by
! channel for each subassembly on Cards 0310 not required because WFGES(1) is non-zero
0.90        0.95        1.05        1.10                              Card(12)0309
0.09        0.09        0.09        0.09        0.09                  Card(12)0310
0.901       0.951       1.049       1.099                             Card(12)0309
0.09        0.09        0.09        0.09        0.09                  Card(12)0310
0.902       0.952       1.048       1.098                             Card(12)0309
0.09        0.09        0.09        0.09        0.09                  Card(12)0310
0.903       0.953       1.047       1.097                             Card(12)0309
0.09        0.09        0.09        0.09        0.09                  Card(12)0310
0.904       0.954       1.046       1.096                             Card(12)0309
0.09        0.09        0.09        0.09        0.09                  Card(12)0310
0.905       0.955       1.045       1.095                             Card(12)0309
0.09        0.09        0.09        0.09        0.09                  Card(12)0310
0.906       0.956       1.044       1.094                             Card(12)0309
0.09        0.09        0.09        0.09        0.09                  Card(12)0310
0.907       0.957       1.043       1.093                             Card(12)0309
0.09        0.09        0.09        0.09        0.09                  Card(12)0310
0.908       0.958       1.042       1.092                             Card(12)0309
0.09        0.09        0.09        0.09        0.09                  Card(12)0310
0.909       0.959       1.041       1.091                             Card(12)0309
0.09        0.09        0.09        0.09        0.09                  Card(12)0310
0.910       0.960       1.040       1.090                             Card(12)0309
0.09        0.09        0.09        0.09        0.09                  Card(12)0310
0.911       0.961       1.039       1.089                             Card(12)0309
0.09        0.09        0.09        0.09        0.09                  Card(12)0310
! DP0       DDP         DPMAX       POWER       TIN         PIN
0.10        0.10        0.20        1.00        45.0        1.40      Card(1)0500
  50 0.0001     25.0        0.00        1.00                          Card(1)0600
  11                                                                  Card(1)0700
0.00        1.00                                                      Card(11)0701
0.10        1.00                                                      Card(11)0701
0.20        1.00                                                      Card(11)0701
0.30        1.00                                                      Card(11)0701
0.40        1.00                                                      Card(11)0701
0.50        1.00                                                      Card(11)0701
0.60        1.00                                                      Card(11)0701
0.70        1.00                                                      Card(11)0701
0.80        1.00                                                      Card(11)0701
0.90        1.00                                                      Card(11)0701
1.00        1.00                                                      Card(11)0701
   0                                                                  Card(11)0702
```

## Table 3. Input Filename *input.2assemblies* Used as Standard Problem 3 in PLTEMP/ANL Verification Script

```
 Test Problem: 2 subassemblies (of identical geometry) producing 1 MWt
! Each subassembly has 4 fuel plates and 5 coolant channels
! H2O coolant, Flow is calculated from input pressure drop
! All hot channel factors = 1.0
! No bypass flow, NCTYP=0
! 10 axial heat transfer nodes in the heated length of fuel plates
!  1   2   3   4   5   6   7   8   9  10  11  12  13                   Indices on Card 0200
   0   0   0   1   0   1   1   1   0   0   0   0   0                            Card(1)0200
   2   3 0.50      1.00        1.00        1.00           3                     Card(1)0300
! Using pressure driven mode
   1  20 1.00                                                                   Card(1)0301
   1   1   1                                                                    Card(1)0302
1.20        1.20                                                                Card(2)0303
30.0E-04    0.02955665  0.15        8.00        0.20        15.0E-03            Card(3)0304
30.0E-04    0.02955665  0.75        0.00        0.20        15.0E-03            Card(3)0304
30.0E-04    0.02955665  0.15        8.00        0.20        15.0E-03            Card(3)0304
! Use the code's built-in correlation for friction factor
0.00        0.00        0.00                                                    Card(1)0305
   5   3 0.00       0.75        0.50E-03    0.00        1.00E-03    100.00      Card(1)0306
6.00E-04    5.91133E-03 0.4060      0.20        0.20        3.00E-03            Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03            Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03            Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03            Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.20        0.20        3.00E-03            Card(5)0307
0.20        0.20        0.20        0.20                                        Card(1)0308
! Card 0308a not required
! Radial power peaking factor data by fuel plate for each subassembly. Input flow data by
! channel for each subassembly on Cards 0310 not required because WFGES(1) is non-zero
0.900       0.950       1.050       1.100                                       Card(2)0309
0.901       0.951       1.049       1.099                                       Card(2)0309
! DP0       DDP         DPMAX       POWER       TIN         PIN
0.10        0.04        0.10        1.00        45.0        1.40                Card(1)0500
  50 0.0001     25.0        0.50        1.00                                    Card(1)0600
  11                                                                            Card(1)0700
0.00        0.80                                                                Card(11)0701
0.10        0.88                                                                Card(11)0701
0.20        0.96                                                                Card(11)0701
0.30        1.04                                                                Card(11)0701
0.40        1.12                                                                Card(11)0701
0.50        1.20                                                                Card(11)0701
0.60        1.12                                                                Card(11)0701
0.70        1.04                                                                Card(11)0701
0.80        0.96                                                                Card(11)0701
0.90        0.88                                                                Card(11)0701
1.00        0.80                                                                Card(11)0701
   0                                                                            Card(11)0702
```

## Table 4. Input Filename *input.2subassTypes* Used as Standard Problem 4 in PLTEMP/ANL Verification Script

```
 Test Problem: 4 subassemblies (of identical geometry) producing 2 MWt
! Each subassembly has 4 fuel plates and 5 coolant channels
! H2O coolant, Flow is calculated from input pressure drop
! All hot channel factors = 1.0
! No bypass flow, NCTYP=0
! 10 axial heat transfer nodes in the heated length of fuel plates
!  1   2   3   4   5   6   7   8   9  10  11  12  13                   Indices on Card 0200
   0   0   0   2   0   1   1   1   0   0   0   0   0                             Card(1)0200
!-------------------------------------------------------------------------------------------
! Data for Type 1 fuel subassemblies
   2   3 0.50       1.00        1.00        1.00           3                     Card(1)0300
! Using pressure driven mode
   1  20 1.00                                                                    Card(1)0301
   1   1   1                                                                     Card(1)0302
1.20        1.20                                                                 Card(2)0303
30.0E-04    0.02955665  0.15        8.00        0.20        15.0E-03             Card(3)0304
30.0E-04    0.02955665  0.75        0.00        0.20        15.0E-03             Card(3)0304
30.0E-04    0.02955665  0.15        8.00        0.20        15.0E-03             Card(3)0304
! Use the code's built-in correlation for friction factor
0.00        0.00        0.00                                                     Card(1)0305
   5   3 0.00       0.75        0.50E-03    0.00        1.00E-03    100.00       Card(1)0306
6.00E-04    5.91133E-03 0.4060      0.20        0.20        3.00E-03             Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03             Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03             Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03             Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.20        0.20        3.00E-03             Card(5)0307
0.20        0.20        0.20        0.20                                         Card(1)0308
! Card 0308a not required
! Radial power peaking factor data by fuel plate for each subassembly. Input flow data by
! channel for each subassembly on Cards 0310 not required because WFGES(1) is non-zero
0.700       0.800       0.900       1.000                                        Card(2)0309
1.000       1.100       1.200       1.300                                        Card(2)0309
!-------------------------------------------------------------------------------------------
! Data for Type 2 fuel subassemblies
   2   3 0.50       1.00        1.00        1.00           3                     Card(1)0300
! Using pressure driven mode
   1  20 1.00                                                                    Card(1)0301
   1   1   1                                                                     Card(1)0302
1.20        1.20                                                                 Card(2)0303
30.0E-04    0.02955665  0.15        8.00        0.20        15.0E-03             Card(3)0304
30.0E-04    0.02955665  0.75        0.00        0.20        15.0E-03             Card(3)0304
30.0E-04    0.02955665  0.15        8.00        0.20        15.0E-03             Card(3)0304
! Use the code's built-in correlation for friction factor
0.00        0.00        0.00                                                     Card(1)0305
   5   3 0.00       0.75        0.50E-03    0.00        1.00E-03    100.00       Card(1)0306
6.00E-04    5.91133E-03 0.4060      0.20        0.20        3.00E-03             Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03             Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03             Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03             Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.20        0.20        3.00E-03             Card(5)0307
0.20        0.20        0.20        0.20                                         Card(1)0308
! Card 0308a not required
! Radial power peaking factor data by fuel plate for each subassembly. Input flow data by
! channel for each subassembly on Cards 0310 not required because WFGES(1) is non-zero
0.700       0.800       0.900       1.000                                        Card(2)0309
2.000       2.100       2.200       2.300                                        Card(2)0309
!-------------------------------------------------------------------------------------------
! DP0       DDP         DPMAX       POWER       TIN         PIN
0.10        0.04        0.10        2.00        45.0        1.40                 Card(1)0500
  50 0.0001     25.0        0.50        1.00                                     Card(1)0600
  11                                                                             Card(1)0700
0.00        0.80                                                                 Card(11)0701
0.10        0.88                                                                 Card(11)0701
0.20        0.96                                                                 Card(11)0701
0.30        1.04                                                                 Card(11)0701
0.40        1.12                                                                 Card(11)0701
0.50        1.20                                                                 Card(11)0701
0.60        1.12                                                                 Card(11)0701
0.70        1.04                                                                 Card(11)0701
0.80        0.96                                                                 Card(11)0701
0.90        0.88                                                                 Card(11)0701
1.00        0.80                                                                 Card(11)0701
   0                                                                             Card(11)0702
```

**Table 5. Input Filename *input.DeltaPloop_Powerloop* Used as Standard Problem 5 in PLTEMP/ANL Verification Script**

```
 Test Problem: 2 subassemblies (of identical geometry) producing 1 MWt
! Each subassembly has 4 fuel plates and 5 coolant channels
! H2O coolant, Flow is calculated from input pressure drop
! All hot channel factors = 1.0
! No bypass flow, NCTYP=0
! 10 axial heat transfer nodes in the heated length of fuel plates
!  1   2   3   4   5   6   7   8   9  10  11  12  13                   Indices on Card 0200
   0   0   0   1   0   1   1   1   0   0   0   0   0                            Card(1)0200
   2   3 0.50       1.00        1.00        1.00           3                    Card(1)0300
! Using pressure driven mode
   1  20 1.00                                                                   Card(1)0301
   1   1   1                                                                    Card(1)0302
1.20        1.20                                                                Card(2)0303
30.0E-04    0.02955665  0.15        8.00        0.20        15.0E-03            Card(3)0304
30.0E-04    0.02955665  0.75        0.00        0.20        15.0E-03            Card(3)0304
30.0E-04    0.02955665  0.15        8.00        0.20        15.0E-03            Card(3)0304
! Use the code's built-in correlation for friction factor
0.00        0.00        0.00                                                    Card(1)0305
   5   3 0.00       0.75        0.50E-03    0.00        1.00E-03    100.00      Card(1)0306
6.00E-04    5.91133E-03 0.4060      0.20        0.20        3.00E-03            Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03            Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03            Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03            Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.20        0.20        3.00E-03            Card(5)0307
0.20        0.20        0.20        0.20                                        Card(1)0308
! Card 0308a not required
! Radial power peaking factor data by fuel plate for each subassembly. Input flow data by
! channel for each subassembly on Cards 0310 not required because WFGES(1) is non-zero
0.900       0.950       1.050       1.100                                       Card(2)0309
0.600       0.800       1.200       1.400                                       Card(2)0309
! DP0       DDP         DPMAX       POWER       TIN         PIN
0.10        0.04        0.20        1.00        45.0        1.40                Card(1)0500
!     CONV       ETA        DPWR        PWRM
 -50 0.0001     25.0        0.20        6.00                                    Card(1)0600
  11                                                                            Card(1)0700
0.00        0.80                                                                Card(11)0701
0.10        0.88                                                                Card(11)0701
0.20        0.96                                                                Card(11)0701
0.30        1.04                                                                Card(11)0701
0.40        1.12                                                                Card(11)0701
0.50        1.20                                                                Card(11)0701
0.60        1.12                                                                Card(11)0701
0.70        1.04                                                                Card(11)0701
0.80        0.96                                                                Card(11)0701
0.90        0.88                                                                Card(11)0701
1.00        0.80                                                                Card(11)0701
   0                                                                            Card(11)0702
```

## Table 6. Input Filename *input.fixedflows* Used as Standard Problem 6 in PLTEMP/ANL Verification Script

```
 Test Problem: 2 subassemblies (of identical geometry) producing 1 MWt
! Each subassembly has 4 fuel plates and 5 coolant channels
! H2O coolant, Input coolant flow = 2.5 kg/s per coolant channel
! All hot channel factors = 1.0
! No bypass flow, NCTYP=0
! 10 axial heat transfer nodes in the heated length of fuel plates
!  1   2   3   4   5   6   7   8   9  10  11  12  13                   Indices on Card 0200
   0   0   0   1   0   1   1   1   0   0   0   0   0                            Card(1)0200
   2   3 0.00       1.00        1.00        1.00           3                    Card(1)0300
! Using pressure driven mode
   1  20 1.00                                                                   Card(1)0301
   1   1   1                                                                    Card(1)0302
1.20        1.20                                                                Card(2)0303
30.0E-04    0.02955665  0.15        8.00        0.20        15.0E-03            Card(3)0304
30.0E-04    0.02955665  0.75        0.00        0.20        15.0E-03            Card(3)0304
30.0E-04    0.02955665  0.15        8.00        0.20        15.0E-03            Card(3)0304
! Use the code's built-in correlation for friction factor
0.00        0.00        0.00                                                    Card(1)0305
   5   3 0.00       0.75        0.50E-03    0.00        1.00E-03    100.00      Card(1)0306
6.00E-04    5.91133E-03 0.4060      0.20        0.20        3.00E-03            Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03            Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03            Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03            Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.20        0.20        3.00E-03            Card(5)0307
0.20        0.20        0.20        0.20                                        Card(1)0308
! Card 0308a not required
! Radial power peaking factor data by fuel plate for each subassembly. Input flow data by
! channel for each subassembly on Cards 0310 not required because WFGES(1) is non-zero
0.900       0.950       1.050       1.100                                       Card(2)0309
0.50        0.50        0.50        0.50        0.50                            Card(2)0310
0.600       0.800       1.200       1.400                                       Card(2)0309
0.50        0.50        0.50        0.50        0.50                            Card(2)0310
! DP0       DDP         DPMAX       POWER       TIN         PIN
0.10        0.04        0.10        1.00        45.0        1.40                Card(1)0500
  50 0.0001     25.0        0.50        1.00                                    Card(1)0600
  11                                                                            Card(1)0700
0.00        0.80                                                                Card(11)0701
0.10        0.88                                                                Card(11)0701
0.20        0.96                                                                Card(11)0701
0.30        1.04                                                                Card(11)0701
0.40        1.12                                                                Card(11)0701
0.50        1.20                                                                Card(11)0701
0.60        1.12                                                                Card(11)0701
0.70        1.04                                                                Card(11)0701
0.80        0.96                                                                Card(11)0701
0.90        0.88                                                                Card(11)0701
1.00        0.80                                                                Card(11)0701
   0                                                                            Card(11)0702
```

## Table 7. Input Filename *input.Powerloop* Used as Standard Problem 7 in PLTEMP/ANL Verification Script

```
 Test Problem: 2 subassemblies (of identical geometry) producing 1 MWt
! Each subassembly has 4 fuel plates and 5 coolant channels
! H2O coolant, Flow is calculated from input pressure drop
! All hot channel factors = 1.0
! No bypass flow, NCTYP=0
! 10 axial heat transfer nodes in the heated length of fuel plates
!  1   2   3   4   5   6   7   8   9  10  11  12  13                  Indices on Card 0200
   0   0   0   1   0   1   1   1   0   0   0   0   0                           Card(1)0200
   2   3 0.50       1.00        1.00        1.00           3                   Card(1)0300
! Using pressure driven mode
   1  20 1.00                                                                  Card(1)0301
   1   1   1                                                                   Card(1)0302
1.20        1.20                                                               Card(2)0303
30.0E-04    0.02955665  0.15        8.00        0.20        15.0E-03           Card(3)0304
30.0E-04    0.02955665  0.75        0.00        0.20        15.0E-03           Card(3)0304
30.0E-04    0.02955665  0.15        8.00        0.20        15.0E-03           Card(3)0304
! Use the code's built-in correlation for friction factor
0.00        0.00        0.00                                                   Card(1)0305
   5   3 0.00       0.75        0.50E-03    0.00        1.00E-03    100.00     Card(1)0306
6.00E-04    5.91133E-03 0.4060      0.20        0.20        3.00E-03           Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03           Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03           Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03           Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.20        0.20        3.00E-03           Card(5)0307
0.20        0.20        0.20        0.20                                       Card(1)0308
! Card 0308a not required
! Radial power peaking factor data by fuel plate for each subassembly. Input flow data by
! channel for each subassembly on Cards 0310 not required because WFGES(1) is non-zero
0.900       0.950       1.050       1.100                                      Card(2)0309
0.600       0.800       1.200       1.400                                      Card(2)0309
! DP0       DDP         DPMAX       POWER       TIN         PIN
0.10        0.04        0.10        1.00        45.0        1.40               Card(1)0500
!     CONV        ETA         DPWR        PWRM
 -50 0.0001     25.0        0.20        6.00                                   Card(1)0600
  11                                                                           Card(1)0700
0.00        0.80                                                               Card(11)0701
0.10        0.88                                                               Card(11)0701
0.20        0.96                                                               Card(11)0701
0.30        1.04                                                               Card(11)0701
0.40        1.12                                                               Card(11)0701
0.50        1.20                                                               Card(11)0701
0.60        1.12                                                               Card(11)0701
0.70        1.04                                                               Card(11)0701
0.80        0.96                                                               Card(11)0701
0.90        0.88                                                               Card(11)0701
1.00        0.80                                                               Card(11)0701
   0                                                                           Card(11)0702
```

## Table 8. Input Filename *input.pressuredriven* Used as Standard Problem 8 in PLTEMP/ANL Verification Script

```
 Test Problem: 2 subassemblies (of identical geometry) producing 1 MWt
! Each subassembly has 4 fuel plates and 5 coolant channels
! H2O coolant, Flow is calculated from input pressure drop
! All hot channel factors = 1.0
! No bypass flow, NCTYP=0
! 10 axial heat transfer nodes in the heated length of fuel plates
!  1   2   3   4   5   6   7   8   9  10  11  12  13                  Indices on Card 0200
   0   0   0   1   0   1   1   1   0   0   0   0   0                           Card(1)0200
   2   3 0.50       1.00        1.00        1.00           3                   Card(1)0300
! Using pressure driven mode
   1  20 1.00                                                                  Card(1)0301
   1   1   1                                                                   Card(1)0302
1.20        1.20                                                               Card(2)0303
30.0E-04    0.02955665  0.15        8.00        0.20        15.0E-03           Card(3)0304
30.0E-04    0.02955665  0.75        0.00        0.20        15.0E-03           Card(3)0304
30.0E-04    0.02955665  0.15        8.00        0.20        15.0E-03           Card(3)0304
! Use the code's built-in correlation for friction factor
0.00        0.00        0.00                                                   Card(1)0305
   5   3 0.00       0.75        0.50E-03    0.00        1.00E-03    100.00     Card(1)0306
6.00E-04    5.91133E-03 0.4060      0.20        0.20        3.00E-03           Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03           Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03           Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03           Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.20        0.20        3.00E-03           Card(5)0307
0.20        0.20        0.20        0.20                                       Card(1)0308
! Card 0308a not required
! Radial power peaking factor data by fuel plate for each subassembly. Input flow data by
! channel for each subassembly on Cards 0310 not required because WFGES(1) is non-zero
0.900       0.950       1.050       1.100                                      Card(2)0309
0.600       0.800       1.200       1.400                                      Card(2)0309
! DP0       DDP         DPMAX       POWER       TIN         PIN
0.10        0.04        0.10        1.00        45.0        1.40               Card(1)0500
  50 0.0001     25.0        0.50        1.00                                   Card(1)0600
  11                                                                           Card(1)0700
0.00        0.80                                                               Card(11)0701
0.10        0.88                                                               Card(11)0701
0.20        0.96                                                               Card(11)0701
0.30        1.04                                                               Card(11)0701
0.40        1.12                                                               Card(11)0701
0.50        1.20                                                               Card(11)0701
0.60        1.12                                                               Card(11)0701
0.70        1.04                                                               Card(11)0701
0.80        0.96                                                               Card(11)0701
0.90        0.88                                                               Card(11)0701
1.00        0.80                                                               Card(11)0701
   0                                                                           Card(11)0702
```

## 2. Verification of Exact and Broyden Solutions Available in PLTEMP/ANL Versions 3.0 and 2.21

(June 2006)

The verification script reported earlier (Quarterly Report for January-March 2006) was run for the version 3.0 code stored in directory */home/sol1a/kalimull/pltemp3.0/* (referred to as *users8* earlier). The verification script runs a specified executable for 8 standard problems and compares each problem's output with the stored output obtained by code version 2.14 for the problem. Tables 2 to 9 summarize the mismatch $T_{diff}$ of fuel maximum temperature, and the changes in calculated temperatures. The column 4 shows the biggest mismatch $T_{diff}$ in current code output, searched over all axial nodes of a fuel plate. The column 5 shows the similar mismatch in the old saved output of the standard problem. It is found that there is a marked improvement in code convergence as shown by a decrease in mismatch $T_{diff}$ of fuel maximum temperature (column 4 compared to column 5). For all standard problems, the current $T_{diff}$ is small and acceptable (maximum 0.5 C).

The maximum temperature difference shown in column 2 of each table is the biggest change in coolant, cladding and fuel temperatures, searched over all axial nodes of a fuel plate, between the current output and the saved output. The column 2 basically gives the error in the old calculation.

### 2.1. Comparison of PLTEMP/ANL Exact Solution with RELAP5 Code

Appendix A provides a comparison performed by N. A. Hanan who analyzed an event (blocked inner channel) in the Libyan research reactor IRT-1 using two codes, RELAP5/Mod3.2.1.2 and the exact solution obtained by PLTEMP/ANL V2.21. The results obtained by the two codes, shown in Appendix A, are in good agreement. This provides a verification of the exact solution method implemented in the PLTEMP/ANL code. The PLTEMP/ANL input data file for this analysis has been saved as standard problem 9 (filename: *input.blockage.hanan*) for code verification in the future. The directory */home/kalimull/sol1a/verif_problems* contains the input and output files of all standard problems.

### 2.2. Heat-up of Non-adjacent Coolant Channels Due to Heat Source in a Fuel Plate

Working with A. P. Olson to verify whether or not the heat transfer from a fuel plate to farther non-adjacent coolant channels in a fuel subassembly is modeled in the exact solution method implemented in PLTEMP/ANL code, the version 3.0 was run for a subassembly having 4 fuel plates and 5 coolant channels, producing 0.5 MWt power, with all power being generated in plate 1. The input data file given in Table 10 (standard problem 10) shows the radial power factors of the 4 fuel plates as 1.0, $10^{-8}$, $10^{-8}$, $10^{-8}$. The coolant inlet temperature is 25 C. Coolant channels 1 and 2 are in direct contact with fuel plate 1. Coolant channels 3, 4 and 5 are the non-adjacent channels. Of interest is the heat-up of the coolant channel 5 which is located the farthest from plate 1.

Since water thermal conductivity is very low compared to fuel and cladding conductivities, four cases were run using water conductivity artificially increased by a factor of 1.0, 10.0, 100.0, or

1000.0. To run these cases, a Fortran card (e.g., ZTHCL=ZTHCL*10.0) was put just before RETURN in the source code of the function routine ZTHCL which calculates the thermal conductivity of coolant, and four different executables of PLTEMP/ANL V3.0 were created using each of the four factors. The four outputs obtained by running these executables for the input data given in Table 10 are shown in Tables 11, 12, 13 and 14. The coolant channel outlet temperatures in Tables 11 to 14 are summarized below.

**Table 1. Heat Transfer to Farther Channels in Standard Problem 10 Using the Exact Solution by PLTEMP/ANL V3.0 Code**

| Case | Water Thermal Conductivity Multiplier | Coolant Temperature at Core Outlet, C | | | | | |
|---|---|---|---|---|---|---|---|
| | | Channel 1 | Channel 2 | Channel 3 | Channel 4 | Channel 5 | Mixed Mean |
| 1 | 1 | 63.53 | 109.06 | 40.21 | 26.66 | 25.14 | 62.85 |
| 2 | 10 | 62.84 | 92.62 | 67.74 | 51.28 | 41.05 | 62.86 |
| 3 | 100 | 61.84 | 87.85 | 82.86 | 79.41 | 77.43 | 62.86 |
| 4 | 1000 | 61.77 | 85.58 | 83.95 | 82.09 | 81.34 | 62.86 |

The coolant channel 5 (the farthest from fuel plate 1) does not heat much in case 1 that uses the actual water thermal conductivity. The temperature rise is only 0.136 C. Only channel 3 among the non-adjacent channels in this case has a considerable heat-up (temperature rise 15.214 C). But there is considerable temperature rise in coolant channel 5 in cases 2, 3 and 4, being 16.052, 52.427, and 56.340 C respectively. In case 4, the coolant channel 5 (outlet temperature 81.340 C) is almost as hot as channel 2 (outlet temperature 85.578 C) that is adjacent to fuel plate 1. This verifies that the exact solution method implemented in PLTEMP/ANL V3.0 code models the heat transfer from a fuel plate to farther non-adjacent coolant channels in a fuel subassembly.

## 2.3. Equilibration of Coolant Channel Temperatures in the Axial Direction

Working with A. P. Olson to verify whether or not the heat transfer between coolant channels in a subassembly is modeled in the exact solution method, the PLTEMP/ANL V3.0 code was run for a problem that models a subassembly consisting of four fuel plates, each 10 meters long, of which the fuel meat in the lower 2.5 meters of only two plates (plates 2 and 3) have heat source. The upper 7.5 meters of plates 2 and 3, and the whole length of plates 1 and 4 do not have any heat source. Table 15 shows the input data for the problem (standard problem 11). The coolant inlet temperature is 25 C. The whole 10-meter plate length is divided into 40 axial nodes to calculate the equilibration of the five coolant channel temperatures.

Table 16 shows the code output. At the top of the axial length having heat source, i.e., the axial node 11, the five coolant channel temperatures are 50.83, 78.98, 97.97, 97.97, 78.98, 50.83 C. These coolant channel temperatures are symmetric as expected. There is a wide temperature variation from channel 1 to channel 3, i.e., from 50.83 C to 97.97 C. At the outlet of the subassembly, the five channel temperatures are 72.76, 72.84, 72.90, 72.84, 72.76 C, all within a fraction of a degree of each other. This equilibration occurs over the upper 7.5 meters of unheated plate length. It verifies that the heat transfer between coolant channels in a subassembly is modeled in the exact solution method.

### 2.4. Verification of Implementation of Heat Source in Cladding and Coolant Channels

The exact method, implemented in PLTEMP/ANL version 3.0 for calculating temperature distribution in a fuel subassembly, allows for heat generation sources in the cladding on left and right sides of fuel plates, and for heat source in coolant channels. Working with E. E. Feldman, a verification of this implementation was performed by running the code and comparing the results for three problems (standard problems 12, 13 and 14) which are identical except for the differences in (i) cladding thickness and (ii) the fraction of reactor power produced in cladding, as discussed here. The cladding thickness expressed as a fraction of plate thickness is kept equal to the power produced in cladding expressed as a fraction of reactor power. This makes all three standard problems physically identical (from heat transfer point of view) since the input thermal conductivities of fuel and cladding are equal (10.0 W/m-K) in these problems. Hence all calculated temperatures (of coolant channels, cladding surfaces, fuel) are expected to be the same in these three problems.

The input data and outputs of problems 12, 13 and 14 are given in Tables 17 through 22. The standard problem 12 has a heat source of 350 MW/m$^3$ in fuel meat only (no heat source in cladding and coolant); the fuel meat is 2.0 mm thick and the cladding thickness is negligible (0.5x10$^{-6}$ mm). In problem 13, the cladding is 0.5 mm thick with a power density of 350 MW/m$^3$, producing 50% of reactor power. The fuel meat thickness is reduced from 2.0 mm to 1.0 mm, keeping the plate thickness fixed at 2.0 mm. In problem 14, the cladding is 0.9 mm thick with a power density of 350 MW/m$^3$, producing 90% of reactor power. The fuel meat thickness is further reduced to 0.2 mm, keeping the plate thickness fixed at 2.0 mm.

The outputs of these problems given in Tables 18, 20 and 22 show that all coolant channel temperatures, cladding surface temperatures, and fuel peak temperatures are equal, thus verifying the implementation of cladding heat source in PLTEMP/ANL version 3.0 code.

A verification of the implementation of heat source in coolant channels was performed by running the code for standard problem 15 in which 100% of reactor power is generated in coolant channels. There is no heat source in fuel and cladding in this problem. The input data for the problem (given in Table 23) shows that the radial power factors (on input card 0309) of all four fuel plates in a subassembly are 1.0, and the coolant flow rate (0.25 kg/sec) in the first or last channel is half of the flow rate (0.50 kg/sec) in an internal channel, i.e., channels 2, 3 or 4. These flow rates were selected to heat up each channel equally, based on the reason discussed here. It is because the volumetric heat source in coolant channels is found (in the implementation) from the input fraction QFCOOL (on card 0500) by depositing half of QFCOOL*(power in a fuel plate node) in the two coolant channels on the left and right of the plate. Thus the volumetric heat source in the first and last coolant channels (116.67 MW/m$^3$ as shown in Table 24) turns out to be half of the heat source (233.33 MW/m$^3$ as shown in Table 24) in coolant channels 2, 3 or 4.

The output of problem 15 given in Table 24 shows that, in any axial node, all 5 coolant channel temperatures are equal as expected. The nodal fuel and cladding temperatures are also equal to the coolant nodal temperature. This is because the fuel and cladding have no heat source, and are in steady-state equilibrium with the coolant. This verifies the implementation of heat source in coolant channels.

A further verification is that the mixed mean coolant temperature is the same (104.46 C) in these four standard problems (see Tables 18, 20, 22 and 24), irrespective of the heat source distribution in fuel, cladding and coolant channels. The mixed mean temperature is fixed because these four problems have the same reactor power and coolant flow rate.

### 2.5. Reversed Heat Flux – A Limitation of the Broyden Method

The purpose here is to indicate a limitation of the Broyden method for calculating temperature distribution. It occurs when the location of peak fuel temperature in meat thickness FUELX (i.e., fractional thickness measured from the left side) is 0.0 or 1.0, and the fuel temperature in meat thickness has a non-zero gradient at that location. The heat flux at that location is directed in the *reversed direction*, i.e., into the fuel plate rather out of the plate. To illustrate this, Table 25 shows the exact and Broyden solutions for fuel plate 1 in a subassembly of the University of Florida Training Reactor under nominal conditions, computed by PLTEMP/ANL version 3.0 code using a preliminary input data file provided by A. P. Olson. The two solutions agree for axial nodes 1 through 8, but do not agree for nodes 9 through 13 as discussed below.

In the exact solution, the location FUELX is 0.2964 in axial node 1 (compared to 0.2941 in the Broyden solution), and increases to 1.0 in axial node 9. It remains 1.0 in axial nodes 9 through 13 (shown in red in Table 25). This means that all the heat generated in fuel in these 5 nodes goes to the left side, but the fuel temperature gradient is not zero on the right fuel-cladding interface. Actually, the channel 2 coolant temperature has become higher than the adjacent cladding surface temperature in these nodes (see the exact solution in Table 25), and this causes a heat flux from the coolant channel 2 into the fuel plate, i.e., the reversed heat flux. This heat flux plus the heat generated in fuel meat comes out of the left cladding surface into coolant channel 1. Under this condition, the Broyden solution is found to be inconsistent, as discussed below.

In the Broyden solution for axial nodes 10 through 13 (italicized in Table 25), the channel 2 coolant temperature (e.g., 75.439 C in node 10) equals the adjacent cladding surface temperature which equals the fuel-cladding interface temperature on the right side of meat. If this solution were consistent, the fuel peak temperature in node 10 should be 75.439 C because the FUELX (obtained by the Broyden solution) is 1.0, implying that all the heat generated in fuel goes leftwards (with temperature falling as one moves leftwards in the meat). But the Broyden solution for peak fuel temperature in node 10 is 71.941 C, and not 75.439 C. This inconsistency is found in the nodes 10 through 13. This shows that the Broyden solution is inconsistent in the nodes 10 through 13. This inconsistency may also be seen by examining the heat flux at the right fuel-cladding interface. The Broyden is strictly applicable only to problems that have a temperature peak in the fuel meat interior – not on the boundaries.

### 2.6. List of Standard Problems

Eight standard problems were documented in the March 2006 Quarterly Report. An additional 7 standard problems were developed to verify the exact solution method and its new capabilities. These are listed below:

(9) Standard problem 9 (input data filename *input.blockage.hanan*): It was developed by N. A. Hanan for analyzing an event (blocked inner channel) in the Libyan research reactor.

(10) Standard problem 10 (input data filename *input.Stdproblem10*): It is problem modeling a four-fuel plate subassembly, producing 0.5 MWt power, with all power being generated in only one fuel plate, i.e., plate 1. It was developed to verify coolant temperature equilibration in the radial direction.

(11) Standard problem 11 (input data filename *input.Stdproblem11.channTemp.long*): It is a problem modeling a subassembly consisting of four plates, each 10 meters long, of which the fuel meat in the lower 2.5 meters of only plates 2 and 3 have heat source. It was developed to verify coolant temperature equilibration in the axial direction.

(12) Standard problem 12 (input data filename *input.Stdproblem12.HEATinCladandFuel*): This problem models 2 four-plate subassemblies with a total power of 1.0 MWt. None of this power is generated in the cladding, and the cladding thickness is practically zero ($0.5x10^{-6}$ mm) compared to the total fuel plate thickness (2.0 mm). The fuel plate (and coolant) temperature distribution in this problem must be identical to that in standard problems 13 and 14, since the input thermal conductivities of fuel and cladding are equal (10 W/m-K).

(13) Standard problem 13 (input data filename *input.Stdproblem13.HEATinCladandFuel*): This problem models 2 four-plate subassemblies with a total power of 1.0 MWt. A fraction 0.5 of this power is assumed to be generated in the cladding, and the two cladding thicknesses (each 0.5 mm) add up to 0.5 times the total fuel plate thickness (2 mm). The fuel plate (and coolant) temperature distribution in this problem must be identical to that in standard problems 12 and 14, since the input thermal conductivities of fuel and cladding are equal (10 W/m-K).

(14) Standard problem 14 (input data filename *input.Stdproblem14.HEATinCladandFuel*): This problem models 2 four-plate subassemblies with a total power of 1.0 MWt. A fraction 0.9 of this power is assumed to be generated in the cladding, and the two cladding thicknesses (each 0.9 mm) add up to 0.9 times the total fuel plate thickness (2 mm). The fuel plate (and coolant) temperature distribution in this problem must be identical to that in standard problems 12 and 13, since the input thermal conductivities of fuel and cladding are equal (10 W/m-K).

(15) Standard problem 15 (input data filename *input.Stdproblem15.HEATinCoolant*): This problem models 2 four-plate subassemblies with a total power of 1.0 MWt. All this power is assumed to be generated in coolant channels. There is no heat source in fuel and cladding in this problem. With the input radial power factors of all four plates equal to 1.0, and the coolant flow in the first and the last channel each being half of the flow in an internal channel, each channel must heat up identically.

## Table 2. Comparison of PLTEMP/ANL Versions 3.0 (users8) and 2.14 for Standard Problem 1

| Table Number | Max Temp Diff | Occurs in Axial Node | Max Tdiff Current Output | Max Tdiff Saved Output |
|---|---|---|---|---|
| 1 | 1.420 | 11 | 0.000 | 3.060 |
| 2 | 0.358 | 11 | 0.000 | 0.770 |
| 3 | 0.146 | 11 | 0.010 | 0.330 |
| 4 | 0.428 | 11 | 0.010 | 0.920 |
| 5 | 0.271 | 11 | 0.010 | 0.590 |
| 6 | 0.006 | 5 | 0.000 | 0.010 |

Note: Table number here simply counts the tables of steady-state temperatures printed for each fuel plate by PLTEMP/ANL. If results for the same plate is printed again in the code output, it is counted again.

## Table 3. Comparison of PLTEMP/ANL Versions 3.0 (users8) and 2.14 for Standard Problem 2

| Table Number | Max Temp Diff | Occurs in Axial Node | Max Tdiff Current Output | Max Tdiff Saved Output |
|---|---|---|---|---|
| 1 | 2.873 | 10 | 0.000 | 5.640 |
| 2 | 0.315 | 9 | 0.030 | 0.530 |
| 3 | 0.152 | 10 | 0.040 | 0.150 |
| 4 | 1.866 | 10 | 0.010 | 3.680 |
| 5 | 2.872 | 10 | 0.000 | 5.630 |
| 6 | 0.565 | 10 | 0.000 | 0.870 |
| 7 | 0.238 | 10 | 0.000 | 0.320 |
| 8 | 1.867 | 10 | 0.000 | 3.670 |
| 9 | 2.871 | 10 | 0.000 | 5.480 |
| 10 | 1.585 | 9 | 0.010 | 3.160 |
| 11 | 0.605 | 9 | 0.010 | 1.120 |
| 12 | 1.868 | 10 | 0.000 | 3.740 |
| 13 | 2.863 | 10 | 0.010 | 5.410 |
| 14 | 4.166 | 10 | 0.590 | 8.350 |
| 15 | 1.842 | 10 | 0.360 | 3.390 |
| 16 | 2.081 | 10 | 0.000 | 4.150 |
| 17 | 2.870 | 10 | 0.000 | 5.480 |
| 18 | 1.935 | 9 | 0.000 | 3.870 |
| 19 | 0.329 | 9 | 0.000 | 0.560 |
| 20 | 1.868 | 10 | 0.000 | 3.710 |
| 21 | 2.869 | 10 | 0.000 | 5.550 |
| 22 | 1.870 | 10 | 0.000 | 3.530 |
| 23 | 1.262 | 10 | 0.000 | 2.340 |
| 24 | 1.869 | 10 | 0.000 | 3.660 |
| 25 | 2.870 | 10 | 0.000 | 5.500 |
| 26 | 1.743 | 9 | 0.000 | 3.430 |
| 27 | 0.440 | 9 | 0.000 | 0.790 |
| 28 | 1.873 | 10 | 0.000 | 3.680 |
| 29 | 2.869 | 10 | 0.000 | 5.480 |
| 30 | 4.140 | 10 | 0.100 | 8.290 |
| 31 | 1.831 | 10 | 0.020 | 3.430 |
| 32 | 2.092 | 10 | 0.000 | 4.180 |
| 33 | 2.867 | 10 | 0.000 | 5.620 |
| 34 | 0.440 | 8 | 0.000 | 0.860 |
| 35 | 0.455 | 8 | 0.000 | 0.920 |
| 36 | 1.871 | 10 | 0.000 | 3.630 |
| 37 | 2.867 | 10 | 0.000 | 5.570 |
| 38 | 2.684 | 10 | 0.030 | 5.260 |
| 39 | 1.141 | 10 | 0.010 | 2.110 |
| 40 | 1.871 | 10 | 0.000 | 3.710 |
| 41 | 2.865 | 10 | 0.000 | 5.290 |
| 42 | 8.487 | 10 | 0.000 | 17.040 |
| 43 | 4.803 | 10 | 0.000 | 9.320 |
| 44 | 1.872 | 10 | 0.000 | 3.540 |
| 45 | 2.865 | 10 | 0.000 | 5.600 |
| 46 | 1.182 | 10 | 0.000 | 2.150 |
| 47 | 0.486 | 10 | 0.000 | 0.810 |
| 48 | 1.873 | 10 | 0.000 | 3.690 |

**Table 4. Comparison of PLTEMP/ANL Versions 3.0 (users8) and 2.14 for Standard Problem 3**

| Table Number | Max Temp Diff | Occurs in Axial Node | Max Tdiff Current Output | Max Tdiff Saved Output |
|---|---|---|---|---|
| 1 | 0.448 | 10 | 0.000 | 0.960 |
| 2 | 0.365 | 10 | 0.000 | 0.770 |
| 3 | 0.069 | 10 | 0.000 | 0.140 |
| 4 | 0.145 | 10 | 0.000 | 0.310 |
| 5 | 0.446 | 10 | 0.000 | 0.940 |
| 6 | 0.179 | 10 | 0.000 | 0.380 |
| 7 | 0.121 | 10 | 0.000 | 0.260 |
| 8 | 0.012 | 10 | 0.000 | 0.010 |

**Table 5. Comparison of PLTEMP/ANL Versions 3.0 (users8) and 2.14 for Standard Problem 4**

| Table Number | Max Temp Diff | Occurs in Axial Node | Max Tdiff Current Output | Max Tdiff Saved Output |
|---|---|---|---|---|
| 1 | 0.568 | 10 | 0.000 | 1.200 |
| 2 | 0.076 | 8 | 0.000 | 0.160 |
| 3 | 0.078 | 8 | 0.000 | 0.170 |
| 4 | 0.008 | 10 | 0.000 | 0.000 |
| 5 | 0.609 | 10 | 0.040 | 1.280 |
| 6 | 0.067 | 8 | 0.150 | 0.040 |
| 7 | 0.084 | 8 | 0.180 | 0.050 |
| 8 | 0.013 | 8 | 0.030 | 0.000 |
| 9 | 0.568 | 10 | 0.000 | 1.200 |
| 10 | 0.018 | 10 | 0.000 | 0.010 |
| 11 | 0.010 | 9 | 0.000 | 0.020 |
| 12 | 0.008 | 10 | 0.000 | 0.000 |
| 13 | 1.277 | 10 | 0.000 | 2.710 |
| 14 | 0.054 | 10 | 0.000 | 0.030 |
| 15 | 0.019 | 10 | 0.000 | 0.010 |
| 16 | 0.317 | 10 | 0.000 | 0.690 |

**Table 6. Comparison of PLTEMP/ANL Versions 3.0 (users8) and 2.14 for Standard Problem 5**

| Table Number | Max Temp Diff | Occurs in Axial Node | Max Tdiff Current Output | Max Tdiff Saved Output |
|---|---|---|---|---|
| 1 | 0.447 | 10 | 0.000 | 0.950 |
| 2 | 0.130 | 10 | 0.110 | 0.270 |
| 3 | 0.044 | 10 | 0.030 | 0.100 |
| 4 | 0.013 | 10 | 0.000 | 0.020 |
| 5 | 2.761 | 10 | 0.000 | 5.750 |
| 6 | 0.328 | 10 | 0.000 | 0.660 |
| 7 | 2.360 | 10 | 0.000 | 5.080 |
| 8 | 0.211 | 10 | 0.000 | 0.410 |
| 9 | 0.065 | 10 | 0.000 | 0.140 |
| 10 | 0.185 | 9 | 0.070 | 0.400 |
| 11 | 0.094 | 9 | 0.020 | 0.200 |
| 12 | 0.010 | 10 | 0.000 | 0.000 |
| 13 | 1.298 | 10 | 0.000 | 2.730 |
| 14 | 0.874 | 10 | 0.120 | 1.920 |
| 15 | 0.386 | 10 | 0.260 | 0.840 |
| 16 | 0.327 | 10 | 0.000 | 0.720 |
| 17 | 0.008 | 10 | 0.000 | 0.000 |
| 18 | 0.022 | 8 | 0.050 | 0.000 |
| 19 | 0.031 | 8 | 0.070 | 0.000 |
| 20 | 0.008 | 10 | 0.000 | 0.000 |
| 21 | 1.007 | 10 | 0.000 | 2.150 |
| 22 | 0.039 | 10 | 0.010 | 0.030 |
| 23 | 0.009 | 1 | 0.020 | 0.000 |
| 24 | 0.010 | 10 | 0.000 | 0.000 |
| 25 | 0.656 | 10 | 0.000 | 1.390 |
| 26 | 0.397 | 10 | 0.000 | 0.840 |
| 27 | 0.042 | 10 | 0.010 | 0.080 |
| 28 | 0.070 | 10 | 0.010 | 0.150 |
| 29 | 2.166 | 10 | 0.000 | 4.490 |
| 30 | 0.717 | 9 | 0.000 | 1.560 |
| 31 | 0.390 | 9 | 0.000 | 0.850 |
| 32 | 0.195 | 9 | 0.000 | 0.420 |
| 33 | 0.191 | 10 | 0.000 | 0.410 |
| 34 | 0.009 | 10 | 0.000 | 0.010 |
| 35 | 0.005 | 10 | 0.000 | 0.000 |
| 36 | 0.012 | 10 | 0.000 | 0.000 |
| 37 | 1.571 | 10 | 0.000 | 3.330 |
| 38 | 0.161 | 6 | 0.030 | 0.340 |
| 39 | 0.136 | 9 | 0.010 | 0.290 |
| 40 | 0.032 | 9 | 0.000 | 0.060 |
| 41 | 0.010 | 10 | 0.000 | 0.000 |
| 42 | 0.009 | 3 | 0.020 | 0.000 |
| 43 | 0.006 | 3 | 0.010 | 0.000 |
| 44 | 0.010 | 10 | 0.000 | 0.000 |
| 45 | 1.214 | 10 | 0.010 | 2.590 |
| 46 | 0.079 | 10 | 0.000 | 0.140 |
| 47 | 0.046 | 10 | 0.000 | 0.100 |
| 48 | 0.012 | 10 | 0.000 | 0.010 |
| 49 | 0.894 | 10 | 0.000 | 1.900 |
| 50 | 0.232 | 4 | 0.000 | 0.500 |
| 51 | 0.095 | 4 | 0.000 | 0.200 |
| 52 | 0.147 | 10 | 0.000 | 0.310 |
| 53 | 2.570 | 10 | 0.010 | 5.360 |
| 54 | 0.259 | 9 | 0.020 | 0.530 |
| 55 | 0.087 | 3 | 0.010 | 0.190 |
| 56 | 0.030 | 10 | 0.000 | 0.010 |
| 57 | 0.326 | 10 | 0.000 | 0.670 |
| 58 | 0.386 | 9 | 0.000 | 0.830 |
| 59 | 0.354 | 9 | 0.030 | 0.780 |
| 60 | 0.078 | 7 | 0.000 | 0.170 |
| 61 | 1.859 | 10 | 0.000 | 3.920 |
| 62 | 0.084 | 10 | 0.000 | 0.080 |
| 63 | 0.014 | 10 | 0.000 | 0.000 |
| 64 | 0.018 | 10 | 0.000 | 0.020 |
| 65 | 0.010 | 10 | 0.000 | 0.000 |
| 66 | 0.004 | 10 | 0.000 | 0.000 |
| 67 | 0.006 | 10 | 0.000 | 0.000 |
| 68 | 0.012 | 10 | 0.000 | 0.000 |
| 69 | 1.432 | 10 | 0.000 | 3.060 |
| 70 | 0.149 | 9 | 0.010 | 0.310 |
| 71 | 0.185 | 1 | 0.000 | 0.400 |
| 72 | 0.019 | 9 | 0.000 | 0.030 |
| 73 | 1.154 | 10 | 0.000 | 2.450 |

| | | | | |
|---|---|---|---|---|
| 74 | 0.052 | 10 | 0.000 | 0.050 |
| 75 | 0.202 | 10 | 0.000 | 0.420 |
| 76 | 0.369 | 10 | 0.000 | 0.790 |
| 77 | 3.016 | 10 | 0.000 | 6.280 |
| 78 | 0.161 | 10 | 0.100 | 0.110 |
| 79 | 4.425 | 10 | 0.030 | 9.640 |
| 80 | 0.157 | 10 | 0.050 | 0.060 |
| 81 | 0.479 | 10 | 0.000 | 1.040 |
| 82 | 0.130 | 10 | 0.000 | 0.260 |
| 83 | 0.351 | 10 | 0.000 | 0.780 |
| 84 | 0.035 | 4 | 0.000 | 0.080 |
| 85 | 2.160 | 10 | 0.030 | 4.560 |
| 86 | 0.361 | 10 | 0.020 | 0.680 |
| 87 | 0.388 | 10 | 0.020 | 0.860 |
| 88 | 0.171 | 9 | 0.000 | 0.360 |
| 89 | 0.086 | 10 | 0.000 | 0.190 |
| 90 | 0.011 | 10 | 0.000 | 0.010 |
| 91 | 0.007 | 10 | 0.000 | 0.010 |
| 92 | 0.014 | 10 | 0.000 | 0.000 |
| 93 | 1.658 | 10 | 0.000 | 3.540 |
| 94 | 0.436 | 10 | 0.000 | 0.890 |
| 95 | 0.043 | 10 | 0.000 | 0.100 |
| 96 | 0.045 | 10 | 0.000 | 0.090 |
| 97 | 1.447 | 10 | 0.000 | 3.060 |
| 98 | 0.060 | 10 | 0.020 | 0.030 |
| 99 | 0.019 | 10 | 0.020 | 0.000 |
| 100 | 0.627 | 10 | 0.010 | 1.340 |
| 101 | 3.459 | 10 | 0.110 | 7.190 |
| 102 | 0.365 | 10 | 0.500 | 0.660 |
| 103 | 0.243 | 1 | 0.520 | 0.340 |
| 104 | 0.174 | 10 | 0.040 | 0.350 |
| 105 | 0.656 | 10 | 0.000 | 1.420 |
| 106 | 0.031 | 10 | 0.010 | 0.030 |
| 107 | 0.012 | 10 | 0.000 | 0.010 |
| 108 | 0.020 | 10 | 0.000 | 0.000 |
| 109 | 2.478 | 10 | 0.000 | 5.260 |
| 110 | 0.371 | 10 | 0.000 | 0.780 |
| 111 | 2.424 | 10 | 0.000 | 5.350 |
| 112 | 0.131 | 4 | 0.000 | 0.290 |
| 113 | 0.194 | 10 | 0.000 | 0.430 |
| 114 | 0.014 | 10 | 0.010 | 0.000 |
| 115 | 0.009 | 10 | 0.010 | 0.000 |
| 116 | 0.016 | 10 | 0.020 | 0.000 |
| 117 | 1.898 | 10 | 0.000 | 4.050 |
| 118 | 0.256 | 10 | 0.000 | 0.480 |
| 119 | 0.036 | 10 | 0.000 | 0.070 |
| 120 | 0.170 | 10 | 0.000 | 0.380 |
| 121 | 1.767 | 10 | 0.400 | 3.730 |
| 122 | 0.085 | 10 | 0.060 | 0.000 |
| 123 | 0.164 | 1 | 0.340 | 0.030 |
| 124 | 0.924 | 10 | 0.120 | 1.990 |
| 125 | 3.919 | 10 | 0.000 | 8.140 |
| 126 | 0.594 | 10 | 0.000 | 1.150 |
| 127 | 0.303 | 10 | 0.000 | 0.600 |
| 128 | 0.178 | 10 | 0.000 | 0.390 |
| 129 | 0.851 | 10 | 0.000 | 1.840 |
| 130 | 0.041 | 10 | 0.010 | 0.040 |
| 131 | 0.031 | 6 | 0.000 | 0.050 |
| 132 | 0.021 | 10 | 0.000 | 0.040 |
| 133 | 2.827 | 10 | 0.000 | 5.960 |
| 134 | 0.141 | 10 | 0.000 | 0.040 |
| 135 | 0.163 | 10 | 0.000 | 0.360 |
| 136 | 0.026 | 10 | 0.000 | 0.010 |
| 137 | 0.321 | 10 | 0.000 | 0.710 |
| 138 | 0.048 | 9 | 0.000 | 0.100 |
| 139 | 0.332 | 9 | 0.000 | 0.750 |
| 140 | 0.019 | 10 | 0.000 | 0.000 |
| 141 | 2.164 | 10 | 0.000 | 4.600 |
| 142 | 0.421 | 10 | 0.000 | 0.890 |
| 143 | 0.243 | 10 | 0.000 | 0.500 |
| 144 | 0.024 | 10 | 0.000 | 0.010 |
| 145 | 2.123 | 10 | 0.000 | 4.500 |
| 146 | 0.095 | 10 | 0.010 | 0.070 |
| 147 | 0.050 | 10 | 0.010 | 0.020 |
| 148 | 1.281 | 10 | 0.000 | 2.750 |
| 149 | 4.394 | 10 | 0.000 | 9.120 |
| 150 | 0.858 | 10 | 0.030 | 1.740 |
| 151 | 0.071 | 10 | 0.010 | 0.030 |
| 152 | 0.041 | 10 | 0.000 | 0.030 |
| 153 | 1.064 | 10 | 0.010 | 2.290 |
| 154 | 0.050 | 10 | 0.020 | 0.040 |

| | | | | |
|---|---|---|---|---|
| 155 | 0.022 | 10 | 0.060 | 0.050 |
| 156 | 0.200 | 10 | 0.010 | 0.450 |
| 157 | 3.170 | 10 | 0.000 | 6.690 |
| 158 | 0.194 | 9 | 0.010 | 0.370 |
| 159 | 2.837 | 10 | 0.010 | 6.320 |
| 160 | 0.093 | 10 | 0.000 | 0.020 |
| 161 | 0.463 | 10 | 0.000 | 1.020 |
| 162 | 0.027 | 10 | 0.000 | 0.030 |
| 163 | 0.014 | 10 | 0.000 | 0.020 |
| 164 | 0.031 | 10 | 0.000 | 0.060 |
| 165 | 2.433 | 10 | 0.000 | 5.180 |
| 166 | 0.110 | 10 | 0.000 | 0.080 |
| 167 | 0.057 | 10 | 0.000 | 0.120 |
| 168 | 0.023 | 10 | 0.000 | 0.000 |
| 169 | 2.512 | 10 | 0.000 | 5.320 |
| 170 | 0.112 | 10 | 0.010 | 0.010 |
| 171 | 0.067 | 10 | 0.010 | 0.000 |
| 172 | 1.673 | 10 | 0.000 | 3.610 |
| 173 | 4.880 | 10 | 0.000 | 10.140 |
| 174 | 1.161 | 10 | 0.010 | 2.390 |
| 175 | 0.169 | 10 | 0.010 | 0.250 |
| 176 | 0.053 | 10 | 0.000 | 0.020 |
| 177 | 1.306 | 10 | 0.000 | 2.800 |
| 178 | 0.240 | 1 | 0.000 | 0.520 |
| 179 | 0.730 | 10 | 0.000 | 1.630 |
| 180 | 0.426 | 10 | 0.000 | 0.950 |
| 181 | 3.525 | 10 | 0.010 | 7.420 |
| 182 | 0.187 | 10 | 0.000 | 0.270 |
| 183 | 0.035 | 10 | 0.010 | 0.000 |
| 184 | 0.034 | 10 | 0.000 | 0.000 |
| 185 | 0.617 | 10 | 0.470 | 1.350 |
| 186 | 0.041 | 10 | 0.030 | 0.010 |
| 187 | 0.027 | 2 | 0.050 | 0.000 |
| 188 | 0.035 | 2 | 0.080 | 0.000 |
| 189 | 2.707 | 10 | 0.000 | 5.750 |
| 190 | 0.244 | 10 | 0.080 | 0.450 |
| 191 | 0.183 | 10 | 0.050 | 0.380 |
| 192 | 0.026 | 10 | 0.010 | 0.020 |
| 193 | 2.940 | 10 | 0.000 | 6.230 |
| 194 | 0.141 | 10 | 0.010 | 0.170 |
| 195 | 0.148 | 10 | 0.010 | 0.210 |
| 196 | 2.270 | 10 | 0.000 | 4.810 |
| 197 | 5.390 | 10 | 0.000 | 11.200 |
| 198 | 1.470 | 10 | 0.000 | 3.070 |
| 199 | 0.221 | 10 | 0.000 | 0.350 |
| 200 | 0.352 | 10 | 0.000 | 0.760 |
| 201 | 1.566 | 10 | 0.000 | 3.380 |
| 202 | 0.090 | 10 | 0.080 | 0.050 |
| 203 | 0.129 | 10 | 0.090 | 0.130 |
| 204 | 0.676 | 10 | 0.000 | 1.500 |
| 205 | 3.885 | 10 | 0.000 | 8.160 |
| 206 | 2.082 | 10 | 0.030 | 4.670 |
| 207 | 0.109 | 10 | 0.050 | 0.130 |
| 208 | 0.043 | 10 | 0.000 | 0.020 |
| 209 | 0.788 | 10 | 0.000 | 1.730 |
| 210 | 0.082 | 10 | 0.000 | 0.130 |
| 211 | 0.074 | 10 | 0.000 | 0.140 |
| 212 | 0.029 | 10 | 0.000 | 0.010 |
| 213 | 2.985 | 10 | 0.000 | 6.390 |
| 214 | 0.386 | 10 | 0.000 | 0.690 |
| 215 | 0.235 | 10 | 0.000 | 0.500 |
| 216 | 0.071 | 10 | 0.000 | 0.140 |
| 217 | 3.392 | 10 | 0.000 | 7.030 |
| 218 | 3.395 | 5 | 0.020 | 7.520 |
| 219 | 3.445 | 5 | 0.020 | 7.600 |
| 220 | 2.651 | 10 | 0.000 | 5.830 |
| 221 | 5.919 | 10 | 0.000 | 12.280 |
| 222 | 1.860 | 10 | 0.000 | 3.900 |
| 223 | 0.134 | 10 | 0.000 | 0.010 |
| 224 | 0.757 | 10 | 0.000 | 1.700 |
| 225 | 1.854 | 10 | 0.000 | 4.000 |
| 226 | 0.087 | 10 | 0.150 | 0.060 |
| 227 | 0.047 | 10 | 0.010 | 0.010 |
| 228 | 0.968 | 10 | 0.000 | 2.140 |
| 229 | 4.262 | 10 | 0.000 | 8.990 |
| 230 | 0.593 | 10 | 0.000 | 1.160 |
| 231 | 0.090 | 2 | 0.170 | 0.050 |
| 232 | 0.050 | 10 | 0.020 | 0.060 |
| 233 | 0.983 | 10 | 0.000 | 2.150 |
| 234 | 0.250 | 10 | 0.010 | 0.510 |
| 235 | 0.107 | 10 | 0.000 | 0.230 |

| | | | | |
|---|---|---|---|---|
| 236 | 0.078 | 10 | 0.000 | 0.160 |
| 237 | 3.269 | 10 | 0.000 | 6.980 |
| 238 | 0.163 | 10 | 0.000 | 0.320 |
| 239 | 0.121 | 7 | 0.000 | 0.240 |
| 240 | 0.037 | 10 | 0.000 | 0.020 |
| 241 | 3.949 | 10 | 0.000 | 8.520 |
| 242 | 0.257 | 10 | 0.000 | 0.340 |
| 243 | 0.126 | 10 | 0.000 | 0.050 |
| 244 | 3.158 | 10 | 0.000 | 6.720 |
| 245 | 6.477 | 10 | 0.000 | 13.410 |
| 246 | 2.242 | 10 | 0.050 | 4.840 |
| 247 | 0.145 | 10 | 0.030 | 0.210 |
| 248 | 1.331 | 10 | 0.000 | 2.940 |
| 249 | 2.192 | 10 | 0.060 | 4.680 |
| 250 | 0.129 | 10 | 0.520 | 0.380 |
| 251 | 0.059 | 10 | 0.010 | 0.020 |
| 252 | 1.401 | 10 | 0.000 | 3.060 |
| 253 | 4.650 | 10 | 0.000 | 9.810 |
| 254 | 0.824 | 10 | 0.000 | 1.680 |
| 255 | 0.065 | 10 | 0.000 | 0.040 |
| 256 | 0.058 | 10 | 0.000 | 0.070 |
| 257 | 1.192 | 10 | 0.000 | 2.610 |
| 258 | 0.440 | 10 | 0.000 | 0.920 |
| 259 | 0.181 | 10 | 0.000 | 0.340 |
| 260 | 0.270 | 10 | 0.000 | 0.620 |
| 261 | 3.574 | 10 | 0.000 | 7.630 |
| 262 | 0.190 | 10 | 0.060 | 0.090 |
| 263 | 0.050 | 9 | 0.020 | 0.050 |
| 264 | 0.064 | 9 | 0.000 | 0.110 |
| 265 | 4.700 | 10 | 0.000 | 9.850 |
| 266 | 0.249 | 10 | 0.000 | 0.030 |
| 267 | 0.146 | 10 | 0.010 | 0.000 |
| 268 | 3.671 | 10 | 0.000 | 7.830 |
| 269 | 7.050 | 10 | 0.000 | 14.530 |
| 270 | 4.963 | 10 | 0.000 | 11.100 |
| 271 | 1.989 | 10 | 0.000 | 4.190 |
| 272 | 2.194 | 10 | 0.000 | 4.920 |
| 273 | 2.509 | 10 | 0.000 | 5.410 |
| 274 | 0.358 | 10 | 0.000 | 0.670 |
| 275 | 0.144 | 10 | 0.000 | 0.200 |
| 276 | 1.718 | 10 | 0.000 | 3.710 |
| 277 | 5.054 | 10 | 0.000 | 10.640 |
| 278 | 1.183 | 10 | 0.000 | 2.500 |
| 279 | 0.096 | 10 | 0.000 | 0.010 |
| 280 | 0.274 | 10 | 0.000 | 0.510 |
| 281 | 1.424 | 10 | 0.000 | 3.120 |
| 282 | 0.073 | 10 | 0.000 | 0.060 |
| 283 | 0.037 | 10 | 0.000 | 0.010 |
| 284 | 0.498 | 10 | 0.000 | 1.140 |
| 285 | 3.883 | 10 | 0.000 | 8.290 |
| 286 | 0.237 | 10 | 0.040 | 0.360 |
| 287 | 0.052 | 10 | 0.060 | 0.010 |
| 288 | 0.045 | 10 | 0.010 | 0.010 |
| 289 | 5.225 | 10 | 0.000 | 10.990 |
| 290 | 0.298 | 10 | 0.010 | 0.140 |
| 291 | 0.202 | 9 | 0.000 | 0.370 |
| 292 | 4.232 | 10 | 0.000 | 9.060 |
| 293 | 7.658 | 10 | 0.000 | 15.850 |
| 294 | 3.078 | 10 | 0.040 | 6.580 |
| 295 | 2.183 | 10 | 0.010 | 4.570 |
| 296 | 3.022 | 10 | 0.020 | 6.600 |
| 297 | 2.877 | 10 | 0.030 | 6.280 |
| 298 | 0.643 | 10 | 0.000 | 1.320 |
| 299 | 0.101 | 10 | 0.020 | 0.080 |
| 300 | 2.047 | 10 | 0.000 | 4.440 |
| 301 | 5.473 | 10 | 0.000 | 11.520 |
| 302 | 1.422 | 10 | 0.010 | 3.040 |
| 303 | 0.134 | 1 | 0.000 | 0.270 |
| 304 | 0.135 | 10 | 0.000 | 0.230 |
| 305 | 1.677 | 10 | 0.000 | 3.670 |
| 306 | 0.085 | 10 | 0.010 | 0.010 |
| 307 | 0.049 | 10 | 0.010 | 0.030 |
| 308 | 0.843 | 10 | 0.000 | 1.860 |
| 309 | 4.201 | 10 | 0.000 | 8.950 |
| 310 | 0.424 | 10 | 0.010 | 0.790 |
| 311 | 0.160 | 10 | 0.000 | 0.290 |
| 312 | 0.050 | 10 | 0.000 | 0.030 |
| 313 | 5.802 | 10 | 0.000 | 12.200 |
| 314 | 0.328 | 10 | 0.000 | 0.080 |
| 315 | 0.611 | 10 | 0.000 | 1.080 |
| 316 | 4.949 | 10 | 0.000 | 10.650 |

| | | | | |
|---|---|---|---|---|
| 317 | 8.284 | 10 | 0.010 | 16.360 |
| 318 | 29.514 | 10 | 0.190 | 64.740 |
| 319 | 5.813 | 10 | 0.040 | 11.450 |
| 320 | 3.845 | 10 | 0.000 | 8.360 |
| 321 | 3.455 | 10 | 0.000 | 7.400 |
| 322 | 0.154 | 10 | 0.000 | 0.090 |
| 323 | 0.095 | 10 | 0.000 | 0.010 |
| 324 | 2.413 | 10 | 0.000 | 5.230 |
| 325 | 5.906 | 10 | 0.010 | 12.430 |
| 326 | 1.680 | 10 | 0.010 | 3.610 |
| 327 | 0.224 | 9 | 0.000 | 0.420 |
| 328 | 0.618 | 10 | 0.000 | 1.420 |
| 329 | 1.949 | 10 | 0.000 | 4.270 |
| 330 | 0.097 | 10 | 0.000 | 0.040 |
| 331 | 0.047 | 10 | 0.000 | 0.010 |
| 332 | 1.073 | 10 | 0.000 | 2.370 |
| 333 | 4.532 | 10 | 0.010 | 9.660 |
| 334 | 0.620 | 10 | 0.030 | 1.230 |
| 335 | 0.071 | 10 | 0.000 | 0.040 |
| 336 | 0.055 | 10 | 0.000 | 0.020 |
| 337 | 6.418 | 10 | 0.000 | 13.500 |
| 338 | 0.439 | 9 | 0.010 | 0.860 |
| 339 | 0.272 | 10 | 0.010 | 0.470 |
| 340 | 5.868 | 10 | 0.000 | 12.710 |
| 341 | 8.942 | 10 | 0.000 | 18.530 |
| 342 | 4.224 | 10 | 0.000 | 9.010 |
| 343 | 1.875 | 10 | 0.000 | 3.680 |
| 344 | 4.651 | 10 | 0.000 | 10.270 |
| 345 | 3.873 | 10 | 0.000 | 8.240 |
| 346 | 0.202 | 10 | 0.000 | 0.260 |
| 347 | 0.108 | 10 | 0.000 | 0.080 |
| 348 | 2.826 | 10 | 0.000 | 6.120 |
| 349 | 6.356 | 10 | 0.000 | 13.340 |
| 350 | 1.912 | 10 | 0.000 | 4.220 |
| 351 | 0.962 | 9 | 0.000 | 2.170 |
| 352 | 1.358 | 10 | 0.000 | 3.090 |
| 353 | 2.242 | 10 | 0.000 | 4.970 |
| 354 | 0.113 | 4 | 0.000 | 0.220 |
| 355 | 0.436 | 4 | 0.000 | 0.960 |
| 356 | 1.328 | 10 | 0.000 | 2.950 |
| 357 | 4.873 | 10 | 0.000 | 10.410 |
| 358 | 0.829 | 10 | 0.000 | 1.780 |
| 359 | 0.642 | 9 | 0.000 | 1.450 |
| 360 | 0.074 | 9 | 0.000 | 0.080 |

## Table 7. Comparison of PLTEMP/ANL Versions 3.0 (users8) and 2.14 for Standard Problem 6

| Table Number | Max Temp Diff | Occurs in Axial Node | Max Tdiff Current Output | Max Tdiff Saved Output |
|---|---|---|---|---|
| 1 | 1.988 | 10 | 0.000 | 4.060 |
| 2 | 0.463 | 10 | 0.000 | 0.940 |
| 3 | 0.308 | 10 | 0.000 | 0.610 |
| 4 | 1.353 | 10 | 0.000 | 2.810 |
| 5 | 3.535 | 10 | 0.000 | 7.320 |
| 6 | 1.328 | 10 | 0.140 | 2.640 |
| 7 | 0.957 | 10 | 0.190 | 1.960 |
| 8 | 0.772 | 10 | 0.000 | 1.600 |

## Table 8. Comparison of PLTEMP/ANL Versions 3.0 (users8) and 2.14 for Standard Problem 7

| Table Number | Max Temp Diff | Occurs in Axial Node | Max Tdiff Current Output | Max Tdiff Saved Output |
|---|---|---|---|---|
| 1 | 0.447 | 10 | 0.000 | 0.950 |
| 2 | 0.130 | 10 | 0.110 | 0.270 |
| 3 | 0.044 | 10 | 0.030 | 0.100 |
| 4 | 0.013 | 10 | 0.000 | 0.020 |
| 5 | 2.761 | 10 | 0.000 | 5.750 |
| 6 | 0.328 | 10 | 0.000 | 0.660 |
| 7 | 2.360 | 10 | 0.000 | 5.080 |
| 8 | 0.211 | 10 | 0.000 | 0.410 |
| 9 | 0.656 | 10 | 0.000 | 1.370 |
| 10 | 0.312 | 5 | 0.000 | 0.670 |
| 11 | 0.218 | 5 | 0.000 | 0.470 |
| 12 | 0.015 | 10 | 0.000 | 0.030 |
| 13 | 2.167 | 10 | 0.030 | 4.520 |
| 14 | 0.111 | 10 | 0.030 | 0.090 |
| 15 | 0.046 | 8 | 0.090 | 0.000 |
| 16 | 0.036 | 8 | 0.060 | 0.020 |
| 17 | 0.896 | 10 | 0.000 | 1.890 |
| 18 | 0.088 | 7 | 0.000 | 0.180 |
| 19 | 0.198 | 7 | 0.250 | 0.430 |
| 20 | 0.134 | 10 | 0.000 | 0.300 |
| 21 | 2.570 | 10 | 0.000 | 5.390 |
| 22 | 0.484 | 9 | 0.000 | 0.980 |
| 23 | 0.085 | 9 | 0.000 | 0.180 |
| 24 | 0.200 | 9 | 0.000 | 0.420 |
| 25 | 1.158 | 10 | 0.000 | 2.450 |
| 26 | 0.183 | 10 | 0.000 | 0.360 |
| 27 | 0.261 | 3 | 0.000 | 0.560 |
| 28 | 0.367 | 10 | 0.000 | 0.810 |
| 29 | 3.015 | 10 | 0.000 | 6.280 |
| 30 | 0.161 | 10 | 0.000 | 0.220 |
| 31 | 0.091 | 10 | 0.000 | 0.180 |
| 32 | 0.027 | 10 | 0.000 | 0.000 |
| 33 | 1.446 | 10 | 0.000 | 3.060 |
| 34 | 0.060 | 10 | 0.000 | 0.020 |
| 35 | 0.030 | 10 | 0.000 | 0.030 |
| 36 | 0.625 | 10 | 0.000 | 1.340 |
| 37 | 3.459 | 10 | 0.000 | 7.210 |
| 38 | 0.329 | 10 | 0.000 | 0.600 |
| 39 | 0.190 | 9 | 0.000 | 0.400 |
| 40 | 0.039 | 9 | 0.000 | 0.050 |
| 41 | 1.765 | 10 | 0.000 | 3.730 |
| 42 | 0.074 | 10 | 0.130 | 0.010 |
| 43 | 0.091 | 1 | 0.180 | 0.000 |
| 44 | 0.926 | 10 | 0.110 | 1.990 |
| 45 | 3.919 | 10 | 0.000 | 8.120 |
| 46 | 0.579 | 10 | 0.000 | 1.160 |
| 47 | 0.505 | 9 | 0.100 | 1.110 |
| 48 | 0.062 | 9 | 0.000 | 0.090 |
| 49 | 2.126 | 10 | 0.040 | 4.500 |
| 50 | 0.241 | 2 | 0.510 | 0.020 |
| 51 | 0.245 | 10 | 0.230 | 0.460 |
| 52 | 1.281 | 10 | 0.000 | 2.750 |
| 53 | 4.393 | 10 | 0.000 | 9.120 |
| 54 | 0.847 | 10 | 0.000 | 1.730 |
| 55 | 0.375 | 10 | 0.000 | 0.790 |
| 56 | 0.043 | 10 | 0.000 | 0.020 |
| 57 | 2.511 | 10 | 0.000 | 5.320 |
| 58 | 0.113 | 10 | 0.000 | 0.000 |
| 59 | 0.067 | 10 | 0.010 | 0.000 |
| 60 | 1.672 | 10 | 0.000 | 3.600 |
| 61 | 4.880 | 10 | 0.010 | 10.140 |
| 62 | 1.152 | 10 | 0.000 | 2.380 |
| 63 | 0.234 | 10 | 0.010 | 0.420 |
| 64 | 0.053 | 10 | 0.000 | 0.010 |
| 65 | 2.938 | 10 | 0.000 | 6.230 |
| 66 | 0.131 | 10 | 0.000 | 0.110 |
| 67 | 0.086 | 10 | 0.000 | 0.030 |
| 68 | 2.268 | 10 | 0.000 | 4.820 |
| 69 | 5.389 | 10 | 0.010 | 11.180 |
| 70 | 1.494 | 10 | 0.010 | 3.110 |
| 71 | 0.524 | 10 | 0.000 | 0.990 |
| 72 | 0.351 | 10 | 0.000 | 0.760 |
| 73 | 3.393 | 10 | 0.050 | 7.220 |

| | | | | |
|---|---|---|---|---|
| 74 | 0.207 | 10 | 0.060 | 0.240 |
| 75 | 0.870 | 10 | 0.070 | 1.780 |
| 76 | 2.693 | 10 | 0.000 | 5.700 |
| 77 | 5.924 | 10 | 0.000 | 12.280 |
| 78 | 1.852 | 10 | 0.000 | 3.900 |
| 79 | 0.126 | 10 | 0.000 | 0.010 |
| 80 | 0.765 | 10 | 0.000 | 1.700 |
| 81 | 3.946 | 10 | 0.000 | 8.520 |
| 82 | 0.214 | 10 | 0.000 | 0.190 |
| 83 | 0.127 | 10 | 0.000 | 0.040 |
| 84 | 3.157 | 10 | 0.000 | 6.720 |
| 85 | 6.476 | 10 | 0.000 | 13.410 |
| 86 | 2.246 | 10 | 0.000 | 4.840 |
| 87 | 0.146 | 10 | 0.000 | 0.130 |
| 88 | 1.329 | 10 | 0.000 | 2.930 |

## Table 9. Comparison of PLTEMP/ANL Versions 3.0 (users8) and 2.14 for Standard Problem 8

| Table Number | Max Temp Diff | Occurs in Axial Node | Max Tdiff Current Output | Max Tdiff Saved Output |
|---|---|---|---|---|
| 1 | 0.447 | 10 | 0.000 | 0.950 |
| 2 | 0.130 | 10 | 0.110 | 0.270 |
| 3 | 0.044 | 10 | 0.030 | 0.100 |
| 4 | 0.013 | 10 | 0.000 | 0.020 |
| 5 | 2.761 | 10 | 0.000 | 5.750 |
| 6 | 0.328 | 10 | 0.000 | 0.660 |
| 7 | 2.360 | 10 | 0.000 | 5.080 |
| 8 | 0.211 | 10 | 0.000 | 0.410 |

## Table 10. PLTEMP/ANL V3.0 Input Data for Standard Problem 10, a Subassembly With Heat Source in Fuel Plate 1 Only

```
 Standard Problem 10: 1 subassembly producing 0.5 MWt; All power in Plate 1
! The subassembly has 4 fuel plates and 5 coolant channels
! H2O coolant, Input coolant flow = 3.16 kg/s per coolant channel
! All hot channel factors = 1.0
! No bypass flow, NCTYP=0
! 10 axial heat transfer nodes in the heated length of fuel plates
!  1   2   3   4   5   6   7   8   9  10  11  12  13                   Indices on Card 0200
   0   0   0   1   0   1   1   1   0   0   0   0   0                            Card(1)0200
   1   3 0.00       1.00        1.00        1.00           3                    Card(1)0300
   1  20 1.00                                                                   Card(1)0301
   1   1   1                                                                    Card(1)0302
1.20        1.20                                                                Card(2)0303
30.0E-04    0.02955665  0.15        8.00        0.20        15.0E-03            Card(3)0304
30.0E-04    0.02955665  0.75        0.00        0.20        15.0E-03            Card(3)0304
30.0E-04    0.02955665  0.15        8.00        0.20        15.0E-03            Card(3)0304
! Use the code's biult-in correlation for friction factor
0.00        0.00        0.00                                                    Card(1)0305
   5   3 0.00       0.75        0.50E-03    0.00        1.00E-03    100.00      Card(1)0306
6.00E-04    5.91133E-03 0.4060      0.20        0.20        3.00E-03            Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03            Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03            Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03            Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.20        0.20        3.00E-03            Card(5)0307
0.20        0.20        0.20        0.20                                        Card(1)0308
! Card 0308a not required
! Radial power peaking factor data by fuel plate for each subassembly. Input flow data by
! channel for each subassembly on Cards 0310 not required because WFGES(1) is non-zero
1.000       1.0E-08     1.0E-08     1.0E-08                                     Card(2)0309
3.0         0.4E-01     0.4E-01     0.4E-01     0.4E-01                         Card(2)0310
! DP0       DDP         DPMAX       POWER       TIN         PIN
0.10        0.04        0.10        0.50        25.0        1.40                Card(1)0500
                                                                                Card(2)0500
  50 0.0001     25.0        0.50        1.00                                    Card(1)0600
  11                                                                            Card(1)0700
0.00        1.00                                                                Card(11)0701
0.10        1.00                                                                Card(11)0701
0.20        1.00                                                                Card(11)0701
0.30        1.00                                                                Card(11)0701
0.40        1.00                                                                Card(11)0701
0.50        1.00                                                                Card(11)0701
0.60        1.00                                                                Card(11)0701
0.70        1.00                                                                Card(11)0701
0.80        1.00                                                                Card(11)0701
0.90        1.00                                                                Card(11)0701
1.00        1.00                                                                Card(11)0701
  0                                                                             Card(11)0702
!234567890123456789012345678901234567890123456789012345678901234567890123456789
```

## Table 11. Exact Solution by PLTEMP/ANL V3.0 for a Subassembly With Heat Source in Fuel Plate 1 Only, Heat Transfer to Farther Channels Using Actual Thermal Conductivity of Water

| NODE | COOLANTl | CladSl | FUEL PEAK | CladSr | COOLANTr | HCOFl | HCOFr | ONBRl | ONBRr | ETA'l | ETA'r |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | (C) | (C) | (C) | (C) | (C) | W/C-m^2 | W/C-m^2 | [F Note 1] | | K-cm^3/J | K-cm^3/J |
| FUEL PLATE 1 (ExactSoln) | | | | | | | | | | | |
| | 25.000 | | | | 25.000 | | | | | | |
| 1 | 26.927 | 155.029 | 179.424 | 179.064 | 30.370 | 2.5072E+04 | 8.1729E+02 | 0.75 | 0.52 | 1.138E+02 | 4.003E+01 |
| 2 | 30.778 | 154.555 | 178.937 | 178.573 | 40.967 | 2.5939E+04 | 8.9123E+02 | 0.75 | 0.52 | 1.079E+02 | 3.359E+01 |
| 3 | 34.627 | 154.458 | 178.847 | 178.486 | 51.201 | 2.6799E+04 | 9.5865E+02 | 0.75 | 0.52 | 1.018E+02 | 2.787E+01 |
| 4 | 38.475 | 154.708 | 179.123 | 178.768 | 60.935 | 2.7646E+04 | 1.0181E+03 | 0.75 | 0.52 | 9.572E+01 | 2.265E+01 |
| 5 | 42.324 | 155.264 | 179.715 | 179.369 | 70.076 | 2.8477E+04 | 1.0713E+03 | 0.75 | 0.51 | 8.961E+01 | 1.773E+01 |
| 6 | 46.174 | 156.105 | 180.601 | 180.267 | 78.575 | 2.9290E+04 | 1.1152E+03 | 0.74 | 0.51 | 8.350E+01 | 1.304E+01 |
| 7 | 50.026 | 157.196 | 181.741 | 181.419 | 86.418 | 3.0082E+04 | 1.1523E+03 | 0.73 | 0.51 | 7.739E+01 | 8.477E+00 |
| 8 | 53.880 | 158.503 | 183.095 | 182.785 | 93.632 | 3.0851E+04 | 1.1849E+03 | 0.73 | 0.50 | 7.129E+01 | 3.989E+00 |
| 9 | 57.736 | 160.005 | 184.644 | 184.345 | 100.245 | 3.1597E+04 | 1.2119E+03 | 0.72 | 0.50 | 6.521E+01 | -4.227E-01 |
| 10 | 61.595 | 161.726 | 186.429 | 186.146 | 106.232 | 3.2322E+04 | 1.2119E+03 | 0.71 | 0.49 | 5.911E+01 | -4.786E+00 |
| | 63.525 | | | | 109.060 | | | | | | |
| FUEL PLATE 2 (ExactSoln) | | | | | | | | | | | |
| | 25.000 | | | | 25.000 | | | | | | |
| 1 | 30.370 | 27.764 | 27.758 | 27.731 | 25.093 | 8.0318E+02 | 7.9354E+02 | 99.99 | 27.60 | 9.999E+03 | 2.381E+03 |
| 2 | 40.967 | 33.388 | 33.371 | 33.291 | 25.457 | 8.2103E+02 | 7.9422E+02 | 99.99 | 9.15 | 9.999E+03 | 7.973E+02 |
| 3 | 51.201 | 39.210 | 39.182 | 39.051 | 26.170 | 8.5452E+02 | 7.9555E+02 | 99.99 | 5.42 | 9.999E+03 | 4.795E+02 |
| 4 | 60.935 | 45.407 | 45.367 | 45.184 | 27.218 | 9.2270E+02 | 7.9748E+02 | 99.99 | 3.79 | 9.999E+03 | 3.380E+02 |
| 5 | 70.076 | 51.614 | 51.563 | 51.331 | 28.583 | 9.8570E+02 | 7.9997E+02 | 99.99 | 2.91 | 9.999E+03 | 2.611E+02 |
| 6 | 78.575 | 57.662 | 57.601 | 57.324 | 30.231 | 1.0402E+03 | 8.0293E+02 | 99.99 | 2.38 | 9.999E+03 | 2.134E+02 |
| 7 | 86.418 | 63.472 | 63.402 | 63.083 | 32.126 | 1.0877E+03 | 8.0627E+02 | 99.99 | 2.02 | 9.999E+03 | 1.809E+02 |
| 8 | 93.632 | 69.026 | 68.948 | 68.593 | 34.229 | 1.1311E+03 | 8.0991E+02 | 99.99 | 1.77 | 9.999E+03 | 1.572E+02 |
| 9 | 100.245 | 73.994 | 73.909 | 73.517 | 36.517 | 1.1671E+03 | 8.2805E+02 | 99.99 | 1.59 | 9.999E+03 | 1.378E+02 |
| 10 | 106.232 | 78.208 | 78.117 | 77.696 | 38.960 | 1.1751E+03 | 8.5017E+02 | 99.99 | 1.47 | 9.999E+03 | 1.232E+02 |
| | 109.060 | | | | 40.214 | | | | | | |
| FUEL PLATE 3 (ExactSoln) | | | | | | | | | | | |
| | 25.000 | | | | 25.000 | | | | | | |
| 1 | 25.093 | 25.047 | 25.047 | 25.047 | 25.002 | 7.9354E+02 | 7.9337E+02 | 99.99 | ****** | 9.999E+03 | 1.390E+05 |
| 2 | 25.457 | 25.236 | 25.235 | 25.233 | 25.011 | 7.9422E+02 | 7.9338E+02 | 99.99 | 321.52 | 9.999E+03 | 2.834E+04 |
| 3 | 26.170 | 25.608 | 25.607 | 25.602 | 25.038 | 7.9555E+02 | 7.9344E+02 | 99.99 | 124.69 | 9.999E+03 | 1.116E+04 |
| 4 | 27.218 | 26.165 | 26.163 | 26.152 | 25.094 | 7.9748E+02 | 7.9354E+02 | 99.99 | 65.21 | 9.999E+03 | 5.937E+03 |
| 5 | 28.583 | 26.902 | 26.899 | 26.882 | 25.188 | 7.9997E+02 | 7.9372E+02 | 99.99 | 39.99 | 9.999E+03 | 3.704E+03 |
| 6 | 30.231 | 27.809 | 27.803 | 27.778 | 25.328 | 8.0293E+02 | 7.9398E+02 | 99.99 | 27.13 | 9.999E+03 | 2.554E+03 |
| 7 | 32.126 | 28.868 | 28.861 | 28.827 | 25.521 | 8.0627E+02 | 7.9434E+02 | 99.99 | 19.72 | 9.999E+03 | 1.887E+03 |
| 8 | 34.229 | 30.066 | 30.056 | 30.013 | 25.771 | 8.0991E+02 | 7.9481E+02 | 99.99 | 15.07 | 9.999E+03 | 1.465E+03 |
| 9 | 36.517 | 31.392 | 31.380 | 31.327 | 26.082 | 8.1377E+02 | 7.9539E+02 | 99.99 | 11.96 | 9.999E+03 | 1.179E+03 |
| 10 | 38.960 | 32.831 | 32.817 | 32.753 | 26.457 | 8.1780E+02 | 7.9608E+02 | 99.99 | 9.77 | 9.999E+03 | 9.764E+02 |
| | 40.214 | | | | 26.661 | | | | | | |
| FUEL PLATE 4 (ExactSoln) | | | | | | | | | | | |
| | 25.000 | | | | 25.000 | | | | | | |
| 1 | 25.002 | 25.001 | 25.001 | 25.001 | 25.000 | 7.9337E+02 | 6.6514E+02 | 99.99 | ****** | 9.999E+03 | 8.631E+06 |
| 2 | 25.011 | 25.006 | 25.006 | 25.006 | 25.000 | 7.9338E+02 | 6.6516E+02 | 99.99 | ****** | 9.999E+03 | 1.291E+06 |
| 3 | 25.038 | 25.021 | 25.021 | 25.021 | 25.001 | 7.9344E+02 | 6.6519E+02 | 99.99 | ****** | 9.999E+03 | 3.725E+05 |
| 4 | 25.094 | 25.053 | 25.053 | 25.052 | 25.003 | 7.9354E+02 | 6.6528E+02 | 99.99 | ****** | 9.999E+03 | 1.524E+05 |
| 5 | 25.188 | 25.106 | 25.106 | 25.105 | 25.007 | 7.9372E+02 | 6.6541E+02 | 99.99 | 711.57 | 9.999E+03 | 7.683E+04 |
| 6 | 25.328 | 25.186 | 25.186 | 25.185 | 25.015 | 7.9398E+02 | 6.6564E+02 | 99.99 | 405.52 | 9.999E+03 | 4.435E+04 |
| 7 | 25.521 | 25.297 | 25.297 | 25.295 | 25.029 | 7.9434E+02 | 6.6595E+02 | 99.99 | 254.03 | 9.999E+03 | 2.814E+04 |
| 8 | 25.771 | 25.443 | 25.442 | 25.439 | 25.048 | 7.9481E+02 | 6.6639E+02 | 99.99 | 170.61 | 9.999E+03 | 1.915E+04 |
| 9 | 26.082 | 25.626 | 25.625 | 25.620 | 25.076 | 7.9539E+02 | 6.6695E+02 | 99.99 | 120.84 | 9.999E+03 | 1.374E+04 |
| 10 | 26.457 | 25.848 | 25.847 | 25.841 | 25.114 | 7.9608E+02 | 6.6766E+02 | 99.99 | 89.23 | 9.999E+03 | 1.028E+04 |
| | 26.661 | | | | 25.136 | | | | | | |

[1] The ONB ratio is here defined as (Tonb - Tinlet)/(Tsurf - Tinlet). If the heat flux is negative (the coolant is hotter than the adjacent cladding surface), then the ONB ratio is arbitrarily set to 99.99 .

## Table 12. Exact Solution by PLTEMP/ANL V3.0 for a Subassembly With Heat Source in Fuel Plate 1 Only, Heat Transfer to Farther Channels With Water Thermal Conductivity Multiplied by 10

| NODE | COOLANTl | CladSl | FUEL PEAK | CladSr | COOLANTr | HCOFl | HCOFr | ONBRl | ONBRr | ETA'l | ETA'r |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | (C) | (C) | (C) | (C) | (C) | W/C-m^2 | W/C-m^2 | [F Note 1] | | K-cm^3/J | K-cm^3/J |
| FUEL PLATE 1 (ExactSoln) | | | | | | | | | | | |
| | 25.000 | | | | 25.000 | | | | | | |
| 1 | 26.811 | 54.827 | 76.885 | 75.863 | 37.297 | 1.0776E+05 | 8.1507E+03 | 3.23 | 1.62 | 1.213E+02 | 1.393E+01 |
| 2 | 30.491 | 58.281 | 81.515 | 80.844 | 55.163 | 1.1217E+05 | 8.4188E+03 | 2.91 | 1.45 | 1.116E+02 | 1.445E+01 |
| 3 | 34.252 | 61.346 | 85.076 | 84.542 | 63.973 | 1.1655E+05 | 8.5308E+03 | 2.67 | 1.35 | 1.041E+02 | 1.427E+01 |
| 4 | 38.046 | 64.316 | 88.276 | 87.804 | 69.569 | 1.2092E+05 | 8.5953E+03 | 2.47 | 1.28 | 9.751E+01 | 1.347E+01 |
| 5 | 41.855 | 67.280 | 91.359 | 90.918 | 73.896 | 1.2532E+05 | 8.6415E+03 | 2.29 | 1.21 | 9.120E+01 | 1.229E+01 |
| 6 | 45.671 | 70.293 | 94.436 | 94.011 | 77.657 | 1.2961E+05 | 8.6792E+03 | 2.14 | 1.16 | 8.504E+01 | 1.087E+01 |
| 7 | 49.488 | 73.356 | 97.533 | 97.117 | 81.143 | 1.3383E+05 | 8.7121E+03 | 2.01 | 1.11 | 7.895E+01 | 9.330E+00 |
| 8 | 53.306 | 76.469 | 100.662 | 100.251 | 84.488 | 1.3796E+05 | 8.7419E+03 | 1.89 | 1.06 | 7.291E+01 | 7.718E+00 |
| 9 | 57.122 | 79.629 | 103.829 | 103.419 | 87.760 | 1.4200E+05 | 8.7692E+03 | 1.78 | 1.02 | 6.689E+01 | 6.072E+00 |
| 10 | 60.935 | 82.832 | 107.031 | 106.621 | 91.000 | 1.4595E+05 | 8.7945E+03 | 1.68 | 0.98 | 6.090E+01 | 4.413E+00 |
| | 62.841 | | | | 92.615 | | | | | | |
| FUEL PLATE 2 (ExactSoln) | | | | | | | | | | | |
| | 25.000 | | | | 25.000 | | | | | | |
| 1 | 37.297 | 32.319 | 32.206 | 31.688 | 26.592 | 8.1507E+03 | 7.9633E+03 | 99.99 | 11.60 | 9.999E+03 | 1.204E+02 |
| 2 | 55.163 | 44.257 | 44.002 | 42.829 | 31.424 | 8.4188E+03 | 8.0504E+03 | 99.99 | 4.43 | 9.999E+03 | 4.968E+01 |
| 3 | 63.973 | 51.901 | 51.615 | 50.299 | 37.674 | 8.5308E+03 | 8.1569E+03 | 99.99 | 3.13 | 9.999E+03 | 4.024E+01 |
| 4 | 69.569 | 57.473 | 57.184 | 55.855 | 43.247 | 8.5953E+03 | 8.2461E+03 | 99.99 | 2.57 | 9.999E+03 | 3.627E+01 |
| 5 | 73.896 | 61.989 | 61.703 | 60.388 | 48.018 | 8.6415E+03 | 8.3182E+03 | 99.99 | 2.24 | 9.999E+03 | 3.355E+01 |
| 6 | 77.657 | 65.929 | 65.646 | 64.346 | 52.196 | 8.6792E+03 | 8.3780E+03 | 99.99 | 2.01 | 9.999E+03 | 3.117E+01 |
| 7 | 81.143 | 69.541 | 69.260 | 67.969 | 55.978 | 8.7121E+03 | 8.4297E+03 | 99.99 | 1.84 | 9.999E+03 | 2.888E+01 |
| 8 | 84.488 | 72.961 | 72.681 | 71.393 | 59.504 | 8.7419E+03 | 8.4756E+03 | 99.99 | 1.71 | 9.999E+03 | 2.663E+01 |
| 9 | 87.760 | 76.268 | 75.988 | 74.700 | 62.868 | 8.7692E+03 | 8.5175E+03 | 99.99 | 1.59 | 9.999E+03 | 2.440E+01 |
| 10 | 91.000 | 79.511 | 79.230 | 77.939 | 66.131 | 8.7945E+03 | 8.5563E+03 | 99.99 | 1.50 | 9.999E+03 | 2.218E+01 |
| | 92.615 | | | | 67.744 | | | | | | |
| FUEL PLATE 3 (ExactSoln) | | | | | | | | | | | |
| | 25.000 | | | | 25.000 | | | | | | |
| 1 | 26.592 | 25.942 | 25.928 | 25.861 | 25.209 | 7.9633E+03 | 7.9376E+03 | 99.99 | 87.98 | 9.999E+03 | 9.608E+02 |
| 2 | 31.424 | 28.968 | 28.913 | 28.660 | 26.175 | 8.0504E+03 | 7.9556E+03 | 99.99 | 20.97 | 9.999E+03 | 2.485E+02 |
| 3 | 37.674 | 33.267 | 33.167 | 32.707 | 28.210 | 8.1569E+03 | 7.9929E+03 | 99.99 | 10.05 | 9.999E+03 | 1.329E+02 |
| 4 | 43.247 | 37.562 | 37.432 | 36.833 | 31.005 | 8.2461E+03 | 8.0430E+03 | 99.99 | 6.58 | 9.999E+03 | 9.791E+01 |
| 5 | 48.018 | 41.571 | 41.422 | 40.736 | 34.113 | 8.3182E+03 | 8.0971E+03 | 99.99 | 4.96 | 9.999E+03 | 8.171E+01 |
| 6 | 52.196 | 45.292 | 45.132 | 44.392 | 37.296 | 8.3780E+03 | 8.1507E+03 | 99.99 | 4.03 | 9.999E+03 | 7.208E+01 |
| 7 | 55.978 | 48.791 | 48.623 | 47.848 | 40.462 | 8.4297E+03 | 8.2022E+03 | 99.99 | 3.42 | 9.999E+03 | 6.532E+01 |
| 8 | 59.504 | 52.132 | 51.959 | 51.160 | 43.588 | 8.4756E+03 | 8.2514E+03 | 99.99 | 2.99 | 9.999E+03 | 5.999E+01 |
| 9 | 62.868 | 55.369 | 55.192 | 54.376 | 46.679 | 8.5175E+03 | 8.2983E+03 | 99.99 | 2.67 | 9.999E+03 | 5.545E+01 |
| 10 | 66.131 | 58.541 | 58.361 | 57.531 | 49.747 | 8.5563E+03 | 8.3433E+03 | 99.99 | 2.41 | 9.999E+03 | 5.137E+01 |
| | 67.744 | | | | 51.277 | | | | | | |
| FUEL PLATE 4 (ExactSoln) | | | | | | | | | | | |
| | 25.000 | | | | 25.000 | | | | | | |
| 1 | 25.209 | 25.140 | 25.139 | 25.132 | 25.024 | 7.9376E+03 | 5.0537E+03 | 99.99 | 569.10 | 9.999E+03 | 9.191E+03 |
| 2 | 26.175 | 25.806 | 25.798 | 25.761 | 25.181 | 7.9556E+03 | 5.0556E+03 | 99.99 | 99.25 | 9.999E+03 | 1.698E+03 |
| 3 | 28.210 | 27.264 | 27.243 | 27.146 | 25.653 | 7.9929E+03 | 5.0612E+03 | 99.99 | 35.41 | 9.999E+03 | 6.545E+02 |
| 4 | 31.005 | 29.374 | 29.337 | 29.169 | 26.583 | 8.0430E+03 | 5.0722E+03 | 99.99 | 18.32 | 9.999E+03 | 3.724E+02 |
| 5 | 34.113 | 31.861 | 31.810 | 31.577 | 27.994 | 8.0971E+03 | 5.0887E+03 | 99.99 | 11.66 | 9.999E+03 | 2.627E+02 |
| 6 | 37.296 | 34.550 | 34.488 | 34.201 | 29.821 | 8.1507E+03 | 5.1097E+03 | 99.99 | 8.36 | 9.999E+03 | 2.086E+02 |
| 7 | 40.462 | 37.348 | 37.277 | 36.951 | 31.975 | 8.2022E+03 | 5.1339E+03 | 99.99 | 6.45 | 9.999E+03 | 1.772E+02 |
| 8 | 43.588 | 40.210 | 40.133 | 39.777 | 34.376 | 8.2514E+03 | 5.1604E+03 | 99.99 | 5.22 | 9.999E+03 | 1.566E+02 |
| 9 | 46.679 | 43.116 | 43.034 | 42.656 | 36.957 | 8.2983E+03 | 5.1881E+03 | 99.99 | 4.37 | 9.999E+03 | 1.418E+02 |
| 10 | 49.747 | 46.054 | 45.969 | 45.575 | 39.668 | 8.3433E+03 | 5.2164E+03 | 99.99 | 3.75 | 9.999E+03 | 1.302E+02 |
| | 51.277 | | | | 41.052 | | | | | | |

[1] The ONB ratio is here defined as (Tonb - Tinlet)/(Tsurf - Tinlet). If the heat flux is negative (the coolant is hotter than the adjacent cladding surface), then the ONB ratio is arbitrarily set to 99.99 .

## Table 13. Exact Solution by PLTEMP/ANL V3.0 for a Subassembly With Heat Source in Fuel Plate 1 Only, Heat Transfer to Farther Channels With Water Thermal Conductivity Multiplied by 100

| NODE | COOLANTl | CladSl | FUEL PEAK | CladSr | COOLANTr | HCOFl | HCOFr | ONBRl | ONBRr | ETA'l | ETA'r |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | (C) | (C) | (C) | (C) | (C) | W/C-m^2 | W/C-m^2 | [F Note 1] | | K-cm^3/J | K-cm^3/J |
| FUEL PLATE 1 (ExactSoln) | | | | | | | | | | | |
| | 25.000 | | | | 25.000 | | | | | | |
| 1 | 26.634 | 32.419 | 51.114 | 48.863 | 41.446 | 4.7084E+05 | 8.2179E+04 | 12.87 | 3.56 | 1.348E+02 | 6.704E+00 |
| 2 | 30.116 | 36.390 | 59.209 | 58.418 | 55.443 | 4.9135E+05 | 8.4225E+04 | 8.49 | 2.44 | 1.134E+02 | 1.238E+01 |
| 3 | 33.785 | 39.721 | 62.001 | 61.050 | 57.553 | 5.1178E+05 | 8.4504E+04 | 6.56 | 2.28 | 1.090E+02 | 1.000E+01 |
| 4 | 37.465 | 43.296 | 66.389 | 65.678 | 63.004 | 5.3254E+05 | 8.5191E+04 | 5.29 | 2.00 | 1.007E+02 | 1.129E+01 |
| 5 | 41.185 | 46.802 | 69.920 | 69.217 | 66.580 | 5.5320E+05 | 8.5615E+04 | 4.44 | 1.84 | 9.459E+01 | 1.028E+01 |
| 6 | 44.919 | 50.380 | 73.810 | 73.195 | 70.872 | 5.7376E+05 | 8.6095E+04 | 3.82 | 1.68 | 8.782E+01 | 1.010E+01 |
| 7 | 48.669 | 53.953 | 77.453 | 76.857 | 74.610 | 5.9405E+05 | 8.6489E+04 | 3.35 | 1.56 | 8.165E+01 | 9.043E+00 |
| 8 | 52.427 | 57.558 | 81.192 | 80.632 | 78.522 | 6.1402E+05 | 8.6876E+04 | 2.98 | 1.45 | 7.537E+01 | 8.088E+00 |
| 9 | 56.192 | 61.170 | 84.852 | 84.306 | 82.250 | 6.3362E+05 | 8.7222E+04 | 2.68 | 1.36 | 6.927E+01 | 6.807E+00 |
| 10 | 59.959 | 64.798 | 88.541 | 88.011 | 86.019 | 6.5286E+05 | 8.7548E+04 | 2.44 | 1.28 | 6.316E+01 | 5.483E+00 |
| | 61.843 | | | | 87.845 | | | | | | |
| FUEL PLATE 2 (ExactSoln) | | | | | | | | | | | |
| | 25.000 | | | | 25.000 | | | | | | |
| 1 | 41.446 | 38.487 | 37.811 | 34.704 | 31.686 | 8.2179E+04 | 8.0550E+04 | 99.99 | 8.39 | 9.999E+03 | 1.869E+01 |
| 2 | 55.443 | 51.819 | 50.971 | 47.070 | 43.370 | 8.4225E+04 | 8.2480E+04 | 99.99 | 3.72 | 9.999E+03 | 1.233E+01 |
| 3 | 57.553 | 55.260 | 54.722 | 52.247 | 49.927 | 8.4504E+04 | 8.3459E+04 | 99.99 | 2.96 | 9.999E+03 | 1.716E+01 |
| 4 | 63.004 | 60.564 | 59.987 | 57.331 | 54.861 | 8.5191E+04 | 8.4147E+04 | 99.99 | 2.50 | 9.999E+03 | 1.441E+01 |
| 5 | 66.580 | 64.644 | 64.184 | 62.067 | 60.113 | 8.5615E+04 | 8.4833E+04 | 99.99 | 2.17 | 9.999E+03 | 1.595E+01 |
| 6 | 70.872 | 68.967 | 68.512 | 66.417 | 64.497 | 8.6095E+04 | 8.5371E+04 | 99.99 | 1.94 | 9.999E+03 | 1.433E+01 |
| 7 | 74.610 | 72.915 | 72.508 | 70.635 | 68.928 | 8.6489E+04 | 8.5881E+04 | 99.99 | 1.75 | 9.999E+03 | 1.401E+01 |
| 8 | 78.522 | 76.873 | 76.475 | 74.644 | 72.984 | 8.6876E+04 | 8.6320E+04 | 99.99 | 1.61 | 9.999E+03 | 1.244E+01 |
| 9 | 82.250 | 80.694 | 80.318 | 78.584 | 77.020 | 8.7222E+04 | 8.6730E+04 | 99.99 | 1.49 | 9.999E+03 | 1.115E+01 |
| 10 | 86.019 | 84.496 | 84.126 | 82.422 | 80.892 | 8.7548E+04 | 8.7098E+04 | 99.99 | 1.39 | 9.999E+03 | 9.400E+00 |
| | 87.845 | | | | 82.860 | | | | | | |
| FUEL PLATE 3 (ExactSoln) | | | | | | | | | | | |
| | 25.000 | | | | 25.000 | | | | | | |
| 1 | 31.686 | 30.513 | 30.251 | 29.044 | 27.861 | 8.0550E+04 | 7.9866E+04 | 99.99 | 19.54 | 9.999E+03 | 5.082E+01 |
| 2 | 43.370 | 41.019 | 40.481 | 38.003 | 35.617 | 8.2480E+04 | 8.1226E+04 | 99.99 | 6.21 | 9.999E+03 | 2.208E+01 |
| 3 | 49.927 | 48.023 | 47.581 | 45.551 | 43.625 | 8.3459E+04 | 8.2520E+04 | 99.99 | 3.90 | 9.999E+03 | 2.357E+01 |
| 4 | 54.861 | 53.287 | 52.919 | 51.227 | 49.639 | 8.4147E+04 | 8.3418E+04 | 99.99 | 3.04 | 9.999E+03 | 2.524E+01 |
| 5 | 60.113 | 58.655 | 58.311 | 56.729 | 55.259 | 8.4833E+04 | 8.4200E+04 | 99.99 | 2.51 | 9.999E+03 | 2.398E+01 |
| 6 | 64.497 | 63.233 | 62.934 | 61.555 | 60.284 | 8.5371E+04 | 8.4855E+04 | 99.99 | 2.17 | 9.999E+03 | 2.440E+01 |
| 7 | 68.928 | 67.722 | 67.435 | 66.112 | 64.900 | 8.5881E+04 | 8.5419E+04 | 99.99 | 1.93 | 9.999E+03 | 2.244E+01 |
| 8 | 72.984 | 71.878 | 71.613 | 70.393 | 69.282 | 8.6320E+04 | 8.5921E+04 | 99.99 | 1.74 | 9.999E+03 | 2.126E+01 |
| 9 | 77.020 | 75.948 | 75.689 | 74.501 | 73.425 | 8.6730E+04 | 8.6366E+04 | 99.99 | 1.60 | 9.999E+03 | 1.885E+01 |
| 10 | 80.892 | 79.868 | 79.621 | 78.482 | 77.455 | 8.7098E+04 | 8.6773E+04 | 99.99 | 1.48 | 9.999E+03 | 1.664E+01 |
| | 82.860 | | | | 79.411 | | | | | | |
| FUEL PLATE 4 (ExactSoln) | | | | | | | | | | | |
| | 25.000 | | | | 25.000 | | | | | | |
| 1 | 27.861 | 27.475 | 27.390 | 26.996 | 26.387 | 7.9866E+04 | 5.0699E+04 | 99.99 | 38.71 | 9.999E+03 | 1.589E+02 |
| 2 | 35.617 | 34.571 | 34.335 | 33.249 | 31.594 | 8.1226E+04 | 5.1297E+04 | 99.99 | 9.55 | 9.999E+03 | 5.357E+01 |
| 3 | 43.625 | 42.540 | 42.292 | 41.148 | 39.431 | 8.2520E+04 | 5.2139E+04 | 99.99 | 4.89 | 9.999E+03 | 4.498E+01 |
| 4 | 49.639 | 48.826 | 48.638 | 47.772 | 46.490 | 8.3418E+04 | 5.2839E+04 | 99.99 | 3.44 | 9.999E+03 | 5.244E+01 |
| 5 | 55.259 | 54.511 | 54.336 | 53.531 | 52.351 | 8.4200E+04 | 5.3378E+04 | 99.99 | 2.74 | 9.999E+03 | 5.020E+01 |
| 6 | 60.284 | 59.620 | 59.463 | 58.743 | 57.696 | 8.4855E+04 | 5.3838E+04 | 99.99 | 2.31 | 9.999E+03 | 4.976E+01 |
| 7 | 64.900 | 64.294 | 64.150 | 63.489 | 62.534 | 8.5419E+04 | 5.4227E+04 | 99.99 | 2.03 | 9.999E+03 | 4.792E+01 |
| 8 | 69.282 | 68.710 | 68.573 | 67.945 | 67.045 | 8.5921E+04 | 5.4567E+04 | 99.99 | 1.81 | 9.999E+03 | 4.435E+01 |
| 9 | 73.425 | 72.886 | 72.757 | 72.163 | 71.316 | 8.6366E+04 | 5.4870E+04 | 99.99 | 1.65 | 9.999E+03 | 4.073E+01 |
| 10 | 77.455 | 76.933 | 76.808 | 76.229 | 75.409 | 8.6773E+04 | 5.5141E+04 | 99.99 | 1.52 | 9.999E+03 | 3.580E+01 |
| | 79.411 | | | | 77.427 | | | | | | |

[1] The ONB ratio is here defined as (Tonb - Tinlet)/(Tsurf - Tinlet). If the heat flux is negative (the coolant is hotter than the adjacent cladding surface), then the ONB ratio is arbitrarily set to 99.99 .

## Table 14. Exact Solution by PLTEMP/ANL V3.0 for a Subassembly With Heat Source in Fuel Plate 1 Only, Heat Transfer to Farther Channels With Water Thermal Conductivity Multiplied by 1000

FUEL PLATE 1 (ExactSoln)

| NODE | COOLANTl | CladSl | FUEL PEAK | CladSr | COOLANTr | HCOFl | HCOFr | ONBRl | ONBRr | ETA'l | ETA'r |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | (C) | (C) | (C) | (C) | (C) | W/C-m^2 | W/C-m^2 | [F Note 1] | | K-cm^3/J | K-cm^3/J |
| | 25.000 | | | | 25.000 | | | | | | |
| 1 | 26.547 | 27.746 | 44.889 | 41.941 | 41.023 | 2.1523E+06 | 8.2112E+05 | 34.58 | 5.08 | 1.425E+02 | 5.458E+00 |
| 2 | 29.936 | 31.305 | 53.976 | 53.143 | 52.830 | 2.2428E+06 | 8.3869E+05 | 15.33 | 2.90 | 1.142E+02 | 1.251E+01 |
| 3 | 33.579 | 34.865 | 56.791 | 55.727 | 55.341 | 2.3387E+06 | 8.4211E+05 | 9.78 | 2.68 | 1.104E+02 | 9.556E+00 |
| 4 | 37.266 | 38.557 | 62.146 | 61.573 | 61.353 | 2.4362E+06 | 8.4989E+05 | 7.15 | 2.21 | 9.969E+01 | 1.437E+01 |
| 5 | 41.017 | 42.247 | 65.498 | 64.832 | 64.581 | 2.5343E+06 | 8.5381E+05 | 5.61 | 2.04 | 9.453E+01 | 1.146E+01 |
| 6 | 44.776 | 45.979 | 69.801 | 69.292 | 69.097 | 2.6318E+06 | 8.5900E+05 | 4.62 | 1.81 | 8.716E+01 | 1.277E+01 |
| 7 | 48.552 | 49.707 | 73.333 | 72.772 | 72.559 | 2.7280E+06 | 8.6275E+05 | 3.92 | 1.69 | 8.157E+01 | 1.034E+01 |
| 8 | 52.328 | 53.450 | 77.309 | 76.810 | 76.619 | 2.8224E+06 | 8.6691E+05 | 3.41 | 1.55 | 7.509E+01 | 9.795E+00 |
| 9 | 56.106 | 57.190 | 80.932 | 80.402 | 80.202 | 2.9150E+06 | 8.7034E+05 | 3.01 | 1.45 | 6.930E+01 | 7.822E+00 |
| 10 | 59.881 | 60.935 | 84.785 | 84.284 | 84.095 | 3.0055E+06 | 8.7384E+05 | 2.70 | 1.36 | 6.311E+01 | 6.587E+00 |
| | 61.771 | | | | 85.578 | | | | | | |

FUEL PLATE 2 (ExactSoln)

| NODE | COOLANTl | CladSl | FUEL PEAK | CladSr | COOLANTr | HCOFl | HCOFr | ONBRl | ONBRr | ETA'l | ETA'r |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 25.000 | | | | 25.000 | | | | | | |
| 1 | 41.023 | 40.539 | 39.436 | 34.361 | 33.870 | 8.2112E+05 | 8.0929E+05 | 99.99 | 8.89 | 9.999E+03 | 1.107E+01 |
| 2 | 52.830 | 52.404 | 51.413 | 46.853 | 46.422 | 8.3869E+05 | 8.2945E+05 | 99.99 | 3.79 | 9.999E+03 | 9.972E+00 |
| 3 | 55.341 | 55.133 | 54.646 | 52.406 | 52.197 | 8.4211E+05 | 8.3780E+05 | 99.99 | 2.94 | 9.999E+03 | 1.810E+01 |
| 4 | 61.353 | 61.114 | 60.551 | 57.956 | 57.716 | 8.4989E+05 | 8.4526E+05 | 99.99 | 2.45 | 9.999E+03 | 1.381E+01 |
| 5 | 64.581 | 64.432 | 64.081 | 62.463 | 62.315 | 8.5381E+05 | 8.5107E+05 | 99.99 | 2.13 | 9.999E+03 | 1.972E+01 |
| 6 | 69.097 | 68.916 | 68.485 | 66.503 | 66.322 | 8.5900E+05 | 8.5585E+05 | 99.99 | 1.93 | 9.999E+03 | 1.436E+01 |
| 7 | 72.559 | 72.420 | 72.089 | 70.566 | 70.427 | 8.6275E+05 | 8.6047E+05 | 99.99 | 1.75 | 9.999E+03 | 1.638E+01 |
| 8 | 76.619 | 76.459 | 76.074 | 74.302 | 74.141 | 8.6691E+05 | 8.6440E+05 | 99.99 | 1.62 | 9.999E+03 | 1.229E+01 |
| 9 | 80.202 | 80.063 | 79.729 | 78.191 | 78.052 | 8.7034E+05 | 8.6831E+05 | 99.99 | 1.50 | 9.999E+03 | 1.199E+01 |
| 10 | 84.095 | 83.943 | 83.576 | 81.885 | 81.733 | 8.7384E+05 | 8.7175E+05 | 99.99 | 1.40 | 9.999E+03 | 9.046E+00 |
| | 85.578 | | | | 83.946 | | | | | | |

FUEL PLATE 3 (ExactSoln)

| NODE | COOLANTl | CladSl | FUEL PEAK | CladSr | COOLANTr | HCOFl | HCOFr | ONBRl | ONBRr | ETA'l | ETA'r |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 25.000 | | | | 25.000 | | | | | | |
| 1 | 33.870 | 33.624 | 33.069 | 30.516 | 30.267 | 8.0929E+05 | 8.0299E+05 | 99.99 | 14.66 | 9.999E+03 | 2.322E+01 |
| 2 | 46.422 | 46.091 | 45.328 | 41.817 | 41.482 | 8.2945E+05 | 8.2185E+05 | 99.99 | 4.87 | 9.999E+03 | 1.415E+01 |
| 3 | 52.197 | 52.044 | 51.686 | 50.044 | 49.890 | 8.3780E+05 | 8.3454E+05 | 99.99 | 3.18 | 9.999E+03 | 2.588E+01 |
| 4 | 57.716 | 57.566 | 57.215 | 55.599 | 55.449 | 8.4526E+05 | 8.4226E+05 | 99.99 | 2.60 | 9.999E+03 | 2.336E+01 |
| 5 | 62.315 | 62.197 | 61.918 | 60.635 | 60.517 | 8.5107E+05 | 8.4884E+05 | 99.99 | 2.22 | 9.999E+03 | 2.606E+01 |
| 6 | 66.322 | 66.215 | 65.960 | 64.789 | 64.682 | 8.5585E+05 | 8.5393E+05 | 99.99 | 1.98 | 9.999E+03 | 2.550E+01 |
| 7 | 70.427 | 70.322 | 70.070 | 68.910 | 68.804 | 8.6047E+05 | 8.5868E+05 | 99.99 | 1.80 | 9.999E+03 | 2.272E+01 |
| 8 | 74.141 | 74.044 | 73.811 | 72.739 | 72.642 | 8.6440E+05 | 8.6284E+05 | 99.99 | 1.65 | 9.999E+03 | 2.151E+01 |
| 9 | 78.052 | 77.952 | 77.709 | 76.591 | 76.491 | 8.6831E+05 | 8.6678E+05 | 99.99 | 1.53 | 9.999E+03 | 1.770E+01 |
| 10 | 81.733 | 81.638 | 81.408 | 80.353 | 80.258 | 8.7175E+05 | 8.7040E+05 | 99.99 | 1.42 | 9.999E+03 | 1.568E+01 |
| | 83.946 | | | | 82.088 | | | | | | |

FUEL PLATE 4 (ExactSoln)

| NODE | COOLANTl | CladSl | FUEL PEAK | CladSr | COOLANTr | HCOFl | HCOFr | ONBRl | ONBRr | ETA'l | ETA'r |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 25.000 | | | | 25.000 | | | | | | |
| 1 | 30.267 | 30.164 | 29.935 | 28.879 | 28.717 | 8.0299E+05 | 5.0970E+05 | 99.99 | 20.31 | 9.999E+03 | 5.739E+01 |
| 2 | 41.482 | 41.309 | 40.914 | 39.096 | 38.823 | 8.2185E+05 | 5.2076E+05 | 99.99 | 5.67 | 9.999E+03 | 2.858E+01 |
| 3 | 49.890 | 49.801 | 49.597 | 48.655 | 48.516 | 8.3454E+05 | 5.3030E+05 | 99.99 | 3.32 | 9.999E+03 | 4.639E+01 |
| 4 | 55.449 | 55.381 | 55.222 | 54.490 | 54.384 | 8.4226E+05 | 5.3557E+05 | 99.99 | 2.65 | 9.999E+03 | 5.286E+01 |
| 5 | 60.517 | 60.451 | 60.294 | 59.574 | 59.469 | 8.4884E+05 | 5.3983E+05 | 99.99 | 2.26 | 9.999E+03 | 4.765E+01 |
| 6 | 64.682 | 64.632 | 64.514 | 63.971 | 63.892 | 8.5393E+05 | 5.4332E+05 | 99.99 | 1.99 | 9.999E+03 | 5.622E+01 |
| 7 | 68.804 | 68.749 | 68.617 | 68.008 | 67.921 | 8.5868E+05 | 5.4631E+05 | 99.99 | 1.81 | 9.999E+03 | 4.452E+01 |
| 8 | 72.642 | 72.594 | 72.480 | 71.956 | 71.881 | 8.6284E+05 | 5.4908E+05 | 99.99 | 1.65 | 9.999E+03 | 4.520E+01 |
| 9 | 76.491 | 76.440 | 76.318 | 75.755 | 75.676 | 8.6678E+05 | 5.5158E+05 | 99.99 | 1.53 | 9.999E+03 | 3.641E+01 |
| 10 | 80.258 | 80.210 | 80.095 | 79.564 | 79.489 | 8.7040E+05 | 5.5395E+05 | 99.99 | 1.42 | 9.999E+03 | 3.243E+01 |
| | 82.088 | | | | 81.340 | | | | | | |

[1] The ONB ratio is here defined as (Tonb - Tinlet)/(Tsurf - Tinlet). If the heat flux is negative (the coolant is hotter than the adjacent cladding surface), then the ONB ratio is arbitrarily set to 99.99 .

## Table 15. PLTEMP/ANL V3.0 Input Data for Standard Problem 11 – Equilibration of Coolant Channel Temperatures over Unheated Axial Length

```
 Standard Problem 11: 1 subassembly producing 0.04 MWt
! Each subassembly has 4 fuel plates and 5 coolant channels
! H2O coolant, Input coolant flow = 0.2 kg/s per coolant channel
! All hot channel factors = 1.0
! No bypass flow, NCTYP=0
! 10 axial heat transfer nodes in the heated length of fuel plates
! 1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18        Indices on Card 0200
   0   0   0   1   0   1   1   1   0   0   0   0   0       1       0          Card(1)0200
   1   3 0.00       1.00        1.00        1.00           3                  Card(1)0300
   1  20 1.00                                                                 Card(1)0301
   1   1   1                                                                  Card(1)0302
1.20        1.20                                                              Card(2)0303
30.0E-04    0.02955665  0.15        8.00        0.20        15.0E-03          Card(3)0304
30.0E-04    0.02955665  0.75        0.00        0.20        15.0E-03          Card(3)0304
30.0E-04    0.02955665  0.15        8.00        0.20        15.0E-03          Card(3)0304
! Use the code's biult-in correlation for friction factor
0.00        0.00        0.00                                                  Card(1)0305
   5   6 0.00       10.00        1.00E-03    120.00      1.00E-03    120.00   Card(1)0306
6.00E-04    5.91133E-03 0.4060      0.20        0.20        3.00E-03          Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03          Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03          Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03          Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.20        0.20        3.00E-03          Card(5)0307
0.20        0.20        0.20        0.20                                      Card(1)0308
! Card 0308a not required
! Radial power peaking factor data by fuel plate for each subassembly. Input flow data by
! channel for each subassembly on Cards 0310 not required because WFGES(1) is non-zero
1.0E-04     1.0         1.0         1.0E-04                                   Card(2)0309
0.4E-01     0.4E-01     0.4E-01     0.4E-01     0.4E-01                       Card(2)0310
! DP0       DDP         DPMAX       POWER       TIN         PIN
0.30        0.10        0.40        0.04        25.0        0.40              Card(1)0500
                                                                              Card(2)0500
  50 0.0001     25.0        0.04        0.04                                  Card(1)0600
  41                                                                          Card(1)0700
0.000       1.00                                                              Card(11)0701
0.025       1.00                                                              Card(11)0701
0.050       1.00                                                              Card(11)0701
0.075       1.00                                                              Card(11)0701
0.100       1.00                                                              Card(11)0701
0.125       1.00                                                              Card(11)0701
0.150       1.00                                                              Card(11)0701
0.175       1.00                                                              Card(11)0701
0.200       1.00                                                              Card(11)0701
0.225       1.00                                                              Card(11)0701
0.250       1.00                                                              Card(11)0701
0.275       1.00E-03                                                          Card(11)0701
0.300       1.00E-03                                                          Card(11)0701
0.325       1.00E-03                                                          Card(11)0701
0.350       1.00E-03                                                          Card(11)0701
0.375       1.00E-03                                                          Card(11)0701
0.400       1.00E-03                                                          Card(11)0701
0.425       1.00E-03                                                          Card(11)0701
0.450       1.00E-03                                                          Card(11)0701
0.475       1.00E-03                                                          Card(11)0701
0.500       1.00E-03                                                          Card(11)0701
0.525       1.00E-03                                                          Card(11)0701
0.550       1.00E-03                                                          Card(11)0701
0.575       1.00E-03                                                          Card(11)0701
0.600       1.00E-03                                                          Card(11)0701
0.625       1.00E-03                                                          Card(11)0701
0.650       1.00E-03                                                          Card(11)0701
0.675       1.00E-03                                                          Card(11)0701
0.700       1.00E-03                                                          Card(11)0701
0.725       1.00E-03                                                          Card(11)0701
0.750       1.00E-03                                                          Card(11)0701
0.775       1.00E-03                                                          Card(11)0701
0.800       1.00E-03                                                          Card(11)0701
0.825       1.00E-03                                                          Card(11)0701
0.850       1.00E-03                                                          Card(11)0701
0.875       1.00E-03                                                          Card(11)0701
0.900       1.00E-03                                                          Card(11)0701
0.925       1.00E-03                                                          Card(11)0701
0.950       1.00E-03                                                          Card(11)0701
0.975       1.00E-03                                                          Card(11)0701
1.000       1.00E-03                                                          Card(11)0701
   0                                                                          Card(11)0702
!234567890123456789012345678901234567890123456789012345678901234567890123456789 0
```

## Table 16. Exact Solution by PLTEMP/ANL V3.0 for Standard Problem 11 – Equilibration of Coolant Channel Temperatures over Unheated Axial Length

FUEL PLATE 1 (ExactSoln)

| NODE | COOLANTl (C) | CladSl (C) | FUEL PEAK (C) | CladSr (C) | COOLANTr (C) | HCOFl W/C-m^2 | HCOFr W/C-m^2 | ONBRl [F Note 1] | ONBRr | ETA'l K-cm^3/J | ETA'r K-cm^3/J |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 25.000 | | | | 25.000 | | | | | | |
| 1 | 25.146 | 26.605 | 26.621 | 26.629 | 27.846 | 6.6952E+02 | 7.9875E+02 | 74.01 | 99.99 | 8.107E+03 | 9.999E+03 |
| 2 | 25.721 | 29.914 | 29.962 | 29.985 | 33.507 | 6.8010E+02 | 8.0878E+02 | 24.15 | 99.99 | 2.756E+03 | 9.999E+03 |
| 3 | 26.832 | 33.397 | 33.473 | 33.511 | 39.078 | 6.9431E+02 | 8.1809E+02 | 14.12 | 99.99 | 1.705E+03 | 9.999E+03 |
| 4 | 28.434 | 37.032 | 37.134 | 37.185 | 44.584 | 7.1185E+02 | 8.2677E+02 | 9.84 | 99.99 | 1.250E+03 | 9.999E+03 |
| 5 | 30.496 | 40.911 | 41.038 | 41.101 | 50.050 | 7.3272E+02 | 8.5234E+02 | 7.43 | 99.99 | 9.823E+02 | 9.999E+03 |
| 6 | 33.002 | 45.016 | 45.167 | 45.243 | 55.429 | 7.5678E+02 | 8.9225E+02 | 5.90 | 99.99 | 8.044E+02 | 9.999E+03 |
| 7 | 35.926 | 49.228 | 49.402 | 49.489 | 60.685 | 7.8355E+02 | 9.3065E+02 | 4.87 | 99.99 | 6.814E+02 | 9.999E+03 |
| 8 | 39.225 | 53.516 | 53.710 | 53.807 | 65.806 | 8.1261E+02 | 9.6750E+02 | 4.13 | 99.99 | 5.912E+02 | 9.999E+03 |
| 9 | 42.858 | 57.865 | 58.076 | 58.182 | 70.790 | 8.4351E+02 | 1.0038E+03 | 3.58 | 99.99 | 5.219E+02 | 9.999E+03 |
| 10 | 46.777 | 62.244 | 62.470 | 62.583 | 75.642 | 8.7575E+02 | 1.0370E+03 | 3.15 | 99.99 | 4.673E+02 | 9.999E+03 |
| 11 | 50.833 | 65.825 | 66.052 | 66.165 | 78.982 | 9.0685E+02 | 1.0606E+03 | 2.87 | 99.99 | 4.444E+02 | 9.999E+03 |
| 12 | 54.681 | 67.714 | 67.917 | 68.018 | 79.427 | 9.3350E+02 | 1.0665E+03 | 2.73 | 99.99 | 4.742E+02 | 9.999E+03 |
| 13 | 58.010 | 68.630 | 68.799 | 68.883 | 78.415 | 9.5445E+02 | 1.0634E+03 | 2.67 | 99.99 | 5.456E+02 | 9.999E+03 |
| 14 | 60.767 | 69.360 | 69.499 | 69.569 | 77.442 | 9.7141E+02 | 1.0602E+03 | 2.62 | 99.99 | 6.385E+02 | 9.999E+03 |
| 15 | 63.029 | 69.957 | 70.071 | 70.128 | 76.583 | 9.8510E+02 | 1.0571E+03 | 2.58 | 99.99 | 7.564E+02 | 9.999E+03 |
| 20 | 69.372 | 71.710 | 71.750 | 71.770 | 74.054 | 1.0237E+03 | 1.0478E+03 | 2.45 | 99.99 | 1.945E+03 | 9.999E+03 |
| 25 | 71.579 | 72.384 | 72.397 | 72.404 | 73.202 | 1.0364E+03 | 1.0447E+03 | 2.38 | 99.99 | 5.306E+03 | 9.999E+03 |
| 30 | 72.354 | 72.639 | 72.644 | 72.647 | 72.932 | 1.0409E+03 | 1.0438E+03 | 2.34 | 99.99 | 1.441E+04 | 9.999E+03 |
| 35 | 72.636 | 72.744 | 72.745 | 72.746 | 72.854 | 1.0425E+03 | 1.0436E+03 | 2.31 | 99.99 | 3.709E+04 | 9.999E+03 |
| 40 | 72.748 | 72.795 | 72.795 | 72.796 | 72.843 | 1.0431E+03 | 1.0436E+03 | 2.28 | 99.99 | 8.352E+04 | 9.999E+03 |
| | 72.755 | | | | 72.843 | | | | | | |

FUEL PLATE 2 (ExactSoln)

| NODE | COOLANTl (C) | CladSl (C) | FUEL PEAK (C) | CladSr (C) | COOLANTr (C) | HCOFl W/C-m^2 | HCOFr W/C-m^2 | ONBRl [F Note 1] | ONBRr | ETA'l K-cm^3/J | ETA'r K-cm^3/J |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 25.000 | | | | 25.000 | | | | | | |
| 1 | 27.846 | 52.827 | 53.037 | 52.851 | 30.406 | 7.9875E+02 | 8.0336E+02 | 4.30 | 4.29 | 3.917E+02 | 4.313E+02 |
| 2 | 33.507 | 60.249 | 60.481 | 60.315 | 40.708 | 8.0878E+02 | 8.3421E+02 | 3.39 | 3.38 | 3.430E+02 | 4.312E+02 |
| 3 | 39.078 | 66.600 | 66.849 | 66.699 | 50.092 | 8.3451E+02 | 9.0430E+02 | 2.86 | 2.85 | 3.059E+02 | 4.257E+02 |
| 4 | 44.584 | 72.445 | 72.715 | 72.583 | 58.604 | 8.7931E+02 | 9.6469E+02 | 2.51 | 2.49 | 2.710E+02 | 4.295E+02 |
| 5 | 50.050 | 78.041 | 78.329 | 78.212 | 66.254 | 9.2216E+02 | 1.0180E+03 | 2.24 | 2.23 | 2.423E+02 | 4.313E+02 |
| 6 | 55.429 | 83.386 | 83.690 | 83.584 | 73.174 | 9.6270E+02 | 1.0634E+03 | 2.03 | 2.02 | 2.183E+02 | 4.298E+02 |
| 7 | 60.685 | 88.482 | 88.798 | 88.702 | 79.487 | 1.0009E+03 | 1.1028E+03 | 1.86 | 1.85 | 1.978E+02 | 4.239E+02 |
| 8 | 65.806 | 93.345 | 93.672 | 93.584 | 85.301 | 1.0371E+03 | 1.1377E+03 | 1.73 | 1.72 | 1.800E+02 | 4.130E+02 |
| 9 | 70.790 | 97.987 | 98.323 | 98.241 | 90.708 | 1.0726E+03 | 1.1697E+03 | 1.62 | 1.60 | 1.642E+02 | 3.977E+02 |
| 10 | 75.642 | 102.471 | 102.815 | 102.738 | 95.786 | 1.1049E+03 | 1.2000E+03 | 1.52 | 1.51 | 1.500E+02 | 3.763E+02 |
| 11 | 78.982 | 96.918 | 97.171 | 97.179 | 97.973 | 1.1131E+03 | 1.2006E+03 | 1.63 | 99.99 | 2.106E+02 | 9.999E+03 |
| 12 | 79.427 | 87.414 | 87.560 | 87.633 | 95.101 | 1.1005E+03 | 1.1719E+03 | 1.87 | 99.99 | 4.730E+02 | 9.999E+03 |
| 13 | 78.415 | 84.558 | 84.670 | 84.725 | 90.537 | 1.0911E+03 | 1.1468E+03 | 1.95 | 99.99 | 6.281E+02 | 9.999E+03 |
| 14 | 77.442 | 82.279 | 82.366 | 82.409 | 87.020 | 1.0827E+03 | 1.1274E+03 | 2.03 | 99.99 | 8.134E+02 | 9.999E+03 |
| 15 | 76.583 | 80.449 | 80.518 | 80.552 | 84.257 | 1.0755E+03 | 1.1118E+03 | 2.09 | 99.99 | 1.035E+03 | 9.999E+03 |
| 20 | 74.054 | 75.424 | 75.448 | 75.460 | 76.777 | 1.0544E+03 | 1.0679E+03 | 2.27 | 99.99 | 3.039E+03 | 9.999E+03 |
| 25 | 73.202 | 73.705 | 73.714 | 73.718 | 74.183 | 1.0471E+03 | 1.0520E+03 | 2.32 | 99.99 | 8.279E+03 | 9.999E+03 |
| 30 | 72.932 | 73.126 | 73.129 | 73.131 | 73.289 | 1.0447E+03 | 1.0465E+03 | 2.32 | 99.99 | 2.109E+04 | 9.999E+03 |
| 35 | 72.854 | 72.941 | 72.942 | 72.943 | 72.993 | 1.0439E+03 | 1.0446E+03 | 2.30 | 99.99 | 4.651E+04 | 9.999E+03 |
| 40 | 72.843 | 72.892 | 72.892 | 72.892 | 72.905 | 1.0438E+03 | 1.0441E+03 | 2.27 | 99.99 | 8.045E+04 | 9.999E+03 |
| | 72.843 | | | | 72.901 | | | | | | |

[1] The ONB ratio is here defined as (Tonb - Tinlet)/(Tsurf - Tinlet). If the heat flux is negative (the coola
than the adjacent cladding surface), then the ONB ratio is arbitrarily set to 99.99 .

## Table 16. Cont'd

FUEL PLATE 3 (ExactSoln)

| NODE | COOLANTl (C) | CladSl (C) | FUEL PEAK (C) | CladSr (C) | COOLANTr (C) | HCOFl W/C-m^2 | HCOFr W/C-m^2 | ONBRl [F Note 1] | ONBRr | ETA'l K-cm^3/J | ETA'r K-cm^3/J |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 25.000 | | | | 25.000 | | | | | | |
| 1 | 30.406 | 52.851 | 53.037 | 52.827 | 27.846 | 8.0336E+02 | 7.9875E+02 | 4.29 | 4.30 | 4.313E+02 | 3.917E+02 |
| 2 | 40.708 | 60.315 | 60.481 | 60.249 | 33.507 | 8.3421E+02 | 8.0878E+02 | 3.38 | 3.39 | 4.312E+02 | 3.430E+02 |
| 3 | 50.092 | 66.699 | 66.849 | 66.600 | 39.078 | 9.0430E+02 | 8.3451E+02 | 2.85 | 2.86 | 4.257E+02 | 3.059E+02 |
| 4 | 58.604 | 72.583 | 72.715 | 72.445 | 44.584 | 9.6469E+02 | 8.7931E+02 | 2.49 | 2.51 | 4.295E+02 | 2.710E+02 |
| 5 | 66.254 | 78.212 | 78.329 | 78.041 | 50.050 | 1.0180E+03 | 9.2216E+02 | 2.23 | 2.24 | 4.313E+02 | 2.423E+02 |
| 6 | 73.174 | 83.584 | 83.690 | 83.386 | 55.429 | 1.0634E+03 | 9.6270E+02 | 2.02 | 2.03 | 4.298E+02 | 2.183E+02 |
| 7 | 79.487 | 88.702 | 88.798 | 88.482 | 60.685 | 1.1028E+03 | 1.0009E+03 | 1.85 | 1.86 | 4.239E+02 | 1.978E+02 |
| 8 | 85.301 | 93.584 | 93.672 | 93.345 | 65.806 | 1.1377E+03 | 1.0371E+03 | 1.72 | 1.73 | 4.130E+02 | 1.800E+02 |
| 9 | 90.708 | 98.241 | 98.323 | 97.987 | 70.790 | 1.1697E+03 | 1.0726E+03 | 1.60 | 1.62 | 3.977E+02 | 1.642E+02 |
| 10 | 95.786 | 102.738 | 102.815 | 102.471 | 75.642 | 1.2000E+03 | 1.1049E+03 | 1.51 | 1.52 | 3.763E+02 | 1.500E+02 |
| 11 | 97.973 | 97.179 | 97.171 | 96.918 | 78.982 | 1.2006E+03 | 1.1131E+03 | 99.99 | 1.63 | 9.999E+03 | 2.106E+02 |
| 12 | 95.101 | 87.633 | 87.560 | 87.414 | 79.427 | 1.1719E+03 | 1.1005E+03 | 99.99 | 1.87 | 9.999E+03 | 4.730E+02 |
| 13 | 90.537 | 84.725 | 84.670 | 84.558 | 78.415 | 1.1468E+03 | 1.0911E+03 | 99.99 | 1.95 | 9.999E+03 | 6.281E+02 |
| 14 | 87.020 | 82.409 | 82.366 | 82.279 | 77.442 | 1.1274E+03 | 1.0827E+03 | 99.99 | 2.03 | 9.999E+03 | 8.134E+02 |
| 15 | 84.257 | 80.552 | 80.518 | 80.449 | 76.583 | 1.1118E+03 | 1.0755E+03 | 99.99 | 2.09 | 9.999E+03 | 1.035E+03 |
| 20 | 76.777 | 75.460 | 75.448 | 75.424 | 74.054 | 1.0679E+03 | 1.0544E+03 | 99.99 | 2.27 | 9.999E+03 | 3.039E+03 |
| 25 | 74.183 | 73.718 | 73.714 | 73.705 | 73.202 | 1.0520E+03 | 1.0471E+03 | 99.99 | 2.32 | 9.999E+03 | 8.279E+03 |
| 30 | 73.289 | 73.131 | 73.129 | 73.126 | 72.932 | 1.0465E+03 | 1.0447E+03 | 99.99 | 2.32 | 9.999E+03 | 2.109E+04 |
| 35 | 72.993 | 72.943 | 72.942 | 72.941 | 72.854 | 1.0446E+03 | 1.0439E+03 | 99.99 | 2.30 | 9.999E+03 | 4.651E+04 |
| 40 | 72.905 | 72.892 | 72.892 | 72.892 | 72.843 | 1.0441E+03 | 1.0438E+03 | 99.99 | 2.27 | 9.999E+03 | 8.045E+04 |
| | 72.901 | | | | 72.843 | | | | | | |

FUEL PLATE 4 (ExactSoln)

| NODE | COOLANTl (C) | CladSl (C) | FUEL PEAK (C) | CladSr (C) | COOLANTr (C) | HCOFl W/C-m^2 | HCOFr W/C-m^2 | ONBRl [F Note 1] | ONBRr | ETA'l K-cm^3/J | ETA'r K-cm^3/J |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 25.000 | | | | 25.000 | | | | | | |
| 1 | 27.846 | 26.629 | 26.621 | 26.605 | 25.146 | 7.9875E+02 | 6.6952E+02 | 99.99 | 74.01 | 9.999E+03 | 8.107E+03 |
| 2 | 33.507 | 29.985 | 29.962 | 29.914 | 25.721 | 8.0878E+02 | 6.8010E+02 | 99.99 | 24.15 | 9.999E+03 | 2.756E+03 |
| 3 | 39.078 | 33.511 | 33.473 | 33.397 | 26.832 | 8.1809E+02 | 6.9431E+02 | 99.99 | 14.12 | 9.999E+03 | 1.705E+03 |
| 4 | 44.584 | 37.185 | 37.134 | 37.032 | 28.434 | 8.2677E+02 | 7.1185E+02 | 99.99 | 9.84 | 9.999E+03 | 1.250E+03 |
| 5 | 50.050 | 41.101 | 41.038 | 40.911 | 30.496 | 8.5234E+02 | 7.3272E+02 | 99.99 | 7.43 | 9.999E+03 | 9.823E+02 |
| 6 | 55.429 | 45.243 | 45.167 | 45.016 | 33.002 | 8.9225E+02 | 7.5678E+02 | 99.99 | 5.90 | 9.999E+03 | 8.044E+02 |
| 7 | 60.685 | 49.489 | 49.402 | 49.228 | 35.926 | 9.3065E+02 | 7.8355E+02 | 99.99 | 4.87 | 9.999E+03 | 6.814E+02 |
| 8 | 65.806 | 53.807 | 53.710 | 53.516 | 39.225 | 9.6750E+02 | 8.1261E+02 | 99.99 | 4.13 | 9.999E+03 | 5.912E+02 |
| 9 | 70.790 | 58.182 | 58.076 | 57.865 | 42.858 | 1.0038E+03 | 8.4351E+02 | 99.99 | 3.58 | 9.999E+03 | 5.219E+02 |
| 10 | 75.642 | 62.583 | 62.470 | 62.244 | 46.777 | 1.0370E+03 | 8.7575E+02 | 99.99 | 3.15 | 9.999E+03 | 4.673E+02 |
| 11 | 78.982 | 66.165 | 66.052 | 65.825 | 50.833 | 1.0606E+03 | 9.0685E+02 | 99.99 | 2.87 | 9.999E+03 | 4.444E+02 |
| 12 | 79.427 | 68.018 | 67.917 | 67.714 | 54.681 | 1.0665E+03 | 9.3350E+02 | 99.99 | 2.73 | 9.999E+03 | 4.742E+02 |
| 13 | 78.415 | 68.883 | 68.799 | 68.630 | 58.010 | 1.0634E+03 | 9.5445E+02 | 99.99 | 2.67 | 9.999E+03 | 5.456E+02 |
| 14 | 77.442 | 69.569 | 69.499 | 69.360 | 60.767 | 1.0602E+03 | 9.7141E+02 | 99.99 | 2.62 | 9.999E+03 | 6.385E+02 |
| 15 | 76.583 | 70.128 | 70.071 | 69.957 | 63.029 | 1.0571E+03 | 9.8510E+02 | 99.99 | 2.58 | 9.999E+03 | 7.564E+02 |
| 20 | 74.054 | 71.770 | 71.750 | 71.710 | 69.372 | 1.0478E+03 | 1.0237E+03 | 99.99 | 2.45 | 9.999E+03 | 1.945E+03 |
| 25 | 73.202 | 72.404 | 72.397 | 72.384 | 71.579 | 1.0447E+03 | 1.0364E+03 | 99.99 | 2.38 | 9.999E+03 | 5.306E+03 |
| 30 | 72.932 | 72.647 | 72.644 | 72.639 | 72.354 | 1.0438E+03 | 1.0409E+03 | 99.99 | 2.34 | 9.999E+03 | 1.441E+04 |
| 35 | 72.854 | 72.746 | 72.745 | 72.744 | 72.636 | 1.0436E+03 | 1.0425E+03 | 99.99 | 2.31 | 9.999E+03 | 3.709E+04 |
| 40 | 72.843 | 72.796 | 72.795 | 72.795 | 72.748 | 1.0436E+03 | 1.0431E+03 | 99.99 | 2.28 | 9.999E+03 | 8.352E+04 |
| | 72.843 | | | | 72.755 | | | | | | |

[1] The ONB ratio is here defined as (Tonb - Tinlet)/(Tsurf - Tinlet). If the heat flux is negative (the coola than the adjacent cladding surface), then the ONB ratio is arbitrarily set to 99.99 .

## Table 17. Standard Problem 12 Input Data for PLTEMP/ANL V3.0: Practically Zero Cladding Thickness, Heat Source in Fuel, and No Heat Source in Cladding and Coolant (Fuel Meat Thickness = 2.0 mm)

```
 Standard Problem 12: 2 subassemblies (of identical geometry) producing 1 MWt
! Each subassembly has 4 fuel plates and 5 coolant channels
! Each fuel plate has equal power all of which is directly deposited in
! coolant channels. See card(2) 0500.
! H2O coolant, Input coolant flow = 0.50 kg/s in channel 2, 3, or 4
!                                  = 0.25 kg/s in channel 1, or 5
! All hot channel factors = 1.0
! No bypass flow, NCTYP=0
! 10 axial heat transfer nodes in the heated length of fuel plates
!  1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18        Indices Card 0200
   0   0   5   1   0   1   1   1   0   0   0   0   0           1                Card(1)0200
   2   3 0.00       1.00        1.00        1.00           3                    Card(1)0300
! Using pressure driven mode
   1  20 1.00                                                                   Card(1)0301
   1   1   1                                                                    Card(1)0302
1.20        1.20                                                                Card(2)0303
30.0E-04    0.02955665  0.15        8.00        0.20        15.0E-03            Card(3)0304
30.0E-04    0.02955665  0.75        0.00        0.20        15.0E-03            Card(3)0304
30.0E-04    0.02955665  0.15        8.00        0.20        15.0E-03            Card(3)0304
! Use the code's biult-in correlation for friction factor
0.00        0.00        0.00                                                    Card(1)0305
   5   3 0.00       0.75        0.50E-09    10.00       2.00E-03    10.00       Card(1)0306
6.00E-04    5.91133E-03 0.4060      0.20        0.20        3.00E-03            Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03            Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03            Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03            Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.20        0.20        3.00E-03            Card(5)0307
0.20        0.20        0.20        0.20                                        Card(1)0308
! Card 0308a not required
! Radial power peaking factor data by fuel plate for each subassembly. Input flow data by
! channel for each subassembly on Cards 0310 not required because WFGES(1) is non-zero
1.000       1.000       1.000       1.000                                       Card(2)0309
0.25        0.50        0.50        0.50        0.25                            Card(2)0310
1.000       1.000       1.000       1.000                                       Card(2)0309
0.25        0.50        0.50        0.50        0.25                            Card(2)0310
! DP0       DDP         DPMAX       POWER       TIN         PIN
0.32336     0.04        0.36136     1.00        45.0        0.12                Card(2)0500
0.0         0.0                                                                 Card(2)0500
  50 0.0001     25.0        0.50        1.00                                    Card(1)0600
  11                                                                            Card(1)0700
0.00        0.80                                                                Card(11)0701
0.10        0.88                                                                Card(11)0701
0.20        0.96                                                                Card(11)0701
0.30        1.04                                                                Card(11)0701
0.40        1.12                                                                Card(11)0701
0.50        1.20                                                                Card(11)0701
0.60        1.12                                                                Card(11)0701
0.70        1.04                                                                Card(11)0701
0.80        0.96                                                                Card(11)0701
0.90        0.88                                                                Card(11)0701
1.00        0.80                                                                Card(11)0701
   0                                                                            Card(11)0702
```

## Table 18. Exact Solution of Standard Problem 12: Practically Zero Cladding Thickness, Heat Source in Fuel, No Heat Source in Cladding and Coolant (Fuel Meat Thickness = 2.0 mm)

Input Power Densities (MW/m**3) in Axial Node 1 of Subassembly 1 of Type 1:

| FUEL PLATE | COOLANTl | CLADDINGl | FUEL MEAT | CLADDINGr | COOLANTr |
|---|---|---|---|---|---|
| 1 | 0.0000E+00 | 0.0000E+00 | 3.5000E+02 | 0.0000E+00 | 0.0000E+00 |
| 2 | 0.0000E+00 | 0.0000E+00 | 3.5000E+02 | 0.0000E+00 | 0.0000E+00 |
| 3 | 0.0000E+00 | 0.0000E+00 | 3.5000E+02 | 0.0000E+00 | 0.0000E+00 |
| 4 | 0.0000E+00 | 0.0000E+00 | 3.5000E+02 | 0.0000E+00 | 0.0000E+00 |

FUEL PLATE 1 (ExactSoln)

| NODE | COOLANTl (C) | CladSl (C) | FUEL PEAK (C) | CladSr (C) | COOLANTr (C) | HCOFl W/C-m^2 | HCOFr W/C-m^2 | ONBRl [F Note 1] | ONBRr | ETA'l K-cm^3/J | ETA'r K-cm^3/J |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 45.000 | | | | 45.000 | | | | | | |
| 1 | 47.083 | 117.096 | 129.129 | 105.142 | 47.725 | 4.1454E+03 | 7.1368E+03 | 1.37 | 1.65 | 1.364E+02 | 1.919E+02 |
| 2 | 51.462 | 125.641 | 139.015 | 113.016 | 53.420 | 4.3167E+03 | 7.4915E+03 | 1.22 | 1.46 | 1.173E+02 | 1.645E+02 |
| 3 | 56.269 | 134.230 | 148.979 | 121.013 | 59.605 | 4.4969E+03 | 7.8614E+03 | 1.10 | 1.30 | 1.008E+02 | 1.406E+02 |
| 4 | 61.504 | 143.113 | 159.201 | 129.215 | 66.278 | 4.6626E+03 | 8.2540E+03 | 1.00 | 1.18 | 8.661E+01 | 1.190E+02 |
| 5 | 67.161 | 152.388 | 169.802 | 137.778 | 73.436 | 4.8140E+03 | 8.6473E+03 | 0.91 | 1.06 | 7.404E+01 | 9.956E+01 |
| 6 | 73.049 | 156.523 | 174.243 | 142.631 | 80.814 | 4.9581E+03 | 8.9424E+03 | 0.88 | 1.01 | 6.692E+01 | 8.821E+01 |
| 7 | 78.783 | 155.384 | 172.267 | 143.344 | 87.889 | 5.0887E+03 | 9.2002E+03 | 0.88 | 1.00 | 6.434E+01 | 8.307E+01 |
| 8 | 84.164 | 154.345 | 170.350 | 144.052 | 94.408 | 5.2037E+03 | 9.4298E+03 | 0.88 | 0.98 | 6.192E+01 | 7.792E+01 |
| 9 | 89.184 | 153.281 | 168.369 | 144.636 | 100.377 | 5.3060E+03 | 9.6380E+03 | 0.89 | 0.97 | 5.969E+01 | 7.277E+01 |
| 10 | 93.838 | 152.109 | 166.250 | 145.033 | 105.803 | 5.3992E+03 | 9.8237E+03 | 0.89 | 0.96 | 5.766E+01 | 6.763E+01 |
| | 96.073 | | | | 108.381 | | | | | | |

FUEL PLATE 2 (ExactSoln)

| NODE | COOLANTl | CladSl | FUEL PEAK | CladSr | COOLANTr | HCOFl | HCOFr | ONBRl | ONBRr | ETA'l | ETA'r |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 45.000 | | | | 45.000 | | | | | | |
| 1 | 47.725 | 97.260 | 114.732 | 97.204 | 47.513 | 7.0601E+03 | 7.0492E+03 | 1.90 | 1.90 | 2.249E+02 | 2.250E+02 |
| 2 | 53.420 | 105.018 | 124.097 | 104.842 | 52.781 | 7.4123E+03 | 7.3801E+03 | 1.65 | 1.65 | 1.921E+02 | 1.926E+02 |
| 3 | 59.605 | 112.957 | 133.635 | 112.646 | 58.531 | 7.7807E+03 | 7.7283E+03 | 1.45 | 1.46 | 1.635E+02 | 1.645E+02 |
| 4 | 66.278 | 121.078 | 143.360 | 120.642 | 64.760 | 8.1720E+03 | 8.0915E+03 | 1.30 | 1.30 | 1.381E+02 | 1.396E+02 |
| 5 | 73.436 | 129.502 | 153.353 | 128.868 | 71.469 | 8.5642E+03 | 8.4759E+03 | 1.16 | 1.17 | 1.154E+02 | 1.173E+02 |
| 6 | 80.814 | 134.602 | 158.354 | 133.769 | 78.420 | 8.9085E+03 | 8.8077E+03 | 1.09 | 1.11 | 1.018E+02 | 1.042E+02 |
| 7 | 87.889 | 136.309 | 158.298 | 135.281 | 85.137 | 9.1875E+03 | 9.0767E+03 | 1.07 | 1.08 | 9.527E+01 | 9.829E+01 |
| 8 | 94.408 | 137.955 | 158.190 | 136.749 | 91.383 | 9.4298E+03 | 9.3174E+03 | 1.04 | 1.06 | 8.883E+01 | 9.241E+01 |
| 9 | 100.377 | 139.454 | 157.955 | 138.112 | 97.156 | 9.6380E+03 | 9.5237E+03 | 1.02 | 1.04 | 8.242E+01 | 8.663E+01 |
| 10 | 105.803 | 140.698 | 157.484 | 139.256 | 102.456 | 9.8237E+03 | 9.7068E+03 | 1.00 | 1.02 | 7.603E+01 | 8.096E+01 |
| | 108.381 | | | | 104.988 | | | | | | |

FUEL PLATE 3 (ExactSoln)

| NODE | COOLANTl | CladSl | FUEL PEAK | CladSr | COOLANTr | HCOFl | HCOFr | ONBRl | ONBRr | ETA'l | ETA'r |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 45.000 | | | | 45.000 | | | | | | |
| 1 | 47.513 | 97.204 | 114.732 | 97.260 | 47.725 | 7.0492E+03 | 7.0601E+03 | 1.90 | 1.90 | 2.250E+02 | 2.249E+02 |
| 2 | 52.781 | 104.842 | 124.097 | 105.018 | 53.420 | 7.3801E+03 | 7.4123E+03 | 1.65 | 1.65 | 1.926E+02 | 1.921E+02 |
| 3 | 58.531 | 112.646 | 133.635 | 112.957 | 59.605 | 7.7283E+03 | 7.7807E+03 | 1.46 | 1.45 | 1.645E+02 | 1.635E+02 |
| 4 | 64.760 | 120.642 | 143.360 | 121.078 | 66.278 | 8.0915E+03 | 8.1720E+03 | 1.30 | 1.30 | 1.396E+02 | 1.381E+02 |
| 5 | 71.469 | 128.868 | 153.353 | 129.502 | 73.436 | 8.4759E+03 | 8.5642E+03 | 1.17 | 1.16 | 1.173E+02 | 1.154E+02 |
| 6 | 78.420 | 133.769 | 158.354 | 134.602 | 80.814 | 8.8077E+03 | 8.9085E+03 | 1.11 | 1.09 | 1.042E+02 | 1.018E+02 |
| 7 | 85.137 | 135.281 | 158.298 | 136.309 | 87.889 | 9.0767E+03 | 9.1875E+03 | 1.08 | 1.07 | 9.829E+01 | 9.527E+01 |
| 8 | 91.383 | 136.749 | 158.190 | 137.955 | 94.408 | 9.3174E+03 | 9.4298E+03 | 1.06 | 1.04 | 9.241E+01 | 8.883E+01 |
| 9 | 97.156 | 138.112 | 157.955 | 139.454 | 100.377 | 9.5237E+03 | 9.6380E+03 | 1.04 | 1.02 | 8.663E+01 | 8.242E+01 |
| 10 | 102.456 | 139.256 | 157.484 | 140.698 | 105.803 | 9.7068E+03 | 9.8237E+03 | 1.02 | 1.00 | 8.096E+01 | 7.603E+01 |
| | 104.988 | | | | 108.381 | | | | | | |

FUEL PLATE 4 (ExactSoln)

| NODE | COOLANTl | CladSl | FUEL PEAK | CladSr | COOLANTr | HCOFl | HCOFr | ONBRl | ONBRr | ETA'l | ETA'r |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 45.000 | | | | 45.000 | | | | | | |
| 1 | 47.725 | 105.142 | 129.129 | 117.096 | 47.083 | 7.1368E+03 | 4.1454E+03 | 1.65 | 1.37 | 1.919E+02 | 1.364E+02 |
| 2 | 53.420 | 113.016 | 139.015 | 125.641 | 51.462 | 7.4915E+03 | 4.3167E+03 | 1.46 | 1.22 | 1.645E+02 | 1.173E+02 |
| 3 | 59.605 | 121.013 | 148.979 | 134.230 | 56.269 | 7.8614E+03 | 4.4969E+03 | 1.30 | 1.10 | 1.406E+02 | 1.008E+02 |
| 4 | 66.278 | 129.215 | 159.201 | 143.113 | 61.504 | 8.2540E+03 | 4.6626E+03 | 1.18 | 1.00 | 1.190E+02 | 8.661E+01 |
| 5 | 73.436 | 137.778 | 169.802 | 152.388 | 67.161 | 8.6473E+03 | 4.8140E+03 | 1.06 | 0.91 | 9.956E+01 | 7.404E+01 |
| 6 | 80.814 | 142.631 | 174.243 | 156.523 | 73.049 | 8.9424E+03 | 4.9581E+03 | 1.01 | 0.88 | 8.821E+01 | 6.692E+01 |
| 7 | 87.889 | 143.344 | 172.267 | 155.384 | 78.783 | 9.2002E+03 | 5.0887E+03 | 1.00 | 0.88 | 8.307E+01 | 6.434E+01 |
| 8 | 94.408 | 144.052 | 170.350 | 154.345 | 84.164 | 9.4298E+03 | 5.2037E+03 | 0.98 | 0.88 | 7.792E+01 | 6.192E+01 |
| 9 | 100.377 | 144.636 | 168.369 | 153.281 | 89.184 | 9.6380E+03 | 5.3060E+03 | 0.97 | 0.89 | 7.277E+01 | 5.969E+01 |
| 10 | 105.803 | 145.033 | 166.250 | 152.109 | 93.838 | 9.8237E+03 | 5.3992E+03 | 0.96 | 0.89 | 6.763E+01 | 5.766E+01 |
| | 108.381 | | | | 96.073 | | | | | | |

[1] The ONB ratio is here defined as (Tonb - Tinlet)/(Tsurf - Tinlet). If the heat flux is negative (the coolant is hotter than the adjacent cladding surface), then the ONB ratio is arbitrarily set to 99.99 .

MIXED MEAN TEMP. (CORE FLOW ONLY)= 104.456
WORK: TBAR RETURNED FROM FINLED= 104.459

## Table 19. Standard Problem 13 Input Data for PLTEMP/ANL V3.0: 50% of Reactor Power Produced in Fuel and 50% in Cladding, No Heat Source in Coolant (Cladding Thickness = 0.5 mm)

```
 Standard Problem 13: 2 subassemblies (of identical geometry) producing 1 MWt
! Each subassembly has 4 fuel plates and 5 coolant channels
! Each fuel plate has equal power all of which is directly deposited in
! coolant channels. See card(2) 0500.
! H2O coolant, Input coolant flow = 0.50 kg/s in channel 2, 3, or 4
!                                  = 0.25 kg/s in channel 1, or 5
! All hot channel factors = 1.0
! No bypass flow, NCTYP=0
! 10 axial heat transfer nodes in the heated length of fuel plates
!  1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18        Indices Card 0200
   0   0   5   1   0   1   1   1   0   0   0   0   0           1                Card(1)0200
   2   3 0.00       1.00        1.00        1.00           3                    Card(1)0300
! Using pressure driven mode
   1  20 1.00                                                                   Card(1)0301
   1   1   1                                                                    Card(1)0302
1.20        1.20                                                                Card(2)0303
30.0E-04    0.02955665  0.15        8.00        0.20        15.0E-03            Card(3)0304
30.0E-04    0.02955665  0.75        0.00        0.20        15.0E-03            Card(3)0304
30.0E-04    0.02955665  0.15        8.00        0.20        15.0E-03            Card(3)0304
! Use the code's biult-in correlation for friction factor
0.00        0.00        0.00                                                    Card(1)0305
   5   3 0.00       0.75        0.50E-03    10.00       1.00E-03    10.00       Card(1)0306
6.00E-04    5.91133E-03 0.4060      0.20        0.20        3.00E-03            Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03            Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03            Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03            Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.20        0.20        3.00E-03            Card(5)0307
0.20        0.20        0.20        0.20                                        Card(1)0308
! Card 0308a not required
! Radial power peaking factor data by fuel plate for each subassembly. Input flow data by
! channel for each subassembly on Cards 0310 not required because WFGES(1) is non-zero
1.000       1.000       1.000       1.000                                       Card(2)0309
0.25        0.50        0.50        0.50        0.25                            Card(2)0310
1.000       1.000       1.000       1.000                                       Card(2)0309
0.25        0.50        0.50        0.50        0.25                            Card(2)0310
! DP0       DDP         DPMAX       POWER       TIN         PIN
0.32336     0.04        0.36136     1.00        45.0        0.12                Card(2)0500
0.5         0.0                                                                 Card(2)0500
  50 0.0001     25.0        0.50        1.00                                    Card(1)0600
  11                                                                            Card(1)0700
0.00        0.80                                                                Card(11)0701
0.10        0.88                                                                Card(11)0701
0.20        0.96                                                                Card(11)0701
0.30        1.04                                                                Card(11)0701
0.40        1.12                                                                Card(11)0701
0.50        1.20                                                                Card(11)0701
0.60        1.12                                                                Card(11)0701
0.70        1.04                                                                Card(11)0701
0.80        0.96                                                                Card(11)0701
0.90        0.88                                                                Card(11)0701
1.00        0.80                                                                Card(11)0701
   0                                                                            Card(11)0702
```

## Table 20. Exact Solution of Standard Problem 13: 50% of Reactor Power Produced in Fuel and 50% in Cladding, No Heat Source in Coolant (Cladding Thickness = 0.5 mm)

```
Input Power Densities (MW/m**3) in Axial Node   1 of Subassembly   1 of Type   1:
FUEL PLATE  COOLANTl     CLADDINGl   FUEL MEAT   CLADDINGr   COOLANTr
     1      0.0000E+00  3.5000E+02  3.5000E+02  3.5000E+02  0.0000E+00
     2      0.0000E+00  3.5000E+02  3.5000E+02  3.5000E+02  0.0000E+00
     3      0.0000E+00  3.5000E+02  3.5000E+02  3.5000E+02  0.0000E+00
     4      0.0000E+00  3.5000E+02  3.5000E+02  3.5000E+02  0.0000E+00

 FUEL PLATE   1 (ExactSoln)
 NODE    COOLANTl  CladSl  FUEL PEAK   CladSr  COOLANTr   HCOFl      HCOFr    ONBRl  ONBRr  ETA'l     ETA'r
            (C)     (C)       (C)       (C)       (C)     W/C-m^2    W/C-m^2   [F Note 1]  K-cm^3/J  K-cm^3/J
          45.000                                45.000
    1     47.083   117.096   129.129   105.142    47.725 4.1454E+03 7.1368E+03  1.37  1.65 1.364E+02 1.919E+02
    2     51.462   125.641   139.015   113.016    53.420 4.3167E+03 7.4915E+03  1.22  1.46 1.173E+02 1.645E+02
    3     56.269   134.230   148.979   121.013    59.605 4.4969E+03 7.8614E+03  1.10  1.30 1.008E+02 1.406E+02
    4     61.504   143.113   159.201   129.215    66.278 4.6626E+03 8.2540E+03  1.00  1.18 8.661E+01 1.190E+02
    5     67.161   152.388   169.802   137.778    73.436 4.8140E+03 8.6473E+03  0.91  1.06 7.404E+01 9.956E+01
    6     73.049   156.523   174.243   142.631    80.814 4.9581E+03 8.9424E+03  0.88  1.01 6.692E+01 8.821E+01
    7     78.783   155.384   172.267   143.344    87.889 5.0887E+03 9.2002E+03  0.88  1.00 6.434E+01 8.307E+01
    8     84.164   154.345   170.350   144.052    94.408 5.2037E+03 9.4298E+03  0.88  0.98 6.192E+01 7.792E+01
    9     89.184   153.281   168.369   144.636   100.377 5.3060E+03 9.6380E+03  0.89  0.97 5.969E+01 7.277E+01
   10     93.838   152.109   166.250   145.033   105.803 5.3992E+03 9.8237E+03  0.89  0.96 5.766E+01 6.763E+01
          96.073                               108.381

 FUEL PLATE   2 (ExactSoln)
          45.000                                45.000
    1     47.725    97.260   114.732    97.204    47.513 7.0601E+03 7.0492E+03  1.90  1.90 2.249E+02 2.250E+02
    2     53.420   105.018   124.097   104.842    52.781 7.4123E+03 7.3801E+03  1.65  1.65 1.921E+02 1.926E+02
    3     59.605   112.957   133.635   112.646    58.531 7.7807E+03 7.7283E+03  1.45  1.46 1.635E+02 1.645E+02
    4     66.278   121.078   143.360   120.642    64.760 8.1720E+03 8.0915E+03  1.30  1.30 1.381E+02 1.396E+02
    5     73.436   129.502   153.353   128.868    71.469 8.5642E+03 8.4759E+03  1.16  1.17 1.154E+02 1.173E+02
    6     80.814   134.602   158.354   133.769    78.420 8.9085E+03 8.8077E+03  1.09  1.11 1.018E+02 1.042E+02
    7     87.889   136.309   158.298   135.281    85.137 9.1875E+03 9.0767E+03  1.07  1.08 9.527E+01 9.829E+01
    8     94.408   137.955   158.190   136.749    91.383 9.4298E+03 9.3174E+03  1.04  1.06 8.883E+01 9.241E+01
    9    100.377   139.454   157.955   138.112    97.156 9.6380E+03 9.5237E+03  1.02  1.04 8.242E+01 8.663E+01
   10    105.803   140.698   157.484   139.256   102.456 9.8237E+03 9.7068E+03  1.00  1.02 7.603E+01 8.096E+01
         108.381                               104.988

FUEL PLATE   3 (ExactSoln)
 NODE
          45.000                                45.000
    1     47.513    97.204   114.732    97.260    47.725 7.0492E+03 7.0601E+03  1.90  1.90 2.250E+02 2.249E+02
    2     52.781   104.842   124.097   105.018    53.420 7.3801E+03 7.4123E+03  1.65  1.65 1.926E+02 1.921E+02
    3     58.531   112.646   133.635   112.957    59.605 7.7283E+03 7.7807E+03  1.46  1.45 1.645E+02 1.635E+02
    4     64.760   120.642   143.360   121.078    66.278 8.0915E+03 8.1720E+03  1.30  1.30 1.396E+02 1.381E+02
    5     71.469   128.868   153.353   129.502    73.436 8.4759E+03 8.5642E+03  1.17  1.16 1.173E+02 1.154E+02
    6     78.420   133.769   158.354   134.602    80.814 8.8077E+03 8.9085E+03  1.11  1.09 1.042E+02 1.018E+02
    7     85.137   135.281   158.298   136.309    87.889 9.0767E+03 9.1875E+03  1.08  1.07 9.829E+01 9.527E+01
    8     91.383   136.749   158.190   137.955    94.408 9.3174E+03 9.4298E+03  1.06  1.04 9.241E+01 8.883E+01
    9     97.156   138.112   157.955   139.454   100.377 9.5237E+03 9.6380E+03  1.04  1.02 8.663E+01 8.242E+01
   10    102.456   139.256   157.484   140.698   105.803 9.7068E+03 9.8237E+03  1.02  1.00 8.096E+01 7.603E+01
         104.988                               108.381

 FUEL PLATE   4 (ExactSoln)
          45.000                                45.000
    1     47.725   105.142   129.129   117.096    47.083 7.1368E+03 4.1454E+03  1.65  1.37 1.919E+02 1.364E+02
    2     53.420   113.016   139.015   125.641    51.462 7.4915E+03 4.3167E+03  1.46  1.22 1.645E+02 1.173E+02
    3     59.605   121.013   148.979   134.230    56.269 7.8614E+03 4.4969E+03  1.30  1.10 1.406E+02 1.008E+02
    4     66.278   129.215   159.201   143.113    61.504 8.2540E+03 4.6626E+03  1.18  1.00 1.190E+02 8.661E+01
    5     73.436   137.778   169.802   152.388    67.161 8.6473E+03 4.8140E+03  1.06  0.91 9.956E+01 7.404E+01
    6     80.814   142.631   174.243   156.523    73.049 8.9424E+03 4.9581E+03  1.01  0.88 8.821E+01 6.692E+01
    7     87.889   143.344   172.267   155.384    78.783 9.2002E+03 5.0887E+03  1.00  0.88 8.307E+01 6.434E+01
    8     94.408   144.052   170.350   154.345    84.164 9.4298E+03 5.2037E+03  0.98  0.88 7.792E+01 6.192E+01
    9    100.377   144.636   168.369   153.281    89.184 9.6380E+03 5.3060E+03  0.97  0.89 7.277E+01 5.969E+01
   10    105.803   145.033   166.250   152.109    93.838 9.8237E+03 5.3992E+03  0.96  0.89 6.763E+01 5.766E+01
         108.381                                96.073
[1] The ONB ratio is here defined as (Tonb - Tinlet)/(Tsurf - Tinlet). If the heat flux is negative (the
    coolant is hotter than the adjacent cladding surface), then the ONB ratio is arbitrarily set to 99.99 .


