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Transmutation Fuel Performance Code Thermal Model Verification

Gregory K. Miller
Pavel G. Medvedev

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Idaho National Laboratory
Idaho Falls, Idaho 83415

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Approved by:

Gregory K. Miller	Date
Author	
Pavel G. Medvedev	Date
Principal Investigator	
Steven L. Hayes	Date
GNEP Fuels Irradiation Experiments Technical Lead	
Jon Carmack	Date
GNEP Fuels Deputy Campaign Director	

ABSTRACT

FRAPCON fuel performance code is being modified to be able to model performance of the nuclear fuels of interest to the Global Nuclear Energy Partnership (GNEP). The present report documents the effort for verification of the FRAPCON thermal model. It was found that, with minor modifications, FRAPCON thermal model temperature calculation agrees with that of the commercial software ABAQUS (Version 6.4-4). This report outlines the methodology of the verification, code input, and calculation results.

CONTENTS

FIGURES

ACRONYMS

TRU	transuranic
MOX	mixed oxide

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1. INTRODUCTION

The thermal model in the Transuranic (TRU) Fuel Performance Code is used to calculate the temperature distribution through the fuel and cladding at axial nodal locations along the height of the fuel. Temperatures are calculated for (1) the coolant, (2) the inside and outside surfaces of the cladding, and (3) radial locations throughout the fuel, including its outside surface. Assuming symmetry about the fuel axis and no heat conduction in the axial direction, a one-dimensional temperature distribution is determined at each of the axial locations.

The bulk coolant temperatures along the height of the fuel rod are calculated assuming a single, closed coolant channel with a known inlet temperature. The mass flux and coolant heat capacity correspond to liquid sodium coolant. Convective heat transfer for a liquid sodium coolant is assumed in determining the cladding surface temperature. The Borishanskii, Gotovskii, and Firsova correlation (Reference 1) is used for the convective heat transfer coefficient because it agrees well with experimental data for liquid sodium.

The temperature drop across the cladding is calculated assuming steady-state conduction heat transfer through a cylinder with a uniform thermal conductivity representing that of HT9 stainless steel (Reference 2).

In mixed-oxide (MOX) fuel, the gap between the fuel and cladding is occupied by gas. The temperature drop across the gap includes the effects of conductive heat transfer through the gas and contact conductance between the fuel and cladding when the fuel and cladding make contact. In addition, the effect of radiation heat transfer from the fuel to the cladding is included. The code lumps these contributions into a total effective conductance for the gap, then uses this and the known heat flux at the gap location to determine the temperature drop across the gap.

The temperature distribution across the radius of the fuel is determined assuming steady-state heat conduction through the fuel. The temperatures are calculated at several nodes across the radius using the finite-difference model that has been built into the FRAPCON-3 Code. The source term in the equation is based on an axial power function representative of the fuel modeled. The thermal conductivity for the fuel is currently that used for oxide fuel in the FRAPCON-3 Code.

The solution in the thermal model is obtained iteratively at each power time step, so that material properties are consistent with the temperatures calculated. Also, results are communicated between the temperature, deformation, and gas pressure models, so that the temperatures, gap size, and gas pressure converge at each step.

As described herein, the thermal model has been verified for use on a fuel rod in a fast reactor by comparing its results with those obtained from finite element heat transfer analysis.

2. VERIFICATION APPROACH

The approach to verifying the thermal model was to perform analyses on three sample problems using both the TRU Code and the ABAQUS (Version 6.4-4) finite element analysis computer program (Reference 3). Calculated temperatures obtained from the two codes for the three cases analyzed are compared as a means of evaluating accuracy of the code's results. The three cases analyzed have geometry, power history, cladding, and coolant that are characteristic of a TRU fuel rod.

3. TRU FUEL PERFORMANCE CODE ANALYSES

The input file to the TRU Code for the cases evaluated is contained in Appendix A. The model consists of 11 radial nodes from the center of the fuel to the outside radius of the fuel pellet, and 4 nodes in the axial direction. The first case involves a power time step that occurs early during irradiation, when the power level is relatively low. The temperature distribution corresponding to axial region 2 and time step 4 was selected for this comparison.

The second case involves a time step occurring later during irradiation when the fuel centerline reaches a temperature of 2,000°C. The temperature distribution corresponding to axial region 4 and time step 10 was used for this comparison.

The third case involves closure of the gap between the fuel and cladding. Gap closure was attained in this analysis by reducing the initial gap thickness from 0.005 in. to 0.0005 in. in the input file. In all other respects, the input file is the same as that used for the cases above. Again, the temperature distribution corresponding to axial region 4 and time step 10 was used for this comparison.

The analyses using the TRU Code were performed on a Sun Fire V20Z with AMD Opteron processors and Mandrake Linux 10.0 operating system.

4. ABAQUS FINITE ELEMENT HEAT TRANSFER ANALYSES

The finite element model used in the ABAQUS heat transfer analyses is shown in Figure 1. As with the model used in the TRU Code, it consists of ten elements through the thickness of the fuel, a gap with conductance and radiation between two surfaces, and one element for the cladding. The elements are axisymmetric finite elements arranged in the same graduated mesh as was used in the TRU Code analysis. Parameters used in the heat transfer analyses consist of nodal dimensions, thermal conductivities and power densities for each finite element in the fuel, conductance for the gas in the gap, emissivities for the fuel and cladding surfaces at the gap, cladding conductivity, film coefficient for convection at the outer surface of the cladding, and the coolant temperature. Values used as input to the ABAQUS analyses were obtained from the TRU Code analysis. For example, radiation in the gap was modeled using surface emissivities obtained from the TRU Code analysis, and heat conduction across the gap was modeled using the gas conductance obtained from the TRU Code analysis. Units of W, cm, and K were used in the ABAQUS analyses, so quantities obtained from the fuel performance code were converted to these units where necessary. The values used for these parameters are listed in tables in Appendix B for the cases analyzed. The ABAQUS input files for the three cases are also contained in Appendix B.

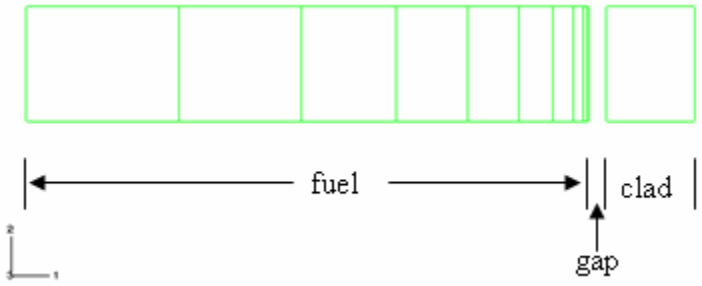

Figure 1. ABAQUS finite element model for heat transfer analysis.

5. COMPARISON OF RESULTS

5.1 Case 1

The calculated temperature distributions obtained from the two codes for Case 1 are presented in Figure 2. The distributions shown extend from the fuel centerline to the outside surface of the cladding. The large temperature drop occurring at a radius of about 0.25 cm is that due to the gas gap between the fuel and cladding. The comparison shows reasonable agreement in results.

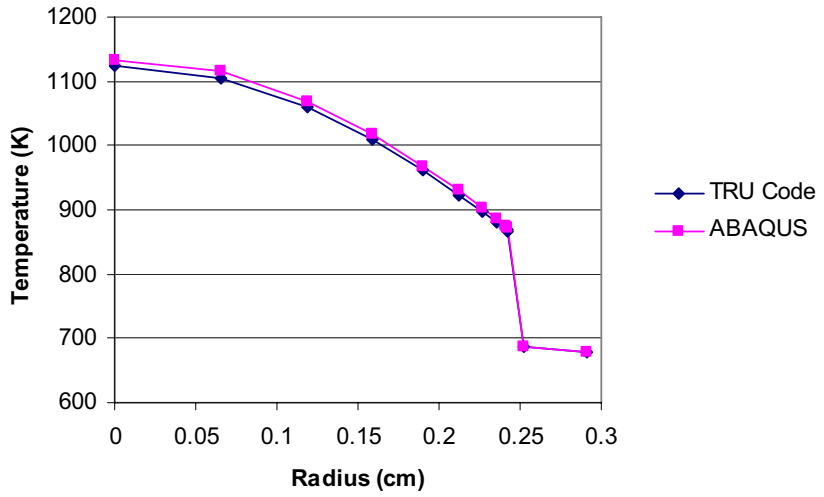

Figure 2. Comparison between calculated temperature distributions across the fuel rod for Case 1.

