Sandia National Laboratories

Securing the future of Nuclear Energy

Radiant Heat Transfer Modeling

2024 European MELCOR Users' Group Meeting

April 15th-18th, 2024

SAND2024-04206PE

Multiple Models for Radiant Heat Transfer

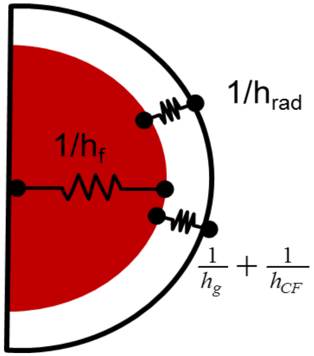
- COR Package
  - Intracell radiation
    - Fuel to clad gap
    - Radiation in porous media
  - Intercell radiation
    - Radiative Exchange Factors
      - Ring to Ring Radiation
      - Axial radiation
    - Optical Beam Length Model
  - Multi-rod modeling
  - Radiation from molten pool surface
  - Radiation from outer surface of lower head
  - User defined heat transfer paths
  - Radiation to small scale experiments
  - Effect of frozen conglomerate mass
  - Radiation to participating media
- HS Package
  - Surface to surface radiant heat transfer
  - Radiation enclosure model
  - Radiation to participating media (i.e., steam)
  - Radiation to aerosols
- Radiation between COR package components & HS package

Heat Transfer
Radiation across fuell-cladding gap

Pellet/Clad Gap

$$\frac{1}{h_{gap}} = \frac{1}{h_f} + \frac{1}{\dfrac{1}{\dfrac{1}{h_g} + \dfrac{1}{h_{CF}}} + h_{rad}}$$

Where:



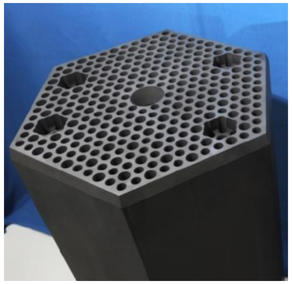
$$h_{rad} = \frac{4 \ \sigma \ T_a^3}{\dfrac{1}{\varepsilon_f} + \dfrac{1}{\varepsilon_c} - 1}$$

$$h_f = 4 \ k_f \ / \ r_f$$

$$h_g = k_g \ / \ \Delta r_g$$

COR Intercell Conduction

• Effective conductivity prescription for PD (LWR) and PMR



- Tanaka and Chisaka expression for effective radial conductivity (of a single PMR hex block)

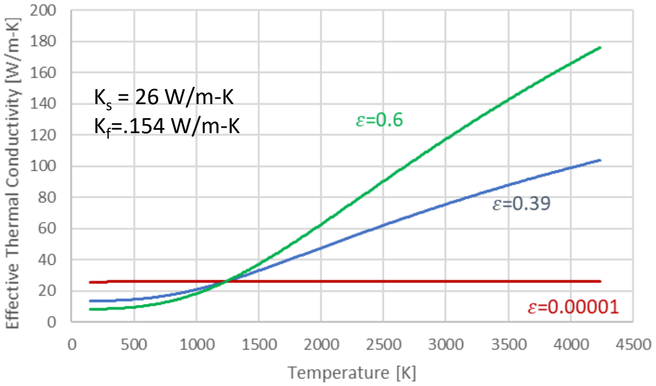
$$k_{eff} = k_s\left[A + (1-A)\frac{\ln\left(1 + 2B\left(k_{por}/k_s - 1\right)\right)}{2B\left(1 - k_s/k_{por}\right)}\right]$$

- A radiation term is incorporated in parallel with the pore conductivity

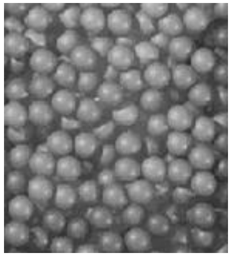
$$k_{rad} = 4\varepsilon_r \sigma T^3 D$$

- Thermal resistance of helium gaps between hex block fuel elements is added in parallel via a gap conductance term

$$k_{er} = \left({}^{1}/_{h_{gap}D_{blk}} + {}^{1}/_{k_{eff}}\right)^{-1}$$

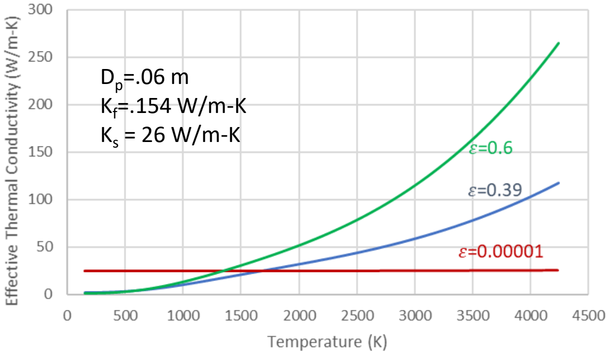


• Effective conductivity prescription for PBR (bed conductance)



- Zehner-Schlunder-Bauer with Breitbach-Barthels modification to the radiation term

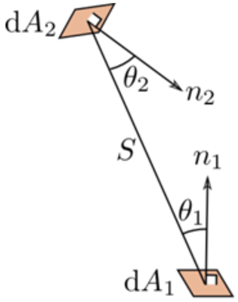
$$k_{eff} = \left(1 - \sqrt{1-\varepsilon}\right)\varepsilon 4\sigma T^3 D_p + \left(1 - \sqrt{1-\varepsilon}\right)k_f + \sqrt{1-\varepsilon}\,k_c(T, D_p, \varepsilon, k_f, k_s, k_r)$$



Radiative Exchange Factors Model

- Geometric Radiative Exchange Factors
  - Qualitatively represent radiation geometric view factors
    - Actual geometry may be too complicated

$$F_{1-2} = \frac{1}{A_1}\int_{A_1}\int_{A_2} \frac{\cos(\theta_1)\cos(\theta_2)}{\pi S^2}\, dA_1 dA_2$$



    - Can be calculated by Monte Carlo
      - MELCOR model (may have some issues still)
      - CFD codes often calculate view factors
  - Assume the combination of distance and view factor obstruction can be approximated as a simple exponential
    - fraction of un-obscured solid angle remaining visible to a differential surface at depth x is $e^{-\alpha x}$
    - Can be validated against more exact methods (Monte Carlo)
- Effective Exchange Factors
  - Effective exchange factors cannot account for the fact that for thick cells, radiation at the cell boundary “sees” only a fraction of the average temperature difference between cells.

MELCOR Radiative Exchange Factors (Zero order parametric model)

- Simple model for radiant heat exchange between components or COR cells.
  - Radiation Exchange Factors

$$A_1F_{12} \equiv A_2F_{21} \equiv AF = \min\left(A_1, A_2, A_{cell,x}\right)F_{cell,x}$$
$$= A_{cell,x}F_{cell,x}\min\left(A_1/A_{cell,x}, A_2/A_{cell,x}, 1\right)$$

  - where $F_{cell,x}$ is the effective inter-cell view factor input by the user and x may be r (radial) or a (axial),
  - A_1 is the surface area of the component in cell 1,
  - A_2 is the surface of the component in cell 2, and
  - F_{12} is the actual view factor between components in cells 1 and 2.

View factor	Default Value	Notes
FCNCL	0.25	Radiative exchange factor for radiation heat transfer from the canister wall to the fuel rod cladding surfaces. Reference manual suggests a value significantly smaller than unity to capture temperature gradient SFP_BWR: Redefined for radiation exchange between CB and CL
FSSCN	0.25	Radiative exchange factor for radiation from NS (e.g., control blades) to the adjacent canister walls or to fuel rods and debris if canister is not present. Note: Reference Manual recommends a value close to unity since control blade is close to adjacent surface SFP_BWR: • Redefined for radiation exchange from CL to RK SFP_PWR: • Redefined for radiation exchange from CL to RK • and for radiation exchange between fuel rods and control rods in PWR
FCELR	0.1	Radiative exchange factor for radiation heat transfer radially outward from the cell/node boundary to the adjacent cell/node boundary. SFP_BWR & SFP_PWR: Outer rack surface to fuel rods in adjacent ring
FCELA	0.1	Radiative exchange factor for radiation heat transfer axially upward from the cell/node boundary to the next adjacent cell/node boundary.
FLPUP	0.25	Radiative exchange factor for radiation from the liquid pool to the core components.

