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Thermal Analysis of a Flexible Rabbit Design for Irradiating PWR Cladding

C.M. Petrie
K. Terrani

May 16, 2016

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

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Reactor & Nuclear Systems Division, Thermal Hydraulics & Irradiation Engineering Group

THERMAL ANALYSIS OF A FLEXIBLE RABBIT DESIGN FOR IRRADIATING PWR CLADDING

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DESIGN ANALYSIS AND CALCULATION

CALCULATION NO.:	DAC-16-01-FLEXCLAD01, Rev.0
CALCULATION TITLE:	Thermal Analysis of a Flexible Rabbit Design for Irradiating PWR Cladding
ORGANIZATION:	Reactor & Nuclear Systems Division, Thermal Hydraulics & Irradiation Engineering Group
PROJECT/TASK:	Flexible Cladding Rabbit Thermal Design
REVISION:	0
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ABSTRACT:

This calculation summarizes thermal analyses of a flexible rabbit design for irradiating a variety of pressurized water reactor (PWR) cladding materials (stainless steel, iron-chromium aluminum [FeCrAl], Zircaloy, and Inconel) with variable dimensions at a temperature of 350 °C in the flux trap of the High Flux Isotope Reactor (HFIR). The design can accommodate standard cladding for outer diameters (ODs) of approximately 9.50 mm with thickness ranging from 0.30 mm to 0.70 mm. The length is generally between 10 and 50 mm. The specimens contain moly inserts with a variable OD that provides the heat flux necessary to achieve the design temperature with such a small fixed gas gap. The primary outer containment is an Al-6061 housing with a slightly enlarged inner diameter (ID) of 9.60 mm. The specimen temperature is controlled by determining a helium/argon gas mixture specific to the as-built specimen and housing. Variables that affect the required gas mixture are the cladding material (thermal expansion, density, heat generation rate), cladding OD, housing ID, and cladding ID. This calculation documents the analyses performed to determine required gas mixtures for a variety of scenarios.

CALCULATION REVISION LOG

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1. PURPOSE

This calculation summarizes thermal analyses of a flexible rabbit design for irradiating a variety of pressurized water reactor (PWR) cladding materials (stainless steel, iron-chromium-aluminum [FeCrAl], Zircaloy, and Inconel) with variable dimensions at a temperature of 350 °C in the flux trap of the High Flux Isotope Reactor (HFIR). The design can accommodate standard cladding outer diameters (ODs) of approximately 9.50 mm with thicknesses ranging from 0.30 mm to 0.70 mm. The specimens contain moly inserts with a variable OD that provides the heat flux necessary to achieve the design temperature with such a small fixed gas gap. The primary outer containment is an Al-6061 housing with a slightly enlarged inner diameter (ID) of 9.60 mm. The specimen temperature is controlled by determining a helium/argon gas mixture specific to the as-built specimen and housing. This calculation documents the analyses performed to determine required gas mixtures for a variety of scenarios.

2. CALCULATION INPUT AND SOURCES OF INPUT

2.1 DESIGN DESCRIPTION

Table 2-1 lists design drawings for the flexible cladding rabbits.

Table 2-1. Flexible cladding rabbit experiment design drawings

Drawing No.	Title
X3E020977A689, Rev. 0	Target Capsule Housing Assembly (1)
X3E020977A690, Rev. 0	Target Capsule Housing Details (2)
X3E020977A634, Rev. A	Target Capsule Housing/End Cap Detail (3)
S16-10-FLEXCLAD01, Rev. 0	Flexible Cladding Rabbits Assembly (4)
S16-11-FLEXCLAD02, Rev. 0	Flexible Cladding Rabbits Assembly and Part Details (5)

The overall design is shown in the section view of Fig. 2-1. In this design, insert pieces or sleeves are inserted inside the cladding specimens. The insert pieces are centered using centering thimbles on both ends. Wires are inserted through the inserts and the thimbles to keep the thimbles in place. Thermometry pieces are placed inside the inserts and held in place with quartz wool. Additional grafoil is placed between the centering thimbles and the bottom and top of the housing to reduce axial heat losses.

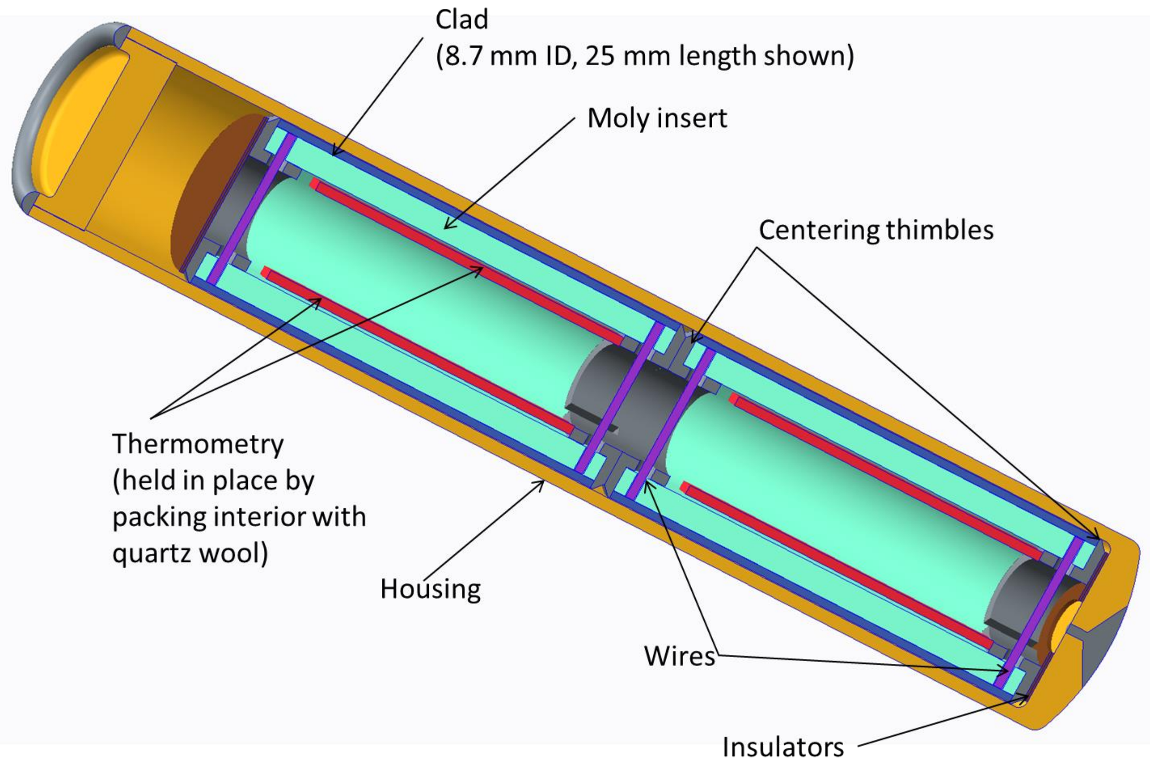

Fig. 2-1. Section view showing the flexible cladding rabbits.

2.2 MATERIALS OF CONSTRUCTION

Material properties for this calculation are taken from the design and analysis calculations (DACs) shown in Table 2-2. In addition, DAC-12-08-GAS_MIXTURE (6) is used to determine thermal properties of gas mixtures.

Table 2-2. Material property references

Part(s)	Material	Reference
Housing, end cap	Aluminum 6061	DAC-10-03-PROP_AL6061 (7)
Cladding	Steel or FeCrAl	DAC-10-16-PROP_SS304 (8)
Cladding	Zircaloy	DAC-11-03-PROP_ZIRCALOY (9)
Cladding	Inconel	DAC-13-01-PROP_INCONEL (10)
Centering thimbles	Ti-6Al4V	DAC-11-14-PROP_TI6AL4V (11)
Insulators	Grafoil	DAC-11-16-PROP_GRAFOIL (12)
Thermometry	Silicon carbide	DAC-10-06-PROP_SIC(IRR) (13)
Insert, or sleeve, and wires	Moly	DAC-10-11-PROP_MOLY (14)
Fill gas	Argon	DAC-10-09-PROP_ARGON (15)
Fill gas	Helium	DAC-10-02-PROP_HELIUM (16)

2.3 THERMAL BOUNDARY CONDITIONS

Peak heat generation rates, parameters for determining axial profiles for the heat generation rates, and convection parameters are summarized in Table 2-3. The axial profiles for the heat generation rates, as well as the peak heat generation rates for all materials (except Ti-6Al4V and Zircaloy) are taken from DAC-10-18-RAB02 (17). The peak heat generation rate for Ti-6Al4V is taken from C-HFIR-2013-003 (18). The peak heat generation rate for Zircaloy is taken from DAC-11-04-FCM01 (19). The convection parameters (heat transfer coefficient and bulk temperature) are taken from DAC-11-01-RAB03 (20).

Table 2-3. Thermal boundary conditions

Heat transfer coefficient	47.1 kW/m²·°C
Bulk fluid temperature (all regions)	52 °C
Peak heat generation rate for Al6061	32.5 W/g
Peak heat generation rate for Ti-6Al4V	35.2 W/g
Peak heat generation rate for steel (as well as Inconel and FeCrAl)	39.3 W/g
Peak heat generation rate for Zircaloy	37.91 W/g
Peak heat generation rate for SiC	32.9 W/g
Peak heat generation rate for grafoil	33.7 W/g
Peak heat generation rate for moly	43.3 W/g
Correlating parameter (σ)	30.07 cm

The local heat generation rate is estimated using the following profile:

$$q(material, z) = q_{peak}(material) \cdot exp\left[-\left(\frac{z}{\sigma}\right)^2\right]$$

where:

q — local heat generation rate as a function of the material and axial location
q_{peak} — heat generation rate at the HFIR midplane as a function of material
z — axial location in HFIR, where the midplane is at zero
σ — correlating parameter

2.4 FINITE ELEMENT MODEL

The design drawings for this project were created in Pro-E, and the Pro-E assemblies were imported directly into ANSYS Workbench. Therefore, the geometric model is essentially identical to that used to create the design drawings, which are listed in Table 2-1. The only difference between the geometric model used in ANSYS and the Pro-E model is that the ANSYS model ignores minor features such as welds. The ANSYS input scripts used to evaluate the model are included in Appendix A. Other ANSYS input scripts used to evaluate the models and summarize the results are documented elsewhere (21) (22). Fig. 2-2 shows the complete meshed model using ¼ symmetry.

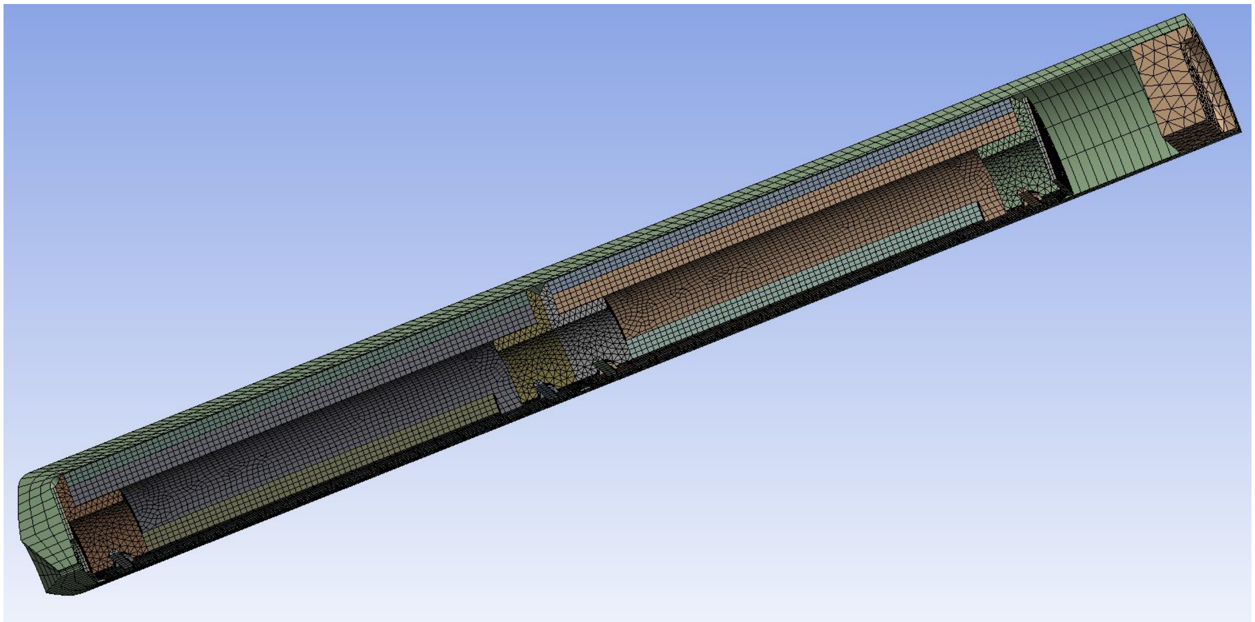

Fig. 2-2. Meshed model using ¼ symmetry

In addition to a 3D model, a 1D model was developed in Microsoft Excel so that a large number of simulations could be run for various irradiation locations (facility and axial position), cladding materials, cladding thicknesses, and gas gaps, taking into account the clad OD and housing ID. The model is used to determine the heat flux through the cladding/housing gas gap for various cladding and insert dimensions. The outer surface temperature of the cladding is fixed at 345 °C, and the inner surface temperature of the housing is fixed at 64 °C. The 1D model is used to determine the approximate gas mixture required to achieve these fixed temperatures for each design case. This gas mixture is determined by considering the effects of thermal expansion by calculating a hot gap based on thermal expansion data for the cladding and housing. The 3D model can be used to verify that the gas mixture predicted by the 1D model gives the desired temperatures. 3D simulations will be performed using the as-built conditions once housings and cladding specimens have been received and inspected. In this document, a few select 3D cases are presented to demonstrate the accuracy of the 1D model.