MIXED MEAN TEMP. (CORE FLOW ONLY)=   104.456
 WORK: TBAR RETURNED FROM FINLED= 104.459
```

**Table 21. Standard Problem 14 Input Data for PLTEMP/ANL V3.0: 10% of Reactor Power Produced in Fuel and 90% in Cladding, No Heat Source in Coolant (Cladding Thickness = 0.9 mm)**

```
 Standard Problem 14: 2 subassemblies (of identical geometry) producing 1 MWt
! Each subassembly has 4 fuel plates and 5 coolant channels
! Each fuel plate has equal power all of which is directly deposited in
! coolant channels. See card(2) 0500.
! H2O coolant, Input coolant flow = 0.50 kg/s in channel 2, 3, or 4
!                                  = 0.25 kg/s in channel 1, or 5
! All hot channel factors = 1.0
! No bypass flow, NCTYP=0
! 10 axial heat transfer nodes in the heated length of fuel plates
!  1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18        Indices Card 0200
   0   0   5   1   0   1   1   1   0   0   0   0   0           1                Card(1)0200
   2   3 0.00       1.00        1.00        1.00          3                     Card(1)0300
! Using pressure driven mode
   1  20 1.00                                                                   Card(1)0301
   1   1   1                                                                    Card(1)0302
1.20        1.20                                                                Card(2)0303
30.0E-04    0.02955665  0.15        8.00        0.20        15.0E-03            Card(3)0304
30.0E-04    0.02955665  0.75        0.00        0.20        15.0E-03            Card(3)0304
30.0E-04    0.02955665  0.15        8.00        0.20        15.0E-03            Card(3)0304
! Use the code's biult-in correlation for friction factor
0.00        0.00        0.00                                                    Card(1)0305
   5   3 0.00       0.75        0.90E-03    10.00       0.20E-03    10.00       Card(1)0306
6.00E-04    5.91133E-03 0.4060      0.20        0.20        3.00E-03            Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03            Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03            Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03            Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.20        0.20        3.00E-03            Card(5)0307
0.20        0.20        0.20        0.20                                        Card(1)0308
! Card 0308a not required
! Radial power peaking factor data by fuel plate for each subassembly. Input flow data by
! channel for each subassembly on Cards 0310 not required because WFGES(1) is non-zero
1.000       1.000       1.000       1.000                                       Card(2)0309
0.25        0.50        0.50        0.50        0.25                            Card(2)0310
1.000       1.000       1.000       1.000                                       Card(2)0309
0.25        0.50        0.50        0.50        0.25                            Card(2)0310
! DP0       DDP         DPMAX       POWER       TIN         PIN
0.32336     0.04        0.36136     1.00        45.0        0.12                Card(2)0500
0.9         0.0                                                                 Card(2)0500
  50 0.0001     25.0        0.50        1.00                                    Card(1)0600
  11                                                                            Card(1)0700
0.00        0.80                                                                Card(11)0701
0.10        0.88                                                                Card(11)0701
0.20        0.96                                                                Card(11)0701
0.30        1.04                                                                Card(11)0701
0.40        1.12                                                                Card(11)0701
0.50        1.20                                                                Card(11)0701
0.60        1.12                                                                Card(11)0701
0.70        1.04                                                                Card(11)0701
0.80        0.96                                                                Card(11)0701
0.90        0.88                                                                Card(11)0701
1.00        0.80                                                                Card(11)0701
   0                                                                            Card(11)0702
```

## Table 22. Exact Solution of Standard Problem 14: 10% of Reactor Power Produced in Fuel and 90% in Cladding, No Heat Source in Coolant (Cladding Thickness = 0.9 mm)

```
Input Power Densities (MW/m**3) in Axial Node   1 of Subassembly   1 of Type   1:
FUEL PLATE  COOLANTl    CLADDINGl   FUEL MEAT   CLADDINGr   COOLANTr
     1      0.0000E+00  3.5000E+02  3.5000E+02  3.5000E+02  0.0000E+00
     2      0.0000E+00  3.5000E+02  3.5000E+02  3.5000E+02  0.0000E+00
     3      0.0000E+00  3.5000E+02  3.5000E+02  3.5000E+02  0.0000E+00
     4      0.0000E+00  3.5000E+02  3.5000E+02  3.5000E+02  0.0000E+00

 FUEL PLATE   1 (ExactSoln)
 NODE    COOLANTl  CladSl  FUEL PEAK   CladSr  COOLANTr   HCOFl      HCOFr     ONBRl  ONBRr  ETA'l     ETA'r
          (C)       (C)       (C)       (C)       (C)    W/C-m^2    W/C-m^2    [F Note 1]  K-cm^3/J  K-cm^3/J
         45.000                                  45.000
    1    47.083   117.096   129.041   105.142    47.725 4.1454E+03 7.1368E+03  1.37   1.65 1.364E+02 1.919E+02
    2    51.462   125.641   138.934   113.016    53.420 4.3167E+03 7.4915E+03  1.22   1.46 1.173E+02 1.645E+02
    3    56.269   134.230   148.908   121.013    59.605 4.4969E+03 7.8614E+03  1.10   1.30 1.008E+02 1.406E+02
    4    61.504   143.113   159.134   129.215    66.278 4.6626E+03 8.2540E+03  1.00   1.18 8.661E+01 1.190E+02
    5    67.161   152.388   169.738   137.778    73.436 4.8140E+03 8.6473E+03  0.91   1.06 7.404E+01 9.956E+01
    6    73.049   156.523   174.197   142.631    80.814 4.9581E+03 8.9424E+03  0.88   1.01 6.692E+01 8.821E+01
    7    78.783   155.384   172.241   143.344    87.889 5.0887E+03 9.2002E+03  0.88   1.00 6.434E+01 8.307E+01
    8    84.164   154.345   170.338   144.052    94.408 5.2037E+03 9.4298E+03  0.88   0.98 6.192E+01 7.792E+01
    9    89.184   153.281   168.366   144.636   100.377 5.3060E+03 9.6380E+03  0.89   0.97 5.969E+01 7.277E+01
   10    93.838   152.109   166.250   145.033   105.803 5.3992E+03 9.8237E+03  0.89   0.96 5.766E+01 6.763E+01
         96.073                                 108.381

 FUEL PLATE   2 (ExactSoln)
         45.000                                  45.000
    1    47.725    97.260   114.732    97.204    47.513 7.0601E+03 7.0492E+03  1.90   1.90 2.249E+02 2.250E+02
    2    53.420   105.018   124.097   104.842    52.781 7.4123E+03 7.3801E+03  1.65   1.65 1.921E+02 1.926E+02
    3    59.605   112.957   133.635   112.646    58.531 7.7807E+03 7.7283E+03  1.45   1.46 1.635E+02 1.645E+02
    4    66.278   121.078   143.360   120.642    64.760 8.1720E+03 8.0915E+03  1.30   1.30 1.381E+02 1.396E+02
    5    73.436   129.502   153.353   128.868    71.469 8.5642E+03 8.4759E+03  1.16   1.17 1.154E+02 1.173E+02
    6    80.814   134.602   158.354   133.769    78.420 8.9085E+03 8.8077E+03  1.09   1.11 1.018E+02 1.042E+02
    7    87.889   136.309   158.298   135.281    85.137 9.1875E+03 9.0767E+03  1.07   1.08 9.527E+01 9.829E+01
    8    94.408   137.955   158.190   136.749    91.383 9.4298E+03 9.3174E+03  1.04   1.06 8.883E+01 9.241E+01
    9   100.377   139.454   157.955   138.112    97.156 9.6380E+03 9.5237E+03  1.02   1.04 8.242E+01 8.663E+01
   10   105.803   140.698   157.484   139.256   102.456 9.8237E+03 9.7068E+03  1.00   1.02 7.603E+01 8.096E+01
        108.381                                 104.988

FUEL PLATE   3 (ExactSoln)
         45.000                                  45.000
    1    47.513    97.204   114.732    97.260    47.725 7.0492E+03 7.0601E+03  1.90   1.90 2.250E+02 2.249E+02
    2    52.781   104.842   124.097   105.018    53.420 7.3801E+03 7.4123E+03  1.65   1.65 1.926E+02 1.921E+02
    3    58.531   112.646   133.635   112.957    59.605 7.7283E+03 7.7807E+03  1.46   1.45 1.645E+02 1.635E+02
    4    64.760   120.642   143.360   121.078    66.278 8.0915E+03 8.1720E+03  1.30   1.30 1.396E+02 1.381E+02
    5    71.469   128.868   153.353   129.502    73.436 8.4759E+03 8.5642E+03  1.17   1.16 1.173E+02 1.154E+02
    6    78.420   133.769   158.354   134.602    80.814 8.8077E+03 8.9085E+03  1.11   1.09 1.042E+02 1.018E+02
    7    85.137   135.281   158.298   136.309    87.889 9.0767E+03 9.1875E+03  1.08   1.07 9.829E+01 9.527E+01
    8    91.383   136.749   158.190   137.955    94.408 9.3174E+03 9.4298E+03  1.06   1.04 9.241E+01 8.883E+01
    9    97.156   138.112   157.955   139.454   100.377 9.5237E+03 9.6380E+03  1.04   1.02 8.663E+01 8.242E+01
   10   102.456   139.256   157.484   140.698   105.803 9.7068E+03 9.8237E+03  1.02   1.00 8.096E+01 7.603E+01
        104.988                                 108.381

 FUEL PLATE   4 (ExactSoln)
         45.000                                  45.000
    1    47.725   105.142   129.041   117.096    47.083 7.1368E+03 4.1454E+03  1.65   1.37 1.919E+02 1.364E+02
    2    53.420   113.016   138.934   125.641    51.462 7.4915E+03 4.3167E+03  1.46   1.22 1.645E+02 1.173E+02
    3    59.605   121.013   148.908   134.230    56.269 7.8614E+03 4.4969E+03  1.30   1.10 1.406E+02 1.008E+02
    4    66.278   129.215   159.134   143.113    61.504 8.2540E+03 4.6626E+03  1.18   1.00 1.190E+02 8.661E+01
    5    73.436   137.778   169.738   152.388    67.161 8.6473E+03 4.8140E+03  1.06   0.91 9.956E+01 7.404E+01
    6    80.814   142.631   174.197   156.523    73.049 8.9424E+03 4.9581E+03  1.01   0.88 8.821E+01 6.692E+01
    7    87.889   143.344   172.241   155.384    78.783 9.2002E+03 5.0887E+03  1.00   0.88 8.307E+01 6.434E+01
    8    94.408   144.052   170.338   154.345    84.164 9.4298E+03 5.2037E+03  0.98   0.88 7.792E+01 6.192E+01
    9   100.377   144.636   168.366   153.281    89.184 9.6380E+03 5.3060E+03  0.97   0.89 7.277E+01 5.969E+01
   10   105.803   145.033   166.250   152.109    93.838 9.8237E+03 5.3992E+03  0.96   0.89 6.763E+01 5.766E+01
        108.381                                  96.073
[1] The ONB ratio is here defined as (Tonb - Tinlet)/(Tsurf - Tinlet). If the heat flux is negative (the
    coolant is hotter than the adjacent cladding surface), then the ONB ratio is arbitrarily set to 99.99 .

MIXED MEAN TEMP. (CORE FLOW ONLY)=   104.456

 WORK: TBAR RETURNED FROM FINLED= 104.459
```

## Table 23. Standard Problem 15 Input Data for PLTEMP/ANL V3.0: 100% of Reactor Power Directly Deposited in Coolant (No Heat Source in Fuel and Cladding)

```
 Standard Problem 15: 2 subassemblies (of identical geometry) producing 1 MWt
! Each subassembly has 4 fuel plates and 5 coolant channels
! Each fuel plate has equal power all of which is directly deposited in
! coolant channels. See card(2) 0500.
! H2O coolant, Input coolant flow = 0.50 kg/s in channel 2, 3, or 4
!                                 = 0.25 kg/s in channel 1, or 5
! All hot channel factors = 1.0
! No bypass flow, NCTYP=0
! 10 axial heat transfer nodes in the heated length of fuel plates
!  1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18        Indices Card 0200
   0   0   5   1   0   1   1   1   0   0   0   0   0           1                Card(1)0200
   2   3 0.00       1.00       1.00        1.00          3                      Card(1)0300
! Using pressure driven mode
   1  20 1.00                                                                   Card(1)0301
   1   1   1                                                                    Card(1)0302
1.20        1.20                                                                Card(2)0303
30.0E-04    0.02955665  0.15        8.00        0.20        15.0E-03            Card(3)0304
30.0E-04    0.02955665  0.75        0.00        0.20        15.0E-03            Card(3)0304
30.0E-04    0.02955665  0.15        8.00        0.20        15.0E-03            Card(3)0304
! Use the code's biult-in correlation for friction factor
0.00        0.00        0.00                                                    Card(1)0305
   5   3 0.00       0.75        0.50E-03    10.00       1.00E-03    10.00       Card(1)0306
6.00E-04    5.91133E-03 0.4060      0.20        0.20        3.00E-03            Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03            Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03            Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03            Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.20        0.20        3.00E-03            Card(5)0307
0.20        0.20        0.20        0.20                                        Card(1)0308
! Card 0308a not required
! Radial power peaking factor data by fuel plate for each subassembly. Input flow data by
! channel for each subassembly on Cards 0310 not required because WFGES(1) is non-zero
1.000       1.000       1.000       1.000                                       Card(2)0309
0.25        0.50        0.50        0.50        0.25                            Card(2)0310
1.000       1.000       1.000       1.000                                       Card(2)0309
0.25        0.50        0.50        0.50        0.25                            Card(2)0310
! DP0       DDP         DPMAX       POWER       TIN         PIN
0.32336     0.04        0.36136     1.00        45.0        0.12                Card(2)0500
0.0         .99999999999                                                        Card(2)0500
  50 0.0001     25.0        0.50        1.00                                    Card(1)0600
  11                                                                            Card(1)0700
0.00        0.80                                                                Card(11)0701
0.10        0.88                                                                Card(11)0701
0.20        0.96                                                                Card(11)0701
0.30        1.04                                                                Card(11)0701
0.40        1.12                                                                Card(11)0701
0.50        1.20                                                                Card(11)0701
0.60        1.12                                                                Card(11)0701
0.70        1.04                                                                Card(11)0701
0.80        0.96                                                                Card(11)0701
0.90        0.88                                                                Card(11)0701
1.00        0.80                                                                Card(11)0701
   0                                                                            Card(11)0702
```

## Table 24. Exact Solution of Standard Problem 15: 100% of Reactor Power Directly Deposited in Coolant (No Heat Source in Fuel and Cladding)

Input Power Densities (MW/m**3) in Axial Node 1 of Subassembly 1 of Type 1:

| FUEL PLATE | COOLANTl | CLADDINGl | FUEL MEAT | CLADDINGr | COOLANTr |
|---|---|---|---|---|---|
| 1 | 1.1667E+02 | 0.0000E+00 | 7.0000E-09 | 0.0000E+00 | 2.3333E+02 |
| 2 | 2.3333E+02 | 0.0000E+00 | 7.0000E-09 | 0.0000E+00 | 2.3333E+02 |
| 3 | 2.3333E+02 | 0.0000E+00 | 7.0000E-09 | 0.0000E+00 | 2.3333E+02 |
| 4 | 2.3333E+02 | 0.0000E+00 | 7.0000E-09 | 0.0000E+00 | 1.1667E+02 |

FUEL PLATE 1 (ExactSoln)

| NODE | COOLANTl (C) | CladSl (C) | FUEL PEAK (C) | CladSr (C) | COOLANTr (C) | HCOFl W/C-m^2 | HCOFr W/C-m^2 | ONBRl [F Note 1] | ONBRr [F Note 1] | ETA'l K-cm^3/J | ETA'r K-cm^3/J |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 45.000 | | | | 45.000 | | | | | | |
| 1 | 47.511 | 47.511 | 47.511 | 47.511 | 47.511 | 3.7008E+03 | 6.4434E+03 | 37.75 | 37.75 | 1.375E+13 | 1.907E+13 |
| 2 | 52.771 | 52.771 | 52.771 | 52.771 | 52.771 | 3.8824E+03 | 6.7597E+03 | 12.15 | 12.15 | 1.166E+13 | 1.647E+13 |
| 3 | 58.503 | 58.503 | 58.503 | 58.503 | 58.503 | 4.0745E+03 | 7.0940E+03 | 6.97 | 6.97 | 9.874E+12 | 1.419E+13 |
| 4 | 64.705 | 64.705 | 64.705 | 64.705 | 64.705 | 4.2757E+03 | 7.4444E+03 | 4.75 | 4.75 | 8.315E+12 | 1.215E+13 |
| 5 | 71.376 | 71.376 | 71.376 | 71.376 | 71.376 | 4.4908E+03 | 7.8190E+03 | 3.54 | 3.54 | 6.939E+12 | 1.030E+13 |
| 6 | 78.275 | 78.275 | 78.275 | 78.275 | 78.275 | 4.6928E+03 | 8.1706E+03 | 2.79 | 2.79 | 6.118E+12 | 9.252E+12 |
| 7 | 84.926 | 84.926 | 84.926 | 84.926 | 84.926 | 4.8756E+03 | 8.4888E+03 | 2.32 | 2.32 | 5.722E+12 | 8.849E+12 |
| 8 | 91.093 | 91.093 | 91.093 | 91.093 | 91.093 | 5.0391E+03 | 8.7735E+03 | 2.00 | 2.00 | 5.341E+12 | 8.448E+12 |
| 9 | 96.776 | 96.776 | 96.776 | 96.776 | 96.776 | 5.1903E+03 | 9.0368E+03 | 1.77 | 1.77 | 4.972E+12 | 8.054E+12 |
| 10 | 101.979 | 101.979 | 101.979 | 101.979 | 101.979 | 5.3290E+03 | 9.2783E+03 | 1.60 | 1.60 | 4.618E+12 | 7.669E+12 |
| | 104.459 | | | | 104.459 | | | | | | |

FUEL PLATE 2 (ExactSoln)

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 45.000 | | | | 45.000 | | | | | | |
| 1 | 47.511 | 47.511 | 47.511 | 47.511 | 47.511 | 6.4434E+03 | 6.4434E+03 | 37.75 | 37.75 | 2.255E+13 | 2.250E+13 |
| 2 | 52.771 | 52.771 | 52.771 | 52.771 | 52.771 | 6.7597E+03 | 6.7597E+03 | 12.15 | 12.15 | 1.938E+13 | 1.924E+13 |
| 3 | 58.503 | 58.503 | 58.503 | 58.503 | 58.503 | 7.0940E+03 | 7.0940E+03 | 6.97 | 6.97 | 1.660E+13 | 1.642E+13 |
| 4 | 64.705 | 64.705 | 64.705 | 64.705 | 64.705 | 7.4444E+03 | 7.4444E+03 | 4.75 | 4.75 | 1.414E+13 | 1.394E+13 |
| 5 | 71.376 | 71.376 | 71.376 | 71.376 | 71.376 | 7.8190E+03 | 7.8190E+03 | 3.54 | 3.54 | 1.193E+13 | 1.172E+13 |
| 6 | 78.275 | 78.275 | 78.275 | 78.275 | 78.275 | 8.1706E+03 | 8.1706E+03 | 2.79 | 2.79 | 1.065E+13 | 1.042E+13 |
| 7 | 84.926 | 84.926 | 84.926 | 84.926 | 84.926 | 8.4888E+03 | 8.4888E+03 | 2.32 | 2.32 | 1.012E+13 | 9.847E+12 |
| 8 | 91.093 | 91.093 | 91.093 | 91.093 | 91.093 | 8.7735E+03 | 8.7735E+03 | 2.00 | 2.00 | 9.591E+12 | 9.283E+12 |
| 9 | 96.776 | 96.776 | 96.776 | 96.776 | 96.776 | 9.0368E+03 | 9.0368E+03 | 1.77 | 1.77 | 9.072E+12 | 8.733E+12 |
| 10 | 101.979 | 101.979 | 101.979 | 101.979 | 101.979 | 9.2783E+03 | 9.2783E+03 | 1.60 | 1.60 | 8.566E+12 | 8.201E+12 |
| | 104.459 | | | | 104.459 | | | | | | |

FUEL PLATE 3 (ExactSoln)

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 45.000 | | | | 45.000 | | | | | | |
| 1 | 47.511 | 47.511 | 47.511 | 47.511 | 47.511 | 6.4434E+03 | 6.4434E+03 | 37.75 | 37.75 | 2.250E+13 | 2.255E+13 |
| 2 | 52.771 | 52.771 | 52.771 | 52.771 | 52.771 | 6.7597E+03 | 6.7597E+03 | 12.15 | 12.15 | 1.924E+13 | 1.938E+13 |
| 3 | 58.503 | 58.503 | 58.503 | 58.503 | 58.503 | 7.0940E+03 | 7.0940E+03 | 6.97 | 6.97 | 1.642E+13 | 1.660E+13 |
| 4 | 64.705 | 64.705 | 64.705 | 64.705 | 64.705 | 7.4444E+03 | 7.4444E+03 | 4.75 | 4.75 | 1.394E+13 | 1.414E+13 |
| 5 | 71.376 | 71.376 | 71.376 | 71.376 | 71.376 | 7.8190E+03 | 7.8190E+03 | 3.54 | 3.54 | 1.172E+13 | 1.193E+13 |
| 6 | 78.275 | 78.275 | 78.275 | 78.275 | 78.275 | 8.1706E+03 | 8.1706E+03 | 2.79 | 2.79 | 1.042E+13 | 1.065E+13 |
| 7 | 84.926 | 84.926 | 84.926 | 84.926 | 84.926 | 8.4888E+03 | 8.4888E+03 | 2.32 | 2.32 | 9.846E+12 | 1.012E+13 |
| 8 | 91.093 | 91.093 | 91.093 | 91.093 | 91.093 | 8.7735E+03 | 8.7735E+03 | 2.00 | 2.00 | 9.282E+12 | 9.592E+12 |
| 9 | 96.776 | 96.776 | 96.776 | 96.776 | 96.776 | 9.0368E+03 | 9.0368E+03 | 1.77 | 1.77 | 8.733E+12 | 9.073E+12 |
| 10 | 101.979 | 101.979 | 101.979 | 101.979 | 101.979 | 9.2783E+03 | 9.2783E+03 | 1.60 | 1.60 | 8.200E+12 | 8.567E+12 |
| | 104.459 | | | | 104.459 | | | | | | |

FUEL PLATE 4 (ExactSoln)

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 45.000 | | | | 45.000 | | | | | | |
| 1 | 47.511 | 47.511 | 47.511 | 47.511 | 47.511 | 6.4434E+03 | 3.7008E+03 | 37.75 | 37.75 | 1.907E+13 | 1.375E+13 |
| 2 | 52.771 | 52.771 | 52.771 | 52.771 | 52.771 | 6.7597E+03 | 3.8824E+03 | 12.15 | 12.15 | 1.647E+13 | 1.166E+13 |
| 3 | 58.503 | 58.503 | 58.503 | 58.503 | 58.503 | 7.0940E+03 | 4.0745E+03 | 6.97 | 6.97 | 1.419E+13 | 9.874E+12 |
| 4 | 64.705 | 64.705 | 64.705 | 64.705 | 64.705 | 7.4444E+03 | 4.2757E+03 | 4.75 | 4.75 | 1.215E+13 | 8.315E+12 |
| 5 | 71.376 | 71.376 | 71.376 | 71.376 | 71.376 | 7.8190E+03 | 4.4908E+03 | 3.54 | 3.54 | 1.030E+13 | 6.939E+12 |
| 6 | 78.275 | 78.275 | 78.275 | 78.275 | 78.275 | 8.1706E+03 | 4.6928E+03 | 2.79 | 2.79 | 9.252E+12 | 6.118E+12 |
| 7 | 84.926 | 84.926 | 84.926 | 84.926 | 84.926 | 8.4888E+03 | 4.8756E+03 | 2.32 | 2.32 | 8.849E+12 | 5.722E+12 |
| 8 | 91.093 | 91.093 | 91.093 | 91.093 | 91.093 | 8.7735E+03 | 5.0391E+03 | 2.00 | 2.00 | 8.449E+12 | 5.340E+12 |
| 9 | 96.776 | 96.776 | 96.776 | 96.776 | 96.776 | 9.0368E+03 | 5.1903E+03 | 1.77 | 1.77 | 8.054E+12 | 4.972E+12 |
| 10 | 101.979 | 101.979 | 101.979 | 101.979 | 101.979 | 9.2783E+03 | 5.3290E+03 | 1.60 | 1.60 | 7.669E+12 | 4.617E+12 |
| | 104.459 | | | | 104.459 | | | | | | |

[1] The ONB ratio is here defined as (Tonb - Tinlet)/(Tsurf - Tinlet). If the heat flux is negative (the coolant is hotter than the adjacent cladding surface), then the ONB ratio is arbitrarily set to 99.99 .

MIXED MEAN TEMP. (CORE FLOW ONLY)= 104.459

WORK: TBAR RETURNED FROM FINLED= 104.459

## Table 25. PLTEMP/ANL Version 3.0 Output for Fuel Plate 1 of the University of Florida Training Reactor (Based on a Preliminary Input Data File *florida.new.hcf.v1.inp*)

BEGINNING OF NOMINAL STEADY-STATE RESULTS FOR HCF TREATMENT OPTION 2

FUEL PLATE 1 (ExactSoln)

| NODE | COOLANTl | CladSl | FUEL PEAK | CladSr | COOLANTr | HCOFl | HCOFr | ONBRl | ONBRr | ETA'l | | ETA'r |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | (C) | (C) | (C) | (C) | (C) | W/C-m^2 | W/C-m^2 | [F Note 1] | | K-cm^3/J | | K-cm^3/J |
| | 30.000 | | | | 30.000 | | | | | | | |
| 1 | 30.093 | 39.801 | 39.808 | 39.784 | 32.645 | 2.7236E | 8.7920E | 7.46 | 7.51 | 5.285E | 7.783E | 30.185 |
| 2 | 30.323 | 44.622 | 44.633 | 44.612 | 37.897 | 2.7553E | 8.8888E | 5.00 | 5.02 | 3.529E | 7.551E | 30.461 |
| 3 | 30.648 | 49.738 | 49.754 | 49.736 | 43.216 | 2.7890E | 8.9814E | 3.70 | 3.71 | 2.594E | 7.043E | 30.834 |
| 4 | 31.067 | 54.616 | 54.638 | 54.622 | 48.649 | 2.8218E | 9.0704E | 2.97 | 2.96 | 2.062E | 6.890E | 31.300 |
| 5 | 31.577 | 59.294 | 59.321 | 59.308 | 54.060 | 2.8541E | 9.1536E | 2.49 | 2.48 | 1.716E | 6.960E | 31.854 |
| 6 | 32.169 | 63.356 | 63.389 | 63.380 | 59.267 | 2.8843E | 9.2286E | 2.19 | 2.17 | 1.494E | 7.820E | 32.484 |
| 7 | 32.833 | 66.956 | 66.996 | 66.990 | 64.095 | 2.9144E | 9.2936E | 1.97 | 1.95 | 1.335E | 9.737E | 33.181 |
| 8 | 33.555 | 69.883 | 69.929 | 69.927 | 68.437 | 2.9414E | 9.3484E | 1.83 | 1.80 | 1.227E | 1.655E | 33.929 |
| 9 | 34.321 | 72.057 | 72.110 | 72.110 | 72.148 | 2.9659E | 9.3926E | 1.73 | 99.99 | 1.156E | 9.999E | 34.713 |
| 10 | 35.114 | 73.434 | 73.492 | 73.494 | 75.119 | 2.9876E | 9.4262E | 1.67 | 99.99 | 1.114E | 9.999E | 35.515 |
| 11 | 35.918 | 74.197 | 74.260 | 74.264 | 77.329 | 3.0072E | 9.4501E | 1.64 | 99.99 | 1.092E | 9.999E | 36.321 |
| 12 | 36.521 | 74.379 | 74.445 | 74.451 | 78.570 | 3.0203E | 9.4632E | 1.63 | 99.99 | 1.087E | 9.999E | 36.721 |
| 13 | 36.923 | 74.946 | 75.012 | 75.018 | 79.229 | 3.0308E | 9.4700E | 1.61 | 99.99 | 1.071E | 9.999E | 37.124 |
| | 37.124 | | | | 79.568 | | | | | | | |

FUEL PLATE 1 (ExactSoln)

| NODE | FLUX l | FLUX right | FUEL X | Tsat, C | Tdiff | FUEL-CLADinterface left (C) | right(C) | P(bar) | Z-mid | Z-int |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.6441E+03 | 6.2770E+03 | 0.2964 | 102.278 | | 39.805 | 39.794 | 1.09849 | 0.0417 | 0.0833 |
| 2 | 3.9397E+03 | 5.9689E+03 | 0.3976 | 102.138 | | 44.628 | 44.621 | 1.09307 | 0.1250 | 0.1667 |
| 3 | 5.3244E+03 | 5.8557E+03 | 0.4762 | 101.998 | | 49.746 | 49.745 | 1.08768 | 0.2083 | 0.2500 |
| 4 | 6.6450E+03 | 5.4180E+03 | 0.5509 | 101.858 | | 54.626 | 54.630 | 1.08232 | 0.2917 | 0.3333 |
| 5 | 7.9106E+03 | 4.8038E+03 | 0.6222 | 101.717 | | 59.306 | 59.315 | 1.07697 | 0.3750 | 0.4167 |
| 6 | 8.9952E+03 | 3.7960E+03 | 0.7032 | 101.577 | | 63.369 | 63.386 | 1.07162 | 0.4583 | 0.5000 |
| 7 | 9.9451E+03 | 2.6906E+03 | 0.7871 | 101.435 | | 66.971 | 66.994 | 1.06628 | 0.5417 | 0.5833 |
| 8 | 1.0685E+04 | 1.3926E+03 | 0.8847 | 101.293 | | 69.899 | 69.929 | 1.06093 | 0.6250 | 0.6667 |
| 9 | 1.1192E+04 | -3.6214E+01 | 1.0000 | 101.150 | | 72.074 | 72.110 | 1.05555 | 0.7083 | 0.7500 |
| 10 | 1.1448E+04 | -1.5314E+03 | 1.0000 | 101.005 | | 73.451 | 73.492 | 1.05014 | 0.7917 | 0.8333 |
| 11 | 1.1511E+04 | -2.8966E+03 | 1.0000 | 100.860 | | 74.214 | 74.260 | 1.04474 | 0.8750 | 0.9167 |
| 12 | 1.1435E+04 | -3.8983E+03 | 1.0000 | 100.748 | | 74.397 | 74.445 | 1.04060 | 0.9375 | 0.9583 |
| 13 | 1.1524E+04 | -3.9877E+03 | 1.0000 | 100.676 | | 74.963 | 75.012 | 1.03793 | 0.9792 | 1.0000 |

FUEL PLATE 1 (BroydenSoln)

| NODE | COOLANTl | CladSl | FUEL PEAK | CladSr | COOLANTr | HCOFl | HCOFr | ONBRl | ONBRr | ETA'l | | ETA'r |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | (C) | (C) | (C) | (C) | (C) | W/C-m^2 | W/C-m^2 | [F Note 1] | | K-cm^3/J | | K-cm^3/J |
| | 30.000 | | | | 30.000 | | | | | | | |
| 1 | 30.092 | 39.721 | 39.777 | 39.804 | 32.682 | 2.7249E | 8.8428E | 7.52 | 7.49 | 5.325E | 7.754E | 30.183 |
| 2 | 30.321 | 44.625 | 44.644 | 44.632 | 37.958 | 2.7580E | 8.9357E | 5.00 | 5.01 | 3.524E | 7.551E | 30.458 |
| 3 | 30.644 | 49.658 | 49.742 | 49.792 | 43.289 | 2.7923E | 9.0281E | 3.72 | 3.70 | 2.602E | 7.016E | 30.829 |
| 4 | 31.062 | 54.682 | 54.655 | 54.591 | 48.680 | 2.8268E | 9.1124E | 2.96 | 2.97 | 2.052E | 6.927E | 31.295 |
| 5 | 31.571 | 59.228 | 59.265 | 59.262 | 54.033 | 2.8593E | 9.1928E | 2.50 | 2.49 | 1.717E | 6.961E | 31.847 |
| 6 | 32.161 | 63.267 | 63.333 | 63.357 | 59.254 | 2.8902E | 9.2629E | 2.19 | 2.17 | 1.495E | 7.812E | 32.474 |
| 7 | 32.822 | 66.897 | 66.956 | 66.969 | 64.093 | 2.9211E | 9.3233E | 1.98 | 1.95 | 1.334E | 9.769E | 33.169 |
| 8 | 33.543 | 69.860 | 69.907 | 69.905 | 68.444 | 2.9488E | 9.3730E | 1.83 | 1.80 | 1.225E | 1.684E | 33.916 |
| 9 | 34.306 | 71.831 | 72.006 | 72.130 | 72.129 | 2.9727E | 9.4113E | 1.74 | 1.69 | 1.160E | 3.615E | 34.695 |
| 10 | 35.041 | 68.396 | 71.941 | ***75.439*** | ***75.439*** | 2.9732E | 9.4477E | 1.89 | 1.56 | 1.288E | 2.372E | 35.387 |
| 11 | 35.688 | 64.707 | 71.663 | ***78.579*** | ***78.579*** | 2.9685E | 9.4786E | 2.08 | 99.99 | 1.464E | 9.999E | 35.988 |
| 12 | 36.120 | 61.581 | 71.185 | ***80.754*** | ***80.754*** | 2.9599E | 9.4925E | 2.28 | 99.99 | 1.660E | 9.999E | 36.251 |
| 13 | 36.383 | 61.790 | 71.986 | ***82.147*** | ***82.147*** | 2.9662E | 9.5062E | 2.27 | 99.99 | 1.651E | 9.999E | 36.514 |
| | 36.514 | | | | 82.850 | | | | | | | |

FUEL PLATE 1 (BroydenSoln)

| NODE | FLUX l | FLUX right | FUEL X | Tsat, C | Tdiff | FUEL-CLADinterface left (C) | right(C) | P(bar) | Z-mid | Z-int |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.6239E-03 | 6.2973E-03 | 0.2941 | 102.278 | -0.10 | 39.725 | 39.813 | 1.09849 | 0.0417 | 0.0833 |
| 2 | 3.9451E-03 | 5.9635E-03 | 0.3981 | 102.138 | -0.02 | 44.630 | 44.641 | 1.09307 | 0.1250 | 0.1667 |
| 3 | 5.3092E-03 | 5.8709E-03 | 0.4749 | 101.998 | -0.14 | 49.666 | 49.801 | 1.08768 | 0.2083 | 0.2500 |
| 4 | 6.6768E-03 | 5.3862E-03 | 0.5535 | 101.858 | 0.10 | 54.692 | 54.599 | 1.08232 | 0.2917 | 0.3333 |
| 5 | 7.9080E-03 | 4.8063E-03 | 0.6220 | 101.717 | -0.02 | 59.240 | 59.269 | 1.07697 | 0.3750 | 0.4167 |
| 6 | 8.9903E-03 | 3.8009E-03 | 0.7029 | 101.577 | -0.07 | 63.280 | 63.363 | 1.07162 | 0.4583 | 0.5000 |
| 7 | 9.9537E-03 | 2.6819E-03 | 0.7877 | 101.435 | -0.04 | 66.912 | 66.973 | 1.06628 | 0.5417 | 0.5833 |
| 8 | 1.0709E-02 | 1.3689E-03 | 0.8867 | 101.293 | 0.00 | 69.876 | 69.907 | 1.06093 | 0.6250 | 0.6667 |
| 9 | 1.1155E-02 | 5.6319E-07 | 0.9999 | 101.150 | -0.25 | 71.848 | ***72.130*** | 1.05555 | 0.7083 | 0.7500 |
| 10 | 9.9170E-03 | 7.5631E-11 | 1.0000 | 101.005 | -7.00 | 68.411 | ***75.439*** | 1.05015 | 0.7917 | 0.8333 |
| 11 | 8.6145E-03 | 0.0000E | 1.0000 | 100.860 | -13.83 | 64.720 | ***78.579*** | 1.04473 | 0.8750 | 0.9167 |
| 12 | 7.5362E-03 | 0.0000E | 1.0000 | 100.749 | -19.14 | 61.592 | ***80.754*** | 1.04062 | 0.9375 | 0.9583 |
| 13 | 7.5362E-03 | 0.0000E | 1.0000 | 100.676 | -20.32 | 61.801 | ***82.147*** | 1.03794 | 0.9792 | 1.0000 |

[1] The ONB ratio is here defined as (Tonb - Tinlet)/(Tsurf - Tinlet). If the heat flux is negative (the coolant is hotter than the adjacent cladding surface), then the ONB ratio is arbitrarily set to 99.99 .

**APPENDIX A**
**IRT-1 LEU Steady State Analysis with Inner Channel Blocked**
**RELAP5/Mod3.2.1.2 Vs. PLTEMP w/Exact Solution**

One of the events to be analyzed for the IRT-1 LEU Safety Analysis is a blocked inner channel for the 8-tube fuel assembly with the highest power peak. This analysis was first performed using the RELAP5/Mod3.2.1.2 code because the existing version of PLTEMP (v2.1) had a convergence problem. Recently, an analytical solution for the problem with parallel plates has been implemented. This new code is still in testing mode and was used in this analysis. Note that this code can use only one axial power distribution for all the parallel plates (in this analysis the tubes are modeled as parallel plates). In RELAP, calculated distributions can be used for each of the plates, and this is a small modification that should be implemented in a future version of PLTEMP code.

The results are presented below for two cases:

1. Figures 1a/1c: Results for the outer tube (tube 8) and for the two inner tubes (tube 7 and tube 8) are presented for the case in which RELAP uses the calculated axial distributions for each tube. These figures show that even in this (not consistent) case both codes yield essentially the same results. Small differences do exist mainly at the ends of the fuel element because of the different axial power shapes for the inner tubes.
2. Figures 2a/2c: The RELAP input was modified to use the same axial distribution for all tubes as in PLTEMP. These figures show that the results are in very good agreement.

It is concluded that the analytical solution implemented in the new PLTEMP is performing correctly.

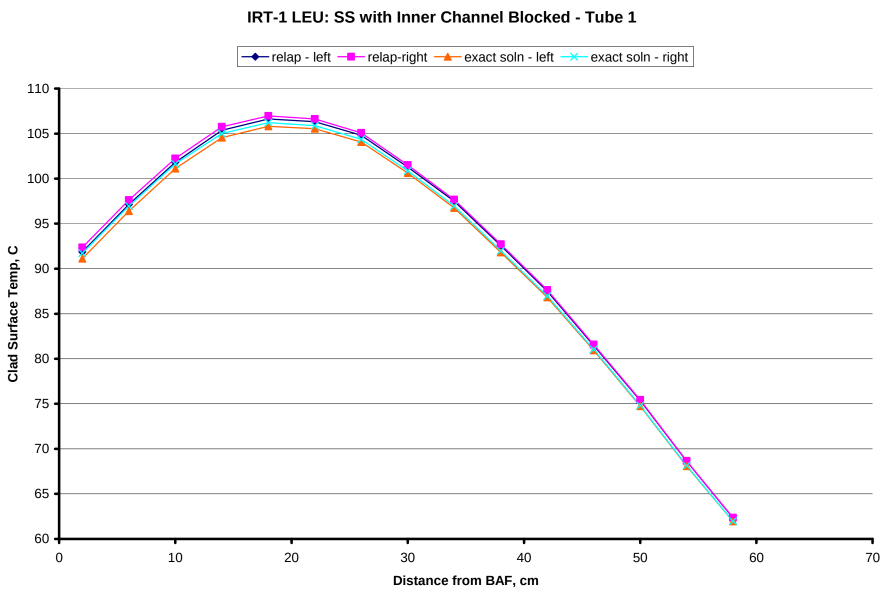


**Figure 1a. Tube 8 (Outer Tube) Comparison: RELAP w/Calculated Axial Power Distributions for Each Tube and PLTEMP (Exact Solution) with All Tubes Using Axial Power Distribution from Tube 1**

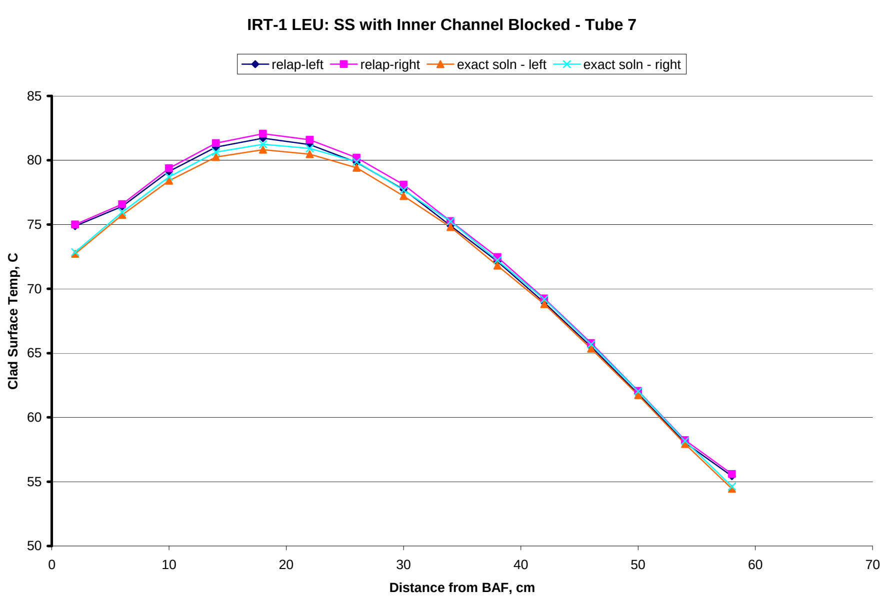


**Figure 1b. Tube 7 Comparison: RELAP w/Calculated Axial Power Distributions for Each Tube and PLTEMP (Exact Solution) with All Tubes Using Axial Power Distribution from Tube 1**

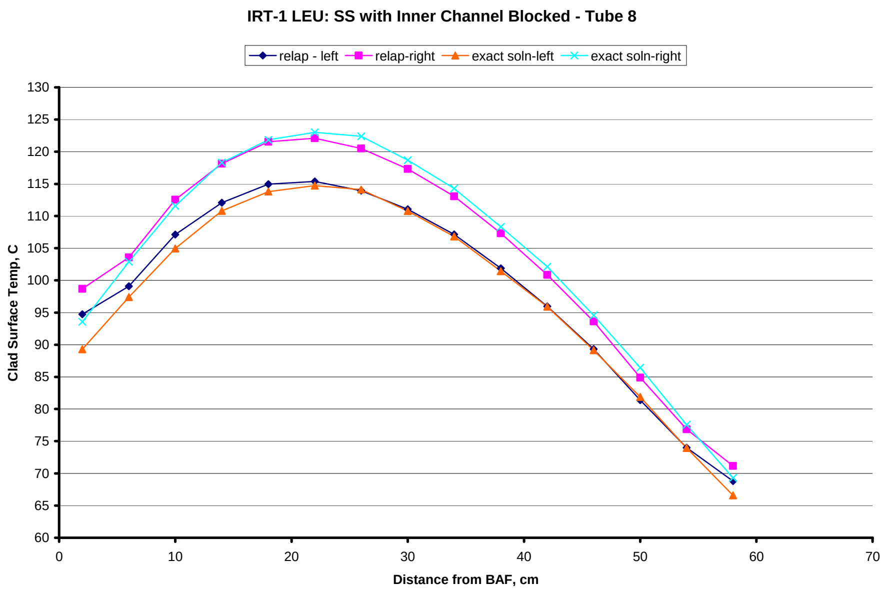


**Figure 1c. Tube 8 (Inner Tube) Comparison: RELAP w/Calculated Axial Power Distributions for Each Tube and PLTEMP (Exact Solution) with All Tubes Using Axial Power Distribution from Tube 1**

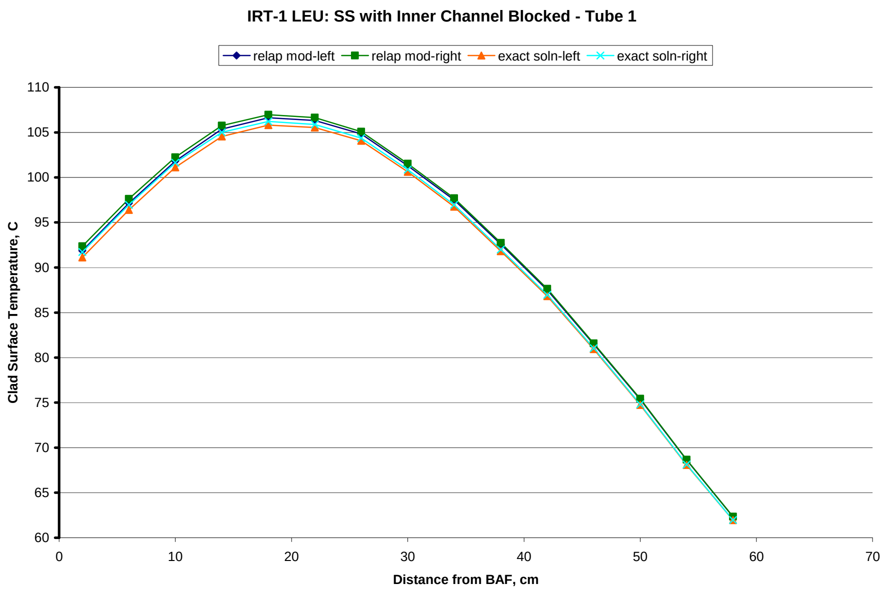


**Figure 2a. Tube 1 (Outer Tube) Comparison: Same Axial Power Distribution in All Tubes**

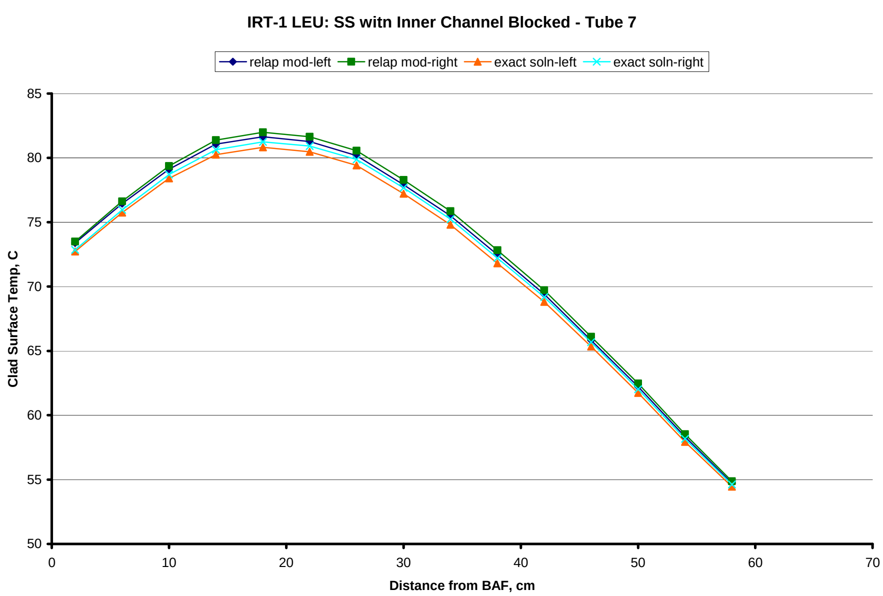


**Figure 2b. Tube 7 Comparison: Same Axial Power Distribution in All Tubes**

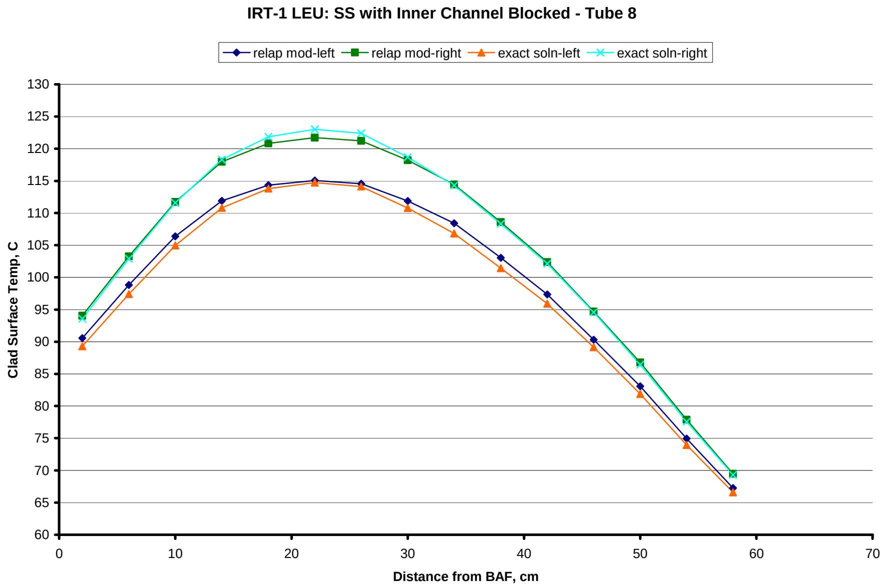


**Figure 2c. Tube 8 (Inner Tube) Comparison: Same Axial Power Distribution in All Tubes**

## 3. Validation Tests of PLTEMP/ANL V3.0 Code Performed in Conjunction with the Solution to the KFKI Benchmark Problem

(November 2006)

### 3.1. Introduction

While the thermal analysis of the KFKI benchmark problem (see Appendix B) was being performed with the PLTEMP/ANL V3.0, tests were made on the internal consistency of the analytical results. The benchmark problem is an assembly with three coaxial fueled tubes. The assembly was analyzed at three power levels, but only the 90 kW results were used in the consistency tests. The tests uncovered shortcomings in the code in the treatment of fuel tubes. These shortcomings were not visible in cases where the effects of tube curvature were small enough to make the tube and flat-plate solutions essentially the same. After the shortcomings were fixed, the consistency tests were repeated and consistent results were obtained. Since PLTEMP/ANL V3.0 is a frozen version of the code, the fixes are part of PLTEMP/ANL V3.1.

### 3.2. Consistency Tests

The following consistency tests were performed:

1. For each of the three tubes, the heat flux of each tube, as provided by PLTEMP, was integrated over the surface area of the tube to obtain the total power of the tube. This agreed very well with the power generated by the tube, which was deduced from PLTEMP inputs.

2. For both the inner and outer sides of the fifth axial level of each tube, two methods for determining power per unit length were used and the results were compared. For the first method a closed-form analytical solution was used to determine the power per unit length exiting each fuel meat surface. This required the values of the coolant temperatures and the film coefficients at both clad surfaces, which were obtained from the PLTEMP code output. Since no power is generated in the clad, the power per unit length exiting each fuel meat surface also exits the outer surface of its adjacent clad. For the second method the power per unit length exiting a clad surface was determined from the heat flux exiting the clad surface, which is a PLTEMP code output.

3. For the fifth axial level of each tube, the power per unit length exiting each surface of the fuel, as determined in the previous test, was used to determine the radius at which the peak temperature occurs. This is possible because all of the power must flow away from the location of the highest fuel temperature. The calculated location of the peak fuel temperature in each was found to be totally consistent with the PLTEMP output.

4. For the fifth axial level of each tube, another closed-form analytical solution was used to determine the radius at which the peak fuel temperature occurs in a fuel tube. This solution uses the temperatures at the fuel meat surfaces as the boundary conditions rather

than the coolant temperatures and the film coefficients at the clad outer surfaces. The results were totally consistent with the PLTEMP results.

5. In the PLTEMP code coaxial tubes can be ordered from biggest to smallest or from smallest to biggest. The code determines which it is, based on whether the radii are increasing or decreasing in size. When there is only one tube, the code assumes that the first of the two coolant channels is the outer channel. As an additional check, the 90 kW case was run twice – once with each way of ordering the tubes. The temperatures, heat fluxes, film coefficients, and locations of the peak fuel temperature for each tube were manually compared. Although the results were essentially the same for both runs, the run with the tubes ordered smallest to biggest seemed to produce slightly better results and in fewer iterations. The run with the smallest tube first produced a solution in 200 iterations with all values of "TDIFF" at 0.00. The other run had two non-zero values of TDIFF after 800 iterations. These were −0.07 and 0.02 at the first and second axial levels, respectively, of the middle tube. However, it is not reasonable to make a general conclusion using only a single comparison.

### 3.3. Code Corrections

The following corrections were made to the PLTEMP/ANL V3.0 code:

1. The code was modified so that when the radial tube geometry is used, the code output identifies the tube surfaces as "inner" and "outer" instead of "left" and "right".

2. Subroutine FUNCV was originally correct as coded to a first order in the curvature correction term, Δ. By simply replacing terms like (1 + Δ) with 1/(1 − Δ), full accuracy was produced in computing the tube surface heat fluxes. Here $\Delta = (t_{clad} + t_{meat}/2) / R_{mid}$, where $t_{clad}$ is the clad thickness, $t_{meat}$ is the fuel meat thickness, and $R_{mid}$ is the radius of the tube centerline.

### 3.4. Discussion and Conclusions

In the PLTEMP code, the quantity "FUEL X" is a ratio of two fuel cross-sectional areas. The numerator for this ratio is the area between the first edge of the fuel meat (i.e., the edge nearest to the lower numbered coolant channel) and the location at which the peak fuel temperature occurs. The denominator for this ratio is the total tube meat cross-sectional area. Thus, for the tube solution, the ratio is the ratio of the areas of the appropriate two fuel annuli. For a flat plate this area ratio is also equal to the distance from the first edge of the fuel meat to the location of the peak temperature divided by the total fuel meat thickness.

The above consistency tests enabled shortcomings in the tube solution of the PLTEMP/ANL V3.0 code to be uncovered and fixed before final results for the KFKI benchmark problem were obtained. The shortcomings have no impact on the PLTEMP flat-plate solution and no impact on the PLTEMP tube solution when the effects of tube curvature were small enough to make the tube and flat-plate solutions essentially the same.

**APPENDIX B**
**STEADY-STATE THERMAL ANALYSIS FOR A BENCHMARK PROBLEM SPECIFIED BY KFKI FOR THE BUDAPEST RESEARCH REACTOR**

SUMMARY

Steady-state thermal analysis has been performed for a benchmark problem specified by KFKI that is related to the WWR-M2 fuel assembly used in the Budapest Research Reactor. The analyses were done using the PLTEMP/ANL V3.0 code.[1] The WWR-M2 fuel assembly consists of three concentric fueled tubes. Three assembly power levels were requested. Axial distribution of clad surface temperature and heat transfer coefficient for each surface of each tube, the axial distribution of peak fuel temperature for each fuel tube, and the axial distribution of coolant temperature and coolant density for each coolant channel are provided.

## I. INTRODUCTION

The KFKI specifications for the benchmark problem are shown in Table 1. The assembly to be analyzed consists of three concentric fueled tubes, as shown in Figure 1. The outer most tube is hexagonal with rounded corners. The inner two tubes are circular. The wall of each tube is 2.5 mm thick, with a 0.98 mm thick fuel meat and 0.76 mm thick cladding. The assembly is assumed to be inside an infinite array of identical assemblies that are all on a 35 mm hexagonal pitch. The assembly can be thought of as being located at the center of a unit cell that is 35 mm across flats.

The calculations do not include any hot channel factors or other means of accounting for manufacturing tolerances or uncertainties in the analytical models.

## II. POWER AND POWER DISTRIBUTION

The relative axial distribution of power of each tube is the same – a cosine shape with zero values at the beginning and the end of the 58-cm fuel length. In the analysis the fuel length is to be divided into eight equal axial levels. The equation for the normalized axial power shape, $P(x)/P_0$ is:

$$\frac{P(x)}{P_0} = \frac{4\pi}{L}\sin\left(\pi\frac{x}{L}\right) \qquad (1)$$

where L is the length and x is the axial location from the inlet of the fuel. For the eight segments the relative average power is obtained by integrating equation (1) over each segment. Then the relative power over each segment, $P_i/P_0$ is given by:

$$\frac{P_i}{P_0} = 4\left[\cos\left(i\,\frac{\pi}{8}\right) - \cos\left((i-1)\frac{\pi}{8}\right)\right], \text{ for } i = 1, 8 \qquad (2)$$

Equation (2) was evaluated to produce the axial power distribution given in Table 2. The sum of all eight relative values equals 8.00.

The benchmark problem is to be solved for assembly powers of 90, 140, and 190 kW.

## III. KEY PARAMETERS AND CORRELATIONS

The flow areas, perimeters, and hydraulic diameters that are needed to perform the required analysis can be calculated from a few key tube dimensions. Table 3 shows the values of key dimensions in bold type. A computer spreadsheet was used to perform the calculations. Needed quantities are listed in the table essentially in the order that they were produced. The calculations start at the outside of the assembly near the top of the table and proceed to the innermost tube. Some of the thick horizontal lines in the table tend to separate the data for each tube from those of the other two.

The value of flow velocity for each of the four coolant channels was provided, as shown in bold type in Table 4. The first channel is at the center of the assembly. The fourth one is between the outer perimeter of the hexagonal outer tube and the boundary of the hexagonal unit cell. As indicated in the table the volumetric flow rate for each channel is deduced from the flow area and the velocity. The total volumetric flow rate is also shown in bold type in the table. This value is only 0.86% greater than the 6.0 $m^3/h$ value that was specified as part of the benchmark problem definition. The channel velocities are assumed to correspond to the channel inlet where the temperature is 50º C and the local pressure is 1.3 bar. For these conditions the coolant water density is 988.08 $kg/m^3$. With this density and the volumetric flow rates shown in the table, one can deduced the mass flow rates in kg/s that are shown in the table and were used as inputs to the PLTEMP code. Some of the data in Table 2 is repeated in Table 5, where it is used to determine quantities for the three fuel tubes that are used in the PLTEMP code input.

In the PLTEMP code, there are several choices of correlations for Nusselt number, Nu, for turbulent flow. For the analysis the Sieder-Tate correlation, $Nu = 0.027\ Re^{0.8}\ Pr^{0.4}\ (\mu/\mu_w)^{0.14}$, was used. Here Re is Reynolds number, Pr is Prandtl number, $\mu$ is the dynamic viscosity of the bulk fluid, and $\mu_w$ is the dynamic viscosity of the fluid at the surface of the clad.

The inlet of the assembly is assumed to be at an absolute pressure of 1.3 bar and the fluid is assumed to be at its inlet velocity. Over the 58-cm length of the fuel, the pressure in the reactor vessel increases by about 5600 Pa due solely to the change in the depth of the water. However, within the coolant channels it is estimated that the friction pressure drop along the 58-cm length is about 8700 Pa. Thus, there is a net loss in pressure of about 3000 Pa, or 0.03 bar. Therefore, in the PLTEMP code the inlet pressure is taken to be 1.30 bar and the outlet is taken to be 1.27 bar. The local pressure between the inlet and the outlet is assumed to vary linearly. Small differences in local pressure are not important in the current calculations because the margin to the onset of nuclear boiling is not included in the results.

## IV. RESULTS

The requested results are:

- the axial distribution of clad outer surface temperature and heat transfer coefficient for each surface of each tube,
- the axial distribution of fuel centerline temperature for each fuel tube, and
- the axial distribution of coolant temperature and coolant density for each coolant channel.

The PLTEMP/ANL code computes the peak temperature in the fuel meat, which may not occur at the fuel meat centerline. As a result, peak temperatures are provided in this report instead of centerline temperatures.

Tables 6a, 6b, and 6c provide all of the required results for the innermost, center, and outmost tubes, respectively, for an assembly power of 90 KW. Similarly, Tables 7a, 7b, and 7c provide the results for 140 kW and Tables 8a, 8b, and 8c provide the results for 190 kW.

It is worth noting that the PLTEMP results indicate that for the highest power (190 kW) case, there is no bulk boiling, but the Bergles and Rohsenow correlation indicates that the onset of nucleate boiling occurs at the surface of the clad at some locations.

## V. CONCLUSIONS

The requested calculations have been performed and input quantities and the required analytical results are provided in tables.

## REFERENCES:


1. Arne P. Olson and Kalimullah, “A Users Guide to the PLTEMP/ANL V3.0 Code,” Reduced Enrichment for Research and Test Reactors (RERTR) Program, Argonne National Laboratory, May 16, 2006.

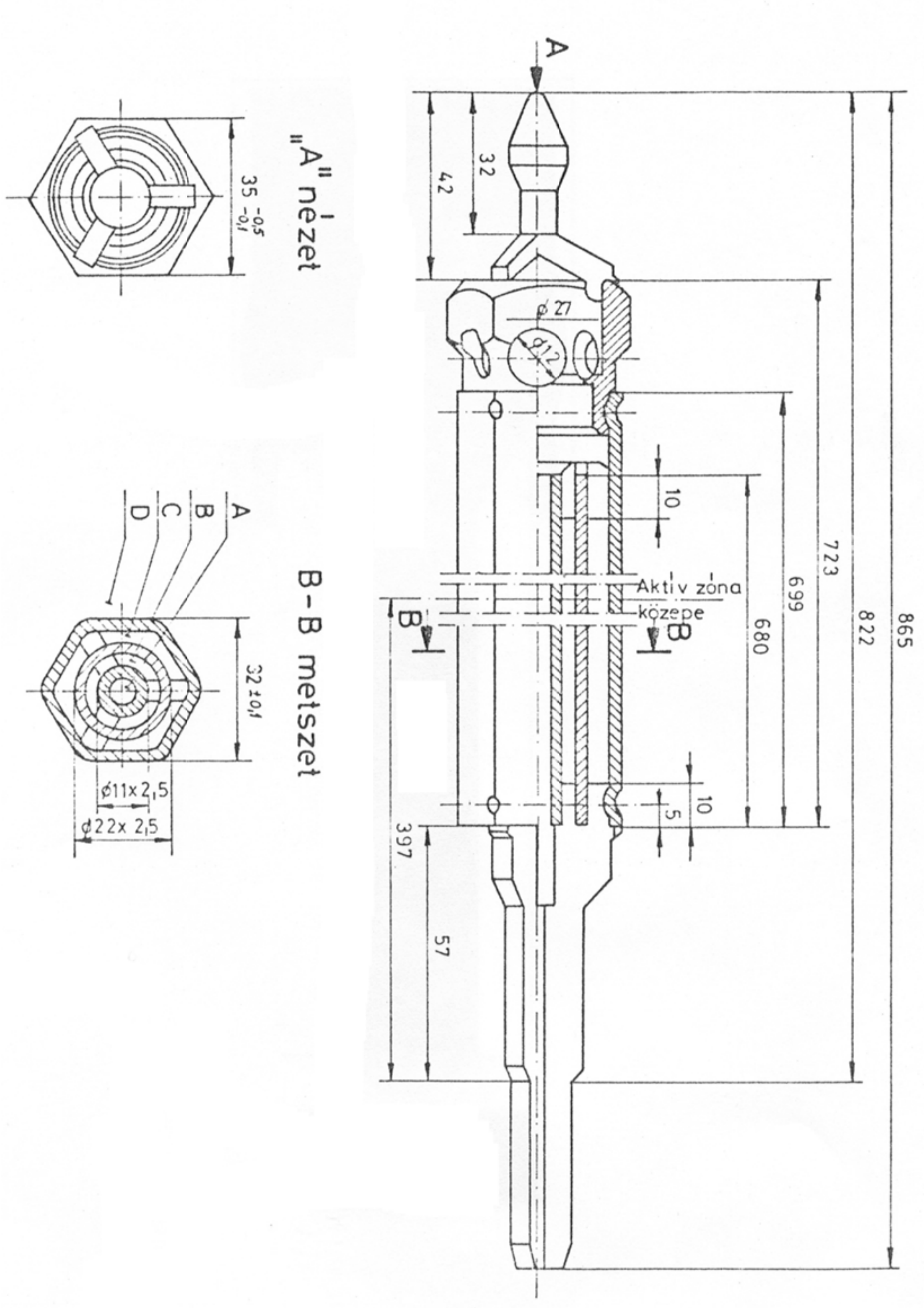


Figure 1 – WWR-M2 Fuel Assembly

# Table 1 – KFKI Benchmark Specifications*

**Stationary test problems for VVRSzM type thermohydraulics at different assembly power values:**

The middle active length of the fuel, 58 cm, is to be calculated.

Inlet temperature: 50 $^{o}$C
(The inlet is at the top.)

Total inlet flow to the 4 concentric channels: 6 m$^{3}$/h

Inlet velocities equivalent for each sub-channel

Pressure at the inlet:1,3 bar

Assembly power values: 90 kW, 140kW, 190 kW

Power distribution: Flat in radial direction, cosinus type in axial direction, with zero values at the edge of the 58 cm active length

Meat thickness: 0.98 mm

Thermal data for the meat:
Cp= 633 J/kg/K
` LAMBDA: 180 W/m/K
RO: 3534 kg/m3

Thermal data for cladding:
Cp= 860 J/kg/K
` LAMBDA: 206 W/m/K
RO: 2700 kg/m3

**Output quantities to be computed in 8 axial meshes:**

- Axial distribution of the azimuth average cladding surface temperature on the 6 radial surface elements
- Axial distribution of the azimuth average heat transfer coefficients on the 6 radial surface elements
- Axial distribution of the azimuth average fuel centerline temperature of the 3 fuel meet layers
- Coolant temperature and density axial and radial distribution

*In addition to the above, the following was sent by email:

The velocities at 6m3/h from a very old calculation starting from the innermost sub-channel are

2.7943 m/s
2.7931 m/s
2.8529 m/s
2.8870 m/s.

Table 2
Power
Distribution

| **Axial Level** | **Relative Power** |
|---|---|
| 1 | 0.30448 |
| 2 | 0.86709 |
| 3 | 1.29769 |
| 4 | 1.53073 |
| 5 | 1.53073 |
| 6 | 1.29769 |
| 7 | 0.86709 |
| 8 | 0.30448 |

## Table 3 – Key Geometric Parameters

| Item | Value |
|---|---|
| total fuel length, m | **0.58** |
| number of axial fuel segments (nodes) | **8** |
| length of one segment, m | 0.0725 |
| thickness of all fuel tubes, mm | **2.5** |
| meat thickness of all tubes, mm | **0.98** |
| clad thickness of all tubes, mm | 0.76 |
| hexagonal pitch between assemblies, mm | **35** |
| area inside hexagonal unit cell of assembly, $mm^2$ | 1060.9 |
| flat-to-flat outer dimension of hex tube, mm | **32** |
| flat-to flat midline dimension of hex tube, mm | 29.5 |
| flat-to-flat inner dimension of hex tube, mm | 27 |
| outer corner radius of hex tube, mm | **4.3** |
| midline corner radius of hex tube, mm | 3.05 |
| inner corner radius of hex tube, mm | 1.8 |
| outer perimeter of hex tube, mm | 108.08 |
| midline circumference of hex tube, mm | 100.22 |
| inner perimeter of hex tube, mm | 92.370 |
| area inside outer circumference of hex tube, $mm^2$ | 880.85 |
| area inside inner circumference of hex tube, $mm^2$ | 630.29 |
| equivalent radius of hex tube based on midline circumference, mm | 15.951 |
| flow area outside of hex tube, $mm^2$ | 180.03 |
| hydraulic diameter between assemblies, mm | 6.6631 |
| outer diameter of middle tube, which is circular, mm | **22** |
| midline diameter of middle tube, which is circular, mm | 19.5 |
| inner diameter of middle tube, which is circular, mm | 17 |
| outer perimeter of middle tube, mm | 69.115 |
| midline circumference of middle tube, mm | 61.261 |
| inner perimeter of middle tube, mm | 53.407 |
| area inside outer perimeter of middle tube, $mm^2$ | 380.13 |
| area inside inner perimeter of middle tube, $mm^2$ | 226.98 |
| outer diameter of inner tube, which is circular, mm | **11** |
| midline diameter of inner tube, which is circular, mm | 8.5 |
| inner diameter of inner tube, which is circular, mm | 6 |
| outer perimeter of inner tube, mm | 34.558 |
| midline circumference of inner tube, mm | 26.704 |
| inner perimeter of inner tube, mm | 18.850 |
| area inside outer perimeter of inner tube, $mm^2$ | 95.033 |
| area inside inner perimeter of inner tube, $mm^2$ | 28.274 |
| flow area between hex tube and middle tube, $mm^2$ | 250.15 |
| wetted perimeter of channel between hex & middle tubes, mm | 161.48 |
| hydraulic diameter of channel between hex & middle tubes, mm | 6.1964 |
| flow area between middle and center tubes, $mm^2$ | 131.95 |
| wetted perimeter of channel between middle & inner tubes, mm | 87.965 |
| hydraulic diameter of channel between middle & inner tubes, mm | 6 |

Table 4 – Coolant Channel Parameters

| | Channel Number | | | | |
|---|---|---|---|---|---|
| **Item** | **1 (center)** | **2** | **3** | **4** | **Total** |
| flow area, $m^2$ | 2.8274E-05 | 1.3195E-04 | 2.5015E-04 | 1.8003E-04 | |
| hydraulic diameter, m | 6.0000E-03 | 6.0000E-03 | 6.1964E-03 | 6.6631E-03 | |
| wetted perimeter, m | 1.8850E-02 | 8.7965E-02 | 1.6148E-01 | 1.0808E-01 | |
| heated perimeter, m | 1.8850E-02 | 8.7965E-02 | 1.6148E-01 | 1.0808E-01 | |
| **velocity, m/s** | **2.7943** | **2.7931** | **2.8529** | **2.8870** | |
| volumetric flow rate,$m^3$/h | 0.28443 | 1.32675 | 2.56920 | 1.87113 | **6.05151** |
| mass flow rate, kg/s | 0.07807 | 0.36415 | 0.70516 | 0.51356 | 1.66094 |

Table 5 – Fuel Tube Parameters

| | Tube Number | | | |
|---|---|---|---|---|
| **Item** | **1 (center)** | **2** | **3** | **Total** |
| centerline arc length, m | 2.6704E-02 | 6.1261E-02 | 1.0022E-01 | |
| centerline radius, m | 0.00425 | 0.00975 | 0.0159511 | |
| fuel volume, $m^3$ | 1.5178E-05 | 3.4821E-05 | 5.6967E-05 | 1.0697E-04 |
| fraction of total fuel volume | 0.14190 | 0.32553 | 0.53257 | 1.00000 |
| heat transfer area, $m^2$ | 0.03098 | 0.07106 | 0.11626 | 0.21830 |

Table 6a – 90 kW Results for Innermost Tube

| | Temperature, C | | | | |
|---|---|---|---|---|---|
| | Inner | | Maximum | Outer | |
| Level | Coolant | Clad | Fuel | Clad | Coolant |
| inlet | 50.0 | | | | 50.0 |
| 1 | 50.3 | 57.6 | 58.1 | 57.4 | 50.3 |
| 2 | 51.3 | 71.4 | 72.9 | 70.8 | 51.3 |
| 3 | 53.2 | 82.3 | 84.6 | 81.4 | 53.1 |
| 4 | 55.7 | 89.1 | 91.8 | 88.1 | 55.6 |
| 5 | 58.4 | 91.2 | 93.8 | 90.1 | 58.2 |
| 6 | 60.9 | 88.4 | 90.6 | 87.4 | 60.6 |
| 7 | 62.8 | 81.1 | 82.6 | 80.5 | 62.5 |
| 8 | 63.8 | 70.2 | 70.7 | 69.9 | 63.5 |
| outlet | 64.0 | | | | 63.7 |

| | Coolant Density, $kg/m^3$ | | Heat Transfer Coefficient, $W/m^2$-C | |
|---|---|---|---|---|
| Level | Inner | Outer | Inner | Outer |
| inlet | | | | |
| 1 | 988.4 | 988.4 | 17,481 | 17,465 |
| 2 | 987.7 | 987.7 | 18,152 | 18,121 |
| 3 | 986.6 | 986.7 | 18,750 | 18,706 |
| 4 | 985.4 | 985.4 | 19,255 | 19,200 |
| 5 | 984.0 | 984.1 | 19,623 | 19,561 |
| 6 | 982.8 | 983.0 | 19,805 | 19,741 |
| 7 | 982.0 | 982.2 | 19,765 | 19,704 |
| 8 | 981.8 | 981.9 | 19,468 | 19,417 |
| outlet | | | | |

Table 6b – 90 kW Results for Center Tube

| | Temperature, C | | | | |
|---|---|---|---|---|---|
| | Inner | | Maximum | Outer | |
| **Level** | **Coolant** | **Clad** | **Fuel** | **Clad** | **Coolant** |
| **inlet** | 50.0 | | | | 50.0 |
| **1** | 50.3 | 57.5 | 58.0 | 57.4 | 50.3 |
| **2** | 51.3 | 71.0 | 72.7 | 70.7 | 51.2 |
| **3** | 53.1 | 81.7 | 84.2 | 81.3 | 53.0 |
| **4** | 55.6 | 88.4 | 91.3 | 87.9 | 55.3 |
| **5** | 58.2 | 90.4 | 93.3 | 89.9 | 57.8 |
| **6** | 60.6 | 87.6 | 90.1 | 87.1 | 60.1 |
| **7** | 62.5 | 80.4 | 82.0 | 80.1 | 61.9 |
| **8** | 63.5 | 69.6 | 70.2 | 69.5 | 62.8 |
| **outlet** | 63.7 | | | | 63.1 |

| | Coolant Density, $kg/m^3$ | | Heat Transfer Coefficient, $W/m^2$-C | |
|---|---|---|---|---|
| **Level** | **Inner** | **Outer** | **Inner** | **Outer** |
| **inlet** | | | | |
| **1** | 988.4 | 988.4 | 17,469 | 17,647 |
| **2** | 987.7 | 987.7 | 18,128 | 18,300 |
| **3** | 986.7 | 986.8 | 18,716 | 18,878 |
| **4** | 985.4 | 985.6 | 19,209 | 19,361 |
| **5** | 984.1 | 984.4 | 19,568 | 19,710 |
| **6** | 983.0 | 983.3 | 19,745 | 19,878 |
| **7** | 982.2 | 982.5 | 19,702 | 19,831 |
| **8** | 981.9 | 982.3 | 19,406 | 19,536 |
| **outlet** | | | | |

Table 6c – 90 kW Results for Outermost (Hexagonal) Tube

| | Temperature, C | | | | |
|---|---|---|---|---|---|
| | Inner | | Maximum | Outer | |
| Level | Coolant | Clad | Fuel | Clad | Coolant |
| inlet | 50.0 | | | | 50.0 |
| 1 | 50.3 | 57.4 | 58.0 | 57.3 | 50.2 |
| 2 | 51.2 | 70.8 | 72.6 | 70.7 | 51.1 |
| 3 | 53.0 | 81.4 | 84.0 | 81.2 | 52.7 |
| 4 | 55.3 | 88.0 | 91.0 | 87.7 | 54.8 |
| 5 | 57.8 | 89.8 | 92.8 | 89.5 | 57.1 |
| 6 | 60.1 | 86.9 | 89.5 | 86.6 | 59.3 |
| 7 | 61.9 | 79.6 | 81.3 | 79.4 | 60.9 |
| 8 | 62.8 | 68.8 | 69.4 | 68.7 | 61.8 |
| outlet | 63.1 | | | | 62.1 |

| | Coolant Density, kg/m$^3$ | | Heat Transfer Coefficient, W/m$^2$-C | |
|---|---|---|---|---|
| Level | Inner | Outer | Inner | Outer |
| inlet | | | | |
| 1 | 988.4 | 988.4 | 17,648 | 17,553 |
| 2 | 987.7 | 987.8 | 18,303 | 18,186 |
| 3 | 986.8 | 986.9 | 18,881 | 18,738 |
| 4 | 985.6 | 985.9 | 19,363 | 19,191 |
| 5 | 984.4 | 984.7 | 19,708 | 19,512 |
| 6 | 983.3 | 983.8 | 19,872 | 19,659 |
| 7 | 982.5 | 983.1 | 19,818 | 19,598 |
| 8 | 982.3 | 982.8 | 19,513 | 19,298 |
| outlet | | | | |

Table 7a – 140 kW Results for Innermost Tube

| | Temperature, C | | | | |
|---|---|---|---|---|---|
| | Inner | | Maximum | Outer | |
| Level | Coolant | Clad | Fuel | Clad | Coolant |
| inlet | 50.0 | | | | 50.0 |
| 1 | 50.4 | 61.7 | 62.5 | 61.4 | 50.4 |
| 2 | 52.0 | 82.5 | 84.8 | 81.6 | 52.0 |
| 3 | 55.0 | 98.6 | 102.1 | 97.2 | 54.9 |
| 4 | 58.9 | 108.4 | 112.6 | 106.8 | 58.6 |
| 5 | 63.0 | 111.5 | 115.6 | 109.8 | 62.7 |
| 6 | 66.9 | 107.1 | 110.6 | 105.7 | 66.5 |
| 7 | 69.9 | 96.7 | 99.0 | 95.7 | 69.4 |
| 8 | 71.4 | 80.8 | 81.6 | 80.5 | 70.9 |
| outlet | 71.9 | | | | 71.3 |

| | Coolant Density, $kg/m^3$ | | Heat Transfer Coefficient, $W/m^2$-C | |
|---|---|---|---|---|
| Level | Inner | Outer | Inner | Outer |
| inlet | | | | |
| 1 | 988.2 | 988.2 | 17,670 | 17,650 |
| 2 | 987.2 | 987.2 | 18,624 | 18,582 |
| 3 | 985.5 | 985.6 | 19,483 | 19,420 |
| 4 | 983.4 | 983.5 | 20,200 | 20,161 |
| 5 | 981.2 | 981.4 | 20,679 | 20,630 |
| 6 | 979.2 | 979.4 | 21,095 | 21,011 |
| 7 | 977.8 | 978.1 | 21,060 | 20,971 |
| 8 | 977.3 | 977.6 | 20,672 | 20,600 |
| outlet | | | | |

Table 7b – 140 kW Results for Center Tube

| | Temperature, C | | | | |
|---|---|---|---|---|---|
| | Inner | | Maximum | Outer | |
| Level | Coolant | Clad | Fuel | Clad | Coolant |
| inlet | 50.0 | | | | 50.0 |
| 1 | 50.4 | 61.5 | 62.4 | 61.3 | 50.4 |
| 2 | 52.0 | 81.9 | 84.5 | 81.5 | 51.9 |
| 3 | 54.9 | 97.7 | 101.6 | 97.1 | 54.6 |
| 4 | 58.6 | 107.4 | 111.9 | 106.6 | 58.2 |
| 5 | 62.7 | 110.3 | 114.8 | 109.5 | 62.1 |
| 6 | 66.5 | 106.0 | 109.8 | 105.2 | 65.7 |
| 7 | 69.4 | 95.6 | 98.2 | 95.1 | 68.5 |
| 8 | 70.9 | 80.0 | 80.8 | 79.7 | 70.0 |
| outlet | 71.3 | | | | 70.3 |

| | Coolant Density, kg/m$^3$ | | Heat Transfer Coefficient, W/m$^2$-C | |
|---|---|---|---|---|
| Level | Inner | Outer | Inner | Outer |
| inlet | | | | |
| 1 | 988.2 | 988.3 | 17,654 | 17,831 |
| 2 | 987.2 | 987.3 | 18,592 | 18,759 |
| 3 | 985.6 | 985.7 | 19,434 | 19,585 |
| 4 | 983.5 | 983.8 | 20,162 | 20,309 |
| 5 | 981.4 | 981.7 | 20,630 | 20,770 |
| 6 | 979.4 | 979.9 | 21,018 | 21,125 |
| 7 | 978.1 | 978.7 | 20,969 | 21,072 |
| 8 | 977.6 | 978.2 | 20,585 | 20,691 |
| outlet | | | | |

Table 7c – 140 kW Results for Outermost (Hexagonal) Tube

| | Temperature, C | | | | |
|---|---|---|---|---|---|
| | Inner | | Maximum | Outer | |
| Level | Coolant | Clad | Fuel | Clad | Coolant |
| inlet | 50.0 | | | | 50.0 |
| 1 | 50.4 | 61.4 | 62.3 | 61.3 | 50.4 |
| 2 | 51.9 | 81.7 | 84.4 | 81.4 | 51.7 |
| 3 | 54.6 | 97.3 | 101.3 | 96.9 | 54.2 |
| 4 | 58.2 | 106.7 | 111.4 | 106.3 | 57.5 |
| 5 | 62.1 | 109.4 | 114.1 | 108.9 | 61.1 |
| 6 | 65.7 | 105.0 | 109.0 | 104.5 | 64.4 |
| 7 | 68.5 | 94.5 | 97.1 | 94.1 | 67.0 |
| 8 | 70.0 | 78.8 | 79.6 | 78.5 | 68.4 |
| outlet | 70.3 | | | | 68.7 |

| | Coolant Density, kg/m$^3$ | | Heat Transfer Coefficient, W/m$^2$-C | |
|---|---|---|---|---|
| Level | Inner | Outer | Inner | Outer |
| inlet | | | | |
| 1 | 988.3 | 988.3 | 17,834 | 17,733 |
| 2 | 987.3 | 987.4 | 18,764 | 18,632 |
| 3 | 985.7 | 986.0 | 19,591 | 19,417 |
| 4 | 983.8 | 984.2 | 20,313 | 20,096 |
| 5 | 981.7 | 982.4 | 20,770 | 20,528 |
| 6 | 979.9 | 980.7 | 21,118 | 20,814 |
| 7 | 978.7 | 979.6 | 21,054 | 20,765 |
| 8 | 978.2 | 979.1 | 20,659 | 20,381 |
| outlet | | | | |

Table 8a – 190 kW Results for Innermost Tube

| | Temperature, C | | | | |
|---|---|---|---|---|---|
| | Inner | | Maximum | Outer | |
| Level | Coolant | Clad | Fuel | Clad | Coolant |
| inlet | 50.0 | | | | 50.0 |
| 1 | 50.6 | 65.7 | 66.8 | 65.3 | 50.6 |
| 2 | 52.7 | 93.2 | 96.4 | 91.9 | 52.7 |
| 3 | 56.8 | 114.4 | 119.2 | 112.5 | 56.6 |
| 4 | 62.0 | 127.9 | 133.5 | 125.6 | 61.7 |
| 5 | 67.7 | 131.5 | 137.1 | 129.3 | 67.3 |
| 6 | 73.0 | 125.7 | 130.5 | 123.8 | 72.4 |
| 7 | 77.0 | 111.6 | 114.7 | 110.3 | 76.3 |
| 8 | 79.1 | 91.2 | 92.3 | 90.7 | 78.4 |
| outlet | 79.7 | | | | 79.0 |

| | Coolant Density, $kg/m^3$ | | Heat Transfer Coefficient, $W/m^2$-C | |
|---|---|---|---|---|
| Level | Inner | Outer | Inner | Outer |
| inlet | | | | |
| 1 | 988.1 | 988.1 | 17,851 | 17,826 |
| 2 | 986.6 | 986.7 | 19,053 | 19,000 |
| 3 | 984.3 | 984.4 | 19,997 | 19,964 |
| 4 | 981.3 | 981.5 | 20,654 | 20,606 |
| 5 | 978.1 | 978.4 | 21,304 | 21,243 |
| 6 | 975.2 | 975.6 | 21,804 | 21,734 |
| 7 | 973.2 | 973.6 | 22,120 | 22,044 |
| 8 | 972.5 | 972.9 | 21,760 | 21,669 |
| outlet | | | | |

Table 8b – 190 kW Results for Center Tube

| | Temperature, C | | | | |
|---|---|---|---|---|---|
| | Inner | | Maximum | Outer | |
| Level | Coolant | Clad | Fuel | Clad | Coolant |
| inlet | 50.0 | | | | 50.0 |
| 1 | 50.6 | 65.4 | 66.7 | 65.2 | 50.5 |
| 2 | 52.7 | 92.4 | 96.0 | 91.9 | 52.6 |
| 3 | 56.6 | 113.3 | 118.5 | 112.4 | 56.3 |
| 4 | 61.7 | 126.4 | 132.6 | 125.4 | 61.2 |
| 5 | 67.3 | 130.0 | 136.1 | 128.9 | 66.5 |
| 6 | 72.4 | 124.2 | 129.4 | 123.2 | 71.4 |
| 7 | 76.3 | 110.2 | 113.6 | 109.5 | 75.1 |
| 8 | 78.4 | 90.1 | 91.2 | 89.7 | 77.1 |
| outlet | 79.0 | | | | 77.6 |

| | Coolant Density, kg/m$^3$ | | Heat Transfer Coefficient, W/m$^2$-C | |
|---|---|---|---|---|
| Level | Inner | Outer | Inner | Outer |
| inlet | | | | |
| 1 | 988.1 | 988.1 | 17,832 | 18,007 |
| 2 | 986.7 | 986.8 | 19,014 | 19,175 |
| 3 | 984.4 | 984.6 | 19,964 | 20,126 |
| 4 | 981.5 | 981.9 | 20,606 | 20,747 |
| 5 | 978.4 | 978.9 | 21,243 | 21,366 |
| 6 | 975.6 | 976.3 | 21,734 | 21,844 |
| 7 | 973.6 | 974.5 | 22,044 | 22,147 |
| 8 | 972.9 | 973.8 | 21,650 | 21,738 |
| outlet | | | | |

Table 8c – 190 kW Results for Outermost (Hexagonal) Tube

| | Temperature, C | | | | |
|---|---|---|---|---|---|
| | Inner | | Maximum | Outer | |
| **Level** | **Coolant** | **Clad** | **Fuel** | **Clad** | **Coolant** |
| inlet | 50.0 | | | | 50.0 |
| 1 | 50.5 | 65.3 | 66.6 | 65.2 | 50.5 |
| 2 | 52.6 | 92.1 | 95.8 | 91.8 | 52.3 |
| 3 | 56.3 | 112.7 | 118.1 | 112.2 | 55.7 |
| 4 | 61.2 | 125.6 | 132.0 | 125.0 | 60.2 |
| 5 | 66.5 | 128.9 | 135.3 | 128.2 | 65.1 |
| 6 | 71.4 | 122.8 | 128.2 | 122.2 | 69.6 |
| 7 | 75.1 | 108.6 | 112.2 | 108.1 | 73.0 |
| 8 | 77.1 | 88.4 | 89.6 | 88.1 | 74.9 |
| outlet | 77.6 | | | | 75.4 |

| | Coolant Density, kg/m$^3$ | | Heat Transfer Coefficient, W/m$^2$-C | |
|---|---|---|---|---|
| **Level** | **Inner** | **Outer** | **Inner** | **Outer** |
| inlet | | | | |
| 1 | 988.1 | 988.2 | 18,011 | 17,905 |
| 2 | 986.8 | 986.9 | 19,182 | 19,034 |
| 3 | 984.6 | 985.0 | 20,126 | 19,936 |
| 4 | 981.9 | 982.5 | 20,747 | 20,505 |
| 5 | 978.9 | 979.9 | 21,366 | 21,078 |
| 6 | 976.3 | 977.5 | 21,844 | 21,527 |
| 7 | 974.5 | 975.8 | 22,147 | 21,817 |
| 8 | 973.8 | 975.2 | 21,698 | 21,367 |
| outlet | | | | |

## 4. Verification of the Radial Geometry Analytical Solution Method in PLTEMP/ANL Version 3.2

(March 2007)

To verify the implementation in PLTEMP/ANL code [1] of the radial geometry analytical solution method for calculating temperature distribution in a fuel assembly made of multiple coaxial fuel tubes, 7 sample problems (with assemblies having 1 to 6 fuel tubes) and their solution by the following four methods are documented:

(1) Hand calculation aided by *Mathematica*
(2) Standalone routine SLICEHTR [2]
(3) Broyden method of PLTEMP/ANL code
(4) Newly-implemented analytical method in PLTEMP/ANL code

The Hungarian reactor benchmark problem and an ASTRA2 six-tube assembly problem are included in these. The first 5 sample problems have a single fuel tube with two coolant channels. Some selected results are printed to 12 or more significant digits and compared to check the code because such small differences, although of no practical significance in reactor analysis, may be indicative of a coding error.

Currently, the radial geometry analytical method requires that the input data be prepared numbering the fuel tubes in the order of increasing radii.

**4.1. Radial Geometry Problem 1:** Find the temperature difference across the thickness of a 60 cm long tube which is generating a power of 9 kW. The inner surface of the tube is perfectly insulated. The inner radius of the tube is 0.5 cm, the outer radius is 4.5 cm, and the thermal conductivity is 7 W/m-°C. What is the coolant (water) temperature rise in the outer channel with a flow rate of 0.05 kg/s and $C_p$ = 4180.0 J/kg-°C.

### 4.1.1. Hand Calculation for Problem 1

Input data given: $r_a = 0.005$ m, $r_d = 0.045$ m, $L = 0.6$ m, $K = 7$ W/m-°C

Volumetric heat source $q = \dfrac{9000.0}{\pi(r_d^{\,2} - r_a^{\,2})\,L} = \dfrac{9000.0}{\pi(0.045^2 - 0.005^2)\,0.6}$

$$= 2.3873{,}2414{,}6378{,}4300\text{x}10^6 \text{ W/m}^3 \tag{1}$$

The solution of the steady-state heat conduction equation in a tube with a uniform heat source gives the temperature distribution T(r).

$T(r) = A_2 + A_1 \mathrm{Log}(r/r_d) - \dfrac{qr^2}{4K}$ ($A_1$ and $A_2$ are constants of integration)

Putting $r = r_a$ and $r = r_d$ in the above equation for T(r), and getting the difference we get

Temperature difference across tube thickness = $T(r_a) - T(r_d) = A_1 Log(r_a/r_d) + \frac{q(r_d^{\ 2} - r_a^{\ 2})}{4K}$ (2)

$A_1$ is found by setting the temperature derivative to zero at radius $r_a$

$\frac{dT}{dr} = \frac{A_1}{r} - \frac{q\,r}{2K} = 0$ at $r = r_a$ This boundary condition gives $A_1 = \frac{q\,r_a^{\ 2}}{2K}$ (3)

Substituting Eq. (3) and the input data into Eq. (2), the temperature difference becomes

$T(r_a) - T(r_d) = \frac{q\,r_a^{\ 2}}{2K} Log(r_a/r_d) + \frac{q(r_d^{\ 2} - r_a^{\ 2})}{4K}$ = **161.1562,1172,6154,12 °C** (4)

Coolant temperature rise = $\frac{9000}{4180 \times 0.05}$ = **43.0622,0095,6937,80 °C** (5)

### 4.1.2. Solution of Problem 1 by Standalone Routine SLICEHTR

This routine is based on the radial geometry analytical solution described in Appendix VII of PLTEMP/ANL Users Guide. It has been implemented in the PLTEMP/ANL version 3.2 code but it can also be used as a standalone program. The standalone routine was run for this calculation. In order to use the routine, the total thickness of the tube ($r_a$ = 0.005 m, $r_d$ = 0.045 m) was conceptually divided into 3 layers (to correspond to the inner cladding, fuel meat, and outer cladding in a reactor fuel tube) of equal thermal conductivity (7 W/m-°C) with $r_a$ = 0.005 m, $r_b$ = 0.015 m, $r_c$ = 0.035 m, $r_d$ = 0.045 m. The heat source in each of the 3 layers was set to the value in Eq. (1). The film coefficient at the inner surface of the tube was set exactly to zero. The whole length (0.6 m) of the tube was treated as a single axial node because the standalone routine can handle only one node. A small main program was written to define these input data and to call the routine. The output of the routine is shown in Fig. 1. The temperature drop across the tube thickness and the coolant temperature rise in the outer channel are noted below. All 16 digits in these values agree with the above hand calculated results in Eqs. (4) and (5).

Temperature difference across tube thickness From Fig. 1 = 161.1562,1172,6154,1 °C (6)
Node-center coolant temperature from Fig. 1 = 71.5311,0047,8468,90 °C
Coolant temperature rise = 2 x (71.53110047846890 - 50) = 43.0622,0095,6937,80 °C (7)

If the problem is slightly modified, i.e., the film coefficient at the inner surface of the tube is set to $10^{-6}$ W/m$^2$-°C instead of exactly zero, then the routine's output is shown in Fig. 2. These results are slightly different from those in Eqs. (4) and (5). Only 8 or 9 significant digits agree. The results changed presumably due to the slight change in the inner surface boundary condition.

Temperature difference across tube thickness from Fig. 2 = 161.1562,1235,9536,1 °C (8)
Node-center coolant temperature from Fig. 2 = 71.5311,0046,9959,36 °C
Coolant temperature rise = 2 x (71.53110046995936 – 50) = 43.0622,0093,9918,72 °C (9)

The modified problem is useful (for comparing the Broyden and analytical methods in the PLTEMP/ANL code) because the Broyden method is not designed to handle zero film coefficient on the inner surface of the innermost or the outer surface of the outermost fuel tube of an assembly. The routine SLICEHTR based on the analytical method is designed to handle zero film coefficient.

### 4.1.3. Solution of Modified Problem 1 by PLTEMP/ANL Version 3.2

Only the analytical method of the code could be used to solve this problem because of heat generation in the cladding. In order to apply the code, the total thickness of the tube ($r_a$ = 0.005 m, $r_d$ = 0.045 m) was again conceptually divided into 3 layers (inner cladding, fuel meat, and outer cladding) of equal thermal conductivity (7 W/m-°C) as above: $r_a$ = 0.005 m, $r_b$ = 0.015 m, $r_c$ = 0.035 m, $r_d$ = 0.045 m. In order to have a uniform heat source in the whole thickness of the tube, the input data QFCLAD on card 500 (i.e., the cladding power fraction) is set to 0.5 because the combined inner and outer cladding cross sectional area equals the fuel cross sectional area. The film coefficient at the inner surface was set to $1.0^{-6}$ W/m$^2$-°C. The input data has 10 axial nodes (with axially uniform heat source) in the 0.6 meter length of the tube. The constant coolant specific heat option (ICP = 1 on input card 200) is used ($C_p$ = 4180.0 J/kg-°C). The input data file used is shown in Fig. 3. The relevant parts of the PLTEMP output are shown in Fig. 4. For comparison, the results of all four methods are summarized in Table 1.

**Table 1. Comparison of Results by Four Methods for Radial Geometry Problem 1**

| Method | Temperature Difference Across Tube Thickness, °C | Coolant Temperature Rise, °C | Comments |
|---|---|---|---|
| Hand Calculation | 161.1562,1172,6154,12 | 43.0622,0095,6937,80 | All digits good |
| Standalone Routine SLICEHTR | 161.1562,1172,6154,1 | 43.0622,0095,6937,80 | All digits good |
| Standalone Routine SLICEHTR for the Modified Problem | 161.1562,1235,9536,1 | 43.0622,0093,9918,72 | All digits presumed good |
| Analytical Method in PLTEMP/ANL Version 3.2 for the Modified Problem | 161.1562,1008,5305,20 [a]<br>161.1562,1332,9713,50 [b] | 43.0622,0093,9615,2 | Agrees to 8 digits |

a. The smallest value in the 10 axial nodes used over the length of fuel tube.
b. The largest value in the 10 axial nodes used over the length of fuel tube.

Each axial node has practically the same temperature difference between the inner and outer surfaces of the tube, as expected. For all axial nodes, the temperature difference is found to be $\mathbf{161.15621_{3}^{0}}$ **°C** (meaning that the 9$^{th}$ digit varies from 0 to 3). This agrees to 8 significant digits with the value in Eq. (8) obtained by the standalone routine SLICEHTR for the modified problem. As indicated in Section 4.1.2, a comparison of the results of Eqs. (4) and (6) shows that the routine SLICEHTR is capable of an accuracy to 16 significant digits. The accuracy of the PLTEMP analytical method is limited to 8 digits presumably because the accuracy of the input data (especially the tube circumference CIRCF) to the code is limited to 10 digits due to the 12-column data fields.

The coolant temperature rise calculated by PLTEMP/ANL is **43.0622,0093,9**615,2 °C. The highlighted 11 digits of this value agree with the more accurate value given in Eq. (9) that was obtained by the standalone routine SLICEHTR for the modified problem.
In summary, the PLTEMP analytical method calculated coolant temperature rise is good to 11 significant digits, and the temperature difference across the tube thickness is good to 8 digits for problem 1.

**4.2. Radial Geometry Problem 2:** Find the temperature difference across the thickness of a 60 cm long fuel tube whose fuel meat is generating a power of 9 kW (no power in the cladding). The inner surface of the tube is perfectly insulated. The tube inner radius is 0.5 cm, the meat inner radius is 1.5 cm, the meat outer radius is 3.5 cm, the tube outer radius is 4.5 cm, and the thermal conductivities of cladding and meat are 7 and 8 W/m-°C. What is the coolant (water) temperature rise in the outer channel with a flow rate of 0.05 kg/s and $C_p$ = 4180.0 J/kg-°C.

### 4.2.1. Hand Calculation for Problem 2

Input data given: $r_a$ = 0.005 m, $r_b$ = 0.015 m, $r_c$ = 0.035 m, $r_d$ = 0.045 m,
L = 0.6 m, $K_c$ = 7 W/m-°C, $K_f$ = 8 W/m-°C

Volumetric heat source $q = \dfrac{9000.0}{\pi(r_c^2 - r_b^2)L} = \dfrac{9000.0}{\pi(0.035^2 - 0.015^2)0.6}$

$$= 4.7746,4829,2756,8601\text{x}10^6 \text{ W/m}^3 \qquad (10)$$

There is no radial heat flux in the inner cladding, and therefore the temperature difference across its thickness is zero.

$$T(r_a) - T(r_b) = 0 \qquad (11)$$

The solution of the steady-state heat conduction equation in the meat with a uniform heat source gives the temperature distribution T(r).

$$T(r) = A_4 + A_3 \text{Log}(r/r_c) - \frac{qr^2}{4K_f}$$ ($A_3$ and $A_4$ are constants of integration)

Putting $r = r_b$ and $r = r_c$ in the above equation for T(r), and getting the difference we get

Temperature difference across meat thickness = $T(r_b) - T(r_c) = A_3 \text{Log}(r_b/r_c) + \dfrac{q(r_c^2 - r_b^2)}{4K_f}$ (12)

$A_3$ is found by setting the temperature derivative to zero at radius $r_b$

$\dfrac{dT}{dr} = \dfrac{A_3}{r} - \dfrac{qr}{2K_f} = 0$ at $r = r_b$ The boundary condition gives $A_3 = \dfrac{q r_b^2}{2K_f}$ (13)

Substituting Eq. (13) and the input data into Eq. (12), the temperature difference across the meat thickness becomes

$$T(r_b) - T(r_c) = \frac{q\, r_b^{\,2}}{2\,K_f} \mathrm{Log}(r_b/r_c) + \frac{q(r_c^{\,2} - r_b^{\,2})}{4\,K_f} = 92.3172{,}2236{,}2732{,}004\ °\mathrm{C} \qquad (14)$$

The solution of heat conduction equation in the outer cladding *without heat source* is given by

$$T_c(r) = A_6 + A_5 \mathrm{Log}(r/r_d) \qquad (A_5 \text{ and } A_6 \text{ are constants of integration}) \qquad (15)$$

The temperature difference across the outer cladding thickness is given

$$T(r_c) - T(r_d) = A_5 \mathrm{Log}(r_c/r_d) \qquad (16)$$

The constant $A_5$ can be evaluated using the heat flux boundary condition at the outer surface of the tube. The power generated in the meat (9000 W) flows radially outwards in the outer cladding, giving the following heat flux at the tube outer surface.

$$q''(r_d) = \frac{9000}{2\,\pi\, r_d L} \ \mathrm{W/m^2} \qquad (17)$$

The heat flux obtained from Eq.(15), i.e., $-K_c\, dT_c/dr$ at $r = r_d$ becomes $-K_c A_5/r_d$ which is equated to the value in Eq. (17). This gives the following value of $A_5$.

$$A_5 = -\frac{9000}{2\,\pi\, K_c\, L} \qquad (18)$$

Putting the value of $A_5$ into Eq. (16), the temperature difference across the outer cladding thickness becomes

$$T(r_c) - T(r_d) = \frac{9000}{2\,\pi\, K_c\, L} \mathrm{Log}(r_d/r_c) = 85.7098{,}5756{,}6899{,}611\ °\mathrm{C} \qquad (19)$$

The sum of Eqs. (11), (14) and (19) gives the total temperature difference across the tube thickness.

$T(r_a) - T(r_d)$ = **178.0270,7992,9631,615 °C** (20)

The coolant temperature rise is the same as that in problem 1.

Coolant temperature rise = $\frac{9000}{4180 \times 0.05}$ = **43.0622,0095,6937,80 °C** (21)

#### 4.2.2. Solution of Problem 2 by Standalone Routine SLICEHTR

The standalone routine was run for this calculation. The heat source in the meat was set to the value in Eq. (10), and that in the cladding was set to zero. The film coefficient at the inner surface of the tube was set exactly to zero. The whole length (0.6 m) of the tube was treated as a single axial node because the standalone routine can handle only one node. A small main program was written to define these input data and to call the routine. The output of the routine is shown in Fig. 5. The temperature drop across the tube thickness and the coolant temperature rise in the outer channel are noted below. All 16 digits in these values agree with the hand calculated results in Eqs. (20) and (21).

Temperature difference across tube thickness from Fig. 5 = 178.0270,7992,9631,6 °C (22)
Node-center coolant temperature from Fig. 5 = 71.5311,0047,8468,90 °C
Coolant temperature rise = 2 x (71.53110047846890 - 50) = 43.0622,0095,6937,80 °C (23)

If the problem is slightly modified, i.e., the film coefficient at the inner surface of the tube is set to $10^{-6}$ W/m$^2$-°C instead of exactly zero, then the routine's output is shown in Fig. 6. These results are slightly different from those in Eqs. (20) and (21). Only 8 or 9 significant digits agree. The results changed presumably due to the slight change in the inner surface boundary condition.

Temperature difference across tube thickness from Fig. 6 = 161.1562,1235,9536,1 °C (24)
Node-center coolant temperature from Fig. 6 = 71.5311,0046,9198,58 °C
Coolant temperature rise = 2 x (71.53110046919858 – 50) = 43.0622,0093,8397,16 °C (25)

### 4.2.3. Solution of Modified Problem 2 by PLTEMP Code Version 3.2

The problem was solved by the Broyden method and the newly-implemented analytical method. The input data file (for the Broyden method) used is shown in Fig. 7. The film coefficient at the inner surface was set to $1.0^{-6}$ W/m$^2$-°C. The input data has 10 axial nodes (with axially uniform heat source) in the 0.6 meter length of the tube. The constant coolant specific heat option (ICP = 1 on card 200) was used ($C_p$ = 4180.0 J/kg-°C). The code was run for the input file shown in Fig. 7. The relevant part of the output for the Broyden solution is shown in Fig. 8, and that for the analytical solution is shown in Fig. 9. For comparison, the results of all five methods are summarized in Table 2.

**Table 2. Comparison of Results by Five Methods for Radial Geometry Problem 2**

| Method | Temperature Difference Across Tube Thickness, °C | Coolant Temperature Rise, °C | Comments |
|---|---|---|---|
| Hand Calculation | 178.0270,7992,9631,615 | 43.0622,0095,6937,80 | All digits good |
| Standalone Routine SLICEHTR | 178.0270,7992,9631,6 | 43.0622,0095,6937,80 | All digits good |
| Standalone Routine SLICEHTR for the Modified Problem | 178.0270,7962,2544,8 | 43.0622,0093,8397,16 | All digits presumed good |
| Broyden Method in PLTEMP v3.2 for the Modified Problem | 178.0270,7822,6028 [a]<br>178.0270,7828,0832 [b] | 43.0622,0093,8102,2 | Agrees to 8 digits or more |
| Analytical Method in PLTEMP v3.2 for the Modified Problem | 178.0270,7958,9524,00 [a]<br>178.0270,7964,3935,80 [b] | 43.0622,0093,8093,5 | Agrees to 9 digits |

a. The smallest value in the 10 axial nodes used over the length of fuel tube.
b. The largest value in the 10 axial nodes used over the length of fuel tube.

For the PLTEMP Broyden method, each axial node gives practically the same temperature difference between the inner and outer surfaces of the tube, as expected. For all axial nodes, the temperature difference is found to be **178.0270,782**$^{2}_{8}$ **°C** (meaning that the 11$^{th}$ digit varies from 2 to 8**)**. This can be compared with the hand-calculated value in Eq. (20) or the routine SLICEHTR-calculated value in Eq. (22) for the *unmodified* problem 2. But more appropriately, the Broyden method calculated value should be compared with the routine SLICEHTR-calculated value in Eq. (24) for the *modified* problem 2. There is agreement to 8 significant digits with the value in Eq. (24).

The coolant temperature rise calculated by the Broyden method is **43.0622,0093,8**102,2 °C. The highlighted 11 digits of this value agree with the more accurate value given in Eq. (25) that was obtained by the standalone routine SLICEHTR for the modified problem.

For the PLTEMP analytical method, each axial node gives practically the same temperature difference between the inner and outer surfaces of the tube, as expected. For all axial nodes, the temperature difference is found to be **178.0270,79**$^{59}_{64}$ **°C** (meaning that the 10$^{th}$ and 11$^{th}$ digits vary from 59 to 64**)**. This can be compared with the hand-calculated value in Eq. (20) or the routine SLICEHTR-calculated value in Eq. (22) for the *unmodified* problem 2. But more appropriately, the analytical method calculated value should be compared with the routine SLICEHTR-calculated value in Eq. (24) for the *modified* problem 2. There is agreement to 9 significant digits with the value in Eq. (24). As indicated in Section 4.2.2, a comparison of the results of Eqs. (20) and (22) shows that the routine SLICEHTR is capable of an accuracy to 16 significant digits. The accuracy of the analytical method is here limited to 9 digits presumably because the accuracy of the input data (especially the tube circumference CIRCF) to the code is limited to 10 digits due to the 12-column data fields.

The coolant temperature rise calculated by the analytical method is **43.0622,0093,8**093,5 °C. The highlighted 11 digits of this value agree with the more accurate value given in Eq. (25) that was obtained by the standalone routine SLICEHTR for the modified problem.

### 4.3. Calculation of Film Coefficient in the Broyden Method

Figures 8 and 9 (solutions of the same problem by the Broyden and analytical methods) show a difference in film coefficient in channel 2. The film coefficient to channel 2 calculated in the Broyden and analytical methods are not in good agreement, in spite of a precise agreement (to 11 significant digits) in the channel 2 coolant temperature rise calculated by the two methods. This agreement in coolant temperature is shown in Figs. 8 and 9 and was discussed in Section 4.2. An example of the disagreement in film coefficient to channel 2 is 5029.9 versus 4963.8 W/m$^2$-°C in axial mesh interval 1 in the Broyden and analytical methods respectively, also shown in Figs. 8 and 9.

The reason for this disagreement was traced to the use (in routine FUNCV) of coolant thermal properties at the *outlet* of an axial mesh interval (rather than the mesh *center*) in film coefficient calculation in the Broyden method. This was subsequently changed to use the coolant properties at the mesh center. After this improvement, problem 2 was solved again by the Broyden method, and the results are compared with the analytical solution in Fig. 10 (printed to 13 digits using the option KPRINT = 1). The film coefficients for the axial nodes 1 to 9 now agree to 13 digits for this problem. The agreement in the axial node 10 is only to 5 digits (i.e., 6348.184 versus 6348.170 W/m$^2$-°C). This is unexpected because the coolant temperatures in all axial nodes (1 to 10) agree to 13 digits.

**4.4. Radial Geometry Problem 3:** Find the temperature difference across the thickness of a 60 cm long fuel tube whose fuel meat is generating a power of 9 kW (no power in the cladding). Use a film coefficient of $10^{-6}$ W/m$^2$-°C on the inner surface of the fuel tube, and the Sieder-Tate correlation of film coefficient on the outer surface. The tube inner radius is 0.5 cm, the meat inner radius is 1.5 cm, the meat outer radius is 3.5 cm, the tube outer radius is 4.5 cm, and the thermal conductivities of cladding and meat are 7 and 8 W/m-°C. What is the coolant (water) temperature rise using the actual enthalpy and specific heat of the coolant (water) with a flow rate of 0.05 kg/s in each channel?

### 4.4.1. Solution of Problem 3 by PLTEMP Code Version 3.2

Since the actual enthalpy and specific heat of the coolant are used in problem 3, a comparison of the solutions by the Broyden and the analytical methods shows the differences actually experienced in reactor conversion analyses. The input data for the problem is shown in Fig. 11. This input file is obtained from that for problem 2 simply by setting the option ICP to zero (on input card 200). All other data remain unchanged. The solutions obtained by the Broyden and analytical methods are shown in Figs. 11 and 12.

The total temperature difference across the fuel tube thickness for each axial node is the same as that in problem 2, i.e., **178.0270,782$^{2}_{8}$ °C** by the Broyden method (see Fig. 12) and **178.0270,79$^{59}_{64}$ °C** by the analytical method (see Fig. 13). The temperature differences across the tube thickness calculated by the two methods agree to 8 significant digits. The coolant temperatures do not agree this accurately although their difference is less than **0.127 °C** which is investigated below in items 1 and 2. The film coefficients of the first axial node in the two solutions agree to 5 significant digits (4987.77 versus 4987.84 W/m$^2$-°C) but the difference between the film coefficients grows in the flow direction due to the growing coolant temperature difference. In the last axial node, the film coefficients in the two solutions agree to only 3 digits (6425.53 versus 6421.81 W/m$^2$-°C).

The following differences between the coolant temperatures calculated by the two methods and their explanation are noted:

(1) The coolant outlet temperature in channel 2 found by the Broyden method is 92.9923 °C compared to 92.8645 °C found by the analytical method (i.e., a difference of 0.1268 °C). In order to determine which of these values is more accurate, a hand calculation was done based on the coolant enthalpy used by the PLTEMP/ANL code. The hand calculation reported in Section 4.4.2 below gives a value of 92.8624 °C. This implies that the analytical method calculated value is more accurate. The difference between the values obtained by hand calculation and the analytical method is 0.0021 °C. The reason for this difference is believed to be related to the uncertainty (or jumps shown below in Table 3)

in the values of $\partial h/\partial P$ evaluated using different values of ΔP in the enthalpy routine ZHLIQ of the PLTEMP/ANL code.

**Table 3. Pressure Derivative of Water Enthalpy at 1.5 bar and 50 °C Calculated From PLTEMP Code**

| Case No. | ΔP, bar | ΔT, °C | $\partial h/\partial P$, J/kg-bar |
|---|---|---|---|
| Method: $\partial h/\partial P$ at (T,P) = {h(T, P+0.5ΔP) - h(T, P-0.5ΔP)}/ ΔP | | | |
| 1 | 0.1 | | 138.9 |
| 2 | 0.2 | | 69.43 |
| 3 | 0.5 | | 83.31 |
| $\partial h/\partial P$ at (T,P) = {h(T+0.5ΔT, P+0.5ΔP) - h(T-0.5ΔT, P-0.5ΔP) – ΔT $C_p$(T,P)}/ ΔP | | | |
| 4 | 0.05 | 2.0 | 131.5 |
| 5 | 0.1 | 2.0 | 131.5 |
| 6 | 0.1 | 4.0 | 65.75 |
| 7 | 0.25 | 2.0 | 81.84 |
| 8 | 0.5 | 2.0 | 82.58 |

(2) The coolant outlet temperature in channel 1 found by the Broyden method is 50.0000 °C compared to 50.0199 °C found by the analytical method (i.e., a difference of 0.0199 °C). The film coefficient to coolant channel 1 is input to be $1.0\text{x}10^{-6}$ W/m$^2$-°C, and hence the heat transfer to the coolant in channel 1 is very small. The coolant temperature rise in channel 1 is found in Section 4.4.2 to be less than $2.0\text{x}10^{-8}$ °C if the pressure-dependence of coolant enthalpy is ignored. This agrees with the result by the Broyden method.

In Section 4.4.2, the coolant temperature rise in channel 1 is also estimated accounting for the pressure-dependence of coolant enthalpy, and found to be about 0.0214 °C. The coolant temperature rise in channel 1 is 0.0199 °C in the analytical method due to the fact that the pressure dependence of coolant enthalpy is accounted for by the method.

### 4.4.2 Hand Calculation for Problem 3

Coolant Temperature Rise in Channel 1: The film coefficient to coolant channel 1 is input to be $1.0\text{x}10^{-6}$ W/m$^2$-°C, and the heat transfer to the coolant in channel 1 is very small. Hence the temperature rise is very small if the pressure-dependence of coolant enthalpy is not accounted for. Therefore, the temperature rise is calculated in two ways, first ignoring the pressure-dependence of enthalpy, and then accounting for the pressure-dependence of enthalpy.

Temperature Rise in Channel 1 Ignoring Pressure-Dependence of Enthalpy:

Input data: $h_1 = 1.0\text{x}10^{-6}$ W/m$^2$-°C, $r_a = 0.005$ m, $T_s \leq 277$ °C (see Fig. 12),

$L = 0.6$ m, $T_{in} = 50$ °C, $W = 0.05$ kg/s,
$C_p = 4180$ J/kg-°C,

Coolant temperature rise in channel 1 $\leq \dfrac{2\pi r_a L h_1 (T_s - T_{in})}{W C_p} = 2.0\text{x}10^{-8}$ °C

Temperature Rise in Channel 1 Accounting for Pressure-Dependence of Enthalpy:
The value of $C_T$, i.e., the partial derivative $\partial h / \partial P$ at constant temperature varies from 74.6 to 104.6 J/kg-°C-bar over the coolant temperature and pressure range of the problem (50 to 90 °C and 1 to 2 bar). It is assumed to have a mean value of 89.6 J/kg-bar in the estimation of the coolant temperature rise $\Delta T$ in channel 1, *without any heat addition*, due only to the pressure drop from the channel inlet to outlet (i.e., 2 bar to 1 bar). Setting the enthalpy change from the inlet to outlet to zero, we get

$$C_p \, \Delta T + C_T \, \Delta P = 0 \tag{26}$$

Equation (26) can be rewritten as

$$\Delta T = - C_T \, \Delta P \, / \, C_p \tag{27}$$

Putting $\Delta P = -1.0$ bar and $C_p = 4180$ J/kg-°C, we get from Eq. (27)

Coolant temperature rise in channel 1 = $\Delta T \approx -89.6 \text{ x } (-1.0)/4180 =$ **0.0214 °C** (28)

Coolant Outlet Temperature in Channel 2: In the code, the enthalpy and specific heat of water is treated as a function of temperature and pressure. The enthalpy of water used by the code (calculated in the subroutine ZHLIQ) is tabulated in Appendix C for the temperature range 1 to 100 °C and the pressure range 1 to 10 bars. In problem 3, the input inlet and outlet pressures are 2 bar and 1 bar respectively. Almost all the heat generated in the fuel goes to coolant channel 2 because the film coefficient to channel 1 is $10^{-6}$ W/m$^2$-°C, i.e., very small compared to the values of ~5000 W/m$^2$-°C in channel 2. Hence the channel 2 outlet temperature can be found by equating the total power (9000 W) generated in the fuel to the heat removal rate by the coolant in channel 2, as follows.

$$W \, [\, h(T_{out}, 1\text{bar}) - h(T_{in}, 2\text{bar}) \,] = 9000 \tag{29}$$

where $W = 0.05$ kg/s
$T_{in} = 50$ °C
$h(T_{in}, 2\text{bar}) = 208{,}844.8334$ J/kg (from Appendix C)

Equation (29) gives the channel 2 outlet enthalpy.

$$h(T_{out}, 1\text{bar}) = 208{,}844.8334 + 9000/0.05 = 388{,}844.8334 \text{ J/kg} \tag{30}$$

The outlet enthalpy in Eq. (30) lies between the following enthalpy data given in Appendix C at the outlet pressure of 1 bar.

h(92 °C,1bar) = 385,204.5441 J/kg
h(93 °C,1bar) = 389,425.7355 J/kg
Change $\Delta$h = 4221.1914 J/kg
Using the above data and the channel 2 outlet enthalpy of Eq. (30), the outlet temperature in channel 2 is interpolated as follows.

$T_{out}$ = 92 + (388,844.8334 - 385,204.5441) / 4221.1914 **= 92.8624 °C** (31)

**4.5. Radial Geometry Problem 4:** Find the temperature difference across the thickness of a 60 cm long fuel tube whose fuel meat is generating a power of 9 kW (no power in the cladding). Use a film coefficient of 1000 W/m$^2$-°C on the inner and outer surfaces of the fuel tube. The tube inner radius is 0.5 cm, the meat inner radius is 1.5 cm, the meat outer radius is 3.5 cm, the tube outer radius is 4.5 cm, and the thermal conductivities of cladding and meat are 7 and 8 W/m-°C. What is the coolant (water) temperature rise using the actual enthalpy and specific heat of the coolant (water) with a flow rate of 0.05 kg/s in each channel?

### 4.5.1. Solution of Problem 4 by PLTEMP Code Version 3.1

Problem 4 is identical to problem 3 in all respects except that the film coefficients on the inner and outer surfaces of the tube are different. This problem has an input film coefficient of 1000 W/m$^2$-°C on each side of the tube whereas problem 3 had an input value of $10^{-6}$ W/m$^2$-°C on the inner surface and a film coefficient calculated by the code using the Sieder-Tate correlation on the outer surface. Figure 14 shows the input file for problem 4 (same for versions 3.1 and 3.2 of PLTEMP/ANL). This input file was obtained by changing only two data on card 300, i.e., by setting the flag IBCA to 3, and the film coefficient HBC to 1000.

Figure 15 shows the results of running 200 iterations of the Broyden method in the version 3.1 of PLTEMP/ANL. The results are not good because the calculation did not converge as indicated by the large values of temperature mismatch $T_{diff}$ (> 100 °C) in all axial nodes (see Fig. 15). The lack of convergence is due to an unsuitable initial guess for the location of the peak fuel temperature in meat thickness. The initial guess is unsuitable because it is provided by the *slab geometry* analytical solution of the problem in this version of the code (because it does not have a radial geometry analytical method). The Broyden method in this version converges in the radial geometry for many actual reactor assemblies (e.g., the ASTRA2 six-tube assembly problem 3 reported below) using the initial guess provided by the slab geometry analytical solution when the fuel areal fraction (called X) inside the peak fuel temperature, $(r_{\max}^2 - r_b^2)/(r_c^2 - r_b^2)$, is close to 0.5 in each fuel tube. The code may not converge if X is far from 0.5 in any fuel tube, i.e., X < 0.2 or X > 0.8.

### 4.5.2. Solution of Problem 4 by PLTEMP Code Version 3.2

The input file given in Fig. 14 was also used in the version 3.2 of the code. Figure 16 shows the results of running 200 iterations of the Broyden method, and Fig. 17 shows the results of running the newly implemented analytical method in the version 3.2. Although no change was made in the iteration strategy of the Broyden method, the method converged this time as indicated by negligible $T_{diff}$ shown in Fig. 16, and the results are good. This is because the initial guess for the peak fuel temperature location in meat thickness is good. The initial guess is good because it is provided by the analytical solution of the actual radial geometry problem (after the implementation of the radial geometry analytical method in version 3.2 of the code).

Table 4 shows a comparison of temperatures calculated by the two methods for problem 4. Using a previously developed utility *differ.x*, it is found that the maximum difference between the two solutions in all coolant, cladding, and fuel temperatures given in Figs. 16 and 17 is 0.055 °C that occurs in the outer channel outlet temperature. The agreement between the two methods provides a verification of the implementation of the analytical method.

**Table 4. Summary of PLTEMP/ANL Code Results for Problem 4**

| PLTEMP/ANL Version and Method | **Temperature of Coolant Outlet or Fuel Tube Axial Node 10, °C** | | | | | Comments |
|---|---|---|---|---|---|---|
| | Inner Coolant | Inner Clad Surface | Meat Maximum | Outer Clad Surface | Outer Coolant | |
| Broyden Method in Version 3.1 | 80.095 | 115.726 | 276.651 | 205.492 | 62.898 | Results did not converge |
| Broyden Method in Version 3.2 | 58.444 | 156.246 | 244.382 | 124.977 | 84.548 | Good results |
| Analytical Method in Version 3.2 | 58.466 | 156.238 | 244.346 | 124.925 | 84.484 | Good results |

**4.6. Slab Geometry Problem 5:** Turn the radial geometry problem 3 into a slab geometry problem by just setting the option IGOM to 0 (on the input card 200), and solve the resulting problem for a fuel plate of width 5π cm, length 60 cm, generating a power of 9 kW (no power in the cladding). Use a film coefficient of $10^{-6}$ W/m$^2$-°C on the left surface of the fuel plate, and the Sieder-Tate correlation of film coefficient on the right surface. The thicknesses of cladding and meat remain unchanged, i.e., 1.0 cm and 2.0 cm respectively, and the thermal conductivities of cladding and meat are 7 and 8 W/m-°C. What is the coolant (water) temperature rise using the actual enthalpy and specific heat of the coolant (water) with a flow rate of 0.05 kg/s in each channel?

The purpose in this section is to solve the flat fuel plate problem 5 in two ways: first by the slab geometry analytical method in the PLTEMP/ANL version 3.2 code and then by the radial geometry analytical method in the code by using a practically infinite mean radius for the fuel tube. The solution obtained by the radial geometry analytical method should approach the solution by the slab geometry analytical method, thus proving a verification of the newly implemented radial geometry analytical method.

### 4.6.1. Hand Calculation for Problem 5

Input data given: $t_c = 0.01$ m, $t_f = 0.02$ m, $w = 0.05\pi$ m,
$K_c = 7$ W/m-°C, $K_f = 8$ W/m-°C, $L = 0.6$ m, $P = 9000$ W

The left fuel-cladding interface is practically adiabatic due to the negligible film coefficient on the left surface of the fuel plate. Hence there is no temperature difference across the left cladding thickness. The volumetric heat source in the meat and the temperature drop across the meat thickness are given by

$$q''' = \frac{P}{L\,w\,t_f} = 4.77464829275686\text{x}10^6 \text{ W/m}^3 \tag{32}$$

$$\Delta T_f = \frac{q''' t_f^{\,2}}{2K_f} = 119.3662073189215 \text{ °C} \tag{33}$$

All the power conducts through the right side cladding, and therefore the heat flux and temperature difference across the right cladding thickness are given by

$$q'' = \frac{P}{Lw} = 95492.9658551372 \text{ W/m}^2 \tag{34}$$

$$\Delta T_c = \frac{q'' t_c}{K_c} = 136.418522650196 \text{ °C} \tag{35}$$

The sum of Eqs. (33) and (35) gives the total temperature drop across the plate thickness, from the right cladding surface to the left cladding surface.

$$T_{csr} - T_{csl} = 255.7847299691175 \text{ °C} \tag{36}$$

### 4.6.2. Comparison of Solutions of Problem 5 by Slab Geometry Analytical Method and Radial Geometry Analytical Method

Figure 18 shows the PLTEMP input data file for problem 5 that was obtained by setting the input flag IGOM to 0 (on the input card 200) in the input file of problem 3 shown in Fig. 11. It is the only difference between these input files. On the other hand, Fig. 19 shows the input data file to solve problem 5 using the radial geometry analytical method. This input file was obtained by setting the mean tube radius to 1000 m instead of 0.025 m in the input file for problem 3 (input RMID on card 308A). It is the only difference between the input files shown in Figs. 11 and 19.

The PLTEMP/ANL version 3.2 code was run for these two input files (Figs. 18 and 19), and the results are shown in Figs. 20 and 21 respectively. By running the latter input file using mean radii smaller than 1000 m it was found that 1000 m is practically infinite. Using a previously developed utility *differ.x*, it is found that the maximum difference in all coolant, cladding, and fuel temperatures between the two solutions given in Figs. 20 and 21 is 0.004 °C that occurs in axial node 1 of the left side cladding. This provides a verification of the radial geometry analytical method implemented in the version 3.2 of the code.

Setting the print option KPRINT = 1, the total temperature drop across the fuel plate thickness was obtained to 13 significant digits for comparison with the accurate hand calculation given in Eq. (36). The total temperature drop in the solution by the slab geometry analytical method gives $255.784728_{3}^{5}$ °C (meaning that the 10$^{th}$ digit varies from 3 to 5 for the 10 axial nodes used). This agrees with the hand calculation of Eq. (36) to 8 significant digits (the 9$^{th}$ digit in the PLTEMP solution should be 9 instead of 8), verifying the result of the slab geometry analytical method. The total temperature drop in the solution of problem 5 by the radial geometry analytical method gives $255.781891_{6}^{8}$ °C (meaning that the 10$^{th}$ digit varies from 6 to 8 for the 10 axial nodes used). This agrees with the hand calculation of Eq. (36) *only to 5 significant digits*, and has an error of 0.0028 °C.

Table 5 summarizes several solutions of problem 5 by the radial geometry analytical method using increasing values of the input mean radius for the fuel tube. It is noted that the most accurate solution (with an error of 0.0006 °C in the temperature drop across the fuel plate thickness) is obtained by using a tube radius of 10000 m. The solution deteriorates (presumably due to round-ff error) if the input tube radius is increased beyond 10000 m. However, this comparison shows that the solution of a slab geometry problem by the radial geometry analytical method approaches the actual solution as the fuel tube radius is made very large (practically infinite). This provides a verification of the radial geometry analytical method.

**Table 5. Solution of Flat Plate Problem 5 by the Radial Geometry Analytical Method Using Increasing Values of the Input Mean Radius of the Fuel Tube**

| Calculation Method | Input Tube Radius, m | Temperature Drop Across Plate Thickness, °C | Comments |
|---|---|---|---|
| Hand Calculation | Not used | 255.7847299691175 | All digits good |
| Slab Geometry Analytical Method | Not used | $255.784728_{3}^{5}$ | Agrees to 8 digits |
| Radial Geometry Analytical Method | 500 | $255.779054_{0}^{1}$ | Error = 0.0057 °C |
| | $10^3$ | $255.781891_{6}^{8}$ | Error = 0.0028 °C |
| | $10^4$ | $255.78410_{78}^{80}$ | Error = 0.0006 °C |
| | $10^5$ | $255.861963_{0}^{3}$ | Error = 0.0772 °C |
| | $5\times10^5$ | $255.330459_{0}^{7}$ | Error = 0.4543 °C |
| | $10^6$ | $219.21695_{1}^{4}$ | Error = 36.5678 °C |

## 4.7. Hungarian Reactor Benchmark Problem with a Power of 90 kW

The temperature distribution in the Hungarian reactor benchmark problem was calculated [3] using the PLTEMP/ANL version 3.1 code in September 2006. Figure 22 shows the input data file used. The fuel assembly in this problem consists of 3 fuel tubes. For a verification of the newly implemented radial geometry analytical method in PLTEMP/ANL version 3.2, five solutions to this problem obtained by the following methods are compared in this section.

(1) The Broyden method in version 3.2 using the constant coolant $C_p$ option
(2) The radial geometry analytical method in version 3.2 using the constant $C_p$ option

(3) The Broyden method in version 3.1 using the actual coolant properties (identical to E. E. Feldman's calculation of September 2006)
(4) The Broyden method in version 3.2 using the actual coolant properties
(5) The radial geometry analytical method in version 3.2 using the actual coolant properties

The first two solutions (i.e., the Broyden and analytical methods using constant $C_p$) give identical standard output files that are printed to 4 decimal digits using the print flag KPRINT = 0. The two solutions were then printed to 13 significant digits by setting the print flag KPRINT = 1, and are compared in Fig. 23. All coolant, cladding, and meat temperatures and film coefficients (except 3 temperatures highlighted in Fig. 23) agree to 6 significant digits. The three exceptions are the fuel peak temperatures in axial nodes 2 and 3 of fuel tube 1, and in axial node 2 of fuel tube 3. By entering more digits in the input data, an agreement better than this was shown for problem 2 in Section 4.3.

The three calculations performed using the actual coolant properties (shown in Figs. 24, 25, and 26) are compared in Table 6 by reporting the maximum difference $\Delta T_{max}$ between a (selected) pair of solutions for all coolant, cladding, and fuel temperatures of a fuel tube and its two adjacent channels. A previously developed utility *differ.x* was used to find the difference $\Delta T_{max}$.

**Table 6. Comparison of Three Solutions for the Hungarian Reactor Benchmark Problem (Using Actual Coolant Properties)**

| Calculation Methods Compared | $\Delta T_{max}$ Maximum Temperature Difference, °C | | | Location of $\Delta T_{max}$ | Comments |
|---|---|---|---|---|---|
| | Tube 1 | Tube 2 | Tube 3 | | |
| Broyden Method in PLTEMP/ANL Version 3.1 versus Broyden Method in Version 3.2 | 0.257 | 0.249 | 0.235 | Meat in Axial Node 4 | Due to node outlet vs node center coolant temperature used in film coefficient |
| Broyden Method in PLTEMP/ANL Version 3.2 versus Radial Geometry Analytical Method in Version 3.2 | 0.005 | 0.007 | 0.007 | Coolant in Axial Node 8 | Due to not accounting for $\partial h/\partial P$ in Broyden method |

The maximum difference between the solutions 3 and 4 (i.e., the solution by the Broyden method in version 3.1 and the solution by the Broyden method in version 3.2) is about 0.25 °C (as shown in Table 6). This difference is due to using the coolant *node center* temperature for calculating film coefficient in version 3.2 instead of using the coolant *node outlet* temperature for calculating film coefficient in version 3.1.

The maximum difference between the solutions 4 and 5 (i.e., the solution by the Broyden method in version 3.2 and the solution by the radial geometry analytical method in version 3.2) is about 0.007 °C. This difference is because the analytical method accounts for the pressure derivative of coolant enthalpy whereas the Broyden method does not. This provides a verification of the analytical method.

## 4.8. ASTRA2 Six-Tube Assembly Problem 3 Case 1

The temperature distribution in a six-tube radial geometry problem (called ASTRA2 Problem 3 Case 1) was calculated earlier by Russian authors using their ASTRA2 code and provided to ANL [4, 5]. For comparison purposes, a solution to this problem was calculated by A. P. Olson using the PLTEMP/ANL code version of May 22, 2003. The input and output files of this calculation are available. The fuel tubes were arranged in the order of decreasing mean radii in A. P. Olson's calculation. Since the currently implemented radial geometry analytical method requires the tubes to be arranged in the order of increasing radii, the input card types 307, 308, 308A, 309, and 310 were rearranged in the reverse order. The resulting input data file is shown in Fig. 27, and the May 2003 results (rearranged accordingly) are shown in Fig. 28.

Using this input file (Fig. 27), the temperature distribution in the ASTRA2 radial geometry problem 3 case 1 was recalculated by the Broyden method using the current versions 3.1 and 3.2 of the PLTEMP/ANL code (using 200 iterations), and by the radial geometry analytical method in version 3.2 of the code. The results of the three recalculations are shown in Figs. 29, 30, and 31. The Broyden solution using version 3.1 has fuel peak temperature mismatches (i.e., $T_{diff}$ which is a measure of convergence) of 0.19 to 0.61 °C in 4 of the 66 axial nodes used in the problem (11 nodes per tube × 6 tubes). The Broyden solution using version 3.2 has temperature mismatches $T_{diff}$ of 0.01 °C in only 2 of the 66 axial nodes used in the problem.

**Table 7. Comparison of Solutions for ASTRA2 Radial Geometry Problem 3 Case 1 (Using the Constant Coolant $C_p$ Option)**

| Calculation Methods Compared | $\Delta T_{max}$ Maximum Temperature Difference, °C | Location of $\Delta T_{max}$ | Comments |
|---|---|---|---|
| Broyden Method in Version 3.1 versus Broyden Method in Version 3.2 | 0.171 | Inner Cladding of Tube 5 in Axial Node 11 | (1) Due to node outlet vs. node center coolant temperature used in film coefficient |
| Broyden Method in Version 3.2 versus Radial Geometry Analytical Method in Version 3.2 | 0.089 | Meat of Tube 1 in Axial Node 7 | (2) Perhaps due to a difference between the methods in use of the redundant input data |
| Broyden Method in Version 3.1 versus Radial Geometry Analytical Method in Version 3.2 | 0.203 | Meat of Tube 5 in Axial Node 6 | Comments 1 and 2 |
| PLTEMP/ANL of May 2003 versus Broyden Method in Version 3.1 | 5.987 | Meat of Tube 6 in Axial Node 10 | Code improvements after May 2003 |

Table 7 compares these three recalculations with the older May 2003 results by reporting the maximum difference $\Delta T_{max}$ in the coolant, cladding, and fuel temperatures of *all channels and tubes* between a pair of solutions. Selected results of all four PLTEMP/ANL calculations are compared in Table 8 with the results obtained by Russian authors using their ASTRA2 code.

Based on Table 7, the following observations are made in numbered paragraphs. A verification of the radial geometry analytical method is provided in paragraph number 2.

(1) Comparing the Broyden solutions obtained by PLTEMP/ANL versions 3.1 and 3.2 (shown in Figs. 29 and 30), it is found that the maximum temperature difference $\Delta T_{max}$ is 0.171 °C. This difference is due to using node outlet versus node center coolant temperature in calculating film coefficient in the versions 3.1 and 3.2. The latter solution is considered to be more accurate. The solution obtained by the newly implemented radial geometry analytical method is therefore checked against the latter.

(2) Comparing the radial geometry analytical solution and the Broyden solution by PLTEMP/ANL version 3.2 (Fig. 30 and Fig. 31), it is found that the maximum temperature difference $\Delta T_{max}$ is 0.089 °C. This difference is perhaps due to a difference between the methods in use of the redundant input data (e.g., XIF on input card 307, CIRCF on card 308, and RMID on card 308A). This difference is not due to the lack of accounting for $\partial h/\partial P$ in the Broyden method because the constant coolant $C_p$ option (ICP = 1 on input card 200) is used in this problem, and $\partial h/\partial P$ is zero in both methods when this option is used (as shown by the comparison given in Fig. 23 for the Hungarian reactor benchmark problem in Section 4.7). However, the difference $\Delta T_{max}$ is small, and the comparison for the ASTRA2 problem provides a verification of the radial geometry analytical method.

(3) Comparing the radial geometry analytical solution with the Broyden solution by PLTEMP/ANL version 3.1, it is found that the maximum temperature difference $\Delta T_{max}$ is 0.203 °C. This difference is due to (i) using node outlet versus node center coolant temperature in calculating film coefficient in the versions 3.1 and 3.2, and (ii) also perhaps due to a difference between the methods in use of redundant input data, as discussed above in paragraph number 2. This temperature difference is not due to the lack of accounting for $\partial h/\partial P$ in the Broyden method, as discussed above.

(4) Comparing the May 2003 results with the Broyden solution by PLTEMP/ANL version 3.1, the maximum temperature difference $\Delta T_{max}$ is found to be 5.987 °C which occurs in axial node 11 of the meat of tube 6 (outermost). This difference is significantly large. It is due to the code improvements done after May 2003, and also perhaps because the solution converged only approximately. The solution had temperature mismatches $T_{diff}$ (a measure of convergence) of 0.11 to 0.77 °C in 29 of the 66 axial nodes used in the problem. The Broyden solution of May 2003 is less accurate than the current Broyden solutions.

As a side remark, it is noted that the Broyden method in PLTEMP/ANL *version 3.1* converges for this radial geometry problem. The convergence of the Broyden method in version 3.1 shows that the initial guess for fuel areal fraction (called X) inside the peak fuel temperature, i.e., $(r_{\max}^2 - r_b^2)/(r_c^2 - r_b^2)$, in each fuel tube is suitable for convergence. The initial guess in the version 3.1 is provided by the *slab geometry* analytical method. The radial geometry analytical method is not available in this version. However, the Broyden method converges because the fuel areal fraction X in each tube is close to 0.5 (in the range 0.35 to 0.60). The Broyden method in PLTEMP/ANL *version 3.1* may not converge for some other radial geometry problems, as it did not for problem 4 discussed in Section 4.5.1.

### 4.9. Conclusions

In summary, for the constant coolant specific heat option in the code (ICP = 1 on input card 200), the coolant temperature rise calculated by the newly-implemented analytical method in PLTEMP/ANL code is good to 11 significant digits, and the temperature difference across the tube thickness is good to 8 digits in problem 1. The coolant temperature rise calculated by the analytical method is good to 11 significant digits, and the temperature difference across the tube thickness is good to 9 digits in problem 2.

When using the actual thermal properties of the coolant in problem 3 (otherwise identical to problem 2), there is a difference of 0.0021 °C in the coolant temperature rise calculated by the analytical method and hand calculation, and the temperature difference across the tube thickness is good to 9 digits. There is a difference of 0.13 °C in the coolant temperature rise calculated by the Broyden method and hand calculation.

The solution of a slab geometry problem by the radial geometry analytical method approaches the actual solution as the fuel tube radius (input RMID on card 308A) is made very large (about 1000 m).

For the Hungarian reactor benchmark problem, the radial geometry analytical solution and the Broyden solution by PLTEMP/ANL version 3.2 were compared to find that the maximum difference in the coolant, cladding, and fuel temperatures of *all channels and tubes* is 0.007 °C.

For the ASTRA2 six-tube assembly, the radial geometry analytical solution and the Broyden solution by PLTEMP/ANL version 3.2 were compared to find that the maximum difference in the coolant, cladding, and fuel temperatures of *all channels and tubes* is 0.089 °C.

**REFERENCES**


1. A. P. Olson and Kalimullah, Argonne National Laboratory, unpublished information, November 20, 2006.

2. M. Kalimullah, E. E. Feldman, and A. P. Olson, Argonne National Laboratory, Argonne, unpublished information, February 26, 2007.

3. E. E. Feldman, Argonne National Laboratory, private communication, September 30, 2006.

4. A. P. Olson, Argonne National Laboratory, private communication, February 26, 2007.

5. Pavel Egorenkov, Kurchatov Institute, Kurchatov Square 1, 123182, Moscow, private communication of Results to J. E. Matos of Argonne National Laboratory, 2002.

## Table 8. Temperature Distribution in ASTRA2 Radial Geometry Problem 3 Case 1 With the Innermost Fuel Tube as the First

| | Tube | ASTRA2 Code | PLTEMP/ANL of May 22, 2003 [a] | PLTEMP/ANL Version 3.1 Broyden Method | PLTEMP/ANL Version 3.2 Broyden Method | PLTEMP/ANL Version 3.2 Analytical Method |
|---|---|---|---|---|---|---|
| Geometry | | Cylinder | Cylinder | Cylinder | Cylinder | Cylinder |
| Power, MW | | 0.66288 | 0.66288 | 0.66288 | 0.66288 | 0.66288 |
| Flow, kg/s | | 7.7588 | 7.7588 | 7.7588 | 7.7588 | 7.7588 |
| Fuel Heated Area, $m^2$ | | 1.1097 | 1.1097 | 1.1097 | 1.1097 | |
| Velocity in Channel 7, m/s | | 3.21 | 3.21 | 3.21 | 3.21 | 3.21 |
| Tube 6 Power Fraction | | 0.25486 | 0.25486 | 0.25486 | 0.25486 | 0.25486 |
| Coolant ΔT, °C | | 20.4392 | 20.4398 | 20.439 | 20.439 | 20.4392 |
| Peak Fuel Temperature, °C | | 103.0 | 103.159 In Tube 6 | 102.903 In Tube 5 | 103.016 In Tube 5 | 103.079 In Tube 5 |
| **Location of Temperature** | | **Coolant Channel Outlet Temperature or Fuel Tube Last Axial Node Temperature, °C** | | | | |
| Channel 1 Outlet | | 55.4 | 55.231 | 55.524 | 55.525 | 55.305 |
| Inner Clad Surface | 1 | | 71.723 | 74.728 | 74.732 | 74.713 |
| Peak Fuel | | | 79.077 | 76.460 | 76.467 | 76.516 |
| Outer Clad Surface | | | 77.936 | 75.408 | 75.419 | 75.433 |
| Channel 2 Outlet | | 63.6 | 63.681 | 63.585 | 63.578 | 63.578 |
| Inner Clad Surface | 2 | | 80.854 | 81.557 | 81.301 | 81.293 |
| Peak Fuel | | | 83.451 | 82.974 | 82.990 | 83.036 |
| Outer Clad Surface | | | 82.347 | 81.466 | 81.758 | 81.769 |
| Channel 3 Outlet | | 66.8 | 66.861 | 66.759 | 66.758 | 66.761 |
| Inner Clad Surface | 3 | | 85.482 | 85.772 | 85.541 | 85.542 |
| Peak Fuel | | | 87.129 | 87.112 | 87.116 | 87.157 |
| Outer Clad Surface | | | 85.680 | 85.352 | 85.593 | 85.593 |
| Channel 4 Outlet | | 68.5 | 68.503 | 68.512 | 68.515 | 68.514 |
| Inner Clad Surface | 4 | | 87.118 | 88.529 | 88.450 | 88.445 |
| Peak Fuel | | | 91.324 | 90.215 | 90.230 | 90.267 |
| Outer Clad Surface | | | 89.895 | 88.576 | 88.686 | 88.689 |
| Channel 5 Outlet | | 70.9 | 70.840 | 70.891 | 70.891 | 70.890 |
| Inner Clad Surface | 5 | | 91.017 | 92.543 | 92.471 | 92.471 |
| Peak Fuel | | | 96.234 | 94.363 | 94.378 | 94.418 |
| Outer Clad Surface | | | 94.715 | 92.633 | 92.736 | 92.742 |
| Channel 6 Outlet | | 72.8 | 73.320 | 72.594 | 72.591 | 72.597 |
| Inner Clad Surface | 6 | | 94.691 | 89.615 | 89.629 | 89.651 |
| Peak Fuel | | | 96.156 | 90.876 | 90.892 | 90.936 |
| Outer Clad Surface | | | 83.606 | 88.257 | 88.274 | 88.256 |
| Channel 7 Outlet | | 58.5 | 58.176 | 58.652 | 58.657 | 58.653 |

Note a. Output File: output.astra2p3c1r.1

**Fig. 1. Solution of Radial Geometry Problem 1 Obtained by the Standalone Routine SLICEHTR**

```
Coolant Temperatures (C) of All Channels at the Center of Axial Node (Exact Solution by SLICE1):
             50.0000000000000000     71.5311004784689000

SLICEHTR: Power source in fuel+clad+coolant vs Power removed by coolant  9.000000D+03 9.000000D+03 W

q1``, q2``   =    0.0000000000000000D+00  5.3051647697298440D+04

Temp diff across tube thickness = 161.1562117261541

CHECKING BOUNDARY AND INTERFACE CONDITIONS ON TEMPERATURE (C) AND HEAT FLUX (W/cm**2) FOR FUEL TUBE  1:
                    Inner Cladding             Fuel Meat                  Fuel Meat                Outer Cladding
                    Inner Surface            Inner Surface              Outer Surface              Outer Surface
Temp Conds:    238.7041  =  238.7041      226.3353  =  226.3353      144.6858  =  144.6858       77.5479  =   77.5479
Flux Conds:   0.00000D+00=-9.09495D-13   1.59155D+04= 1.59155D+04   4.09256D+04= 4.09256D+04   5.30516D+04= 5.30516D+04
Temp diff across tube thickness = 161.1562117261541

Here, positive heat flux means it is directed radially outward.
```

**Fig. 2. Solution of Radial Geometry Problem 1 Slightly Modified by Setting $h_1 = 10^{-6}$ W/m$^2$-°C, Obtained by the Standalone Routine SLICEHTR**

```
Coolant Temperatures (C) of All Channels at the Center of Axial Node (Exact Solution by SLICE1):
             50.0000000085095400     71.5311004699593600

SLICEHTR: Power source in fuel+clad+coolant vs Power removed by coolant  9.000000D+03 9.000000D+03 W

q1``, q2``   =    1.8870414803855670D-04  5.3051647676331310D+04

Temp diff across tube thickness = 161.1562123595361

CHECKING BOUNDARY AND INTERFACE CONDITIONS ON TEMPERATURE (C) AND HEAT FLUX (W/cm**2) FOR FUEL TUBE  1:
                    Inner Cladding             Fuel Meat                  Fuel Meat                Outer Cladding
                    Inner Surface            Inner Surface              Outer Surface              Outer Surface
Temp Conds:    238.7041  =  238.7041      226.3353  =  226.3353      144.6858  =  144.6858       77.5479  =   77.5479
Flux Conds:  -1.88704D-04=-1.88704D-04   1.59155D+04= 1.59155D+04   4.09256D+04= 4.09256D+04   5.30516D+04= 5.30516D+04
Temp diff across tube thickness = 161.1562123595361

Here, positive heat flux means it is directed radially outward.
```

**Fig. 3. PLTEMP/ANL Version 3.2 Code Input Data for Radial Geometry Problem 1 Slightly Modified by Setting $h_1 = 10^{-6}$ W/m$^2$-°C**

```
  Radial Geometry Test Problem 1: One fuel tube, Total power=9 kW, Length=60 cm  Card 100
! Tube radii: Ra=0.5 cm, Rb=1.5 cm, Rc=3.5 cm, Rd=4.5 cm
!234567890123456789012345678901234567890123456789012345678901234567890
!  1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18
   0   0   5   1   0   0   1   1   1   1   0   0   0   0   2   1   0   0         Card 200
         1.0         1.0         1.0                                             Card 201
   1   3        0.0         1.0         1.0         1.0   0   1     1.0D-06     Card 300
         1.0         1.0         1.0                                             Card 300A
   1   2        1.0                                                              Card 301
   1   1   1                                                                     Card 302
        1.00                                                                     Card 303
         1.0         1.0         1.0         1.0         1.0         1.0         Card 304
         0.0         0.0        0.60         0.0         0.0         0.0         Card 304
         1.0         1.0         1.0         1.0         1.0         1.0         Card 304
         0.0         0.0         0.0                                             Card 305
   2   0        0.0        0.60         .01         7.0       0.020         7.0 Card 306
7.8539816D-5        0.01 .0314159265 .0314159265         1.0         1.0         Card 307
7.8539816D-5        0.01 .2827433388 .2827433388         1.0         1.0         Card 307
.15707963268                                                                     Card 308
.02500000000                                                                     Card 308A
         1.0                                                                     Card 309
      5.0D-2      5.0D-2                                                         Card 310
       0.1D0       0.001       0.2D0      9.0D-3      50.0D0                     Card 500
      0.50D0      0.0D0                                                          Card 500
   1      0.0001        36.8         0.0         1.0                             Card 600
  11                                                                             Card 700
      0.00D0      1.00D0                                                         Card 701
      0.10D0      1.00D0                                                         Card 701
      0.20D0      1.00D0                                                         Card 701
      0.30D0      1.00D0                                                         Card 701
      0.40D0      1.00D0                                                         Card 701
      0.50D0      1.00D0                                                         Card 701
      0.60D0      1.00D0                                                         Card 701
      0.70D0      1.00D0                                                         Card 701
      0.80D0      1.00D0                                                         Card 701
      0.90D0      1.00D0                                                         Card 701
      1.00D0      1.00D0                                                         Card 701
   0                                                                             Card 702
```

## Fig. 4. Solution of Radial Geometry Problem 1 Slightly Modified by Setting $h_1 = 10^{-6}$ W/m$^2$-°C, Obtained by the Analytical Method in PLTEMP/ANL Version 3.2

```
NPH = 7, Temp diff across tube thickness =  1.6115621122278600D+02
NPH = 7, Temp diff across tube thickness =  1.6115621018189140D+02
NPH = 7, Temp diff across tube thickness =  1.6115621332971350D+02
NPH = 7, Temp diff across tube thickness =  1.6115621087903860D+02
NPH = 7, Temp diff across tube thickness =  1.6115621258905200D+02
NPH = 7, Temp diff across tube thickness =  1.6115621156698840D+02
NPH = 7, Temp diff across tube thickness =  1.6115621220764980D+02
NPH = 7, Temp diff across tube thickness =  1.6115621008530520D+02
NPH = 7, Temp diff across tube thickness =  1.6115621127580810D+02
NPH = 7, Temp diff across tube thickness =  1.6115621105099810D+02
```

FUEL PLATE 1 (ExactSoln)

| NODE | COOLANT inner(C) | CladSurf inner(C) | FUEL PEAK (C) | CladSurf outer(C) | COOLANT outer(C) | HCOFinner W/C-m^2 | HCOFouter W/C-m^2 | ONBRin | ONBRout [F Note 1] | ETAin K-cm^3/J | ETAout K-cm^3/J | COOLNT at inner(C) | NodeOutlet outer(C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 50.000 | | | | 50.000 | | | | | | | | |
| 1 | 50.000 | 223.997 | 211.628 | 62.841 | 52.153 | 1.0000E-06 | 4.9638E+03 | 0.40 | 5.59 | 2.540E+11 | 8.074E+02 | 50.000 | 54.306 |
| 2 | 50.000 | 227.938 | 215.569 | 66.782 | 56.459 | 1.0000E-06 | 5.1395E+03 | 0.38 | 4.19 | 2.425E+11 | 7.359E+02 | 50.000 | 58.612 |
| 3 | 50.000 | 231.915 | 219.547 | 70.759 | 60.766 | 1.0000E-06 | 5.3085E+03 | 0.36 | 3.30 | 2.312E+11 | 6.636E+02 | 50.000 | 62.919 |
| 4 | 50.000 | 235.922 | 223.553 | 74.766 | 65.072 | 1.0000E-06 | 5.4726E+03 | 0.35 | 2.70 | 2.200E+11 | 5.902E+02 | 50.000 | 67.225 |
| 5 | 50.000 | 239.944 | 227.576 | 78.788 | 69.378 | 1.0000E-06 | 5.6377E+03 | 0.33 | 2.26 | 2.090E+11 | 5.158E+02 | 50.000 | 71.531 |
| 6 | 50.000 | 244.003 | 231.634 | 82.846 | 73.684 | 1.0000E-06 | 5.7902E+03 | 0.31 | 1.92 | 1.981E+11 | 4.401E+02 | 50.000 | 75.837 |
| 7 | 50.000 | 248.084 | 235.715 | 86.928 | 77.990 | 1.0000E-06 | 5.9361E+03 | 0.29 | 1.66 | 1.872E+11 | 3.630E+02 | 50.000 | 80.144 |
| 8 | 50.000 | 252.183 | 239.815 | 91.027 | 82.297 | 1.0000E-06 | 6.0765E+03 | 0.28 | 1.44 | 1.763E+11 | 2.843E+02 | 50.000 | 84.450 |
| 9 | 50.000 | 256.297 | 243.929 | 95.141 | 86.603 | 1.0000E-06 | 6.2133E+03 | 0.26 | 1.26 | 1.654E+11 | 2.038E+02 | 50.000 | 88.756 |
| 10 | 50.000 | 260.422 | 248.053 | 99.266 | 90.909 | 1.0000E-06 | 6.3482E+03 | 0.24 | 1.10 | 1.543E+11 | 1.211E+02 | 50.000 | 93.062 |
| | 50.000 | | | | 93.062 | | | | | | | | |

Coolant temp rise (out - in) in channels =  1.73227761024464D-08  4.30622009396152D+01
Temp diff across plate thickness(node10) =  1.61156211050998D+02 L&R surf temps =  2.60422300386202D+02  9.92660893352038D+01
[1] The ONB ratio is here defined as (Tonb - Tinlet)/(Tsurf - Tinlet). If the heat flux is negative (the coolant is hotter than the adjacent cladding surface), then the ONB ratio is arbitrarily set to 99.99 .

FUEL PLATE 1 (ExactSoln)

| NODE | FLUX inner MW/m^2 | FLUX outer MW/m^2 | AREAL FUEL X inner | Tsat (C) | Tdiff (C) | FUEL-CLADinterface inner (C) | outer (C) | Pressure (bar) | Z-mid | Z-int |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.7400E-10 | 5.3052E-02 | 0.0000 | 119.432 | | 211.628 | 129.979 | 1.95000 | 0.0500 | 0.1000 |
| 2 | 1.7794E-10 | 5.3052E-02 | 0.0000 | 117.784 | | 215.569 | 133.919 | 1.85000 | 0.1500 | 0.2000 |
| 3 | 1.8192E-10 | 5.3052E-02 | 0.0000 | 116.061 | | 219.547 | 137.897 | 1.75000 | 0.2500 | 0.3000 |
| 4 | 1.8592E-10 | 5.3052E-02 | 0.0000 | 114.256 | | 223.553 | 141.904 | 1.65000 | 0.3500 | 0.4000 |
| 5 | 1.8994E-10 | 5.3052E-02 | 0.0000 | 112.359 | | 227.576 | 145.926 | 1.55000 | 0.4500 | 0.5000 |
| 6 | 1.9400E-10 | 5.3052E-02 | 0.0000 | 110.358 | | 231.634 | 149.984 | 1.45000 | 0.5500 | 0.6000 |
| 7 | 1.9808E-10 | 5.3052E-02 | 0.0000 | 108.241 | | 235.715 | 154.065 | 1.35000 | 0.6500 | 0.7000 |
| 8 | 2.0218E-10 | 5.3052E-02 | 0.0000 | 105.990 | | 239.815 | 158.165 | 1.25000 | 0.7500 | 0.8000 |
| 9 | 2.0630E-10 | 5.3052E-02 | 0.0000 | 103.585 | | 243.929 | 162.279 | 1.15000 | 0.8500 | 0.9000 |
| 10 | 2.1042E-10 | 5.3052E-02 | 0.0000 | 101.001 | | 248.053 | 166.404 | 1.05000 | 0.9500 | 1.0000 |

### Fig. 5. Solution of Radial Geometry Problem 2 Obtained by the Standalone Routine SLICEHTR