FCNCL and, FSSCN are intra-cell exchange factors

FCELR, FCELA, and FLPUP are inter-cell exchange factors

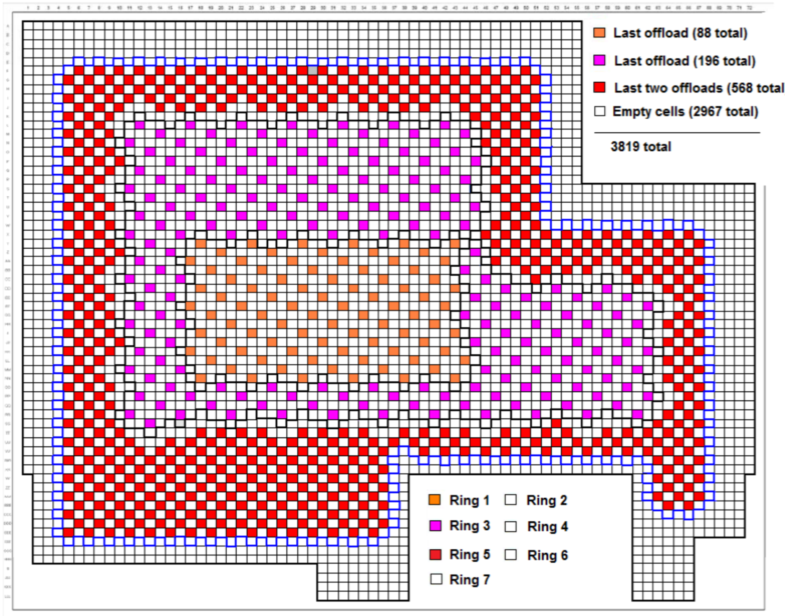
Exceptions to the Radiation Exchange Factors

User Supplied View Factors for COR Support.

- **COR_PR** – Global Downward Radiation from SS to Pool or Lower Head
  - By default, the general radiation model and radiation exchange factors are used for radiation from the lowest surface in the core to a pool or the lower head below. The view-factor-times-area product is taken as FLPUP MIN(Asurf, ASCELA) or FCELA MIN(Asurf, ALH), respectively. Here, the user can specify VFA and/or the emissivity to use for downward radiation

Reactor Modeling Requiring Special Treatment of Radiation Exchange Factors

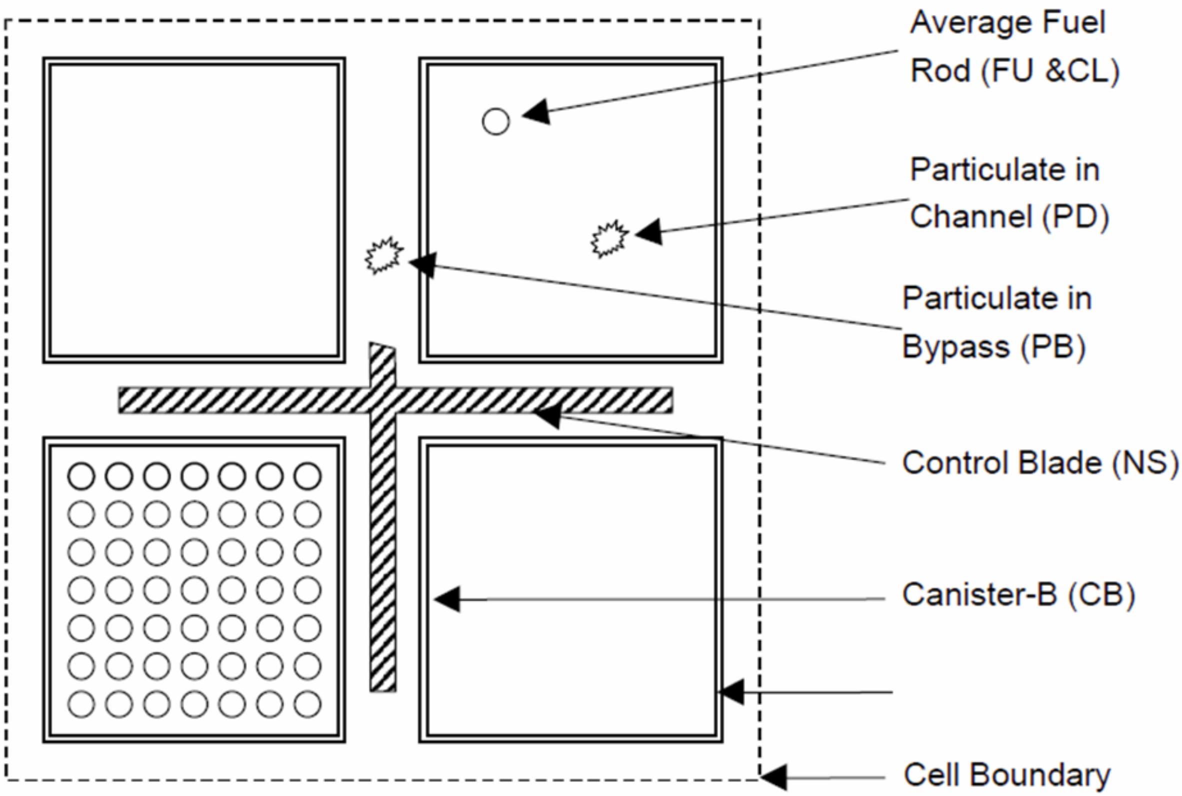
- HPR Modeling
  - User disables general radiation model
  - User provides User-defined heat transfer paths
- SFP Modeling
  - User disables general radiation model
  - User provides user-defined heat transfer paths
- Small-scale experiments
  - User disables general radiation model
  - User provides user-defined heat transfer paths



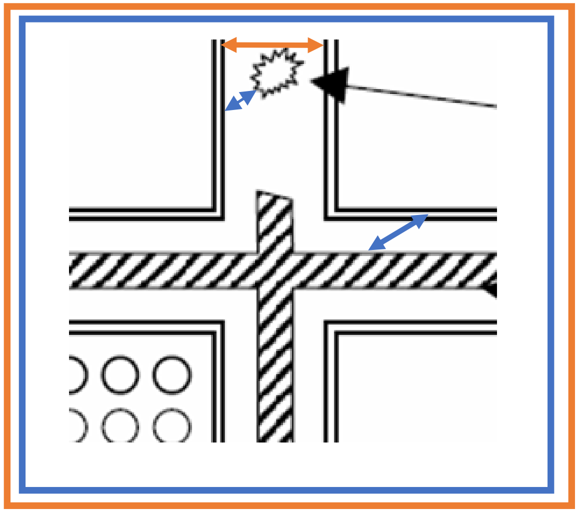
COR_HTR heat transfer paths are leveraged extensively in SFP modeling where the geometry is not concentric rings but regions with complex connections.

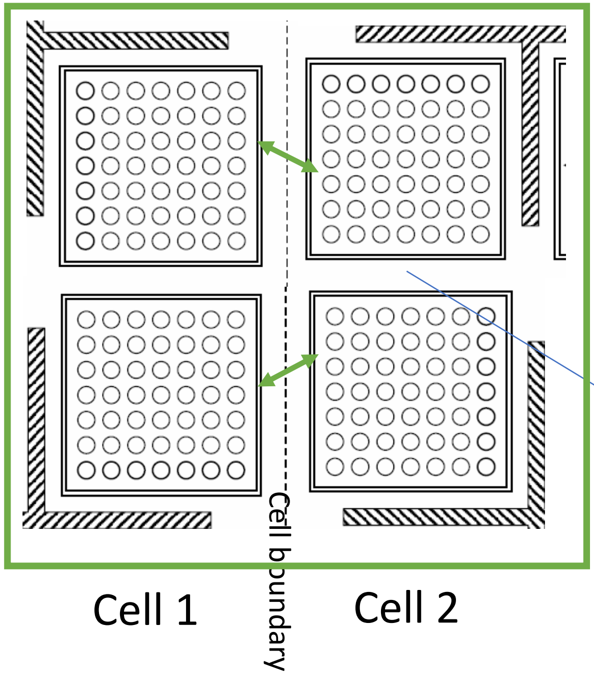
COR Component-wise Radiant Heat Transfer Model

- The determination of which surfaces “see” which other surfaces is not exhaustive but
  - The most important radiation exchange paths are included and
  - No surface is isolated, with each being allowed to radiate to at least one other surface.
- Radial case,
  - surfaces in the next cell are considered in the following order: outside of CN, CL, and FU and then inside of CB, NS, SS, FM, and PD.
  - If none of these exists, the next radial cell is considered.
- In the axial case
  - The order is CL, FU, inside of CN, inside of CB, NS, SS, FM, and PD.
  - If none of these exists, the next axial cell is considered.