3. COMPUTATIONS AND ANALYSES

3.1 1D SIMULATION RESULTS

The 1D model was used to perform simulations with the following parameters:

- Target rod rabbit holder positions 3 and 5 (equivalent positions)
- Stainless steel, Zircaloy, and Inconel cladding materials
- A fixed cladding diameter of 9.50 mm, with a housing ID ranging from 9.58 to 9.66 mm (cold gas gap ranging from 40 to 80 µm)
- A cladding ID ranging from 8.10 to 8.90 mm (cladding thickness ranging from 0.30 to 0.70 mm)

Fig. 3-1 shows the predicted helium gas concentration vs. cold gas gap with cladding thickness as a parameter for steel, Zircaloy, and Inconel cladding materials. These gas concentrations are required to achieve a clad surface temperature of 345 °C. It is shown later in this calculation that the temperature difference between the cladding inner and outer surfaces is typically on the order of 10 °C, with an average cladding temperature of approximately 350 °C.

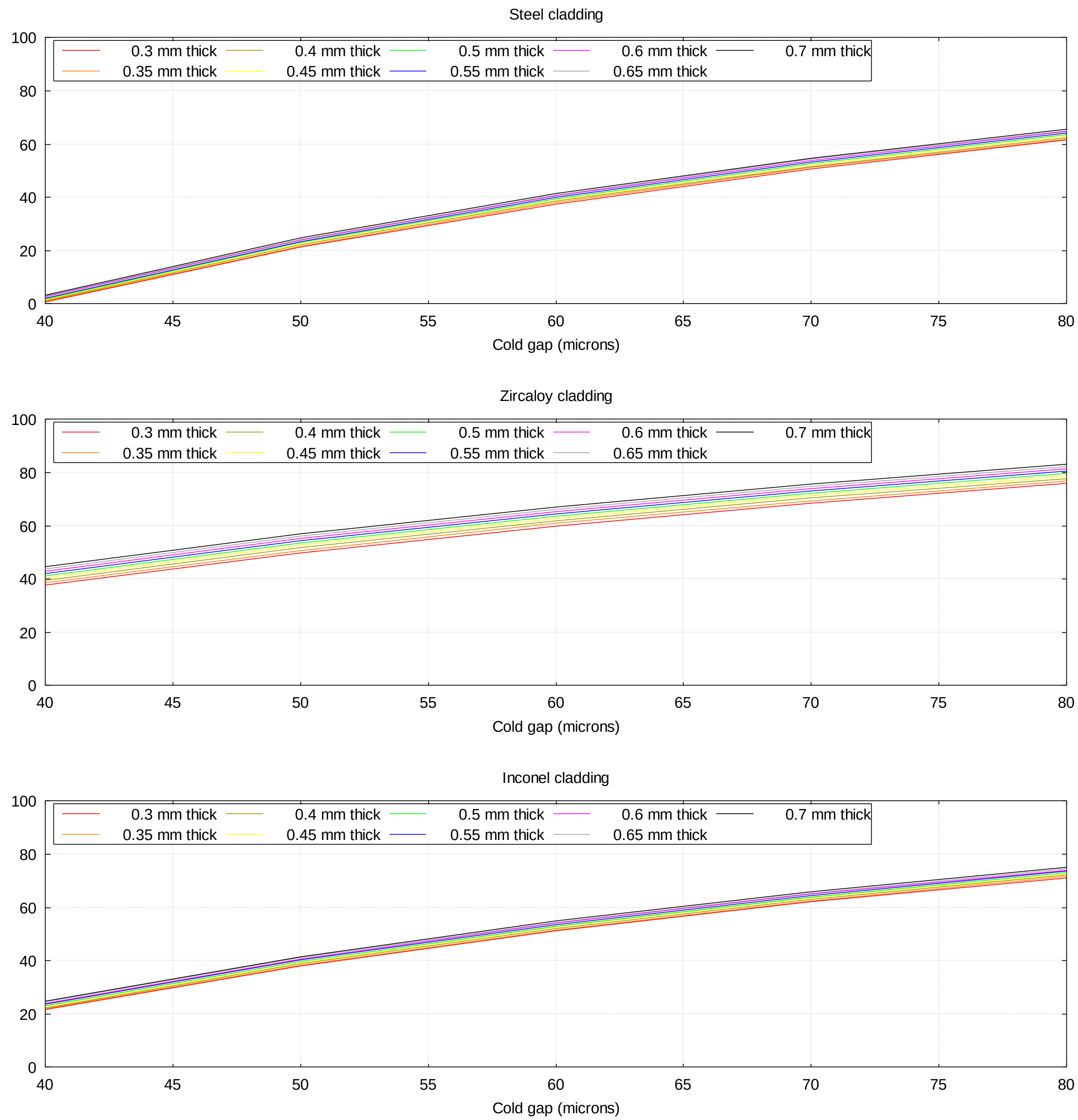

Fig. 3-1. Helium gas concentration predicted using the 1D model vs. cold gas gap with cladding thickness as a parameter for steel, Zircaloy, and Inconel cladding materials.

The results shown in Fig. 3-1 are also stored in a filtered Microsoft Excel database that can be used to look up an approximate gas mixture given an as-built cladding material, cladding thickness, and cold gas gap. Based on the approximate gas mixture, 3D simulations can be quickly performed using the ANSYS model described in this calculation. The 3D model confirms that the concentrations predicted using the 1D model will indeed give the desired cladding temperatures. The tabular results of the 1D model are provided in Attachment 1.

3.2 3D SIMULATION RESULT – STEEL CLADDING

3D simulation results are shown for three cases: a steel cladding, a Zircaloy cladding, and an Inconel cladding. Each case assumes nominal dimensions of 9.50 mm for the cladding OD and 9.60 mm for the housing ID (50 µm cold gas gap). The cladding thickness is set to 0.40 mm. Cladding specimens that are 25 mm in length were modeled in all 3D analyses. The fill gas mixtures were estimated from the results of the 1D simulations. The temperatures predicted for the steel cladding using 3D simulations are summarized in Table 3-1. Fig. 3-2 shows temperature contour plots for various parts of the rabbit capsule.

Table 3-1. Results of 3D simulations for a steel cladding rabbit

Design case	Design temp (ºC)	Clad material, clad ID, clad OD, housing ID	Location, fill gas	Part	Temperature (°C) average (min–max)
		Steel clad,		Housing	64 (54–77)
		8.70 mm clad ID	TRRH-5	Cladding 1	361 (348–407)
A	350	9.50 mm clad OD	23.9% He	Cladding 2	362 (355–403)
		9.60 mm housing ID	76.1% Ar	Thermometry 1	633 (570–647)
		(50 µm cold gas gap)		Thermometry 2	638 (627–642)

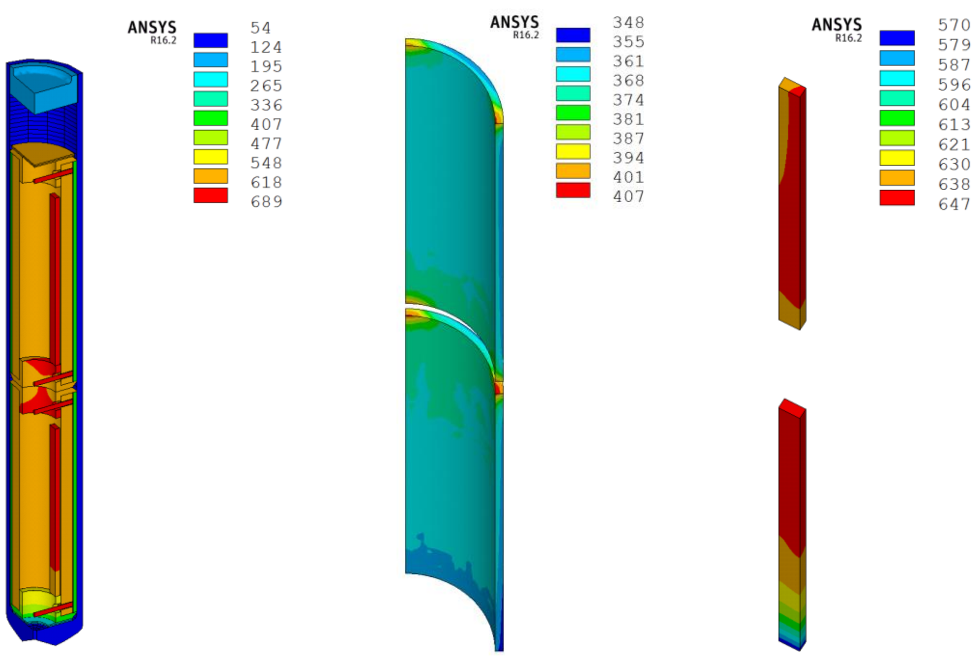

Fig. 3-2. Contour temperature plots (°C) for a steel cladding rabbit showing the assembly (left), cladding (center), and thermometry (right).

3.3 3D SIMULATION RESULT – ZIRCALOY CLADDING

The temperatures predicted for Zircaloy cladding using 3D simulations are summarized in Table 3-2. Fig. 3-**3** shows temperature contour plots for various parts of the rabbit capsule.

Table 3-2. Results of 3D simulations for a Zircaloy cladding rabbit

Design case	Design temp (°C)	Clad material, clad ID, clad OD, housing ID	Location, fill gas	Part	Temperature (°C) average (min–max)
A	350	Zircaloy clad,		Housing	64 (54–76)
		8.70 mm clad ID	TRRH-5	Cladding 1	368 (326–399)
		9.50 mm clad OD	55.2% He	Cladding 2	369 (361–393)
		9.60 mm housing ID	44.8% Ar	Thermometry 1	456 (419–466)
		(50 μm cold gas gap)		Thermometry 2	459 (453–462)

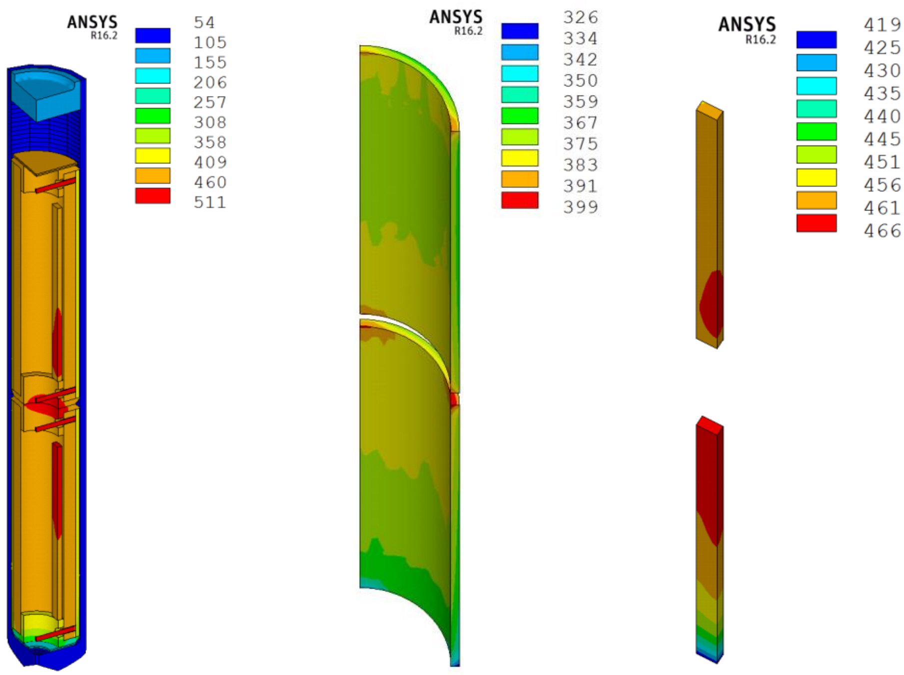

Fig. 3-3. Contour temperature plots (°C) for a Zircaloy cladding rabbit showing the assembly (left), cladding (center), and thermometry (right).

