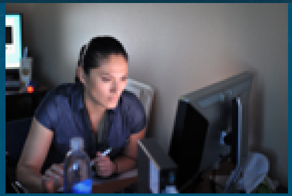
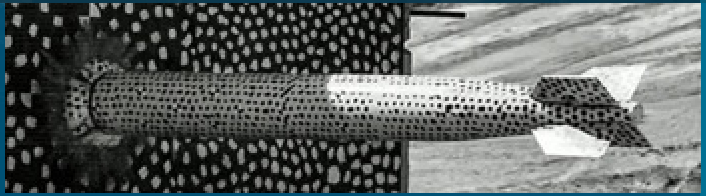
SAND2022-8112C

MELCOR for High Temperature Gas-cooled and Fluoride High Temperature Reactor Modeling





MELCOR Workshop
June 13-17, 2021

PRESENTED BY

Brad Beeny

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MELCOR HTGR and FHR Modeling and Development Thermal Hydraulics – Practice/Exercises

Overview

COR thermal hydraulics input structures and best practice recommendations

- Global
- Support
- Heat transfer (conduction, convection)
- Components and materials (FU/FUXM, MX, and RF)
- Point reactor kinetics

COR thermal hydraulics exercises

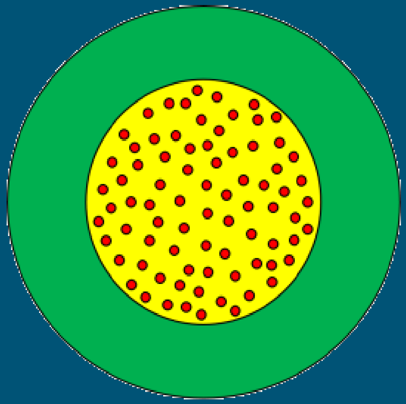
- PBR COR nodalization and components/materials configuration
- PBR point reactor kinetics demonstration

Output processing

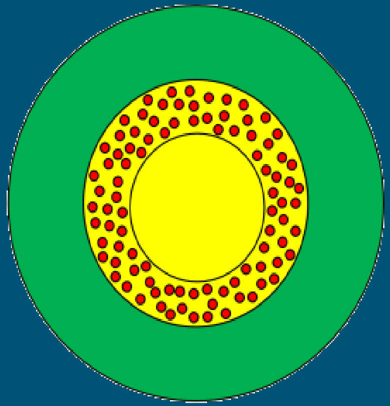
Conclusions

...Inputs and Best Practices...

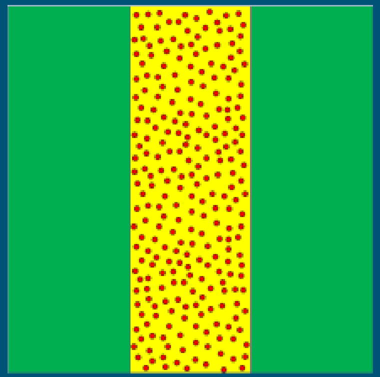
Conventional Pebble Fuel Element (HTGR/PBR)



Annular Pebble Fuel Element (FHR)



Prismatic Fuel Element (HTGR/PMR)



TRISO	Fuel (FU)
GRAPHITE	Fuel Extra Material (FUXM)
GRAPHITE	Matrix (MX)

Inputs and Practices - Global

COR_RT and COR_GP entail global COR inputs for PBR, PMR, and FHR reactor types

- COR_RT declares reactor type and permits access to special PBR, PMR, or FHR models and capabilities
- COR_GP declares geometric parameters useful for thermal hydraulics and heat transfer calculations

Use ‘PBR’ on COR_RT for pebble bed reactor or FHR types, use ‘PMR’ on COR_RT for prismatic reactor types

- Permits access to certain applicable code thermal hydraulics and heat transfer models/capabilities, e.g:
  - Proper effective conductivity model for MX component
  - Proper conduction heat transfer logic (intercell, intracell)
  - Proper Nusselt number correlations
- Exposes MX and RF for configuration
- Presence of FLiBe with COR_RT declaration of PBR implies FHR (may also use ‘FHR’ on COR_RT)