COR Component Radiant Heat Transfer Logic Control Blade & Canister

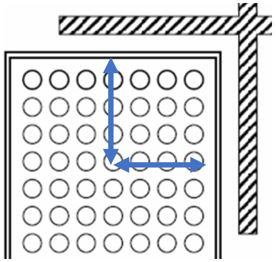




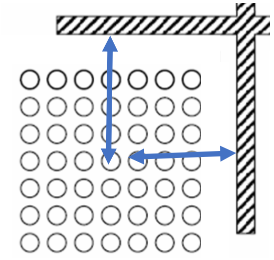
- That portion of the outer surface of intact canister CB in a core cell that does not see other outer CB surface in the same cell must radiate to NS representing the control blade and/or to PB in the same core cell. Similarly, some portion of the NS surface may radiate to PB.
- The remaining portions of these surfaces, $A'_{surf} = \mathrm{MAX}(A_{surf} - AF_{surf,pb}, 0)$, see each other accounting for that fact that porosity may result in large holes through the debris bed.
- That portion of the outer surface of intact canister CN in a core cell that does not see other outer CN surface in the same cell radiates to a component in the next radial cell:

Fraction of intact canister, CN, that sees CN in the SAME cell

COR Component Radiant Heat Transfer Logic
Fuel Rods

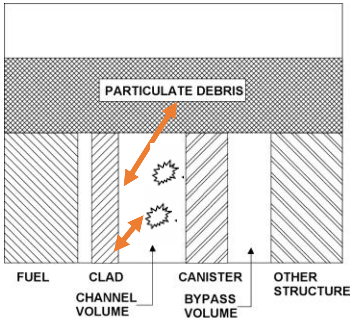


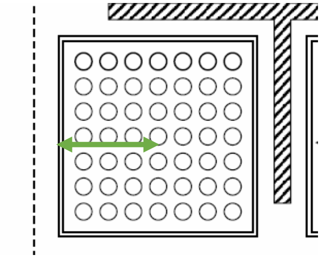
CB Intact



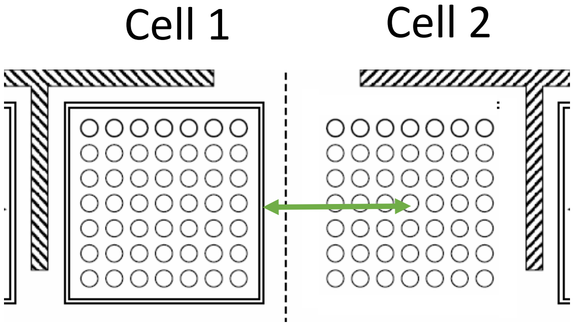
CB Gone

PD Present
(Debris Exclusion Off)





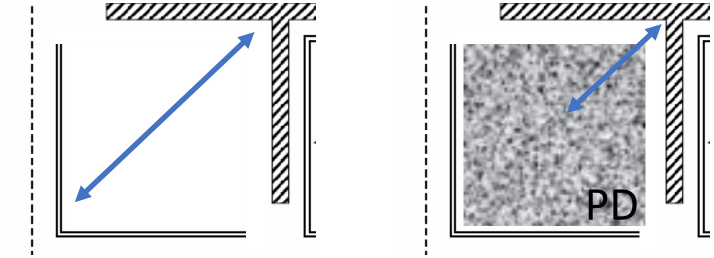
CN Intact



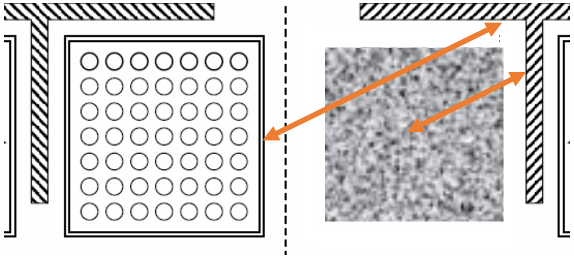
CN Gone in Cell 2

- Fuel rods radiate to the inner surface of canister CB in the same cell, if present ($AF = A_{cb} F_{cn,cl}$); otherwise they radiate to other structures (SS or NS) present in the same core cell ($AF = A_{xs} F_{ss,cn}$),
- Fuel rods radiate to PD in the same core cell ($AF = \mathrm{MIN}(A_{rod}, A_{pd}) 1)$, if any is present.
- If intact canister CN is present in the same core cell, fuel rods radiate to its inner surface ($AF = A_{cn} F_{cn,cl}$); otherwise, they radiate to a selected component in the next radial cell
- Fuel rods also radiate to a selected component in the next axial cell

COR Component Radiant Heat Transfer Logic
Fuel Rods and CB missing in cell



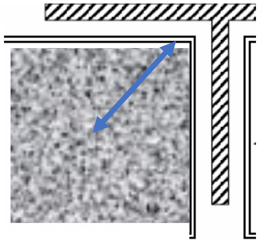
CN Intact, CB Missing

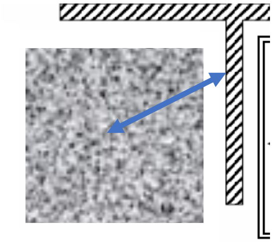


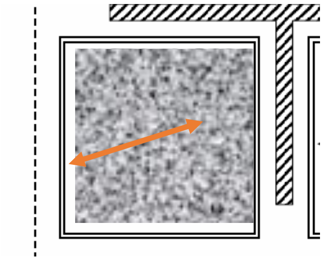
CN & CB Missing

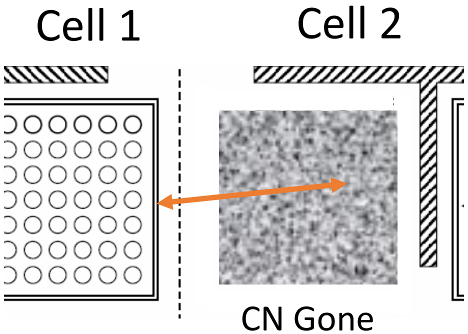
- In the absence of fuel rods and canister CB in a cell, NS or SS radiate to the inner surface of canister CN (AF = Axs Fss,cn) unless there is PD in the same cell.
- In the absence of fuel rods and both canister components (CN and CB) in a cell, NS or SS partition radiation between any PD in the same cell and selected surfaces in the next axial and radial cells. The fraction going to other cells is taken to be MAX(0, 1-Apd/AxS), where xS represents NS or SS, with NS taking precedence over SS, as previously discussed. AF = MIN(Acell,y, Axs, As,out) Fcell,y, , where y is a or r.

COR Component Radiant Heat Transfer Logic
Radiation from PD in the absence of fuel rods

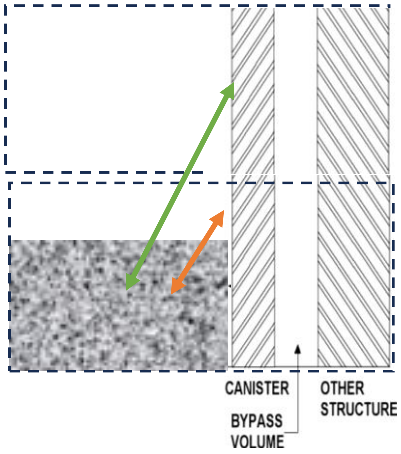

CB Intact


CB Gone


CN Intact
CN Intact



CN Gone



- In the absence of fuel rods, PD radiates to the inner surface of canister CB with AF = MIN(Acb, Apd) Fcn,cl ,or if there is no CB, to some other structures (NS or SS) in the same cell with AF = MIN(Axs, Apd) Fss,cn. (As with intercell radiation, NS takes precedence over SS.)
- In the absence of fuel rods, PD also radiates to the inner surface of canister CN (AF = MIN(Acn, Apd) Fcn,cl) or, if there is no CN, to a selected component in the next radial cell (AF = MIN(Acell,r, Apd, As,out) Fcell,r).
- In the absence of fuel rods, PD also radiates to a selected component in the next axial cell (AF = MIN(Acell,a, Apd, As,up) Fcell,a).

Improvements on Zero Order Radiative Exchange Factors

- By default, FCELR and FCELA are defined globally only

```
!          FCNCL   FSSCN   FCELR   FCELA   FLPUP
COR_RF      0.25    0.25    0.25    0.25    0.25
```

- FCELR and FCELA can also be defined locally
  - Can be defined as a local constant
  - Can be defined as a local control function
  - Can be calculated locally by internal model

```
COR_FCEL  4  FCELR
     7   .5     -     0.0   !IA=7,  FCELR(IR=1), FCELR(IR=2), FCELR(IR=3)
     8   .5   0.25    0.0
     9   .5   0.25    0.0
     10   MODEL   MODEL   0.0
COR_FCEL  1  FCELRCF
     7   -   5   -     !CF-5 used (alternatively could specify CF character name)
```

- The Intercell radiation model
  - Can be selected for any or all COR cells
  - Accounts for temperature gradient (optical thickness)
  - Developed for rodded geometry

Intercell Radiation Model (FCELR)

- Geometric view factor (no accounting for temperature effects)
  - The view factor between a cell of thickness of L_1 and one of thickness L_2 may be estimated as

$$A_1F_{12} = \int_{-L_1}^{0} dx_1 A_{cell} \left(\frac{A}{V}\right)_1 e^{\alpha_1 x_1} \int_{0}^{L_2} dx_2 \alpha_2 e^{-\alpha_e x_2}$$