3.4 3D SIMULATION RESULT – INCONEL CLADDING

The temperatures predicted for Inconel cladding using 3D simulations are summarized in Table 3-3. Fig. 3-4 shows temperature contour plots for various parts of the rabbit capsule.

Table 3-3. Results of 3D simulations for an Inconel cladding rabbit

Design case	Design temp (°C)	Clad material, clad ID, clad OD, housing ID	Location, fill gas	Part	Temperature (°C) average (min–max)
A	350	Inconel clad,		Housing	64 (54–77)
		8.70 mm clad ID	TRRH-5	Cladding 1	365 (335–407)
		9.50 mm clad OD	40.7% He	Cladding 2	366 (357–402)
		9.60 mm housing ID	59.3% Ar	Thermometry 1	533 (486–545)
		(50 μm cold gas gap)		Thermometry 2	537 (530–540)

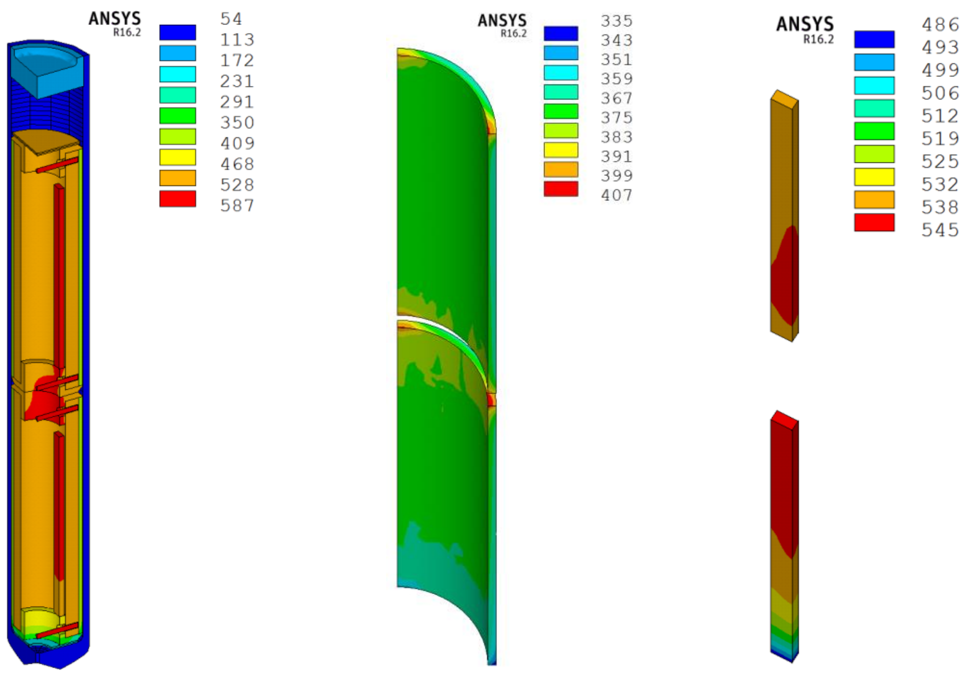

Fig. 3-4. Contour temperature plots (°C) for an Inconel cladding rabbit showing the assembly (left), cladding (center), and thermometry (right).

4. CONCLUSIONS

This calculation establishes helium/argon gas mixtures that give a cladding temperature of 350 °C during irradiation in the flux trap of the HFIR. The gas mixtures are calculated as a function of irradiation location, cladding diameters, gas gap, and cladding material (stainless steel, FeCrAl, Zircaloy, and Inconel). This calculation uses a 1D calculation to determine the required gas mixtures for a wide variety of parameters, and a 3D calculation is used to verify results for a smaller set of specific parameters. The two models generally agree to within about 10–20 °C. The primary outer containment is an Al-6061 housing with an ID that is nominally 9.60 mm, which is slightly larger than the standard non-finned rabbit housing.