Geometric parameters on COR_GP are similar to those for PWR/BWR with different interpretations

RFUEL – Fuel outer radius – Use a pebble (PBR/FHR) or compact (PMR) fueled zone radius

RCLAD – Matrix outer radius – Use a pebble (PBR/FHR) unfueled zone radius or an equivalent graphite web radius (PMR)

DRGAP – FU/MX gap – If any gap exists, specify its thickness (may only apply to PMR, factors into gap resistance)

Inputs and Practices - Support

Support logic requires that non-supporting (NS) transmits load (self and like NS above) to support below

- FU and MX are non-supporting
- RF is non-supporting
- FU, MX, and RF must be arranged in COR cells so that they rely on SS below for support

Some support problems arise naturally from HTGR core layout

- Top reflector that hangs over an active core (RF over FU/MX with no SS)
- Active core that sits atop bottom reflectors (FU/MX over RF with no SS)
- Easily remedied with incorporation of graphite-bearing SS between RF and MX

COR_SS and COR_UDSS allows definition of SS support rules with graphite as the material

Generally, best practice is to avoid mixing SS with MX-bearing or RF-bearing COR cells if possible

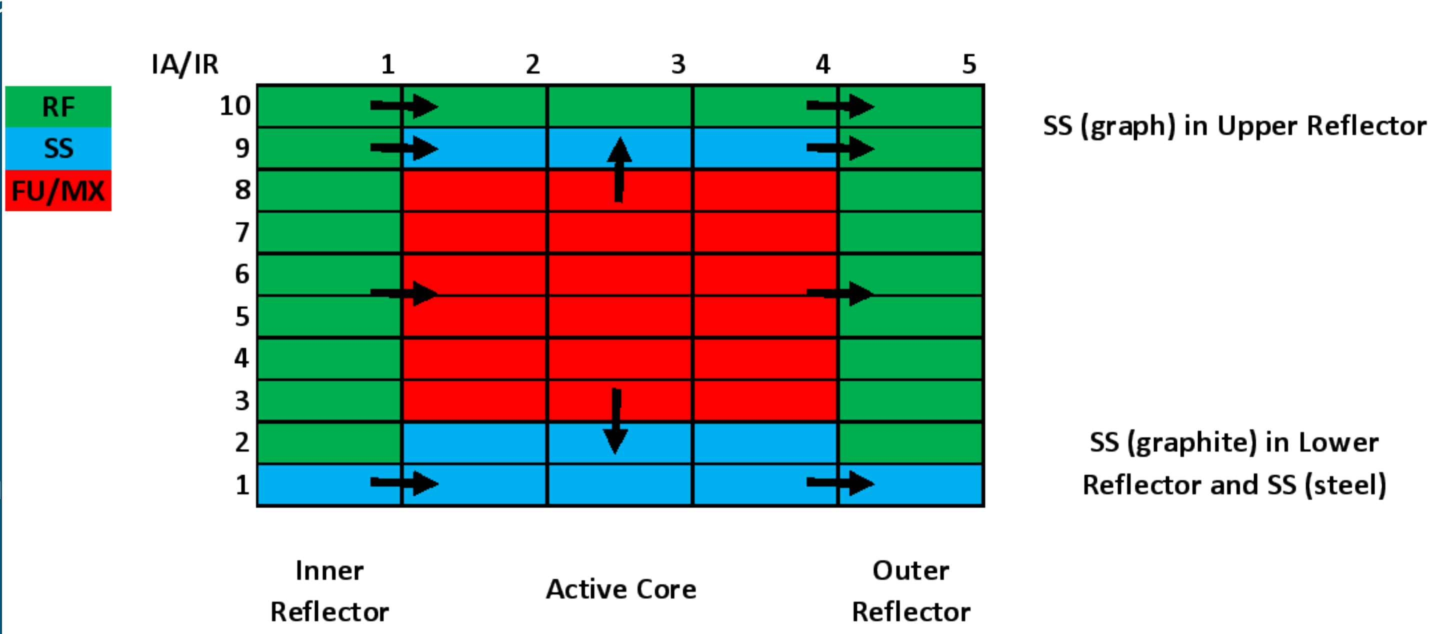
Inputs and Practices – Heat Transfer

COR nodalization to facilitate conduction

- COR_ZP and COR_RP define axial level and radial ring boundaries as always
- COR mass and surface area records indicate which cells bear which components
- FU/MX collocation implies FU/MX intracell conduction
- Intercell conduction (MX-to-MX, MX-to-RF, RF-to-MX, MX-to-SS, SS-to-MX, RF-to-SS, SS-to-RF, RF-to-RF, SS-to-SS)
- COR SC1507 disables cell component volume fraction scaling for radial conduction
- Physically impossible conduction pathways are logically excluded, e.g. FU-to-FU intercell axial/radial conduction for PBRs

Other best practices

- Use RF in cells that comprise reflectors
- Use FU and MX only in active core cells
- Use SS for core support structures
- SS (graphite) can behave like RF (graph



Inputs and Practices – Heat Transfer

Effective conductivity and porosity

- COR_TKE applies to PBR/FHR and PMR, but utilized differently pending RTYPE
- PORCHAN for PMR only and should reflect the hexagonal fuel element block porosity due to coolant hole perforation
- DBLK, BLKGAP for PMR
- Note the TF option

Effective conductivity for MX

PBR/FHR porosity:

- COR_ZP PORDP by axial level, or COR_CPOR by COR cell
  - Both connect to same variables
  - Used for packed bed porosity (blockage)
  - Used for effective conductivity
- Default to PD porosity on COR_ZP in absence of COR_CPOR

COR_TKE – Core Effective Thermal Conductance

Optional for PBR and PMR.