In the FRAPCON-3 Code, the radial dimensions of the fuel and cladding are recalculated at each time step to account for thermal expansion and swelling of the fuel and thermal expansion and structural deformations of the cladding. The code does not, however, actually use these modified dimensions in calculating the temperature distribution for the fuel rod, using instead the initial dimensions of the fuel rod. The ABAQUS results shown above, though, were based on the modified radial dimensions. A second ABAQUS analysis was performed using the initial radial dimensions throughout the fuel rod. This change resulted in very close agreement between the two codes, as shown in Figure 3.

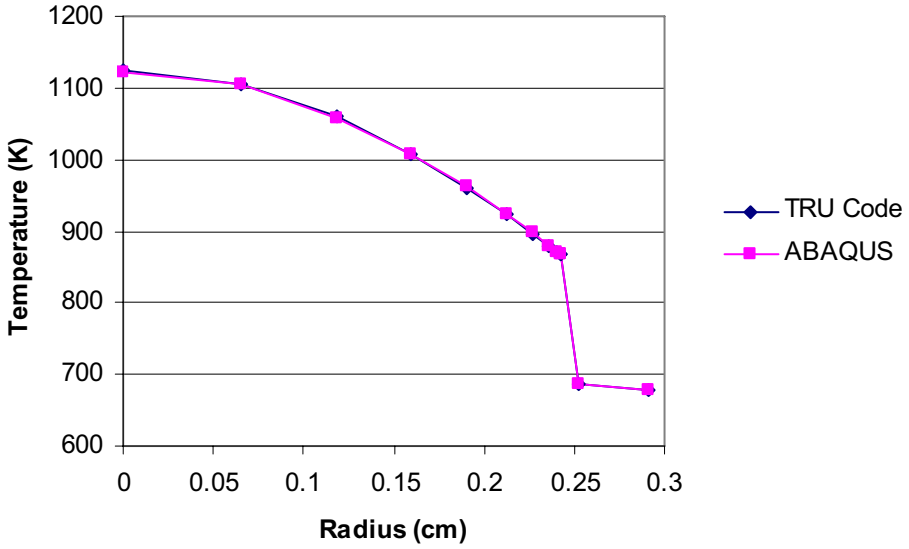

Figure 3. Comparison between calculated temperature distributions across the fuel rod for Case 1 (using initial radial dimensions in both codes).

5.2 Case 2

This case involved higher power levels, and therefore higher fuel temperatures than those of Case 1. Comparisons between ABAQUS and TRU Code results are shown in Figure 4. The results show a measurable difference between the two codes.

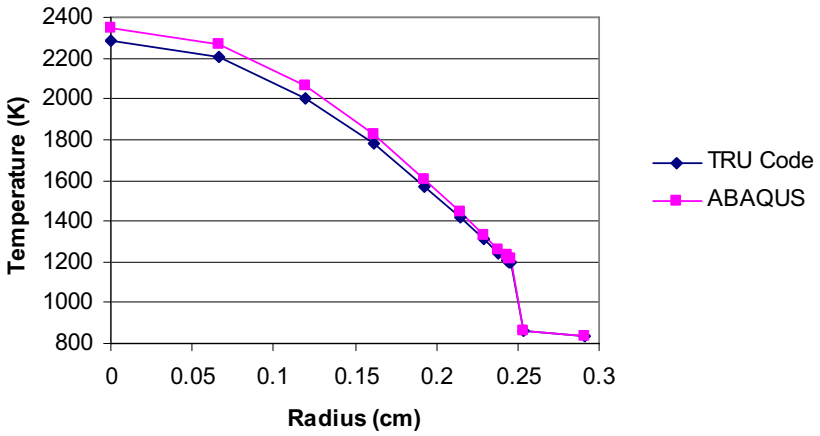

Figure 4. Comparison between calculated temperature distributions across the fuel rod for Case 2.

The ABAQUS results shown in Figure 4 were obtained using modified radial dimensions in the analysis. A second ABAQUS analysis was again performed using initial radial dimensions throughout the fuel rod. Results are plotted in Figure 5, which again show that the two codes are in very close agreement when the same radii are used.

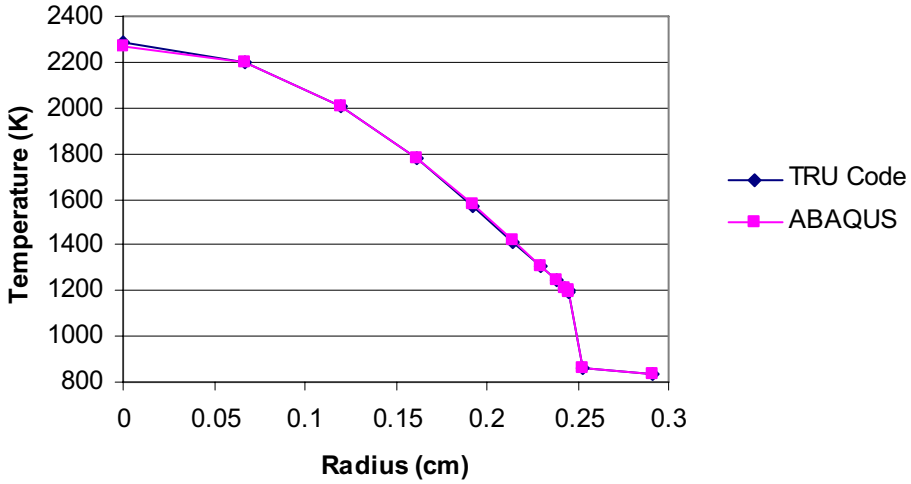

Figure 5. Comparison between calculated temperature distributions across the fuel rod for Case 2 (using initial radial dimensions in both codes).

5.3 Case 3

In this calculation, the initial gap between the fuel and cladding was narrowed from 0.005 in. to 0.0005 in. so that the gap would close during irradiation. Comparisons between TRU and ABAQUS results are shown in Figure 6 for the same power time step and axial location as in Case 2. It is evident that closure of the gap significantly decreased the temperature drop across the gap, and resulted in a lower fuel centerline temperature. These results show reasonable agreement between the two codes. Because of the lower fuel temperatures, the difference in results between codes is not as pronounced as in Case 2 (Figure 4).

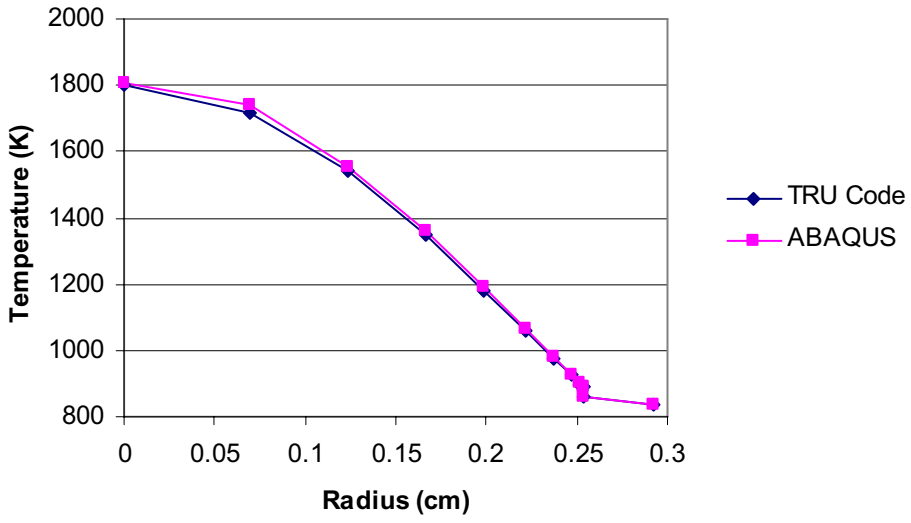

Figure 6. Comparison between calculated temperature distributions across the fuel rod for Case 3.

The ABAQUS results shown in Figure 6 were obtained using modified radial dimensions in the analysis. A second ABAQUS analysis was again performed using initial radial dimensions throughout the fuel rod. Results are plotted in Figure 7, which again show that the two codes are in very close agreement when the same radii are used.