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APPENDIX A

ANSYS SCRIPT USED TO EVALUATE CAPSULE DESIGNS

```
!******************************************************************************
!*    MACRO RUN_FLEXCLAD                                                      *
!*                                                                            *
!******************************************************************************
!------------------------------------------------------------------------------
! INPUT SPECIFICATIONS
!------------------------------------------------------------------------------
 Solution_Type=2
 Tdesign=350  ! °C
 des_dose=2.3 ! dose (dpa)
 CladMat=ARG1 ! 1=steel, 2=zircaloy, 3=inconel
 He_frac=ARG2 ! helium mole fraction
 Nsubsteps=5
 SymAngle=90          ! symmetry angle
 pf=1.0

 Problem_Type='3D'
 ContactExp=20.0
 RadHeatTransfer=1  ! 0 - include, 1 - exclude
! Target axial position and heat generation parameters
 IrrLoc=2            ! 1 Peripheral target position, 2 = Target rod rabbit holder, 3 =
Hydraulic tube
 TargetPos=ARG3      ! Target Position
 pf_st=0.3007 ! Peaking factor above midplane in meters
 pf_sb=0.3007 ! Peaking factor below midplane in meters

 CladID=ARG4
 CladOD=ARG5
 HousID=ARG6

!------------------------------------------------------------------------------
! GENERAL DEFINITIONS
!------------------------------------------------------------------------------
 PI=3.1415926536
 in=0.0254
 main_gap=(HousID-CladOD)/2*1e3

*IF,CladMat,EQ,1,THEN
       gsJOBName=strcat('FC_SS_Gap_',chrval(main_gap))
*ELSEIF,CladMat,EQ,2,THEN
       gsJOBName=strcat('FC_Zircaloy_Gap_',chrval(main_gap))
*ELSEIF,CladMat,EQ,3,THEN
       gsJOBName=strcat('FC_Inconel_Gap_',chrval(main_gap))
*ENDIF
gsJOBName=strcat(gsJOBName,'_um_CID_')
gsJOBName=strcat(gsJOBName,chrval(CladID*1e3))
gsJOBName=strcat(gsJOBName,'_um')
FINISH
/FILNAME,%gsJOBName%,1
 SAVE
/PREP7
*ULIB,CONTACT_LIBRARY_R6,ULIB

! HEAT TRANSFER COEFFICIENT
*IF,IrrLoc,EQ,1,THEN
 facility='PTP'
 Hfilm=48400          ! heat transfer coefficient (W/m²·°C)
 Tcoolant=54          ! bulk coolant temperature (°C)
 Z_Bottom=-0.2794+(TargetPos-1)*2.573*in
 Q_Ti=35600*pf          ! C-HFIR-2013-003
 Q_Al=33300*pf          ! DAC-10-18-RAB02
 Q_SiC=34000*pf         ! DAC-10-18-RAB02
 Q_Mo=44100*pf          ! DAC-10-18-RAB02
 Q_Graphite=35000*pf    ! DAC-10-18-RAB02
```

```
 Q_Steel=40000*pf       ! DAC-10-18-RAB02
 Q_V=46300*pf           ! DAC-10-18-RAB02
 Q_Nb1Zr=46600*pf       ! DAC-10-18-RAB02
 Q_W=50300*pf           ! C-HFIR-2014-022
 Q_SiO2=31700*pf     ! C-HFIR-2014-022
 Q_Cu=62200*pf       ! C-HFIR-2005-157
 Q_Zr=38490*pf       ! DAC-11-04-FCM01
*ELSEIF,IrrLoc,EQ,2,THEN
 facility='TRRH'
 Hfilm=47100          ! heat transfer coefficient (W/m²·°C)
 Tcoolant=52          ! bulk coolant temperature (°C)
 Z_Bottom=-0.23324+(TargetPos-1)*2.573*in
 Q_Ti=35200*pf          ! C-HFIR-2013-003
 Q_Al=32500*pf          ! DAC-10-18-RAB02
 Q_SiC=32900*pf         ! DAC-10-18-RAB02
 Q_Mo=43300*pf          ! DAC-10-18-RAB02
 Q_Graphite=33700*pf    ! DAC-10-18-RAB02
 Q_Steel=39300*pf       ! DAC-10-18-RAB02
 Q_V=46800*pf           ! DAC-10-18-RAB02
 Q_Nb1Zr=45500*pf       ! DAC-10-18-RAB02
 Q_W=50000*pf           ! C-HFIR-2014-022
 Q_SiO2=30800*pf     ! C-HFIR-2014-022
 Q_Cu=62200*pf       ! C-HFIR-2005-157
 Q_Zr=36760*pf       ! DAC-11-04-FCM01
*ELSEIF,IrrLoc,EQ,3,THEN
 facility='HT'
 Hfilm=31600          ! heat transfer coefficient (W/m²·°C)
 Tcoolant=53          ! bulk coolant temperature (°C)
 Z_Bottom=-0.29454+(TargetPos-1)*2.573*in
 Q_Ti=34700*pf          ! C-HFIR-2013-003
 Q_Al=31500*pf          ! DAC-10-18-RAB02
 Q_SiC=31900*pf         ! DAC-10-18-RAB02
 Q_Mo=42300*pf          ! DAC-10-18-RAB02
 Q_Graphite=32300*pf    ! DAC-10-18-RAB02
 Q_Steel=38700*pf       ! DAC-10-18-RAB02
 Q_V=47400*pf           ! DAC-10-18-RAB02
 Q_Nb1Zr=44000*pf       ! DAC-10-18-RAB02
 Q_W=48300*pf           ! C-HFIR-2014-022
 Q_SiO2=29500*pf     ! C-HFIR-2014-022
 Q_Cu=62200*pf       ! C-HFIR-2005-157
 Q_Zr=37910*pf       ! DAC-11-04-FCM01
*ENDIF
 Z_CL=Z_Bottom+2.573/2*in

!-------------------------------------------------------------------------------
! MATERIAL/PART DEFINITION
!-------------------------------------------------------------------------------
*USE,WB_EXTRACT_MODEL

 Qmass=
*DIM,Qmass,ARRAY,nItems,3

! Define extra material property arrays
 xprpTmelt=
*DIM,xprpTmelt,ARRAY,nItems                ! melting point
 xprpMatName=
*DIM,xprpMatName,CHAR,nItems               ! material name
 xprpMolecularWeight=
*DIM,xprpMolecularWeight,ARRAY,nItems      ! molecular weight
 xprpRatioSpHeat=
*DIM,xprpRatioSpHeat,ARRAY,nItems          ! ratio of specific heat
 xprpSurfaceRoughness=
*DIM,xprpSurfaceRoughness,ARRAY,nItems     ! surface roughness
 xprpMicroHardness=
```

```
*DIM,xprpMicroHardness,ARRAY,nItems       ! microhardness
 grUserGasGap=
*DIM,grUserGasGap,ARRAY,nItems              ! gas gaps
 grContactPressure=
*DIM,grContactPressure,ARRAY,nItems         ! contact pressure
! Fill the array parameter grUserGap(1) with constant values of 99
*VFILL,grUserGasGap(1),RAMP,99,0
! Fill the array parameter grContactPressure(1) with constant values of -1
*VFILL,grContactPressure(1),RAMP,-1,0

! Set effective radius for thermal expansion for clad/housing, sleeve/clad, and
thimble/housing gas gaps
grUserGasGap(thimble1a_to_hous)=-(9.55+HousID)/4*1e-3
grUserGasGap(thimble2a_to_hous)=-(9.55+HousID)/4*1e-3
grUserGasGap(thimble1b_to_hous)=-(9.55+HousID)/4*1e-3
grUserGasGap(thimble2b_to_hous)=-(9.55+HousID)/4*1e-3
grUserGasGap(clad1_to_hous)=-(CladOD+HousID)/4*1e-3
grUserGasGap(clad2_to_hous)=-(CladOD+HousID)/4*1e-3
grUserGasGap(sleeve1_to_clad1)=-(CladID)/2*1e-3
grUserGasGap(sleeve2_to_clad2)=-(CladID)/2*1e-3

*DO,matid,1,iContactStart-1
     *IF,STRPOS(PartName(1,matid),'Housing'),EQ,1,THEN
           MPDELE,ALL,matid,,,,NOCHECK
           MAT_AL6061, matid, 1
           Qmass(matid,1)=pf*Q_Al
     *ELSEIF,STRPOS(PartName(1,matid),'Cap'),EQ,1,THEN
           MPDELE,ALL,matid,,,,NOCHECK
           MAT_AL6061, matid, 1
           Qmass(matid,1)=pf*Q_Al
     *ELSEIF,STRPOS(PartName(1,matid),'Clad'),EQ,1,THEN
          *IF,CladMat,EQ,1,THEN
              MPDELE,ALL,matid,,,,NOCHECK
              MAT_SS304, matid, 1
              Qmass(matid,1)=pf*Q_Steel
          *ELSEIF,CladMat,EQ,2,THEN
              MPDELE,ALL,matid,,,,NOCHECK
              MAT_ZIRCALOY, matid, 1
              xprpMicroHardness(matid)=3.35E+09
              Qmass(matid,1)=pf*Q_Zr
          *ELSEIF,CladMat,EQ,3,THEN
              MPDELE,ALL,matid,,,,NOCHECK
              MAT_INCONEL, matid, 1
              Qmass(matid,1)=pf*Q_Steel
          *ENDIF
     *ELSEIF,STRPOS(PartName(1,matid),'Grafoil'),EQ,1,THEN
           MPDELE,ALL,matid,,,,NOCHECK
           MAT_GRAFOIL, matid, 1
           Qmass(matid,1)=pf*Q_Graphite
     *ELSEIF,STRPOS(PartName(1,matid),'Thimble'),EQ,1,THEN
           MPDELE,ALL,matid,,,,NOCHECK
           MAT_TI6AL4V, matid, 1
           Qmass(matid,1)=pf*Q_Ti
     *ELSEIF,STRPOS(PartName(1,matid),'Sleeve'),EQ,1,THEN
           MPDELE,ALL,matid,,,,NOCHECK
           MAT_MOLY, matid, 1
           Qmass(matid,1)=pf*Q_Mo
     *ELSEIF,STRPOS(PartName(1,matid),'Wire'),EQ,1,THEN
           MPDELE,ALL,matid,,,,NOCHECK
           MAT_MOLY, matid, 1
           Qmass(matid,1)=pf*Q_Mo
     *ELSEIF,STRPOS(PartName(1,matid),'TM'),EQ,1,THEN
           MPDELE,ALL,matid,,,,NOCHECK
           MAT_SIC-IRR, matid, 1, Tdesign, des_dose
```

```
          Qmass(matid,1)=pf*Q_SiC
     *ENDIF
*ENDDO

MPDELE,ALL,iContactStart,,,,NOCHECK
MAT_HE,iContactStart
MPDELE,ALL,iContactStart+1,,,,NOCHECK
MAT_AR,iContactStart+1
GAS_MAT_NAME=STRCAT(CHRVAL(He_frac*1000),'HE_')
GAS_MAT_NAME=STRCAT(GAS_MAT_NAME,CHRVAL((1-He_frac)*1000))
GAS_MAT_NAME=STRCAT(GAS_MAT_NAME,'AR')
GASMIXTURE,GAS_MAT_NAME,iContactStart,He_frac,iContactStart+1,1-He_frac
MPDELE,ALL,iContactStart,,,,NOCHECK
MPDELE,ALL,iContactStart+1,,,,NOCHECK
FillGas=GAS_MAT_NAME

!-------------------------------------------------------------------------------
!     SETUP PROBLEM
!-------------------------------------------------------------------------------

*GET,giMaxType,ETYP,0,NUM,MAX
*DO,iType,1,giMaxType
     *GET,ElemType,ETYP,iType,ATTR,ENAM
     *IF,ElemType,EQ,174,THEN
          xprpSurfaceRoughness(iType)=63E-06*in
          *IF,Solution_Type,EQ,0.,THEN
              KEYOPT,iType,1,1  ! set this to 1 for coupled!
           *ELSE
              KEYOPT,iType,1,2
           *ENDIF
     *ELSEIF,ElemType,EQ,170,THEN
          xprpSurfaceRoughness(iType)=63E-06*in
     *ELSEIF,ElemType,EQ,186,THEN
          *IF,Solution_Type,EQ,0.,THEN
              ET,iType,SOLID226,11,0
           *ELSE
              ET,iType,SOLID90
           *ENDIF
     *ELSEIF,ElemType,EQ,187,THEN
          *IF,Solution_Type,EQ,0.,THEN
              ET,iType,SOLID227,11,0
           *ELSE
              ET,iType,SOLID87
           *ENDIF
     *ENDIF
*ENDDO

 Pcapsule=101325*(Tdesign+273)/293

*USE,SETUP,Problem_Type,FillGas,RadHeatTransfer,SymAngle,Pcapsule,Tcoolant,ContactExp

!* ARG1 - Problem type:  '2D'  - 2D in the r-theta plane                    *
!*                       '2DA' - 2D axisymmetric                            *
!*                       '3D'  - 3D                                         *
!* ARG2 - Gas material (i.e., 'AR', 'HE', or 'NE')                          *
!* ARG3 - Radiation [0 = include; 1 = exclude]                              *
!* ARG4 - Symmetry angle [default=360]                                      *
!* ARG5 - Internal gas pressure [default=101325 Pa]                         *
!* ARG6 - Sink temperature (°C) [default=60°C]                              *
!* ARG7 - Contact pressure exponent (typically, 0.6-0.94)                   *
!*            0.95       = optically flat surfaces, Gaussian distribution    *
!*            0.6 - 0.75 = surfaces with waviness, flatness deviation, etc.  *
!*            0.68       =  default value                                   *
!--------------------------------------------------------------------------
```

```
!     CREATE BOUNDARY CONDITION FILES
!---------------------------------------------------------------------------
*CREATE,'BC','INP'
 ALLSEL

! SETTING BOUNDARY CONDITION INPUT FOR CONVECTION
 CMSEL,S,'Convection'
 SF,ALL,CONV,Hfilm,Tcoolant
 ALLSEL

*IF,Solution_Type,LT,2.,THEN
! Set Z-restraint
CMSEL,S,'SymmetryZ'
D,ALL,UZ,0.0

! Set Y-restraint
CMSEL,S,'SymmetryY'
D,ALL,UY,0.0

 ! Set X-restraint
CMSEL,S,'SymmetryX'
D,ALL,UX,0.0
 ALLSEL
*ENDIF

*END

/COM, CALCULATING INTERNAL HEAT GENERATION FOR EACH ELEMENT
*USE,HEAT_GENERATION,Z_Bottom,pf_st,pf_sb

!--------------------------------------------------------------------------------
!     SOLVE
!--------------------------------------------------------------------------------
 SAVE
*USE,STATIC_SOLVER,'BC',Nsubsteps
 SAVE

!--------------------------------------------------------------------------------
!     POST PROCESSING
!--------------------------------------------------------------------------------
/POST1
 SET,LAST
/DELETE,'BC','INP'

 CMSEL,S,'Housing'
*USE,RESULT_SUMMARY,'TEMP',''
 Thous_avg=RSLTAvg
 Thous_min=RSLTMin
 Thous_max=RSLTMax

 CMSEL,S,'Clad'
*USE,RESULT_SUMMARY,'TEMP',''
 Tclad_avg=RSLTAvg
 Tclad_min=RSLTMin
 Tclad_max=RSLTMax

!- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
! WRITE REPORT
!- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
*CFOPEN,%gsJOBName%,'txt'
*VWRITE,
 ******************************************************************************
*VWRITE,
                             OUTPUT SUMMARY FILE
```

```
*VWRITE,
 *******************************************************************************%/&
 %/&
 -------------------------------------------------------------------------------%/&
 INPUTS%/
*IF,Solution_Type,EQ,0.,THEN
*VWRITE,
 * Normal coupled field solution
*ELSEIF,Solution_Type,EQ,2.,THEN
*VWRITE,
 * Thermal only solution with calculated gaps
*ENDIF

*VWRITE,SymAngle
 (' * Symmetry angle: ',F6.2,' degrees')

*VWRITE,FillGas
 (' * Fill gas: ',A)

*IF,RadHeatTransfer,EQ,0.,THEN
*VWRITE,
 * Radiative heat transfer included
*ELSEIF,RadHeatTransfer,EQ,1.,THEN
*VWRITE,
 * Radiative heat transfer excluded
*ENDIF

*VWRITE,Problem_Type
 (' * ',A3,' problem geometry')

*VWRITE,Tdesign
 (' * Target temperature: ',F6.1,' °C')

*VWRITE,des_dose
 (' * Target dose (in SiC): ',F7.3,' dpa')

*VWRITE,Pcapsule/1000
 (' * Capsule pressure: ',F7.2,' kPa')

*IF,CladMat,EQ,1,THEN
*VWRITE,
 * Cladding Material: Steel
*ELSEIF,CladMat,EQ,2,THEN
*VWRITE,
 * Cladding Material: Zircaloy
*ELSEIF,CladMat,EQ,3,THEN
*VWRITE,
 * Cladding Material: Inconel
*ENDIF

*VWRITE,CladID,CladOD,HousID
 (' * Clad ID = ',F7.4,' mm, Clad OD = ',F7.4,' mm, Housing ID = ',F7.4,' mm')

*VWRITE,main_gap
 (' * Gas gap: ',F7.2,' µm')

*VWRITE,He_frac*100,(1-He_frac)*100
 (' * Backfill gas: ',F7.2,'% He, ',F7.2,'% Ar')

*VWRITE,facility
 (' * Irradiation facility: ',A4)

*VWRITE,chrval(TargetPos)
 (' * Axial position: ',A)
```

```
*VWRITE,Z_CL*100,Z_CL*100/2.54
 (' * Capsule centerline position = ',F6.2,' cm (',F6.2,' in)')

*VWRITE,pf_st*100
 (' * Axial peaking factor above the core midplane: ',F6.3,' cm')

*VWRITE,pf_sb*100
 (' * Axial peaking factor below the core midplane: ',F6.3,' cm')

*VWRITE,
%/ -------------------------------------------------------------------------------%/&
 BOUNDARY CONDITIONS %C %/

*VWRITE,pf,Hfilm,Tcoolant
  Heat generation rate scaling factor = %6.4F %/&
 Heat transfer coefficient = %7.0F W/m²·°C %/&
 Bulk coolant temperature  = %7.1F °C %/

*USE,REPORT_TABLE,'HGEN'
*USE,REPORT_TABLE,'TEMP'
*USE,REPORT_TABLE,'PROP'
*USE,REPORT_TABLE,'ENER'

*VWRITE,
%/ -------------------------------------------------------------------------------%/&
 CLAD TO HOUSING GAP REPORTS %C %/

*USE,REPORT_TABLE,'GAP',,clad1_to_hous
*USE,REPORT_TABLE,'GAP',,clad2_to_hous

*CFCLOS
 ALLSEL
*ULIB

/EOF
```

APPENDIX B

ANSYS DESIGN REPORTS

APPENDIX B TABLE OF CONTENTS

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B-1. Steel Cladding B-3
B-2. Zircaloy Cladding B-7
B-3. Inconel Cladding B-11

B-1. STEEL CLADDING

****

OUTPUT SUMMARY FILE

****

INPUTS

* Thermal only solution with calculated gaps
* Symmetry angle: 90.00 degrees
* Fill gas: 239HE_76
* Radiative heat transfer excluded
* 3D problem geometry
* Target temperature: 350.0 °C
* Target dose (in SiC): 2.300 dpa
* Capsule pressure: 215.45 kPa
* Cladding Material: Steel
* Clad ID = 8.7000 mm, Clad OD = 9.5000 mm, Housing ID = 9.6000 mm
* Gas gap: 50.00 µm
* Backfill gas: 23.90% He, 76.10% Ar
* Irradiation facility: TRRH
* Axial position: 5
* Capsule centerline position = 6.09 cm (2.40 in)
* Axial peaking factor above the core midplane: 30.070 cm
* Axial peaking factor below the core midplane: 30.070 cm