```
Coolant Temperatures (C) of All Channels at the Center of Axial Node (Exact Solution by SLICE1):
             50.0000000000000000     71.5311004784689000

SLICEHTR: Power source in fuel+clad+coolant vs Power removed by coolant  9.000000D+03 9.000000D+03 W

q1``, q2``   =    0.0000000000000000D+00  5.3051647697298460D+04

Temp diff across tube thickness = 178.0270799296316

CHECKING BOUNDARY AND INTERFACE CONDITIONS ON TEMPERATURE (C) AND HEAT FLUX (W/cm**2) FOR FUEL TUBE  1:
                    Inner Cladding               Fuel Meat                  Fuel Meat                Outer Cladding
                    Inner Surface              Inner Surface              Outer Surface              Outer Surface
Temp Conds:    255.5750  =  255.5750      255.5750  =  255.5750      163.2578  =  163.2578       77.5479  =   77.5479
Flux Conds:   0.00000D+00= 0.00000D+00   0.00000D+00= 0.00000D+00   6.82093D+04= 6.82093D+04   5.30516D+04= 5.30516D+04

Here, positive heat flux means it is directed radially outward.
```

### Fig. 6. Solution of Radial Geometry Problem 2 Slightly Modified by Setting $h_1 = 10^{-6}$ W/m$^2$-°C, Obtained by the Standalone Routine SLICEHTR

```
Coolant Temperatures (C) of All Channels at the Center of Axial Node (Exact Solution by SLICE1):
             50.0000000092703300     71.5311004691985800

SLICEHTR: Power source in fuel+clad+coolant vs Power removed by coolant  9.000000D+03 9.000000D+03 W

q1``, q2``   =    2.0557501622937420D-04  5.3051647674456790D+04

Temp diff across tube thickness = 178.0270796225448

CHECKING BOUNDARY AND INTERFACE CONDITIONS ON TEMPERATURE (C) AND HEAT FLUX (W/cm**2) FOR FUEL TUBE  1:
                    Inner Cladding               Fuel Meat                  Fuel Meat                Outer Cladding
                    Inner Surface              Inner Surface              Outer Surface              Outer Surface
Temp Conds:    255.5750  =  255.5750      255.5750  =  255.5750      163.2578  =  163.2578       77.5479  =   77.5479
Flux Conds:  -2.05575D-04=-2.05575D-04  -6.85250D-05=-6.85250D-05   6.82093D+04= 6.82093D+04   5.30516D+04= 5.30516D+04

Here, positive heat flux means it is directed radially outward.
```

**Fig. 7. PLTEMP/ANL Version 3.2 Code Input Data for Radial Geometry Problem 2 Slightly Modified by Setting $h_1 = 10^{-6}$ W/m$^2$-°C**

```
  Radial Geometry Test Problem 2: One fuel tube, Total power=9 kW, Length=60 cm  Card 100
! Tube radii: Ra=0.5 cm, Rb=1.5 cm, Rc=3.5 cm, Rd=4.5 cm
!23456789012345678901234567890123456789012345678901234567890123456789012345678901234567890
!  1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18
   0   0   5   1   0   0   1   1   1   1   0   0   0   0   2   1   0 200         Card 200
         1.0         1.0         1.0                                             Card 201
   1   3        0.0         1.0         1.0         1.0   0   1     1.0D-06     Card 300
         1.0         1.0         1.0                                             Card 300A
   1   2        1.0                                                              Card 301
   1   1   1                                                                     Card 302
        1.00                                                                     Card 303
         1.0         1.0         1.0         1.0         1.0         1.0         Card 304
         0.0         0.0        0.60         0.0         0.0         0.0         Card 304
         1.0         1.0         1.0         1.0         1.0         1.0         Card 304
         0.0         0.0         0.0                                             Card 305
   2   0        0.0        0.60         .01         7.0       0.020         8.0 Card 306
7.8539816D-5        0.01 .0314159265 .0314159265         1.0         1.0         Card 307
7.8539816D-5        0.01 .2827433388 .2827433388         1.0         1.0         Card 307
.15707963268                                                                     Card 308
.02500000000                                                                     Card 308A
         1.0                                                                     Card 309
      5.0D-2      5.0D-2                                                         Card 310
       0.1D0       0.001       0.2D0      9.0D-3      50.0D0                     Card 500
       0.0D0       0.0D0                                                         Card 500
   1      0.0001        36.8         0.0         1.0                             Card 600
  11                                                                             Card 700
      0.00D0      1.00D0                                                         Card 701
      0.10D0      1.00D0                                                         Card 701
      0.20D0      1.00D0                                                         Card 701
      0.30D0      1.00D0                                                         Card 701
      0.40D0      1.00D0                                                         Card 701
      0.50D0      1.00D0                                                         Card 701
      0.60D0      1.00D0                                                         Card 701
      0.70D0      1.00D0                                                         Card 701
      0.80D0      1.00D0                                                         Card 701
      0.90D0      1.00D0                                                         Card 701
      1.00D0      1.00D0                                                         Card 701
   0                                                                             Card 702
```

## Fig. 8. Solution of Radial Geometry Problem 2 Slightly Modified by Setting $h_1 = 10^{-6}$ W/m$^2$-°C, Obtained by the Broyden Method in PLTEMP/ANL Version 3.2

```
Node  1, Temp diff across plate thickness =  1.78027078280832D+02 L&R surf temps =  2.40727374372441D+02  6.27002960916090D+01
Node  2, Temp diff across plate thickness =  1.78027078274102D+02 L&R surf temps =  2.44681152384974D+02  6.66540741108715D+01
Node  3, Temp diff across plate thickness =  1.78027078268861D+02 L&R surf temps =  2.48669935856409D+02  7.06428575875474D+01
Node  4, Temp diff across plate thickness =  1.78027078263333D+02 L&R surf temps =  2.52675969763550D+02  7.46488915002179D+01
Node  5, Temp diff across plate thickness =  1.78027078256786D+02 L&R surf temps =  2.56718787261212D+02  7.86917090044256D+01
Node  6, Temp diff across plate thickness =  1.78027078250659D+02 L&R surf temps =  2.60786683822159D+02  8.27596055715000D+01
Node  7, Temp diff across plate thickness =  1.78027078244552D+02 L&R surf temps =  2.64875941026020D+02  8.68488627814688D+01
Node  8, Temp diff across plate thickness =  1.78027078238480D+02 L&R surf temps =  2.68982450728101D+02  9.09553724896214D+01
Node  9, Temp diff across plate thickness =  1.78027078232276D+02 L&R surf temps =  2.73101560972909D+02  9.50744827406335D+01
Node 10, Temp diff across plate thickness =  1.78027078226028D+02 L&R surf temps =  2.77229672643710D+02  9.92025944176820D+01
```

FUEL PLATE 1 (BroydenSoln)

| NODE | COOLANT inner(C) | CladSurf inner(C) | FUEL PEAK (C) | CladSurf outer(C) | COOLANT outer(C) | HCOFinner W/C-m^2 | HCOFouter W/C-m^2 | ONBRin | ONBRout [F Note 1] | ETAin K-cm^3/J | ETAout K-cm^3/J | COOLNT at NodeOutlet inner(C) | outer(C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 50.000 | | | | 50.000 | | | | | | | | |
| 1 | 50.000 | 240.727 | 240.727 | 62.700 | 52.153 | 1.0000E-06 | 5.0299E+03 | 0.36 | 5.66 | 2.318E+11 | 8.074E+02 | 50.000 | 54.306 |
| 2 | 50.000 | 244.681 | 244.681 | 66.654 | 56.459 | 1.0000E-06 | 5.2038E+03 | 0.35 | 4.22 | 2.217E+11 | 7.359E+02 | 50.000 | 58.612 |
| 3 | 50.000 | 248.670 | 248.670 | 70.643 | 60.766 | 1.0000E-06 | 5.3711E+03 | 0.33 | 3.32 | 2.117E+11 | 6.636E+02 | 50.000 | 62.919 |
| 4 | 50.000 | 252.676 | 252.676 | 74.649 | 65.072 | 1.0000E-06 | 5.5394E+03 | 0.32 | 2.71 | 2.018E+11 | 5.902E+02 | 50.000 | 67.225 |
| 5 | 50.000 | 256.719 | 256.719 | 78.692 | 69.378 | 1.0000E-06 | 5.6961E+03 | 0.30 | 2.27 | 1.920E+11 | 5.158E+02 | 50.000 | 71.531 |
| 6 | 50.000 | 260.787 | 260.787 | 82.760 | 73.684 | 1.0000E-06 | 5.8457E+03 | 0.29 | 1.93 | 1.823E+11 | 4.401E+02 | 50.000 | 75.837 |
| 7 | 50.000 | 264.876 | 264.876 | 86.849 | 77.990 | 1.0000E-06 | 5.9888E+03 | 0.27 | 1.66 | 1.726E+11 | 3.630E+02 | 50.000 | 80.144 |
| 8 | 50.000 | 268.982 | 268.982 | 90.955 | 82.297 | 1.0000E-06 | 6.1270E+03 | 0.26 | 1.44 | 1.628E+11 | 2.843E+02 | 50.000 | 84.450 |
| 9 | 50.000 | 273.102 | 273.102 | 95.074 | 86.603 | 1.0000E-06 | 6.2623E+03 | 0.24 | 1.26 | 1.529E+11 | 2.038E+02 | 50.000 | 88.756 |
| 10 | 50.000 | 277.230 | 277.230 | 99.203 | 90.909 | 1.0000E-06 | 6.3968E+03 | 0.22 | 1.10 | 1.429E+11 | 1.211E+02 | 50.000 | 93.062 |
| | 50.000 | | | | 93.062 | | | | | | | | |

Coolant temp rise (out - in) in channels = 1.88355713248711D-08 4.30622009381022D+01

[1] The ONB ratio is here defined as (Tonb - Tinlet)/(Tsurf - Tinlet). If the heat flux is negative (the coolant is hotter than the adjacent cladding surface), then the ONB ratio is arbitrarily set to 99.99 .

FUEL PLATE 1 (BroydenSoln) AREAL

| NODE | FLUX inner MW/m^2 | FLUX outer MW/m^2 | FUEL X inner | Tsat (C) | Tdiff (C) | FUEL-CLADinterface inner (C) | outer (C) | Pressure (bar) | Z-mid | Z-int |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.9073E-10 | 5.3052E-02 | 0.0000 | 119.432 | 0.00 | 240.727 | 148.410 | 1.95000 | 0.0500 | 0.1000 |
| 2 | 1.9468E-10 | 5.3052E-02 | 0.0000 | 117.784 | 0.00 | 244.681 | 152.364 | 1.85000 | 0.1500 | 0.2000 |
| 3 | 1.9867E-10 | 5.3052E-02 | 0.0000 | 116.061 | 0.00 | 248.670 | 156.353 | 1.75000 | 0.2500 | 0.3000 |
| 4 | 2.0268E-10 | 5.3052E-02 | 0.0000 | 114.256 | 0.00 | 252.676 | 160.359 | 1.65000 | 0.3500 | 0.4000 |
| 5 | 2.0672E-10 | 5.3052E-02 | 0.0000 | 112.359 | 0.00 | 256.719 | 164.402 | 1.55000 | 0.4500 | 0.5000 |
| 6 | 2.1079E-10 | 5.3052E-02 | 0.0000 | 110.358 | 0.00 | 260.787 | 168.469 | 1.45000 | 0.5500 | 0.6000 |
| 7 | 2.1488E-10 | 5.3052E-02 | 0.0000 | 108.241 | 0.00 | 264.876 | 172.559 | 1.35000 | 0.6500 | 0.7000 |
| 8 | 2.1898E-10 | 5.3052E-02 | 0.0000 | 105.990 | 0.00 | 268.982 | 176.665 | 1.25000 | 0.7500 | 0.8000 |
| 9 | 2.2310E-10 | 5.3052E-02 | 0.0000 | 103.585 | 0.00 | 273.102 | 180.784 | 1.15000 | 0.8500 | 0.9000 |
| 10 | 2.2723E-10 | 5.3052E-02 | 0.0000 | 101.001 | 0.00 | 277.230 | 184.912 | 1.05000 | 0.9500 | 1.0000 |

## Fig. 9. Solution of Radial Geometry Problem 2 Slightly Modified by Setting $h_1 = 10^{-6}$ W/m$^2$-°C, Obtained by the Analytical Method in PLTEMP/ANL Version 3.2

```
NPH = 7, Temp diff across tube thickness =  1.7802707964393580D+02
NPH = 7, Temp diff across tube thickness =  1.7802707963804910D+02
NPH = 7, Temp diff across tube thickness =  1.7802707963210740D+02
NPH = 7, Temp diff across tube thickness =  1.7802707962612240D+02
NPH = 7, Temp diff across tube thickness =  1.7802707962011370D+02
NPH = 7, Temp diff across tube thickness =  1.7802707961405150D+02
NPH = 7, Temp diff across tube thickness =  1.7802707960795520D+02
NPH = 7, Temp diff across tube thickness =  1.7802707960183100D+02
NPH = 7, Temp diff across tube thickness =  1.7802707959568550D+02
NPH = 7, Temp diff across tube thickness =  1.7802707958952400D+02
```

FUEL PLATE 1 (ExactSoln)

| NODE | COOLANT inner(C) | CladSurf inner(C) | FUEL PEAK (C) | CladSurf outer(C) | COOLANT outer(C) | HCOFinner W/C-m^2 | HCOFouter W/C-m^2 | ONBRin [F Note 1] | ONBRout | ETAin K-cm^3/J | ETAout K-cm^3/J | COOLNT at NodeOutlet inner(C) | outer(C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 50.000 | | | | 50.000 | | | | | | | | |
| 1 | 50.000 | 240.868 | 240.868 | 62.841 | 52.153 | 1.0000E-06 | 4.9638E+03 | 0.36 | 5.59 | 2.316E+11 | 8.074E+02 | 50.000 | 54.306 |
| 2 | 50.000 | 244.809 | 244.809 | 66.782 | 56.459 | 1.0000E-06 | 5.1395E+03 | 0.35 | 4.19 | 2.215E+11 | 7.359E+02 | 50.000 | 58.612 |
| 3 | 50.000 | 248.786 | 248.786 | 70.759 | 60.766 | 1.0000E-06 | 5.3085E+03 | 0.33 | 3.30 | 2.116E+11 | 6.636E+02 | 50.000 | 62.919 |
| 4 | 50.000 | 252.793 | 252.793 | 74.766 | 65.072 | 1.0000E-06 | 5.4726E+03 | 0.32 | 2.70 | 2.017E+11 | 5.902E+02 | 50.000 | 67.225 |
| 5 | 50.000 | 256.815 | 256.815 | 78.788 | 69.378 | 1.0000E-06 | 5.6377E+03 | 0.30 | 2.26 | 1.920E+11 | 5.158E+02 | 50.000 | 71.531 |
| 6 | 50.000 | 260.874 | 260.874 | 82.846 | 73.684 | 1.0000E-06 | 5.7902E+03 | 0.29 | 1.92 | 1.822E+11 | 4.401E+02 | 50.000 | 75.837 |
| 7 | 50.000 | 264.955 | 264.955 | 86.928 | 77.990 | 1.0000E-06 | 5.9361E+03 | 0.27 | 1.66 | 1.725E+11 | 3.630E+02 | 50.000 | 80.144 |
| 8 | 50.000 | 269.054 | 269.054 | 91.027 | 82.297 | 1.0000E-06 | 6.0765E+03 | 0.26 | 1.44 | 1.627E+11 | 2.843E+02 | 50.000 | 84.450 |
| 9 | 50.000 | 273.168 | 273.168 | 95.141 | 86.603 | 1.0000E-06 | 6.2133E+03 | 0.24 | 1.26 | 1.529E+11 | 2.038E+02 | 50.000 | 88.756 |
| 10 | 50.000 | 277.293 | 277.293 | 99.266 | 90.909 | 1.0000E-06 | 6.3482E+03 | 0.22 | 1.10 | 1.428E+11 | 1.211E+02 | 50.000 | 93.062 |
| | 50.000 | | | | 93.062 | | | | | | | | |

Coolant temp rise (out - in) in channels = 1.88443181059483D-08 4.30622009380935D+01

[1] The ONB ratio is here defined as (Tonb - Tinlet)/(Tsurf - Tinlet). If the heat flux is negative (the coolant is hotter than the adjacent cladding surface), then the ONB ratio is arbitrarily set to 99.99 .

FUEL PLATE 1 (ExactSoln)

| NODE | FLUX inner MW/m^2 | FLUX outer MW/m^2 | AREAL FUEL X inner | Tsat (C) | Tdiff (C) | FUEL-CLADinterface inner (C) | FUEL-CLADinterface outer (C) | Pressure (bar) | Z-mid | Z-int |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.9087E-10 | 5.3052E-02 | 0.0000 | 119.432 | | 240.868 | 148.551 | 1.95000 | 0.0500 | 0.1000 |
| 2 | 1.9481E-10 | 5.3052E-02 | 0.0000 | 117.784 | | 244.809 | 152.491 | 1.85000 | 0.1500 | 0.2000 |
| 3 | 1.9879E-10 | 5.3052E-02 | 0.0000 | 116.061 | | 248.786 | 156.469 | 1.75000 | 0.2500 | 0.3000 |
| 4 | 2.0279E-10 | 5.3052E-02 | 0.0000 | 114.256 | | 252.793 | 160.476 | 1.65000 | 0.3500 | 0.4000 |
| 5 | 2.0682E-10 | 5.3052E-02 | 0.0000 | 112.359 | | 256.815 | 164.498 | 1.55000 | 0.4500 | 0.5000 |
| 6 | 2.1087E-10 | 5.3052E-02 | 0.0000 | 110.358 | | 260.874 | 168.556 | 1.45000 | 0.5500 | 0.6000 |
| 7 | 2.1495E-10 | 5.3052E-02 | 0.0000 | 108.241 | | 264.955 | 172.637 | 1.35000 | 0.6500 | 0.7000 |
| 8 | 2.1905E-10 | 5.3052E-02 | 0.0000 | 105.990 | | 269.054 | 176.737 | 1.25000 | 0.7500 | 0.8000 |
| 9 | 2.2317E-10 | 5.3052E-02 | 0.0000 | 103.585 | | 273.168 | 180.851 | 1.15000 | 0.8500 | 0.9000 |
| 10 | 2.2729E-10 | 5.3052E-02 | 0.0000 | 101.001 | | 277.293 | 184.976 | 1.05000 | 0.9500 | 1.0000 |

**Fig. 10. Comparison of Solutions of Problem 2 by the Broyden Method with Improved Film Coefficient and the Analytical Method (For Each Axial Node the Broyden Method is Followed by Analytical Method)**

```
FUEL PLATE   1 (BroydenSoln)
FUEL PLATE   1 (ExactSoln)
NODE    COOLANT             CladSurf            FUEL PEAK           CladSurf            COOLANT             HCOFinner           HCOFouter
        inner(C)            inner(C)               (C)              outer(C)            outer(C)            W/C-m^2             W/C-m^2
        50.000                                                                          50.000
   1  5.000000000086D+01  2.408679387878D+02  2.408679327685D+02  6.284084816924D+01  5.215311004699D+01  1.000000000000D-06  4.963786263200D+03
   1  5.000000000086D+01  2.408679278132D+02  2.408679279630D+02  6.284084816924D+01  5.215311004699D+01  1.000000000000D-06  4.963786263200D+03

   2  5.000000000260D+01  2.448086636406D+02  2.448086705129D+02  6.678159880489D+01  5.645933014094D+01  1.000000000000D-06  5.139533701612D+03
   2  5.000000000260D+01  2.448086784429D+02  2.448086785958D+02  6.678159880489D+01  5.645933014094D+01  1.000000000000D-06  5.139533701612D+03

   3  5.000000000437D+01  2.487863241341D+02  2.487863180811D+02  7.075923344748D+01  6.076555023486D+01  1.000000000000D-06  5.308518045486D+03
   3  5.000000000437D+01  2.487863130796D+02  2.487863132356D+02  7.075923344748D+01  6.076555023486D+01  1.000000000000D-06  5.308518045486D+03

   4  5.000000000619D+01  2.527928575830D+02  2.527928590708D+02  7.476578197768D+01  6.507177032874D+01  1.000000000000D-06  5.472620582252D+03
   4  5.000000000619D+01  2.527928616038D+02  2.527928617629D+02  7.476578197768D+01  6.507177032874D+01  1.000000000000D-06  5.472620582252D+03

   5  5.000000000803D+01  2.568152834519D+02  2.568152863527D+02  7.878821067221D+01  6.937799042259D+01  1.000000000000D-06  5.637662697246D+03
   5  5.000000000803D+01  2.568152902923D+02  2.568152904546D+02  7.878821067221D+01  6.937799042259D+01  1.000000000000D-06  5.637662697246D+03

   6  5.000000000992D+01  2.608735837414D+02  2.608735801704D+02  8.284649801797D+01  7.368421051640D+01  1.000000000000D-06  5.790218617854D+03
   6  5.000000000992D+01  2.608735776320D+02  2.608735777975D+02  8.284649801797D+01  7.368421051640D+01  1.000000000000D-06  5.790218617854D+03

   7  5.000000001184D+01  2.649545967321D+02  2.649546013745D+02  8.692752743504D+01  7.799043061017D+01  1.000000000000D-06  5.936116471920D+03
   7  5.000000001184D+01  2.649546070430D+02  2.649546072117D+02  8.692752743504D+01  7.799043061017D+01  1.000000000000D-06  5.936116471920D+03

   8  5.000000001379D+01  2.690543622609D+02  2.690543566559D+02  9.102727246865D+01  8.229665070391D+01  1.000000000000D-06  6.076502808431D+03
   8  5.000000001379D+01  2.690543520705D+02  2.690543522424D+02  9.102727246865D+01  8.229665070391D+01  1.000000000000D-06  6.076502808431D+03

   9  5.000000001579D+01  2.731683636709D+02  2.731683554766D+02  9.514126869991D+01  8.660287079761D+01  1.000000000000D-06  6.213302340719D+03
   9  5.000000001579D+01  2.731683482956D+02  2.731683484707D+02  9.514126869991D+01  8.660287079761D+01  1.000000000000D-06  6.213302340719D+03

  10  5.000000001782D+01  2.772931714088D+02  2.772931601897D+02  9.926607038775D+01  9.090909089127D+01  1.000000000000D-06  6.348184495870D+03
  10  5.000000001782D+01  2.772931689230D+02  2.772931691013D+02  9.926608933346D+01  9.090909089127D+01  1.000000000000D-06  6.348170104237D+03
        50.000                                                                          93.062
Coolant temp rise (out - in) in channels =  1.88442825788115D-08  4.30622009380935D+01
Coolant temp rise (out - in) in channels =  1.88443181059483D-08  4.30622009380935D+01
```

**Fig. 11. PLTEMP/ANL Version 3.2 Code Input Data for Radial Geometry Problem 3**

```
  Radial Geometry Test Problem 3: One fuel tube, Total power=9 kW, Length=60 cm  Card 100
! Tube radii: Ra=0.5 cm, Rb=1.5 cm, Rc=3.5 cm, Rd=4.5 cm
!234567890123456789012345678901234567890123456789012345678901234567890123456789 0
!  1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18
   0   0   5   1   0   0   1   1   1   0   0   0   0   0   2   0   0  20        Card 200
         1.0         1.0         1.0                                            Card 201
   1   3        0.0         1.0         1.0         1.0   0   1     1.0D-06     Card 300
         1.0         1.0         1.0                                            Card 300A
   1   2        1.0                                                             Card 301
   1   1   1                                                                    Card 302
        1.00                                                                    Card 303
         1.0         1.0         1.0         1.0         1.0         1.0        Card 304
         0.0         0.0        0.60         0.0         0.0         0.0        Card 304
         1.0         1.0         1.0         1.0         1.0         1.0        Card 304
         0.0         0.0         0.0                                            Card 305
   2   0        0.0        0.60         .01         7.0       0.020         8.0 Card 306
7.8539816D-5        0.01 .0314159265 .0314159265         1.0         1.0        Card 307
7.8539816D-5        0.01 .2827433388 .2827433388         1.0         1.0        Card 307
.15707963268                                                                    Card 308
.02500000000                                                                    Card 308A
         1.0                                                                    Card 309
      5.0D-2      5.0D-2                                                        Card 310
       0.1D0       0.001       0.2D0      9.0D-3      50.0D0                    Card 500
       0.0D0       0.0D0                                                        Card 500
   1      0.0001        36.8         0.0         1.0                            Card 600
  11                                                                            Card 700
      0.00D0      1.00D0                                                        Card 701
      0.10D0      1.00D0                                                        Card 701
      0.20D0      1.00D0                                                        Card 701
      0.30D0      1.00D0                                                        Card 701
      0.40D0      1.00D0                                                        Card 701
      0.50D0      1.00D0                                                        Card 701
      0.60D0      1.00D0                                                        Card 701
      0.70D0      1.00D0                                                        Card 701
      0.80D0      1.00D0                                                        Card 701
      0.90D0      1.00D0                                                        Card 701
      1.00D0      1.00D0                                                        Card 701
   0                                                                            Card 702
```

## Fig. 12. Solution of Radial Geometry Problem 3 by the Broyden Method in PLTEMP/ANL Version 3.2

```
 FUEL PLATE   1 (BroydenSoln)
 NODE    COOLANT             CladSurf            FUEL PEAK           CladSurf            COOLANT             HCOFinner           HCOFouter
         inner(C)            inner(C)               (C)              outer(C)            outer(C)            W/C-m^2             W/C-m^2
         50.000                                                                          50.000
    1  5.000000000086D+01  2.408130311637D+02  2.408130313135D+02  6.278595288319D+01  5.214961306879D+01  1.000000000000D-06  4.987772918283D+03
    2  5.000000000259D+01  2.447422928116D+02  2.447422929644D+02  6.671521453693D+01  5.644883920635D+01  1.000000000000D-06  5.167514918088D+03
    3  5.000000000437D+01  2.487081790474D+02  2.487081792034D+02  7.068110077871D+01  6.074806534387D+01  1.000000000000D-06  5.340930073497D+03
    4  5.000000000617D+01  2.527025488215D+02  2.527025489806D+02  7.467547055880D+01  6.504729148136D+01  1.000000000000D-06  5.510039566974D+03
    5  5.000000000802D+01  2.567127611149D+02  2.567127612771D+02  7.868568285812D+01  6.934651761881D+01  1.000000000000D-06  5.680555629409D+03
    6  5.000000000990D+01  2.607584455871D+02  2.607584457525D+02  8.273136733630D+01  7.364574375623D+01  1.000000000000D-06  5.839076119120D+03
    7  5.000000001181D+01  2.648267104676D+02  2.648267106362D+02  8.679963222306D+01  7.794496989360D+01  1.000000000000D-06  5.991380100041D+03
    8  5.000000001377D+01  2.689135127894D+02  2.689135129613D+02  9.088643455104D+01  8.224419603095D+01  1.000000000000D-06  6.138646549671D+03
    9  5.000000001575D+01  2.730144349952D+02  2.730144351702D+02  9.498735676285D+01  8.654342216825D+01  1.000000000000D-06  6.282811298215D+03
   10  5.000000001778D+01  2.771261083709D+02  2.771261085491D+02  9.909903014458D+01  9.084264830552D+01  1.000000000000D-06  6.425532237486D+03
         50.000                                                                          92.992
 Coolant temp rise (out - in) in channels =  1.88038029591553D-08  4.29922613741454D+01

 FUEL PLATE   1 (BroydenSoln) AREAL                     FUEL-CLADinterface
 NODE FLUX inner FLUX outer  FUEL X   Tsat     Tdiff     inner     outer     Pressure  Z-mid     Z-int
        MW/m^2     MW/m^2     inner   (C)       (C)       (C)       (C)       (bar)
    1 1.9081E-10 5.3052E-02  0.0000 119.432     0.00     240.813   148.496   1.95000   0.0500    0.1000
    2 1.9474E-10 5.3052E-02  0.0000 117.784     0.00     244.742   152.425   1.85000   0.1500    0.2000
    3 1.9871E-10 5.3052E-02  0.0000 116.061     0.00     248.708   156.391   1.75000   0.2500    0.3000
    4 2.0270E-10 5.3052E-02  0.0000 114.256     0.00     252.703   160.385   1.65000   0.3500    0.4000
    5 2.0671E-10 5.3052E-02  0.0000 112.359     0.00     256.713   164.396   1.55000   0.4500    0.5000
    6 2.1076E-10 5.3052E-02  0.0000 110.358     0.00     260.758   168.441   1.45000   0.5500    0.6000
    7 2.1483E-10 5.3052E-02  0.0000 108.241     0.00     264.827   172.509   1.35000   0.6500    0.7000
    8 2.1891E-10 5.3052E-02  0.0000 105.990     0.00     268.914   176.596   1.25000   0.7500    0.8000
    9 2.2301E-10 5.3052E-02  0.0000 103.585     0.00     273.014   180.697   1.15000   0.8500    0.9000
   10 2.2713E-10 5.3052E-02  0.0000 101.001     0.00     277.126   184.809   1.05000   0.9500    1.0000
```

**Fig. 13. Solution of Radial Geometry Problem 3 by the Analytical Method in PLTEMP/ANL Version 3.2**

```
FUEL PLATE   1 (ExactSoln)
NODE    COOLANT             CladSurf            FUEL PEAK           CladSurf            COOLANT             HCOFinner           HCOFouter
        inner(C)            inner(C)               (C)              outer(C)            outer(C)            W/C-m^2             W/C-m^2
        50.000                                                                          50.000
   1  5.000082986697D+01  2.408146262689D+02  2.408146264186D+02  6.278754662484D+01  5.215135742965D+01  1.000000000000D-06  4.987843550196D+03
   2  5.000248959589D+01  2.447455662490D+02  2.447455664018D+02  6.671848661085D+01  5.645238559675D+01  1.000000000000D-06  5.167652997241D+03
   3  5.000497916546D+01  2.487106748134D+02  2.487106749694D+02  7.068359518122D+01  6.075080931948D+01  1.000000000000D-06  5.341064270742D+03
   4  5.000746872476D+01  2.527010494421D+02  2.527010496012D+02  7.467396981584D+01  6.504567660604D+01  1.000000000000D-06  5.509974251779D+03
   5  5.000912842336D+01  2.567028724349D+02  2.567028725971D+02  7.867579281461D+01  6.933602948623D+01  1.000000000000D-06  5.680191864493D+03
   6  5.001078811219D+01  2.607373849617D+02  2.607373851270D+02  8.271030534740D+01  7.362338697539D+01  1.000000000000D-06  5.838244111127D+03
   7  5.001244779101D+01  2.647904765363D+02  2.647904767049D+02  8.676339692812D+01  7.790677928927D+01  1.000000000000D-06  5.990057360108D+03
   8  5.001410745980D+01  2.688581330139D+02  2.688581331857D+02  9.083105341180D+01  8.218605489029D+01  1.000000000000D-06  6.136686725952D+03
   9  5.001576711883D+01  2.729357841035D+02  2.729357842785D+02  9.490870450748D+01  8.646105771571D+01  1.000000000000D-06  6.280050406940D+03
  10  5.001825658304D+01  2.770190455049D+02  2.770190456831D+02  9.899196591498D+01  9.073079758482D+01  1.000000000000D-06  6.421809307311D+03
        50.020                                                                          92.865
Coolant temp rise (out - in) in channels =  1.99162201240739D-02  4.28645368259166D+01

FUEL PLATE   1 (ExactSoln)   AREAL                      FUEL-CLADinterface
NODE FLUX inner FLUX outer  FUEL X   Tsat     Tdiff      inner     outer    Pressure  Z-mid     Z-int
       MW/m^2     MW/m^2     inner   (C)       (C)        (C)       (C)      (bar)
   1 1.9081E-10 5.3052E-02  0.0000 119.432             240.815   148.497   1.95000   0.0500    0.1000
   2 1.9474E-10 5.3052E-02  0.0000 117.784             244.746   152.428   1.85000   0.1500    0.2000
   3 1.9871E-10 5.3052E-02  0.0000 116.061             248.711   156.393   1.75000   0.2500    0.3000
   4 2.0269E-10 5.3052E-02  0.0000 114.256             252.701   160.384   1.65000   0.3500    0.4000
   5 2.0669E-10 5.3052E-02  0.0000 112.359             256.703   164.386   1.55000   0.4500    0.5000
   6 2.1073E-10 5.3052E-02  0.0000 110.358             260.737   168.420   1.45000   0.5500    0.6000
   7 2.1478E-10 5.3052E-02  0.0000 108.241             264.790   172.473   1.35000   0.6500    0.7000
   8 2.1884E-10 5.3052E-02  0.0000 105.990             268.858   176.541   1.25000   0.7500    0.8000
   9 2.2292E-10 5.3052E-02  0.0000 103.585             272.936   180.619   1.15000   0.8500    0.9000
  10 2.2700E-10 5.3052E-02  0.0000 101.001             277.019   184.702   1.05000   0.9500    1.0000
```

## Fig. 14. Input Data for Radial Geometry Problem 4 for PLTEMP Versions 3.1 and 3.2

```
  Radial Geometry Test Problem 4: One fuel tube, Total power=9 kW, Length=60 cm  Card 100
! Tube radii: Ra=0.5 cm, Rb=1.5 cm, Rc=3.5 cm, Rd=4.5 cm
!234567890123456789012345678901234567890123456789012345678901234567890123456789
!  1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18
   0   0   5   1   0   0   1   1   1   0   0   0   0   0   2   0   0   0         Card 200
        1.0         1.0         1.0                                              Card 201
   1   3         0.0         1.0         1.0         1.0   0   3     1.0D+03     Card 300
        1.0         1.0         1.0                                              Card 300A
   1   2         1.0                                                             Card 301
   1   1   1                                                                     Card 302
       1.00                                                                      Card 303
        1.0         1.0         1.0         1.0         1.0         1.0          Card 304
        0.0         0.0        0.60         0.0         0.0         0.0          Card 304
        1.0         1.0         1.0         1.0         1.0         1.0          Card 304
        0.0         0.0         0.0                                              Card 305
   2   0         0.0        0.60         .01         7.0       0.020         8.0 Card 306
7.8539816D-5        0.01 .0314159265 .0314159265         1.0         1.0         Card 307
7.8539816D-5        0.01 .2827433388 .2827433388         1.0         1.0         Card 307
.15707963268                                                                     Card 308
.02500000000                                                                     Card 308A
        1.0                                                                      Card 309
     5.0D-2      5.0D-2                                                          Card 310
      0.1D0       0.001       0.2D0      9.0D-3      50.0D0                      Card 500
      0.0D0       0.0D0                                                          Card 500
   1      0.0001        36.8         0.0         1.0                             Card 600
  11                                                                             Card 700
     0.00D0      1.00D0                                                          Card 701
     0.10D0      1.00D0                                                          Card 701
     0.20D0      1.00D0                                                          Card 701
     0.30D0      1.00D0                                                          Card 701
     0.40D0      1.00D0                                                          Card 701
     0.50D0      1.00D0                                                          Card 701
     0.60D0      1.00D0                                                          Card 701
     0.70D0      1.00D0                                                          Card 701
     0.80D0      1.00D0                                                          Card 701
     0.90D0      1.00D0                                                          Card 701
     1.00D0      1.00D0                                                          Card 701
   0                                                                             Card 702
```

## Fig. 15. Solution of Radial Geometry Problem 4 by the Broyden Method in PLTEMP/ANL Version 3.1

FUEL PLATE 1 (BroydenSoln)

| NODE | COOLANT outer(C) | CladSurf outer(C) | FUEL PEAK (C) | CladSurf inner(C) | COOLANT inner(C) | HCOFouter W/C-m^2 | HCOFinner W/C-m^2 | ONBRout | ONBRin [F Note 1] | ETAout K-cm^3/J | ETAin K-cm^3/J | COOLNT at outer(C) | NodeOutlet inner(C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 50.000 | | | | 50.000 | | | | | | | | |
| 1 | 51.505 | 88.641 | 257.304 | 193.884 | 50.645 | 1.0000E+03 | 1.0000E+03 | 1.85 | 0.51 | 1.184E+03 | 3.108E+02 | 53.009 | 51.290 |
| 2 | 54.514 | 91.650 | 259.454 | 195.174 | 51.935 | 1.0000E+03 | 1.0000E+03 | 1.68 | 0.49 | 1.103E+03 | 2.976E+02 | 56.019 | 52.580 |
| 3 | 57.524 | 94.660 | 261.603 | 196.464 | 53.224 | 1.0000E+03 | 1.0000E+03 | 1.53 | 0.48 | 1.020E+03 | 2.839E+02 | 59.028 | 53.869 |
| 4 | 60.533 | 97.669 | 263.753 | 197.754 | 54.514 | 1.0000E+03 | 1.0000E+03 | 1.39 | 0.46 | 9.364E+02 | 2.700E+02 | 62.038 | 55.159 |
| 5 | 63.543 | 100.679 | 265.903 | 199.043 | 55.804 | 1.0000E+03 | 1.0000E+03 | 1.28 | 0.45 | 8.508E+02 | 2.556E+02 | 65.047 | 56.449 |
| 6 | 66.552 | 103.688 | 268.052 | 200.333 | 57.094 | 1.0000E+03 | 1.0000E+03 | 1.17 | 0.43 | 7.635E+02 | 2.407E+02 | 68.057 | 57.739 |
| 7 | 69.561 | 106.698 | 270.202 | 201.623 | 58.383 | 1.0000E+03 | 1.0000E+03 | 1.07 | 0.41 | 6.742E+02 | 2.253E+02 | 71.066 | 59.028 |
| 8 | 72.571 | 109.707 | 272.352 | 202.913 | 59.673 | 1.0000E+03 | 1.0000E+03 | 0.98 | 0.40 | 5.825E+02 | 2.093E+02 | 74.076 | 60.318 |
| 9 | 75.580 | 112.717 | 274.501 | 204.202 | 60.963 | 1.0000E+03 | 1.0000E+03 | 0.90 | 0.38 | 4.881E+02 | 1.926E+02 | 77.085 | 61.608 |
| 10 | 78.590 | 115.726 | 276.651 | 205.492 | 62.253 | 1.0000E+03 | 1.0000E+03 | 0.82 | 0.36 | 3.906E+02 | 1.751E+02 | 80.095 | 62.898 |
| | 80.095 | | | | 62.898 | | | | | | | | |

[1] The ONB ratio is here defined as (Tonb - Tinlet)/(Tsurf - Tinlet). If the heat flux is negative (the coolant is hotter than the adjacent cladding surface), then the ONB ratio is arbitrarily set to 99.99 .

FUEL PLATE 1 (BroydenSoln)

| NODE | FLUX outer MW/m^2 | FLUX inner MW/m^2 | AREAL FUEL X outer | Tsat (C) | Tdiff (C) | FUEL-CLADinterface outer (C) | FUEL-CLADinterface inner (C) | Pressure (bar) | Z-mid | Z-int |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 3.7136E-02 | 1.4324E-01 | 0.7000 | 119.432 | -141.19 | 148.638 | 306.288 | 1.95000 | 0.0500 | 0.1000 |
| 2 | 3.7136E-02 | 1.4324E-01 | 0.7000 | 117.784 | -139.47 | 151.647 | 307.577 | 1.85000 | 0.1500 | 0.2000 |
| 3 | 3.7136E-02 | 1.4324E-01 | 0.7000 | 116.061 | -137.75 | 154.657 | 308.867 | 1.75000 | 0.2500 | 0.3000 |
| 4 | 3.7136E-02 | 1.4324E-01 | 0.7000 | 114.256 | -136.03 | 157.666 | 310.157 | 1.65000 | 0.3500 | 0.4000 |
| 5 | 3.7136E-02 | 1.4324E-01 | 0.7000 | 112.359 | -134.31 | 160.676 | 311.447 | 1.55000 | 0.4500 | 0.5000 |
| 6 | 3.7136E-02 | 1.4324E-01 | 0.7000 | 110.358 | -132.59 | 163.685 | 312.736 | 1.45000 | 0.5500 | 0.6000 |
| 7 | 3.7136E-02 | 1.4324E-01 | 0.7000 | 108.241 | -130.87 | 166.695 | 314.026 | 1.35000 | 0.6500 | 0.7000 |
| 8 | 3.7136E-02 | 1.4324E-01 | 0.7000 | 105.990 | -129.15 | 169.704 | 315.316 | 1.25000 | 0.7500 | 0.8000 |
| 9 | 3.7136E-02 | 1.4324E-01 | 0.7000 | 103.585 | -127.43 | 172.713 | 316.606 | 1.15000 | 0.8500 | 0.9000 |
| 10 | 3.7136E-02 | 1.4324E-01 | 0.7000 | 101.001 | -125.71 | 175.723 | 317.896 | 1.05000 | 0.9500 | 1.0000 |

**Fig. 16. Solution of Radial Geometry Problem 4 by the Broyden Method in PLTEMP/ANL Version 3.2**

FUEL PLATE 1 (BroydenSoln)

| NODE | COOLANT inner(C) | CladSurf inner(C) | FUEL PEAK (C) | CladSurf outer(C) | COOLANT outer(C) | HCOFinner W/C-m^2 | HCOFouter W/C-m^2 | ONBRin [F Note 1] | ONBRout [F Note 1] | ETAin K-cm^3/J | ETAout K-cm^3/J | COOLNT at NodeOutlet inner(C) | COOLNT at NodeOutlet outer(C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 50.000 | | | | 50.000 | | | | | | | | |
| 1 | 50.402 | 139.628 | 218.919 | 94.886 | 51.748 | 1.0000E+03 | 1.0000E+03 | 0.81 | 1.60 | 5.008E+02 | 1.016E+03 | 50.803 | 53.496 |
| 2 | 51.210 | 141.466 | 221.761 | 98.262 | 55.239 | 1.0000E+03 | 1.0000E+03 | 0.78 | 1.45 | 4.774E+02 | 9.410E+02 | 51.616 | 56.982 |
| 3 | 52.027 | 143.306 | 224.599 | 101.631 | 58.721 | 1.0000E+03 | 1.0000E+03 | 0.74 | 1.32 | 4.541E+02 | 8.649E+02 | 52.438 | 60.460 |
| 4 | 52.854 | 145.148 | 227.435 | 104.990 | 62.194 | 1.0000E+03 | 1.0000E+03 | 0.71 | 1.21 | 4.306E+02 | 7.874E+02 | 53.269 | 63.928 |
| 5 | 53.689 | 146.993 | 230.267 | 108.342 | 65.657 | 1.0000E+03 | 1.0000E+03 | 0.68 | 1.11 | 4.070E+02 | 7.082E+02 | 54.109 | 67.387 |
| 6 | 54.534 | 148.839 | 233.097 | 111.685 | 69.112 | 1.0000E+03 | 1.0000E+03 | 0.65 | 1.02 | 3.831E+02 | 6.271E+02 | 54.958 | 70.837 |
| 7 | 55.387 | 150.688 | 235.923 | 115.020 | 72.558 | 1.0000E+03 | 1.0000E+03 | 0.62 | 0.94 | 3.590E+02 | 5.439E+02 | 55.816 | 74.278 |
| 8 | 56.250 | 152.539 | 238.746 | 118.347 | 75.994 | 1.0000E+03 | 1.0000E+03 | 0.58 | 0.86 | 3.344E+02 | 4.584E+02 | 56.683 | 77.710 |
| 9 | 57.121 | 154.391 | 241.566 | 121.666 | 79.422 | 1.0000E+03 | 1.0000E+03 | 0.55 | 0.79 | 3.092E+02 | 3.702E+02 | 57.559 | 81.134 |
| 10 | 58.002 | 156.246 | 244.382 | 124.977 | 82.841 | 1.0000E+03 | 1.0000E+03 | 0.52 | 0.72 | 2.833E+02 | 2.790E+02 | 58.444 | 84.548 |
| | 58.444 | | | | 84.548 | | | | | | | | |

[1] The ONB ratio is here defined as (Tonb - Tinlet)/(Tsurf - Tinlet). If the heat flux is negative (the coolant is hotter than the adjacent cladding surface), then the ONB ratio is arbitrarily set to 99.99 .

FUEL PLATE 1 (BroydenSoln)

| NODE | FLUX inner MW/m^2 | FLUX outer MW/m^2 | AREAL FUEL X inner | Tsat (C) | Tdiff (C) | FUEL-CLADinterface inner (C) | FUEL-CLADinterface outer (C) | Pressure (bar) | Z-mid | Z-int |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 8.9226E-02 | 4.3138E-02 | 0.1869 | 119.432 | 0.00 | 209.645 | 164.578 | 1.95000 | 0.0500 | 0.1000 |
| 2 | 9.0256E-02 | 4.3023E-02 | 0.1890 | 117.784 | 0.00 | 212.292 | 167.770 | 1.85000 | 0.1500 | 0.2000 |
| 3 | 9.1279E-02 | 4.2910E-02 | 0.1912 | 116.061 | 0.00 | 214.934 | 170.955 | 1.75000 | 0.2500 | 0.3000 |
| 4 | 9.2295E-02 | 4.2797E-02 | 0.1933 | 114.256 | 0.00 | 217.574 | 174.132 | 1.65000 | 0.3500 | 0.4000 |
| 5 | 9.3304E-02 | 4.2685E-02 | 0.1954 | 112.359 | 0.00 | 220.210 | 177.303 | 1.55000 | 0.4500 | 0.5000 |
| 6 | 9.4306E-02 | 4.2573E-02 | 0.1975 | 110.358 | 0.00 | 222.843 | 180.466 | 1.45000 | 0.5500 | 0.6000 |
| 7 | 9.5301E-02 | 4.2463E-02 | 0.1996 | 108.241 | 0.00 | 225.472 | 183.623 | 1.35000 | 0.6500 | 0.7000 |
| 8 | 9.6289E-02 | 4.2353E-02 | 0.2017 | 105.990 | 0.00 | 228.099 | 186.772 | 1.25000 | 0.7500 | 0.8000 |
| 9 | 9.7270E-02 | 4.2244E-02 | 0.2037 | 103.585 | 0.00 | 230.722 | 189.915 | 1.15000 | 0.8500 | 0.9000 |
| 10 | 9.8245E-02 | 4.2136E-02 | 0.2058 | 101.001 | 0.00 | 233.341 | 193.051 | 1.05000 | 0.9500 | 1.0000 |

## Fig. 17. Solution of Radial Geometry Problem 4 by the Analytical Method in PLTEMP/ANL Version 3.2

FUEL PLATE 1 (ExactSoln)

| NODE | COOLANT inner(C) | CladSurf inner(C) | FUEL PEAK (C) | CladSurf outer(C) | COOLANT outer(C) | HCOFinner W/C-m^2 | HCOFouter W/C-m^2 | ONBRin | ONBRout [F Note 1] | ETAin K-cm^3/J | ETAout K-cm^3/J | COOLNT at inner(C) | NodeOutlet outer(C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 50.000 | | | | 50.000 | | | | | | | | |
| 1 | 50.403 | 139.629 | 218.921 | 94.888 | 51.750 | 1.0000E+03 | 1.0000E+03 | 0.81 | 1.60 | 5.008E+02 | 1.016E+03 | 50.806 | 53.500 |
| 2 | 51.214 | 141.470 | 221.766 | 98.268 | 55.245 | 1.0000E+03 | 1.0000E+03 | 0.78 | 1.45 | 4.774E+02 | 9.409E+02 | 51.622 | 56.990 |
| 3 | 52.034 | 143.313 | 224.606 | 101.638 | 58.728 | 1.0000E+03 | 1.0000E+03 | 0.74 | 1.32 | 4.540E+02 | 8.648E+02 | 52.445 | 60.467 |
| 4 | 52.862 | 145.156 | 227.441 | 104.996 | 62.199 | 1.0000E+03 | 1.0000E+03 | 0.71 | 1.21 | 4.306E+02 | 7.873E+02 | 53.278 | 63.931 |
| 5 | 53.700 | 147.000 | 230.271 | 108.344 | 65.659 | 1.0000E+03 | 1.0000E+03 | 0.68 | 1.11 | 4.069E+02 | 7.081E+02 | 54.122 | 67.386 |
| 6 | 54.547 | 148.846 | 233.097 | 111.682 | 69.108 | 1.0000E+03 | 1.0000E+03 | 0.65 | 1.02 | 3.831E+02 | 6.271E+02 | 54.973 | 70.830 |
| 7 | 55.403 | 150.693 | 235.918 | 115.010 | 72.546 | 1.0000E+03 | 1.0000E+03 | 0.62 | 0.94 | 3.589E+02 | 5.441E+02 | 55.833 | 74.261 |
| 8 | 56.268 | 152.541 | 238.732 | 118.325 | 75.971 | 1.0000E+03 | 1.0000E+03 | 0.58 | 0.86 | 3.343E+02 | 4.588E+02 | 56.703 | 77.680 |
| 9 | 57.141 | 154.389 | 241.542 | 121.631 | 79.384 | 1.0000E+03 | 1.0000E+03 | 0.55 | 0.79 | 3.091E+02 | 3.708E+02 | 57.580 | 81.089 |
| 10 | 58.023 | 156.238 | 244.346 | 124.925 | 82.786 | 1.0000E+03 | 1.0000E+03 | 0.52 | 0.72 | 2.832E+02 | 2.798E+02 | 58.466 | 84.484 |
| | 58.466 | | | | 84.484 | | | | | | | | |

[1] The ONB ratio is here defined as (Tonb - Tinlet)/(Tsurf - Tinlet). If the heat flux is negative (the coolant is hotter than the adjacent cladding surface), then the ONB ratio is arbitrarily set to 99.99 .

FUEL PLATE 1 (ExactSoln)

| NODE | FLUX inner MW/m^2 | FLUX outer MW/m^2 | AREAL FUEL X inner | Tsat (C) | Tdiff (C) | FUEL-CLADinterface inner (C) | outer (C) | Pressure (bar) | Z-mid | Z-int |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 8.9226E-02 | 4.3138E-02 | 0.1869 | 119.432 | | 209.647 | 164.581 | 1.95000 | 0.0500 | 0.1000 |
| 2 | 9.0257E-02 | 4.3023E-02 | 0.1890 | 117.784 | | 212.297 | 167.776 | 1.85000 | 0.1500 | 0.2000 |
| 3 | 9.1279E-02 | 4.2910E-02 | 0.1912 | 116.061 | | 214.942 | 170.962 | 1.75000 | 0.2500 | 0.3000 |
| 4 | 9.2294E-02 | 4.2797E-02 | 0.1933 | 114.256 | | 217.580 | 174.138 | 1.65000 | 0.3500 | 0.4000 |
| 5 | 9.3300E-02 | 4.2685E-02 | 0.1954 | 112.359 | | 220.215 | 177.305 | 1.55000 | 0.4500 | 0.5000 |
| 6 | 9.4299E-02 | 4.2574E-02 | 0.1975 | 110.358 | | 222.845 | 180.465 | 1.45000 | 0.5500 | 0.6000 |
| 7 | 9.5290E-02 | 4.2464E-02 | 0.1996 | 108.241 | | 225.469 | 183.614 | 1.35000 | 0.6500 | 0.7000 |
| 8 | 9.6273E-02 | 4.2355E-02 | 0.2016 | 105.990 | | 228.088 | 186.753 | 1.25000 | 0.7500 | 0.8000 |
| 9 | 9.7248E-02 | 4.2246E-02 | 0.2037 | 103.585 | | 230.702 | 189.884 | 1.15000 | 0.8500 | 0.9000 |
| 10 | 9.8216E-02 | 4.2139E-02 | 0.2057 | 101.001 | | 233.311 | 193.004 | 1.05000 | 0.9500 | 1.0000 |

**Fig. 18. PLTEMP/ANL Version 3.2 Code Input Data for Slab Geometry Problem 5 Using the Slab Geometry Analytical Method**

```
  Slab Geometry Test Problem 5: One fuel tube, Total power=9 kW, Length=60 cm    Card 100
! Tube radii: Ra=0.5 cm, Rb=1.5 cm, Rc=3.5 cm, Rd=4.5 cm
!234567890123456789012345678901234567890123456789012345678901234567890123456789
!  1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18
   0   0   5   1   0   0   1   1   0   0   0   0   0   0   2   0   0   0        Card 200
        1.0         1.0         1.0                                              Card 201
   1   3        0.0         1.0         1.0         1.0   0   1     1.0D-06     Card 300
        1.0         1.0         1.0                                              Card 300A
   1   2        1.0                                                              Card 301
   1   1   1                                                                     Card 302
       1.00                                                                      Card 303
        1.0         1.0         1.0         1.0         1.0         1.0          Card 304
        0.0         0.0        0.60         0.0         0.0         0.0          Card 304
        1.0         1.0         1.0         1.0         1.0         1.0          Card 304
        0.0         0.0         0.0                                              Card 305
   2   0        0.0        0.60         .01         7.0       0.020         8.0 Card 306
7.8539816D-5       0.01 .0314159265 .0314159265         1.0         1.0          Card 307
7.8539816D-5       0.01 .2827433388 .2827433388         1.0         1.0          Card 307
.15707963268                                                                     Card 308
.02500000000                                                                     Card 308A
        1.0                                                                      Card 309
     5.0D-2      5.0D-2                                                          Card 310
      0.1D0       0.001       0.2D0      9.0D-3      50.0D0                      Card 500
      0.0D0       0.0D0                                                          Card 500
   1      0.0001        36.8         0.0         1.0                             Card 600
  11                                                                             Card 700
     0.00D0      1.00D0                                                          Card 701
     0.10D0      1.00D0                                                          Card 701
     0.20D0      1.00D0                                                          Card 701
     0.30D0      1.00D0                                                          Card 701
     0.40D0      1.00D0                                                          Card 701
     0.50D0      1.00D0                                                          Card 701
     0.60D0      1.00D0                                                          Card 701
     0.70D0      1.00D0                                                          Card 701
     0.80D0      1.00D0                                                          Card 701
     0.90D0      1.00D0                                                          Card 701
     1.00D0      1.00D0                                                          Card 701
   0                                                                             Card 702
```

**Fig. 19. PLTEMP/ANL Version 3.2 Code Input Data for Slab Geometry Problem 5 Using the Radial Geometry Analytical Method with a Mean Tube Radius of 1000 m**

```
  Slab Geometry Test Problem 5: One fuel tube, Total power=9 kW, Length=60 cm    Card 100
! Using Radial Geometry Analytical Method with Infinite Tube Radius
! Tube radii: Ra=0.5 cm, Rb=1.5 cm, Rc=3.5 cm, Rd=4.5 cm
!234567890123456789012345678901234567890123456789012345678901234567890
!  1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18
   0   0   5   1   0   0   1   1   1   0   0   0   0   0   2   0   0   0         Card 200
         1.0         1.0         1.0                                             Card 201
   1   3         0.0         1.0         1.0         1.0   0   1     1.0D-06     Card 300
         1.0         1.0         1.0                                             Card 300A
   1   2         1.0                                                             Card 301
   1   1   1                                                                     Card 302
        1.00                                                                     Card 303
         1.0         1.0         1.0         1.0         1.0         1.0         Card 304
         0.0         0.0        0.60         0.0         0.0         0.0         Card 304
         1.0         1.0         1.0         1.0         1.0         1.0         Card 304
         0.0         0.0         0.0                                             Card 305
   2   0         0.0        0.60         .01         7.0       0.020         8.0 Card 306
7.8539816D-5        0.01 .0314159265 .0314159265         1.0         1.0         Card 307
7.8539816D-5        0.01 .2827433388 .2827433388         1.0         1.0         Card 307
.15707963268                                                                     Card 308
1000.0000000                                                                     Card 308A
         1.0                                                                     Card 309
      5.0D-2      5.0D-2                                                         Card 310
       0.1D0       0.001       0.2D0      9.0D-3      50.0D0                     Card 500
       0.0D0       0.0D0                                                         Card 500
   1      0.0001        36.8         0.0         1.0                             Card 600
  11                                                                             Card 700
      0.00D0      1.00D0                                                         Card 701
      0.10D0      1.00D0                                                         Card 701
      0.20D0      1.00D0                                                         Card 701
      0.30D0      1.00D0                                                         Card 701
      0.40D0      1.00D0                                                         Card 701
      0.50D0      1.00D0                                                         Card 701
      0.60D0      1.00D0                                                         Card 701
      0.70D0      1.00D0                                                         Card 701
      0.80D0      1.00D0                                                         Card 701
      0.90D0      1.00D0                                                         Card 701
      1.00D0      1.00D0                                                         Card 701
   0                                                                             Card 702
```

**Fig. 20. Solution of Slab Geometry Problem 5 by the Slab Geometry Analytical Method in PLTEMP/ANL Version 3.2**

FUEL PLATE 1 (ExactSoln)

| NODE | COOLANTl (C) | CladSl (C) | FUEL PEAK (C) | CladSr (C) | COOLANTr (C) | HCOFl W/C-m^2 | HCOFr W/C-m^2 | ONBRl | ONBRr [F Note 1] | ETA'l K-cm^3/J | ETA'r K-cm^3/J | COOLNT at left(C) | NodeOutlet right(C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 50.000 | | | | 50.000 | | | | | | | | |
| 1 | 50.001 | 326.776 | 326.776 | 70.991 | 52.151 | 1.0000E-06 | 5.0688E+03 | 0.25 | 3.46 | 3.231E+12 | 4.560E+02 | 50.002 | 54.303 |
| 2 | 50.002 | 330.454 | 330.454 | 74.669 | 56.452 | 1.0000E-06 | 5.2420E+03 | 0.24 | 2.88 | 3.113E+12 | 4.157E+02 | 50.003 | 58.602 |
| 3 | 50.005 | 334.184 | 334.184 | 78.399 | 60.751 | 1.0000E-06 | 5.4109E+03 | 0.23 | 2.44 | 2.994E+12 | 3.749E+02 | 50.007 | 62.900 |
| 4 | 50.007 | 337.957 | 337.957 | 82.172 | 65.046 | 1.0000E-06 | 5.5757E+03 | 0.22 | 2.10 | 2.874E+12 | 3.336E+02 | 50.008 | 67.192 |
| 5 | 50.009 | 341.750 | 341.750 | 85.965 | 69.336 | 1.0000E-06 | 5.7426E+03 | 0.21 | 1.83 | 2.753E+12 | 2.916E+02 | 50.010 | 71.480 |
| 6 | 50.011 | 345.598 | 345.598 | 89.814 | 73.623 | 1.0000E-06 | 5.8981E+03 | 0.20 | 1.61 | 2.630E+12 | 2.490E+02 | 50.012 | 75.767 |
| 7 | 50.012 | 349.479 | 349.479 | 93.694 | 77.907 | 1.0000E-06 | 6.0487E+03 | 0.19 | 1.42 | 2.505E+12 | 2.056E+02 | 50.013 | 80.047 |
| 8 | 50.014 | 353.385 | 353.385 | 97.600 | 82.186 | 1.0000E-06 | 6.1951E+03 | 0.18 | 1.26 | 2.377E+12 | 1.613E+02 | 50.015 | 84.325 |
| 9 | 50.016 | 357.313 | 357.313 | 101.528 | 86.461 | 1.0000E-06 | 6.3379E+03 | 0.17 | 1.12 | 2.246E+12 | 1.161E+02 | 50.017 | 88.597 |
| 10 | 50.018 | 361.345 | 361.345 | 105.560 | 90.731 | 1.0000E-06 | 6.4396E+03 | 0.16 | 1.00 | 2.110E+12 | 6.961E+01 | 50.020 | 92.865 |
| | 50.020 | | | | 92.865 | | | | | | | | |

[1] The ONB ratio is here defined as (Tonb - Tinlet)/(Tsurf - Tinlet). If the heat flux is negative (the coolant is hotter than the adjacent cladding surface), then the ONB ratio is arbitrarily set to 99.99 .

FUEL PLATE 1 (ExactSoln)

| NODE | FLUX left MW/m^2 | FLUX right MW/m^2 | AREAL FUEL X left | Tsat (C) | Tdiff (C) | FUEL-CLADinterface left (C) | FUEL-CLADinterface right (C) | Pressure (bar) | Z-mid | Z-int |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.7677E-10 | 9.5493E-02 | 0.0000 | 119.432 | | 326.776 | 207.409 | 1.95000 | 0.0500 | 0.1000 |
| 2 | 2.8045E-10 | 9.5493E-02 | 0.0000 | 117.784 | | 330.454 | 211.088 | 1.85000 | 0.1500 | 0.2000 |
| 3 | 2.8418E-10 | 9.5493E-02 | 0.0000 | 116.061 | | 334.184 | 214.818 | 1.75000 | 0.2500 | 0.3000 |
| 4 | 2.8795E-10 | 9.5493E-02 | 0.0000 | 114.256 | | 337.957 | 218.591 | 1.65000 | 0.3500 | 0.4000 |
| 5 | 2.9174E-10 | 9.5493E-02 | 0.0000 | 112.359 | | 341.750 | 222.384 | 1.55000 | 0.4500 | 0.5000 |
| 6 | 2.9559E-10 | 9.5493E-02 | 0.0000 | 110.358 | | 345.598 | 226.232 | 1.45000 | 0.5500 | 0.6000 |
| 7 | 2.9947E-10 | 9.5493E-02 | 0.0000 | 108.241 | | 349.479 | 230.113 | 1.35000 | 0.6500 | 0.7000 |
| 8 | 3.0337E-10 | 9.5493E-02 | 0.0000 | 105.990 | | 353.385 | 234.019 | 1.25000 | 0.7500 | 0.8000 |
| 9 | 3.0730E-10 | 9.5493E-02 | 0.0000 | 103.585 | | 357.313 | 237.946 | 1.15000 | 0.8500 | 0.9000 |
| 10 | 3.1133E-10 | 9.5493E-02 | 0.0000 | 101.001 | | 361.345 | 241.978 | 1.05000 | 0.9500 | 1.0000 |

**Fig. 21. Solution of Slab Geometry Problem 5 by the <u>Radial Geometry</u> Analytical Method in PLTEMP/ANL Version 3.2 (Using a Mean Tube Radius of 1000 m)**

FUEL PLATE 1 (ExactSoln)

| NODE | COOLANT inner(C) | CladSurf inner(C) | FUEL PEAK (C) | CladSurf outer(C) | COOLANT outer(C) | HCOFinner W/C-m^2 | HCOFouter W/C-m^2 | ONBRin [F Note 1] | ONBRout [F Note 1] | ETAin K-cm^3/J | ETAout K-cm^3/J | COOLNT at inner(C) | NodeOutlet outer(C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 50.000 | | | | 50.000 | | | | | | | | |
| 1 | 50.001 | 326.772 | 326.772 | 70.990 | 52.151 | 1.0000E-06 | 5.0688E+03 | 0.25 | 3.46 | 1.624E+11 | 4.560E+02 | 50.002 | 54.303 |
| 2 | 50.002 | 330.451 | 330.451 | 74.669 | 56.452 | 1.0000E-06 | 5.2420E+03 | 0.24 | 2.88 | 1.564E+11 | 4.157E+02 | 50.003 | 58.602 |
| 3 | 50.005 | 334.181 | 334.181 | 78.399 | 60.751 | 1.0000E-06 | 5.4109E+03 | 0.23 | 2.44 | 1.505E+11 | 3.749E+02 | 50.007 | 62.900 |
| 4 | 50.007 | 337.954 | 337.954 | 82.172 | 65.046 | 1.0000E-06 | 5.5757E+03 | 0.22 | 2.10 | 1.444E+11 | 3.336E+02 | 50.008 | 67.192 |
| 5 | 50.009 | 341.747 | 341.747 | 85.965 | 69.336 | 1.0000E-06 | 5.7425E+03 | 0.21 | 1.83 | 1.383E+11 | 2.916E+02 | 50.010 | 71.480 |
| 6 | 50.011 | 345.595 | 345.595 | 89.813 | 73.623 | 1.0000E-06 | 5.8981E+03 | 0.20 | 1.61 | 1.321E+11 | 2.490E+02 | 50.012 | 75.767 |
| 7 | 50.012 | 349.476 | 349.476 | 93.694 | 77.907 | 1.0000E-06 | 6.0487E+03 | 0.19 | 1.42 | 1.259E+11 | 2.056E+02 | 50.013 | 80.047 |
| 8 | 50.014 | 353.382 | 353.382 | 97.600 | 82.186 | 1.0000E-06 | 6.1951E+03 | 0.18 | 1.26 | 1.194E+11 | 1.613E+02 | 50.015 | 84.325 |
| 9 | 50.016 | 357.310 | 357.310 | 101.528 | 86.461 | 1.0000E-06 | 6.3379E+03 | 0.17 | 1.12 | 1.128E+11 | 1.161E+02 | 50.017 | 88.597 |
| 10 | 50.018 | 361.341 | 361.341 | 105.559 | 90.731 | 1.0000E-06 | 6.4396E+03 | 0.16 | 1.00 | 1.060E+11 | 6.962E+01 | 50.020 | 92.865 |
| | 50.020 | | | | 92.865 | | | | | | | | |

[1] The ONB ratio is here defined as (Tonb - Tinlet)/(Tsurf - Tinlet). If the heat flux is negative (the coolant is hotter than the adjacent cladding surface), then the ONB ratio is arbitrarily set to 99.99 .

FUEL PLATE 1 (ExactSoln)

| NODE | FLUX inner MW/m^2 | FLUX outer MW/m^2 | AREAL FUEL X inner | Tsat (C) | Tdiff (C) | FUEL-CLADinterface inner (C) | FUEL-CLADinterface outer (C) | Pressure (bar) | Z-mid | Z-int |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.7677E-10 | 9.5491E-02 | 0.0000 | 119.432 | | 326.772 | 207.407 | 1.95000 | 0.0500 | 0.1000 |
| 2 | 2.8045E-10 | 9.5491E-02 | 0.0000 | 117.784 | | 330.451 | 211.085 | 1.85000 | 0.1500 | 0.2000 |
| 3 | 2.8418E-10 | 9.5491E-02 | 0.0000 | 116.061 | | 334.181 | 214.815 | 1.75000 | 0.2500 | 0.3000 |
| 4 | 2.8795E-10 | 9.5491E-02 | 0.0000 | 114.256 | | 337.954 | 218.588 | 1.65000 | 0.3500 | 0.4000 |
| 5 | 2.9174E-10 | 9.5491E-02 | 0.0000 | 112.359 | | 341.747 | 222.381 | 1.55000 | 0.4500 | 0.5000 |
| 6 | 2.9558E-10 | 9.5491E-02 | 0.0000 | 110.358 | | 345.595 | 226.230 | 1.45000 | 0.5500 | 0.6000 |
| 7 | 2.9946E-10 | 9.5491E-02 | 0.0000 | 108.241 | | 349.476 | 230.110 | 1.35000 | 0.6500 | 0.7000 |
| 8 | 3.0337E-10 | 9.5491E-02 | 0.0000 | 105.990 | | 353.382 | 234.017 | 1.25000 | 0.7500 | 0.8000 |
| 9 | 3.0729E-10 | 9.5491E-02 | 0.0000 | 103.585 | | 357.310 | 237.944 | 1.15000 | 0.8500 | 0.9000 |
| 10 | 3.1132E-10 | 9.5491E-02 | 0.0000 | 101.001 | | 361.341 | 241.976 | 1.05000 | 0.9500 | 1.0000 |

## Fig. 22. Input Data File for the Hungarian Reactor Benchmark Problem for PLTEMP/ANL Code Versions 3.1 and 3.2

```
! September 13, 2006
Hungarian Reactor Benchmark Problem;  90 kW                                       Card 100
   0   0   5   1   0   0   0   0   1   0   0   0   0   0   1   1   0 200         Card 200
   1   3        0.0         1.0         1.0         1.0   0   0                   Card 300
   1   2        1.0                                                               Card 301
   1   1   1                                                                      Card 302
       1.53                                                                       Card 303
        1.0         1.0         1.0         1.0         1.0         1.0           Card 304
        1.0         1.0         1.0         1.0         1.0         1.0           Card 304
        1.0         1.0         1.0         1.0         1.0         1.0           Card 304
        0.0         0.0         0.0                                               Card 305
   4   0        0.0        0.58     0.76e-3        206.     0.98e-3        180. Card 306
  2.8274E-05  6.0000E-03  1.8850E-02  1.8850E-02         1.0         1.0          Card 307
  1.3195E-04  6.0000E-03  8.7965E-02  8.7965E-02         1.0         1.0          Card 307
  2.5015E-04  6.1964E-03  1.6148E-01  1.6148E-01         1.0         1.0          Card 307
  1.8003E-04  6.6631E-03  1.0808E-01  1.0808E-01         1.0         1.0          Card 307
  2.6704E-02  6.1261E-02  1.0022E-01                                              Card 308
   0.0042500   0.0097500   0.0159511                                              Card 308A
        1.0         1.0         1.0                                               Card 309
  7.8065E-02  3.6415E-01  7.0516E-01  5.1356E-01                                  Card 310
      0.127       0.001       0.130      90.e-3         50.                       Card 500
        0.0         0.0                                                           Card 500
   1      0.0001        36.8         0.0         1.0                              Card 600
  -9                                                                              Card 700
      0.000      0.0625     0.30448                                               Card 701
      0.125      0.1875     0.86709                                               Card 701
      0.250      0.3125     1.29769                                               Card 701
      0.375      0.4375     1.53073                                               Card 701
      0.500      0.5625     1.53073                                               Card 701
      0.625      0.6875     1.29769                                               Card 701
      0.750      0.8125     0.86709                                               Card 701
      0.875      0.9375     0.30448                                               Card 701
      1.000                                                                       Card 701
   0                                                                              Card 702
```

**Fig. 23. Comparison of Solutions of Hungarian Reactor Benchmark Problem Using Constant Coolant Specific Heat Option ICP = 1 by PLTEMP/ANL Version 3.2 (For Each Axial Node Broyden Method is Followed by Analytical Method)**

```
FUEL PLATE   1 (BroydenSoln)
FUEL PLATE   1 (ExactSoln)
NODE    COOLANT             CladSurf            FUEL PEAK           CladSurf            COOLANT             HCOFinner           HCOFouter
        inner(C)            inner(C)               (C)              outer(C)            outer(C)            W/C-m^2             W/C-m^2
        50.000                                                                          50.000
   1  5.026788168178D+01  5.763033403660D+01  5.815674542593D+01  5.741790622196D+01  5.026207746876D+01  1.737546797787D+04  1.736044227160D+04
   1  5.026788168178D+01  5.763033403660D+01  5.815674238644D+01  5.741790622196D+01  5.026207746876D+01  1.737546797787D+04  1.736044227160D+04

   2  5.129912585683D+01  7.156699603522D+01  7.306725519855D+01  7.096425694763D+01  5.127033738507D+01  1.798617003496D+04  1.795706158604D+04
   2  5.129912585683D+01  7.156699603522D+01  7.306724654413D+01  7.096425694763D+01  5.127033738507D+01  1.798617003496D+04  1.795706158604D+04

   3  5.320520901445D+01  8.264683041186D+01  8.489275304379D+01  8.174596745034D+01  5.313286079191D+01  1.853507502551D+04  1.849488203967D+04
   3  5.320520899932D+01  8.264683000694D+01  8.489274004557D+01  8.174596776521D+01  5.313286089371D+01  1.853507502551D+04  1.849488203967D+04

   4  5.569575227254D+01  8.955443068083D+01  9.220342425820D+01  8.849130790231D+01  5.556537428244D+01  1.900985134219D+04  1.895945257020D+04
   4  5.569575224228D+01  8.955443065057D+01  9.220340906724D+01  8.849130810591D+01  5.556537448604D+01  1.900985134219D+04  1.895945257020D+04

   5  5.839057541372D+01  9.159689947923D+01  9.424397306363D+01  9.053012017051D+01  5.819669872016D+01  1.937148707849D+04  1.931350829851D+04
   5  5.839057538346D+01  9.159689944897D+01  9.424395787045D+01  9.053012037411D+01  5.819669892377D+01  1.937148707849D+04  1.931350829851D+04

   6  6.087764969365D+01  8.869923970638D+01  9.093898179580D+01  8.778660352537D+01  6.062521504470D+01  1.956892568815D+04  1.950877827538D+04
   6  6.087764966339D+01  8.869923967612D+01  9.093896892377D+01  8.778660372897D+01  6.062521524831D+01  1.956892568815D+04  1.950877827538D+04

   7  6.277640973990D+01  8.129552158824D+01  8.278486831557D+01  8.067198223197D+01  6.248008601000D+01  1.956401945259D+04  1.950665141504D+04
   7  6.277640970964D+01  8.129552155798D+01  8.278485973500D+01  8.067198243557D+01  6.248008621360D+01  1.956401945259D+04  1.950665141504D+04

   8  6.379638748880D+01  7.025584218194D+01  7.076691989025D+01  7.001410016907D+01  6.347782810713D+01  1.931725037000D+04  1.926862574114D+04
   8  6.379638745854D+01  7.025584215168D+01  7.076691691857D+01  7.001410037267D+01  6.347782831073D+01  1.931725037000D+04  1.926862574114D+04

Coolant temp rise (out - in) in channels =  1.40576789239336D+01  1.37340636570114D+01
Coolant temp rise (out - in) in channels =  1.40576788936754D+01  1.37340638606144D+01

FUEL PLATE   2 (BroydenSoln)
FUEL PLATE   2 (ExactSoln)
NODE    COOLANT             CladSurf            FUEL PEAK           CladSurf            COOLANT             HCOFinner           HCOFouter
        inner(C)            inner(C)               (C)              outer(C)            outer(C)            W/C-m^2             W/C-m^2
      50.000                                                                          50.000
   1  5.026207746876D+01  5.749962056227D+01  5.808350216372D+01  5.740004408121D+01  5.024996183759D+01  1.736347889400D+04  1.754227608636D+04
   1  5.026207746876D+01  5.749962056227D+01  5.808350232547D+01  5.740004408121D+01  5.024996183759D+01  1.736347889400D+04  1.754227608636D+04

   2  5.127033738507D+01  7.118980820391D+01  7.285235283615D+01  7.090580945633D+01  5.121152245339D+01  1.796426073518D+04  1.813835351449D+04
   2  5.127033738507D+01  7.118980820391D+01  7.285235329679D+01  7.090580945633D+01  5.121152245339D+01  1.796426073518D+04  1.813835351449D+04

   3  5.313286079191D+01  8.206102033617D+01  8.454766215957D+01  8.163298620280D+01  5.298758123502D+01  1.850358710542D+04  1.867058756623D+04
   3  5.313286089371D+01  8.206102462578D+01  8.454766330259D+01  8.163298280415D+01  5.298758104346D+01  1.850358710542D+04  1.867058756623D+04
```

```
   4  5.556537428244D+01  8.882483962945D+01  9.175503764515D+01  8.831405418463D+01  5.530685251994D+01  1.896834187896D+04  1.912537186204D+04
   4  5.556537448604D+01  8.882483983305D+01  9.175503836874D+01  8.831405380151D+01  5.530685213682D+01  1.896834187896D+04  1.912537186204D+04

   5  5.819669872016D+01  9.080064373893D+01  9.372545891293D+01  9.027928317303D+01  5.781527826289D+01  1.932084927442D+04  1.946778118060D+04
   5  5.819669892377D+01  9.080064394254D+01  9.372545963668D+01  9.027928278991D+01  5.781527787977D+01  1.932084927442D+04  1.946778118060D+04

   6  6.062521504470D+01  8.791505833827D+01  9.038576312458D+01  8.745570239806D+01  6.012990332273D+01  1.951232651802D+04  1.965101395700D+04
   6  6.062521524831D+01  8.791505854187D+01  9.038576372476D+01  8.745570201494D+01  6.012990293961D+01  1.951232651802D+04  1.965101395700D+04

   7  6.248008601000D+01  8.059770820383D+01  8.223475363207D+01  8.026353728310D+01  6.189725682700D+01  1.950443939117D+04  1.963771512444D+04
   7  6.248008621360D+01  8.059770840744D+01  8.223475400378D+01  8.026353689998D+01  6.189725644388D+01  1.950443939117D+04  1.963771512444D+04

   8  6.347782810713D+01  6.970724168720D+01  7.025874076289D+01  6.954356476011D+01  6.284729445379D+01  1.925783984674D+04  1.938933953762D+04
   8  6.347782831073D+01  6.970724189081D+01  7.025874083613D+01  6.954356437699D+01  6.284729407067D+01  1.925783984674D+04  1.938933953762D+04

Coolant temp rise (out - in) in channels =  1.37340636570114D+01  1.30909891747219D+01
Coolant temp rise (out - in) in channels =  1.37340638606144D+01  1.30909887916010D+01

FUEL PLATE   3 (BroydenSoln)
FUEL PLATE   3 (ExactSoln)
NODE    COOLANT             CladSurf            FUEL PEAK           CladSurf            COOLANT             HCOFinner           HCOFouter
        inner(C)            inner(C)               (C)              outer(C)            outer(C)            W/C-m^2             W/C-m^2
      50.000                                                                          50.000
   1  5.024996183759D+01  5.744292780031D+01  5.804989826450D+01  5.738904377431D+01  5.022806893706D+01  1.754390501053D+04  1.745152848655D+04
   1  5.024996183759D+01  5.744292780031D+01  5.804990461580D+01  5.738904377431D+01  5.022806893706D+01  1.754390501053D+04  1.745152848655D+04

   2  5.121152245339D+01  7.100791169903D+01  7.273504855628D+01  7.085174311896D+01  5.110598465145D+01  1.814162159711D+04  1.803335901499D+04
   2  5.121152245339D+01  7.100791169903D+01  7.273506664426D+01  7.085174311896D+01  5.110598465145D+01  1.814162159711D+04  1.803335901499D+04

   3  5.298758123502D+01  8.173809939468D+01  8.431925145590D+01  8.149709551110D+01  5.272935168345D+01  1.867355577266D+04  1.854294322766D+04
   3  5.298758104346D+01  8.173809257182D+01  8.431927805860D+01  8.149710141168D+01  5.272935187660D+01  1.867355577266D+04  1.854294322766D+04

   4  5.530685251994D+01  8.836406625288D+01  9.140269181829D+01  8.806782640925D+01  5.485279457261D+01  1.912670569428D+04  1.897026637291D+04
   4  5.530685213682D+01  8.836406586976D+01  9.140272375898D+01  8.806782679554D+01  5.485279495890D+01  1.912670569428D+04  1.897026637291D+04

   5  5.781527826289D+01  9.021424927870D+01  9.324330732332D+01  8.989909062739D+01  5.715513182533D+01  1.946598591476D+04  1.928488498526D+04
   5  5.781527787977D+01  9.021424889557D+01  9.324333927102D+01  8.989909101368D+01  5.715513221161D+01  1.946598591476D+04  1.928488498526D+04

   6  6.012990332273D+01  8.722277060633D+01  8.977611313126D+01  8.692674483760D+01  5.928831594404D+01  1.964453198255D+04  1.944433432213D+04
   6  6.012990293961D+01  8.722277022321D+01  8.977614022690D+01  8.692674522389D+01  5.928831633033D+01  1.964453198255D+04  1.944433432213D+04

   7  6.189725682700D+01  7.983033829728D+01  8.151441046396D+01  7.958881284154D+01  6.093017532097D+01  1.962464281158D+04  1.941422500136D+04
   7  6.189725644388D+01  7.983033791416D+01  8.151442858897D+01  7.958881322782D+01  6.093017570726D+01  1.962464281158D+04  1.941422500136D+04

   8  6.284729445379D+01  6.890809185249D+01  6.946289762652D+01  6.874982373794D+01  6.183308349649D+01  1.936669056720D+04  1.915698572822D+04
   8  6.284729407067D+01  6.890809146937D+01  6.946290404128D+01  6.874982412423D+01  6.183308388278D+01  1.936669056720D+04  1.915698572822D+04

Coolant temp rise (out - in) in channels =  1.30909891747219D+01  1.20749017955535D+01
Coolant temp rise (out - in) in channels =  1.30909887916010D+01  1.20749021818406D+01
```

**Fig. 23. Continued**

```
FUEL PLATE   1 (BroydenSoln) AREAL
FUEL PLATE   1 (ExactSoln)   AREAL                      FUEL-CLADinterface
NODE FLUX inner FLUX outer  FUEL X   Tsat     Tdiff      inner      outer    Pressure  Z-mid     Z-int
       MW/m^2     MW/m^2     inner   (C)       (C)        (C)        (C)      (bar)
   1 1.2793E-01 1.2423E-01  0.3597 107.091     0.00      58.051     57.911   1.29812   0.0625    0.1250
   2 3.6454E-01 3.5364E-01  0.3599 107.006     0.00      72.766     72.368   1.29438   0.1875    0.2500
   3 5.4570E-01 5.2920E-01  0.3600 106.921     0.00      84.441     83.847   1.29062   0.3125    0.3750
   4 6.4365E-01 6.2426E-01  0.3600 106.836     0.00      91.671     90.970   1.28688   0.4375    0.5000
   5 6.4326E-01 6.2447E-01  0.3597 106.751     0.00      93.712     93.010   1.28313   0.5625    0.6250
   6 5.4444E-01 5.2989E-01  0.3592 106.666     0.00      90.490     89.890   1.27938   0.6875    0.7500
   7 3.6231E-01 3.5486E-01  0.3577 106.580     0.00      82.487     82.081   1.27562   0.8125    0.8750
   8 1.2478E-01 1.2594E-01  0.3508 106.495     0.00      70.666     70.514   1.27188   0.9375    1.0000

   1 1.2793E-01 1.2423E-01  0.3597 107.091               58.051     57.911   1.29812   0.0625    0.1250
   2 3.6454E-01 3.5364E-01  0.3599 107.006               72.766     72.368   1.29438   0.1875    0.2500
   3 5.4570E-01 5.2920E-01  0.3600 106.921               84.441     83.847   1.29062   0.3125    0.3750
   4 6.4365E-01 6.2426E-01  0.3600 106.836               91.671     90.970   1.28688   0.4375    0.5000
   5 6.4326E-01 6.2447E-01  0.3597 106.751               93.712     93.010   1.28313   0.5625    0.6250
   6 5.4444E-01 5.2989E-01  0.3592 106.666               90.490     89.890   1.27938   0.6875    0.7500
   7 3.6231E-01 3.5486E-01  0.3577 106.580               82.487     82.081   1.27562   0.8125    0.8750
   8 1.2478E-01 1.2594E-01  0.3508 106.495               70.666     70.514   1.27188   0.9375    1.0000

FUEL PLATE   2 (BroydenSoln) AREAL
FUEL PLATE   2 (ExactSoln)   AREAL                      FUEL-CLADinterface
NODE FLUX inner FLUX outer  FUEL X   Tsat     Tdiff      inner      outer    Pressure  Z-mid     Z-int
       MW/m^2     MW/m^2     inner   (C)       (C)        (C)        (C)      (bar)
   1 1.2567E-01 1.2543E-01  0.4364 107.091     0.00      57.944     57.880   1.29812   0.0625    0.1250
   2 3.5784E-01 3.5722E-01  0.4363 107.006     0.00      72.454     72.271   1.29438   0.1875    0.2500
   3 5.3527E-01 5.3483E-01  0.4361 106.921     0.00      83.952     83.678   1.29062   0.3125    0.3750
   4 6.3088E-01 6.3128E-01  0.4357 106.836     0.00      91.054     90.727   1.28688   0.4375    0.5000
   5 6.2994E-01 6.3200E-01  0.4351 106.751     0.00      93.027     92.695   1.28313   0.5625    0.6250
   6 5.3249E-01 5.3698E-01  0.4338 106.666     0.00      89.797     89.509   1.27938   0.6875    0.7500
   7 3.5337E-01 3.6067E-01  0.4309 106.580     0.00      81.846     81.642   1.27562   0.8125    0.8750
   8 1.1997E-01 1.2984E-01  0.4166 106.495     0.00      70.131     70.040   1.27188   0.9375    1.0000

   1 1.2567E-01 1.2543E-01  0.4364 107.091               57.944     57.880   1.29812   0.0625    0.1250
   2 3.5784E-01 3.5722E-01  0.4363 107.006               72.454     72.271   1.29438   0.1875    0.2500
   3 5.3527E-01 5.3483E-01  0.4361 106.921               83.952     83.678   1.29062   0.3125    0.3750
   4 6.3088E-01 6.3128E-01  0.4357 106.836               91.054     90.727   1.28688   0.4375    0.5000
   5 6.2994E-01 6.3200E-01  0.4351 106.751               93.027     92.695   1.28313   0.5625    0.6250
   6 5.3249E-01 5.3698E-01  0.4338 106.666               89.797     89.509   1.27938   0.6875    0.7500
   7 3.5337E-01 3.6067E-01  0.4309 106.580               81.846     81.642   1.27562   0.8125    0.8750
   8 1.1997E-01 1.2984E-01  0.4166 106.495               70.131     70.040   1.27188   0.9375    1.0000
```

**Fig. 23. Continued**

```
 FUEL PLATE   3 (BroydenSoln) AREAL
 FUEL PLATE   3 (ExactSoln)   AREAL                     FUEL-CLADinterface
 NODE FLUX inner FLUX outer  FUEL X   Tsat     Tdiff     inner      outer    Pressure  Z-mid     Z-int
       MW/m^2     MW/m^2      inner   (C)       (C)       (C)        (C)      (bar)
    1 1.2619E-01 1.2497E-01  0.4632 107.091     0.00      57.897     57.861   1.29812   0.0625    0.1250
    2 3.5914E-01 3.5608E-01  0.4629 107.006     0.00      72.300     72.195   1.29438   0.1875    0.2500
    3 5.3687E-01 5.3344E-01  0.4624 106.921     0.00      83.669     83.510   1.29062   0.3125    0.3750
    4 6.3228E-01 6.3010E-01  0.4617 106.836     0.00      90.638     90.445   1.28688   0.4375    0.5000
    5 6.3068E-01 6.3146E-01  0.4605 106.751     0.00      92.483     92.282   1.28313   0.5625    0.6250
    6 5.3223E-01 5.3741E-01  0.4584 106.666     0.00      89.137     88.955   1.27938   0.6875    0.7500
    7 3.5193E-01 3.6224E-01  0.4537 106.580     0.00      81.096     80.956   1.27562   0.8125    0.8750
    8 1.1738E-01 1.3250E-01  0.4309 106.495     0.00      69.330     69.250   1.27188   0.9375    1.0000

    1 1.2619E-01 1.2497E-01  0.4632 107.091               57.897     57.861   1.29812   0.0625    0.1250
    2 3.5914E-01 3.5608E-01  0.4629 107.006               72.300     72.195   1.29438   0.1875    0.2500
    3 5.3687E-01 5.3344E-01  0.4624 106.921               83.669     83.510   1.29062   0.3125    0.3750
    4 6.3228E-01 6.3010E-01  0.4617 106.836               90.638     90.445   1.28688   0.4375    0.5000
    5 6.3068E-01 6.3146E-01  0.4605 106.751               92.483     92.282   1.28313   0.5625    0.6250
    6 5.3223E-01 5.3741E-01  0.4584 106.666               89.137     88.955   1.27938   0.6875    0.7500
    7 3.5193E-01 3.6224E-01  0.4537 106.580               81.096     80.956   1.27562   0.8125    0.8750
    8 1.1738E-01 1.3250E-01  0.4309 106.495               69.330     69.250   1.27188   0.9375    1.0000
```

## Fig. 24. Solution of Hungarian Reactor Benchmark Problem by the Broyden Method in PLTEMP/ANL Version 3.1 (Using Actual Coolant Properties)

FUEL PLATE 1 (BroydenSoln)

| NODE | COOLANT inner(C) | CladSurf inner(C) | FUEL PEAK (C) | CladSurf outer(C) | COOLANT outer(C) | HCOFinner W/C-m^2 | HCOFouter W/C-m^2 | ONBRin [F Note 1] | ONBRout [F Note 1] | ETAin K-cm^3/J | ETAout K-cm^3/J | COOLNT at inner(C) | NodeOutlet outer(C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 50.000 | | | | 50.000 | | | | | | | | |
| 1 | 50.267 | 57.586 | 58.113 | 57.374 | 50.262 | 1.7481E+04 | 1.7465E+04 | 8.11 | 8.34 | 1.246E+03 | 1.281E+03 | 50.535 | 50.523 |
| 2 | 51.297 | 71.384 | 72.885 | 70.782 | 51.268 | 1.8152E+04 | 1.8121E+04 | 3.01 | 3.09 | 4.287E+02 | 4.414E+02 | 52.060 | 52.013 |
| 3 | 53.201 | 82.312 | 84.559 | 81.413 | 53.128 | 1.8750E+04 | 1.8706E+04 | 2.03 | 2.09 | 2.761E+02 | 2.847E+02 | 54.342 | 54.243 |
| 4 | 55.688 | 89.126 | 91.776 | 88.065 | 55.557 | 1.9255E+04 | 1.9200E+04 | 1.70 | 1.74 | 2.229E+02 | 2.301E+02 | 57.034 | 56.871 |
| 5 | 58.379 | 91.169 | 93.817 | 90.104 | 58.184 | 1.9623E+04 | 1.9561E+04 | 1.61 | 1.65 | 2.109E+02 | 2.178E+02 | 59.724 | 59.497 |
| 6 | 60.863 | 88.359 | 90.599 | 87.447 | 60.609 | 1.9805E+04 | 1.9741E+04 | 1.71 | 1.75 | 2.360E+02 | 2.434E+02 | 62.001 | 61.720 |
| 7 | 62.759 | 81.092 | 82.582 | 80.469 | 62.461 | 1.9765E+04 | 1.9704E+04 | 2.05 | 2.09 | 3.393E+02 | 3.482E+02 | 63.516 | 63.201 |
| 8 | 63.777 | 70.186 | 70.697 | 69.944 | 63.457 | 1.9468E+04 | 1.9417E+04 | 3.02 | 3.06 | 9.607E+02 | 9.569E+02 | 64.038 | 63.713 |
| | 64.038 | | | | 63.713 | | | | | | | | |

FUEL PLATE 2 (BroydenSoln)

| NODE | COOLANT inner(C) | CladSurf inner(C) | FUEL PEAK (C) | CladSurf outer(C) | COOLANT outer(C) | HCOFinner W/C-m^2 | HCOFouter W/C-m^2 | ONBRin [F Note 1] | ONBRout [F Note 1] | ETAin K-cm^3/J | ETAout K-cm^3/J | COOLNT at inner(C) | NodeOutlet outer(C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 50.000 | | | | 50.000 | | | | | | | | |
| 1 | 50.262 | 57.456 | 58.040 | 57.357 | 50.250 | 1.7469E+04 | 1.7647E+04 | 8.25 | 8.36 | 1.266E+03 | 1.296E+03 | 50.523 | 50.499 |
| 2 | 51.268 | 71.011 | 72.674 | 70.728 | 51.210 | 1.8128E+04 | 1.8300E+04 | 3.06 | 3.10 | 4.361E+02 | 4.468E+02 | 52.013 | 51.920 |
| 3 | 53.128 | 81.735 | 84.222 | 81.308 | 52.983 | 1.8716E+04 | 1.8878E+04 | 2.07 | 2.10 | 2.814E+02 | 2.885E+02 | 54.243 | 54.046 |
| 4 | 55.557 | 88.407 | 91.338 | 87.898 | 55.299 | 1.9209E+04 | 1.9361E+04 | 1.72 | 1.75 | 2.276E+02 | 2.335E+02 | 56.871 | 56.551 |
| 5 | 58.184 | 90.383 | 93.308 | 89.863 | 57.803 | 1.9568E+04 | 1.9710E+04 | 1.64 | 1.66 | 2.159E+02 | 2.215E+02 | 59.497 | 59.055 |
| 6 | 60.609 | 87.582 | 90.053 | 87.124 | 60.114 | 1.9745E+04 | 1.9878E+04 | 1.74 | 1.76 | 2.422E+02 | 2.480E+02 | 61.720 | 61.173 |
| 7 | 62.461 | 80.398 | 82.035 | 80.064 | 61.879 | 1.9702E+04 | 1.9831E+04 | 2.10 | 2.12 | 3.496E+02 | 3.545E+02 | 63.201 | 62.584 |
| 8 | 63.457 | 69.638 | 70.189 | 69.474 | 62.827 | 1.9406E+04 | 1.9536E+04 | 3.10 | 3.13 | 1.005E+03 | 9.618E+02 | 63.713 | 63.070 |
| | 63.713 | | | | 63.070 | | | | | | | | |

FUEL PLATE 3 (BroydenSoln)

| NODE | COOLANT inner(C) | CladSurf inner(C) | FUEL PEAK (C) | CladSurf outer(C) | COOLANT outer(C) | HCOFinner W/C-m^2 | HCOFouter W/C-m^2 | ONBRin [F Note 1] | ONBRout [F Note 1] | ETAin K-cm^3/J | ETAout K-cm^3/J | COOLNT at inner(C) | NodeOutlet outer(C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 50.000 | | | | 50.000 | | | | | | | | |
| 1 | 50.250 | 57.401 | 58.008 | 57.347 | 50.228 | 1.7648E+04 | 1.7553E+04 | 8.31 | 8.37 | 1.288E+03 | 1.316E+03 | 50.499 | 50.455 |
| 2 | 51.210 | 70.835 | 72.563 | 70.680 | 51.104 | 1.8303E+04 | 1.8186E+04 | 3.08 | 3.10 | 4.443E+02 | 4.542E+02 | 51.920 | 51.753 |
| 3 | 52.983 | 81.425 | 84.007 | 81.185 | 52.724 | 1.8881E+04 | 1.8738E+04 | 2.09 | 2.10 | 2.873E+02 | 2.940E+02 | 54.046 | 53.696 |
| 4 | 55.299 | 87.962 | 91.002 | 87.668 | 54.844 | 1.9363E+04 | 1.9191E+04 | 1.75 | 1.76 | 2.331E+02 | 2.388E+02 | 56.551 | 55.992 |
| 5 | 57.803 | 89.811 | 92.841 | 89.498 | 57.142 | 1.9708E+04 | 1.9512E+04 | 1.66 | 1.68 | 2.219E+02 | 2.273E+02 | 59.055 | 58.292 |
| 6 | 60.114 | 86.901 | 89.454 | 86.605 | 59.271 | 1.9872E+04 | 1.9659E+04 | 1.77 | 1.79 | 2.501E+02 | 2.552E+02 | 61.173 | 60.250 |
| 7 | 61.879 | 79.636 | 81.320 | 79.394 | 60.910 | 1.9818E+04 | 1.9598E+04 | 2.15 | 2.17 | 3.633E+02 | 3.647E+02 | 62.584 | 61.570 |
| 8 | 62.827 | 68.840 | 69.394 | 68.681 | 61.812 | 1.9513E+04 | 1.9298E+04 | 3.23 | 3.27 | 1.065E+03 | 9.752E+02 | 63.070 | 62.054 |
| | 63.070 | | | | 62.054 | | | | | | | | |

[1] The ONB ratio is here defined as (Tonb - Tinlet)/(Tsurf - Tinlet). If the heat flux is negative (the coolant is hotter than the adjacent cladding surface), then the ONB ratio is arbitrarily set to 99.99 .

**Fig. 24. Continued**

| FUEL PLATE 1 (BroydenSoln) AREAL | | | | | FUEL-CLADinterface | | | | |
|---|---|---|---|---|---|---|---|---|---|
| NODE FLUX inner MW/m^2 | FLUX outer MW/m^2 | FUEL X inner | Tsat (C) | Tdiff (C) | inner (C) | outer (C) | Pressure (bar) | Z-mid | Z-int |
| 1 1.2794E-01 | 1.2422E-01 | 0.3597 | 107.091 | 0.00 | 58.007 | 57.867 | 1.29812 | 0.0625 | 0.1250 |
| 2 3.6462E-01 | 3.5360E-01 | 0.3600 | 107.006 | 0.00 | 72.583 | 72.186 | 1.29438 | 0.1875 | 0.2500 |
| 3 5.4586E-01 | 5.2911E-01 | 0.3601 | 106.921 | 0.00 | 84.107 | 83.514 | 1.29062 | 0.3125 | 0.3750 |
| 4 6.4385E-01 | 6.2415E-01 | 0.3601 | 106.836 | 0.00 | 91.243 | 90.543 | 1.28688 | 0.4375 | 0.5000 |
| 5 6.4344E-01 | 6.2437E-01 | 0.3598 | 106.751 | 0.00 | 93.285 | 92.583 | 1.28313 | 0.5625 | 0.6250 |
| 6 5.4456E-01 | 5.2982E-01 | 0.3592 | 106.666 | 0.00 | 90.149 | 89.551 | 1.27938 | 0.6875 | 0.7500 |
| 7 3.6235E-01 | 3.5484E-01 | 0.3577 | 106.580 | 0.00 | 82.284 | 81.878 | 1.27562 | 0.8125 | 0.8750 |
| 8 1.2476E-01 | 1.2596E-01 | 0.3508 | 106.495 | 0.00 | 70.596 | 70.444 | 1.27188 | 0.9375 | 1.0000 |

| FUEL PLATE 2 (BroydenSoln) AREAL | | | | | FUEL-CLADinterface | | | | |
|---|---|---|---|---|---|---|---|---|---|
| NODE FLUX inner MW/m^2 | FLUX outer MW/m^2 | FUEL X inner | Tsat (C) | Tdiff (C) | inner (C) | outer (C) | Pressure (bar) | Z-mid | Z-int |
| 1 1.2568E-01 | 1.2542E-01 | 0.4364 | 107.091 | 0.00 | 57.900 | 57.836 | 1.29812 | 0.0625 | 0.1250 |
| 2 3.5790E-01 | 3.5717E-01 | 0.4364 | 107.006 | 0.00 | 72.276 | 72.093 | 1.29438 | 0.1875 | 0.2500 |
| 3 5.3540E-01 | 5.3473E-01 | 0.4362 | 106.921 | 0.00 | 83.627 | 83.353 | 1.29062 | 0.3125 | 0.3750 |
| 4 6.3103E-01 | 6.3116E-01 | 0.4358 | 106.836 | 0.00 | 90.637 | 90.311 | 1.28688 | 0.4375 | 0.5000 |
| 5 6.3008E-01 | 6.3189E-01 | 0.4352 | 106.751 | 0.00 | 92.609 | 92.279 | 1.28313 | 0.5625 | 0.6250 |
| 6 5.3258E-01 | 5.3691E-01 | 0.4339 | 106.666 | 0.00 | 89.464 | 89.176 | 1.27938 | 0.6875 | 0.7500 |
| 7 3.5341E-01 | 3.6065E-01 | 0.4309 | 106.580 | 0.00 | 81.647 | 81.443 | 1.27562 | 0.8125 | 0.8750 |
| 8 1.1995E-01 | 1.2985E-01 | 0.4165 | 106.495 | 0.00 | 70.062 | 69.970 | 1.27188 | 0.9375 | 1.0000 |

| FUEL PLATE 3 (BroydenSoln) AREAL | | | | | FUEL-CLADinterface | | | | |
|---|---|---|---|---|---|---|---|---|---|
| NODE FLUX inner MW/m^2 | FLUX outer MW/m^2 | FUEL X inner | Tsat (C) | Tdiff (C) | inner (C) | outer (C) | Pressure (bar) | Z-mid | Z-int |
| 1 1.2620E-01 | 1.2496E-01 | 0.4633 | 107.091 | 0.00 | 57.855 | 57.818 | 1.29812 | 0.0625 | 0.1250 |
| 2 3.5921E-01 | 3.5602E-01 | 0.4630 | 107.006 | 0.00 | 72.128 | 72.023 | 1.29438 | 0.1875 | 0.2500 |
| 3 5.3702E-01 | 5.3331E-01 | 0.4625 | 106.921 | 0.00 | 83.356 | 83.198 | 1.29062 | 0.3125 | 0.3750 |
| 4 6.3246E-01 | 6.2994E-01 | 0.4618 | 106.836 | 0.00 | 90.237 | 90.045 | 1.28688 | 0.4375 | 0.5000 |
| 5 6.3083E-01 | 6.3134E-01 | 0.4606 | 106.751 | 0.00 | 92.080 | 91.880 | 1.28313 | 0.5625 | 0.6250 |
| 6 5.3230E-01 | 5.3735E-01 | 0.4585 | 106.666 | 0.00 | 88.815 | 88.633 | 1.27938 | 0.6875 | 0.7500 |
| 7 3.5192E-01 | 3.6225E-01 | 0.4536 | 106.580 | 0.00 | 80.902 | 80.761 | 1.27562 | 0.8125 | 0.8750 |
| 8 1.1732E-01 | 1.3255E-01 | 0.4307 | 106.495 | 0.00 | 69.262 | 69.181 | 1.27188 | 0.9375 | 1.0000 |

## Fig. 25. Solution of Hungarian Reactor Benchmark Problem by the Broyden Method in PLTEMP/ANL Version 3.2 (Using Actual Coolant Properties)

FUEL PLATE 1 (BroydenSoln)

| NODE | COOLANT inner(C) | CladSurf inner(C) | FUEL PEAK (C) | CladSurf outer(C) | COOLANT outer(C) | HCOFinner W/C-m^2 | HCOFouter W/C-m^2 | ONBRin [F Note 1] | ONBRout | ETAin K-cm^3/J | ETAout K-cm^3/J | COOLNT at inner(C) | NodeOutlet outer(C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 50.000 | | | | 50.000 | | | | | | | | |
| 1 | 50.267 | 57.599 | 58.125 | 57.387 | 50.262 | 1.7450E+04 | 1.7435E+04 | 8.10 | 8.32 | 1.246E+03 | 1.281E+03 | 50.535 | 50.523 |
| 2 | 51.297 | 71.479 | 72.979 | 70.876 | 51.268 | 1.8065E+04 | 1.8035E+04 | 2.99 | 3.07 | 4.288E+02 | 4.414E+02 | 52.059 | 52.013 |
| 3 | 53.200 | 82.510 | 84.756 | 81.610 | 53.128 | 1.8620E+04 | 1.8579E+04 | 2.02 | 2.07 | 2.762E+02 | 2.847E+02 | 54.341 | 54.242 |
| 4 | 55.687 | 89.383 | 92.033 | 88.321 | 55.556 | 1.9103E+04 | 1.9052E+04 | 1.68 | 1.73 | 2.230E+02 | 2.301E+02 | 57.033 | 56.870 |
| 5 | 58.378 | 91.412 | 94.059 | 90.346 | 58.183 | 1.9474E+04 | 1.9415E+04 | 1.60 | 1.64 | 2.110E+02 | 2.178E+02 | 59.723 | 59.496 |
| 6 | 60.861 | 88.527 | 90.767 | 87.615 | 60.608 | 1.9681E+04 | 1.9619E+04 | 1.70 | 1.74 | 2.360E+02 | 2.434E+02 | 61.999 | 61.720 |
| 7 | 62.757 | 81.165 | 82.655 | 80.542 | 62.460 | 1.9683E+04 | 1.9624E+04 | 2.05 | 2.09 | 3.394E+02 | 3.482E+02 | 63.514 | 63.200 |
| 8 | 63.775 | 70.194 | 70.705 | 69.952 | 63.456 | 1.9440E+04 | 1.9390E+04 | 3.02 | 3.06 | 9.607E+02 | 9.570E+02 | 64.036 | 63.712 |
| | 64.036 | | | | 63.712 | | | | | | | | |

FUEL PLATE 2 (BroydenSoln)

| NODE | COOLANT inner(C) | CladSurf inner(C) | FUEL PEAK (C) | CladSurf outer(C) | COOLANT outer(C) | HCOFinner W/C-m^2 | HCOFouter W/C-m^2 | ONBRin [F Note 1] | ONBRout | ETAin K-cm^3/J | ETAout K-cm^3/J | COOLNT at inner(C) | NodeOutlet outer(C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 50.000 | | | | 50.000 | | | | | | | | |
| 1 | 50.262 | 57.468 | 58.052 | 57.369 | 50.250 | 1.7438E+04 | 1.7618E+04 | 8.24 | 8.35 | 1.266E+03 | 1.296E+03 | 50.523 | 50.499 |
| 2 | 51.268 | 71.102 | 72.765 | 70.818 | 51.210 | 1.8042E+04 | 1.8217E+04 | 3.04 | 3.08 | 4.362E+02 | 4.467E+02 | 52.013 | 51.920 |
| 3 | 53.128 | 81.925 | 84.412 | 81.498 | 52.983 | 1.8588E+04 | 1.8755E+04 | 2.06 | 2.08 | 2.814E+02 | 2.885E+02 | 54.242 | 54.045 |
| 4 | 55.556 | 88.656 | 91.586 | 88.145 | 55.298 | 1.9061E+04 | 1.9218E+04 | 1.71 | 1.74 | 2.276E+02 | 2.335E+02 | 56.870 | 56.551 |
| 5 | 58.183 | 90.618 | 93.543 | 90.097 | 57.803 | 1.9423E+04 | 1.9569E+04 | 1.63 | 1.65 | 2.159E+02 | 2.215E+02 | 59.496 | 59.054 |
| 6 | 60.608 | 87.745 | 90.216 | 87.286 | 60.113 | 1.9623E+04 | 1.9761E+04 | 1.73 | 1.75 | 2.422E+02 | 2.480E+02 | 61.720 | 61.173 |
| 7 | 62.460 | 80.470 | 82.107 | 80.136 | 61.878 | 1.9622E+04 | 1.9754E+04 | 2.09 | 2.12 | 3.496E+02 | 3.545E+02 | 63.200 | 62.583 |
| 8 | 63.456 | 69.646 | 70.197 | 69.482 | 62.826 | 1.9379E+04 | 1.9509E+04 | 3.10 | 3.13 | 1.005E+03 | 9.619E+02 | 63.712 | 63.070 |
| | 63.712 | | | | 63.070 | | | | | | | | |

FUEL PLATE 3 (BroydenSoln)

| NODE | COOLANT inner(C) | CladSurf inner(C) | FUEL PEAK (C) | CladSurf outer(C) | COOLANT outer(C) | HCOFinner W/C-m^2 | HCOFouter W/C-m^2 | ONBRin [F Note 1] | ONBRout | ETAin K-cm^3/J | ETAout K-cm^3/J | COOLNT at inner(C) | NodeOutlet outer(C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 50.000 | | | | 50.000 | | | | | | | | |
| 1 | 50.250 | 57.412 | 58.019 | 57.358 | 50.228 | 1.7619E+04 | 1.7526E+04 | 8.30 | 8.36 | 1.288E+03 | 1.316E+03 | 50.499 | 50.455 |
| 2 | 51.210 | 70.920 | 72.648 | 70.764 | 51.104 | 1.8220E+04 | 1.8112E+04 | 3.07 | 3.09 | 4.443E+02 | 4.542E+02 | 51.920 | 51.753 |
| 3 | 52.983 | 81.604 | 84.185 | 81.363 | 52.725 | 1.8758E+04 | 1.8627E+04 | 2.08 | 2.09 | 2.873E+02 | 2.939E+02 | 54.045 | 53.697 |
| 4 | 55.298 | 88.197 | 91.236 | 87.901 | 54.845 | 1.9219E+04 | 1.9061E+04 | 1.73 | 1.75 | 2.331E+02 | 2.387E+02 | 56.551 | 55.993 |
| 5 | 57.803 | 90.035 | 93.064 | 89.720 | 57.143 | 1.9568E+04 | 1.9383E+04 | 1.65 | 1.67 | 2.220E+02 | 2.273E+02 | 59.054 | 58.294 |
| 6 | 60.113 | 87.056 | 89.610 | 86.761 | 59.273 | 1.9754E+04 | 1.9551E+04 | 1.76 | 1.78 | 2.502E+02 | 2.551E+02 | 61.173 | 60.252 |
| 7 | 61.878 | 79.705 | 81.389 | 79.464 | 60.912 | 1.9741E+04 | 1.9526E+04 | 2.15 | 2.17 | 3.633E+02 | 3.647E+02 | 62.583 | 61.572 |
| 8 | 62.826 | 68.849 | 69.403 | 68.690 | 61.814 | 1.9486E+04 | 1.9272E+04 | 3.23 | 3.27 | 1.064E+03 | 9.753E+02 | 63.070 | 62.055 |
| | 63.070 | | | | 62.055 | | | | | | | | |

[1] The ONB ratio is here defined as (Tonb - Tinlet)/(Tsurf - Tinlet). If the heat flux is negative (the coolant is hotter than the adjacent cladding surface), then the ONB ratio is arbitrarily set to 99.99 .

## Fig. 25. Continued

FUEL PLATE 1 (BroydenSoln) AREAL

| NODE | FLUX inner MW/m^2 | FLUX outer MW/m^2 | FUEL X inner | Tsat (C) | Tdiff (C) | FUEL-CLADinterface inner (C) | FUEL-CLADinterface outer (C) | Pressure (bar) | Z-mid | Z-int |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.2793E-01 | 1.2422E-01 | 0.3597 | 107.091 | 0.00 | 58.020 | 57.880 | 1.29812 | 0.0625 | 0.1250 |
| 2 | 3.6457E-01 | 3.5363E-01 | 0.3599 | 107.006 | 0.00 | 72.677 | 72.280 | 1.29438 | 0.1875 | 0.2500 |
| 3 | 5.4575E-01 | 5.2917E-01 | 0.3600 | 106.921 | 0.00 | 84.305 | 83.711 | 1.29062 | 0.3125 | 0.3750 |
| 4 | 6.4370E-01 | 6.2423E-01 | 0.3600 | 106.836 | 0.00 | 91.500 | 90.799 | 1.28688 | 0.4375 | 0.5000 |
| 5 | 6.4332E-01 | 6.2444E-01 | 0.3598 | 106.751 | 0.00 | 93.528 | 92.825 | 1.28313 | 0.5625 | 0.6250 |
| 6 | 5.4449E-01 | 5.2986E-01 | 0.3592 | 106.666 | 0.00 | 90.318 | 89.719 | 1.27938 | 0.6875 | 0.7500 |
| 7 | 3.6234E-01 | 3.5485E-01 | 0.3577 | 106.580 | 0.00 | 82.357 | 81.951 | 1.27562 | 0.8125 | 0.8750 |
| 8 | 1.2477E-01 | 1.2595E-01 | 0.3508 | 106.495 | 0.00 | 70.604 | 70.452 | 1.27188 | 0.9375 | 1.0000 |

FUEL PLATE 2 (BroydenSoln) AREAL

| NODE | FLUX inner MW/m^2 | FLUX outer MW/m^2 | FUEL X inner | Tsat (C) | Tdiff (C) | FUEL-CLADinterface inner (C) | FUEL-CLADinterface outer (C) | Pressure (bar) | Z-mid | Z-int |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.2567E-01 | 1.2543E-01 | 0.4364 | 107.091 | 0.00 | 57.912 | 57.848 | 1.29812 | 0.0625 | 0.1250 |
| 2 | 3.5785E-01 | 3.5721E-01 | 0.4363 | 107.006 | 0.00 | 72.367 | 72.184 | 1.29438 | 0.1875 | 0.2500 |
| 3 | 5.3529E-01 | 5.3481E-01 | 0.4361 | 106.921 | 0.00 | 83.817 | 83.542 | 1.29062 | 0.3125 | 0.3750 |
| 4 | 6.3091E-01 | 6.3125E-01 | 0.4358 | 106.836 | 0.00 | 90.885 | 90.558 | 1.28688 | 0.4375 | 0.5000 |
| 5 | 6.2997E-01 | 6.3198E-01 | 0.4351 | 106.751 | 0.00 | 92.844 | 92.513 | 1.28313 | 0.5625 | 0.6250 |
| 6 | 5.3251E-01 | 5.3696E-01 | 0.4339 | 106.666 | 0.00 | 89.627 | 89.339 | 1.27938 | 0.6875 | 0.7500 |
| 7 | 3.5339E-01 | 3.6066E-01 | 0.4309 | 106.580 | 0.00 | 81.718 | 81.514 | 1.27562 | 0.8125 | 0.8750 |
| 8 | 1.1995E-01 | 1.2985E-01 | 0.4165 | 106.495 | 0.00 | 70.070 | 69.978 | 1.27188 | 0.9375 | 1.0000 |

FUEL PLATE 3 (BroydenSoln) AREAL

| NODE | FLUX inner MW/m^2 | FLUX outer MW/m^2 | FUEL X inner | Tsat (C) | Tdiff (C) | FUEL-CLADinterface inner (C) | FUEL-CLADinterface outer (C) | Pressure (bar) | Z-mid | Z-int |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.2619E-01 | 1.2497E-01 | 0.4632 | 107.091 | 0.00 | 57.866 | 57.830 | 1.29812 | 0.0625 | 0.1250 |
| 2 | 3.5914E-01 | 3.5608E-01 | 0.4629 | 107.006 | 0.00 | 72.212 | 72.108 | 1.29438 | 0.1875 | 0.2500 |
| 3 | 5.3689E-01 | 5.3343E-01 | 0.4624 | 106.921 | 0.00 | 83.535 | 83.376 | 1.29062 | 0.3125 | 0.3750 |
| 4 | 6.3230E-01 | 6.3008E-01 | 0.4617 | 106.836 | 0.00 | 90.471 | 90.278 | 1.28688 | 0.4375 | 0.5000 |
| 5 | 6.3070E-01 | 6.3144E-01 | 0.4605 | 106.751 | 0.00 | 92.303 | 92.102 | 1.28313 | 0.5625 | 0.6250 |
| 6 | 5.3224E-01 | 5.3740E-01 | 0.4584 | 106.666 | 0.00 | 88.971 | 88.788 | 1.27938 | 0.6875 | 0.7500 |
| 7 | 3.5193E-01 | 3.6224E-01 | 0.4536 | 106.580 | 0.00 | 80.971 | 80.831 | 1.27562 | 0.8125 | 0.8750 |
| 8 | 1.1735E-01 | 1.3252E-01 | 0.4308 | 106.495 | 0.00 | 69.271 | 69.190 | 1.27188 | 0.9375 | 1.0000 |

## Fig. 26. Solution of Hungarian Reactor Benchmark Problem by the Analytical Method in PLTEMP/ANL Version 3.2 (Using Actual Coolant Properties)

FUEL PLATE 1 (ExactSoln)

| NODE | COOLANT inner(C) | CladSurf inner(C) | FUEL PEAK (C) | CladSurf outer(C) | COOLANT outer(C) | HCOFinner W/C-m^2 | HCOFouter W/C-m^2 | ONBRin [F Note 1] | ONBRout | ETAin K-cm^3/J | ETAout K-cm^3/J | COOLNT at NodeOutlet inner(C) | outer(C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 50.000 | | | | 50.000 | | | | | | | | |
| 1 | 50.268 | 57.599 | 58.125 | 57.387 | 50.261 | 1.7450E+04 | 1.7435E+04 | 8.10 | 8.32 | 1.246E+03 | 1.281E+03 | 50.536 | 50.523 |
| 2 | 51.298 | 71.479 | 72.979 | 70.877 | 51.268 | 1.8065E+04 | 1.8035E+04 | 2.99 | 3.07 | 4.288E+02 | 4.414E+02 | 52.061 | 52.014 |
| 3 | 53.202 | 82.511 | 84.757 | 81.611 | 53.129 | 1.8620E+04 | 1.8580E+04 | 2.02 | 2.07 | 2.762E+02 | 2.847E+02 | 54.343 | 54.245 |
| 4 | 55.689 | 89.385 | 92.034 | 88.322 | 55.559 | 1.9103E+04 | 1.9052E+04 | 1.68 | 1.73 | 2.229E+02 | 2.300E+02 | 57.035 | 56.873 |
| 5 | 58.378 | 91.413 | 94.060 | 90.347 | 58.185 | 1.9474E+04 | 1.9416E+04 | 1.60 | 1.64 | 2.110E+02 | 2.178E+02 | 59.722 | 59.497 |
| 6 | 60.859 | 88.526 | 90.766 | 87.614 | 60.608 | 1.9681E+04 | 1.9619E+04 | 1.70 | 1.74 | 2.360E+02 | 2.434E+02 | 61.996 | 61.718 |
| 7 | 62.753 | 81.162 | 82.652 | 80.539 | 62.457 | 1.9682E+04 | 1.9624E+04 | 2.05 | 2.09 | 3.394E+02 | 3.482E+02 | 63.510 | 63.196 |
| 8 | 63.770 | 70.189 | 70.700 | 69.947 | 63.451 | 1.9439E+04 | 1.9389E+04 | 3.02 | 3.06 | 9.607E+02 | 9.571E+02 | 64.030 | 63.707 |
| | 64.030 | | | | 63.707 | | | | | | | | |

FUEL PLATE 2 (ExactSoln)

| NODE | COOLANT inner(C) | CladSurf inner(C) | FUEL PEAK (C) | CladSurf outer(C) | COOLANT outer(C) | HCOFinner W/C-m^2 | HCOFouter W/C-m^2 | ONBRin [F Note 1] | ONBRout | ETAin K-cm^3/J | ETAout K-cm^3/J | COOLNT at NodeOutlet inner(C) | outer(C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 50.000 | | | | 50.000 | | | | | | | | |
| 1 | 50.261 | 57.468 | 58.052 | 57.369 | 50.250 | 1.7438E+04 | 1.7618E+04 | 8.24 | 8.35 | 1.266E+03 | 1.296E+03 | 50.523 | 50.499 |
| 2 | 51.268 | 71.103 | 72.765 | 70.819 | 51.210 | 1.8042E+04 | 1.8217E+04 | 3.04 | 3.08 | 4.362E+02 | 4.467E+02 | 52.014 | 51.921 |
| 3 | 53.129 | 81.927 | 84.413 | 81.499 | 52.984 | 1.8588E+04 | 1.8756E+04 | 2.06 | 2.08 | 2.814E+02 | 2.884E+02 | 54.245 | 54.047 |
| 4 | 55.559 | 88.657 | 91.587 | 88.146 | 55.299 | 1.9061E+04 | 1.9218E+04 | 1.71 | 1.74 | 2.276E+02 | 2.335E+02 | 56.873 | 56.552 |
| 5 | 58.185 | 90.618 | 93.543 | 90.097 | 57.802 | 1.9423E+04 | 1.9569E+04 | 1.63 | 1.65 | 2.159E+02 | 2.215E+02 | 59.497 | 59.053 |
| 6 | 60.608 | 87.744 | 90.215 | 87.285 | 60.111 | 1.9623E+04 | 1.9761E+04 | 1.73 | 1.75 | 2.422E+02 | 2.480E+02 | 61.718 | 61.169 |
| 7 | 62.457 | 80.466 | 82.103 | 80.132 | 61.873 | 1.9622E+04 | 1.9754E+04 | 2.09 | 2.12 | 3.497E+02 | 3.545E+02 | 63.196 | 62.576 |
| 8 | 63.451 | 69.640 | 70.191 | 69.476 | 62.819 | 1.9378E+04 | 1.9508E+04 | 3.10 | 3.13 | 1.005E+03 | 9.619E+02 | 63.707 | 63.061 |
| | 63.707 | | | | 63.061 | | | | | | | | |

FUEL PLATE 3 (ExactSoln)

| NODE | COOLANT inner(C) | CladSurf inner(C) | FUEL PEAK (C) | CladSurf outer(C) | COOLANT outer(C) | HCOFinner W/C-m^2 | HCOFouter W/C-m^2 | ONBRin [F Note 1] | ONBRout | ETAin K-cm^3/J | ETAout K-cm^3/J | COOLNT at NodeOutlet inner(C) | outer(C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 50.000 | | | | 50.000 | | | | | | | | |
| 1 | 50.250 | 57.412 | 58.019 | 57.358 | 50.228 | 1.7619E+04 | 1.7527E+04 | 8.30 | 8.36 | 1.288E+03 | 1.316E+03 | 50.499 | 50.455 |
| 2 | 51.210 | 70.921 | 72.648 | 70.765 | 51.104 | 1.8221E+04 | 1.8112E+04 | 3.07 | 3.09 | 4.443E+02 | 4.542E+02 | 51.921 | 51.753 |
| 3 | 52.984 | 81.604 | 84.186 | 81.363 | 52.725 | 1.8759E+04 | 1.8627E+04 | 2.08 | 2.09 | 2.873E+02 | 2.939E+02 | 54.047 | 53.697 |
| 4 | 55.299 | 88.197 | 91.236 | 87.901 | 54.845 | 1.9220E+04 | 1.9061E+04 | 1.73 | 1.75 | 2.331E+02 | 2.387E+02 | 56.552 | 55.992 |
| 5 | 57.802 | 90.034 | 93.063 | 89.719 | 57.142 | 1.9568E+04 | 1.9383E+04 | 1.65 | 1.67 | 2.220E+02 | 2.273E+02 | 59.053 | 58.291 |
| 6 | 60.111 | 87.054 | 89.607 | 86.758 | 59.270 | 1.9754E+04 | 1.9550E+04 | 1.76 | 1.78 | 2.502E+02 | 2.551E+02 | 61.169 | 60.248 |
| 7 | 61.873 | 79.701 | 81.385 | 79.459 | 60.907 | 1.9740E+04 | 1.9525E+04 | 2.15 | 2.17 | 3.633E+02 | 3.647E+02 | 62.576 | 61.566 |
| 8 | 62.819 | 68.842 | 69.396 | 68.683 | 61.807 | 1.9485E+04 | 1.9271E+04 | 3.23 | 3.27 | 1.064E+03 | 9.755E+02 | 63.061 | 62.047 |
| | 63.061 | | | | 62.047 | | | | | | | | |

[1] The ONB ratio is here defined as (Tonb - Tinlet)/(Tsurf - Tinlet). If the heat flux is negative (the coolant is hotter than the adjacent cladding surface), then the ONB ratio is arbitrarily set to 99.99 .

## Fig. 26. Continued

| FUEL PLATE 1 (ExactSoln) | | | AREAL | | | FUEL-CLADinterface | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| NODE | FLUX inner | FLUX outer | FUEL X | Tsat | Tdiff | inner | outer | Pressure | Z-mid | Z-int |
| | MW/m^2 | MW/m^2 | inner | (C) | (C) | (C) | (C) | (bar) | | |
| 1 | 1.2793E-01 | 1.2423E-01 | 0.3597 | 107.091 | | 58.020 | 57.880 | 1.29812 | 0.0625 | 0.1250 |
| 2 | 3.6456E-01 | 3.5363E-01 | 0.3599 | 107.006 | | 72.678 | 72.281 | 1.29438 | 0.1875 | 0.2500 |
| 3 | 5.4575E-01 | 5.2917E-01 | 0.3600 | 106.921 | | 84.306 | 83.712 | 1.29062 | 0.3125 | 0.3750 |
| 4 | 6.4371E-01 | 6.2422E-01 | 0.3600 | 106.836 | | 91.502 | 90.801 | 1.28688 | 0.4375 | 0.5000 |
| 5 | 6.4332E-01 | 6.2444E-01 | 0.3598 | 106.751 | | 93.528 | 92.826 | 1.28313 | 0.5625 | 0.6250 |
| 6 | 5.4450E-01 | 5.2985E-01 | 0.3592 | 106.666 | | 90.317 | 89.718 | 1.27938 | 0.6875 | 0.7500 |
| 7 | 3.6235E-01 | 3.5484E-01 | 0.3577 | 106.580 | | 82.354 | 81.948 | 1.27562 | 0.8125 | 0.8750 |
| 8 | 1.2478E-01 | 1.2594E-01 | 0.3508 | 106.495 | | 70.599 | 70.447 | 1.27188 | 0.9375 | 1.0000 |

| FUEL PLATE 2 (ExactSoln) | | | AREAL | | | FUEL-CLADinterface | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| NODE | FLUX inner | FLUX outer | FUEL X | Tsat | Tdiff | inner | outer | Pressure | Z-mid | Z-int |
| | MW/m^2 | MW/m^2 | inner | (C) | (C) | (C) | (C) | (bar) | | |
| 1 | 1.2568E-01 | 1.2542E-01 | 0.4364 | 107.091 | | 57.912 | 57.848 | 1.29812 | 0.0625 | 0.1250 |
| 2 | 3.5785E-01 | 3.5721E-01 | 0.4363 | 107.006 | | 72.367 | 72.184 | 1.29438 | 0.1875 | 0.2500 |
| 3 | 5.3529E-01 | 5.3481E-01 | 0.4361 | 106.921 | | 83.818 | 83.543 | 1.29062 | 0.3125 | 0.3750 |
| 4 | 6.3089E-01 | 6.3126E-01 | 0.4358 | 106.836 | | 90.886 | 90.560 | 1.28688 | 0.4375 | 0.5000 |
| 5 | 6.2995E-01 | 6.3199E-01 | 0.4351 | 106.751 | | 92.844 | 92.513 | 1.28313 | 0.5625 | 0.6250 |
| 6 | 5.3250E-01 | 5.3697E-01 | 0.4338 | 106.666 | | 89.626 | 89.338 | 1.27938 | 0.6875 | 0.7500 |
| 7 | 3.5336E-01 | 3.6068E-01 | 0.4309 | 106.580 | | 81.715 | 81.510 | 1.27562 | 0.8125 | 0.8750 |
| 8 | 1.1992E-01 | 1.2987E-01 | 0.4164 | 106.495 | | 70.064 | 69.972 | 1.27188 | 0.9375 | 1.0000 |

| FUEL PLATE 3 (ExactSoln) | | | AREAL | | | FUEL-CLADinterface | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| NODE | FLUX inner | FLUX outer | FUEL X | Tsat | Tdiff | inner | outer | Pressure | Z-mid | Z-int |
| | MW/m^2 | MW/m^2 | inner | (C) | (C) | (C) | (C) | (bar) | | |
| 1 | 1.2619E-01 | 1.2497E-01 | 0.4632 | 107.091 | | 57.866 | 57.829 | 1.29812 | 0.0625 | 0.1250 |
| 2 | 3.5914E-01 | 3.5608E-01 | 0.4629 | 107.006 | | 72.213 | 72.108 | 1.29438 | 0.1875 | 0.2500 |
| 3 | 5.3688E-01 | 5.3344E-01 | 0.4624 | 106.921 | | 83.536 | 83.376 | 1.29062 | 0.3125 | 0.3750 |
| 4 | 6.3229E-01 | 6.3009E-01 | 0.4617 | 106.836 | | 90.472 | 90.279 | 1.28688 | 0.4375 | 0.5000 |
| 5 | 6.3069E-01 | 6.3145E-01 | 0.4605 | 106.751 | | 92.303 | 92.102 | 1.28313 | 0.5625 | 0.6250 |
| 6 | 5.3224E-01 | 5.3740E-01 | 0.4584 | 106.666 | | 88.969 | 88.786 | 1.27938 | 0.6875 | 0.7500 |
| 7 | 3.5193E-01 | 3.6224E-01 | 0.4537 | 106.580 | | 80.967 | 80.826 | 1.27562 | 0.8125 | 0.8750 |
| 8 | 1.1736E-01 | 1.3252E-01 | 0.4308 | 106.495 | | 69.264 | 69.183 | 1.27188 | 0.9375 | 1.0000 |

**Fig. 27. ASTRA2 Problem 3 Case 1 Input Data File for PLTEMP/ANL Code Versions 3.1 and 3.2**
(Using $C_p$ = 4180 J/kg-°C, and $\rho$ = 1000 kg/m$^3$, Same as ASTRA2 Code Input)

```
IRT-3M 36% Enr. FA - 6 0.58 m Height - ASTRA2 P3, INCREASING RADII, astra2p3c1r
! Input card types 307, 308, 308A, 309, 310 were rearranged
!2345678901234567890123456789012345678901234567890123456789012345678901234567890
!  1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18
   4   1   2   1   1   1   1   0   1   1   0   0   0   0   2   0   0  20        Card(1)0200
 1.0        1.0         1.0                                                     Card(1)0201
   1   3  0.0        1.00        1.000       1.00                               Card(1)0300
 1.0        1.0         1.0                                                     Card(1)300A
   7   7  1.000                                                                 Card(1)0301
   1   2   1                                                                    Card(1)0302
 1.3135                                                                         Card(1)0303
 0.0043433  0.038540    0.10        0.5                                         Card(3)0304
 0.0        0.0         0.580       0.0                                         Card(3)0304
 0.0043433  0.038540    0.035       1.0                                         Card(3)0304
 0.316      0.250                                                               Card(1)0305
   7  0 0.0         0.580         0.450E-03  170.        0.500E-03  100.        Card(1)0306
  1.9353E-04  0.0         0.18881    0.18881                                    Card(1)0307
  2.3797E-04  0.0         0.23216    0.23216                                    Card(2)0307
  2.8241E-04  0.0         0.27552    0.27552                                    Card(3)0307
  3.2684E-04  0.0         0.31887    0.31887                                    Card(4)0307
  3.7128E-04  0.0         0.36223    0.36223                                    Card(5)0307
  4.1572E-04  0.0         0.40558    0.40558                                    Card(6)0307
  5.1808E-04 4.60000E-03  0.22525    0.22525                                    Card(7)0307
 0.105243   0.126920    0.148597    0.170274    0.191951    0.213628            Card(1)0308
  .0188      .02225      .0257       .02915      .0326       .0363              Card(1)308A
0.85731    0.90175     0.9579      1.0234      1.0901      1.1696               Card(1)0309
0.717522   0.903667    0.917400    1.10792     1.21088     1.23838              Card(1)0310
1.663038                                                                        Card(2)0310
   1   1         1.0                                                            Card(1)0400
  1.1545E-04    3.00E-03    0.680          1.4                                  Card(1)0401
       0.316    0.25                                                            Card(1)0402
 .100633     .0005        .12540     0.662880     45.0        .135              Card(1)0500
 0.0         0.0                                                                Card(2)0500
 100 1.00000E-04   25.0        0.0000        0.66288                            Card(1)0600
 -12                                                                            Card(1)0700
0.00000      0.025       0.52323                                                Card(1)0701
0.05000      0.100       0.62029                                                Card(2)0701
0.15         0.20        0.85886                                                Card(3)0701
0.25         0.30        1.06336                                                Card(4)0701
0.35         0.40        1.24058                                                Card(5)0701
0.45         0.50        1.34964                                                Card(6)0701
0.55         0.60        1.36328                                                Card(7)0701
0.65         0.70        1.27466                                                Card(8)0701
0.75         0.80        1.09062                                                Card(9)0701
0.85         0.90        0.85886                                                Card(10)701
0.95         0.975       0.75662                                                Card(11)701
1.00000                                                                         Card(12)701
0
```

**Fig. 28. Solution of ASTRA2 Problem 3 Case 1 by PLTEMP/ANL of May 22 2003**
(From PLTEMP/ANL Output File output.astra2p3c1r.1)

```
FUEL PLATE   1 (BroydenSoln)
NODE    COOLANT  CladSurf FUEL PEAK  CladSurf  COOLANT
       inner(C)  inner(C)    (C)     outer(C)  outer(C)
         45.000                                  45.000
   1     45.128    57.615    58.441    56.668    45.233
   2     45.552    59.783    60.890    59.749    46.032
   3     46.269    66.000    67.356    65.369    47.368
   4     47.207    70.933    72.881    70.975    49.103
   5     48.334    75.772    78.077    75.883    51.189
   6     49.615    79.394    81.943    79.595    53.526
   7     50.957    80.431    84.373    82.318    55.982
   8     52.285    81.165    83.695    81.592    58.359
   9     53.480    77.160    83.041    81.397    60.468
  10     54.438    73.284    80.065    78.770    62.212
  11     55.045    71.723    79.077    77.936    63.333
         55.231                                  63.681

FUEL PLATE   2 (BroydenSoln)
NODE    COOLANT  CladSurf FUEL PEAK  CladSurf  COOLANT
       inner(C)  inner(C)    (C)     outer(C)  outer(C)
         45.000                                  45.000
   1     45.233    58.213    59.474    58.653    45.282
   2     46.032    61.419    62.682    61.563    46.217
   3     47.368    67.938    69.856    68.478    47.791
   4     49.103    74.184    76.368    74.467    49.830
   5     51.189    79.856    82.414    80.205    52.253
   6     53.526    84.254    87.051    84.662    54.975
   7     55.982    86.789    89.628    87.227    57.825
   8     58.359    87.196    89.882    87.667    60.592
   9     60.468    84.178    88.992    87.278    63.081
  10     62.212    81.333    85.251    83.932    65.149
  11     63.333    80.854    83.451    82.347    66.463
         63.681                                  66.861

FUEL PLATE   3 (BroydenSoln)
NODE    COOLANT  CladSurf FUEL PEAK  CladSurf  COOLANT
       inner(C)  inner(C)    (C)     outer(C)  outer(C)
         45.000                                  45.000
   1     45.282    60.267    61.176    59.437    45.293
   2     46.217    63.251    64.476    63.163    46.288
   3     47.791    71.205    72.700    70.003    47.957
   4     49.830    77.377    79.485    77.242    50.129
   5     52.253    83.653    86.118    83.509    52.740
   6     54.975    88.526    91.217    88.387    55.677
   7     57.825    91.341    94.069    91.220    58.755
   8     60.592    91.837    94.403    91.754    61.751
   9     63.081    89.217    92.634    90.665    64.453
  10     65.149    86.523    88.418    86.800    66.688
  11     66.463    85.482    87.129    85.680    68.086
         66.861                                  68.503
```

**Fig. 28. Continued**

FUEL PLATE 4 (BroydenSoln)

| NODE | COOLANT inner(C) | CladSurf inner(C) | FUEL PEAK (C) | CladSurf outer(C) | COOLANT outer(C) |
|---|---|---|---|---|---|
| | 45.000 | | | | 45.000 |
| 1 | 45.293 | 60.825 | 61.929 | 60.737 | 45.326 |
| 2 | 46.288 | 64.359 | 65.729 | 64.379 | 46.428 |
| 3 | 47.957 | 72.428 | 74.085 | 71.975 | 48.273 |
| 4 | 50.129 | 79.321 | 81.684 | 79.383 | 50.671 |
| 5 | 52.740 | 85.991 | 88.756 | 86.080 | 53.553 |
| 6 | 55.677 | 91.185 | 94.204 | 91.304 | 56.792 |
| 7 | 58.755 | 94.218 | 97.283 | 94.368 | 60.185 |
| 8 | 61.751 | 94.824 | 97.710 | 95.004 | 63.482 |
| 9 | 64.453 | 92.836 | 95.454 | 93.287 | 66.425 |
| 10 | 66.688 | 89.464 | 91.516 | 89.798 | 68.840 |
| 11 | 68.086 | 87.118 | 91.324 | 89.895 | 70.372 |
| | 68.503 | | | | 70.840 |

FUEL PLATE 5 (BroydenSoln)

| NODE | COOLANT inner(C) | CladSurf inner(C) | FUEL PEAK (C) | CladSurf outer(C) | COOLANT outer(C) |
|---|---|---|---|---|---|
| | 45.000 | | | | 45.000 |
| 1 | 45.326 | 62.525 | 63.801 | 62.627 | 45.373 |
| 2 | 46.428 | 66.478 | 67.982 | 66.579 | 46.612 |
| 3 | 48.273 | 75.105 | 77.195 | 75.261 | 48.669 |
| 4 | 50.671 | 82.955 | 85.546 | 83.155 | 51.323 |
| 5 | 53.553 | 90.247 | 93.277 | 90.495 | 54.477 |
| 6 | 56.792 | 95.890 | 99.196 | 96.178 | 57.993 |
| 7 | 60.185 | 99.150 | 102.501 | 99.464 | 61.637 |
| 8 | 63.482 | 99.738 | 102.886 | 100.060 | 65.130 |
| 9 | 66.425 | 97.032 | 100.713 | 98.621 | 68.331 |
| 10 | 68.840 | 93.427 | 96.321 | 94.702 | 71.061 |
| 11 | 70.372 | 91.017 | 96.234 | 94.715 | 72.792 |
| | 70.840 | | | | 73.320 |

FUEL PLATE 6 (BroydenSoln)

| NODE | COOLANT inner(C) | CladSurf inner(C) | FUEL PEAK (C) | CladSurf outer(C) | COOLANT outer(C) |
|---|---|---|---|---|---|
| | 45.000 | | | | 45.000 |
| 1 | 45.373 | 64.486 | 65.593 | 63.492 | 45.156 |
| 2 | 46.612 | 67.991 | 69.461 | 67.815 | 45.694 |
| 3 | 48.669 | 76.975 | 78.878 | 76.465 | 46.611 |
| 4 | 51.323 | 84.764 | 87.207 | 84.304 | 47.815 |
| 5 | 54.477 | 91.941 | 94.745 | 91.309 | 49.277 |
| 6 | 57.993 | 97.232 | 100.223 | 96.421 | 50.939 |
| 7 | 61.637 | 99.889 | 102.830 | 98.904 | 52.706 |
| 8 | 65.130 | 99.635 | 102.284 | 98.501 | 54.457 |
| 9 | 68.331 | 100.938 | 103.159 | 91.022 | 55.982 |
| 10 | 71.061 | 97.247 | 99.026 | 84.809 | 57.173 |
| 11 | 72.792 | 94.691 | 96.156 | 83.606 | 57.934 |
| | 73.320 | | | | 58.176 |

**Fig. 29. Solution of ASTRA2 Problem 3 Case 1 by the Broyden Method in PLTEMP/ANL Version 3.1**
(Using Coolant $C_p$ = 4180 J/kg-°C, and $\rho$ = 1000 kg/m$^3$, Same as ASTRA2 Code Input)

| NODE | COOLANT inner(C) | CladSurf inner(C) | FUEL PEAK (C) | CladSurf outer(C) | COOLANT outer(C) | HCOFinner W/C-m^2 | HCOFouter W/C-m^2 | ONBRin [F Note 1] | ONBRout [F Note 1] | ETAin K-cm^3/J | ETAout K-cm^3/J | COOLNT at inner(C) | NodeOutlet outer(C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| FUEL PLATE 1 (BroydenSoln) | | | | | | | | | | | | | |
| | 45.000 | | | | 45.000 | | | | | | | | |
| 1 | 45.123 | 57.164 | 58.086 | 57.110 | 45.239 | 2.0902E+04 | 2.1314E+04 | 6.11 | 6.14 | 8.959E+02 | 9.110E+02 | 45.247 | 45.478 |
| 2 | 45.542 | 59.802 | 60.911 | 59.770 | 46.043 | 2.1167E+04 | 2.1618E+04 | 5.06 | 5.06 | 7.366E+02 | 7.609E+02 | 45.838 | 46.608 |
| 3 | 46.252 | 65.698 | 67.255 | 65.695 | 47.388 | 2.1714E+04 | 2.2222E+04 | 3.68 | 3.67 | 5.151E+02 | 5.370E+02 | 46.665 | 48.168 |
| 4 | 47.183 | 70.962 | 72.915 | 71.009 | 49.131 | 2.2216E+04 | 2.2791E+04 | 2.96 | 2.95 | 4.010E+02 | 4.203E+02 | 47.701 | 50.094 |
| 5 | 48.311 | 75.805 | 78.115 | 75.921 | 51.214 | 2.2654E+04 | 2.3300E+04 | 2.52 | 2.49 | 3.298E+02 | 3.463E+02 | 48.921 | 52.335 |
| 6 | 49.593 | 79.430 | 81.983 | 79.635 | 53.551 | 2.2992E+04 | 2.3712E+04 | 2.25 | 2.22 | 2.891E+02 | 3.041E+02 | 50.265 | 54.766 |
| 7 | 50.955 | 81.296 | 83.928 | 81.607 | 55.989 | 2.3201E+04 | 2.3988E+04 | 2.13 | 2.09 | 2.712E+02 | 2.871E+02 | 51.644 | 57.212 |
| 8 | 52.303 | 81.203 | 83.734 | 81.627 | 58.350 | 2.3270E+04 | 2.4113E+04 | 2.11 | 2.05 | 2.730E+02 | 2.941E+02 | 52.962 | 59.487 |
| 9 | 53.544 | 79.165 | 81.409 | 79.676 | 60.453 | 2.3193E+04 | 2.4074E+04 | 2.20 | 2.12 | 2.971E+02 | 3.340E+02 | 54.127 | 61.418 |
| 10 | 54.607 | 75.910 | 77.801 | 76.544 | 62.170 | 2.3010E+04 | 2.3917E+04 | 2.37 | 2.26 | 3.470E+02 | 4.233E+02 | 55.087 | 62.922 |
| 11 | 55.305 | 74.728 | 76.460 | 75.408 | 63.253 | 2.2945E+04 | 2.3863E+04 | 2.43 | 2.30 | 3.717E+02 | 4.808E+02 | 55.524 | 63.585 |
| | 55.524 | | | | 63.585 | | | | | | | | |
| FUEL PLATE 2 (BroydenSoln) | | | | | | | | | | | | | |
| | 45.000 | | | | 45.000 | | | | | | | | |
| 1 | 45.239 | 58.385 | 59.446 | 58.496 | 45.276 | 2.1429E+04 | 1.8926E+04 | 5.60 | 5.51 | 8.182E+02 | 7.876E+02 | 45.478 | 45.552 |
| 2 | 46.043 | 61.435 | 62.697 | 61.576 | 46.205 | 2.1765E+04 | 1.9233E+04 | 4.59 | 4.51 | 6.740E+02 | 6.516E+02 | 46.608 | 46.859 |
| 3 | 47.388 | 68.114 | 69.869 | 68.324 | 47.764 | 2.2443E+04 | 1.9849E+04 | 3.32 | 3.26 | 4.696E+02 | 4.549E+02 | 48.168 | 48.668 |
| 4 | 49.131 | 74.206 | 76.386 | 74.479 | 49.788 | 2.3040E+04 | 2.0395E+04 | 2.65 | 2.60 | 3.627E+02 | 3.518E+02 | 50.094 | 50.907 |
| 5 | 51.214 | 79.879 | 82.436 | 80.223 | 52.213 | 2.3590E+04 | 2.0902E+04 | 2.24 | 2.19 | 2.948E+02 | 2.857E+02 | 52.335 | 53.518 |
| 6 | 53.551 | 84.279 | 87.075 | 84.682 | 54.938 | 2.4038E+04 | 2.1319E+04 | 1.99 | 1.94 | 2.547E+02 | 2.467E+02 | 54.766 | 56.357 |
| 7 | 55.989 | 86.802 | 89.646 | 87.247 | 57.789 | 2.4347E+04 | 2.1613E+04 | 1.86 | 1.81 | 2.352E+02 | 2.279E+02 | 57.212 | 59.221 |
| 8 | 58.350 | 87.204 | 89.891 | 87.673 | 60.559 | 2.4500E+04 | 2.1765E+04 | 1.82 | 1.77 | 2.335E+02 | 2.271E+02 | 59.487 | 61.896 |
| 9 | 60.453 | 85.454 | 87.789 | 85.925 | 63.038 | 2.4483E+04 | 2.1764E+04 | 1.86 | 1.81 | 2.525E+02 | 2.486E+02 | 61.418 | 64.180 |
| 10 | 62.170 | 82.344 | 84.228 | 82.801 | 65.076 | 2.4344E+04 | 2.1650E+04 | 1.96 | 1.90 | 2.963E+02 | 2.998E+02 | 62.922 | 65.971 |
| 11 | 63.253 | 81.557 | 82.974 | 81.466 | 66.365 | 2.4322E+04 | 2.1608E+04 | 1.97 | 1.93 | 3.133E+02 | 3.346E+02 | 63.585 | 66.759 |
| | 63.585 | | | | 66.759 | | | | | | | | |
| FUEL PLATE 3 (BroydenSoln) | | | | | | | | | | | | | |
| | 45.000 | | | | 45.000 | | | | | | | | |
| 1 | 45.276 | 59.884 | 60.916 | 59.806 | 45.296 | 1.9034E+04 | 1.9690E+04 | 5.03 | 5.06 | 7.087E+02 | 7.195E+02 | 45.552 | 45.592 |
| 2 | 46.205 | 63.259 | 64.486 | 63.174 | 46.294 | 1.9362E+04 | 2.0034E+04 | 4.13 | 4.15 | 5.834E+02 | 5.935E+02 | 46.859 | 46.996 |
| 3 | 47.764 | 70.647 | 72.348 | 70.534 | 47.968 | 2.0016E+04 | 2.0716E+04 | 2.99 | 3.01 | 4.053E+02 | 4.129E+02 | 48.668 | 48.940 |
| 4 | 49.788 | 77.379 | 79.493 | 77.256 | 50.145 | 2.0587E+04 | 2.1316E+04 | 2.39 | 2.40 | 3.118E+02 | 3.178E+02 | 50.907 | 51.349 |
| 5 | 52.213 | 83.661 | 86.131 | 83.523 | 52.755 | 2.1114E+04 | 2.1871E+04 | 2.02 | 2.02 | 2.519E+02 | 2.567E+02 | 53.518 | 54.161 |
| 6 | 54.938 | 88.538 | 91.232 | 88.402 | 55.691 | 2.1549E+04 | 2.2332E+04 | 1.79 | 1.80 | 2.160E+02 | 2.199E+02 | 56.357 | 57.221 |
| 7 | 57.789 | 91.352 | 94.084 | 91.236 | 58.768 | 2.1857E+04 | 2.2662E+04 | 1.67 | 1.68 | 1.978E+02 | 2.013E+02 | 59.221 | 60.315 |
| 8 | 60.559 | 91.848 | 94.417 | 91.768 | 61.763 | 2.2015E+04 | 2.2836E+04 | 1.63 | 1.64 | 1.946E+02 | 1.981E+02 | 61.896 | 63.210 |
| 9 | 63.038 | 90.006 | 92.207 | 89.944 | 64.451 | 2.2010E+04 | 2.2840E+04 | 1.67 | 1.67 | 2.086E+02 | 2.137E+02 | 64.180 | 65.691 |
| 10 | 65.076 | 86.636 | 88.404 | 86.656 | 66.671 | 2.1888E+04 | 2.2733E+04 | 1.75 | 1.75 | 2.438E+02 | 2.523E+02 | 65.971 | 67.650 |
| 11 | 66.365 | 85.772 | 87.112 | 85.352 | 68.081 | 2.1878E+04 | 2.2688E+04 | 1.76 | 1.77 | 2.572E+02 | 2.760E+02 | 66.759 | 68.512 |
| | 66.759 | | | | 68.512 | | | | | | | | |

## Fig. 29. Continued

FUEL PLATE 4 (BroydenSoln)

| NODE | COOLANT inner(C) | CladSurf inner(C) | FUEL PEAK (C) | CladSurf outer(C) | COOLANT outer(C) | HCOFinner W/C-m^2 | HCOFouter W/C-m^2 | ONBRin [F Note 1] | ONBRout | ETAin K-cm^3/J | ETAout K-cm^3/J | COOLNT at inner(C) | NodeOutlet outer(C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 45.000 | | | | 45.000 | | | | | | | | |
| 1 | 45.296 | 60.786 | 61.938 | 60.795 | 45.327 | 1.9769E+04 | 1.9171E+04 | 4.77 | 4.76 | 6.713E+02 | 6.666E+02 | 45.592 | 45.654 |
| 2 | 46.294 | 64.372 | 65.743 | 64.392 | 46.429 | 2.0128E+04 | 1.9527E+04 | 3.92 | 3.90 | 5.516E+02 | 5.493E+02 | 46.996 | 47.205 |
| 3 | 47.968 | 72.200 | 74.104 | 72.239 | 48.279 | 2.0836E+04 | 2.0226E+04 | 2.84 | 2.83 | 3.823E+02 | 3.811E+02 | 48.940 | 49.353 |
| 4 | 50.145 | 79.352 | 81.712 | 79.406 | 50.683 | 2.1455E+04 | 2.0840E+04 | 2.27 | 2.26 | 2.930E+02 | 2.922E+02 | 51.349 | 52.012 |
| 5 | 52.755 | 86.019 | 88.785 | 86.108 | 53.564 | 2.2027E+04 | 2.1411E+04 | 1.92 | 1.90 | 2.357E+02 | 2.347E+02 | 54.161 | 55.115 |
| 6 | 55.691 | 91.214 | 94.234 | 91.333 | 56.803 | 2.2504E+04 | 2.1890E+04 | 1.70 | 1.69 | 2.010E+02 | 1.997E+02 | 57.221 | 58.491 |
| 7 | 58.768 | 94.246 | 97.312 | 94.396 | 60.195 | 2.2847E+04 | 2.2238E+04 | 1.59 | 1.58 | 1.827E+02 | 1.812E+02 | 60.315 | 61.900 |
| 8 | 61.763 | 94.851 | 97.738 | 95.031 | 63.493 | 2.3028E+04 | 2.2425E+04 | 1.55 | 1.53 | 1.782E+02 | 1.767E+02 | 63.210 | 65.085 |
| 9 | 64.451 | 92.982 | 95.480 | 93.191 | 66.448 | 2.3029E+04 | 2.2445E+04 | 1.58 | 1.56 | 1.894E+02 | 1.886E+02 | 65.691 | 67.810 |
| 10 | 66.671 | 89.541 | 91.539 | 89.766 | 68.880 | 2.2914E+04 | 2.2330E+04 | 1.65 | 1.63 | 2.188E+02 | 2.211E+02 | 67.650 | 69.950 |
| 11 | 68.081 | 88.529 | 90.215 | 88.576 | 70.421 | 2.2889E+04 | 2.2297E+04 | 1.67 | 1.64 | 2.310E+02 | 2.382E+02 | 68.512 | 70.891 |
| | 68.512 | | | | 70.891 | | | | | | | | |

FUEL PLATE 5 (BroydenSoln)

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 45.000 | | | | 45.000 | | | | | | | | |
| 1 | 45.327 | 62.543 | 63.807 | 62.619 | 45.368 | 1.9306E+04 | 1.7966E+04 | 4.32 | 4.28 | 5.947E+02 | 5.822E+02 | 45.654 | 45.736 |
| 2 | 46.429 | 66.480 | 67.984 | 66.582 | 46.602 | 1.9700E+04 | 1.8342E+04 | 3.55 | 3.52 | 4.878E+02 | 4.788E+02 | 47.205 | 47.467 |
| 3 | 48.279 | 75.117 | 77.204 | 75.266 | 48.657 | 2.0422E+04 | 1.9028E+04 | 2.58 | 2.55 | 3.370E+02 | 3.310E+02 | 49.353 | 49.847 |
| 4 | 50.683 | 82.966 | 85.558 | 83.167 | 51.309 | 2.1061E+04 | 1.9637E+04 | 2.07 | 2.04 | 2.573E+02 | 2.524E+02 | 52.012 | 52.771 |
| 5 | 53.564 | 90.264 | 93.294 | 90.510 | 54.464 | 2.1657E+04 | 2.0206E+04 | 1.75 | 1.73 | 2.058E+02 | 2.014E+02 | 55.115 | 56.156 |
| 6 | 56.803 | 95.906 | 99.212 | 96.192 | 57.981 | 2.2162E+04 | 2.0689E+04 | 1.56 | 1.54 | 1.742E+02 | 1.700E+02 | 58.491 | 59.805 |
| 7 | 60.195 | 99.167 | 102.518 | 99.479 | 61.626 | 2.2523E+04 | 2.1035E+04 | 1.46 | 1.43 | 1.570E+02 | 1.528E+02 | 61.900 | 63.447 |
| 8 | 63.493 | 99.756 | 102.903 | 100.075 | 65.120 | 2.2709E+04 | 2.1221E+04 | 1.42 | 1.40 | 1.518E+02 | 1.474E+02 | 65.085 | 66.794 |
| 9 | 66.448 | 97.641 | 100.340 | 97.925 | 68.189 | 2.2716E+04 | 2.1216E+04 | 1.45 | 1.42 | 1.598E+02 | 1.557E+02 | 67.810 | 69.584 |
| 10 | 68.880 | 93.761 | 95.916 | 94.042 | 70.639 | 2.2573E+04 | 2.1079E+04 | 1.52 | 1.49 | 1.836E+02 | 1.803E+02 | 69.950 | 71.693 |
| 11 | 70.421 | 92.543 | 94.363 | 92.633 | 72.144 | 2.2538E+04 | 2.1033E+04 | 1.53 | 1.51 | 1.934E+02 | 1.924E+02 | 70.891 | 72.594 |
| | 70.891 | | | | 72.594 | | | | | | | | |

FUEL PLATE 6 (BroydenSoln)

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 45.000 | | | | 45.000 | | | | | | | | |
| 1 | 45.368 | 64.032 | 65.294 | 63.927 | 45.160 | 1.8065E+04 | 1.8713E+04 | 3.98 | 4.02 | 5.352E+02 | 5.555E+02 | 45.736 | 45.319 |
| 2 | 46.602 | 67.997 | 69.468 | 67.822 | 45.702 | 1.8440E+04 | 1.9047E+04 | 3.32 | 3.36 | 4.447E+02 | 4.556E+02 | 47.467 | 46.084 |
| 3 | 48.657 | 76.878 | 78.884 | 76.572 | 46.620 | 1.9126E+04 | 1.9685E+04 | 2.43 | 2.48 | 3.105E+02 | 3.174E+02 | 49.847 | 47.156 |
| 4 | 51.309 | 84.773 | 87.218 | 84.315 | 47.826 | 1.9727E+04 | 2.0220E+04 | 1.97 | 2.01 | 2.392E+02 | 2.458E+02 | 52.771 | 48.496 |
| 5 | 54.464 | 91.953 | 94.758 | 91.323 | 49.287 | 2.0285E+04 | 2.0700E+04 | 1.68 | 1.72 | 1.929E+02 | 2.008E+02 | 56.156 | 50.077 |
| 6 | 57.981 | 97.244 | 100.237 | 96.435 | 50.948 | 2.0747E+04 | 2.1080E+04 | 1.51 | 1.56 | 1.649E+02 | 1.746E+02 | 59.805 | 51.819 |
| 7 | 61.626 | 99.901 | 102.844 | 98.918 | 52.714 | 2.1058E+04 | 2.1313E+04 | 1.42 | 1.48 | 1.509E+02 | 1.621E+02 | 63.447 | 53.608 |
| 8 | 65.120 | 99.646 | 102.297 | 98.514 | 54.464 | 2.1197E+04 | 2.1377E+04 | 1.41 | 1.47 | 1.494E+02 | 1.614E+02 | 66.794 | 55.319 |
| 9 | 68.189 | 96.483 | 98.623 | 95.239 | 56.075 | 2.1135E+04 | 2.1266E+04 | 1.46 | 1.54 | 1.642E+02 | 1.738E+02 | 69.584 | 56.832 |
| 10 | 70.639 | 91.506 | 93.039 | 90.192 | 57.458 | 2.0935E+04 | 2.1037E+04 | 1.56 | 1.67 | 2.036E+02 | 2.006E+02 | 71.693 | 58.083 |
| 11 | 72.144 | 89.615 | 90.876 | 88.257 | 58.368 | 2.0862E+04 | 2.0953E+04 | 1.59 | 1.72 | 2.275E+02 | 2.133E+02 | 72.594 | 58.652 |
| | 72.594 | | | | 58.652 | | | | | | | | |

**Fig. 29. Continued**

```
FUEL PLATE   1 (BroydenSoln) AREAL                     FUEL-CLADinterface
NODE FLUX inner FLUX outer  FUEL X   Tsat     Tdiff     inner     outer    Pressure  Z-mid     Z-int
       MW/m^2     MW/m^2     inner   (C)       (C)       (C)       (C)      (bar)
   1 2.5168E-01 2.5302E-01  0.4801 105.939     0.00     57.823    57.788   1.24781   0.0250    0.0500
   2 3.0183E-01 2.9675E-01  0.4856 105.504     0.00     60.591    60.564   1.22923   0.1000    0.1500
   3 4.2227E-01 4.0683E-01  0.4907 104.915     0.00     66.803    66.785   1.20447   0.2000    0.2500
   4 5.2829E-01 4.9863E-01  0.4958 104.317     0.00     72.343    72.345   1.17970   0.3000    0.3500
   5 6.2285E-01 5.7568E-01  0.5011 103.708     0.00     77.434    77.463   1.15493   0.4000    0.4500
   6 6.8599E-01 6.1850E-01  0.5073 103.088     0.00     81.224    81.291   1.13017   0.5000    0.5500
   7 7.0395E-01 6.1452E-01  0.5153 102.457     0.00     83.136    83.252   1.10540   0.6000    0.6500
   8 6.7249E-01 5.6130E-01  0.5265 101.814     0.00     82.961    83.131   1.08063   0.7000    0.7500
   9 5.9422E-01 4.6278E-01  0.5438 101.158     0.03     80.719    80.915   1.05586   0.8000    0.8500
  10 4.9019E-01 3.4380E-01  0.5696 100.490     0.00     77.192    77.465   1.03110   0.9000    0.9500
  11 4.4564E-01 2.9005E-01  0.5878  99.980     0.01     75.893    76.185   1.01252   0.9750    1.0000

FUEL PLATE   2 (BroydenSoln) AREAL                     FUEL-CLADinterface
NODE FLUX inner FLUX outer  FUEL X   Tsat     Tdiff     inner     outer    Pressure  Z-mid     Z-int
       MW/m^2     MW/m^2     inner   (C)       (C)       (C)       (C)      (bar)
   1 2.8170E-01 2.5021E-01  0.5139 105.939     0.00     59.123    59.165   1.24781   0.0250    0.0500
   2 3.3502E-01 2.9562E-01  0.5155 105.504     0.00     62.313    62.366   1.22923   0.1000    0.1500
   3 4.6517E-01 4.0810E-01  0.5170 104.915     0.00     69.333    69.415   1.20447   0.2000    0.2500
   4 5.7774E-01 5.0358E-01  0.5186 104.317     0.00     75.719    75.825   1.17970   0.3000    0.3500
   5 6.7620E-01 5.8547E-01  0.5203 103.708     0.00     81.651    81.788   1.15493   0.4000    0.4500
   6 7.3864E-01 6.3412E-01  0.5224 103.088     0.00     86.214    86.377   1.13017   0.5000    0.5500
   7 7.5021E-01 6.3668E-01  0.5253 102.457     0.00     88.767    88.949   1.10540   0.6000    0.6500
   8 7.0692E-01 5.9014E-01  0.5294 101.814     0.00     89.056    89.250   1.08063   0.7000    0.7500
   9 6.1213E-01 4.9811E-01  0.5357 101.158     0.00     87.058    87.256   1.05586   0.8000    0.8500
  10 4.9111E-01 3.8375E-01  0.5458 100.490     0.00     83.630    83.826   1.03110   0.9000    0.9500
  11 4.4517E-01 3.2631E-01  0.5616  99.980     0.61     82.723    82.338   1.01252   0.9750    1.0000