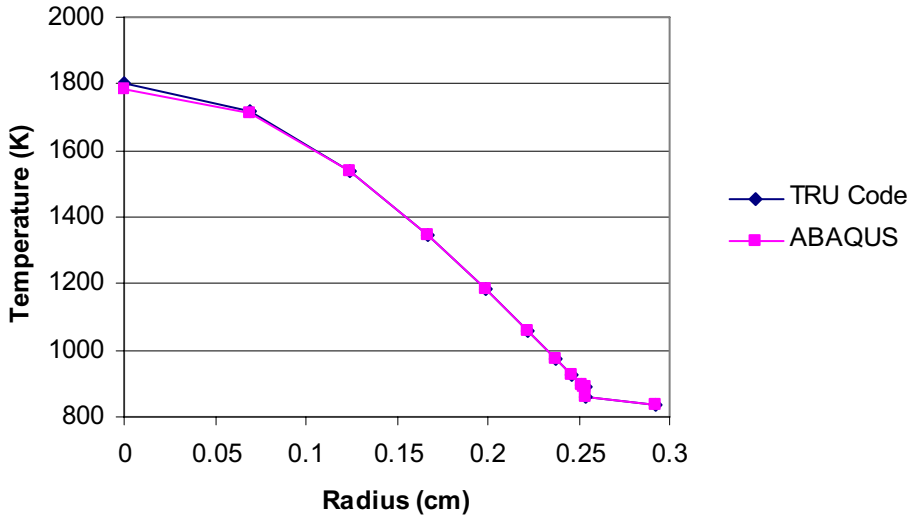

Figure 7. Comparison between calculated temperature distributions across the fuel rod for Case 3 (using initial radial dimensions in both codes).

6. MODIFICATIONS TO THE TRU CODE TEMPERATURE CALCULATION TO ACCOUNT FOR HOT FUEL RING AND CLADDING RADII

As stated above, the FRAPCON-3 thermal model uses the initial (cold) radial dimensions in calculating the temperature distribution across the fuel rod. Based on results shown above, this caused some deviation from ABAQUS results when the ABAQUS analysis was based on hot radial dimensions for the fuel and cladding. It is noted that FRAPCON-3 does use hot radii to monitor the size of the gap between the fuel and cladding at each power time step. This gap size is then used to determine the gap conductance at each step, which is essential to calculating an accurate temperature drop across the gap.

Modifications were made to the TRU Code so that it would account for changing radii in its calculation of the temperature distribution through the fuel. This required changes to the *frpcon*, *tmpsub*, and *fueltp* subroutines so that the finite difference solution for the temperature distribution would use the hot fuel ring radii. It was also necessary to assure that the power densities for the fuel rings were based on the changing radii. Changes also were made to the *cladrp* subroutine so that the temperature drop across the cladding was based on hot cladding radii. Once these changes were made, then Case 2 above was rerun in both the TRU Code and ABAQUS. The ABAQUS analysis had to be rerun because the modifications to the TRU Code resulted in changes to the fuel radii, conductivities, and power densities, and to the gap conductance for this problem. The ABAQUS input file is included in Appendix B. Results for this case, which account for changing radii in both codes, are presented in Figure 8. These results serve to verify that changes were correctly implemented to account for changing radii in the TRU Code thermal model.

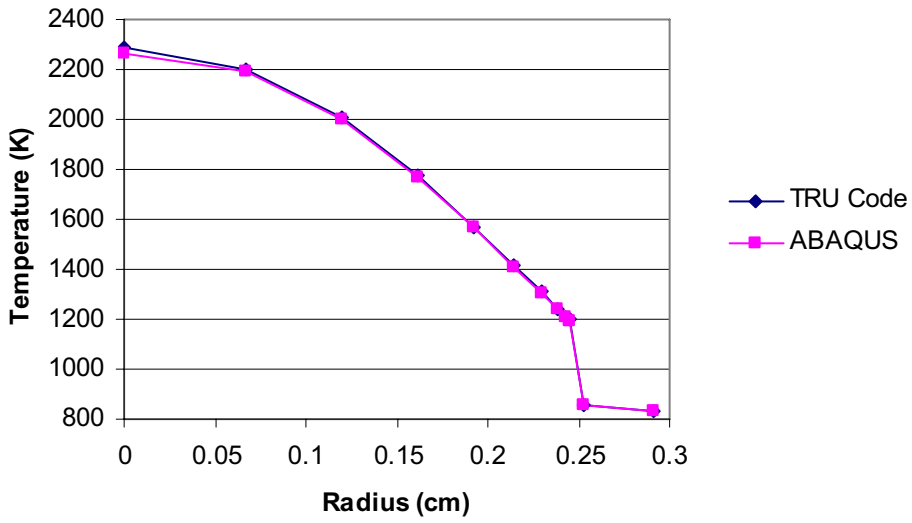

Figure 8. Comparison between calculated temperature distributions across the fuel rod for Case 2 (using hot radial dimensions in both codes).

7. EVALUATION OF THE NODAL MESH

FRAPCON-3 employs variable nodal meshing, which places a greater density of nodes near the outer surface of the fuel. This gives better treatment of the larger temperature gradients and volume of material present at radii near the outer surface of the fuel. An assessment as to how well this meshing scheme performs when calculating the temperature distribution was made by performing an additional ABAQUS analysis, where 20 finite elements were spaced uniformly over the radius of the fuel (Figure 9). In this analysis, the cladding was divided into two elements instead of the single element used in FRAPCON-3. The fuel conductivities and power densities for each of the elements were adjusted according to the dimensions of the element, and are listed in Table 6 of Appendix B. Results obtained from using this mesh on Case 2 are compared in Figure 10 to ABAQUS results that were based on a FRAPCON-3 mesh having 11 nodes over the radius of the fuel. This comparison shows that the refined mesh had little effect on the calculated temperatures.

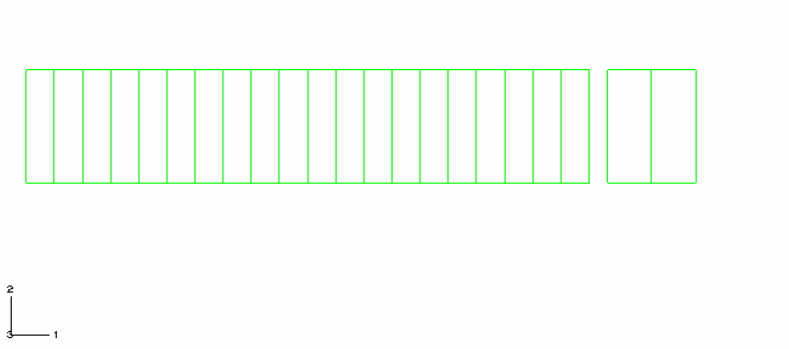

Figure 9. ABAQUS finite element model with refined mesh and uniform nodal spacing.

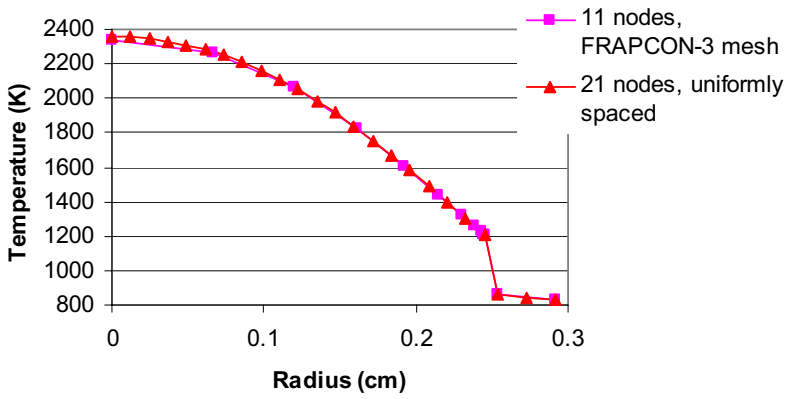

Figure 10. Comparison in ABAQUS results (Case 2) for an 11-node FRAPCON-3 mesh vs. a 21-node uniformly spaced mesh.

A second comparison relative to mesh evaluation was made by analyzing Case 2 in the TRU Code with a 21-node mesh. Utilizing the built-in FRAPCON-3 meshing scheme, the nodes were arranged as shown in Figure 11. Results obtained with the 21-node mesh are compared in Figure 12 to results obtained from the analysis using the TRU Code with an 11-node mesh. The mesh refinement had a very minor effect on results.

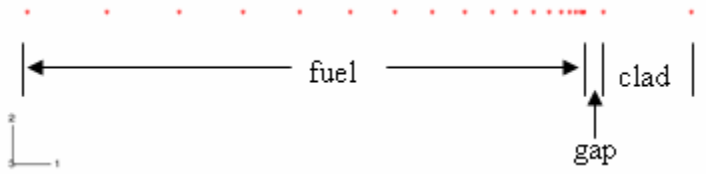

Figure 11. Refined nodal mesh used in TRU Code analysis.