BOUNDARY CONDITIONS

Heat generation rate scaling factor = 1.0000
Heat transfer coefficient = 47100. $W/m^2 \cdot °C$
Bulk coolant temperature = 52.0 °C

HEAT GENERATION

Part	Material	Heat Gen. @Midplane (W/kg)	------ Heat Load ----- @Midplane (W)	@Location (W)
1) Housing	AL-6061	32500.	132.8	127.5
2) Cap	AL-6061	32500.	17.1	15.6
3) Grafoil1	GRAFOIL	33700.	0.2	0.2
4) Grafoil2	GRAFOIL	33700.	0.2	0.2
5) Grafoil3	GRAFOIL	33700.	0.3	0.3
6) Grafoil4	GRAFOIL	33700.	0.3	0.3
7) Thimble1a	Ti-6Al4V	35200.	7.1	7.0
8) Clad1	SS304	39300.	90.2	88.3
9) Thimble1b	Ti-6Al4V	35200.	7.1	6.8
10) Sleeve1	Moly	43300.	341.2	333.8
11) TM1	SiC(Irr)	32900.	4.0	3.9
12) Thimble2a	Ti-6Al4V	35200.	7.1	6.8
13) Clad2	SS304	39300.	90.2	85.4
14) Thimble2b	Ti-6Al4V	35200.	7.1	6.5
15) Sleeve2	Moly	43300.	341.2	323.0
16) TM2	SiC(Irr)	32900.	4.0	3.8
17) Wire1	Moly	43300.	0.8	0.7
18) Wire2	Moly	43300.	0.8	0.7
19) Wire3	Moly	43300.	0.8	0.7
20) Wire4	Moly	43300.	0.8	0.7
			1052.9	1012.3

CAPSULE TEMPERATURE SUMMARY

Name	Material	Tavg	Tmin	Tmax	T.025	T.975
1) Housing	AL-6061	64.	54.	77.	54.	75.
2) Cap	AL-6061	162.	161.	164.	161.	164.
3) Grafoil1	GRAFOIL	165.	156.	174.	161.	168.
4) Grafoil2	GRAFOIL	249.	222.	268.	225.	261.
5) Grafoil3	GRAFOIL	602.	592.	605.	594.	605.
6) Grafoil4	GRAFOIL	602.	596.	605.	597.	605.
7) Thimble1a	Ti-6Al4V	429.	331.	537.	343.	527.
8) Clad1	SS304	361.	348.	407.	353.	369.
9) Thimble1b	Ti-6Al4V	614.	516.	621.	579.	621.
10) Sleeve1	Moly	587.	569.	599.	571.	597.
11) TM1	SiC(Irr)	633.	570.	647.	583.	646.
12) Thimble2a	Ti-6Al4V	612.	515.	623.	574.	621.
13) Clad2	SS304	362.	355.	403.	357.	371.
14) Thimble2b	Ti-6Al4V	606.	512.	613.	575.	613.
15) Sleeve2	Moly	589.	585.	597.	586.	595.
16) TM2	SiC(Irr)	638.	627.	642.	633.	641.
17) Wire1	Moly	650.	634.	661.	636.	661.
18) Wire2	Moly	678.	661.	689.	663.	689.
19) Wire3	Moly	676.	659.	687.	661.	686.
20) Wire4	Moly	667.	651.	678.	653.	677.

PROPERTY SUMMARY AT THE AVERAGE PART TEMPERATURE

Name	Material	Thermal Cond. (W/m·°C)	Thermal Exp. Coeff. (μm/m·°C)	Emis (---)
1) Housing	AL-6061	167.128	24.21	0.050
2) Cap	AL-6061	176.000	0.00	0.050
3) Grafoil1	GRAFOIL	38.000	1.00	0.500
4) Grafoil2	GRAFOIL	38.000	1.00	0.500
5) Grafoil3	GRAFOIL	38.000	1.00	0.500
6) Grafoil4	GRAFOIL	38.000	1.00	0.500
7) Thimble1a	Ti-6Al4V	15.154	10.11	0.398
8) Clad1	SS304	20.275	20.01	0.143
9) Thimble1b	Ti-6Al4V	18.892	10.51	0.495
10) Sleeve1	Moly	116.210	5.29	0.088
11) TM1	SiC(Irr)	8.534	4.00	0.900
12) Thimble2a	Ti-6Al4V	18.862	10.50	0.494
13) Clad2	SS304	20.286	20.01	0.143
14) Thimble2b	Ti-6Al4V	18.736	10.49	0.488
15) Sleeve2	Moly	116.127	5.30	0.088
16) TM2	SiC(Irr)	8.530	4.00	0.900
17) Wire1	Moly	114.306	0.00	0.095
18) Wire2	Moly	113.468	0.00	0.098
19) Wire3	Moly	113.535	0.00	0.098
20) Wire4	Moly	113.795	0.00	0.097

STORED ENERGY SUMMARY AT THE AVERAGE PART TEMPERATURE

Name	Material	Mass (g)	Tavg (°C)	Specific Heat (J/kg°C)	Stored Energy (J)
1) Housing	AL-6061	4.085	64.	888.	159.
2) Cap	AL-6061	0.527	162.	958.	72.
3) Grafoil1	GRAFOIL	0.006	165.	700.	1.
4) Grafoil2	GRAFOIL	0.006	249.	700.	1.
5) Grafoil3	GRAFOIL	0.008	602.	700.	3.
6) Grafoil4	GRAFOIL	0.008	602.	700.	3.
7) Thimble1a	Ti-6Al4V	0.200	429.	740.	61.
8) Clad1	SS304	2.296	361.	393.	307.

```
   9) Thimble1b                    Ti-6Al4V    0.200     614.     850.     101.
  10) Sleeve1                      Moly        7.879     587.     280.    1250.
  11) TM1                          SiC(Irr)    0.122     633.    1163.      87.
  12) Thimble2a                    Ti-6Al4V    0.200     612.     849.     101.
  13) Clad2                        SS304       2.296     362.     393.     308.
  14) Thimble2b                    Ti-6Al4V    0.200     606.     842.      99.
  15) Sleeve2                      Moly        7.879     589.     280.    1256.
  16) TM2                          SiC(Irr)    0.122     638.    1165.      88.
  17) Wire1                        Moly        0.017     650.     284.       3.
  18) Wire2                        Moly        0.017     678.     285.       3.
  19) Wire3                        Moly        0.017     676.     285.       3.
  20) Wire4                        Moly        0.017     667.     285.       3.
                                            --------                  --------
                                              26.106                     3909.

 ------------------------------------------------------------------------------
  CLAD TO HOUSING GAP REPORTS


-------------------------------------------------------------------------------
CONTACT SUMMARY FOR CONTACT ID 39: Clad1 To Housing {Frictionless}
   Contact surface material:        SS304
   Target surface material:       AL-6061
   Interstitial gas:             239HE_76
   Effective surface roughness:     2.263 µm
   Effective asperity slope:        0.214 rad
   Effective microhardness:         1.220 GPa

                                              Average      Minimum      Maximum
                                         ------------ ------------ ------------
   ~~~~~~~~~~~ direct results ~~~~~~~~~~
   Contact status                               1.000        1.000        1.000
   Contact temperature (°C)                   355.741      348.496      389.121
   Target temperature (°C)                     65.545       63.109       65.824
   Geometric gas gap (µm)                      49.882       49.837       49.969
   Contact pressure (MPa)                       0.000        0.000        0.000
   Gap conduction heat flux (kW/m²)           563.726      531.652      745.536
   Radiation heat flux (kW/m²)                  0.000        0.000        0.000
   Contact conduction heat flux (kW/m²)         0.000        0.000        0.000
   Total heat flux (kW/m²)                    563.726      531.652      745.536
   Thermal contact conductance (W/m²·C)      1942.124     1877.587     2291.524
   ~~~~~~~~~~ derived results ~~~~~~~~~~
   Effective gas gap (µm)                      23.027       19.856       23.720
   Contact thermal jump distance (µm)           0.349        0.344        0.370
   Target thermal jump distance (µm)            0.275        0.272        0.285
   Effective contact pressure (MPa)             0.000        0.000        0.000
   Pressure index                              19.236       19.171       19.252
   Gas thermal conductivity (W/m·°C)            0.046        0.046        0.047
   Solid spot conductance (W/m²·C)              0.000        0.000        0.000
   Gas gap conductance (W/m²·C)              1940.570     1876.446     2289.005

   Contact status codes:
    ----------------------------------------------
    0=open/no heat transfer, 1=near-field contact
    2=closed and sliding,    3=closed and sticking

-------------------------------------------------------------------------------
CONTACT SUMMARY FOR CONTACT ID 41: Clad2 To Housing {Frictionless}
   Contact surface material:        SS304
   Target surface material:       AL-6061
   Interstitial gas:             239HE_76
   Effective surface roughness:     2.263 µm
   Effective asperity slope:        0.214 rad
   Effective microhardness:         1.220 GPa

                                              Average      Minimum      Maximum
                                         ------------ ------------ ------------
   ~~~~~~~~~~~ direct results ~~~~~~~~~~
```

```
Contact status                              1.000       1.000       1.000
Contact temperature (°C)                  356.456     354.623     385.047
Target temperature (°C)                    65.229      60.450      65.716
Geometric gas gap (µm)                     49.882      49.837      49.969
Contact pressure (MPa)                      0.000       0.000       0.000
Gap conduction heat flux (kW/m²)          568.263     557.101     737.894
Radiation heat flux (kW/m²)                 0.000       0.000       0.000
Contact conduction heat flux (kW/m²)        0.000       0.000       0.000
Total heat flux (kW/m²)                   568.263     557.101     737.894
Thermal contact conductance (W/m²·C)     1950.859    1926.210    2276.961
~~~~~~~~~~ derived results ~~~~~~~~~~
Effective gas gap (µm)                     22.927      19.884      23.200
Contact thermal jump distance (µm)          0.349       0.346       0.367
Target thermal jump distance (µm)           0.275       0.271       0.284
Effective contact pressure (MPa)            0.000       0.000       0.000
Pressure index                             19.235      19.179      19.239
Gas thermal conductivity (W/m·°C)           0.046       0.046       0.047
Solid spot conductance (W/m²·C)             0.000       0.000       0.000
Gas gap conductance (W/m²·C)             1949.305    1924.736    2274.928

Contact status codes:
 ----------------------------------------------
 0=open/no heat transfer, 1=near-field contact
 2=closed and sliding,    3=closed and sticking
```

B-2. ZIRCALOY CLADDING

```
****************************************************************************
                             OUTPUT SUMMARY FILE
****************************************************************************

 ----------------------------------------------------------------------------
 INPUTS

* Thermal only solution with calculated gaps
* Symmetry angle:  90.00 degrees
* Fill gas: 552HE_44
* Radiative heat transfer excluded
* 3D  problem geometry
* Target temperature:  350.0 °C
* Target dose (in SiC):   2.300 dpa
* Capsule pressure:  215.45 kPa
* Cladding Material: Zircaloy
* Clad ID =  8.7000 mm, Clad OD =  9.5000 mm, Housing ID =  9.6000 mm
* Gas gap:   50.00 µm
* Backfill gas:   55.20% He,   44.80% Ar
* Irradiation facility: TRRH
* Axial position: 5
* Capsule centerline position =   6.09 cm (  2.40 in)
* Axial peaking factor above the core midplane: 30.070 cm
* Axial peaking factor below the core midplane: 30.070 cm

 ----------------------------------------------------------------------------
 BOUNDARY CONDITIONS

 Heat generation rate scaling factor = 1.0000
 Heat transfer coefficient =  47100. W/m²·°C
 Bulk coolant temperature  =    52.0 °C

 ----------------------------------------------------------------------------
 HEAT GENERATION
```