This is a new record recognized for the PBR and PMR COR types that can be used to specify the effective bed conductance (PBR) or radial core conductance (PMR). This model has been implemented in MELCOR by adding a Zehner-Schlunder-Bauer model for pebble bed thermal conductance and a Tanaka-Chisaka porosity model for the block radial conductivity model in PMRs.

The input parameters are

(1) TKETF

Name of tabular function to be used for effective radial bed conductivity. If 'NO' is entered, no TF is used. If, present, the tabular function is used instead of the internal conductivity models.

(type = character, default = '', units = none)

(2) PORCHAN

Effective block porosity to use in the Tanaka-Chisaka model for effective radial conductivity for **PMR**.

(type = real, default = 0.0, units = none)

(3) DBLK

Effective size of the graphite block for the gap model for effective radial conductivity of **PMR**.

(type = real, default = 1.0, units = m)

(4) BLKGAP

Gap width between graphite blocks for the gap model for effective radial conductivity of **PMR**.

(type = real, default = 0.0, units = m)

Inputs and Practices – Heat Transfer

Effective conductivity and porosity

- PBR/FHR invokes an effective conductivity model that has a notion of porosity

COR_CPOR – Porosity by core cell
Optional.

(1) NUMSTR
Number of table records.
(type = integer, default = none, units = none)
The following data are input as a table with length NUMSTR:

(1) NSTR
Table record index.
(type = integer, default = none, units = none)

(2) IA
The axial level number…
*(type = integer / character*7, default = none, units = none)*

(3) IR
The radial ring number…
*(type = integer / character*7, default = none, units = none)*

(4) CPOR
Porosity value
(type = real, default = 0.0, units = none)

COR_ZP – Axial Level Parameters
Required.
This record specifies various data for all axial levels:

(1) NAXL
Total number of axial levels in the core and lower plenum.
(type = integer, default = none, units = none)

…

(4) PORDP
Porosity of particulate debris for all cells in the given axial level IA. The value must be nonnegative and < 1.0.
(type = real, default = none, units = none)

Inputs and Practices – Heat Transfer

Boundary conduction

- COR_BCP configures core structure to core radial boundary HS conduction
- Between an outer core ring (e.g. w/ RF or SS) and a radial boundary HS (e.g. made of steel or graphite)

COR_BCP – Core Boundary Conduction Parameters
Optional..
This record specifies parameters for calculating conduction from the outer core ring to the boundary heat structures specified on record COR_ZP…

(1) **ICBCD**
…name of component that conducts to boundary heat structures…
(type = Integer/character, default = none, units = none)