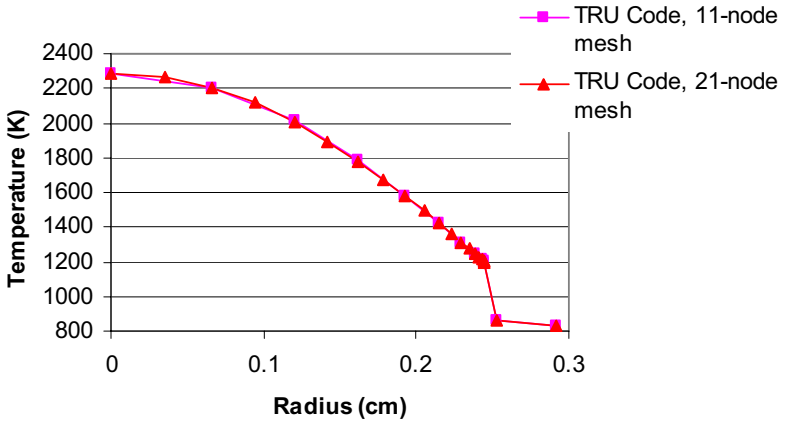

Figure 12. Comparison in TRU Code results (Case 2) for an 11-node vs. a 21-node mesh.

8. CONCLUSION

The thermal model in the TRU Code calculates a temperature distribution across the radius of a fuel rod. Validity of this model was verified herein by comparing results obtained from the analysis of an oxide fuel under fast reactor conditions with results obtained from finite element heat transfer analysis using the ABAQUS Code. Three basic cases considered were low power, high power, and a case where the fuel contacts the cladding. Favorable agreement in results for the two codes was attained in two of the cases, serving to verify the thermal model. However, there was a measurable difference in results for the case involving high power (and, therefore, high fuel temperatures).

In the FRAPCON-3 Code (which is the basis for the TRU Code), the radial dimensions of the fuel and cladding are recalculated at each time step to account for thermal expansion and swelling of the fuel and thermal expansion and structural deformations of the cladding. This code does not, however, actually use these modified dimensions in calculating the temperature distribution for the fuel rod, using instead the initial dimensions of the fuel rod. The ABAQUS analyses, though, were based on the modified radial dimensions. When the ABAQUS analyses were rerun using the initial radial dimensions, results from the TRU Code and ABAQUS agreed closely in all cases. This indicated that the difference in treatment of the radial dimensions accounted for the difference in code results. Therefore, the TRU Code was modified such that updated radial dimensions are used in the thermal model for the fuel rod. When this modified version of the code was applied to the case involving high fuel temperatures, close agreement was obtained with results from ABAQUS for the same problem.

The suitability of the meshing scheme used in the TRU Code for determining the temperature distribution was also evaluated. This was done by comparing results obtained from the graduated mesh used in the TRU Code with results obtained from a more refined mesh having uniform nodal spacing. The agreement in results indicated that the meshing scheme in the TRU Code works well for the temperature calculation. Additionally, a very close agreement in results was obtained from analyses performed with the TRU Code involving two different mesh densities, which further indicates that the thermal model is working effectively.

The thermal model in the TRU Code also treats heat transfer across the sodium bond in metal fuel. This aspect of the code will be tested when thermal conductivities of metal fuel are incorporated in the code.

9. REFERENCES

1. Waltar, A. E. and A. B. Reynolds, *Fast Breeder Reactors*, Pergamon Press, 1981.
2. AFCI Materials Handbook, Rev. 4.
3. *ABAQUS User's Manual*, Version 6.4-4, Hibbitt, Karlsson, and Sorenson, Inc., 2003, Run on a Sun Fire 4800 with Solaris 9 operating system.

Appendix A

Input to TRU Code Heat Transfer Analysis

Appendix A
Input to TRU Code Heat Transfer Analysis

Following is a listing of the input file used for the TRU Code analyses. The initial gap thickness was reduced from 0.005 in. to 0.0005 in. for the case involving a closed gap.

```
*****************************************************************
******
*        frapcon3, steady-state fuel rod analysis code
*                  *
*---------------------------------------------------------------
**
*
*
*         CASE DESCRIPTION: GNEP test case 1
*
*
*
*UNIT     FILE DESCRIPTION
*
*----     ------------------------------------------------Output:
*
*         Output :
*
*    6         STANDARD PRINTER OUTPUT
*
*
*
*         Scratch:
*
*    5         SCRATCH INPUT FILE FROM ECH01
*
*
*
*  Input:   FRAPCON3 INPUT FILE (UNIT 55)
*
*
*
*****************************************************************
******
* GOESINS:
FILE05='nullfile', STATUS='scratch', FORM='FORMATTED',
         CARRIAGE CONTROL='LIST'
*
* GOESOUTS:
FILE06='out.n',    STATUS='UNKNOWN', CARRIAGE CONTROL='LIST'
FILE66='plot.n', STATUS='UNKNOWN', FORM='FORMATTED'
/*****************************************************************
******

 $frpcn

 ! number of power steps
```

```
im=19,

!Number of equal-length axial regions along the rod, for
!which calculations are performed and output
na=4,

! number of radial boundaries in the pellet
nr=11,

!number of equal-volume radial rings in the pellet
!for gas release calculations
ngasr = 45,

$end
$frpcon

! fuel column length, feet
totl = 3,

! cold plenum length, inches
cpl = 48,

! cladding outer diameter, inches
dco = .228,

! cladding thickness, inches
thkcld = 0.015,

! pitch, inches
pitch = .290,

! as-fabricated fuel density, % TD
den = 85.5,

! fuel cladding radial gap thickness, inches
thkgap=0.005,

! if annular pellet, fuel pellet inner radius, inches
rc = 0,

! fuel pellet U-235 enrichment, atom % U-235 in total U
enrch = 20,

! initial fuel pin fill gas pressure (taken at room temperature), psia
fgpav = 14,

! height (length) of each pellet, inches
hplt = 0.5,

! cladding type indicator
icm = 3,

! index for crud model
icor = 0,

! initial fill gas type indicator
idxgas = 1,
```

```
! type of reactor
iplant = -6,

! cladding surface arithmetic mean
!roughness, peak-to-average, inches
roughc = 2.5e-5,

! fuel surface arithmetic mean
! roughness, peak-to-average, inches
roughf = 8.5e-5,

nunits = 1,

! increase in pellet density expected
! during in-reactor operation (determined
! from a standard re-sintering test)
rsntr = 75.,

nplot=1,

flux = 5*5.0e15,

! coolant pressure, psia
p2(1) = 203,

! coolant temperature, F
tw(1) = 710.6,

! mass flux of coolant around fuel rod, lb/hr-ft2
go(1) = 0.8e+7,

imox = 0,

! output print control:
! 0 = all axial nodes
! 1 = peak-power axial node
jdlpr = 0,

! cumulative time at the end of each time step
ProblemTime = 0.001,0.1,0.2,0.3,0.4,0.5,0.6,0.7,0.8,0.9,1
1.1,1.2,1.3,1.4,1.5,1.6,1.7,1.8,1.9

! indicator for axial power shape
!0- user input, 1- chopped cosine
iq = 1,

! peak-to-average power ratio for cosine type
!axial power distribution
fa = 1.000001,

! LHGR at each time step. This equals the rod-average
! value if IQ = 0 and the peak value if IQ= 1, kW/ft
qmpy = 0.001,1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19

!Limit on swelling, volume %
slim = .05,
```

```
$end
$frpmox
$end
$frptru

!wire wrap diameter, inches
s = 0.056

$end
```

Appendix B

Input to ABAQUS Heat Transfer Analysis

Appendix B
Input to ABAQUS Heat Transfer Analysis

Following are tables that list values for various parameters used as input to the ABAQUS heat transfer analyses.

Table 1. Case 1 input.