  - In terms of dimensionless variables

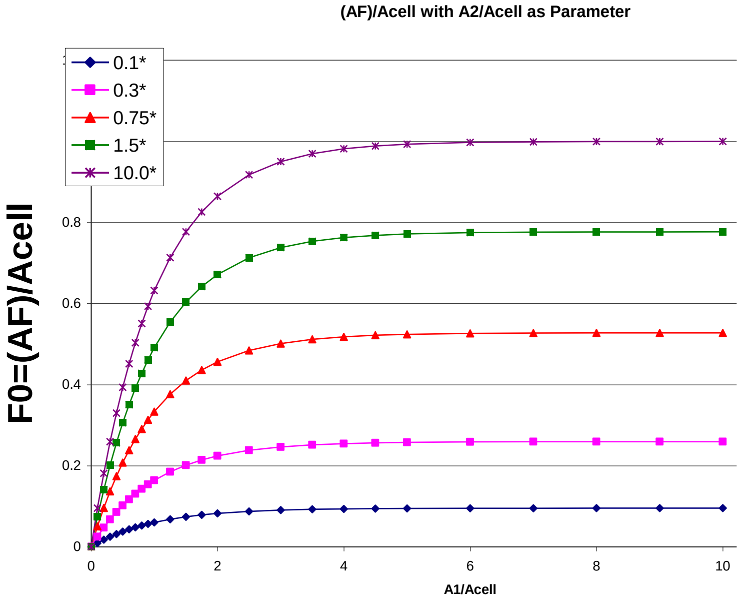
$$A_1F_{12} = A_{cell}\left(\frac{A}{\alpha V}\right)_1 \int_{-\alpha_1 L_1}^{0} dy_1 e^{y_1} \int_{-\alpha_2 L_2}^{0} dy_2 e^{y_2} = A_{cell}\left(\frac{A}{\alpha V}\right)_1 \left(1-e^{-\alpha_1 L_1}\right)\left(1-e^{-\alpha_2 L_2}\right)$$

$$where \quad \alpha_i L_i = \frac{A_i}{KA_{cell}}$$

  - By reciprocity

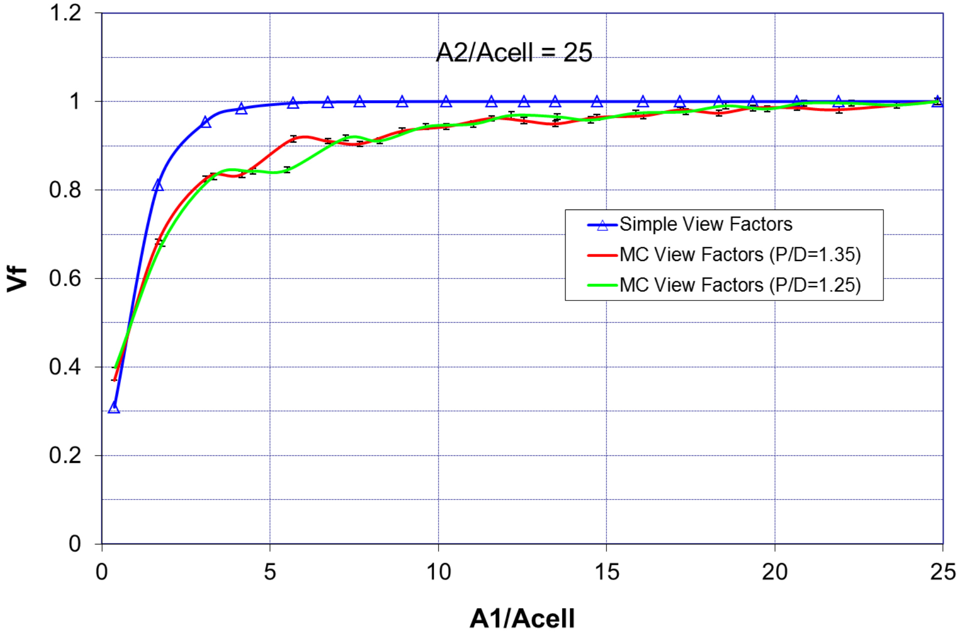
$$A_2F_{21} = A_2F_{21} = AF = A_{cell}F_0 = A_{cell}K\left(1-e^{-\alpha_1 L_1}\right)\left(1-e^{-\alpha_2 L_2}\right)$$

  - In limits (reasonable therefore to assume K = 1)
    - Both cells large $AF \to A_{cell}K$
    - Cell 1 small and cell 2 large $AF \to A_1$
    - Both cells small $AF \to \frac{A_1 A_2}{KA_{cell}}$



Geometric Radiative Exchange Factors – Assessment against Monte Carlo

- Simple geometric radiation exchange factors compared to Monte Carlo evaluated view factors.
  - Simple model is adequate for A/Acell > 10
- Monte Carlo utility was created for calculating both FCELR and FCELA exchange factors from fuel rod arrays.
  - Partially implemented as an option for PWR at MELGEN but only used for testing/assessment of model



Effective Radiative Exchange Factors

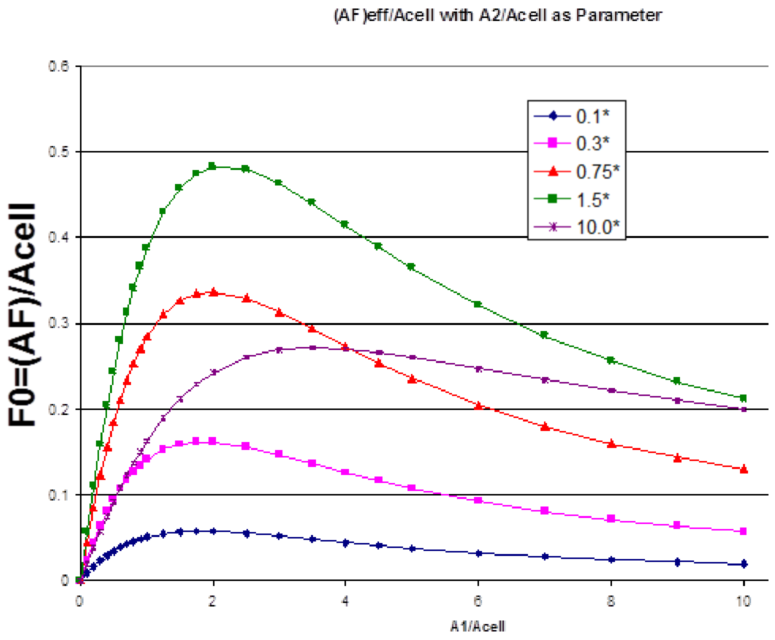
- Accounting for temperature variation in cell

$$(AF)_{eff} = -A_{cell}K \int_{-\alpha_1 L_1}^{0} dy_1 e^{y_1} \int_{-\alpha_2 L_2}^{0} dy_2 e^{y_2} \frac{2(y_1 + y_2)}{\alpha_1 L_1 + \alpha_2 L_2}$$

  - where the fraction in the integrand is the fraction of the average difference in T⁴ between point 1 and point 2.
- Using K=1 defined for geometric exchange factor and simplifying

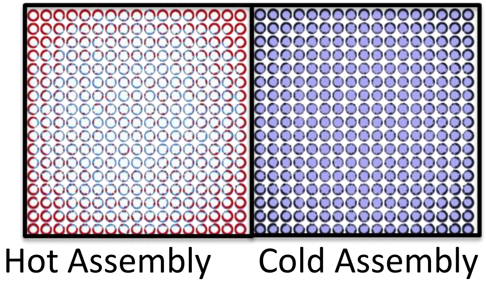
$$(AF)_{eff} = 2\frac{(A_{cell})^2}{A_1 + A_2}$$
$$\left\{\left[1-(1+\alpha_1 L_1)e^{-\alpha_1 L_1}\right]\left(1-e^{-\alpha_2 L_2}\right) + \left(1-e^{-\alpha_1 L_1}\right)\left[1-(1+\alpha_2 L_2)e^{-\alpha_2 L_2}\right]\right\}$$

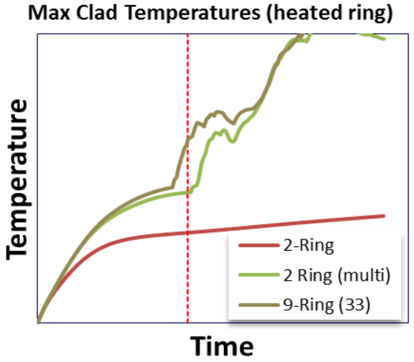
- Limits for Exchange factors
  - both cells large $(AF)_{eff} \to 4\frac{(A_{cell})^2}{A_1 + A_2}$
  - cell 1 small and cell 2 large $(AF)_{eff} \to \frac{A_1 A_{cell}}{A_1 + A_2}$
  - both cells small $(AF)_{eff} \to \frac{1}{2}\frac{A_1^2 + A_2^2}{A_1 + A_2}$

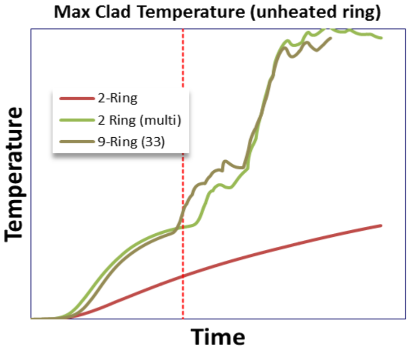


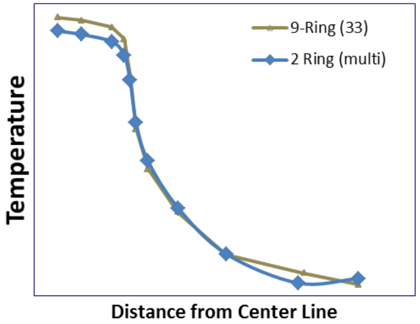
Multi-Rod Model

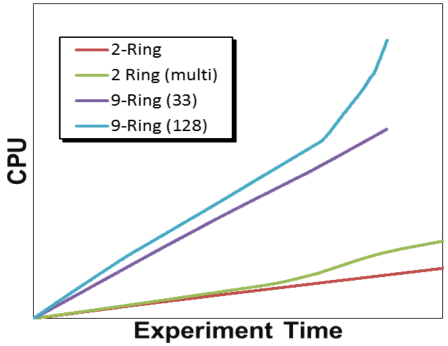
- Motivation
  - It is desirable to model an entire assembly within a single MELCOR ring
- Challenge
  - When hot assembly reaches ignition, heat transfer to cold assembly is problematic