FUEL PLATE   3 (BroydenSoln) AREAL                     FUEL-CLADinterface
NODE FLUX inner FLUX outer  FUEL X   Tsat     Tdiff     inner     outer    Pressure  Z-mid     Z-int
       MW/m^2     MW/m^2     inner   (C)       (C)       (C)       (C)      (bar)
   1 2.7805E-01 2.8572E-01  0.4796 105.939     0.00     60.613    60.569   1.24781   0.0250    0.0500
   2 3.3020E-01 3.3818E-01  0.4804 105.504     0.00     64.126    64.077   1.22923   0.1000    0.1500
   3 4.5802E-01 4.6747E-01  0.4813 104.915     0.00     71.848    71.782   1.20447   0.2000    0.2500
   4 5.6802E-01 5.7789E-01  0.4821 104.317    -0.01     78.869    78.798   1.17970   0.3000    0.3500
   5 6.6402E-01 6.7293E-01  0.4831 103.708     0.00     85.404    85.319   1.15493   0.4000    0.4500
   6 7.2406E-01 7.3051E-01  0.4842 103.088     0.00     90.437    90.352   1.13017   0.5000    0.5500
   7 7.3358E-01 7.3581E-01  0.4856 102.457     0.00     93.276    93.201   1.10540   0.6000    0.6500
   8 6.8883E-01 6.8520E-01  0.4877 101.814     0.00     93.655    93.597   1.08063   0.7000    0.7500
   9 5.9358E-01 5.8228E-01  0.4912 101.158     0.03     91.563    91.499   1.05586   0.8000    0.8500
  10 4.7189E-01 4.5433E-01  0.4959 100.490     0.00     87.874    87.869   1.03110   0.9000    0.9500
  11 4.2459E-01 3.9184E-01  0.5064  99.980     0.52     86.886    86.398   1.01252   0.9750    1.0000
```

**Fig. 29. Continued**

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FUEL PLATE   4 (BroydenSoln) AREAL                     FUEL-CLADinterface
NODE FLUX inner FLUX outer  FUEL X   Tsat     Tdiff     inner     outer    Pressure  Z-mid     Z-int
       MW/m^2     MW/m^2     inner   (C)       (C)       (C)       (C)      (bar)
   1 3.0622E-01 2.9655E-01  0.4960 105.939     0.00     61.590    61.586   1.24781   0.0250    0.0500
   2 3.6387E-01 3.5076E-01  0.4972 105.504     0.00     65.328    65.327   1.22923   0.1000    0.1500
   3 5.0491E-01 4.8462E-01  0.4982 104.915     0.00     73.526    73.532   1.20447   0.2000    0.2500
   4 6.2663E-01 5.9859E-01  0.4994 104.317     0.01     80.998    81.003   1.17970   0.3000    0.3500
   5 7.3270E-01 6.9679E-01  0.5006 103.708     0.00     87.943    87.967   1.15493   0.4000    0.4500
   6 7.9942E-01 7.5585E-01  0.5020 103.088     0.00     93.313    93.349   1.13017   0.5000    0.5500
   7 8.1059E-01 7.6054E-01  0.5039 102.457     0.00     96.375    96.424   1.10540   0.6000    0.6500
   8 7.6195E-01 7.0724E-01  0.5066 101.814     0.00     96.852    96.917   1.08063   0.7000    0.7500
   9 6.5705E-01 6.0025E-01  0.5106 101.158    -0.01     94.708    94.792   1.05586   0.8000    0.8500
  10 5.2406E-01 4.6637E-01  0.5171 100.490     0.00     90.918    91.010   1.03110   0.9000    0.9500
  11 4.6803E-01 4.0480E-01  0.5243  99.980     0.21     89.758    89.656   1.01252   0.9750    1.0000

FUEL PLATE   5 (BroydenSoln) AREAL                     FUEL-CLADinterface
NODE FLUX inner FLUX outer  FUEL X   Tsat     Tdiff     inner     outer    Pressure  Z-mid     Z-int
       MW/m^2     MW/m^2     inner   (C)       (C)       (C)       (C)      (bar)
   1 3.3237E-01 3.0992E-01  0.5067 105.939     0.00     63.417    63.445   1.24781   0.0250    0.0500
   2 3.9500E-01 3.6648E-01  0.5080 105.504     0.00     67.519    67.558   1.22923   0.1000    0.1500
   3 5.4810E-01 5.0631E-01  0.5091 104.915     0.00     76.558    76.615   1.20447   0.2000    0.2500
   4 6.7993E-01 6.2559E-01  0.5101 104.317     0.00     84.753    84.834   1.17970   0.3000    0.3500
   5 7.9483E-01 7.2834E-01  0.5111 103.708     0.00     92.354    92.451   1.15493   0.4000    0.4500
   6 8.6661E-01 7.9054E-01  0.5122 103.088     0.00     98.184    98.299   1.13017   0.5000    0.5500
   7 8.7777E-01 7.9623E-01  0.5136 102.457     0.00    101.474   101.601   1.10540   0.6000    0.6500
   8 8.2353E-01 7.4177E-01  0.5154 101.814     0.00    101.921   102.052   1.08063   0.7000    0.7500
   9 7.0859E-01 6.3088E-01  0.5183 101.158     0.03     99.504    99.606   1.05586   0.8000    0.8500
  10 5.6164E-01 4.9333E-01  0.5217 100.490     0.00     95.238    95.357   1.03110   0.9000    0.9500
  11 4.9859E-01 4.3096E-01  0.5257  99.980     0.19     93.853    93.782   1.01252   0.9750    1.0000

FUEL PLATE   6 (BroydenSoln) AREAL                     FUEL-CLADinterface
NODE FLUX inner FLUX outer  FUEL X   Tsat     Tdiff     inner     outer    Pressure  Z-mid     Z-int
       MW/m^2     MW/m^2     inner   (C)       (C)       (C)       (C)      (bar)
   1 3.3716E-01 3.5119E-01  0.4802 105.939     0.00     64.918    64.862   1.24781   0.0250    0.0500
   2 3.9452E-01 4.2132E-01  0.4739 105.504     0.00     69.035    68.944   1.22923   0.1000    0.1500
   3 5.3977E-01 5.8961E-01  0.4683 104.915     0.00     78.298    78.143   1.20447   0.2000    0.2500
   4 6.6017E-01 7.3781E-01  0.4626 104.317     0.00     86.510    86.280   1.17970   0.3000    0.3500
   5 7.6046E-01 8.7014E-01  0.4568 103.708     0.00     93.953    93.640   1.15493   0.4000    0.4500
   6 8.1461E-01 9.5886E-01  0.4498 103.088     0.00     99.387    98.988   1.13017   0.5000    0.5500
   7 8.0600E-01 9.8476E-01  0.4406 102.457     0.00    102.021   101.541   1.10540   0.6000    0.6500
   8 7.3184E-01 9.4168E-01  0.4278 101.814     0.00    101.571   101.022   1.08063   0.7000    0.7500
   9 5.9799E-01 8.3284E-01  0.4086 101.158     0.00     98.056    97.457   1.05586   0.8000    0.8500
  10 4.3685E-01 6.8864E-01  0.3790 100.490     0.00     92.655    92.026   1.03110   0.9000    0.9500
  11 3.6448E-01 6.2626E-01  0.3590  99.980     0.00     90.574    89.925   1.01252   0.9750    1.0000
```

**Fig. 30. Solution of ASTRA2 Problem 3 Case 1 by the Broyden Method in PLTEMP/ANL Version 3.2**
(Using Coolant $C_p$ = 4180 J/kg-°C, and $\rho$ = 1000 kg/m$^3$, Same as ASTRA2 Code Input)

| NODE | COOLANT | CladSurf | FUEL PEAK | CladSurf | COOLANT | HCOFinner | HCOFouter | ONBRin | ONBRout | ETAin | ETAout | COOLNT at | NodeOutlet |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | inner(C) | inner(C) | (C) | outer(C) | outer(C) | W/C-m^2 | W/C-m^2 | [F Note 1] | | K-cm^3/J | K-cm^3/J | inner(C) | outer(C) |
| FUEL PLATE 1 (BroydenSoln) | | | | | | | | | | | | | |
| | 45.000 | | | | 45.000 | | | | | | | | |
| 1 | 45.123 | 57.170 | 58.092 | 57.116 | 45.239 | 2.0895E+04 | 2.1301E+04 | 6.11 | 6.14 | 8.958E+02 | 9.111E+02 | 45.247 | 45.478 |
| 2 | 45.542 | 59.817 | 60.926 | 59.785 | 46.043 | 2.1151E+04 | 2.1587E+04 | 5.05 | 5.06 | 7.363E+02 | 7.611E+02 | 45.838 | 46.608 |
| 3 | 46.252 | 65.726 | 67.283 | 65.724 | 47.387 | 2.1693E+04 | 2.2179E+04 | 3.67 | 3.66 | 5.149E+02 | 5.372E+02 | 46.666 | 48.167 |
| 4 | 47.184 | 71.002 | 72.956 | 71.051 | 49.130 | 2.2189E+04 | 2.2738E+04 | 2.96 | 2.94 | 4.008E+02 | 4.205E+02 | 47.701 | 50.093 |
| 5 | 48.312 | 75.857 | 78.168 | 75.975 | 51.214 | 2.2621E+04 | 2.3240E+04 | 2.51 | 2.49 | 3.296E+02 | 3.464E+02 | 48.922 | 52.334 |
| 6 | 49.595 | 79.488 | 82.043 | 79.696 | 53.550 | 2.2956E+04 | 2.3647E+04 | 2.25 | 2.22 | 2.890E+02 | 3.043E+02 | 50.267 | 54.765 |
| 7 | 50.957 | 81.353 | 83.987 | 81.666 | 55.988 | 2.3165E+04 | 2.3925E+04 | 2.13 | 2.08 | 2.712E+02 | 2.872E+02 | 51.647 | 57.211 |
| 8 | 52.306 | 81.252 | 83.784 | 81.678 | 58.349 | 2.3236E+04 | 2.4055E+04 | 2.11 | 2.05 | 2.729E+02 | 2.941E+02 | 52.965 | 59.486 |
| 9 | 53.547 | 79.188 | 81.445 | 79.725 | 60.452 | 2.3162E+04 | 2.4027E+04 | 2.19 | 2.11 | 2.972E+02 | 3.338E+02 | 54.128 | 61.418 |
| 10 | 54.609 | 75.933 | 77.823 | 76.567 | 62.170 | 2.2985E+04 | 2.3881E+04 | 2.37 | 2.25 | 3.471E+02 | 4.232E+02 | 55.089 | 62.921 |
| 11 | 55.307 | 74.732 | 76.467 | 75.419 | 63.250 | 2.2934E+04 | 2.3847E+04 | 2.43 | 2.29 | 3.718E+02 | 4.806E+02 | 55.525 | 63.578 |
| | 55.525 | | | | 63.578 | | | | | | | | |
| FUEL PLATE 2 (BroydenSoln) | | | | | | | | | | | | | |
| | 45.000 | | | | 45.000 | | | | | | | | |
| 1 | 45.239 | 58.394 | 59.455 | 58.505 | 45.276 | 2.1416E+04 | 1.8912E+04 | 5.59 | 5.51 | 8.182E+02 | 7.877E+02 | 45.478 | 45.552 |
| 2 | 46.043 | 61.458 | 62.721 | 61.601 | 46.205 | 2.1734E+04 | 1.9201E+04 | 4.58 | 4.50 | 6.740E+02 | 6.516E+02 | 46.608 | 46.859 |
| 3 | 47.387 | 68.156 | 69.912 | 68.367 | 47.764 | 2.2401E+04 | 1.9805E+04 | 3.31 | 3.25 | 4.696E+02 | 4.550E+02 | 48.167 | 48.668 |
| 4 | 49.130 | 74.265 | 76.447 | 74.542 | 49.788 | 2.2988E+04 | 2.0342E+04 | 2.65 | 2.60 | 3.627E+02 | 3.518E+02 | 50.093 | 50.907 |
| 5 | 51.214 | 79.956 | 82.513 | 80.301 | 52.213 | 2.3530E+04 | 2.0840E+04 | 2.23 | 2.18 | 2.948E+02 | 2.858E+02 | 52.334 | 53.518 |
| 6 | 53.550 | 84.365 | 87.162 | 84.769 | 54.938 | 2.3974E+04 | 2.1253E+04 | 1.98 | 1.94 | 2.546E+02 | 2.467E+02 | 54.765 | 56.357 |
| 7 | 55.988 | 86.886 | 89.730 | 87.330 | 57.789 | 2.4284E+04 | 2.1548E+04 | 1.86 | 1.81 | 2.352E+02 | 2.279E+02 | 57.211 | 59.221 |
| 8 | 58.349 | 87.273 | 89.961 | 87.743 | 60.559 | 2.4442E+04 | 2.1707E+04 | 1.82 | 1.77 | 2.335E+02 | 2.271E+02 | 59.486 | 61.896 |
| 9 | 60.452 | 85.504 | 87.839 | 85.974 | 63.037 | 2.4436E+04 | 2.1715E+04 | 1.86 | 1.80 | 2.525E+02 | 2.486E+02 | 61.418 | 64.179 |
| 10 | 62.170 | 82.374 | 84.258 | 82.831 | 65.075 | 2.4307E+04 | 2.1613E+04 | 1.96 | 1.90 | 2.963E+02 | 2.998E+02 | 62.921 | 65.970 |
| 11 | 63.250 | 81.301 | 82.990 | 81.758 | 66.364 | 2.4286E+04 | 2.1610E+04 | 1.99 | 1.92 | 3.182E+02 | 3.283E+02 | 63.578 | 66.758 |
| | 63.578 | | | | 66.758 | | | | | | | | |
| FUEL PLATE 3 (BroydenSoln) | | | | | | | | | | | | | |
| | 45.000 | | | | 45.000 | | | | | | | | |
| 1 | 45.276 | 59.895 | 60.927 | 59.817 | 45.296 | 1.9021E+04 | 1.9675E+04 | 5.03 | 5.06 | 7.087E+02 | 7.195E+02 | 45.552 | 45.592 |
| 2 | 46.205 | 63.289 | 64.515 | 63.203 | 46.294 | 1.9330E+04 | 1.9998E+04 | 4.12 | 4.15 | 5.833E+02 | 5.936E+02 | 46.859 | 46.996 |
| 3 | 47.764 | 70.698 | 72.400 | 70.586 | 47.968 | 1.9972E+04 | 2.0667E+04 | 2.98 | 3.00 | 4.053E+02 | 4.130E+02 | 48.668 | 48.940 |
| 4 | 49.788 | 77.456 | 79.568 | 77.327 | 50.145 | 2.0533E+04 | 2.1256E+04 | 2.39 | 2.40 | 3.118E+02 | 3.178E+02 | 50.907 | 51.349 |
| 5 | 52.213 | 83.757 | 86.225 | 83.616 | 52.755 | 2.1053E+04 | 2.1803E+04 | 2.01 | 2.02 | 2.519E+02 | 2.567E+02 | 53.518 | 54.160 |
| 6 | 54.938 | 88.642 | 91.336 | 88.507 | 55.691 | 2.1484E+04 | 2.2260E+04 | 1.79 | 1.79 | 2.160E+02 | 2.199E+02 | 56.357 | 57.221 |
| 7 | 57.789 | 91.455 | 94.185 | 91.335 | 58.768 | 2.1793E+04 | 2.2591E+04 | 1.67 | 1.67 | 1.978E+02 | 2.013E+02 | 59.221 | 60.314 |
| 8 | 60.559 | 91.932 | 94.501 | 91.853 | 61.762 | 2.1956E+04 | 2.2771E+04 | 1.63 | 1.63 | 1.946E+02 | 1.981E+02 | 61.896 | 63.210 |
| 9 | 63.037 | 90.050 | 92.267 | 90.020 | 64.451 | 2.1961E+04 | 2.2787E+04 | 1.66 | 1.66 | 2.088E+02 | 2.136E+02 | 64.179 | 65.692 |
| 10 | 65.075 | 86.673 | 88.441 | 86.693 | 66.671 | 2.1850E+04 | 2.2691E+04 | 1.75 | 1.74 | 2.438E+02 | 2.523E+02 | 65.970 | 67.651 |
| 11 | 66.364 | 85.541 | 87.116 | 85.593 | 68.083 | 2.1846E+04 | 2.2684E+04 | 1.77 | 1.76 | 2.607E+02 | 2.722E+02 | 66.758 | 68.515 |
| | 66.758 | | | | 68.515 | | | | | | | | |

**Fig. 30. Continued**

```
FUEL PLATE   4 (BroydenSoln)
NODE    COOLANT  CladSurf FUEL PEAK  CladSurf  COOLANT  HCOFinner HCOFouter ONBRin ONBRout  ETAin     ETAout  COOLNT at NodeOutlet
        inner(C)  inner(C)    (C)     outer(C)  outer(C) W/C-m^2    W/C-m^2    [F Note 1]  K-cm^3/J  K-cm^3/J  inner(C)  outer(C)
         45.000                                  45.000
   1     45.296    60.798    61.951    60.809    45.327 1.9754E+04 1.9155E+04  4.77   4.75 6.713E+02 6.666E+02    45.592    45.654
   2     46.294    64.405    65.776    64.425    46.430 2.0092E+04 1.9489E+04  3.91   3.89 5.515E+02 5.493E+02    46.996    47.205
   3     47.968    72.259    74.163    72.299    48.279 2.0788E+04 2.0174E+04  2.83   2.82 3.823E+02 3.812E+02    48.940    49.353
   4     50.145    79.432    81.797    79.495    50.683 2.1395E+04 2.0776E+04  2.27   2.25 2.931E+02 2.922E+02    51.349    52.013
   5     52.755    86.125    88.892    86.217    53.564 2.1958E+04 2.1338E+04  1.91   1.90 2.357E+02 2.347E+02    54.160    55.116
   6     55.691    91.332    94.353    91.451    56.803 2.2432E+04 2.1813E+04  1.70   1.69 2.010E+02 1.997E+02    57.221    58.491
   7     58.768    94.358    97.426    94.510    60.196 2.2776E+04 2.2163E+04  1.59   1.57 1.827E+02 1.812E+02    60.314    61.900
   8     61.762    94.946    97.833    95.125    63.493 2.2963E+04 2.2357E+04  1.55   1.53 1.782E+02 1.767E+02    63.210    65.086
   9     64.451    93.053    95.548    93.256    66.447 2.2975E+04 2.2388E+04  1.58   1.56 1.894E+02 1.886E+02    65.692    67.809
  10     66.671    89.582    91.581    89.808    68.879 2.2872E+04 2.2286E+04  1.65   1.63 2.188E+02 2.210E+02    67.651    69.950
  11     68.083    88.450    90.230    88.686    70.420 2.2865E+04 2.2284E+04  1.67   1.64 2.322E+02 2.369E+02    68.515    70.891
         68.515                                  70.891

FUEL PLATE   5 (BroydenSoln)
         45.000                                  45.000
   1     45.327    62.558    63.822    62.634    45.368 1.9290E+04 1.7949E+04  4.31   4.28 5.947E+02 5.822E+02    45.654    45.736
   2     46.430    66.522    68.025    66.622    46.601 1.9662E+04 1.8303E+04  3.54   3.51 4.877E+02 4.789E+02    47.205    47.467
   3     48.279    75.189    77.276    75.338    48.656 2.0370E+04 1.8974E+04  2.57   2.55 3.370E+02 3.310E+02    49.353    49.845
   4     50.683    83.069    85.659    83.266    51.306 2.0998E+04 1.9571E+04  2.06   2.04 2.572E+02 2.525E+02    52.013    52.768
   5     53.564    90.391    93.420    90.635    54.460 2.1584E+04 2.0132E+04  1.74   1.72 2.057E+02 2.014E+02    55.116    56.152
   6     56.803    96.043    99.349    96.329    57.976 2.2085E+04 2.0612E+04  1.55   1.53 1.742E+02 1.700E+02    58.491    59.799
   7     60.196    99.300   102.648    99.605    61.620 2.2448E+04 2.0960E+04  1.45   1.43 1.570E+02 1.528E+02    61.900    63.440
   8     63.493    99.868   103.016   100.188    65.113 2.2641E+04 2.1147E+04  1.42   1.40 1.518E+02 1.474E+02    65.086    66.786
   9     66.447    97.702   100.413    98.010    68.182 2.2658E+04 2.1164E+04  1.45   1.42 1.599E+02 1.556E+02    67.809    69.577
  10     68.879    93.805    95.958    94.084    70.632 2.2529E+04 2.1040E+04  1.52   1.49 1.836E+02 1.803E+02    69.950    71.687
  11     70.420    92.471    94.378    92.736    72.139 2.2514E+04 2.1022E+04  1.53   1.51 1.942E+02 1.915E+02    70.891    72.591
         70.891                                  72.591

FUEL PLATE   6 (BroydenSoln)
         45.000                                  45.000
   1     45.368    64.044    65.306    63.939    45.160 1.8048E+04 1.8706E+04  3.98   4.01 5.353E+02 5.554E+02    45.736    45.319
   2     46.601    68.031    69.501    67.854    45.702 1.8399E+04 1.9030E+04  3.31   3.35 4.450E+02 4.554E+02    47.467    46.085
   3     48.656    76.939    78.943    76.629    46.621 1.9071E+04 1.9660E+04  2.43   2.47 3.107E+02 3.172E+02    49.845    47.157
   4     51.306    84.859    87.302    84.396    47.827 1.9661E+04 2.0189E+04  1.97   2.01 2.394E+02 2.456E+02    52.768    48.498
   5     54.460    92.061    94.863    91.423    49.289 2.0210E+04 2.0664E+04  1.68   1.72 1.931E+02 2.006E+02    56.152    50.080
   6     57.976    97.362   100.352    96.547    50.951 2.0669E+04 2.1041E+04  1.51   1.55 1.651E+02 1.744E+02    59.799    51.823
   7     61.620   100.013   102.955    99.027    52.718 2.0983E+04 2.1273E+04  1.42   1.48 1.510E+02 1.621E+02    63.440    53.613
   8     65.113    99.746   102.396    98.611    54.468 2.1122E+04 2.1340E+04  1.41   1.47 1.495E+02 1.613E+02    66.786    55.324
   9     68.182    96.549    98.689    95.305    56.081 2.1081E+04 2.1232E+04  1.46   1.54 1.643E+02 1.737E+02    69.577    56.837
  10     70.632    91.545    93.079    90.233    57.463 2.0896E+04 2.1010E+04  1.56   1.67 2.035E+02 2.006E+02    71.687    58.088
  11     72.139    89.629    90.892    88.274    58.372 2.0845E+04 2.0940E+04  1.59   1.72 2.275E+02 2.133E+02    72.591    58.657
         72.591                                  58.657
```

**Fig. 30. Continued**

FUEL PLATE 1 (BroydenSoln) AREAL

| NODE | FLUX inner MW/m^2 | FLUX outer MW/m^2 | FUEL X inner | Tsat (C) | Tdiff (C) | FUEL-CLADinterface inner (C) | outer (C) | Pressure (bar) | Z-mid | Z-int |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.5172E-01 | 2.5299E-01 | 0.4801 | 105.939 | 0.00 | 57.828 | 57.793 | 1.24781 | 0.0250 | 0.0500 |
| 2 | 3.0192E-01 | 2.9666E-01 | 0.4858 | 105.504 | 0.00 | 60.606 | 60.580 | 1.22923 | 0.1000 | 0.1500 |
| 3 | 4.2243E-01 | 4.0668E-01 | 0.4909 | 104.915 | 0.00 | 66.830 | 66.813 | 1.20447 | 0.2000 | 0.2500 |
| 4 | 5.2850E-01 | 4.9843E-01 | 0.4960 | 104.317 | 0.00 | 72.384 | 72.386 | 1.17970 | 0.3000 | 0.3500 |
| 5 | 6.2310E-01 | 5.7544E-01 | 0.5013 | 103.708 | 0.00 | 77.486 | 77.516 | 1.15493 | 0.4000 | 0.4500 |
| 6 | 6.8625E-01 | 6.1827E-01 | 0.5075 | 103.088 | 0.00 | 81.283 | 81.351 | 1.13017 | 0.5000 | 0.5500 |
| 7 | 7.0414E-01 | 6.1435E-01 | 0.5155 | 102.457 | 0.00 | 83.194 | 83.312 | 1.10540 | 0.6000 | 0.6500 |
| 8 | 6.7260E-01 | 5.6119E-01 | 0.5266 | 101.814 | 0.00 | 83.011 | 83.181 | 1.08063 | 0.7000 | 0.7500 |
| 9 | 5.9391E-01 | 4.6307E-01 | 0.5435 | 101.158 | 0.00 | 80.741 | 80.965 | 1.05586 | 0.8000 | 0.8500 |
| 10 | 4.9015E-01 | 3.4383E-01 | 0.5696 | 100.490 | 0.00 | 77.215 | 77.488 | 1.03110 | 0.9000 | 0.9500 |
| 11 | 4.4548E-01 | 2.9020E-01 | 0.5876 | 99.980 | 0.00 | 75.897 | 76.196 | 1.01252 | 0.9750 | 1.0000 |

FUEL PLATE 2 (BroydenSoln) AREAL

| NODE | FLUX inner MW/m^2 | FLUX outer MW/m^2 | FUEL X inner | Tsat (C) | Tdiff (C) | FUEL-CLADinterface inner (C) | outer (C) | Pressure (bar) | Z-mid | Z-int |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.8173E-01 | 2.5018E-01 | 0.5139 | 105.939 | 0.00 | 59.132 | 59.174 | 1.24781 | 0.0250 | 0.0500 |
| 2 | 3.3503E-01 | 2.9561E-01 | 0.5156 | 105.504 | 0.00 | 62.336 | 62.391 | 1.22923 | 0.1000 | 0.1500 |
| 3 | 4.6523E-01 | 4.0805E-01 | 0.5170 | 104.915 | 0.00 | 69.375 | 69.457 | 1.20447 | 0.2000 | 0.2500 |
| 4 | 5.7779E-01 | 5.0354E-01 | 0.5186 | 104.317 | 0.00 | 75.778 | 75.888 | 1.17970 | 0.3000 | 0.3500 |
| 5 | 6.7630E-01 | 5.8537E-01 | 0.5203 | 103.708 | 0.00 | 81.728 | 81.866 | 1.15493 | 0.4000 | 0.4500 |
| 6 | 7.3876E-01 | 6.3401E-01 | 0.5225 | 103.088 | 0.00 | 86.301 | 86.464 | 1.13017 | 0.5000 | 0.5500 |
| 7 | 7.5033E-01 | 6.3656E-01 | 0.5253 | 102.457 | 0.00 | 88.851 | 89.032 | 1.10540 | 0.6000 | 0.6500 |
| 8 | 7.0698E-01 | 5.9009E-01 | 0.5294 | 101.814 | 0.00 | 89.125 | 89.321 | 1.08063 | 0.7000 | 0.7500 |
| 9 | 6.1216E-01 | 4.9808E-01 | 0.5358 | 101.158 | 0.00 | 87.108 | 87.306 | 1.05586 | 0.8000 | 0.8500 |
| 10 | 4.9111E-01 | 3.8375E-01 | 0.5458 | 100.490 | 0.00 | 83.660 | 83.856 | 1.03110 | 0.9000 | 0.9500 |
| 11 | 4.3840E-01 | 3.3266E-01 | 0.5531 | 99.980 | 0.00 | 82.450 | 82.647 | 1.01252 | 0.9750 | 1.0000 |

FUEL PLATE 3 (BroydenSoln) AREAL

| NODE | FLUX inner MW/m^2 | FLUX outer MW/m^2 | FUEL X inner | Tsat (C) | Tdiff (C) | FUEL-CLADinterface inner (C) | outer (C) | Pressure (bar) | Z-mid | Z-int |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.7807E-01 | 2.8570E-01 | 0.4796 | 105.939 | 0.00 | 60.625 | 60.579 | 1.24781 | 0.0250 | 0.0500 |
| 2 | 3.3023E-01 | 3.3815E-01 | 0.4805 | 105.504 | 0.00 | 64.155 | 64.106 | 1.22923 | 0.1000 | 0.1500 |
| 3 | 4.5805E-01 | 4.6744E-01 | 0.4813 | 104.915 | 0.00 | 71.900 | 71.834 | 1.20447 | 0.2000 | 0.2500 |
| 4 | 5.6813E-01 | 5.7778E-01 | 0.4822 | 104.317 | 0.00 | 78.947 | 78.869 | 1.17970 | 0.3000 | 0.3500 |
| 5 | 6.6409E-01 | 6.7286E-01 | 0.4831 | 103.708 | 0.00 | 85.499 | 85.413 | 1.15493 | 0.4000 | 0.4500 |
| 6 | 7.2410E-01 | 7.3048E-01 | 0.4842 | 103.088 | 0.00 | 90.541 | 90.457 | 1.13017 | 0.5000 | 0.5500 |
| 7 | 7.3368E-01 | 7.3572E-01 | 0.4857 | 102.457 | 0.01 | 93.380 | 93.299 | 1.10540 | 0.6000 | 0.6500 |
| 8 | 6.8883E-01 | 6.8520E-01 | 0.4877 | 101.814 | 0.00 | 93.739 | 93.682 | 1.08063 | 0.7000 | 0.7500 |
| 9 | 5.9321E-01 | 5.8263E-01 | 0.4909 | 101.158 | 0.00 | 91.606 | 91.575 | 1.05586 | 0.8000 | 0.8500 |
| 10 | 4.7192E-01 | 4.5431E-01 | 0.4959 | 100.490 | 0.00 | 87.911 | 87.906 | 1.03110 | 0.9000 | 0.9500 |
| 11 | 4.1894E-01 | 3.9719E-01 | 0.4997 | 99.980 | 0.00 | 86.640 | 86.653 | 1.01252 | 0.9750 | 1.0000 |

**Fig. 30. Continued**

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FUEL PLATE   4 (BroydenSoln) AREAL                     FUEL-CLADinterface
NODE FLUX inner FLUX outer  FUEL X   Tsat     Tdiff     inner     outer    Pressure  Z-mid     Z-int
       MW/m^2     MW/m^2     inner   (C)       (C)       (C)       (C)      (bar)
   1 3.0622E-01 2.9656E-01  0.4960 105.939     0.00     61.602    61.600   1.24781   0.0250    0.0500
   2 3.6390E-01 3.5073E-01  0.4972 105.504     0.00     65.361    65.361   1.22923   0.1000    0.1500
   3 5.0496E-01 4.8457E-01  0.4983 104.915     0.00     73.586    73.591   1.20447   0.2000    0.2500
   4 6.2661E-01 5.9861E-01  0.4994 104.317     0.00     81.078    81.092   1.17970   0.3000    0.3500
   5 7.3276E-01 6.9673E-01  0.5006 103.708     0.00     88.049    88.075   1.15493   0.4000    0.4500
   6 7.9950E-01 7.5577E-01  0.5021 103.088     0.00     93.432    93.467   1.13017   0.5000    0.5500
   7 8.1063E-01 7.6050E-01  0.5039 102.457     0.00     96.487    96.539   1.10540   0.6000    0.6500
   8 7.6199E-01 7.0720E-01  0.5066 101.814     0.00     96.947    97.012   1.08063   0.7000    0.7500
   9 6.5712E-01 6.0019E-01  0.5106 101.158     0.00     94.778    94.856   1.05586   0.8000    0.8500
  10 5.2401E-01 4.6642E-01  0.5171 100.490     0.00     90.958    91.052   1.03110   0.9000    0.9500
  11 4.6569E-01 4.0703E-01  0.5216  99.980     0.00     89.673    89.771   1.01252   0.9750    1.0000

FUEL PLATE   5 (BroydenSoln) AREAL                     FUEL-CLADinterface
NODE FLUX inner FLUX outer  FUEL X   Tsat     Tdiff     inner     outer    Pressure  Z-mid     Z-int
       MW/m^2     MW/m^2     inner   (C)       (C)       (C)       (C)      (bar)
   1 3.3239E-01 3.0990E-01  0.5068 105.939     0.00     63.432    63.460   1.24781   0.0250    0.0500
   2 3.9506E-01 3.6643E-01  0.5081 105.504     0.00     67.560    67.598   1.22923   0.1000    0.1500
   3 5.4815E-01 5.0626E-01  0.5091 104.915     0.00     76.630    76.687   1.20447   0.2000    0.2500
   4 6.8003E-01 6.2550E-01  0.5102 104.317     0.00     84.856    84.933   1.17970   0.3000    0.3500
   5 7.9489E-01 7.2828E-01  0.5111 103.708     0.00     92.481    92.576   1.15493   0.4000    0.4500
   6 8.6662E-01 7.9053E-01  0.5122 103.088     0.00     98.321    98.436   1.13017   0.5000    0.5500
   7 8.7782E-01 7.9619E-01  0.5137 102.457     0.01    101.607   101.727   1.10540   0.6000    0.6500
   8 8.2357E-01 7.4173E-01  0.5154 101.814     0.00    102.033   102.165   1.08063   0.7000    0.7500
   9 7.0816E-01 6.3128E-01  0.5180 101.158     0.00     99.564    99.693   1.05586   0.8000    0.8500
  10 5.6155E-01 4.9342E-01  0.5216 100.490     0.00     95.281    95.399   1.03110   0.9000    0.9500
  11 4.9647E-01 4.3299E-01  0.5234  99.980     0.00     93.776    93.890   1.01252   0.9750    1.0000

FUEL PLATE   6 (BroydenSoln) AREAL                     FUEL-CLADinterface
NODE FLUX inner FLUX outer  FUEL X   Tsat     Tdiff     inner     outer    Pressure  Z-mid     Z-int
       MW/m^2     MW/m^2     inner   (C)       (C)       (C)       (C)      (bar)
   1 3.3707E-01 3.5127E-01  0.4801 105.939     0.00     64.931    64.874   1.24781   0.0250    0.0500
   2 3.9429E-01 4.2154E-01  0.4737 105.504     0.00     69.068    68.977   1.22923   0.1000    0.1500
   3 5.3940E-01 5.8997E-01  0.4680 104.915     0.00     78.358    78.200   1.20447   0.2000    0.2500
   4 6.5968E-01 7.3829E-01  0.4623 104.317     0.00     86.595    86.362   1.17970   0.3000    0.3500
   5 7.5992E-01 8.7066E-01  0.4565 103.708     0.00     94.060    93.742   1.15493   0.4000    0.4500
   6 8.1408E-01 9.5937E-01  0.4495 103.088     0.00     99.503    99.103   1.13017   0.5000    0.5500
   7 8.0560E-01 9.8514E-01  0.4403 102.457     0.00    102.132   101.650   1.10540   0.6000    0.6500
   8 7.3152E-01 9.4199E-01  0.4277 101.814     0.00    101.670   101.120   1.08063   0.7000    0.7500
   9 5.9801E-01 8.3282E-01  0.4086 101.158     0.00     98.122    97.523   1.05586   0.8000    0.8500
  10 4.3699E-01 6.8850E-01  0.3791 100.490     0.00     92.694    92.067   1.03110   0.9000    0.9500
  11 3.6459E-01 6.2615E-01  0.3591  99.980     0.00     90.588    89.941   1.01252   0.9750    1.0000
```

**Fig. 31. Solution of ASTRA2 Problem 3 Case 1 by the Radial Geometry Analytical Method in PLTEMP/ANL Version 3.2**
(Using Coolant $C_p$ = 4180 J/kg-°C, and $\rho$ = 1000 kg/m$^3$, Same as ASTRA2 Code Input)

| NODE | COOLANT inner(C) | CladSurf inner(C) | FUEL PEAK (C) | CladSurf outer(C) | COOLANT outer(C) | HCOFinner W/C-m^2 | HCOFouter W/C-m^2 | ONBRin | ONBRout [F Note 1] | ETAin K-cm^3/J | ETAout K-cm^3/J | COOLNT at NodeOutlet inner(C) | COOLNT at NodeOutlet outer(C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| FUEL PLATE 1 (ExactSoln) | | | | | | | | | | | | | |
| | 45.000 | | | | 45.000 | | | | | | | | |
| 1 | 45.123 | 57.172 | 58.127 | 57.114 | 45.239 | 2.0895E+04 | 2.1301E+04 | 6.11 | 6.14 | 8.956E+02 | 9.113E+02 | 45.247 | 45.478 |
| 2 | 45.542 | 59.818 | 60.967 | 59.784 | 46.043 | 2.1151E+04 | 2.1587E+04 | 5.05 | 5.06 | 7.362E+02 | 7.612E+02 | 45.838 | 46.607 |
| 3 | 46.252 | 65.727 | 67.339 | 65.723 | 47.387 | 2.1693E+04 | 2.2179E+04 | 3.67 | 3.66 | 5.148E+02 | 5.372E+02 | 46.666 | 48.167 |
| 4 | 47.184 | 71.002 | 73.026 | 71.051 | 49.130 | 2.2189E+04 | 2.2738E+04 | 2.96 | 2.94 | 4.008E+02 | 4.204E+02 | 47.702 | 50.093 |
| 5 | 48.312 | 75.855 | 78.249 | 75.977 | 51.213 | 2.2621E+04 | 2.3240E+04 | 2.51 | 2.48 | 3.296E+02 | 3.464E+02 | 48.922 | 52.334 |
| 6 | 49.595 | 79.484 | 82.131 | 79.699 | 53.549 | 2.2956E+04 | 2.3647E+04 | 2.25 | 2.22 | 2.891E+02 | 3.042E+02 | 50.267 | 54.764 |
| 7 | 50.957 | 81.346 | 84.076 | 81.672 | 55.987 | 2.3165E+04 | 2.3925E+04 | 2.13 | 2.08 | 2.712E+02 | 2.872E+02 | 51.646 | 57.210 |
| 8 | 52.305 | 81.242 | 83.867 | 81.686 | 58.348 | 2.3235E+04 | 2.4056E+04 | 2.11 | 2.05 | 2.730E+02 | 2.940E+02 | 52.964 | 59.485 |
| 9 | 53.545 | 79.174 | 81.515 | 79.736 | 60.451 | 2.3161E+04 | 2.4028E+04 | 2.19 | 2.11 | 2.974E+02 | 3.336E+02 | 54.127 | 61.417 |
| 10 | 54.607 | 75.916 | 77.879 | 76.580 | 62.169 | 2.2984E+04 | 2.3882E+04 | 2.37 | 2.25 | 3.473E+02 | 4.228E+02 | 55.087 | 62.920 |
| 11 | 55.305 | 74.713 | 76.516 | 75.433 | 63.249 | 2.2932E+04 | 2.3848E+04 | 2.43 | 2.29 | 3.721E+02 | 4.800E+02 | 55.523 | 63.578 |
| | 55.523 | | | | 63.578 | | | | | | | | |
| FUEL PLATE 2 (ExactSoln) | | | | | | | | | | | | | |
| | 45.000 | | | | 45.000 | | | | | | | | |
| 1 | 45.239 | 58.392 | 59.485 | 58.507 | 45.276 | 2.1416E+04 | 1.8912E+04 | 5.59 | 5.50 | 8.183E+02 | 7.875E+02 | 45.478 | 45.552 |
| 2 | 46.043 | 61.456 | 62.757 | 61.603 | 46.205 | 2.1734E+04 | 1.9202E+04 | 4.58 | 4.50 | 6.741E+02 | 6.515E+02 | 46.607 | 46.859 |
| 3 | 47.387 | 68.153 | 69.962 | 68.371 | 47.764 | 2.2400E+04 | 1.9806E+04 | 3.31 | 3.25 | 4.696E+02 | 4.549E+02 | 48.167 | 48.669 |
| 4 | 49.130 | 74.260 | 76.509 | 74.547 | 49.789 | 2.2988E+04 | 2.0342E+04 | 2.65 | 2.59 | 3.628E+02 | 3.517E+02 | 50.093 | 50.908 |
| 5 | 51.213 | 79.950 | 82.586 | 80.308 | 52.214 | 2.3529E+04 | 2.0841E+04 | 2.23 | 2.18 | 2.948E+02 | 2.857E+02 | 52.334 | 53.520 |
| 6 | 53.549 | 84.358 | 87.241 | 84.777 | 54.939 | 2.3973E+04 | 2.1254E+04 | 1.98 | 1.94 | 2.547E+02 | 2.466E+02 | 54.764 | 56.359 |
| 7 | 55.987 | 86.877 | 89.810 | 87.340 | 57.791 | 2.4284E+04 | 2.1549E+04 | 1.86 | 1.81 | 2.352E+02 | 2.279E+02 | 57.210 | 59.223 |
| 8 | 58.348 | 87.265 | 90.036 | 87.753 | 60.561 | 2.4442E+04 | 2.1707E+04 | 1.82 | 1.77 | 2.335E+02 | 2.270E+02 | 59.485 | 61.898 |
| 9 | 60.451 | 85.496 | 87.904 | 85.985 | 63.040 | 2.4435E+04 | 2.1716E+04 | 1.86 | 1.80 | 2.526E+02 | 2.485E+02 | 61.417 | 64.182 |
| 10 | 62.169 | 82.366 | 84.310 | 82.841 | 65.078 | 2.4307E+04 | 2.1613E+04 | 1.96 | 1.90 | 2.964E+02 | 2.996E+02 | 62.920 | 65.974 |
| 11 | 63.249 | 81.293 | 83.036 | 81.769 | 66.367 | 2.4286E+04 | 2.1611E+04 | 1.99 | 1.92 | 3.183E+02 | 3.281E+02 | 63.578 | 66.761 |
| | 63.578 | | | | 66.761 | | | | | | | | |
| FUEL PLATE 3 (ExactSoln) | | | | | | | | | | | | | |
| | 45.000 | | | | 45.000 | | | | | | | | |
| 1 | 45.276 | 59.897 | 60.955 | 59.815 | 45.296 | 1.9021E+04 | 1.9675E+04 | 5.02 | 5.06 | 7.086E+02 | 7.196E+02 | 45.552 | 45.592 |
| 2 | 46.205 | 63.291 | 64.549 | 63.201 | 46.294 | 1.9331E+04 | 1.9998E+04 | 4.12 | 4.15 | 5.832E+02 | 5.936E+02 | 46.859 | 46.995 |
| 3 | 47.764 | 70.701 | 72.446 | 70.584 | 47.968 | 1.9972E+04 | 2.0667E+04 | 2.98 | 3.00 | 4.053E+02 | 4.130E+02 | 48.669 | 48.940 |
| 4 | 49.789 | 77.459 | 79.625 | 77.324 | 50.144 | 2.0534E+04 | 2.1256E+04 | 2.38 | 2.40 | 3.118E+02 | 3.179E+02 | 50.908 | 51.349 |
| 5 | 52.214 | 83.759 | 86.292 | 83.614 | 52.754 | 2.1053E+04 | 2.1803E+04 | 2.01 | 2.02 | 2.519E+02 | 2.567E+02 | 53.520 | 54.160 |
| 6 | 54.939 | 88.645 | 91.409 | 88.504 | 55.690 | 2.1484E+04 | 2.2260E+04 | 1.79 | 1.79 | 2.160E+02 | 2.200E+02 | 56.359 | 57.220 |
| 7 | 57.791 | 91.456 | 94.259 | 91.335 | 58.767 | 2.1793E+04 | 2.2591E+04 | 1.67 | 1.67 | 1.978E+02 | 2.013E+02 | 59.223 | 60.314 |
| 8 | 60.561 | 91.935 | 94.570 | 91.851 | 61.762 | 2.1956E+04 | 2.2771E+04 | 1.63 | 1.63 | 1.945E+02 | 1.982E+02 | 61.898 | 63.210 |
| 9 | 63.040 | 90.052 | 92.326 | 90.019 | 64.450 | 2.1961E+04 | 2.2787E+04 | 1.66 | 1.66 | 2.087E+02 | 2.136E+02 | 64.182 | 65.691 |
| 10 | 65.078 | 86.674 | 88.488 | 86.694 | 66.670 | 2.1850E+04 | 2.2691E+04 | 1.75 | 1.74 | 2.438E+02 | 2.523E+02 | 65.974 | 67.650 |
| 11 | 66.367 | 85.542 | 87.157 | 85.593 | 68.082 | 2.1847E+04 | 2.2684E+04 | 1.77 | 1.76 | 2.607E+02 | 2.722E+02 | 66.761 | 68.514 |
| | 66.761 | | | | 68.514 | | | | | | | | |

## Fig. 31. Continued

```
FUEL PLATE   4 (ExactSoln)
NODE    COOLANT  CladSurf FUEL PEAK  CladSurf  COOLANT  HCOFinner HCOFouter ONBRin ONBRout  ETAin    ETAout  COOLNT at NodeOutlet
       inner(C)  inner(C)    (C)     outer(C)  outer(C) W/C-m^2    W/C-m^2    [F Note 1]  K-cm^3/J  K-cm^3/J  inner(C)   outer(C)
        45.000                                  45.000
   1    45.296    60.798    61.977    60.808    45.327 1.9754E+04 1.9155E+04  4.77   4.76 6.713E+02 6.666E+02    45.592    45.654
   2    46.294    64.405    65.807    64.426    46.429 2.0092E+04 1.9490E+04  3.91   3.89 5.516E+02 5.493E+02    46.995    47.205
   3    47.968    72.259    74.206    72.299    48.279 2.0787E+04 2.0174E+04  2.83   2.82 3.823E+02 3.812E+02    48.940    49.353
   4    50.144    79.432    81.850    79.495    50.683 2.1395E+04 2.0776E+04  2.27   2.25 2.931E+02 2.922E+02    51.349    52.013
   5    52.754    86.125    88.955    86.216    53.564 2.1958E+04 2.1338E+04  1.91   1.90 2.357E+02 2.347E+02    54.160    55.115
   6    55.690    91.330    94.421    91.452    56.803 2.2432E+04 2.1813E+04  1.70   1.69 2.010E+02 1.997E+02    57.220    58.491
   7    58.767    94.357    97.494    94.511    60.195 2.2776E+04 2.2162E+04  1.59   1.57 1.827E+02 1.812E+02    60.314    61.899
   8    61.762    94.943    97.897    95.127    63.492 2.2963E+04 2.2357E+04  1.55   1.53 1.782E+02 1.767E+02    63.210    65.085
   9    64.450    93.049    95.602    93.258    66.447 2.2975E+04 2.2388E+04  1.58   1.56 1.894E+02 1.886E+02    65.691    67.808
  10    66.670    89.579    91.624    89.809    68.879 2.2872E+04 2.2287E+04  1.65   1.63 2.188E+02 2.210E+02    67.650    69.949
  11    68.082    88.445    90.267    88.689    70.419 2.2865E+04 2.2284E+04  1.67   1.64 2.322E+02 2.368E+02    68.514    70.890
        68.514                                  70.890

FUEL PLATE   5 (ExactSoln)
        45.000                                  45.000
   1    45.327    62.557    63.847    62.635    45.368 1.9290E+04 1.7949E+04  4.31   4.27 5.947E+02 5.822E+02    45.654    45.736
   2    46.429    66.521    68.055    66.623    46.602 1.9662E+04 1.8303E+04  3.54   3.51 4.877E+02 4.788E+02    47.205    47.467
   3    48.279    75.187    77.317    75.340    48.656 2.0370E+04 1.8974E+04  2.57   2.54 3.370E+02 3.310E+02    49.353    49.846
   4    50.683    83.066    85.711    83.269    51.307 2.0998E+04 1.9572E+04  2.06   2.04 2.572E+02 2.524E+02    52.013    52.769
   5    53.564    90.388    93.481    90.640    54.461 2.1584E+04 2.0132E+04  1.74   1.72 2.058E+02 2.014E+02    55.115    56.153
   6    56.803    96.040    99.415    96.333    57.978 2.2085E+04 2.0612E+04  1.55   1.53 1.742E+02 1.700E+02    58.491    59.802
   7    60.195    99.294   102.714    99.613    61.622 2.2448E+04 2.0961E+04  1.45   1.43 1.570E+02 1.528E+02    61.899    63.443
   8    63.492    99.865   103.079   100.193    65.117 2.2641E+04 2.1147E+04  1.42   1.40 1.518E+02 1.474E+02    65.085    66.791
   9    66.447    97.700   100.468    98.016    68.187 2.2658E+04 2.1164E+04  1.45   1.42 1.599E+02 1.556E+02    67.808    69.582
  10    68.879    93.802    96.002    94.090    70.638 2.2529E+04 2.1041E+04  1.52   1.49 1.836E+02 1.802E+02    69.949    71.693
  11    70.419    92.471    94.418    92.742    72.145 2.2514E+04 2.1022E+04  1.53   1.51 1.942E+02 1.915E+02    70.890    72.597
        70.890                                  72.597

FUEL PLATE   6 (ExactSoln)
        45.000                                  45.000
   1    45.368    64.046    65.333    63.937    45.160 1.8048E+04 1.8705E+04  3.98   4.02 5.352E+02 5.555E+02    45.736    45.319
   2    46.602    68.034    69.534    67.851    45.702 1.8400E+04 1.9029E+04  3.31   3.35 4.449E+02 4.554E+02    47.467    46.085
   3    48.656    76.944    78.988    76.624    46.621 1.9072E+04 1.9660E+04  2.43   2.47 3.106E+02 3.172E+02    49.846    47.156
   4    51.307    84.867    87.358    84.389    47.827 1.9661E+04 2.0189E+04  1.97   2.01 2.393E+02 2.457E+02    52.769    48.498
   5    54.461    92.070    94.929    91.416    49.288 2.0210E+04 2.0663E+04  1.68   1.72 1.930E+02 2.007E+02    56.153    50.079
   6    57.978    97.375   100.424    96.536    50.950 2.0670E+04 2.1040E+04  1.50   1.55 1.650E+02 1.745E+02    59.802    51.822
   7    61.622   100.029   103.028    99.013    52.716 2.0984E+04 2.1272E+04  1.42   1.48 1.509E+02 1.621E+02    63.443    53.611
   8    65.117    99.764   102.464    98.595    54.466 2.1124E+04 2.1339E+04  1.41   1.47 1.494E+02 1.614E+02    66.791    55.322
   9    68.187    96.569    98.748    95.288    56.078 2.1083E+04 2.1231E+04  1.46   1.54 1.641E+02 1.738E+02    69.582    56.834
  10    70.638    91.566    93.128    90.215    57.459 2.0897E+04 2.1008E+04  1.56   1.67 2.033E+02 2.007E+02    71.693    58.084
  11    72.145    89.651    90.936    88.256    58.368 2.0847E+04 2.0939E+04  1.59   1.72 2.272E+02 2.134E+02    72.597    58.653
        72.597                                  58.653
```

**Fig. 31. Continued**

FUEL PLATE 1 (ExactSoln)

| NODE | FLUX inner MW/m^2 | FLUX outer MW/m^2 | AREAL FUEL X inner | Tsat (C) | Tdiff (C) | FUEL-CLADinterface inner (C) | outer (C) | Pressure (bar) | Z-mid | Z-int |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.5176E-01 | 2.5295E-01 | 0.4802 | 105.939 | | 57.830 | 57.791 | 1.24781 | 0.0250 | 0.0500 |
| 2 | 3.0195E-01 | 2.9663E-01 | 0.4858 | 105.504 | | 60.608 | 60.578 | 1.22923 | 0.1000 | 0.1500 |
| 3 | 4.2245E-01 | 4.0667E-01 | 0.4909 | 104.915 | | 66.831 | 66.812 | 1.20447 | 0.2000 | 0.2500 |
| 4 | 5.2849E-01 | 4.9844E-01 | 0.4960 | 104.317 | | 72.383 | 72.386 | 1.17970 | 0.3000 | 0.3500 |
| 5 | 6.2305E-01 | 5.7549E-01 | 0.5012 | 103.708 | | 77.484 | 77.518 | 1.15493 | 0.4000 | 0.4500 |
| 6 | 6.8614E-01 | 6.1837E-01 | 0.5074 | 103.088 | | 81.278 | 81.355 | 1.13017 | 0.5000 | 0.5500 |
| 7 | 7.0397E-01 | 6.1450E-01 | 0.5154 | 102.457 | | 83.187 | 83.317 | 1.10540 | 0.6000 | 0.6500 |
| 8 | 6.7236E-01 | 5.6142E-01 | 0.5264 | 101.814 | | 83.000 | 83.190 | 1.08063 | 0.7000 | 0.7500 |
| 9 | 5.9359E-01 | 4.6337E-01 | 0.5432 | 101.158 | | 80.726 | 80.977 | 1.05586 | 0.8000 | 0.8500 |
| 10 | 4.8978E-01 | 3.4417E-01 | 0.5691 | 100.490 | | 77.197 | 77.502 | 1.03110 | 0.9000 | 0.9500 |
| 11 | 4.4509E-01 | 2.9057E-01 | 0.5871 | 99.980 | | 75.877 | 76.211 | 1.01252 | 0.9750 | 1.0000 |

FUEL PLATE 2 (ExactSoln)

| NODE | FLUX inner MW/m^2 | FLUX outer MW/m^2 | AREAL FUEL X inner | Tsat (C) | Tdiff (C) | FUEL-CLADinterface inner (C) | outer (C) | Pressure (bar) | Z-mid | Z-int |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.8167E-01 | 2.5023E-01 | 0.5139 | 105.939 | | 59.129 | 59.176 | 1.24781 | 0.0250 | 0.0500 |
| 2 | 3.3498E-01 | 2.9566E-01 | 0.5155 | 105.504 | | 62.333 | 62.394 | 1.22923 | 0.1000 | 0.1500 |
| 3 | 4.6515E-01 | 4.0812E-01 | 0.5170 | 104.915 | | 69.371 | 69.462 | 1.20447 | 0.2000 | 0.2500 |
| 4 | 5.7768E-01 | 5.0364E-01 | 0.5185 | 104.317 | | 75.773 | 75.893 | 1.17970 | 0.3000 | 0.3500 |
| 5 | 6.7617E-01 | 5.8549E-01 | 0.5202 | 103.708 | | 81.722 | 81.873 | 1.15493 | 0.4000 | 0.4500 |
| 6 | 7.3859E-01 | 6.3417E-01 | 0.5224 | 103.088 | | 86.293 | 86.472 | 1.13017 | 0.5000 | 0.5500 |
| 7 | 7.5012E-01 | 6.3676E-01 | 0.5252 | 102.457 | | 88.842 | 89.042 | 1.10540 | 0.6000 | 0.6500 |
| 8 | 7.0680E-01 | 5.9026E-01 | 0.5293 | 101.814 | | 89.117 | 89.331 | 1.08063 | 0.7000 | 0.7500 |
| 9 | 6.1196E-01 | 4.9826E-01 | 0.5356 | 101.158 | | 87.099 | 87.317 | 1.05586 | 0.8000 | 0.8500 |
| 10 | 4.9093E-01 | 3.8392E-01 | 0.5456 | 100.490 | | 83.652 | 83.867 | 1.03110 | 0.9000 | 0.9500 |
| 11 | 4.3822E-01 | 3.3284E-01 | 0.5528 | 99.980 | | 82.441 | 82.659 | 1.01252 | 0.9750 | 1.0000 |

FUEL PLATE 3 (ExactSoln)

| NODE | FLUX inner MW/m^2 | FLUX outer MW/m^2 | AREAL FUEL X inner | Tsat (C) | Tdiff (C) | FUEL-CLADinterface inner (C) | outer (C) | Pressure (bar) | Z-mid | Z-int |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.7810E-01 | 2.8567E-01 | 0.4797 | 105.939 | | 60.626 | 60.578 | 1.24781 | 0.0250 | 0.0500 |
| 2 | 3.3027E-01 | 3.3811E-01 | 0.4805 | 105.504 | | 64.158 | 64.103 | 1.22923 | 0.1000 | 0.1500 |
| 3 | 4.5809E-01 | 4.6740E-01 | 0.4814 | 104.915 | | 71.903 | 71.832 | 1.20447 | 0.2000 | 0.2500 |
| 4 | 5.6818E-01 | 5.7773E-01 | 0.4822 | 104.317 | | 78.950 | 78.867 | 1.17970 | 0.3000 | 0.3500 |
| 5 | 6.6413E-01 | 6.7283E-01 | 0.4831 | 103.708 | | 85.502 | 85.411 | 1.15493 | 0.4000 | 0.4500 |
| 6 | 7.2415E-01 | 7.3042E-01 | 0.4842 | 103.088 | | 90.545 | 90.454 | 1.13017 | 0.5000 | 0.5500 |
| 7 | 7.3366E-01 | 7.3573E-01 | 0.4857 | 102.457 | | 93.381 | 93.299 | 1.10540 | 0.6000 | 0.6500 |
| 8 | 6.8886E-01 | 6.8517E-01 | 0.4877 | 101.814 | | 93.742 | 93.680 | 1.08063 | 0.7000 | 0.7500 |
| 9 | 5.9322E-01 | 5.8263E-01 | 0.4909 | 101.158 | | 91.609 | 91.574 | 1.05586 | 0.8000 | 0.8500 |
| 10 | 4.7187E-01 | 4.5435E-01 | 0.4958 | 100.490 | | 87.911 | 87.907 | 1.03110 | 0.9000 | 0.9500 |
| 11 | 4.1892E-01 | 3.9722E-01 | 0.4997 | 99.980 | | 86.641 | 86.653 | 1.01252 | 0.9750 | 1.0000 |

**Fig. 31. Continued**

FUEL PLATE 4 (ExactSoln)

| NODE | FLUX inner MW/m^2 | FLUX outer MW/m^2 | AREAL FUEL X inner | Tsat (C) | Tdiff (C) | FUEL-CLADinterface inner (C) | outer (C) | Pressure (bar) | Z-mid | Z-int |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 3.0623E-01 | 2.9655E-01 | 0.4960 | 105.939 | | 61.602 | 61.599 | 1.24781 | 0.0250 | 0.0500 |
| 2 | 3.6390E-01 | 3.5073E-01 | 0.4972 | 105.504 | | 65.361 | 65.361 | 1.22923 | 0.1000 | 0.1500 |
| 3 | 5.0496E-01 | 4.8458E-01 | 0.4983 | 104.915 | | 73.585 | 73.591 | 1.20447 | 0.2000 | 0.2500 |
| 4 | 6.2661E-01 | 5.9861E-01 | 0.4994 | 104.317 | | 81.078 | 81.092 | 1.17970 | 0.3000 | 0.3500 |
| 5 | 7.3277E-01 | 6.9672E-01 | 0.5006 | 103.708 | | 88.050 | 88.074 | 1.15493 | 0.4000 | 0.4500 |
| 6 | 7.9947E-01 | 7.5580E-01 | 0.5020 | 103.088 | | 93.430 | 93.468 | 1.13017 | 0.5000 | 0.5500 |
| 7 | 8.1061E-01 | 7.6053E-01 | 0.5039 | 102.457 | | 96.486 | 96.539 | 1.10540 | 0.6000 | 0.6500 |
| 8 | 7.6193E-01 | 7.0726E-01 | 0.5066 | 101.814 | | 96.944 | 97.014 | 1.08063 | 0.7000 | 0.7500 |
| 9 | 6.5705E-01 | 6.0025E-01 | 0.5106 | 101.158 | | 94.774 | 94.859 | 1.05586 | 0.8000 | 0.8500 |
| 10 | 5.2396E-01 | 4.6647E-01 | 0.5170 | 100.490 | | 90.955 | 91.053 | 1.03110 | 0.9000 | 0.9500 |
| 11 | 4.6561E-01 | 4.0711E-01 | 0.5215 | 99.980 | | 89.668 | 89.775 | 1.01252 | 0.9750 | 1.0000 |

FUEL PLATE 5 (ExactSoln)

| NODE | FLUX inner MW/m^2 | FLUX outer MW/m^2 | AREAL FUEL X inner | Tsat (C) | Tdiff (C) | FUEL-CLADinterface inner (C) | outer (C) | Pressure (bar) | Z-mid | Z-int |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 3.3237E-01 | 3.0992E-01 | 0.5067 | 105.939 | | 63.431 | 63.461 | 1.24781 | 0.0250 | 0.0500 |
| 2 | 3.9504E-01 | 3.6645E-01 | 0.5080 | 105.504 | | 67.559 | 67.599 | 1.22923 | 0.1000 | 0.1500 |
| 3 | 5.4812E-01 | 5.0629E-01 | 0.5091 | 104.915 | | 76.628 | 76.689 | 1.20447 | 0.2000 | 0.2500 |
| 4 | 6.7998E-01 | 6.2555E-01 | 0.5101 | 104.317 | | 84.854 | 84.936 | 1.17970 | 0.3000 | 0.3500 |
| 5 | 7.9481E-01 | 7.2836E-01 | 0.5111 | 103.708 | | 92.477 | 92.581 | 1.15493 | 0.4000 | 0.4500 |
| 6 | 8.6656E-01 | 7.9059E-01 | 0.5122 | 103.088 | | 98.318 | 98.440 | 1.13017 | 0.5000 | 0.5500 |
| 7 | 8.7768E-01 | 7.9632E-01 | 0.5136 | 102.457 | | 101.601 | 101.735 | 1.10540 | 0.6000 | 0.6500 |
| 8 | 8.2353E-01 | 7.4177E-01 | 0.5154 | 101.814 | | 102.030 | 102.170 | 1.08063 | 0.7000 | 0.7500 |
| 9 | 7.0813E-01 | 6.3132E-01 | 0.5180 | 101.158 | | 99.561 | 99.699 | 1.05586 | 0.8000 | 0.8500 |
| 10 | 5.6151E-01 | 4.9346E-01 | 0.5215 | 100.490 | | 95.278 | 95.405 | 1.03110 | 0.9000 | 0.9500 |
| 11 | 4.9646E-01 | 4.3300E-01 | 0.5234 | 99.980 | | 93.775 | 93.896 | 1.01252 | 0.9750 | 1.0000 |

FUEL PLATE 6 (ExactSoln)

| NODE | FLUX inner MW/m^2 | FLUX outer MW/m^2 | AREAL FUEL X inner | Tsat (C) | Tdiff (C) | FUEL-CLADinterface inner (C) | outer (C) | Pressure (bar) | Z-mid | Z-int |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 3.3711E-01 | 3.5124E-01 | 0.4801 | 105.939 | | 64.933 | 64.872 | 1.24781 | 0.0250 | 0.0500 |
| 2 | 3.9435E-01 | 4.2149E-01 | 0.4737 | 105.504 | | 69.072 | 68.974 | 1.22923 | 0.1000 | 0.1500 |
| 3 | 5.3950E-01 | 5.8987E-01 | 0.4681 | 104.915 | | 78.363 | 78.195 | 1.20447 | 0.2000 | 0.2500 |
| 4 | 6.5982E-01 | 7.3815E-01 | 0.4624 | 104.317 | | 86.602 | 86.355 | 1.17970 | 0.3000 | 0.3500 |
| 5 | 7.6010E-01 | 8.7049E-01 | 0.4566 | 103.708 | | 94.070 | 93.734 | 1.15493 | 0.4000 | 0.4500 |
| 6 | 8.1434E-01 | 9.5912E-01 | 0.4496 | 103.088 | | 99.517 | 99.090 | 1.13017 | 0.5000 | 0.5500 |
| 7 | 8.0591E-01 | 9.8484E-01 | 0.4405 | 102.457 | | 102.149 | 101.636 | 1.10540 | 0.6000 | 0.6500 |
| 8 | 7.3187E-01 | 9.4166E-01 | 0.4279 | 101.814 | | 101.689 | 101.103 | 1.08063 | 0.7000 | 0.7500 |
| 9 | 5.9837E-01 | 8.3248E-01 | 0.4088 | 101.158 | | 98.143 | 97.505 | 1.05586 | 0.8000 | 0.8500 |
| 10 | 4.3735E-01 | 6.8816E-01 | 0.3795 | 100.490 | | 92.717 | 92.048 | 1.03110 | 0.9000 | 0.9500 |
| 11 | 3.6494E-01 | 6.2581E-01 | 0.3594 | 99.980 | | 90.611 | 89.922 | 1.01252 | 0.9750 | 1.0000 |

## APPENDIX C. Enthalpy of Liquid Water Used in the PLTEMP Code

| T ,C | h(T, 1bar) J/kg | h(T, 2bar) J/kg | h(T, 3bar) J/kg | h(T, 4bar) J/kg | h(T, 5bar) J/kg | h(T, 6bar) J/kg | h(T, 7bar) J/kg | h(T, 8bar) J/kg | h(T, 9bar) J/kg | h(T,10bar) J/kg |
|---|---|---|---|---|---|---|---|---|---|---|
| 1.00 | 4554.4434 | 4658.5846 | 4755.7831 | 4859.9243 | 4957.1228 | 5061.2640 | 5158.4625 | 5262.6038 | 5359.8022 | 5463.9435 |
| 2.00 | 8713.1500 | 8810.3485 | 8914.4897 | 9011.6882 | 9108.8867 | 9213.0280 | 9317.1692 | 9414.3677 | 9511.5662 | 9615.7074 |
| 3.00 | 12864.9139 | 12962.1124 | 13066.2537 | 13163.4521 | 13267.5934 | 13364.7919 | 13468.9331 | 13566.1316 | 13663.3301 | 13767.4713 |
| 4.00 | 17016.6779 | 17120.8191 | 17218.0176 | 17315.2161 | 17419.3573 | 17516.5558 | 17620.6970 | 17717.8955 | 17815.0940 | 17919.2352 |
| 5.00 | 21175.3845 | 21272.5830 | 21369.7815 | 21473.9227 | 21571.1212 | 21675.2625 | 21772.4609 | 21869.6594 | 21973.8007 | 22070.9991 |
| 6.00 | 25327.1484 | 25431.2897 | 25528.4882 | 25632.6294 | 25729.8279 | 25827.0264 | 25924.2249 | 26028.3661 | 26125.5646 | 26222.7631 |
| 7.00 | 29485.8551 | 29583.0536 | 29687.1948 | 29784.3933 | 29881.5918 | 29978.7903 | 30082.9315 | 30180.1300 | 30284.2712 | 30381.4697 |
| 8.00 | 33644.5618 | 33741.7603 | 33838.9587 | 33936.1572 | 34040.2985 | 34137.4969 | 34234.6954 | 34338.8367 | 34436.0352 | 34533.2336 |
| 9.00 | 37796.3257 | 37900.4669 | 37997.6654 | 38094.8639 | 38199.0051 | 38296.2036 | 38393.4021 | 38490.6006 | 38587.7991 | 38684.9976 |
| 10.00 | 41955.0323 | 42059.1736 | 42156.3721 | 42253.5706 | 42350.7690 | 42447.9675 | 42545.1660 | 42649.3073 | 42746.5057 | 42843.7042 |
| 11.00 | 46113.7390 | 46210.9375 | 46315.0787 | 46412.2772 | 46509.4757 | 46606.6742 | 46703.8727 | 46808.0139 | 46905.2124 | 47002.4109 |
| 12.00 | 50272.4457 | 50376.5869 | 50473.7854 | 50570.9839 | 50668.1824 | 50765.3809 | 50862.5793 | 50959.7778 | 51056.9763 | 51154.1748 |
| 13.00 | 54431.1523 | 54528.3508 | 54632.4921 | 54729.6906 | 54826.8890 | 54924.0875 | 55021.2860 | 55118.4845 | 55215.6830 | 55312.8815 |
| 14.00 | 58596.8018 | 58694.0002 | 58791.1987 | 58888.3972 | 58985.5957 | 59082.7942 | 59179.9927 | 59277.1912 | 59374.3896 | 59471.5881 |
| 15.00 | 62755.5084 | 62852.7069 | 62949.9054 | 63047.1039 | 63144.3024 | 63241.5009 | 63338.6993 | 63435.8978 | 63533.0963 | 63630.2948 |
| 16.00 | 66914.2151 | 67011.4136 | 67108.6121 | 67205.8105 | 67303.0090 | 67400.2075 | 67497.4060 | 67594.6045 | 67691.8030 | 67789.0015 |
| 17.00 | 71079.8645 | 71177.0630 | 71274.2615 | 71371.4600 | 71468.6584 | 71565.8569 | 71656.1127 | 71753.3112 | 71850.5096 | 71947.7081 |
| 18.00 | 75238.5712 | 75335.7697 | 75432.9681 | 75530.1666 | 75627.3651 | 75724.5636 | 75821.7621 | 75918.9606 | 76009.2163 | 76106.4148 |
| 19.00 | 79404.2206 | 79501.4191 | 79591.6748 | 79688.8733 | 79786.0718 | 79883.2703 | 79980.4688 | 80077.6672 | 80174.8657 | 80272.0642 |
| 20.00 | 83562.9272 | 83660.1257 | 83757.3242 | 83854.5227 | 83951.7212 | 84048.9197 | 84146.1182 | 84236.3739 | 84333.5724 | 84430.7709 |
| 21.00 | 87728.5767 | 87825.7751 | 87922.9736 | 88020.1721 | 88117.3706 | 88207.6263 | 88304.8248 | 88402.0233 | 88499.2218 | 88589.4775 |
| 22.00 | 91894.2261 | 91991.4246 | 92088.6230 | 92178.8788 | 92276.0773 | 92373.2758 | 92470.4742 | 92560.7300 | 92657.9285 | 92755.1270 |
| 23.00 | 96059.8755 | 96157.0740 | 96247.3297 | 96344.5282 | 96441.7267 | 96538.9252 | 96629.1809 | 96726.3794 | 96823.5779 | 96920.7764 |
| 24.00 | 100225.5249 | 100322.7234 | 100412.9791 | 100510.1776 | 100607.3761 | 100697.6318 | 100794.8303 | 100892.0288 | 100989.2273 | 101079.4830 |
| 25.00 | 104391.1743 | 104488.3728 | 104578.6285 | 104675.8270 | 104773.0255 | 104863.2812 | 104960.4797 | 105057.6782 | 105154.8767 | 105245.1324 |
| 26.00 | 108556.8237 | 108654.0222 | 108751.2207 | 108841.4764 | 108938.6749 | 109028.9307 | 109126.1292 | 109223.3276 | 109313.5834 | 109410.7819 |
| 27.00 | 112722.4731 | 112819.6716 | 112916.8701 | 113007.1259 | 113104.3243 | 113194.5801 | 113291.7786 | 113388.9771 | 113479.2328 | 113576.4313 |
| 28.00 | 116895.0653 | 116985.3210 | 117082.5195 | 117179.7180 | 117269.9738 | 117367.1722 | 117457.4280 | 117554.6265 | 117644.8822 | 117742.0807 |
| 29.00 | 121060.7147 | 121157.9132 | 121248.1689 | 121345.3674 | 121435.6232 | 121532.8217 | 121623.0774 | 121720.2759 | 121817.4744 | 121907.7301 |
| 30.00 | 125233.3069 | 125323.5626 | 125420.7611 | 125511.0168 | 125608.2153 | 125698.4711 | 125795.6696 | 125885.9253 | 125983.1238 | 126073.3795 |
| 31.00 | 129398.9563 | 129496.1548 | 129586.4105 | 129683.6090 | 129773.8647 | 129871.0632 | 129961.3190 | 130058.5175 | 130148.7732 | 130245.9717 |
| 32.00 | 133571.5485 | 133661.8042 | 133759.0027 | 133849.2584 | 133946.4569 | 134036.7126 | 134133.9111 | 134224.1669 | 134314.4226 | 134411.6211 |
| 33.00 | 137744.1406 | 137834.3964 | 137931.5948 | 138021.8506 | 138119.0491 | 138209.3048 | 138299.5605 | 138396.7590 | 138487.0148 | 138577.2705 |
| 34.00 | 141916.7328 | 142006.9885 | 142104.1870 | 142194.4427 | 142284.6985 | 142381.8970 | 142472.1527 | 142562.4084 | 142659.6069 | 142749.8627 |
| 35.00 | 146089.3250 | 146179.5807 | 146269.8364 | 146367.0349 | 146457.2906 | 146547.5464 | 146644.7449 | 146735.0006 | 146825.2563 | 146922.4548 |
| 36.00 | 150261.9171 | 150352.1729 | 150449.3713 | 150539.6271 | 150629.8828 | 150720.1385 | 150817.3370 | 150907.5928 | 150997.8485 | 151088.1042 |
| 37.00 | 154434.5093 | 154524.7650 | 154615.0208 | 154712.2192 | 154802.4750 | 154892.7307 | 154989.9292 | 155080.1849 | 155170.4407 | 155267.6392 |
| 38.00 | 158607.1014 | 158697.3572 | 158794.5557 | 158884.8114 | 158975.0671 | 159072.2656 | 159162.5214 | 159252.7771 | 159343.0328 | 159433.2886 |
| 39.00 | 162786.6364 | 162876.8921 | 162967.1478 | 163057.4036 | 163154.6021 | 163244.8578 | 163335.1135 | 163425.3693 | 163515.6250 | 163612.8235 |
| 40.00 | 166959.2285 | 167049.4843 | 167139.7400 | 167236.9385 | 167327.1942 | 167417.4500 | 167507.7057 | 167597.9614 | 167695.1599 | 167785.4156 |
| 41.00 | 171138.7634 | 171229.0192 | 171319.2749 | 171409.5306 | 171499.7864 | 171590.0421 | 171680.2979 | 171777.4963 | 171867.7521 | 171958.0078 |
| 42.00 | 175311.3556 | 175401.6113 | 175498.8098 | 175589.0656 | 175679.3213 | 175769.5770 | 175859.8328 | 175950.0885 | 176040.3442 | 176130.6000 |
| 43.00 | 179490.8905 | 179581.1462 | 179671.4020 | 179761.6577 | 179851.9135 | 179942.1692 | 180039.3677 | 180122.6807 | 180219.8792 | 180310.1349 |
| 44.00 | 183670.4254 | 183760.6812 | 183850.9369 | 183941.1926 | 184031.4484 | 184121.7041 | 184211.9598 | 184302.2156 | 184392.4713 | 184482.7271 |
| 45.00 | 187849.9603 | 187940.2161 | 188030.4718 | 188120.7275 | 188210.9833 | 188301.2390 | 188391.4948 | 188481.7505 | 188572.0062 | 188662.2620 |

| T ,C | h(T, 1bar) J/kg | h(T, 2bar) J/kg | h(T, 3bar) J/kg | h(T, 4bar) J/kg | h(T, 5bar) J/kg | h(T, 6bar) J/kg | h(T, 7bar) J/kg | h(T, 8bar) J/kg | h(T, 9bar) J/kg | h(T,10bar) J/kg |
|---|---|---|---|---|---|---|---|---|---|---|
| 46.00 | 192029.4952 | 192119.7510 | 192210.0067 | 192300.2625 | 192390.5182 | 192480.7739 | 192571.0297 | 192661.2854 | 192751.5411 | 192841.7969 |
| 47.00 | 196209.0302 | 196299.2859 | 196389.5416 | 196479.7974 | 196570.0531 | 196660.3088 | 196750.5646 | 196840.8203 | 196924.1333 | 197021.3318 |
| 48.00 | 200395.5078 | 200478.8208 | 200569.0765 | 200659.3323 | 200749.5880 | 200839.8437 | 200930.0995 | 201020.3552 | 201103.6682 | 201200.8667 |
| 49.00 | 204575.0427 | 204665.2985 | 204755.5542 | 204838.8672 | 204929.1229 | 205019.3787 | 205109.6344 | 205199.8901 | 205290.1459 | 205380.4016 |
| 50.00 | 208754.5776 | 208844.8334 | 208935.0891 | 209025.3448 | 209115.6006 | 209198.9136 | 209289.1693 | 209379.4250 | 209469.6808 | 209559.9365 |
| 51.00 | 212941.0553 | 213031.3110 | 213114.6240 | 213204.8798 | 213295.1355 | 213385.3912 | 213475.6470 | 213558.9600 | 213649.2157 | 213739.4714 |
| 52.00 | 217127.5330 | 217210.8459 | 217301.1017 | 217391.3574 | 217481.6132 | 217571.8689 | 217655.1819 | 217745.4376 | 217835.6934 | 217919.0063 |
| 53.00 | 221307.0679 | 221397.3236 | 221487.5793 | 221577.8351 | 221661.1481 | 221751.4038 | 221841.6595 | 221931.9153 | 222015.2283 | 222105.4840 |
| 54.00 | 225500.4883 | 225583.8013 | 225674.0570 | 225764.3127 | 225847.6257 | 225937.8815 | 226028.1372 | 226111.4502 | 226201.7059 | 226291.9617 |
| 55.00 | 229680.0232 | 229770.2789 | 229860.5347 | 229943.8477 | 230034.1034 | 230124.3591 | 230207.6721 | 230297.9279 | 230388.1836 | 230471.4966 |
| 56.00 | 233873.4436 | 233956.7566 | 234047.0123 | 234137.2681 | 234220.5811 | 234310.8368 | 234394.1498 | 234484.4055 | 234567.7185 | 234657.9742 |
| 57.00 | 238059.9213 | 238150.1770 | 238233.4900 | 238316.8030 | 238407.0587 | 238497.3145 | 238580.6274 | 238670.8832 | 238761.1389 | 238844.4519 |
| 58.00 | 242246.3989 | 242336.6547 | 242419.9677 | 242510.2234 | 242593.5364 | 242683.7921 | 242774.0479 | 242857.3608 | 242940.6738 | 243030.9296 |
| 59.00 | 246439.8193 | 246523.1323 | 246613.3881 | 246696.7010 | 246786.9568 | 246870.2698 | 246960.5255 | 247043.8385 | 247134.0942 | 247217.4072 |
| 60.00 | 250626.2970 | 250716.5527 | 250799.8657 | 250890.1215 | 250973.4344 | 251063.6902 | 251147.0032 | 251230.3162 | 251320.5719 | 251410.8276 |
| 61.00 | 254819.7174 | 254909.9731 | 254993.2861 | 255076.5991 | 255166.8549 | 255250.1678 | 255340.4236 | 255423.7366 | 255507.0496 | 255597.3053 |
| 62.00 | 259013.1378 | 259096.4508 | 259186.7065 | 259270.0195 | 259353.3325 | 259443.5883 | 259526.9012 | 259617.1570 | 259700.4700 | 259783.7830 |
| 63.00 | 263206.5582 | 263289.8712 | 263380.1270 | 263463.4399 | 263546.7529 | 263637.0087 | 263720.3217 | 263803.6346 | 263893.8904 | 263977.2034 |
| 64.00 | 267399.9786 | 267483.2916 | 267573.5474 | 267656.8604 | 267740.1733 | 267823.4863 | 267913.7421 | 267997.0551 | 268087.3108 | 268170.6238 |
| 65.00 | 271593.3990 | 271683.6548 | 271766.9678 | 271850.2808 | 271933.5937 | 272016.9067 | 272107.1625 | 272190.4755 | 272280.7312 | 272364.0442 |
| 66.00 | 275793.7622 | 275877.0752 | 275960.3882 | 276043.7012 | 276127.0142 | 276217.2699 | 276300.5829 | 276383.8959 | 276474.1516 | 276557.4646 |
| 67.00 | 279987.1826 | 280070.4956 | 280153.8086 | 280237.1216 | 280327.3773 | 280410.6903 | 280494.0033 | 280584.2590 | 280667.5720 | 280750.8850 |
| 68.00 | 284180.6030 | 284270.8588 | 284354.1718 | 284437.4847 | 284520.7977 | 284604.1107 | 284694.3665 | 284777.6794 | 284860.9924 | 284944.3054 |
| 69.00 | 288380.9662 | 288464.2792 | 288554.5349 | 288637.8479 | 288721.1609 | 288804.4739 | 288887.7869 | 288971.0999 | 289054.4128 | 289137.7258 |
| 70.00 | 292581.3293 | 292664.6423 | 292747.9553 | 292831.2683 | 292914.5813 | 292997.8943 | 293088.1500 | 293171.4630 | 293254.7760 | 293338.0890 |
| 71.00 | 296781.6925 | 296865.0055 | 296948.3185 | 297031.6315 | 297114.9445 | 297198.2574 | 297281.5704 | 297371.8262 | 297455.1392 | 297538.4521 |
| 72.00 | 300982.0557 | 301065.3687 | 301148.6816 | 301231.9946 | 301315.3076 | 301398.6206 | 301481.9336 | 301565.2466 | 301648.5596 | 301731.8726 |
| 73.00 | 305182.4188 | 305265.7318 | 305349.0448 | 305432.3578 | 305515.6708 | 305598.9838 | 305682.2968 | 305765.6097 | 305848.9227 | 305932.2357 |
| 74.00 | 309382.7820 | 309466.0950 | 309549.4080 | 309632.7209 | 309716.0339 | 309799.3469 | 309882.6599 | 309965.9729 | 310049.2859 | 310132.5989 |
| 75.00 | 313590.0879 | 313673.4009 | 313756.7139 | 313840.0269 | 313923.3398 | 314006.6528 | 314089.9658 | 314173.2788 | 314256.5918 | 314332.9620 |
| 76.00 | 317797.3938 | 317880.7068 | 317964.0198 | 318040.3900 | 318123.7030 | 318207.0160 | 318290.3290 | 318373.6420 | 318456.9550 | 318540.2679 |
| 77.00 | 321997.7570 | 322081.0699 | 322164.3829 | 322247.6959 | 322331.0089 | 322414.3219 | 322490.6921 | 322574.0051 | 322657.3181 | 322740.6311 |
| 78.00 | 326205.0629 | 326288.3759 | 326371.6888 | 326455.0018 | 326531.3721 | 326614.6851 | 326697.9980 | 326781.3110 | 326864.6240 | 326947.9370 |
| 79.00 | 330412.3688 | 330495.6818 | 330578.9948 | 330662.3077 | 330738.6780 | 330821.9910 | 330905.3040 | 330988.6169 | 331071.9299 | 331148.3002 |
| 80.00 | 334626.6174 | 334702.9877 | 334786.3007 | 334869.6136 | 334945.9839 | 335029.2969 | 335112.6099 | 335195.9229 | 335279.2358 | 335355.6061 |
| 81.00 | 338833.9233 | 338917.2363 | 338993.6066 | 339076.9196 | 339153.2898 | 339236.6028 | 339319.9158 | 339403.2288 | 339486.5417 | 339562.9120 |
| 82.00 | 343041.2292 | 343124.5422 | 343207.8552 | 343284.2255 | 343367.5385 | 343443.9087 | 343527.2217 | 343610.5347 | 343693.8477 | 343770.2179 |
| 83.00 | 347255.4779 | 347331.8481 | 347415.1611 | 347498.4741 | 347574.8444 | 347658.1573 | 347734.5276 | 347817.8406 | 347901.1536 | 347984.4666 |
| 84.00 | 351469.7266 | 351546.0968 | 351629.4098 | 351705.7800 | 351789.0930 | 351872.4060 | 351948.7762 | 352032.0892 | 352108.4595 | 352191.7725 |
| 85.00 | 355677.0325 | 355760.3455 | 355843.6584 | 355920.0287 | 356003.3417 | 356079.7119 | 356163.0249 | 356239.3951 | 356322.7081 | 356399.0784 |
| 86.00 | 359891.2811 | 359974.5941 | 360050.9644 | 360134.2773 | 360217.5903 | 360293.9606 | 360370.3308 | 360453.6438 | 360536.9568 | 360613.3270 |
| 87.00 | 364105.5298 | 364188.8428 | 364272.1558 | 364348.5260 | 364424.8962 | 364508.2092 | 364591.5222 | 364667.8925 | 364744.2627 | 364827.5757 |
| 88.00 | 368326.7212 | 368403.0914 | 368486.4044 | 368562.7747 | 368646.0876 | 368722.4579 | 368805.7709 | 368882.1411 | 368965.4541 | 369041.8243 |
| 89.00 | 372540.9698 | 372624.2828 | 372700.6531 | 372783.9661 | 372860.3363 | 372936.7065 | 373020.0195 | 373096.3898 | 373179.7028 | 373256.0730 |
| 90.00 | 376762.1613 | 376838.5315 | 376921.8445 | 376998.2147 | 377074.5850 | 377157.8979 | 377234.2682 | 377317.5812 | 377393.9514 | 377477.2644 |
| 91.00 | 380983.3527 | 381059.7229 | 381143.0359 | 381219.4061 | 381295.7764 | 381379.0894 | 381455.4596 | 381531.8298 | 381615.1428 | 381691.5131 |
| 92.00 | 385204.5441 | 385280.9143 | 385357.2845 | 385440.5975 | 385516.9678 | 385593.3380 | 385669.7083 | 385753.0212 | 385829.3915 | 385905.7617 |
| 93.00 | 389425.7355 | 389502.1057 | 389578.4760 | 389654.8462 | 389738.1592 | 389814.5294 | 389890.8997 | 389974.2126 | 390050.5829 | 390126.9531 |
| 94.00 | 393646.9269 | 393723.2971 | 393806.6101 | 393882.9803 | 393959.3506 | 394035.7208 | 394112.0911 | 394195.4041 | 394271.7743 | 394348.1445 |

| T ,C | h(T, 1bar) J/kg | h(T, 2bar) J/kg | h(T, 3bar) J/kg | h(T, 4bar) J/kg | h(T, 5bar) J/kg | h(T, 6bar) J/kg | h(T, 7bar) J/kg | h(T, 8bar) J/kg | h(T, 9bar) J/kg | h(T,10bar) J/kg |
|---|---|---|---|---|---|---|---|---|---|---|
| 95.00 | 397875.0610 | 397951.4313 | 398027.8015 | 398104.1718 | 398180.5420 | 398263.8550 | 398340.2252 | 398416.5955 | 398492.9657 | 398569.3359 |
| 96.00 | 402096.2524 | 402172.6227 | 402248.9929 | 402332.3059 | 402408.6761 | 402485.0464 | 402561.4166 | 402637.7869 | 402714.1571 | 402790.5273 |
| 97.00 | 406324.3866 | 406400.7568 | 406477.1271 | 406553.4973 | 406629.8676 | 406706.2378 | 406789.5508 | 406865.9210 | 406942.2913 | 407018.6615 |
| 98.00 | 410552.5208 | 410628.8910 | 410705.2612 | 410781.6315 | 410858.0017 | 410934.3719 | 411010.7422 | 411087.1124 | 411163.4827 | 411246.7957 |
| 99.00 | 414780.6549 | 414857.0251 | 414933.3954 | 415009.7656 | 415086.1359 | 415162.5061 | 415238.8763 | 415315.2466 | 415391.6168 | 415467.9871 |
| 100.0 | 419008.7891 | 419085.1593 | 419161.5295 | 419237.8998 | 419314.2700 | 419390.6403 | 419467.0105 | 419543.3807 | 419619.7510 | 419696.1212 |

## 5. Numbering the Outermost Fuel Tube as the First When Using the Radial Geometry Exact Method in PLTEMP – Implementation and Verification

(October 2007)

### 5.1. Introduction

The PLTEMP/ANL code [1] is used in the Reduced Enrichment for Research and Test Reactor (RERTR) Program to do thermal hydraulic analysis of experimental reactors having multi-tube fuel assemblies. The code has a radial geometry capability to calculate temperature distribution in a multi-tube fuel assembly, the based on the Broyden minimization method. The input data for the code could be prepared either numbering the innermost tube as 1, or numbering the outermost tube as 1.

To improve the accuracy and speed of the code, an exact method (also called the exact method) to calculate the temperature distribution in a multi-tube fuel assembly was added to the code recently and is available in the code version 3.2 (V3.2 for brevity) [see Appendix VII in Ref. 1]. That exact method restricts the user to number the innermost fuel tube as 1 during input data preparation. The exact method has now been improved (available in V3.4) to remove this restriction. The input data could now be prepared either numbering the innermost tube as 1, or numbering the outermost tube as 1, even when using the exact method.

The purpose of this memorandum is to document the technique used for this improvement, and the verification of the implemented technique by solving a modified benchmark problem [2]. At the end, a historical perspective on the accuracy of the last five PLTEMP/ANL versions is also presented. V3.4 exact and Broyden solutions agree when tubes are numbered in either direction.

### 5.2. Technique Used if Input Data Has the Outermost Tube First

The exact method used in PLTEMP/ANL when the fuel tubes are numbered in the input data starting from the innermost tube as 1, has been described earlier [Appendix VII in Ref. 1]. In order to handle an input data file having the outermost tube numbered as 1, the code internally rearranges the input data that depend on the *numbering* of fuel tubes and coolant channels, then solves the problem using the earlier method [1], and finally rearranges the solution obtained [3]. The input data card types 307, 308, 308A, 309 and 310 contain all the tube-numbering-dependent input data, altogether 10 arrays. The calculated data that are saved in the direct access file written on logical units 19 and 20, are rearranged after the solution. All rearranging is done in the subroutine SLICE1, using variables that have the suffix _R (e.g., AFF_R, DFF_R). It is noted that the input data arrays read from the input file are never changed during the whole technique. This technique was recently implemented in V3.4 of the PLTEMP/ANL code.

### 5.3. Verification of the Implementation of the Technique

The implementation of the above technique for calculating temperature distribution in radial geometry problems in which the fuel tubes are numbered starting from the outermost tube as 1, was performed by analyzing such a problem, i.e., the Standard Problem 17 whose input data is given in Table 1. This input data file was obtained by modifying a three-tube benchmark problem [2] so that the differences (in coolant, cladding and fuel meat temperatures, and heat transfer coefficients) among the channels are exaggerated so that any possible coding discrepancy can be easily identified in the code output. To obtain the Standard Problem 17 given in Table 1, three changes were made to the older benchmark problem [2]: (i) The cladding thermal conductivity was reduced from 206.0 W/m-°C to 6.0 W/m-°C, (ii) The fuel meat thermal conductivity was reduced from 180.0 W/m-°C to 4.0 W/m-°C, and (iii) The coolant flow rate in coolant channel 2 (the channel inside the outermost fuel tube) was increased 10 times, i.e., was changed from 0.70516 kg/s to 7.0516 kg/s. The changes (i) and (ii) will make the temperature drops across fuel and cladding thicknesses about 40 times larger in Problem 17 compared to those in the original benchmark problem [2]. The change (iii) will make the cladding-to-coolant temperature drop in channel 2 of Problem 17 about one-sixth of that in the original KFKI benchmark problem [2]. This is because the Reynolds number will be 10 times larger, making the heat transfer coefficient about 6 times larger ($10^{0.8} = 6.3$).

Table 2 shows the input data file of a companion problem (Standard Problem 18) obtained from Problem 17 by manually reversing the data on the input card types 307, 308, 308A, 309 and 310 that contain all the tube-numbering-dependent input data.

Six PLTEMP/ANL calculations were performed for these two input data files, using the older code V3.2 and the code V3.4 in which the technique was implemented. Table 3 briefly shows a comparison of these calculations and is discussed below. Tables 4 through 9 show the temperature distribution and heat fluxes obtained in the six calculations. The six calculations are:

(1) Solution of Problem 17 by the Broyden method using the code V3.2
(2) Solution of Problem 18 by the Broyden method using the code V3.2
(3) Solution of Problem 17 by the Broyden method using the code V3.4
(4) Solution of Problem 18 by the Broyden method using the code V3.4
(5) Solution of Problem 17 by the Exact method using the code V3.4
(6) Solution of Problem 18 by the Exact method using the code V3.4

The results in columns A through F of Table 3 are taken from Tables 4 to 9 respectively, and each column presents a solution of a single problem, Standard Problem 17. The results of Problem 18 (from Tables 5, 7, and 9) are given in Table 3 in the reversed order, thus inferring a solution of Problem 17 from each solution of Problem 18. *The objective is to verify the results in column E* obtained by the code V3.4 using the newly implemented technique, for Problem 17 (input data file in Table 1). The first four solutions by the Broyden method (columns A to D of Table 3) establish a solution by a verified existing method that is used to verify the newly implemented technique.

The following observations, specially item (iv), are made to provide a verification of the implementation of the technique:

(i) For each problem (Problem 17 or Problem 18), the Broyden solution obtained after 20 iterations was found to be identical (by the UNIX diff command) to the solution obtained after 200 iterations or 2000 iterations. This is true for both code versions 3.2 and 3.4.

(ii) In each Broyden solution, all Tdiff's (i.e., the mismatch between the peak fuel temperatures computed from the inner and outer surfaces of a tube) are zero, due to good initial guess for starting the Broyden iteration. This implies that each Broyden solution is reliable.

(iii) Table 3 compares the coolant channel temperatures and the location of the maximum temperature in meat thickness, at the channel exit. These quantities are found to be equal in the four Broyden solutions (columns A to D of Table 3). This comparison provides further confidence in the Broyden solutions. A more detailed comparison of these four solutions using Tables 4 to 7 is discussed below in item (v).

(iv) The solution of Problem 17 (column E of Table 3) by the newly-implemented technique is verified by its agreement with the solutions by the Broyden method shown in columns A to D. Furthermore, the column E agrees precisely with the column F which is the solution of Problem 18 obtained by the previously-implemented and verified exact method. Table 8, the source of column E, was hand-compared with Table 9 in the reverse order (the source of column F), and it was found that all the output temperatures, heat fluxes, and heat transfer coefficients in the two tables agree *precisely*. This provides a verification of the newly-implemented technique.

(v) A detailed comparison of the Broyden solutions of Problems 17 and 18 by the code V3.2 (Tables 4 and 5) shows small differences in the fuel and cladding temperatures. The largest difference occurs in fuel assembly's innermost fuel tube (tube 3 of Problem 17, which corresponds to tube 1 of Problem 18) in the cladding surface temperature of axial node 4, and is 0.010 °C (shown underlined and in boldface in Tables 4 and 5). The largest difference between Tables 4 and 5 in tube 1 (of Problem 17) is 0.007 °C, and that in tube 2 is 0.008 °C (shown in boldface in Tables 4 and 5). The V3.2 Broyden solutions for the two companion problems are not exactly the same. *This minor discrepancy is present in the code V3.2 but not in the code V3.4 as discussed next.*

A detailed comparison of the V3.4 Broyden solutions of Problems 17 and 18 (Tables 6 and 7) shows no difference in the fuel and cladding temperatures, or in heat transfer coefficients. Turning to the exact method, a detailed comparison of the V3.4 exact solutions of Problems 17 and 18 (Tables 8 and 9) also shows no difference in the fuel and cladding temperatures, or in heat transfer coefficients. This improvement is probably due to calculating the coolant specific heat in the subroutines HCOEF1 and HCOEF at the actual coolant temperature, rather than using the value of the specific heat already available in the common block A1 (which is done in the code V3.2).

(vi) The Broyden solutions given in Tables 6 and 7 may be considered to be better than the Broyden solutions of Tables 4 and 5 because Tables 6 and 7 are precisely consistent with each other whereas Tables 4 and 5 are only approximately consistent, as discussed in item (v). The maximum temperature difference between the exact solution given in Table 8 or 9 (precisely consistent with each other) and the Broyden solution given in Table 6 or

7 is 0.009 °C (65.802 °C versus 65.811 °C, occurring in channel 4 coolant temperature of node 8) as summarized in Table 3. The cause of this difference is not clear.

### 5.4. Historical Perspective on PLTEMP/ANL Code Versions

To get a historical perspective on the improvements made in PLTEMP/ANL, five code versions V3.0, V3.1, V3.2, V3.3, and V3.4 were run for Problems 17 and 18, using both the Broyden and the exact methods. Out of the 20 runs, two did not produce a solution. These two are the runs of PLTEMP/ANL V3.2 and V3.3 for Problem 17 using the exact method. This is because these versions do not have an exact method to handle radial geometry problems in which the outermost fuel tube is numbered as the first. PLTEMP/ANL V3.2 and V3.3 do have the exact method to handle radial geometry problems in which the innermost fuel tube is numbered as the first. It is noted that PLTEMP/ANL V3.0 and V3.1 do not have any radial geometry exact method (although do have the slab geometry exact method) but they run for both Problems 17 and 18 by using the slab geometry exact method (which is acceptable in problems with high thermal conductivity solids and large fuel tube radii). PLTEMP/ANL V3.0 and V3.1 should not be used for problems with low thermal conductivity solids (e.g., Problems 17 and 18).

Altogether 18 solutions were obtained: 5 Broyden solutions for Problem 17, 5 Broyden solutions for Problem 18, 3 exact solutions for Problem 17, and 5 exact solutions for Problem 18. Fifteen iterations were used in the Broyden solutions, and each Tdiff was found to be zero in all 10 Broyden solutions.

The 18 solutions obtained are compared in Table 10. First, each version's Broyden solution is compared with the Broyden solution of the latest version, i.e., V3.4. Next, each version's exact solution is compared with the exact solution of V3.4 (see Table 10). Finally, each exact solution is compared with the Broyden solution obtained by the same code version. All these comparisons were made using a program *differ.f* developed earlier to compare two PLTEMP/ANL output files and to find the maximum temperature difference for each fuel tube in the output file. The maximum difference is determined over all cladding, fuel, and adjacent coolant channel temperatures of a fuel tube (i.e., a table in the code output file).

Table 10 shows that the Problems 17 and 18 solutions by the V3.0 Broyden method are not good. There is an error of 10.0 °C in the innermost fuel tube for these problems (see Table 10). By running V3.0 for the original benchmark problems [2], it is found that this error is 3.2 °C (which is lower but still not acceptable). Also, the solutions by the (slab geometry) exact method in V3.0 and V3.1 are not good for these radial geometry problems. Altogether, six solutions are not good. The remaining 12 solutions are good, and are listed below:

(i) The Broyden solutions of both problems by V3.1, V3.2, V3.3, and V3.4 (8 solutions)
(ii) The exact solutions of Problem 18 by V3.2, V3.3, and V3.4 (3 solutions)
(ii) The exact solution of Problem 17 by V3.4

In conclusion, the code V3.4 has a maximum difference of 0.009 °C between the solutions obtained by the Broyden and exact methods for Problems 17 and 18. This provides an additional verification of the implementation of the technique.

## REFERENCES


1. A. P. Olson and M. Kalimullah, Argonne National Laboratory, unpublished information, April 14, 2007.

2. E. E. Feldman, Argonne National Laboratory, unpublished information, October 2006.

3. E. E. Feldman and A. P. Olson, Argonne National Laboratory, private communication, August 2007.

**Table 1. Input Data for Standard Problem 17 Having the Outermost Tube Numbered First in the Input Data**

```
Stdproblem 17, Outermost Tube First, Based on Hungarian Reactor Benchmark; 90 kW Card 100
   0   0   5   1   0   0   0   0   1   0   0   0   0   0   1   1   0   0        Card 200
   1   3         0.0         1.0         1.0         1.0   0   0                Card 300
   1   2         1.0                                                            Card 301
   1   1   1                                                                    Card 302
       1.53                                                                     Card 303
        1.0         1.0         1.0         1.0         1.0         1.0         Card 304
        1.0         1.0         1.0         1.0         1.0         1.0         Card 304
        1.0         1.0         1.0         1.0         1.0         1.0         Card 304
        0.0         0.0         0.0                                             Card 305
   4   0         0.0        0.58      0.76e-3        6.00      0.98e-3        4.00 Card 306
  1.8003E-04  6.6631E-03  1.0808E-01  1.0808E-01        1.0         1.0         Card 307
  2.5015E-04  6.1964E-03  1.6148E-01  1.6148E-01        1.0         1.0         Card 307
  1.3195E-04  6.0000E-03  8.7965E-02  8.7965E-02        1.0         1.0         Card 307
  2.8274E-05  6.0000E-03  1.8850E-02  1.8850E-02        1.0         1.0         Card 307
  1.0022E-01  6.1261E-02  2.6704E-02                                            Card 308
   0.0159511   0.0097500   0.0042500                                            Card 308A
        1.0         1.0         1.0                                             Card 309
  5.1356E-01  7.0516E-00  3.6415E-01  7.8065E-02                                Card 310
      0.127       0.001       0.130      90.e-3         50.                     Card 500
        0.0         0.0                                                         Card 500
   1      0.0001        36.8         0.0         1.0                            Card 600
  -9                                                                            Card 701
      0.000      0.0625     0.30448                                             Card 701
      0.125      0.1875     0.86709                                             Card 701
      0.250      0.3125     1.29769                                             Card 701
      0.375      0.4375     1.53073                                             Card 701
      0.500      0.5625     1.53073                                             Card 701
      0.625      0.6875     1.29769                                             Card 701
      0.750      0.8125     0.86709                                             Card 701
      0.875      0.9375     0.30448                                             Card 701
      1.000                                                                     Card 701
   0                                                                            Card 702
```

## Table 2. Input Data for Standard Problem 18 Having the Innermost Tube Numbered First in the Input Data

```
Stdproblem 18, Innermost Tube First, Based on Hungarian Reactor Benchmark; 90 kW Card 100
   0   0   5   1   0   0   0   0   1   0   0   0   0   0   1   1   0   0         Card 200
   1   3         0.0         1.0         1.0         1.0   0   0                 Card 300
   1   2         1.0                                                             Card 301
   1   1   1                                                                     Card 302
        1.53                                                                     Card 303
         1.0         1.0         1.0         1.0         1.0         1.0         Card 304
         1.0         1.0         1.0         1.0         1.0         1.0         Card 304
         1.0         1.0         1.0         1.0         1.0         1.0         Card 304
         0.0         0.0         0.0                                             Card 305
   4   0         0.0        0.58     0.76e-3        6.00     0.98e-3        4.00 Card 306
  2.8274E-05  6.0000E-03  1.8850E-02  1.8850E-02         1.0         1.0         Card 307
  1.3195E-04  6.0000E-03  8.7965E-02  8.7965E-02         1.0         1.0         Card 307
  2.5015E-04  6.1964E-03  1.6148E-01  1.6148E-01         1.0         1.0         Card 307
  1.8003E-04  6.6631E-03  1.0808E-01  1.0808E-01         1.0         1.0         Card 307
  2.6704E-02  6.1261E-02  1.0022E-01                                             Card 308
   0.0042500   0.0097500   0.0159511                                             Card 308A
         1.0         1.0         1.0                                             Card 309
  7.8065E-02  3.6415E-01  7.0516E-00  5.1356E-01                                 Card 310
       0.127       0.001       0.130      90.e-3         50.                     Card 500
         0.0         0.0                                                         Card 500
   1      0.0001        36.8         0.0         1.0                             Card 600
  -9                                                                             Card 700
       0.000      0.0625     0.30448                                             Card 701
       0.125      0.1875     0.86709                                             Card 701
       0.250      0.3125     1.29769                                             Card 701
       0.375      0.4375     1.53073                                             Card 701
       0.500      0.5625     1.53073                                             Card 701
       0.625      0.6875     1.29769                                             Card 701
       0.750      0.8125     0.86709                                             Card 701
       0.875      0.9375     0.30448                                             Card 701
       1.000                                                                     Card 701
   0                                                                             Card 702
```

**Table 3. Comparison of Six Solutions of Standard Problem 17 to Verify PLTEMP/ANL V3.4**

| | PLTEMP/ANL V3.2 | | PLTEMP/ANL V3.4 | | | |
|---|---|---|---|---|---|---|
| | Problem 17 by Broyden Method | Solve Problem 18 by Broyden Method and then Reverse the Results | Problem17 by Broyden Method | Solve Problem 18 by Broyden Method and then Reverse the Results | Problem 17 by Exact Method | Solve Problem 18 by Exact Method and then Reverse the Results |
| | A | B | C | D | E | F |
| Table Showing Code Output | Table 4 | Table 5 | Table 6 | Table 7 | Table 8 | Table 9 |
| Channel Number | **Coolant Exit Temperature in Channel, °C** | | | | | |
| 1 | 60.512 | 60.512 | 60.512 | 60.512 | 60.510 | 60.510 |
| 2 | 51.439 | 51.439 | 51.439 | 51.439 | 51.440 | 51.440 |
| 3 | 62.885 | 62.885 | 62.885 | 62.885 | 62.885 | 62.885 |
| 4 | 66.105 | 66.105 | 66.105 | 66.105 | 66.097 | 66.097 |
| | **Maximum Difference Between Code Runs in Coolant, Cladding and Fuel Temperatures, °C** | | | | | |
| Table 8 or 9 vs. Table 4 | | | | | 0.012 | |
| Table 8 or 9 vs. Table 5 | | | | | | 0.017 |
| Table 8 or 9 vs. Table 6 | | | | | 0.009 | 0.009 |
| Table 8 or 9 vs. Table 7 | | | | | 0.009 | 0.009 |
| Fuel Tube Number | **Location of Maximum Temperature in Meat At Exit, Outer Areal Fraction** | | | | | |
| 1 | 0.4182 | 0.4182 | 0.4182 | 0.4182 | 0.4182 | 0.4182 |
| 2 | 0.6516 | 0.6516 | 0.6516 | 0.6516 | 0.6516 | 0.6516 |
| 3 | 0.6045 | 0.6045 | 0.6045 | 0.6045 | 0.6044 | 0.6044 |
| Number of Broyden Iterations | 20 (Note 1) | 20 (Note 1) | 20 (Note 1) | 20 (Note 1) | - | - |
| Maximum $T_{diff}$, °C | 0.0 | 0.0 | 0.0 | 0.0 | - | - |
| Note 1. Using 20 iterations gave the same results as using 200 iterations. | | | | | | |

## Table 4. PLTEMP V3.2 Output for Problem 17 Having the Outermost Tube First in Input Data – Broyden Method

| NODE | COOLANT outer(C) | CladSurf outer(C) | FUEL PEAK (C) | CladSurf inner(C) | COOLANT inner(C) | HCOFouter W/C-m^2 | HCOFinner W/C-m^2 | ONBRout | ONBRin [F Note 1] | ETAout K-cm^3/J | ETAin K-cm^3/J | COOLNT at outer(C) | NodeOutlet inner(C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| FUEL PLATE 1 (BroydenSoln) | | | | | | | | | | | | | |
| | 50.000 | | | | 50.000 | | | | | | | | |
| 1 | 50.202 | 56.552 | 77.664 | 51.327 | 50.027 | 1.7498E+04 | 1.0952E+05 | 9.35 | 46.54 | 1.481E+03 | 1.143E+04 | 50.405 | 50.054 |
| 2 | 50.982 | 68.547 | 128.734 | 53.808 | 50.131 | 1.8029E+04 | 1.1023E+05 | 3.44 | 16.98 | 5.118E+02 | 4.003E+03 | 51.559 | 50.208 |
| 3 | 52.422 | **78.024** | 168.023 | 55.798 | 50.324 | 1.8499E+04 | 1.1086E+05 | 2.32 | 11.41 | 3.329E+02 | 2.660E+03 | 53.285 | 50.439 |
| 4 | 54.301 | **83.819** | 189.706 | 57.016 | 50.575 | 1.8889E+04 | 1.1135E+05 | 1.94 | 9.52 | 2.726E+02 | 2.238E+03 | 55.317 | 50.712 |
| 5 | 56.329 | 85.297 | 190.626 | 57.297 | 50.849 | 1.9171E+04 | 1.1162E+05 | 1.86 | 9.15 | 2.626E+02 | 2.215E+03 | 57.340 | 50.986 |
| 6 | 58.191 | 82.382 | 170.727 | 56.608 | 51.103 | 1.9307E+04 | 1.1164E+05 | 2.00 | 9.99 | 3.003E+02 | 2.579E+03 | 59.042 | 51.219 |
| 7 | 59.600 | 75.492 | 133.034 | 55.048 | 51.299 | 1.9259E+04 | 1.1140E+05 | 2.48 | 12.75 | 4.440E+02 | 3.775E+03 | 60.158 | 51.379 |
| 8 | 60.335 | 65.463 | 83.222 | 52.838 | 51.409 | 1.8987E+04 | 1.1093E+05 | 3.91 | 21.66 | 1.372E+03 | 9.913E+03 | 60.512 | 51.439 |
| | 60.512 | | | | 51.439 | | | | | | | | |
| FUEL PLATE 2 (BroydenSoln) | | | | | | | | | | | | | |
| | 50.000 | | | | 50.000 | | | | | | | | |
| 1 | 50.027 | 51.203 | 77.794 | 57.207 | 50.248 | 1.0949E+05 | 1.7431E+04 | 51.16 | 8.52 | 1.264E+04 | 1.312E+03 | 50.054 | 50.495 |
| 2 | 50.131 | 53.459 | 129.104 | 70.396 | 51.201 | 1.1014E+05 | 1.8016E+04 | 18.59 | 3.14 | 4.426E+03 | 4.519E+02 | 50.208 | 51.906 |
| 3 | 50.324 | 55.280 | 168.601 | 80.847 | 52.961 | 1.1074E+05 | 1.8543E+04 | 12.45 | 2.12 | 2.941E+03 | 2.922E+02 | 50.439 | 54.016 |
| 4 | 50.575 | 56.409 | 190.441 | **87.284** | 55.258 | 1.1120E+05 | 1.8994E+04 | 10.35 | 1.77 | 2.474E+03 | 2.375E+02 | 50.712 | 56.500 |
| 5 | 50.849 | 56.691 | 191.462 | 89.030 | 57.739 | 1.1147E+05 | 1.9333E+04 | 9.91 | 1.69 | 2.448E+03 | 2.269E+02 | 50.986 | 58.977 |
| 6 | 51.103 | 56.094 | 171.613 | 86.010 | 60.021 | 1.1151E+05 | 1.9513E+04 | 10.76 | 1.81 | 2.847E+03 | 2.576E+02 | 51.219 | 61.064 |
| 7 | 51.299 | 54.703 | 133.919 | 78.666 | 61.751 | 1.1132E+05 | 1.9494E+04 | 13.61 | 2.22 | 4.161E+03 | 3.807E+02 | 51.379 | 62.438 |
| 8 | 51.409 | 52.716 | 84.086 | 67.878 | 62.661 | 1.1090E+05 | 1.9234E+04 | 22.55 | 3.38 | 1.084E+04 | 1.223E+03 | 51.439 | 62.885 |
| | 51.439 | | | | 62.885 | | | | | | | | |
| FUEL PLATE 3 (BroydenSoln) | | | | | | | | | | | | | |
| | 50.000 | | | | 50.000 | | | | | | | | |
| 1 | 50.248 | 56.785 | 81.516 | 58.704 | 50.307 | 1.7415E+04 | 1.7501E+04 | 9.04 | 7.11 | 1.398E+03 | 1.084E+03 | 50.495 | 50.614 |
| 2 | 51.201 | 69.222 | 139.574 | 74.524 | 51.490 | 1.7978E+04 | 1.8188E+04 | 3.32 | 2.64 | 4.824E+02 | 3.718E+02 | 51.906 | 52.366 |
| 3 | 52.961 | 79.171 | 184.426 | 87.029 | 53.677 | 1.8495E+04 | 1.8805E+04 | 2.24 | 1.79 | 3.117E+02 | 2.382E+02 | 54.016 | 54.988 |
| 4 | 55.258 | 85.446 | 209.621 | **94.755** | 56.535 | 1.8944E+04 | 1.9353E+04 | 1.86 | 1.50 | 2.526E+02 | 1.908E+02 | 56.500 | 58.081 |
| 5 | 57.739 | 87.408 | 211.708 | 96.989 | 59.626 | 1.9289E+04 | 1.9778E+04 | 1.76 | 1.42 | 2.398E+02 | 1.789E+02 | 58.977 | 61.171 |
| 6 | 60.021 | 84.968 | 190.623 | 93.695 | 62.477 | 1.9483E+04 | 2.0013E+04 | 1.86 | 1.51 | 2.687E+02 | 1.984E+02 | 61.064 | 63.783 |
| 7 | 61.751 | 78.496 | 149.569 | 85.359 | 64.650 | 1.9488E+04 | 2.0021E+04 | 2.23 | 1.82 | 3.847E+02 | 2.838E+02 | 62.438 | 65.517 |
| 8 | 62.661 | 68.749 | 94.532 | 72.931 | 65.811 | 1.9266E+04 | 1.9759E+04 | 3.24 | 2.67 | 1.047E+03 | 8.114E+02 | 62.885 | 66.105 |
| | 62.885 | | | | 66.105 | | | | | | | | |

[1] The ONB ratio is here defined as (Tonb - Tinlet)/(Tsurf - Tinlet). If the heat flux is negative (the coolant is hotter than the adjacent cladding surface), then the ONB ratio is arbitrarily set to 99.99 .

FUEL PLATE 1 (BroydenSoln) AREAL

| NODE | FLUX outer MW/m^2 | FLUX inner MW/m^2 | FUEL X outer | Tsat (C) | Tdiff (C) | FUEL-CLADinterface outer (C) | FUEL-CLADinterface inner (C) | Pressure (bar) | Z-mid | Z-int |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.1111E-01 | 1.4241E-01 | 0.4772 | 107.091 | 0.00 | 70.947 | 68.915 | 1.29812 | 0.0625 | 0.1250 |
| 2 | 3.1667E-01 | 4.0525E-01 | 0.4776 | 107.006 | 0.00 | 109.572 | 103.856 | 1.29438 | 0.1875 | 0.2500 |
| 3 | 4.7362E-01 | 6.0686E-01 | 0.4773 | 106.921 | 0.00 | 139.382 | 130.746 | 1.29062 | 0.3125 | 0.3750 |
| 4 | 5.5759E-01 | 7.1712E-01 | 0.4764 | 106.836 | 0.00 | 156.055 | 145.580 | 1.28688 | 0.4375 | 0.5000 |
| 5 | 5.5537E-01 | 7.1972E-01 | 0.4745 | 106.751 | 0.00 | 157.245 | 146.183 | 1.28313 | 0.5625 | 0.6250 |
| 6 | 4.6703E-01 | 6.1457E-01 | 0.4707 | 106.666 | 0.00 | 142.886 | 132.508 | 1.27938 | 0.6875 | 0.7500 |
| 7 | 3.0608E-01 | 4.1765E-01 | 0.4616 | 106.580 | 0.00 | 115.144 | 106.628 | 1.27562 | 0.8125 | 0.8750 |
| 8 | 9.7362E-02 | 1.5850E-01 | 0.4182 | 106.495 | 0.00 | 78.076 | 72.412 | 1.27188 | 0.9375 | 1.0000 |

FUEL PLATE 2 (BroydenSoln)

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.2879E-01 | 1.2131E-01 | 0.5788 | 107.091 | 0.00 | 68.108 | 71.925 | 1.29812 | 0.0625 | 0.1250 |
| 2 | 3.6649E-01 | 3.4584E-01 | 0.5783 | 107.006 | 0.00 | 101.563 | 112.354 | 1.29438 | 0.1875 | 0.2500 |
| 3 | 5.4888E-01 | 5.1709E-01 | 0.5787 | 106.921 | 0.00 | 127.324 | 143.580 | 1.29062 | 0.3125 | 0.3750 |
| 4 | 6.4872E-01 | 6.0830E-01 | 0.5798 | 106.836 | 0.00 | 141.557 | 161.084 | 1.28688 | 0.4375 | 0.5000 |
| 5 | 6.5131E-01 | 6.0495E-01 | 0.5822 | 106.751 | 0.00 | 142.179 | 162.423 | 1.28313 | 0.5625 | 0.6250 |
| 6 | 5.5658E-01 | 5.0712E-01 | 0.5868 | 106.666 | 0.00 | 129.147 | 147.534 | 1.27938 | 0.6875 | 0.7500 |
| 7 | 3.7893E-01 | 3.2975E-01 | 0.5979 | 106.580 | 0.00 | 104.440 | 118.671 | 1.27562 | 0.8125 | 0.8750 |
| 8 | 1.4500E-01 | 1.0034E-01 | 0.6516 | 106.495 | 0.00 | 71.749 | 80.051 | 1.27188 | 0.9375 | 1.0000 |

FUEL PLATE 3 (BroydenSoln)

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.1385E-01 | 1.4695E-01 | 0.5869 | 107.091 | 0.00 | 72.305 | 75.295 | 1.29812 | 0.0625 | 0.1250 |
| 2 | 3.2398E-01 | 4.1892E-01 | 0.5864 | 107.006 | 0.00 | 113.386 | 121.822 | 1.29438 | 0.1875 | 0.2500 |
| 3 | 4.8475E-01 | 6.2718E-01 | 0.5863 | 106.921 | 0.00 | 145.252 | 157.840 | 1.29062 | 0.3125 | 0.3750 |
| 4 | 5.7187E-01 | 7.3970E-01 | 0.5863 | 106.836 | 0.00 | 163.402 | 178.269 | 1.28688 | 0.4375 | 0.5000 |
| 5 | 5.7228E-01 | 7.3894E-01 | 0.5867 | 106.751 | 0.00 | 165.420 | 180.418 | 1.28313 | 0.5625 | 0.6250 |
| 6 | 4.8607E-01 | 6.2477E-01 | 0.5879 | 106.666 | 0.00 | 151.228 | 164.234 | 1.27938 | 0.6875 | 0.7500 |
| 7 | 3.2634E-01 | 4.1460E-01 | 0.5907 | 106.580 | 0.00 | 122.982 | 132.169 | 1.27562 | 0.8125 | 0.8750 |
| 8 | 1.1727E-01 | 1.4068E-01 | 0.6045 | 106.495 | 0.00 | 84.735 | 88.814 | 1.27188 | 0.9375 | 1.0000 |

## Table 5. PLTEMP V3.2 Output for Problem 18 Having the Innermost Tube First in Input Data – Broyden Method

| NODE | COOLANT inner(C) | CladSurf inner(C) | FUEL PEAK (C) | CladSurf outer(C) | COOLANT outer(C) | HCOFinner W/C-m^2 | HCOFouter W/C-m^2 | ONBRin [F Note 1] | ONBRout | ETAin K-cm^3/J | ETAout K-cm^3/J | COOLNT at inner(C) | NodeOutlet outer(C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| FUEL PLATE 1 (BroydenSoln) | | | | | | | | | | | | | |
| | 50.000 | | | | 50.000 | | | | | | | | |
| 1 | 50.307 | 58.706 | 81.518 | 56.787 | 50.248 | 1.7496E+04 | 1.7411E+04 | 7.10 | 9.03 | 1.084E+03 | 1.398E+03 | 50.614 | 50.495 |
| 2 | 51.490 | 74.529 | 139.580 | 69.226 | 51.201 | 1.8183E+04 | 1.7973E+04 | 2.64 | 3.32 | 3.718E+02 | 4.824E+02 | 52.366 | 51.906 |
| 3 | 53.677 | 87.037 | 184.433 | 79.178 | 52.961 | 1.8800E+04 | 1.8490E+04 | 1.79 | 2.24 | 2.382E+02 | 3.117E+02 | 54.988 | 54.016 |
| 4 | 56.535 | **94.765** | 209.629 | 85.453 | 55.258 | 1.9349E+04 | 1.8939E+04 | 1.50 | 1.86 | 1.908E+02 | 2.526E+02 | 58.081 | 56.500 |
| 5 | 59.626 | 96.998 | 211.716 | 87.416 | 57.739 | 1.9773E+04 | 1.9284E+04 | 1.42 | 1.76 | 1.789E+02 | 2.398E+02 | 61.171 | 58.977 |
| 6 | 62.477 | 93.703 | 190.630 | 84.975 | 60.020 | 2.0008E+04 | 1.9479E+04 | 1.51 | 1.86 | 1.985E+02 | 2.687E+02 | 63.783 | 61.064 |
| 7 | 64.650 | 85.364 | 149.574 | 78.500 | 61.751 | 2.0016E+04 | 1.9483E+04 | 1.82 | 2.23 | 2.838E+02 | 3.847E+02 | 65.517 | 62.437 |
| 8 | 65.811 | 72.932 | 94.534 | 68.750 | 62.661 | 1.9754E+04 | 1.9261E+04 | 2.67 | 3.24 | 8.114E+02 | 1.047E+03 | 66.105 | 62.885 |
| | 66.105 | | | | 62.885 | | | | | | | | |
| FUEL PLATE 2 (BroydenSoln) | | | | | | | | | | | | | |
| | 50.000 | | | | 50.000 | | | | | | | | |
| 1 | 50.248 | 57.209 | 77.796 | 51.204 | 50.027 | 1.7427E+04 | 1.0946E+05 | 8.52 | 51.14 | 1.312E+03 | 1.264E+04 | 50.495 | 50.054 |
| 2 | 51.201 | 70.401 | 129.107 | 53.460 | 50.131 | 1.8012E+04 | 1.1011E+05 | 3.14 | 18.58 | 4.519E+02 | 4.426E+03 | 51.906 | 50.208 |
| 3 | 52.961 | 80.854 | 168.605 | 55.282 | 50.324 | 1.8538E+04 | 1.1071E+05 | 2.12 | 12.44 | 2.923E+02 | 2.941E+03 | 54.016 | 50.439 |
| 4 | 55.258 | **87.292** | 190.446 | 56.411 | 50.575 | 1.8989E+04 | 1.1117E+05 | 1.77 | 10.35 | 2.375E+02 | 2.474E+03 | 56.500 | 50.712 |
| 5 | 57.739 | 89.037 | 191.467 | 56.693 | 50.849 | 1.9328E+04 | 1.1144E+05 | 1.69 | 9.91 | 2.269E+02 | 2.448E+03 | 58.977 | 50.986 |
| 6 | 60.020 | 86.016 | 171.617 | 56.095 | 51.103 | 1.9508E+04 | 1.1148E+05 | 1.81 | 10.76 | 2.576E+02 | 2.847E+03 | 61.064 | 51.220 |
| 7 | 61.751 | 78.670 | 133.922 | 54.704 | 51.299 | 1.9489E+04 | 1.1129E+05 | 2.22 | 13.61 | 3.807E+02 | 4.161E+03 | 62.437 | 51.379 |
| 8 | 62.661 | 67.879 | 84.087 | 52.717 | 51.409 | 1.9229E+04 | 1.1087E+05 | 3.38 | 22.55 | 1.223E+03 | 1.084E+04 | 62.885 | 51.439 |
| | 62.885 | | | | 51.439 | | | | | | | | |
| FUEL PLATE 3 (BroydenSoln) | | | | | | | | | | | | | |
| | 50.000 | | | | 50.000 | | | | | | | | |
| 1 | 50.027 | 51.328 | 77.665 | 56.554 | 50.202 | 1.0949E+05 | 1.7493E+04 | 46.53 | 9.35 | 1.143E+04 | 1.481E+03 | 50.054 | 50.405 |
| 2 | 50.131 | 53.809 | 128.737 | 68.551 | 50.982 | 1.1020E+05 | 1.8024E+04 | 16.97 | 3.44 | 4.003E+03 | 5.118E+02 | 50.208 | 51.559 |
| 3 | 50.324 | 55.799 | 168.027 | **78.030** | 52.422 | 1.1084E+05 | 1.8494E+04 | 11.41 | 2.32 | 2.660E+03 | 3.329E+02 | 50.439 | 53.285 |
| 4 | 50.575 | 57.018 | 189.711 | **83.826** | 54.301 | 1.1132E+05 | 1.8885E+04 | 9.52 | 1.94 | 2.238E+03 | 2.726E+02 | 50.712 | 55.317 |
| 5 | 50.849 | 57.298 | 190.630 | 85.304 | 56.328 | 1.1159E+05 | 1.9166E+04 | 9.15 | 1.86 | 2.215E+03 | 2.627E+02 | 50.986 | 57.340 |
| 6 | 51.103 | 56.609 | 170.731 | 82.387 | 58.191 | 1.1161E+05 | 1.9302E+04 | 9.98 | 2.00 | 2.579E+03 | 3.003E+02 | 51.220 | 59.042 |
| 7 | 51.299 | 55.049 | 133.037 | 75.496 | 59.600 | 1.1137E+05 | 1.9255E+04 | 12.75 | 2.48 | 3.775E+03 | 4.440E+02 | 51.379 | 60.158 |
| 8 | 51.409 | 52.838 | 83.223 | 65.464 | 60.335 | 1.1090E+05 | 1.8982E+04 | 21.66 | 3.91 | 9.913E+03 | 1.372E+03 | 51.439 | 60.512 |
| | 51.439 | | | | 60.512 | | | | | | | | |

[1] The ONB ratio is here defined as (Tonb - Tinlet)/(Tsurf - Tinlet). If the heat flux is negative (the coolant is hotter than the adjacent cladding surface), then the ONB ratio is arbitrarily set to 99.99 .

FUEL PLATE 1 (BroydenSoln) AREAL

| NODE | FLUX inner MW/m^2 | FLUX outer MW/m^2 | FUEL X inner | Tsat (C) | Tdiff (C) | FUEL-CLADinterface inner (C) | outer (C) | Pressure (bar) | Z-mid | Z-int |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.4695E-01 | 1.1385E-01 | 0.4131 | 107.091 | 0.00 | 75.297 | 72.307 | 1.29812 | 0.0625 | 0.1250 |
| 2 | 4.1892E-01 | 3.2398E-01 | 0.4136 | 107.006 | 0.00 | 121.827 | 113.391 | 1.29438 | 0.1875 | 0.2500 |
| 3 | 6.2717E-01 | 4.8476E-01 | 0.4137 | 106.921 | 0.00 | 157.847 | 145.259 | 1.29062 | 0.3125 | 0.3750 |
| 4 | 7.3969E-01 | 5.7187E-01 | 0.4137 | 106.836 | 0.00 | 178.278 | 163.410 | 1.28688 | 0.4375 | 0.5000 |
| 5 | 7.3894E-01 | 5.7228E-01 | 0.4132 | 106.751 | 0.00 | 180.427 | 165.428 | 1.28313 | 0.5625 | 0.6250 |
| 6 | 6.2477E-01 | 4.8607E-01 | 0.4121 | 106.666 | 0.00 | 164.241 | 151.235 | 1.27938 | 0.6875 | 0.7500 |
| 7 | 4.1460E-01 | 3.2634E-01 | 0.4093 | 106.580 | 0.00 | 132.173 | 122.987 | 1.27562 | 0.8125 | 0.8750 |
| 8 | 1.4068E-01 | 1.1727E-01 | 0.3955 | 106.495 | 0.00 | 88.815 | 84.736 | 1.27188 | 0.9375 | 1.0000 |

FUEL PLATE 2 (BroydenSoln)

| NODE | FLUX inner MW/m^2 | FLUX outer MW/m^2 | FUEL X inner | Tsat (C) | Tdiff (C) | FUEL-CLADinterface inner (C) | outer (C) | Pressure (bar) | Z-mid | Z-int |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.2131E-01 | 1.2880E-01 | 0.4212 | 107.091 | 0.00 | 71.926 | 68.109 | 1.29812 | 0.0625 | 0.1250 |
| 2 | 3.4583E-01 | 3.6650E-01 | 0.4217 | 107.006 | 0.00 | 112.357 | 101.564 | 1.29438 | 0.1875 | 0.2500 |
| 3 | 5.1708E-01 | 5.4889E-01 | 0.4213 | 106.921 | 0.00 | 143.585 | 127.326 | 1.29062 | 0.3125 | 0.3750 |
| 4 | 6.0829E-01 | 6.4873E-01 | 0.4201 | 106.836 | 0.00 | 161.090 | 141.560 | 1.28688 | 0.4375 | 0.5000 |
| 5 | 6.0494E-01 | 6.5132E-01 | 0.4178 | 106.751 | 0.00 | 162.429 | 142.182 | 1.28313 | 0.5625 | 0.6250 |
| 6 | 5.0711E-01 | 5.5659E-01 | 0.4132 | 106.666 | 0.00 | 147.539 | 129.150 | 1.27938 | 0.6875 | 0.7500 |
| 7 | 3.2974E-01 | 3.7893E-01 | 0.4021 | 106.580 | 0.00 | 118.674 | 104.441 | 1.27562 | 0.8125 | 0.8750 |
| 8 | 1.0033E-01 | 1.4501E-01 | 0.3484 | 106.495 | 0.00 | 80.051 | 71.750 | 1.27188 | 0.9375 | 1.0000 |

FUEL PLATE 3 (BroydenSoln)

| NODE | FLUX inner MW/m^2 | FLUX outer MW/m^2 | FUEL X inner | Tsat (C) | Tdiff (C) | FUEL-CLADinterface inner (C) | outer (C) | Pressure (bar) | Z-mid | Z-int |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.4241E-01 | 1.1111E-01 | 0.5228 | 107.091 | 0.00 | 68.916 | 70.948 | 1.29812 | 0.0625 | 0.1250 |
| 2 | 4.0526E-01 | 3.1667E-01 | 0.5224 | 107.006 | 0.00 | 103.858 | 109.576 | 1.29438 | 0.1875 | 0.2500 |
| 3 | 6.0687E-01 | 4.7361E-01 | 0.5227 | 106.921 | 0.00 | 130.749 | 139.387 | 1.29062 | 0.3125 | 0.3750 |
| 4 | 7.1713E-01 | 5.5758E-01 | 0.5236 | 106.836 | 0.00 | 145.583 | 156.061 | 1.28688 | 0.4375 | 0.5000 |
| 5 | 7.1973E-01 | 5.5536E-01 | 0.5255 | 106.751 | 0.00 | 146.186 | 157.251 | 1.28313 | 0.5625 | 0.6250 |
| 6 | 6.1458E-01 | 4.6703E-01 | 0.5293 | 106.666 | 0.00 | 132.511 | 142.891 | 1.27938 | 0.6875 | 0.7500 |
| 7 | 4.1765E-01 | 3.0607E-01 | 0.5384 | 106.580 | 0.00 | 106.630 | 115.147 | 1.27562 | 0.8125 | 0.8750 |
| 8 | 1.5850E-01 | 9.7361E-02 | 0.5818 | 106.495 | 0.00 | 72.413 | 78.077 | 1.27188 | 0.9375 | 1.0000 |

## Table 6. PLTEMP V3.4 Output for Problem 17 Having the Outermost Tube First in Input Data – Broyden Method

| NODE | COOLANT outer(C) | CladSurf outer(C) | FUEL PEAK (C) | CladSurf inner(C) | COOLANT inner(C) | HCOFouter W/C-m^2 | HCOFinner W/C-m^2 | ONBRout [F Note 1] | ONBRin [F Note 1] | ETAout K-cm^3/J | ETAin K-cm^3/J | ONB Temp outer(C) | ONB Temp inner(C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| FUEL PLATE 1 (BroydenSoln) | | | | | | | | | | | | | |
| | 50.000 | | | | 50.000 | | | | | | | | |
| 1 | 50.202 | 56.556 | 77.666 | 51.328 | 50.027 | 1.7488E+04 | 1.0946E+05 | 9.34 | 46.51 | 1.481E+03 | 1.143E+04 | 111.262 | 111.774 |
| 2 | 50.982 | 68.555 | 128.740 | 53.810 | 50.131 | 1.8019E+04 | 1.1017E+05 | 3.44 | 16.97 | 5.118E+02 | 4.003E+03 | 113.810 | 114.638 |
| 3 | 52.422 | 78.035 | 168.030 | 55.801 | 50.324 | 1.8491E+04 | 1.1080E+05 | 2.32 | 11.40 | 3.329E+02 | 2.660E+03 | 115.139 | 116.145 |
| 4 | 54.301 | 83.828 | 189.712 | 57.019 | 50.575 | 1.8883E+04 | 1.1129E+05 | 1.94 | 9.52 | 2.726E+02 | 2.238E+03 | 115.715 | 116.819 |
| 5 | 56.328 | 85.303 | 190.630 | 57.300 | 50.849 | 1.9167E+04 | 1.1156E+05 | 1.86 | 9.15 | 2.627E+02 | 2.215E+03 | 115.626 | 116.764 |
| 6 | 58.191 | 82.384 | 170.730 | 56.610 | 51.103 | 1.9305E+04 | 1.1158E+05 | 2.00 | 9.98 | 3.003E+02 | 2.579E+03 | 114.864 | 115.982 |
| 7 | 59.600 | 75.492 | 133.035 | 55.050 | 51.299 | 1.9260E+04 | 1.1135E+05 | 2.48 | 12.75 | 4.440E+02 | 3.775E+03 | 113.324 | 114.374 |
| 8 | 60.335 | 65.463 | 83.222 | 52.838 | 51.409 | 1.8988E+04 | 1.1087E+05 | 3.91 | 21.66 | 1.371E+03 | 9.913E+03 | 110.457 | 111.466 |
| | 60.512 | | | | 51.439 | | | | | | | | |
| FUEL PLATE 2 (BroydenSoln) | | | | | | | | | | | | | |
| | 50.000 | | | | 50.000 | | | | | | | | |
| 1 | 50.027 | 51.204 | 77.797 | 57.211 | 50.248 | 1.0943E+05 | 1.7421E+04 | 51.12 | 8.52 | 1.264E+04 | 1.312E+03 | 111.560 | 111.437 |
| 2 | 50.131 | 53.461 | 129.109 | 70.405 | 51.201 | 1.1008E+05 | 1.8007E+04 | 18.58 | 3.14 | 4.426E+03 | 4.519E+02 | 114.289 | 114.095 |
| 3 | 50.324 | 55.283 | 168.607 | 80.857 | 52.961 | 1.1068E+05 | 1.8535E+04 | 12.44 | 2.12 | 2.941E+03 | 2.923E+02 | 115.723 | 115.482 |
| 4 | 50.575 | 56.412 | 190.447 | 87.292 | 55.258 | 1.1114E+05 | 1.8989E+04 | 10.35 | 1.77 | 2.474E+03 | 2.375E+02 | 116.364 | 116.083 |
| 5 | 50.849 | 56.695 | 191.465 | 89.034 | 57.739 | 1.1141E+05 | 1.9331E+04 | 9.90 | 1.69 | 2.448E+03 | 2.269E+02 | 116.309 | 115.986 |
| 6 | 51.103 | 56.096 | 171.614 | 86.009 | 60.020 | 1.1146E+05 | 1.9513E+04 | 10.75 | 1.81 | 2.847E+03 | 2.576E+02 | 115.562 | 115.185 |
| 7 | 51.299 | 54.705 | 133.919 | 78.664 | 61.751 | 1.1126E+05 | 1.9496E+04 | 13.61 | 2.22 | 4.161E+03 | 3.807E+02 | 114.029 | 113.562 |
| 8 | 51.409 | 52.717 | 84.086 | 67.877 | 62.661 | 1.1084E+05 | 1.9238E+04 | 22.55 | 3.38 | 1.084E+04 | 1.223E+03 | 111.264 | 110.513 |
| | 51.439 | | | | 62.885 | | | | | | | | |
| FUEL PLATE 3 (BroydenSoln) | | | | | | | | | | | | | |
| | 50.000 | | | | 50.000 | | | | | | | | |
| 1 | 50.248 | 56.789 | 81.520 | 58.709 | 50.307 | 1.7406E+04 | 1.7491E+04 | 9.03 | 7.10 | 1.398E+03 | 1.084E+03 | 111.310 | 111.843 |
| 2 | 51.201 | 69.231 | 139.584 | 74.535 | 51.490 | 1.7969E+04 | 1.8179E+04 | 3.32 | 2.64 | 4.824E+02 | 3.718E+02 | 113.883 | 114.757 |
| 3 | 52.961 | 79.182 | 184.437 | 87.041 | 53.677 | 1.8488E+04 | 1.8798E+04 | 2.24 | 1.79 | 3.117E+02 | 2.382E+02 | 115.229 | 116.287 |
| 4 | 55.258 | 85.453 | 209.628 | 94.762 | 56.535 | 1.8939E+04 | 1.9350E+04 | 1.86 | 1.50 | 2.526E+02 | 1.908E+02 | 115.821 | 116.964 |
| 5 | 57.739 | 87.411 | 211.710 | 96.989 | 59.626 | 1.9286E+04 | 1.9778E+04 | 1.76 | 1.42 | 2.398E+02 | 1.789E+02 | 115.751 | 116.888 |
| 6 | 60.020 | 84.967 | 190.620 | 93.690 | 62.477 | 1.9484E+04 | 2.0017E+04 | 1.86 | 1.51 | 2.688E+02 | 1.984E+02 | 115.018 | 116.054 |
| 7 | 61.751 | 78.493 | 149.565 | 85.352 | 64.650 | 1.9491E+04 | 2.0028E+04 | 2.23 | 1.82 | 3.847E+02 | 2.838E+02 | 113.528 | 114.348 |
| 8 | 62.661 | 68.747 | 94.530 | 72.928 | 65.811 | 1.9270E+04 | 1.9768E+04 | 3.24 | 2.67 | 1.047E+03 | 8.114E+02 | 110.816 | 111.198 |
| | 62.885 | | | | 66.105 | | | | | | | | |

[1] The ONB ratio is here defined as (Tonb - Tinlet)/(Tsurf - Tinlet). If the heat flux is negative (the coolant is hotter than the adjacent cladding surface), then the ONB ratio is arbitrarily set to 99.99 .

FUEL PLATE 1 (BroydenSoln) AREAL

| NODE | FLUX outer MW/m^2 | FLUX inner MW/m^2 | FUEL X outer | Tsat (C) | Tdiff (C) | FUEL-CLADinterface outer (C) | FUEL-CLADinterface inner (C) | Pressure (bar) | Z-mid | Z-int |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.1110E-01 | 1.4242E-01 | 0.4772 | 107.091 | 0.00 | 70.949 | 68.917 | 1.29812 | 0.0625 | 0.1250 |
| 2 | 3.1666E-01 | 4.0526E-01 | 0.4776 | 107.006 | 0.00 | 109.579 | 103.860 | 1.29438 | 0.1875 | 0.2500 |
| 3 | 4.7361E-01 | 6.0688E-01 | 0.4773 | 106.921 | 0.00 | 139.391 | 130.751 | 1.29062 | 0.3125 | 0.3750 |
| 4 | 5.5758E-01 | 7.1713E-01 | 0.4764 | 106.836 | 0.00 | 156.063 | 145.585 | 1.28688 | 0.4375 | 0.5000 |
| 5 | 5.5536E-01 | 7.1972E-01 | 0.4745 | 106.751 | 0.00 | 157.250 | 146.187 | 1.28313 | 0.5625 | 0.6250 |
| 6 | 4.6703E-01 | 6.1457E-01 | 0.4707 | 106.666 | 0.00 | 142.888 | 132.511 | 1.27938 | 0.6875 | 0.7500 |
| 7 | 3.0608E-01 | 4.1764E-01 | 0.4616 | 106.580 | 0.00 | 115.145 | 106.630 | 1.27562 | 0.8125 | 0.8750 |
| 8 | 9.7364E-02 | 1.5849E-01 | 0.4182 | 106.495 | 0.00 | 78.076 | 72.412 | 1.27188 | 0.9375 | 1.0000 |

FUEL PLATE 2 (BroydenSoln)

| NODE | FLUX outer | FLUX inner | FUEL X outer | Tsat | Tdiff | outer | inner | Pressure | Z-mid | Z-int |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.2880E-01 | 1.2131E-01 | 0.5788 | 107.091 | 0.00 | 68.110 | 71.928 | 1.29812 | 0.0625 | 0.1250 |
| 2 | 3.6650E-01 | 3.4583E-01 | 0.5783 | 107.006 | 0.00 | 101.566 | 112.361 | 1.29438 | 0.1875 | 0.2500 |
| 3 | 5.4889E-01 | 5.1707E-01 | 0.5787 | 106.921 | 0.00 | 127.328 | 143.589 | 1.29062 | 0.3125 | 0.3750 |
| 4 | 6.4873E-01 | 6.0829E-01 | 0.5799 | 106.836 | 0.00 | 141.561 | 161.091 | 1.28688 | 0.4375 | 0.5000 |
| 5 | 6.5131E-01 | 6.0495E-01 | 0.5822 | 106.751 | 0.00 | 142.182 | 162.426 | 1.28313 | 0.5625 | 0.6250 |
| 6 | 5.5657E-01 | 5.0713E-01 | 0.5868 | 106.666 | 0.00 | 129.149 | 147.535 | 1.27938 | 0.6875 | 0.7500 |
| 7 | 3.7892E-01 | 3.2975E-01 | 0.5979 | 106.580 | 0.00 | 104.440 | 118.670 | 1.27562 | 0.8125 | 0.8750 |
| 8 | 1.4500E-01 | 1.0034E-01 | 0.6516 | 106.495 | 0.00 | 71.749 | 80.050 | 1.27188 | 0.9375 | 1.0000 |

FUEL PLATE 3 (BroydenSoln)

| NODE | FLUX outer | FLUX inner | FUEL X outer | Tsat | Tdiff | outer | inner | Pressure | Z-mid | Z-int |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.1385E-01 | 1.4695E-01 | 0.5869 | 107.091 | 0.00 | 72.309 | 75.299 | 1.29812 | 0.0625 | 0.1250 |
| 2 | 3.2398E-01 | 4.1892E-01 | 0.5864 | 107.006 | 0.00 | 113.396 | 121.832 | 1.29438 | 0.1875 | 0.2500 |
| 3 | 4.8476E-01 | 6.2717E-01 | 0.5863 | 106.921 | 0.00 | 145.263 | 157.851 | 1.29062 | 0.3125 | 0.3750 |
| 4 | 5.7187E-01 | 7.3970E-01 | 0.5863 | 106.836 | 0.00 | 163.409 | 178.276 | 1.28688 | 0.4375 | 0.5000 |
| 5 | 5.7227E-01 | 7.3895E-01 | 0.5867 | 106.751 | 0.00 | 165.423 | 180.419 | 1.28313 | 0.5625 | 0.6250 |
| 6 | 4.8606E-01 | 6.2478E-01 | 0.5878 | 106.666 | 0.00 | 151.226 | 164.230 | 1.27938 | 0.6875 | 0.7500 |
| 7 | 3.2633E-01 | 4.1461E-01 | 0.5907 | 106.580 | 0.00 | 122.979 | 132.163 | 1.27562 | 0.8125 | 0.8750 |
| 8 | 1.1727E-01 | 1.4068E-01 | 0.6045 | 106.495 | 0.00 | 84.733 | 88.811 | 1.27188 | 0.9375 | 1.0000 |

**Table 7. PLTEMP V3.4 Output for Problem 18 Having the Innermost Tube First in Input Data – Broyden Method**

| NODE | COOLANT inner(C) | CladSurf inner(C) | FUEL PEAK (C) | CladSurf outer(C) | COOLANT outer(C) | HCOFinner W/C-m^2 | HCOFouter W/C-m^2 | ONBRin [F Note 1] | ONBRout [F Note 1] | ETAin K-cm^3/J | ETAout K-cm^3/J | ONB Temp inner(C) | ONB Temp outer(C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| FUEL PLATE 1 (BroydenSoln) | | | | | | | | | | | | | |
| | 50.000 | | | | 50.000 | | | | | | | | |
| 1 | 50.307 | 58.709 | 81.520 | 56.789 | 50.248 | 1.7491E+04 | 1.7406E+04 | 7.10 | 9.03 | 1.084E+03 | 1.398E+03 | 111.843 | 111.310 |
| 2 | 51.490 | 74.535 | 139.584 | 69.231 | 51.201 | 1.8179E+04 | 1.7969E+04 | 2.64 | 3.32 | 3.718E+02 | 4.824E+02 | 114.757 | 113.883 |
| 3 | 53.677 | 87.041 | 184.437 | 79.182 | 52.961 | 1.8798E+04 | 1.8488E+04 | 1.79 | 2.24 | 2.382E+02 | 3.117E+02 | 116.287 | 115.229 |
| 4 | 56.535 | 94.762 | 209.628 | 85.453 | 55.258 | 1.9350E+04 | 1.8939E+04 | 1.50 | 1.86 | 1.908E+02 | 2.526E+02 | 116.964 | 115.821 |
| 5 | 59.626 | 96.989 | 211.710 | 87.411 | 57.739 | 1.9778E+04 | 1.9286E+04 | 1.42 | 1.76 | 1.789E+02 | 2.398E+02 | 116.888 | 115.751 |
| 6 | 62.477 | 93.690 | 190.620 | 84.967 | 60.020 | 2.0017E+04 | 1.9484E+04 | 1.51 | 1.86 | 1.984E+02 | 2.688E+02 | 116.054 | 115.018 |
| 7 | 64.650 | 85.352 | 149.565 | 78.493 | 61.751 | 2.0028E+04 | 1.9491E+04 | 1.82 | 2.23 | 2.838E+02 | 3.847E+02 | 114.348 | 113.528 |
| 8 | 65.811 | 72.928 | 94.530 | 68.747 | 62.661 | 1.9768E+04 | 1.9270E+04 | 2.67 | 3.24 | 8.114E+02 | 1.047E+03 | 111.198 | 110.816 |
| | 66.105 | | | | 62.885 | | | | | | | | |
| FUEL PLATE 2 (BroydenSoln) | | | | | | | | | | | | | |
| | 50.000 | | | | 50.000 | | | | | | | | |
| 1 | 50.248 | 57.211 | 77.797 | 51.204 | 50.027 | 1.7421E+04 | 1.0943E+05 | 8.52 | 51.12 | 1.312E+03 | 1.264E+04 | 111.437 | 111.560 |
| 2 | 51.201 | 70.405 | 129.109 | 53.461 | 50.131 | 1.8007E+04 | 1.1008E+05 | 3.14 | 18.58 | 4.519E+02 | 4.426E+03 | 114.095 | 114.289 |
| 3 | 52.961 | 80.857 | 168.607 | 55.283 | 50.324 | 1.8535E+04 | 1.1068E+05 | 2.12 | 12.44 | 2.923E+02 | 2.941E+03 | 115.482 | 115.723 |
| 4 | 55.258 | 87.292 | 190.447 | 56.412 | 50.575 | 1.8989E+04 | 1.1114E+05 | 1.77 | 10.35 | 2.375E+02 | 2.474E+03 | 116.083 | 116.364 |
| 5 | 57.739 | 89.034 | 191.465 | 56.695 | 50.849 | 1.9331E+04 | 1.1141E+05 | 1.69 | 9.90 | 2.269E+02 | 2.448E+03 | 115.986 | 116.309 |
| 6 | 60.020 | 86.009 | 171.614 | 56.096 | 51.103 | 1.9513E+04 | 1.1146E+05 | 1.81 | 10.75 | 2.576E+02 | 2.847E+03 | 115.185 | 115.562 |
| 7 | 61.751 | 78.664 | 133.919 | 54.705 | 51.299 | 1.9496E+04 | 1.1126E+05 | 2.22 | 13.61 | 3.807E+02 | 4.161E+03 | 113.562 | 114.029 |
| 8 | 62.661 | 67.877 | 84.086 | 52.717 | 51.409 | 1.9238E+04 | 1.1084E+05 | 3.38 | 22.55 | 1.223E+03 | 1.084E+04 | 110.513 | 111.264 |
| | 62.885 | | | | 51.439 | | | | | | | | |
| FUEL PLATE 3 (BroydenSoln) | | | | | | | | | | | | | |
| | 50.000 | | | | 50.000 | | | | | | | | |
| 1 | 50.027 | 51.328 | 77.666 | 56.556 | 50.202 | 1.0946E+05 | 1.7488E+04 | 46.51 | 9.34 | 1.143E+04 | 1.481E+03 | 111.774 | 111.262 |
| 2 | 50.131 | 53.810 | 128.740 | 68.555 | 50.982 | 1.1017E+05 | 1.8019E+04 | 16.97 | 3.44 | 4.003E+03 | 5.118E+02 | 114.638 | 113.810 |
| 3 | 50.324 | 55.801 | 168.030 | 78.035 | 52.422 | 1.1080E+05 | 1.8491E+04 | 11.40 | 2.32 | 2.660E+03 | 3.329E+02 | 116.145 | 115.139 |
| 4 | 50.575 | 57.019 | 189.712 | 83.828 | 54.301 | 1.1129E+05 | 1.8883E+04 | 9.52 | 1.94 | 2.238E+03 | 2.726E+02 | 116.819 | 115.715 |
| 5 | 50.849 | 57.300 | 190.630 | 85.303 | 56.328 | 1.1156E+05 | 1.9167E+04 | 9.15 | 1.86 | 2.215E+03 | 2.627E+02 | 116.764 | 115.626 |
| 6 | 51.103 | 56.610 | 170.730 | 82.384 | 58.191 | 1.1158E+05 | 1.9305E+04 | 9.98 | 2.00 | 2.579E+03 | 3.003E+02 | 115.982 | 114.864 |
| 7 | 51.299 | 55.050 | 133.035 | 75.492 | 59.600 | 1.1135E+05 | 1.9260E+04 | 12.75 | 2.48 | 3.775E+03 | 4.440E+02 | 114.374 | 113.324 |
| 8 | 51.409 | 52.838 | 83.222 | 65.463 | 60.335 | 1.1087E+05 | 1.8988E+04 | 21.66 | 3.91 | 9.913E+03 | 1.371E+03 | 111.466 | 110.457 |
| | 51.439 | | | | 60.512 | | | | | | | | |

[1] The ONB ratio is here defined as (Tonb - Tinlet)/(Tsurf - Tinlet). If the heat flux is negative (the coolant is hotter than the adjacent cladding surface), then the ONB ratio is arbitrarily set to 99.99 .

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FUEL PLATE   1 (BroydenSoln) AREAL                     FUEL-CLADinterface
NODE FLUX inner FLUX outer  FUEL X   Tsat     Tdiff     inner      outer    Pressure  Z-mid     Z-int
       MW/m^2     MW/m^2     inner   (C)       (C)       (C)        (C)      (bar)
   1 1.4695E-01 1.1385E-01  0.4131 107.091     0.00     75.299     72.309   1.29812   0.0625    0.1250
   2 4.1892E-01 3.2398E-01  0.4136 107.006     0.00    121.832    113.396   1.29438   0.1875    0.2500
   3 6.2717E-01 4.8476E-01  0.4137 106.921     0.00    157.851    145.263   1.29062   0.3125    0.3750
   4 7.3970E-01 5.7187E-01  0.4137 106.836     0.00    178.276    163.409   1.28688   0.4375    0.5000
   5 7.3895E-01 5.7227E-01  0.4133 106.751     0.00    180.419    165.423   1.28313   0.5625    0.6250
   6 6.2478E-01 4.8606E-01  0.4122 106.666     0.00    164.230    151.226   1.27938   0.6875    0.7500
   7 4.1461E-01 3.2633E-01  0.4093 106.580     0.00    132.163    122.979   1.27562   0.8125    0.8750
   8 1.4068E-01 1.1727E-01  0.3955 106.495     0.00     88.811     84.733   1.27188   0.9375    1.0000

FUEL PLATE   2 (BroydenSoln)
   1 1.2131E-01 1.2880E-01  0.4212 107.091     0.00     71.928     68.110   1.29812   0.0625    0.1250
   2 3.4583E-01 3.6650E-01  0.4217 107.006     0.00    112.361    101.566   1.29438   0.1875    0.2500
   3 5.1707E-01 5.4889E-01  0.4213 106.921     0.00    143.589    127.328   1.29062   0.3125    0.3750
   4 6.0829E-01 6.4873E-01  0.4201 106.836     0.00    161.091    141.561   1.28688   0.4375    0.5000
   5 6.0495E-01 6.5131E-01  0.4178 106.751     0.00    162.426    142.182   1.28313   0.5625    0.6250
   6 5.0713E-01 5.5657E-01  0.4132 106.666     0.00    147.535    129.149   1.27938   0.6875    0.7500
   7 3.2975E-01 3.7892E-01  0.4021 106.580     0.00    118.670    104.440   1.27562   0.8125    0.8750
   8 1.0034E-01 1.4500E-01  0.3484 106.495     0.00     80.050     71.749   1.27188   0.9375    1.0000

FUEL PLATE   3 (BroydenSoln)
   1 1.4242E-01 1.1110E-01  0.5228 107.091     0.00     68.917     70.949   1.29812   0.0625    0.1250
   2 4.0526E-01 3.1666E-01  0.5224 107.006     0.00    103.860    109.579   1.29438   0.1875    0.2500
   3 6.0688E-01 4.7361E-01  0.5227 106.921     0.00    130.751    139.391   1.29062   0.3125    0.3750
   4 7.1713E-01 5.5758E-01  0.5236 106.836     0.00    145.585    156.063   1.28688   0.4375    0.5000
   5 7.1972E-01 5.5536E-01  0.5255 106.751     0.00    146.187    157.250   1.28313   0.5625    0.6250
   6 6.1457E-01 4.6703E-01  0.5293 106.666     0.00    132.511    142.888   1.27938   0.6875    0.7500
   7 4.1764E-01 3.0608E-01  0.5384 106.580     0.00    106.630    115.145   1.27562   0.8125    0.8750
   8 1.5849E-01 9.7364E-02  0.5818 106.495     0.00     72.412     78.076   1.27188   0.9375    1.0000
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**Table 8. PLTEMP V3.4 Output for Problem 17 Having the Outermost Tube First in Input Data – Exact Method**

| NODE | COOLANT outer(C) | CladSurf outer(C) | FUEL PEAK (C) | CladSurf inner(C) | COOLANT inner(C) | HCOFouter W/C-m^2 | HCOFinner W/C-m^2 | ONBRout [F Note 1] | ONBRin [F Note 1] | ETAout K-cm^3/J | ETAin K-cm^3/J | ONB Temp outer(C) | ONB Temp inner(C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| FUEL PLATE 1 (ExactSoln) | | | | | | | | | | | | | |
| | 50.000 | | | | 50.000 | | | | | | | | |
| 1 | 50.202 | 56.556 | 77.667 | 51.328 | 50.027 | 1.7488E+04 | 1.0946E+05 | 9.35 | 46.51 | 1.481E+03 | 1.143E+04 | 111.263 | 111.774 |
| 2 | 50.982 | 68.555 | 128.741 | 53.810 | 50.131 | 1.8019E+04 | 1.1017E+05 | 3.44 | 16.97 | 5.118E+02 | 4.003E+03 | 113.810 | 114.638 |
| 3 | 52.422 | 78.035 | 168.031 | 55.801 | 50.324 | 1.8491E+04 | 1.1080E+05 | 2.32 | 11.40 | 3.329E+02 | 2.660E+03 | 115.139 | 116.145 |
| 4 | 54.301 | 83.828 | 189.714 | 57.020 | 50.577 | 1.8884E+04 | 1.1129E+05 | 1.94 | 9.52 | 2.726E+02 | 2.238E+03 | 115.715 | 116.819 |
| 5 | 56.328 | 85.302 | 190.632 | 57.301 | 50.850 | 1.9167E+04 | 1.1156E+05 | 1.86 | 9.14 | 2.627E+02 | 2.215E+03 | 115.626 | 116.764 |
| 6 | 58.190 | 82.383 | 170.731 | 56.611 | 51.103 | 1.9305E+04 | 1.1158E+05 | 2.00 | 9.98 | 3.003E+02 | 2.579E+03 | 114.864 | 115.982 |
| 7 | 59.598 | 75.490 | 133.035 | 55.050 | 51.299 | 1.9259E+04 | 1.1135E+05 | 2.48 | 12.75 | 4.440E+02 | 3.775E+03 | 113.324 | 114.374 |
| 8 | 60.332 | 65.460 | 83.222 | 52.839 | 51.410 | 1.8988E+04 | 1.1087E+05 | 3.91 | 21.65 | 1.371E+03 | 9.913E+03 | 110.457 | 111.466 |
| | 60.510 | | | | 51.440 | | | | | | | | |
| FUEL PLATE 2 (ExactSoln) | | | | | | | | | | | | | |
| | 50.000 | | | | 50.000 | | | | | | | | |
| 1 | 50.027 | 51.204 | 77.797 | 57.211 | 50.248 | 1.0943E+05 | 1.7421E+04 | 51.12 | 8.52 | 1.264E+04 | 1.312E+03 | 111.560 | 111.437 |
| 2 | 50.131 | 53.461 | 129.110 | 70.406 | 51.202 | 1.1008E+05 | 1.8008E+04 | 18.58 | 3.14 | 4.426E+03 | 4.519E+02 | 114.289 | 114.095 |
| 3 | 50.324 | 55.284 | 168.608 | 80.859 | 52.963 | 1.1068E+05 | 1.8536E+04 | 12.44 | 2.12 | 2.941E+03 | 2.922E+02 | 115.724 | 115.482 |
| 4 | 50.577 | 56.414 | 190.448 | 87.294 | 55.261 | 1.1114E+05 | 1.8989E+04 | 10.35 | 1.77 | 2.474E+03 | 2.374E+02 | 116.364 | 116.083 |
| 5 | 50.850 | 56.696 | 191.467 | 89.035 | 57.741 | 1.1141E+05 | 1.9331E+04 | 9.90 | 1.69 | 2.448E+03 | 2.269E+02 | 116.309 | 115.986 |
| 6 | 51.103 | 56.097 | 171.615 | 86.010 | 60.022 | 1.1146E+05 | 1.9514E+04 | 10.75 | 1.81 | 2.847E+03 | 2.576E+02 | 115.562 | 115.185 |
| 7 | 51.299 | 54.705 | 133.920 | 78.665 | 61.751 | 1.1126E+05 | 1.9496E+04 | 13.61 | 2.22 | 4.161E+03 | 3.807E+02 | 114.029 | 113.562 |
| 8 | 51.410 | 52.718 | 84.086 | 67.877 | 62.662 | 1.1084E+05 | 1.9238E+04 | 22.54 | 3.38 | 1.084E+04 | 1.223E+03 | 111.264 | 110.513 |
| | 51.440 | | | | 62.885 | | | | | | | | |
| FUEL PLATE 3 (ExactSoln) | | | | | | | | | | | | | |
| | 50.000 | | | | 50.000 | | | | | | | | |
| 1 | 50.248 | 56.789 | 81.520 | 58.709 | 50.307 | 1.7406E+04 | 1.7491E+04 | 9.03 | 7.10 | 1.398E+03 | 1.084E+03 | 111.310 | 111.843 |
| 2 | 51.202 | 69.232 | 139.585 | 74.535 | 51.490 | 1.7969E+04 | 1.8179E+04 | 3.32 | 2.64 | 4.824E+02 | 3.718E+02 | 113.883 | 114.757 |
| 3 | 52.963 | 79.183 | 184.437 | 87.041 | 53.678 | 1.8488E+04 | 1.8799E+04 | 2.24 | 1.79 | 3.117E+02 | 2.382E+02 | 115.229 | 116.287 |
| 4 | 55.261 | 85.456 | 209.629 | 94.763 | 56.536 | 1.8939E+04 | 1.9350E+04 | 1.86 | 1.50 | 2.526E+02 | 1.908E+02 | 115.821 | 116.964 |
| 5 | 57.741 | 87.413 | 211.710 | 96.989 | 59.625 | 1.9287E+04 | 1.9778E+04 | 1.76 | 1.42 | 2.398E+02 | 1.789E+02 | 115.751 | 116.888 |
| 6 | 60.022 | 84.968 | 190.619 | 93.687 | 62.473 | 1.9484E+04 | 2.0016E+04 | 1.86 | 1.51 | 2.687E+02 | 1.985E+02 | 115.018 | 116.054 |
| 7 | 61.751 | 78.493 | 149.562 | 85.347 | 64.643 | 1.9491E+04 | 2.0026E+04 | 2.23 | 1.82 | 3.847E+02 | 2.838E+02 | 113.528 | 114.348 |
| 8 | 62.662 | 68.747 | 94.526 | 72.921 | 65.802 | 1.9270E+04 | 1.9767E+04 | 3.24 | 2.67 | 1.047E+03 | 8.115E+02 | 110.815 | 111.198 |
| | 62.885 | | | | 66.097 | | | | | | | | |

[1] The ONB ratio is here defined as (Tonb - Tinlet)/(Tsurf - Tinlet). If the heat flux is negative (the coolant is hotter than the adjacent cladding surface), then the ONB ratio is arbitrarily set to 99.99 .

| FUEL PLATE 1 (ExactSoln) | | | AREAL | | | FUEL-CLADinterface | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| NODE | FLUX outer MW/m^2 | FLUX inner MW/m^2 | FUEL X outer | Tsat (C) | Tdiff (C) | outer (C) | inner (C) | Pressure (bar) | Z-mid | Z-int |
| 1 | 1.1110E-01 | 1.4242E-01 | 0.4772 | 107.091 | | 70.949 | 68.917 | 1.29812 | 0.0625 | 0.1250 |
| 2 | 3.1666E-01 | 4.0526E-01 | 0.4776 | 107.006 | | 109.579 | 103.860 | 1.29438 | 0.1875 | 0.2500 |
| 3 | 4.7361E-01 | 6.0688E-01 | 0.4773 | 106.921 | | 139.391 | 130.751 | 1.29062 | 0.3125 | 0.3750 |
| 4 | 5.5758E-01 | 7.1712E-01 | 0.4764 | 106.836 | | 156.063 | 145.586 | 1.28688 | 0.4375 | 0.5000 |
| 5 | 5.5537E-01 | 7.1972E-01 | 0.4745 | 106.751 | | 157.250 | 146.187 | 1.28313 | 0.5625 | 0.6250 |
| 6 | 4.6704E-01 | 6.1457E-01 | 0.4707 | 106.666 | | 142.888 | 132.511 | 1.27938 | 0.6875 | 0.7500 |
| 7 | 3.0608E-01 | 4.1764E-01 | 0.4616 | 106.580 | | 115.144 | 106.629 | 1.27562 | 0.8125 | 0.8750 |
| 8 | 9.7370E-02 | 1.5849E-01 | 0.4182 | 106.495 | | 78.075 | 72.412 | 1.27188 | 0.9375 | 1.0000 |
| FUEL PLATE 2 (ExactSoln) | | | | | | | | | | |
| 1 | 1.2880E-01 | 1.2131E-01 | 0.5788 | 107.091 | | 68.110 | 71.928 | 1.29812 | 0.0625 | 0.1250 |
| 2 | 3.6651E-01 | 3.4582E-01 | 0.5783 | 107.006 | | 101.567 | 112.362 | 1.29438 | 0.1875 | 0.2500 |
| 3 | 5.4890E-01 | 5.1707E-01 | 0.5787 | 106.921 | | 127.329 | 143.590 | 1.29062 | 0.3125 | 0.3750 |
| 4 | 6.4873E-01 | 6.0829E-01 | 0.5799 | 106.836 | | 141.562 | 161.093 | 1.28688 | 0.4375 | 0.5000 |
| 5 | 6.5131E-01 | 6.0495E-01 | 0.5822 | 106.751 | | 142.183 | 162.428 | 1.28313 | 0.5625 | 0.6250 |
| 6 | 5.5658E-01 | 5.0713E-01 | 0.5868 | 106.666 | | 129.150 | 147.536 | 1.27938 | 0.6875 | 0.7500 |
| 7 | 3.7892E-01 | 3.2975E-01 | 0.5979 | 106.580 | | 104.441 | 118.671 | 1.27562 | 0.8125 | 0.8750 |
| 8 | 1.4500E-01 | 1.0034E-01 | 0.6516 | 106.495 | | 71.750 | 80.051 | 1.27188 | 0.9375 | 1.0000 |
| FUEL PLATE 3 (ExactSoln) | | | | | | | | | | |
| 1 | 1.1385E-01 | 1.4695E-01 | 0.5869 | 107.091 | | 72.310 | 75.299 | 1.29812 | 0.0625 | 0.1250 |
| 2 | 3.2398E-01 | 4.1892E-01 | 0.5864 | 107.006 | | 113.397 | 121.833 | 1.29438 | 0.1875 | 0.2500 |
| 3 | 4.8475E-01 | 6.2718E-01 | 0.5863 | 106.921 | | 145.264 | 157.852 | 1.29062 | 0.3125 | 0.3750 |
| 4 | 5.7187E-01 | 7.3970E-01 | 0.5863 | 106.836 | | 163.412 | 178.278 | 1.28688 | 0.4375 | 0.5000 |
| 5 | 5.7227E-01 | 7.3896E-01 | 0.5867 | 106.751 | | 165.424 | 180.419 | 1.28313 | 0.5625 | 0.6250 |
| 6 | 4.8606E-01 | 6.2479E-01 | 0.5878 | 106.666 | | 151.226 | 164.228 | 1.27938 | 0.6875 | 0.7500 |
| 7 | 3.2633E-01 | 4.1463E-01 | 0.5906 | 106.580 | | 122.978 | 132.159 | 1.27562 | 0.8125 | 0.8750 |
| 8 | 1.1726E-01 | 1.4070E-01 | 0.6044 | 106.495 | | 84.732 | 88.806 | 1.27188 | 0.9375 | 1.0000 |

## Table 9. PLTEMP V3.4 Output for Problem 18 Having the Innermost Tube First in Input Data – Exact Method

| NODE | COOLANT inner(C) | CladSurf inner(C) | FUEL PEAK (C) | CladSurf outer(C) | COOLANT outer(C) | HCOFinner W/C-m^2 | HCOFouter W/C-m^2 | ONBRin [F Note 1] | ONBRout | ETAin K-cm^3/J | ETAout K-cm^3/J | ONB Temp inner(C) | ONB Temp outer(C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| FUEL PLATE 1 (ExactSoln) | | | | | | | | | | | | | |
| | 50.000 | | | | 50.000 | | | | | | | | |
| 1 | 50.307 | 58.709 | 81.520 | 56.789 | 50.248 | 1.7491E+04 | 1.7406E+04 | 7.10 | 9.03 | 1.084E+03 | 1.398E+03 | 111.843 | 111.310 |
| 2 | 51.490 | 74.535 | 139.585 | 69.232 | 51.202 | 1.8179E+04 | 1.7969E+04 | 2.64 | 3.32 | 3.718E+02 | 4.824E+02 | 114.757 | 113.883 |
| 3 | 53.678 | 87.041 | 184.437 | 79.183 | 52.963 | 1.8799E+04 | 1.8488E+04 | 1.79 | 2.24 | 2.382E+02 | 3.117E+02 | 116.287 | 115.229 |
| 4 | 56.536 | 94.763 | 209.629 | 85.456 | 55.261 | 1.9350E+04 | 1.8939E+04 | 1.50 | 1.86 | 1.908E+02 | 2.526E+02 | 116.964 | 115.821 |
| 5 | 59.625 | 96.989 | 211.710 | 87.413 | 57.741 | 1.9778E+04 | 1.9287E+04 | 1.42 | 1.76 | 1.789E+02 | 2.398E+02 | 116.888 | 115.751 |
| 6 | 62.473 | 93.687 | 190.619 | 84.968 | 60.022 | 2.0016E+04 | 1.9484E+04 | 1.51 | 1.86 | 1.985E+02 | 2.687E+02 | 116.054 | 115.018 |
| 7 | 64.643 | 85.347 | 149.562 | 78.493 | 61.751 | 2.0026E+04 | 1.9491E+04 | 1.82 | 2.23 | 2.838E+02 | 3.847E+02 | 114.348 | 113.528 |
| 8 | 65.802 | 72.921 | 94.526 | 68.747 | 62.662 | 1.9767E+04 | 1.9270E+04 | 2.67 | 3.24 | 8.115E+02 | 1.047E+03 | 111.198 | 110.815 |
| | 66.097 | | | | 62.885 | | | | | | | | |
| FUEL PLATE 2 (ExactSoln) | | | | | | | | | | | | | |
| | 50.000 | | | | 50.000 | | | | | | | | |
| 1 | 50.248 | 57.211 | 77.797 | 51.204 | 50.027 | 1.7421E+04 | 1.0943E+05 | 8.52 | 51.12 | 1.312E+03 | 1.264E+04 | 111.437 | 111.560 |
| 2 | 51.202 | 70.406 | 129.110 | 53.461 | 50.131 | 1.8008E+04 | 1.1008E+05 | 3.14 | 18.58 | 4.519E+02 | 4.426E+03 | 114.095 | 114.289 |
| 3 | 52.963 | 80.859 | 168.608 | 55.284 | 50.324 | 1.8536E+04 | 1.1068E+05 | 2.12 | 12.44 | 2.922E+02 | 2.941E+03 | 115.482 | 115.724 |
| 4 | 55.261 | 87.294 | 190.448 | 56.414 | 50.577 | 1.8989E+04 | 1.1114E+05 | 1.77 | 10.35 | 2.374E+02 | 2.474E+03 | 116.083 | 116.364 |
| 5 | 57.741 | 89.035 | 191.467 | 56.696 | 50.850 | 1.9331E+04 | 1.1141E+05 | 1.69 | 9.90 | 2.269E+02 | 2.448E+03 | 115.986 | 116.309 |
| 6 | 60.022 | 86.010 | 171.615 | 56.097 | 51.103 | 1.9514E+04 | 1.1146E+05 | 1.81 | 10.75 | 2.576E+02 | 2.847E+03 | 115.185 | 115.562 |
| 7 | 61.751 | 78.665 | 133.920 | 54.705 | 51.299 | 1.9496E+04 | 1.1126E+05 | 2.22 | 13.61 | 3.807E+02 | 4.161E+03 | 113.562 | 114.029 |
| 8 | 62.662 | 67.877 | 84.086 | 52.718 | 51.410 | 1.9238E+04 | 1.1084E+05 | 3.38 | 22.54 | 1.223E+03 | 1.084E+04 | 110.513 | 111.264 |
| | 62.885 | | | | 51.440 | | | | | | | | |
| FUEL PLATE 3 (ExactSoln) | | | | | | | | | | | | | |
| | 50.000 | | | | 50.000 | | | | | | | | |
| 1 | 50.027 | 51.328 | 77.667 | 56.556 | 50.202 | 1.0946E+05 | 1.7488E+04 | 46.51 | 9.35 | 1.143E+04 | 1.481E+03 | 111.774 | 111.263 |
| 2 | 50.131 | 53.810 | 128.741 | 68.555 | 50.982 | 1.1017E+05 | 1.8019E+04 | 16.97 | 3.44 | 4.003E+03 | 5.118E+02 | 114.638 | 113.810 |
| 3 | 50.324 | 55.801 | 168.031 | 78.035 | 52.422 | 1.1080E+05 | 1.8491E+04 | 11.40 | 2.32 | 2.660E+03 | 3.329E+02 | 116.145 | 115.139 |
| 4 | 50.577 | 57.020 | 189.714 | 83.828 | 54.301 | 1.1129E+05 | 1.8884E+04 | 9.52 | 1.94 | 2.238E+03 | 2.726E+02 | 116.819 | 115.715 |
| 5 | 50.850 | 57.301 | 190.632 | 85.302 | 56.328 | 1.1156E+05 | 1.9167E+04 | 9.14 | 1.86 | 2.215E+03 | 2.627E+02 | 116.764 | 115.626 |
| 6 | 51.103 | 56.611 | 170.731 | 82.383 | 58.190 | 1.1158E+05 | 1.9305E+04 | 9.98 | 2.00 | 2.579E+03 | 3.003E+02 | 115.982 | 114.864 |
| 7 | 51.299 | 55.050 | 133.035 | 75.490 | 59.598 | 1.1135E+05 | 1.9259E+04 | 12.75 | 2.48 | 3.775E+03 | 4.440E+02 | 114.374 | 113.324 |
| 8 | 51.410 | 52.839 | 83.222 | 65.460 | 60.332 | 1.1087E+05 | 1.8988E+04 | 21.65 | 3.91 | 9.913E+03 | 1.371E+03 | 111.466 | 110.457 |
| | 51.440 | | | | 60.510 | | | | | | | | |

[1] The ONB ratio is here defined as (Tonb - Tinlet)/(Tsurf - Tinlet). If the heat flux is negative (the coolant is hotter than the adjacent cladding surface), then the ONB ratio is arbitrarily set to 99.99 .

FUEL PLATE 1 (ExactSoln)

| NODE | FLUX inner MW/m^2 | FLUX outer MW/m^2 | AREAL FUEL X inner | Tsat (C) | Tdiff (C) | FUEL-CLADinterface inner (C) | FUEL-CLADinterface outer (C) | Pressure (bar) | Z-mid | Z-int |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.4695E-01 | 1.1385E-01 | 0.4131 | 107.091 | | 75.299 | 72.310 | 1.29812 | 0.0625 | 0.1250 |
| 2 | 4.1892E-01 | 3.2398E-01 | 0.4136 | 107.006 | | 121.833 | 113.397 | 1.29438 | 0.1875 | 0.2500 |
| 3 | 6.2718E-01 | 4.8475E-01 | 0.4137 | 106.921 | | 157.852 | 145.264 | 1.29062 | 0.3125 | 0.3750 |
| 4 | 7.3970E-01 | 5.7187E-01 | 0.4137 | 106.836 | | 178.278 | 163.412 | 1.28688 | 0.4375 | 0.5000 |
| 5 | 7.3896E-01 | 5.7227E-01 | 0.4133 | 106.751 | | 180.419 | 165.424 | 1.28313 | 0.5625 | 0.6250 |
| 6 | 6.2479E-01 | 4.8606E-01 | 0.4122 | 106.666 | | 164.228 | 151.226 | 1.27938 | 0.6875 | 0.7500 |
| 7 | 4.1463E-01 | 3.2633E-01 | 0.4094 | 106.580 | | 132.159 | 122.978 | 1.27562 | 0.8125 | 0.8750 |
| 8 | 1.4070E-01 | 1.1726E-01 | 0.3956 | 106.495 | | 88.806 | 84.732 | 1.27188 | 0.9375 | 1.0000 |

FUEL PLATE 2 (ExactSoln)

| NODE | FLUX inner MW/m^2 | FLUX outer MW/m^2 | AREAL FUEL X inner | Tsat (C) | Tdiff (C) | FUEL-CLADinterface inner (C) | FUEL-CLADinterface outer (C) | Pressure (bar) | Z-mid | Z-int |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.2131E-01 | 1.2880E-01 | 0.4212 | 107.091 | | 71.928 | 68.110 | 1.29812 | 0.0625 | 0.1250 |
| 2 | 3.4582E-01 | 3.6651E-01 | 0.4217 | 107.006 | | 112.362 | 101.567 | 1.29438 | 0.1875 | 0.2500 |
| 3 | 5.1707E-01 | 5.4890E-01 | 0.4213 | 106.921 | | 143.590 | 127.329 | 1.29062 | 0.3125 | 0.3750 |
| 4 | 6.0829E-01 | 6.4873E-01 | 0.4201 | 106.836 | | 161.093 | 141.562 | 1.28688 | 0.4375 | 0.5000 |
| 5 | 6.0495E-01 | 6.5131E-01 | 0.4178 | 106.751 | | 162.428 | 142.183 | 1.28313 | 0.5625 | 0.6250 |
| 6 | 5.0713E-01 | 5.5658E-01 | 0.4132 | 106.666 | | 147.536 | 129.150 | 1.27938 | 0.6875 | 0.7500 |
| 7 | 3.2975E-01 | 3.7892E-01 | 0.4021 | 106.580 | | 118.671 | 104.441 | 1.27562 | 0.8125 | 0.8750 |
| 8 | 1.0034E-01 | 1.4500E-01 | 0.3484 | 106.495 | | 80.051 | 71.750 | 1.27188 | 0.9375 | 1.0000 |

FUEL PLATE 3 (ExactSoln)

| NODE | FLUX inner MW/m^2 | FLUX outer MW/m^2 | AREAL FUEL X inner | Tsat (C) | Tdiff (C) | FUEL-CLADinterface inner (C) | FUEL-CLADinterface outer (C) | Pressure (bar) | Z-mid | Z-int |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.4242E-01 | 1.1110E-01 | 0.5228 | 107.091 | | 68.917 | 70.949 | 1.29812 | 0.0625 | 0.1250 |
| 2 | 4.0526E-01 | 3.1666E-01 | 0.5224 | 107.006 | | 103.860 | 109.579 | 1.29438 | 0.1875 | 0.2500 |
| 3 | 6.0688E-01 | 4.7361E-01 | 0.5227 | 106.921 | | 130.751 | 139.391 | 1.29062 | 0.3125 | 0.3750 |
| 4 | 7.1712E-01 | 5.5758E-01 | 0.5236 | 106.836 | | 145.586 | 156.063 | 1.28688 | 0.4375 | 0.5000 |
| 5 | 7.1972E-01 | 5.5537E-01 | 0.5255 | 106.751 | | 146.187 | 157.250 | 1.28313 | 0.5625 | 0.6250 |
| 6 | 6.1457E-01 | 4.6704E-01 | 0.5293 | 106.666 | | 132.511 | 142.888 | 1.27938 | 0.6875 | 0.7500 |
| 7 | 4.1764E-01 | 3.0608E-01 | 0.5384 | 106.580 | | 106.629 | 115.144 | 1.27562 | 0.8125 | 0.8750 |
| 8 | 1.5849E-01 | 9.7370E-02 | 0.5818 | 106.495 | | 72.412 | 78.075 | 1.27188 | 0.9375 | 1.0000 |

## Table 10. Comparison of Solutions by Different PLTEMP/ANL Versions for Standards Problems 17 and 18

| | Maximum Temperature Difference in Cladding, Fuel, and Adjacent Coolant Channels of a Fuel Tube , °C | | | | | | Comments |
|---|---|---|---|---|---|---|---|
| | **Problem 17 Tube 1 is the outermost** | | | **Problem 18 Tube 1 is innermost** | | | |
| Code Versions Compared | Tube 1 | Tube 2 | Tube 3 | Tube 1 | Tube 2 | Tube 3 | |
| | **Broyden Solution History [Note 1, 2]** | | | | | | |
| Broyden V3.0 vs. Broyden V3.4 | 0.697 | 1.712 | 10.005 | 9.999 | 1.708 | 0.693 | |
| Broyden V3.1 vs. Broyden V3.4 | 0.173 | 0.218 | 0.331 | 0.322 | 0.211 | 0.166 | |
| Broyden V3.2 vs. Broyden V3.4 | 0.011 | 0.010 | 0.012 | 0.013 | 0.007 | 0.005 | |
| Broyden V3.3 vs. Broyden V3.4 | 0.011 | 0.010 | 0.012 | 0.013 | 0.007 | 0.005 | |
| | **Exact Solution History [Note 1]** | | | | | | |
| Exact V3.0 vs. Exact V3.4 | 0.744 | 1.784 | 4.512 | 4.504 | 1.777 | 0.751 | Note 3 |
| Exact V3.1 vs. Exact V3.4 | 0.744 | 1.785 | 4.511 | 4.502 | 1.778 | 0.751 | Note 3 |
| Exact V3.2 vs. Exact V3.4 | | | | 0.014 | 0.005 | 0.005 | Note 4 |
| Exact V3.3 vs. Exact V3.4 | | | | 0.014 | 0.005 | 0.005 | Note 4 |
| | **Exact vs. Broyden Solutions of a Code Version** | | | | | | |
| Exact V3.0 vs. Broyden V3.0 | 1.087 | 1.358 | 8.619 | 8.619 | 1.358 | 1.087 | Note 3 |
| Exact V3.1 vs. Broyden V3.1 | 2.178 | 4.004 | 11.511 | 4.179 | 1.565 | 0.917 | Note 3 |
| Exact V3.2 vs. Broyden V3.2 | | | | 0.009 | 0.003 | 0.002 | Note 4 |
| Exact V3.3 vs. Broyden V3.3 | | | | 0.009 | 0.003 | 0.002 | Note 4 |
| Exact V3.4 vs. Broyden V3.4 | 0.003 | 0.003 | 0.009 | 0.009 | 0.003 | 0.003 | |

Note 1. PLTEMP/ANL V3.4 is used as the base version in these comparisons because it is the first version to have the radial geometry exact method that allows fuel tube numbering in both directions (the innermost tube first or the outermost tube first).

Note 2. Each Tdiff iz zero in all 5 Broyden solutions of Problem 17, and in all 5 Broyden solutions of Problem 18.

Note 3. Only the slab geometry exact method was available in PLTEMP/ANL V3.0 and V3.1. So this difference is due to the use of the slab geometry exact method in a radial geometry problem.

Note 4. PLTEMP/ANL V3.2 and V3.3 have the radial geometry exact method for problems in which the innermost tube is numbered as the first, and therefore give the exact solution for Problem 18. These versions do not give an exact solution for Problem 17 because the outermost tube is numbered as the first.

## 6. Verification of Carnavos Correlation Implemented in PLTEMP/ANL for Heat Transfer Coefficient and Friction Factor in Finned Coolant Channels

(September 2007)

### 6.1. Introduction

The MIT Reactor coolant channels have straight longitudinal internal fins of rectangular cross section. In preparation for the thermal hydraulic analysis of this reactor, the PLTEMP/ANL code has been improved to handle heat transfer coefficient and friction factor in finned channels. Fins of different cross sections (triangular and rectangular), with the fin axis parallel to the channel axis or making an angle (called helix angle) with the channel axis, are used in heat exchangers. The fins of trapezoidal cross section (that covers both triangular and rectangular cross sections) at a user-input helix angle (0 to 30°) were recently modeled in PLTEMP/ANL Version 3.3.

Figure 1 shows reactor coolant channels with straight longitudinal inner fins of trapezoidal cross section. Channels of two cross-sectional shapes are shown: (i) the circular tube, and (ii) the channel between parallel plates. The detailed geometry of the fins used in calculating the heat transfer area and the coolant flow area is shown in Fig. 2. The correlations of Carnavos [1, 2] for heat transfer coefficient and friction factor in a tube having internal longitudinal fins (straight or helical) were implemented in the PLTEMP/ANL Version 3.3 code, as described below. Although developed based on measured data for tubes, the correlations are used for rectangular cross-section channels also, based on hydraulic diameter, flow area, and heated perimeter.

A verification of the implemented fin model by hand calculation is presented in this memorandum. The friction factor, coolant flow rate, heat transfer coefficient, Groeneveld critical heat flux calculations were verified with and without fins. The Users Guide of the code has also been updated by describing the method and the new input card required. The older input decks should work without any change. The onset-of-nucleate boiling (ONB) temperatures are also now printed in the code's main output. PLTEMP/ANL Version 3.3 code was also verified for a standard set of 14 test problems without fins, and found to reproduce all coolant, cladding, and fuel temperatures saved earlier from the Version 3.2 of the code. The flow instability edits are *not yet revised* to include the effect of fins.

### 6.2. Carnavos Correlation and its Implementation

Based on his experimental data for 14 tubes with and without fins, Carnavos obtained the following correlations for heat transfer coefficient and Darcy-Weisbach friction factor, each representing the data to within ±10%. The heat transfer coefficient correlation is basically the Dittus-Boelter correlation multiplied by a factor that is a function of the fin geometry. The friction factor correlation is basically the McAdams correlation multiplied by a factor that is a function of the fin geometry. Equations (1) and (2) give these correlations, assuming the fins to be of a trapezoidal cross section as shown in Fig. 2.

$$\mathrm{Nu} = 0.023\,\mathrm{Re}_a^{0.8}\,\mathrm{Pr}^{0.4}\left(\frac{A_{fa}}{A_{fc}}\right)^{0.1}\left(\frac{P_n}{P_a}\right)^{0.5}\sec^3\alpha \qquad (1)$$

$$f_a = \frac{0.184}{Re_a^{0.2}} \left( \frac{A_{fn}}{A_{fa}} \right)^{0.5} (\cos\alpha)^{0.75} \tag{2}$$

where the actual and nominal heat transfer areas, the actual and nominal coolant flow areas, and the actual and nominal hydraulic diameters are given by the following equations based on the trapezoidal cross section of the fins. The equations for a rectangular channel are a theoretical extension of the experimental data for tubes. It should be noted that, in the implementation, the *nominal perimeters and flow areas input on Card type 0307 are used* rather than the values obtained from Eq. (3), Eq. (5), and the input channel width and thickness.

$$P_n = \begin{cases} \pi D_i & \text{for tube} \\ 2(W_{ch} + T_{ch}) & \text{for rectangular channel} \end{cases} \tag{3}$$

$$P_a = P_n + n\, P_{fin} \sec\alpha \tag{4}$$

$$A_{fn} = \begin{cases} \dfrac{\pi D_i^2}{4} & \text{for tube} \\ W_{ch} T_{ch} & \text{for rectangular channel} \end{cases} \tag{5}$$

$$A_{fa} = A_{fn} - n\, A_{fin} \sec\alpha \tag{6}$$

$$A_{fc} = \begin{cases} \dfrac{\pi (D_i - 2e - 2\delta)^2}{4} & \text{for tube} \\ W_{ch}\, (T_{ch} - 2e) & \text{for rectangular channel} \end{cases} \tag{7}$$

$$\begin{aligned} P_{fin} &= \text{Sides EB} + \text{BC} + \text{CF} - \text{Arc length EF (in Fig. 2)} \\ &= \begin{cases} t + 2\sqrt{e^2 + \{(b-t)/2\}^2} - \beta D_i/2 & \text{for tube} \\ t + 2\sqrt{e^2 + \{(b-t)/2\}^2} - b & \text{for rectangular channel} \end{cases} \end{aligned} \tag{8}$$

$$A_{fin} = \begin{cases} \dfrac{e(b+t)}{2} + \dfrac{\beta D_i^2}{8} - \dfrac{b\sqrt{D_i^2 - b^2}}{4} & \text{for tube} \\ \dfrac{e(b+t)}{2} & \text{for rectangular channel} \end{cases} \tag{9}$$

$$D_{ha} = \frac{4 A_{fa}}{P_a}, \qquad D_{hn} = \frac{4 A_{fn}}{P_n} \tag{10}$$

$$Re_a = \frac{W\ D_{ha}}{A_{fa}\ \mu}\ , \quad Re_n = \frac{W\ D_{hn}}{A_{fn}\ \mu} \tag{11}$$

$$Pr = \frac{\mu\ C_p}{K} \tag{12}$$

$$D_c = D_i - 2(e + \delta) \tag{13}$$

$$\delta = \frac{D_i - \sqrt{D_i^{\ 2} - b^2}}{2} \tag{14}$$

$$\beta = 2\sin^{-1}(b/D_i) \tag{15}$$

$$A_\delta = \frac{\beta\ D_i^{\ 2}}{8} - \frac{b\sqrt{D_i^{\ 2} - b^2}}{4} \tag{16}$$

The range of applicability of correlations in Eqs. (1) and (2) is given below [1,2]. The last three restrictions on fin geometry are given in Refs. [3, 4].

| | |
|---|---|
| Helix angle range: | $0 < \alpha < 30°$ |
| Reynolds number range: | $10{,}000 < Re < 100{,}000$ |
| Prandtl number range: | $0.7 < Pr < 30$ |
| Fin pitch: | $3.3 < p/e < 5.6$ |
| Fin height: | $e/D_i < 0.29$ |
| Fin aspect ratio: | $\frac{e}{0.5(b+t)} < 3.5$ |

The Reynolds number and the other five above problem parameters are checked against their range. If the Reynolds number or any parameter is found to be out of range, then a warning message is printed, identifying the parameter which was found to be out of range. A maximum of 12 messages is printed. The solution is not stopped due to any number of warnings.

Equation (1) results in Eq. (17) below for the finned tube heat transfer coefficient $h_a$ that is based on the *actual* heat transfer area ($P_a$). For use in the PLTEMP/ANL code, one needs to express the coefficient $h_a$ given by Eq. (17) as a heat transfer coefficient $h_{a\_n}$ based on the *nominal* heat transfer area $P_n$ , preserving the heat transfer rate as done by Eq. (18).

$$h_a = \frac{Nu\ K}{D_{ha}} \tag{17}$$

$$h_{a\_n} = \frac{P_a\ h_a}{P_n} \tag{18}$$

Equation (2) gives the finned tube friction factor $f_a$ that is based on the *actual* hydraulic diameter $D_{ha}$. For use in PLTEMP/ANL, one needs to express the friction factor $f_a$ as a friction factor $f_{a\_n}$ based on the *nominal* hydraulic diameter ($D_{hn}$). To do this, one must equate the pressure drop due to friction. For a given flow rate W in the channel, the pressure drop due to the finned tube friction factor $f_a$ over a length L of the channel can be written as Eq. (19). The first factor on the right hand side of Eq. (19) must be preserved because the second factor is the same whether the nominal or the actual hydraulic diameter is used. Equating the first factor on the right hand side of Eq. (19) results in Eq. (20), which is rewritten as Eq. (21) below.

$$\Delta p_a = \left( \frac{f_a}{A_{fa}^{\ 2} D_{ha}} \right) \left( \frac{L W^2}{2 \rho} \right) \tag{19}$$

$$\frac{f_{a\_n}}{A_{fn}^{\ 2} D_{hn}} = \frac{f_a}{A_{fa}^{\ 2} D_{ha}} \tag{20}$$

$$f_{a\_n} = \frac{A_{fn}^{\ 2} D_{hn} f_a}{A_{fa}^{\ 2} D_{ha}} \tag{21}$$

A subroutine CARNAVOS was developed to calculate the results of Eqs. (18) and (21). The subroutine has been implemented into the PLTEMP/ANL Version 3.3. The subroutine CARNAVOS is called by the existing multi-option heat transfer subroutine HCOEF1 of the code.

### 6.3. Verification of Carnavos Correlation Implemented in PLTEMP/ANL

The purpose here is to verify the heat transfer coefficient, friction factor, and coolant flow rate calculated by PLTEMP/ANL Version 3.3 for a sample problem with finned coolant channels. Figure 3 shows a sample input deck (Test Problem 16) to model the coolant channels of the MIT Reactor. The sample problem has two assemblies of a single type, each having 9 fuel plates and 10 coolant channels. The reactor core axial region (region 2) of each assembly has the fin geometry of the MIT Reactor. The first and third axial regions (the inlet and exit regions) are each made artificially short (0.01 mm), and the minor loss coefficients are set to zero, so that the coolant flow rate in a channel could be hand-calculated. The power produced is set artificially small so that there is a negligible coolant temperature rise in channels and the coolant properties only at the inlet temperature are required in the hand calculation of friction factor, flow rate and heat transfer coefficient.

The newly developed PLTEMP/ANL Version 3.3 code was run for this sample deck, *with the fins* (Run 1), for an input frictional pressure drop of 0.1 MPa. The code was also run *without the fins* (Run 2), by modifying the input cards 200 and 202 of the deck (i.e., setting option IH=1 and fin height to zero). Table 1 provides the geometry of the finned channel, the needed coolant properties, and some data from the debug outputs printed by the code (using input KPRINT = 2). The columns 1 and 2 of Table 1 show selected results from the run with fins, and the column 3 shows results from the run without fins.

### 6.3.1. Verification of Friction Factor and Flow Rate in Finned Coolant Channels

In the first run, the code calculated a flow rate of 0.58046 kg/s per coolant channel with fins. This flow rate is established by a frictional pressure drop of 0.1 MPa. In the second run, it calculated a flow rate of 1.11814 kg/s per coolant channel without fins, at the same frictional pressure drop (0.1 MPa). The actual Reynolds number and friction factor, $f_a$ in the finned channel (column 1 of Table 1) were hand-calculated as follows. The value of $f_a$ at the flow rate of 0.58046 kg/s per coolant channel is found using the Carnavos correlation, i.e., Eq. (2).

$$Re_a = \frac{D_{ha}\ W}{\mu\ A_{fa}} = \frac{0.0021817 \text{ x } 0.58046}{5.9309 \text{ x} 10^{-4} \text{ x } 1.13548 \text{ x} 10^{-4}} = 18805.2$$

$$f_a = \frac{0.184}{(18805.2)^{0.2}} \left( \frac{1.26451}{1.13548} \right)^{0.5} \text{ x } 1.0 = 0.027123$$

The frictional pressure drop in the finned channel can be hand-calculated as follows.

$$\Delta p_a = \left( \frac{f_a\ L}{D_{ha}} \right) \left( \frac{W^2}{2\ \rho\ A_{fa}{}^2} \right)$$

$$= \frac{0.027123 \text{ x } 0.61}{0.0021817} \text{ x } \frac{(0.58046)^2}{2 \text{ x } 991.148 \text{ x } (1.13548 \text{ x} 10^{-4})^2} = 0.099975 \quad \text{MPa}$$

The above values of actual Reynolds number, friction factor, and pressure drop agree with those printed by the code and shown in column 1 of Table 1.

The Reynolds number $Re_n$ and friction factor, $f_n$ in the un-finned channel at the same flow rate, 0.58046 kg/s, were hand-calculated using $Re_n = D_{hn}\ W/(\mu\ A_{fn})$ and $f_n = 0.184 / Re_n^{0.2}$.

$$Re_n = \frac{D_{hn}\ W}{\mu\ A_{fn}} = \frac{0.0047459 \text{ x } 0.58046}{5.9309 \text{ x} 10^{-4} \text{ x } 1.26451 \text{ x} 10^{-4}} = 36732.0$$

$$f_n = \frac{0.184}{(36732.0)^{0.2}} = 0.022481$$

These nominal values are shown in columns 2 of Table 1, and agree with those printed by the code. The frictional pressure drop, $\Delta p_n$ in the un-finned channel at this flow rate (0.58046 kg/s) can be hand-calculated as follows.

$$\Delta p_n = \left( \frac{f_n\ L}{D_{hn}} \right) \left( \frac{W^2}{2\ \rho\ A_{fn}{}^2} \right)$$

$$= \frac{0.022481 \text{ x } 0.61}{0.0047459} \text{ x } \frac{(0.58046)^2}{2 \text{ x } 991.148 \text{ x } (1.26451 \text{ x} 10^{-4})^2} = 0.0307156 \quad \text{MPa}$$

At the flow rate 0.58046 kg/s, the ratio of pressure drop in the finned channel to that in the un-finned channel is hand-calculated to be 3.25487, which agrees with the ratio printed by the code.

$$\frac{\Delta p_a}{\Delta p_n} = \frac{0.099975}{0.0307156} = 3.25487$$

The flow rate $W_3$ in the un-finned channel at the input pressure drop of 0.1 MPa (Run 2) should be about $\sqrt{3.25487}$ times 0.58046 kg/s = 1.04722 kg/s. Actually it will be more than this value because the un-finned friction factor will be lower than 0.022481, because of the increase in Reynolds number at the increased flow rate. The code-calculated $W_3$ is 1.11814 kg/s as shown in column 3 of Table 1. This flow rate is verified by hand-calculating the corresponding Reynolds number, friction factor, and pressure drop, as follows.

$$Re_3 = \frac{D_{hn}\ W_3}{\mu\ A_{fn}} = \frac{0.0047459 \text{ x } 1.11814}{5.9341 \text{x} 10^{-4} \text{ x } 1.26451 \text{x} 10^{-4}} = 70719.2$$

$$f_3 = \frac{0.184}{(70719.2)^{0.2}} = 0.019720$$

$$\Delta p_3 = \left(\frac{f_3\ L}{D_{hn}}\right)\left(\frac{W_3^{\ 2}}{2\ \rho\ A_{fn}^{\ 2}}\right)$$

$$= \frac{0.019720 \text{ x } 0.61}{0.0047459} \text{ x } \frac{(1.11814)^2}{2 \text{ x } 991.223 \text{ x } (1.26451 \text{x} 10^{-4})^2} = 0.099968 \quad \text{MPa}$$

The value of $\Delta p_3$ agrees with the input pressure drop of 0.1 MPa, and this agreement verifies the code calculated results shown in column 3 of Table 1. In summary, the hand-calculated values of friction factor and coolant flow rate in the three cases are found to agree with the code-calculated values shown in Table 1. This verifies the implementation of the Carnavos correlation for friction factor.

### 6.3.2. Verification of Heat Transfer Coefficient

The actual heat transfer coefficient in the finned channel (column 1 of Table 1) was hand-calculated as follows, using the Carnavos correlation, i.e., Eq. (1).

$$\frac{h_a D_{ha}}{K} = 0.023 \text{ x } (18805.2)^{0.8}\ (3.86247)^{0.4} \left(\frac{1.13548}{1.00645}\right)^{0.1} \left(\frac{0.10658}{0.20818}\right)^{0.5} \text{ x } 1.0 = 75.11963$$

$$h_a = \frac{75.11963 \text{ x } 0.64130}{0.0021817} = 22081.0 \quad \text{W/m}^2 - {}^\circ\text{C} \ \text{(based on actual heat transfer area)}$$

The above actual heat transfer coefficient (22081.0) is based on the heat transfer area with fins. This value agrees with the value (22080.4) printed by the code. Since the code has all along used un-finned coolant channels, the heat transfer coefficients and heat transfer areas used throughout the code are those of the un-finned coolant channel. Therefore, the above heat transfer coefficient must be expressed as an equivalent heat transfer coefficient, $h_{a\_n}$ that is based on the heat transfer area of the un-finned coolant channel (nominal heat transfer area), such that the heat transfer rate and the temperature difference between the bulk coolant and cladding surface remain unchanged. The equivalent heat transfer coefficient is found using Eq. (18), as follows.

$$h_{a\_n} = \frac{h_a P_a}{P_n} = \frac{22081.0 \text{ x } 0.20818}{0.10658} = 43130.3 \quad \text{W/m}^2 - {}^\circ\text{C} \text{ (based on nominal heat transfer area)}$$

This is the value that is printed in the main temperature edits of PLTEMP/ANL Version 3.3. To evaluate the heat transfer enhancement caused by the fins, the actual heat transfer rate is compared below with the heat transfer rate without fins at the same coolant flow rate (0.58046 kg/s). The heat transfer coefficient, $h_n$ in the un-finned channel is given by

$$\frac{h_n D_{hn}}{K} = 0.023 \text{ x } (36732.0)^{0.8} \text{ x } (3.86247)^{0.4} = 177.2187$$

$$h_n = \frac{177.2187 \text{ x } 0.64130}{0.0047459} = 23947.1 \quad \text{W/m}^2 - {}^\circ\text{C} \text{ (based on nominal heat transfer area)}$$

This value of the nominal heat transfer coefficient (23947.1) agrees with the value printed by the code (shown in column 2). The heat transfer enhancement factor provided by the fins is given by

$$\text{Enhancement factor} = \frac{h_{a\_n}}{h_n} = \frac{43130.3}{23947.1} = 1.8010$$

This value of the heat transfer enhancement factor agrees with the value printed by the code.

### 6.3.3 Comparison of Zero-Height Fin Option with No Fin Option

The output obtained by running the code with fins of zero height (using option IH = -1 on input card 200, and fin height EFIN = 0.0 on input card 202), and that obtained by running the code without fins (using option IH = 1 without providing the input card 202) were compared to verify that the code gave the same results in both cases. It was found that the code does give the same results. A previously-developed PLTEMP/ANL output comparing utility program *differ.x* was used to compare the two cases. The maximum temperature difference for coolant, cladding, and fuel peak was found to be 0.001 °C. Two points of detail are noted here:

(1) In the latter case (without fins), the selected coolant flow friction factor uses input values of FCOEF, FEXPF, and ROUGH (0.184, 0.2, and 0.0) on the card 305. This was done because the finned friction factor correlation (Carnavos correlation) implemented in the

code, is based on the McAdams correlation ($f = 0.184/Re^{0.2}$) and reduces to it in the absence of fins.

(2) In the latter case (without fins), IH is selected to be 1, implying the Dittus-Boelter correlation (not one of the other correlations available in the code). The reason for this is that the finned heat transfer correlation (Carnavos correlation) implemented in the code, is based on the Dittus-Boelter correlation and reduces to it in the absence of fins.

Without these two input choices, the code may not give the same results in the two cases discussed above.

The case without fins of this problem (Test Problem 16) was also run using the older version of PLTEMP/ANL (Version 3.2), and the results were compared with that obtained by Version 3.3. This comparison was performed at two power levels: 0.0024 MW and 0.24 MW. Using the utility program *differ.x*, the maximum temperature difference for coolant, cladding, and fuel peak was found to be zero, in the comparison at each power level. This verifies the implementation of Carnavos correlations in the coolant flow rate and temperature calculations in the code.

### 6.4. Code Output for Finned Coolant Channels

The following should be accounted for when using the code output. The flow instability edits are *not yet revised* to include the effect of fins.

(1) The heat transfer area (when using the fin option IH = -1) in the code are left unchanged as the *nominal* area without fins (just as it was calculated before implementing the fin option). The code performs the temperature calculation using the enhanced heat transfer coefficients expressed based on the nominal heat transfer area, $2(W_{ch} + T_{ch})$ $m^2$ per meter, of the coolant channel. The calculated heat fluxes are therefore based on the nominal heat transfer area. The heat transfer coefficients printed in the temperature table of code output (see part of output in Table 2) are based on the nominal heat transfer area in the channel without fins.

(2) The heat fluxes printed by the code in the table of heat fluxes are based on the *nominal* heat transfer area, $2(W_{ch} + T_{ch})$ $m^2$ per meter, in the coolant channel without fins.

(3) The *actual* heat flux (not the *nominal* heat flux) is used in finding the ONB temperature used to calculate the ONB ratio in subroutines FINLED, FINLED6, FINLEDIT, and FINLEDIT6. The actual heat flux $q_a$ equals the nominal heat flux $q_n$ divided by the actual-to-nominal perimeter ratio ($P_a$ / $P_n$). The ratio $P_a/P_n$ is stored in the COMMON block FINGEOM.

$$q_a = \frac{q_n}{(P_a / P_n)}$$

(4) The *actual* heat flux is used in calculating the DNB ratio. All six critical heat flux correlations in the code (i.e., Mirshak-Durant-Towell, Bernath, Labuntsov, Mishima, and Weatherhead correlations, and the Groeneveld table) in the subroutines DNB and DNB2

were revised to use the actual (with fins) flow area, perimeter, hydraulic diameter, and coolant velocity. A hand calculation (shown below) of the Groeneveld critical heat flux (code input option ICHF = 5) was done to verify the code calculated value with fins. The code has the 1995 version of the Groeneveld critical heat flux table. The needed parts of the table [5] at pressures of 1000 kPa and 3000 kPa (that bracket the coolant outlet pressure of 1300 kPa in Test Problem 16) are given below. All interpolations are also shown.

| | CHF, kW/m² At 1000 kPa | | CHF, kW/m² At 3000 kPa | | CHF, kW/m² At Outlet Pressure of 1300 kPa | | |
|---|---|---|---|---|---|---|---|
| Quality → | -0.4 | -0.3 | -0.4 | -0.3 | -0.4 | -0.3 | -0.3173 |
| Mass Flux, kg/m²-s ↓ | | | | | | | |
| 5000.0 | 14574 | 12447 | 14778 | 13200 | 14604.6 | 12560.0 | 12913.7 |
| 5500.0 | 15273 | 13033 | 15454 | 13765 | 15300.2 | 13142.8 | 13516.0 |
| 5112.1 | | | | | | | **13048.7** |

As mentioned above, the coolant temperature rise is small (only 0.06 °C) (see the code output shown in Table 2), the coolant outlet temperature is 45.06 °C, and outlet pressure is 1300 kPa (=1.4 MPa inlet pressure – 0.1 MPa pressure drop). Using these values, the exit quality is found as follows:

$h_{f,sat}$ = Saturated liquid enthalpy at 1300 kPa = 814.70 kJ/kg
$h_{g,sat}$ = Saturated vapor enthalpy at 1300 kPa = 2785.43 kJ/kg
$h_f$ = Liquid enthalpy at 45.06 °C (from ASME Steam Table) = 189.48 kJ/kg

Quality of the sub-cooled liquid, $x = \dfrac{189.48 - 814.70}{2785.42 - 814.70} = -0.3173$

Using the coolant flow rate and actual flow area in a single channel (shown in Table 1), the coolant mass flux *with fins* is found to be ($0.58046/1.13548\text{x}10^{-4}$) = 5112.1 kg/m²-s. The critical heat flux for the reference 8-mm diameter tube, and that for the finned channel are shown below.

CHF(1300 kPa, 5112.1 kg/m²-s, -0.3171) for diameter 8 mm = 13048.7 kW/m²

CHF(1300 kPa, 5112.1 kg/m²-s, -0.3171) for hydraulic diameter 2.1817 mm

$$= 13048.7\left(\frac{8}{2.1817}\right)^{0.3333} = 20121.8\ \text{kW/m}^2$$

The above hand-calculated critical heat flux of 20121.8 kW/m² is in agreement with the code-calculated value of 20241 kW/m² (see part of code output in Table 2).

## NOMENCLATURE

$P_a$ = Actual perimeter, i.e., actual heat transfer area per unit length of the tube with fins, m² per meter

$P_n$ = Nominal perimeter, i.e., nominal heat transfer area per unit length of the tube, based on tube ID as if the fins were not present, $m^2$ per meter

$P_{fin}$ = *Additional* heated perimeter provided by a single fin. It is the additional is over the tube perimeter covered by the fin, m

$A_{fa}$ = Actual flow area in the tube with fins, $m^2$

$A_{fc}$ = Core flow area, i.e., the flow area inside the circle touching the fin tips, (see Fig. 2), $m^2$

$A_{fn}$ = Nominal flow area in the tube, based on tube ID as if the fins were not present, $m^2$

b = Fin thickness at the bottom, m

$A_{fin}$ = Cross sectional area of a single fin. $m^2$

$C_p$ = Specific heat of the coolant, J/kg-°C

$D_c$ = Core diameter of a channel, i.e., diameter inside the fin tips, m

$D_i$ = Inner diameter of the tube, m

$D_{ha}$ = Actual hydraulic diameter of the finned channel, m

$D_{hn}$ = Nominal hydraulic diameter of the channel without fins, m

e = Height of fins, m

$f_a$ = Finned tube Darcy-Weisbach friction factor based on the *actual* hydraulic diameter $D_{ha}$

$f_{a\_n}$ = Finned tube Darcy-Weisbach friction factor expressed as a friction factor based on the *nominal* flow area $A_{fn}$ and hydraulic diameter $D_{hn}$

$h_a$ = Finned tube heat transfer coefficient based on the *actual* heat transfer area, $W/m^2$-°C

$h_{a\_n}$ = Finned tube heat transfer coefficient expressed as a coefficient based on the *nominal* heat transfer area, $W/m^2$-°C

K = Thermal conductivity of the coolant, W/m-°C

L = Channel length, m

n = Number of fins in a channel

Nu = $\dfrac{h_a D_{ha}}{K}$ = Nusselt number based on $P_a$ and $A_{fa}$ (i.e., actual perimeter and actual flow area)

p = Circumferential pitch of fins = $\pi D_i/n$ for tube = $2W_{ch}/n$ for rectangular channel

Pr = Prandtl number of the coolant

$\Delta p_a$ = Actual pressure drop due to friction in the finned channel, $N/m^2$

$Re_a$ = $\dfrac{W\, D_{ha}}{\mu\, A_{fa}}$ = Reynolds number based on $P_a$ and $A_{fa}$ (i.e., actual perimeter and actual flow area)

$Re_n$ = $\dfrac{W\, D_{hn}}{\mu\, A_{fn}}$ = Reynolds number based on $P_n$ and $A_{fn}$ (i.e., nominal perimeter and nominal flow area)

t = Fin thickness at the tip, m

$T_{ch}$ = Channel thickness between the parallel plates, m

$W_{ch}$ = Channel width of the channel between the parallel plates, m

W = Coolant flow rate in the channel, kg/s

$\alpha$ = Angle between the spiral fin's longitudinal axis and the tube axis (called helix angle)

$\rho$ = Density of the coolant, $kg/m^3$

$\mu$ = Dynamic viscosity of the coolant, $N\text{-}s/m^2$

## REFERENCES


1. T. C. Carnavos, "Heat Transfer Performance of Internally Finned Tubes in Turbulent Flow," AIChE Paper presented at the 18th National Heat Transfer Conference, San Diego, CA (Aug. 1979).

2. T. C. Carnavos, "Heat Transfer Performance of Internally Finned Tubes in Turbulent Flow," Heat Transfer Eng., Vol. 1, No. 4, pp. 32-37 (Apr-June 1980).

3. R. L. Webb and M. J. Scott, "A Parametric Analysis of the Performance of Internally Finned Tubes for Heat Exchanger Application," J. of Heat Transfer, Trans. of the ASME, Vol. 102, pp. 38-43 (Feb. 1980).

4. N. H. Kim and R. L. Web, "Analytic Prediction of the Friction and Heat Transfer for Turbulent Flow in Axial Internal Fin Tubes," J. of Heat Transfer, Trans. of the ASME, Vol. 115, pp. 553-559 (Aug. 1993).

5. D. C. Groeneveld, et. al., "The 1995 Look-up Table for Critical Heat Flux in Tubes," Nuclear Eng. Design, Vol. 163, pp. 1-28 (1996).

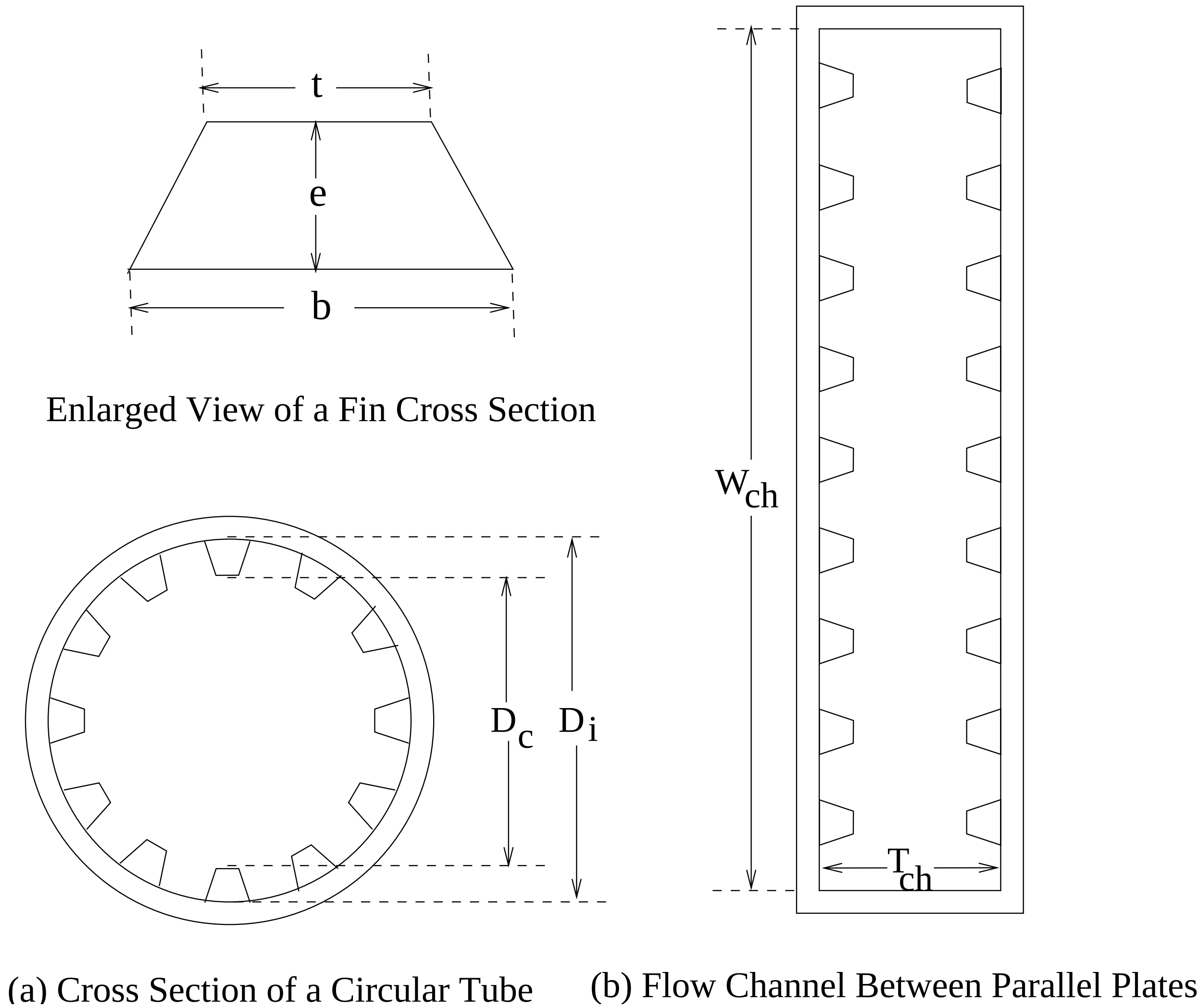


**Fig. 1. Reactor Coolant Channels with Longitudinal Inner Fins: (a) Circular Tube, and (b) Channel between Parallel Plates**

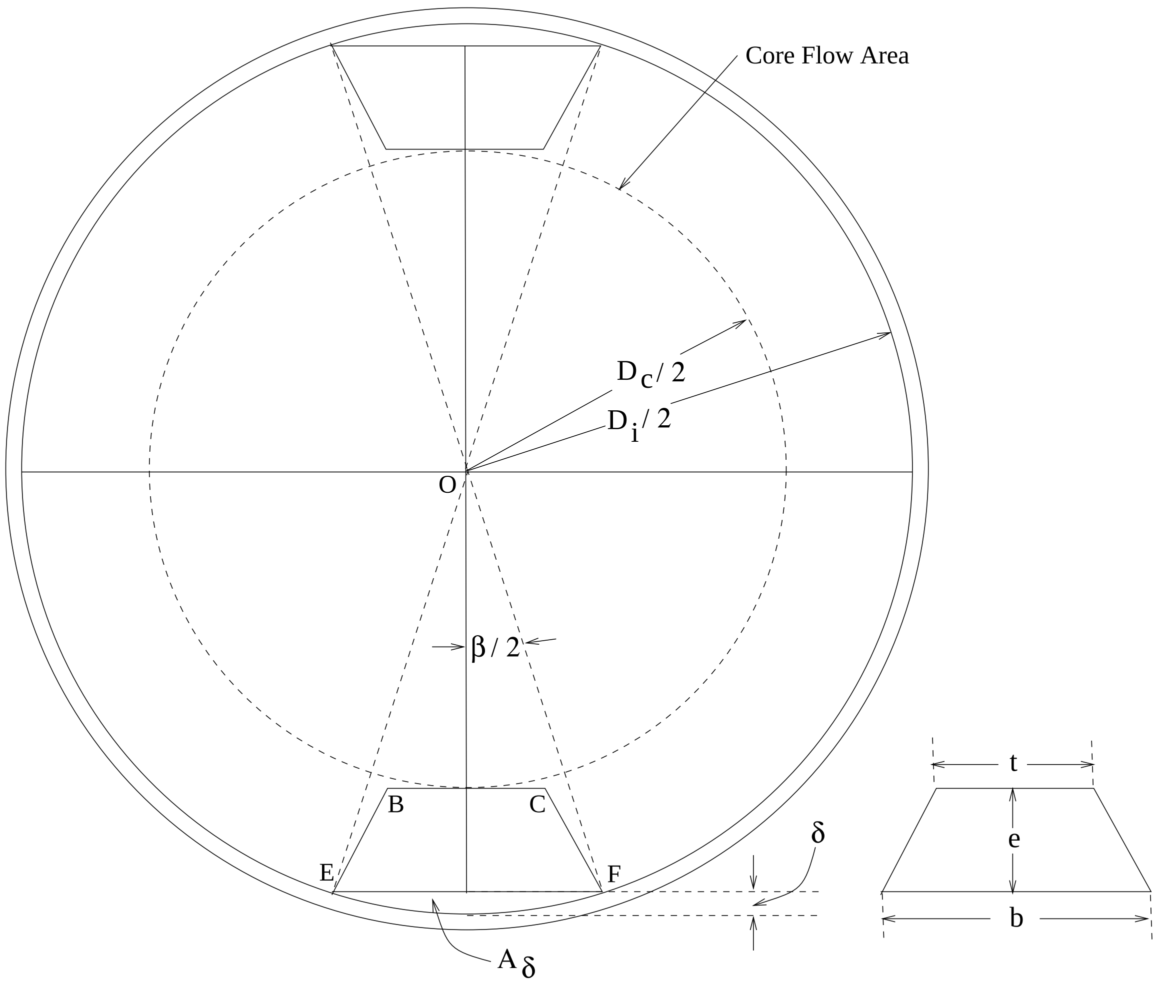


**Fig. 2. Fin Geometry Used in Calculating Coolant Flow Area in a Circular Tube Having Longitudinal Internal Fins**

## Fig. 3. Input Data for Test Problem 16 Having MITR-Type Finned Coolant Channels