Node	Radius[1] (cm)	Thermal Conductivity (W/cm-K)	Power density (W/cm^3)
centerline	0		
1	0.06578	0.026897	527.045
2	0.11843	0.027582	531.605
3	0.15941	0.028656	538.638
4	0.19019	0.029842	546.125
5	0.21223	0.030945	552.831
6	0.22700	0.031943	558.120
7	0.23596	0.032484	561.806
8	0.24056	0.032873	564.013
9	0.24226	0.033060	565.066
10	0.24250	0.033118	565.396
clad inner surface	0.25259		
clad outer surface	0.29087		
Other parameters			
Gap conductance	0.33159 W/cm^2-K		
Film coefficient	17.702 W/cm^2-K		
Emissivities	0.7988 (fuel) 0.7657 (clad)		
Clad conductivity	0.26356 W/cm-K		
Coolant temperature	674.5 K		

[1] The initial radii, which were used in the second ABAQUS analysis, were 0, 0.06470, 0.11651, 0.15686, 0.18719, 0.20891, 0.22348, 0.23231, 0.23685, 0.23852, 0.23880, 0.25150, and 0.28960 cm.

Table 2. Case 2 input.

Node	Radius[1] (cm)	Thermal Conductivity (W/cm-K)	Power density (W/cm^3)
centerline	0		
1	0.06672	0.018530	1504.932
2	0.12004	0.018189	1517.944
3	0.16144	0.018371	1538.013
4	0.19247	0.019469	1559.382
5	0.21465	0.021111	1578.526
6	0.22949	0.022740	1593.637
7	0.23848	0.024013	1604.183
8	0.24310	0.024822	1610.523
9	0.24480	0.025218	1613.579
10	0.24540	0.025343	1614.571
clad inner surface	0.25319		
clad outer surface	0.29155		
Other parameters			
Gap conductance	0.49964 W/cm^2-K		
Film coefficient	16.026 W/cm^2-K		
Emissivities	0.8038 (fuel) 0.7884 (clad)		
Clad conductivity	0.26974 W/cm-K		
Coolant temperature	824.8 K		

[1] The initial radii, which were used in the second ABAQUS analysis, were 0, 0.06470, 0.11651, 0.15686, 0.18719, 0.20891, 0.22348, 0.23231, 0.23685, 0.23852, 0.23880, 0.25150, and 0.28960 cm.

Table 3. Case 3 input.

Node	Radius[1] (cm)	Thermal Conductivity (W/cm-K)	Power density (W/cm^3)
centerline	0		
1	0.06896	0.018962	1366.036
2	0.12408	0.019867	1379.007
3	0.16691	0.021740	1399.023
4	0.19902	0.024235	1420.347
5	0.22198	0.026821	1439.462
6	0.23736	0.029075	1454.556
7	0.24668	0.030759	1465.090
8	0.25147	0.031814	1471.421
9	0.25323	0.032328	1474.468
10	0.25348	0.032490	1475.452
clad inner surface	0.25348		
clad outer surface	0.29180		
Other parameters			
Gap conductance	5.7592 W/cm^2-K		
Film coefficient	16.026 W/cm^2-K		
Clad conductivity	0.27064 W/cm-K		
Coolant temperature	824.8 K		

[1] The initial radii, which were used in the second ABAQUS analysis, were 0, 0.06780, 0.12221, 0.16437, 0.19615, 0.21892, 0.23418, 0.24343, 0.24819, 0.24994, 0.25019, 0.25146, and 0.28956 cm.

[2] Radiation across the gap was not included in this analysis. With contact between the fuel and cladding, radiation makes a negligible contribution to the heat transfer.

Table 4. Refined Mesh with Uniform Nodal Spacing.

Node	Radius (cm)	Thermal Conductivity (W/cm-K)	Power density (W/cm^3)
centerline	0		
1	0.01225	0.018547	1504.932
2	0.02451	0.018547	1504.932
3	0.03676	0.018547	1504.932
4	0.04901	0.018547	1504.932
5	0.06126	0.018547	1504.932
6	0.07352	0.018351	1512.150
7	0.08577	0.018194	1517.940
8	0.09802	0.018194	1517.940
9	0.11027	0.018194	1517.940
10	0.12253	0.018227	1521.990
11	0.13478	0.018358	1538.010
12	0.14703	0.018358	1538.010
13	0.15928	0.018358	1538.010
14	0.17154	0.019248	1555.600
15	0.18379	0.019439	1559.380
16	0.19604	0.019912	1564.940
17	0.20829	0.021068	1578.530
18	0.22054	0.021846	1585.780
19	0.23280	0.023031	1596.480
20	0.24505	0.024455	1608.070
clad inner surface	0.25319		
clad mid-surface	0.27237		
clad outer surface	0.29155		
Other parameters			
Gap conductance	0.50098 W/cm^2-K		
Film coefficient	16.026 W/cm^2-K		
Emissivities	0.8039 (fuel) 0.7884 (clad)		
Clad conductivity	0.27064 W/cm-K		
Coolant temperature	824.8 K		

Following are listings of the input files for the ABAQUS analyses performed.

Case 1

```
*HEADING
VERIFICATION OF TRU THERMAL MODEL, CASE 1
*NODE,SYSTEM=R
 1,0.,0.
 2,0.06578,0.
 3,0.11843,0.
 4,0.15941,0.
 5,0.19019,0.
 6,0.21223,0.
 7,0.22700,0.
 8,0.23596,0.
 9,0.24056,0.
10,0.24226,0.
11,0.24250,0.
12,0.25259,0.
13,0.29087,0.
14,0.,0.05
15,0.06578,0.05
16,0.11843,0.05
17,0.15941,0.05
18,0.19019,0.05
19,0.21223,0.05
20,0.22700,0.05
21,0.23596,0.05
22,0.24056,0.05
23,0.24226,0.05
24,0.24250,0.05
25,0.25259,0.05
26,0.29087,0.05
*NSET,NSET=ALLNODES,GENERATE
1,26
*ELEMENT,TYPE=DCAX4
1,1,2,15,14
*ELGEN,ELSET=FUEL
1,10,1,1
*ELEMENT,TYPE=DCAX4,ELSET=CLAD
11,12,13,26,25
*ELSET,ELSET=FUEL1
1
*ELSET,ELSET=FUEL2
2
*ELSET,ELSET=FUEL3
3
*ELSET,ELSET=FUEL4
4
*ELSET,ELSET=FUEL5
5
*ELSET,ELSET=FUEL6
6
*ELSET,ELSET=FUEL7
7
*ELSET,ELSET=FUEL8
```

```
8
*ELSET,ELSET=FUEL9
9
*ELSET,ELSET=FUEL10
10
*MATERIAL,NAME=FUEL1
*CONDUCTIVITY
0.0268969
*MATERIAL,NAME=FUEL2
*CONDUCTIVITY
0.0275818
*MATERIAL,NAME=FUEL3
*CONDUCTIVITY
0.0286559
*MATERIAL,NAME=FUEL4
*CONDUCTIVITY
0.0298422
*MATERIAL,NAME=FUEL5
*CONDUCTIVITY
0.0309452
*MATERIAL,NAME=FUEL6
*CONDUCTIVITY
0.0318433
*MATERIAL,NAME=FUEL7
*CONDUCTIVITY
0.0324839
*MATERIAL,NAME=FUEL8
*CONDUCTIVITY
0.0328730
*MATERIAL,NAME=FUEL9
*CONDUCTIVITY
0.0330597
*MATERIAL,NAME=FUEL10
*CONDUCTIVITY
0.0331180
*MATERIAL,NAME=CLAD
*CONDUCTIVITY
0.26356
*SOLID SECTION, MATERIAL=FUEL1, ELSET=FUEL1
*SOLID SECTION, MATERIAL=FUEL2, ELSET=FUEL2
*SOLID SECTION, MATERIAL=FUEL3, ELSET=FUEL3
*SOLID SECTION, MATERIAL=FUEL4, ELSET=FUEL4
*SOLID SECTION, MATERIAL=FUEL5, ELSET=FUEL5
*SOLID SECTION, MATERIAL=FUEL6, ELSET=FUEL6
*SOLID SECTION, MATERIAL=FUEL7, ELSET=FUEL7
*SOLID SECTION, MATERIAL=FUEL8, ELSET=FUEL8
*SOLID SECTION, MATERIAL=FUEL9, ELSET=FUEL9
*SOLID SECTION, MATERIAL=FUEL10, ELSET=FUEL10
*SOLID SECTION, MATERIAL=CLAD, ELSET=CLAD
*SURFACE INTERACTION, NAME=GAPHEAT
*GAP CONDUCTANCE
.33159,0.
.33159,.1
*GAP RADIATION
.7988, .7657
1.,0.
1.,.1
```

```
*CONTACT PAIR, INTERACTION=GAPHEAT
CLADSURF,FUELSURF
*SURFACE,NAME=CLADSURF,TYPE=ELEMENT
CLAD,S4
*SURFACE,NAME=FUELSURF,TYPE=ELEMENT
FUEL10,S2
*PHYSICAL CONSTANTS, ABSOLUTE ZERO=-273., STEFAN BOLTZMANN=5.6698E-12
*INITIAL CONDITIONS, TYPE=TEMPERATURE
ALLNODES, 400.
*STEP
HEAT TRANSFER THROUGH FUEL AND CLADDING
*HEAT TRANSFER, STEADY STATE
1.,1.,1.,1.
*DFLUX
FUEL1,BF,527.0447
FUEL2,BF,531.6047
FUEL3,BF,538.6377
FUEL4,BF,546.1250
FUEL5,BF,552.8308
FUEL6,BF,558.1201
FUEL7,BF,561.8057
FUEL8,BF,564.0129
FUEL9,BF,565.0658
FUEL10,BF,565.3956
*FILM
CLAD,F2,674.5,17.702
*NODE PRINT, NSET=ALLNODES
NT
*NODE FILE, NSET=ALLNODES
NT
*OUTPUT,FIELD
*NODE OUTPUT,NSET=ALLNODES
NT
*END STEP
```