(2) **MATBCD**
…gap material for conduction…
(type = Character, default = none, units = none)

(3) **DXBCD**
gap thickness
(type = Real, default = none, units = m)

(4) **CDFBCD**
Boundary conduction thermal diffusion constant
(type = Real, default = none, units = $m^2Ks^{1/2}/J$)

Optional…

(5) **CFTSFW**
…switch…CF or TF
(type = character, default = none, units = none)

(6) **CFTFNAM**
…TF or CF name defining new thermal conductivity calculation for MATBCD…
(type = Character, default = none, units = none)

Note:

- MATBCD any NCG gas or MP material, but the user could optionally change THC rule to CF/TF (likely the best route for FHR)
- DXBCD might reflect a gap between a reflector and core barrel or perhaps part of a riser region
- CDFBCD supposed to mitigate oscillations from numerically explicit coupling of COR to HS across core boundary

Inputs and Practices – Components and Materials

Fuel and Reflector component

- Masses entered through COR_KFU and COR_KRF
- FU surface area entered on COR_SA ; RF surface area entered on COR_RFA (channel and bypass)
- RF equivalent diameters entered on COR_RFD
- Special RF orientation/geometry information entered on COR_RFG

FU primary material is UO_2

FUXM on COR_FUM

RF materials on COR_RFM

- Global specification, or
- Cell-by-cell specification

COR_RFG – Reflector Geometry Record
Optional, processed only for PBR and PMR.
This record specifies the reflector geometry …

(1) **NUMSTR**
Number of table records.
(type = integer, default = none, units = none)
…

(4) **RADI**
Reflector channel-side radius…
(type = real, default = none, units = m)

(5) **THKRF**
Reflector thickness…
(type = real, default = none, units = m)

(6) **IGEOMRF**
Geometry flag
(type = integer, default = none, units = m)

(7) **FACRF**
The factor to split the thermal conductances…
(type = integer, default = none, units = none)

Inputs and Practices – Components and Materials

Matrix component

- The UDM capability (MP) should define a new primary material templated to graphite (to include built-in oxidation)
  - MP_ID declares material long name, the identity as COR-USER-METAL and the material short name
  - MP_BHVR templates the new material to graphite and implicitly invokes built-in oxidation models
- COR_MXM should reference the short name of that UDM
- COR_NMAT should specify the mass of UDM
- COR_SA should specify MX surface area and COR_EDR should specify MX equivalent diameter

```
! Long name = PBRGRAPH, a generic oxidizable COR material, short name = PBRG
!         MATNAM      USERCORMATTYPE   MPSHORT
MP_ID PBRGRAPH   COR-USER-METAL     PBRG
!               TEMPMAT
MP_BHVR GRAPHITE
…
COR_MXM PBRG ! invoke short name from MP
```

Inputs and Practices – Point Reactor Kinetics

COR_PKMXX records configure point kinetics parameters:

- COR_PKM01 activates the point kinetics model and configures the start time and initial power level
- COR_PKM02 configures external reactivity inputs and an optional neutron source
- COR_PKM03 configures default or user-supplied feedback models
  - Doppler
  - Fuel density
  - Moderator density

COR_TAVG defines regions of core cells over which temperature averages are taken for feedback calculations

Complement of COR SCs set kinetics and feedback model parameters (COR SC 1404-1406)

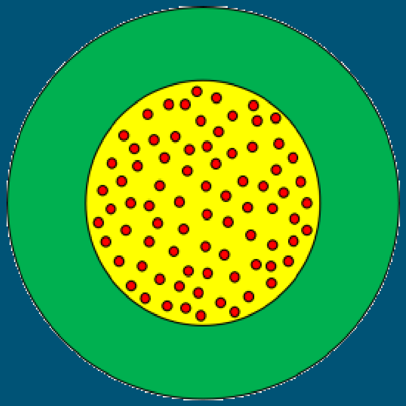
SC1404 has temperature feedback coefficients for Doppler, fuel density, and moderator density