- Validation
  - Validation was performed against the Sandia PWR Spent Fuel Pool Experiments
  - Comparisons between 2-ring (2 rods) model; 2-ring, (9 rods) model; and 9-ring model.
- CPU time is greatly reduced for multi-rod model
- Simplified input requirements
- Fuel rod degradation modeling is nearly complete
- Recently extended to PWR reactor type in addition to PWR-SFP

User Defined Arbitrary Heat Transfer Paths

- COR_HTR
  - Allows the user to define arbitrary heat transfer paths
    - Radiation
    - Conduction
  - Constant or Control Function
    - Conduction: Total conductance (KA/dx)
    - Radiation: product of the view factor and area (VF x A)
  - User can specify heat transfer from any core component at any cell location to another core component
    - Rack to rack radiation conduction
    - Former conduction
    - Unique degradation based radiative heat transfer
  - Caveat
    - User should zero the exchange factors so that radiation isn't double counted
    - Though the area is supplied by the user, MELCOR also uses the component areas in calculating heat transfer

$$\dot{Q} = \sigma_B \frac{(T_1^4 - T_2^4)}{\frac{1-\epsilon_1}{A_1\varepsilon_1} + \frac{1-\epsilon_2}{A_2\varepsilon_2} + \frac{1}{F_{1-2}A_1}}$$

Quantity in red is supplied by user. All other areas determined from components

User-Defined Heat Transfer Paths

HTRMDL

Type of heat transfer path:

(1 or RADIATE-CONST
(2 or CONDUCT-CONST
(3 or RADIATE-CF
(4 or CONDUCT-CF

COR_HTR NHTR

N IAFROM IRFROM ICMP1 IATO IRTO ICMP2 HTRMDL VFA CND ICFVFA ICFCND

IAFROM IRFROM ICMP1:

- Axial elevation,
- Radial ring,
- Component number of 'from' component

IATO IRTO ICMP2:

- Axial elevation,
- Radial ring,
- Component number of 'to' component

Or

- HS number,
- HS side,
- 'HS' designator

VFA CND: Constant Values

ICFVFA ICFCND: Control Functions

VFA

Product of the view factor and area for this radiative path

CND

Total conductance for this conductive path. It represents an effective value of and, when multiplied by the temperature difference, should give the total heat flow in W.

Components

(FU
(CL
(CN
(CB
(PD
(SS
(NS

(PB
(RK
(BRK
(CH
(FM
(PT
(CT

(FUx

If multi-rod modeling is enabled, x may be replaced with an integer representing the rod group.

(CLx

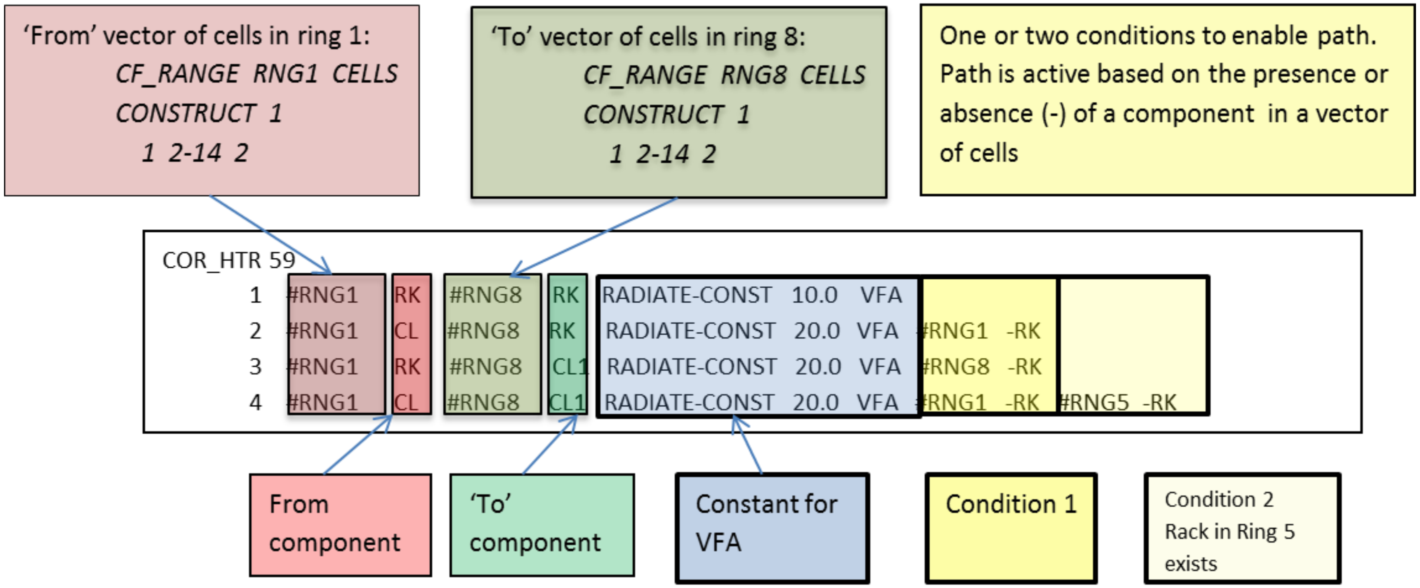
If multi-rod modeling is enabled, x may be replaced with an integer representing the rod group.

(NSx

If multi-rod modeling is enabled, x may be replaced with an integer representing the rod group.

Vectorized COR_HTR Input

- Reduces number of input records significantly.
  - Otherwise input is required cell by cell.
  - Unnecessary CF logic required to determine existence of components.
  - Difficult to read (QA)
    - Input for a cell is scattered among COR_HTR records and multiple CF records
  - One example reduced number of records from over 7000 records to under 100



‘From’ vector of cells in ring 1:

CF_RANGE RNG1 CELLS
CONSTRUCT 1
1 2-14 2

‘To’ vector of cells in ring 8:

CF_RANGE RNG8 CELLS
CONSTRUCT 1
1 2-14 2

One or two conditions to enable path. Path is active based on the presence or absence (-) of a component in a vector of cells

```
COR_HTR 59
     1  #RNG1  RK  #RNG8  RK   RADIATE-CONST  10.0  VFA
     2  #RNG1  CL  #RNG8  RK   RADIATE-CONST  20.0  VFA  #RNG1  -RK
     3  #RNG1  RK  #RNG8  CL1  RADIATE-CONST  20.0  VFA  #RNG8  -RK
     4  #RNG1  CL  #RNG8  CL1  RADIATE-CONST  20.0  VFA  #RNG1  -RK  #RNG5  -RK
```

From component

‘To’ component

Constant for VFA

Condition 1

Condition 2
Rack in Ring 5
exists

Multi-Rod Model

- Implement additional fuel rod components to capture temperature gradient
  - Temperature in edge region simulated
  - Oxidation and ignition captured
- Minimal User Input
  - Specify ring geometry as usual
  - Specify fraction associated with each rod type
  - Specify view factors connecting types
- Implement sub-grid radiation model
  - User provides view factors between rows of rods
    - Geometric view factor now meaningful

Fraction of mass for each rod type

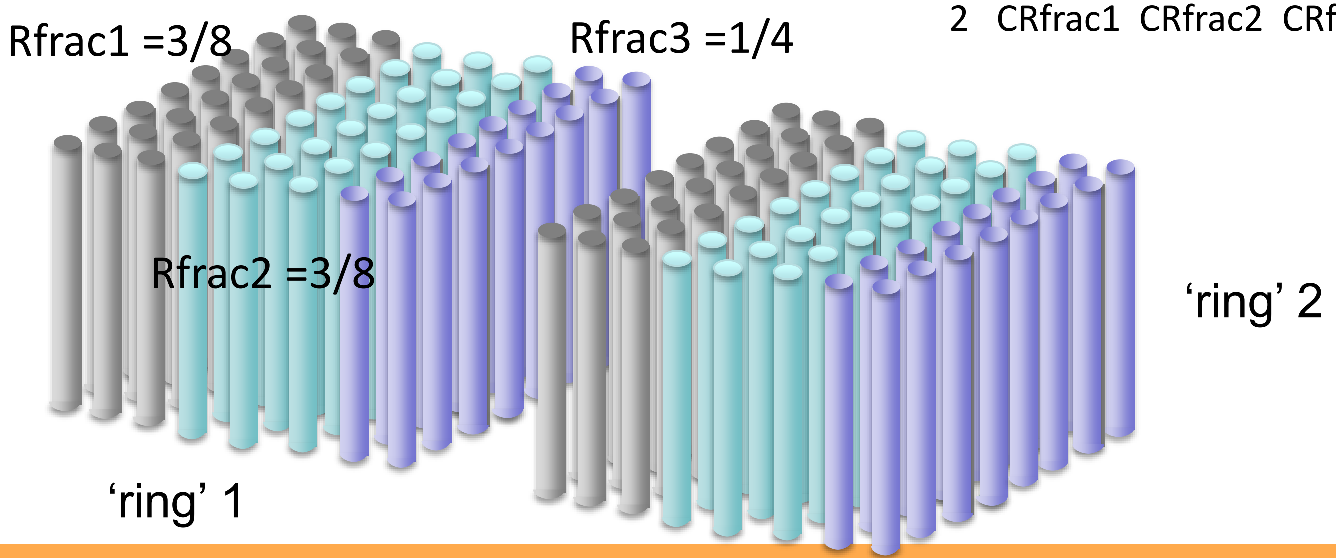
```
COR_ROD2    2 !  Two ‘rings’
        1  rfrac1, rfrac2, rfrac3, rfrac4
        2  rfrac1, rfrac2, rfrac3, rfrac4
```