Case 2

```
*HEADING
VERIFICATION OF TRU THERMAL MODEL, 2000 C FUEL TEMP, CASE 2
*NODE,SYSTEM=R
 1,0.,0.
 2,0.06672,0.
 3,0.12004,0.
 4,0.16144,0.
 5,0.19247,0.
 6,0.21465,0.
 7,0.22949,0.
 8,0.23848,0.
 9,0.24310,0.
10,0.24480,0.
11,0.24540,0.
12,0.25319,0.
13,0.29155,0.
14,0.,0.05
15,0.06672,0.05
16,0.12004,0.05
17,0.16144,0.05
18,0.19247,0.05
19,0.21465,0.05
20,0.22949,0.05
21,0.23848,0.05
22,0.24310,0.05
23,0.24480,0.05
24,0.24540,0.05
25,0.25319,0.05
26,0.29155,0.05
*NSET,NSET=ALLNODES,GENERATE
1,26
*ELEMENT,TYPE=DCAX4
1,1,2,15,14
*ELGEN,ELSET=FUEL
1,10,1,1
*ELEMENT,TYPE=DCAX4,ELSET=CLAD
11,12,13,26,25
*ELSET,ELSET=FUEL1
1
*ELSET,ELSET=FUEL2
2
*ELSET,ELSET=FUEL3
3
*ELSET,ELSET=FUEL4
4
*ELSET,ELSET=FUEL5
5
*ELSET,ELSET=FUEL6
6
*ELSET,ELSET=FUEL7
7
*ELSET,ELSET=FUEL8
8
*ELSET,ELSET=FUEL9
```

```
9
*ELSET,ELSET=FUEL10
10
*ELSET,ELSET=ALLELS,GENERATE
1,11
*MATERIAL,NAME=FUEL1
*CONDUCTIVITY
0.0185302
*MATERIAL,NAME=FUEL2
*CONDUCTIVITY
0.0181887
*MATERIAL,NAME=FUEL3
*CONDUCTIVITY
0.0183712
*MATERIAL,NAME=FUEL4
*CONDUCTIVITY
0.0194694
*MATERIAL,NAME=FUEL5
*CONDUCTIVITY
0.0211109
*MATERIAL,NAME=FUEL6
*CONDUCTIVITY
0.0227399
*MATERIAL,NAME=FUEL7
*CONDUCTIVITY
0.0240131
*MATERIAL,NAME=FUEL8
*CONDUCTIVITY
0.0248221
*MATERIAL,NAME=FUEL9
*CONDUCTIVITY
0.0252185
*MATERIAL,NAME=FUEL10
*CONDUCTIVITY
0.0253431
*MATERIAL,NAME=CLAD
*CONDUCTIVITY
0.26974
*SOLID SECTION, MATERIAL=FUEL1, ELSET=FUEL1
*SOLID SECTION, MATERIAL=FUEL2, ELSET=FUEL2
*SOLID SECTION, MATERIAL=FUEL3, ELSET=FUEL3
*SOLID SECTION, MATERIAL=FUEL4, ELSET=FUEL4
*SOLID SECTION, MATERIAL=FUEL5, ELSET=FUEL5
*SOLID SECTION, MATERIAL=FUEL6, ELSET=FUEL6
*SOLID SECTION, MATERIAL=FUEL7, ELSET=FUEL7
*SOLID SECTION, MATERIAL=FUEL8, ELSET=FUEL8
*SOLID SECTION, MATERIAL=FUEL9, ELSET=FUEL9
*SOLID SECTION, MATERIAL=FUEL10, ELSET=FUEL10
*SOLID SECTION, MATERIAL=CLAD, ELSET=CLAD
*SURFACE INTERACTION, NAME=GAPHEAT
*GAP CONDUCTANCE
.49964,0.
.49964,.1
*GAP RADIATION
.8038, .7884
1.,0.
1.,.1
```

```
*CONTACT PAIR, INTERACTION=GAPHEAT
CLADSURF,FUELSURF
*SURFACE,NAME=CLADSURF,TYPE=ELEMENT
CLAD,S4
*SURFACE,NAME=FUELSURF,TYPE=ELEMENT
FUEL10,S2
*PHYSICAL CONSTANTS, ABSOLUTE ZERO=-273., STEFAN BOLTZMANN=5.6698E-12
*INITIAL CONDITIONS, TYPE=TEMPERATURE
ALLNODES, 400.
*STEP
HEAT TRANSFER THROUGH FUEL AND CLADDING
*HEAT TRANSFER, STEADY STATE
1.,1.,1.,1.
*DFLUX
FUEL1,BF,1504.932
FUEL2,BF,1517.944
FUEL3,BF,1538.013
FUEL4,BF,1559.382
FUEL5,BF,1578.526
FUEL6,BF,1593.637
FUEL7,BF,1604.183
FUEL8,BF,1610.523
FUEL9,BF,1613.579
FUEL10,BF,1614.571
*FILM
CLAD,F2,824.8,16.026
*NODE PRINT, NSET=ALLNODES
NT
*NODE FILE, NSET=ALLNODES
NT
*EL PRINT, ELSET=ALLELS
HFL
*CONTACT PRINT,SLAVE=CLADSURF
HFL
*OUTPUT,FIELD
*NODE OUTPUT,NSET=ALLNODES
NT
*END STEP
```