Part	Material	Heat Gen. @Midplane (W/kg)	------ Heat Load ----- @Midplane (W)	@Location (W)
1) Housing	AL-6061	32500.	132.8	127.5
2) Cap	AL-6061	32500.	17.1	15.6
3) Grafoil1	GRAFOIL	33700.	0.2	0.2
4) Grafoil2	GRAFOIL	33700.	0.2	0.2
5) Grafoil3	GRAFOIL	33700.	0.3	0.3
6) Grafoil4	GRAFOIL	33700.	0.3	0.3
7) Thimble1a	Ti-6Al4V	35200.	7.1	7.0
8) Clad1	Zircaloy	36760.	68.8	67.3
9) Thimble1b	Ti-6Al4V	35200.	7.1	6.8
10) Sleeve1	Moly	43300.	341.2	333.8
11) TM1	SiC(Irr)	32900.	4.0	3.9
12) Thimble2a	Ti-6Al4V	35200.	7.1	6.8
13) Clad2	Zircaloy	36760.	68.8	65.2
14) Thimble2b	Ti-6Al4V	35200.	7.1	6.5
15) Sleeve2	Moly	43300.	341.2	323.0
16) TM2	SiC(Irr)	32900.	4.0	3.8
17) Wire1	Moly	43300.	0.8	0.7
18) Wire2	Moly	43300.	0.8	0.7
19) Wire3	Moly	43300.	0.8	0.7
20) Wire4	Moly	43300.	0.8	0.7
			1010.1	971.1

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 CAPSULE TEMPERATURE SUMMARY
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Name	Material	Tavg	Tmin	Tmax	T.025	T.975
1) Housing	AL-6061	64.	54.	76.	54.	74.
2) Cap	AL-6061	116.	114.	117.	114.	117.
3) Grafoil1	GRAFOIL	126.	117.	135.	121.	129.
4) Grafoil2	GRAFOIL	178.	155.	196.	157.	189.
5) Grafoil3	GRAFOIL	452.	444.	454.	445.	454.
6) Grafoil4	GRAFOIL	451.	445.	454.	446.	454.
7) Thimble1a	Ti-6Al4V	315.	234.	408.	242.	400.
8) Clad1	Zircaloy	368.	326.	399.	354.	379.
9) Thimble1b	Ti-6Al4V	459.	391.	467.	444.	466.
10) Sleeve1	Moly	425.	408.	437.	411.	436.
11) TM1	SiC(Irr)	456.	419.	466.	428.	465.
12) Thimble2a	Ti-6Al4V	457.	390.	467.	439.	466.
13) Clad2	Zircaloy	369.	361.	393.	364.	377.
14) Thimble2b	Ti-6Al4V	450.	385.	457.	438.	456.
15) Sleeve2	Moly	427.	423.	435.	423.	434.
16) TM2	SiC(Irr)	459.	453.	462.	456.	462.
17) Wire1	Moly	474.	460.	484.	461.	484.
18) Wire2	Moly	500.	486.	511.	487.	510.
19) Wire3	Moly	498.	483.	508.	485.	508.
20) Wire4	Moly	491.	476.	500.	478.	500.

PROPERTY SUMMARY AT THE AVERAGE PART TEMPERATURE

Name	Material	Thermal Cond. (W/m·°C)	Thermal Exp. Coeff. (μm/m·°C)	Emis (---)
1) Housing	AL-6061	167.080	24.21	0.050
2) Cap	AL-6061	172.736	0.00	0.050
3) Grafoil1	GRAFOIL	38.000	1.00	0.500
4) Grafoil2	GRAFOIL	38.000	1.00	0.500
5) Grafoil3	GRAFOIL	38.000	1.00	0.500
6) Grafoil4	GRAFOIL	38.000	1.00	0.500
7) Thimble1a	Ti-6Al4V	12.789	9.90	0.362
8) Clad1	Zircaloy	16.969	4.85	0.699
9) Thimble1b	Ti-6Al4V	15.788	10.17	0.402
10) Sleeve1	Moly	122.078	5.13	0.070
11) TM1	SiC(Irr)	8.672	3.67	0.900
12) Thimble2a	Ti-6Al4V	15.756	10.16	0.402
13) Clad2	Zircaloy	16.988	4.85	0.699
14) Thimble2b	Ti-6Al4V	15.604	10.15	0.401
15) Sleeve2	Moly	121.993	5.14	0.070
16) TM2	SiC(Irr)	8.670	3.68	0.900
17) Wire1	Moly	120.126	0.00	0.075
18) Wire2	Moly	119.067	0.00	0.077
19) Wire3	Moly	119.161	0.00	0.077
20) Wire4	Moly	119.453	0.00	0.076

STORED ENERGY SUMMARY AT THE AVERAGE PART TEMPERATURE

Name	Material	Mass (g)	Tavg (°C)	Specific Heat (J/kg°C)	Stored Energy (J)
1) Housing	AL-6061	4.085	64.	887.	158.
2) Cap	AL-6061	0.527	116.	927.	47.
3) Grafoil1	GRAFOIL	0.006	126.	700.	0.
4) Grafoil2	GRAFOIL	0.006	178.	700.	1.
5) Grafoil3	GRAFOIL	0.008	452.	700.	2.
6) Grafoil4	GRAFOIL	0.008	451.	700.	2.
7) Thimble1a	Ti-6Al4V	0.200	315.	694.	41.
8) Clad1	Zircaloy	1.873	368.	331.	216.

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   9) Thimble1b                  Ti-6Al4V    0.200     459.     751.      66.
  10) Sleeve1                    Moly        7.879     425.     272.     868.
  11) TM1                        SiC(Irr)    0.122     456.    1098.      58.
  12) Thimble2a                  Ti-6Al4V    0.200     457.     750.      66.
  13) Clad2                      Zircaloy    1.873     369.     331.     217.
  14) Thimble2b                  Ti-6Al4V    0.200     450.     748.      64.
  15) Sleeve2                    Moly        7.879     427.     272.     873.
  16) TM2                        SiC(Irr)    0.122     459.    1099.      59.
  17) Wire1                      Moly        0.017     474.     274.       2.
  18) Wire2                      Moly        0.017     500.     275.       2.
  19) Wire3                      Moly        0.017     498.     275.       2.
  20) Wire4                      Moly        0.017     491.     275.       2.
                                          --------                   --------
                                            25.260                      2747.

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  CLAD TO HOUSING GAP REPORTS


------------------------------------------------------------------------------
CONTACT SUMMARY FOR CONTACT ID 39: Clad1 To Housing {Frictionless}
   Contact surface material:     Zircaloy
   Target surface material:       AL-6061
   Interstitial gas:             552HE_44
   Effective surface roughness:     2.263 µm
   Effective asperity slope:        0.214 rad
   Effective microhardness:         1.220 GPa

                                             Average      Minimum      Maximum
                                        ------------ ------------ ------------
   ~~~~~~~~~~~ direct results ~~~~~~~~~~
   Contact status                              1.000        1.000        1.000
   Contact temperature (°C)                  361.626      331.063      383.441
   Target temperature (°C)                    65.031       62.637       65.351
   Geometric gas gap (µm)                     49.882       49.837       49.969
   Contact pressure (MPa)                      0.000        0.000        0.000
   Gap conduction heat flux (kW/m²)          536.860      464.385      597.708
   Radiation heat flux (kW/m²)                 0.000        0.000        0.000
   Contact conduction heat flux (kW/m²)        0.000        0.000        0.000
   Total heat flux (kW/m²)                   536.860      464.385      597.708
   Thermal contact conductance (W/m²·C)     1809.812     1746.356     1864.960
   ~~~~~~~~~~ derived results ~~~~~~~~~~
   Effective gas gap (µm)                     47.174       46.368       47.875
   Contact thermal jump distance (µm)          0.749        0.699        0.784
   Target thermal jump distance (µm)           0.484        0.466        0.496
   Effective contact pressure (MPa)            0.000        0.000        0.000
   Pressure index                             15.099       14.990       15.247
   Gas thermal conductivity (W/m·°C)           0.088        0.086        0.089
   Solid spot conductance (W/m²·C)             0.000        0.000        0.000
   Gas gap conductance (W/m²·C)             1810.388     1746.815     1865.961

   Contact status codes:
    ---------------------------------------------
    0=open/no heat transfer, 1=near-field contact
    2=closed and sliding,    3=closed and sticking

------------------------------------------------------------------------------
CONTACT SUMMARY FOR CONTACT ID 41: Clad2 To Housing {Frictionless}
   Contact surface material:     Zircaloy
   Target surface material:       AL-6061
   Interstitial gas:             552HE_44
   Effective surface roughness:     2.263 µm
   Effective asperity slope:        0.214 rad
   Effective microhardness:         1.220 GPa

                                             Average      Minimum      Maximum
                                        ------------ ------------ ------------
   ~~~~~~~~~~~ direct results ~~~~~~~~~~
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Contact status                                 1.000        1.000        1.000
Contact temperature (°C)                     363.237      360.982      376.953
Target temperature (°C)                       64.730       60.119       65.241
Geometric gas gap (µm)                        49.882       49.837       49.969
Contact pressure (MPa)                         0.000        0.000        0.000
Gap conduction heat flux (kW/m²)             541.547      534.140      588.928
Radiation heat flux (kW/m²)                    0.000        0.000        0.000
Contact conduction heat flux (kW/m²)           0.000        0.000        0.000
Total heat flux (kW/m²)                      541.547      534.140      588.928
Thermal contact conductance (W/m²·C)        1814.125     1805.028     1859.276
~~~~~~~~~~ derived results ~~~~~~~~~~
Effective gas gap (µm)                        47.101       46.207       47.284
Contact thermal jump distance (µm)             0.751        0.745        0.773
Target thermal jump distance (µm)              0.485        0.480        0.492
Effective contact pressure (MPa)               0.000        0.000        0.000
Pressure index                                15.091       15.023       15.102
Gas thermal conductivity (W/m·°C)              0.088        0.087        0.089
Solid spot conductance (W/m²·C)                0.000        0.000        0.000
Gas gap conductance (W/m²·C)                1814.819     1805.606     1859.801

Contact status codes:
 ----------------------------------------------
 0=open/no heat transfer, 1=near-field contact
 2=closed and sliding,    3=closed and sticking
```

B-3. INCONEL CLADDING

```
********************************************************************************
                             OUTPUT SUMMARY FILE
 ********************************************************************************

  --------------------------------------------------------------------------------
  INPUTS

 * Thermal only solution with calculated gaps
 * Symmetry angle:  90.00 degrees
 * Fill gas: 407HE_59
 * Radiative heat transfer excluded
 * 3D  problem geometry
 * Target temperature:  350.0 °C
 * Target dose (in SiC):   2.300 dpa
 * Capsule pressure:  215.45 kPa
 * Cladding Material: Inconel
 * Clad ID =  8.7000 mm, Clad OD =  9.5000 mm, Housing ID =  9.6000 mm
 * Gas gap:   50.00 µm
 * Backfill gas:   40.70% He,   59.30% Ar
 * Irradiation facility: TRRH
 * Axial position: 5
 * Capsule centerline position =   6.09 cm (  2.40 in)
 * Axial peaking factor above the core midplane: 30.070 cm
 * Axial peaking factor below the core midplane: 30.070 cm

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  BOUNDARY CONDITIONS

  Heat generation rate scaling factor = 1.0000
  Heat transfer coefficient =  47100. W/m²·°C
  Bulk coolant temperature  =    52.0 °C

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  HEAT GENERATION

                                              Heat Gen.   ------ Heat Load -----
                                              @Midplane   @Midplane    @Location
   Part                              Material  (W/kg)       (W)          (W)
 ----------------------------------- --------  ---------   ---------    ---------
   1) Housing                        AL-6061      32500.       132.8        127.5
   2) Cap                            AL-6061      32500.        17.1         15.6
   3) Grafoil1                       GRAFOIL      33700.         0.2          0.2
   4) Grafoil2                       GRAFOIL      33700.         0.2          0.2
   5) Grafoil3                       GRAFOIL      33700.         0.3          0.3
   6) Grafoil4                       GRAFOIL      33700.         0.3          0.3
   7) Thimble1a                      Ti-6Al4V     35200.         7.1          7.0
   8) Clad1                          Inconel      39300.        93.0         91.0
   9) Thimble1b                      Ti-6Al4V     35200.         7.1          6.8
  10) Sleeve1                        Moly         43300.       341.2        333.8
  11) TM1                            SiC(Irr)     32900.         4.0          3.9
  12) Thimble2a                      Ti-6Al4V     35200.         7.1          6.8
  13) Clad2                          Inconel      39300.        93.0         88.1
  14) Thimble2b                      Ti-6Al4V     35200.         7.1          6.5
  15) Sleeve2                        Moly         43300.       341.2        323.0
  16) TM2                            SiC(Irr)     32900.         4.0          3.8
  17) Wire1                          Moly         43300.         0.8          0.7
  18) Wire2                          Moly         43300.         0.8          0.7
  19) Wire3                          Moly         43300.         0.8          0.7
  20) Wire4                          Moly         43300.         0.8          0.7
 ----------------------------------- --------  ---------   ---------    ---------
                                                              1058.5       1017.7