View Factor Matrix

```
COR_ROD_VF   5
        1    VF11  VF12 VF13 VF14 VF15 VF1RK
        2    VF21  VF22 VF23 VF24 VF25 VF2RK
        3   VF31  VF32 VF33 VF34 VF35 VF3RK
        4   VF41  VF42 VF43 VF44 VF45 VF4RK
        5   VF51  VF52 VF53 VF54 VF55 VF5RK
```

Fraction of mass for each control rod type

```
COR_CR2    2
        1   CRfrac1  CRfrac2  CRfrac3  CRfrac4
        2   CRfrac1  CRfrac2  CRfrac3  CRfrac4
```

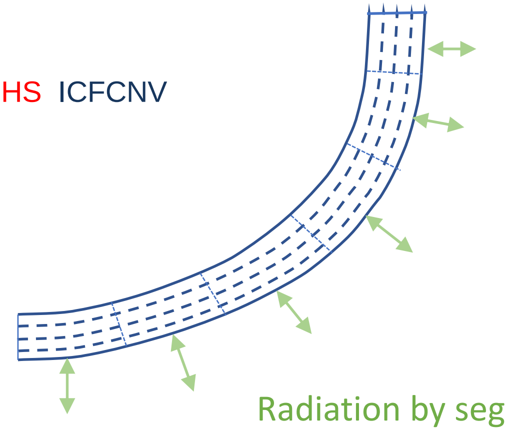


Radiant Heat Transfer from Outer Lower Head Surface

- **COR_LHD** – Lower Head Segments Record

```
COR_LHD   NLHT  NLHTA  !TABLE Input
          IS   TLH   RADLH   ICVCAV   IHSCAV  HSSIDE   VFLHHS   ICFELH   ICFEHS  ICFCNV
```

- If the heat structure name IHSCAV is present, then radiation from the lower head segment to the heat structure is enabled.
- If IHSCAV was used to enable radiation, then HSSIDE and VFLHHS must also be specified
  - HSSIDE - Left (LHS) or right side of heat structure
  - VFLHHS - View factor from outer surface to heat structure.
- ICFELH and ICFEHS are optional
  - ICFELH - Control function name or number for emissivity of outer surface.
  - ICFEHS - Control function name or number for emissivity of heat structure



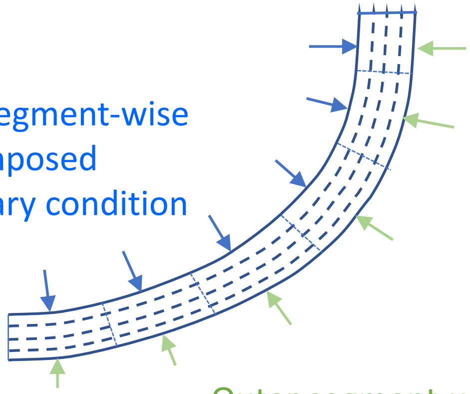
Radiation by segment to HS

- **COR_LHBC, COR_LHBC2** – Imposed BC on Lower Head Surface

- Over-rides other heat transfer mechanisms to vessel surface.
- Useful for assessing lower head response.
  - Validation experiments such as LHF & OLHF
- Boundary conditions permitted
  - Specified temperature
  - Specified heat flux
  - Radiation to a specified temperature
  - Calculated from model
- Mixed types can be defined by segment

```
COR_LHBC  BCINNER   BCOUTER
COR_LHBC2  10
1  1   TEMP  QFLUX
2  2   TEMP  QFLUX
3  3   TEMP  QFLUX
4  4   TEMP  QFLUX
5  5     -   TRAD
6  6     -   TRAD
7  7     -   TRAD
8  8     -   TRAD
9  9     -   TRAD
10 10    -   TRAD
```

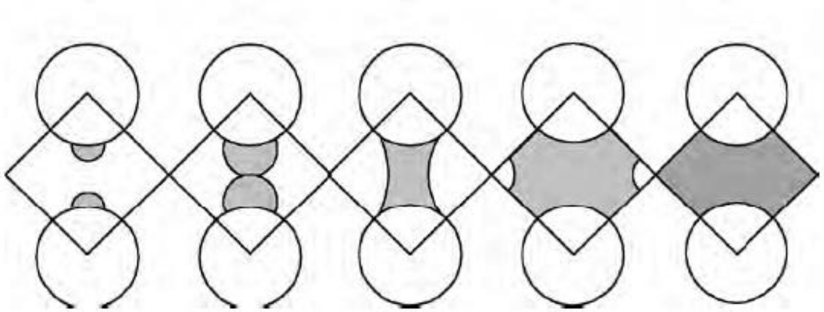
Inner segment-wise user-imposed boundary condition

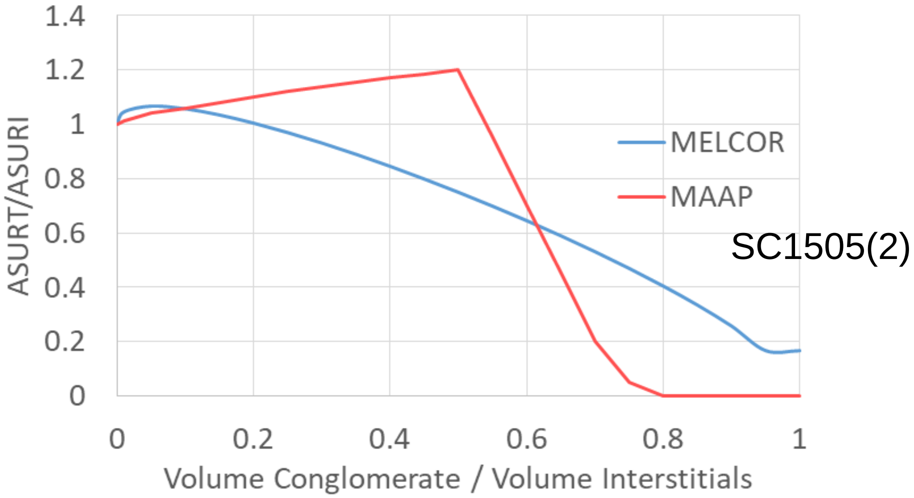


Outer segment-wise user-imposed boundary condition

Modified Surface Areas Due to Conglomerate Freezing

- The MELCOR candling model calculates modified surface areas used for both oxidation and heat transfer
  - Similar to rodded geometry but modified for spheres
  - Oxidation and convective heat transfer use reduced surface areas:
    - ASURC - Conglomerate
    - ASURY - exposed intact surface area
  - Sensitivity coefficient used to set minimum surface area
    - SC1505(2) = 0.05 SOARCA Best Practice
    - Was 0.001 in M186
    - Currently 0.001 for M2.2 default





How Are they Used

- ASURT - Convective Heat Transfer
- ASURI - Radiation
- ASURI - Intact component area
- ASURC, ASURY – Oxidation

ASURT=ASURC+ASURY

COR Radiant Heat Transfer to Participating Media Beam Length

COR_BL – Beam Length Record (Optional)

This record specifies the method for the mean beam length calculation. The mean beam length is used to calculate the absorptivity and emissivity of steam, which determines the radiation heat transfer to the medium. Depending on the method selected, this card can also be used to specify lengths which would be used in the mean beam length calculation. If this card is omitted then the beam length calculation is governed by BLFLAG=0, making use of the default values of parameters BLRC, BLCCB, and BLCC.

(1) BLFLAG

Beam length calculation option:

(a) 0 or 'DEF'

- Default lengths given BLRC, BLCCB, and BLCC are used in the mean beam length calculation.

(a) 1 or 'EDR'

- The equivalent diameter records on COR_EDR are used in the mean beam length calculation. Note that this option is only available if the reactor type (RTYPE) is BWR or SBWR. Once selected, the lengths defined on BLRC, BLCCB, and BLCC below would be replaced by the following COR_EDR input:
  - BLRC = DHYCNC(IA,IR)
  - BLCCB = DHYNS(IA,IR)
  - BLCC = DHYCNB(IA,IR)

(a) 2 or 'USER'

- Specify lengths directly to be used in the mean beam length calculation.