```
 Test Problem 16: MITR with fins
! 2 assemblies of one type, each producing 1.2 kWt
! Each assembly has 9 fuel plates and 10 coolant channels
! H2O coolant, Flow is calculated from input pressure drop
! All hot channel factors = 1.0
! No bypass flow, NCTYP=0
! 10 axial heat transfer nodes in the heated length of fuel plates
!  1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18        Indices
  -1   0   5   1   0   1   1   1   0   0   0   0   0       1   2      00       Card(1)0200
 0.000254   0.000254    0.000254    0.0         200                            Card(1)0202
   2   3 5.00       1.00        1.00        1.00           3                   Card(1)0300
! Using pressure driven mode
   1  20 1.00                                                                  Card(1)0301
   1   1   1                                                                   Card(1)0302
1.20        1.20                                                               Card(2)0303
12.645E-04  4.74585E-03 0.00001     0.00        0.0508      2.4892E-03         Card(3)0304
12.645E-04  4.74585E-03 0.61        0.00        0.0508      2.4892E-03         Card(3)0304
12.645E-04  4.74585E-03 0.00001     0.00        0.0508      2.4892E-03         Card(3)0304
! Use the code's biult-in correlation for friction factor
0.184       0.20        0.00                                                   Card(1)0305
  10   3 0.00       0.61        0.25E-03    0.00        0.55E-03    100.00     Card(1)0306
1.2645E-04  4.74585E-03 0.106578    0.0508      0.0508      2.4892E-03         Card(5)0307
1.2645E-04  4.74585E-03 0.106578    0.1016      0.0508      2.4892E-03         Card(5)0307
1.2645E-04  4.74585E-03 0.106578    0.1016      0.0508      2.4892E-03         Card(5)0307
1.2645E-04  4.74585E-03 0.106578    0.1016      0.0508      2.4892E-03         Card(5)0307
1.2645E-04  4.74585E-03 0.106578    0.1016      0.0508      2.4892E-03         Card(5)0307
1.2645E-04  4.74585E-03 0.106578    0.1016      0.0508      2.4892E-03         Card(5)0307
1.2645E-04  4.74585E-03 0.106578    0.1016      0.0508      2.4892E-03         Card(5)0307
1.2645E-04  4.74585E-03 0.106578    0.1016      0.0508      2.4892E-03         Card(5)0307
1.2645E-04  4.74585E-03 0.106578    0.1016      0.0508      2.4892E-03         Card(5)0307
1.2645E-04  4.74585E-03 0.106578    0.0508      0.0508      2.4892E-03         Card(5)0307
0.0508      0.0508      0.0508      0.0508      0.0508      0.0508             Card(1)0308
0.0508      0.0508      0.0508                                                 Card(1)0308
! Card 0308A not required in slab geometry
! Radial power peaking factor data by fuel plate for each subassembly. Input flow data by
! channel for each subassembly on Cards 0310 not required because WFGES(1) is non-zero
0.800       0.850       0.900       0.950       1.000       1.050              Card(2)0309
1.100       1.150       1.200                                                  Card(2)0309
0.801       0.851       0.901       0.951       1.001       1.051              Card(2)0309
1.101       1.151       1.201                                                  Card(2)0309
! DP0       DDP         DPMAX       POWER       TIN         PIN
0.10        0.04        0.10        2.4E-03     45.0        1.40               Card(1)0500
0.00        0.00                                                               Card(2)0500
  50 0.0001     25.0        0.50        2.0E-03                                Card(1)0600
  11                                                                           Card(1)0700
0.00        0.80                                                               Card(11)0701
0.10        0.88                                                               Card(11)0701
0.20        0.96                                                               Card(11)0701
0.30        1.04                                                               Card(11)0701
0.40        1.12                                                               Card(11)0701
0.50        1.20                                                               Card(11)0701
0.60        1.12                                                               Card(11)0701
0.70        1.04                                                               Card(11)0701
0.80        0.96                                                               Card(11)0701
0.90        0.88                                                               Card(11)0701
1.00        0.80                                                               Card(11)0701
   0                                                                           Card(11)0702
```

**Table 1. Comparison of PLTEMP Calculations With and Without Fins in Internal Coolant Channels of Test Problem 16**

| Parameter | With Fins at 0.1 MPa Pressure Drop (Run 1) | Without Fins at Finned Channel Flow Rate (Run 1) | Without Fins at 0.1 MPa Pressure Drop (Run 2) |
|---|---|---|---|
| Column Number | 1 | 2 | 3 |
| **PLTEMP/ANL Input** | | | |
| Nominal thickness of channel, mm | 2.4892 | | |
| Nominal width of channel, mm | 50.8 | | |
| Channel Length, m | 0.61 | | |
| Number of fins in a channel | 200 | | |
| Fin height, mm | 0.254 | | |
| Fin thickness (uniform), mm | 0.254 | | |
| **PLTEMP/ANL Output** | | | |
| Core flow area (within fin tips), $A_{fc}$ , $m^2$ | $1.00645x10^{-4}$ | | |
| Flow area ($A_{fa}$ and $A_{fn}$), $m^2$ | $1.13548x10^{-4}$ | $1.26451x10^{-4}$ | |
| Perimeter ($P_a$ and $P_n$) , m | 0.20818 | 0.10658 | |
| Hydraulic diameter ($D_{ha}$ and $D_{hn}$) , m | 0.0021817 | 0.0047459 | |
| Coolant density, $kg/m^3$ | 991.148 | | 991.223 |
| Coolant specific heat, J/kg-°C | 4176.421 | | |
| Coolant dynamic viscosity, $N\text{-}s/m^2$ | $5.9309x10^{-4}$ | | $5.9341x10^{-4}$ |
| Coolant thermal conductivity, W/m-°C | 0.64130 | | |
| Prandtl number | 3.86247 | | |
| Flow rate in a channel, kg/s | 0.58046 | | 1.11814 |
| Reynolds number | 18805.2 | 36732.0 | 70719.2 |
| Darcy-Weisbach Friction Factor | 0.027123 | 0.022481 | 0.019720 |
| Pressure drop increase factor $\Delta p_a$ / $\Delta p_n$ | 3.2548 | | |
| Actual heat transfer coefficient, $W/m^2$-°C | 22080.4 | 23947.2 | |
| Enhancement factor $h_aP_a$ / ($h_nP_n$) | 1.8010 | | |
| **Hand Calculation** | | | |
| Pressure Drop ($\Delta p$), MPa | 0.099975 | 0.030716 | 0.099968 |

## Table 2. Portion of PLTEMP/ANL V3.3 Output for Test Problem 16 Having MITR-Type Finned Coolant Channels

FUEL PLATE 2 (ExactSoln)

| NODE | COOLANTl | CladSl | FUEL PEAK | CladSr | COOLANTr | HCOFl | HCOFr | ONBRl | ONBRr | ETA'l | ETA'r | ONB Temp | ONB Temp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | (C) | (C) | (C) | (C) | (C) | W/C-m^2 | W/C-m^2 | [F Note 1] | | K-cm^3/J | K-cm^3/J | left(C) | right(C) |
| | | | | | | [F Note 2] | [F Note 2] | | | | | | |
| | 45.000 | | | | 45.000 | | | | | | | | |
| 1 | 45.003 | 45.039 | 45.043 | 45.039 | 45.003 | 4.3130E+04 | 4.3130E+04 | 4.E+03 | 4.E+03 | 5.037E+05 | 5.034E+05 | 194.966 | 194.966 |
| 2 | 45.010 | 45.049 | 45.054 | 45.049 | 45.010 | 4.3132E+04 | 4.3132E+04 | 3.E+03 | 3.E+03 | 4.569E+05 | 4.604E+05 | 194.616 | 194.616 |
| 3 | 45.016 | 45.059 | 45.065 | 45.060 | 45.018 | 4.3134E+04 | 4.3135E+04 | 3.E+03 | 3.E+03 | 4.156E+05 | 4.264E+05 | 194.264 | 194.263 |
| 4 | 45.022 | 45.069 | 45.075 | 45.069 | 45.025 | 4.3137E+04 | 4.3138E+04 | 2.E+03 | 2.E+03 | 3.776E+05 | 4.007E+05 | 193.911 | 193.907 |
| 5 | 45.027 | 45.079 | 45.085 | 45.080 | 45.033 | 4.3138E+04 | 4.3140E+04 | 2.E+03 | 2.E+03 | 3.440E+05 | 3.799E+05 | 193.555 | 193.549 |
| 6 | 45.033 | 45.086 | 45.092 | 45.087 | 45.041 | 4.3140E+04 | 4.3143E+04 | 2.E+03 | 2.E+03 | 3.378E+05 | 3.857E+05 | 193.193 | 193.184 |
| 7 | 45.040 | 45.089 | 45.095 | 45.090 | 45.048 | 4.3143E+04 | 4.3146E+04 | 2.E+03 | 2.E+03 | 3.583E+05 | 4.181E+05 | 192.823 | 192.814 |
| 8 | 45.047 | 45.093 | 45.098 | 45.094 | 45.055 | 4.3145E+04 | 4.3149E+04 | 2.E+03 | 2.E+03 | 3.838E+05 | 4.534E+05 | 192.450 | 192.441 |
| 9 | 45.053 | 45.096 | 45.102 | 45.098 | 45.063 | 4.3148E+04 | 4.3151E+04 | 2.E+03 | 2.E+03 | 4.092E+05 | 5.016E+05 | 192.076 | 192.064 |
| 10 | 45.059 | 45.099 | 45.104 | 45.100 | 45.069 | 4.3150E+04 | 4.3153E+04 | 1.E+03 | 1.E+03 | 4.392E+05 | 5.602E+05 | 191.699 | 191.686 |
| | 45.061 | | | | 45.071 | | | | | | | | |

[1] The ONB ratio is here defined as (Tonb - Tinlet)/(Tsurf - Tinlet). If the heat flux is negative (the coolant is hotter than the adjacent cladding surface), then the ONB ratio is arbitrarily set to 99.99 .

[2] The finned heat transfer coeff is here expressed as an average over the nominal heat transfer area in the unfinned coolant channel. It equals (actual finned surface heat transfer coeff)X( 1.9533 1.9533, finned-to-unfinned heat transfer area ratio).

Departure from Nucleate Boiling Ratio (DNBR) (ExactSoln)
Using Groeneveld Tables for CHF(Pressure, MassFlux, Quality)

NOTE: The coolant channel has fins. The CHF and peak heat flux are here based on the actual (not nominal) flow area, perimeter, and hydraulic diameter.

```
FUEL PLATE  1  LEFT SIDE: DNBR = 9.2017E+03, CHF = 2.0309E+01 MW/m**2, PEAK HEAT FLUX= 1.4947E-03 MW/m**2 of finned surface
FUEL PLATE  1 RIGHT SIDE: DNBR = 1.1195E+04, CHF = 2.0242E+01 MW/m**2, PEAK HEAT FLUX= 9.2567E-04 MW/m**2 of finned surface
FUEL PLATE  2  LEFT SIDE: DNBR = 8.9538E+03, CHF = 2.0242E+01 MW/m**2, PEAK HEAT FLUX= 1.1574E-03 MW/m**2 of finned surface
FUEL PLATE  2 RIGHT SIDE: DNBR = 1.0046E+04, CHF = 2.0241E+01 MW/m**2, PEAK HEAT FLUX= 1.0316E-03 MW/m**2 of finned surface
FUEL PLATE  3  LEFT SIDE: DNBR = 9.0431E+03, CHF = 2.0241E+01 MW/m**2, PEAK HEAT FLUX= 1.1459E-03 MW/m**2 of finned surface
FUEL PLATE  3 RIGHT SIDE: DNBR = 8.9510E+03, CHF = 2.0241E+01 MW/m**2, PEAK HEAT FLUX= 1.1577E-03 MW/m**2 of finned surface
FUEL PLATE  4  LEFT SIDE: DNBR = 8.4010E+03, CHF = 2.0241E+01 MW/m**2, PEAK HEAT FLUX= 1.2335E-03 MW/m**2 of finned surface
FUEL PLATE  4 RIGHT SIDE: DNBR = 8.6062E+03, CHF = 2.0241E+01 MW/m**2, PEAK HEAT FLUX= 1.2041E-03 MW/m**2 of finned surface
FUEL PLATE  5  LEFT SIDE: DNBR = 8.0426E+03, CHF = 2.0241E+01 MW/m**2, PEAK HEAT FLUX= 1.2885E-03 MW/m**2 of finned surface
FUEL PLATE  5 RIGHT SIDE: DNBR = 8.1786E+03, CHF = 2.0241E+01 MW/m**2, PEAK HEAT FLUX= 1.2670E-03 MW/m**2 of finned surface
FUEL PLATE  6  LEFT SIDE: DNBR = 7.5341E+03, CHF = 2.0241E+01 MW/m**2, PEAK HEAT FLUX= 1.3754E-03 MW/m**2 of finned surface
FUEL PLATE  6 RIGHT SIDE: DNBR = 7.8488E+03, CHF = 2.0241E+01 MW/m**2, PEAK HEAT FLUX= 1.3202E-03 MW/m**2 of finned surface
FUEL PLATE  7  LEFT SIDE: DNBR = 7.4072E+03, CHF = 2.0241E+01 MW/m**2, PEAK HEAT FLUX= 1.3990E-03 MW/m**2 of finned surface
FUEL PLATE  7 RIGHT SIDE: DNBR = 7.3034E+03, CHF = 2.0241E+01 MW/m**2, PEAK HEAT FLUX= 1.4188E-03 MW/m**2 of finned surface
FUEL PLATE  8  LEFT SIDE: DNBR = 6.9616E+03, CHF = 2.0241E+01 MW/m**2, PEAK HEAT FLUX= 1.4885E-03 MW/m**2 of finned surface
FUEL PLATE  8 RIGHT SIDE: DNBR = 7.1311E+03, CHF = 2.0241E+01 MW/m**2, PEAK HEAT FLUX= 1.4531E-03 MW/m**2 of finned surface
FUEL PLATE  9  LEFT SIDE: DNBR = 7.4507E+03, CHF = 2.0241E+01 MW/m**2, PEAK HEAT FLUX= 1.3908E-03 MW/m**2 of finned surface
FUEL PLATE  9 RIGHT SIDE: DNBR = 6.1030E+03, CHF = 2.0308E+01 MW/m**2, PEAK HEAT FLUX= 2.2535E-03 MW/m**2 of finned surface
```

## 7. Verification of Babelli-Ishii Flow Instability Criterion with 75 Tests Performed by Whittle and Forgan

(February 2008)

The PLTEMP/ANL code was recently improved to model heat transfer coefficient and friction factor in finned coolant channels. The routines used in the code to check for excursive flow instability criteria also needed to be modified to account for the fin geometry if the fuel plates had fins (i.e., if the input option IH = -1). In this memorandum, the Babelli-Ishii flow instability criterion based on the Subcooling number and the Zuber number (available in the present code) is tested and verified for the purpose of modifying the criterion for use in the case of finned channels. A program has been developed to apply the Babelli-Ishii flow instability criterion of Eq. (1) or the simple criterion of Eq. (5) to 75 tests (using uniform heat flux) reported by Whittle and Forgan. The comparison of the measured and calculated (using either criterion) coolant inlet velocities at the onset of flow instability in these tests shows that both criteria are conservative. Based on this work, the following three improvements were made to the PLTEMP/ANL code.

(i) The older versions of the code (the version 3.3 and older) printed the results of the simplified Babelli-Ishii flow instability criterion of Eq. (5). Now, the version 3.4 of the code also prints the results of the main Babelli-Ishii flow instability criterion of Eq. (1).

(ii) An error in the implementation of the simplified Babelli-Ishii flow instability criterion was corrected. The error was related to the adjustment (to account for axially non-uniform heat flux) of the dimensionless non-boiling length. To adjust the uniform-heat-flux-based non-boiling length for heat flux non-uniformity, it may be divided by the peak/average heat flux ratio in the channel, but it was incorrectly divided by the peak heat flux. This has been corrected.

(iii) The coding in PLTEMP/ANL version 3.4 of the Babelli-Ishii criteria, both the main criterion and the simplified criterion, was improved to account for the fin geometry if the fuel plates have fins (i.e., if the input option IH = -1). Along with this, the coding of the other two flow instability criteria available in PLTEMP/ANL (i.e., the Whittle and Forgan criterion, and the ORNL criterion) was also improved to account for the fin geometry if the fuel plates have fins.

### 7.1. Babelli-Ishii Criterion for Flow Instability

This section summarizes the Babelli-Ishii criterion [1] for excursive flow instability after boiling inception. Figure 1 shows a coolant channel with downward flow. The results are applicable to upward flow also. Babelli and Ishii obtained Eq. (1) given below as a criterion for excursive flow instability due to boiling inception in a coolant channel heated by a *uniform* wall heat flux, based on their theoretical and experimental work and the experimental data of Dougherty [2]. This equation is Eq. (5) of Babelli and Ishii [1], after substituting the value of $\rho_{in} V_{in} \Delta h_{nvg} / q''_w$ from Eq. (6) of Babelli and Ishii [1] which is basically the Saha-Zuber correlation [3] for net vapor generation. The channel flow is *stable* if the ratio $N_{sub}/N_{zu}$ on the left hand side of Eq. (1) is greater than the quantity on the right hand side, and *unstable* if the ratio $N_{sub}/N_{zu}$ is smaller.

$$\frac{N_{sub}}{N_{zu}} = \left(\frac{L_{nvg}}{L}\right)_{critical} + \frac{A_F}{\zeta_H\, L}\begin{Bmatrix} 0.0022\,Pe & if & Pe < 70000 \\ 154 & if & Pe > 70000 \end{Bmatrix} \qquad (1)$$

where

$N_{sub}$ = Subcooling number = $\dfrac{\Delta h_{in}}{h_{fg}}\dfrac{(\rho_{f,nvg} - \rho_{g,nvg})}{\rho_{g,nvg}}$ (2)

$N_{zu}$ = Zuber number = $\dfrac{q''_w \zeta_H L}{\rho_{in}\, V_{in}\, A_F\, h_{fg}}\dfrac{(\rho_{f,nvg} - \rho_{g,nvg})}{\rho_{g,nvg}}$ (3)

$N_{sub}/N_{zu}$ = Ratio of Subcooling number to Zuber number = $\dfrac{\rho_{in}\, V_{in}\, A_F\, \Delta h_{in}}{q''_w\, \zeta_H\, L}$ (4)

$\Delta h_{in}$ = Subcooling at the start of heated length, J/kg = $h_f(P_{in}) - h_{in} \approx h_f(P_{nvg}) - h_{in}$

$\Delta h_{nvg}$ = Subcooling at the NVG position, J/kg = $h_f(P_{in}) - h_{nvg} \approx h_f(P_{nvg}) - h_{nvg}$

$L$ = Channel heated length, m

$L_{nvg}$ = Non-boiling length, i.e., the distance from the start of heated length of channel to the position of net vapor generation, m

$L_{nvg}/L$ = Dimensionless non-boiling length

$(L_{nvg}/L)_{critical}$ = Critical value of the dimensionless non-boiling length. Based on experimental data for freon-113 and water, it is plotted in Fig. 4 of Ref. [1] as function of the Subcooling number, and the same data is tabulated here in Table 1.

$A_F$ = Flow area of channel, $m^2$

$\zeta_H$ = Heated perimeter of channel, m

$\rho_{in}$ = Coolant density at inlet, $kg/m^3$

$V_{in}$ = Coolant velocity at inlet, m/s

$q''_w$ = Wall heat flux, $W/m^2$

Pe = Peclet number = $\rho_{in}\, C_p V_{in} D_h/K$

The Peclet number dependent quantity inside the curly brackets on the right hand side of Eq. (1) can also be found in Ref. [4]. In the case of *upward flow*, the quantity is calculated as shown in Eq. (1) given above. However, in the case of *downward flow*, Babelli and Ishii suggest (based on the experimental data of Johnston [5]) that the quantity is always 154. Saha and Zuber [3] have discussed two regions, i.e., the region Pe < 70,000 and the region Pe > 70,000, as follows:

In the region Pe < 70,000 (i.e., at low mass flow rates), bubbles form attached to the wall downstream of the position at which the condition for the onset of nucleate boiling is satisfied, the local subcooling is still high, the bubbles that detach and move to the liquid core get immediately condensed, and the detached bubbles are forced to stay near the wall. The bubbles flow downstream while remaining close to the wall, until the local subcooling is low enough to initiate a rapid increase in void fraction. This is the position of net vapor generation. The region Pe < 70,000 is called the thermally controlled region.

In the region Pe > 70,000 (i.e., at high mass flow rates), the Stanton number $q''_w / \rho_{in} V_{in} \Delta h_{nvg}$ reaches the value of 0.0065, the bubbles attached to the wall grow in size acting like wall surface roughness, the bubbles detach due to hydrodynamic forces at the point where the surface roughness reaches a characteristic value of 0.02, the detached bubbles can move to the liquid core without being rapidly condensed, and this results in a rapid increase in vapor void fraction at the point of bubble detachment. The region Pe > 70,000 is called the hydrodynamically controlled region.

**Table 1. Critical Value of Dimensionless Non-boiling Length $(L_{nvg}/L)_{critical}$ as Function of Subcooling Number**

| Subcooling Number, $N_{sub}$ | Experimental Value of $(L_{nvg}/L)_{critical}$ | |
|---|---|---|
| | Lower Limit | Upper Limit |
| 2.69 | 0.0232 | 0.0232 |
| 5.38 | 0.0684 | 0.414 |
| 8.07 | 0.141 | 0.594 |
| 10.76 | 0.256 | 0.756 |
| 21.51 | 0.440 | 1.083 |
| 32.27 | 0.527 | 1.222 |
| 43.03 | 0.594 | 1.297 |
| 53.78 | 0.711 | 1.222 |
| 64.54 | 0.905 | 1.083 |
| 69.92 | 1.00 | 1.00 |
| 160.00 | 1.00 | 1.00 |

To calculate the Subcooling number using Eq. (2), the system reference pressure could be assumed equal to $P_{in}$ or $P_{nvg}$ , i.e., the coolant pressure at the start of the heated section or the pressure at the NVG position. The latter value is preferred as discussed in Appendix D.

A simpler criterion for flow instability due to boiling inception may also be inferred from Fig. 5 of Ref. [1] which is a plot on the $N_{sub}$-$N_{zu}$ plane of several flow instability test data for Freon-113 and water. The plot suggests the following simple criterion for flow instability.

$$\frac{N_{sub}}{N_{zu}} = \begin{cases} > 1.36 & \text{clearly stable} \\ < 1.36 \text{ to } 1.0 & \text{may be stable or unstable} \\ < 1.0 & \text{clearly unstable} \end{cases} \tag{5}$$

To calculate the quantities in Eq. (1) for evaluating flow instability, one needs the channel exit temperature and pressure. The *first estimates* of the exit enthalpy $h_{out}$, and total pressure drop $\Delta P$ are calculated using Eqs. (6) and (7) where the thermally-induced change in coolant density is calculated using Eq. (8). The exit temperature $T_{out}$ is estimated for use in Eq. (7), from $h_{out}$ by assuming the exit pressure $P_{out} = P_{in}$. These estimates are improved by iteration.

$$h_{out} = h_{in} + \frac{q''_w \zeta_H L}{\rho_{in} V_{in} A_F} \tag{6}$$

$$\Delta P = \left\{ K_{orifice} + \frac{f\,L}{D_h} \right\} \frac{W^2}{2\rho_{ave}\,A_F^{\;2}} \pm \left( \rho_{in} - \frac{\Delta\rho}{2} \right) g\,L + \rho_{in}\,V_{in}^{\;2}(\rho_{in}/\rho_{out} - 1)\,,$$

use + for upflow, and – for downflow (7)

$$\Delta\rho = \rho_{in} - \rho_{out} = \frac{\beta_{ave}\,Q}{C_{p,in} V_{in}\,A_F} \quad (8)$$

In Eq. (7), the terms in the curly brackets are the orifice loss and frictional pressure drop, the terms (having ± sign) in the parentheses are the gravitational pressure drop, and the last term is the pressure drop due to velocity increase at exit caused by the coolant density decrease. In the absence of boiling at higher flow rates, the last term is negligible. ΔP *decreases* with decreasing inlet velocity $V_{in}$ because the frictional pressure drop (the terms in the curly brackets of Eq. (7)) are then dominant, and these terms decrease with $V_{in}$. The term ΔρgL/2 *increases* in magnitude with decreasing inlet velocity, and it is positive in downflow. Therefore, in the absence of boiling in downflow, there is a *minimum* in the ΔP versus $V_{in}$ plot, i.e., $\partial(\Delta P)/\partial V_{in} = 0$ at a certain inlet velocity. At this minimum, the flow in the channel is unstable. In the absence of boiling in upflow, there is no such *minimum* in the ΔP versus $V_{in}$ plot.

In the case of boiling and voiding, the last term may become as large as ~1000 times the inlet velocity head, and the frictional drop from the ONB position to the channel exit also becomes much greater than its liquid-phase value, thus increasing ΔP at low inlet velocities. This results in a *minimum* in the ΔP versus $V_{in}$ plot, in both downflow and upflow.

### 7.2. Liquid-Phase Pressure Drop in a Channel Heated by a Given Power

Using the light water properties used in the PLTEMP/ANL code, the liquid-phase total pressure drop ΔP was calculated in a coolant channel removing a given power of 7 kW at an assumed value of inlet coolant velocity $V_{in}$ (varied from 0.08 to 2.0 m/s). Both downflow and upflow cases were computed. The purpose here is to check if there exists a minimum in the ΔP versus $V_{in}$ plot in the liquid-phase also, in addition to the minimum in the two-phase case discussed above. The channel data used in the computation are typical of a research reactor, and are given below.

| | |
|---|---|
| Channel heated length | = 0.6 m |
| Gap between the surrounding fuel plates | = 5 mm |
| Hydraulic diameter based on heated perimeter | = 10 mm |
| Heated width of plate | = 50 mm |
| Coolant inlet temperature | = 35 °C |
| Coolant inlet pressure | = 1.5 bar |
| Power in the channel (uniform over length) | = 7 kW |

The calculated total pressure drop ΔP and its components for the channel with downflow are shown in Table 2 and plotted in Fig. 2. It is noted that there is a minimum ΔP in this case at 0.2 m/s. This indicates a flow instability in liquid-phase in the case of a channel with downflow.

The calculated total pressure drop $\Delta P$ and its components for the channel with upflow are shown in Table 3 and plotted in Fig. 3. It is noted that there is no minimum $\Delta P$ in this case. This indicates an absence of flow instability in liquid-phase *before the onset of nucleation*, in the case of upflow.

### 7.3. Application of Babelli-Ishii Criterion to the Channel Heated by a Given Power

The Babelli-Ishii flow instability criterion of Eq. (1) or Eq. (5) was applied to the above coolant channel. The second part of Table 2 shows the results of applying the criterion of Eq. (1). This predicts flow instability at inlet velocities below 0.2 m/s. The flow instability results shown in the column titled 'Stable?' of Table 2 are based on this criterion. However, instead of Eq. (1), one may simply compare the ratio $N_{sub}/N_{zu}$ with 1.36 as shown in Eq. (5), to check flow instability. Eq. (5) also predicts the same, i.e., flow instability at inlet velocities below 0.2 m/s.

The second part of Table 3 shows the results of applying the Babelli-Ishii criterion of Eq. (1). This predicts flow instability at inlet velocities below 0.1 m/s. The flow instability results shown in the column titled 'Stable?' of Table 3 are based on this criterion. However, instead of Eq. (1), one may simply compare the ratio $N_{sub}/N_{zu}$ with 1.36 as shown in Eq. (5), to check flow instability. Eq. (5) also predicts the same, i.e., flow instability at inlet velocities below 0.1 m/s.

### 7.4. Application of Babelli-Ishii Flow Instability Criterion to Whittle and Forgan Tests

The Babelli-Ishii criterion for the onset of flow instability (OFI) was applied to all 75 tests performed by Whittle and Forgan at a uniform heat flux [6]. The geometry data used in the present calculation of these 75 tests are listed in Table 4. The last column of Table 4 is an operating data, i.e., the measured ratio $\Delta T_{sub,o}/\Delta T_c$ at OFI, which is used for comparison with the present calculation. Eight tests (Test Numbers 17 to 24) performed in Test Section 1A using non-uniform heat fluxes were not analyzed. A program *Babelli.WFtests.f* was developed (listed in Appendix E) to calculate for each test, the coolant exit temperature, single-phase pressure drop, Subcooling number, Zuber number, and other needed quantities, for an *assumed* coolant inlet velocity.

#### 7.4.1. Application of Flow Instability Criterion of Equation (1)

The coolant inlet velocity was varied in steps of 0.001 m/s from a suitable low value to a higher value, in search of the inlet velocity at which the ratio $N_{sub}/N_{zub}$, the left hand side of Eq. (1) becomes higher than the right hand side, i.e., the flow becomes stable. The inlet velocity just before the flow becomes stable is the inlet velocity at OFI. Table 5 shows the exit coolant temperatures and pressure drops at different inlet velocities calculated for the application of the flow instability criterion of Eq. (1) to a typical Whittle and Forgan test (Test Number 1 for example). Using the data of Table 5, the application of Babelli and Ishii flow instability criterion of Eq. (1) to Test Number 1 is shown in Table 6. The data line shown in bold letters in Table 6, at the inlet velocity of 2.712 m/s, marks the onset of flow instability.

The inlet velocity at OFI was calculated for each test listed in Table 4, and the results are shown in Table 7. The results for all 75 tests remain unchanged irrespective of whether the upper or the lower limit of $(L_{nvg} / L)_{critical}$ (given in Table 1) is used in the calculation. This is because the upper and lower limits of $(L_{nvg} / L)_{critical}$ , i.e., two limits exist only if the Subcooling number is less than 69.92. However, in all the 75 tests the Subcooling number is greater than 69.92, as shown in Table 7.

The measured coolant inlet velocity and flow rate at OFI are also shown in Table 7. The measured flow rate (W) and inlet velocity at OFI ($V_{in}$) were calculated from the measured exit coolant temperature using Eq. (7). This equation is obtained by equating the total power to the coolant enthalpy change times flow rate.

$$\rho_{in} V_{in} A_F = W = \frac{Q}{h(P_{out}, T_{out}) - h(P_{in}, T_{in})} \tag{7}$$

The measured exit temperature was itself calculated from the measured ratio $\Delta T_{sat,out}/\Delta T_c$ reported by Whittle and Forgan [6], using Eq. (8). To derive this equation, one substitutes the definitions $\Delta T_{sat,out} = T_{sat,out} - T_{out}$ and $\Delta T_c = T_{out} - T_{in}$ into the definition $\Delta T_{sat,out}/\Delta T_c = r$, obtains the relationship $(T_{sat,out} - T_{out})/(T_{out} - T_{in}) = r$, and then solves for $T_{out}$.

$$T_{out} = \frac{T_{sat,out} + r\, T_{in}}{1 + r} \tag{8}$$

where r = the measured ratio $\Delta T_{sat,out}/\Delta T_c$ at OFI reported by Whittle and Forgan, and shown in Table 4. See nomenclature for the other symbols.

The measured flow rates at OFI thus obtained were found to be in agreement with those obtained by A. P. Olson using a different approach during an earlier analysis of these tests [7]. The difference between the measured and calculated inlet velocities at OFI in a test determines the error in the Babelli and Ishii flow instability criterion. A statistical analysis was done to find the mean and the standard deviation of the difference between the calculated and measured inlet velocities (calculated – measured), and the results are shown below and in Table 7.

| | |
|---|---|
| Mean error in the calculated inlet velocity at OFI | = 0.384 m/s |
| Standard deviation of the error in the calculated inlet velocity at OFI | = 0.242 m/s |

The mean error is positive, implying that the criterion predicts flow instability at a higher inlet velocity (and hence higher flow rate) than that measured experimentally. Figure 4 shows a comparison of the calculated versus the measured coolant inlet velocity at OFI. The data points are generally above the line of slope 1, indicating that the criterion is conservative. The mean value of the Whittle and Forgan parameter $\eta$ at OFI is found to be 37.55 with a standard deviation of 3.16.

In these tests, Table 7 shows that the calculated ratio $\Delta T_c/\Delta T_{sat}$ at OFI, i.e., coolant temperature change divided by the difference between the saturation temperature at exit and the inlet temperature, has a mean value of 0.7314 which is smaller than the measured value of about 0.8 reported by Whittle and Forgan. This implies that the Babelli-Ishii criterion predicts flow instability earlier than it should, i.e., at a smaller coolant temperature rise than that measured experimentally. This also indicates that the criterion is conservative.

### 7.4.2. Application of Flow Instability Criterion of Eq. (5)

The simple flow instability criterion of Eq. (5) was also applied to the above 75 tests reported by Whittle and Forgan. The coolant inlet velocity was varied in steps of 0.001 m/s from a suitable low value to a higher value, in search of the inlet velocity at which the ratio $N_{sub}/N_{zub}$ becomes greater than 1.36, i.e., the flow becomes stable according to Eq. (5). The inlet velocity just before the ratio $N_{sub}/N_{zub}$ becomes greater than 1.36 is the inlet velocity at OFI. Table 5 is independent of the flow instability criterion used, i.e., whether Eq. (1) or Eq. (5) is used. This table shows the exit coolant temperatures and pressure drops at different inlet velocities calculated for the application of the flow instability criterion of Eq. (5) to a typical Whittle and Forgan test (Test Number 1 for example). Using the data of Table 5, the application of the flow instability criterion of Eq. (5) to Test Number 1 is shown by the underlined line in Table 6. The data in the underlined line in Table 6, at the inlet velocity of 2.620 m/s, marks the onset of flow instability.

The inlet velocity at OFI was calculated for each test listed in Table 4, and the results are shown in Table 8. The last column of Table 8 gives the ratio $N_{sub}/N_{zub}$ calculated at OFI and is 1.36 for all tests as required by the criterion. The difference between the measured and calculated inlet velocities at OFI in a test determines the error in this flow instability criterion. A statistical analysis was done to find the mean and the standard deviation of the difference between the calculated and measured inlet velocities (calculated – measured), and the results are shown below and in Table 8.

Mean error in the calculated inlet velocity at OFI = 0.363 m/s
Standard deviation of the error in the calculated inlet velocity at OFI = 0.319 m/s

Again, the mean error is positive, implying that the criterion predicts instability at a higher inlet velocity (and hence flow rate) than that measured experimentally. It is noted that the mean error for the criterion of Eq. (5) is somewhat smaller than that for the criterion of Eq. (1), and the standard deviation for the criterion of Eq. (5) is greater than that for the criterion of Eq. (1). Figure 5 shows a comparison of the calculated versus the measured coolant inlet velocity at OFI. The data points in Fig. 5 are generally above the line of slope 1, indicating that the criterion is conservative.

A comparison of the scatter of data points in Figs. 4 and 5 also shows that the standard deviation in Fig. 5 is greater than that in Fig. 4. For the 12 tests done by Whittle and Forgan in their test section number 3 (having a $L/D_H = 190.9$), the simple criterion finds the parameter $\eta$ at OFI to be about 68.2 which is about two times the values of $\eta$ at OFI found for all other tests. This happens because the parameter $\eta$ at OFI *calculated based on Eq. (5)* equals $0.36(L/D_H)$, as explained in Section 5 below.

The average value of the calculated ratio $\Delta T_c/\Delta T_{sat}$ at OFI determined by the simple criterion is 0.7367 which is closer (compared to the former criterion) to the measured value of about 0.8 reported by Whittle and Forgan. This implies that the simple criterion also predicts flow instability earlier than it should, i.e., at a smaller coolant temperature rise than that measured experimentally. This criterion also is conservative.

### 7.4.3. Approach to Flow Instability

To understand how a research reactor approaches the flow instability condition in a typical channel, seven important quantities tabulated in Table 6 for Whittle and Forgan Test Number 1 are plotted in Fig. 6 as functions of the inlet velocity. These quantities include the left and right hand sides of Babelli-Ishii criterion given by Eq. (1). The program *Babelli.WFtests.f* developed to apply the flow instability criteria of Eq. (1) and Eq. (5) to Whittle and Forgan tests saves the data shown in Table 6 and Fig. 6 in an output file named *flow.instability.unit9*. If Eq. (1) is used to find flow instability as the coolant inlet velocity decreases from 7.5 m/s, the ratio $(L_{nvg}/L)_{critical}$ on the right hand side (RHS) of Eq. (1) is always 1.0 because the Subcooling number, 129.41, remains greater than 69.92 (see Table 1). Furthermore, the Peclet number is always greater than 70,000, thus making the quantity in the curly brackets on the RHS of Eq. (1) constant at 154. Therefore, using the channel thickness, width, and heated length given in Table 4, the RHS of Eq. (1) becomes constant at 1.407 $\left( = 1.0 + \dfrac{0.127}{2 \times 24.0} \times 154 \right)$ as shown in Fig. 6. The ratio $N_{sub}/N_{zub}$ on the left hand side of Eq. (1) decreases linearly with the coolant inlet velocity (from 3.891 at $V_{in}$ = 7.5 m/s to 0.830 at $V_{in}$ = 1.6 m/s). The ratio $N_{sub}/N_{zub}$ at inlet velocity $V_{in}$ is 3.891*$V_{in}$ / 7.5. Therefore, the inlet velocity at which the ratio $N_{sub}/N_{zub}$ equals 1.407 is 1.407x7.5/3.891 = 2.712 m/s. This is the calculated inlet velocity at OFI in Test Number 1, according to the Babelli-Ishii criterion of Eq. (1).

It is noted that the ratio $N_{sub}/N_{zub}$ at OFI is 1.407, and not 1.36 as required by the simple instability criterion given by Eq. (5). From the above description it is seen that the ratio $N_{sub}/N_{zub}$ at OFI equals 1.0 + 77x(channel thickness/heated length) for channels of rectangular cross section. The ratio $N_{sub}/N_{zub}$ at OFI is therefore not constant. It depends on the channel thickness and length. The values of this ratio for the 75 tests are given in the last column of Table 7. They vary from 1.107 to 1.462.

### 7.5. Value of Parameter η According to the Instability Criterion of Equation (5)

It is shown in this section that the simple flow instability criterion of Eq. (5) implies that the parameter η at OFI is about 0.36(L / $D_H$). This explains why in Table 8 the values of parameter η at OFI for Test Numbers 63 to 74 are about twice the values of η at OFI found for all other tests. The reason is that Test Numbers 63 to 74 were performed in a test section having an L/$D_H$ nearly twice the L/$D_H$ in all other tests (see L/$D_H$ of all tests in Table 4).

To show that the parameter η at OFI based on Eq. (5) is about 0.36(L / $D_H$), it is noted that the ratio $N_{sub}/N_{zub}$ at OFI equals 1.36 according to this criterion. The ratio $N_{sub}/N_{zub}$ is defined above by Eq. (4). The numerator of Eq. (4) can be written as Eq. (9), and the denominator of Eq. (4) is simply the total heat transferred, Q, to the coolant in the channel. Thus the ratio $N_{sub}/N_{zub}$ equals $W\Delta h_{in}/Q$ as shown in Eq. (10). Noting that Q/W equals $\Delta h_c$ (the coolant enthalpy rise in the channel), the ratio $N_{sub}/N_{zub}$ is given by $\Delta h_{in}/\Delta h_c$ as shown in Eq. (10). Therefore, at OFI, the criterion of Eq. (5) implies Eq. (11).

$\rho_{in}\, V_{in}\, A_F\, \Delta h_{in} = W\, \Delta h_{in}$ (9)

$$\frac{N_{sub}}{N_{zub}} = \frac{W\,\Delta h_{in}}{Q} = \frac{\Delta h_{in}}{\Delta h_c} \qquad (10)$$

$\Delta h_{in} = 1.36\, \Delta h_c$ at OFI (11)

Noting that $\Delta h_{in} = \Delta h_{out} + \Delta h_c$ , Eq. (11) gives $\Delta h_{out}$ at the onset of flow instability.

$\Delta h_{out} = 0.36\, \Delta h_c$ at OFI (12)

The purpose here is to find the value of the Whittle and Forgan parameter η at OFI which is defined by Eq. (13). In Eq. (13), the ratio of temperature differences, $\Delta T_{sub,o}/\Delta T_c$, can be estimated by the ratio of the corresponding enthalpy differences, as written below in Eq. (14).

$$\eta = \frac{\Delta T_{sub,o}}{\Delta T_c}\frac{L}{D_H} \quad \text{at OFI} \qquad (13)$$

$$\frac{\Delta T_{sub,o}}{\Delta T_c} = \frac{T_{sat,out} - T_{out}}{T_{out} - T_{in}} = \frac{(h_f - h_{out})/C_p}{(h_{out} - h_{in})/C_p} = \frac{\Delta h_{out}}{\Delta h_c} \quad \text{at OFI} \qquad (14)$$

Using Eq. (14) in Eq. (13), the parameter η can be approximated by Eq. (15).

$$\eta = \frac{\Delta h_{out}}{\Delta h_c}\frac{L}{D_H} \quad \text{at OFI} \qquad (15)$$

Using the value of $\Delta h_{out}$ at OFI obtained in Eq. (12), one gets from Eq. (15) the value of parameter η at OFI.

$$\eta = \frac{0.36\,\Delta h_c}{\Delta h_c}\frac{L}{D_H} = 0.36\frac{L}{D_H} \quad \text{at OFI} \qquad (16)$$

Equation (16) is the desired result of this section. It means that the Whittle and Forgan parameter η at OFI based on the simple flow instability criterion of Eq. (5) is not constant. It varies linearly with the heated length-to-hydraulic diameter ratio. That is why the parameter η at OFI calculated based on Eq. (5) is about 68.2 in Test Numbers 63 to 74 (having $L/D_H = 190.9$).

### 7.6. A Program for Applying the Instability Criteria to Whittle and Forgan Tests

A program *Babelli.WFtests.f* was developed to apply the flow instability criteria of Eq. (1) and Eq. (5) to the 75 tests reported by Whittle and Forgan. It reads an input file containing the geometry and operating data of the tests. The input data are shown in Table 4. It saves the output results shown in Tables 5, 6, and 7 (or 8 depending upon the criterion chosen) in three output files as listed below. The listing of the program is given in Appendix E.

| | | |
|---|---|---|
| (1) Input file | Babelli.WFtests.Input.Data | contains the data shown in Table 4. |
| (2) Output file | flow.instability.unit6 | contains the results shown in Table 5. |
| (3) Output file | flow.instability.unit9 | contains the results shown in Table 6. |
| (4) Output file | flow.instability.summary | contains the results shown in Table 7 or 8. |

There is an internally set input variable IEQ (see the bold line in the source code of the program in Appendix E) to choose one of the two instability criteria, as defined below, and there is an internally set input variable DELVIN to define the step size for coolant inlet velocity (usually DELVIN = 0.001 m/s).

IEQ = 1, use Babelli-Ishii Eq. (1) to predict flow instability
= 2, use Nsub/Nzu > 1.36 for stability

### 7.7. Conclusions

A program has been developed to apply the Babelli-Ishii flow instability criterion of Eq. (1) or the simple criterion of Eq. (5) to 75 tests reported by Whittle and Forgan. The comparison of the calculated (using either criterion) and measured coolant inlet velocities at OFI in these tests shows that both criteria are conservative. Both criteria, Eqs. (1) and (5), are implemented in the PLTEMP/ANL version 3.4 code [7].

## NOMENCLATURE

### Symbols

$A_F$ = Flow area of channel, $m^2$
$C_p$ = Specific heat of the coolant, J/kg-°C
$D_h$ = Hydraulic diameter based on the *wetted* perimeter of the channel, m
$D_H$ = Hydraulic diameter based on the *heated* perimeter of the channel, m
h(P,T) = Liquid coolant enthalpy as a function of coolant pressure P and temperature T, J/kg
$h_{in}$ = Coolant enthalpy at the heated length inlet = $h(P_{in}, T_{in})$, J/kg
$h_{out}$ = Coolant enthalpy at the heated length exit = $h(P_{out}, T_{out})$, J/kg
$h_{f,in}$ = Saturated liquid enthalpy at the heated length inlet pressure = $h(P_{in})$, J/kg
$h_{f,out}$ = Saturated liquid enthalpy at the heated length exit pressure = $h(P_{out})$, J/kg
$h_{fg}(P)$ = Latent heat of vaporization as a function of coolant pressure P
$\Delta h_c$ = $h_{out} - h_{in}$ = Coolant enthalpy rise in the channel, J/kg
$\Delta h_{in}$ = $h_{f,out} - h_{in}$ = Inlet subcooling in terms of enthalpy, J/kg
$\Delta h_{out}$ = $h_{f,out} - h_{out}$ = Exit subcooling in terms of enthalpy, J/kg
K = Coolant thermal conductivity, W/m-°C
L = Channel heated length, m
$L_{nvg}$ = Non-boiling length, i.e., the distance from start of heated length of channel to the position of net vapor generation, m
$N_{zu}$ = Zuber number

$N_{sub}$ = Subcooling number
$P$ = Coolant pressure, Pa
Pe = Peclet number = Re Pr = $\rho_{in} C_p V_{in} D_h/K$
Pr = Prandtl number = $\mu C_p/K$
$P_{in}$ = Channel inlet pressure, Pa
$P_{out}$ = Channel outlet pressure, Pa
$q_w^{"}$ = Wall heat flux (assumed uniform over the channel length), W/m$^2$
$Q$ = $q_w^{"} \zeta_H L$ = Total power input to the coolant, W
Re = Reynolds number = $\rho_{in} V_{in} D_h/\mu$
$\rho$ = Coolant density, kg/m$^3$
$T$ = Coolant temperature, °C
$T_{in}$ = Coolant temperature at the channel inlet, °C
$T_{out}$ = Coolant temperature at the channel outlet, °C
$T_{sat}(P)$ = Coolant saturation temperature at a specific pressure P, °C
$T_{sat,in}$ = Coolant saturation temperature at channel inlet , °C
$T_{sat,out}$ = Coolant saturation temperature at channel outlet, °C
$\Delta T_c$ = $T_{out} - T_{in}$ = Coolant temperature rise at OFI, °C
$\Delta T_{sat}$ = $T_{sat,out} - T_{in}$ = Saturation temperature at exit minus inlet temperature at OFI, °C
$\Delta T_{sub,o}$ = $T_{sat,out} - T_{out}$ = Exit subcooling at the onset of flow instability, °C
$\eta$ = $\dfrac{T_{sat,out} - T_{out}}{T_{out} - T_{in}} \dfrac{L}{D_H}$ = A parameter used by Whittle and Forgan in their analysis of the flow instability tests
$\mu$ = Absolute viscosity of the coolant, Pa-s
$V$ = Coolant velocity, m/s
$W$ = $\rho_{in} V_{in} A_F$ = Coolant flow rate, kg/s
$\zeta_H$ = Heated perimeter, m

**Subscripts**

c = coolant
F = flow
f = saturated liquid
g = saturated vapor
fg = liquid to vapor phase change
H = heated
h = hydraulic
in = channel heated length inlet
nvg = position of net vapor generation
out = channel heated length outlet
sat = saturated

## REFERENCES


[1] I. Babelli and M. Ishii, “Flow Excursion Instability in Downward Flow Systems, Part II: Two-Phase Instability,” Nuclear Engineering and Design, Vol. 206, pp. 97-104 (2001).

[2] T. Dougherty, C. Fighetti, G. Reddy, B. Yang, E. McAssey Jr., and Z. Qureshi, “Flow Instability in Vertical Channels,” ASME Heat Transfer Division, HTD-Vol. 159, pp. 177-186 (1991).

[3] P. Saha and N. Zuber, “Point of Net Vapor Generation and Vapor Void Fraction in Subcooled Boiling,” Proc. Fifth International Heat Transfer Conf., Vol. 4, pp. 175-179 (1974).

[4] W. M. Rohsenow, J. P. Hartnett, and Y. I. Cho, “Handbook of Heat Transfer,” McGraw-Hill, Washington D.C., Third Edition, p. 15.92, (1998).

[5] B. S. Johnston, “ Subcooled Boiling of Downward Flow in a Vertical Annulus,” ASME Heat Transfer Division, HTD-Vol. 109, pp. 149-156 (1989).

[6] W. H. Whittle and R. Forgan, “A Correlation for the Minima in the Pressure Drop Versus Flow-Rate Curves for Sub-cooled Water Flowing in Narrow Heated Channels,” Nuclear Engineering and Design, Vol. 6, pp. 89-99 (1967).

[7] A. P. Olson, and M. Kalimullah, Argonne National Laboratory, unpublished information, January 10, 2008.

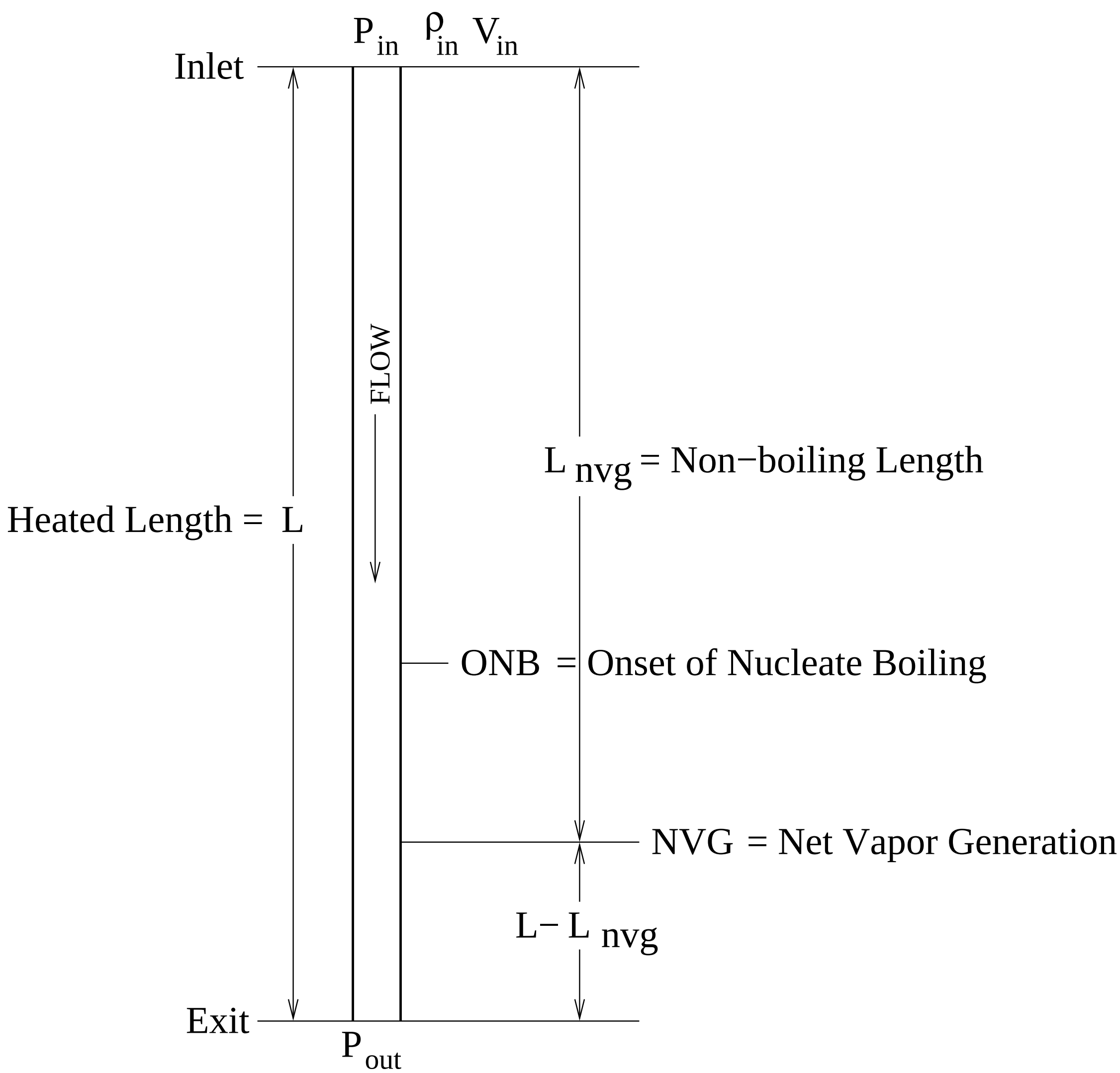


**Fig. 1. Schematic Diagram of a Heated Coolant Channel with Downward Flow**

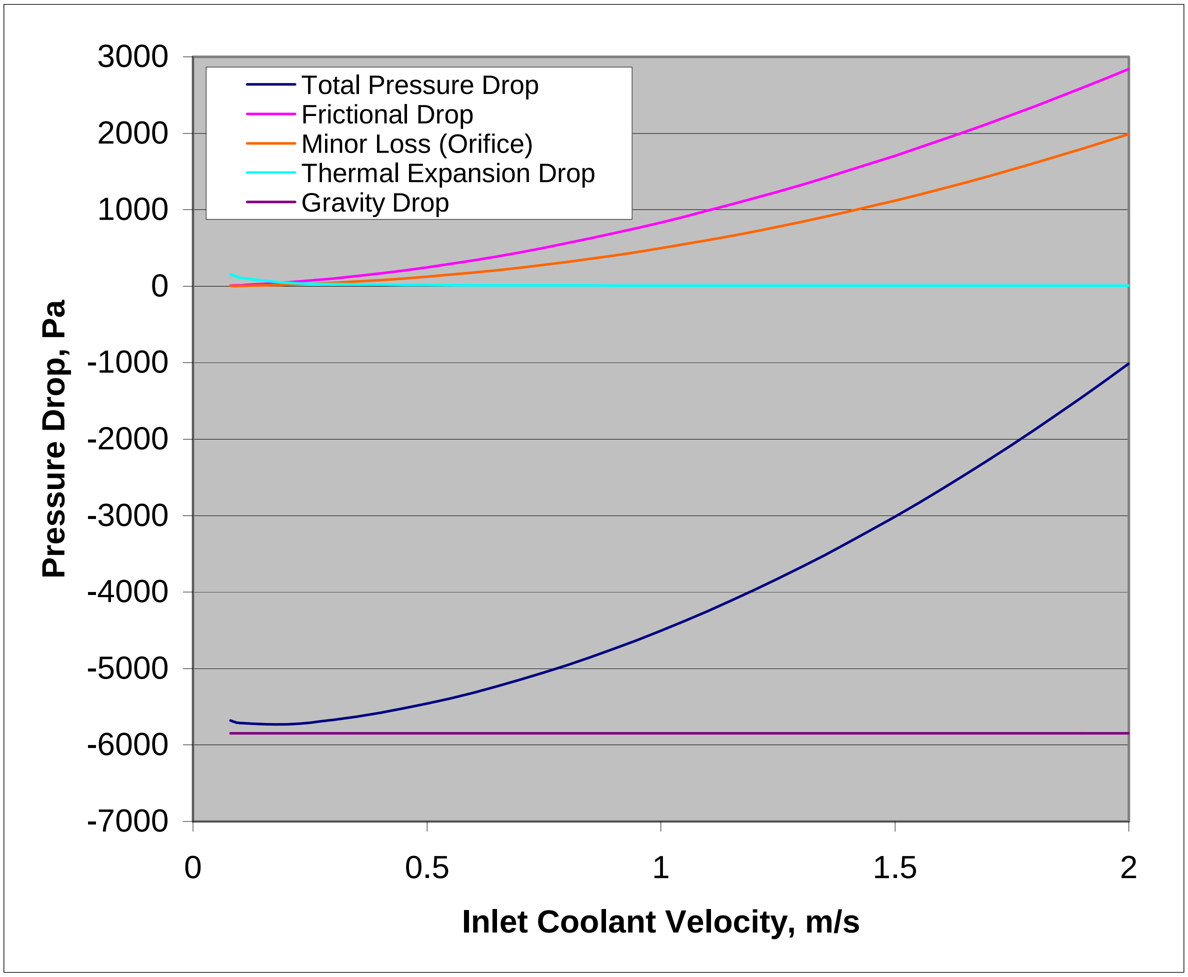


**Fig. 2. Dependence of Total Pressure Drop on Inlet Velocity for a Coolant Channel with Downflow of Water at a Given Power of 7 kW**

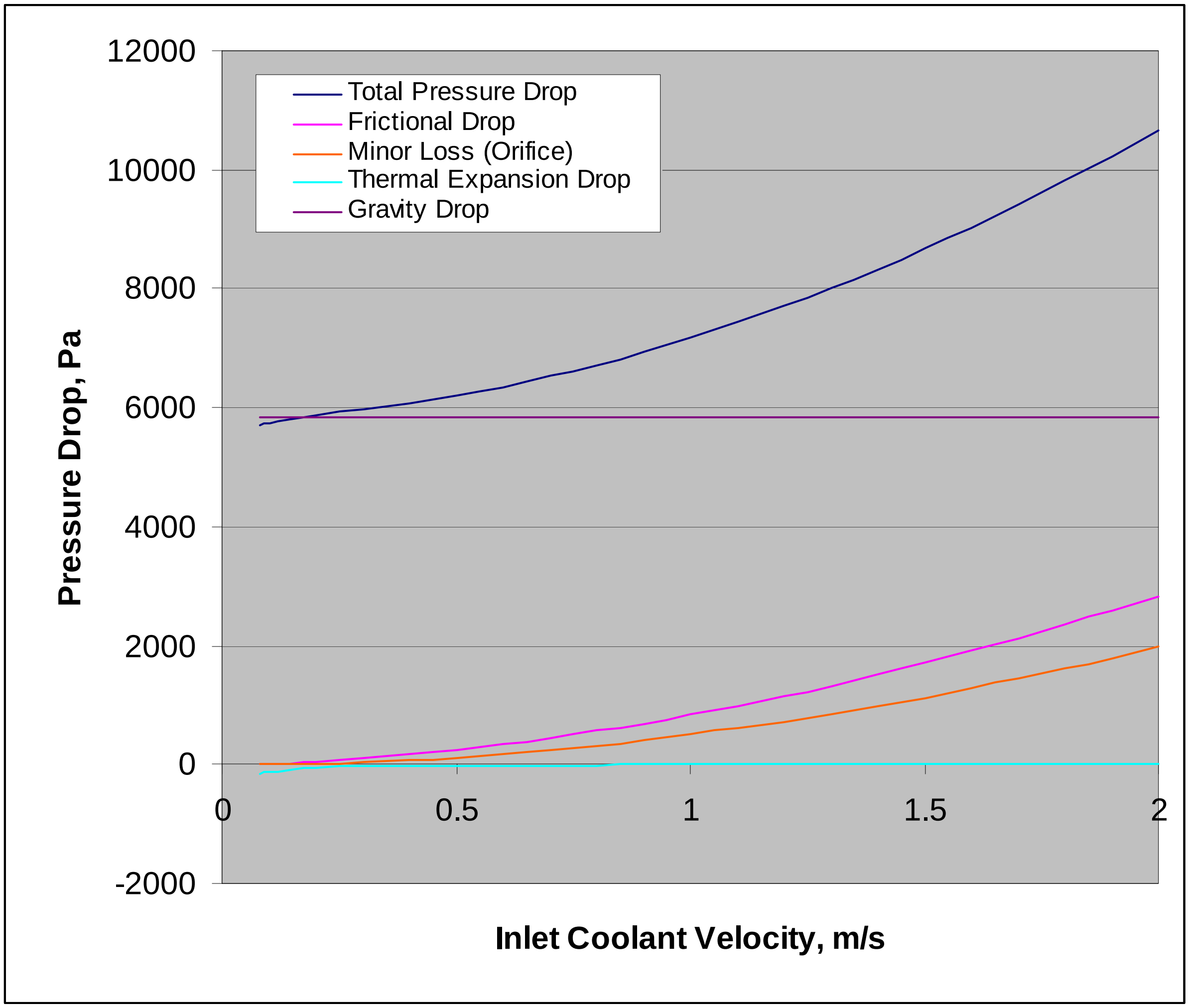


**Fig. 3. Dependence of Total Pressure Drop on Inlet Velocity for a Coolant Channel with Upflow of Water at a Given Power of 7 kW**

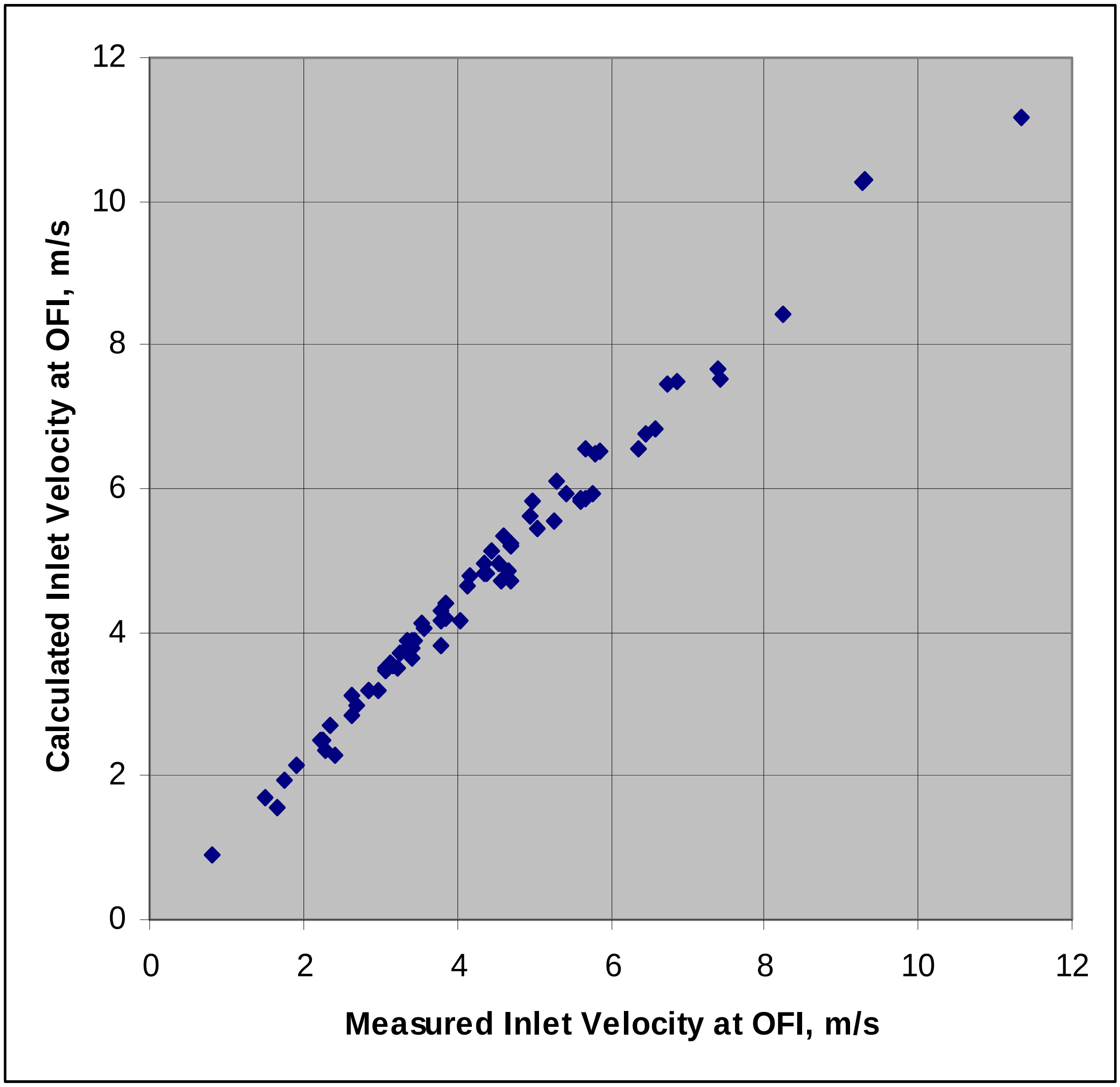


**Fig. 4. Comparison of Coolant Inlet Velocity at OFI Calculated Using Eq. (1) Versus its Measured Value in 75 Tests Reported by Whittle and Forgan**

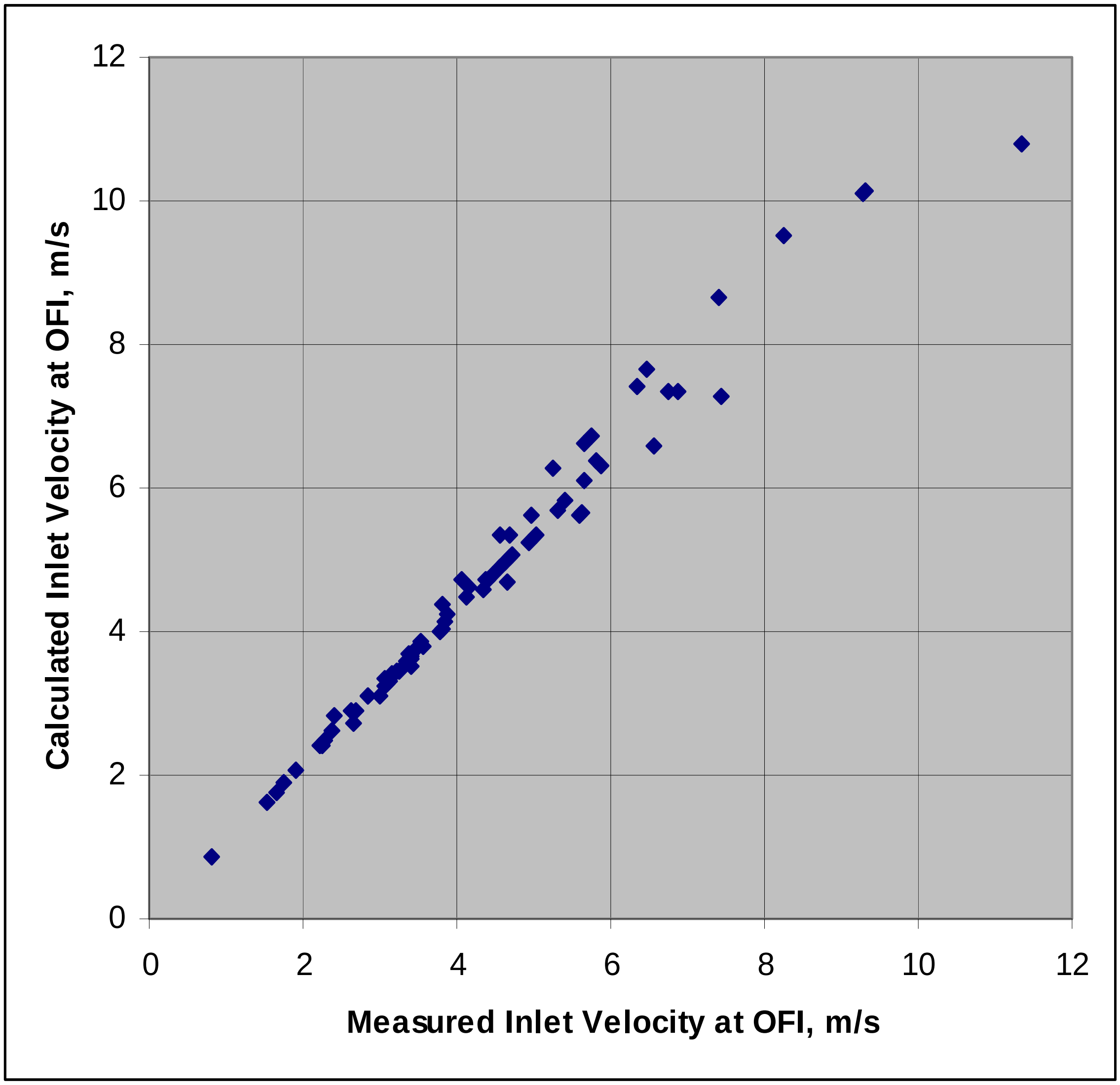


**Fig. 5. Comparison of Coolant Inlet Velocity at OFI Calculated Using Eq. (5) Versus its Measured Value in 75 Tests Reported by Whittle and Forgan**

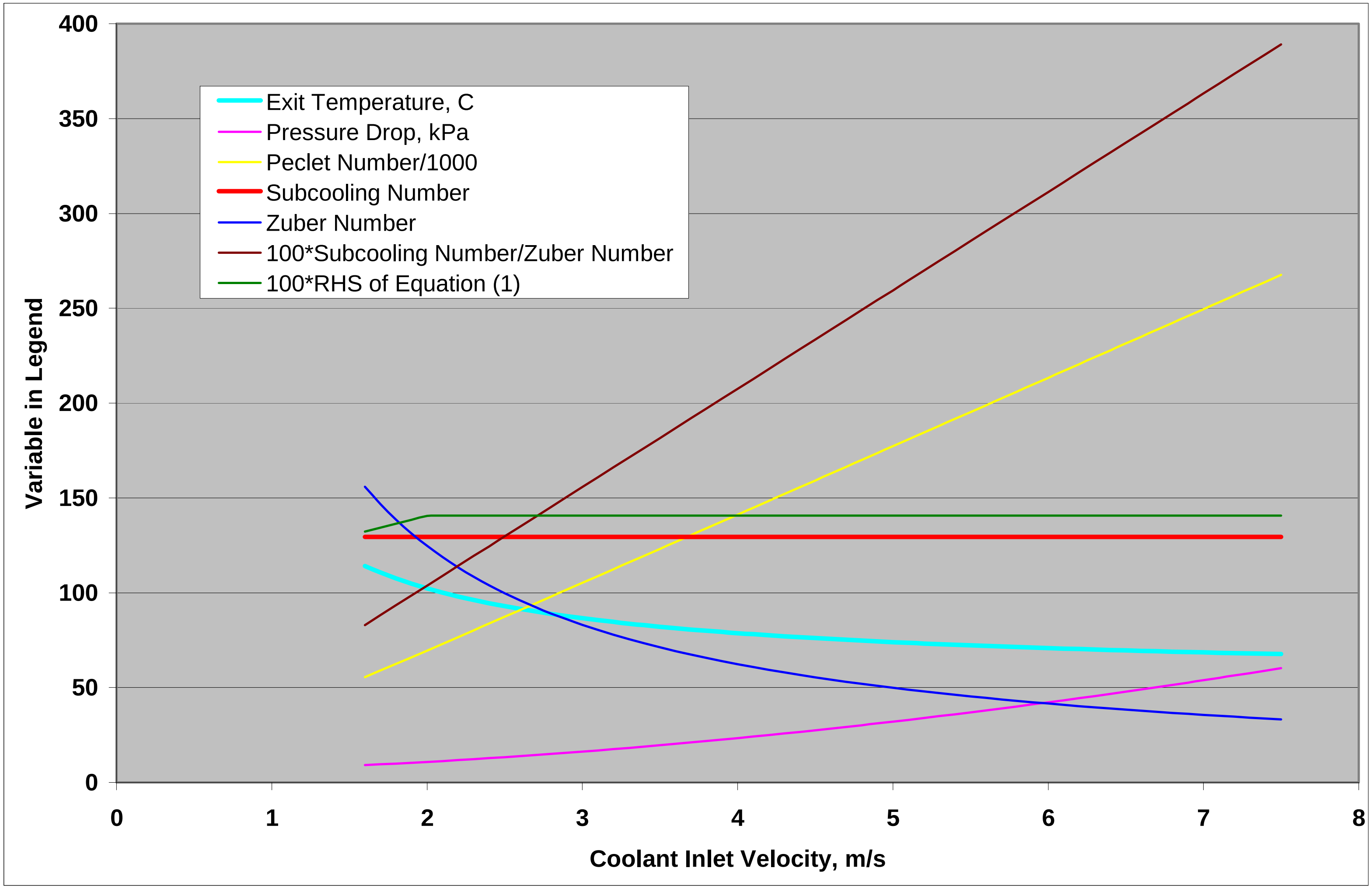


**Fig. 6. Variation of Ratio $N_{sub}/N_{zub}$ and Right Hand Side of Eq. (1) Over the Heated Length of Channel in Whittle and Forgan Test 1.**

**Table 2. Application of Babelli and Ishii Flow Instability Criterion to a Channel With Downflow**

```
Hydraulic diameter, mm               = 10
Channel heated length, m             = 0.6
Channel flow area, m**2              = 2.5E-04
Total minor loss coefficient         = 1.0
Pressure at heated section inlet, Pa = 1.5E+05
Inlet temperature, °C                = 35.0
Power removed by the channel, kW     = 7.0
```

EXIT TEMPERATURE AND PRESSURE DROP AT DIFFERENT INLET VELOCITIES

| Inlet Vel, m/s | Exit Temp, C | Average Temp, C | Friction Factor | Beta per C | Total Press Drop, Pa | Friction Drop, Pa | Orifice Drop, Pa | Therm Exp Drop, Pa | Gravity Drop, Pa | Reynolds Number |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.08 | 118.65 | 76.83 | 0.0445 | 6.26E-04 | -5679.17 | 8.67 | 3.25 | 154.61 | -5845.70 | 2155.46 |
| 0.09 | 109.45 | 72.22 | 0.0442 | 6.00E-04 | -5699.14 | 10.86 | 4.10 | 131.61 | -5845.70 | 2294.36 |
| 0.10 | 102.06 | 68.53 | 0.0446 | 5.77E-04 | -5713.08 | 13.49 | 5.05 | 114.08 | -5845.70 | 2430.80 |
| 0.20 | 68.65 | 51.82 | 0.0406 | 4.67E-04 | -5730.51 | 48.78 | 20.01 | 46.40 | -5845.70 | 3777.67 |
| 0.30 | 57.46 | 46.23 | 0.0371 | 4.27E-04 | -5672.22 | 100.06 | 44.92 | 28.50 | -5845.70 | 5141.98 |
| 0.40 | 51.85 | 43.42 | 0.0347 | 4.06E-04 | -5579.15 | 166.22 | 79.77 | 20.57 | -5845.70 | 6510.81 |
| 0.50 | 48.48 | 41.74 | 0.0329 | 3.93E-04 | -5458.72 | 246.24 | 124.56 | 16.18 | -5845.70 | 7881.83 |
| 0.60 | 46.24 | 40.62 | 0.0316 | 3.85E-04 | -5313.57 | 339.42 | 179.29 | 13.43 | -5845.70 | 9254.71 |
| 0.70 | 44.63 | 39.82 | 0.0304 | 3.79E-04 | -5144.98 | 445.20 | 243.96 | 11.56 | -5845.70 | 10628.61 |
| 0.80 | 43.43 | 39.22 | 0.0295 | 3.74E-04 | -4953.72 | 563.19 | 318.57 | 10.23 | -5845.70 | 12002.96 |
| 0.90 | 42.49 | 38.75 | 0.0287 | 3.70E-04 | -4740.32 | 693.01 | 403.13 | 9.24 | -5845.70 | 13377.56 |
| 1.00 | 41.75 | 38.37 | 0.0279 | 3.67E-04 | -4505.21 | 834.38 | 497.63 | 8.48 | -5845.70 | 14752.78 |
| 1.10 | 41.13 | 38.07 | 0.0273 | 3.65E-04 | -4248.70 | 987.05 | 602.07 | 7.89 | -5845.70 | 16128.30 |
| 1.20 | 40.62 | 37.81 | 0.0268 | 3.63E-04 | -3971.04 | 1150.78 | 716.45 | 7.43 | -5845.70 | 17503.61 |
| 1.30 | 40.19 | 37.59 | 0.0263 | 3.61E-04 | -3672.49 | 1325.38 | 840.77 | 7.06 | -5845.70 | 18879.27 |
| 1.40 | 39.82 | 37.41 | 0.0258 | 3.60E-04 | -3353.24 | 1510.66 | 975.04 | 6.76 | -5845.70 | 20255.33 |
| 1.50 | 39.50 | 37.25 | 0.0254 | 3.59E-04 | -3013.44 | 1706.50 | 1119.24 | 6.52 | -5845.70 | 21630.90 |
| 1.60 | 39.22 | 37.11 | 0.0250 | 3.58E-04 | -2653.27 | 1912.71 | 1273.39 | 6.33 | -5845.70 | 23007.23 |
| 1.70 | 38.97 | 36.98 | 0.0247 | 3.57E-04 | -2272.86 | 2129.19 | 1437.48 | 6.17 | -5845.70 | 24382.89 |
| 1.80 | 38.75 | 36.87 | 0.0244 | 3.56E-04 | -1872.36 | 2355.78 | 1611.51 | 6.05 | -5845.70 | 25759.19 |
| 1.90 | 38.55 | 36.78 | 0.0241 | 3.55E-04 | -1451.88 | 2592.39 | 1795.49 | 5.95 | -5845.70 | 27135.59 |
| 2.00 | 38.37 | 36.69 | 0.0238 | 3.54E-04 | -1011.51 | 2838.92 | 1989.40 | 5.87 | -5845.70 | 28511.15 |

**Table 2. Cont'd.**

APPLICATION OF BABELLI-ISHII FLOW INSTABILITY CRITERION

| Inlet Vel, m/s | Exit Temp, C | Tot Press Drop, Pa | Exit Press Pa | Peclet Number | Inlet Subc J/kg | Subcool Number | Zuber Number | Nsub/Nzu | RHS of Eq. (1) | Stable? | Critical Lnvg/L | 0.0022Pe or 154.0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.08 | 118.65 | -5679.17 | 155679.17 | 4883.42 | 325857.93 | 156.76 | 169.36 | 0.926 | 1.642 | unstable | 1.000 | 154.000 |
| 0.09 | 109.45 | -5699.14 | 155699.14 | 5500.01 | 325871.81 | 156.75 | 150.53 | 1.041 | 1.642 | unstable | 1.000 | 154.000 |
| 0.10 | 102.06 | -5713.08 | 155713.08 | 6124.39 | 325885.70 | 156.74 | 135.46 | 1.157 | 1.642 | unstable | 1.000 | 154.000 |
| 0.20 | 68.65 | -5730.51 | 155730.51 | 12550.12 | 325899.58 | 156.73 | 67.73 | 2.314 | 1.642 | stable | 1.000 | 154.000 |
| 0.30 | 57.46 | -5672.22 | 155672.22 | 19085.24 | 325850.98 | 156.77 | 45.17 | 3.471 | 1.642 | stable | 1.000 | 154.000 |
| 0.40 | 51.85 | -5579.15 | 155579.15 | 25651.29 | 325774.61 | 156.82 | 33.89 | 4.627 | 1.642 | stable | 1.000 | 154.000 |
| 0.50 | 48.48 | -5458.72 | 155458.72 | 32230.41 | 325677.41 | 156.88 | 27.13 | 5.782 | 1.642 | stable | 1.000 | 154.000 |
| 0.60 | 46.24 | -5313.57 | 155313.57 | 38816.35 | 325559.39 | 156.96 | 22.63 | 6.936 | 1.642 | stable | 1.000 | 154.000 |
| 0.70 | 44.63 | -5144.98 | 155144.98 | 45406.30 | 325413.59 | 157.05 | 19.42 | 8.088 | 1.642 | stable | 1.000 | 154.000 |
| 0.80 | 43.43 | -4953.72 | 154953.72 | 51998.71 | 325253.91 | 157.15 | 17.01 | 9.239 | 1.642 | stable | 1.000 | 154.000 |
| 0.90 | 42.49 | -4740.32 | 154740.32 | 58592.98 | 325080.34 | 157.27 | 15.14 | 10.388 | 1.642 | stable | 1.000 | 154.000 |
| 1.00 | 41.75 | -4505.21 | 154505.21 | 65188.43 | 324885.94 | 157.39 | 13.64 | 11.535 | 1.642 | stable | 1.000 | 154.000 |
| 1.10 | 41.13 | -4248.70 | 154248.70 | 71784.77 | 324670.72 | 157.53 | 12.42 | 12.681 | 1.642 | stable | 1.000 | 154.000 |
| 1.20 | 40.62 | -3971.04 | 153971.04 | 78381.67 | 324441.60 | 157.68 | 11.41 | 13.824 | 1.642 | stable | 1.000 | 154.000 |
| 1.30 | 40.19 | -3672.49 | 153672.49 | 84979.14 | 324191.67 | 157.85 | 10.55 | 14.964 | 1.642 | stable | 1.000 | 154.000 |
| 1.40 | 39.82 | -3353.24 | 153353.24 | 91577.07 | 323927.84 | 158.02 | 9.81 | 16.102 | 1.642 | stable | 1.000 | 154.000 |
| 1.50 | 39.50 | -3013.44 | 153013.44 | 98175.25 | 323643.19 | 158.21 | 9.18 | 17.237 | 1.642 | stable | 1.000 | 154.000 |
| 1.60 | 39.22 | -2653.27 | 152653.27 | 104773.74 | 323344.65 | 158.41 | 8.62 | 18.369 | 1.642 | stable | 1.000 | 154.000 |
| 1.70 | 38.97 | -2272.86 | 152272.86 | 111372.76 | 323025.28 | 158.62 | 8.14 | 19.498 | 1.642 | stable | 1.000 | 154.000 |
| 1.80 | 38.75 | -1872.36 | 151872.36 | 117971.49 | 322685.09 | 158.84 | 7.70 | 20.623 | 1.642 | stable | 1.000 | 154.000 |
| 1.90 | 38.55 | -1451.88 | 151451.88 | 124570.71 | 322331.01 | 159.07 | 7.32 | 21.745 | 1.642 | stable | 1.000 | 154.000 |
| 2.00 | 38.37 | -1011.51 | 151011.51 | 131170.04 | 321963.04 | 159.32 | 6.97 | 22.863 | 1.642 | stable | 1.000 | 154.000 |

**Table 3. Application of Babelli and Ishii Flow Instability Criterion to a Channel with Upflow**