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  CAPSULE TEMPERATURE SUMMARY
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Name	Material	Tavg	Tmin	Tmax	T.025	T.975
1) Housing	AL-6061	64.	54.	77.	54.	75.
2) Cap	AL-6061	133.	132.	135.	132.	135.
3) Grafoil1	GRAFOIL	142.	133.	151.	137.	145.
4) Grafoil2	GRAFOIL	207.	182.	226.	185.	219.
5) Grafoil3	GRAFOIL	516.	506.	519.	508.	519.
6) Grafoil4	GRAFOIL	516.	509.	519.	510.	519.
7) Thimble1a	Ti-6Al4V	365.	277.	467.	285.	458.
8) Clad1	Inconel	365.	335.	407.	354.	374.
9) Thimble1b	Ti-6Al4V	526.	438.	533.	499.	532.
10) Sleeve1	Moly	496.	479.	509.	481.	507.
11) TM1	SiC(Irr)	533.	486.	545.	496.	544.
12) Thimble2a	Ti-6Al4V	524.	437.	532.	494.	531.
13) Clad2	Inconel	366.	357.	402.	361.	374.
14) Thimble2b	Ti-6Al4V	517.	433.	523.	495.	522.
15) Sleeve2	Moly	499.	494.	506.	495.	505.
16) TM2	SiC(Irr)	537.	530.	540.	534.	540.
17) Wire1	Moly	549.	534.	560.	535.	559.
18) Wire2	Moly	576.	560.	587.	562.	587.
19) Wire3	Moly	574.	558.	584.	560.	584.
20) Wire4	Moly	566.	551.	576.	552.	576.

PROPERTY SUMMARY AT THE AVERAGE PART TEMPERATURE

Name	Material	Thermal Cond. (W/m·°C)	Thermal Exp. Coeff. (μm/m·°C)	Emis (---)
1) Housing	AL-6061	167.141	24.21	0.050
2) Cap	AL-6061	174.351	0.00	0.050
3) Grafoil1	GRAFOIL	38.000	1.00	0.500
4) Grafoil2	GRAFOIL	38.000	1.00	0.500
5) Grafoil3	GRAFOIL	38.000	1.00	0.500
6) Grafoil4	GRAFOIL	38.000	1.00	0.500
7) Thimble1a	Ti-6Al4V	13.864	9.99	0.382
8) Clad1	Inconel	16.404	13.72	0.925
9) Thimble1b	Ti-6Al4V	17.080	10.31	0.404
10) Sleeve1	Moly	119.221	5.20	0.077
11) TM1	SiC(Irr)	8.611	3.83	0.900
12) Thimble2a	Ti-6Al4V	17.052	10.30	0.404
13) Clad2	Inconel	16.418	13.72	0.925
14) Thimble2b	Ti-6Al4V	16.934	10.29	0.404
15) Sleeve2	Moly	119.129	5.20	0.077
16) TM2	SiC(Irr)	8.608	3.84	0.900
17) Wire1	Moly	117.337	0.00	0.083
18) Wire2	Moly	116.521	0.00	0.086
19) Wire3	Moly	116.592	0.00	0.086
20) Wire4	Moly	116.827	0.00	0.085

STORED ENERGY SUMMARY AT THE AVERAGE PART TEMPERATURE

Name	Material	Mass (g)	Tavg (°C)	Specific Heat (J/kg°C)	Stored Energy (J)
1) Housing	AL-6061	4.085	64.	888.	160.
2) Cap	AL-6061	0.527	133.	939.	56.
3) Grafoil1	GRAFOIL	0.006	142.	700.	1.
4) Grafoil2	GRAFOIL	0.006	207.	700.	1.
5) Grafoil3	GRAFOIL	0.008	516.	700.	3.
6) Grafoil4	GRAFOIL	0.008	516.	700.	3.
7) Thimble1a	Ti-6Al4V	0.200	365.	714.	49.
8) Clad1	Inconel	2.367	365.	511.	417.

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  9) Thimble1b                  Ti-6Al4V    0.200     526.     783.      79.
 10) Sleeve1                    Moly        7.879     496.     275.    1032.
 11) TM1                        SiC(Irr)    0.122     533.    1129.      71.
 12) Thimble2a                  Ti-6Al4V    0.200     524.     782.      79.
 13) Clad2                      Inconel     2.367     366.     511.     419.
 14) Thimble2b                  Ti-6Al4V    0.200     517.     778.      78.
 15) Sleeve2                    Moly        7.879     499.     275.    1037.
 16) TM2                        SiC(Irr)    0.122     537.    1130.      71.
 17) Wire1                      Moly        0.017     549.     277.       3.
 18) Wire2                      Moly        0.017     576.     279.       3.
 19) Wire3                      Moly        0.017     574.     279.       3.
 20) Wire4                      Moly        0.017     566.     279.       3.
                                           --------                  --------
                                            26.249                    3565.

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  CLAD TO HOUSING GAP REPORTS


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CONTACT SUMMARY FOR CONTACT ID 39: Clad1 To Housing {Frictionless}
   Contact surface material:      Inconel
   Target surface material:       AL-6061
   Interstitial gas:             407HE_59
   Effective surface roughness:     2.263 µm
   Effective asperity slope:        0.214 rad
   Effective microhardness:         1.127 GPa

                                              Average      Minimum      Maximum
                                         ------------ ------------ ------------
   ~~~~~~~~~~~ direct results ~~~~~~~~~~
   Contact status                               1.000        1.000        1.000
   Contact temperature (°C)                   358.315      338.323      388.010
   Target temperature (°C)                     65.684       63.185       66.005
   Geometric gas gap (µm)                      49.882       49.837       49.969
   Contact pressure (MPa)                       0.000        0.000        0.000
   Gap conduction heat flux (kW/m²)           568.089      501.012      691.605
   Radiation heat flux (kW/m²)                  0.000        0.000        0.000
   Contact conduction heat flux (kW/m²)         0.000        0.000        0.000
   Total heat flux (kW/m²)                    568.089      501.012      691.605
   Thermal contact conductance (W/m²·C)      1940.920     1837.272     2132.499
   ~~~~~~~~~~ derived results ~~~~~~~~~~
   Effective gas gap (µm)                      33.121       30.654       34.529
   Contact thermal jump distance (µm)           0.492        0.474        0.519
   Target thermal jump distance (µm)            0.377        0.368        0.390
   Effective contact pressure (MPa)             0.000        0.000        0.000
   Pressure index                              21.309       21.223       21.367
   Gas thermal conductivity (W/m·°C)            0.066        0.065        0.067
   Solid spot conductance (W/m²·C)              0.000        0.000        0.000
   Gas gap conductance (W/m²·C)              1939.716     1835.929     2131.190

   Contact status codes:
    ---------------------------------------------
    0=open/no heat transfer, 1=near-field contact
    2=closed and sliding,    3=closed and sticking

--------------------------------------------------------------------------------
CONTACT SUMMARY FOR CONTACT ID 41: Clad2 To Housing {Frictionless}
   Contact surface material:      Inconel
   Target surface material:       AL-6061
   Interstitial gas:             407HE_59
   Effective surface roughness:     2.263 µm
   Effective asperity slope:        0.214 rad
   Effective microhardness:         1.127 GPa

                                              Average      Minimum      Maximum
                                         ------------ ------------ ------------
   ~~~~~~~~~~~ direct results ~~~~~~~~~~
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Contact status                              1.000       1.000       1.000
Contact temperature (°C)                  359.274     357.435     382.935
Target temperature (°C)                    65.366      60.508      65.886
Geometric gas gap (µm)                     49.882      49.837      49.969
Contact pressure (MPa)                      0.000       0.000       0.000
Gap conduction heat flux (kW/m²)          572.516     563.379     682.392
Radiation heat flux (kW/m²)                 0.000       0.000       0.000
Contact conduction heat flux (kW/m²)        0.000       0.000       0.000
Total heat flux (kW/m²)                   572.516     563.379     682.392
Thermal contact conductance (W/m²·C)     1947.749    1930.924    2117.974
~~~~~~~~~~ derived results ~~~~~~~~~~
Effective gas gap (µm)                     33.014      30.692      33.273
Contact thermal jump distance (µm)          0.493       0.488       0.514
Target thermal jump distance (µm)           0.378       0.373       0.388
Effective contact pressure (MPa)            0.000       0.000       0.000
Pressure index                             21.307      21.238      21.312
Gas thermal conductivity (W/m·°C)           0.066       0.066       0.067
Solid spot conductance (W/m²·C)             0.000       0.000       0.000
Gas gap conductance (W/m²·C)             1946.414    1929.541    2116.963