Case 3

```
*HEADING
VERIFICATION OF TRU THERMAL MODEL, CASE 3, CLOSED GAP
*NODE,SYSTEM=R
 1,0.,0.
 2,0.06896,0.
 3,0.12408,0.
 4,0.16691,0.
 5,0.19902,0.
 6,0.22198,0.
 7,0.23736,0.
 8,0.24668,0.
 9,0.25147,0.
10,0.25323,0.
11,0.25348,0.
12,0.25348,0.
13,0.29181,0.
14,0.,0.05
15,0.06896,0.05
16,0.12408,0.05
17,0.16691,0.05
18,0.19902,0.05
19,0.22198,0.05
20,0.23736,0.05
21,0.24668,0.05
22,0.25147,0.05
23,0.25323,0.05
24,0.25348,0.05
25,0.25348,0.05
26,0.29181,0.05
*NSET,NSET=ALLNODES,GENERATE
1,26
*ELEMENT,TYPE=DCAX4
1,1,2,15,14
*ELGEN,ELSET=FUEL
1,10,1,1
*ELEMENT,TYPE=DCAX4,ELSET=CLAD
11,12,13,26,25
*ELSET,ELSET=FUEL1
1
*ELSET,ELSET=FUEL2
2
*ELSET,ELSET=FUEL3
3
*ELSET,ELSET=FUEL4
4
*ELSET,ELSET=FUEL5
5
*ELSET,ELSET=FUEL6
6
*ELSET,ELSET=FUEL7
7
*ELSET,ELSET=FUEL8
8
*ELSET,ELSET=FUEL9
```

```
9
*ELSET,ELSET=FUEL10
10
*ELSET,ELSET=ALLELS,GENERATE
1,11
*MATERIAL,NAME=FUEL1
*CONDUCTIVITY
0.0186200
*MATERIAL,NAME=FUEL2
*CONDUCTIVITY
0.0198670
*MATERIAL,NAME=FUEL3
*CONDUCTIVITY
0.0217400
*MATERIAL,NAME=FUEL4
*CONDUCTIVITY
0.0242350
*MATERIAL,NAME=FUEL5
*CONDUCTIVITY
0.0268210
*MATERIAL,NAME=FUEL6
*CONDUCTIVITY
0.0290750
*MATERIAL,NAME=FUEL7
*CONDUCTIVITY
0.0307590
*MATERIAL,NAME=FUEL8
*CONDUCTIVITY
0.0318140
*MATERIAL,NAME=FUEL9
*CONDUCTIVITY
0.0323280
*MATERIAL,NAME=FUEL10
*CONDUCTIVITY
0.0324900
*MATERIAL,NAME=CLAD
*CONDUCTIVITY
0.27064
*SOLID SECTION, MATERIAL=FUEL1, ELSET=FUEL1
*SOLID SECTION, MATERIAL=FUEL2, ELSET=FUEL2
*SOLID SECTION, MATERIAL=FUEL3, ELSET=FUEL3
*SOLID SECTION, MATERIAL=FUEL4, ELSET=FUEL4
*SOLID SECTION, MATERIAL=FUEL5, ELSET=FUEL5
*SOLID SECTION, MATERIAL=FUEL6, ELSET=FUEL6
*SOLID SECTION, MATERIAL=FUEL7, ELSET=FUEL7
*SOLID SECTION, MATERIAL=FUEL8, ELSET=FUEL8
*SOLID SECTION, MATERIAL=FUEL9, ELSET=FUEL9
*SOLID SECTION, MATERIAL=FUEL10, ELSET=FUEL10
*SOLID SECTION, MATERIAL=CLAD, ELSET=CLAD
*SURFACE INTERACTION, NAME=GAPHEAT
*GAP CONDUCTANCE
5.7592,0.
5.7592,.1
**GAP RADIATION
**.7991, .7884
**1.,0.
**1.,.1
```

```
*CONTACT PAIR, INTERACTION=GAPHEAT
CLADSURF,FUELSURF
*SURFACE,NAME=CLADSURF,TYPE=ELEMENT
CLAD,S4
*SURFACE,NAME=FUELSURF,TYPE=ELEMENT
FUEL10,S2
*PHYSICAL CONSTANTS, ABSOLUTE ZERO=-273., STEFAN BOLTZMANN=5.6698E-12
*INITIAL CONDITIONS, TYPE=TEMPERATURE
ALLNODES, 400.
*STEP
HEAT TRANSFER THROUGH FUEL AND CLADDING
*HEAT TRANSFER, STEADY STATE
1.,1.,1.,1.
*DFLUX
FUEL1,BF,1366.036
FUEL2,BF,1379.007
FUEL3,BF,1399.023
FUEL4,BF,1420.347
FUEL5,BF,1439.462
FUEL6,BF,1454.556
FUEL7,BF,1465.090
FUEL8,BF,1471.421
FUEL9,BF,1474.468
FUEL10,BF,1475.452
*FILM
CLAD,F2,824.8,16.026
*NODE PRINT, NSET=ALLNODES
NT
*NODE FILE, NSET=ALLNODES
NT
*EL PRINT, ELSET=ALLELS
HFL
*CONTACT PRINT,SLAVE=CLADSURF
HFL
*OUTPUT,FIELD
*NODE OUTPUT,NSET=ALLNODES
NT
*END STEP
```

Case 2, Refined Mesh with Uniform Nodal Spacing

```
*HEADING
VERIFICATION OF TRU THERMAL MODEL, CASE 2, 20 ELEMENTS IN FUEL, UNIFORM
SPACING
*NODE,SYSTEM=R
1,0.,0.
2,.01225,0.
3,.024505,0.
4,.036758,0.
5,.04901,0.
6,.061263,0.
7,.073515,0.
8,.085768,0.
9,.09802,0.
10,.110273,0.
11,.122525,0.
12,.134778,0.
13,.14703,0.
14,.159283,0.
15,.17154,0.
16,.18379,0.
17,.19604,0.
18,.20829,0.
19,.22054,0.
20,.23280,0.
21,.24505,0.
22,.25319,0.
23,.27237,0.
24,.29155,0.
25,0.,0.05
26,.01225,0.05
27,.024505,0.05
28,.036758,0.05
29,.04901,0.05
30,.061263,0.05
31,.073515,0.05
32,.085768,0.05
33,.09802,0.05
34,.110273,0.05
35,.122525,0.05
36,.134778,0.05
37,.14703,0.05
38,.159283,0.05
39,.17154,0.05
40,.18379,0.05
41,.19604,0.05
42,.20829,0.05
43,.22054,0.05
44,.23280,0.05
45,.24505,0.05
46,.25319,0.05
47,.27237,0.05
48,.29155,0.05
*NSET,NSET=ALLNODES,GENERATE
1,48
```

```
*ELEMENT,TYPE=DCAX4
1,1,2,26,25
*ELGEN,ELSET=FUEL
1,20,1,1
*ELEMENT,TYPE=DCAX4,ELSET=CLAD
21,22,23,47,46
22,23,24,48,47
*ELSET,ELSET=FUEL1
1
*ELSET,ELSET=FUEL2
2
*ELSET,ELSET=FUEL3
3
*ELSET,ELSET=FUEL4
4
*ELSET,ELSET=FUEL5
5
*ELSET,ELSET=FUEL6
6
*ELSET,ELSET=FUEL7
7
*ELSET,ELSET=FUEL8
8
*ELSET,ELSET=FUEL9
9
*ELSET,ELSET=FUEL10
10
*ELSET,ELSET=FUEL11
11
*ELSET,ELSET=FUEL12
12
*ELSET,ELSET=FUEL13
13
*ELSET,ELSET=FUEL14
14
*ELSET,ELSET=FUEL15
15
*ELSET,ELSET=FUEL16
16
*ELSET,ELSET=FUEL17
17
*ELSET,ELSET=FUEL18
18
*ELSET,ELSET=FUEL19
19
*ELSET,ELSET=FUEL20
20
*ELSET,ELSET=ALLELS,GENERATE
1,22
*MATERIAL,NAME=FUEL1
*CONDUCTIVITY
0.0185470
*MATERIAL,NAME=FUEL2
*CONDUCTIVITY
0.0185470
*MATERIAL,NAME=FUEL3
*CONDUCTIVITY
```

```
0.0185470
*MATERIAL,NAME=FUEL4
*CONDUCTIVITY
0.0185470
*MATERIAL,NAME=FUEL5
*CONDUCTIVITY
0.0185470
*MATERIAL,NAME=FUEL6
*CONDUCTIVITY
0.0183510
*MATERIAL,NAME=FUEL7
*CONDUCTIVITY
0.0181940
*MATERIAL,NAME=FUEL8
*CONDUCTIVITY
0.0181940
*MATERIAL,NAME=FUEL9
*CONDUCTIVITY
0.0181940
*MATERIAL,NAME=FUEL10
*CONDUCTIVITY
0.0182270
*MATERIAL,NAME=FUEL11
*CONDUCTIVITY
0.0183580
*MATERIAL,NAME=FUEL12
*CONDUCTIVITY
0.0183580
*MATERIAL,NAME=FUEL13
*CONDUCTIVITY
0.0183580
*MATERIAL,NAME=FUEL14
*CONDUCTIVITY
0.0192480
*MATERIAL,NAME=FUEL15
*CONDUCTIVITY
0.0194390
*MATERIAL,NAME=FUEL16
*CONDUCTIVITY
0.0199120
*MATERIAL,NAME=FUEL17
*CONDUCTIVITY
0.0210680
*MATERIAL,NAME=FUEL18
*CONDUCTIVITY
0.0218460
*MATERIAL,NAME=FUEL19
*CONDUCTIVITY
0.0230310
*MATERIAL,NAME=FUEL20
*CONDUCTIVITY
0.0244550
*MATERIAL,NAME=CLAD
*CONDUCTIVITY
0.26974
*SOLID SECTION, MATERIAL=FUEL1, ELSET=FUEL1
*SOLID SECTION, MATERIAL=FUEL2, ELSET=FUEL2
```

```
*SOLID SECTION, MATERIAL=FUEL3, ELSET=FUEL3
*SOLID SECTION, MATERIAL=FUEL4, ELSET=FUEL4
*SOLID SECTION, MATERIAL=FUEL5, ELSET=FUEL5
*SOLID SECTION, MATERIAL=FUEL6, ELSET=FUEL6
*SOLID SECTION, MATERIAL=FUEL7, ELSET=FUEL7
*SOLID SECTION, MATERIAL=FUEL8, ELSET=FUEL8
*SOLID SECTION, MATERIAL=FUEL9, ELSET=FUEL9
*SOLID SECTION, MATERIAL=FUEL10, ELSET=FUEL10
*SOLID SECTION, MATERIAL=FUEL11, ELSET=FUEL11
*SOLID SECTION, MATERIAL=FUEL12, ELSET=FUEL12
*SOLID SECTION, MATERIAL=FUEL13, ELSET=FUEL13
*SOLID SECTION, MATERIAL=FUEL14, ELSET=FUEL14
*SOLID SECTION, MATERIAL=FUEL15, ELSET=FUEL15
*SOLID SECTION, MATERIAL=FUEL16, ELSET=FUEL16
*SOLID SECTION, MATERIAL=FUEL17, ELSET=FUEL17
*SOLID SECTION, MATERIAL=FUEL18, ELSET=FUEL18
*SOLID SECTION, MATERIAL=FUEL19, ELSET=FUEL19
*SOLID SECTION, MATERIAL=FUEL20, ELSET=FUEL20
*SOLID SECTION, MATERIAL=CLAD, ELSET=CLAD
*SURFACE INTERACTION, NAME=GAPHEAT
*GAP CONDUCTANCE
.49964,0.
.49964,.1
*GAP RADIATION
.8038, .7884
1.,0.
1.,.1
*CONTACT PAIR, INTERACTION=GAPHEAT
CLADSURF,FUELSURF
*SURFACE,NAME=CLADSURF,TYPE=ELEMENT
21,S4
*SURFACE,NAME=FUELSURF,TYPE=ELEMENT
20,S2
*PHYSICAL CONSTANTS, ABSOLUTE ZERO=-273., STEFAN BOLTZMANN=5.6698E-12
*INITIAL CONDITIONS, TYPE=TEMPERATURE
ALLNODES, 400.
*STEP
HEAT TRANSFER THROUGH FUEL AND CLADDING
*HEAT TRANSFER, STEADY STATE
1.,1.,1.,1.
*DFLUX
FUEL1,BF,1504.932
FUEL2,BF,1504.932
FUEL3,BF,1504.932
FUEL4,BF,1504.932
FUEL5,BF,1504.932
FUEL6,BF,1512.150
FUEL7,BF,1517.940
FUEL8,BF,1517.940
FUEL9,BF,1517.940
FUEL10,BF,1521.990
FUEL11,BF,1538.010
FUEL12,BF,1538.010
FUEL13,BF,1538.010
FUEL14,BF,1555.600
FUEL15,BF,1559.380
FUEL16,BF,1564.940
```

```
FUEL17,BF,1578.530
FUEL18,BF,1585.780
FUEL19,BF,1596.480
FUEL20,BF,1608.070
*FILM
22,F2,824.8,16.026
*NODE PRINT, NSET=ALLNODES
NT
*NODE FILE, NSET=ALLNODES
NT
*EL PRINT, ELSET=ALLELS
HFL
*CONTACT PRINT,SLAVE=CLADSURF
HFL
*OUTPUT,FIELD
*NODE OUTPUT,NSET=ALLNODES
NT
*END STEP
```