```
Hydraulic diameter, mm               = 10
Channel heated length, m             = 0.6
Channel flow area, m**2              = 2.5E-04
Total minor loss coefficient         = 1.0
Pressure at heated section inlet, Pa = 1.5E+05
Inlet temperature, C                 = 35.0
Power removed by the channel, kW     = 7.0
```

EXIT TEMPERATURE AND PRESSURE DROP AT DIFFERENT INLET VELOCITIES

| Inlet Vel, m/s | Exit Temp, C | Average Temp, C | Friction Factor | Beta per C | Total Press Drop, Pa | Friction Drop, Pa | Orifice Drop, Pa | Therm Exp Drop, Pa | Gravity Drop, Pa | Reynolds Number |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.08 | 118.65 | 76.83 | 0.0445 | 6.26E-04 | 5703.35 | 8.67 | 3.25 | -154.27 | 5845.70 | 2155.46 |
| 0.09 | 109.45 | 72.22 | 0.0442 | 6.00E-04 | 5729.41 | 10.86 | 4.10 | -131.24 | 5845.70 | 2294.36 |
| 0.10 | 102.06 | 68.53 | 0.0446 | 5.77E-04 | 5750.54 | 13.49 | 5.05 | -113.70 | 5845.70 | 2430.80 |
| 0.20 | 68.65 | 51.82 | 0.0406 | 4.67E-04 | 5868.72 | 48.78 | 20.01 | -45.77 | 5845.70 | 3777.67 |
| 0.30 | 57.46 | 46.23 | 0.0371 | 4.27E-04 | 5963.04 | 100.06 | 44.92 | -27.64 | 5845.70 | 5141.98 |
| 0.40 | 51.85 | 43.42 | 0.0347 | 4.06E-04 | 6072.20 | 166.22 | 79.77 | -19.48 | 5845.70 | 6510.81 |
| 0.50 | 48.48 | 41.74 | 0.0329 | 3.93E-04 | 6201.64 | 246.24 | 124.56 | -14.86 | 5845.70 | 7881.83 |
| 0.60 | 46.24 | 40.62 | 0.0316 | 3.85E-04 | 6352.53 | 339.42 | 179.29 | -11.88 | 5845.70 | 9254.71 |
| 0.70 | 44.63 | 39.82 | 0.0304 | 3.79E-04 | 6525.09 | 445.20 | 243.96 | -9.78 | 5845.70 | 10628.61 |
| 0.80 | 43.43 | 39.22 | 0.0295 | 3.74E-04 | 6719.25 | 563.19 | 318.57 | -8.22 | 5845.70 | 12002.96 |
| 0.90 | 42.49 | 38.75 | 0.0287 | 3.70E-04 | 6934.85 | 693.01 | 403.13 | -7.00 | 5845.70 | 13377.56 |
| 1.00 | 41.75 | 38.37 | 0.0279 | 3.67E-04 | 7171.70 | 834.38 | 497.63 | -6.02 | 5845.70 | 14752.78 |
| 1.10 | 41.13 | 38.07 | 0.0273 | 3.65E-04 | 7429.62 | 987.05 | 602.07 | -5.20 | 5845.70 | 16128.30 |
| 1.20 | 40.62 | 37.81 | 0.0268 | 3.63E-04 | 7708.43 | 1150.78 | 716.45 | -4.51 | 5845.70 | 17503.61 |
| 1.30 | 40.19 | 37.59 | 0.0263 | 3.61E-04 | 8007.95 | 1325.38 | 840.77 | -3.91 | 5845.70 | 18879.27 |
| 1.40 | 39.82 | 37.41 | 0.0258 | 3.60E-04 | 8328.02 | 1510.66 | 975.04 | -3.38 | 5845.70 | 20255.33 |
| 1.50 | 39.50 | 37.25 | 0.0254 | 3.59E-04 | 8668.53 | 1706.50 | 1119.24 | -2.91 | 5845.70 | 21630.90 |
| 1.60 | 39.22 | 37.11 | 0.0250 | 3.58E-04 | 9029.31 | 1912.71 | 1273.39 | -2.49 | 5845.70 | 23007.23 |
| 1.70 | 38.97 | 36.98 | 0.0247 | 3.57E-04 | 9410.27 | 2129.19 | 1437.48 | -2.10 | 5845.70 | 24382.89 |
| 1.80 | 38.75 | 36.87 | 0.0244 | 3.56E-04 | 9811.24 | 2355.78 | 1611.51 | -1.75 | 5845.70 | 25759.19 |
| 1.90 | 38.55 | 36.78 | 0.0241 | 3.55E-04 | 10232.15 | 2592.39 | 1795.49 | -1.42 | 5845.70 | 27135.59 |
| 2.00 | 38.37 | 36.69 | 0.0238 | 3.54E-04 | 10672.91 | 2838.92 | 1989.40 | -1.12 | 5845.70 | 28511.15 |

**Table 3. Cont'd.**

APPLICATION OF BABELLI-ISHII FLOW INSTABILITY CRITERION

| Inlet Vel, m/s | Exit Temp, C | Tot Press Drop, Pa | Exit Press Pa | Peclet Number | Inlet Subc J/kg | Subcool Number | Zuber Number | Nsub/Nzu | RHS of Eq. (1) | Stable? | Critical Lnvg/L | 0.0022Pe or 154.0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.08 | 118.65 | 5703.35 | 144296.65 | 4883.46 | 316179.73 | 163.19 | 181.71 | 0.898 | 1.045 | unstable | 1.000 | 10.744 |
| 0.09 | 109.45 | 5729.41 | 144270.59 | 5500.05 | 316158.91 | 163.21 | 161.54 | 1.010 | 1.050 | unstable | 1.000 | 12.100 |
| 0.10 | 102.06 | 5750.54 | 144249.46 | 6124.44 | 316138.08 | 163.22 | 145.41 | 1.122 | 1.056 | stable | 1.000 | 13.474 |
| 0.20 | 68.65 | 5868.72 | 144131.28 | 12550.26 | 316033.94 | 163.29 | 72.76 | 2.244 | 1.115 | stable | 1.000 | 27.611 |
| 0.30 | 57.46 | 5963.04 | 144036.96 | 19085.42 | 315950.62 | 163.34 | 48.54 | 3.365 | 1.175 | stable | 1.000 | 41.988 |
| 0.40 | 51.85 | 6072.20 | 143927.80 | 25651.53 | 315853.42 | 163.41 | 36.43 | 4.486 | 1.235 | stable | 1.000 | 56.433 |
| 0.50 | 48.48 | 6201.64 | 143798.36 | 32230.82 | 315742.34 | 163.49 | 29.17 | 5.605 | 1.295 | stable | 1.000 | 70.908 |
| 0.60 | 46.24 | 6352.53 | 143647.47 | 38816.84 | 315610.43 | 163.58 | 24.33 | 6.724 | 1.356 | stable | 1.000 | 85.397 |
| 0.70 | 44.63 | 6525.09 | 143474.91 | 45406.88 | 315457.69 | 163.68 | 20.88 | 7.840 | 1.416 | stable | 1.000 | 99.895 |
| 0.80 | 43.43 | 6719.25 | 143280.75 | 51999.38 | 315284.12 | 163.80 | 18.29 | 8.956 | 1.477 | stable | 1.000 | 114.399 |
| 0.90 | 42.49 | 6934.85 | 143065.15 | 58593.74 | 315096.66 | 163.93 | 16.28 | 10.069 | 1.537 | stable | 1.000 | 128.906 |
| 1.00 | 41.75 | 7171.70 | 142828.30 | 65189.09 | 314888.38 | 164.07 | 14.67 | 11.180 | 1.598 | stable | 1.000 | 143.416 |
| 1.10 | 41.13 | 7429.62 | 142570.38 | 71785.49 | 314659.27 | 164.23 | 13.36 | 12.290 | 1.642 | stable | 1.000 | 154.000 |
| 1.20 | 40.62 | 7708.43 | 142291.57 | 78382.46 | 314409.33 | 164.39 | 12.27 | 13.396 | 1.642 | stable | 1.000 | 154.000 |
| 1.30 | 40.19 | 8007.95 | 141992.05 | 84980.00 | 314145.51 | 164.58 | 11.35 | 14.500 | 1.642 | stable | 1.000 | 154.000 |
| 1.40 | 39.82 | 8328.02 | 141671.98 | 91578.27 | 313860.86 | 164.77 | 10.56 | 15.602 | 1.642 | stable | 1.000 | 154.000 |
| 1.50 | 39.50 | 8668.53 | 141331.47 | 98176.54 | 313562.32 | 164.98 | 9.88 | 16.700 | 1.642 | stable | 1.000 | 154.000 |
| 1.60 | 39.22 | 9029.31 | 140970.69 | 104775.13 | 313236.01 | 165.20 | 9.28 | 17.795 | 1.642 | stable | 1.000 | 154.000 |
| 1.70 | 38.97 | 9410.27 | 140589.73 | 111373.89 | 312895.81 | 165.44 | 8.76 | 18.886 | 1.642 | stable | 1.000 | 154.000 |
| 1.80 | 38.75 | 9811.24 | 140188.76 | 117973.05 | 312534.79 | 165.68 | 8.29 | 19.974 | 1.642 | stable | 1.000 | 154.000 |
| 1.90 | 38.55 | 10232.15 | 139767.85 | 124571.99 | 312159.88 | 165.95 | 7.88 | 21.059 | 1.642 | stable | 1.000 | 154.000 |
| 2.00 | 38.37 | 10672.91 | 139327.09 | 131171.38 | 311757.20 | 166.22 | 7.51 | 22.138 | 1.642 | stable | 1.000 | 154.000 |

## Table 4. Geometry and Operating Data for 75 Flow Instability Tests Performed by Whittle and Forgan

| Test No. | Flow Direction* | Inlet Temp °C | Heat Flux W/cm² | Channel Thickness inch | Channel Width inch | Heated Length inch | Minor Loss Coeff | Exit Pressure psia | $\Delta T_{sub,o}/\Delta T_c$ |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 55.0 | 104.0 | 0.127 | 1.0 | 24.0 | 0.0 | 17.0 | 0.224 |
| 2 | 1 | 55.0 | 145.0 | 0.127 | 1.0 | 24.0 | 0.0 | 17.0 | 0.266 |
| 3 | 1 | 55.0 | 184.0 | 0.127 | 1.0 | 24.0 | 0.0 | 17.0 | 0.220 |
| 4 | 1 | 55.0 | 250.0 | 0.127 | 1.0 | 24.0 | 0.0 | 17.0 | 0.266 |
| 5 | 1 | 55.0 | 82.0 | 0.127 | 1.0 | 24.0 | 0.0 | 17.0 | 0.250 |
| 6 | 1 | 55.0 | 136.0 | 0.127 | 1.0 | 24.0 | 0.0 | 17.0 | 0.250 |
| 7 | 1 | 55.0 | 160.0 | 0.127 | 1.0 | 24.0 | 0.0 | 17.0 | 0.282 |
| 8 | 1 | 55.0 | 200.0 | 0.127 | 1.0 | 24.0 | 0.0 | 17.0 | 0.266 |
| 9 | 1 | 45.0 | 160.0 | 0.127 | 1.0 | 24.0 | 0.0 | 17.0 | 0.250 |
| 10 | 1 | 45.0 | 180.0 | 0.127 | 1.0 | 24.0 | 0.0 | 17.0 | 0.250 |
| 11 | 1 | 45.0 | 204.0 | 0.127 | 1.0 | 24.0 | 0.0 | 17.0 | 0.234 |
| 12 | 1 | 60.0 | 110.0 | 0.127 | 1.0 | 24.0 | 0.0 | 17.0 | 0.250 |
| 13 | 1 | 60.0 | 160.0 | 0.127 | 1.0 | 24.0 | 0.0 | 17.0 | 0.250 |
| 14 | 1 | 60.0 | 180.0 | 0.127 | 1.0 | 24.0 | 0.0 | 17.0 | 0.266 |
| 15 | 1 | 60.0 | 200.0 | 0.127 | 1.0 | 24.0 | 0.0 | 17.0 | 0.204 |
| 16 | 1 | 35.0 | 136.0 | 0.127 | 1.0 | 24.0 | 0.0 | 17.0 | 0.250 |
| 25 | 0 | 45.0 | 78.0 | 0.127 | 1.0 | 24.0 | 0.0 | 17.0 | 0.266 |
| 26 | 0 | 45.0 | 116.0 | 0.127 | 1.0 | 24.0 | 0.0 | 17.0 | 0.266 |
| 27 | 0 | 45.0 | 148.0 | 0.127 | 1.0 | 24.0 | 0.0 | 17.0 | 0.250 |
| 28 | 0 | 55.0 | 115.0 | 0.127 | 1.0 | 24.0 | 0.0 | 17.0 | 0.266 |
| 29 | 0 | 55.0 | 75.0 | 0.127 | 1.0 | 24.0 | 0.0 | 17.0 | 0.266 |
| 30 | 0 | 55.0 | 146.0 | 0.127 | 1.0 | 24.0 | 0.0 | 17.0 | 0.250 |
| 31 | 0 | 45.0 | 42.0 | 0.127 | 1.0 | 24.0 | 0.0 | 17.0 | 0.282 |
| 32 | 1 | 55.0 | 147.0 | 0.096 | 1.0 | 16.0 | 0.0 | 17.0 | 0.282 |
| 33 | 1 | 55.0 | 170.0 | 0.096 | 1.0 | 16.0 | 0.0 | 17.0 | 0.282 |
| 34 | 1 | 55.0 | 180.0 | 0.096 | 1.0 | 16.0 | 0.0 | 17.0 | 0.282 |
| 35 | 1 | 55.0 | 215.0 | 0.096 | 1.0 | 16.0 | 0.0 | 17.0 | 0.266 |
| 36 | 1 | 45.0 | 196.0 | 0.096 | 1.0 | 16.0 | 0.0 | 17.0 | 0.282 |
| 37 | 1 | 45.0 | 250.0 | 0.096 | 1.0 | 16.0 | 0.0 | 17.0 | 0.282 |
| 38 | 1 | 45.0 | 180.0 | 0.096 | 1.0 | 16.0 | 0.0 | 17.0 | 0.282 |
| 39 | 1 | 65.0 | 177.0 | 0.096 | 1.0 | 16.0 | 0.0 | 17.0 | 0.266 |
| 40 | 1 | 65.0 | 203.0 | 0.096 | 1.0 | 16.0 | 0.0 | 17.0 | 0.266 |
| 41 | 1 | 65.0 | 218.0 | 0.096 | 1.0 | 16.0 | 0.0 | 17.0 | 0.261 |
| 42 | 1 | 65.0 | 123.0 | 0.096 | 1.0 | 16.0 | 0.0 | 17.0 | 0.282 |
| 43 | 1 | 45.0 | 250.0 | 0.096 | 1.0 | 16.0 | 0.0 | 25.0 | 0.250 |
| 44 | 1 | 65.0 | 242.0 | 0.096 | 1.0 | 16.0 | 0.0 | 25.0 | 0.282 |
| 45 | 1 | 65.0 | 134.0 | 0.096 | 1.0 | 16.0 | 0.0 | 25.0 | 0.234 |

**Table 4. Cont'd.**

| Test No. | Flow Direc- tion | Inlet Temp °C | Heat Flux W/cm$^2$ | Channel Thickness inch | Channel Width inch | Heated Length inch | Minor Loss Coeff | Exit Pressure psia | $\Delta T_{sub,o}$ /$\Delta T_c$ |
|---|---|---|---|---|---|---|---|---|---|
| 46 | 1 | 55.0 | 200.0 | 0.096 | 1.0 | 16.0 | 0.0 | 25.0 | 0.266 |
| 47 | 1 | 55.0 | 180.0 | 0.096 | 1.0 | 16.0 | 0.0 | 25.0 | 0.282 |
| 48 | 1 | 55.0 | 177.0 | 0.080 | 1.0 | 16.0 | 0.0 | 17.0 | 0.266 |
| 49 | 1 | 55.0 | 218.0 | 0.080 | 1.0 | 16.0 | 0.0 | 17.0 | 0.266 |
| 50 | 1 | 55.0 | 276.0 | 0.080 | 1.0 | 16.0 | 0.0 | 17.0 | 0.266 |
| 51 | 1 | 65.0 | 141.0 | 0.080 | 1.0 | 16.0 | 0.0 | 17.0 | 0.250 |
| 52 | 1 | 65.0 | 218.0 | 0.080 | 1.0 | 16.0 | 0.0 | 17.0 | 0.250 |
| 53 | 1 | 65.0 | 300.0 | 0.080 | 1.0 | 16.0 | 0.0 | 17.0 | 0.250 |
| 54 | 1 | 65.0 | 110.0 | 0.080 | 1.0 | 16.0 | 0.0 | 17.0 | 0.250 |
| 55 | 1 | 45.0 | 221.0 | 0.080 | 1.0 | 16.0 | 0.0 | 17.0 | 0.266 |
| 56 | 1 | 45.0 | 289.0 | 0.080 | 1.0 | 16.0 | 0.0 | 17.0 | 0.234 |
| 57 | 1 | 35.0 | 283.0 | 0.080 | 1.0 | 16.0 | 0.0 | 17.0 | 0.282 |
| 58 | 1 | 35.0 | 219.0 | 0.080 | 1.0 | 16.0 | 0.0 | 17.0 | 0.266 |
| 59 | 1 | 35.0 | 183.0 | 0.080 | 1.0 | 16.0 | 0.0 | 17.0 | 0.266 |
| 60 | 1 | 55.0 | 93.0 | 0.080 | 1.0 | 16.0 | 0.0 | 17.0 | 0.250 |
| 61 | 1 | 75.0 | 223.0 | 0.080 | 1.0 | 16.0 | 0.0 | 17.0 | 0.250 |
| 62 | 1 | 55.0 | 66.0 | 0.080 | 1.0 | 16.0 | 0.0 | 17.0 | 0.282 |
| 63 | 1 | 55.0 | 170.0 | 0.055 | 1.0 | 21.0 | 0.0 | 17.0 | 0.163 |
| 64 | 1 | 55.0 | 93.0 | 0.055 | 1.0 | 21.0 | 0.0 | 17.0 | 0.163 |
| 65 | 1 | 55.0 | 130.0 | 0.055 | 1.0 | 21.0 | 0.0 | 17.0 | 0.163 |
| 66 | 1 | 45.0 | 127.0 | 0.055 | 1.0 | 21.0 | 0.0 | 17.0 | 0.190 |
| 67 | 1 | 45.0 | 176.0 | 0.055 | 1.0 | 21.0 | 0.0 | 17.0 | 0.163 |
| 68 | 1 | 45.0 | 67.0 | 0.055 | 1.0 | 21.0 | 0.0 | 17.0 | 0.163 |
| 69 | 1 | 45.0 | 226.0 | 0.055 | 1.0 | 21.0 | 0.0 | 17.0 | 0.177 |
| 70 | 1 | 35.0 | 122.0 | 0.055 | 1.0 | 21.0 | 0.0 | 17.0 | 0.177 |
| 71 | 1 | 65.0 | 119.0 | 0.055 | 1.0 | 21.0 | 0.0 | 17.0 | 0.149 |
| 72 | 1 | 65.0 | 98.0 | 0.055 | 1.0 | 21.0 | 0.0 | 17.0 | 0.136 |
| 73 | 1 | 65.0 | 83.0 | 0.055 | 1.0 | 21.0 | 0.0 | 17.0 | 0.163 |
| 74 | 1 | 35.0 | 187.0 | 0.055 | 1.0 | 21.0 | 0.0 | 17.0 | 0.163 |
| 75 | 1 | 55.0 | 186.0 | 0.127 | 0.399 | 24.0 | 0.0 | 17.0 | 0.351 |
| 76 | 1 | 55.0 | 262.0 | 0.127 | 0.399 | 24.0 | 0.0 | 17.0 | 0.351 |
| 77 | 1 | 55.0 | 140.0 | 0.127 | 0.399 | 24.0 | 0.0 | 17.0 | 0.315 |
| 78 | 1 | 45.0 | 148.0 | 0.127 | 0.399 | 24.0 | 0.0 | 17.0 | 0.315 |
| 79 | 1 | 45.0 | 270.0 | 0.127 | 0.399 | 24.0 | 0.0 | 17.0 | 0.351 |
| 80 | 1 | 45.0 | 348.0 | 0.127 | 0.399 | 24.0 | 0.0 | 17.0 | 0.389 |
| 81 | 1 | 65.0 | 86.0 | 0.127 | 0.399 | 24.0 | 0.0 | 17.0 | 0.315 |
| 82 | 1 | 65.0 | 178.0 | 0.127 | 0.399 | 24.0 | 0.0 | 17.0 | 0.351 |
| 83 | 1 | 65.0 | 340.0 | 0.127 | 0.399 | 24.0 | 0.0 | 17.0 | 0.428 |

* 1 implies upward flow, 0 implies downward flow.

**Table 5. Exit Temperature and Pressure Drop at Different Inlet Velocities Calculated in the Application of Babelli and Ishii Flow Instability Criterion to a Typical Whittle and Forgan Test (Number 1)**

| | | |
|---|---|---|
| Whittle & Forgan Test Numner | = | 1 |
| Hydraulic diameter (heated), m | = | 0.00645 |
| Hydraulic diameter (wetted), m | = | 0.00572 |
| Channel heated length, m | = | 0.6096 |
| Total minor loss coefficient | = | 0.0000 |
| Inlet temperature, C | = | 55.000 |
| Power removed by the channel, W | = | 3.22064E+04 |
| Pressure at heated section exit, Pa | = | 1.17211E+05 |
| Saturation temperature at exit, C | = | 104.131 |
| Channel flow area, m**2 | = | 8.19353E-05 |
| Heated perimeter, m | = | 0.05080 |
| Measured ratio of exit subcooling-to-coolant temp rise, at flow instability | = | 0.224 |
| Measured coolant velocity at OFI, m/s | = | 2.361 |
| Measured flow rate at OFI, kg/s | = | 0.191 |

| Inlet Vel, m/s | Inlet Temp, C | Exit Temp, C | Friction Factor | Beta per C | Total Press Drop, Pa | Friction Drop, Pa | Orifice Drop, Pa | Mom Change Drop, Pa | Gravity Drop, Pa | Reynolds Number | Inlet Press, Pa |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2.500 | 55.00 | 92.92 | 0.0224 | 6.10E-04 | 13394.79 | 7423.94 | 0.00 | 146.79 | 5824.05 | 36997.61 | 130605.45 |
| 2.510 | 55.00 | 92.77 | 0.0224 | 6.09E-04 | 13449.43 | 7477.80 | 0.00 | 147.25 | 5824.37 | 37111.60 | 130660.09 |
| 2.520 | 55.00 | 92.62 | 0.0224 | 6.09E-04 | 13504.25 | 7531.84 | 0.00 | 147.71 | 5824.69 | 37225.56 | 130714.91 |
| 2.530 | 55.00 | 92.48 | 0.0223 | 6.08E-04 | 13559.23 | 7586.05 | 0.00 | 148.17 | 5825.01 | 37339.53 | 130769.90 |
| 2.540 | 55.00 | 92.33 | 0.0223 | 6.08E-04 | 13614.39 | 7640.44 | 0.00 | 148.63 | 5825.32 | 37453.46 | 130825.05 |
| 2.550 | 55.00 | 92.18 | 0.0223 | 6.08E-04 | 13669.72 | 7695.00 | 0.00 | 149.09 | 5825.63 | 37567.41 | 130880.38 |
| 2.560 | 55.00 | 92.04 | 0.0223 | 6.07E-04 | 13725.22 | 7749.73 | 0.00 | 149.55 | 5825.94 | 37681.32 | 130935.88 |
| 2.570 | 55.00 | 91.89 | 0.0223 | 6.07E-04 | 13780.88 | 7804.63 | 0.00 | 150.01 | 5826.25 | 37795.24 | 130991.55 |
| 2.580 | 55.00 | 91.75 | 0.0223 | 6.06E-04 | 13836.72 | 7859.70 | 0.00 | 150.47 | 5826.55 | 37909.12 | 131047.38 |
| 2.590 | 55.00 | 91.61 | 0.0222 | 6.06E-04 | 13892.73 | 7914.95 | 0.00 | 150.93 | 5826.85 | 38023.02 | 131103.39 |
| 2.600 | 55.00 | 91.47 | 0.0222 | 6.06E-04 | 13948.90 | 7970.38 | 0.00 | 151.38 | 5827.14 | 38136.90 | 131159.56 |
| 2.610 | 55.00 | 91.33 | 0.0222 | 6.05E-04 | 14005.25 | 8025.97 | 0.00 | 151.84 | 5827.44 | 38250.74 | 131215.91 |
| 2.620 | 55.00 | 91.19 | 0.0222 | 6.05E-04 | 14061.76 | 8081.73 | 0.00 | 152.30 | 5827.73 | 38364.60 | 131272.42 |
| 2.630 | 55.00 | 91.06 | 0.0222 | 6.04E-04 | 14118.53 | 8137.75 | 0.00 | 152.76 | 5828.02 | 38478.44 | 131329.19 |
| 2.640 | 55.00 | 90.92 | 0.0222 | 6.04E-04 | 14175.39 | 8193.86 | 0.00 | 153.22 | 5828.31 | 38592.26 | 131386.05 |
| 2.650 | 55.00 | 90.79 | 0.0222 | 6.04E-04 | 14232.41 | 8250.15 | 0.00 | 153.68 | 5828.59 | 38706.09 | 131443.08 |
| 2.660 | 55.00 | 90.65 | 0.0221 | 6.03E-04 | 14289.60 | 8306.60 | 0.00 | 154.13 | 5828.87 | 38819.89 | 131500.27 |
| 2.670 | 55.00 | 90.52 | 0.0221 | 6.03E-04 | 14346.97 | 8363.22 | 0.00 | 154.59 | 5829.15 | 38933.69 | 131557.62 |
| 2.680 | 55.00 | 90.39 | 0.0221 | 6.02E-04 | 14404.50 | 8420.02 | 0.00 | 155.05 | 5829.43 | 39047.47 | 131615.16 |
| 2.690 | 55.00 | 90.26 | 0.0221 | 6.02E-04 | 14462.20 | 8476.99 | 0.00 | 155.51 | 5829.70 | 39161.25 | 131672.86 |
| 2.700 | 55.00 | 90.13 | 0.0221 | 6.02E-04 | 14520.07 | 8534.13 | 0.00 | 155.97 | 5829.98 | 39275.00 | 131730.73 |
| 2.710 | 55.00 | 90.00 | 0.0221 | 6.01E-04 | 14578.11 | 8591.44 | 0.00 | 156.42 | 5830.25 | 39388.77 | 131788.78 |
| 2.711 | 55.00 | 89.98 | 0.0221 | 6.01E-04 | 14583.92 | 8597.18 | 0.00 | 156.47 | 5830.27 | 39400.14 | 131794.58 |
| 2.712 | 55.00 | 89.97 | 0.0221 | 6.01E-04 | 14589.74 | 8602.92 | 0.00 | 156.52 | 5830.30 | 39411.52 | 131800.41 |
| 2.713 | 55.00 | 89.96 | 0.0221 | 6.01E-04 | 14595.55 | 8608.67 | 0.00 | 156.56 | 5830.33 | 39422.89 | 131806.22 |
| 2.714 | 55.00 | 89.95 | 0.0221 | 6.01E-04 | 14601.37 | 8614.41 | 0.00 | 156.61 | 5830.35 | 39434.27 | 131812.03 |
| 2.715 | 55.00 | 89.93 | 0.0221 | 6.01E-04 | 14607.19 | 8620.16 | 0.00 | 156.65 | 5830.38 | 39445.64 | 131817.86 |

**Table 5. Cont'd.**

| Inlet Vel, m/s | Inlet Temp, C | Exit Temp, C | Friction Factor | Beta per C | Total Press Drop, Pa | Friction Drop, Pa | Orifice Drop, Pa | Mom Change Drop, Pa | Gravity Drop, Pa | Reynolds Number | Inlet Press, Pa |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2.716 | 55.00 | 89.92 | 0.0221 | 6.01E-04 | 14613.01 | 8625.91 | 0.00 | 156.70 | 5830.41 | 39457.02 | 131823.67 |
| 2.717 | 55.00 | 89.91 | 0.0221 | 6.01E-04 | 14618.84 | 8631.66 | 0.00 | 156.75 | 5830.43 | 39468.39 | 131829.50 |
| 2.718 | 55.00 | 89.89 | 0.0221 | 6.01E-04 | 14624.66 | 8637.41 | 0.00 | 156.79 | 5830.46 | 39479.77 | 131835.33 |
| 2.719 | 55.00 | 89.88 | 0.0221 | 6.01E-04 | 14630.49 | 8643.17 | 0.00 | 156.84 | 5830.49 | 39491.13 | 131841.16 |
| 2.720 | 55.00 | 89.87 | 0.0220 | 6.01E-04 | 14636.31 | 8648.92 | 0.00 | 156.88 | 5830.51 | 39502.51 | 131846.98 |
| 2.730 | 55.00 | 89.74 | 0.0220 | 6.00E-04 | 14694.69 | 8706.57 | 0.00 | 157.34 | 5830.78 | 39616.23 | 131905.36 |
| 2.740 | 55.00 | 89.62 | 0.0220 | 6.00E-04 | 14753.23 | 8764.39 | 0.00 | 157.80 | 5831.04 | 39729.97 | 131963.89 |
| 2.750 | 55.00 | 89.49 | 0.0220 | 6.00E-04 | 14811.95 | 8822.39 | 0.00 | 158.25 | 5831.30 | 39843.68 | 132022.61 |
| 2.760 | 55.00 | 89.37 | 0.0220 | 5.99E-04 | 14870.82 | 8880.55 | 0.00 | 158.71 | 5831.56 | 39957.39 | 132081.48 |
| 2.770 | 55.00 | 89.24 | 0.0220 | 5.99E-04 | 14929.87 | 8938.88 | 0.00 | 159.17 | 5831.82 | 40071.08 | 132140.53 |
| 2.780 | 55.00 | 89.12 | 0.0220 | 5.99E-04 | 14989.09 | 8997.38 | 0.00 | 159.63 | 5832.08 | 40184.77 | 132199.75 |
| 2.790 | 55.00 | 89.00 | 0.0219 | 5.98E-04 | 15048.47 | 9056.06 | 0.00 | 160.08 | 5832.33 | 40298.44 | 132259.12 |
| 2.800 | 55.00 | 88.88 | 0.0219 | 5.98E-04 | 15108.02 | 9114.90 | 0.00 | 160.54 | 5832.58 | 40412.11 | 132318.69 |
| 2.810 | 55.00 | 88.76 | 0.0219 | 5.98E-04 | 15167.74 | 9173.91 | 0.00 | 161.00 | 5832.83 | 40525.75 | 132378.41 |
| 2.820 | 55.00 | 88.64 | 0.0219 | 5.97E-04 | 15227.62 | 9233.09 | 0.00 | 161.46 | 5833.08 | 40639.43 | 132438.28 |
| 2.830 | 55.00 | 88.52 | 0.0219 | 5.97E-04 | 15287.68 | 9292.44 | 0.00 | 161.91 | 5833.32 | 40753.07 | 132498.34 |
| 2.840 | 55.00 | 88.40 | 0.0219 | 5.96E-04 | 15347.90 | 9351.96 | 0.00 | 162.37 | 5833.56 | 40866.69 | 132558.56 |
| 2.850 | 55.00 | 88.28 | 0.0219 | 5.96E-04 | 15408.28 | 9411.65 | 0.00 | 162.83 | 5833.80 | 40980.31 | 132618.95 |

## Table 6. Application of Babelli and Ishii Flow Instability Criterion to a Typical Whittle and Forgan Test (Number 1)

| Inlet Vel, m/s | Exit Temp, C | Tot Press Drop, Pa | Exit Press Pa | Peclet Number | Inlet Subc J/kg | Subcool Number | Zuber Number | Nsub/Nzu | RHS of Eq. (1) | Stable? | Critical Lnvg/L | 0.0022Pe or 154.0 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2.500 | 92.92 | 13394.79 | 117210.66 | 87332.46 | 206803.64 | 129.41 | 99.75 | 1.297 | 1.407 | unstable | 1.000 | 154.000 | |
| 2.510 | 92.77 | 13449.43 | 117210.66 | 87689.20 | 206803.64 | 129.41 | 99.35 | 1.303 | 1.407 | unstable | 1.000 | 154.000 | |
| 2.520 | 92.62 | 13504.25 | 117210.66 | 88046.04 | 206803.64 | 129.41 | 98.96 | 1.308 | 1.407 | unstable | 1.000 | 154.000 | |
| 2.530 | 92.48 | 13559.23 | 117210.66 | 88402.89 | 206803.64 | 129.41 | 98.57 | 1.313 | 1.407 | unstable | 1.000 | 154.000 | |
| 2.540 | 92.33 | 13614.39 | 117210.66 | 88759.84 | 206803.64 | 129.41 | 98.18 | 1.318 | 1.407 | unstable | 1.000 | 154.000 | |
| 2.550 | 92.18 | 13669.72 | 117210.66 | 89116.76 | 206803.64 | 129.41 | 97.79 | 1.323 | 1.407 | unstable | 1.000 | 154.000 | |
| 2.560 | 92.04 | 13725.22 | 117210.66 | 89473.73 | 206803.64 | 129.41 | 97.41 | 1.328 | 1.407 | unstable | 1.000 | 154.000 | |
| 2.570 | 91.89 | 13780.88 | 117210.66 | 89830.73 | 206803.64 | 129.41 | 97.03 | 1.334 | 1.407 | unstable | 1.000 | 154.000 | |
| 2.580 | 91.75 | 13836.72 | 117210.66 | 90187.84 | 206803.64 | 129.41 | 96.65 | 1.339 | 1.407 | unstable | 1.000 | 154.000 | |
| 2.590 | 91.61 | 13892.73 | 117210.66 | 90544.95 | 206803.64 | 129.41 | 96.28 | 1.344 | 1.407 | unstable | 1.000 | 154.000 | |
| 2.600 | 91.47 | 13948.90 | 117210.66 | 90902.08 | 206803.64 | 129.41 | 95.91 | 1.349 | 1.407 | unstable | 1.000 | 154.000 | |
| 2.610 | 91.33 | 14005.25 | 117210.66 | 91259.28 | 206803.64 | 129.41 | 95.54 | 1.354 | 1.407 | unstable | 1.000 | 154.000 | |
| 2.620 | 91.19 | 14061.76 | 117210.66 | 91616.52 | 206803.64 | 129.41 | 95.18 | 1.360 | 1.407 | unstable | 1.000 | 154.000 | Eq. (5) |
| 2.630 | 91.06 | 14118.53 | 117210.66 | 91973.76 | 206803.64 | 129.41 | 94.82 | 1.365 | 1.407 | unstable | 1.000 | 154.000 | |
| 2.640 | 90.92 | 14175.39 | 117210.66 | 92331.06 | 206803.64 | 129.41 | 94.46 | 1.370 | 1.407 | unstable | 1.000 | 154.000 | |
| 2.650 | 90.79 | 14232.41 | 117210.66 | 92688.41 | 206803.64 | 129.41 | 94.10 | 1.375 | 1.407 | unstable | 1.000 | 154.000 | |
| 2.660 | 90.65 | 14289.60 | 117210.66 | 93045.74 | 206803.64 | 129.41 | 93.75 | 1.380 | 1.407 | unstable | 1.000 | 154.000 | |
| 2.670 | 90.52 | 14346.97 | 117210.66 | 93403.16 | 206803.64 | 129.41 | 93.40 | 1.386 | 1.407 | unstable | 1.000 | 154.000 | |
| 2.680 | 90.39 | 14404.50 | 117210.66 | 93760.57 | 206803.64 | 129.41 | 93.05 | 1.391 | 1.407 | unstable | 1.000 | 154.000 | |
| 2.690 | 90.26 | 14462.20 | 117210.66 | 94118.10 | 206803.64 | 129.41 | 92.70 | 1.396 | 1.407 | unstable | 1.000 | 154.000 | |
| 2.700 | 90.13 | 14520.07 | 117210.66 | 94475.60 | 206803.64 | 129.41 | 92.36 | 1.401 | 1.407 | unstable | 1.000 | 154.000 | |
| 2.710 | 90.00 | 14578.11 | 117210.66 | 94833.12 | 206803.64 | 129.41 | 92.02 | 1.406 | 1.407 | unstable | 1.000 | 154.000 | |
| 2.710 | 90.00 | 14578.11 | 117210.66 | 94833.12 | 206803.64 | 129.41 | 92.02 | 1.406 | 1.407 | unstable | 1.000 | 154.000 | |
| 2.711 | 89.98 | 14583.92 | 117210.66 | 94868.88 | 206803.64 | 129.41 | 91.98 | 1.407 | 1.407 | unstable | 1.000 | 154.000 | |
| **2.712** | **89.97** | **14589.74** | **117210.66** | **94904.67** | **206803.64** | **129.41** | **91.95** | **1.407** | **1.407** | **unstable** | **1.000** | **154.000** | **Eq. (1)** |
| 2.713 | 89.96 | 14595.55 | 117210.66 | 94940.33 | 206803.64 | 129.41 | 91.92 | 1.408 | 1.407 | stable | 1.000 | 154.000 | |
| 2.714 | 89.95 | 14601.37 | 117210.66 | 94976.14 | 206803.64 | 129.41 | 91.88 | 1.408 | 1.407 | stable | 1.000 | 154.000 | |
| 2.715 | 89.93 | 14607.19 | 117210.66 | 95011.90 | 206803.64 | 129.41 | 91.85 | 1.409 | 1.407 | stable | 1.000 | 154.000 | |
| 2.716 | 89.92 | 14613.01 | 117210.66 | 95047.68 | 206803.64 | 129.41 | 91.82 | 1.409 | 1.407 | stable | 1.000 | 154.000 | |
| 2.717 | 89.91 | 14618.84 | 117210.66 | 95083.46 | 206803.64 | 129.41 | 91.78 | 1.410 | 1.407 | stable | 1.000 | 154.000 | |
| 2.718 | 89.89 | 14624.66 | 117210.66 | 95119.23 | 206803.64 | 129.41 | 91.75 | 1.410 | 1.407 | stable | 1.000 | 154.000 | |
| 2.719 | 89.88 | 14630.49 | 117210.66 | 95154.93 | 206803.64 | 129.41 | 91.71 | 1.411 | 1.407 | stable | 1.000 | 154.000 | |
| 2.720 | 89.87 | 14636.32 | 117210.66 | 95190.72 | 206803.64 | 129.41 | 91.68 | 1.412 | 1.407 | stable | 1.000 | 154.000 | |
| 2.720 | 89.87 | 14636.31 | 117210.66 | 95190.69 | 206803.64 | 129.41 | 91.68 | 1.412 | 1.407 | stable | 1.000 | 154.000 | |
| 2.730 | 89.74 | 14694.69 | 117210.66 | 95548.28 | 206803.64 | 129.41 | 91.34 | 1.417 | 1.407 | stable | 1.000 | 154.000 | |
| 2.740 | 89.62 | 14753.23 | 117210.66 | 95905.96 | 206803.64 | 129.41 | 91.01 | 1.422 | 1.407 | stable | 1.000 | 154.000 | |
| 2.750 | 89.49 | 14811.95 | 117210.66 | 96263.64 | 206803.64 | 129.41 | 90.68 | 1.427 | 1.407 | stable | 1.000 | 154.000 | |
| 2.760 | 89.37 | 14870.82 | 117210.66 | 96621.38 | 206803.64 | 129.41 | 90.35 | 1.432 | 1.407 | stable | 1.000 | 154.000 | |
| 2.770 | 89.24 | 14929.87 | 117210.66 | 96979.12 | 206803.64 | 129.41 | 90.03 | 1.437 | 1.407 | stable | 1.000 | 154.000 | |
| 2.780 | 89.12 | 14989.09 | 117210.66 | 97336.86 | 206803.64 | 129.41 | 89.70 | 1.443 | 1.407 | stable | 1.000 | 154.000 | |
| 2.790 | 89.00 | 15048.47 | 117210.66 | 97694.67 | 206803.64 | 129.41 | 89.38 | 1.448 | 1.407 | stable | 1.000 | 154.000 | |
| 2.800 | 88.88 | 15108.02 | 117210.66 | 98052.58 | 206803.64 | 129.41 | 89.06 | 1.453 | 1.407 | stable | 1.000 | 154.000 | |
| 2.810 | 88.76 | 15167.74 | 117210.66 | 98410.45 | 206803.64 | 129.41 | 88.74 | 1.458 | 1.407 | stable | 1.000 | 154.000 | |
| 2.820 | 88.64 | 15227.62 | 117210.66 | 98768.30 | 206803.64 | 129.41 | 88.43 | 1.463 | 1.407 | stable | 1.000 | 154.000 | |
| 2.830 | 88.52 | 15287.68 | 117210.66 | 99126.25 | 206803.64 | 129.41 | 88.12 | 1.469 | 1.407 | stable | 1.000 | 154.000 | |
| 2.840 | 88.40 | 15347.90 | 117210.66 | 99484.29 | 206803.64 | 129.41 | 87.81 | 1.474 | 1.407 | stable | 1.000 | 154.000 | |
| 2.850 | 88.28 | 15408.28 | 117210.66 | 99842.28 | 206803.64 | 129.41 | 87.50 | 1.479 | 1.407 | stable | 1.000 | 154.000 | |

The underlined line marks the flow instability predicted by the simple criterion of Eq. (5).

**Table 7. Comparison of Coolant Inlet Velocity at OFI Calculated Using Eq. (1) Versus its Measured Value in 75 Tests Reported by Whittle and Forgan**

| Test No. | Calc. Inlet Vel,m/s | Inlet Temp C | Heat Flux W/cm^2 | $L/D_H$ Ratio | Exit Press psia | Exit Temp C | Ratio $\Delta T_c/\Delta T_{sat}$ | η W&F | Measured at OFI Inlet Vel,m/s | Measured at OFI Flow kg/s | Peclet Number | Subcool Number | Zuber Number | Ratio $N_{sub}/N_{zub}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.712 | 55.000 | 104.000 | 94.488 | 17.000 | 89.971 | 0.712 | 38.260 | 2.361 | 0.1908 | 94905. | 129.406 | 91.950 | 1.407 |
| 2 | 3.781 | 55.000 | 145.000 | 94.488 | 17.000 | 89.974 | 0.712 | 38.248 | 3.406 | 0.2752 | 132314. | 129.402 | 91.954 | 1.407 |
| 3 | 4.798 | 55.000 | 184.000 | 94.488 | 17.000 | 89.975 | 0.712 | 38.244 | 4.164 | 0.3365 | 167903. | 129.397 | 91.953 | 1.407 |
| 4 | 6.520 | 55.000 | 250.000 | 94.488 | 17.000 | 89.975 | 0.712 | 38.246 | 5.872 | 0.4745 | 228166. | 129.384 | 91.938 | 1.407 |
| 5 | 2.138 | 55.000 | 82.000 | 94.488 | 17.000 | 89.976 | 0.712 | 38.240 | 1.902 | 0.1537 | 74818. | 129.406 | 91.964 | 1.407 |
| 6 | 3.546 | 55.000 | 136.000 | 94.488 | 17.000 | 89.977 | 0.712 | 38.236 | 3.154 | 0.2549 | 124090. | 129.402 | 91.962 | 1.407 |
| 7 | 4.172 | 55.000 | 160.000 | 94.488 | 17.000 | 89.977 | 0.712 | 38.238 | 3.806 | 0.3075 | 145996. | 129.397 | 91.957 | 1.407 |
| 8 | 5.216 | 55.000 | 200.000 | 94.488 | 17.000 | 89.972 | 0.712 | 38.257 | 4.697 | 0.3796 | 182532. | 129.393 | 91.939 | 1.407 |
| 9 | 3.455 | 45.000 | 160.000 | 94.488 | 17.000 | 87.105 | 0.712 | 38.210 | 3.073 | 0.2494 | 121664. | 155.577 | 110.556 | 1.407 |
| 10 | 3.887 | 45.000 | 180.000 | 94.488 | 17.000 | 87.103 | 0.712 | 38.214 | 3.457 | 0.2806 | 136876. | 155.577 | 110.552 | 1.407 |
| 11 | 4.405 | 45.000 | 204.000 | 94.488 | 17.000 | 87.107 | 0.712 | 38.201 | 3.868 | 0.3139 | 155117. | 155.572 | 110.559 | 1.407 |
| 12 | 3.200 | 60.000 | 110.000 | 94.488 | 17.000 | 91.406 | 0.712 | 38.284 | 2.845 | 0.2293 | 111606. | 116.295 | 82.629 | 1.407 |
| 13 | 4.654 | 60.000 | 160.000 | 94.488 | 17.000 | 91.412 | 0.712 | 38.262 | 4.138 | 0.3336 | 162317. | 116.290 | 82.638 | 1.407 |
| 14 | 5.236 | 60.000 | 180.000 | 94.488 | 17.000 | 91.412 | 0.712 | 38.261 | 4.715 | 0.3801 | 182616. | 116.286 | 82.634 | 1.407 |
| 15 | 5.818 | 60.000 | 200.000 | 94.488 | 17.000 | 91.410 | 0.712 | 38.267 | 4.982 | 0.4016 | 202915. | 116.286 | 82.631 | 1.407 |
| 16 | 2.505 | 35.000 | 136.000 | 94.488 | 17.000 | 84.247 | 0.712 | 38.152 | 2.229 | 0.1816 | 88704. | 181.713 | 129.155 | 1.407 |
| 25 | 1.684 | 45.000 | 78.000 | 94.488 | 17.000 | 87.108 | 0.712 | 38.200 | 1.517 | 0.1232 | 59299. | 155.590 | 110.578 | 1.407 |
| 26 | 2.505 | 45.000 | 116.000 | 94.488 | 17.000 | 87.100 | 0.712 | 38.226 | 2.257 | 0.1832 | 88210. | 155.585 | 110.551 | 1.407 |
| 27 | 3.196 | 45.000 | 148.000 | 94.488 | 17.000 | 87.100 | 0.712 | 38.225 | 2.843 | 0.2307 | 112543. | 155.585 | 110.552 | 1.407 |
| 28 | 2.998 | 55.000 | 115.000 | 94.488 | 17.000 | 89.979 | 0.712 | 38.228 | 2.701 | 0.2183 | 104912. | 129.410 | 91.977 | 1.407 |
| 29 | 1.955 | 55.000 | 75.000 | 94.488 | 17.000 | 89.982 | 0.712 | 38.219 | 1.762 | 0.1424 | 68413. | 129.415 | 91.987 | 1.407 |
| 30 | 3.807 | 55.000 | 146.000 | 94.488 | 17.000 | 89.973 | 0.712 | 38.251 | 3.386 | 0.2736 | 133223. | 129.406 | 91.956 | 1.407 |
| 31 | 0.907 | 45.000 | 42.000 | 94.488 | 17.000 | 87.097 | 0.712 | 38.233 | 0.827 | 0.0672 | 31939. | 155.590 | 110.550 | 1.407 |
| 32 | 3.512 | 55.000 | 147.000 | 83.333 | 17.000 | 88.671 | 0.685 | 38.263 | 3.084 | 0.1884 | 95608. | 129.402 | 88.514 | 1.462 |
| 33 | 4.061 | 55.000 | 170.000 | 83.333 | 17.000 | 88.675 | 0.685 | 38.249 | 3.566 | 0.2178 | 110553. | 129.402 | 88.525 | 1.462 |
| 34 | 4.300 | 55.000 | 180.000 | 83.333 | 17.000 | 88.674 | 0.685 | 38.252 | 3.776 | 0.2307 | 117060. | 129.402 | 88.522 | 1.462 |
| 35 | 5.136 | 55.000 | 215.000 | 83.333 | 17.000 | 88.676 | 0.685 | 38.244 | 4.454 | 0.2721 | 139819. | 129.397 | 88.524 | 1.462 |
| 36 | 3.878 | 45.000 | 196.000 | 83.333 | 17.000 | 85.534 | 0.685 | 38.233 | 3.406 | 0.2090 | 106263. | 155.577 | 106.414 | 1.462 |
| 37 | 4.946 | 45.000 | 250.000 | 83.333 | 17.000 | 85.539 | 0.686 | 38.218 | 4.344 | 0.2665 | 135528. | 155.572 | 106.423 | 1.462 |
| 38 | 3.561 | 45.000 | 180.000 | 83.333 | 17.000 | 85.539 | 0.686 | 38.218 | 3.128 | 0.1919 | 97576. | 155.577 | 106.427 | 1.462 |
| 39 | 5.331 | 65.000 | 177.000 | 83.333 | 17.000 | 91.812 | 0.685 | 38.288 | 4.621 | 0.2808 | 144098. | 103.170 | 70.576 | 1.462 |
| 40 | 6.115 | 65.000 | 203.000 | 83.333 | 17.000 | 91.810 | 0.685 | 38.299 | 5.300 | 0.3221 | 165290. | 103.166 | 70.566 | 1.462 |
| 41 | 6.566 | 65.000 | 218.000 | 83.333 | 17.000 | 91.813 | 0.685 | 38.284 | 5.669 | 0.3445 | 177481. | 103.166 | 70.575 | 1.462 |
| 42 | 3.704 | 65.000 | 123.000 | 83.333 | 17.000 | 91.813 | 0.685 | 38.283 | 3.252 | 0.1976 | 100119. | 103.179 | 70.588 | 1.462 |
| 43 | 4.137 | 45.000 | 250.000 | 83.333 | 25.000 | 93.422 | 0.686 | 38.159 | 3.543 | 0.2174 | 112790. | 130.125 | 89.009 | 1.462 |
| 44 | 5.629 | 65.000 | 242.000 | 83.333 | 25.000 | 99.683 | 0.686 | 38.231 | 4.943 | 0.3004 | 151549. | 93.463 | 63.930 | 1.462 |
| 45 | 3.116 | 65.000 | 134.000 | 83.333 | 25.000 | 99.690 | 0.686 | 38.207 | 2.634 | 0.1601 | 83891. | 93.469 | 63.949 | 1.462 |

**Table 7. Cont'd.**

| Test No. | Calc. Inlet Vel,m/s | Inlet Temp C | Heat Flux W/cm^2 | $L/D_H$ Ratio | Exit Press psia | Exit Temp C | Ratio $\Delta T_c/\Delta T_{sat}$ | η W&F | Measured at OFI Inlet Vel,m/s | Measured at OFI Flow kg/s | Peclet Number | Subcool Number | Zuber Number | Ratio $N_{sub}/N_{zub}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 46 | 3.868 | 55.000 | 200.000 | 83.333 | 25.000 | 96.556 | 0.686 | 38.180 | 3.355 | 0.2050 | 104826. | 111.814 | 76.493 | 1.462 |
| 47 | 3.481 | 55.000 | 180.000 | 83.333 | 25.000 | 96.558 | 0.686 | 38.173 | 3.058 | 0.1868 | 94338. | 111.814 | 76.497 | 1.462 |
| 48 | 4.807 | 55.000 | 177.000 | 100.000 | 17.000 | 90.538 | 0.723 | 38.249 | 4.400 | 0.2240 | 110537. | 129.397 | 93.439 | 1.385 |
| 49 | 5.921 | 55.000 | 218.000 | 100.000 | 17.000 | 90.538 | 0.723 | 38.249 | 5.419 | 0.2759 | 136154. | 129.389 | 93.430 | 1.385 |
| 50 | 7.497 | 55.000 | 276.000 | 100.000 | 17.000 | 90.540 | 0.723 | 38.244 | 6.861 | 0.3493 | 172396. | 129.376 | 93.421 | 1.385 |
| 51 | 4.828 | 65.000 | 141.000 | 100.000 | 17.000 | 93.296 | 0.723 | 38.295 | 4.361 | 0.2209 | 110269. | 103.170 | 74.495 | 1.385 |
| 52 | 7.466 | 65.000 | 218.000 | 100.000 | 17.000 | 93.296 | 0.723 | 38.291 | 6.743 | 0.3415 | 170522. | 103.153 | 74.480 | 1.385 |
| 53 | 10.276 | 65.000 | 300.000 | 100.000 | 17.000 | 93.299 | 0.723 | 38.276 | 9.279 | 0.4699 | 234706. | 103.131 | 74.466 | 1.385 |
| 54 | 3.766 | 65.000 | 110.000 | 100.000 | 17.000 | 93.298 | 0.723 | 38.283 | 3.402 | 0.1723 | 86013. | 103.175 | 74.506 | 1.385 |
| 55 | 4.971 | 45.000 | 221.000 | 100.000 | 17.000 | 87.779 | 0.723 | 38.226 | 4.550 | 0.2327 | 115013. | 155.568 | 112.326 | 1.385 |
| 56 | 6.500 | 45.000 | 289.000 | 100.000 | 17.000 | 87.785 | 0.724 | 38.205 | 5.799 | 0.2965 | 150390. | 155.559 | 112.334 | 1.385 |
| 57 | 5.430 | 35.000 | 283.000 | 100.000 | 17.000 | 85.033 | 0.724 | 38.172 | 5.035 | 0.2584 | 126321. | 181.699 | 131.215 | 1.385 |
| 58 | 4.202 | 35.000 | 219.000 | 100.000 | 17.000 | 85.032 | 0.724 | 38.175 | 3.848 | 0.1974 | 97753. | 181.704 | 131.216 | 1.385 |
| 59 | 3.511 | 35.000 | 183.000 | 100.000 | 17.000 | 85.034 | 0.724 | 38.169 | 3.215 | 0.1650 | 81677. | 181.708 | 131.226 | 1.385 |
| 60 | 2.369 | 55.000 | 93.000 | 100.000 | 17.000 | 92.875 | 0.771 | 29.718 | 2.282 | 0.1162 | 54400. | 129.406 | 99.621 | 1.299 |
| 61 | 10.311 | 75.000 | 223.000 | 100.000 | 17.000 | 96.062 | 0.723 | 38.311 | 9.308 | 0.4686 | 233771. | 76.856 | 55.494 | 1.385 |
| 62 | 1.546 | 55.000 | 66.000 | 100.000 | 17.000 | 96.172 | 0.838 | 19.331 | 1.661 | 0.0846 | 35439. | 129.406 | 108.335 | 1.195 |
| 63 | 7.651 | 55.000 | 170.000 | 190.909 | 17.000 | 95.934 | 0.833 | 38.233 | 7.408 | 0.2593 | 123456. | 129.341 | 107.638 | 1.202 |
| 64 | 4.154 | 55.000 | 93.000 | 190.909 | 17.000 | 96.226 | 0.839 | 36.608 | 4.053 | 0.1418 | 67016. | 129.389 | 108.460 | 1.193 |
| 65 | 5.849 | 55.000 | 130.000 | 190.909 | 17.000 | 95.937 | 0.833 | 38.215 | 5.665 | 0.1983 | 94377. | 129.367 | 107.673 | 1.201 |
| 66 | 4.732 | 45.000 | 127.000 | 190.909 | 17.000 | 94.269 | 0.833 | 38.214 | 4.691 | 0.1649 | 76753. | 155.555 | 129.453 | 1.202 |
| 67 | 6.558 | 45.000 | 176.000 | 190.909 | 17.000 | 94.275 | 0.833 | 38.189 | 6.352 | 0.2233 | 106373. | 155.533 | 129.445 | 1.202 |
| 68 | 2.300 | 45.000 | 67.000 | 190.909 | 17.000 | 98.442 | 0.904 | 20.323 | 2.418 | 0.0850 | 37229. | 155.577 | 140.510 | 1.107 |
| 69 | 8.423 | 45.000 | 226.000 | 190.909 | 17.000 | 94.274 | 0.833 | 38.193 | 8.255 | 0.2902 | 136627. | 155.503 | 129.412 | 1.202 |
| 70 | 3.803 | 35.000 | 122.000 | 190.909 | 17.000 | 93.738 | 0.850 | 33.779 | 3.803 | 0.1341 | 61920. | 181.695 | 154.190 | 1.178 |
| 71 | 6.751 | 65.000 | 119.000 | 190.909 | 17.000 | 97.600 | 0.833 | 38.249 | 6.457 | 0.2248 | 108283. | 103.131 | 85.836 | 1.201 |
| 72 | 5.559 | 65.000 | 98.000 | 190.909 | 17.000 | 97.597 | 0.833 | 38.266 | 5.257 | 0.1830 | 89163. | 103.149 | 85.847 | 1.202 |
| 73 | 4.708 | 65.000 | 83.000 | 190.909 | 17.000 | 97.595 | 0.833 | 38.281 | 4.559 | 0.1587 | 75513. | 103.157 | 85.850 | 1.202 |
| 74 | 5.945 | 35.000 | 187.000 | 190.909 | 17.000 | 92.610 | 0.833 | 38.178 | 5.759 | 0.2032 | 96859. | 181.669 | 151.183 | 1.202 |
| 75 | 4.851 | 55.000 | 186.000 | 94.488 | 17.000 | 89.971 | 0.712 | 38.261 | 4.663 | 0.1504 | 145126. | 129.393 | 91.936 | 1.407 |
| 76 | 6.833 | 55.000 | 262.000 | 94.488 | 17.000 | 89.976 | 0.712 | 38.241 | 6.569 | 0.2118 | 204422. | 129.380 | 91.937 | 1.407 |
| 77 | 3.651 | 55.000 | 140.000 | 94.488 | 17.000 | 89.972 | 0.712 | 38.256 | 3.416 | 0.1102 | 109225. | 129.397 | 91.944 | 1.407 |
| 78 | 3.196 | 45.000 | 148.000 | 94.488 | 17.000 | 87.103 | 0.712 | 38.215 | 2.991 | 0.0969 | 96212. | 155.577 | 110.552 | 1.407 |
| 79 | 5.831 | 45.000 | 270.000 | 94.488 | 17.000 | 87.106 | 0.712 | 38.206 | 5.607 | 0.1816 | 175538. | 155.559 | 110.542 | 1.407 |
| 80 | 7.517 | 45.000 | 348.000 | 94.488 | 17.000 | 87.102 | 0.712 | 38.218 | 7.431 | 0.2407 | 226297. | 155.546 | 110.519 | 1.407 |
| 81 | 2.827 | 65.000 | 86.000 | 94.488 | 17.000 | 92.848 | 0.712 | 38.284 | 2.645 | 0.0848 | 83993. | 103.179 | 73.321 | 1.407 |
| 82 | 5.853 | 65.000 | 178.000 | 94.488 | 17.000 | 92.846 | 0.712 | 38.295 | 5.624 | 0.1804 | 173901. | 103.162 | 73.298 | 1.407 |
| 83 | 11.184 | 65.000 | 340.000 | 94.488 | 17.000 | 92.853 | 0.712 | 38.262 | 11.357 | 0.3643 | 332305. | 103.114 | 73.268 | 1.407 |

Mean error in calculated inlet velocity at OFI, m/s = 0.384
Standard deviation of the error in calculated inlet velocity at OFI, m/s = 0.242

**Table 8. Comparison of Coolant Inlet Velocity at OFI Calculated Using Eq. (5) Versus its Measured Value in 75 Tests Reported by Whittle and Forgan**

| Test No. | Calc. Inlet Vel,m/s | Inlet Temp C | Heat Flux W/cm^2 | $L/D_H$ Ratio | Exit Press psia | Exit Temp C | Ratio $\Delta T_c/\Delta T_{sat}$ | η W&F | Measured at OFI Inlet Vel,m/s | Measured at OFI Flow kg/s | Peclet Number | Subcool Number | Zuber Number | Ratio $N_{sub}/N_{zub}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.620 | 55.000 | 104.000 | 94.488 | 17.000 | 91.194 | 0.737 | 33.775 | 2.361 | 0.1908 | 91617. | 129.406 | 95.179 | 1.360 |
| 2 | 3.654 | 55.000 | 145.000 | 94.488 | 17.000 | 91.184 | 0.736 | 33.808 | 3.406 | 0.2752 | 127775. | 129.402 | 95.150 | 1.360 |
| 3 | 4.637 | 55.000 | 184.000 | 94.488 | 17.000 | 91.184 | 0.736 | 33.808 | 4.164 | 0.3365 | 162149. | 129.397 | 95.145 | 1.360 |
| 4 | 6.300 | 55.000 | 250.000 | 94.488 | 17.000 | 91.189 | 0.737 | 33.792 | 5.872 | 0.4745 | 220303. | 129.389 | 95.149 | 1.360 |
| 5 | 2.066 | 55.000 | 82.000 | 94.488 | 17.000 | 91.190 | 0.737 | 33.789 | 1.902 | 0.1537 | 72244. | 129.406 | 95.169 | 1.360 |
| 6 | 3.427 | 55.000 | 136.000 | 94.488 | 17.000 | 91.187 | 0.737 | 33.801 | 3.154 | 0.2549 | 119837. | 129.402 | 95.155 | 1.360 |
| 7 | 4.032 | 55.000 | 160.000 | 94.488 | 17.000 | 91.186 | 0.737 | 33.802 | 3.806 | 0.3075 | 140993. | 129.397 | 95.150 | 1.360 |
| 8 | 5.040 | 55.000 | 200.000 | 94.488 | 17.000 | 91.188 | 0.737 | 33.797 | 4.697 | 0.3796 | 176241. | 129.393 | 95.149 | 1.360 |
| 9 | 3.339 | 45.000 | 160.000 | 94.488 | 17.000 | 88.560 | 0.737 | 33.776 | 3.073 | 0.2494 | 117464. | 155.577 | 114.397 | 1.360 |
| 10 | 3.756 | 45.000 | 180.000 | 94.488 | 17.000 | 88.565 | 0.737 | 33.763 | 3.457 | 0.2806 | 132134. | 155.577 | 114.408 | 1.360 |
| 11 | 4.257 | 45.000 | 204.000 | 94.488 | 17.000 | 88.562 | 0.737 | 33.769 | 3.868 | 0.3139 | 149759. | 155.577 | 114.403 | 1.360 |
| 12 | 3.092 | 60.000 | 110.000 | 94.488 | 17.000 | 92.499 | 0.736 | 33.820 | 2.845 | 0.2293 | 107770. | 116.295 | 85.515 | 1.360 |
| 13 | 4.497 | 60.000 | 160.000 | 94.488 | 17.000 | 92.504 | 0.737 | 33.801 | 4.138 | 0.3336 | 156741. | 116.290 | 85.523 | 1.360 |
| 14 | 5.060 | 60.000 | 180.000 | 94.488 | 17.000 | 92.500 | 0.736 | 33.817 | 4.715 | 0.3801 | 176365. | 116.286 | 85.508 | 1.360 |
| 15 | 5.622 | 60.000 | 200.000 | 94.488 | 17.000 | 92.501 | 0.736 | 33.812 | 4.982 | 0.4016 | 195954. | 116.286 | 85.512 | 1.360 |
| 16 | 2.421 | 35.000 | 136.000 | 94.488 | 17.000 | 85.946 | 0.737 | 33.728 | 2.229 | 0.1816 | 85623. | 181.713 | 133.636 | 1.360 |
| 25 | 1.627 | 45.000 | 78.000 | 94.488 | 17.000 | 88.576 | 0.737 | 33.729 | 1.517 | 0.1232 | 57236. | 155.590 | 114.452 | 1.359 |
| 26 | 2.420 | 45.000 | 116.000 | 94.488 | 17.000 | 88.570 | 0.737 | 33.748 | 2.257 | 0.1832 | 85133. | 155.590 | 114.434 | 1.360 |
| 27 | 3.088 | 45.000 | 148.000 | 94.488 | 17.000 | 88.565 | 0.737 | 33.761 | 2.843 | 0.2307 | 108633. | 155.585 | 114.419 | 1.360 |
| 28 | 2.897 | 55.000 | 115.000 | 94.488 | 17.000 | 91.194 | 0.737 | 33.775 | 2.701 | 0.2183 | 101302. | 129.410 | 95.183 | 1.360 |
| 29 | 1.889 | 55.000 | 75.000 | 94.488 | 17.000 | 91.199 | 0.737 | 33.757 | 1.762 | 0.1424 | 66054. | 129.415 | 95.201 | 1.359 |
| 30 | 3.679 | 55.000 | 146.000 | 94.488 | 17.000 | 91.185 | 0.736 | 33.806 | 3.386 | 0.2736 | 128648. | 129.406 | 95.155 | 1.360 |
| 31 | 0.876 | 45.000 | 42.000 | 94.488 | 17.000 | 88.578 | 0.737 | 33.723 | 0.827 | 0.0672 | 30816. | 155.594 | 114.462 | 1.359 |
| 32 | 3.267 | 55.000 | 147.000 | 83.333 | 17.000 | 91.184 | 0.736 | 29.819 | 3.084 | 0.1884 | 88798. | 129.406 | 95.152 | 1.360 |
| 33 | 3.778 | 55.000 | 170.000 | 83.333 | 17.000 | 91.187 | 0.737 | 29.809 | 3.566 | 0.2178 | 102688. | 129.402 | 95.156 | 1.360 |
| 34 | 4.000 | 55.000 | 180.000 | 83.333 | 17.000 | 91.189 | 0.737 | 29.803 | 3.776 | 0.2307 | 108721. | 129.402 | 95.162 | 1.360 |
| 35 | 4.778 | 55.000 | 215.000 | 83.333 | 17.000 | 91.189 | 0.737 | 29.803 | 4.454 | 0.2721 | 129868. | 129.397 | 95.157 | 1.360 |
| 36 | 3.607 | 45.000 | 196.000 | 83.333 | 17.000 | 88.565 | 0.737 | 29.776 | 3.406 | 0.2090 | 98631. | 155.577 | 114.410 | 1.360 |
| 37 | 4.601 | 45.000 | 250.000 | 83.333 | 17.000 | 88.563 | 0.737 | 29.782 | 4.344 | 0.2665 | 125812. | 155.577 | 114.403 | 1.360 |
| 38 | 3.312 | 45.000 | 180.000 | 83.333 | 17.000 | 88.571 | 0.737 | 29.761 | 3.128 | 0.1919 | 90564. | 155.581 | 114.429 | 1.360 |
| 39 | 4.959 | 65.000 | 177.000 | 83.333 | 17.000 | 93.815 | 0.736 | 29.837 | 4.621 | 0.2808 | 133891. | 103.175 | 75.871 | 1.360 |
| 40 | 5.688 | 65.000 | 203.000 | 83.333 | 17.000 | 93.813 | 0.736 | 29.842 | 5.300 | 0.3221 | 153574. | 103.170 | 75.863 | 1.360 |
| 41 | 6.108 | 65.000 | 218.000 | 83.333 | 17.000 | 93.816 | 0.736 | 29.830 | 5.669 | 0.3445 | 164914. | 103.166 | 75.867 | 1.360 |
| 42 | 3.446 | 65.000 | 123.000 | 83.333 | 17.000 | 93.814 | 0.736 | 29.840 | 3.252 | 0.1976 | 93040. | 103.179 | 75.873 | 1.360 |
| 43 | 3.848 | 45.000 | 250.000 | 83.333 | 25.000 | 97.037 | 0.737 | 29.720 | 3.543 | 0.2174 | 104716. | 130.125 | 95.694 | 1.360 |
| 44 | 5.236 | 65.000 | 242.000 | 83.333 | 25.000 | 102.274 | 0.737 | 29.782 | 4.943 | 0.3004 | 140825. | 93.463 | 68.729 | 1.360 |
| 45 | 2.899 | 65.000 | 134.000 | 83.333 | 25.000 | 102.274 | 0.737 | 29.781 | 2.634 | 0.1601 | 77969. | 93.469 | 68.736 | 1.360 |

**Table 8. Cont'd.**

| Test No. | Calc. Inlet Vel,m/s | Inlet Temp C | Heat Flux W/cm^2 | $L/D_H$ Ratio | Exit Press psia | Exit Temp C | Ratio $\Delta T_c/\Delta T_{sat}$ | η W&F | Measured at OFI Inlet Vel,m/s | Measured at OFI Flow kg/s | Peclet Number | Subcool Number | Zuber Number | Ratio $N_{sub}/N_{zub}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 46 | 3.598 | 55.000 | 200.000 | 83.333 | 25.000 | 99.657 | 0.737 | 29.741 | 3.355 | 0.2050 | 97372. | 111.814 | 82.233 | 1.360 |
| 47 | 3.238 | 55.000 | 180.000 | 83.333 | 25.000 | 99.660 | 0.737 | 29.734 | 3.058 | 0.1868 | 87629. | 111.814 | 82.238 | 1.360 |
| 48 | 4.720 | 55.000 | 177.000 | 100.000 | 17.000 | 91.190 | 0.737 | 35.758 | 4.400 | 0.2240 | 108494. | 129.397 | 95.161 | 1.360 |
| 49 | 5.814 | 55.000 | 218.000 | 100.000 | 17.000 | 91.189 | 0.737 | 35.762 | 5.419 | 0.2759 | 133641. | 129.389 | 95.150 | 1.360 |
| 50 | 7.362 | 55.000 | 276.000 | 100.000 | 17.000 | 91.187 | 0.737 | 35.772 | 6.861 | 0.3493 | 169225. | 129.380 | 95.134 | 1.360 |
| 51 | 4.741 | 65.000 | 141.000 | 100.000 | 17.000 | 93.813 | 0.736 | 35.812 | 4.361 | 0.2209 | 108251. | 103.170 | 75.862 | 1.360 |
| 52 | 7.331 | 65.000 | 218.000 | 100.000 | 17.000 | 93.814 | 0.736 | 35.808 | 6.743 | 0.3415 | 167391. | 103.157 | 75.851 | 1.360 |
| 53 | 10.090 | 65.000 | 300.000 | 100.000 | 17.000 | 93.819 | 0.736 | 35.783 | 9.279 | 0.4699 | 230392. | 103.131 | 75.839 | 1.360 |
| 54 | 3.698 | 65.000 | 110.000 | 100.000 | 17.000 | 93.816 | 0.736 | 35.795 | 3.402 | 0.1723 | 84436. | 103.175 | 75.876 | 1.360 |
| 55 | 4.881 | 45.000 | 221.000 | 100.000 | 17.000 | 88.562 | 0.737 | 35.741 | 4.550 | 0.2327 | 112872. | 155.572 | 114.397 | 1.360 |
| 56 | 6.383 | 45.000 | 289.000 | 100.000 | 17.000 | 88.565 | 0.737 | 35.730 | 5.799 | 0.2965 | 147606. | 155.559 | 114.393 | 1.360 |
| 57 | 5.332 | 35.000 | 283.000 | 100.000 | 17.000 | 85.947 | 0.737 | 35.691 | 5.035 | 0.2584 | 123959. | 181.699 | 133.627 | 1.360 |
| 58 | 4.126 | 35.000 | 219.000 | 100.000 | 17.000 | 85.948 | 0.737 | 35.689 | 3.848 | 0.1974 | 95921. | 181.704 | 133.633 | 1.360 |
| 59 | 3.448 | 35.000 | 183.000 | 100.000 | 17.000 | 85.943 | 0.737 | 35.703 | 3.215 | 0.1650 | 80159. | 181.708 | 133.624 | 1.360 |
| 60 | 2.480 | 55.000 | 93.000 | 100.000 | 17.000 | 91.187 | 0.737 | 35.769 | 2.282 | 0.1162 | 57005. | 129.406 | 95.162 | 1.360 |
| 61 | 10.125 | 75.000 | 223.000 | 100.000 | 17.000 | 96.448 | 0.736 | 35.825 | 9.308 | 0.4686 | 229510. | 76.856 | 56.514 | 1.360 |
| 62 | 1.760 | 55.000 | 66.000 | 100.000 | 17.000 | 91.187 | 0.737 | 35.769 | 1.661 | 0.0846 | 40455. | 129.406 | 95.162 | 1.360 |
| 63 | 8.660 | 55.000 | 170.000 | 190.909 | 17.000 | 91.194 | 0.737 | 68.241 | 7.408 | 0.2593 | 140103. | 129.324 | 95.096 | 1.360 |
| 64 | 4.735 | 55.000 | 93.000 | 190.909 | 17.000 | 91.193 | 0.737 | 68.245 | 4.053 | 0.1418 | 76600. | 129.380 | 95.151 | 1.360 |
| 65 | 6.621 | 55.000 | 130.000 | 190.909 | 17.000 | 91.189 | 0.737 | 68.276 | 5.665 | 0.1983 | 107113. | 129.358 | 95.118 | 1.360 |
| 66 | 5.355 | 45.000 | 127.000 | 190.909 | 17.000 | 88.568 | 0.737 | 68.195 | 4.691 | 0.1649 | 87154. | 155.551 | 114.392 | 1.360 |
| 67 | 7.423 | 45.000 | 176.000 | 190.909 | 17.000 | 88.568 | 0.737 | 68.199 | 6.352 | 0.2233 | 120814. | 155.520 | 114.360 | 1.360 |
| 68 | 2.825 | 45.000 | 67.000 | 190.909 | 17.000 | 88.562 | 0.737 | 68.232 | 2.418 | 0.0850 | 45977. | 155.572 | 114.397 | 1.360 |
| 69 | 9.534 | 45.000 | 226.000 | 190.909 | 17.000 | 88.571 | 0.737 | 68.177 | 8.255 | 0.2902 | 155176. | 155.481 | 114.330 | 1.360 |
| 70 | 4.389 | 35.000 | 122.000 | 190.909 | 17.000 | 85.942 | 0.737 | 68.168 | 3.803 | 0.1341 | 71813. | 181.691 | 133.602 | 1.360 |
| 71 | 7.642 | 65.000 | 119.000 | 190.909 | 17.000 | 93.819 | 0.736 | 68.309 | 6.457 | 0.2248 | 122809. | 103.118 | 75.827 | 1.360 |
| 72 | 6.292 | 65.000 | 98.000 | 190.909 | 17.000 | 93.818 | 0.736 | 68.322 | 5.257 | 0.1830 | 101113. | 103.140 | 75.845 | 1.360 |
| 73 | 5.329 | 65.000 | 83.000 | 190.909 | 17.000 | 93.815 | 0.736 | 68.352 | 4.559 | 0.1587 | 85637. | 103.149 | 75.845 | 1.360 |
| 74 | 6.728 | 35.000 | 187.000 | 190.909 | 17.000 | 85.947 | 0.737 | 68.138 | 5.759 | 0.2032 | 110086. | 181.660 | 133.587 | 1.360 |
| 75 | 4.687 | 55.000 | 186.000 | 94.488 | 17.000 | 91.189 | 0.737 | 33.792 | 4.663 | 0.1504 | 140114. | 129.393 | 95.153 | 1.360 |
| 76 | 6.603 | 55.000 | 262.000 | 94.488 | 17.000 | 91.189 | 0.737 | 33.793 | 6.569 | 0.2118 | 197394. | 129.380 | 95.140 | 1.360 |
| 77 | 3.528 | 55.000 | 140.000 | 94.488 | 17.000 | 91.186 | 0.737 | 33.802 | 3.416 | 0.1102 | 105467. | 129.397 | 95.150 | 1.360 |
| 78 | 3.088 | 45.000 | 148.000 | 94.488 | 17.000 | 88.568 | 0.737 | 33.752 | 2.991 | 0.0969 | 92870. | 155.577 | 114.418 | 1.360 |
| 79 | 5.635 | 45.000 | 270.000 | 94.488 | 17.000 | 88.561 | 0.737 | 33.772 | 5.607 | 0.1816 | 169472. | 155.564 | 114.387 | 1.360 |
| 80 | 7.263 | 45.000 | 348.000 | 94.488 | 17.000 | 88.565 | 0.737 | 33.761 | 7.431 | 0.2407 | 218436. | 155.551 | 114.384 | 1.360 |
| 81 | 2.732 | 65.000 | 86.000 | 94.488 | 17.000 | 93.813 | 0.736 | 33.838 | 2.645 | 0.0848 | 81127. | 103.179 | 75.871 | 1.360 |
| 82 | 5.655 | 65.000 | 178.000 | 94.488 | 17.000 | 93.817 | 0.736 | 33.819 | 5.624 | 0.1804 | 167928. | 103.162 | 75.865 | 1.360 |
| 83 | 10.807 | 65.000 | 340.000 | 94.488 | 17.000 | 93.818 | 0.736 | 33.814 | 11.357 | 0.3643 | 320930. | 103.118 | 75.824 | 1.360 |

Mean error in calculated inlet velocity at OFI, m/s = 0.363
Standard deviation of the error in calculated inlet velocity at OFI, m/s = 0.319

## APPENDIX D. Derivation of Babelli and Ishii Flow Instability Equation

Equation (2) of Ref. [1] is the starting point of Babelli and Ishii in obtaining the flow instability criterion. The purpose of this Appendix is to point out an inherent assumption or approximation in the derivation that affects the calculation of Subcooling number.

The coolant flow rate times the enthalpy change from channel inlet to the NVG position is related to the power generated in the fuel and transferred to the coolant over the non-boiling length, $q_w^{"} \zeta_H L_{nvg}$.

$$\left(h_{nvg} - h_{in}\right) = \frac{q_w^{"} \zeta_H L_{nvg}}{\rho_{in} V_{in} A_F} \tag{A-1}$$

Assume the coolant pressure $P_{in}$ at the start of the heated section to be a *reference pressure* for calculating coolant subcooling at inlet and at the NVG position. Then the enthalpy difference between any pair of axial positions exactly equals the corresponding subcooling difference. The inlet subcooling $\Delta h_{in} = h_f(P_{in}) - h_{in}$ , the subcooling at the NVG position $\Delta h_{nvg} = h_f(P_{in}) - h_{nvg}$ , and the left hand side of Eq. (A-1) is

$$(h_{nvg} - h_{in}) = \Delta h_{in} - \Delta h_{nvg} \tag{A-2}$$

If the coolant pressure at the NVG position (instead of the pressure $P_{in}$ at the start of the heated section) were used as the system *reference pressure*, then inlet subcooling $\Delta h_{in} = h_f(P_{nvg}) - h_{in}$ , the subcooling at the NVG position $\Delta h_{nvg} = h_f(P_{nvg}) - h_{nvg}$ , and Eq. (A-2) remains unchanged. With this assumption the subcooling at the NVG position is accurate and the subcooling at inlet is approximate, whereas with the former assumption, the subcooling at the NVG position is approximate and the subcooling at inlet is accurate (the reverse is true).

Substituting Eq. (A-2) into Eq. (A-1), and solving for the non-boiling length $L_{nvg}$ , one gets

$$\frac{L_{nvg}}{L} = \frac{\rho_{in} V_{in} A_F \left(\Delta h_{in} - \Delta h_{nvg}\right)}{q_w^{"} \zeta_H L} \tag{A-3}$$

Equation (A-3) is the desired Eq. (2) of Ref. [1]. Using the Subcooling number and Zuber number defined above by Eqs. (2) and (3), Babelli and Ishii recast Eq. (A-3) as

$$\frac{N_{sub}}{N_{zu}} = \frac{L_{nvg}}{L} + \frac{A_F}{\zeta_H L}\left\{\frac{\rho_{in} V_{in} \Delta h_{nvg}}{q_w^{"}}\right\} \tag{A-4}$$

The ratio inside the curly brackets on the right hand side of Eq. (A-4) is obtained from the Zuber correlation for the net vapor generation. For an accurate application of the Zuber correlation, it is preferred that the system *reference pressure* is assumed equal to the coolant pressure at the NVG position (rather than the pressure $P_{in}$ at the start of the heated section), making the value of the subcooling at the NVG position accurate. This suggestion is the main purpose of this Appendix.

## APPENDIX E. *Babelli.WFtests.f* Program for Applying Flow Instability Criteria of Eqs. (1) or Eq. (5) to Whittle and Forgan Tests.

(The thermal property subroutines of PLTEMP/ANL code were used with this program but are not listed here for brevity.)

```
C     Application of Babelli-Ishii Flow Instability Criterion
C     on Whittle and Forgan Tests. See Refs. [1, 2].
C     M. Kalimullah and A. P. Olson, November 27, 2007
C     Find when partial derivative of pressure drop (in a heated channel) with
C     respect to inlet coolant velocity is zero.
C     References:
C     (1) Babelli and Ishii, Nuclear Eng & Design, Vol. 96, pp. 91-96 (2001).
C     (2) Babelli and Ishii, Nuclear Eng & Design, Vol. 96, pp. 97-104 (2001).
C     (3) Whittle and Forgan, Nuclear Eng & Design, Vol. 6, pp. 89-99 (1967).
C
C     Friction Factor     =GETF(RE,ROUGH)
C     Tsat                =FUNCTION ZTSAT(P,IFLUID)
C     Liquid
C     Enthalpy            =FUNCTION ZHLIQ(P,T,IFLUID)
C     Density             =FUNCTION ZROLIQ(H,P,T,IFLUID)
C     Kinematic Viscosity =FUNCTION ZVISLIQ(H,P,T,RHO,IFLUID)
C     Cp                  =FUNCTION ZCPLIQ(H,P,T,IFLUID)
C     Thermal Conductivity=FUNCTION ZTHCL(H,P,T,IFLUID)
C     Temperature         =FUNCTION ZTLIQ(P,H,IFLUID,HFUNCL)
C     Vapor
C     Enthalpy            =FUNCTION ZHVAP(P,T,IFLUID)
C     Density             =FUNCTION ZROVAP(H,P,T,IFLUID)
      REAL LENGTH,KORIF,NSUB,NZUB,LENGTHI
      CHARACTER*8 STABLE
      EXTERNAL HFUNCL
C
C     Whittle and Forgan Tests Data in the Original Units
C     ---------------------------------------------------
C     ITEST   = Whittle and Forgan test number in Ref. [3]
C     HTFLXI  = Heat flux in the test, W/cm**2
C     GAPI    = Gap between plates (dimension 'A'), inch
C     WIDTHI  = Width of heated plates (dimension 'B'), inch
C     LENGTHI = Heated length, inch
C     KORIF   = Minor loss coefficient (if any)
C     POUTI   = Exit pressure in the test, psia
C
C     Whittle and Forgan Tests Data in MKS Units
C     ------------------------------------------
C     HTFLX   = Heat flux in the test, W/m**2
C     GAP     = Gap between plates (dimension 'A'), m
C     WIDTH   = Width of heated plates (dimension 'B'), m
C     LENGTH  = Heated length, m
C     POUT    = Exit pressure in the test, Pa
C     IFLUID  = 0 implies light water, IFLUID = 1 implies heavy water.
C     IFLOW   = 0 implies downflow, and IFLOW = 1 implies upflow.
C     LLP     = Number of iterations done to find the inlet pressure.
C     AAF     = Channel flow area, m**2
C     PPH     = Heated perimeter, m
C     QQ      = Power input per channel, W
C     TSATOUT = Saturation temperature at the exit pressure, C
C     HFOUT   = Saturated liquid enthalpy at the exit pressure, J/kg
C     WW      = Flow rate in channel, kg/s
C     IEQ     = 1, use Babelli-Ishii Eq. (1) to predict flow instability
C             = 2, use Nsub/Nzu > 1.36 for stability
C
      IEQ=1
```

```
      DELVIN=0.001
C     DELVIN = Step size for coolant inlet velocity, m/s
      IFLUID=0
      LLP=3
      GRAV=9.8
      ROUGH=0.0
      OPEN(UNIT=8,FILE='Babelli.WFtests.Input.Data',
     1 STATUS='OLD',FORM='FORMATTED')
      OPEN(UNIT=9,FILE='flow.instability.unit9',
     1 STATUS='UNKNOWN',FORM='FORMATTED')
      OPEN(UNIT=10,FILE='flow.instability.summary',
     1 STATUS='UNKNOWN',FORM='FORMATTED')
      WRITE(10,38)
      READ(8,*)
      READ(8,*)
C
C     Loop over the 75 tests of Whittle and Forgan.
C
      SUM1=0.0
      SUM2=0.0
      SUM3=0.0
   10 CONTINUE
      READ(8,8,END=9) ITEST,IFLOW,TIN,HTFLXI,GAPI,WIDTHI,
     1 LENGTHI,KORIF,POUTI,DTSUB0_DTC
      GO TO 11
    9 GO TO 45
   11 CONTINUE
      WRITE(6,8) ITEST,IFLOW,TIN,HTFLXI,GAPI,WIDTHI,
     1 LENGTHI,KORIF,POUTI,DTSUB0_DTC
    8 FORMAT(4X,I4,4X,I4,8F8.3)
      HTFLX=HTFLXI*1.0E+04
      GAP=GAPI*0.0254
      WIDTH=WIDTHI*0.0254
      LENGTH=LENGTHI*0.0254
      POUT=POUTI*1.0E+06/145.038
      AAF=GAP*WIDTH
      PPH=2.0*WIDTH
      DHH=4.0*AAF/PPH
      PPW=2.0*(WIDTH+GAP)
      DHW=4.0*AAF/PPW
C     DHH = Hydraulic diameter, based on heated perimeter
C     DHW = Hydraulic diameter, based on wetted perimeter
      QQ=HTFLX*PPH*LENGTH
      TSATOUT=ZTSAT(POUT,IFLUID)
      HFOUT=ZHLIQ(POUT,TSATOUT,IFLUID)
C     DTSUB0_DTC = Measured ratio of exit subcooling to coolant
C                  temp rise, at flow instability
      TOUT_MEAS=(TSATOUT+DTSUB0_DTC*TIN)/(DTSUB0_DTC+1.0)
      HOUT_MEAS=ZHLIQ(POUT,TOUT_MEAS,IFLUID)
      HIN=ZHLIQ(POUT,TIN,IFLUID)
      RHOIN=ZROLIQ(HIN,POUT,TIN,IFLUID)
      WW_MEAS=QQ/(HOUT_MEAS - HIN)
      VIN_MEAS=WW_MEAS/(RHOIN*AAF)
      WRITE(6,3) ITEST,DHH,DHW,LENGTH,KORIF,TIN,QQ,POUT,TSATOUT,AAF,
     1 PPH,DTSUB0_DTC,VIN_MEAS,WW_MEAS
    3 FORMAT(/,
     1 'Whittle & Forgan Test Numner                   =',I4,/,
     2 'Hydraulic diameter (heated), m                 =',F12.5,/,
     2 'Hydraulic diameter (wetted), m                 =',F12.5,/,
     3 'Channel heated length, m                       =',F12.4,/,
     4 'Total minor loss coefficient                   =',F12.4,/,
     5 'Inlet temperature, C                           =',F12.3,/,
     6 'Power removed by the channel, W                =',1P,E12.5,/,
```

```
     7 'Pressure at heated section exit, Pa            =',E12.5,0P,/,
     8 'Saturation temperature at exit, C              =',F12.3,/,
     9 'Channel flow area, m**2                        =',1P,E12.5,0P,/,
     1 'Heated perimeter, m                            =',F12.5,/,
     2 'Measured ratio of exit subcooling-to-coolant',/,
     3 'temp rise, at flow instability                 =',F12.3,/,
     4 'Measured coolant velocity at OFI, m/s          =',F12.3,/,
     5 'Measured flow rate at OFI, kg/s                =',F12.3)
C
C      Tabulate Pressure drop vs. Inlet velocity
C
       WRITE(6,6) ITEST
     6 FORMAT(/,'W&F Test',I4,': EXIT TEMPERATURE AND PRESSURE DROP AT DI
     1FFERENT INLET VELOCITIES',/)
       WRITE(6,1)
     1 FORMAT(/,T4,'Inlet',T12,'Inlet',T20,'Exit',T27,
     1 'Friction',T37,'Beta',T44,'Total Press',T57,'Friction',
     2 T68,'Orifice',T78,'Mom Change',T90,'Gravity',T101,'Reynolds',
     3 T112,'Inlet', /,
     1 T2,'Vel, m/s',T11,'Temp, C',T19,'Temp, C',T27,'Factor',
     2 T36,'per C',T46,'Drop, Pa',T57,'Drop, Pa',T68,'Drop, Pa',
     3 T79,'Drop, Pa',T90,'Drop, Pa',T102,'Number',T111,'Press, Pa')
C
       WRITE(9,41) ITEST
    41 FORMAT(/,'W&F Test',I4,': APPLICATION OF BABELLI-ISHII FLOW INSTAB
     1ILITY CRITERION',/)
       WRITE(9,44)
    44 FORMAT(/,T4,'Inlet',T13,'Exit',T20,'Tot Press',T32,
     1 'Exit Press',T46,'Peclet',T55,'Inlet Subc',T66,'Subcool',
     2 T75,'Zuber',T82,'Nsub/Nzu',T92,'RHS of',T100,'Stable?',
     3 T108,'Critical',T118,'0.0022Pe',/,
     1 T2,'Vel, m/s',T11,'Temp, C',T21,'Drop, Pa',T35,'Pa',
     2 T46,'Number',T58,'J/kg',T67,'Number',T75,'Number',T91,
     3 'Eq. (1)',T109,'Lnvg/L',T118,'or 154.0')
C
C      Loop over VIN = Inlet coolant velocity, m/s
       IFLAG=0
       II=6.0/DELVIN
       VIN_MIN=QQ/(1000.0*AAF*4186.0*(115-TIN))
       MIN=VIN_MIN/DELVIN
       VIN_MIN=MIN*DELVIN
       DO 40 I=1,II
       VIN=DELVIN*FLOAT(I)+VIN_MIN
C      Guess PIN = POUT. Find guess values of coolant properties at inlet.
    31 PIN=POUT
       DO 35 LP=1,LLP
       TSATIN=ZTSAT(PIN,IFLUID)
       HFIN=ZHLIQ(PIN,TSATIN,IFLUID)
       HIN=ZHLIQ(PIN,TIN,IFLUID)
       RHOIN=ZROLIQ(HIN,PIN,TIN,IFLUID)
       CPIN=ZCPLIQ(HIN,PIN,TIN,IFLUID)
       CONDIN=ZTHCL(HIN,PIN,TIN,IFLUID)
C      WRITE(6,*) 'TSATIN =',TSATIN,' HIN    =',HIN,'  RHOIN  =',RHOIN
C      WRITE(6,*) 'CPIN   =',CPIN,' CONDIN =',CONDIN
       WW=RHOIN*VIN*AAF
       HOUT=HIN+QQ/WW
       TOUT=ZTLIQ(POUT,HOUT,IFLUID,HFUNCL)
C      TOUT = Exit coolant temperature. Its above value is an estimate because it
C             is based on the inlet pressure PIN, not the actual exit pressure.
       RHOOUT=ZROLIQ(HOUT,POUT,TOUT,IFLUID)
C      Find pressure drop in channel using the estimate TOUT and then refine.
       TAVE=0.5*(TIN+TOUT)
       HAVE=0.5*(HIN+HOUT)
```

```
      PAVE=0.5*(PIN+POUT)
      RHOAVE=ZROLIQ(HAVE,PAVE,TAVE,IFLUID)
      VISCAVE=ZVISLIQ(HAVE,PAVE,TAVE,RHOAVE,IFLUID)
C     VISCAVE  = Kinematic viscosity at the average temperature, m**2/s
C     VISCAVE*RHOAVE = Absolute viscosity at the average temperature, Pa-s
      REAVE=WW*DHW/(VISCAVE*RHOAVE*AAF)
      FRIC=GETF(REAVE,ROUGH)
      VELHEAD=0.5*(WW/AAF)**2/RHOAVE
      VELHEADI=0.5*(WW/AAF)**2/RHOIN
C     DPFRIC  = Frictional pressure drop, Pa
C     DPORIF  = Orifice (minor) loss, Pa
C     DPTHEXP = Thermal expansion pressure drop, Pa
C     DPGRAV  = Gravitational pressure drop, Pa
C     DPMFLX  = Pressure drop due to the change in momentum flux from
C               inlet to exit [i.e., the last term of Eq. (7)], Pa
      DPORIF=KORIF*VELHEAD
      DPFRIC=FRIC*LENGTH/DHW*VELHEAD
      BETA=0.28E-4 + 9.9E-6*TAVE - 2.75E-8*TAVE**2
C     This equation for BETA was fitted to the data on p. 2.36 of Rohsenow's
C     Handbook of Heat Transfer
      IF(IFLOW .EQ. 1) THEN
C     Upflow
      DPTHEXP=-BETA*QQ/(2.0*CPIN*VIN*AAF)*GRAV*LENGTH
      DPGRAV= RHOIN*GRAV*LENGTH + DPTHEXP
      ELSE
C     Downflow
      DPTHEXP= BETA*QQ/(2.0*CPIN*VIN*AAF)*GRAV*LENGTH
      DPGRAV=-RHOIN*GRAV*LENGTH + DPTHEXP
      ENDIF
      DPMFLX=2.0*VELHEADI*(RHOIN/RHOOUT-1.0)
      DELP=DPFRIC+DPORIF+DPGRAV+DPMFLX
      PIN=POUT+DELP
      IF(LP .EQ. LLP .AND. IFLAG .NE. 1)
     1 WRITE(6,2) VIN,TIN,TOUT,FRIC,BETA,DELP,DPFRIC,
     2 DPORIF,DPMFLX,DPGRAV,REAVE,PIN
    2 FORMAT(F8.3,2F8.2,F8.4,1P,E10.2,0P,7F11.2)
   35 CONTINUE
C
C     Find Subcooling Number and Zuber Number
C     Assume: System reference pressure  P3 = Pressure at exit
C
      P3=POUT
      T3=TOUT
      H3=ZHLIQ(P3,T3,IFLUID)
      RHO3 =ZROLIQ (H3,P3,T3,IFLUID)
      VISC3=ZVISLIQ(H3,P3,T3,RHO3,IFLUID)
      CP3=ZCPLIQ(H3,P3,T3,IFLUID)
      THC3=ZTHCL(H3,P3,T3,IFLUID)
      RE3=WW*DHW/(VISC3*RHO3*AAF)
      PR3=RHO3*VISC3*CP3/THC3
      PE3=RE3 * PR3
C     Get saturated fluid properties
      TSAT3=ZTSAT(P3,IFLUID)
      HF3=ZHLIQ(P3,TSAT3,IFLUID)
      HG3=ZHVAP(P3,TSAT3,IFLUID)
      HFG3=HG3 - HF3
      RHOF3=ZROLIQ(HF3,P3,TSAT3,IFLUID)
      RHOG3=ZROVAP(HG3,P3,TSAT3,IFLUID)
C
      NSUB=(HF3 - HIN)/HFG3 *(RHOF3 - RHOG3)/RHOG3
CX    NSUB=(HFIN - HIN)/HFG3 *(RHOF3 - RHOG3)/RHOG3
      NZUB=QQ/(WW*HFG3) *(RHOF3 - RHOG3)/RHOG3
C     Use Eq. (1) of the memorandum
```

```
      PEFL=154.0
      IF(IFLOW .EQ. 1 .AND. PE3 .LT. 70000.0) PEFL=0.0022*PE3
      CRITL=CRITLNVG(NSUB)
      RATIO=CRITL+AAF/(LENGTH*2.0*WIDTH)*PEFL
      STABLE='stable'
      IF(NSUB/NZUB .LT. RATIO) STABLE='unstable'
      IF(IEQ .EQ. 2) THEN
C     Use Eq. (5) of the memorandum
      STABLE='stable'
      IF(NSUB/NZUB .LT. 1.36) STABLE='unstable'
      ENDIF
      IF(IFLAG .NE. 1)
     1 WRITE(9,42) VIN,TOUT,DELP,P3,PE3,HF3-HIN,NSUB,NZUB,
     1 NSUB/NZUB,RATIO,STABLE,CRITL,PEFL
C     WRITE(9,43) VISC3,RE3,PR3,TSAT3,HF3,HFG3,RHOF3,RHOG3,PR3,RE3
C
C     Save inlet velocity and other quantities to find Whittle and Forgan ETA
C     at the onset of flow instability.
C     IFLAG  = 0, the onset of flow instability is not found
C            = 1, the onset of flow instability is found, stable VIN
C            = 2, the onset of flow instability is found, unstable VIN
C
      IF((STABLE .EQ. 'stable' .AND. IFLAG .EQ. 0) .OR.
     1 (STABLE .EQ. 'unstable' .AND. IFLAG .EQ. 1)) THEN
      IFLAG=IFLAG+1
C     Reduce VIN to its previous value, re-run, and print results.
      IF(IFLAG .EQ. 1) VIN=VIN-DELVIN
      IF(IFLAG .EQ. 1) GO TO 31
      DELTC=TOUT-TIN
      DELTSUB0=TSATOUT-TOUT
      ETA=(DELTSUB0/DELTC)*(LENGTH/DHH)
      WRITE(9,36) ITEST,VIN,TIN,HTFLXI,LENGTH/DHH,POUTI,TOUT,
     1 DELTC/(TSATOUT-TIN),ETA,VIN_MEAS,WW_MEAS,PE3,NSUB,NZUB,NSUB/NZUB
      WRITE(10,37) ITEST,VIN,TIN,HTFLXI,LENGTH/DHH,POUTI,TOUT,
     1 DELTC/(TSATOUT-TIN),ETA,VIN_MEAS,WW_MEAS,PE3,NSUB,NZUB,NSUB/NZUB
      SUM1=SUM1+1.0
      SUM2=SUM2+VIN-VIN_MEAS
      SUM3=SUM3+(VIN-VIN_MEAS)**2
C     WRITE(10,*) SUM1,SUM2,SUM3
      ENDIF
   40 CONTINUE
      WRITE(6,12)
      WRITE(9,12)
      GO TO 10
   12 FORMAT(126('-'))
   36 FORMAT('Test',I4,': Vin =',9F8.3,F8.4,F8.0,3F8.3)
   37 FORMAT(I4,9F8.3,F8.4,F8.0,3F8.3)
   42 FORMAT(F8.3,F8.2,4F12.2,2F8.2,2F8.3,A10,F8.3,3X,F8.3)
   43 FORMAT(12X,1P,10E12.4)
   38 FORMAT(T2,'Test',T8,'Inlet',T15,'Inlet',T22,'Heat',T31,'Lh/Dhh',
     1 T40,'Exit',T47,'Exit',T55,'delTc',T64,'ETA',T70,'Measured at OFI'
     2 ,T86,'Peclet',T94,'Subcool',T103,'Zuber',T112,'Nsub',/,
     3 T3,'No.',T9,'Vel',T15,'Temp',T22,'Flux',T31,'Ratio',
     4 T40,'Press',T47,'Temp',T54,'-------',T64,'W&F',T70,'Inlet',
     5 T80,'Flow',T86,'Number',T94,'Number',T103,'Number',T112,'----',/,
     6 T9,'m/s',T16,'C',T22,'W/cm^2',T40,'psia',T48,'C',T54,'delTsat',
     7 T70,'Vel,m/s',T80,'kg/s',T112,'Nzub')
   45 CONTINUE
      VIN_ERM=SUM2/SUM1
      VIN_RMS=SQRT(SUM3/SUM1)
      VIN_ERD=SQRT(VIN_RMS**2 - VIN_ERM**2)
C     VIN_ERM = Mean error in calculated inlet coolant velocity at OFI, m/s
C     VIN_RMS = RMS value of this error, m/s
```

```
C     VIN_ERD = Standard deviation of the error, m/s
      WRITE(10,39) VIN_ERM,VIN_ERD
C     WRITE(10,*) 'SUM1, SUM2, SUM3 =',SUM1,SUM2,SUM3
  39  FORMAT(/,
     1 'Mean error in calculated inlet velocity at OFI, m/s
     2         =',F8.3,/,
     3 'Standard deviation of the error in calculated inlet velocity at
     4OFI, m/s =',F8.3)
      END
      REAL FUNCTION CRITLNVG(NSUB)
      REAL NSUB
C     CRITLNVG  = (Lnvg/L)critical at an input Subcooling number NSUB,
C                 found by interpolating an experimentally determined table
C     SUBN(N)   = Subcooling numbers in an experimentally determined table
C                 of Subcooling number versus (Lnvg/L)critical
C     CRITLUP(N)= Corresponding values of (Lnvg/L)critical, its upper bound
C                 reported by Babelli and Ishii
C     CRITLOW(N)= Corresponding values of (Lnvg/L)critical, its lower bound
C                 reported by Babelli and Ishii
C     CRITLV(N) = Corresponding values of (Lnvg/L)critical, its value adjusted
C                 to fit 75 flow instability tests of Whittle & Forgan [Ref 3]
C
      DIMENSION SUBN(12),CRITLUP(12),CRITLOW(12),CRITLV(12)
      DATA NTAB/12/
      DATA SUBN/0.0,2.69,5.38,8.07,10.76,21.51,32.27,43.03,53.78,
     1 64.54,69.92,300.0/
      DATA CRITLUP/0.0,0.0232,0.414,0.594,0.756,1.083,1.222,1.297,
     1 1.222,1.083,1.0,1.0/
      DATA CRITLOW/0.0,0.0232,0.0684,0.141,0.256,0.440,0.527,0.594,
     1 0.711,0.905,1.0,1.0/
C     The above two tables are the upper and lower bounds reported by Babelli
C     and Ishii [Fig. 4 of Ref 2, listed at the top of the program]
      DO 1 N=1,NTAB
C     CRITLV(N)=CRITLOW(N)
      CRITLV(N)=CRITLUP(N)
C     CRITLV(N)=CRITLOW(N)+0.5*(CRITLUP(N)-CRITLOW(N))
   1  CONTINUE
      DO 10 N=2,NTAB
      IF(NSUB .LE. SUBN(N)) GO TO 11
C     WRITE(6,*) NSUB,N,SUBN(N)
  10  CONTINUE
      CRITLNVG=1.0
      WRITE(6,*) 'Subr CRITLNVG: Input Subcooling number is out of range
     1. (Lnvg/L)critical was assumed to be 1.0'
      RETURN
  11  CONTINUE
C
C     Interpolate (Lnvg/L)critical from array CRITLV
C     WRITE(6,*) NSUB,N,SUBN(N-1),SUBN(N),CRITLV(N-1),CRITLV(N)
      CRITLNVG=CRITLV(N-1)+(CRITLV(N)-CRITLV(N-1))/
     1 (SUBN(N)-SUBN(N-1))*(NSUB-SUBN(N-1))
      RETURN
      END
```

## 8. PLTEMP/ANL V3.4 Code Failure in the Case of Colburn Heat Transfer Correlation

(February 2008)

PLTEMP/ANL version 3.4 fails to run in the case of Colburn heat transfer correlation because the variable VISC (i.e., the coolant viscosity at the mean of cladding surface and bulk coolant temperatures) in the routine HCOEF1 was left undefined. The variable VISC is defined in the case of all other heat transfer correlations, and the code version 3.4 runs correctly.

In the earlier versions of the code (i.e., versions 3.0, 3.1, 3.2, 3.3, 3.3.1), the variable VISC was passed to the routine HCOEF1 through the common block /A1/. The value passed was found to be incorrect, resulting in an incorrect heat transfer coefficient. Hence the common block /A1/ was discarded in the code V3.4, the variable VISC was locally defined in the heat transfer routine HCOEF, but the variable was left undefined in the case of Colburn correlation in the companion routine HCOEF1.

### 8.1. Verification of the Corrected Code

To correct the error, the variable VISC is locally defined in routine HCOEF1 using the coolant viscosity routine ZVISLIQ. The corrected code was run for a sample problem provided by Sai-Chi Mo (input file inp3). A verification of the Colburn heat transfer coefficient calculated by the corrected version 3.4 is provided below, using the data taken from the code output and debug prints for axial node 11 of fuel plate 6 right hand side. After this, for comparison purposes, the heat transfer coefficient calculation by the code version 3.0 is shown using the data taken from the code output and debug prints for the same axial node of fuel plate 6. Note that the kinematic viscosity ($46274\text{x}10^{-7}$ $m^2/s$) used to calculate the Colburn heat transfer coefficient is not correct in the code version 3.0. It should be $4.3490\text{x}10^{-7}$ $m^2/s$, i.e., the value at 65.6746 °C, the mean of cladding surface and bulk coolant temperatures (76.0920 °C and 55.2572 °C).

Both sets of data are summarized and compared in Table 1.

<u>Calculation of Heat Transfer Coefficient from the Right Surface of Fuel Plate 6 to Coolant Channel 7 in Axial Node 11, in PLTEMP/ANL Code V3.4</u>

| | |
|---|---|
| $T_m$ | = 65.3211 °C |
| P | = 101252.2 Pa |
| ν | = Kinematic Viscosity at ($T_m$ , P) = ν(65.3211 , 101252.2) = $4.3697\text{x}10^{-7}$ $m^2/s$ |
| | = Fortran Variable VISC locally defined in routine HCOEF1 |
| Pr | = $\rho\ \nu\ C_p/ K$ = 1000.0 x $4.3697\text{x}10^{-7}$ x 4180.0 / 0.66216 = 2.7584 |
| Re | = $W\ D_h/(\rho\ \nu\ A)$ = 0.91358 x $4.2708\text{x}10^{-3}$ / (1000.0 x $4.3697\text{x}10^{-7}$ x $2.4641\text{x}10^{-4}$) |
| | = 36236.5 |
| Nu | = $0.023\ Re^{0.8}\ Pr^{0.3}$ = 0.023 x $(36236.5)^{0.8}$ x $(2.7584)^{0.3}$ = 138.4337 |
| | = 138.4348 printed by code |
| h | = Nu K / $D_h$ = 138.4348 x 0.66216 / $4.2708\text{x}10^{-3}$ = 21463.4 $W/m^2$-°C |
| | = 21463.5 $W/m^2$-°C printed by code |
| $T_w$ | = $T_b + q''/h$ = 55.2198 + $0.43362\text{x}10^6$/21463.5 = 55.2198 + 20.2027 = 75.4225 °C |

Calculation of Heat Transfer Coefficient from the Right Surface of Fuel Plate 6 to Coolant Channel 7 in Axial Node 11, in PLTEMP/ANL Code V3.0

$T_m$ = 65.6746 °C
P = 101252.2 Pa
ν = Kinematic Viscosity at ($T_m$ , P) = ν(65.6746 , 101252.2) = 4.3490x$10^{-7}$ $m^2/s$
≠ Fortran Variable VISC in COMMON/A1/ = 4.6274x$10^{-7}$ $m^2/s$
Pr = $\rho\ \nu\ C_p/\ K$ = 1000.0 x 4.6274x$10^{-7}$ x 4180.0 / 0.66248 = 2.9197
Re = W $D_h/(\rho\ \nu\ A)$ = 0.91358 x 4.2708x$10^{-3}$ / (1000.0 x 4.6274x$10^{-7}$ x 2.4641x$10^{-4}$)
= 34218.5
Nu = 0.023 $Re^{0.8}\ Pr^{0.3}$ = 0.023 x $(34218.5)^{0.8}$ x $(2.9197)^{0.3}$ = 134.5050
= 134.5050 printed by code
h = Nu K / $D_h$ = 134.5050 x 0.66248 / 4.2708x$10^{-3}$ = 20864.2 W/$m^2$-°C
= 20864.4 W/$m^2$-°C printed by code
$T_w$ = $T_b + q''/h$ = 55.2572 + 0.43470x$10^6$/20864.4 = 55.2572 + 20.8345 = 76.0917 °C

**8.2. Conclusion**

Due to the error in the Colburn heat transfer coefficient calculated by the code version 3.0, the cladding wall surface temperature changes by 0.670 °C (from 75.422 °C to 76.092 °C), although the bulk coolant temperature changes by a smaller amount of 0.037 °C. The wall surface temperature change is mainly due to the change in the temperature drop from cladding wall to bulk coolant, ($T_w$ – $T_b$). The change in the temperature drop is 0.630 °C. The bulk coolant temperature changes due to the small change in the fraction of the fuel plate 6 power that is transferred to channel 7, due to the changes in heat transfer coefficient on both sides of plate 6.

**Table 1. Comparison between Versions 3.4 and 3.0 of PLTEMP/ANL Code in Calculating Colburn Heat Transfer Coefficient**

| Variable | PLTEMP/ANL Code V3.4 | PLTEMP/ANL Code V3.0 | Comments |
|---|---|---|---|
| $D_h$ , m | $4.2708 \times 10^{-3}$ | $4.2708 \times 10^{-3}$ | |
| A , $m^2$ | $2.4641 \times 10^{-4}$ | $2.4641 \times 10^{-4}$ | |
| $T_w$ , °C | 75.4224 | 76.0920 | |
| $T_b$, °C | 55.2198 | 55.2572 | |
| P , Pa | 101252.2 | 101252.2 | |
| $T_{sat}$ , °C | 99.9802 | 99.9802 | |
| $T_m$ , °C = $(T_w+T_b)/2$ | 65.3211 | 65.6746 | |
| ν , $m^2/s$<br>Variable VISC used to get Nu | $4.3697 \times 10^{-7}$<br>$4.3697 \times 10^{-7}$ | $4.3490 \times 10^{-7}$<br>$4.6274 \times 10^{-7}$ | Error in V3.0 |
| W , kg/s | 0.91358 | 0.91358 | |
| ρ , $kg/m^3$ | 1000.0 | 1000.0 | |
| $C_p$ , J/kg-°C | 4180.0 | 4180.0 | |
| K , W/m-°C | 0.66216 | 0.66248 | |
| $Pr = \rho \nu C_p / K$ | 2.7584 | 2.9197 | |
| $Re = W D_h/(\rho \nu A)$ | 36236.5 | 34218.5 | |
| $Nu = 0.023 Re^{0.8} Pr^{0.3}$ | 138.4337 | 134.5050 | |
| $h = Nu K / D_h$ , $W/m^2$-°C | 21463.4 | 20864.2 | Error in V3.0 |

## 9. Verification of the Natural Circulation Option Implemented in the PLTEMP/ANL V3.5 Code

(June 2008)

A natural circulation option was recently implemented in the PLTEMP/ANL Version 3.5 code. For the verification of this option, a natural circulation test problem was solved by hand calculation, by *Mathematica*, by the NATCON code, by the RELAP5-3D code, and by the PLTEMP/ANL code. The *Mathematica* solution was performed three times, using the sets of coolant properties used in the three codes, i.e., the NATCON code, the PLTEMP/ANL code, and the RELAP5-3D code. The hand calculation and the *Mathematica* calculations were done starting from an assumed flow rate in the coolant channel, which was manually adjusted so that the buoyancy equals the frictional pressure drop in the channel. These seven solutions are summarized in Table 1. Five of these solutions agree well with the PLTEMP/ANL solution, and this provides a verification of the natural circulation calculation of PLTEMP/ANL. The RELAP5-3D solution is found to be slightly inaccurate because the nodal coolant temperatures at node exit are used by the code as node-centered temperatures in calculating buoyancy and frictional pressure drop, as discussed in Section 9.5. That is why the RELAP5-3D-calculated flow rate is about 5% higher than the PLTEMP/ANL- calculated flow rate.

### 9.1. Introduction

The PLTEMP/ANL code [1] was improved to model coolant flow by natural circulation upward through the fuel assemblies and downward in the reactor pool. The purpose of this report is to document the solution of a natural circulation test problem that is used in the verification of this model. The test problem is defined in Section 9.2, and referred to as Sample Problem 20. Its solution by seven methods/codes are reported and compared here:
(1) hand calculation,
(2) three *Mathematica* calculations using the different sets of coolant properties used in the NATCON code, the PLTEMP/ANL code, and the RELAP5-3D code,
(3) the NATCON code [2],
(4) the RELAP5-3D code [3], and
(5) the PLTEMP/ANL Version 3.5 code.

The solutions by codes/methods other than PLTEMP/ANL were obtained for a single coolant channel, and the PLTEMP/ANL solution was obtained for a four-plate fuel assembly.

### 9.2. Hand Calculation for a Natural Circulation Test Problem

<u>Problem Definition</u>: Calculate the coolant flow rate caused by natural circulation in a 1.05 m long vertical coolant channel with a 0.75 m long heated length. The lower unheated length is 0.15 m, and the upper unheated length is 0.15 m. The heated length has a power of 25 kW distributed uniformly over the 0.75 m length, with an inlet temperature of 25 °C. The channel has a rectangular cross section of thickness 3 mm, width 0.3 m, inlet pressure loss coefficient 0.5, and exit pressure loss coefficient 1.0. The absolute pressure at the channel inlet is 5 bar, corresponding to the channel inlet being 40.81 m below the free surface of water in the pool.

The values of input variables (see nomenclature given at the end) for this problem are as follows:

$D_h$ = 0.0059406 m, g = 9.8 m/s$^2$, $H_{in}$ = 41.81 m, $K_{in}$ = 0.5,
$K_{ex}$ = 1.0, $L_1$ = 0.15 m, $L_2$ = 0.75 m, $L_3$ = 0.15 m,
L = 1.05 m, Q = 25000 W, $P_{in}$ = 5.0 bar, $T_{in}$ = 25 °C,
$T_{ch}$ = 0.003 m, $W_{ch}$ = 0.3 m, f = 96/Re
W = 0.1086 kg/s (*assumed value*)

The assumed flow rate was adjusted in the hand calculation given below so that the buoyancy induced driving pressure head is equal to the frictional pressure drop plus the momentum flux term in the channel. The steps in the hand calculation are shown below for the finally obtained flow rate which makes the buoyancy equal to the frictional pressure drop. The results of hand calculation, and their comparison with other calculations are summarized in Table 1.

Coolant Exit Temperature: For the above assumed flow rate, the exit temperature is calculated as shown by Eq. (1) below, using a coolant specific heat $C_p$ of 4188 J/kg-°C, obtained by averaging the temperature-dependent water specific heat over the coolant temperature range 25 to 80 °C that is expected in the problem.

$$T_{ex} = T_{in} + \frac{Q}{WC_p} = 25\,(^\circ C) + \frac{25000\,(J/s)}{0.1086\,(kg/s) \times 4188\,(J/kg-{}^\circ C)} = 79.967\,^\circ C \qquad (1)$$

Average Coolant Density: The coolant density difference between the cold liquid outside the channel (in the pool) and the hot liquid inside the coolant channel causes a pressure head (buoyancy) that drives the upward flow in the channel, i.e., natural circulation. The coolant density variation over the channel height is used to find the buoyancy pressure head as shown by Eq. (2) for the channel shown in Fig. 1.

$$\Delta P_{buoyancy} = \rho_1\, g\, L - \int_{z=0}^{z=L} \rho(z)\, g\, dz \qquad (2a)$$

$$\Delta P_{buoyancy} = \rho_1\, g\, (L_1 + L_h + L_3) - g\left[\rho_1 L_1 + \int_{z=L_1}^{z=L_1+L_h} \rho(z)\, dz + \rho_3 L_3\right] \qquad (2b)$$

where the symbols are defined in the nomenclature given at the end.

In Eqs. (2a) and (2b), the first term on the right hand side is the gravity head of cold liquid in the pool, and the second term is the gravity head in the heated channel. The second term is smaller than the first, and opposes the first. The difference between these terms gives the pressure head driving the natural circulation flow in the channel. Equation (2) is good irrespective of whether the power profile over the heated channel length is uniform or not. The power profile in the test problem is axially uniform, and this results in the simplification that the coolant temperature varies linearly with position over the heated length, as shown by Eq. (3). The differential of Eq. (3) is given by Eq. (4).

$$T(z) = T_{in} + (T_{ex} - T_{in}) \frac{(z - L_1)}{L_h} \qquad (3)$$

$$dT = \frac{(T_{ex} - T_{in})}{L_h} dz \qquad (4)$$

Substituting Eq. (4) into Eq. (2b), the pressure head due to buoyancy is given by Eq. (5).

$$\Delta P_{buoyancy} = g\left[(\rho_1 - \rho_{ave})\, L_h + (\rho_1 - \rho_3)\, L_3\right] \qquad (5)$$

where $\rho_{ave}$ is the coolant density averaged over temperature from the inlet temperature to the exit temperature, as shown by Eq. (6). This simplification (i.e., averaging over temperature rather than axial position z as required by Eq. (2)) is not possible for non-uniform power profile.

$$\rho_{ave} = \frac{1}{(T_{ex} - T_{in})} \int_{T=T_{in}}^{T=T_{ex}} \rho(T)\, dT \qquad (6)$$

The coolant density in the 0.15 m long unheated axial region 1 below the heated length does not vary with height. It equals the coolant density at the inlet temperature 25 °C. The coolant density in the 0.15 m long unheated axial region 3 above the heated length does not vary with height. It equals the coolant density at the exit temperature given by Eq. (1). The average coolant density over the heated length is calculated as follows, using *Mathematica*, by numerically integrating the temperature-dependent density data taken from the NATCON code. The coolant density and dynamic viscosity data used are given in Table 2.

$$\rho_{ave} = \frac{1}{(T_{ex} - T_{in})} \int_{T_{in}}^{T_{ex}} \rho(T)\, dT = \frac{1}{(79.967 - 25)} \int_{T=25}^{79.967} \rho(T)\, dT = 986.541 \text{ kg/m}^3 \qquad (7)$$

<u>Pressure Head due to Buoyancy</u>: The pressure head due to buoyancy is calculated using Eq. (5). The densities at channel inlet and exit required in this calculation are interpolated from Table 2. For the assumed flow rate of 0.1086 kg/s in the channel, the pressure head due to buoyancy is found as follows.

$\rho_1$ = coolant density at inlet = ρ(25 °C) = 996.842 kg/m$^3$

$\rho_3$ = coolant density at exit = ρ(79.967 °C) = 972.325 kg/m$^3$

$\Delta P_{buoy}$ = 9.8 [(996.842 – 986.541) x 0.75 + (996.842 – 972.325) x 0.15]
= 75.716 + 36.040
= 111.756 Pa (8)

<u>Frictional Pressure Drops in Lower and Upper Unheated Lengths</u>: The coolant in the whole lower unheated length (axial region 1) is at the inlet temperature 25 °C, and the coolant in the whole upper unheated length (axial region 3) is at the exit temperature 79.967 °C. The coolant

dynamic viscosity required in calculating the frictional pressure drop $\Delta P_{fric1}$ in axial region 1 is found by interpolating the temperature-dependent viscosity data given in Table 2 for temperature 25 °C. The viscosity required in calculating the frictional pressure drop $\Delta P_{fric3}$ in axial region 3 is found by interpolating the viscosity data for temperature 79.967 °C.

$\mu_1 = 9.0170 \times 10^{-4}$ Pa-s (9a)

$\mu_3 = 3.5606 \times 10^{-4}$ Pa-s (9b)

The Reynolds numbers in axial regions 1 and 3 are calculated as follows.

$$Re_1 = \frac{\rho_1 V_1 D_h}{\mu_1} = \frac{W D_h}{\mu_1 W_{ch} T_{ch}} = \frac{0.1086 \times 0.0059406}{9.0170 \times 10^{-4} \times 0.3 \times 0.003} = 794.98 \tag{10a}$$

$$Re_3 = \frac{W D_h}{\mu_3 W_{ch} T_{ch}} = \frac{0.1086 \times 0.0059406}{3.5606 \times 10^{-4} \times 0.3 \times 0.003} = 2013.24 \tag{10b}$$

The width-to-thickness ratio of the rectangular cross section of the coolant channel is 100 which is large enough to calculate the laminar friction factor as 96/Re. Therefore, the friction factors in axial regions 1 and 3 are calculated as follows.

$f_1 = 96/Re_1 = 96/794.98 = 0.120758$ (11a)

$f_3 = 96/Re_3 = 96/2013.24 = 0.047684$ (11b)

The frictional pressure drop $\Delta P_{fric1}$ in axial region 1 (i.e., the lower unheated length) consists of two parts: (1) the pressure drop due to the input loss coefficient $K_{in}$ of 0.5 at inlet, and (2) the pressure drop due to wall shear over the length 0.15 m, as shown below by Eq. (12).

$$\Delta P_{fric1} = \left( K_{in} + \frac{f_1 L_1}{D_h} \right) \frac{1}{2\rho_1} \left( \frac{W}{W_{ch} T_{ch}} \right)^2 \tag{12}$$

$$\Delta P_{fric1} = \left( 0.5 + \frac{0.120758 \times 0.15}{0.0059406} \right) \frac{1}{2 \times 996.842} \left( \frac{0.1086}{0.3 \times 0.003} \right)^2 = 25.920 \text{ Pa} \tag{13}$$

The frictional pressure drop $\Delta P_{fric3}$ in axial region 3 (i.e., the upper unheated length) consists of two parts: (1) the pressure drop due to the input loss coefficient $K_{ex}$ of 1.0 at exit, and (2) the pressure drop due to wall shear over the length 0.15 m, as shown below by Eq. (14).

$$\Delta P_{fric3} = \left( K_{ex} + \frac{f_3 L_3}{D_h} \right) \frac{1}{2\rho_3} \left( \frac{W}{W_{ch} T_{ch}} \right)^2 \tag{14}$$

$$\Delta P_{fric3} = \left(1.0 + \frac{0.047684 \times 0.15}{0.0059406}\right)\frac{1}{2 \times 972.325}\left(\frac{0.1086}{0.3 \times 0.003}\right)^2 = 16.502 \text{ Pa} \quad (15)$$

Frictional Pressure Drop in Heated Section: The pressure drop $\Delta P_{fric2}$ over the heated section (axial region 2) of length 0.75 m is calculated by dividing this length into 5 equal sub-sections (each 0.15 m long) to account for the temperature dependence of coolant viscosity. These sub-sections are numbered i = 1 to 5, starting from the lower end of the heated section. As pointed out above, the coolant temperature rises linearly with axial position in the heated length, and therefore, the average coolant temperature $T_{2i}$ in the $i^{th}$ sub-section is calculated as follows.

$$T_{2i} = T_{in} + (T_{ex} - T_{in})(i - 0.5) / 5 \text{ , } i = 1, 2, 3, 4, 5 \quad (16a)$$

$$T_{2i} = 30.497, 41.490, 52.484, 63.477, 74.470 \text{ °C} \quad (16b)$$

In each of these 5 parts, the coolant density and dynamic viscosity are interpolated from Table 2. The Reynolds number, friction factor, and frictional pressure drop are calculated using formulas like Eqs. (10), (11) and (12) in *Mathematica*. The results are summarized below and in Table 1.

**Frictional Pressure Drop Calculation in the Heated Section Using Five Sub-sections**

| Heated Sub-section Number | Coolant Temperature °C | Length m | Dynamic Viscosity Pa-s | Reynolds Number | Friction Factor | Density kg/m$^3$ | Frictional Pressure Drop, Pa |
|---|---|---|---|---|---|---|---|
| Symbol → | $T_{2i}$ | $L_{2i}$ | $\mu_{2i}$ | $Re_{2i}$ | $f_{2i}$ | $\rho_{2i}$ | $\Delta P_{fric2i}$ |
| 1 | 30.497 | 0.15 | 7.9546x10$^{-4}$ | 901.154 | 0.10653 | 995.48 | 19.672 |
| 2 | 41.490 | 0.15 | 6.3381x10$^{-4}$ | 1130.99 | 0.084882 | 992.01 | 15.729 |
| 3 | 52.484 | 0.15 | 5.2097x10$^{-4}$ | 1375.95 | 0.069770 | 987.52 | 12.988 |
| 4 | 63.477 | 0.15 | 4.3925x10$^{-4}$ | 1631.95 | 0.058825 | 982.12 | 11.010 |
| 5 | 74.470 | 0.15 | 3.7934x10$^{-4}$ | 1889.70 | 0.050802 | 975.76 | 9.571 |
| **Total** | | **0.75** | | | | | **68.970** |

The pressure drop $\Delta P_{fric2}$ over the heated section of length 0.75 m is found to be 68.970 Pa.

$$\Delta P_{fric2} = \Delta P_{fric21} + \Delta P_{fric22} + \Delta P_{fric23} + \Delta P_{fric24} + \Delta P_{fric25} = 68.970 \text{ Pa} \quad (17)$$

Pressure Drop due to Momentum Flux: The pressure drop due to momentum flux from the channel inlet to the exit is given by

$$\Delta P_{mom} = \rho_1 V_1^2 \left(\frac{\rho_1}{\rho_3} - 1\right) \quad (18)$$

$$V_1 = \frac{W}{\rho_1 \; W_{ch} \; T_{ch}} = \frac{0.1086}{996.842 \times 0.3 \times 0.003} = 0.12105 \text{ m/s}$$

$$\Delta P_{mon} = 996.842 \text{ x } (0.12105)^2 \text{ x } (996.842/972.325 - 1) = 0.3683 \text{ Pa} \quad (19)$$

Total Frictional Pressure Drop: The total frictional pressure drop in the channel, including the small pressure drop due to momentum flux, is found by adding Eqs. (13), (15), (17), and (19).

$$\Delta P_{fric} = \Delta P_{fric1} + \Delta P_{fric2} + \Delta P_{fric3} + \Delta P_{mom} \tag{20}$$

$$\Delta P_{fric} = 25.920 + 16.502 + 68.970 + 0.3683$$
$$= 111.760 \text{ Pa} \tag{21}$$

### 9.3. Frictional Pressure Drop Calculation in the Heated Section Without Dividing it into Sub-sections

In Section 9.2, the heated section was divided into 5 sub-sections for calculating the frictional pressure drop, to account for the temperature dependence of water viscosity and density. In the current section, the frictional pressure drop in the heated section is calculated without dividing it into sub-sections, using a single set of water properties, i.e., viscosity and density at the mean of inlet and exit coolant temperatures. This calculation is done at the natural circulation flow rate of 0.1086 kg/s found in Section 9.2 because the purpose here is to get an estimate of the error in the frictional pressure drop if it is calculated using a single set of water properties. The results are summarized below. The subscript *2m* implies mean value for the whole heated length.

| | |
|---|---|
| Coolant flow rate in channel, W | = 0.1086 kg/s |
| Coolant exit temperature, $T_{ex}$ | = 79.967 °C |
| Coolant mean temperature, $T_{2m} = (T_{in} + T_{ex})/2$ | = 52.484 °C |
| Heated length, $L_2$ | = 0.75 m |
| Dynamic viscosity at the mean temperature, $\mu_{2m}$ | = 5.2097x10$^{-4}$ Pa-s |
| Coolant density at the mean temperature, $\rho_{2m}$ | = 987.53 kg/m$^3$ |
| Reynolds number at the mean temperature, $Re_{2m} = W D_h/(\mu_{2m} W_{ch} T_{ch})$ | = 1375.95 |
| Friction factor, $f_{2m} = 96/Re_{2m}$ | = 0.069770 |
| Frictional pressure drop, $\Delta P_{fric2} = 0.5 (f_{2m} L_2/D_h) [W/(W_{ch} T_{ch})]^2$ | = 64.938 Pa |

The frictional drop in the heated section, based on this approximate calculation, is 64.938 Pa compared to 68.970 Pa calculated more accurately by dividing the heated section into five sub-sections (in Section 9.2). There is an error of 5.8 % in the approximate calculation. These results are useful for comparison with PLTEMP/ANL output because the *forced flow option* in the code is currently coded to use a single set of coolant properties in calculating the frictional pressure drop in the heated section.

### 9.4. *Mathematica* Calculations Using Three Sets of Coolant Properties

The codes NATCON, RELAP5-3D, and PLTEMP/ANL have different built-in coolant properties. To account for the effect of the difference in coolant properties, solutions to the test problem were obtained by *Mathematica* calculations, using the coolant properties built in each code. A *Mathematica* program was written in which any set of coolant properties could be inserted. Appendix F gives a listing of this program with the coolant properties of the PLTEMP/ANL code.

The program uses 21 axial nodes (mesh intervals) of equal length in the total channel length of 1.05 m, with three each in the lower and upper unheated lengths of the channel, and 15 in the heated length. Starting from a guess flow rate, the program calculates the coolant enthalpy at each node exit, the coolant temperature at the node exit, and the temperature at the node-center. Using the node-center temperatures, the program finds the nodal Reynolds number, friction factor, nodal frictional pressure drop, and the nodal contribution to buoyancy. It finds the inlet and outlet pressure losses. The calculation ends after printing the total buoyancy and the total frictional pressure drop in the channel. It runs so fast that several guess flow rates could tried in a few minutes. To find the steady-state natural circulation flow rate, the user reruns the program several times, each time using a more improved guess of the flow rate, in order to make the total buoyancy equal to the total frictional pressure drop.

The *Mathematica* program uses coolant enthalpy as a function of temperature, as shown by the program listing in Appendix F. However, the NATCON code uses built-in coolant specific heat (rather than enthalpy), as shown in Table 2. When using the coolant properties of the NATCON code, some additional statements were added to the program to find the corresponding enthalpy by integrating the specific heat.

Using this program, three solutions to Sample Problem 20 were obtained, using the coolant properties of (1) the NATCON code, (2) the RELAP5-3D code, and (3) the PLTEMP/ANL code. These solutions are given in Tables 3, 4, and 5. It is noted that the flow rate of 0.1114 kg/s per channel, calculated using the coolant properties of RELAP5-3D, is 2.4 % higher than the flow rate based on the coolant properties of NATCON and PLTEMP/ANL. The three *Mathematica* calculations are summarized in Table 1.

### 9.5. NATCON Code Calculation

Table 6 shows the input data used in the NATCON calculation[3]. As the input data shows, the heated length was divided into 20 axial mesh intervals (or nodes). The code computes the coolant temperature, density, viscosity, Reynolds number, friction factor, buoyancy head, and frictional pressure drop for each axial node, for a guessed value of channel flow rate. The code finds the total buoyancy head and frictional pressure drop, and then adjusts the channel flow rate to make the total buoyancy head equal to the total frictional pressure drop. The momentum flux term is ignored in the code because it is small. The results obtained are summarized in Table 1.

### 9.6. RELAP5-3D Code Calculation

This calculation was performed by Feldman (see Appendix G) using the RELAP5-3D code which uses liquid water properties from the 1967 ASME Steam Tables. The channel length of 1.05 m was divided into 21 axial nodes (mesh intervals) of equal length, with three each in the lower and upper unheated lengths of the channel, and 15 in the heated length. The natural circulation test problem (Sample Problem 20) was solved by running a thermal-hydraulic transient model of a single coolant channel for a long enough time to reach a steady-state, using a fixed channel inlet pressure of 5.0 bar and a fixed channel exit pressure of 4.897305 bar. This input exit pressure is equal to the inlet pressure minus the gravity head of water at the pool temperature of 25 °C.

Input Pressure at Channel Exit = 500000 Pa - 997.340 kg/m$^3$ × 1.05 m × 9.80655 m/s$^2$
= 4.897305 bar

Here, the value 997.340 kg/m$^3$ is the coolant density at the pool temperature of 25 °C, and 9.80655 m/s$^2$ is the acceleration due to gravity used in the RELAP5-3D calculation.

The code finds a steady-state natural circulation flow rate of 0.11409 kg/s per channel and an exit temperature of 77.437 °C but there is a discrepancy in these results. The discrepancy is that the code computes nodal coolant temperatures at the node exit, but uses these nodal temperatures as node-centered values in computing nodal gravity head, nodal buoyancy and nodal frictional pressure drop, as discussed below. The printed solution of the code is shown in Table 7, with two analyses of the solution for the purpose of pointing out the discrepancy. The analyses were done by transferring the code-printed results to a Microsoft Spreadsheet.

<u>RELAP5-3D-Printed Results</u>: Column 2 of Table 7 shows the code-printed nodal pressures, $P_n$ . The pressure differences, $P_{n-1}$-$P_n$ , are shown in column 6. The difference for the first node, $P_0$-$P_1$ , is found to be 253.0 Pa, about half of the difference for other nodes (1 through 21). Based on this observation, the nodal pressures are inferred to be node-centered values. Column 3 of Table 7 shows the code-printed nodal coolant temperatures. The temperature for node 18, i.e., the last node in the heated length of the channel, is 350.589 K, equal to the nodal temperature of the nodes 19, 20 and 21 in the unheated length of the channel. If the temperature for node 18 were *node-centered*, it would be less than the nodal temperatures in the unheated length. Based on this observation, the nodal temperatures are inferred to be *node-exit* values. Based on similar observations in columns 4 and 5 of Table 7, the nodal Reynolds numbers and coolant densities are inferred to be *node-exit* values.

<u>Analyses of Printed Results</u>: Table 7 shows two analyses done on a Microsoft Spreadsheet to calculate the gravity head, the buoyancy and the frictional pressure drop due to each node, using the code-printed nodal densities, $\rho_n$ , and Reynolds numbers, $Re_n$ . The first analysis (shown in columns 7 to 9) was done by treating the code-printed nodal densities and Reynolds numbers to be node-exit values, as they actually are. The second analysis (shown in columns 10 to 12) was done treating the code-printed nodal densities and Reynolds numbers to be node-centered values. In each analysis, the channel gravity head and the channel buoyancy were found by summing the nodal values. The channel frictional pressure drop was determined by two techniques in each analysis: (i) Technique 1: The channel frictional pressure drop equals the sum of the nodal frictional pressure drops, and the inlet and outlet losses; (ii) Technique 2: The channel frictional pressure drop equals the RELAP5-3D-printed pressure difference between the channel inlet and outlet minus the channel gravity head. This is based on that the pressure difference between any pair of axial positions is the sum of the gravity head and the frictional pressure drop between the two positions. The nodal equations used in the two analyses are given below.

<u>Equations Used on Spreadsheet in the First Analysis</u>:
Gravity head of node n $= 0.5(\rho_{n-1}+\rho_n)\ g\ \Delta z_n$
Buoyancy due to node n $= \{\rho_1 - 0.5(\rho_{n-1}+\rho_n)\}\ g\ \Delta z_n$

Frictional pressure drop over node n = $\dfrac{96\,\Delta z_n}{0.5\,(Re_{n-1}+Re_n)\,D_h}\dfrac{1}{(\rho_{n-1}+\rho_n)}\left(\dfrac{W}{W_{ch}T_{ch}}\right)^2$

<u>Equations Used on Spreadsheet in the Second Analysis</u>:
Gravity head of node n = $\rho_n\, g\, \Delta z_n$
Buoyancy due to node n = $(\rho_1 - \rho_n)\, g\, \Delta z_n$
Frictional pressure drop over node n = $\dfrac{96\,\Delta z_n}{Re_n\, D_h}\dfrac{1}{2\rho_n}\left(\dfrac{W}{W_{ch}T_{ch}}\right)^2$

The channel buoyancy is found to be 111.936 Pa by the first analysis, and 117.797 Pa by the second analysis, as noted in Table 7. There is a difference of 5.2 % between the two values. The channel frictional pressure drop is found by technique 1 to be 118.590 Pa in the first analysis, and 116.420 Pa in the second analysis. To determine the channel frictional pressure drop by technique 2, the RELAP5-3D-printed pressure difference between the channel inlet and outlet is 10269.0 Pa as shown in column 6 of Table 7. The frictional pressure drop equals this pressure difference minus the gravity head of 10157.657 Pa in the first analysis, or of 10151.795 Pa in the second analysis, as given below.

Technique 2 in the First Analysis:
Channel Frictional Pressure Drop = 10269.0 – 10157.657 =111.343 Pa

Technique 2 in the Second Analysis:
Channel Frictional Pressure Drop = 10269.0 – 10151.795 =117.205 Pa

The values of channel buoyancy and channel frictional pressure drop obtained by the two analyses for Sample Problem 20 are given in Table 7, and also summarized below.

| Technique Used | First Analysis | | Second Analysis | |
|---|---|---|---|---|
| | Channel Buoyancy, Pa | Channel Frictional Pressure Drop, Pa | Channel Buoyancy, Pa | Channel Frictional Pressure Drop, Pa |
| Technique 1 | 111.936 | 118.590 | 117.797 | 116.420 |
| Technique 2 | | 111.343 | | 117.205 |

In the first analysis, there are two discrepancies: (i) The channel buoyancy (111.936 Pa) and the channel frictional pressure drop (118.590 Pa) are not equal as they should be in the steady-state natural circulation. (ii) The two techniques give different values of the channel frictional pressure drop, 118.590 Pa and 111.343 Pa. Hence it is inferred that RELAP5-3D does not use the assumption of the first analysis to calculate the buoyancy and the frictional pressure drop.

In the second analysis, the values of channel frictional pressure drop (116.420 and 117.205 Pa) found by the two techniques are nearly equal. The channel buoyancy (117.797 Pa) and the channel frictional pressure drop (117.205 Pa) are nearly equal as they should be in the steady-state natural circulation. Hence it is inferred that RELAP5-3D uses the assumption of the second analysis to calculate the buoyancy and the frictional pressure drop, i.e., *it treats the node-exit* *densities and Reynolds numbers as node-center values.* This assumption artificially increases the channel buoyancy which causes a higher flow rate.

Concluding Remarks: Using the node-exit densities and Re as node-centered values makes the RELAP5-3D solution slightly inaccurate. The RELAP5-3D solution can be used for only an approximate verification (within 6 %) of the PLTEMP/ANL V3.5 natural circulation calculation. The buoyancy and the frictional pressure drop obtained in the second analysis are shown in Table 1 because they are preferred over those obtained in the first analysis.

### 9.7. PLTEMP/ANL Version 3.5 Code Calculation

To solve Sample Problem 20 using the PLTEMP/ANL code, the problem defined above in Section 9.2 is turned into a problem for a research reactor fuel assembly consisting of (arbitrarily) four plates cooled by five coolant channels. Each fuel plate produces 25 kW as defined in Section 9.2, and the fuel assembly has a power of 100 kW. The internal channels (channels 2, 3, and 4) are of the thickness 3 mm as defined in Section 9.2. In order to have identical axial profiles of coolant temperature in each channel, the first and the last channels are of half thickness, i.e., 1.5 mm. Based on symmetry, it is noted that exactly half of each fuel plate's power goes to each coolant channel adjacent to the plate. Table 8 gives the input data used in the PLTEMP/ANL code. It is noted that there are two identical fuel assemblies in the PLTEMP/ANL problem, and hence the total power in the input data is 0.2 MW.

In the input data of Table 8, the friction factor is obtained using the code's built-in correlation which accounts for laminar, transition, or turbulent flow as the case may be. This input data produces the results shown in the last column (column 9) of Table 1. The flow is found to remain always laminar in this problem, and the friction factor is given by C/Re where C is 94.7174 based on the thickness-to-width ratio of the coolant channel.

To do a fair comparison, another PLTEMP/ANL calculation was done using the friction factor (i.e., f = 96/Re) that was used in all the other calculations shown in Table 1. The results of the PLTEMP/ANL calculation using the friction factor of 96/Re are shown in column 8 of Table 1. This calculation agrees well with the *Mathematica* solution obtained using the coolant properties of PLTEMP/ANL given in column 4 of Table 1. This comparison provides a verification of the natural circulation option of the PLTEMP/ANL Version 3.5 code.

### 9.8. Conclusion

There is a good agreement among the following four solutions of Sample Problem 20, as shown in Table 1: (1) hand calculation, (2) *Mathematica* solution using the coolant properties of the NATCON code, (3) *Mathematica* solution using the coolant properties of the PLTEMP/ANL code, and (4) NATCON code solution. The natural circulation flow rate is 0.1088 kg/s and the channel frictional pressure drop is 111.8 Pa. These values are accurately equal to the flow rate and channel frictional pressure drop calculated by the PLTEMP/ANL Version 3.5 code using the frictional factor 96/Re. This provides a verification of the recently implemented natural circulation calculation capability of PLTEMP/ANL.

The RELAP5-3D solution is found to be slightly inaccurate because the coolant temperatures at each node exit are used by the code as node-centered temperatures in calculating buoyancy and frictional pressure drop, as discussed in Section 9.5. That is why the RELAP5-3D-calculated flow rate is about 5% higher than the PLTEMP/ANL-calculated flow rate.

The only difference between the two solutions by PLTEMP/ANL (given in the last two columns of Table 1) is in the value of the constant C in the laminar friction factor C/Re. The solution in the last column of Table 1 uses C = 94.7174 (instead of 96 for parallel plates) based on the aspect ratio of the rectangular cross section of the coolant channel. This causes a difference of 0.5 % in the flow rate.

**NOMENCLATURE**

| | |
|---|---|
| $\Delta P_{buoy}$ | Pressure head due to buoyancy, Pa |
| $\Delta P_{fric}$ | Total frictional pressure drop in the coolant channel, Pa |
| $C_p$ | Coolant specific heat averaged over the temperature range 25 to 80 °C existing in the problem, J/kg-°C |
| $D_h$ | Hydraulic diameter of the channel, m |
| g | Acceleration due to gravity, m/s$^2$ |
| $H_{in}$ | Water depth at the channel inlet, m |
| $L_1$ | Unheated channel length below the heated section, m |
| $L_2$ | Heated length of channel, m |
| $L_3$ | Unheated channel length above the heated section, m |
| L | Channel height = $L_1 + L_2 + L_3$ , m |
| $K_{in}$ | Pressure loss coefficient at the channel inlet |
| $K_{ex}$ | Pressure loss coefficient at the channel exit |
| $P_{in}$ | Pressure at the channel inlet, Pa |
| Q | Power in the channel, W |
| $V_1$ | Coolant velocity at channel inlet, m/s |
| $V_3$ | Coolant velocity at channel exit, m/s |
| T | Coolant temperature at an axial location, °C |
| $T_{in}$ | Coolant temperature at the channel inlet, °C |
| $T_{ex}$ | Coolant temperature at the channel exit, °C |
| $T_{ch}$ | Channel thickness, m |
| W | Coolant flow rate in the channel, kg/s |
| $W_{ch}$ | Channel width, m |
| z | Axial position, m |
| $\rho(z)$ | Coolant density at position z, kg/m$^3$ |
| $\rho(T)$ | Coolant density as a function of temperature T, kg/m$^3$ |
| $\rho_1$ | Coolant density at the channel inlet temperature, kg/m$^3$ |
| $\rho_{ave}$ | Coolant density averaged over the heated length of the channel, kg/m$^3$ |
| $\rho_3$ | Coolant density at the channel exit temperature, kg/m$^3$ |
| $\mu(T)$ | Coolant dynamic viscosity as a function of temperature T, Pa-s |
| $\mu_1$ | Coolant dynamic viscosity at channel inlet, Pa-s |
| $\mu_3$ | Coolant dynamic viscosity at channel exit, Pa-s |

## REFERENCES

[1] Arne P. Olson and M. Kalimullah, Argonne National Laboratory, unpublished, February 20, 2008.

[2] R. S. Smith and W. L. Woodruff, "A Computer Code, Natcon, for the Analyses of Steady-State Thermal-Hydraulics and Safety Margins in Plate-Type Research Reactors Cooled by Natural Convection," ANL/RERTR/TM-12, Argonne National Laboratory, December 1988.

[3] The RELAP5-3D© Code Development Team, RELAP5-3D© Code Manual, Version 2.3, INEEL-EXT-98-00834, Idaho National Laboratory, April 2005.

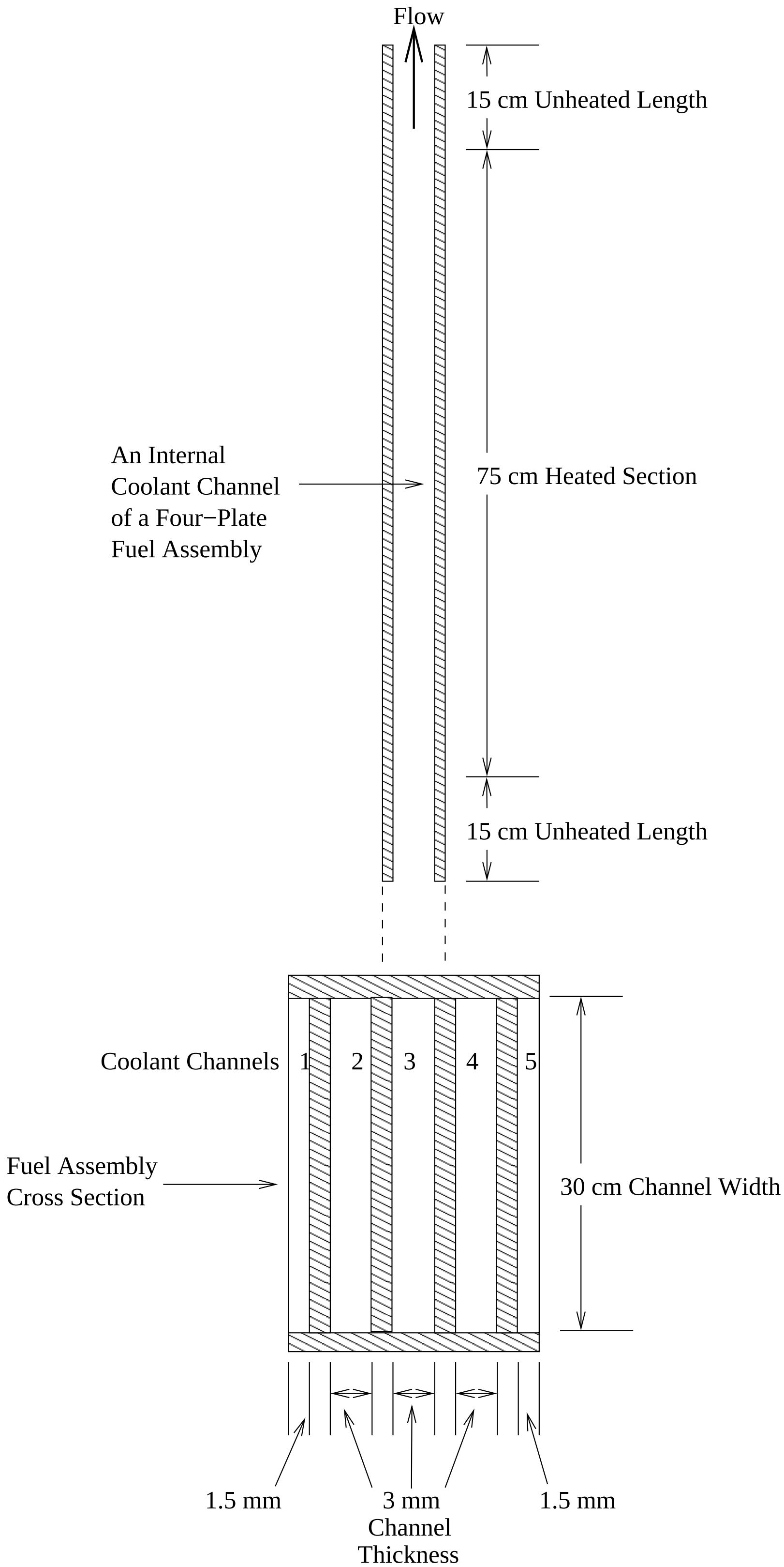


**Fig. 1. Geometry of a Coolant Channel in a Four-Plate Fuel Assembly Used in Sample Problem 20**

**Table 1. Solution of Sample Problem 20 by Different Codes Used to Verify the Natural Circulation Option of PLTEMP/ANL Version 3.5**

| Input or Calculated Quantity | Hand Calculation Using NATCON Properties | *Mathematica* Calculation | | | NATCON Code Solution | RELAP5 Code Solution | PLTEMP/ANL V3.5 Solution | |
|---|---|---|---|---|---|---|---|---|
| | | Using NATCON Coolant Properties | Using PLTEMP Coolant Properties | Using RELAP5 Coolant Properties | | | General Method, Friction Factor = 96/Re | General Method, Friction Factor = 94.7174/Re |
| Inlet Temp, °C | 25 | 25 | 25 | 25 | 25 | 25 | 25 | 25 |
| Power per Channel, W | 25000 | 25000 | 25000 | 25000 | 25000 | 25000 | 25000 | 25000 |
| Loss Coeff. at Inlet | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| Loss Coeff. at Exit | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| **CALCULATED QUANTITIES** | | | | | | | | |
| Flow per Channel, kg/s | 0.1086 | 0.1088 | 0.1088 | 0.1114 | 0.1087 | 0.1141 | 0.1088 | 0.1093 |
| Exit Temp, °C | 79.967 | 79.900 | 79.891 | 78.660 | 79.970 | 77.44 | 79.891 | 79.646 |
| **BUOYANCY $\Delta P_{buoy}$ , Pa** | | | | | | | | |
| Axial Region 1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.005 | 0.0 | 0.0 |
| Axial Region 2 (Heated Section) | 75.716 | 75.761 | 75.793 | 78.965 | 75.783 | 82.620 | 75.786 | 75.342 |
| Axial Region 3 | 36.040 | 36.001 | 36.009 | 36.272 | 36.034 | 35.172 | 36.015 | 35.785 |
| Channel $\Delta P_{buoy}$ | 111.756 | 111.762 | 111.802 | 115.237 | 111.817 | 117.797 | 111.801 | 111.127 |
| **FRICTIONAL PRESSURE DROP $\Delta P_{fric}$ , Pa** | | | | | | | | |
| Inlet Loss | 3.652 | 3.664 | 3.667 | 3.840 | 3.659 | 4.028 | 3.667 | 3.700 |
| Axial Region 1 | 22.268 | 22.307 | 22.300 | 22.542 | 22.348 | 23.084 | 22.300 | 22.101 |
| Axial Region 2 (Heated Length) | 68.970 | 69.239 | 69.276 | 71.619 | 69.275 | 71.417 | 69.275 | 68.758 |
| Axial Region 3 | 9.015 | 9.037 | 9.041 | 9.360 | 9.033 | 9.637 | 9.042 | 8.894 |
| Exit Loss | 7.487 | 7.513 | 7.518 | 7.875 | 7.503 | 8.254 | 7.518 | 7.585 |
| Momentum Flux Term | 0.368 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Channel $\Delta P_{fric}$ | 111.760 | 111.761 | 111.802 | 115.236 | 111.817 | 116.420 | 111.803 | 111.126 |

Note 1. Laminar friction factor = 96/Re, except as noted in the last column.
Note 2. The RELAP5-3D solution is not accurate because the nodal coolant temperatures at node exit are used as node-centered temperatures in calculating buoyancy and frictional pressure drop (as discussed in Section 9.5).

**Table 2. Water Properties Used in the NATCON Code, RELAP5-3D Code, and PLTEMP/ANL Code**

| Water Properties Used in NATCON Code and Hand Calculation | | | | Water Properties Used in in RELAP5-3D Code at 5.0 bar | | | | Water Properties Used in in PLTEMP/ANL Code at 5.0 bar | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Temp °C | Specific Heat kJ/kg-°C | Water Density kg/m$^3$ | Dynamic Viscosity µ Pa-s | Temp °C | Enthalpy kJ/kg | Water Density kg/m$^3$ | Dynamic Viscosity µ Pa-s | Temp °C | Enthalpy kJ/kg | Water Density kg/m$^3$ | Dynamic Viscosity µ Pa-s |
| 21.718 | 4.165 | 997.54 | 974 | 20 | 84.33 | 998.505 | 1001.8 | 20 | 83.952 | 997.988 | 1014.5 |
| 27.301 | 4.168 | 996.30 | 855 | 25 | 105.23 | 997.339 | 890.3 | 25 | 104.773 | 996.982 | 901.17 |
| 32.879 | 4.171 | 994.81 | 755 | 30 | 126.12 | 995.930 | 797.6 | 30 | 125.608 | 995.759 | 804.50 |
| 38.450 | 4.175 | 993.08 | 673 | 35 | 147.00 | 994.300 | 719.6 | 35 | 146.457 | 994.321 | 722.29 |
| 44.022 | 4.179 | 991.06 | 604 | 40 | 167.89 | 992.466 | 653.3 | 40 | 167.327 | 992.672 | 652.48 |
| 49.583 | 4.183 | 988.79 | 547 | 45 | 188.78 | 990.443 | 596.4 | 45 | 188.211 | 990.815 | 593.26 |
| 55.144 | 4.187 | 986.30 | 499 | 50 | 209.68 | 988.244 | 547.1 | 50 | 209.116 | 988.754 | 542.91 |
| 60.694 | 4.192 | 983.57 | 458 | 55 | 230.58 | 985.879 | 504.2 | 55 | 230.034 | 986.495 | 499.92 |
| 66.239 | 4.196 | 980.62 | 422 | 60 | 251.49 | 983.357 | 466.6 | 60 | 250.973 | 984.042 | 462.93 |
| 71.778 | 4.201 | 977.39 | 392 | 65 | 272.42 | 980.685 | 433.5 | 65 | 271.934 | 981.403 | 430.75 |
| 77.311 | 4.206 | 974.00 | 367 | 70 | 293.36 | 977.871 | 404.1 | 70 | 292.915 | 978.583 | 401.28 |
| 82.839 | 4.212 | 970.46 | 345 | 75 | 314.31 | 974.922 | 377.9 | 75 | 313.923 | 975.590 | 377.03 |
| 88.356 | 4.217 | 966.66 | 326 | 80 | 335.28 | 971.843 | 354.5 | 80 | 334.946 | 972.432 | 355.98 |
| 93.867 | 4.223 | 962.76 | 309 | 85 | 356.26 | 968.638 | 333.4 | 85 | 356.003 | 969.117 | 337.40 |
| 99.370 | 4.230 | 958.67 | 292 | 90 | 377.27 | 965.313 | 314.5 | 90 | 377.075 | 965.655 | 320.63 |
| 104.867 | 4.236 | 954.44 | 277 | 95 | 398.30 | 961.871 | 297.3 | 95 | 398.181 | 962.055 | 304.97 |
| 110.356 | 4.244 | 950.09 | 263 | 100 | 419.36 | 958.315 | 281.8 | 100 | 419.314 | 958.326 | 290.21 |
| 115.828 | 4.251 | 945.66 | 250 | 105 | 440.45 | 954.647 | 267.6 | 105 | 440.476 | 954.482 | 276.41 |
| 121.294 | 4.259 | 941.16 | 238 | 110 | 461.57 | 950.869 | 254.7 | 110 | 461.672 | 950.532 | 263.52 |
| 127.190 | 4.268 | 936.20 | 226 | 115 | 482.73 | 946.983 | 242.9 | 115 | 482.896 | 946.490 | 251.49 |
| 132.340 | 4.276 | 931.85 | 216 | 120 | 503.93 | 942.990 | 232.0 | 120 | 504.162 | 942.367 | 240.27 |
| | | | | 125 | 525.17 | 938.890 | 222.1 | 125 | 525.455 | 938.181 | 229.83 |
| | | | | 130 | 546.46 | 934.684 | 212.9 | 130 | 546.797 | 933.940 | 220.10 |

**Table 3. *Mathematica* Solution of Standard Problem 20, Using Coolant Properties of NATCON Code**

Flow rate per coolant channel = 0.108788 kg/s

| Node | Nodal Power W | Temp at Node Exit °C | Temp at Node Center, °C | Density at Node Center kg/m$^3$ | Buoyancy due to Node, Pa | Re at Node Center | Friction Factor at Node Center | Frictional Pressure Drop, Pa |
|---|---|---|---|---|---|---|---|---|
| Inlet | | | | 996,842 | | | | 3.6643 |
| 1 | 0 | 25. | 25. | 996.842 | 0. | 796.356 | 0.120549 | 7.43576 |
| 2 | 0 | 25. | 25. | 996.842 | 0. | 796.356 | 0.120549 | 7.43576 |
| 3 | 0 | 25. | 25. | 996.842 | 0. | 796.356 | 0.120549 | 7.43576 |
| 4 | 1666.67 | 28.676 | 26.838 | 996.413 | 0.210597 | 830.971 | 0.115527 | 7.12908 |
| 5 | 1666.67 | 32.3502 | 30.5131 | 995.472 | 0.671721 | 903.04 | 0.106308 | 6.56633 |
| 6 | 1666.67 | 36.0223 | 34.1862 | 994.428 | 1.1839 | 977.855 | 0.0981741 | 6.07031 |
| 7 | 1666.67 | 39.6923 | 37.8573 | 993.277 | 1.74805 | 1054.41 | 0.0910465 | 5.63612 |
| 8 | 1666.67 | 43.3599 | 41.5261 | 991.998 | 2.37497 | 1133.73 | 0.0846761 | 5.24852 |
| 9 | 1666.67 | 47.0252 | 45.1925 | 990.602 | 3.05961 | 1214.78 | 0.0790267 | 4.90526 |
| 10 | 1666.67 | 50.6882 | 48.8567 | 989.1 | 3.7963 | 1296.46 | 0.074048 | 4.60321 |
| 11 | 1666.67 | 54.3488 | 52.5185 | 987.505 | 4.57842 | 1379.1 | 0.0696094 | 4.33427 |
| 12 | 1666.67 | 58.0069 | 56.1779 | 985.809 | 5.40968 | 1462.77 | 0.0656287 | 4.09344 |
| 13 | 1666.67 | 61.6624 | 59.8347 | 984.008 | 6.29302 | 1547.65 | 0.0620294 | 3.87602 |
| 14 | 1666.67 | 65.3153 | 63.4888 | 982.115 | 7.22126 | 1635.06 | 0.0587134 | 3.67589 |
| 15 | 1666.67 | 68.9656 | 67.1405 | 980.11 | 8.20403 | 1723.08 | 0.0557142 | 3.49525 |
| 16 | 1666.67 | 72.6133 | 70.7895 | 977.982 | 9.24774 | 1808.92 | 0.0530702 | 3.33663 |
| 17 | 1666.67 | 76.2581 | 74.4357 | 975.781 | 10.3267 | 1892.18 | 0.0507351 | 3.197 |
| 18 | 1666.67 | 79.8997 | 78.0789 | 973.52 | 11.4355 | 1973.99 | 0.0486324 | 3.07162 |
| 19 | 0 | 79.8997 | 79.8997 | 972.368 | 12.0003 | 2015.2 | 0.0476379 | 3.01238 |
| 20 | 0 | 79.8997 | 79.8997 | 972.368 | 12.0003 | 2015.2 | 0.0476379 | 3.01238 |
| 21 | 0 | 79.8997 | 79.8997 | 972.368 | 12.0003 | 2015.2 | 0.0476379 | 3.01238 |
| Outlet | | | | | | | | 7.5131 |
| Total | | | | | 111.762 | | | 111.761 |

**Table 4. *Mathematica* Solution of Standard Problem 20, Using Coolant Properties of PLTEMP/ANL Code**

Flow rate per coolant channel = 0.108838 kg/s

| Node | Nodal Power W | Temp at Node Exit °C | Temp at Node Center, °C | Density at Node Center kg/m$^3$ | Buoyancy due to Node, Pa | Re at Node Center | Friction Factor at Node Center | Frictional Pressure Drop, Pa |
|---|---|---|---|---|---|---|---|---|
| Inlet | | 25. | | 996.982 | | | | 3.6666 |
| 1 | 0 | 25. | 25. | 996.982 | 0. | 797.13 | 0.120432 | 7.43323 |
| 2 | 0 | 25. | 25. | 996.982 | 0. | 797.13 | 0.120432 | 7.43323 |
| 3 | 0 | 25. | 25. | 996.982 | 0. | 797.13 | 0.120432 | 7.43323 |
| 4 | 1666.67 | 28.6755 | 26.8377 | 996.558 | 0.208068 | 831.596 | 0.115441 | 7.12818 |
| 5 | 1666.67 | 32.3492 | 30.5123 | 995.622 | 0.667042 | 903.077 | 0.106303 | 6.57014 |
| 6 | 1666.67 | 36.0207 | 34.185 | 994.57 | 1.18254 | 977.625 | 0.0981972 | 6.07556 |
| 7 | 1666.67 | 39.6895 | 37.8551 | 993.405 | 1.75386 | 1054.81 | 0.0910119 | 5.6376 |
| 8 | 1666.67 | 43.3566 | 41.523 | 992.128 | 2.38013 | 1134.12 | 0.0846472 | 5.2501 |
| 9 | 1666.67 | 47.0212 | 45.1889 | 990.74 | 3.06046 | 1215.06 | 0.0790086 | 4.90724 |
| 10 | 1666.67 | 50.6834 | 48.8523 | 989.244 | 3.794 | 1297.22 | 0.0740045 | 4.60339 |
| 11 | 1666.67 | 54.3439 | 52.5137 | 987.642 | 4.57954 | 1380.21 | 0.0695545 | 4.33359 |
| 12 | 1666.67 | 58.0018 | 56.1729 | 985.936 | 5.41603 | 1463.78 | 0.0655835 | 4.09325 |
| 13 | 1666.67 | 61.6569 | 59.8294 | 984.129 | 6.30224 | 1547.81 | 0.062023 | 3.87814 |
| 14 | 1666.67 | 65.3095 | 63.4832 | 982.223 | 7.23685 | 1632.13 | 0.0588188 | 3.68492 |
| 15 | 1666.67 | 68.9594 | 67.1344 | 980.221 | 8.21851 | 1719.81 | 0.0558203 | 3.50421 |
| 16 | 1666.67 | 72.6056 | 70.7825 | 978.126 | 9.24574 | 1808.57 | 0.0530806 | 3.33936 |
| 17 | 1666.67 | 76.2495 | 74.4276 | 975.941 | 10.3171 | 1892.35 | 0.0507304 | 3.19866 |
| 18 | 1666.67 | 79.8914 | 78.0704 | 973.67 | 11.4307 | 1974.73 | 0.0486142 | 3.07238 |
| 19 | 0 | 79.8914 | 79.8914 | 972.503 | 12.003 | 2015.52 | 0.0476303 | 3.01381 |
| 20 | 0 | 79.8914 | 79.8914 | 972.503 | 12.003 | 2015.52 | 0.0476303 | 3.01381 |
| 21 | 0 | 79.8914 | 79.8914 | 972.503 | 12.003 | 2015.52 | 0.0476303 | 3.01381 |
| Outlet | | | | | | | | 7.5178 |
| Total | | | | | 111.802 | | | 111.802 |

**Table 5. *Mathematica* Solution of Standard Problem 20, Using Coolant Properties of RELAP5-3D Code**

Flow rate per coolant channel = 0.111395 kg/s

| Node | Nodal Power W | Temp at Node Exit °C | Temp at Node Center, °C | Density at Node Center kg/m$^3$ | Buoyancy due to Node, Pa | Re at Node Center | Friction Factor at Node Center | Frictional Pressure Drop, Pa |
|---|---|---|---|---|---|---|---|---|
| Inlet | | | | 997.339 | | | | 3.8401 |
| 1 | 0 | 25. | 25. | 997.339 | 0. | 825.879 | 0.11624 | 7.51396 |
| 2 | 0 | 25. | 25. | 997.339 | 0. | 825.879 | 0.11624 | 7.51396 |
| 3 | 0 | 25. | 25. | 997.339 | 0. | 825.879 | 0.11624 | 7.51396 |
| 4 | 1666.67 | 28.5808 | 26.7904 | 996.861 | 0.234251 | 859.818 | 0.111652 | 7.22083 |
| 5 | 1666.67 | 32.1632 | 30.372 | 995.816 | 0.746781 | 929.173 | 0.103318 | 6.68886 |
| 6 | 1666.67 | 35.7457 | 33.9545 | 994.658 | 1.31466 | 1000.59 | 0.0959429 | 6.21865 |
| 7 | 1666.67 | 39.3268 | 37.5363 | 993.394 | 1.93444 | 1073.95 | 0.0893898 | 5.80127 |
| 8 | 1666.67 | 42.908 | 41.1174 | 992.03 | 2.60328 | 1149.18 | 0.0835381 | 5.42896 |
| 9 | 1666.67 | 46.4883 | 44.6982 | 990.571 | 3.31876 | 1226.28 | 0.0782855 | 5.0951 |
| 10 | 1666.67 | 50.0676 | 48.2779 | 989.021 | 4.07856 | 1305.32 | 0.0735454 | 4.79409 |
| 11 | 1666.67 | 53.6471 | 51.8573 | 987.385 | 4.88091 | 1386.08 | 0.0692602 | 4.52225 |
| 12 | 1666.67 | 57.2257 | 55.4364 | 985.665 | 5.7241 | 1468.45 | 0.0653751 | 4.27602 |
| 13 | 1666.67 | 60.8024 | 59.014 | 983.866 | 6.60621 | 1552.43 | 0.0618387 | 4.05211 |
| 14 | 1666.67 | 64.3766 | 62.5895 | 981.991 | 7.52554 | 1637.79 | 0.0586156 | 3.84824 |
| 15 | 1666.67 | 67.9495 | 66.163 | 980.043 | 8.48081 | 1724.59 | 0.0556653 | 3.66181 |
| 16 | 1666.67 | 71.5214 | 69.7354 | 978.024 | 9.47095 | 1812.95 | 0.0529524 | 3.49054 |
| 17 | 1666.67 | 75.0918 | 73.3066 | 975.936 | 10.4948 | 1902.7 | 0.0504546 | 3.33301 |
| 18 | 1666.67 | 78.6595 | 76.8757 | 973.782 | 11.5509 | 1993.6 | 0.0481541 | 3.18808 |
| 19 | 0 | 78.6595 | 78.6595 | 972.681 | 12.0908 | 2039.46 | 0.0470713 | 3.11992 |
| 20 | 0 | 78.6595 | 78.6595 | 972.681 | 12.0908 | 2039.46 | 0.0470713 | 3.11992 |
| 21 | 0 | 78.6595 | 78.6595 | 972.681 | 12.0908 | 2039.46 | 0.0470713 | 3.11992 |
| Outlet | | | | | | | | 7.8749 |
| Total | | | | | 115.237 | | | 115.236 |

**Table 6. NATCON Input Data for Sample Problem 20 Used in the Verification of Natural Circulation Calculation of PLTEMP/ANL Version 3.5**

```
PLTEMP Sample Problem 20 on natural circulation modeled by NATCON               Card 0
    20     1     2     4     0     0     2     1     0                          Card 1
0.75        0.3         0.001       100.0       0.0005      180.0               Card 2
1.05        0.3         0.003       40.81       0.0         25.0                Card 3
0.0001      0.5         1.000       200.0                                       Card 4
1.000       1.000       1.000       1.000       1.000       1.000               Card 5
0.0         1.000                                                               Card 6
0.050       1.000                                                               Card 6
0.100       1.000                                                               Card 6
0.150       1.000                                                               Card 6
0.200       1.000                                                               Card 6
0.250       1.000                                                               Card 6
0.300       1.000                                                               Card 6
0.350       1.000                                                               Card 6
0.400       1.000                                                               Card 6
0.450       1.000                                                               Card 6
0.500       1.000                                                               Card 6
0.550       1.000                                                               Card 6
0.600       1.000                                                               Card 6
0.650       1.000                                                               Card 6
0.700       1.000                                                               Card 6
0.750       1.000                                                               Card 6
0.800       1.000                                                               Card 6
0.850       1.000                                                               Card 6
0.900       1.000                                                               Card 6
0.950       1.000                                                               Card 6
1.0         1.000                                                               Card 6
```

## Table 7. RELAP5-3D-Calculated Solution of Sample Problem 20 and Two Analyses of the Solution

Flow rate per coolant channel = 0.11409 kg/s (practically constant at 400 s into the transient)

| | RELAP5-3D Printed Output | | | | | First Analysis | | | Second Analysis | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| Axial Node Number | $P_n$ Pressure at Node Center, Pa | Coolant Temp at Node Exit, K | Reynolds Number at Node Exit | Density at Node Exit kg/m^3 | $P_{n-1}$ - $P_n$ Pressure Drop Pa | Nodal Gravity Head Pa | Buoyancy Due to the Node Pa | Frictional Pressure Drop in the Node Pa | Nodal Gravity Head Pa | Buoyancy Due to the Node Pa | Frictional Pressure Drop in the Node Pa |
| | 500000.00 | | 845.83 | 997.340 | | | | 4.0282 | | | 4.0282 |
| 1 | 499747.00 | 298.155 | 845.83 | 997.340 | 253.000 | 489.028 | 0.0000 | 7.6960 | 489.028 | 0.0000 | 7.6960 |
| 2 | 499251.00 | 298.162 | 845.96 | 997.340 | 496.000 | 489.028 | 0.0000 | 7.6954 | 489.028 | 0.0000 | 7.6948 |
| 3 | 498754.00 | 298.171 | 846.13 | 997.330 | 497.000 | 489.026 | 0.0025 | 7.6941 | 489.023 | 0.0049 | 7.6934 |
| 4 | 498258.00 | 301.669 | 914.80 | 996.370 | 496.000 | 488.788 | 0.2403 | 7.3969 | 488.553 | 0.4756 | 7.1227 |
| 5 | 497762.00 | 305.168 | 985.80 | 995.300 | 496.000 | 488.290 | 0.7380 | 6.8603 | 488.028 | 1.0003 | 6.6168 |
| 6 | 497268.00 | 308.667 | 1059.00 | 994.120 | 494.000 | 487.739 | 1.2896 | 6.3837 | 487.449 | 1.5789 | 6.1668 |
| 7 | 496775.00 | 312.166 | 1134.40 | 992.840 | 493.000 | 487.136 | 1.8927 | 5.9586 | 486.822 | 2.2065 | 5.7643 |
| 8 | 496283.00 | 315.664 | 1211.70 | 991.470 | 492.000 | 486.486 | 2.5424 | 5.5782 | 486.150 | 2.8783 | 5.4040 |
| 9 | 495792.00 | 319.162 | 1291.10 | 990.010 | 491.000 | 485.792 | 3.2362 | 5.2364 | 485.434 | 3.5941 | 5.0792 |
| 10 | 495302.00 | 322.659 | 1372.20 | 988.470 | 490.000 | 485.057 | 3.9717 | 4.9283 | 484.679 | 4.3492 | 4.7864 |
| 11 | 494813.00 | 326.155 | 1455.10 | 986.840 | 489.000 | 484.279 | 4.7489 | 4.6499 | 483.880 | 5.1485 | 4.5212 |
| 12 | 494325.00 | 329.650 | 1539.60 | 985.140 | 488.000 | 483.463 | 5.5653 | 4.3974 | 483.046 | 5.9821 | 4.2804 |
| 13 | 493838.00 | 333.144 | 1625.70 | 983.360 | 487.000 | 482.610 | 6.4185 | 4.1677 | 482.173 | 6.8548 | 4.0611 |
| 14 | 493353.00 | 336.636 | 1713.20 | 981.510 | 485.000 | 481.720 | 7.3084 | 3.9584 | 481.266 | 7.7620 | 3.8609 |
| 15 | 492868.00 | 340.127 | 1802.20 | 979.590 | 485.000 | 480.796 | 8.2327 | 3.7668 | 480.325 | 8.7034 | 3.6774 |
| 16 | 492385.00 | 343.616 | 1892.40 | 977.600 | 483.000 | 479.837 | 9.1913 | 3.5913 | 479.349 | 9.6792 | 3.5093 |
| 17 | 491902.00 | 347.103 | 1983.80 | 975.550 | 483.000 | 478.846 | 10.1818 | 3.4301 | 478.344 | 10.6843 | 3.3546 |
| 18 | 491421.00 | 350.589 | 2076.30 | 973.430 | 481.000 | 477.824 | 11.2041 | 3.2818 | 477.304 | 11.7239 | 3.2122 |
| 19 | 490941.00 | 350.589 | 2076.30 | 973.430 | 480.000 | 477.304 | 11.7239 | 3.2122 | 477.304 | 11.7239 | 3.2122 |
| 20 | 490460.00 | 350.589 | 2076.30 | 973.430 | 481.000 | 477.304 | 11.7239 | 3.2122 | 477.304 | 11.7239 | 3.2122 |
| 21 | 489980.00 | 350.587 | 2076.30 | 973.430 | 480.000 | 477.304 | 11.7239 | 3.2122 | 477.304 | 11.7239 | 3.2122 |
| | 489731.00 | | | | 249.000 | | | 8.2542 | | | 8.2542 |
| Total | | | | | 10269.000 | 10157.657 | **111.936** | **118.590** | 10151.795 | **117.797** | **116.420** |
| Channel Fric Press Drop given by Press Drop minus Gravity Head | | | | | | | | **111.343** | | | **117.205** |

## Table 8. PLTEMP/ANL Input Data for Sample Problem 20 Used in the Verification of Natural Circulation Calculation by the Code

```
 Test Problem 20: Flow is calculated by natural circulation
! 2 assemblies, Total power = 0.20 MWt, Axially uniform power profile
! Each assembly has 4 fuel plates and 5 coolant channels
! H2O coolant, All hot channel factors = 1.0, No bypass flow, NCTYP=0
! 14 axial heat transfer nodes in the heated length of fuel plates
!  1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18  19    #  Card 200
   5   0   0   1   0   1   1   1   0   0   0   0   0   0   1   0   0   0   1    Card(1)0200
   2   3 0.50      1.00        1.00        1.00          0                      Card(1)0300
! Using pressure driven mode
   1   1 1.00                                                                   Card(1)0301
   1   1   1                                                                    Card(1)0302
1.00        1.00                                                                Card(2)0303
36.0E-04    5.94059E-03 0.15        0.50        0.30        3.00E-03            Card(3)0304
0.00        5.94059E-03 0.75        0.00        0.30        3.00E-03            Card(3)0304
36.0E-04    5.94059E-03 0.15        1.00        0.30        3.00E-03            Card(3)0304
! Use the code's biult-in correlation for friction factor
0.00        0.00        0.00                                                    Card(1)0305
   5   3 0.00       0.75        0.50E-03    180.00        1.00E-03    100.00    Card(1)0306
4.50E-04    5.94059E-03 0.3030      0.30        0.30        3.00E-03            Card(5)0307
9.00E-04    5.94059E-03 0.6060      0.60        0.30        3.00E-03            Card(5)0307
9.00E-04    5.94059E-03 0.6060      0.60        0.30        3.00E-03            Card(5)0307
9.00E-04    5.94059E-03 0.6060      0.60        0.30        3.00E-03            Card(5)0307
4.50E-04    5.94059E-03 0.3030      0.30        0.30        3.00E-03            Card(5)0307
0.30        0.30        0.30        0.30                                        Card(1)0308
! Card 0308A not required
! Radial power peaking factor data by fuel plate for each subassembly. Input flow data by
! channel for each subassembly on Cards 0310 not required because WFGES(1) is non-zero
1.000       1.000       1.000       1.000                                       Card(2)0309
1.000       1.000       1.000       1.000                                       Card(2)0309
! DP0       DDP         DPMAX       POWER       TIN         PIN
0.0003275   0.04        0.00        0.200       25.0        0.50                Card(1)0500
0.00        0.00                                                                Card(2)0500
  50 0.0001     25.0        0.00        0.00                                    Card(1)0600
  15                                                                            Card(1)0700
0.0         1.000                                                               Card(11)0701
0.100       1.000                                                               Card(11)0701
0.167       1.000                                                               Card(11)0701
0.233       1.000                                                               Card(11)0701
0.300       1.000                                                               Card(11)0701
0.367       1.000                                                               Card(11)0701
0.433       1.000                                                               Card(11)0701
0.5         1.000                                                               Card(11)0701
0.567       1.000                                                               Card(11)0701
0.633       1.000                                                               Card(11)0701
0.700       1.000                                                               Card(11)0701
0.767       1.000                                                               Card(11)0701
0.833       1.000                                                               Card(11)0701
0.900       1.000                                                               Card(11)0701
1.0         1.000                                                               Card(11)0701
   0                                                                            Card(11)0702
```

**APPENDIX F. *Mathematica* Program for Solving Sample Problem 20, Using Coolant Properties of the PLTEMP/ANL Code**

```
(" SOLUTION OF NATURAL CIRCULATION STANDARD PROBLEM 20, Using Water Properties of the PLTEMP/ANL V3.5 Code ")
data={kin→0.5,kex→1.0,Dh→0.00594059,len1→0.15,len2→0.75,len3→0.15,wch→0.3,tch→0.003,grav→9.80665,Cfric→96,tin→25.0,powr→25000.0};
flow=0.10883; ←——— This guess flow was adjusted and the program was rerun to achieve channel
                   channel buoyancy (buoy) equal to channel frictional pressure drop (delp).
(* power = 25 kW per plate, total power = 200 kW in 8 plates *)
Print["Subcooled water density, kg/m**3, at 5 bar absolute used in the PLTEMP/ANL V3.5 Code"];
rho={{20.,997.9875},{25.,996.9820},{30.,995.7591},{35.,994.3214},{40.,992.6718},{45.,990.8146},{50.,988.7536},{55.,986.4945},{60.,984.0422},{65.,981.4029},{70.,978.5832},{75.,975.5897},{80.,972.4324},{85.,969.1167},{90.,965.6552},{95.,962.0546},{100.,958.3263},{105.,954.4819},{110.,950.5318},{115.,946.4900},{120.,942.3674},{125.,938.1805},{130.,933.9403},{135.,929.6651},{140.,925.3685},{145.,921.0693},{150.,916.7842}};
Plot[Interpolation[rho][temp],{temp,20,150}];
Print["Subcooled water enthalpy, kJ/kg, at 5 bar absolute used in the PLTEMP/ANL V3.5 Code"];
enthalpy={{20.,83.9517},{25.,104.7730},{30.,125.6082},{35.,146.4573},{40.,167.3272},{45.,188.2110},{50.,209.1156},{55.,230.0341},{60.,250.9734},{65.,271.9336},{70.,292.9146},{75.,313.9233},{80.,334.9460},{85.,356.0033},{90.,377.0746},{95.,398.1805},{100.,419.3143},{105.,440.4758},{110.,461.6720},{115.0,482.8960},{120.,504.1616},{125.,525.4550},{130.,546.7970},{135.,568.1738},{140.,589.5991},{145.,611.0661},{150.,632.5816}};
Plot[Interpolation[enthalpy][temp],{temp,20,150}];
Print["Dynamic viscosity, micro Pa-s, of water used in the PLTEMP/ANL V3.5 Code"];
visc={{20.,1014.5},{25.,901.17},{30.,804.50},{35.,722.29},{40.,652.48},{45.,593.26},{50.,542.91},{55.,499.92},{60.,462.93},{65.,430.75},{70.,401.28},{75.,377.03},{80.,355.98},{85.,337.40},{90.,320.63},{95.,304.97},{100.,290.21},{105.,276.41},{110.,263.52},{115.,251.49},{120.,240.27},{125.,229.83},{130.,220.10},{135.,211.05},{140.,202.64},{145.,194.82},{150.,187.56}};
Plot[Interpolation[visc][temp],{temp,20,150}];
Print["Inlet and Exit temperatures, C"];
tin=tin/.data
Cfric=Cfric/.data;
grav=grav/.data;
hin=1000*Interpolation[enthalpy][tin];
hout=hin+powr/flow/.data;
tout=tx/.FindRoot[hout==1000*Interpolation[enthalpy][tx],{tx,tin}]
rhoin=Interpolation[rho][tin];
rhoout=Interpolation[rho][tout];
Print["Density at inlet =",rhoin,", Density at exit =",rhoout];
rhoave=NIntegrate[Interpolation[rho][temp],{temp,tin,tout}]/(tout-tin);
Print["Integrated average coolant density over (",tin," to ",tout,") = ",rhoave];
buoy2=(rhoin-rhoave)*grav*len2 /.data;
buoy3=(rhoin-rhoout)*grav*len3 /.data;
buoy=buoy2+buoy3;
Print["DRIVING PRESSURE HEAD DUE TO BUOYANCY in Section 1 =0.0, Section 2 =",buoy2,", Section 3 =",buoy3,", Total buoyancy (Pa) =",buoy];
velin=flow/(rhoin*wch*tch)/.data;
```

```
Print["Coolant inlet velocity, m/s = ",velin];
visc1=0.000001*Interpolation[visc][tin];
visc3=0.000001*Interpolation[visc][tout];
Print["Coolant dynamic viscosity, Pa-s, in axial regions 1 and 3 =",visc1," ",visc3]
reyn1=flow*Dh/(wch*tch*visc1)/.data;
reyn3=flow*Dh/(wch*tch*visc3)/.data;
Print["Reynolds numbers in axial regions 1 and 3 =",reyn1," ",reyn3];
fric2300=Cfric/2300.0;
fric4000=0.184/4000.0^0.2;
frica=If[reyn1<2300.0,Cfric/reyn1,fric2300+(fric4000-fric2300)*(reyn1-2300.0)/1700.0];
fric1=If[reyn1>4000.0,0.184/reyn1^0.2,frica];
frica=If[reyn3<2300.0,Cfric/reyn3,fric2300+(fric4000-fric2300)*(reyn3-2300.0)/1700.0];
fric3=If[reyn3>4000.0,0.184/reyn3^0.2,frica];
Print["Friction factors in Sections 1 and 3 =",fric1," ",fric3];
Print["FRICTIONAL PRESSURE DROP IN SECTION 1"]
delp1s=(fric1*len1/Dh)*0.5*(flow/(wch*tch))^2/rhoin/.data;
delp1m=kin*0.5*(flow/(wch*tch))^2/rhoin/.data;
delp1=delp1s+delp1m;
Print["Total pressure drop in Section 1 =",delp1,", Minor loss = ",delp1m,", Wall shear =",delp1s]
Print["FRICTIONAL PRESSURE DROP IN SECTION 3"]
delp3s=(fric3*len3/Dh)*0.5*(flow/(wch*tch))^2/rhoout/.data;
delp3m=kex*0.5*(flow/(wch*tch))^2/rhoout/.data;
delp3=delp3s+delp3m;
Print["Total pressure drop in Section 3 =",delp3,", Minor loss = ",delp3m,", Wall shear =",delp3s]
delp4=rhoin*velin*velin*(rhoin/rhoout-1.0)/.data;
Print["Pressure drop due to momentum flux (Pa) =",delp4];
Print["Flow =",flow,", g =",grav,", Temp at inlet and exit =",tin,", ",tout,", Density at inlet and exit
=",rhoin,", ",rhoout,", Gravity head =",grav*(rhoin*len1+rhoave*len2+rhoout*len3)/.data,", Total
buoyancy =",buoy,", Buoyancy in Section 2 =",buoy2,", Buoyancy in Section 3 =",buoy3,", Power into
coolant (W) =",flow*(hout-hin)]
Print["LOOP OVER 21 AXIAL SEGMENTS"];
powr1=powr/15/.data;
delz=len2/15/.data;
enth1=hin;
temp1=tin;
delp2p=0;
buoy2p=0;
Do[powr2=powr1;
  If[j<4,powr2=0];
  If[j>18,powr2=0];
  enth2=enth1+powr2/flow;
  temp2=tx/.FindRoot[enth2==1000*Interpolation[enthalpy][tx],{tx,temp1}];
  tempj=0.5*(temp2+temp1);
  viscj=0.000001*Interpolation[visc][tempj];
  rhoj=Interpolation[rho][tempj];
  buoy2s=buoy2p+grav*(rhoin-rhoj)*delz;
  reynj=flow*Dh/(wch*tch*viscj)/.data;
  frica=If[reynj<2300.0,Cfric/reynj,fric2300+(fric4000-fric2300)*(reynj-2300.0)/1700.0];
  fricj=If[reynj>4000.0,0.184/reynj^0.2,frica];
  delpj=(fricj*delz/Dh)*0.5*(flow/(wch*tch))^2/rhoj/.data;
  delp2=delp2p+delpj;
```