- The following input are only required if BLFLAG = 2:

(2) BLRC

The shortest distance between the outer clad surface and the canister wall.

(Type = real, default = 0.004, units = metres)

(3) BLCCB

The shortest distance between the canister surface on the bypass side and the control blade.

(Type = real, default = 0.00505, units = metres)

(4) BLCC

The shortest distance between the canister surfaces on the bypass side away from the blade.

(Type = real, default = 0.014, units = metres)

Optical Depth (cm-atm)	Temperature (K)						
	370	600	1000	1500	2000	2500	3000
1.0	0.12	0.09	0.041	0.02	0.01	0.0063	0.004
3.2	0.25	0.195	0.11	0.06	0.03	0.019	0.011
10.0	0.37	0.315	0.23	0.145	0.085	0.053	0.033
32.0	0.47	0.425	0.37	0.29	0.20	0.135	0.086
100.0	0.56	0.533	0.55	0.47	0.365	0.277	0.193
320.0	0.65	0.625	0.70	0.66	0.555	0.47	0.35
1000.0	0.73	0.71	0.82	0.80	0.74	0.65	0.52
3200.0	0.79	0.78	0.92	0.90	0.88	0.78	0.65
10000.0	0.85	0.85	1.00	0.92	0.92	0.85	0.73

Steam emissivity vs temperature and optical depth

COR Surface	Abbreviation	Equation
Fuel	FU	$BL = 3.5(P - 2R_{CL})$
Clad	CL	$BL = 3.5(P - 2R_{CL})$
Channel facing canister away from the blade.	CN	$BL = 1.8BLRC$
Channel facing canister adjacent to the blade.	CB	$BL = 1.8BLRC$
Supporting Structure	SS	$BL = 1.8BLCCB$
Core Support Plate	CSP	$BL = 1.8BLCCB$
Non-supporting Structure	NS	$BL = 1.8BLCCB$
Bypass facing canister – no blade	CNB	$BL = 1.8BLCC$
Bypass facing canister adjacent to the blade	CBB	$BL = 1.8BLCCB$
All other surfaces		$BL = 0$

Optical Depth:

$$P_{OD} = \mathrm{BL}\frac{P\ [Pa]}{1013.25}$$

Note: depressurization reduces optical length, steam emissivity and absorptivity

Absorptivity of Steam:

$$\alpha_v = \varepsilon_m(T_v(IA,IR),OD)\left(\frac{T_v(IA,IR)}{T_s}\right)^{0.45}$$

Equations used in calculating the beam length, where

P = Rod pitch

RCL = Clad outer radius

BLRC = Distance between the outer fuel rods and the canister (Default = 4mm)

BLCCB = Distance between the canister and the blade (Default = 5.05 mm)

BLCC = Distance between adjacent canister walls (default = 14 mm)

COR Radiation Modeling in Small Scale Experiments

Plant Modeling

COR_RF – Radiative Exchange Factors

Optional.

This record specifies the radiative exchange factors used to model thermal radiation in the core. These exchange factors roughly correspond to the traditional view factors describing the geometric orientation between two pairs of surfaces. This record is not required but, if included, from one to five fields must be present. Each value must be a nonnegative real number less than or equal to 1.0. For more details on the interpretation given to these parameters, see the COR Package Reference Manual, Section 2.1.3.

(1) FCNCL

Radiative exchange factor for radiation from the canister wall to the fuel rod cladding. A value must be entered for PWRs but it is not used.

(type = real, default = 0.25, units = none)

(2) FSSCN

Radiative exchange factor for radiation from NS (e.g., control blades) to the adjacent canister walls or to fuel rods and debris if canister is not present.

(type = real, default = 0.25, units = none)

(3) FCELR

Radiative exchange factor for radiation radially outward from the cell boundary to the next adjacent cell. Alternatively, the word 'MODEL' can be input and MELCOR calculates the value based on an internal model.

(type = real or character*7, default = 0.1, units = none)

(4) FCELA

Radiative exchange factor for radiation axially upward from the cell boundary to the next adjacent cell.

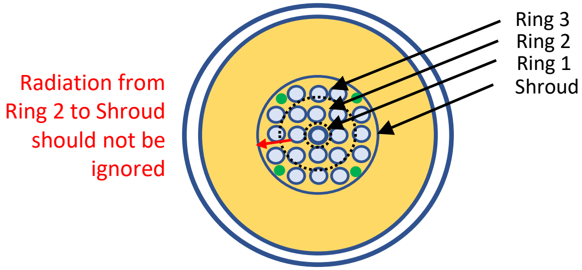
(type = real, default = 0.1, units = none)

(5) FLPUP

Radiative exchange factor for radiation from the liquid pool to the core components.

(type = real, default = 0.25, units = none)

- Small Scale Test Modeling
  - The default radiative exchange factor modeling for radiation between COR cells may be adequate for a large plant model. However, for small bundle tests, radiation between the bundle elements and the boundary structures plays an important and sensitive modeling issue that deserves closer attention.
    - In particular, radiation from inner rings, through outer rings, to the outer boundary may be significant.
      - Requires additional user-defined radiant heat transfer paths



```
COR_HTR 32
1   3   2   CL   3   3  SH  RADIATE-CONST   8.655E-03
 2   4   2   CL   4   3  SH  RADIATE-CONST   8.655E-03
 3   5   2   CL   5   3  SH  RADIATE-CONST   8.655E-03
```

HS Radiant Heat Transfer Modeling

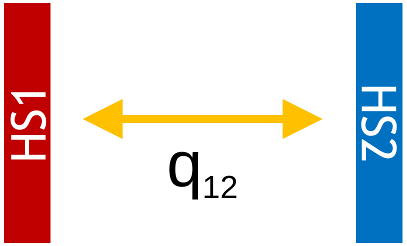
- Previous HS radiation model
  - Radiation defined only for surface pairs
  - Radiation to gas performed independently for each surface
    - Does not account for transmissivity of gas
      - Radiation between surfaces is calculated even for optically opaque gases
    - Does not account for reflection among surfaces
- New enclosure model
  - Multiple enclosure networks, each with multiple heat structures defined by the user.
    - Memory dynamically allocated
  - User defines <u>all</u> surfaces exchanging radiant heat
    - Matrix of view factors connecting surfaces
    - View factors can be control functions
    - Accounts for surface submerged below pool
  - Participating gas
    - Transmissivity accounts for reduction in radiation between surfaces
    - Only 1 CV associated with all surfaces
      - Does not account for rising pool in CV (yet)
    - User supplies beam length (similar to COR package)

Structure-to-Structure Radiation Input (Previous HS Radiation Model)

- Basic input for each surface pair

```
HS_RD     2
       !  first surface        side          second surface        side     view factor
    1        HS1            LEFT               HS2              LEFT       0.15
    2        HS1            RIGHT              HS2              RIGHT      0.075

! left side of HS1 sees left of HS2
! right side of HS1 sees right of HS2
```



◆ **To override built-in emissivity model**

```
HS_RD   1
    1    'HS1'    LEFT    'HS2'    LEFT    0.15        NO            CFemissivity
```

'NO' means that the emissivity as a function of temperature is determined by core

control function whose value is the emissivity of surface 2.

Radiation to Fluids
(Not to be used with enclosure network)

- Radiation between surface and gases
  - Calculated only if input record HS_LBR or HS_RBR included
  - Two options, “equivalent band model” and “gray” gas

HS_LBR	0.9	gray-gas-a	0.1
	wall emissivity of surface		**radiation path length**

  - This should not be active when radiation enclosure model is used because radiation to gas is already in enclosure model.

Emissivity is constant for the transient

Radiation to H2O, CO, and CO2.

Not to other non-condensible gases

Not to aerosols

Mechanistic model is used for radiation on film covered surfaces

Gray Gas Model
Beam Length

- ***Equivalent path length representing the average contribution of different beam lengths from the gas body to the surface*.**

Geometry:	L
Sphere: internal radiation	0.65 x D
Hemisphere: Radiating to element at center of base	0.5 x D
Circular cylinder of infinite height: Internal radiation	0.95 D
Circular cylinder of semi-infinite height	
Element at center of base	0.9 D
Entire base	0.65 D
Circular cylinder of height equal to two diameters radiating to:	
Plane end	0.43 D
Cylindrical surface	0.46 D
Entire surface	0.45 D
Cube radiating to any face	0.6 x edge
Gas volume outside infinite bank of tubes radiating to a single tube (P = pitch)	
Equilateral-triangle array:	
P=2D	3.0(P-D)
P=3D	3.8x(S-D)
Square Array	3.5x(S-D)
Arbitrary shape of volume V	3.6 V/A

Multi HS Radiation Enclosure Model

- The space between surfaces may or may not be filled with a participating medium,
  - Participating gas may absorb, emit, and scatter radiation emitted by the surfaces.
- Each surface is assumed to be isothermal, opaque, diffuse, and gray, and are characterized by uniform radiosity.
  - The absorptivity (a) of a surface is equal to the emissivity (e) and the sum of the absorptivity and reflectivity (r) is 1.0

$$\varepsilon_i = \alpha_i = 1 - \rho_i$$

- Reciprocity is also assumed between surface pairs
- It is assumed the sum of the view factors from a surface to all surfaces in the enclosure network, is equal to 1.0.
  - a surface may also radiate to itself.