Contact status codes:
 ----------------------------------------------
 0=open/no heat transfer, 1=near-field contact
 2=closed and sliding,    3=closed and sticking
```

ATTACHMENT 1

1D SIMULATION RESULTS

Case #	Loc	Pos	Clad ID (mm)	Clad OD (mm)	Hous ID (mm)	Cold gap (mm)	Material (1=SS, 2=Zirc, 3=Inc)	Hot gap (mm)	Heat Flux (W/m^2)	Effective k (W/m-K)	He mole %
1	TRRH	5	8.100	9.500	9.580	0.040	1	0.014	530362	0.027	0.6%
2	TRRH	5	8.100	9.500	9.600	0.050	1	0.024	529807	0.046	21.3%
3	TRRH	5	8.100	9.500	9.620	0.060	1	0.034	529252	0.064	37.5%
4	TRRH	5	8.100	9.500	9.640	0.070	1	0.044	528699	0.083	50.7%
5	TRRH	5	8.100	9.500	9.660	0.080	1	0.054	528147	0.102	61.5%
6	TRRH	5	8.200	9.500	9.580	0.040	1	0.014	535542	0.027	0.9%
7	TRRH	5	8.200	9.500	9.600	0.050	1	0.024	534981	0.046	21.7%
8	TRRH	5	8.200	9.500	9.620	0.060	1	0.034	534422	0.065	38.0%
9	TRRH	5	8.200	9.500	9.640	0.070	1	0.044	533863	0.084	51.2%
10	TRRH	5	8.200	9.500	9.660	0.080	1	0.054	533306	0.103	62.0%
11	TRRH	5	8.300	9.500	9.580	0.040	1	0.014	540786	0.027	1.3%
12	TRRH	5	8.300	9.500	9.600	0.050	1	0.024	540220	0.046	22.2%
13	TRRH	5	8.300	9.500	9.620	0.060	1	0.034	539655	0.066	38.5%
14	TRRH	5	8.300	9.500	9.640	0.070	1	0.044	539091	0.085	51.7%
15	TRRH	5	8.300	9.500	9.660	0.080	1	0.054	538528	0.104	62.5%
16	TRRH	5	8.400	9.500	9.580	0.040	1	0.014	546094	0.028	1.6%
17	TRRH	5	8.400	9.500	9.600	0.050	1	0.024	545523	0.047	22.6%
18	TRRH	5	8.400	9.500	9.620	0.060	1	0.034	544952	0.066	39.0%
19	TRRH	5	8.400	9.500	9.640	0.070	1	0.044	544382	0.085	52.2%
20	TRRH	5	8.400	9.500	9.660	0.080	1	0.054	543814	0.105	63.1%
21	TRRH	5	8.500	9.500	9.580	0.040	1	0.014	551467	0.028	1.9%
22	TRRH	5	8.500	9.500	9.600	0.050	1	0.024	550889	0.047	23.0%
23	TRRH	5	8.500	9.500	9.620	0.060	1	0.034	550313	0.067	39.5%
24	TRRH	5	8.500	9.500	9.640	0.070	1	0.044	549738	0.086	52.7%
25	TRRH	5	8.500	9.500	9.660	0.080	1	0.054	549164	0.106	63.6%
26	TRRH	5	8.600	9.500	9.580	0.040	1	0.014	556903	0.028	2.3%
27	TRRH	5	8.600	9.500	9.600	0.050	1	0.024	556320	0.048	23.5%
28	TRRH	5	8.600	9.500	9.620	0.060	1	0.034	555738	0.068	40.0%
29	TRRH	5	8.600	9.500	9.640	0.070	1	0.044	555157	0.087	53.2%
30	TRRH	5	8.600	9.500	9.660	0.080	1	0.054	554578	0.107	64.1%
31	TRRH	5	8.700	9.500	9.580	0.040	1	0.014	562404	0.028	2.6%
32	TRRH	5	8.700	9.500	9.600	0.050	1	0.024	561815	0.048	23.9%
33	TRRH	5	8.700	9.500	9.620	0.060	1	0.034	561227	0.068	40.5%
34	TRRH	5	8.700	9.500	9.640	0.070	1	0.044	560641	0.088	53.8%
35	TRRH	5	8.700	9.500	9.660	0.080	1	0.054	560055	0.108	64.6%
36	TRRH	5	8.800	9.500	9.580	0.040	1	0.014	567968	0.029	2.9%
37	TRRH	5	8.800	9.500	9.600	0.050	1	0.024	567374	0.049	24.4%
38	TRRH	5	8.800	9.500	9.620	0.060	1	0.034	566780	0.069	41.0%
39	TRRH	5	8.800	9.500	9.640	0.070	1	0.044	566188	0.089	54.3%

Case #	Loc	Pos	Clad ID (mm)	Clad OD (mm)	Hous ID (mm)	Cold gap (mm)	Material (1=SS, 2=Zirc, 3=Inc)	Hot gap (mm)	Heat Flux (W/m^2)	Effective k (W/m-K)	He mole %
40	TRRH	5	8.800	9.500	9.660	0.080	1	0.054	565597	0.109	65.2%
41	TRRH	5	8.900	9.500	9.580	0.040	1	0.014	573597	0.029	3.3%
42	TRRH	5	8.900	9.500	9.600	0.050	1	0.024	572997	0.049	24.8%
43	TRRH	5	8.900	9.500	9.620	0.060	1	0.034	572397	0.070	41.5%
44	TRRH	5	8.900	9.500	9.640	0.070	1	0.044	571799	0.090	54.8%
45	TRRH	5	8.900	9.500	9.660	0.080	1	0.054	571202	0.110	65.7%
46	TRRH	5	8.100	9.500	9.580	0.040	2	0.038	483825	0.065	37.9%
47	TRRH	5	8.100	9.500	9.600	0.050	2	0.048	483318	0.082	49.9%
48	TRRH	5	8.100	9.500	9.620	0.060	2	0.058	482812	0.099	60.0%
49	TRRH	5	8.100	9.500	9.640	0.070	2	0.068	482308	0.116	68.6%
50	TRRH	5	8.100	9.500	9.660	0.080	2	0.078	481804	0.133	76.0%
51	TRRH	5	8.200	9.500	9.580	0.040	2	0.038	492083	0.066	38.7%
52	TRRH	5	8.200	9.500	9.600	0.050	2	0.048	491568	0.083	50.8%
53	TRRH	5	8.200	9.500	9.620	0.060	2	0.058	491054	0.101	60.9%
54	TRRH	5	8.200	9.500	9.640	0.070	2	0.068	490541	0.118	69.5%
55	TRRH	5	8.200	9.500	9.660	0.080	2	0.078	490028	0.135	76.9%
56	TRRH	5	8.300	9.500	9.580	0.040	2	0.038	500444	0.067	39.6%
57	TRRH	5	8.300	9.500	9.600	0.050	2	0.048	499920	0.085	51.7%
58	TRRH	5	8.300	9.500	9.620	0.060	2	0.058	499397	0.102	61.8%
59	TRRH	5	8.300	9.500	9.640	0.070	2	0.068	498875	0.120	70.4%
60	TRRH	5	8.300	9.500	9.660	0.080	2	0.078	498354	0.138	77.8%
61	TRRH	5	8.400	9.500	9.580	0.040	2	0.038	508906	0.068	40.4%
62	TRRH	5	8.400	9.500	9.600	0.050	2	0.048	508373	0.086	52.6%
63	TRRH	5	8.400	9.500	9.620	0.060	2	0.058	507841	0.104	62.7%
64	TRRH	5	8.400	9.500	9.640	0.070	2	0.068	507311	0.122	71.3%
65	TRRH	5	8.400	9.500	9.660	0.080	2	0.078	506781	0.140	78.7%
66	TRRH	5	8.500	9.500	9.580	0.040	2	0.038	517470	0.069	41.2%
67	TRRH	5	8.500	9.500	9.600	0.050	2	0.048	516928	0.088	53.5%
68	TRRH	5	8.500	9.500	9.620	0.060	2	0.058	516388	0.106	63.6%
69	TRRH	5	8.500	9.500	9.640	0.070	2	0.068	515848	0.124	72.2%
70	TRRH	5	8.500	9.500	9.660	0.080	2	0.078	515310	0.142	79.6%
71	TRRH	5	8.600	9.500	9.580	0.040	2	0.038	526136	0.070	42.1%
72	TRRH	5	8.600	9.500	9.600	0.050	2	0.048	525585	0.089	54.4%
73	TRRH	5	8.600	9.500	9.620	0.060	2	0.058	525036	0.108	64.5%
74	TRRH	5	8.600	9.500	9.640	0.070	2	0.068	524487	0.126	73.1%
75	TRRH	5	8.600	9.500	9.660	0.080	2	0.078	523940	0.145	80.5%
76	TRRH	5	8.700	9.500	9.580	0.040	2	0.038	534904	0.072	42.9%
77	TRRH	5	8.700	9.500	9.600	0.050	2	0.048	534344	0.090	55.2%
78	TRRH	5	8.700	9.500	9.620	0.060	2	0.058	533785	0.109	65.4%

Case #	Loc	Pos	Clad ID (mm)	Clad OD (mm)	Hous ID (mm)	Cold gap (mm)	Material (1=SS, 2=Zirc, 3=Inc)	Hot gap (mm)	Heat Flux (W/m^2)	Effective k (W/m-K)	He mole %
79	TRRH	5	8.700	9.500	9.640	0.070	2	0.068	533228	0.128	74.0%
80	TRRH	5	8.700	9.500	9.660	0.080	2	0.078	532671	0.147	81.4%
81	TRRH	5	8.800	9.500	9.580	0.040	2	0.038	543774	0.073	43.8%
82	TRRH	5	8.800	9.500	9.600	0.050	2	0.048	543205	0.092	56.1%
83	TRRH	5	8.800	9.500	9.620	0.060	2	0.058	542637	0.111	66.3%
84	TRRH	5	8.800	9.500	9.640	0.070	2	0.068	542070	0.130	74.9%
85	TRRH	5	8.800	9.500	9.660	0.080	2	0.078	541504	0.149	82.2%
86	TRRH	5	8.900	9.500	9.580	0.040	2	0.038	552746	0.074	44.6%
87	TRRH	5	8.900	9.500	9.600	0.050	2	0.048	552167	0.093	57.0%
88	TRRH	5	8.900	9.500	9.620	0.060	2	0.058	551590	0.113	67.2%
89	TRRH	5	8.900	9.500	9.640	0.070	2	0.068	551013	0.132	75.8%
90	TRRH	5	8.900	9.500	9.660	0.080	2	0.078	550438	0.152	83.1%
91	TRRH	5	8.100	9.500	9.580	0.040	3	0.024	536475	0.046	21.6%
92	TRRH	5	8.100	9.500	9.600	0.050	3	0.034	535913	0.065	38.0%
93	TRRH	5	8.100	9.500	9.620	0.060	3	0.044	535352	0.084	51.2%
94	TRRH	5	8.100	9.500	9.640	0.070	3	0.054	534793	0.103	62.0%
95	TRRH	5	8.100	9.500	9.660	0.080	3	0.064	534235	0.122	71.2%
96	TRRH	5	8.200	9.500	9.580	0.040	3	0.024	541250	0.046	22.0%
97	TRRH	5	8.200	9.500	9.600	0.050	3	0.034	540683	0.065	38.4%
98	TRRH	5	8.200	9.500	9.620	0.060	3	0.044	540118	0.085	51.7%
99	TRRH	5	8.200	9.500	9.640	0.070	3	0.054	539553	0.104	62.5%
100	TRRH	5	8.200	9.500	9.660	0.080	3	0.064	538990	0.123	71.6%
101	TRRH	5	8.300	9.500	9.580	0.040	3	0.024	546085	0.047	22.4%
102	TRRH	5	8.300	9.500	9.600	0.050	3	0.034	545513	0.066	38.9%
103	TRRH	5	8.300	9.500	9.620	0.060	3	0.044	544943	0.085	52.1%
104	TRRH	5	8.300	9.500	9.640	0.070	3	0.054	544373	0.105	63.0%
105	TRRH	5	8.300	9.500	9.660	0.080	3	0.064	543805	0.124	72.1%
106	TRRH	5	8.400	9.500	9.580	0.040	3	0.024	550979	0.047	22.8%
107	TRRH	5	8.400	9.500	9.600	0.050	3	0.034	550402	0.067	39.3%
108	TRRH	5	8.400	9.500	9.620	0.060	3	0.044	549826	0.086	52.6%
109	TRRH	5	8.400	9.500	9.640	0.070	3	0.054	549252	0.105	63.5%
110	TRRH	5	8.400	9.500	9.660	0.080	3	0.064	548678	0.125	72.6%
111	TRRH	5	8.500	9.500	9.580	0.040	3	0.024	555932	0.048	23.2%
112	TRRH	5	8.500	9.500	9.600	0.050	3	0.034	555350	0.067	39.8%
113	TRRH	5	8.500	9.500	9.620	0.060	3	0.044	554769	0.087	53.1%
114	TRRH	5	8.500	9.500	9.640	0.070	3	0.054	554189	0.106	64.0%
115	TRRH	5	8.500	9.500	9.660	0.080	3	0.064	553611	0.126	73.1%
116	TRRH	5	8.600	9.500	9.580	0.040	3	0.024	560944	0.048	23.6%
117	TRRH	5	8.600	9.500	9.600	0.050	3	0.034	560357	0.068	40.2%

Case #	Loc	Pos	Clad ID (mm)	Clad OD (mm)	Hous ID (mm)	Cold gap (mm)	Material (1=SS, 2=Zirc, 3=Inc)	Hot gap (mm)	Heat Flux (W/m^2)	Effective k (W/m-K)	He mole %
118	TRRH	5	8.600	9.500	9.620	0.060	3	0.044	559771	0.088	53.5%
119	TRRH	5	8.600	9.500	9.640	0.070	3	0.054	559186	0.107	64.5%
120	TRRH	5	8.600	9.500	9.660	0.080	3	0.064	558602	0.127	73.6%
121	TRRH	5	8.700	9.500	9.580	0.040	3	0.024	566016	0.048	24.0%
122	TRRH	5	8.700	9.500	9.600	0.050	3	0.034	565423	0.068	40.7%
123	TRRH	5	8.700	9.500	9.620	0.060	3	0.044	564832	0.088	54.0%
124	TRRH	5	8.700	9.500	9.640	0.070	3	0.054	564241	0.108	64.9%
125	TRRH	5	8.700	9.500	9.660	0.080	3	0.064	563652	0.128	74.0%
126	TRRH	5	8.800	9.500	9.580	0.040	3	0.024	571146	0.049	24.4%
127	TRRH	5	8.800	9.500	9.600	0.050	3	0.034	570548	0.069	41.1%
128	TRRH	5	8.800	9.500	9.620	0.060	3	0.044	569951	0.089	54.5%
129	TRRH	5	8.800	9.500	9.640	0.070	3	0.054	569356	0.109	65.4%
130	TRRH	5	8.800	9.500	9.660	0.080	3	0.064	568762	0.129	74.5%
131	TRRH	5	8.900	9.500	9.580	0.040	3	0.024	576336	0.049	24.8%
132	TRRH	5	8.900	9.500	9.600	0.050	3	0.034	575732	0.070	41.6%
133	TRRH	5	8.900	9.500	9.620	0.060	3	0.044	575130	0.090	55.0%
134	TRRH	5	8.900	9.500	9.640	0.070	3	0.054	574529	0.110	65.9%
135	TRRH	5	8.900	9.500	9.660	0.080	3	0.064	573930	0.131	75.0%