```
  (*Print["Axial segment =",j,", Flow, kg/s =",flow,", delz (m) =",delz,"Power in segment (W) =",powr2,",
Enthalpy at segment exit (J/kg) =",enth2,", Enthalpy at segment center (J/kg) =",0.5(enth1+enth2),",
Temp at segment exit (C) =",temp2,", Segment mean temp (C) =",tempj,", Segment mean density
(kg/m^3) =",rhoj,", Buoyancy due to segments 1 through ",j," (Pa) =",buoy2s,", Viscosity (Pa-s)
=",viscj,", Reynolds number =",reynj,", Friction factor =",fricj,", fl/Dh of segment (Pa) =",delpj,",
Cumulative sum fL/Dh of segments 1 through ",j", (Pa) =",delp2];*)
  Print[j,"   ",powr2,"   ",temp2,"   ",tempj,"   ",rhoj,"   ",grav*(rhoin-rhoj)*delz,"   ",reynj,"   ",fricj,"
",delpj];
  buoy2p=buoy2s;
  delp2p=delp2;
  temp1=temp2;
  enth1=enth2,
  {j,1,21}]
Print["BALANCE OF BUOYANCY AND FRICTIONAL PRESSURE DROP:"]
delp=delp2+delp1m+delp3m;
buoy=buoy2s;
Print["Total buoyancy (Pa) =",buoy,", Total frictional pressure drop (Pa) =",delp];
```

## APPENDIX G. Natural Convective Test Case for PLEMP/ANL Solved with RELAP5

### 1. INTRODUCTION

There is an effort currently underway to expand the capabilities of the PLTEMP/ANL code[0] to include analysis where the core flow rate is driven solely by natural convection. Because the Natcon code[0], which does consider such flows, considers only a single fueled channel at a time, it can not include heat transfer through the fuel plates to adjacent coolant channels. Incorporating the capabilities of Natcon into PLTEMP/ANL would enable PLTEMP/ANL to consider both force flow and convective flow in all channels with a single model setup.

A single-channel test problem was devised to assist in the development and testing of the expanded capabilities of PLTEMP/ANL. This test problem was analyzed with the RELAP5 code[0] because RELAP5 was externally and independently developed, is well documented, and is widely used among reactor analysts. The test problem model was extremely easy to develop by adapting parts of two other similar natural-convective flow RELAP5 models that had been developed and successfully deployed in the immediate past.

### 2. THE TEST PROBLEM

The test problem was designed to be extremely simple so that differences between RELAP5 and PLTEMP predictions would be easy to trace. This test problem is a vertical rectangular channel whose key parameters are provided in Table 1. The duct is 3 mm thick by 0.3 m wide, yielding an aspect ratio of 0.01. The duct length is 1.05 m. The first and last 0.15-meter channel lengths are unheated. The middle 0.75-meter channel length is uniformly heated over the two 0.3-m wide opposing walls of the duct with a total power of 25 kW. Although there is a K-loss (or form-loss) at the inlet of 0.5 and a K-loss of 1.0 at the exit, it is assumed that there is no area change at either end of the duct.

The inlet temperature of the coolant is 25° C. The coolant pressure at the inlet it 5.0 bar. The pressure of the coolant at the inlet is greater than that at the outlet only because the coolant is 1.05 m deeper at the inlet than at the outlet. This pressure difference is equal to the water density (997.3390 kg/m$^3$) times the acceleration due to gravity (9.80655 m/s$^2$) times the elevation difference (1.05 m), or 10269.48 Pa = 0.1026948 bar. Thus, the outlet pressure is 4.8973052 bar. The density is based on the 1967 ASME Steam Tables, which are also used by RELAP5. There may be a few non-significant digits in the outlet pressure, but they were maintained in the model input since the entire buoyancy pressure drop, as will be shown later, is only 117.80 Pa.

**Table 1. Key Parameters**

| Parameter | Value |
|---|---|
| Channel Thickness, mm | 3.0 |
| Channel Width, m | 0.30 |
| Channel Length, m | 1.05 |
| Channel Heated Length, m | 0.75 |
| Channel Heated Width, m | 0.30 |
| Heated Length Below Channel, m | 0.15 |
| Heated Length Above Channel, m | 0.15 |
| Inlet Temperature, C | 25 |
| Power Shape | Uniform |
| Channel Power, kW | 25 |
| Inlet Form Loss (K-loss) | 0.5 |
| Outlet Form Loss (K-loss) | 1.0 |
| Hot Channel Factors (All) | 1.0 |
| Inlet Pressure, bar | 5.0 |
| Inlet − Outlet Press., m 25° C $H_2O$ | 1.05 |
| Laminar Friction Factor × Rey. No. | 96 |

In the RELAP5 model the 1.05 m channel length was divided into 21 layer, or nodes, of 0.05 m each. A RELAP5 time-dependent node was used at the inlet as a pressure and temperature source and another time-dependent node was used at the exit as a pressure sink. The steady-state solution was obtained via a 400-s pseudo-transient.

For laminar flow, RELAP5 assumes that the Moody friction factor is 64/(Re × Φ), where Re is the Reynolds number and Φ is an input parameter. For infinite parallel plates the laminar flow Moody friction factor is 96/Re. Since the duct aspect ratio is only 0.01, it behaves essentially like parallel plates. Because the PLTEMP/ANL code uses the infinite parallel plate model for this aspect ratio, Φ was set to 0.6667.

The flow area is the product of the channel width and thickness, or $9.0 \times 10^{-4}$ $m^2$. The hydraulic diameter is 4 times the flow area divided by the wetted perimeter, or 5.940594 mm.

## 3. RESULTS

RELAP5 predicted a flow rate of 0.1141 kg/s and an outlet temperature of 77.44° C. The code also provided a value of coolant density at each of the 21 axial levels. The buoyancy pressure drop, which is what drives the flow, can be obtained from these 21 density values. These 21 values were summed and then multiplied by the product of the acceleration due to gravity and the 0.05-m node thickness, to obtain a value of 10151.69 Pa. The buoyancy pressure drop is the difference between the 10269.48 Pa calculated above, due to 1.05 m of 25° C water, and 10151.69 Pa. Thus, the gravity pressure difference is 117.80 Pa.

## REFERENCES


[1] Arne P. Olson and M. Kalimullah, Argonne National Laboratory, unpublished, February 20, 2008.

[2] R. S. Smith and W. L. Woodruff, "A Computer Code, Natcon, for the Analyses of Steady-State Thermal-Hydraulics and Safety Margins in Plate-Type Research Reactors Cooled by Natural Convection," ANL/RERTR/TM-12, Argonne National Laboratory, December 1988.

[3] The RELAP5-3D© Code Development Team, RELAP5-3D© Code Manual, Version 2.3, INEEL-EXT-98-00834, Idaho National Laboratory, April 2005.

## 10. Verification of the Chimney Model in Natural Circulation Calculation Implemented in the PLTEMP/ANL V3.6 Code

(December 2008)

A natural circulation calculation implemented in the PLTEMP/ANL V3.5 code was verified earlier. A chimney model was added recently in the V3.6 code. For the verification of the chimney model, a natural circulation test problem for a 4-fuel-plate assembly entering a 2.0 m high chimney, was solved by *Mathematica*, by the NATCON code, and by PLTEMP/ANL V3.6. *Mathematica* solutions were performed using, in turn, the sets of coolant properties used in PLTEMP/ANL and NATCON. The *Mathematica* calculations were done starting from an assumed flow rate in a coolant channel which was manually adjusted so that the buoyancy equals the frictional pressure drop in the channel. All four solutions are summarized in Table 1. The *Mathematica* and NATCON code solutions agree well with the PLTEMP/ANL solution, and this provides a verification of the chimney model in PLTEMP/ANL.

### 10.1. Introduction

The PLTEMP/ANL code was improved to model a chimney of a user-specified height in the coolant flow calculation by natural circulation, upward through the fuel assemblies and downward in the reactor pool. All fuel assemblies in the problem or a group of fuel assemblies enter into a common chimney. In the latter case, the problem has more than one chimney. The schematic and physical geometries of the model are shown in Figs. 1 and 2. The thermal-hydraulic equations to model the chimney and the method of solution are described in the PLTEMP/ANL V3.6 Users Guide [1].

The purpose of this report is to document the solution of a natural circulation test problem that is used in the verification of this model. The test problem is defined in Section 10.2, and referred to as Test Problem 22. Its solution by four methods/codes are reported and compared here:

(1) *Mathematica* calculation using the coolant properties used in the PLTEMP/ANL code,
(2) *Mathematica* calculation using the coolant properties used in the NATCON code,
(3) Solution by the NATCON code [2], and
(4) Solution by the PLTEMP/ANL Version 3.6 code.

The solutions by NATCON and by *Mathematica* were obtained for a single coolant channel, and the PLTEMP/ANL solution was obtained for a four-plate fuel assembly.

### 10.2. A Test Problem with Chimney

<u>Problem Definition</u>: Calculate the coolant flow rate caused by natural circulation in a 1.05 m long vertical coolant channel entering a chimney of height 2.0 m. The heated length of the channel is 0.75 m, the lower unheated length is 0.15 m, and the upper unheated length is 0.15 m. The heated length has a power of 25 kW distributed uniformly over the 0.75 m length, with an inlet temperature of 25 °C. The channel has a rectangular cross section of thickness 3 mm, width 0.3 m, inlet pressure loss coefficient 0.5, and exit pressure loss coefficient 1.0. The absolute

pressure at the channel inlet is 5 bar, corresponding to the channel inlet being 40.81 m below the free surface of water in the pool.

The values of input variables (see nomenclature given at the end) for this problem are as follows:

| | | | |
|---|---|---|---|
| $D_h$ = 0.0059406 m, | $g$ = 9.8 m/s$^2$, | $H_{in}$ = 41.81 m, | $K_{in}$ = 0.5, |
| $K_{ex}$ = 1.0, | $L_1$ = 0.15 m, | $L_2$ = 0.75 m, | $L_3$ = 0.15 m, |
| $L$ = 1.05 m, | $L_{ch}$ = 2.00 m, | $Q$ = 25000 W, | $P_{in}$ = 5.0 bar, |
| $T_{in}$ = 25 °C, | $T_{ch}$ = 0.003 m, | $W_{ch}$ = 0.3 m, | |

$W$ = 0.1980283 kg/s (*assumed value*)

### 10.3. *Mathematica* Calculations

The codes NATCON and PLTEMP/ANL have slightly different built-in coolant properties, as shown in Table 2. To account for the effect of the difference between coolant properties, two solutions to the test problem were obtained by *Mathematica* calculations, using the coolant properties built in each code. In each *Mathematica* calculation, the same friction factor correlations were used, i.e., the correlations used in the PLTEMP/ANL code. A *Mathematica* program was written in which any set of coolant properties could be inserted. Appendix H gives a listing of this program with the coolant properties of the PLTEMP/ANL code.

The program uses 21 axial nodes (mesh intervals) of equal length in the total channel length of 1.05 m, with three each in the lower and upper unheated lengths of the channel, and 15 in the heated length. Starting from a guessed flow rate, the program calculates the coolant enthalpy at each node exit, the coolant temperature at the node exit, and the temperature at the node-center. Using the node-center temperature, the program finds the nodal Reynolds number, friction factor, nodal frictional pressure drop, and the nodal contribution to buoyancy. It finds the channel inlet and outlet pressure losses. It finds the buoyancy due to the chimney. The frictional pressure drop in the chimney is assumed to be negligible. The momentum flux term is ignored because it is small. The calculation ends after printing the total buoyancy and the total frictional pressure drop in the channel. It runs so fast that several guessed flow rates could be tried in a few minutes. To find the steady-state natural circulation flow rate, the user reruns the program several times, each time using a more improved guess of the flow rate, in order to make the total buoyancy equal to the total frictional pressure drop.

The *Mathematica* program uses coolant enthalpy as a function of temperature, as shown by the program listing in Appendix H. However, the NATCON code uses built-in coolant specific heat (rather than enthalpy), as shown in Table 2. When using the coolant properties of the NATCON code, some additional statements were added to the program to find the corresponding enthalpy by integrating the specific heat.

The two solutions to Test Problem 22, obtained using the coolant properties of PLTEMP/ANL and NATCON are given in Tables 3 and 4. The two *Mathematica* calculations are summarized in Table 1. It is noted that the two calculated flow rates, 0.19803 and 0.19796 kg/s, are in good agreement (with a small difference of 0.035 %).

### 10.4. NATCON Code Calculation

Table 5 shows the input data for Test Problem 22 used in the NATCON Version 2.2 calculation[2]. As the input data shows, the heated length was divided into 15 axial mesh intervals (or nodes). The chimney height (2.0 m) is the fifth input datum on Card 3. The code computes the coolant temperature, density, viscosity, Reynolds number, friction factor, buoyancy head, and frictional pressure drop for each axial node, for a guessed value of channel flow rate. The code finds the total buoyancy head and frictional pressure drop, and then adjusts the channel flow rate to make the total buoyancy head equal to the total frictional pressure drop. The momentum flux term is ignored in the code because it is small. The results obtained are given in Table 6 which is summarized in Table 1 for comparison with other solutions of the problem.

### 10.5. PLTEMP/ANL Version 3.6 Code Calculation

To solve Test Problem 22 using the PLTEMP/ANL V3.6 code, the problem defined above in Section 10.2 is turned into a problem for a research reactor fuel assembly consisting of (arbitrarily) four plates cooled by five coolant channels (Fig. 3). Each fuel plate produces 25 kW as specified in the problem definition, and the fuel assembly has a power of 100 kW. The internal channels (channels 2, 3, and 4) are of the thickness 3 mm as specified in the problem definition. In order to have identical axial profiles of coolant temperature in each channel, the first and the last channels are of half thickness, i.e., 1.5 mm. Based on symmetry, it is noted that exactly half of each fuel plate's power goes to each coolant channel adjacent to the plate. Table 7 gives the input data used in the PLTEMP/ANL V3.6 code. It is noted that there are two identical fuel assemblies in the PLTEMP/ANL problem, and hence the total power in the input data is 0.2 MW.

In the input data of Table 7, the friction factor is obtained using the PLTEMP/ANL V3.6 code's built-in correlations which accounts for laminar, transition, or turbulent flow as the case may be. The results obtained are given in Table 8 which is summarized in Table 1 for comparison with other solutions of the problem. The flow is laminar over the lower part of the channel, and then changes to the transition regime over the upper part of the channel. The Darcy-Weisbach friction factor is calculated using the following correlations.

$$f = \begin{cases} f_{lam}(Re, a) & \text{if } Re \le 2200 \\ \left(3.75 - \dfrac{8250}{Re}\right)\left(f_a - f_{2200}\right) + f_{2200} & \text{if } 2200 < Re < 3000 \end{cases} \tag{1}$$

where

$$f_{lam}(Re, a) = \frac{96\left(1 - 1.3553\,a + 1.9467\,a^2 - 1.7012\,a^3 + 0.9564\,a^4 - 0.2537\,a^5\right)}{Re} \tag{2}$$

$f_{2200} = f_{lam}(2200,a)$ (3)

$$f_a = \left[ -2\ \mathrm{Log}_{10} \left\{ \frac{E_{rel}}{3.7} + \frac{2.51}{\mathrm{Re}} \left\{ 1.14 - 2\ \mathrm{Log}_{10} \left( E_{rel} + 21.25\ \mathrm{Re}^{-0.9} \right) \right\} \right\} \right]^{-2} \quad (4)$$

a = Channel aspect ratio = Channel thickness/width ratio, always ≤ 1.0
$E_{rel}$ = Relative roughness

The numerator of Eq. (2) for the laminar friction factor is found to be 94.7174/Re based on the thickness-to-width ratio of the coolant channel. The results of the PLTEMP/ANL calculation agree well with the *Mathematica* solution obtained using the coolant properties of PLTEMP/ANL given in column 2 of Table 1. This comparison provides a verification of the chimney model in the natural circulation calculation implemented in the PLTEMP/ANL V3.6 code.

## 10.6. Conclusion

There is a good agreement among the following four solutions of Test Problem 22, as shown in Table 1: (1) PLTEMP/ANL V3.6 calculation, (2) *Mathematica* solution using the coolant properties of the PLTEMP/ANL code, (3) *Mathematica* solution using the coolant properties of the NATCON code, and (4) NATCON code solution. The natural circulation flow rate per channel calculated by the PLTEMP/ANL V3.6 code is 0.19809 kg/s, compared to 0.19803 kg/s calculated by *Mathematica* using the PLTEMP/ANL coolant properties. This provides a verification of the chimney model implemented in the PLTEMP/ANL V3.6 code.

The flow rate 0.19967 kg/s calculated by the NATCON V2.2 code is 0.8 % higher than that calculated by PLTEMP/ANL V3.6. This is mainly due to the difference between the friction factors used in the two codes. NATCON V2.2 has no provision for transition-flow-regime friction factor whereas PLTEMP/ANL V3.6 provides for it as shown in Eq. (1) to Eq. (4). Only a small difference in the flow rate is caused by the coolant property differences between the two codes, as shown by a comparison between the two *Mathematica* solutions.

## NOMENCLATURE

| | |
|---|---|
| a | Channel aspect ratio = Channel thickness/width ratio, always ≤ 1.0 |
| $C_p$ | Coolant specific heat averaged over the temperature range 25 to 80 °C existing in the problem, J/kg-°C |
| $D_h$ | Hydraulic diameter of the channel, m |
| $E_{rel}$ | Relative roughness |
| g | Acceleration due to gravity, m/s$^2$ |
| $H_{in}$ | Water depth at the channel inlet, m |
| $L_1$ | Unheated channel length below the heated section, m |
| $L_2$ | Heated length of channel, m |
| $L_3$ | Unheated channel length above the heated section, m |
| L | Channel height = $L_1 + L_2 + L_3$ , m |
| $L_{ch}$ | Effective chimney height, m |
| $K_{in}$ | Pressure loss coefficient at the channel inlet |
| $K_{ex}$ | Pressure loss coefficient at the channel exit |
| $\Delta P_{buoy}$ | Pressure head due to buoyancy, Pa |
| $\Delta P_{fric}$ | Total frictional pressure drop in the coolant channel, Pa |
| $P_{in}$ | Pressure at the channel inlet, Pa |
| Q | Power in the channel, W |
| $V_1$ | Coolant velocity at channel inlet, m/s |
| $V_3$ | Coolant velocity at channel exit, m/s |
| T | Coolant temperature at an axial location, °C |
| $T_{in}$ | Coolant temperature at the channel inlet, °C |
| $T_{ex}$ | Coolant temperature at the channel exit, °C |
| $T_{ch}$ | Channel thickness, m |
| W | Coolant flow rate in the channel, kg/s |
| $W_{ch}$ | Channel width, m |

## REFERENCES

1. A. P. Olson and M. Kalimullah, Argonne National Laboratory, unpublished information, November 12, 2008.

2. R. S. Smith and W. L. Woodruff, "A Computer Code, NATCON, for the Analysis of Steady-State Thermal-Hydraulics and Safety Margins in Plate-Type Research Reactors Cooled by Natural Convection," ANL/RERTR/TM-12, Argonne National Laboratory, IL (December 1988).

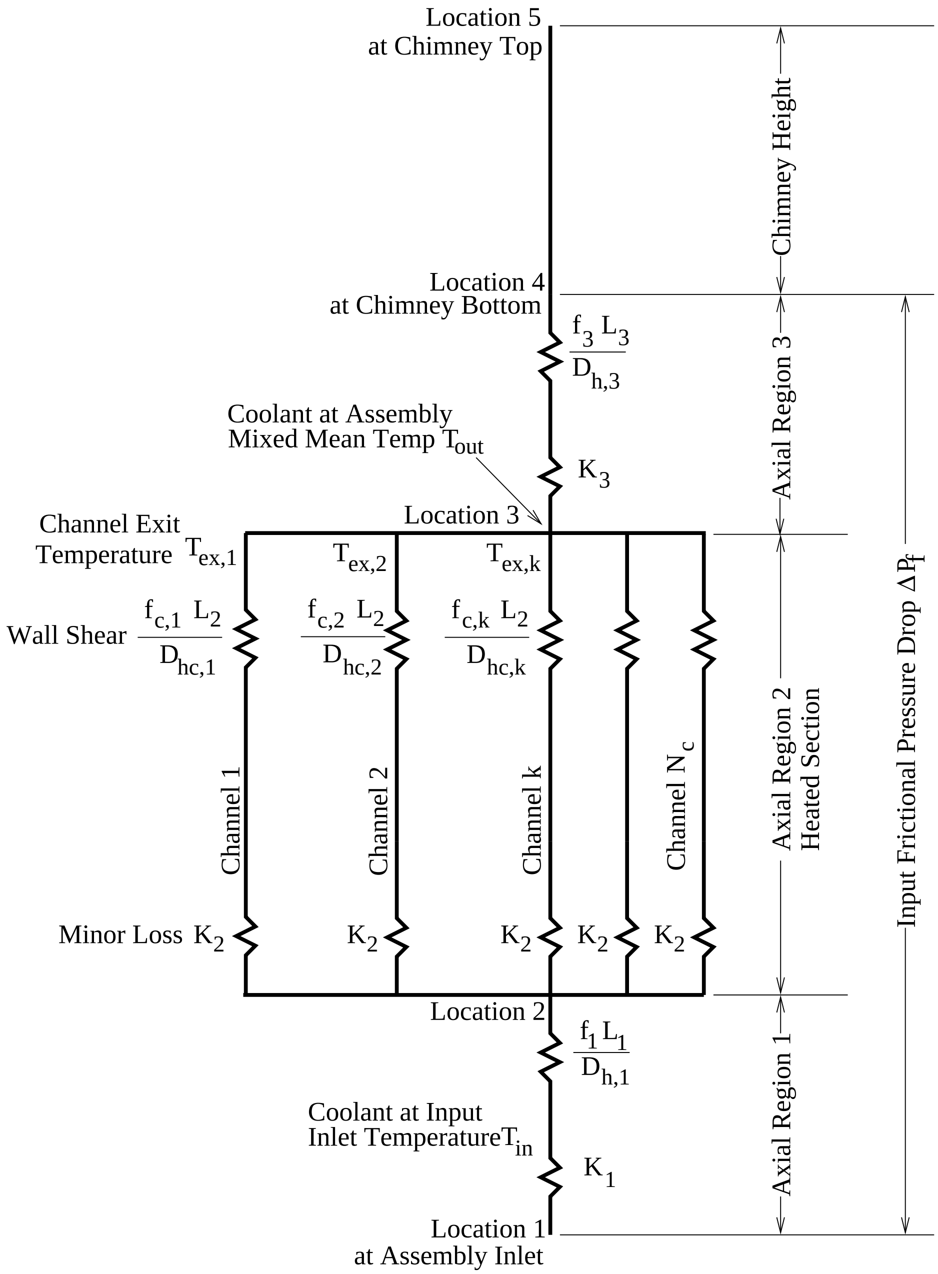


**Fig. 1. Coolant Flow Path in a Fuel Assembly and Chimney Modeled in PLTEMP/ANL (Multiple Axial Regions Downstream of the Heated Section Are Allowed)**

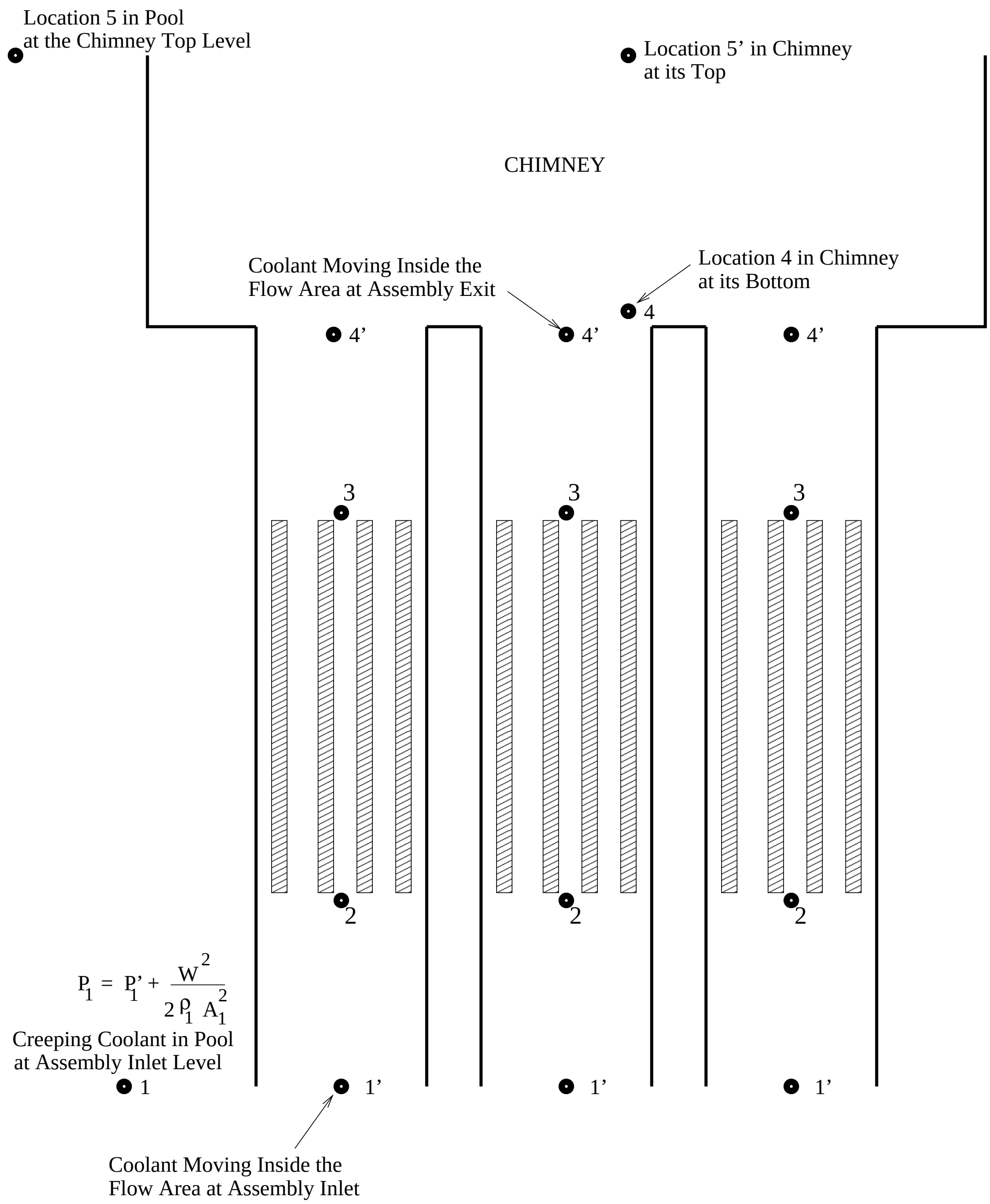


**Fig. 2. Locations of Coolant Pressure in a Group of Fuel Assemblies Exiting into a Common Chimney**

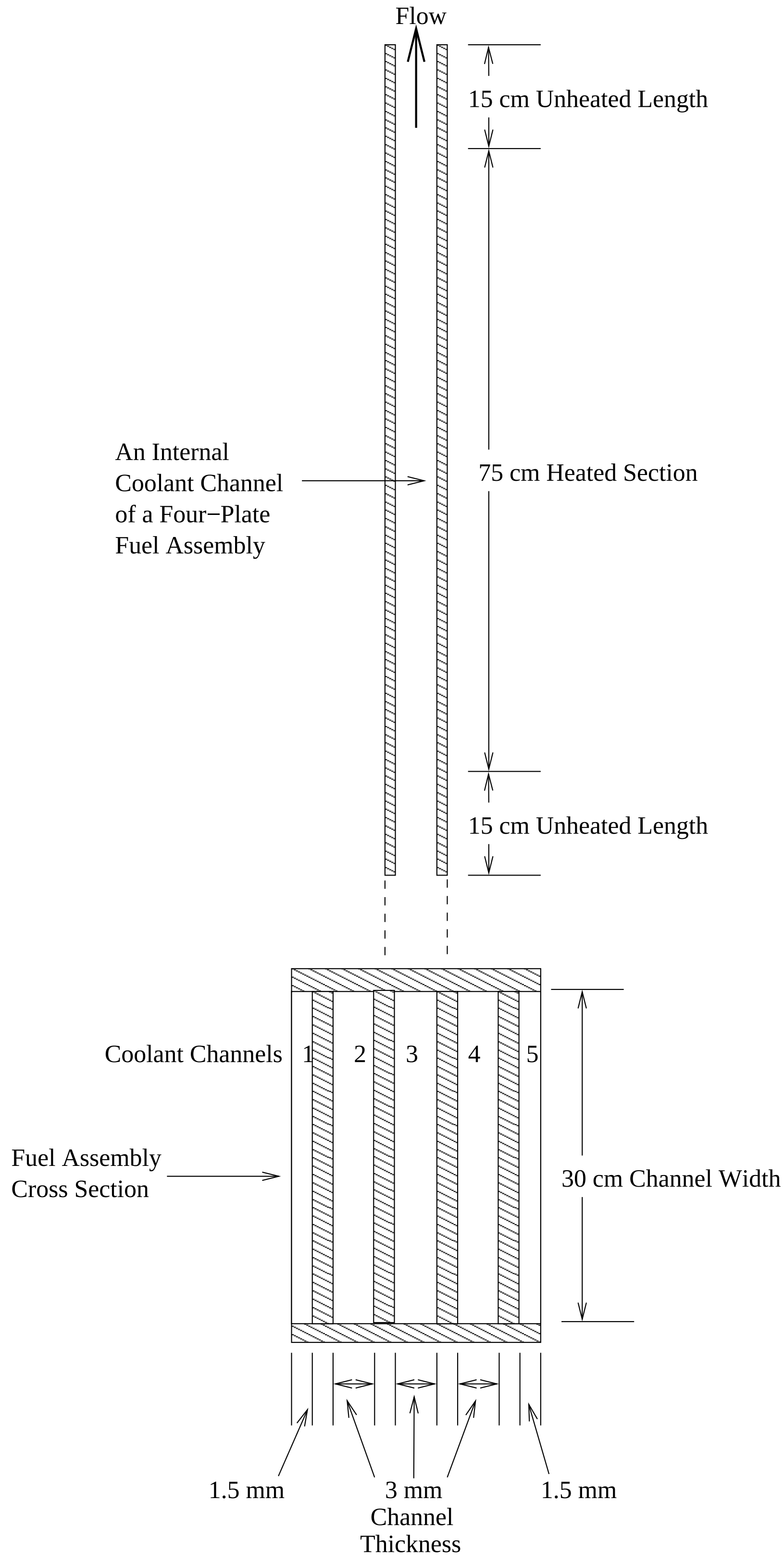


**Fig. 3. Geometry of a Coolant Channel in a Four-Plate Fuel Assembly Used in Test Problem 22**

**Table 1. Solution of Test Problem 22 by Different Codes Used to Verify the Chimney Model in Natural Circulation Calculation in PLTEMP/ANL V3.6**

| Input or Calculated Quantity | PLTEMP/ANL Version 3.6 Solution | *Mathematica* Calculation Using PLTEMP/ANL Coolant Properties | *Mathematica* Calculation Using NATCON Coolant Properties | NATCON V2.2 Code Solution |
|---|---|---|---|---|
| Inlet Temp, °C | 25 | | | |
| Power per Channel, W | 25000 | | | |
| Loss Coeff. at Inlet | 0.5 | | | |
| Loss Coeff. at Exit | 1.0 | | | |
| | **Calculated Quantities** | | | |
| Flow per Channel, kg/s | 0.19809 | 0.19803 | 0.19796 | 0.19967 |
| Exit Temp, °C | 55.225 | 55.235 | 55.253 | 54.990 |
| | **Buoyancy Head, Pa** | | | |
| Axial Region 1 | 0.0 | 0.0 | 0.0 | 0.0 |
| Axial Region 2 (Heated Section) | 34.359 | 34.352 | 34.363 | 33.888 |
| Axial Region 3 | 15.592 | 15.590 | 15.583 | 15.350 |
| Chimney | 207.984 | 207.871 | 207.768 | 204.670 |
| **Total Buoyancy** | **257.935** | **257.813** | **257.715** | **253.904** |
| | **Frictional Pressure Drop, Pa** | | | |
| Inlet Loss | 12.148 | 12.140 | 12.133 | 12.344 |
| Axial Region 1 | 40.047 | 40.035 | 40.049 | 41.050 |
| Axial Region 2 (Heated Length) | 153.696 | 153.627 | 153.552 | 152.600 |
| Axial Region 3 | 27.487 | 27.470 | 27.454 | 22.959 |
| Exit Loss | 24.557 | 24.541 | 24.527 | 24.949 |
| Chimney | 0.0 | 0.0 | 0.0 | 0.0 |
| **Total Pressure Drop** | **257.935** | **257.813** | **257.715** | **253.904** |

## Table 2. Water Properties Used in the NATCON Code and PLTEMP/ANL Code

| Water Properties Used in NATCON Code | | | | Water Properties Used in in PLTEMP/ANL Code at 5.0 bar | | | |
|---|---|---|---|---|---|---|---|
| Temp °C | Specific Heat kJ/kg-°C | Water Density kg/m$^3$ | Dynamic Viscosity μ Pa-s | Temp °C | Enthalpy kJ/kg | Water Density kg/m$^3$ | Dynamic Viscosity μ Pa-s |
| 21.718 | 4.165 | 997.54 | 974 | 20 | 83.952 | 997.988 | 1014.5 |
| 27.301 | 4.168 | 996.30 | 855 | 25 | 104.773 | 996.982 | 901.17 |
| 32.879 | 4.171 | 994.81 | 755 | 30 | 125.608 | 995.759 | 804.50 |
| 38.450 | 4.175 | 993.08 | 673 | 35 | 146.457 | 994.321 | 722.29 |
| 44.022 | 4.179 | 991.06 | 604 | 40 | 167.327 | 992.672 | 652.48 |
| 49.583 | 4.183 | 988.79 | 547 | 45 | 188.211 | 990.815 | 593.26 |
| 55.144 | 4.187 | 986.30 | 499 | 50 | 209.116 | 988.754 | 542.91 |
| 60.694 | 4.192 | 983.57 | 458 | 55 | 230.034 | 986.495 | 499.92 |
| 66.239 | 4.196 | 980.62 | 422 | 60 | 250.973 | 984.042 | 462.93 |
| 71.778 | 4.201 | 977.39 | 392 | 65 | 271.934 | 981.403 | 430.75 |
| 77.311 | 4.206 | 974.00 | 367 | 70 | 292.915 | 978.583 | 401.28 |
| 82.839 | 4.212 | 970.46 | 345 | 75 | 313.923 | 975.590 | 377.03 |
| 88.356 | 4.217 | 966.66 | 326 | 80 | 334.946 | 972.432 | 355.98 |
| 93.867 | 4.223 | 962.76 | 309 | 85 | 356.003 | 969.117 | 337.40 |
| 99.370 | 4.230 | 958.67 | 292 | 90 | 377.075 | 965.655 | 320.63 |
| 104.867 | 4.236 | 954.44 | 277 | 95 | 398.181 | 962.055 | 304.97 |
| 110.356 | 4.244 | 950.09 | 263 | 100 | 419.314 | 958.326 | 290.21 |
| 115.828 | 4.251 | 945.66 | 250 | 105 | 440.476 | 954.482 | 276.41 |
| 121.294 | 4.259 | 941.16 | 238 | 110 | 461.672 | 950.532 | 263.52 |
| 127.190 | 4.268 | 936.20 | 226 | 115 | 482.896 | 946.490 | 251.49 |
| 132.340 | 4.276 | 931.85 | 216 | 120 | 504.162 | 942.367 | 240.27 |
| | | | | 125 | 525.455 | 938.181 | 229.83 |
| | | | | 130 | 546.797 | 933.940 | 220.10 |

**Table 3. Solution of Test Problem 22 with a Chimney by *Mathematica* Using PLTEMP/ANL Coolant Properties and Laminar and Transition Flow Friction Factor Correlations of PLTEMP/ANL**

Flow rate per coolant channel = 0.19803 kg/s

| Region or Axial Node | Nodal Power W | Temp at Node Exit, °C | Temp at Node Center, °C | Density at Node Center kg/m$^3$ | Buoyancy due to Node, Pa | Re at Node Center | Friction Factor at Node Center | Frictional Pressure Drop, Pa |
|---|---|---|---|---|---|---|---|---|
| Inlet | | | | 996.982 | | | | 12.1401 |
| Region 1 | 0.0 | 25.0 | 25.0 | 996.982 | 0.0 | 1450.47 | 0.0653014 | 40.0347 |
| 1 | 1666.67 | 27.0201 | 26.0101 | 996.752 | 0.112582 | 1484.74 | 0.0637941 | 13.0399 |
| 2 | 1666.67 | 29.0397 | 28.0299 | 996.267 | 0.350721 | 1554.72 | 0.0609225 | 12.459 |
| 3 | 1666.67 | 31.0588 | 30.0493 | 995.746 | 0.606063 | 1626.53 | 0.0582328 | 11.9151 |
| 4 | 1666.67 | 33.0774 | 32.0681 | 995.19 | 0.878518 | 1700.07 | 0.0557138 | 11.4061 |
| 5 | 1666.67 | 35.0952 | 34.0863 | 994.6 | 1.16795 | 1775.19 | 0.0533563 | 10.9299 |
| 6 | 1666.67 | 37.1121 | 36.1036 | 993.975 | 1.47425 | 1851.76 | 0.05115 | 10.4845 |
| 7 | 1666.67 | 39.1282 | 38.1201 | 993.317 | 1.79727 | 1929.64 | 0.0490854 | 10.068 |
| 8 | 1666.67 | 41.1439 | 40.136 | 992.624 | 2.13687 | 2008.67 | 0.0471542 | 9.67867 |
| 9 | 1666.67 | 43.1591 | 42.1515 | 991.898 | 2.49291 | 2088.71 | 0.0453473 | 9.31461 |
| 10 | 1666.67 | 45.1735 | 44.1663 | 991.139 | 2.86524 | 2169.59 | 0.0436569 | 8.97425 |
| 11 | 1666.67 | 47.187 | 46.1802 | 990.346 | 3.25371 | 2251.2 | 0.0434203 | 8.93277 |
| 12 | 1666.67 | 49.1997 | 48.1934 | 989.521 | 3.65815 | 2333.41 | 0.0438629 | 9.03134 |
| 13 | 1666.67 | 51.2121 | 50.2059 | 988.664 | 4.07837 | 2416.1 | 0.0441508 | 9.0985 |
| 14 | 1666.67 | 53.2239 | 52.218 | 987.776 | 4.51418 | 2499.21 | 0.0443059 | 9.13867 |
| 15 | 1666.67 | 55.235 | 54.2294 | 986.855 | 4.96541 | 2582.62 | 0.044347 | 9.15567 |
| Region 2 | | 55.235 | | | 34.3522 | | | 153.627 |
| Region 3 | 0.0 | 55.235 | 55.235 | 986.384 | 15.5903 | 2624.43 | 0.04433 | 27.4696 |
| Reg 3 Exit | | 55.235 | | 986.384 | | | | 24.5411 |
| Chimney | | 55.235 | 55.235 | 986.384 | 207.871 | | | |
| Total | | | | | 257.813 | | | 257.813 |

**Table 4. Solution of Test Problem 22 with a Chimney by *Mathematica* Using NATCON Coolant Properties and Laminar and Transition Flow Friction Factor Correlations of PLTEMP/ANL**

Flow rate per coolant channel = 0.19796 kg/s

| Region or Axial Node | Nodal Power W | Temp at Node Exit, °C | Temp at Node Center, °C | Density at Node Center $kg/m^3$ | Buoyancy due to Node, Pa | Re at Node Center | Friction Factor at Node Center | Frictional Pressure Drop, Pa |
|---|---|---|---|---|---|---|---|---|
| Inlet | | | | 996.842 | | | | 12.1329 |
| Region 1 | 0.0 | 25.0 | 25.0 | 996.842 | 0.0 | 1449.09 | 0.0653635 | 40.0491 |
| 1 | 1666.67 | 27.0211 | 26.0105 | 996.609 | 0.114119 | 1483.49 | 0.0638479 | 13.0432 |
| 2 | 1666.67 | 29.0416 | 28.0313 | 996.119 | 0.354515 | 1553.94 | 0.060953 | 12.4579 |
| 3 | 1666.67 | 31.0616 | 30.0516 | 995.596 | 0.610922 | 1626.41 | 0.0582372 | 11.9091 |
| 4 | 1666.67 | 33.0811 | 32.0714 | 995.041 | 0.883126 | 1700.58 | 0.055697 | 11.396 |
| 5 | 1666.67 | 35.1002 | 34.0906 | 994.456 | 1.16996 | 1775.77 | 0.0533387 | 10.9199 |
| 6 | 1666.67 | 37.1186 | 36.1094 | 993.839 | 1.4723 | 1851.84 | 0.0511476 | 10.4778 |
| 7 | 1666.67 | 39.1363 | 38.1275 | 993.188 | 1.79188 | 1929.06 | 0.0491004 | 10.065 |
| 8 | 1666.67 | 41.1533 | 40.1448 | 992.495 | 2.13167 | 2008.09 | 0.0471679 | 9.67564 |
| 9 | 1666.67 | 43.1696 | 42.1615 | 991.765 | 2.48965 | 2088.41 | 0.0453538 | 9.31037 |
| 10 | 1666.67 | 45.1852 | 44.1774 | 991.0 | 2.86461 | 2169.56 | 0.0436574 | 8.96904 |
| 11 | 1666.67 | 47.2001 | 46.1927 | 990.202 | 3.25569 | 2250.89 | 0.0434184 | 8.92712 |
| 12 | 1666.67 | 49.2144 | 48.2072 | 989.373 | 3.66212 | 2332.64 | 0.0438596 | 9.02539 |
| 13 | 1666.67 | 51.2279 | 50.2211 | 988.516 | 4.08255 | 2414.9 | 0.0441476 | 9.09255 |
| 14 | 1666.67 | 53.2407 | 52.2343 | 987.632 | 4.51603 | 2497.78 | 0.0443042 | 9.13296 |
| 15 | 1666.67 | 55.2528 | 54.2467 | 986.718 | 4.96427 | 2581.16 | 0.0443471 | 9.15027 |
| Region 2 | | 55.2528 | | | 34.3634 | | | 153.552 |
| Region 3 | 0.0 | 55.2528 | 55.2528 | 986.249 | 15.5826 | 2623.05 | 0.0443309 | 27.4538 |
| Reg 3 Exit | | 55.2528 | | 986.249 | | | | 24.5265 |
| Chimney | | 55.2528 | 55.2528 | 986.249 | 207.768 | | | |
| Total | | | | | 257.715 | | | 257.715 |

## Table 5. NATCON Input Data for Test Problem 22 Used in the Verification of the Chimney Model

```
PLTEMP Sample Problem 22 on natural circ with chimney modeled by NATCON         Card 0
   15     1     2     4     0     0     2     1     0                         Card 1
0.75        0.3         0.001       100.0       0.0005      180.0             Card 2
1.05        0.3         0.003       40.81       2.0         25.0              Card 3
0.0001      0.5         1.000       200.0                                     Card 4
1.000       1.000       1.000       1.000       1.000       1.000             Card 5
0.0         1.000                                                             Card 6
0.066667    1.000                                                             Card 6
0.133333    1.000                                                             Card 6
0.200000    1.000                                                             Card 6
0.266667    1.000                                                             Card 6
0.333333    1.000                                                             Card 6
0.400000    1.000                                                             Card 6
0.466667    1.000                                                             Card 6
0.533333    1.000                                                             Card 6
0.600000    1.000                                                             Card 6
0.666667    1.000                                                             Card 6
0.733333    1.000                                                             Card 6
0.800000    1.000                                                             Card 6
0.866667    1.000                                                             Card 6
0.933333    1.000                                                             Card 6
1.000000    1.000                                                             Card 6
```

**Table 6. Solution of Test Problem 22 with Chimney by NATCON Code Using its Built-in Coolant Properties and Friction Factor.**

Flow rate per channel = 0.19967 kg/s

| Region or Axial Node of Heated Length, m | Axial Length, m | Coolant Temp at Node Exit, C | Coolant Temp at Node Center, C | Coolant Density, kg/m$^3$ | Buoyancy Due to Node, Pa | Reynolds Number | Friction Factor | Frictional Pressure Drop, Pa |
|---|---|---|---|---|---|---|---|---|
| Inlet | | | | | | | | 12.3440 |
| Region 1 | 0.1500 | | | | 0.0000 | | | 41.0500 |
| 1 | 0.0500 | 27.003 | 26.002 | 996.590 | 0.1090 | 1493.100 | 0.06430 | 13.3630 |
| 2 | 0.0500 | 29.006 | 28.005 | 996.110 | 0.3425 | 1564.500 | 0.06136 | 12.7590 |
| 3 | 0.0500 | 31.009 | 30.008 | 995.580 | 0.6047 | 1634.200 | 0.05875 | 12.2220 |
| 4 | 0.0500 | 33.011 | 32.010 | 995.040 | 0.8668 | 1710.300 | 0.05613 | 11.6840 |
| 5 | 0.0500 | 35.012 | 34.012 | 994.460 | 1.1528 | 1785.000 | 0.05378 | 11.2010 |
| 6 | 0.0500 | 37.013 | 36.013 | 993.840 | 1.4574 | 1859.200 | 0.05164 | 10.7610 |
| 7 | 0.0500 | 39.013 | 38.013 | 993.220 | 1.7618 | 1939.800 | 0.04949 | 10.3210 |
| 8 | 0.0500 | 41.013 | 40.013 | 992.510 | 2.1059 | 2016.300 | 0.04761 | 9.9361 |
| 9 | 0.0500 | 43.012 | 42.012 | 991.790 | 2.4610 | 2095.700 | 0.04581 | 9.5669 |
| 10 | 0.0500 | 45.010 | 44.011 | 991.060 | 2.8160 | 2181.500 | 0.04401 | 9.1971 |
| 11 | 0.0500 | 47.007 | 46.009 | 990.250 | 3.2153 | 2258.100 | 0.04251 | 8.8922 |
| 12 | 0.0500 | 49.004 | 48.006 | 989.430 | 3.6148 | 2340.200 | 0.04102 | 8.5875 |
| 13 | 0.0500 | 51.000 | 50.002 | 988.600 | 4.0223 | 2425.400 | 0.03958 | 8.2928 |
| 14 | 0.0500 | 52.995 | 51.998 | 987.710 | 4.4601 | 2504.800 | 0.03833 | 8.0370 |
| 15 | 0.7500 | 54.990 | 53.993 | 986.820 | 4.8979 | 2589.600 | 0.03707 | 7.7812 |
| Region 2 | 0.7500 | 54.990 | | | 33.8883 | | | 152.6000 |
| Region 3 | 0.1500 | 54.990 | 54.990 | 986.370 | 15.3500 | 2634.100 | 0.03645 | 22.9590 |
| Region 3 Exit | | 54.990 | | 986.370 | | | | 24.9490 |
| Chimney | 2.0000 | 54.990 | 54.990 | 986.370 | 204.6700 | | | |
| Total | 3.0500 | | | | 253.9040 | | | 253.9040 |

## Table 7. PLTEMP/ANL Input Data for Test Problem 22 Used in the Verification of the Chimney Model

```
 Test Problem 22: Natural Circulation, 2.0 m chimney, f = 94.7174/Re
! 2 assemblies, Total power = 0.20 MWt, Axially uniform power profile
! Each assembly has 4 fuel plates and 5 coolant channels
! H2O coolant, All hot channel factors = 1.0, No bypass flow, NCTYP=0
! 14 axial heat transfer nodes in the heated length of fuel plates
!  1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18  19  20 # Card 200
   5   0   0   1   0   1   1   1   0   0   0   0   0   0   1   1   0   0   0   1   Card 200
   1                                                                              Card 200A
   2   3 0.50       1.00        1.00        1.00           0                      Card(1)0300
! Using pressure driven mode
   1   1 1.00                                                                     Card(1)0301
   1   1   1                                                                      Card(1)0302
1.00       1.00                                                                   Card(2)0303
36.0E-04    5.94059E-03 0.15        0.50        0.30        3.00E-03              Card(3)0304
0.00        5.94059E-03 0.75        0.00        0.30        3.00E-03              Card(3)0304
36.0E-04    5.94059E-03 0.15        1.00        0.30        3.00E-03              Card(3)0304
! Use the code's built-in correlation for friction factor
!                                   CHIMNY
0.00        0.00        0.00        2.0                                           Card(1)0305
   5   3 0.00       0.75        0.50E-03    180.00        1.00E-03    100.00    Card(1)0306
4.50E-04    5.94059E-03 0.3030      0.30        0.30        3.00E-03              Card(5)0307
9.00E-04    5.94059E-03 0.6060      0.60        0.30        3.00E-03              Card(5)0307
9.00E-04    5.94059E-03 0.6060      0.60        0.30        3.00E-03              Card(5)0307
9.00E-04    5.94059E-03 0.6060      0.60        0.30        3.00E-03              Card(5)0307
4.50E-04    5.94059E-03 0.3030      0.30        0.30        3.00E-03              Card(5)0307
0.30        0.30        0.30        0.30                                          Card(1)0308
! Card 0308A not required
! Radial power peaking factor data by fuel plate for each subassembly. Input flow data by
! channel for each subassembly on Cards 0310 not required because WFGES(1) is non-zero
1.000       1.000       1.000       1.000                                         Card(2)0309
1.000       1.000       1.000       1.000                                         Card(2)0309
! DP0       DDP         DPMAX       POWER       TIN         PIN
0.0003275   0.04        0.00        0.200       25.0        0.50                  Card(1)0500
0.00        0.00                                                                  Card(2)0500
  50 0.0001     25.0        0.00        0.00                                      Card(1)0600
  16                                                                              Card(1)0700
0.000000    1.000                                                                 Card(15)0701
0.066667    1.000                                                                 Card(15)0701
0.133333    1.000                                                                 Card(15)0701
0.200000    1.000                                                                 Card(15)0701
0.266667    1.000                                                                 Card(15)0701
0.333333    1.000                                                                 Card(15)0701
0.400000    1.000                                                                 Card(15)0701
0.466667    1.000                                                                 Card(15)0701
0.533333    1.000                                                                 Card(15)0701
0.600000    1.000                                                                 Card(15)0701
0.666667    1.000                                                                 Card(15)0701
0.733333    1.000                                                                 Card(15)0701
0.800000    1.000                                                                 Card(15)0701
0.866667    1.000                                                                 Card(15)0701
0.933333    1.000                                                                 Card(15)0701
1.000000    1.000                                                                 Card(15)0701
   0                                                                              Card(11)0702
```

**Table 8. Solution of Test Problem 22 with a Chimney by PLTEMP/ANL V3.6 Code Using its Laminar and Transition Flow Friction Factor Correlations**

Flow rate per coolant channel = 0.19809 kg/s

| Region or Axial Node of Heated Length | Axial Length, m | Fraction of Left/Right Fuel Plate Power Going to Channel | Coolant Temp at Node Exit, °C | Coolant Temp at Node Center, °C | Coolant Density, kg/m$^3$ | Buoyancy Due to Node, Pa | Reynolds Number | Friction Factor | Frictional Pressure Drop, Pa |
|---|---|---|---|---|---|---|---|---|---|
| Inlet | | | 25.000 | | 996.982 | | | | 12.1478 |
| Region 1 | 0.150 | | 25.000 | 25.000 | 996.982 | 0.0000 | 1450.93 | 0.065281 | 40.0473 |
| 1 | 0.050 | 0.50/0.50 | | 26.010 | 996.752 | 0.1130 | 1485.21 | 0.063774 | 13.0440 |
| 2 | 0.050 | 0.50/0.50 | | 28.030 | 996.266 | 0.3512 | 1555.20 | 0.060904 | 12.4630 |
| 3 | 0.050 | 0.50/0.50 | | 30.049 | 995.745 | 0.6066 | 1627.03 | 0.058215 | 11.9191 |
| 4 | 0.050 | 0.50/0.50 | | 32.067 | 995.189 | 0.8791 | 1700.57 | 0.055697 | 11.4100 |
| 5 | 0.050 | 0.50/0.50 | | 34.085 | 994.599 | 1.1686 | 1775.71 | 0.053341 | 10.9336 |
| 6 | 0.050 | 0.50/0.50 | | 36.102 | 993.975 | 1.4747 | 1852.23 | 0.051137 | 10.4885 |
| 7 | 0.050 | 0.50/0.50 | | 38.118 | 993.316 | 1.7977 | 1930.12 | 0.049073 | 10.0720 |
| 8 | 0.050 | 0.50/0.50 | | 40.133 | 992.623 | 2.1373 | 2009.15 | 0.047143 | 9.6825 |
| 9 | 0.050 | 0.50/0.50 | | 42.149 | 991.897 | 2.4934 | 2089.20 | 0.045337 | 9.3184 |
| 10 | 0.050 | 0.50/0.50 | | 44.164 | 991.138 | 2.8657 | 2170.10 | 0.043647 | 8.9778 |
| 11 | 0.050 | 0.50/0.50 | | 46.177 | 990.345 | 3.2542 | 2251.73 | 0.043424 | 8.9391 |
| 12 | 0.050 | 0.50/0.50 | | 48.190 | 989.520 | 3.6587 | 2333.95 | 0.043865 | 9.0376 |
| 13 | 0.050 | 0.50/0.50 | | 50.202 | 988.663 | 4.0789 | 2416.67 | 0.044152 | 9.1046 |
| 14 | 0.050 | 0.50/0.50 | | 52.214 | 987.775 | 4.5147 | 2499.78 | 0.044307 | 9.1446 |
| 15 | 0.050 | 0.50/0.50 | 55.225 | 54.224 | 986.855 | 4.9655 | 2583.14 | 0.044347 | 9.1615 |
| Region 2 | 0.750 | | 55.225 | | | 34.3589 | | | 153.6962 |
| Region 3 | 0.150 | | 55.225 | 55.225 | 986.383 | 15.5918 | 2624.97 | 0.044330 | 27.4868 |
| Region 3 Exit | | | 55.225 | | 986.383 | | | | 24.5566 |
| Chimney | 2.000 | | 55.225 | 55.225 | 986.383 | 207.9840 | | | |
| Total | 3.050 | | | | | 257.9347 | | | 257.9347 |

## APPENDIX H. *Mathematica* Program for Solving Test Problem 22

```
(" SOLUTION OF NATURAL CIRCULATION STANDARD PROBLEM 20, Using Water Properties of
the PLTEMP/ANL V3.5 Code ")
data={kin=0.5,kex=1.0,Dh=0.00594059,len1=0.15,len2=0.75,len3=0.15,wch=0.3,tch=0.003,grav=9.8066
5,erel=0.0,tin=25.0,powr=25000.0};
flow=0.1980283;
flow=0.1980283; <———— This guess flow was adjusted and the program was rerun to achieve channel
                      channel buoyancy (buoy) equal to channel frictional pressure drop (delp).
chimny=2.0
(* power = 25 kW per plate, total power = 200 kW in 8 plates *)
Print["Subcooled water density, kg/m**3, at 5 bar absolute used in the PLTEMP/ANL V3.5 Code"];
rho={{20.,997.9875},{25.,996.9820},{30.,995.7591},{35.,994.3214},{40.,992.6718},{45.,990.8146},{5
0.,988.7536},{55.,986.4945},{60.,984.0422},{65.,981.4029},{70.,978.5832},{75.,975.5897},{80.,972.43
24},{85.,969.1167},{90.,965.6552},{95.,962.0546},{100.,958.3263},{105.,954.4819},{110.,950.5318},{
115.,946.4900},{120.,942.3674},{125.,938.1805},{130.,933.9403},{135.,929.6651},{140.,925.3685},{1
45.,921.0693},{150.,916.7842}};
Plot[Interpolation[rho][temp],{temp,20,150}];
Print["Subcooled water enthalpy, kJ/kg, at 5 bar absolute used in the PLTEMP/ANL V3.5 Code"];
enthalpy={{20.,83.9517},{25.,104.7730},{30.,125.6082},{35.,146.4573},{40.,167.3272},{45.,188.2110}
,{50.,209.1156},{55.,230.0341},{60.,250.9734},{65.,271.9336},{70.,292.9146},{75.,313.9233},{80.,334
.9460},{85.,356.0033},{90.,377.0746},{95.,398.1805},{100.,419.3143},{105.,440.4758},{110.,461.6720
},{115.0,482.8960},{120.,504.1616},{125.,525.4550},{130.,546.7970},{135.,568.1738},{140.,589.5991
},{145.,611.0661},{150.,632.5816}};
Plot[Interpolation[enthalpy][temp],{temp,20,150}];
Print["Dynamic viscosity, micro Pa-s, of water used in the PLTEMP/ANL V3.5 Code"];
visc={{20.,1014.5},{25.,901.17},{30.,804.50},{35.,722.29},{40.,652.48},{45.,593.26},{50.,542.91},{55
.,499.92},{60.,462.93},{65.,430.75},{70.,401.28},{75.,377.03},{80.,355.98},{85.,337.40},{90.,320.63},
{95.,304.97},{100.,290.21},{105.,276.41},{110.,263.52},{115.,251.49},{120.,240.27},{125.,229.83},{1
30.,220.10},{135.,211.05},{140.,202.64},{145.,194.82},{150.,187.56}};
Plot[Interpolation[visc][temp],{temp,20,150}];
Print["Inlet and Exit temperatures, C"];
tin=tin/.data
grav=grav/.data;
hin=1000*Interpolation[enthalpy][tin];
hout=hin+powr/flow/.data;
tout=tx/.FindRoot[hout==1000*Interpolation[enthalpy][tx],{tx,tin}]
rhoin=Interpolation[rho][tin];
rhoout=Interpolation[rho][tout];
Print["Density at inlet =",rhoin,", Density at exit =",rhoout];
rhoave=NIntegrate[Interpolation[rho][temp],{temp,tin,tout}]/(tout-tin);
Print["Integrated average coolant density over (",tin," to ",tout,") = ",rhoave];
buoy2=(rhoin-rhoave)*grav*len2 /.data;
buoy3=(rhoin-rhoout)*grav*len3 /.data;
buoychimny=(rhoin-rhoout)*grav*chimny /.data;
Print["Buoyancy due to chimney =",buoychimny];
buoy=buoy2+buoy3;
Print["DRIVING PRESSURE HEAD DUE TO BUOYANCY in Section 1 =0.0, Section 2 =",buoy2,",
Section 3 =",buoy3,", Total buoyancy (Pa) =",buoy];
```

```
velin=flow/(rhoin*wch*tch)/.data;
Print["Coolant inlet velocity, m/s = ",velin];
visc1=0.000001*Interpolation[visc][tin];
visc3=0.000001*Interpolation[visc][tout];
Print["Coolant dynamic viscosity, Pa-s, in axial regions 1 and 3 =",visc1," ",visc3]
reyn1=flow*Dh/(wch*tch*visc1)/.data;
reyn3=flow*Dh/(wch*tch*visc3)/.data;
Print["Reynolds numbers in axial regions 1 and 3 =",reyn1," ",reyn3];
aspect=tch/wch/.data;
erela=If[0<erel<0.00000001,0.00000001,erel]/.data;
Cfric=96*(1-1.3553*aspect+1.9467*aspect^2-1.7012*aspect^3+0.9564*aspect^4-0.2537*aspect^5)
fric2200=Cfric/2200.0;
reyn=reyn1;
fa=1/(-2*Log[10,erela/3.7+2.51/reyn*(1.14-2*Log[10,erela+21.25/reyn^0.9])])^2;
If[reyn>=3000 && erela==0,fb=4*fric/.FindRoot[fric==6.25002/(1-
8.68591*Log[reyn*fric^0.5]+18.8612*(Log[reyn*fric^0.5])^2),{fric,0.1}]];
If[reyn>=3000 && erela>=0.00000001,
   fb=4*fric/.FindRoot[fric==0.331369/(Log[0.27027*erela+1.255/(reyn*fric^0.5)])^2,{fric,0.1}]];
If[reyn>=3000,Print["Turbulent friction factor fb = ",fb,", Re = ",reyn,", Rel roughness = ",erela]];
frica=If[reyn<=2200.0,Cfric/reyn,fric2200+(fa-fric2200)*(3.75-8250/reyn)];
fric1=If[reyn>=3000.0,fb,frica];
reyn=reyn3;
fa=1/(-2*Log[10,erela/3.7+2.51/reyn*(1.14-2*Log[10,erela+21.25/reyn^0.9])])^2;
If[reyn>=3000 && erela==0,fb=4*fric/.FindRoot[fric==6.25002/(1-
8.68591*Log[reyn*fric^0.5]+18.8612*(Log[reyn*fric^0.5])^2),{fric,0.1}]];
If[reyn>=3000 && erela>=0.00000001,
   fb=4*fric/.FindRoot[fric==0.331369/(Log[0.27027*erela+1.255/(reyn*fric^0.5)])^2,{fric,0.1}]];
If[reyn>=3000,Print["Turbulent friction factor fb = ",fb,", Re = ",reyn,", Rel roughness = ",erela]];
frica=If[reyn<=2200.0,Cfric/reyn,fric2200+(fa-fric2200)*(3.75-8250/reyn)];
fric3=If[reyn>=3000.0,fb,frica];
Print["Friction factors in Sections 1 and 3 =",fric1," ",fric3];
Print["FRICTIONAL PRESSURE DROP IN SECTION 1"]
delp1s=(fric1*len1/Dh)*0.5*(flow/(wch*tch))^2/rhoin/.data;
delp1m=kin*0.5*(flow/(wch*tch))^2/rhoin/.data;
delp1=delp1s+delp1m;
Print["Total pressure drop in Section 1 =",delp1,", Minor loss = ",delp1m,", Wall shear =",delp1s]
Print["FRICTIONAL PRESSURE DROP IN SECTION 3"]
delp3s=(fric3*len3/Dh)*0.5*(flow/(wch*tch))^2/rhoout/.data;
delp3m=kex*0.5*(flow/(wch*tch))^2/rhoout/.data;
delp3=delp3s+delp3m;
Print["Total pressure drop in Section 3 =",delp3,", Minor loss = ",delp3m,", Wall shear =",delp3s]
delp4=rhoin*velin*velin*(rhoin/rhoout-1.0)/.data;
Print["Pressure drop due to momentum flux (Pa) =",delp4];
Print["Flow =",flow,", g =",grav,", Temp at inlet and exit =",tin,", ",tout,", Density at inlet and exit
=",rhoin,", ",rhoout,", Gravity head =",grav*(rhoin*len1+rhoave*len2+rhoout*len3)/.data,", Total
buoyancy =",buoy,", Buoyancy in Section 2 =",buoy2,", Buoyancy in Section 3 =",buoy3,", Power into
coolant (W) =",flow*(hout-hin)]
Print["LOOP OVER 21 AXIAL SEGMENTS"];
powr1=powr/15/.data;
delz=len2/15/.data;
enth1=hin;
```

```
temp1=tin;
delp2p=0;
buoy2p=0;
Do[powr2=powr1;
  If[j<4,powr2=0];
  If[j>18,powr2=0];
  enth2=enth1+powr2/flow;
  temp2=tx/.FindRoot[enth2==1000*Interpolation[enthalpy][tx],{tx,temp1}];
  tempj=0.5*(temp2+temp1);
  viscj=0.000001*Interpolation[visc][tempj];
  rhoj=Interpolation[rho][tempj];
  buoy2s=buoy2p+grav*(rhoin-rhoj)*delz;
  reynj=flow*Dh/(wch*tch*viscj)/.data;
  reyn=reynj;
  fa=1/(-2*Log[10,erela/3.7+2.51/reyn*(1.14-2*Log[10,erela+21.25/reyn^0.9])])^2;
  If[reyn>=3000 && erela==0,fb=4*fric/.FindRoot[fric==6.25002/(1-
8.68591*Log[reyn*fric^0.5]+18.8612*(Log[reyn*fric^0.5])^2),{fric,0.1}]];
  If[reyn>=3000 && erela>=0.00000001,
    fb=4*fric/.FindRoot[fric==0.331369/(Log[0.27027*erela+1.255/(reyn*fric^0.5)])^2,{fric,0.1}]];
  If[reyn>=3000,Print["Turbulent friction factor fb = ",fb,", Re = ",reyn,", Rel roughness = ",erela]];
  frica=If[reyn<=2200.0,Cfric/reyn,fric2200+(fa-fric2200)*(3.75-8250/reyn)];
  fricj=If[reyn>=3000.0,fb,frica];
  delpj=(fricj*delz/Dh)*0.5*(flow/(wch*tch))^2/rhoj/.data;
  delp2=delp2p+delpj;
  (*Print["Axial segment =",j,", Flow, kg/s =",flow,", delz (m) =",delz,"Power in segment (W) =",powr2,",
Enthalpy at segment exit (J/kg) =",enth2,", Enthalpy at segment center (J/kg) =",0.5(enth1+enth2),",
Temp at segment exit (C) =",temp2,", Segment mean temp (C) =",tempj,", Segment mean density
(kg/m^3) =",rhoj,", Buoyancy due to segments 1 through ",j," (Pa) =",buoy2s,", Viscosity (Pa-s)
=",viscj,", Reynolds number =",reynj,", Friction factor =",fricj,", fl/Dh of segment (Pa) =",delpj,",
Cumulative sum fL/Dh of segments 1 through ",j", (Pa) =",delp2];*)
  Print[j,"  ",powr2,"  ",temp2,"  ",tempj,"  ",rhoj,"  ",grav*(rhoin-rhoj)*delz,"  ",reynj,"  ",fricj,"
",delpj];
  buoy2p=buoy2s;
  delp2p=delp2;
  temp1=temp2;
  enth1=enth2,
  {j,1,21}]
Print["Pressure drop due to wall shear in region 2 = ",delp2-delp1s-delp3s]
Print["BALANCE OF BUOYANCY AND FRICTIONAL PRESSURE DROP:"]
delp=delp2+delp1m+delp3m;
buoy=buoy2s+buoychimny;
Print["Total buoyancy (Pa) =",buoy,", Total frictional pressure drop (Pa) =",delp];
```

## 11. Verification of the Hot Channel Factors Option in Natural Circulation Calculation by PLTEMP/ANL V3.6

(January 2009)

### Executive Summary

A natural circulation calculation was implemented in the PLTEMP/ANL V3.5 code. In V3.6 of the code, the treatment of uncertainties in fuel assembly geometry and in thermal-hydraulic data and methods that is available for forced flow calculations in V3.5 of the code (using six hot channel factors), was recently extended to the case of natural circulation calculations. For the verification of this extension of the six hot channel factors treatment, a natural circulation test problem for a 4-fuel-plate assembly was solved by PLTEMP/ANL V3.6 and verified by *Mathematica* calculations. *Mathematica* calculations were done for (i) the nominal case without applying any hot channel factors and (ii) with only the three global hot channel factors. These *Mathematica* solutions agree well with the PLTEMP/ANL solution as shown in Table 1. This provides a verification of the implementation of the six hot channel factors in the case of natural circulation calculation in PLTEMP/ANL V3.6. Table 2 summarizes the effect of global and local hot channel factors on the solution of the test problem.

### 11.1. Introduction

The PLTEMP/ANL code was improved to model natural circulation flow upward through the fuel assemblies and downward in the reactor pool. In the model, the flows of all fuel assemblies in the problem can enter into a common chimney, or the flows of a group of fuel assemblies enter into a common chimney. In the latter case, the problem will have more than one chimney. The schematic and physical geometries of the model are shown in Figs. 1 and 2. The thermal-hydraulic equations to model the chimney and the method of solution are described in the PLTEMP/ANL V3.6 Users Guide[1]. There was a need for incorporating in the model hot channel factors for treating uncertainties in fuel assembly geometry and in thermal-hydraulic data and methods in research reactor conversion analyses.  In the case of forced flow calculations, an option for treating the uncertainties using six hot channel factors was already available. This hot channel factors treatment was recently extended to the case of natural circulation calculation in the PLTEMP/ANL V3.6 code.

This memorandum documents a verification of this extension of the six hot channel factors treatment to a natural circulation calculation, using a natural circulation test problem. The test problem is defined in Section 11.2, and referred to as Test Problem 21. Its solution by two methods/codes are reported and compared here: (1) *Mathematica* calculation using the coolant properties used in the PLTEMP/ANL code, and (2) Solution by the PLTEMP/ANL Version 3.6 code. The solutions by *Mathematica* were obtained for a single coolant channel, and the PLTEMP/ANL solution was obtained for a four-plate fuel assembly.

### 11.2. Test Problem Used in Verification

Problem Definition: Calculate the coolant flow rate caused by natural circulation in a 1.05 m long vertical coolant channel having a heated length of 0.75 m. The lower unheated length is 0.15 m, and the upper unheated length is 0.15 m. The heated length has a power of 12.5 kW distributed uniformly over the 0.75 m length, with an inlet temperature of 25 °C. The channel has a rectangular cross section of thickness 3 mm, width 0.3 m, inlet pressure loss coefficient 0.5, and exit pressure loss coefficient 1.0. The absolute pressure at the channel inlet is 5 bar, corresponding to the channel inlet being 40.81 m below the free surface of water in the pool. Also calculate the effect of the following values of the six hot channel factors used in treatment option 2 (IHCF = 2) in PLTEMP/ANL input data[1].

System-wide hot channel factors: FPOWER = 1.20, FFLOW = 1.20, FNUSLT = 1.15,
Random or local hot channel factors: FBULK = 1.15, FFILM = 1.18, FFLUX = 1.22

where

| | |
|---|---|
| FPOWER | = A factor to account for the uncertainty in total reactor power measurement |
| FFLOW | = A factor to account for the uncertainty in total reactor flow measurement |
| FNUSLT | = A factor to account for the uncertainty in Nusselt number correlation |
| FBULK | = A factor to account for the uncertainty in local bulk coolant temperature rise |
| FFILM | = A factor to account for the uncertainty in local temperature rise across the coolant film (from the bulk coolant to the cladding surface) |
| FFLUX | = A factor to account for the uncertainty in local heat flux from the cladding surface to the coolant. |

The thermal-hydraulic input data (see nomenclature given at the end) for the problem are as follows:

| | | | |
|---|---|---|---|
| $D_h$ = 0.0059406 m, | $g$ = 9.8 m/s$^2$, | $H_{in}$ = 41.81 m, | $K_{in}$ = 0.5, |
| $K_{ex}$ = 1.0, | $L_1$ = 0.15 m, | $L_2$ = 0.75 m, | $L_3$ = 0.15 m, |
| $L$ = 1.05 m, | $L_{ch}$ = 2.00 m, | $Q$ = 12500 W, | $P_{in}$ = 5.0 bar, |
| $T_{in}$ = 25 °C, | $T_{ch}$ = 0.003 m, | $W_{ch}$ = 0.3 m, | |

$W$ = 0.072086 kg/s (*assumed value*)

### 11.3. *Mathematica* Calculations

A *Mathematica* program was written in which any set of coolant properties and friction factor correlations could be inserted. In the current calculations, the coolant properties and friction factor correlations of the PLTEMP/ANL code were inserted into the *Mathematica* program. The *Mathematica* program uses coolant enthalpy as a function of temperature, as shown by the program listing given in Appendix I.

The program uses 21 axial nodes (mesh intervals) of equal length in the total channel length of 1.05 m, with three each in the lower and upper unheated lengths of the channel, and 15 in the heated length. Starting from a guessed flow rate, the program calculates the coolant enthalpy at each node exit, the coolant temperature at the node exit, and the temperature at the node-center. Using the node-center temperature, the program finds the nodal Reynolds number, friction factor, nodal frictional pressure drop, and the nodal contribution to buoyancy. It finds the channel inlet and outlet pressure losses. It finds the buoyancy due to the chimney. The frictional pressure drop in the chimney is assumed to be negligible. The momentum flux term is ignored because it is small. The calculation ends after printing the total buoyancy and the total frictional pressure drop in the channel. It runs so fast that several guessed flow rates could be tried in a few minutes. To find the steady-state natural circulation flow rate, the user reruns the program several times, each time using a more improved guess of the flow rate, in order to make the total buoyancy equal to the total frictional pressure drop.

The following three solutions to Test Problem 21 were obtained using the Mathematica program:

(1) A solution using the nominal power (12.5 kW) whose results are given in Table 3. This solution gives a flow rate of 0.072071 kg/s per channel.

(2) A solution using a power of 15.0 kW which is obtained by multiplying the nominal power by the global hot channel factor for power, i.e., 1.20x12.5 kW. This solution gives a flow rate of 0.080415 kg/s per channel. The results of this solution are given in Table 4.

(3) A coolant temperature distribution calculation at a channel flow rate of 0.0670128 kg/s which equals the flow rate found in the second calculation divided by the global hot channel factor FFLOW for flow, i.e., 0.080415/1.20 = 0.0670128 kg/s. The results of this calculation are given in Table 5.

The three *Mathematica* calculations given in Tables 3, 4 and 5 are summarized in Table 1 for comparison with PLTEMP/ANL calculation.

## 11.4. PLTEMP/ANL Version 3.6 Code Calculation

To solve Test Problem 21 using the PLTEMP/ANL V3.6 code, the problem defined above in Section 11.2 is turned into a research reactor problem of two geometrically identical and equal-power fuel assemblies, each consisting of (arbitrarily) four fuel plates cooled by five coolant channels (Fig. 3). Only the first fuel assembly in the test problem is relevant to the present verification. The second fuel assembly is not used in the verification. The purpose of the second fuel assembly is to illustrate the effect of unequal fuel plate powers on channel flow rates, the resulting unequal partitioning of each plate power into its two adjacent coolant channels, and the effect of hot channel factors on such a fuel assembly.

In the first fuel assembly, each fuel plate produces an equal nominal power of 12.5 kW as specified in the problem definition, and the fuel assembly has a power of 50 kW. The internal channels (channels 2, 3, and 4) are of the thickness 3 mm as specified in the problem definition. In order to have identical axial profiles of coolant temperature in each channel, the first and the last channels are of half thickness, i.e., 1.5 mm. Based on symmetry, it is noted that exactly half of each fuel plate's power goes to each coolant channel adjacent to the plate.

In the second fuel assembly, the fuel plates produce unequal powers as specified by the radial power factors input on Card 0309. The only difference between the two fuel assemblies is in the radial power factors. The fuel plates 1, 2, 3, and 4 produce nominal powers of 7.5 kW, 17.5 kW, 17.5 kW, and 7.5 kW respectively, and the fuel assembly has a power of 50 kW. Hence the total power in the input data is 0.1 MW. Table 6 gives the input data used in the PLTEMP/ANL V3.6 code.

In the input data of Table 6, the friction factor is obtained using the PLTEMP/ANL V3.6 code's built-in correlations which accounts for laminar, transition, or turbulent flow as the case may be. The code calculates three solutions in one run: (1) the nominal power solution given in Table 7, (2) the solution with global hot channel factors applied, given in Table 8, and (3) the temperature distribution with both global and local hot channel factors applied, given in Table 9. The input and output files are saved in the following files:

/home/sol1a/kalimull/natcirc.pltemp/input.Stdproblem21.ihcf=2_v36.all6hcf
/home/sol1a/kalimull/natcirc.pltemp/output.Stdproblem21.ihcf=2_v36.all6hcf

These results are summarized in Table 1 for comparison with the *Mathematica* solutions of the problem. The flow is laminar over the whole part of the channel. The Darcy-Weisbach friction factor is calculated using the following correlations.

$$f = \begin{cases} f_{lam}(\mathrm{Re}, a) & \text{if } \mathrm{Re} \le 2200 \\ \left(3.75 - \dfrac{8250}{\mathrm{Re}}\right)\left(f_a - f_{2200}\right) + f_{2200} & \text{if } 2200 < \mathrm{Re} < 3000 \end{cases} \quad (1)$$

where

$$f_{lam}(\mathrm{Re}, a) = \frac{96\left(1 - 1.3553\,a + 1.9467\,a^2 - 1.7012\,a^3 + 0.9564\,a^4 - 0.2537\,a^5\right)}{\mathrm{Re}} \quad (2)$$

$$f_{2200} = f_{lam}(2200, a) \quad (3)$$

$$f_a = \left[-2\,\mathrm{Log}_{10}\left\{\frac{E_{rel}}{3.7} + \frac{2.51}{\mathrm{Re}}\left\{1.14 - 2\,\mathrm{Log}_{10}\left(E_{rel} + 21.25\,\mathrm{Re}^{-0.9}\right)\right\}\right\}\right]^{-2} \quad (4)$$

$a$ = Channel aspect ratio = Channel thickness/width ratio, always ≤ 1.0
$E_{rel}$ = Relative roughness

The numerator of Eq. (2) for the laminar friction factor is found to be 94.7174/Re based on the thickness-to-width ratio of the coolant channel. The results of the PLTEMP/ANL calculation at the nominal power agree well with the corresponding *Mathematica* solution given in column 3 of Table 1. Also, the results of the PLTEMP/ANL calculation at the global hot channel factors applied power agree well with the corresponding *Mathematica* solution given in column 5 of Table 1. These comparisons provide a verification of the implementation of hot channel factors treatment in the natural circulation calculation implemented in the PLTEMP/ANL V3.6 code.

**11.5. Conclusions**

There is a good agreement between the PLTEMP/ANL V3.6 and *Mathematica* solutions of the test problem, as shown in Table 1. The flow rate per channel calculated by PLTEMP/ANL V3.6 at the nominal power is 0.072086 kg/s, compared to 0.072071 kg/s calculated by *Mathematica*.

With the global hot channel factors applied, the flow rate per channel calculated by PLTEMP/ANL V3.6 is 0.067016 kg/s, compared to 0.067013 kg/s calculated by *Mathematica*. This provides a verification of the hot channel factors treatment in the natural circulation calculation in the PLTEMP/ANL V3.6 code.

## NOMENCLATURE

| | |
|---|---|
| a | Channel aspect ratio = Channel thickness/width ratio, always ≤ 1.0 |
| $C_p$ | Coolant specific heat averaged over the temperature range 25 to 80 °C existing in the problem, J/kg-°C |
| $D_h$ | Hydraulic diameter of the channel, m |
| $E_{rel}$ | Relative roughness |
| g | Acceleration due to gravity, m/s$^2$ |
| $H_{in}$ | Water depth at the channel inlet, m |
| $L_1$ | Unheated channel length below the heated section, m |
| $L_2$ | Heated length of channel, m |
| $L_3$ | Unheated channel length above the heated section, m |
| L | Channel height = $L_1 + L_2 + L_3$ , m |
| $L_{ch}$ | Effective chimney height, m |
| $K_{in}$ | Pressure loss coefficient at the channel inlet |
| $K_{ex}$ | Pressure loss coefficient at the channel exit |
| $\Delta P_{buoy}$ | Pressure head due to buoyancy, Pa |
| $\Delta P_{fric}$ | Total frictional pressure drop in the coolant channel, Pa |
| $P_{in}$ | Pressure at the channel inlet, Pa |
| Q | Power in the channel, W |
| $V_1$ | Coolant velocity at channel inlet, m/s |
| $V_3$ | Coolant velocity at channel exit, m/s |
| T | Coolant temperature at an axial location, °C |
| $T_{in}$ | Coolant temperature at the channel inlet, °C |
| $T_{ex}$ | Coolant temperature at the channel exit, °C |
| $T_{ch}$ | Channel thickness, m |
| W | Coolant flow rate in the channel, kg/s |
| $W_{ch}$ | Channel width, m |

## REFERENCES

1. A. P. Olson and M. Kalimullah, Argonne National Laboratory, unpublished information, November 12, 2008.

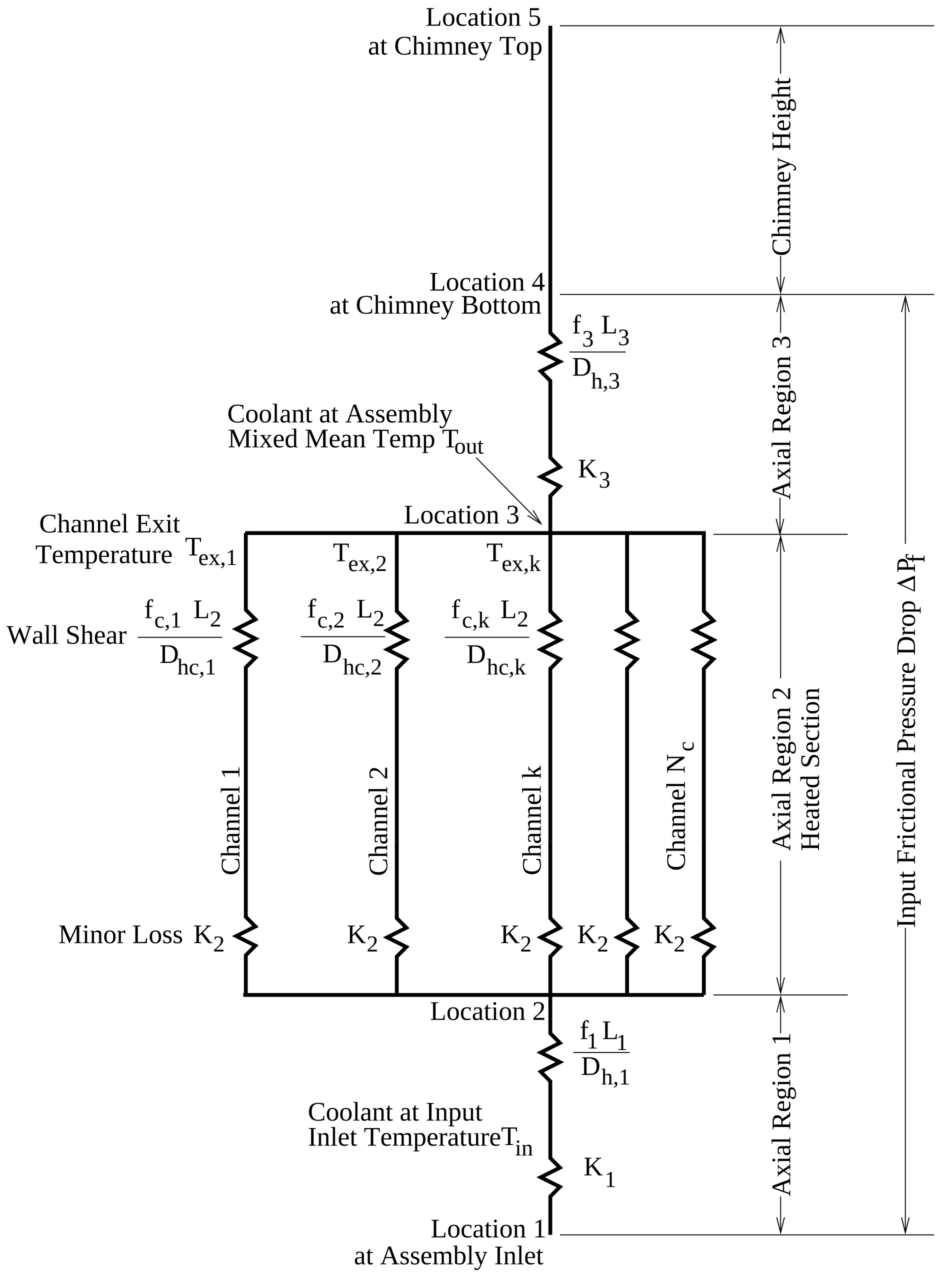


**Fig. 1. Coolant Flow Path in a Fuel Assembly and Chimney Modeled in PLTEMP/ANL (Multiple Axial Regions Downstream of the Heated Section Are Allowed)**

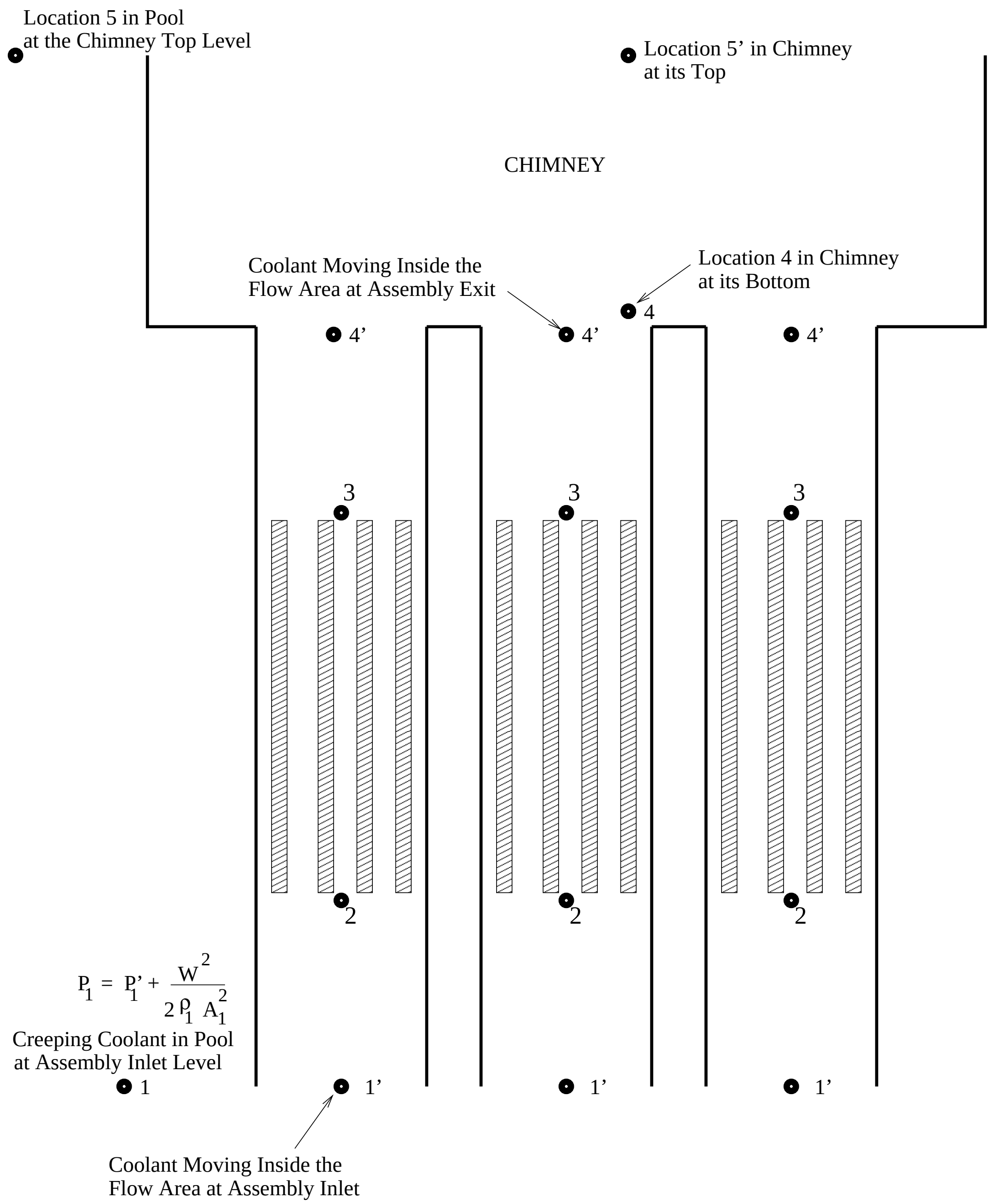


**Fig. 2. Locations of Coolant Pressure in a Group of Fuel Assemblies Exiting into a Common Chimney**

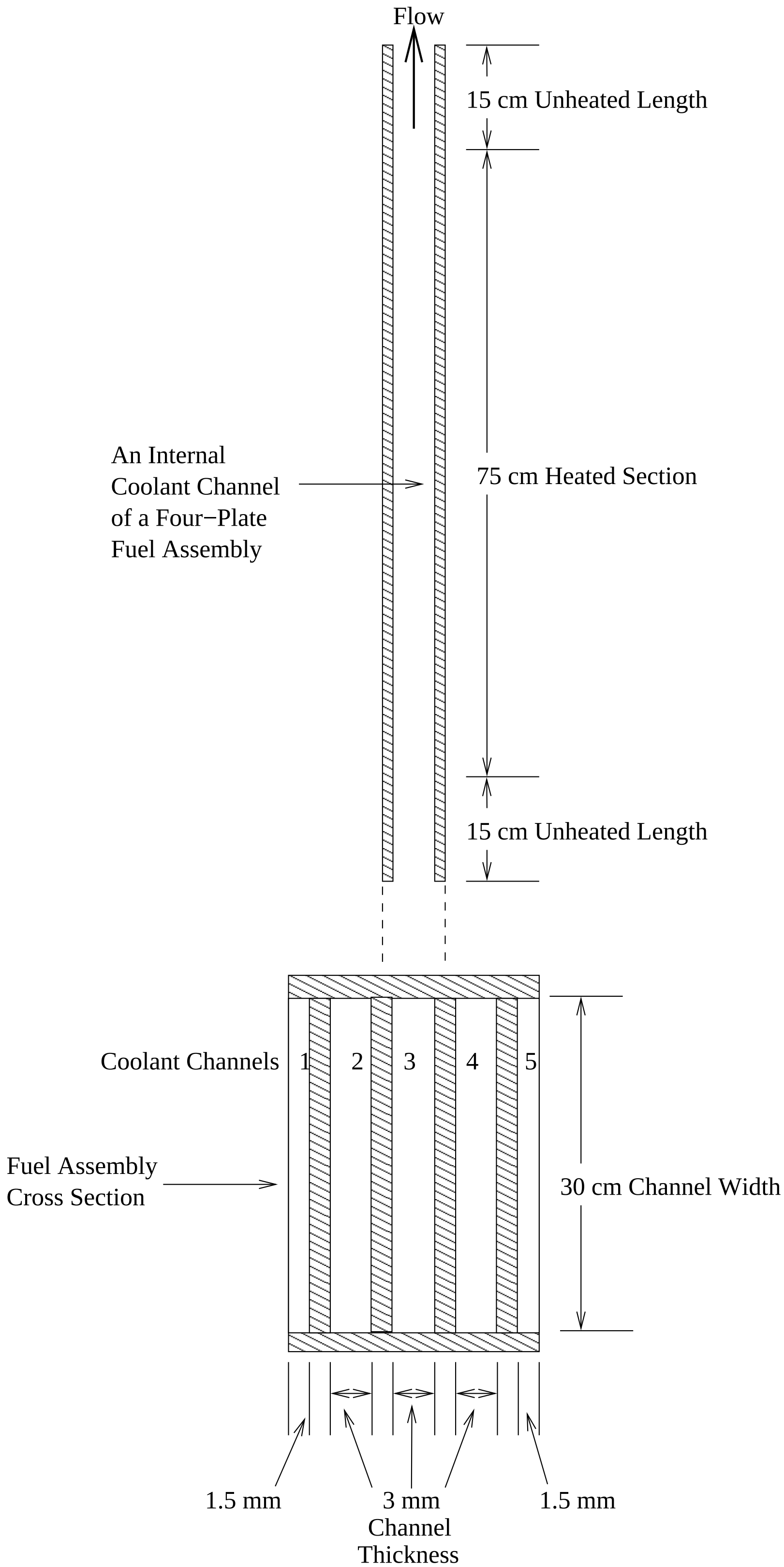


**Fig. 3. Geometry of a Coolant Channel in a Four-Plate Fuel Assembly Used in Test Problem 22**

**Table 1. Comparison of PLTEMP/ANL V3.6 and *Mathematica* Solutions of Test Problem 21 Fuel Assembly 1, With and Without Global Hot Channel Factors**

| | **Nominal Solution** | | **Solution with Global Hot Channel Factors** | |
|---|---|---|---|---|
| Input or Calculated Quantity | PLTEMP/ANL V3.6 Solution | *Mathematica* Calculation | PLTEMP/ANL V3.6 Solution | *Mathematica* Calculation |
| Inlet Temp, °C | 25 | 25 | 25 | 25 |
| Power per Channel, kW | 12.5 | 12.5 | 15.0 | 15.0 |
| Loss Coeff. at Inlet | 0.5 | 0.5 | 0.5 | 0.5 |
| Loss Coeff. at Exit | 1.0 | 1.0 | 1.0 | 1.0 |
| | **Calculated Quantities** | | | |
| Flow per Channel, kg/s | 0.072086 | 0.072071 | 0.067016 | 0.067013 |
| Exit Temp, °C | 66.488 | 66.497 | 78.491 | 78.494 |
| | **Buoyancy Head, Pa** | | | |
| Axial Region 1 | 0.0 | 0.0 | 0.0 | 0.0 |
| Axial Region 2 (Heated Section) | 51.991 | 51.859 | 57.129 | 57.138 |
| Axial Region 3 | 24.132 | 24.131 | 26.743 | 26.737 |
| **Total Buoyancy** | **75.991** | **75.991** | **83.872** | **83.876** |
| | **Frictional Pressure Drop, Pa** | | | |
| Inlet Loss | 16.182 | 1.608 | 18.260 | 2.002 |
| Axial Region 1 | | 14.570 | | 16.257 |
| Axial Region 2 (Heated Length) | 49.623 | 49.613 | 54.123 | 54.126 |
| Axial Region 3 | 10.186 | 6.929 | 11.490 | 7.412 |
| | | 3.270 | | 4.078 |
| **Total Pressure Drop** | **75.991** | **75.991** | **83.873** | **83.876** |

**Table 2. PLTEMP/ANL Results for Sample Problem 21 with Six Hot Channel Factors**
System-wide Factors: FPOWER = 1.20, FFLOW = 1.20, FNUSLT = 1.15,
Local Factors: FBULK = 1.15, FFILM = 1.18, FFLUX = 1.22

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Assembly 1, Nominal Case, Power = 50 kW | | | | | | | |
| Assembly Flow, kg/s | 0.28834 | | | | | | | |
| **Channel Number** | **1** | | **2** | | **3** | | **4** | **5** |
| Plate Number | | 1 | | 2 | | 3 | | 4 | |
| Plate Power, kW | | 12.5 | | 12.5 | | 12.5 | | 12.5 | |
| Channel Flow, kg/s | 0.036043 | | 0.072086 | | 0.072086 | | 0.072086 | | 0.036043 |
| Ch Exit Temp, °C | 66.488 | | 66.488 | | 66.488 | | 66.488 | | 66.488 |
| ONBR[1] at Inlet, L/R | 3.417 | | 3.417, 3.417 | | 3.417, 3.417 | | 3.417, 3.417 | | 3.417 |
| ONBR[1] at Exit, L/R | 1.757 | | 1.757, 1.757 | | 1.757, 1.757 | | 1.757, 1.757 | | 1.757 |
| | Assembly 1 with Systemic Uncertainties, Power = 60 kW | | | | | | | | |
| Assembly Flow, kg/s | 0.32168 / 1.2 = 0.26806 | | | | | | | | |
| Plate Power, kW | | 15.0 | | 15.0 | | 15.0 | | 15.0 | |
| Channel Flow, kg/s | 0.033508 | | 0.067016 | | 0.067016 | | 0.067016 | | 0.033508 |
| Ch Exit Temp, °C | 78.491 | | 78.491 | | 78.491 | | 78.491 | | 78.491 |
| ONBR at Inlet, L/R | 2.486 | | 2.486, 2.486 | | 2.486, 2.486 | | 2.486, 2.486 | | 2.486 |
| ONBR at Exit, L/R | 1.329 | | 1.329, 1.329 | | 1.329, 1.329 | | 1.329, 1.329 | | 1.329 |
| | Assembly 1 with Systemic and Local Uncertainties, Power = 60 kW | | | | | | | | |
| Assembly Flow, kg/s | 0.26806 | | | | | | | | |
| Plate Power, kW | | 15.0 | | 15.0 | | 15.0 | | 15.0 | |
| Channel Flow, kg/s | 0.033508 | | 0.067016 | | 0.067016 | | 0.067016 | | 0.033508 |
| Ch Exit Temp, °C | 86.515 | | 86.515 | | 86.515 | | 86.515 | | 86.515 |
| ONBR at Inlet, L/R | 2.110 | | 2.110, 2.110 | | 2.110, 2.110 | | 2.110, 2.110 | | 2.110 |
| ONBR at Exit, L/R | 1.142 | | 1.142, 1.142 | | 1.142, 1.142 | | 1.142, 1.142 | | 1.142 |
| | Assembly 2, Nominal Case, Power = 50 kW | | | | | | | | |
| Assembly Flow, kg/s | 0.28687 | | | | | | | | |
| Plate Power, kW | | 7.5 | | 17.5 | | 17.5 | | 7.5 | |
| Channel Flow, kg/s | 0.027193 | | 0.072094 | | 0.072094 | | 0.072094 | | 0.027193 |
| Ch Exit Temp, °C | 60.543 | | 66.272 | | 71.186 | | 66.272 | | 60.543 |
| ONBR at Inlet, L/R | 5.538 | | 5.537, 2.474 | | 2.474, 2.474 | | 2.474, 5.537 | | 5.538 |
| ONBR at Exit, L/R | 2.259 | | 2.255, 1.453 | | 1.451, 1.451 | | 1.453, 2.255 | | 2.259 |
| | Assembly 2 with Systemic Uncertainties, Power = 60 kW | | | | | | | | |
| Assembly Flow, kg/s | 0.31999 / 1.2 = 0.26666 | | | | | | | | |
| Plate Power, kW | | 9.0 | | 21.0 | | 21.0 | | 9.0 | |
| Channel Flow, kg/s | 0.025038 | | 0.067056 | | 0.082470 | | 0.067056 | | 0.025038 |
| Ch Exit Temp, °C | 70.991 | | 78.205 | | 84.408 | | 78.205 | | 70.991 |
| ONBR at Inlet, L/R | 4.034 | | 4.033, 1.799 | | 1.799, 1.799 | | 1.799, 4.033 | | 4.033 |
| ONBR at Exit, L/R | 1.716 | | 1.713, 1.095 | | 1.094, 1.094 | | 1.095, 1.713 | | 1.716 |
| | Assembly 2 with Systemic and Local Uncertainties, Power = 60 kW | | | | | | | | |
| Assembly Flow, kg/s | 0.26666 | | | | | | | | |
| Plate Power, kW | | 9.0 | | 21.0 | | 21.0 | | 9.0 | |
| Channel Flow, kg/s | 0.025038 | | 0.067056 | | 0.082470 | | 0.067056 | | 0.025038 |
| Ch Exit Temp, °C | 77.890 | | 86.185 | | 93.319 | | 86.185 | | 77.890 |
| ONBR at Inlet, L/R | 3.426 | | 3.426, 1.526 | | 1.526, 1.526 | | 1.526, 3.426 | | 3.426 |
| ONBR at Exit, L/R | 1.476 | | 1.477, 0.939 | | 0.939, 0.939 | | 0.939, 1.477 | | 1.476 |

1. Heat flux based ONB ratio on the left and right surfaces of the fuel plate

**Table 3. Solution of Test Problem 21 Fuel Assembly 1 by *Mathematica* Using PLTEMP/ANL Coolant Properties, Nominal Case**

Flow rate per coolant channel = 0.072071 kg/s

| Region or Axial Node | Nodal Power W | Temp at Node Exit, °C | Temp at Node Center, °C | Density at Node Center kg/m$^3$ | Buoyancy due to Node, Pa | Re at Node Center | Friction Factor at Node Center | Frictional Pressure Drop, Pa |
|---|---|---|---|---|---|---|---|---|
| Inlet | | | | 996.982 | | | | 1.60802 |
| Region 1 | 0.0 | 25.0 | 25.0 | 996.982 | 0.0 | 527.889 | 0.179427 | 14.5704 |
| 1 | 833.333 | 27.7752 | 26.3876 | 996.664 | 0.155776 | 545.069 | 0.173771 | 4.70522 |
| 2 | 833.333 | 30.5494 | 29.1623 | 995.979 | 0.491785 | 580.407 | 0.163191 | 4.42178 |
| 3 | 833.333 | 33.3226 | 31.936 | 995.228 | 0.860166 | 616.961 | 0.153522 | 4.16294 |
| 4 | 833.333 | 36.0943 | 34.7085 | 994.411 | 1.26061 | 654.607 | 0.144694 | 3.92675 |
| 5 | 833.333 | 38.8645 | 37.4794 | 993.53 | 1.69282 | 693.229 | 0.136632 | 3.71127 |
| 6 | 833.333 | 41.6337 | 40.2491 | 992.584 | 2.1564 | 732.67 | 0.129277 | 3.51483 |
| 7 | 833.333 | 44.4018 | 43.0177 | 991.575 | 2.65098 | 772.795 | 0.122565 | 3.33573 |
| 8 | 833.333 | 47.1682 | 45.785 | 990.504 | 3.17619 | 813.462 | 0.116437 | 3.17239 |
| 9 | 833.333 | 49.9333 | 48.5507 | 989.372 | 3.73162 | 854.563 | 0.110837 | 3.02327 |
| 10 | 833.333 | 52.6976 | 51.3154 | 988.178 | 4.31676 | 895.989 | 0.105713 | 2.88697 |
| 11 | 833.333 | 55.4605 | 54.079 | 986.925 | 4.93114 | 937.657 | 0.101015 | 2.76218 |
| 12 | 833.333 | 58.2219 | 56.8412 | 985.614 | 5.57429 | 979.521 | 0.0966977 | 2.64765 |
| 13 | 833.333 | 60.9817 | 59.6018 | 984.244 | 6.24564 | 1021.55 | 0.0927196 | 2.54226 |
| 14 | 833.333 | 63.74 | 62.3608 | 982.819 | 6.94463 | 1063.62 | 0.0890523 | 2.44524 |
| 15 | 833.333 | 66.4969 | 65.1184 | 981.338 | 7.67068 | 1106.29 | 0.0856169 | 2.35446 |
| Region 2 | | 66.4969 | | | 51.85944 | | | 49.6129 |
| Region 3 | 0.0 | 66.4969 | 66.4969 | 980.577 | 24.13116 | 1128.55 | 0.0839282 | 6.92943 |
| Reg 3 Exit | | 66.4969 | | 980.577 | | | | 3.26985 |
| Total | | | | | 75.9906 | | | 75.9906 |

**Table 4. Solution of Test Problem 21 Fuel Assembly 1 by *Mathematica* Using PLTEMP/ANL Coolant Properties, with Global Hot Channel Factors**

Flow rate per coolant channel at 15 kW (FPOWER*12.5 kW) = 0.0804153 kg/s

| Region or Axial Node | Nodal Power W | Temp at Node Exit, °C | Temp at Node Center, °C | Density at Node Center kg/m$^3$ | Buoyancy due to Node, Pa | Re at Node Center | Friction Factor at Node Center | Frictional Pressure Drop, Pa |
|---|---|---|---|---|---|---|---|---|
| Inlet | | | | 996.982 | | | | 2.00191 |
| Region 1 | 0.0 | 25.0 | 25.0 | 996.982 | 0.0 | 589.005 | 0.160809 | 16.25727 |
| 1 | 1000. | 27.9846 | 26.4923 | 996.64 | 0.167865 | 609.636 | 0.155367 | 5.2375 |
| 2 | 1000. | 30.9681 | 29.4764 | 995.897 | 0.531874 | 652.155 | 0.145238 | 4.89968 |
| 3 | 1000. | 33.9504 | 32.4593 | 995.079 | 0.93329 | 696.228 | 0.136044 | 4.59329 |
| 4 | 1000. | 36.9309 | 35.4407 | 994.184 | 1.37172 | 741.679 | 0.127707 | 4.31569 |
| 5 | 1000. | 39.9097 | 38.4203 | 993.216 | 1.84678 | 788.34 | 0.120148 | 4.0642 |
| 6 | 1000. | 42.8876 | 41.3986 | 992.173 | 2.35799 | 835.999 | 0.113299 | 3.83654 |
| 7 | 1000. | 45.8638 | 44.3757 | 991.058 | 2.90487 | 884.458 | 0.107091 | 3.63042 |
| 8 | 1000. | 48.8382 | 47.351 | 989.871 | 3.48697 | 933.554 | 0.101459 | 3.44362 |
| 9 | 1000. | 51.8114 | 50.3248 | 988.613 | 4.10368 | 983.118 | 0.096344 | 3.27417 |
| 10 | 1000 . | 54.7834 | 53.2974 | 987.286 | 4.75441 | 1033.04 | 0.091688 | 3.12013 |
| 11 | 1000. | 57.7535 | 56.2685 | 985.89 | 5.43856 | 1083.22 | 0.0874407 | 2.9798 |
| 12 | 1000. | 60.7219 | 59.2377 | 984.428 | 6.15548 | 1133.62 | 0.0835531 | 2.85155 |
| 13 | 1000. | 63.6885 | 62.2052 | 982.901 | 6.90446 | 1184.1 | 0.0799913 | 2.73423 |
| 14 | 1000. | 66.6535 | 65.171 | 981.309 | 7.68478 | 1235.31 | 0.0766748 | 2.62512 |
| 15 | 1000. | 69.6165 | 68.135 | 979.656 | 8.49569 | 1288.97 | 0.0734829 | 2.52009 |
| Region 2 | 15000.0 | 69.6165 | | | 57.1384 | | | 54.126 |
| Region 3 | 0.0 | 69.6165 | 69.6165 | 978.806 | 26.7373 | 1315.84 | 0.0719824 | 7.41231 |
| Reg 3 Exit | | 69.6165 | | 978.806 | | 1315.84 | | 4.07818 |
| Total | 15000.0 | | | | 83.8757 | | | 83.8757 |

**Table 5. Temperature Distribution in Test Problem 21 Fuel Assembly 1 at the Channel Flow Rate Obtained by Applying Global Hot Channel Factors**

Flow rate per coolant channel = 0.0804153/FFLOW = 0.0670128 kg/s

| Region or Axial Node | Nodal Power W | Temp at Node Exit, °C | Temp at Node Center, °C |
|---|---|---|---|
| Inlet | | 25.0 | |
| Region 1 | 0.0 | 25.0 | 25.0 |
| 1 | 1000.0. | 28.5814 | 26.7907 |
| 2 | 1000.0. | 32.1612 | 30.3713 |
| 3 | 1000.0. | 35.739 | 33.9501 |
| 4 | 1000.0 | 39.3141 | 37.5265 |
| 5 | 1000.0. | 42.8876 | 41.1008 |
| 6 | 1000.0. | 46.4588 | 44.6732 |
| 7 | 1000.0. | 50.0275 | 48.2432 |
| 8 | 1000.0. | 53.5948 | 51.8112 |
| 9 | 1000.0. | 57.1596 | 55.3772 |
| 10 | 1000.0. | 60.7219 | 58.9408 |
| 11 | 1000.0. | 64.2816 | 62.5018 |
| 12 | 1000.0. | 67.8389 | 66.0603 |
| 13 | 1000.0. | 71.3931 | 69.616 |
| 14 | 1000.0. | 74.9441 | 73.1686 |
| 15 | 1000.0. | 78.4939 | 76.719 |
| Region 2 | 15000.0 | 78.4939 | |
| Region 3 | 0.0 | 78.4939 | 78.4939 |
| Reg 3 Exit | | 78.4939 | |

## Table 6. PLTEMP/ANL Input Data for Test Problem 21 Used in the Verification of Hot Channel Factors Treatment in Case of Natural Circulation

```
 Test Problem 21: Flow is calculated by natural circulation
! 2 assemblies, Each assembly has 4 fuel plates and 5 coolant channels
! H2O coolant, No bypass flow, NCTYP=0
! Total power = 0.10 MWt, Axially uniform power profile
! 14 axial heat transfer nodes in the heated length of fuel plates
!  1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18  19    #  Card 200
   5   0   1   1   0   1   1   1   0   0   0   0   0   0   2   0   0   0   0    Card(1)0200
1.20        1.20        1.15                                                    Card(1)0201
   2   3 0.50       1.00        1.00        1.00           0                    Card(1)0300
1.15        1.18        1.22                                                    Card(1)0300A
! Using pressure driven mode
1.00        1.00                                                                Card(2)0303
36.0E-04    5.94059E-03 0.15        0.50        0.30        3.00E-03            Card(3)0304
0.00        5.94059E-03 0.75        0.00        0.30        3.00E-03            Card(3)0304
36.0E-04    5.94059E-03 0.15        1.00        0.30        3.00E-03            Card(3)0304
! Use the code's biult-in correlation for friction factor
0.00        0.00        0.00                                                    Card(1)0305
! Use laminar friction factor
!94.7174     1.00        0.00                                                    Card(1)0305
   5   3 0.00       0.75        0.50E-03    180.00       1.00E-03    100.00     Card(1)0306
4.50E-04    5.94059E-03 0.3030      0.30        0.30        3.00E-03            Card(5)0307
9.00E-04    5.94059E-03 0.6060      0.60        0.30        3.00E-03            Card(5)0307
9.00E-04    5.94059E-03 0.6060      0.60        0.30        3.00E-03            Card(5)0307
9.00E-04    5.94059E-03 0.6060      0.60        0.30        3.00E-03            Card(5)0307
4.50E-04    5.94059E-03 0.3030      0.30        0.30        3.00E-03            Card(5)0307
0.30        0.30        0.30        0.30                                        Card(1)0308
! Card 0308A not required
! Radial power peaking factor data by fuel plate for each subassembly. Input flow data by
! channel for each subassembly on Cards 0310 not required because WFGES(1) is non-zero
1.000       1.000       1.000       1.000                                       Card(2)0309
0.600       1.400       1.400       0.600                                       Card(2)0309
! DP0       DDP         DPMAX       POWER       TIN         PIN
0.0000      0.04        0.00        0.100       25.0        0.50                Card(1)0500
0.00        0.00                                                                Card(2)0500
  50 1.E-04     25.0        0.00        0.00                                    Card(1)0600
  15                                                                            Card(1)0700
0.0         1.000                                                               Card(11)0701
0.100       1.000                                                               Card(11)0701
0.167       1.000                                                               Card(11)0701
0.233       1.000                                                               Card(11)0701
0.300       1.000                                                               Card(11)0701
0.367       1.000                                                               Card(11)0701
0.433       1.000                                                               Card(11)0701
0.5         1.000                                                               Card(11)0701
0.567       1.000                                                               Card(11)0701
0.633       1.000                                                               Card(11)0701
0.700       1.000                                                               Card(11)0701
0.767       1.000                                                               Card(11)0701
0.833       1.000                                                               Card(11)0701
0.900       1.000                                                               Card(11)0701
1.0         1.000                                                               Card(11)0701
   0                                                                            Card(11)0702
```

## Table 7. Solution of Test Problem 21 Assembly 1 by PLTEMP/ANL V3.6 Code – Nominal Case

Flow Rate in the Assembly = 2.8834E-01 kg/s

| Channel | Flow Rate kg/s | Velocity m/s |
|---|---|---|
| 1 | 3.60431E-02 | 8.03383E-02 |
| 2 | 7.20862E-02 | 8.03383E-02 |
| 3 | 7.20862E-02 | 8.03383E-02 |
| 4 | 7.20862E-02 | 8.03383E-02 |
| 5 | 3.60431E-02 | 8.03383E-02 |

| NODE | COOLANTl (C) | CladSl (C) | FUEL PEAK (C) | CladSr (C) | COOLANTr (C) | HCOFl W/C-m^2 | HCOFr W/C-m^2 | ONBRl [F Note 1] | ONBRr | ETA'l K-cm^3/J [Note 3] | ETA'r K-cm^3/J [Note 3] | ONB Temp left(C) | ONB Temp right(C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 25.000 | | | | 25.000 | | | | | | | | |
| 1 | 27.081 | 62.654 | 62.801 | 62.654 | 27.081 | 7.8086E+02 | 7.8086E+02 | 3.39 | 3.39 | 3.604E+02 | 3.604E+02 | 152.792 | 152.792 |
| 2 | 30.556 | 65.852 | 65.999 | 65.852 | 30.556 | 7.8700E+02 | 7.8700E+02 | 3.13 | 3.13 | 3.503E+02 | 3.503E+02 | 152.746 | 152.746 |
| 3 | 33.322 | 68.407 | 68.553 | 68.407 | 33.322 | 7.9174E+02 | 7.9174E+02 | 2.94 | 2.94 | 3.422E+02 | 3.422E+02 | 152.710 | 152.710 |
| 4 | 36.086 | 70.968 | 71.115 | 70.968 | 36.086 | 7.9634E+02 | 7.9634E+02 | 2.78 | 2.78 | 3.341E+02 | 3.341E+02 | 152.673 | 152.673 |
| 5 | 38.870 | 73.556 | 73.702 | 73.556 | 38.870 | 8.0084E+02 | 8.0084E+02 | 2.63 | 2.63 | 3.259E+02 | 3.259E+02 | 152.637 | 152.637 |
| 6 | 41.631 | 76.130 | 76.277 | 76.130 | 41.631 | 8.0517E+02 | 8.0517E+02 | 2.50 | 2.50 | 3.178E+02 | 3.178E+02 | 152.600 | 152.600 |
| 7 | 44.391 | 78.712 | 78.858 | 78.712 | 44.391 | 8.0937E+02 | 8.0937E+02 | 2.37 | 2.37 | 3.097E+02 | 3.097E+02 | 152.564 | 152.564 |
| 8 | 47.171 | 81.318 | 81.465 | 81.318 | 47.171 | 8.1347E+02 | 8.1347E+02 | 2.26 | 2.26 | 3.016E+02 | 3.016E+02 | 152.527 | 152.527 |
| 9 | 49.929 | 83.912 | 84.059 | 83.912 | 49.929 | 8.1741E+02 | 8.1741E+02 | 2.16 | 2.16 | 2.935E+02 | 2.935E+02 | 152.491 | 152.491 |
| 10 | 52.687 | 86.512 | 86.658 | 86.512 | 52.687 | 8.2122E+02 | 8.2122E+02 | 2.07 | 2.07 | 2.854E+02 | 2.854E+02 | 152.454 | 152.454 |
| 11 | 55.462 | 89.135 | 89.282 | 89.135 | 55.462 | 8.2492E+02 | 8.2492E+02 | 1.99 | 1.99 | 2.773E+02 | 2.773E+02 | 152.418 | 152.418 |
| 12 | 58.216 | 91.745 | 91.891 | 91.745 | 58.216 | 8.2847E+02 | 8.2847E+02 | 1.91 | 1.91 | 2.692E+02 | 2.692E+02 | 152.381 | 152.381 |
| 13 | 60.968 | 94.359 | 94.505 | 94.359 | 60.968 | 8.3189E+02 | 8.3189E+02 | 1.84 | 1.84 | 2.611E+02 | 2.611E+02 | 152.344 | 152.344 |
| 14 | 64.421 | 97.648 | 97.794 | 97.648 | 64.421 | 8.3601E+02 | 8.3601E+02 | 1.75 | 1.75 | 2.510E+02 | 2.510E+02 | 152.298 | 152.298 |
| | 66.488 | | | | 66.488 | | | | | | | | |

[1] The ONB ratio is here defined as (Tonb - Tinlet)/(Tsurf - Tinlet). If the heat flux is negative (the coolant is hotter than the adjacent cladding surface), then the ONB ratio is arbitrarily set to 99.99 .

[3] The column gives ETA' = (Coolant Velocity)*(Tsat - Coolant Temp)/(Heat Flux). ETA' in the units chosen here, equals Whittle and Forgan dimensionless ETA for water-cooled reactors: ETA = ETA'*Coolant Density*Cp/4. The last value in the colunm (at exit) should be greater than 32.5 to avoid excursive flow instability. ETA is also used in the equation R = 1/(1+ETA*Dh/Lh)

## Table 8. Solution of Test Problem 21 Assembly 1 by PLTEMP/ANL V3.6 Code – Global Hot Channel Factors Applied FPOWER = 1.20, FFLOW = 1.20, FNUSLT = 1.15

Flow Rate at Power 15 kW (i.e., FPOWER*12.5 kW)

| Channel | Flow Rate kg/s | Velocity m/s |
|---|---|---|
| 1 | 4.02097E-02 | 8.96262E-02 |
| 2 | 8.04195E-02 | 8.96262E-02 |
| 3 | 8.04195E-02 | 8.96262E-02 |
| 4 | 8.04195E-02 | 8.96262E-02 |
| 5 | 4.02097E-02 | 8.96262E-02 |
| Total | 3.21680E-01 | |

Flow Rate at Power 15.0 kW with Hot Channel Factor FFLOW Applied

| Channel | Flow Rate kg/s | Velocity m/s |
|---|---|---|
| 1 | 3.35081E-02 | 7.46885E-02 |
| 2 | 6.70162E-02 | 7.46885E-02 |
| 3 | 6.70162E-02 | 7.46885E-02 |
| 4 | 6.70162E-02 | 7.46885E-02 |
| 5 | 3.35081E-02 | 7.46885E-02 |
| Total | 2.68067E-01 | |

| NODE | COOLANT ON LEFT (C) | CLAD SURF ON LEFT (C) | FUEL PEAK (C) | CLAD SURF ON RIGHT (C) | COOLANT ON RIGHT (C) | H ON LEFT W/C-m^2 | H ON RIGHT W/C-m^2 | ONBR LEFT [F Note 1] | ONBR RIGHT | ETA LEFT K-cm^3/J [Note 3] | ETA RIGHT K-cm^3/J [Note 3] | ONB TEMP LEFT (C) [Note 1] | ONB TEMP RIGHT (C) [Note 1] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 25.000 | | | | 25.000 | | | | | | | | |
| 1 | 27.686 | 76.709 | 76.885 | 76.709 | 27.686 | 6.7995E+02 | 6.7995E+02 | 2.47 | 2.47 | 2.779E+02 | 2.779E+02 | 152.891 | 152.891 |
| 2 | 32.170 | 80.707 | 80.883 | 80.707 | 32.170 | 6.8676E+02 | 6.8676E+02 | 2.29 | 2.29 | 2.677E+02 | 2.677E+02 | 152.845 | 152.845 |
| 3 | 35.738 | 83.910 | 84.086 | 83.910 | 35.738 | 6.9197E+02 | 6.9197E+02 | 2.17 | 2.17 | 2.597E+02 | 2.597E+02 | 152.809 | 152.809 |
| 4 | 39.305 | 87.130 | 87.306 | 87.130 | 39.305 | 6.9698E+02 | 6.9698E+02 | 2.06 | 2.06 | 2.516E+02 | 2.516E+02 | 152.773 | 152.773 |
| 5 | 42.896 | 90.391 | 90.567 | 90.391 | 42.896 | 7.0183E+02 | 7.0183E+02 | 1.95 | 1.95 | 2.435E+02 | 2.435E+02 | 152.736 | 152.736 |
| 6 | 46.459 | 93.642 | 93.818 | 93.642 | 46.459 | 7.0646E+02 | 7.0646E+02 | 1.86 | 1.86 | 2.354E+02 | 2.354E+02 | 152.700 | 152.700 |
| 7 | 50.018 | 96.908 | 97.084 | 96.908 | 50.018 | 7.1090E+02 | 7.1090E+02 | 1.78 | 1.78 | 2.273E+02 | 2.273E+02 | 152.663 | 152.663 |
| 8 | 53.603 | 100.212 | 100.388 | 100.212 | 53.603 | 7.1518E+02 | 7.1518E+02 | 1.70 | 1.70 | 2.192E+02 | 2.192E+02 | 152.627 | 152.627 |
| 9 | 57.159 | 103.504 | 103.680 | 103.504 | 57.159 | 7.1924E+02 | 7.1924E+02 | 1.63 | 1.63 | 2.112E+02 | 2.112E+02 | 152.590 | 152.590 |
| 10 | 60.712 | 106.809 | 106.985 | 106.809 | 60.712 | 7.2311E+02 | 7.2311E+02 | 1.56 | 1.56 | 2.031E+02 | 2.031E+02 | 152.554 | 152.554 |
| 11 | 64.290 | 110.151 | 110.327 | 110.151 | 64.290 | 7.2683E+02 | 7.2683E+02 | 1.50 | 1.50 | 1.950E+02 | 1.950E+02 | 152.517 | 152.517 |
| 12 | 67.837 | 113.478 | 113.653 | 113.478 | 67.837 | 7.3034E+02 | 7.3034E+02 | 1.44 | 1.44 | 1.870E+02 | 1.870E+02 | 152.481 | 152.481 |
| 13 | 71.382 | 116.815 | 116.991 | 116.815 | 71.382 | 7.3367E+02 | 7.3367E+02 | 1.39 | 1.39 | 1.790E+02 | 1.790E+02 | 152.444 | 152.444 |
| 14 | 75.829 | 121.021 | 121.197 | 121.021 | 75.829 | 7.3760E+02 | 7.3760E+02 | 1.33 | 1.33 | 1.689E+02 | 1.689E+02 | 152.398 | 152.398 |
| | 78.491 | | | | 78.491 | | | | | | | | |

[1] The ONB ratio is here defined as (Tonb - Tinlet)/(Tsurf - Tinlet). If the heat flux is negative (the coolant is hotter than the adjacent cladding surface), then the ONB ratio is arbitrarily set to 99.99 .

[3] The column gives ETA' = (Coolant Velocity)*(Tsat - Coolant Temp)/(Heat Flux). ETA' in the units chosen here, equals Whittle and Forgan dimensionless ETA for water-cooled reactors: ETA = ETA'*Coolant Density*Cp/4. The last value in the column (at exit) should be greater than 32.5 to avoid excursive flow instability. ETA is also used in the equation R = 1/(1+ETA*Dh/Lh)

**Table 9. Solution of Test Problem 21 Assembly 1 by PLTEMP/ANL V3.6 Code – All Six Hot Channel Factors Applied FPOWER = 1.20, FFLOW = 1.20, FNUSLT = 1.15, FBULK = 1.15, FFILM = 1.18, FFLUX = 1.22**

| NODE | COOLANT ON LEFT (C) | CLAD SURF ON LEFT (C) | FUEL PEAK (C) | CLAD SURF ON RIGHT (C) | COOLANT ON RIGHT (C) | H ON LEFT W/C-m^2 | H ON RIGHT W/C-m^2 | ONBR LEFT [F Note 1] | ONBR RIGHT |
|---|---|---|---|---|---|---|---|---|---|
| | 25.000 | | | | 25.000 | | | | |
| 1 | 28.089 | 85.936 | 86.151 | 85.936 | 28.089 | 6.7995E+02 | 6.7995E+02 | 2.10 | 2.10 |
| 2 | 33.245 | 90.519 | 90.733 | 90.519 | 33.245 | 6.8676E+02 | 6.8676E+02 | 1.95 | 1.95 |
| 3 | 37.349 | 94.191 | 94.406 | 94.191 | 37.349 | 6.9197E+02 | 6.9197E+02 | 1.85 | 1.85 |
| 4 | 41.451 | 97.885 | 98.099 | 97.885 | 41.451 | 6.9698E+02 | 6.9698E+02 | 1.75 | 1.75 |
| 5 | 45.581 | 101.625 | 101.839 | 101.625 | 45.581 | 7.0183E+02 | 7.0183E+02 | 1.67 | 1.67 |
| 6 | 49.677 | 105.354 | 105.569 | 105.354 | 49.677 | 7.0646E+02 | 7.0646E+02 | 1.59 | 1.59 |
| 7 | 53.771 | 109.100 | 109.315 | 109.100 | 53.771 | 7.1090E+02 | 7.1090E+02 | 1.52 | 1.52 |
| 8 | 57.894 | 112.892 | 113.107 | 112.892 | 57.894 | 7.1518E+02 | 7.1518E+02 | 1.45 | 1.45 |
| 9 | 61.983 | 116.670 | 116.885 | 116.670 | 61.983 | 7.1924E+02 | 7.1924E+02 | 1.39 | 1.39 |
| 10 | 66.069 | 120.463 | 120.678 | 120.463 | 66.069 | 7.2311E+02 | 7.2311E+02 | 1.34 | 1.34 |
| 11 | 70.183 | 124.299 | 124.514 | 124.299 | 70.183 | 7.2683E+02 | 7.2683E+02 | 1.28 | 1.28 |
| 12 | 74.262 | 128.118 | 128.333 | 128.118 | 74.262 | 7.3034E+02 | 7.3034E+02 | 1.24 | 1.24 |
| 13 | 78.339 | 131.951 | 132.165 | 131.951 | 78.339 | 7.3367E+02 | 7.3367E+02 | 1.19 | 1.19 |
| 14 | 83.453 | 136.780 | 136.994 | 136.780 | 83.453 | 7.3760E+02 | 7.3760E+02 | 1.14 | 1.14 |
| | 86.515 | | | | 86.515 | | | | |

## APPENDIX I. *Mathematica* Program for Solving Test Problem 21

```
(" SOLUTION OF NATURAL CIRCULATION STANDARD PROBLEM 21, Fuel Assembly 1,
Nominal hcf case, Using Water Properties of the PLTEMP/ANL V3.5 Code ")
data={kin=0.5,kex=1.0,Dh=0.00594059,len1=0.15,len2=0.75,len3=0.15,wch=0.3,tch=0.003,grav=9.8066
5,erel=0.0,tin=25.0,powr=12500.0};
flow=0.072071323; ←—— This guess flow was adjusted and the program was rerun to achieve channel
                       channel buoyancy (buoy) equal to channel frictional pressure drop (delp).
chimny=0.0
(* power = 12.5 kW per plate, total power = 50 kW in 4 plates *)
Print["Subcooled water density, kg/m**3, at 5 bar absolute used in the PLTEMP/ANL V3.5 Code"];
rho={{20.,997.9875},{25.,996.9820},{30.,995.7591},{35.,994.3214},{40.,992.6718},{45.,990.8146},{5
0.,988.7536},{55.,986.4945},{60.,984.0422},{65.,981.4029},{70.,978.5832},{75.,975.5897},{80.,972.43
24},{85.,969.1167},{90.,965.6552},{95.,962.0546},{100.,958.3263},{105.,954.4819},{110.,950.5318},{
115.,946.4900},{120.,942.3674},{125.,938.1805},{130.,933.9403},{135.,929.6651},{140.,925.3685},{1
45.,921.0693},{150.,916.7842}};
Plot[Interpolation[rho][temp],{temp,20,150}];
Print["Subcooled water enthalpy, kJ/kg, at 5 bar absolute used in the PLTEMP/ANL V3.5 Code"];
enthalpy={{20.,83.9517},{25.,104.7730},{30.,125.6082},{35.,146.4573},{40.,167.3272},{45.,188.2110}
,{50.,209.1156},{55.,230.0341},{60.,250.9734},{65.,271.9336},{70.,292.9146},{75.,313.9233},{80.,334
.9460},{85.,356.0033},{90.,377.0746},{95.,398.1805},{100.,419.3143},{105.,440.4758},{110.,461.6720
},{115.0,482.8960},{120.,504.1616},{125.,525.4550},{130.,546.7970},{135.,568.1738},{140.,589.5991
},{145.,611.0661},{150.,632.5816}};
Plot[Interpolation[enthalpy][temp],{temp,20,150}];
Print["Dynamic viscosity, micro Pa-s, of water used in the PLTEMP/ANL V3.5 Code"];
visc={{20.,1014.5},{25.,901.17},{30.,804.50},{35.,722.29},{40.,652.48},{45.,593.26},{50.,542.91},{55
.,499.92},{60.,462.93},{65.,430.75},{70.,401.28},{75.,377.03},{80.,355.98},{85.,337.40},{90.,320.63},
{95.,304.97},{100.,290.21},{105.,276.41},{110.,263.52},{115.,251.49},{120.,240.27},{125.,229.83},{1
30.,220.10},{135.,211.05},{140.,202.64},{145.,194.82},{150.,187.56}};
Plot[Interpolation[visc][temp],{temp,20,150}];
Print["Inlet and Exit temperatures, C"];
tin=tin/.data
grav=grav/.data;
hin=1000*Interpolation[enthalpy][tin];
hout=hin+powr/flow/.data;
tout=tx/.FindRoot[hout==1000*Interpolation[enthalpy][tx],{tx,tin}]
rhoin=Interpolation[rho][tin];
rhoout=Interpolation[rho][tout];
Print["Density at inlet =",rhoin,", Density at exit =",rhoout];
rhoave=NIntegrate[Interpolation[rho][temp],{temp,tin,tout}]/(tout-tin);
Print["Integrated average coolant density over (",tin," to ",tout,") = ",rhoave];
buoy2=(rhoin-rhoave)*grav*len2 /.data;
buoy3=(rhoin-rhoout)*grav*len3 /.data;
buoychimny=(rhoin-rhoout)*grav*chimny /.data;
Print["Buoyancy due to chimney =",buoychimny];
buoy=buoy2+buoy3;
Print["DRIVING PRESSURE HEAD DUE TO BUOYANCY in Section 1 =0.0, Section 2 =",buoy2,",
Section 3 =",buoy3,", Total buoyancy (Pa) =",buoy];
velin=flow/(rhoin*wch*tch)/.data;
```

```
Print["Coolant inlet velocity, m/s = ",velin];
visc1=0.000001*Interpolation[visc][tin];
visc3=0.000001*Interpolation[visc][tout];
Print["Coolant dynamic viscosity, Pa-s, in axial regions 1 and 3 =",visc1," ",visc3]
reyn1=flow*Dh/(wch*tch*visc1)/.data;
reyn3=flow*Dh/(wch*tch*visc3)/.data;
Print["Reynolds numbers in axial regions 1 and 3 =",reyn1," ",reyn3];
aspect=tch/wch/.data;
erela=If[0<erel<0.00000001,0.00000001,erel]/.data;
Cfric=96*(1-1.3553*aspect+1.9467*aspect^2-1.7012*aspect^3+0.9564*aspect^4-0.2537*aspect^5)
fric2200=Cfric/2200.0;
reyn=reyn1;
fa=1/(-2*Log[10,erela/3.7+2.51/reyn*(1.14-2*Log[10,erela+21.25/reyn^0.9])])^2;
If[reyn>=3000 && erela==0,fb=4*fric/.FindRoot[fric==6.25002/(1-
8.68591*Log[reyn*fric^0.5]+18.8612*(Log[reyn*fric^0.5])^2),{fric,0.1}]];
If[reyn>=3000 && erela>=0.00000001,
   fb=4*fric/.FindRoot[fric==0.331369/(Log[0.27027*erela+1.255/(reyn*fric^0.5)])^2,{fric,0.1}]];
If[reyn>=3000,Print["Turbulent friction factor fb = ",fb,", Re = ",reyn,", Rel roughness = ",erela]];
frica=If[reyn<=2200.0,Cfric/reyn,fric2200+(fa-fric2200)*(3.75-8250/reyn)];
fric1=If[reyn>=3000.0,fb,frica];
reyn=reyn3;
fa=1/(-2*Log[10,erela/3.7+2.51/reyn*(1.14-2*Log[10,erela+21.25/reyn^0.9])])^2;
If[reyn>=3000 && erela==0,fb=4*fric/.FindRoot[fric==6.25002/(1-
8.68591*Log[reyn*fric^0.5]+18.8612*(Log[reyn*fric^0.5])^2),{fric,0.1}]];
If[reyn>=3000 && erela>=0.00000001,
   fb=4*fric/.FindRoot[fric==0.331369/(Log[0.27027*erela+1.255/(reyn*fric^0.5)])^2,{fric,0.1}]];
If[reyn>=3000,Print["Turbulent friction factor fb = ",fb,", Re = ",reyn,", Rel roughness = ",erela]];
frica=If[reyn<=2200.0,Cfric/reyn,fric2200+(fa-fric2200)*(3.75-8250/reyn)];
fric3=If[reyn>=3000.0,fb,frica];
Print["Friction factors in Sections 1 and 3 =",fric1," ",fric3];
Print["FRICTIONAL PRESSURE DROP IN SECTION 1"]
delp1s=(fric1*len1/Dh)*0.5*(flow/(wch*tch))^2/rhoin/.data;
delp1m=kin*0.5*(flow/(wch*tch))^2/rhoin/.data;
delp1=delp1s+delp1m;
Print["Total pressure drop in Section 1 =",delp1,", Minor loss = ",delp1m,", Wall shear =",delp1s]
Print["FRICTIONAL PRESSURE DROP IN SECTION 3"]
delp3s=(fric3*len3/Dh)*0.5*(flow/(wch*tch))^2/rhoout/.data;
delp3m=kex*0.5*(flow/(wch*tch))^2/rhoout/.data;
delp3=delp3s+delp3m;
Print["Total pressure drop in Section 3 =",delp3,", Minor loss = ",delp3m,", Wall shear =",delp3s]
delp4=rhoin*velin*velin*(rhoin/rhoout-1.0)/.data;
Print["Pressure drop due to momentum flux (Pa) =",delp4];
Print["Flow =",flow,", g =",grav,", Temp at inlet and exit =",tin,", ",tout,", Density at inlet and exit
=",rhoin,", ",rhoout,", Gravity head =",grav*(rhoin*len1+rhoave*len2+rhoout*len3)/.data,", Total
buoyancy =",buoy,", Buoyancy in Section 2 =",buoy2,", Buoyancy in Section 3 =",buoy3,", Power into
coolant (W) =",flow*(hout-hin)]
Print["LOOP OVER 21 AXIAL SEGMENTS"];
powr1=powr/15/.data;
delz=len2/15/.data;
enth1=hin;
temp1=tin;
```

```
delp2p=0;
buoy2p=0;
Do[powr2=powr1;
  If[j<4,powr2=0];
  If[j>18,powr2=0];
  enth2=enth1+powr2/flow;
  temp2=tx/.FindRoot[enth2==1000*Interpolation[enthalpy][tx],{tx,temp1}];
  tempj=0.5*(temp2+temp1);
  viscj=0.000001*Interpolation[visc][tempj];
  rhoj=Interpolation[rho][tempj];
  buoy2s=buoy2p+grav*(rhoin-rhoj)*delz;
  reynj=flow*Dh/(wch*tch*viscj)/.data;
  reyn=reynj;
  fa=1/(-2*Log[10,erela/3.7+2.51/reyn*(1.14-2*Log[10,erela+21.25/reyn^0.9])])^2;
  If[reyn>=3000 && erela==0,fb=4*fric/.FindRoot[fric==6.25002/(1-
8.68591*Log[reyn*fric^0.5]+18.8612*(Log[reyn*fric^0.5])^2),{fric,0.1}]];
  If[reyn>=3000 && erela>=0.00000001,
    fb=4*fric/.FindRoot[fric==0.331369/(Log[0.27027*erela+1.255/(reyn*fric^0.5)])^2,{fric,0.1}]];
  If[reyn>=3000,Print["Turbulent friction factor fb = ",fb,", Re = ",reyn,", Rel roughness = ",erela]];
  frica=If[reyn<=2200.0,Cfric/reyn,fric2200+(fa-fric2200)*(3.75-8250/reyn)];
  fricj=If[reyn>=3000.0,fb,frica];
  delpj=(fricj*delz/Dh)*0.5*(flow/(wch*tch))^2/rhoj/.data;
  delp2=delp2p+delpj;
  (*Print["Axial segment =",j,", Flow, kg/s =",flow,", delz (m) =",delz,"Power in segment (W) =",powr2,",
Enthalpy at segment exit (J/kg) =",enth2,", Enthalpy at segment center (J/kg) =",0.5(enth1+enth2),",
Temp at segment exit (C) =",temp2,", Segment mean temp (C) =",tempj,", Segment mean density
(kg/m^3) =",rhoj,", Buoyancy due to segments 1 through ",j," (Pa) =",buoy2s,", Viscosity (Pa-s)
=",viscj,", Reynolds number =",reynj,", Friction factor =",fricj,", fl/Dh of segment (Pa) =",delpj,",
Cumulative sum fL/Dh of segments 1 through ",j", (Pa) =",delp2];*)
  Print[j,"   ",powr2,"   ",temp2,"   ",tempj,"   ",rhoj,"   ",grav*(rhoin-rhoj)*delz,"   ",reynj,"   ",fricj,"
",delpj];
  buoy2p=buoy2s;
  delp2p=delp2;
  temp1=temp2;
  enth1=enth2,
  {j,1,21}]
Print["Pressure drop due to wall shear in region 2 = ",delp2-delp1s-delp3s]
Print["BALANCE OF BUOYANCY AND FRICTIONAL PRESSURE DROP:"]
delp=delp2+delp1m+delp3m;
buoy=buoy2s+buoychimny;
Print["Total buoyancy (Pa) =",buoy,", Total frictional pressure drop (Pa) =",delp];
```

12. **Search Capability in PLTEMP/ANL V3.7 – Verification and its Application to Making Reactor Operation Diagrams**

(April 2009)

## 12.1. Introduction

To save the reactor analyst's time, a general search capability (input option ISRCH = 1) has been implemented in the PLTEMP/ANL V3.7 thermal-hydraulics code used for research reactors. The search capability gets a user-specified target value for a specified code output variable (e.g., reactor coolant flow rate) by adjusting a specified input datum (e.g., applied pressure drop). Two basic types of search are implemented: (1) Single search in which *one* input datum is adjusted to achieve a target value for *one* output variable; and (2) Double search in which *two* input data are adjusted to achieve target values for *two* output variables. The logic flow diagram of how a search is performed by the code, basically using the *interval-halving technique*, is given in the Users Guide[1].

Currently, 11 single searches and 5 double searches, listed in Table 1, are available. These searches adjust the input applied pressure drop or/and reactor power to get target values of any one or any two of these calculated quantities: core flow rate, minimum onset of nucleate boiling ratio (ONBR), minimum departure from nucleate boiling ratio (DNBR), minimum flow instability power ratio FIR), maximum cladding surface temperature ($T_{cs,max}$), and maximum coolant exit temperature ($T_{ex,max}$). The search capability is implemented such that new searches can be easily added.

The search capability also works for reactor problems using the hot channel factors option 2 (input IHCF = 2). When the option IHCF is 2, an input datum (depending on the search type) is adjusted so that the value of a code output quantity with *both* global and local hot channel factors applied equals an input target value. Using the search capability, a single run of the code generates all the data needed to plot a reactor operation diagram showing the relationship among three reactor parameters, e.g., nominal or true reactor power, nominal or true core flow, and the global minimum ONBR or minimum DNBR with all hot channel factors applied.

The purpose this memorandum is to present a verification of the search capability, and an example of its application to research reactor analysis.

## 12.2. History Data and Search Capability

At the end of the output file on unit 6, the code prints one line of history data (a summary of the key results of the run) for a problem that does not use the hot channel factors option 2, and two lines of history data for a problem that uses the hot channel factors option 2. The first line is for the nominal case (without applying any hot channel factors), and the second line is for the case with global and local hot channel factors applied.

The history data is useful in plotting the results obtained by the search capability, as demonstrated herein. In a single run of the PLTEMP/ANL V3.7 code, one can make a diagram plotting the *nominal reactor power versus the nominal core flow* at a constant value of the minimum ONBR with global and local hot channel factors applied, parametrically varying the constant value of the minimum ONBR. Using the results of the same run, one can also make some another diagram plotting the *true reactor power versus the true core flow* at constant values of the minimum ONBR with global and local hot channel factors applied.

The following differences are noted between the history data outputs of PLTEMP/ANL V3.7 code and its earlier versions.

**PLTEMP/ANL V3.7**: When using the hot channel factors option IHCF = 2, both global and local hot channel factors are used in calculating the onset of nucleate boiling ratio (ONBR), the departure from nucleate boiling ratio (DNBR), and the flow instability power ratio (FIR). The calculation of the maximum cladding surface temperature ($T_{cs,max}$), and the maximum coolant temperature ($T_{ex,max}$) has been newly added. The code prints one line of HISTORY DATA at the end of the output file on unit 6 if the option IHCF is 1, and prints two lines of HISTORY DATA when using the option IHCF is 2. The first line shows results without incorporating any hot channel factor, and the second line shows results with *all six hot channel factors applied*. It is noted that the meaning of ONBR, DNBR, and FIR printed in the second line has changed.

**PLTEMP/ANL Earlier Versions**: When using the hot channel factors option IHCF = 2, both global and local hot channel factors are used in calculating ONBR. However, *only the global hot channel factors* are used in calculating DNBR and FIR. The maximum cladding surface temperature and the maximum coolant temperature are not calculated. The code prints one line of HISTORY DATA at the end of the output file if the option IHCF is 1, and prints two lines of HISTORY DATA when using the option IHCF is 2. The first line shows results without incorporating any hot channel factor, and the second line shows results with *only* the global hot channel factors applied.

### 12.3. Implementation of the Search Capability

Figure 1 shows a logic flow diagram of how a search is performed by the main program of the code. Basically, each search is performed using the *interval-halving technique*.

In a single search using this technique, the specified input datum is first set at its lower limit X1=XLOW (which is an input); an input data file is written on a scratch file; and the *pre-search* code is run to find the corresponding value Y1 for the specified output variable. The specified input datum is then reset at its upper limit X2=XHIGH (an input); another input data file is written over the scratch file; and the *pre-search* code is re-run to find the corresponding value Y2 for the output variable. The interval between X1 and X2 is then halved, and the specified input datum is reset at the arithmetic mean X3 of its lower and upper limits X1 and X2; a third input data file is written over the scratch file; and the *pre-search* code is re-run to find the corresponding value Y3 for the output variable. If the user-specified target value YTARGT of the output variable lies between Y1 and Y3, then X2 is set equal to X3; or if the target value YTARGT lies between Y3 and Y2, then X1 is set equal to X3. The interval between X1 and X2 is halved again, and the process (of writing an input data file and running the *pre-search* code) is repeated to get another pair of values, X3 and Y3, for the input datum and the output variable. This process is repeated to achieve a convergence, i.e., either the gap between X1 and X2 is a very small fraction of (XHIGH - XLOW), or Y3 is very close to YTARGT. This process is carried out in the subroutine SEARCH1. A single search converges in about 15 to 30 iterations, i.e., passes through the pre-search code.

In a double search using this technique, the same process is carried out in the main program MAINSRCH (Fig. 1) in order to achieve a user-specified target value YTARGT2 of *the second* of the two output variables, by adjusting *the second* of the two specified input data (e.g., reactor power in the case of search type 21). In the main program, instead of running the pre-search code, the subroutine SEARCH1 is called each time to run a single search to adjust *the first* specified input datum (e.g., applied pressure drop in the case of search type 21) to achieve *the first* output variable's specified target value. The process in the main program is repeated till either the gap between the lower and upper limits of the second datum is a very small fraction of (XHIGH2 – XLOW2), or the value of the second output variable at the interval mid-point is very close to YTARGT2. A double search converges in about 300 to 400 iterations, i.e., passes through the pre-search code.

Currently, 11 single searches and 5 double searches are available as listed in Table 1. These searches are listed with the input data required (Cards 0203 and 0204) by each search in the code input description[1]. These searches adjust the input applied pressure drop or/and reactor power to get target values of any one or any two of these calculated quantities: total flow rate, minimum ONBR, minimum DNBR, minimum flow instability power ratio, maximum cladding surface temperature, and maximum coolant exit temperature. The implementation of the search capability is such that new searches can be easily added.

### 12.4. Verification for a Test Problem without Hot Channel Factors

In order to verify PLTEMP/ANL V3.7 for problems not using hot channel factors, Table 2 shows an input data file for a test problem (Test Problem 27) having 2 fuel assemblies of identical geometry, without any bypass channel. Each fuel assembly has 4 fuel plates and 5 coolant channels. The geometry and power distribution in the fuel assemblies are specified in the input data file. The flow through the coolant channels is determined by a pressure drop applied on the fuel assemblies. As specified on input cards 0203 and 0204 in Table 2, this problem exercises the double search type 21 with the objective of verifying the implementation of this search type. The input cards 0203 and 0204 specify that the applied pressure drop be adjusted in the range 0.1 to 0.5 MPa, and the nominal reactor power be adjusted in the range 0.5 to 2.5 MW so that the reactor achieves a core flow of 35.0 kg/s with a minimum ONBR of 5.0.

The following steps were taken in the verification of the code PLTEMP/ANL V3.7:

(1) PLTEMP/ANL V3.7 was run for Test Problem 27 (input file in Table 2). The code writes and saves the input data file (named *input.modified* and shown in Table 3) used in the last iteration of the search which has the converged values of the two input data that are adjusted during the search, i.e., the applied pressure drop (0.32109375 MPa) and the

nominal reactor power (1.4580078 MW, both shown in boldface on the card 0500 in Table 3). The output file and the converged input data file were saved.

(2) The converged input data file saved in step 1 was converted into an input data file *without any search* for the older pre-search code PLTEMP/ANL V3.6, simply by commenting out the input cards 0203 and 0204, and by setting the search option ISRCH to zero on the input card 0200. Table 3 shows the converged input data file thus obtained. Then PLTEMP/ANL V3.6 was run for the converged input data file obtained, and the resulting output file was saved.

(3) The implementation of the search option 21 in PLTEMP/ANL V3.7 is verified if the two codes give the same results. The output files obtained by running the code versions V3.7 and V3.6 were compared. Table 4 shows a comparison of the key results. PLTEMP/ANL V3.6 gives a core flow of 35.0 kg/s and a minimum ONBR of 5.0, the same results as PLTEMP/ANL V3.7. This provides a verification of the implementation of the search option 21.

It is noted that the history data of PLTEMP/ANL V3.6 does not have three key results: the minimum flow instability power ratio $FIR_{min}$, the maximum cladding surface temperature $T_{cs,max}$, and the maximum coolant temperature $T_{ex,max}$. This is because PLTEMP/ANL V3.6 calculates $FIR_{min}$, and prints it in the body of the output file but does not include it in the history data. Its value printed in the body of the output file is 9.1616, identical to that in the output of the code version V3.7. Furthermore, the code version V3.6 does not calculate the other two key data ($T_{cs,max}$ and $T_{ex,max}$) and hence they are not present in its history data. These two data were added in the code version V3.7 in the course of adding the search capability.

## 12.5. Verification for a Test Problem Using Hot Channel Factors

The same approach as used in Section 12.4 (for problems without hot channel factors) is used again to verify the implementation of the search type 21 for a problem with hot channel factors. To verify PLTEMP/ANL V3.7 for problems using the option 2 of hot channel factors, Table 5 shows the input data file for a test problem (Test Problem 28) having 2 fuel assemblies of identical geometry, without any bypass channel. Each fuel assembly has 4 fuel plates and 5 coolant channels. The geometry and power distribution in the fuel assemblies are specified in the input data file. The six hot channel factors that are used in the option 2 are defined in the Code Users Guide[1]. Their values, shown in boldface in Table 5, are:

Global Factors: FPOWER = 1.18, FFLOW = 1.25, FNUSLT = 1.20
Local Factors: FBULK = 1.05, FFILM = 1.06, FFLUX = 1.07

The flow through the coolant channels is determined by a pressure drop applied on the fuel assemblies. As specified on input cards 0203 and 0204 in Table 5, this problem exercises the double search type 21 with the objective of verifying the implementation of this search type. The input cards 0203 and 0204 specify that the applied pressure drop be adjusted in the range 0.1 to 0.5 MPa, and the nominal reactor power be adjusted in the range 0.5 to 3.0 MW so that the reactor achieves, with all hot channel factors applied, a core flow of 6.0 kg/s with a minimum ONBR of 1.2. The following steps were taken to verify the code:

(1) PLTEMP/ANL V3.7 was run for Test Problem 28 (input file in Table 5). The code writes and saves the input data file (named *input.modified* and shown in Table 6) used in the last iteration of the search which has the converged values of the two input data that are adjusted during the search, i.e., the applied pressure drop (0.11537476 MPa) and the nominal reactor power (0.95423889 MW, both shown in boldface on the card 0500 in Table 6). The output file and the converged input data file were saved.

(2) The converged input data file saved in step 1 was converted into an input data file *without any search* for the older pre-search code PLTEMP/ANL V3.6, simply by commenting out the input cards 0203 and 0204, and by setting the search option ISRCH to zero on the input card 0200. Table 6 shows the converged input data file thus obtained. Then PLTEMP/ANL V3.6 was run for the converged input data file obtained, and the resulting output file was saved.

(3) The implementation of the search option 21 in PLTEMP/ANL V3.7 is verified if the two codes give the same results. The output files obtained by running the code versions V3.7 and V3.6 were compared. Table 7 shows a comparison of the key results printed as the history data at the end of the output file. *As discussed below*, PLTEMP/ANL V3.6 gives a core flow of 6.000 kg/s and a minimum ONBR of 1.200 with both global and local hot channel factors, the same results as PLTEMP/ANL V3.7. This provides a verification of the implementation of the search option 21 for problems using hot channel factors.

<u>Discussion of ONBR with Hot Channel Factors</u>: When using the hot channel factors option 2, PLTEMP/ANL V3.6 and the earlier code versions calculate (i) the minimum ONBR with only global hot channel factors, and also (ii) the minimum ONBR with both global and local hot channel factors. Both minima are printed in the main body of the output file. However, the history data printed at the end of the code version V3.6 output file contains the former, not the latter. This discrepancy is removed in PLTEMP/ANL V3.7, and the history data printed at the end of its output file contains the minimum ONBR with both global and local hot channel factors. As shown in Table 7, both code versions calculate a minimum ONBR of 1.268 with only global hot channel factors. Both code versions calculate a minimum ONBR of 1.200 with both global and local hot channel factors.

<u>Discussion of DNBR with Hot Channel Factors</u>: Regarding the DNBR using the hot channel factors option 2, PLTEMP/ANL V3.6 and the earlier code versions calculate the minimum DNBR with only global hot channel factors. The code versions V3.6 and V3.7 calculate a minimum DNBR of 14.092 with only global hot channel factors. The minimum DNBR with both global and local hot channel factors is not calculated by the code version V3.6 and the earlier versions. This discrepancy is removed in the code version V3.7. The minimum DNBR of 12.934 with both global and local hot channel factors is printed in the main body of the PLTEMP/ANL V3.7 output file, and also in the pass 2 of the history data.

<u>Flow Instability Power Ratio (FIR) with Hot Channel Factors</u>: Regarding the FIR using the hot channel factors option 2, PLTEMP/ANL V3.6 and the earlier code versions calculate the minimum FIR with only global hot channel factors. The code versions V3.6 and V3.7 calculate a minimum FIR of 1.807 with only global hot channel factors. The minimum FIR with both global and local hot channel factors is not calculated by the code version V3.6 and the earlier versions. This discrepancy is removed in the code version V3.7. The minimum FIR of 1.721 with both global and local hot channel factors is printed in the main body of the PLTEMP/ANL V3.7 output file, and also in the pass 2 of the history data.

### 12.6. Plotting Reactor Operation Diagrams Using the Search Capability

We now demonstrate how to use the search capability to get, in one run of the code, all the data needed to plot a three-parameter reactor operation diagram, e.g., to plot multiple power versus flow curves, each at a constant value of minimum ONBR, varying the ONBR parametrically. The power and flow could be nominal or true. The value of minimum ONBR could be with or without the global and local hot channel factors applied when the hot channel factors option 2 is used. Instead of the minimum ONBR, the parameter could be (i) the minimum DNBR, (ii) the maximum cladding surface temperature, or (iii) the maximum coolant temperature.

Table 8 shows an input data file (Test Problem 29) for the PLTEMP/ANL V3.7 code that uses the search type 21 to get all the data needed (in a single code run) for plotting a diagram of the nominal power versus the nominal core flow, parametrically varying the minimum ONBR. This problem uses the hot channel factors option 2 (global and local hot channel factors). Therefore, the minimum ONBR mentioned here is its value with all six hot channel factors applied. The search data is provided on input cards 0203 and 0204. The card 0203 specifies that the fuel assembly applied pressure drop be adjusted between 0.1 and 0.5 MPa to achieve a target core flow rate of 6.0 kg/s (the first of the 10 target flow rates 6.0, 6.5, 7.0, 7.5, 8.0, 9.0, 10.0, 11.0, 12.0, and 12.5 kg/s input on card 0203). These flow rates are with all hot channel factors applied. The card 0204 specifies that the reactor power be adjusted between 0.2 and 3.0 MW to achieve a target minimum ONBR of 1.2 (the first of the 4 target ONBR minima 1.2, 1.5, 2.0, and 2.5 input on card 0204). These ONBR minima are with all the hot channel factors applied.

Using 10 target values for the core flow and 4 target values for the minimum ONBR, it is noted that Test Problem 29 has 40 double searches. Each double search involves about 300 to 400 iterations (or runs of the pre-search PLTEMP/ANL code). This problem made a total of 13737 iterations, requiring on the average about 343 iterations per double search, and used an elapsed time of 2.6 hours. An output file *output.srch* newly added to PLTEMP/ANL V3.7 contains a summary of the iterations. The converged results for each double search are saved in the output file on unit 6, as usual. In addition, a summary of the key results for all searches (history data) are saved at the end of the output file on unit 6.

Table 9 shows the summary of the history data calculated for this problem. In the history data, the PLTEMP/ANL V3.7 code writes, for each search with hot channel factors option 2, two lines containing 17 key results per line. Of these 17 results, only 13 are shown in Table 9 for brevity. The first column shows the pass number for each search. It is noted that the data in pass 1 (I = 1) is the nominal case without any hot channel factors whereas the data in pass 2 (I = 2) has all the hot channel factors applied. Thus the summary of the key results for all 40 searches *printed by the code* is a table of 80 rows and 17 columns, whereas the summary shown in Table 9 is a table of 80 rows and 13 columns.

The reactor power in column 2 of pass 1 (Table 9), the core flow in column 4 of pass 1, and the minimum ONBR in column 7 of pass 2 were plotted (on a Microsoft Spreadsheet) to obtain the reactor operation diagram shown in Fig. 2. This is a three-parameter reactor operation diagram, showing the relationship among the nominal reactor power, the nominal core flow, and the minimum ONBR with all six hot channel factors applied.

It is noted that the power and flow data in pass 2 (I = 2) are with the hot channel factors applied, and hence are true reactor power and true flow rate. The reactor power in column 2 of pass 2, the core flow in column 4 of pass 2, and the minimum ONBR in column 7 of pass 2 were plotted to obtain the diagram shown in Fig. 3. This is a three-parameter reactor operation diagram, showing the relationship among the true reactor power, the true core flow, and the minimum ONBR with all six hot channel factors applied.

The maximum cladding surface temperature of column 12 of pass 2, the core flow of column 4 of pass 1, and the minimum ONBR of column 7 of pass 2 were plotted to obtain a third diagram from the data calculated in the same run, and this diagram is shown in Fig. 4. This diagram shows the relationship among the maximum cladding surface temperature, the nominal core flow, and the minimum ONBR. Here all six hot channel factors have been applied to the cladding surface temperature and the ONBR.

The maximum coolant temperature of column 13 of pass 2, the core flow of column 4 of pass 1, and the minimum ONBR of column 7 of pass 2 were plotted to obtain another diagram from the data calculated in the same run, and this diagram is shown in Fig. 5. This diagram shows the relationship among the maximum coolant temperature, the nominal core flow, and the minimum ONBR. Here all six hot channel factors have been applied to the coolant temperature and the ONBR.

The minimum flow instability power ratio of column 11 of pass 2, the core flow of column 4 of pass 1, and the minimum ONBR of column 7 of pass 2 were plotted to obtain another diagram from the data calculated in the same run, and this diagram is shown in Fig. 6. This diagram shows the relationship among the minimum flow instability power ratio, the nominal core flow, and the minimum ONBR. The values of the minimum flow instability power ratio and the minimum ONBR plotted are with all six hot channel factors have been applied.

### 12.7. Conclusions

A general search capability has been implemented in the PLTEMP/ANL V3.7 code for the thermal-hydraulics analysis of research reactors. The method used in the search capability has been described, and a verification of PLTEMP/ANL V3.7 has been performed by comparing it with a previous version of the code. PLTEMP/ANL V3.7 has also been verified for problems using hot channel factors. The utility of the search capability has been demonstrated by plotting some reactor operation diagrams involving three reactor parameters (plotting different sets of three parameters), using data obtained by a single run of the code. This greatly reduces the reactor analyst's effort.

In the course of implementing the search capability, the calculation of minimum DNBR and minimum flow instability power ratio (FIR), with both global and local hot channel factors applied, were added to the code when using the hot channel factors option 2 (input IHCF = 2). The newly calculated ratios are used as target values in some searches available in the code.

## REFERENCES


1. A. P. Olson and M. Kalimullah, Argonne National Laboratory, unpublished information, March 25, 2009.

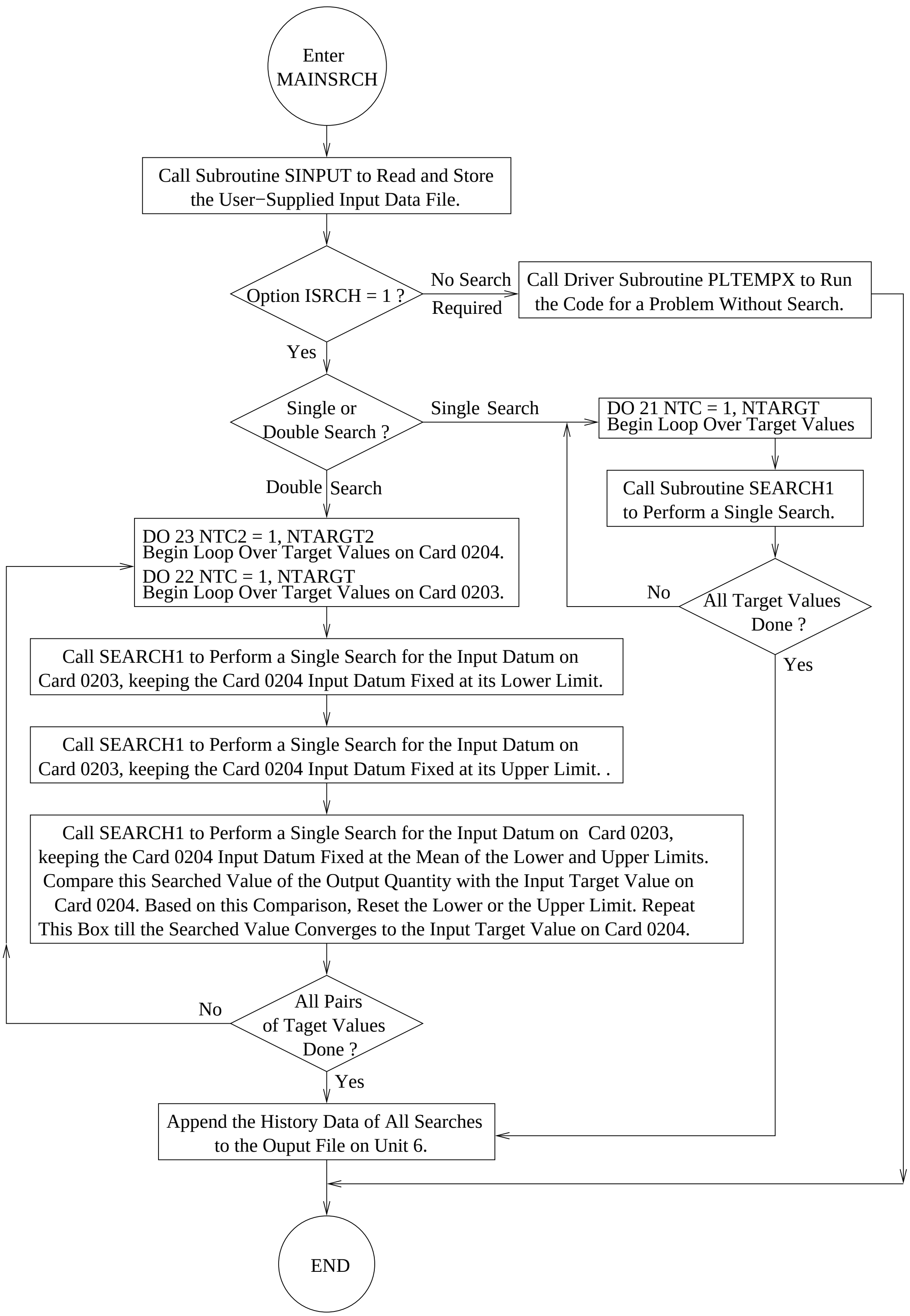


**Fig. 1. Logical Flow Diagram of the Main Program of PLTEMP/ANL V3.7 Code**

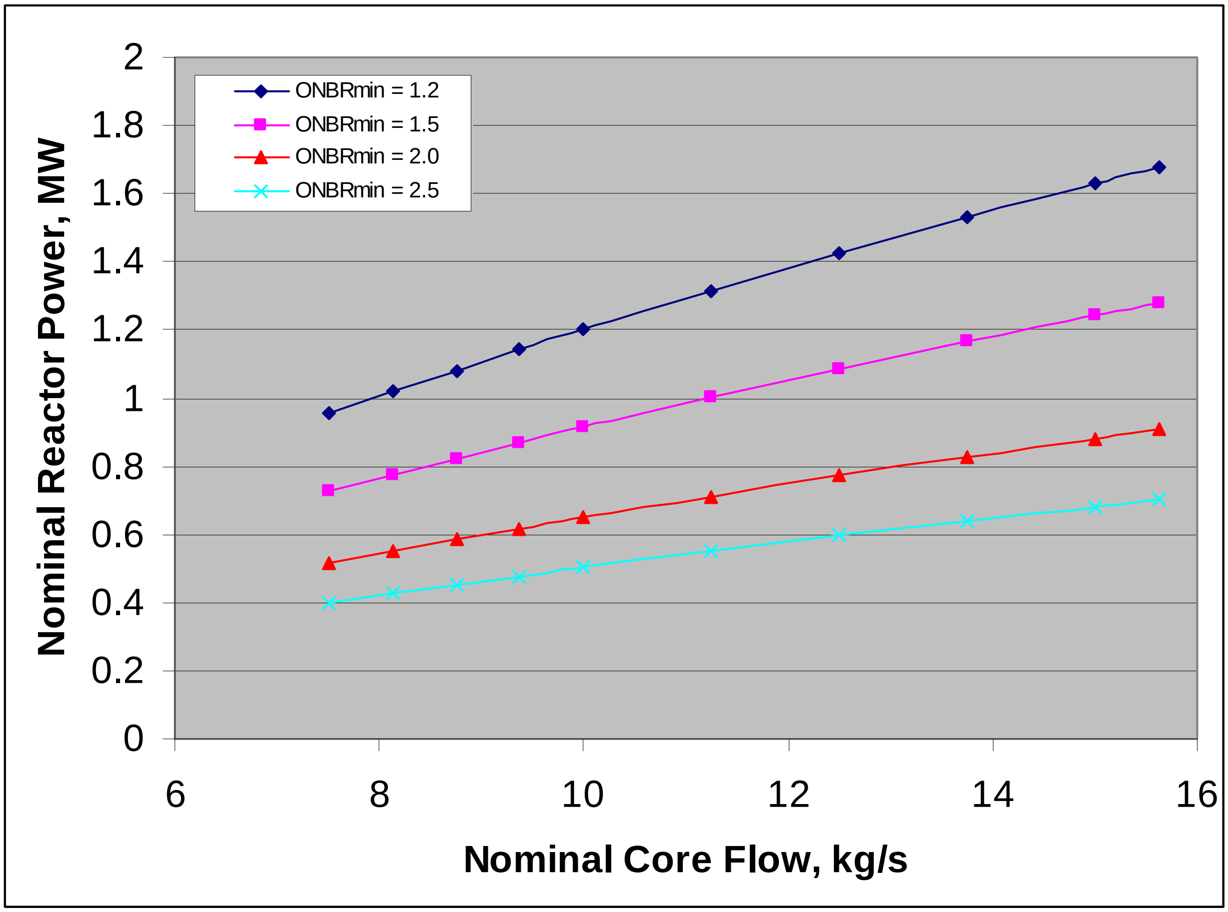


**Fig. 2. Reactor Operation Diagram Showing the Relationship among Nominal Reactor Power, Nominal Core Flow, and the Minimum ONBR with Global and Local Hot Channel Factors**

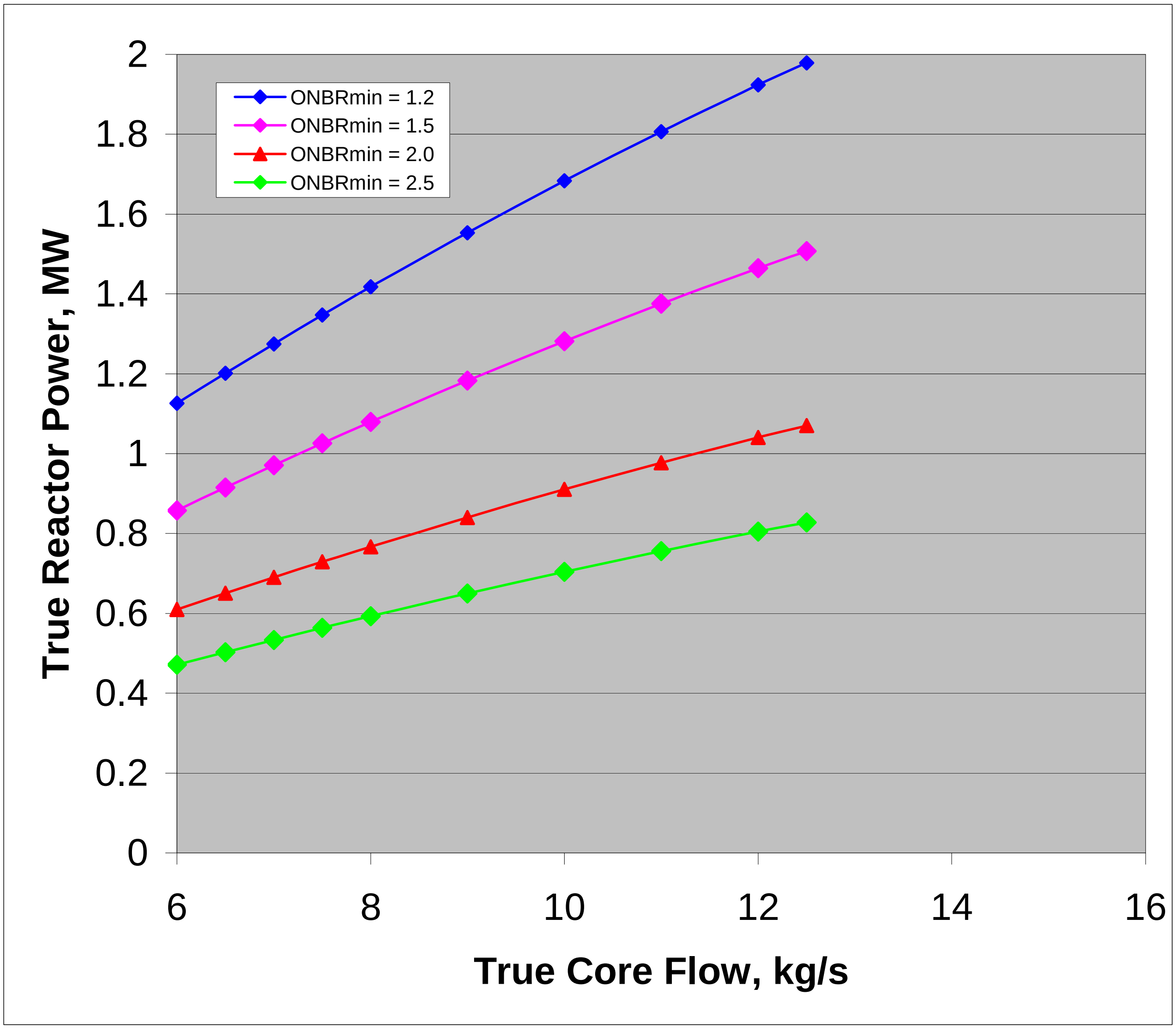


**Fig. 3. Reactor Operation Diagram Showing the Relationship among True Reactor Power, True Core Flow, and the Minimum ONBR with Global and Local Hot Channel Factors Applied**

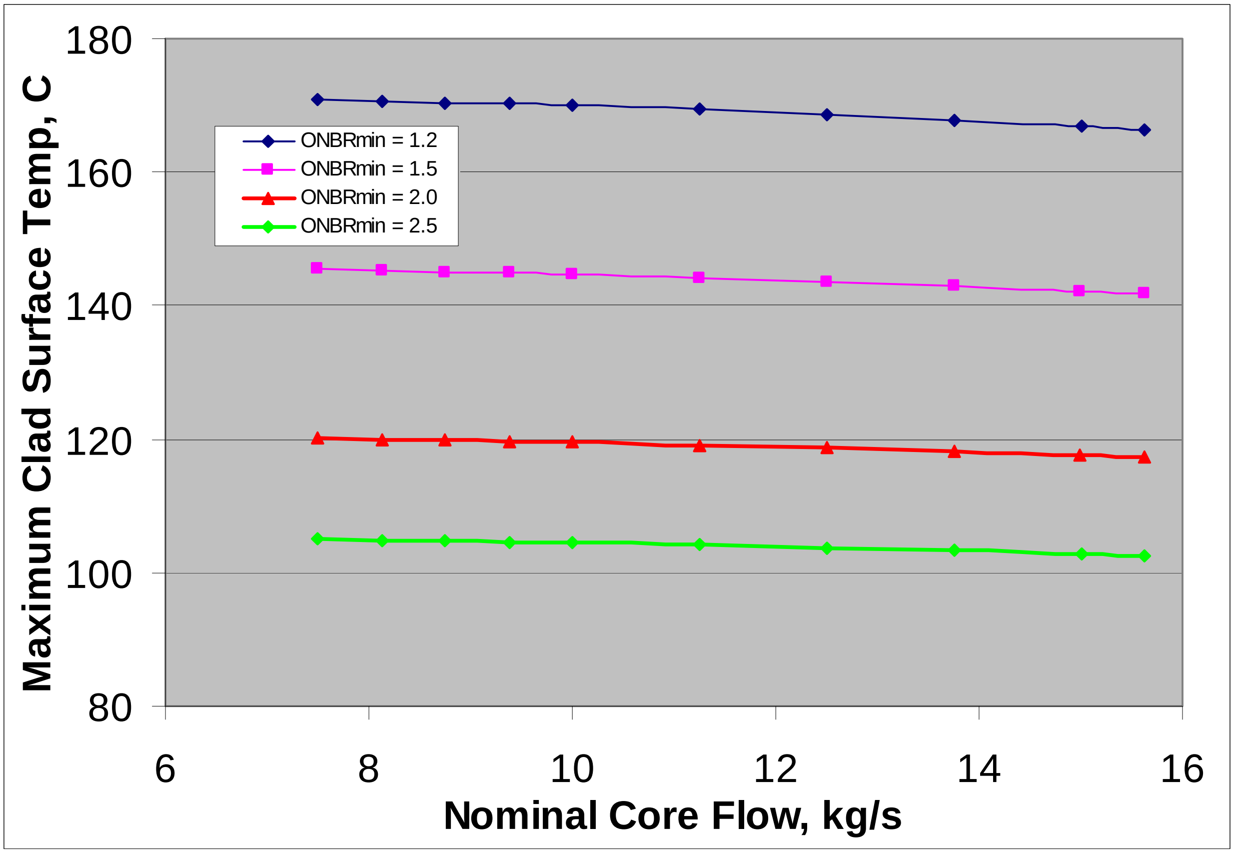


**Fig. 4. Reactor Operation Diagram Showing the Relationship among Nominal Core Flow, Maximum Cladding Surface Temperature, and the Minimum ONBR with Global and Local Hot Channel Factors Applied**

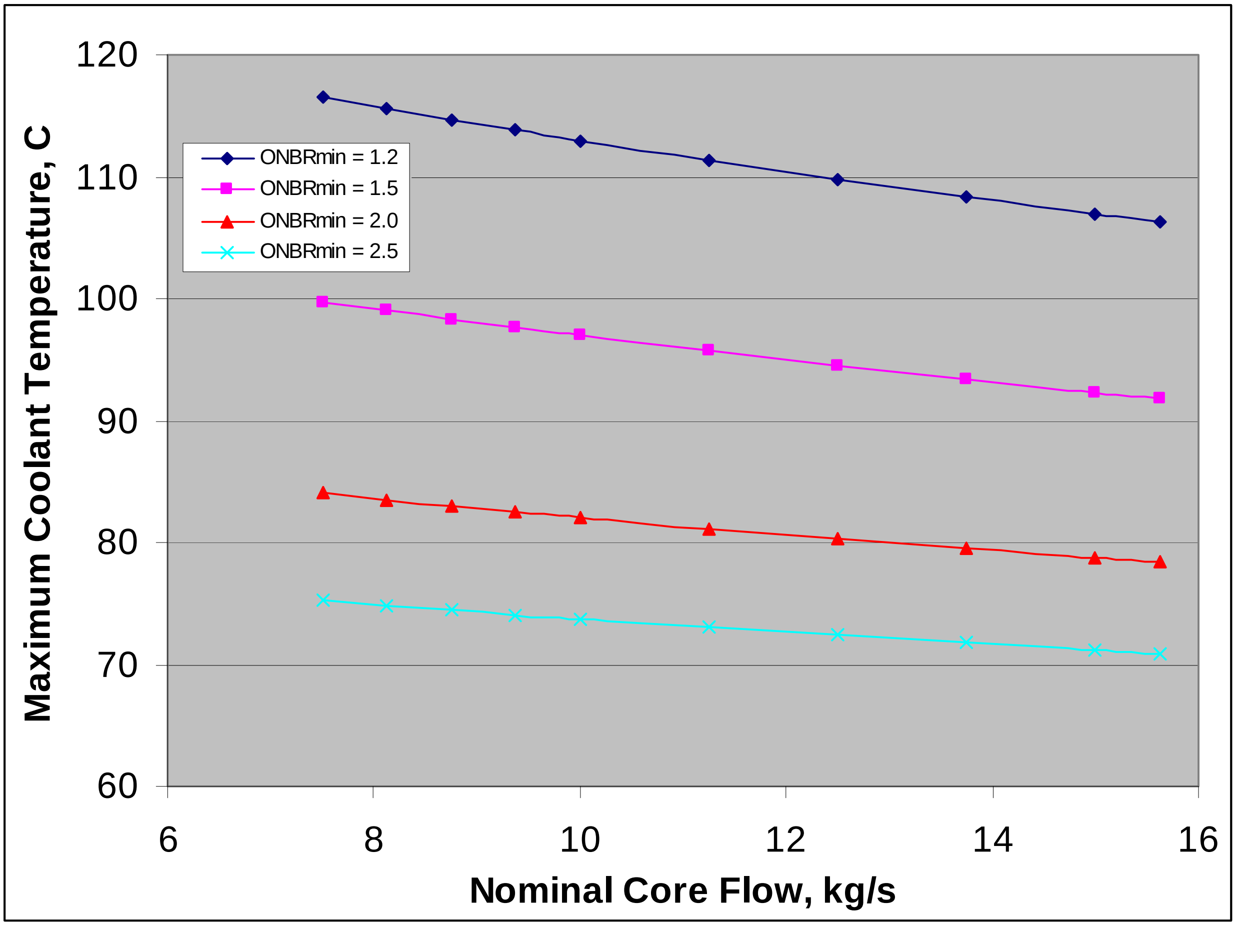


**Fig. 5. Reactor Operation Diagram Showing the Relationship among Nominal Core Flow, Maximum Coolant Temperature, and the Minimum ONBR with Global and Local Hot Channel Factors Applied**

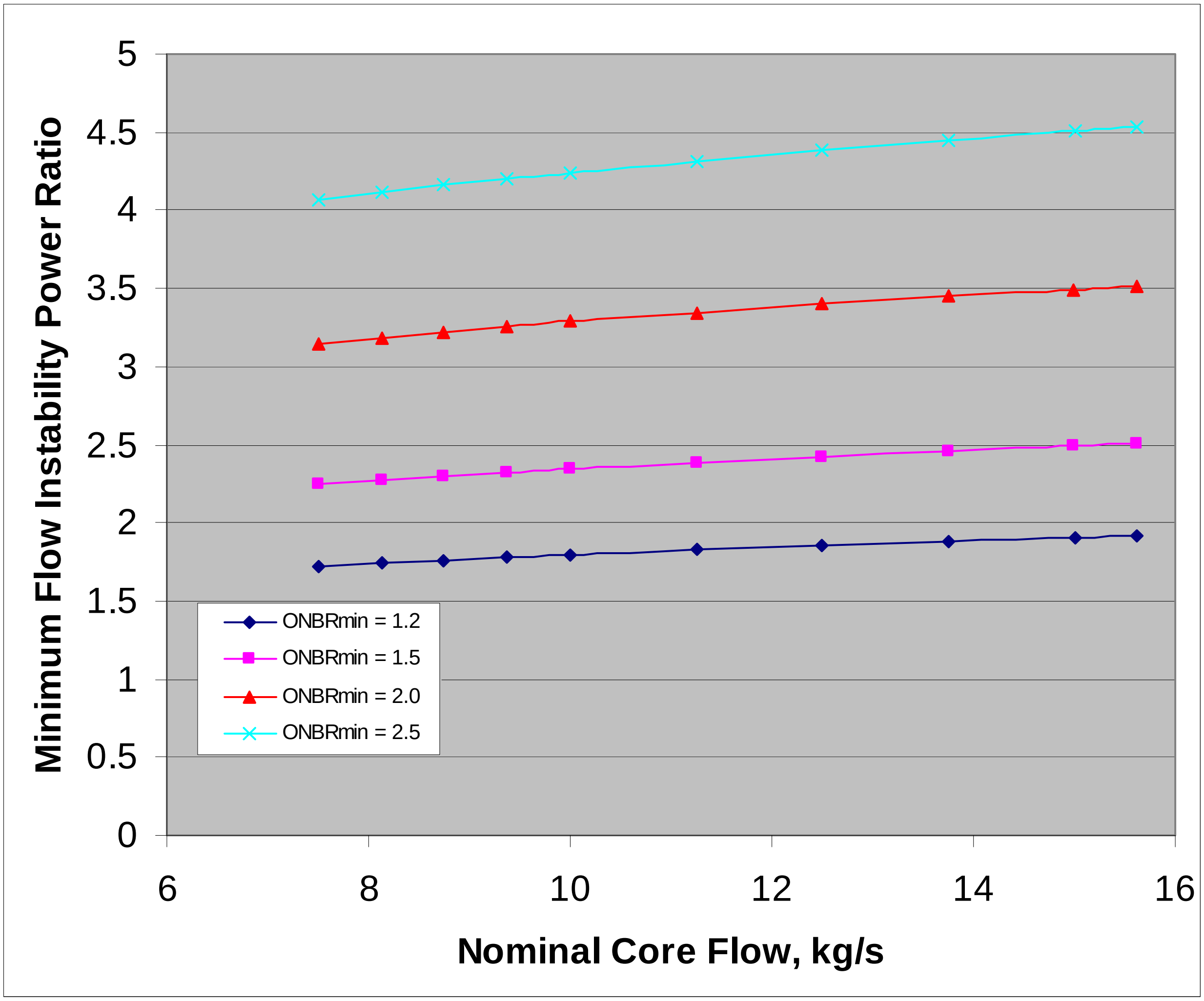


**Fig. 6. Reactor Operation Diagram Showing the Relationship among Nominal Core Flow, Minimum Flow Instability Power Ratio, and the Minimum ONBR with Global and Local Hot Channel Factors Applied**

**TABLE 1. List of Searches Implemented in PLTEMP/ANL V3.7**

| NSRCH, Search Type | Input Datum Being Adjusted | Output Quantity Whose Target Value is Searched | Comments |
|---|---|---|---|
| *Single Searches* | | | |
| 1 | Pressure Drop | Total flow through all fuel assemblies, WT | |
| 2 | Pressure Drop | Onset of nucleate boiling ratio, $ONBR_{min}$ | Desired $ONBR_{min} \geq 1$ |
| 3 | Pressure Drop | Minimum ratio of critical heat flux to reactor heat flux, $DNBR_{min}$ | Desired $DNBR_{min} \geq 1$ |
| 4 | Reactor Power | $ONBR_{min}$ | |
| 5 | Reactor Power | $DNBR_{min}$ | |
| 6 | Pressure Drop | Minimum flow instability power ratio $FIR_{min}$ | Desired $FIR_{min} \geq 1.15$ |
| 7 | Reactor Power | Minimum flow instability power ratio $FIR_{min}$ | |
| 8 | Pressure Drop | Maximum cladding surface temperature $T_{cs,max}$ | |
| 9 | Pressure Drop | Maximum coolant temperature $T_{ex,max}$ | |
| 10 | Reactor Power | $T_{cs,max}$ | |
| 11 | Reactor Power | $T_{ex,max}$ | |
| *Double Searches* | | | |
| 21 | First Pressure Drop, Then Reactor Power | Total flow WT<br>$ONBR_{min}$ | Multiple values of each target may be be input in a run. |
| 22 | First Pressure Drop, Then Reactor Power | Total flow WT<br>$DNBR_{min}$ | |
| 23 | First Pressure Drop, Then Reactor Power | Total flow WT<br>$FIR_{min}$ | |
| 24 | First Pressure Drop, Then Reactor Power | Total flow WT<br>Maximum cladding surface temperature $T_{cs,max}$ | |
| 25 | First Pressure Drop, Then Reactor Power | Total flow WT<br>Maximum coolant temperature $T_{ex,max}$ | |

## TABLE 2. Input File for Test Problem 27 without Hot Channel Factors That Uses Double Search Type 21