SC1405 has delayed neutron group decay constants and relative abundances

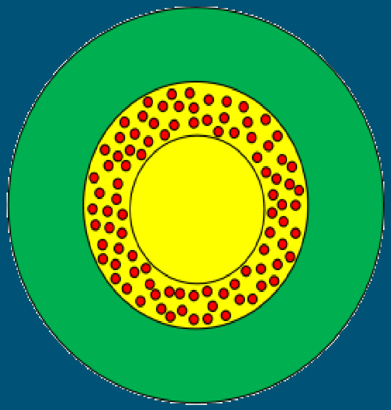
SC1406 has miscellaneous nuclear kinetics data

…Exercise 1 – COR Nodalization…

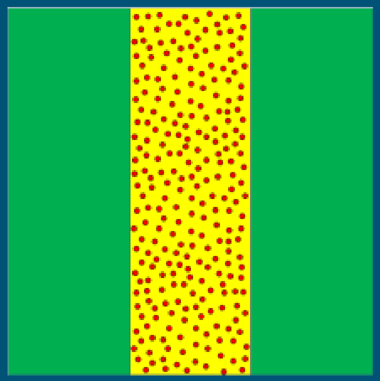
Conventional Pebble Fuel Element (HTGR/PBR)



Annular Pebble Fuel Element (FHR)



Prismatic Fuel Element (HTGR/PMR)



- TRISO — Fuel (FU)
- GRAPHITE — Fuel Extra Material (FUXM)
- GRAPHITE — Matrix (MX)

Exercise 1 – COR Nodalization

Stipulate a PBMR-400 pebble bed core with 27 axial levels and 8 rings

- Nodalization resolution was historically motivated by code-to-code benchmark studies of this particular design
- Active core spans IA=6-27, IR=2-6 with a known P(r,z) power profile
- Core features inner, outer, upper, and lower reflectors
- To facilitate core heat transfer calculations…
  - Where and how to situate FU and MX?
  - Where and how to situate RF?
  - Where and how to utilize SS to facilitate core support?
  - What COR material substitutions/manipulations are required