$$\sum_{i=1}^{N} VF_{i,j} = 1.0$$

The surface radiosity is defined as the total heat flux that departs from an area (reflected and emitted)

$$J_i = \rho_i \cdot G_i + \varepsilon_i E_{b,i}$$

where

G_i= radiation flux incident on surface I from radiation from all other surfaces,

E_{bi}= blackbody emissive power of surface i, σT_i^4

$$J_i = (1 - \varepsilon_i) \cdot \sum_{j}^{N} \left[F_{ij} \cdot \tau_{j,i} \cdot J_j \right] + \varepsilon_i \cdot \sigma \cdot T_i^4 + \rho_i \varepsilon_m E_{bm}$$

$$G_i = \sum_{j}^{N} \left[A_j \cdot F_{j,i} \cdot \tau_{j,i} \cdot J_j \right] / A_i + \varepsilon_m E_{bm}$$

$$q_i = A_i (J_i - G_i)$$

$\tau_{j,i}$ is the transmissivity through gas

Radiation Enclosure Input
HS_RAD Record

HS_RAD –Radiation Enclosure
Optional

(1) NUMBERHS
Number of heat structure surfaces in the network.
(type = integer, default = none, units = none)

(2) NetworkName
User specified network name
(type = character*16, default = none, units = none)

(2) NetworkNumber
User specified network number
(type = integer, default = none, units = none)

Next data are input as a table with number or rows = NUMBERHS:

(1) i
Index for HS in network.
(type = integer, default = none, units = none)

(2) IHSRDi
Name of heat structure i.
(type = character*16,default = none)

(3) LRBNDi
Option to identify the side of surface IHSRDi.
-1 or LEFT
Left side surface of the given heat structure.
1 or RIGHT
Right side surface of the given heat structure.
(type = integer / character*5, default = none, units = none)

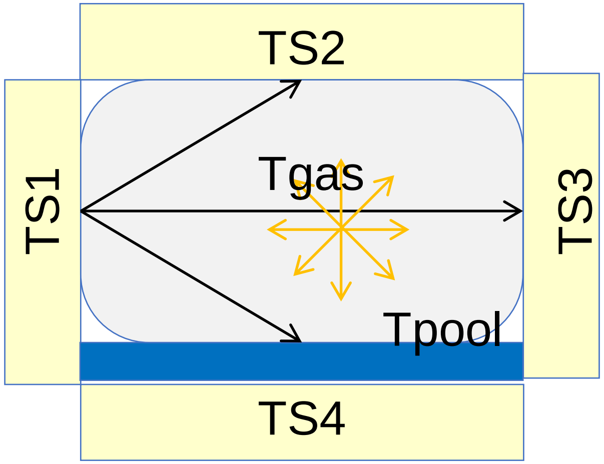
(4) ICFRDi
Optional constant value for emissivity of the surface (real) or real-valued control function name (character*16) whose value is the emissivity of the surface. If neither is specified, MELCOR calculates the emissivity using the COR package relation for oxidized steel surfaces.
(type = real or character*16, default = '-', units = none)

(5) BEAMLi
Radiation path length for the boundary gas associated with the surface i. If the beam length is zero, then the gas is non-participating.
(type = real, default =0.0, units = m)

(5+ NUMBERHS) $\mathrm{VIEW}_{i,\mathrm{NUMBERHS}}$
View factor between surface i and surface NUMBERHS, which must lie in the range of 0.0 to 1.0. If '-' is entered and i<>NUMBERHS, then the viewfactor is calculated by reciprocity from $\mathrm{VIEW}_{\mathrm{NUMBERHS},i}$
(type = real or character*16, default = none, units = none)

Multi HS Radiation Enclosure Model

- Continuation of view factor records onto new line
- View factors can be control functions.
  - Sum of view factors for a surface cannot exceed 1.0
- Radiation to pool surface
  - When pool covers a participating surface on a HS, the pool surface replaces that HS surface in the enclosure network.



```
HS_Rad 4  NET3       !EM      BeamL    VF
  1   HS1C      RIGHT  EM1     0.5        0.0   0.2   0.4    &
                                  'MyLongNamedCF'
  2   HS2C      LEFT    EM2     0.5       0.2  0.0  0.3  0.5
  3   HS3C      LEFT       -       0.5       0.4  0.3  0.2  0.1
  4   HS4C      RIGHT     -       0.5       0.4   0.5  0.1  0.0
```

Try using placeholder in view factor input

- **The radiation enclosure model allows the user to specify a placeholder ‘-’ for a view factor if that missing view factor can be calculated implicitly by reciprocity**

$$V_{i,j} A_i = V_{j,I} A_j$$

- **The sum of view factors from a surface to all other surfaces in the network is equal to 1.0. If it sums to something less, the difference is accounted for by adjusting the self-radiation term.**

MELGEN Input:

```
HS_RAD 7 NET3  3!
!n                          B   1  2  3  4  5    6    7
 1  HS1B    LEFT 'EM3' 0.  -    0.   0.   0.   0.   0.50   0.20       !Area = 10.0
 2  HS2B    LEFT 'EM3' 0.  0.   -    0.   0.   0.   0.50   0.20       !Area = 10.0
 3  HS3B    LEFT 'EM3' 0.  0.   0.   -    0.   0.   0.50   0.20       !Area = 10.0
 4  HS4B    LEFT 'EM3' 0.  0.   0.   0.   -    0.   0.50   0.20       !Area = 10.0
 5  HS5B    LEFT 'EM3' 0.  0.   0.   0.   0.   -    0.50   0.20       !Area = 10.0
 6  HS6B    LEFT 'EM3' 0.  -    -    -    -    -    -      0.0        !Area = 150.0
 7  HS7B    LEFT 'EM3' 0.  -    -    -    -    -    0.0    -          !Area = 100.0
```

MELCOR Output:

```
RADIATION ENCLOSURE NETWORK: NET3
    HS NAME          SURFACE  BEAM L       VIEW FAC
    1   HS1B         LEFT     0.000E+00   0.300   0.000   0.000   0.000   0.000   0.500   0.200
    2   HS2B         LEFT     0.000E+00   0.000   0.300   0.000   0.000   0.000   0.500   0.200
    3   HS3B         LEFT     0.000E+00   0.000   0.000   0.300   0.000   0.000   0.500   0.200
    4   HS4B         LEFT     0.000E+00   0.000   0.000   0.000   0.300   0.000   0.500   0.200
    5   HS5B         LEFT     0.000E+00   0.000   0.000   0.000   0.000   0.300   0.500   0.200
    6   HS6B         LEFT     0.000E+00   0.033   0.033   0.033   0.033   0.033   0.833   0.000
    7   HS7B         LEFT     0.000E+00   0.020   0.020   0.020   0.020   0.020   0.000   0.900
```

$VF_{7,1}=VF_{1,7}*A_1/A_7$

0.02=0.2*10.0/100.0

Radiation to Aerosols Model

- Aerosol cloud emissivity derived per Pilat and Ensor

$$\alpha_{\lambda m} = 4000 C_{\lambda m} f_m$$

- Where $C_{\lambda m}$ is the user defined parameter kmx,
  - Input as part of the radiation enclosure model.
  - f_m is the total aerosol mass concentration (kg/m^3) calculated by the code.
- $C_{\lambda m}$ in this equation is provided to allow the user to account for the effects of wavelength, index of refraction, particle size distribution, and aerosol particle material density.
- $C_{\lambda m}$ = 1, corresponds to soot-like particles with a density of 2000 kg/m^3.

```
! #HS  NetName  #Net  NotUsed   KMX
HS_RAD  5  NET2 1  IGNOREPOOL -  0.25
   1 'top head'     LEFT  EM1        20.3     0.05   0.3   0.15     0.5    0.0
   2 'walls-edge'  LEFT  EM1        7.62     0.1       -        -     0.3     -
   3 'vert-int'      LEFT  EM1        3.81     -        0.9    0.0        -     0.0
   4 'floor'           LEFT  0.65       20.3     0.0   0.25   0.25      0.0   0.5
   5 'horiz-int’      LEFT  EM1        3.81     0.0     0.5    0.0        0.5   0.0
```

M. J. Pilat and D. S. Ensor, “Plume Opacity and Particulate Mass Concentration,” *Atmospheric Environment*, Vol. 4, pp. 163-173, 1970.

Radiant Heat Transfer Between COR and HS Packages

- Radiation to Boundary Heat Structures
  - If no components exist in the next outer or higher cell, the radial ring or axial level beyond that is used, until a boundary heat structure is reached. Thus, components in one cell can communicate to nonadjacent cells all the way across the core if there are no components in intervening cells. The boundary heat structures, both radially and axially, specified on records COR_RP and COR_ZP, respectively, receive energy from the outermost cells that contain a component.
- Radiation from Outer Lower Head surface to Heat Structures
  - Previously described
- Radiation from COR components to arbitrary Heat Structures
  - Using user defined heat transfer paths
  - Previously described