```
Test Problem: Using Search Option, 2 assy (of identical geometry) producing 1 MWt
! Each assembly has 4 fuel plates and 5 coolant channels
! H2O coolant, Flow is calculated from input pressure drop
! All hot channel factors = 1.0
! No bypass flow, NCTYP=0
! 10 axial heat transfer nodes in the heated length of fuel plates
!  1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18  19    # Card 0200
   0   0   0   1   0   1   1   1   0   0   0   0   0           0   1       0    Card(1)0200
  21 0.1        0.5          1 35.0                                             Card(1)0203
 0.5         2.5          1 5.00                                                Card(1)0204
   2   3 0.50      1.00        1.00        1.00          3                      Card(1)0300
! Using pressure driven mode
   1  20 1.00                                                                   Card(1)0301
   1   1   1                                                                    Card(1)0302
1.20        1.20                                                                Card(2)0303
30.0E-04    0.02955665  0.15        8.00        0.20        15.0E-03            Card(3)0304
30.0E-04    5.91133E-03 0.75        0.00        0.20        3.00E-03            Card(3)0304
30.0E-04    0.02955665  0.15        8.00        0.20        15.0E-03            Card(3)0304
! Use the code's biult-in correlation for friction factor
0.00        0.00        0.00                                                    Card(1)0305
   5   3 0.00      0.75        0.50E-03    0.00        1.00E-03    100.00      Card(1)0306
6.00E-04    5.91133E-03 0.4060      0.20        0.20        3.00E-03            Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03            Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03            Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03            Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.20        0.20        3.00E-03            Card(5)0307
0.20        0.20        0.20        0.20                                        Card(1)0308
! Card 0308a not required
! Radial power peaking factor data by fuel plate for each assembly. Input flow data by
! channel for each assembly on Cards 0310 not required because WFGES(1) is non-zero
0.900       0.950       1.050       1.100                                       Card(2)0309
0.901       0.951       1.049       1.099                                       Card(2)0309
! DP0       DDP         DPMAX       POWER       TIN         PIN
0.10        0.04        0.10        1.00        45.0        1.40                Card(1)0500
                                                                                Card(2)0500
  50 0.0001     25.0        0.00        1.00                                    Card(1)0600
  11                                                                            Card(1)0700
0.00        0.80                                                                Card(11)0701
0.10        0.88                                                                Card(11)0701
0.20        0.96                                                                Card(11)0701
0.30        1.04                                                                Card(11)0701
0.40        1.12                                                                Card(11)0701
0.50        1.20                                                                Card(11)0701
0.60        1.12                                                                Card(11)0701
0.70        1.04                                                                Card(11)0701
0.80        0.96                                                                Card(11)0701
0.90        0.88                                                                Card(11)0701
1.00        0.80                                                                Card(11)0701
   0                                                                            Card(11)0702
```

**TABLE 3. Converged Input File for Test Problem 27 without the Search Option**

```
 Test Problem: Using Search Option, 2 assy (identical geometry) producing 1 MW  Card 100
   0   0   0   1   0   1   1   1   0   0   0   0   0   0   0   0   0   0   0   0Card 200
! 21 1.00000E-01 5.00000E-01   1 3.50000E+01
!5.00000E-01 2.50000E+00   1 5.00000E+00
   2   3 5.00000E-01 1.00000E+00 1.00000E+00 1.00000E+00   3   0 0.00000E+00    Card 300
   1  20 1.00000E+00                                                            Card 301
   1   1   1                                                                    Card 302
 1.20000E+00 1.20000E+00                                                        Card 303
 3.00000E-03 2.95567E-02 1.50000E-01 8.00000E+00 2.00000E-01 1.50000E-02        Card 304
 3.00000E-03 5.91133E-03 7.50000E-01 0.00000E+00 2.00000E-01 3.00000E-03        Card 304
 3.00000E-03 2.95567E-02 1.50000E-01 8.00000E+00 2.00000E-01 1.50000E-02        Card 304
 0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00                                Card 305
   5   3 0.00000E+00 7.50000E-01 5.00000E-04 0.00000E+00 1.00000E-03 1.00000E+02Card 306
 6.00000E-04 5.91133E-03 4.06000E-01 2.00000E-01 2.00000E-01 3.00000E-03        Card 307
 6.00000E-04 5.91133E-03 4.06000E-01 4.00000E-01 2.00000E-01 3.00000E-03        Card 307
 6.00000E-04 5.91133E-03 4.06000E-01 4.00000E-01 2.00000E-01 3.00000E-03        Card 307
 6.00000E-04 5.91133E-03 4.06000E-01 4.00000E-01 2.00000E-01 3.00000E-03        Card 307
 6.00000E-04 5.91133E-03 4.06000E-01 2.00000E-01 2.00000E-01 3.00000E-03        Card 307
 2.00000E-01 2.00000E-01 2.00000E-01 2.00000E-01                                Card 308
 9.00000E-01 9.50000E-01 1.05000E+00 1.10000E+00                                Card 309
 9.01000E-01 9.51000E-01 1.04900E+00 1.09900E+00                                Card 309
!-------------------------------------------------------------------------------
3.2109375E-1 4.00000E-02 1.00000E-011.4580078E+0 4.50000E+01 1.40000E+00        Card 500
.00000000000.00000000000                                                        Card 500
  10 1.00000E-04 2.50000E+01 0.00000E+00 1.00000E+00                            Card 600
  11                                                                            Card 700
 0.00000E+00 8.00000E-01                                                        Card 701
 1.00000E-01 8.80000E-01                                                        Card 701
 2.00000E-01 9.60000E-01                                                        Card 701
 3.00000E-01 1.04000E+00                                                        Card 701
 4.00000E-01 1.12000E+00                                                        Card 701
 5.00000E-01 1.20000E+00                                                        Card 701
 6.00000E-01 1.12000E+00                                                        Card 701
 7.00000E-01 1.04000E+00                                                        Card 701
 8.00000E-01 9.60000E-01                                                        Card 701
 9.00000E-01 8.80000E-01                                                        Card 701
 1.00000E+00 8.00000E-01                                                        Card 701
0
```

**TABLE 4. Comparison of Key Results for Test Problem 27 Obtained by PLTEMP/ANL V3.7 and V3.6**

| Pass No. | Power MW | Delta P MPa | Core Flow kg/s | Bypass kg/s | Total kg/s | ONBR Min | DNBR Min | Total m^3/hr | Total gpm | FIR Min | Max Clad Surf T(C) | Max Cool Temp(C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| History Data for Test Problem 27 Calculated by PLTEMP/ANL V3.7 Using Input File of Table 2 | | | | | | | | | | | | |
| 1 | 1.45801 | 0.32109375 | 35.0000 | 0.0000 | 35.0000 | 5.000 | 23.799 | 127.11796 | 559.68352 | 9.162 | 74.489 | 58.035 |
| History Data for Test Problem 27 Calculated by PLTEMP/ANL V3.6 Using Converged Input File of Table 3 | | | | | | | | | | | | |
| 1 | 1.45801 | 0.32109375 | 35.0000 | 0.0000 | 35.0000 | 5.000 | 23.799 | 127.11796 | 559.68352 | | | |

## TABLE 5. Input File for Test Problem 28 with Hot Channel Factors Option 2 That Uses Double Search Type 21

```
 Test Problem: 2 assemblies (of identical geometry) producing 1 MWt
! Each assembly has 4 fuel plates and 5 coolant channels
! H2O coolant, Flow is calculated from input pressure drop
! Uses Earl's hot channel factors, All Arnie's hot channel factors must be 1.0
! No bypass flow, NCTYP=0
! 10 axial heat transfer nodes in the heated length of fuel plates
!  1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18  19  20 #Card 0200
   0   0   0   1   0   1   1   1   0   0   0   0   0   0   2   0   1            Card(1)0200
 1.18      1.25       1.20                                                       Card(1)0201
  21 0.1         0.5         1 6.0                                               Card(1)0203
 0.2         3.0         1 1.2                                                   Card(1)0204
   2   3 0.50       1.00        1.00        1.00           3                     Card(1)0300
! Using pressure driven mode
 1.05      1.06       1.07                                                       Card(1)0300A
   1  20 1.00                                                                    Card(1)0301
   1   1   1                                                                     Card(1)0302
1.20       1.20                                                                  Card(2)0303
30.0E-04   0.02955665  0.15        8.00        0.20        15.0E-03              Card(3)0304
30.0E-04   0.02955665  0.75        0.00        0.20        15.0E-03              Card(3)0304
30.0E-04   0.02955665  0.15        8.00        0.20        15.0E-03              Card(3)0304
! Use the code's biult-in correlation for friction factor
0.00       0.00        0.00                                                      Card(1)0305
   5   3 0.00       0.75        0.50E-03    0.00        1.00E-03    100.00       Card(1)0306
6.00E-04   5.91133E-03 0.4060      0.20        0.20        3.00E-03              Card(5)0307
6.00E-04   5.91133E-03 0.4060      0.40        0.20        3.00E-03              Card(5)0307
6.00E-04   5.91133E-03 0.4060      0.40        0.20        3.00E-03              Card(5)0307
6.00E-04   5.91133E-03 0.4060      0.40        0.20        3.00E-03              Card(5)0307
6.00E-04   5.91133E-03 0.4060      0.20        0.20        3.00E-03              Card(5)0307
0.20       0.20        0.20        0.20                                          Card(1)0308
! Card 0308a not required
! Radial power peaking factor data by fuel plate for each assembly. Input flow data by
! channel for each assembly on Cards 0310 not required because WFGES(1) is non-zero
0.900      0.950       1.050       1.100                                         Card(2)0309
0.600      0.800       1.200       1.400                                         Card(2)0309
! DP0      DDP         DPMAX       POWER       TIN         PIN
0.10       0.04        0.10        1.00        45.0        1.40                  Card(1)0500
                                                                                 Card(2)0500
  50 0.0001     25.0        0.00        1.00                                     Card(1)0600
  11                                                                             Card(1)0700
0.00       0.80                                                                  Card(11)0701
0.10       0.88                                                                  Card(11)0701
0.20       0.96                                                                  Card(11)0701
0.30       1.04                                                                  Card(11)0701
0.40       1.12                                                                  Card(11)0701
0.50       1.20                                                                  Card(11)0701
0.60       1.12                                                                  Card(11)0701
0.70       1.04                                                                  Card(11)0701
0.80       0.96                                                                  Card(11)0701
0.90       0.88                                                                  Card(11)0701
1.00       0.80                                                                  Card(11)0701
   0                                                                             Card(11)0702
```

**TABLE 6. Converged Input File for Test Problem 28 with Hot Channel Factors Option 2 Without the Search Option**

```
 Test Problem: 2 assemblies (of identical geometry) producing 1 MWt            Card 100
   0   0   0   1   0   1   1   1   0   0   0   0   0   0   2   0   0   0   0   0Card 200
 1.18000E+00 1.25000E+00 1.20000E+00                                           Card 201
! 21 1.00000E-01 5.00000E-01   1 6.00000E+00
!2.00000E-01 3.00000E+00   1 1.20000E+00
   2   3 5.00000E-01 1.00000E+00 1.00000E+00 1.00000E+00   3   0 0.00000E+00    Card 300
 1.05000E+00 1.06000E+00 1.07000E+00                                           Card300A
   1  20 1.00000E+00                                                           Card 301
   1   1   1                                                                   Card 302
 1.20000E+00 1.20000E+00                                                       Card 303
 3.00000E-03 2.95567E-02 1.50000E-01 8.00000E+00 2.00000E-01 1.50000E-02       Card 304
 3.00000E-03 2.95567E-02 7.50000E-01 0.00000E+00 2.00000E-01 1.50000E-02       Card 304
 3.00000E-03 2.95567E-02 1.50000E-01 8.00000E+00 2.00000E-01 1.50000E-02       Card 304
 0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00                               Card 305
   5   3 0.00000E+00 7.50000E-01 5.00000E-04 0.00000E+00 1.00000E-03 1.00000E+02Card 306
 6.00000E-04 5.91133E-03 4.06000E-01 2.00000E-01 2.00000E-01 3.00000E-03       Card 307
 6.00000E-04 5.91133E-03 4.06000E-01 4.00000E-01 2.00000E-01 3.00000E-03       Card 307
 6.00000E-04 5.91133E-03 4.06000E-01 4.00000E-01 2.00000E-01 3.00000E-03       Card 307
 6.00000E-04 5.91133E-03 4.06000E-01 4.00000E-01 2.00000E-01 3.00000E-03       Card 307
 6.00000E-04 5.91133E-03 4.06000E-01 2.00000E-01 2.00000E-01 3.00000E-03       Card 307
 2.00000E-01 2.00000E-01 2.00000E-01 2.00000E-01                               Card 308
 9.00000E-01 9.50000E-01 1.05000E+00 1.10000E+00                               Card 309
 6.00000E-01 8.00000E-01 1.20000E+00 1.40000E+00                               Card 309
!-------------------------------------------------------------------------------
1.1537476E-1 4.00000E-02 1.00000E-019.5423889E-1 4.50000E+01 1.40000E+00       Card 500
.00000000000.00000000000                                                       Card 500
  17 1.00000E-04 2.50000E+01 0.00000E+00 1.00000E+00                           Card 600
  11                                                                           Card 700
 0.00000E+00 8.00000E-01                                                       Card 701
 1.00000E-01 8.80000E-01                                                       Card 701
 2.00000E-01 9.60000E-01                                                       Card 701
 3.00000E-01 1.04000E+00                                                       Card 701
 4.00000E-01 1.12000E+00                                                       Card 701
 5.00000E-01 1.20000E+00                                                       Card 701
 6.00000E-01 1.12000E+00                                                       Card 701
 7.00000E-01 1.04000E+00                                                       Card 701
 8.00000E-01 9.60000E-01                                                       Card 701
 9.00000E-01 8.80000E-01                                                       Card 701
 1.00000E+00 8.00000E-01                                                       Card 701
0
! end of input
```

**TABLE 7. Comparison of Key Results for Test Problem 28 Calculated by PLTEMP/ANL V3.7 and V3.6**

| Pass No. | Power MW | Delta P MPa | Core Flow kg/s | Bypass kg/s | Total kg/s | ONBR Min | DNBR Min | Total m^3/hr | Total gpm | FIR Min | Max Clad Surf T(C) | Max Cool Temp(C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| History Data for Test Problem 28 Calculated by PLTEMP/ANL V3.7 Using Input File of Table 5 | | | | | | | | | | | | |
| 1 | 0.95424 | 0.11537476 | 7.5000 | 0.0000 | 7.5000 | 1.926 | 18.953 | 27.23946 | 119.93171 | 2.674 | 123.287 | 91.039 |
| 2* | 1.12600 | 0.11537476 | 6.0000 | 0.0000 | 6.0000 | 1.200 | 12.934 | 21.79156 | 95.94537 | 1.721 | 170.848 | 116.556 |
| **With Only Global Hot Channel Factors** | | | | | | 1.268 | 14.092 | | | 1.807 | | |
| History Data for Test Problem 28 Calculated by PLTEMP/ANL V3.6 Using Converged Input File of Table 6 | | | | | | | | | | | | |
| 1 | 0.95424 | 0.11537476 | 7.5000 | 0.0000 | 7.5000 | 1.926 | 18.953 | 27.23946 | 119.93171 | | | |
| 2** | 1.12600 | 0.11537476 | 6.0000 | 0.0000 | 6.0000 | 1.268 | 14.092 | 21.79156 | 95.94537 | | | |
| **With Global and Local Factors** | | | | | | 1.200 | | | | | | |

* With Global and Local Hot Channel Factors Applied

** With Only Global Hot Channel Factors Applied

**TABLE 8. Input File for Test Problem 29 Using Double Search Type 21 for 40 Target Values**

```
 Test Problem: 2 assemblies (of identical geometry) producing 1 MWt
! Each assembly has 4 fuel plates and 5 coolant channels
! H2O coolant, Flow is calculated from input pressure drop
! Uses Earl's hot channel factors, All Arnie's hot channel factors must be 1.0
! No bypass flow, NCTYP=0
! 10 axial heat transfer nodes in the heated length of fuel plates
!  1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18  19  20 #Card 0200
   0   0   0   1   0   1   1   1   0   0   0   0   0   0   2   0   1            Card(1)0200
 1.18       1.25        1.20                                                    Card(1)0201
  21 0.1          0.5         10 6.0         6.5         7.0           7.5      Card(1)0203
 8.0          9.0        10.0        11.0        12.0        12.5               Card(1)0203
 0.2         3.0           4 1.2         1.5         2.0         2.5            Card(1)0204
   2   3 0.50       1.00        1.00        1.00           3                    Card(1)0300
! Using pressure driven mode
 1.05       1.06        1.07                                                    Card(1)0300A
   1  20 1.00                                                                   Card(1)0301
   1   1   1                                                                    Card(1)0302
1.20        1.20                                                                Card(2)0303
30.0E-04    0.02955665  0.15        8.00        0.20        15.0E-03            Card(3)0304
30.0E-04    0.02955665  0.75        0.00        0.20        15.0E-03            Card(3)0304
30.0E-04    0.02955665  0.15        8.00        0.20        15.0E-03            Card(3)0304
! Use the code's biult-in correlation for friction factor
0.00        0.00        0.00                                                    Card(1)0305
   5   3 0.00       0.75        0.50E-03    0.00        1.00E-03    100.00      Card(1)0306
6.00E-04    5.91133E-03 0.4060      0.20        0.20        3.00E-03            Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03            Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03            Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.40        0.20        3.00E-03            Card(5)0307
6.00E-04    5.91133E-03 0.4060      0.20        0.20        3.00E-03            Card(5)0307
0.20        0.20        0.20        0.20                                        Card(1)0308
! Card 0308a not required
! Radial power peaking factor data by fuel plate for each assembly. Input flow data by
! channel for each assembly on Cards 0310 not required because WFGES(1) is non-zero
0.900       0.950       1.050       1.100                                       Card(2)0309
0.600       0.800       1.200       1.400                                       Card(2)0309
! DP0       DDP         DPMAX       POWER       TIN         PIN
0.10        0.04        0.10        1.00        45.0        1.40                Card(1)0500
                                                                                Card(2)0500
  50 0.0001     25.0        0.00        1.00                                    Card(1)0600
  11                                                                            Card(1)0700
0.00        0.80                                                                Card(11)0701
0.10        0.88                                                                Card(11)0701
0.20        0.96                                                                Card(11)0701
0.30        1.04                                                                Card(11)0701
0.40        1.12                                                                Card(11)0701
0.50        1.20                                                                Card(11)0701
0.60        1.12                                                                Card(11)0701
0.70        1.04                                                                Card(11)0701
0.80        0.96                                                                Card(11)0701
0.90        0.88                                                                Card(11)0701
1.00        0.80                                                                Card(11)0701
   0                                                                            Card(11)0702
```

**TABLE 9. History Data Printed by PLTEMP/ANL V3.7 for the Test Problem 29**

====== BEGIN HISTORY RESULTS FOR ALL SEARCHES ======

| I | Power MW | Delta P MPa | Core Flow kg/s | Bypass kg/s | Total kg/s | ONBR Min | DNBR Min | Total m^3/hr | Total gpm | FIR Min | Max Clad Surf T(C) | Max Cool Temp(C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | **0.95424** | 0.11537476 | **7.5000** | 0.0000 | 7.5000 | 1.926 | 18.953 | 27.23946 | 119.93171 | 2.674 | 123.287 | 91.039 |
| 2 | 1.12600 | 0.11537476 | 6.0000 | 0.0000 | 6.0000 | 1.200 | 12.934 | 21.79156 | 95.94537 | 1.721 | 170.848 | 116.556 |
| 1 | 1.01809 | 0.13475037 | 8.1250 | 0.0000 | 8.1250 | 1.926 | 17.908 | 29.50959 | 129.92680 | 2.704 | 123.139 | 90.418 |
| 2 | 1.20135 | 0.13475037 | 6.5000 | 0.0000 | 6.5000 | 1.200 | 12.211 | 23.60767 | 103.94144 | 1.740 | 170.664 | 115.577 |
| 1 | 1.08051 | 0.15558472 | 8.7499 | 0.0000 | 8.7499 | 1.927 | 16.997 | 31.77929 | 139.91999 | 2.733 | 122.975 | 89.826 |
| 2 | 1.27500 | 0.15558472 | 7.0000 | 0.0000 | 7.0000 | 1.200 | 11.580 | 25.42343 | 111.93599 | 1.759 | 170.455 | 114.657 |
| 1 | 1.14156 | 0.17788086 | 9.3749 | 0.0000 | 9.3749 | 1.928 | 16.191 | 34.04927 | 149.91442 | 2.760 | 122.796 | 89.262 |
| 2 | 1.34705 | 0.17788086 | 7.5000 | 0.0000 | 7.5000 | 1.200 | 11.022 | 27.23942 | 119.93154 | 1.776 | 170.221 | 113.783 |
| 1 | 1.20127 | 0.20163574 | 10.0000 | 0.0000 | 10.0000 | 1.928 | 15.473 | 36.31941 | 159.90953 | 2.786 | 122.605 | 88.728 |
| 2 | 1.41750 | 0.20163574 | 8.0000 | 0.0000 | 8.0000 | 1.200 | 10.526 | 29.05553 | 127.92763 | 1.793 | 169.959 | 112.944 |
| 1 | 1.31616 | 0.25350342 | 11.2500 | 0.0000 | 11.2500 | 1.930 | 14.250 | 40.85949 | 179.89891 | 2.835 | 122.150 | 87.692 |
| 2 | 1.55307 | 0.25350342 | 9.0000 | 0.0000 | 9.0000 | 1.200 | 9.683 | 32.68759 | 143.91913 | 1.825 | 169.360 | 111.322 |
| 1 | 1.42617 | 0.31115723 | 12.5001 | 0.0000 | 12.5001 | 1.931 | 13.230 | 45.39956 | 199.88823 | 2.879 | 121.658 | 86.731 |
| 2 | 1.68289 | 0.31115723 | 10.0001 | 0.0000 | 10.0001 | 1.200 | 8.979 | 36.31965 | 159.91058 | 1.854 | 168.654 | 109.819 |
| 1 | 1.53079 | 0.37457275 | 13.7500 | 0.0000 | 13.7500 | 1.932 | 12.363 | 49.93915 | 219.87546 | 2.920 | 121.101 | 85.801 |
| 2 | 1.80633 | 0.37457275 | 11.0000 | 0.0000 | 11.0000 | 1.200 | 8.382 | 39.95132 | 175.90037 | 1.880 | 167.839 | 108.369 |
| 1 | 1.62986 | 0.44375000 | 15.0000 | 0.0000 | 15.0000 | 1.933 | 11.612 | 54.47921 | 239.86473 | 2.958 | 120.478 | 84.902 |
| 2 | 1.92324 | 0.44375000 | 12.0000 | 0.0000 | 12.0000 | 1.200 | 7.868 | 43.58337 | 191.89179 | 1.905 | 166.913 | 106.958 |
| 1 | 1.67690 | 0.48052979 | 15.6250 | 0.0000 | 15.6250 | 1.934 | 11.272 | 56.74902 | 249.85840 | 2.976 | 120.136 | 84.460 |
| 2 | 1.97875 | 0.48052979 | 12.5000 | 0.0000 | 12.5000 | 1.200 | 7.637 | 45.39922 | 199.88672 | 1.917 | 166.403 | 106.265 |
| 1 | 0.72682 | 0.11635742 | 7.5000 | 0.0000 | 7.5000 | 2.430 | 25.528 | 27.23974 | 119.93295 | 3.498 | 106.885 | 80.196 |
| 2 | 0.85764 | 0.11635742 | 6.0000 | 0.0000 | 6.0000 | 1.500 | 18.555 | 21.79179 | 95.94636 | 2.248 | 145.405 | 99.751 |
| 1 | 0.77537 | 0.13587036 | 8.1250 | 0.0000 | 8.1250 | 2.431 | 24.107 | 29.50968 | 129.92719 | 3.537 | 106.761 | 79.718 |
| 2 | 0.91494 | 0.13587036 | 6.5000 | 0.0000 | 6.5000 | 1.500 | 17.494 | 23.60774 | 103.94176 | 2.275 | 145.245 | 98.990 |
| 1 | 0.82284 | 0.15685425 | 8.7500 | 0.0000 | 8.7500 | 2.432 | 22.869 | 31.77954 | 139.92111 | 3.576 | 106.622 | 79.259 |
| 2 | 0.97095 | 0.15685425 | 7.0000 | 0.0000 | 7.0000 | 1.500 | 16.568 | 25.42363 | 111.93689 | 2.299 | 145.068 | 98.278 |
| 1 | 0.86929 | 0.17930298 | 9.3750 | 0.0000 | 9.3750 | 2.433 | 21.775 | 34.04949 | 149.91538 | 3.612 | 106.472 | 78.822 |
| 2 | 1.02576 | 0.17930298 | 7.5000 | 0.0000 | 7.5000 | 1.500 | 15.751 | 27.23959 | 119.93230 | 2.322 | 144.867 | 97.601 |
| 1 | 0.91470 | 0.20321655 | 10.0000 | 0.0000 | 10.0000 | 2.434 | 20.800 | 36.31951 | 159.90996 | 3.646 | 106.315 | 78.410 |
| 2 | 1.07934 | 0.20321655 | 8.0000 | 0.0000 | 8.0000 | 1.500 | 15.023 | 29.05560 | 127.92797 | 2.344 | 144.648 | 96.954 |
| 1 | 1.00245 | 0.25541992 | 11.2501 | 0.0000 | 11.2501 | 2.435 | 19.132 | 40.85967 | 179.89971 | 3.709 | 105.959 | 77.627 |
| 2 | 1.18290 | 0.25541992 | 9.0001 | 0.0000 | 9.0001 | 1.500 | 13.781 | 32.68774 | 143.91976 | 2.386 | 144.145 | 95.719 |
| 1 | 1.08615 | 0.31342773 | 12.5000 | 0.0000 | 12.5000 | 2.437 | 17.748 | 45.39935 | 199.88733 | 3.767 | 105.552 | 76.885 |
| 2 | 1.28166 | 0.31342773 | 10.0000 | 0.0000 | 10.0000 | 1.500 | 12.752 | 36.31948 | 159.90986 | 2.424 | 143.559 | 94.554 |
| 1 | 1.16569 | 0.37723389 | 13.7501 | 0.0000 | 13.7501 | 2.438 | 16.573 | 49.93941 | 219.87660 | 3.820 | 105.095 | 76.175 |
| 2 | 1.37552 | 0.37723389 | 11.0000 | 0.0000 | 11.0000 | 1.500 | 11.882 | 39.95153 | 175.90128 | 2.459 | 142.885 | 93.442 |
| 1 | 1.24103 | 0.44680176 | 14.9999 | 0.0000 | 14.9999 | 2.440 | 15.554 | 54.47894 | 239.86356 | 3.870 | 104.585 | 75.486 |
| 2 | 1.46441 | 0.44680176 | 12.0000 | 0.0000 | 12.0000 | 1.500 | 11.135 | 43.58315 | 191.89085 | 2.491 | 142.123 | 92.358 |
| 1 | 1.27702 | 0.48375244 | 15.6250 | 0.0000 | 15.6250 | 2.440 | 15.093 | 56.74909 | 249.85871 | 3.894 | 104.306 | 75.142 |
| 2 | 1.50689 | 0.48375244 | 12.5000 | 0.0000 | 12.5000 | 1.500 | 10.795 | 45.39927 | 199.88697 | 2.507 | 141.704 | 91.822 |
| 1 | 0.51669 | 0.11736755 | 7.5000 | 0.0000 | 7.5000 | 3.282 | 36.731 | 27.23963 | 119.93249 | 4.903 | 90.691 | 70.102 |
| 2 | 0.60970 | 0.11736755 | 6.0000 | 0.0000 | 6.0000 | 2.000 | 27.647 | 21.79171 | 95.94599 | 3.149 | 120.082 | 84.082 |
| 1 | 0.55119 | 0.13702087 | 8.1250 | 0.0000 | 8.1250 | 3.284 | 34.672 | 29.50950 | 129.92642 | 4.960 | 90.593 | 69.756 |
| 2 | 0.65041 | 0.13702087 | 6.5000 | 0.0000 | 6.5000 | 2.000 | 26.059 | 23.60760 | 103.94114 | 3.187 | 119.953 | 83.534 |

TABLE 9. Continued

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.58466 | 0.15815430 | 8.7500 | 0.0000 | 8.7500 | 3.286 | 32.892 | 31.77937 | 139.92033 | 5.017 | 90.467 | 69.415 |
| 2 | 0.68990 | 0.15815430 | 7.0000 | 0.0000 | 7.0000 | 2.000 | 24.673 | 25.42349 | 111.93626 | 3.223 | 119.809 | 83.004 |
| 1 | 0.61765 | 0.18076172 | 9.3750 | 0.0000 | 9.3750 | 3.287 | 31.303 | 34.04947 | 149.91531 | 5.067 | 90.351 | 69.102 |
| 2 | 0.72883 | 0.18076172 | 7.5000 | 0.0000 | 7.5000 | 2.000 | 23.447 | 27.23958 | 119.93225 | 3.256 | 119.651 | 82.514 |
| 1 | 0.64988 | 0.20483398 | 10.0000 | 0.0000 | 10.0000 | 3.289 | 29.891 | 36.31937 | 159.90935 | 5.116 | 90.225 | 68.804 |
| 2 | 0.76686 | 0.20483398 | 8.0000 | 0.0000 | 8.0000 | 2.000 | 22.356 | 29.05549 | 127.92748 | 3.287 | 119.478 | 82.050 |
| 1 | 0.71223 | 0.25737305 | 11.2500 | 0.0000 | 11.2500 | 3.291 | 27.472 | 40.85924 | 179.89779 | 5.204 | 89.953 | 68.246 |
| 2 | 0.84043 | 0.25737305 | 9.0000 | 0.0000 | 9.0000 | 2.000 | 20.487 | 32.68739 | 143.91823 | 3.345 | 119.083 | 81.166 |
| 1 | 0.77166 | 0.31574707 | 12.5000 | 0.0000 | 12.5000 | 3.293 | 25.465 | 45.39913 | 199.88633 | 5.284 | 89.643 | 67.723 |
| 2 | 0.91055 | 0.31574707 | 10.0000 | 0.0000 | 10.0000 | 2.000 | 18.938 | 36.31930 | 159.90906 | 3.398 | 118.625 | 80.335 |
| 1 | 0.82818 | 0.37993164 | 13.7500 | 0.0000 | 13.7500 | 3.295 | 23.761 | 49.93917 | 219.87554 | 5.359 | 89.294 | 67.214 |
| 2 | 0.97725 | 0.37993164 | 11.0000 | 0.0000 | 11.0000 | 2.000 | 17.622 | 39.95134 | 175.90043 | 3.447 | 118.103 | 79.542 |
| 1 | 0.88167 | 0.44990234 | 14.9999 | 0.0000 | 14.9999 | 3.297 | 22.286 | 54.47890 | 239.86336 | 5.427 | 88.905 | 66.728 |
| 2 | 1.04037 | 0.44990234 | 11.9999 | 0.0000 | 11.9999 | 2.000 | 16.484 | 43.58312 | 191.89069 | 3.492 | 117.512 | 78.770 |
| 1 | 0.90732 | 0.48706055 | 15.6250 | 0.0000 | 15.6250 | 3.298 | 21.615 | 56.74903 | 249.85847 | 5.459 | 88.696 | 66.490 |
| 2 | 1.07063 | 0.48706055 | 12.5000 | 0.0000 | 12.5000 | 2.000 | 15.968 | 45.39923 | 199.88677 | 3.514 | 117.189 | 78.385 |
| 1 | 0.39934 | 0.11798706 | 7.5001 | 0.0000 | 7.5001 | 4.142 | 48.102 | 27.23975 | 119.93302 | 6.333 | 81.145 | 64.434 |
| 2 | 0.47122 | 0.11798706 | 6.0000 | 0.0000 | 6.0000 | 2.500 | 36.478 | 21.79180 | 95.94642 | 4.066 | 104.950 | 75.268 |
| 1 | 0.42600 | 0.13772583 | 8.1250 | 0.0000 | 8.1250 | 4.144 | 45.395 | 29.50961 | 129.92691 | 6.406 | 81.063 | 64.166 |
| 2 | 0.50268 | 0.13772583 | 6.5000 | 0.0000 | 6.5000 | 2.500 | 34.367 | 23.60769 | 103.94153 | 4.114 | 104.843 | 74.846 |
| 1 | 0.45208 | 0.15894775 | 8.7500 | 0.0000 | 8.7500 | 4.145 | 43.031 | 31.77942 | 139.92058 | 6.476 | 80.976 | 63.911 |
| 2 | 0.53345 | 0.15894775 | 7.0000 | 0.0000 | 7.0000 | 2.500 | 32.525 | 25.42354 | 111.93646 | 4.159 | 104.723 | 74.444 |
| 1 | 0.47758 | 0.18165283 | 9.3751 | 0.0000 | 9.3751 | 4.147 | 40.943 | 34.04980 | 149.91673 | 6.538 | 80.883 | 63.678 |
| 2 | 0.56355 | 0.18165283 | 7.5001 | 0.0000 | 7.5001 | 2.500 | 30.897 | 27.23984 | 119.93338 | 4.202 | 104.592 | 74.065 |
| 1 | 0.50252 | 0.20581665 | 10.0000 | 0.0000 | 10.0000 | 4.148 | 39.085 | 36.31928 | 159.90896 | 6.602 | 80.783 | 63.444 |
| 2 | 0.59298 | 0.20581665 | 8.0000 | 0.0000 | 8.0000 | 2.500 | 29.447 | 29.05542 | 127.92717 | 4.241 | 104.449 | 73.707 |
| 1 | 0.55073 | 0.25855713 | 11.2499 | 0.0000 | 11.2499 | 4.151 | 35.905 | 40.85899 | 179.89669 | 6.715 | 80.561 | 63.012 |
| 2 | 0.64986 | 0.25855713 | 8.9999 | 0.0000 | 8.9999 | 2.500 | 26.966 | 32.68719 | 143.91735 | 4.316 | 104.125 | 73.024 |
| 1 | 0.59673 | 0.31715088 | 12.5000 | 0.0000 | 12.5000 | 4.153 | 33.267 | 45.39928 | 199.88702 | 6.819 | 80.313 | 62.605 |
| 2 | 0.70414 | 0.31715088 | 10.0000 | 0.0000 | 10.0000 | 2.500 | 24.909 | 36.31943 | 159.90962 | 4.384 | 103.750 | 72.379 |
| 1 | 0.64048 | 0.38156738 | 13.7500 | 0.0000 | 13.7500 | 4.155 | 31.029 | 49.93939 | 219.87651 | 6.913 | 80.034 | 62.218 |
| 2 | 0.75577 | 0.38156738 | 11.0000 | 0.0000 | 11.0000 | 2.500 | 23.164 | 39.95151 | 175.90121 | 4.447 | 103.322 | 71.762 |
| 1 | 0.68192 | 0.45178223 | 15.0001 | 0.0000 | 15.0001 | 4.158 | 29.087 | 54.47965 | 239.86667 | 6.998 | 79.724 | 61.846 |
| 2 | 0.80467 | 0.45178223 | 12.0001 | 0.0000 | 12.0001 | 2.500 | 21.654 | 43.58372 | 191.89334 | 4.505 | 102.841 | 71.167 |
| 1 | 0.70174 | 0.48905029 | 15.6250 | 0.0000 | 15.6250 | 4.158 | 28.207 | 56.74904 | 249.85849 | 7.039 | 79.558 | 61.660 |
| 2 | 0.82805 | 0.48905029 | 12.5000 | 0.0000 | 12.5000 | 2.500 | 20.970 | 45.39923 | 199.88680 | 4.533 | 102.578 | 70.872 |

======= END OF HISTORY RESULTS FOR SEARCHES =======
Total Elapsed Time = 9351.06 sec

## 13. Verification of the Sudo-Kaminaga CHF Correlation for Rectangular Channels as Implemented in the PLTEMP/ANL Code.

(May 2010)

### 13.1. Introduction

A thermal-hydraulic safety criterion commonly checked for research reactors is a required minimum critical heat flux ratio (CHFR). Sudo and Kaminaga studied CHF experimentally and theoretically for more than a decade in the course of designing the Japanese research reactors JRR-3 and JRR-4. [1] They proposed a correlation [1, 2] for CHF in rectangular coolant channels of research reactors using plate-type fuel, based on 596 CHF data points from 8 sources [3-10], including their own data [3, 4]. Sudo and Kaminaga included the CHF test data of Mishima [9], and their correlation used and improved upon CHF equations suggested by Mishima [11]. Most of the CHF data (586 out of the 596 data points) were measured at pressures in the range of 1 to 7.2 bars. Only 10 data points from one data source [8] were measured at pressures in the range of 11 to 40 bars, and these data points are not considered adequate to extend the pressure range of applicability of the correlation up to 40 bars. Therefore, the correlation is expected to cover the pressure range of 1 to 7.2 bars. Additional restrictions on the correlation are noted below in Section 13.2 based on the test ranges of other thermodynamic and geometrical variables. Although the correlation covers a mass velocity range of 25800 kg/m$^2$-s downflow to 6250 kg/m$^2$-s upflow of water, it specially focuses on CHF at low mass velocities ($G \leq 600$ kg/m$^2$-s, i.e., natural circulation flow) at near-atmospheric pressure. The correlation was recently implemented in the PLTEMP/ANL code[12] for steady-state thermal-hydraulic analysis of research reactors.

The purpose of this memorandum is to document a verification of this correlation as implemented in PLTEMP/ANL, by comparing the code with some experimental CHF data obtained by Sudo and Kaminaga [1], and by Mirshak, Durant, and Towell [7]. At the end, two parametric studies of the correlation are given to illustrate: (i) the effect of varying channel thickness on the CHF calculated by the correlation, and (ii) the effect of varying coolant mass velocity on the CHF calculated by the correlation.

### 13.2. Sudo-Kaminaga CHF Correlation

To calculate CHF in channels of rectangular cross section, Sudo and Kaminaga [1, 2] improved on Mishima's CHF work [11] at low mass velocities (i.e. $G \leq 600$ kg/m$^2$-s) and suggested a correlation for downflow and upflow over three mass velocity ranges (low, medium, and high) as shown in Fig. 1. The low mass velocity range is from 0.0 to $G_3$ kg/m$^2$-s for upflow (or 0.0 to $G_2$ kg/m$^2$-s for downflow). The medium mass velocity range is from $G_3$ to $G_1$ kg/m$^2$-s for upflow (or $G_2$ to $G_1$ kg/m$^2$-s for downflow). The high mass velocity range is above $G_1$ kg/m$^2$-s for both upflow and downflow. The Sudo-Kaminaga correlation[1] can be written as Eqs. (1) to (5):

$$q_c = \begin{cases} \mathrm{Max}(q_{c3}\,,\, q_{c2}) & \text{for } G < G_1 \quad \text{and} \quad \text{downflow} \\ \mathrm{Max}\left[q_{c3}\,,\, 5\times10^{-6}\, G^{*\;0.611}\, \lambda \left\{\sigma\, \rho_v^{\,2} (\rho_l - \rho_v)\, g\right\}^{0.25}\right] & \text{for } G < G_1 \quad \text{and} \quad \text{upflow} \\ \mathrm{Min}(q_{c1}\,,\, q_{c2}) & \text{for } G \geq G_1 \text{, upflow or downflow} \end{cases} \qquad (1)$$

$$q_{c1} = 5 \times 10^{-6}\, G^{*\,0.611} \left\{1 + 5000\, \Delta h_o/(\lambda\, G^*)\right\} \lambda \left\{\sigma\, \rho_v^{\,2} (\rho_l - \rho_v)\, g\right\}^{0.25} \qquad (2)$$

$$q_{c2} = 0.001\, A_f\, \Delta h_i\, G / A_h \qquad (3)$$

$$q_{c3} = \frac{0.7 \times 10^{-3}\, A_f\, \lambda\, \{g \rho_v (\rho_l - \rho_v) w\}^{0.5}}{A_h \left\{1 + (\rho_v/\rho_l)^{0.25}\right\}^2} \left(1 + 3 \Delta h_i/\lambda\right) \qquad (4)$$

$$G_1 = \left(\frac{0.005\, A_h\, \lambda}{A_f \Delta h_i}\right)^{2.5707} \left\{\sigma\, \rho_v^{\,2} (\rho_l - \rho_v)\, g\right\}^{0.25} \qquad (5)$$

where

$A_f$ = Flow area, $m^2$
$A_h$ = $P_h\, L_h$ = Heated area, $m^2$
$G$ = Mass velocity, kg/$m^2$-s
$G^*$ = $G / \left\{\sigma \rho_v^2 (\rho_l - \rho_v) g\right\}^{0.25}$ = Dimensionless mass velocity corresponding to G
$G_1$ = Mass velocity at which Eq. (2) with $\Delta h_o$ set to zero intersects Eq. (3), kg/$m^2$-s
$G_2$ = Mass velocity at which Eq. (3) intersects Eq. (4), kg/$m^2$-s
$G_3$ = Mass velocity at which Eq. (2) with $\Delta h_o$ set to zero intersects Eq. (4), kg/$m^2$-s
$G_1^*$ = $G_1 / \left\{\sigma \rho_v^2 (\rho_l - \rho_v) g\right\}^{0.25}$ = Dimensionless mass velocity corresponding to $G_1$
$G_2^*$ = $G_2 / \left\{\sigma \rho_v^2 (\rho_l - \rho_v) g\right\}^{0.25}$ = Dimensionless mass velocity corresponding to $G_2$
$G_3^*$ = $G_3 / \left\{\sigma \rho_v^2 (\rho_l - \rho_v) g\right\}^{0.25}$ = Dimensionless mass velocity corresponding to $G_3$
g = Acceleration due to gravity = 9.80665 m/$s^2$
$\Delta h_i$ = Coolant subcooling at inlet, kJ/kg
$\Delta h_o$ = Coolant subcooling at outlet, kJ/kg
$L_h$ = Heated Length, m
$P_h$ = Heated perimeter of the channel, m
$q_c$ = Critical heat flux obtained by the correlation, MW/$m^2$
$q_{c1}$ = Critical heat flux obtained from Eq. (2), MW/$m^2$
$q_{c2}$ = Critical heat flux obtained from Eq. (3), MW/$m^2$
$q_{c3}$ = Critical heat flux obtained from Eq. (4), MW/$m^2$
w = Width (larger dimension) of the channel rectangular cross section, m
$\lambda$ = Latent heat of vaporization at the system (exit) pressure, kJ/kg
$\rho_l$ = Saturated liquid density at the system (exit) pressure, kg/$m^3$
$\rho_v$ = Saturated vapor density at the system (exit) pressure, kg/$m^3$
$\sigma$ = Surface tension of saturated coolant at the system (exit) pressure, N/m
2.5707 = Exponent in Eq. (8) which is related to the exponent 0.611 of Eq. (4) = 1/(1-0.611)

The mass velocities at region boundaries, $G_3$, $G_2$, and $G_1$, are determined by the intersection of an appropriate pair from Eqs. (2), (3), and (4). The boundary of the high mass velocity region, $G_1$, is given by Eq. (5). As shown in Fig. 1, the CHF in downward flow is given by Eq. (4) if the mass velocity $G \leq G_2$; it is given by Eq. (3) if $G_2 \leq G \leq G_1$; it is given by the smaller of Eqs. (2) and (3) for $G \geq G_1$. The CHF in upward flow is given by Eq. (4) if the mass velocity $G \leq G_3$; it is given by Eq. (2) with $\Delta h_o$ set to zero [i.e., the quantity inside the first pair of curly brackets of Eq. (2) set to 1] if $G_3 \leq G \leq G_1$; it is given by the smaller of Eqs. (2) and (3) for $G \geq G_1$. It is noted that the CHF in downward flow is smaller than that in upward flow in the mass velocity range $G_3 \leq G \leq G_1$, and outside this range the CHFs in downward flow and upward flow are equal. The correlation was tested with 596 CHF data for water from 8 sources covering the following geometrical and thermal-hydraulic conditions:

Channel gap: 2.25 to 5.0 mm
Ratio of heated length to hydraulic diameter: 8 to 240
Mass velocity: Downflow of 25,800 to stagnant flow to upflow of 6250 kg/m$^2$-s
System pressure: 0.1 to 0.72 MPa
Inlet subcooling: 1 to 213 °C
Outlet condition: From subcooling of 0 to 74 °C to quality of 0 to 1.0

By comparing with the 596 CHF data, Sudo and Kaminaga[2] found a root-mean-square (RMS) error of ±33 %, and recommended that when the CHF correlation is used in thermal-hydraulic analysis of reactors, the minimum critical heat flux ratio (CHFR) should be greater than 1.5 (which is equivalent to an error of -33 %, i.e., 1/(1 - 0.33) = 1.5). Based on a statistical analysis, Sudo and Kaminaga[1] also reported that the error in the correlation means that there is a 10% possibility of the occurrence of CHF condition even when the minimum CHFR is 1.5. This correlation was recently implemented in the PLTEMP/ANL Version 3.9 code[12] which is used for thermal-hydraulic analysis and design of research reactors.

## 13.3. Verification of the Sudo-Kaminaga CHF Correlation

### 13.3.1. Verification at Lower Coolant Velocities

To verify the implementation of the Sudo-Kaminaga CHF correlation in PLTEMP/ANL at coolant velocities less than 1.0 m/s, the code was compared with some of the CHF data measured and reported by Sudo and Kaminaga [4] in graphical form (in Fig. 3 of Reference 4). The geometry of the test section used in these measurements is shown in Fig. 2, and the test conditions are given in Table 1. Briefly, Sudo and Kaminaga used a single rectangular coolant channel of 2.25 mm thickness, heated on both sides by plates 750 mm long. Each plate had a wetted perimeter of 50 mm with a heated perimeter of 40 mm. The test section was modeled by PLTEMP/ANL, and the input data used is shown in Table 2. The code requires the number of channels to be one greater than the number of fuel plates. Therefore, the input data file of Table 2 assumes 2 plates and 3 coolant channels that are part of an infinite array of identical coolant channels and plates, as shown in Fig. 2. The first and third channels are artificially added half-channels, i.e., of half thickness compared to the actual channel 2 used in the test. The outer boundaries of the first and third channels in the *modeled* test section are lines of symmetry which are adiabatic due to symmetry. The flow in each channel is input to the code. The flow in a half-channel is half of the flow in channel 2 (the actual channel). This makes the temperature distributions in all three channels identical.

The measured CHF data were scaled from Fig. (3) of Reference 4, and are shown in Tables 3 and 4 for upflow and downflow respectively. For each CHF data, the code was run in the search mode to adjust the power to achieve a CHFR of 1.0. For some of the CHF data, the code ran past boiling but these calculations were not acceptable because PLTEMP/ANL is a single-phase code that does not model two-phase flow. In these cases, the code was run several times for the same measured CHF data, using increasing values (greater than 1.0) of the CHFR. It was found that the critical heat flux did not change much from run to run. The practically unchanging CHF values are also included in the comparison. The PLTEMP/ANL-calculated CHF values are compared with the measured data in Tables 3 and 4. The calculated CHF values are found to be in the scatter range of the measured data. This provides a verification of the implementation of the Sudo-Kaminaga correlation in PLTEMP/ANL at coolant velocities less than 1.0 m/s.

### 13.3.2. Verification at Higher Coolant Velocities

To verify the Sudo-Kaminaga CHF correlation implemented in PLTEMP/ANL at coolant velocities greater than 1.0 m/s, the code was compared with 11 of the CHF data measured and reported by Mirshak, Durant, and Towell [7]. The test section geometry and test conditions in these measurements are given in Table 5. In these tests, Mirshak, Durant, and Towell used a single rectangular coolant channel of different thicknesses (3.18 to 6.48 mm), heated on only one side by a Type 304 stainless steel plate which was 2.06 inches (52.32 mm) wide and 19.25 inches (0.48895 m) long. The width of the coolant channel was 2.56 inches (65.02 mm). In order to the tests by PLTEMP/ANL, some of the required input data were calculated from the reported quantities, using the equations given in Note 1 below Table 5. The calculated input data are shown in Table 5. The PLTEMP/ANL input data files prepared for the 11 tests are given in Appendix J. The code requires the number of channels to be one greater than the number of fuel plates. Therefore, the input data files of Appendix J assume one plate and two identical coolant channels. The outer boundary of each channel in the *modeled* test section is adiabatic. The power of the plate in this model is two times the actual power used in the test. The flow in each channel, equal to the actual flow used in the test, is input to the code. The temperature distributions in both channels are identical.

The measured values of CHF reported in Reference 7 are included in Tables 5 and 6. For each CHF test, the code was run twice, first using the Mirshak CHF correlation (ICHF = 0) and then using the Sudo-Kaminaga CHF correlation (ICHF = 8). The PLTEMP/ANL-calculated CHF values are compared with the measured data in Table 6. For the 11 tests analyzed, the errors in the CHF obtained using the Sudo-Kaminaga correlation (compared to the measured CHF) vary from -11.4 to 21.6 %, with an RMS error of 10.8%. This RMS error can be assessed in two ways:

(i) By comparing it with the RMS error of 6.7% in the CHF obtained using the Mirshak correlation. The errors in the CHF obtained using the Mirshak correlation (compared to the measured CHF) vary from -13.2 to 9.0 % as shown in Table 6.
(ii) By comparing it with the reported RMS error of 33 % in the Sudo-Kaminaga correlation[1,2].

The RMS error in the CHF values obtained using the Sudo-Kaminaga correlation is less than the reported RMS error of 33 % in the Sudo-Kaminaga correlation. This provides a verification of the Sudo-Kaminaga correlation as implemented in PLTEMP/ANL at coolant velocities used in the 11 tests, which are greater than 1.0 m/s.

## 13.4. Parametric Studies of Sudo-Kaminaga CHF Correlation

Two parametric studies were done using the Microsoft Spreadsheet given in Table 7. These studies are presented in this section. First, the effect of varying channel thickness on the CHF calculated using the Sudo-Kaminaga correlation is presented to show that the correlation is sensitive to channel thickness and that it should not be used for channel thicknesses less than 2.25 mm as specified by Sudo and Kaminaga [1, 2]. Second, the effect of varying coolant mass velocity on the CHF calculated using the correlation is presented to illustrate how the correlation is a continuous function of mass velocity over the three regions of mass velocity (low, medium, and high) shown in Fig. 1. Both parametric studies were done using a half-channel model of a test section similar to those used in the 1964 Advanced Test Reactor (ATR) burnout heat transfer tests done by Croft [13]. The basic geometrical and thermal hydraulic quantities of the test section used in the Spreadsheet of Table 7 are:

| | | | |
|---|---|---|---|
| Channel width | = 30.48 mm, | Channel length | = 1.2192 m (48 inches) |
| Heated width of plate | = 25.4 mm, | Channel thickness | = varies from 1.37 to 5.0 mm |
| Outlet pressure | = 15.6 bar, | Mass velocity | = varies from 5.0 to 20000.0 kg/m$^2$-s |
| Inlet temperature | = 54.4 °C, | Outlet temperature | = 188.3 °C |

This outlet temperature corresponds to a flow instability power ratio (FIR) of 1.0.

### 13.4.1. Sensitivity of Sudo-Kaminaga CHF Correlation to Coolant Channel Thickness

The effect on CHF of varying the channel thickness from 1.37 to 5.0 mm was studied at a fixed coolant mass velocity of 10141.5 kg/m$^2$-s, and the results are shown in Table 8. The Sudo-Kaminaga CHF correlation is valid only for channel thicknesses in the range 2.25 to 5.00 mm, as noted in Section 13.2. Table 8 shows that the value of boundary mass velocity $G_1$ is very sensitive to the channel thickness. It rises very steeply from 10485.0 to 37424.0 kg/m$^2$-s as the channel thickness decreases from 2.25 to 1.37 mm, i.e., over the invalid range of channel thickness. The values of CHF shown in Table 8 over this range should not be used in reactor analysis.

### 13.4.2. Continuity of Sudo-Kaminaga CHF Correlation as a Function of Mass Velocity

The effect on CHF of varying the coolant mass velocity from 5.0 to 20000.0 kg/m$^2$-s was studied at a fixed channel thickness of 3.5 mm (the valid range is 2.25 to 5.0 mm), and the results are shown in Tables 9 and 10, for upflow and downflow respectively. The Sudo-Kaminaga CHF correlation is valid for both downflow and upflow (from a downflow of 25,800 to an upflow of 6250 kg/m$^2$-s), as noted in Section 13.2. Tables 9 and 10 show (i) the calculated values of the boundary mass velocities $G_3$, $G_2$, and $G_1$ in columns 2 to 4, and (ii) the results of Eqs. (1) to (4) in columns 5 to 9. The boundary mass velocities $G_3$, $G_2$, and $G_1$ do not depend on the mass velocity G at which the value of CHF is being calculated. The boundary mass velocities $G_3$, $G_2$, and $G_1$ are found to be 12.96, 112.7, and 3367.3 kg/m$^2$-s.

Table 9 shows in column 9 the CHF *for upflow* found from Eq. (1), using the heat fluxes found from Eqs. (2) to (4) and shown in columns 5 to 8. In upflow, according to Eq. (1), the CHF for mass velocities up to 12.96 kg/m$^2$-s is shaded in yellow in column 8; the CHF for mass velocities from 12.96 to 3367.3 kg/m$^2$-s is shaded in yellow in column 6; and the CHF for mass velocities above 3367.3 kg/m$^2$-s is given by the smaller of columns 5 and 7 that is shaded in yellow. The columns 5 and 7 intersect at a mass velocity of 6068.5 kg/m$^2$-s. All the yellow-shaded values of CHF for upflow are collected in column 9 for mass velocities from 5.0 to 20000.0 kg/m$^2$-s. It is obvious that the values of CHF given in column 9 for upflow are continuous, i.e., there is not any jump in CHF at any mass velocity.

Table 10 shows in column 9 the CHF *for downflow* found from Eq. (1), using the heat fluxes found from Eqs. (2) to (4) and shown in columns 5 to 8 (same as Table 9). In downflow, according to Eq. (1), the CHF for mass velocities up to 112.7 kg/m$^2$-s is shaded in yellow in column 8; the CHF for mass velocities from 112.7 to 3367.3 kg/m$^2$-s is shaded in yellow in column 7; and the CHF for mass velocities above 3367.3 kg/m$^2$-s is given by the smaller of columns 5 and 7 that is shaded in yellow. All the yellow-shaded values of CHF for downflow are collected in column 9 for mass velocities from 5.0 to 20000.0 kg/m$^2$-s. It is obvious that the values of CHF given in column 9 for downflow are continuous, i.e., there is not any jump in CHF at any mass velocity.

### 13.5. Conclusions

The Sudo-Kaminaga CHF correlation has a root-mean-square (RMS) error of ±33 %. Sudo and Kaminaga recommend that when the correlation is used in thermal-hydraulic analysis of reactors, the minimum critical heat flux ratio (CHFR) should be greater than 1.5. The correlation was recently implemented in the PLTEMP/ANL code. To verify this implementation, the CHF values calculated by PLTEMP/ANL using the correlation were compared with measured CHF data for rectangular channels from two sources. The comparison provided a verification of the implementation of the correlation in the code. Parametric studies of the correlation showed that (i) the correlation is very sensitive to the channel thickness at channel thicknesses smaller than 2.25 mm, and (ii) the correlation is a continuous function of coolant mass velocity.

## REFERENCES


1. M. Kaminaga, K. Yamamoto, and Y. Sudo, "Improvement of Critical Heat Flux Correlation for Research Reactors Using Plate-Type Fuel," J. Nuclear Sci. and Technol., Vol. 35, No. 12, pp. 943-951 (1998).

2. Y. Sudo and M. Kaminaga, "A New CHF Correlation Scheme Proposed for Vertical Rectangular Channels Heated From Both Sides in Nuclear Research Reactors," Transactions of the ASME, J. of Heat Transfer, Vol. 115, pp. 426-434 (1993).

3. Y. Sudo, K. Miyata, H. Ikawa, M. Kaminaga, and M. Ohkawara, "Experimental Study of Differences in DNB Heat Flux Between Upflow and Downflow in Vertical Rectangular Channel," J. Nucl. Sci. Technol., Vol. 22(8), pp. 604-618 (1985).

4. M. Kaminaga, Y. Sudo, Y. Murayama, and T. Usui, "Experimental Study of Critical Heat Flux in Narrow Vertical Rectangular Channel," Heat Transfer – Japanese Research, Vol. 20(1), pp. 72-85 (1991).

5. B. Yucel, and S. Kakac, "Forced Flow Boiling and Burnout in Rectangular Channels," Proc. 6$^{th}$ Int. Heat Transfer Conf., Vol. 1, pp. 387-392 (1978).

6. G. J. Kirby, R. Stanforth, and J. H. Kinneir, "A Visual Study of Forced Convection Boiling, Part 2: Flow Patterns and Burnout for a Round Tube Test Section," AEEW-R506 (1967).

7. S. Mirshak, W. S. Durant, and R. H. Towell, "Heat Flux at Burnout," DP-355, U.S. Atomic Energy Commission (1959).

8. W. R. Gambill, and R. D. Bundy, "HFIR Heat Transfer Studies of Turbulent Water Flow in Thin Rectangular Channels," ORNL-3079, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA (1961).

9. K. Mishima, "Boiling Burnout at Low Flow Rate and Low Pressure Conditions," Dissertation Thesis, Kyoto University, Japan (1984).

10. Y. Komori, M. Kaminaga, F. Sakurai, H. Ando, H. Nakata, Y. Sudo, and Y. Futamura, "Experimental Study on DNB Heat Flux Correlations for JMTR Safety Analysis," Proc. Int. Mtg. on Reduced Enrichment for Research and Test Reactors, Newport, Rhode Island, USA, September 23-27 (1990).

11. K. Mishima, H. Nishihara, and T. Shibata, "CHF Correlations Related to the Core Cooling of a Research Reactor," Proc. Int. Mtg. on Reduced Enrichment for Research and Test Reactors, October 24-27, 1983, Tokai, Japan, JAERI-M-84-073, pp. 311-320 (1983).

12. A. P. Olson and M. Kalimullah, Argonne National Laboratory, unpublished information, November 16, 2009.

13. M. W. Croft, "Advanced Test Reactor Burnout Heat Transfer Tests," ATR-FE-102, Babcock & Wilcox Company, Atomic Energy Division, Lynchburg, Virginia, USA (January 1964).

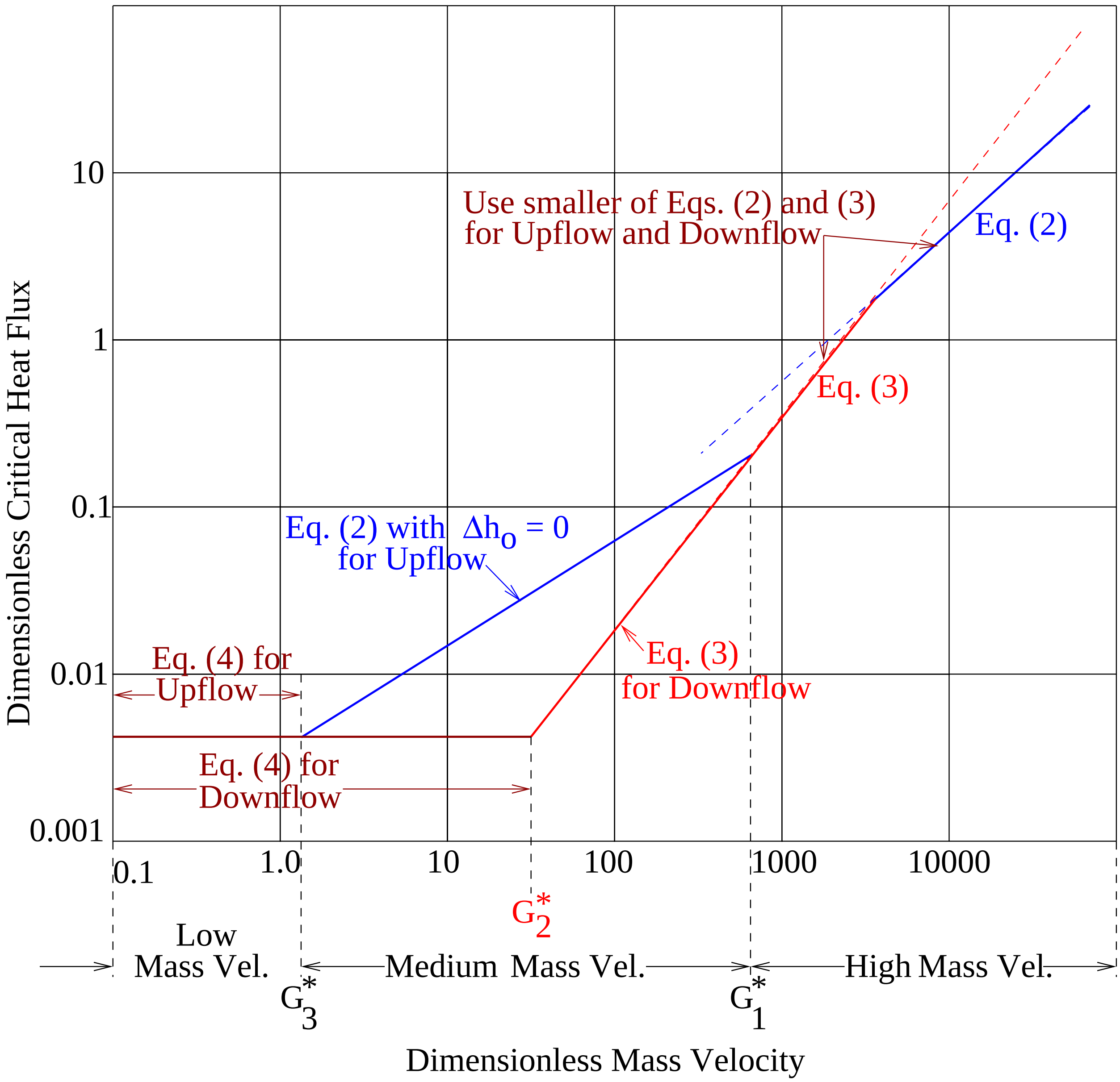


**Fig. 1. Illustration of Sudo-Kaminaga Correlation for Upward and Downward Flows**

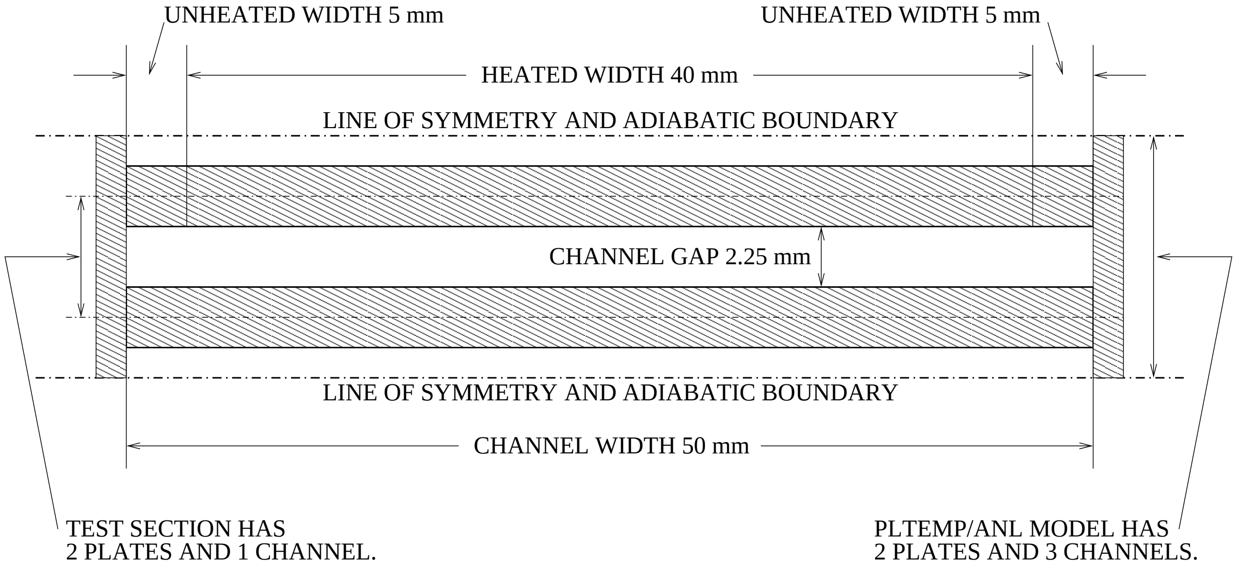


**Fig. 2. Geometry of the Test Section Used by Sudo and Kaminaga for Measuring CHF**

**TABLE 1. Test Section Used by Sudo and Kaminaga for Measuring CHF [Ref. 1]**

| | |
|---|---|
| Flow Channel | 750 mm long × 50 mm wide × 2.25 mm gap |
| Heating Plates | 750 mm long × 40 mm wide |
| Heating Mode | Heated from both sides |
| Coolant | Water |
| Pressure | About 1 atmosphere |

**TABLE 2. PLTEMP/ANL Input Data for the Test Section Used by Sudo and Kaminaga for Measuring CHF**

```
 Sudo-Kaminaga 1991 CHF Test Section
! 2 assemblies (of identical geometry)
! Each assembly has 1 fuel plate and 2 coolant channels
! H2O coolant, All hot channel factors = 1.0, No bypass flow, NCTYP=0
! 10 axial heat transfer nodes in the heated length of fuel plates
!23456789012345678901234567890123456789012345678901234567890123456789012345678901234567890
!  1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18  19  20    Indices
   0   0   8   1   0   1   1   0   0   0   0   0   0           1   1            Card(1)0200
! Search for CHFR = 1.0
   5 0.0005      1.000         1 1.000                                          Card(1)0203
! Search for ONBR = 1.0
!  4 0.020       1.000         1 1.000                                          Card(1)0203
   2   3 0.00       1.00        1.00        1.00           3                    Card(1)0300
! Using pressure driven mode
   1  20 1.00                                                                   Card(1)0301
   1   1   1                                                                    Card(1)0302
1.00        1.00                                                                Card(2)0303
2.25000E-04 4.3062E-03  0.15        8.00        0.050000    2.2500E-03          Card(3)0304
2.25000E-04 4.3062E-03  0.75        0.00        0.050000    2.2500E-03          Card(3)0304
2.25000E-04 4.3062E-03  0.15        8.00        0.050000    2.2500E-03          Card(3)0304
! Use the code's biult-in correlation for friction factor
0.00        0.00        0.00                                                    Card(1)0305
   3   3 5.00E-03   0.75000     0.50E-03    0.00        1.00E-03    100.00      Card(1)0306
0.56250E-04 4.3062E-03  0.05225     0.040000    0.050000    2.2500E-03          Card(5)0307
1.12500E-04 4.3062E-03  0.10450     0.080000    0.050000    2.2500E-03          Card(5)0307
0.56250E-04 4.3062E-03  0.05225     0.040000    0.050000    2.2500E-03          Card(5)0307
0.050000    0.050000                                                            Card(1)0308
! Card 0308a not required
! Radial power peaking factor data by fuel plate for each assembly. Input flow data by
! channel for each assembly on Cards 0310 not required because WFGES(1) is non-zero
! Input for G* = 200
1.00        1.00                                                                Card(2)0309
0.04402     0.08804     0.04402                                                 Card(2)0310
1.00        1.00                                                                Card(2)0309
0.04402     0.08804     0.04402                                                 Card(2)0310
! DP0       DDP         DPMAX       POWER       TIN         PIN
0.101325    0.001       0.101326    1.0         31.0        0.101325            Card(1)0500
                                                                                Card(1)0500
  50 0.0001     25.0        0.00        0.10                                    Card(1)0600
  11                                                                            Card(1)0700
0.00        1.00                                                                Card(11)0701
0.10        1.00                                                                Card(11)0701
0.20        1.00                                                                Card(11)0701
0.30        1.00                                                                Card(11)0701
0.40        1.00                                                                Card(11)0701
0.50        1.00                                                                Card(11)0701
0.60        1.00                                                                Card(11)0701
0.70        1.00                                                                Card(11)0701
0.80        1.00                                                                Card(11)0701
0.90        1.00                                                                Card(11)0701
1.00        1.00                                                                Card(11)0701
   0                                                                            Card(11)0702
```

**TABLE 3. Comparison of PLTEMP/ANL with the Sudo and Kaminaga Experimental CHF Data for Upflow (Inlet Subcooling is 20 to 36 °C)**

| Measured Data | | | | Calculated by PLTEMP/ANL | |
|---|---|---|---|---|---|
| $G^*$ Dimensionless Mass Velocity | Mass Velocity kg/m$^2$-s | Coolant Velocity m/s | $q_c^*$ Dimensionless Critical Heat Flux [Note 1] | $q_c^*$ Dimensionless Critical Heat Flux | Critical Heat Flux MW/m$^2$ |
| 4.0 | 15.7 | 0.016 | 0.00768 – 0.0124 | 0.0118 | 0.102 |
| 10.0 | 39.1 | 0.04 | 0.0129 – 0.0191 | 0.0207 | 0.178 |
| 20.0 | 78.3 | 0.08 | 0.0218 – 0.0308 | 0.0316 | 0.272 |
| 40.0 | 156.6 | 0.16 | 0.0308 – 0.0456 | 0.0483 | 0.416 |
| 60.0 | 234.8 | 0.24 | 0.0400 – 0.0618 | 0.0619 | 0.533 |
| 100.0 | 391.3 | 0.4 | | 0.0845 | 0.728 |
| 200.0 | 782.6 | 0.8 | | 0.129 | 1.11 |

(1) The data range was scaled from Fig. 3 of Reference 1.

**TABLE 4. Comparison of PLTEMP/ANL with the Sudo and Kaminaga Experimental CHF Data for Downflow (Inlet Subcooling is 69 to 78 °C)**

| Measured Data | | | | Calculated by PLTEMP/ANL | |
|---|---|---|---|---|---|
| $G^*$ Dimensionless Mass Velocity | Mass Velocity kg/m$^2$-s | Coolant Velocity m/s | $q_c^*$ Dimensionless Critical Heat Flux [Note 1] | $q_c^*$ Dimensionless Critical Heat Flux | Critical Heat Flux MW/m$^2$ |
| ~ 0.0 | ~ 0.0 | ~ 0.0 | 0.00437 – 0.00619 | 0.0058 | 0.051 [2] |
| 10.0 | 39.1 | 0.04 | 0.00339 – 0.00477 | 0.0058 | 0.051 |
| 20.0 | 78.3 | 0.08 | 0.00543 – 0.00803 | 0.0058 | 0.051 |
| 60.0 | 234.8 | 0.24 | 0.00803 – 0.00957 | 0.0146 | 0.128 |
| 100.0 | 391.3 | 0.4 | 0.0161 – 0.0296 | 0.0243 | 0.214 |
| 200.0 | 782.6 | 0.8 | 0.0367 – 0.0543 | 0.0486 | 0.428 |

(1) The data range was scaled from Fig. 3 of Reference 1.
(2) PLTEM/ANL was run at $G^*$= 2.0, mass velocity = 7.83 kg/m$^2$-s, velocity = 0.0082 m/s.

**TABLE 5. Spreadsheet Calculation of 11 CHF Tests Done by Mirshak, Durant, and Towell to Find the Geometry, Power, and Flow Data Required for Preparing PLTEMP/ANL Input Data Files**

| | Run Number Assigned by Mirshak | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **#1** | **#4** | **#21** | **#22** | **#23** | **#43** | **#24** | **#26** | **#27** | **#36** | **#48** |
| Hydraulic Dia, inch | 0.247 | 0.247 | 0.464 | 0.458 | 0.455 | 0.253 | 0.453 | 0.243 | 0.239 | 0.247 | 0.254 |
| Coolant Velocity, ft/s | 18.8 | 18.6 | 18.8 | 18.9 | 18.9 | 33 | 19.2 | 33.4 | 33.6 | 33.7 | 38.5 |
| Pressure, psia | 38 | 35.6 | 50.1 | 50.7 | 51.4 | 24.5 | 51.2 | 50.4 | 60 | 52 | 55.3 |
| Subcooling $\Delta T_{sub}$, °C | 46 | 44 | 44.7 | 54.5 | 62.7 | 43.5 | 71 | 45 | 55 | 65 | 54 |
| Measured CHF, $10^3$ pcu/hr.ft$^2$ | 875 | 883 | 1000 | 1206 | 1208 | 1208 | 1400 | 1412 | 1642 | 1633 | 1765 |
| Measured CHF, MW/m$^2$ | 4.96825 | 5.01367 | 5.678 | 6.84767 | 6.85902 | 6.85902 | 7.9492 | 8.01734 | 9.32328 | 9.27217 | 10.02167 |
| Calculated Power, MW | 0.127107 | 0.128269 | 0.145265 | 0.17519 | 0.17548 | 0.17548 | 0.203371 | 0.205114 | 0.238525 | 0.237218 | 0.256393 |
| Hydraulic Diameter D, m | 0.006274 | 0.006274 | 0.011786 | 0.011633 | 0.011557 | 0.006426 | 0.011506 | 0.006172 | 0.006071 | 0.006274 | 0.006452 |
| Coolant Velocity, m/s | 5.73024 | 5.66928 | 5.73024 | 5.76072 | 5.76072 | 10.0584 | 5.85216 | 10.18032 | 10.24128 | 10.27176 | 11.7348 |
| Pressure, bar | 2.620003 | 2.454529 | 3.454267 | 3.495636 | 3.543899 | 1.689212 | 3.530109 | 3.474951 | 4.136847 | 3.585267 | 3.812794 |
| Tsat, °C | 128.5733 | 126.8451 | 137.2862 | 137.7183 | 138.2223 | 118.8522 | 138.0783 | 137.5022 | 144.415 | 138.6544 | 141.0306 |
| Tout, °C | 82.57327 | 82.84508 | 92.58621 | 83.21826 | 75.52231 | 75.35222 | 67.0783 | 92.50223 | 89.41498 | 73.65436 | 87.03062 |
| Exit Density, kg/m$^3$ | 969.3074 | 969.1403 | 963.1495 | 968.9108 | 973.6438 | 973.7484 | 978.8368 | 963.2011 | 965.0998 | 974.7926 | 966.5662 |
| Channel Thickness, mm | 3.295901 | 3.295901 | 6.480055 | 6.388029 | 6.342105 | 3.380126 | 6.311522 | 3.239867 | 3.183925 | 3.295901 | 3.394183 |
| Flow Area, $10^{-4}$ m$^2$ | 2.143127 | 2.143127 | 4.213591 | 4.153752 | 4.12389 | 2.197893 | 4.104004 | 2.106691 | 2.070315 | 2.143127 | 2.207034 |
| Wetted Perimeter, m | 0.13664 | 0.13664 | 0.143008 | 0.142824 | 0.142732 | 0.136808 | 0.142671 | 0.136528 | 0.136416 | 0.13664 | 0.136836 |
| Flow Rate, kg/s | 1.190371 | 1.177504 | 2.325514 | 2.318468 | 2.313044 | 2.152693 | 2.350901 | 2.065757 | 2.04627 | 2.145878 | 2.503319 |
| Mass Velocity, kg/s.m$^2$ | 5554.364 | 5494.328 | 5519.078 | 5581.624 | 5608.889 | 9794.351 | 5728.31 | 9805.696 | 9883.857 | 10012.84 | 11342.46 |
| Temp Rise Tout-Tin, °C | 25.48429 | 25.9983 | 14.90829 | 18.03404 | 18.1063 | 19.45501 | 20.64622 | 23.69748 | 27.81999 | 26.38323 | 24.44416 |
| Tin, °C | 57.08898 | 56.84678 | 77.67792 | 65.18422 | 57.41601 | 55.89721 | 46.43208 | 68.80475 | 61.59499 | 47.27113 | 62.58645 |

Note 1. The geometry data common to all the 11 test sections are given first, followed by the equations used to find the required input data from the quantities reported by Mirshak, Durant, and Towell[7].

Channel Length, L = 19.25 inch = 0.48895 m

Heated Perimeter, $P_h$ = 2.06 inch = 0.052324 m

Channel Width, w = 2.56 inch = 0.065024 m

Power, P = (Measured CHF*L $P_h$)

D = Hydraulic Diameter (reported for each test)

Channel Thickness, $t_c = D/(2 - D/w)$

Flow Area, $A_f = w\ t_c$

Exit Temp., $T_o$ = ($T_{sat}$ at Measured P) – (Measured $\Delta T_{sub}$)

Flow Rate, W = $A_f$ (Measured Vel.)*(Density at CHF Location)

Average $C_p$ = 4.19 kJ/kg-°C

Temp. Rise, $\Delta T = P/(W\ C_p)$

$T_{in} = T_o - \Delta T$

**TABLE 6. Comparison of PLTEMP/ANL-Calculated CHF Using the Sudo-Kaminaga Correlation with Measured CHF for 11 CHF Tests Done by Mirshak, Durant, and Towell**

| | Run Number Assigned by Mirshak | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **#1** | **#4** | **#21** | **#22** | **#23** | **#43** | **#24** | **#26** | **#27** | **#36** | **#48** |
| Coolant Velocity, ft/s | 18.8 | 18.6 | 18.8 | 18.9 | 18.9 | 33 | 19.2 | 33.4 | 33.6 | 33.7 | 38.5 |
| Measured CHF, $MW/m^2$ | 4.96825 | 5.01367 | 5.678 | 6.84767 | 6.85902 | 6.85902 | 7.9492 | 8.01734 | 9.32328 | 9.27217 | 10.02167 |
| Mirshak Corr. CHF, $MW/m^2$ | 5.413 | 5.194 | 5.973 | 6.389 | 6.742 | 5.957 | 7.099 | 7.876 | 9.001 | 9.037 | 9.359 |
| % Error in Mirshak CHF | 9.0 | 3.6 | 5.2 | -6.7 | -1.7 | -13.2 | -10.7 | -1.8 | -3.5 | -2.5 | -6.6 |
| Sudo-Kaminaga CHF, $MW/m^2$ | 6.040 | 5.818 | 6.490 | 7.004 | 7.436 | 6.520 | 7.854 | 7.860 | 8.605 | 8.754 | 8.882 |
| % Error in Sudo-Kaminaga CHF | 21.6 | 16.0 | 14.3 | 2.3 | 8.4 | -4.9 | -1.2 | -2.0 | -7.7 | -5.6 | -11.4 |

**TABLE 7. Spreadsheet for Calculating the Effect of Varying Channel Thickness or Mass Velocity on the Sudo-Kaminaga CHF Correlation**

Effect of Channel Thickness and Mass Velocity on Sudo-Kaminaga CHF Correlation by Spreadsheet Calculation for a Half Channel Model of a Test Section Like Those Used in the 1964 ATR Burnout Tests Done by Croft

| INPUT QUANTITIES | | | CALCULATED QUANTITIES | | | |
|---|---|---|---|---|---|---|
| G, Mass Vel | kg/m^2-s | 6068.543 | G* | 506.9079034 | | dimensionless |
| Flow | kg/s | 0.323696084 | G*1 | 281.2757937 | | dimensionless |
| T inlet | C | 54.4 | G*2 | 1.082288889 | 1.082289 | dimensionless |
| T exit | C | 188.34 | G*3 | 9.41230914 | 9.412309 | dimensionless |
| Tsat | C | 200.09 | G1 | 3367.345897 | | kg/m^2-s |
| Cp | kJ/kg | 4.266 | G2 | 12.95682434 | | kg/m^2-s |
| Flow Area, AF | m^2 | 0.00005334 | G3 | 112.6812235 | | kg/m^2-s |
| HeatedArea,AH | m^2 | 0.03096768 | ZZG | 11.97168748 | | kg/m^2-s |
| Ch Width | m | 0.03048 | ZZQ | 22987.55543 | | kW/m^2 |
| Width Heated | m | 0.0254 | C | 3 | | dimensionless |
| Length | m | 1.2192 | LAMDA | 0.002118566 | | m |
| Ch Thickness | m | 0.0035 | DTSUBout | 11.75 | | C |
| RHO Vapor | kg/m^3 | 8.0525 | DTSUBin | 145.69 | | C |
| RHO Liquid | kg/m^3 | 864.73 | DTSUB*out | 0.026104856 | | dimensionless |
| Hfg | kJ/kg | 1920.16 | DTSUB*in | 0.323677996 | | dimensionless |
| SIGMA | N/m | 0.037707 | ZZX | 4.352224795 | | dimensionless |
| GRAVITY | m/s^2 | 9.80665 | QCHF*1 | 0.282609388 | | dimensionless |
| | | | QCHF*2 | 0.282609385 | | dimensionless |
| | | | QCHF*3 | 0.005247515 | | dimensionless |
| | | | QCHF1 | 6496.498983 | | kW/m^2 |
| | | | QCHF2 | 6496.498892 | | kW/m^2 |
| | | | QCHF3 | 120.6275449 | | kW/m^2 |
| | | | AF/AH | 0.001722441 | | dimensionless |
| | | | ZZ1 | 1.257491111 | | dimensionless |
| | | | QCHF1(0) | 5166.238493 | | kW/m^2 |

**TABLE 8. Effect of Varying Channel Thickness for a Fixed Coolant Mass Velocity on the Sudo-Kaminaga CHF Correlation (Mass Velocity = 10141.5 kg/m$^2$-s downflow)**

Outlet Pressure = 15.6 bar
Outlet Temperature = 188.3 °C
Heated Width of Plate = 25.4 mm
Inlet Temperature = 54.4 °C
Channel Width = 30.5 mm
Channel Length = 1.2192 m

| Channel Thickness mm | $G_2$ kg/m$^2$-s | $G_3$ kg/m$^2$-s | $G_1$ kg/m$^2$-s | $q_{c1}$ MW/m$^2$ | $q_{c1}$ at $\Delta T_{sub,o}$=0 MW/m$^2$ | $q_{c2}$ MW/m$^2$ | $q_{c3}$ MW/m$^2$ | CHF[a] in Downflow MW/m$^2$ |
|---|---|---|---|---|---|---|---|---|
| Column→1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 1.37* | 2.8 | 112.7 | 37424.0 | 8.16 | 7.07 | 4.25 | 0.0473 | 4.25* |
| 1.4* | 2.9 | 112.7 | 35503.4 | 8.16 | 7.07 | 4.34 | 0.0483 | 4.34* |
| 1.5* | 3.2 | 112.7 | 29733.3 | 8.16 | 7.07 | 4.65 | 0.0517 | 4.65* |
| 1.6* | 3.6 | 112.7 | 25187.8 | 8.16 | 7.07 | 4.96 | 0.0551 | 4.96* |
| 1.8* | 4.4 | 112.7 | 18607.7 | 8.16 | 7.07 | 5.58 | 0.0620 | 5.58* |
| 2.0* | 5.2 | 112.7 | 14192.7 | 8.16 | 7.07 | 6.20 | 0.0689 | 6.20* |
| 2.25 | 6.3 | 112.7 | 10485.0 | 8.16 | 7.07 | 6.98 | 0.0775 | 6.98 |
| 2.5 | 7.5 | 112.7 | 7997.2 | 8.16 | 7.07 | 7.75 | 0.0862 | 7.74 |
| 2.75 | 8.7 | 112.7 | 6259.4 | 8.16 | 7.07 | 8.53 | 0.0948 | 8.16 |
| 3.0 | 10.1 | 112.7 | 5004.8 | 8.16 | 7.07 | 9.31 | 0.103 | 8.16 |
| 3.5 | 13.0 | 112.7 | 3367.3 | 8.16 | 7.07 | 10.86 | 0.121 | 8.16 |
| 4.0 | 16.1 | 112.7 | 2389.0 | 8.16 | 7.07 | 12.41 | 0.138 | 8.16 |
| 4.5 | 19.5 | 112.7 | 1764.9 | 8.16 | 7.07 | 13.96 | 0.155 | 8.16 |
| 5.0 | 23.2 | 112.7 | 1346.1 | 8.16 | 7.07 | 15.51 | 0.172 | 8.16 |

* The channel thickness is out of the test range 2.25 to 5.0 mm. The correlation is not applicable.
a CHF in downflow is given by column 8 for mass velocities up to $G_3$ (112.7 kg/m$^2$-s), then by column 7 for mass velocities up to $G_1$, and above $G_1$ by the smaller of columns 5 and 7.

**TABLE 9. Effect of Varying Upward Mass Velocity for a Fixed Channel Thickness on the Sudo-Kaminaga CHF Correlation**

Channel Thickness = 3.5 mm,
Inlet Temperature = 54.4 °C,
Channel Width = 30.5 mm,
Channel Length = 1.2192 m

Outlet Pressure = 15.6 bar
Outlet Temperature = 188.3 °C
Heated Width of Plate = 25.4 mm

| Mass Velocity kg/m$^2$-s | $G_2$ kg/m$^2$-s | $G_3$ kg/m$^2$-s | $G_1$ kg/m$^2$-s | $q_{c1}$ MW/m$^2$ | $q_{c1}$ at $\Delta T_{sub,o}$=0 MW/m$^2$ | $q_{c2}$ MW/m$^2$ | $q_{c3}$ MW/m$^2$ | CHF[b] in Uplow MW/m$^2$ |
|---|---|---|---|---|---|---|---|---|
| Column→1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 5.0 | | | | 21.14 | 0.0674 | 0.0054 | 0.121 | 0.121 |
| **12.96** | | | | 14.67 | **0.121** | 0.0139 | **0.121** | **0.121** |
| 20.0 | | | | 12.44 | 0.157 | 0.0214 | 0.121 | 0.157 |
| 50.0 | | | | 8.88 | 0.275 | 0.0535 | 0.121 | 0.275 |
| 75.0 | | | | 7.70 | 0.353 | 0.0803 | 0.121 | 0.353 |
| **112.7** | | | | 6.72 | 0.452 | **0.121** | **0.121** | 0.452 |
| 200.0 | 12.96 | 112.7 | 3367.3 | 5.66 | 0.642 | 0.214 | 0.121 | 0.642 |
| 500.0 | | | | 4.64 | 1.124 | 0.535 | 0.121 | 1.124 |
| 1000.0 | | | | 4.40 | 1.716 | 1.070 | 0.121 | 1.716 |
| 2000.0 | | | | 4.67 | 2.622 | 2.141 | 0.121 | 2.622 |
| **3367.3** | | | | 5.278 | **3.605** | **3.605** | 0.121 | **3.605** |
| 3368.0 | | | | 5.278 | 3.605 | 3.606 | 0.121 | 3.606 |
| 5000.0 | | | | 6.02 | 4.59 | 5.350 | 0.121 | 5.350 |
| 6000.0 | | | | 6.467 | 5.139 | 6.423 | 0.121 | 6.423 |
| **6068.5** | | | | 6.496 | 5.166 | 6.496 | 0.121 | 6.496 |
| 10000.0 | | | | 8.11 | 7.01 | 10.71 | 0.121 | 8.11 |
| 15000.0 | | | | 9.92 | 8.98 | 16.06 | 0.121 | 9.92 |
| 20000.0 | | | | 11.54 | 10.71 | 21.41 | 0.121 | 11.54 |

a CHF in downflow is given by column 8 for mass velocities up to 112.7 kg/m$^2$-s, then by column 7 for mass velocities up to 3367.3 kg/m$^2$-s, and above 3367.3 kg/m$^2$-s by the smaller of columns 5 and 7.
b CHF in upflow is given by column 8 for mass velocities up to 12.96 kg/m$^2$-s, then by column 6 for mass velocities up to 3367.3 kg/m$^2$-s, and above 3367.3 kg/m$^2$-s by the smaller of columns 5 and 7.

**TABLE 10. Effect of Varying Downward Mass Velocity for a Fixed Channel Thickness on the Sudo-Kaminaga CHF Correlation**

Channel Thickness = 3.5 mm,
Inlet Temperature = 54.4 °C,
Channel Width = 30.5 mm,
Channel Length = 1.2192 m

Outlet Pressure = 15.6 bar
Outlet Temperature = 188.3 °C
Heated Width of Plate = 25.4 mm

| Mass Velocity $kg/m^2$-s | $G_2$ $kg/m^2$-s | $G_3$ $kg/m^2$-s | $G_1$ $kg/m^2$-s | $q_{c1}$ $MW/m^2$ | $q_{c1}$ at $\Delta T_{sub,o}$=0 $MW/m^2$ | $q_{c2}$ $MW/m^2$ | $q_{c3}$ $MW/m^2$ | CHF[a] in Downflow $MW/m^2$ |
|---|---|---|---|---|---|---|---|---|
| Column→1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 5.0 | 12.96 | 112.7 | 3367.3 | 21.14 | 0.0674 | 0.0054 | 0.121 | 0.121 |
| **12.96** | | | | 14.67 | **0.121** | 0.0139 | **0.121** | 0.121 |
| 20.0 | | | | 12.44 | 0.157 | 0.0214 | 0.121 | 0.121 |
| 50.0 | | | | 8.88 | 0.275 | 0.0535 | 0.121 | 0.121 |
| 75.0 | | | | 7.70 | 0.353 | 0.0803 | 0.121 | 0.121 |
| **112.7** | | | | 6.72 | 0.452 | **0.121** | **0.121** | **0.121** |
| 200.0 | | | | 5.66 | 0.642 | 0.214 | 0.121 | 0.214 |
| 500.0 | | | | 4.64 | 1.124 | 0.535 | 0.121 | 0.535 |
| 1000.0 | | | | 4.40 | 1.716 | 1.070 | 0.121 | 1.070 |
| 2000.0 | | | | 4.67 | 2.622 | 2.141 | 0.121 | 2.141 |
| **3367.3** | | | | 5.278 | **3.605** | **3.605** | 0.121 | **3.605** |
| 3368.0 | | | | 5.278 | 3.605 | 3.606 | 0.121 | 3.606 |
| 5000.0 | | | | 6.02 | 4.59 | 5.350 | 0.121 | 5.350 |
| 6000.0 | | | | 6.467 | 5.139 | 6.423 | 0.121 | 6.423 |
| **6068.5** | | | | **6.496** | 5.166 | **6.496** | 0.121 | 6.496 |
| 10000.0 | | | | 8.11 | 7.01 | 10.71 | 0.121 | 8.11 |
| 15000.0 | | | | 9.92 | 8.98 | 16.06 | 0.121 | 9.92 |
| 20000.0 | | | | 11.54 | 10.71 | 21.41 | 0.121 | 11.54 |

a CHF in downflow is given by column 8 for mass velocities up to 112.7 $kg/m^2$-s, then by column 7 for mass velocities up to 3367.3 $kg/m^2$-s, and above 3367.3 $kg/m^2$-s by the smaller of columns 5 and 7.
b CHF in upflow is given by column 8 for mass velocities up to 12.96 $kg/m^2$-s, then by column 6 for mass velocities up to 3367.3 $kg/m^2$-s, and above 3367.3 $kg/m^2$-s by the smaller of columns 5 and 7.

## APPENDIX J. PLTEMP/ANL Input Data Files for 11 CHF Tests Done by Mirshak, Durant, and Towell

The following is a listing of all the PLTEMP/ANL input data files used to model 11 of the CHF tests done by Mirshak, Durant, and Towell[7]. The test number is given on the first card.

```
  CHF Run #1, Mirshak, Durant, & Towell, Ref. DP-355 (1959)
! Rectangular channel, down flow, 1-sided heating
!  1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18  19  20
   0   0   0   1   0           0   0   0   0   0   0   0   2   1   0   0   0   00200
          1.          1.          1.                                              0201
!  5        0.20        0.5   1         1.0                                       0203
   1   3          0.          1.          1.          1.   0   0                 00300
          1.          1.          1.                                              0300A
        1.0                                                                       0303
          1.          1.          0.          0.                                  0304
          0.          0.     0.48895          0.    0.065024   0.0032959          0304
          1.          1.          0.          0.                                  0304
          0.          0.          0.                                              0305
   2   0     0.00635     0.48895      3.0e-5         10.      9.7e-4         10.0306
 2.143127e-4    6.274e-3     0.13664    0.052324    0.065024   0.0032959          0307
 2.143127e-4    6.274e-3     0.13664    0.052324    0.065024   0.0032959          0307
    0.065024                                                                      0308
          1.                                                                      0309
    1.190371    1.190371                                                          0310
! 2 x 0.127107 MW = 0.254214 MW
    0.262000          0.    0.262000    0.254214       57.09          0.          0500
          0.          0.                                                          0500
   0      0.0001        32.5          0.          0.                              0600
 -25                                                                              0700
      0.00000     0.02083          1.                                             0701
      0.04167     0.06250          1.                                             0701
      0.08333     0.10417          1.                                             0701
      0.12500     0.14583          1.                                             0701
      0.16667     0.18750          1.                                             0701
      0.20833     0.22917          1.                                             0701
      0.25000     0.27083          1.                                             0701
      0.29167     0.31250          1.                                             0701
      0.33333     0.35417          1.                                             0701
      0.37500     0.39583          1.                                             0701
      0.41667     0.43750          1.                                             0701
      0.45833     0.47917          1.                                             0701
      0.50000     0.52083          1.                                             0701
      0.54167     0.56250          1.                                             0701
      0.58333     0.60417          1.                                             0701
      0.62500     0.64583          1.                                             0701
      0.66667     0.68750          1.                                             0701
      0.70833     0.72917          1.                                             0701
      0.75000     0.77083          1.                                             0701
      0.79167     0.81250          1.                                             0701
      0.83333     0.85417          1.                                             0701
      0.87500     0.89583          1.                                             0701
      0.91667     0.93750          1.                                             0701
      0.95833     0.97917          1.                                             0701
      1.00000                                                                     0701
   0                                                                              0702
```

```
  CHF Run #4, Mirshak, Durant, & Towell, Ref. DP-355 (1959)
! Rectangular channel, down flow, 1-sided heating
!  1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18  19  20
   0   0   0   1   0           0   0   0   0   0   0   0   2   1   0   0   0   00200
          1.          1.          1.                                              0201
!  5        0.20        0.5   1         1.0                                       0203
   1   3          0.          1.          1.          1.   0   0                 00300
          1.          1.          1.                                              0300A
        1.0                                                                       0303
          1.          1.          0.          0.                                  0304
          0.          0.     0.48895          0.   0.0650244   0.0032959          0304
          1.          1.          0.          0.                                  0304
          0.          0.          0.                                              0305
   2   0     0.00635      0.4890      3.0e-5         10.      9.7e-4         10.0306
 2.143127e-4    6.274e-3     0.13664    0.052324    0.065024   0.0032959          0307
 2.143127e-4    6.274e-3     0.13664    0.052324    0.065024   0.0032959          0307
    0.065024                                                                      0308
          1.                                                                      0309
```

```
   1.177504    1.177504                                                    0310
! 2 x 0.128269 MW = 0.256538 MW
   0.245453          0.    0.245453    0.256538       56.85          0.        0500
         0.          0.                                                    0500
  0      0.0001        32.5          0.          0.                        0600
 -25                                                                       0700
    0.00000     0.02083          1.                                        0701
    0.04167     0.06250          1.                                        0701
    0.08333     0.10417          1.                                        0701
    0.12500     0.14583          1.                                        0701
    0.16667     0.18750          1.                                        0701
    0.20833     0.22917          1.                                        0701
    0.25000     0.27083          1.                                        0701
    0.29167     0.31250          1.                                        0701
    0.33333     0.35417          1.                                        0701
    0.37500     0.39583          1.                                        0701
    0.41667     0.43750          1.                                        0701
    0.45833     0.47917          1.                                        0701
    0.50000     0.52083          1.                                        0701
    0.54167     0.56250          1.                                        0701
    0.58333     0.60417          1.                                        0701
    0.62500     0.64583          1.                                        0701
    0.66667     0.68750          1.                                        0701
    0.70833     0.72917          1.                                        0701
    0.75000     0.77083          1.                                        0701
    0.79167     0.81250          1.                                        0701
    0.83333     0.85417          1.                                        0701
    0.87500     0.89583          1.                                        0701
    0.91667     0.93750          1.                                        0701
    0.95833     0.97917          1.                                        0701
    1.00000                                                                0701
  0                                                                        0702
```

**CHF Run #21**, Mirshak, Durant, & Towell, Ref. DP-355 (1959)

```
! Rectangular channel, down flow, 1-sided heating
!  1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18  19  20
   0   0   0   1   0           0   0   0   0   0   0   0   2   1   0   0   0   00200
         1.          1.          1.                                        0201
!  5       0.20         0.5   1         1.0                                0203
   1   3          0.          1.          1.          1.   0   0          00300
         1.          1.          1.                                        0300A
        1.0                                                                0303
         1.          1.          0.          0.                            0304
         0.          0.     0.48895          0.   0.0650244 0.006480055    0304
         1.          1.          0.          0.                            0304
         0.          0.          0.                                        0305
  2   0     0.00635      0.4890      3.0e-5         10.      9.7e-4        10.0306
 4.213591e-4   11.786e-3    0.143008    0.052324    0.065024 0.006480055   0307
 4.213591e-4   11.786e-3    0.143008    0.052324    0.065024 0.006480055   0307
   0.065024                                                                0308
         1.                                                                0309
   2.325514    2.325514                                                    0310
! 2 x 0.145265 MW = 0.290530 MW
   0.345427          0.    0.345427    0.290530       77.68          0.        0500
         0.          0.                                                    0500
  0      0.0001        32.5          0.          0.                        0600
 -25                                                                       0700
    0.00000     0.02083          1.                                        0701
    0.04167     0.06250          1.                                        0701
    0.08333     0.10417          1.                                        0701
    0.12500     0.14583          1.                                        0701
    0.16667     0.18750          1.                                        0701
    0.20833     0.22917          1.                                        0701
    0.25000     0.27083          1.                                        0701
    0.29167     0.31250          1.                                        0701
    0.33333     0.35417          1.                                        0701
    0.37500     0.39583          1.                                        0701
    0.41667     0.43750          1.                                        0701
    0.45833     0.47917          1.                                        0701
    0.50000     0.52083          1.                                        0701
    0.54167     0.56250          1.                                        0701
    0.58333     0.60417          1.                                        0701
    0.62500     0.64583          1.                                        0701
    0.66667     0.68750          1.                                        0701
    0.70833     0.72917          1.                                        0701
    0.75000     0.77083          1.                                        0701
    0.79167     0.81250          1.                                        0701
    0.83333     0.85417          1.                                        0701
    0.87500     0.89583          1.                                        0701
```

```
     0.91667     0.93750          1.                                              0701
     0.95833     0.97917          1.                                              0701
     1.00000                                                                      0701
   0                                                                              0702
```

**CHF Run #22**, Mirshak, Durant, & Towell, Ref. DP-355 (1959)

```
! Rectangular channel, down flow, 1-sided heating
!  1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18  19  20
   0   0   0   1   0           0   0   0   0   0   0   0   2   1   0   0   0   00200
         1.          1.          1.                                               0201
!  5       0.20         0.5   1         1.0                                       0203
   1   3         0.          1.          1.          1.   0   0                  00300
         1.          1.          1.                                               0300A
        1.0                                                                       0303
         1.          1.          0.          0.                                   0304
         0.          0.     0.48895          0.   0.0650244  0.00638803           0304
         1.          1.          0.          0.                                   0304
         0.          0.          0.                                               0305
   2   0     0.00635     0.4890      3.0e-5         10.      9.7e-4         10.0306
 4.153752e-4   11.633e-3    0.142824    0.052324    0.065024  0.00638803          0307
 4.153752e-4   11.633e-3    0.142824    0.052324    0.065024  0.00638803          0307
    0.065024                                                                      0308
         1.                                                                       0309
    2.318468    2.318468                                                          0310
! 2 x 0.17519 MW = 0.350389 MW
    0.349564         0.    0.349564    0.350389       65.18          0.           0500
         0.          0.                                                           0500
   0      0.0001        32.5          0.          0.                              0600
 -25                                                                              0700
     0.00000     0.02083          1.                                              0701
     0.04167     0.06250          1.                                              0701
     0.08333     0.10417          1.                                              0701
     0.12500     0.14583          1.                                              0701
     0.16667     0.18750          1.                                              0701
     0.20833     0.22917          1.                                              0701
     0.25000     0.27083          1.                                              0701
     0.29167     0.31250          1.                                              0701
     0.33333     0.35417          1.                                              0701
     0.37500     0.39583          1.                                              0701
     0.41667     0.43750          1.                                              0701
     0.45833     0.47917          1.                                              0701
     0.50000     0.52083          1.                                              0701
     0.54167     0.56250          1.                                              0701
     0.58333     0.60417          1.                                              0701
     0.62500     0.64583          1.                                              0701
     0.66667     0.68750          1.                                              0701
     0.70833     0.72917          1.                                              0701
     0.75000     0.77083          1.                                              0701
     0.79167     0.81250          1.                                              0701
     0.83333     0.85417          1.                                              0701
     0.87500     0.89583          1.                                              0701
     0.91667     0.93750          1.                                              0701
     0.95833     0.97917          1.                                              0701
     1.00000                                                                      0701
   0                                                                              0702
```

**CHF Run #23**, Mirshak, Durant, & Towell, Ref. DP-355 (1959)

```
! Rectangular channel, down flow, 1-sided heating
!  1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18  19  20
   0   0   0   1   0           0   0   0   0   0   0   0   2   1   0   0   0   00200
         1.          1.          1.                                               0201
!  5       0.20         0.5   1         1.0                                       0203
   1   3         0.          1.          1.          1.   0   0                  00300
         1.          1.          1.                                               0300A
        1.0                                                                       0303
         1.          1.          0.          0.                                   0304
         0.          0.     0.48895          0.   0.0650244 0.006342105           0304
         1.          1.          0.          0.                                   0304
         0.          0.          0.                                               0305
   2   0     0.00635     0.4890      3.0e-5         10.      9.7e-4         10.0306
 4.123890e-4   11.557e-3    0.142732    0.052324    0.065024 0.006342105          0307
 4.123890e-4   11.557e-3    0.142732    0.052324    0.065024 0.006342105          0307
    0.065024                                                                      0308
         1.                                                                       0309
    2.313044    2.313044                                                          0310
! 2 x 0.17548 MW = 0.350960 MW
    0.354390         0.    0.354390    0.350960       57.42          0.           0500
         0.          0.                                                           0500
```

```
  0      0.0001        32.5          0.          0.                              0600
 -25                                                                             0700
    0.00000     0.02083          1.                                              0701
    0.04167     0.06250          1.                                              0701
    0.08333     0.10417          1.                                              0701
    0.12500     0.14583          1.                                              0701
    0.16667     0.18750          1.                                              0701
    0.20833     0.22917          1.                                              0701
    0.25000     0.27083          1.                                              0701
    0.29167     0.31250          1.                                              0701
    0.33333     0.35417          1.                                              0701
    0.37500     0.39583          1.                                              0701
    0.41667     0.43750          1.                                              0701
    0.45833     0.47917          1.                                              0701
    0.50000     0.52083          1.                                              0701
    0.54167     0.56250          1.                                              0701
    0.58333     0.60417          1.                                              0701
    0.62500     0.64583          1.                                              0701
    0.66667     0.68750          1.                                              0701
    0.70833     0.72917          1.                                              0701
    0.75000     0.77083          1.                                              0701
    0.79167     0.81250          1.                                              0701
    0.83333     0.85417          1.                                              0701
    0.87500     0.89583          1.                                              0701
    0.91667     0.93750          1.                                              0701
    0.95833     0.97917          1.                                              0701
    1.00000                                                                      0701
  0                                                                              0702
```

**CHF Run #24**, Mirshak, Durant, & Towell, Ref. DP-355 (1959)

```
! Rectangular channel, down flow, 1-sided heating
!  1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18  19  20
   0   0   0   1   0           0   0   0   0   0   0   0   2   1   0   0   0   00200
          1.          1.          1.                                             0201
!  5        0.20         0.5   1         1.0                                     0203
   1   3          0.          1.          1.          1.   0   0                00300
          1.          1.          1.                                             0300A
         1.0                                                                     0303
          1.          1.          0.          0.                                 0304
          0.          0.     0.48895          0.   0.0650244 0.006311522         0304
          1.          1.          0.          0.                                 0304
          0.          0.          0.                                             0305
   2   0     0.00635      0.4890      3.0e-5         10.      9.7e-4        10.0306
 4.104004e-4   11.557e-3    0.136528    0.052324    0.065024 0.006311522         0307
 4.104004e-4   11.557e-3    0.136528    0.052324    0.065024 0.006311522         0307
   0.065024                                                                      0308
          1.                                                                     0309
   2.350901    2.350901                                                          0310
! 2 x 0.203371 MW = 0.406641 MW
   0.353011          0.    0.353011    0.406641       46.43          0.          0500
          0.          0.                                                         0500
  0      0.0001        32.5          0.          0.                              0600
 -25                                                                             0700
    0.00000     0.02083          1.                                              0701
    0.04167     0.06250          1.                                              0701
    0.08333     0.10417          1.                                              0701
    0.12500     0.14583          1.                                              0701
    0.16667     0.18750          1.                                              0701
    0.20833     0.22917          1.                                              0701
    0.25000     0.27083          1.                                              0701
    0.29167     0.31250          1.                                              0701
    0.33333     0.35417          1.                                              0701
    0.37500     0.39583          1.                                              0701
    0.41667     0.43750          1.                                              0701
    0.45833     0.47917          1.                                              0701
    0.50000     0.52083          1.                                              0701
    0.54167     0.56250          1.                                              0701
    0.58333     0.60417          1.                                              0701
    0.62500     0.64583          1.                                              0701
    0.66667     0.68750          1.                                              0701
    0.70833     0.72917          1.                                              0701
    0.75000     0.77083          1.                                              0701
    0.79167     0.81250          1.                                              0701
    0.83333     0.85417          1.                                              0701
    0.87500     0.89583          1.                                              0701
    0.91667     0.93750          1.                                              0701
    0.95833     0.97917          1.                                              0701
    1.00000                                                                      0701
  0                                                                              0702
```

**CHF Run #26**, Mirshak, Durant, & Towell, Ref. DP-355 (1959)

```
! Rectangular channel, down flow, 1-sided heating
!  1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18  19  20
   0   0   0   1   0           0   0   0   0   0   0   0   2   1   0   0   0   00200
          1.          1.          1.                                            0201
!  5        0.20         0.5   1         1.0                                    0203
   1   3          0.          1.          1.          1.   0   0               00300
          1.          1.          1.                                            0300A
         1.0                                                                    0303
          1.          1.          0.          0.                                0304
          0.          0.     0.48895          0.   0.0650244 0.003239867        0304
          1.          1.          0.          0.                                0304
          0.          0.          0.                                            0305
   2   0     0.00635      0.4890      3.0e-5         10.      9.7e-4         10.0306
 2.106691e-4   6.1720e-3    0.136528    0.052324    0.065024 0.003239867        0307
 2.106691e-4   6.1720e-3    0.136528    0.052324    0.065024 0.003239867        0307
    0.065024                                                                    0308
          1.                                                                    0309
    2.065757    2.065757                                                        0310
! 2 x 0.205114 MW = 0.410228 MW
    0.347495          0.    0.347495    0.410228       68.80          0.        0500
          0.          0.                                                        0500
   0      0.0001        32.5          0.          0.                            0600
 -25                                                                            0700
     0.00000     0.02083          1.                                            0701
     0.04167     0.06250          1.                                            0701
     0.08333     0.10417          1.                                            0701
     0.12500     0.14583          1.                                            0701
     0.16667     0.18750          1.                                            0701
     0.20833     0.22917          1.                                            0701
     0.25000     0.27083          1.                                            0701
     0.29167     0.31250          1.                                            0701
     0.33333     0.35417          1.                                            0701
     0.37500     0.39583          1.                                            0701
     0.41667     0.43750          1.                                            0701
     0.45833     0.47917          1.                                            0701
     0.50000     0.52083          1.                                            0701
     0.54167     0.56250          1.                                            0701
     0.58333     0.60417          1.                                            0701
     0.62500     0.64583          1.                                            0701
     0.66667     0.68750          1.                                            0701
     0.70833     0.72917          1.                                            0701
     0.75000     0.77083          1.                                            0701
     0.79167     0.81250          1.                                            0701
     0.83333     0.85417          1.                                            0701
     0.87500     0.89583          1.                                            0701
     0.91667     0.93750          1.                                            0701
     0.95833     0.97917          1.                                            0701
     1.00000                                                                    0701
   0                                                                            0702
```

**CHF Run #27**, Mirshak, Durant, & Towell, Ref. DP-355 (1959)

```
! Rectangular channel, down flow, 1-sided heating
!  1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18  19  20
   0   0   0   1   0           0   0   0   0   0   0   0   2   1   0   0   0   00200
          1.          1.          1.                                            0201
!  5        0.20         0.5   1         1.0                                    0203
   1   3          0.          1.          1.          1.   0   0               00300
          1.          1.          1.                                            0300A
         1.0                                                                    0303
          1.          1.          0.          0.                                0304
          0.          0.     0.48895          0.   0.0650244 0.003183925        0304
          1.          1.          0.          0.                                0304
          0.          0.          0.                                            0305
   2   0     0.00635      0.4890      3.0e-5         10.      9.7e-4         10.0306
 2.070315e-4   6.0710e-3    0.136416    0.052324    0.065024 0.003183925        0307
 2.070315e-4   6.0710e-3    0.136416    0.052324    0.065024 0.003183925        0307
    0.065024                                                                    0308
          1.                                                                    0309
    2.046270    2.046270                                                        0310
! 2 x 0.238525 MW = 0.477050 MW
   0.4136847          0.   0.4136847    0.477050       61.60          0.        0500
          0.          0.                                                        0500
   0      0.0001        32.5          0.          0.                            0600
 -25                                                                            0700
     0.00000     0.02083          1.                                            0701
     0.04167     0.06250          1.                                            0701
     0.08333     0.10417          1.                                            0701
```

```
      0.12500     0.14583          1.                                           0701
      0.16667     0.18750          1.                                           0701
      0.20833     0.22917          1.                                           0701
      0.25000     0.27083          1.                                           0701
      0.29167     0.31250          1.                                           0701
      0.33333     0.35417          1.                                           0701
      0.37500     0.39583          1.                                           0701
      0.41667     0.43750          1.                                           0701
      0.45833     0.47917          1.                                           0701
      0.50000     0.52083          1.                                           0701
      0.54167     0.56250          1.                                           0701
      0.58333     0.60417          1.                                           0701
      0.62500     0.64583          1.                                           0701
      0.66667     0.68750          1.                                           0701
      0.70833     0.72917          1.                                           0701
      0.75000     0.77083          1.                                           0701
      0.79167     0.81250          1.                                           0701
      0.83333     0.85417          1.                                           0701
      0.87500     0.89583          1.                                           0701
      0.91667     0.93750          1.                                           0701
      0.95833     0.97917          1.                                           0701
      1.00000                                                                   0701
   0                                                                            0702
```

**CHF Run #36**, Mirshak, Durant, & Towell, Ref. DP-355 (1959)

```
! Rectangular channel, down flow, 1-sided heating
!  1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18  19  20
   0   0   0   1   0           0   0   0   0   0   0   0   2   1   0   0   0   00200
         1.          1.          1.                                             0201
!  5        0.20         0.5   1         1.0                                    0203
   1   3          0.          1.          1.          1.   0   0               00300
         1.          1.          1.                                             0300A
        1.0                                                                     0303
         1.          1.          0.          0.                                 0304
         0.          0.     0.48895          0.   0.0650244   0.0032959         0304
         1.          1.          0.          0.                                 0304
         0.          0.          0.                                             0305
   2   0     0.00635      0.4890      3.0e-5         10.      9.7e-4         10.0306
 2.143127e-4    6.274e-3     0.13664    0.052324    0.065024   0.0032959        0307
 2.143127e-4    6.274e-3     0.13664    0.052324    0.065024   0.0032959        0307
    0.065024                                                                    0308
         1.                                                                     0309
    2.145878    2.145878                                                        0310
! 2 x 0.237218 MW = 0.474436 MW
    0.358527          0.    0.358527    0.474436       47.27          0.        0500
         0.          0.                                                         0500
   0      0.0001        32.5          0.          0.                            0600
 -25                                                                            0700
      0.00000     0.02083          1.                                           0701
      0.04167     0.06250          1.                                           0701
      0.08333     0.10417          1.                                           0701
      0.12500     0.14583          1.                                           0701
      0.16667     0.18750          1.                                           0701
      0.20833     0.22917          1.                                           0701
      0.25000     0.27083          1.                                           0701
      0.29167     0.31250          1.                                           0701
      0.33333     0.35417          1.                                           0701
      0.37500     0.39583          1.                                           0701
      0.41667     0.43750          1.                                           0701
      0.45833     0.47917          1.                                           0701
      0.50000     0.52083          1.                                           0701
      0.54167     0.56250          1.                                           0701
      0.58333     0.60417          1.                                           0701
      0.62500     0.64583          1.                                           0701
      0.66667     0.68750          1.                                           0701
      0.70833     0.72917          1.                                           0701
      0.75000     0.77083          1.                                           0701
      0.79167     0.81250          1.                                           0701
      0.83333     0.85417          1.                                           0701
      0.87500     0.89583          1.                                           0701
      0.91667     0.93750          1.                                           0701
      0.95833     0.97917          1.                                           0701
      1.00000                                                                   0701
   0                                                                            0702
```

**CHF Run #43**, Mirshak, Durant, & Towell, Ref. DP-355 (1959)

```
! Rectangular channel, down flow, 1-sided heating
!  1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18  19  20
```

```
   0   0   0   1   0           0   0   0   0   0   0   0   2   1   0   0   0   00200
         1.          1.          1.                                              0201
!  5       0.20         0.5   1         1.0                                      0203
   1   3          0.          1.          1.          1.   0   0                00300
         1.          1.          1.                                              0300A
        1.0                                                                      0303
         1.          1.          0.          0.                                  0304
         0.          0.     0.48895          0.   0.0650244 0.003380126          0304
         1.          1.          0.          0.                                  0304
         0.          0.          0.                                              0305
   2   0     0.00635      0.4890      3.0e-5         10.      9.7e-4         10.0306
 2.197893e-4   6.4260e-3    0.136808    0.052324    0.065024 0.003380126         0307
 2.197893e-4   6.4260e-3    0.136808    0.052324    0.065024 0.003380126         0307
    0.065024                                                                     0308
         1.                                                                      0309
    2.152693    2.152693                                                         0310
! 2 x 0.17548 MW = 0.35096 MW
    0.168212          0.    0.168212     0.35096       55.90          0.         0500
         0.          0.                                                          0500
   0      0.0001        32.5          0.          0.                             0600
 -25                                                                             0700
     0.00000     0.02083          1.                                             0701
     0.04167     0.06250          1.                                             0701
     0.08333     0.10417          1.                                             0701
     0.12500     0.14583          1.                                             0701
     0.16667     0.18750          1.                                             0701
     0.20833     0.22917          1.                                             0701
     0.25000     0.27083          1.                                             0701
     0.29167     0.31250          1.                                             0701
     0.33333     0.35417          1.                                             0701
     0.37500     0.39583          1.                                             0701
     0.41667     0.43750          1.                                             0701
     0.45833     0.47917          1.                                             0701
     0.50000     0.52083          1.                                             0701
     0.54167     0.56250          1.                                             0701
     0.58333     0.60417          1.                                             0701
     0.62500     0.64583          1.                                             0701
     0.66667     0.68750          1.                                             0701
     0.70833     0.72917          1.                                             0701
     0.75000     0.77083          1.                                             0701
     0.79167     0.81250          1.                                             0701
     0.83333     0.85417          1.                                             0701
     0.87500     0.89583          1.                                             0701
     0.91667     0.93750          1.                                             0701
     0.95833     0.97917          1.                                             0701
     1.00000                                                                     0701
   0                                                                             0702
```

**CHF Run #48**, Mirshak, Durant, & Towell, Ref. DP-355 (1959)

```
! Rectangular channel, down flow, 1-sided heating
!  1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18  19  20
   0   0   0   1   0           0   0   0   0   0   0   0   2   1   0   0   0   00200
         1.          1.          1.                                              0201
!  5       0.20         0.5   1         1.0                                      0203
   1   3          0.          1.          1.          1.   0   0                00300
         1.          1.          1.                                              0300A
        1.0                                                                      0303
         1.          1.          0.          0.                                  0304
         0.          0.     0.48895          0.   0.0650244   0.0033942          0304
         1.          1.          0.          0.                                  0304
         0.          0.          0.                                              0305
   2   0     0.00635     0.48895      3.0e-5         10.      9.7e-4         10.0306
 2.207034e-4    6.452e-3    0.136836    0.052324    0.065024   0.0033942         0307
 2.207034e-4    6.452e-3    0.136836    0.052324    0.065024   0.0033942         0307
    0.065024                                                                     0308
         1.                                                                      0309
    2.503319    2.503319                                                         0310
! 2 x 0.256393 MW = 0.512786 MW
    0.381279          0.    0.381279    0.512786       62.59          0.         0500
         0.          0.                                                          0500
   0      0.0001        32.5          0.          0.                             0600
 -25                                                                             0700
     0.00000     0.02083          1.                                             0701
     0.04167     0.06250          1.                                             0701
     0.08333     0.10417          1.                                             0701
     0.12500     0.14583          1.                                             0701
     0.16667     0.18750          1.                                             0701
     0.20833     0.22917          1.                                             0701
     0.25000     0.27083          1.                                             0701
```

```
   0.29167     0.31250           1.                                                0701
   0.33333     0.35417           1.                                                0701
   0.37500     0.39583           1.                                                0701
   0.41667     0.43750           1.                                                0701
   0.45833     0.47917           1.                                                0701
   0.50000     0.52083           1.                                                0701
   0.54167     0.56250           1.                                                0701
   0.58333     0.60417           1.                                                0701
   0.62500     0.64583           1.                                                0701
   0.66667     0.68750           1.                                                0701
   0.70833     0.72917           1.                                                0701
   0.75000     0.77083           1.                                                0701
   0.79167     0.81250           1.                                                0701
   0.83333     0.85417           1.                                                0701
   0.87500     0.89583           1.                                                0701
   0.91667     0.93750           1.                                                0701
   0.95833     0.97917           1.                                                0701
   1.00000                                                                         0701
 0                                                                                 0702
```

## 14. Comparing ONB and OFDNB Correlations

(July 22, 2010)

To compare with the ONB correlations available in the PLTEMP/ANL code, the purpose here is to convert the units in the following ONB/OFDNB correlation attributed to Forster and Grief in a French paper[1] (see for a copy of this paper). The desired unit of heat flux is kW/m$^2$, and the desired unit of pressure is bar.

$$\Delta T_{sat} = 4.57\, q^{0.35} \left(10^{-3}\, P\right)^{-0.23} \tag{1}$$

where

| | |
|---|---|
| ONB | = Onset of nucleate boiling |
| OFNDB | = Onset of fully developed nucleate boiling |
| $\Delta T_{sat}$ | = $T_{onb} - T_{sat}$ = Wall superheat for the onset of boiling, or for the onset of fully developed nucleate boiling as the case may be, °C |
| $T_{sat}$ | = Saturation temperature, °C |
| q | = Heat flux, W/cm$^2$ |
| P | = Coolant pressure, gm/cm$^2$ |
| $q_1$ | = Heat flux, kW/m$^2$ |
| $q_2$ | = Heat flux, W/m$^2$ |
| $P_1$ | = Coolant pressure, bar |

Let us convert $q_1$ kW/m$^2$ to W/cm$^2$ units, $q_2$ W/m$^2$ to W/cm$^2$ units, and $P_1$ bar to gm/cm$^2$ units.

$$q_1 \text{ kW/m}^2 = \frac{1000\, q_1}{100^2} \frac{\text{W}}{\text{cm}^2} = 0.1\, q_1 \quad \text{W/cm}^2 \tag{2}$$

$$q_2 \text{ W/m}^2 = \frac{q_1}{100^2} \frac{\text{W}}{\text{cm}^2} = 0.0001\, q_1 \quad \text{W/cm}^2 \tag{3}$$

$$P_1 \text{ bar} = 14.5038\, P_1 \text{ pounds per sq inch} = \frac{P_1 \times 14.5038 \times 453.6\, \text{gm}}{(2.54)^2\ \text{cm}^2} = 1019.735\, P_1 \quad \text{gm/cm}^2 \tag{4}$$

Substituting Eqs. (2) and (4) into Eq. (1) we get

$$\begin{aligned} \Delta T_{sat} &= 4.57\, (0.0001\, q_1)^{0.35} \left(10^{-3} \times 1019.735\, P_1\right)^{-0.23} \\ &= 4.57\, (0.0001)^{0.35}\, q_1^{\,0.35} \left(10^{-3} \times 1019.735\right)^{-0.23} P_1^{\,-0.23} \\ &= 4.57 \times 0.039811\, q_1^{\,0.35} \times 0.9955\, P_1^{\,-0.23} \\ &= 0.1811\, q_1^{\,0.35} \,/\, P_1^{\,0.23} \end{aligned} \tag{5}$$

Comparing Eq. (5) with the ONB equations given in the PLTEMP/ANL Users Guide, we see that Eq. (5) [and hence Eq. (1)] is what is called Forster and Grief equation for ONB in the Users Guide. However, we have not yet found the connection of this correlation to the work of Forster and Grief reported in their famous paper of 1959. This connection is needed to decide whether this correlation is for ONB or OFDNB.

Substituting Eqs. (3) and (4) into Eq. (1) we get

$$\begin{aligned}\Delta T_{sat} &= 4.57\,(0.1\,q_1)^{0.35}\left(10^{-3}\times 1019.735\,P_1\right)^{-0.23} \\ &= 4.57\,(0.1\,)^{0.35}\,q_1^{\,0.35}\left(10^{-3}\times 1019.735\right)^{-0.23}\,P_1^{\,-0.23} \\ &= 4.57\times 0.44668\,q_1^{\,0.35}\times 0.9955\,P_1^{\,-0.23} \\ &= 2.032\,q_1^{\,0.35}\,/\,P_1^{\,0.23}\end{aligned} \tag{6}$$

Comparing Eq. (6) with the ONB equations given in the PLTEMP/ANL Users Guide, we see that Eq. (6) [and hence Eq. (1)] is very similar to what is called Russian-modified Forster and Grief equation for ONB in the Users Guide. Only the exponent of pressure is slightly different (it is 0.23 instead of 0.25).

## REFERENCES

1. N. Hanan and B. Dionne, Argonne National laboratory, private communication, July 22, 2010.

## 15. Test Problem Comparison of PLTEMP/ANL Code Pressure Drops during Subcooled Nucleate Boiling with Those of the RELAP5 Code

The PLTEMP/ANL [1] code hydraulics model does not include the effects of boiling on the hydraulic resistance. The concern is that when these effects are included the power at which flow instability is predicted to first occur may be reduced. A single-channel test problem was analyzed with both PLTEMP/ANL and RELAP5 [2]. Pressure drop as a function of flow rate for a fixed channel power of 200 kW and an exit pressure of 5 bar was predicted with both codes. A correlation that is independent of both codes, based on experimental data, and believed to be reasonably reliable, predicts the minimum stable flow rate to be about 0.63 kg/s for the channel of the test problem. The results show that for flow rates at or above the predicted minimum stable flow RELAP5 and PLTEMP/ANL pressure drops agree extremely well, with RELAP5 predicting 1.6% more pressure drop at the highest flow, which has no boiling, and 4.2% more at the flow expect to be the minimum stable flow. Thus, for this test case, the exclusion of the effects of boiling in the PLTEMP/ANL hydraulics model can have only a minor adverse impact on the prediction of the power level at which flow instability is expected to first occur.

### 15.1. Background

The PLTEMP/ANL code hydraulics model is based on single-phase flow with no consideration for subcooled nucleate boiling. This model is completely appropriate for conditions from zero power up to conditions that lead to the onset of nucleate boiling. Subcooled nucleate boiling can cause increased hydraulic resistance in the fuel channels where this boiling is occurring and thereby lead to reduced flow rates in these potentially limiting channels. A lower channel flow rate would, in turn, result in higher coolant temperatures in the channel and cause flow instability to occur at a lower power level than it would otherwise occur. IF flow instability occurs, fuel damage is highly likely. Thus, the potential increased hydraulic resistance between the onset of nucleate boiling and the onset of flow instability is of concern. Although there are plans to modify the PLTEMP/ANL code to include the effects of subcooled nucleate boiling on hydraulic resistance, in the interim it is highly desirable to obtain a quick assessment of the potential impact on past and ongoing analyses. Accordingly, it was decided to compare PLTEMP/ANL hydraulic results for a single channel operating at a fixed power with those obtained with RELAP5. Moreover, the analytical data generated for this comparison could be used to aid the planned improvement to the PTEMP code.

### 15.2. Test Case

The conditions chosen for the test case, Table 1, were selected to be a very simplified approximate representation of conditions in the MURR (University of Missouri Research Reactor Center) reactor with upward flow rather than downward flow. A single heated channel that was symmetrically heated by two fuel plates was represented with each code. In both the PLTEMP/ANL and RELAP5 models, the 24-inch heated length was divided into 24 1-inch layers. The full 2-inch by 24-inch width of each fuel plate was assumed to be uniformly heated.

Table 1. Key Parameters

| Parameter | Value |
|---|---|
| Channel Thickness, in. | 0.080 |
| Channel Width, in. | 2.00 |
| Channel Length, in. | 24.0 |
| Heated Width, in. | 2.00 |
| Heated Length, in. | 24.0 |
| Flow Direction | Upward |
| Inlet Temperature, C | 60 |
| Outlet Pressure, bar | 5.0 |
| Power Shape | Uniform |
| Inlet & Outlet Form Losses | 0.0 |
| Hot Channel Factors (All) | 1.0 |
| Channel Power, kW | 200 |

### 15.3. Solution Procedure and Results

The results are presented in Table 2 and Figure 1. In all cases the channel power was assumed to be 200 kW. The analysis was performed by first selecting a friction pressure drop for PLTEMP/ANL and guessing an inlet pressure at the bottom of the channel that would produce an outlet pressure of exactly 5 bar at the top of the channel. If the desired exact outlet pressure was not achieved, the inlet pressure was adjusted and the case was rerun. The reason for this guesswork is that the pressure drop provided in the input does not include the gravity pressure drop portion of the pressure difference between the inlet and the outlet. For example, when a friction pressure drop of 60 kPa was requested, the difference between the inlet and outlet pressures was 65.756 kPa. The extra 5.765 kPa was caused by the inlet being 24 inches below the outlet, and is the gravity pressure drop from the inlet to the outlet. The code output provides the pressure at the center of each layer, or node, including the effects of gravity. A small modification to the Reference 0 version of the code was made by one of the code authors to enable it to output the

Table 2. Pressure Drop vs. Flow

| | PLTEMP/ANL | | RELAP5 | | | |
|---|---|---|---|---|---|---|
| Flow, kg/s | Pressure Drop*, kPa | Boiling | Pressure Drop*, kPa | Boiling | Gravity Pressure Drop, kPa | Exit Void Fraction, % |
| 1.1800 | 185.8 | no | 188.8 | no | 5.80 | 0.0 |
| 1.0285 | 145.8 | no | 148.5 | yes | 5.79 | 0.0 |
| 0.9454 | 125.8 | no | 128.3 | yes | 5.78 | 0.0 |
| 0.7576 | 85.8 | yes | 87.9 | yes | 5.75 | 0.0 |
| 0.6476 | 65.8 | yes | 67.6 | yes | 5.73 | 0.0 |
| 0.6264 | 62.2 | yes | 64.8 | yes | 5.72 | 2.0 |
| 0.6000 | | | 62.4 | yes | 5.69 | 7.2 |
| 0.5600 | | | 62.0 | yes | 5.61 | 22.5 |
| 0.5400 | | | 63.6 | yes | 5.54 | 32.9 |
| 0.5300 | | | 65.0 | yes | 5.49 | 38.5 |
| 0.5250 | | | 65.9 | yes | 5.47 | 41.5 |
| 0.5200 | | | No Stable Solution | | | |
| 0.5194 | 45.7 | yes | | | | |

*Inlet pressure minus outlet pressure, including effects of differences in elevation.

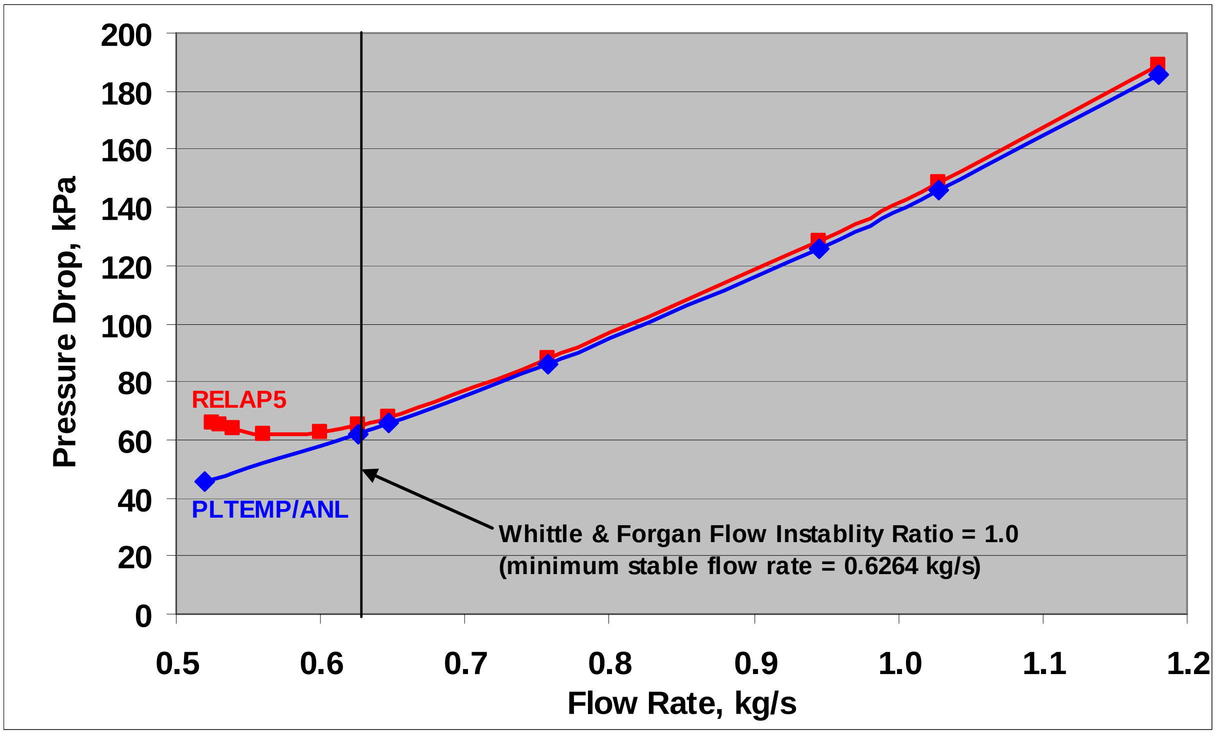


Figure 1. Pressure Drop vs. Flow Rate at 200 kW per Channel and 5.0 bar Exit Pressure

pressure at the inlet of the first node and the outlet of the last node. This new internal unreleased version, which is currently version 3.5, was used for the PLTEMP/ANL analysis.

The flow rate obtained from each PLTEMP/ANL solution was used as the input flow to the RELAP5 model. RELAP5 allows the exit pressure to be specified as 5 bar and determined the corresponding value of the inlet pressure, which was used to obtain the pressure difference between the inlet and the outlet. This pressure difference includes the effects of gravity. Since RELAP5 provides the coolant density at each of the 24 axial layers, it was a simple matter to calculate the gravity pressure drop as the sum over all 24 axial layers of the product of coolant density times the acceleration due to gravity (9.80655 $m/s^2$) times the thickness of the layer (1 inch). The gravity pressure drops are provided in the second to last column of Table 2.

The presence of boiling anywhere in the channel is also indicated in Table 2 for each of the two sets of results. The onset of nucleate boiling is predicted in the PLTEMP/ANL code by the Bergles and Rohsenow correlation [3]. The RELAP5 code outputs an integer to denote the flow region. A "yes" in Table 2 signifies the presence of boiling at at least one of the 24 axial nodes. Thus, there was no boiling predicted only for the highest flow when RELAP5 was used and only for the highest three flows when PLTEMP/ANL was used.

The lowest Reynolds number observed for the lowest flow rate studied is greater than 40,000. Thus, the flow is turbulent at all axial levels in all of the cases.

## 15.4. Analysis

The pressure drop in Figure 1 is the difference between the inlet and outlet pressures, as tabulated in Table 2. The range of interest for the current comparison is from the highest flow down to the onset of flow instability. This limiting stability flow rate was predicted by the Whittle and Forgan correlation [4] via PLTEMP/ANL, with the internal η parameter set to 32.5, as recommended by Reference 5. The 0.6264 kg/s instability flow value calculated by PLTEMP/ANL was carefully verified by hand. The hand calculation produced a value of 0.6282 kg/s, which demonstrates very good agreement with PLTEMP/ANL.

The PLTEMP/ANL flow decreases monotonically with pressure drop, as is expected when the boiling is not included in the model. The RELAP5 results between 0.5200 and 0.6000 kg/s, which have no PLTEMP/ANL counterpart, were included to study the behavior of RELAP5 in this region. As indicated in the last column of Table 2, RELAP5 predicts an increase in the exit void fraction as the flow is decreased from 0.6264 kg/s. The lowest flow rate for which RELAP5 provided a stable solution is 0.5250 kg/s. This case has an exit void fraction of 41.5 %. The increasing volume of vapor with decreasing flow rate causes the pressure drop to have a local minimum value at or near 0.5600 kg/s. Since past experience has shown the Reference 4 flow stability criterion to be reasonably reliable, there is good reason to question the stable flow results predicted by RELAP5 for flows below 0.6264 kg/s, the lowest stable flow predicted by PLTEMP/ANL. Moreover, RELAP5 is known to have difficulty accurately predicting flows at pressures far below the 70 to 140 bar range where water-cooled power reactors typically operate.

At the flow rate where Reference 4 predicts flow instability, the RELAP5 pressure drop is only 4.2% greater than the PLTEMP/ANL one. At the highest flow rate, where neither code predicts boiling, the RELAP5 pressure drop is 1.6% greater than the PLTEMP/ANL one. Thus, if the differences between the two codes that are not related to boiling are taken into account, then the RELAP5 results indicates that at the point of flow instability the PLTEMP/ANL pressure drop should be increased by 4.2% − 1.6%, or 2.6%. Since pressure drop is approximately proportional to the square of flow rate, increasing the pressure drop by 2.3% is approximately equivalent to increasing the flow rate by 2.6%/2, or 1.3%. Thus, flow instability would occur at a flow rate that is about 1.3% higher than PLTEMP/ANL is predicting. The precise value of this difference is not important. What is important and very encouraging is that the PLTEMP/ANL and RELAP5 pressure drops agree very well for all flows at or above the one where flow instability is predicted by Reference 4 to occur. Had there been a large increase in pressure drop due to subcooled nucleated predicted by RELAP5 at flows above, but near, the instability flow predicted by Reference 4, there would be reason for considerable concern. The concern would have been that flow instability occurs at power levels much lower than those indicated by PLTEMP/ANL.

## 15.5. Conclusions

The very good agreement in pressure drop between RELAP5 and PLTEMP/ANL, shown in Figure 1, for flow rates above the one where Reference 4 predicts flow instability to occur support the conclusion that the increased hydraulic resistance expected due to boiling probably will not have a major adverse impact on the power at which PLTEMP/ANL predicts flow instability to occur. Thus, plans to improve the PLTEMP/ANL code in this area are not on the critical path with regard to future reactor conversions from LEU to HEU fuel.

**REFERENCES:**


[1] Arne P. Olson and M. Kalimullah, Argonne National Laboratory, unpublished information, February 20, 2008.

[2] The RELAP5-3D© Code Development Team, RELAP5-3D© Code Manual, Version 2.3, INEEL-EXT-98-00834, Idaho National Laboratory, April 2005.

[3] A. E. Bergles and W. M. Rohsenow, "The Determination of Forced-Convection Surface-Boiling Heat Transfers," Trans. ASME, J. Heat Transfer **86**, 365 (1964).

[4] R. H. Whittle and R. Forgan, "A Correlation for the Minima in the Pressure Drop Versus Flow-Rate Curves for Sub-Cooled Water Flowing in Narrow Heated Channels," *Nuclear Engineering and Design*, 1967.

[5] A. P. Olson, "Analysis of Flow Excursion Experiments Relevant to Research Reactors," 2006 International Meeting on Reduced Enrichment for Research and Test Reactors, October 29-November 3, 2006, Cape Town, South Africa.

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