Case 2, Using Hot Radii in Both the TRU Code and ABAQUS

```
*HEADING
VERIFICATION OF TRU THERMAL MODEL, 2000 C FUEL TEMP, CASE 2
*NODE,SYSTEM=R
 1,0.,0.
 2,0.06672,0.
 3,0.12004,0.
 4,0.16144,0.
 5,0.19247,0.
 6,0.21464,0.
 7,0.22949,0.
 8,0.23848,0.
 9,0.24309,0.
10,0.24479,0.
11,0.24504,0.
12,0.25319,0.
13,0.29155,0.
14,0.,0.05
15,0.06672,0.05
16,0.12004,0.05
17,0.16144,0.05
18,0.19247,0.05
19,0.21464,0.05
20,0.22949,0.05
21,0.23848,0.05
22,0.24309,0.05
23,0.24479,0.05
24,0.24504,0.05
25,0.25319,0.05
26,0.29155,0.05
*NSET,NSET=ALLNODES,GENERATE
1,26
*ELEMENT,TYPE=DCAX4
1,1,2,15,14
*ELGEN,ELSET=FUEL
1,10,1,1
*ELEMENT,TYPE=DCAX4,ELSET=CLAD
11,12,13,26,25
*ELSET,ELSET=FUEL1
1
*ELSET,ELSET=FUEL2
2
*ELSET,ELSET=FUEL3
3
*ELSET,ELSET=FUEL4
4
*ELSET,ELSET=FUEL5
5
*ELSET,ELSET=FUEL6
6
*ELSET,ELSET=FUEL7
7
*ELSET,ELSET=FUEL8
8
*ELSET,ELSET=FUEL9
```

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9
*ELSET,ELSET=FUEL10
10
*ELSET,ELSET=ALLELS,GENERATE
1,11
*MATERIAL,NAME=FUEL1
*CONDUCTIVITY
0.0185302
*MATERIAL,NAME=FUEL2
*CONDUCTIVITY
0.0181867
*MATERIAL,NAME=FUEL3
*CONDUCTIVITY
0.0183748
*MATERIAL,NAME=FUEL4
*CONDUCTIVITY
0.0194835
*MATERIAL,NAME=FUEL5
*CONDUCTIVITY
0.0211304
*MATERIAL,NAME=FUEL6
*CONDUCTIVITY
0.0227571
*MATERIAL,NAME=FUEL7
*CONDUCTIVITY
0.0240238
*MATERIAL,NAME=FUEL8
*CONDUCTIVITY
0.0248267
*MATERIAL,NAME=FUEL9
*CONDUCTIVITY
0.0252194
*MATERIAL,NAME=FUEL10
*CONDUCTIVITY
0.0253428
*MATERIAL,NAME=CLAD
*CONDUCTIVITY
0.26974
*SOLID SECTION, MATERIAL=FUEL1, ELSET=FUEL1
*SOLID SECTION, MATERIAL=FUEL2, ELSET=FUEL2
*SOLID SECTION, MATERIAL=FUEL3, ELSET=FUEL3
*SOLID SECTION, MATERIAL=FUEL4, ELSET=FUEL4
*SOLID SECTION, MATERIAL=FUEL5, ELSET=FUEL5
*SOLID SECTION, MATERIAL=FUEL6, ELSET=FUEL6
*SOLID SECTION, MATERIAL=FUEL7, ELSET=FUEL7
*SOLID SECTION, MATERIAL=FUEL8, ELSET=FUEL8
*SOLID SECTION, MATERIAL=FUEL9, ELSET=FUEL9
*SOLID SECTION, MATERIAL=FUEL10, ELSET=FUEL10
*SOLID SECTION, MATERIAL=CLAD, ELSET=CLAD
*SURFACE INTERACTION, NAME=GAPHEAT
*GAP CONDUCTANCE
.49940,0.
.49940,.1
*GAP RADIATION
.80385, .78843
1.,0.
1.,.1
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*CONTACT PAIR, INTERACTION=GAPHEAT
CLADSURF,FUELSURF
*SURFACE,NAME=CLADSURF,TYPE=ELEMENT
CLAD,S4
*SURFACE,NAME=FUELSURF,TYPE=ELEMENT
FUEL10,S2
*PHYSICAL CONSTANTS, ABSOLUTE ZERO=-273., STEFAN BOLTZMANN=5.6698E-12
*INITIAL CONDITIONS, TYPE=TEMPERATURE
ALLNODES, 400.
*STEP
HEAT TRANSFER THROUGH FUEL AND CLADDING
*HEAT TRANSFER, STEADY STATE
1.,1.,1.,1.
*DFLUX
FUEL1,BF,1428.83
FUEL2,BF,1441.19
FUEL3,BF,1460.24
FUEL4,BF,1480.53
FUEL5,BF,1498.71
FUEL6,BF,1513.07
FUEL7,BF,1523.09
FUEL8,BF,1529.12
FUEL9,BF,1532.04
FUEL10,BF,1533.00
*FILM
CLAD,F2,824.8,16.026
*NODE PRINT, NSET=ALLNODES
NT
*NODE FILE, NSET=ALLNODES
NT
*EL PRINT, ELSET=ALLELS
HFL
*CONTACT PRINT,SLAVE=CLADSURF
HFL
*OUTPUT,FIELD
*NODE OUTPUT,NSET=ALLNODES
NT
*END STEP
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