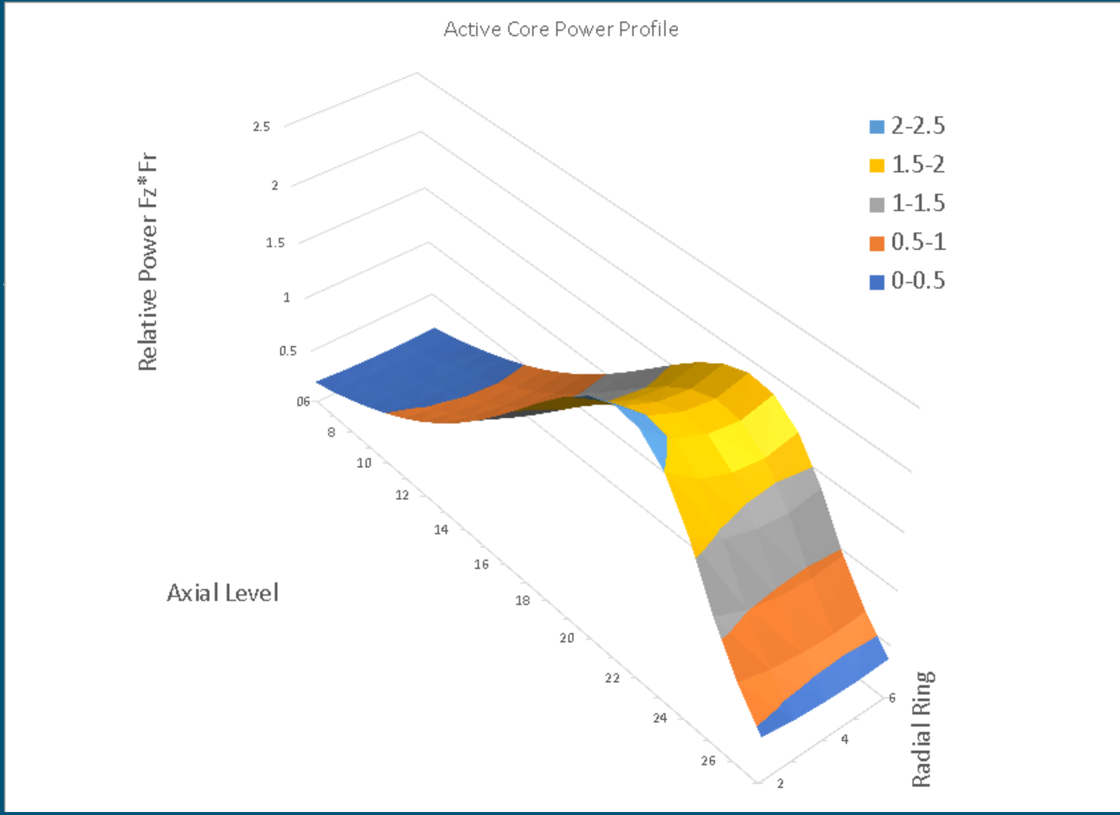
```
! Axial level input -----------------------------------
COR_ZP   29  !Z      DZ     PORDP  IHSA                  FZPOW
    1  -4.35   0.35   0.39  'COR-RAD-BND-A1'   0.0
    2  -4.0    1.0    0.20  'COR-RAD-BND-A2'   0.0
    3  -3.0    1.0    0.20  'COR-RAD-BND-A3'   0.0
    4  -2.0    1.0    0.20  'COR-RAD-BND-A4'   0.0
    5  -1.0    1.0    0.20  'COR-RAD-BND-A5'   0.0
    6   0.0    0.5    0.39  'COR-RAD-BND-A6'   0.173
    7   0.5    0.5    0.39  'COR-RAD-BND-A7'   0.222
    8   1.0    0.5    0.39  'COR-RAD-BND-A8'   0.285
    9   1.5    0.5    0.39  'COR-RAD-BND-A9'   0.355
   10   2.0    0.5    0.39  'COR-RAD-BND-A10'  0.434
   11   2.5    0.5    0.39  'COR-RAD-BND-A11'  0.524
   12   3.0    0.5    0.39  'COR-RAD-BND-A12'  0.628
   13   3.5    0.5    0.39  'COR-RAD-BND-A13'  0.748
   14   4.0    0.5    0.39  'COR-RAD-BND-A14'  0.886
   15   4.5    0.5    0.39  'COR-RAD-BND-A15'  1.040
   16   5.0    0.5    0.39  'COR-RAD-BND-A16'  1.212
   17   5.5    0.5    0.39  'COR-RAD-BND-A17'  1.394
   18   6.0    0.5    0.39  'COR-RAD-BND-A18'  1.579
   19   6.5    0.5    0.39  'COR-RAD-BND-A19'  1.750
   20   7.0    0.5    0.39  'COR-RAD-BND-A20'  1.886
   21   7.5    0.5    0.39  'COR-RAD-BND-A21'  1.958
   22   8.0    0.5    0.39  'COR-RAD-BND-A22'  1.927
   23   8.5    0.5    0.39  'COR-RAD-BND-A23'  1.757
   24   9.0    0.5    0.39  'COR-RAD-BND-A24'  1.428
   25   9.5    0.5    0.39  'COR-RAD-BND-A25'  0.997
   26  10.0    0.5    0.39  'COR-RAD-BND-A26'  0.655
   27  10.5    0.5    0.39  'COR-RAD-BND-A27'  0.388
   28  11.0    0.5    0.39  'COR-RAD-BND-A28'  0.0
   29  11.5    1.5    0.2   'COR-RAD-BND-A29'  0.0
```

```
! Radial ring input
COR_RP    8 !RINGR  IHSR             ICFLHF     ICFCHN     ICFBYP FRPOW
   1  1.0    'TOP-PLATE-R1'  NO   'FLDIRCH'  'FLDIRBY'  0.0
   2  1.17   'TOP-PLATE-R2'  NO   'FLDIRCH'  'FLDIRBY'  1.137
   3  1.34   'TOP-PLATE-R3'  NO   'FLDIRCH'  'FLDIRBY'  1.014
   4  1.51   'TOP-PLATE-R4'  NO   'FLDIRCH'  'FLDIRBY'  0.953
   5  1.68   'TOP-PLATE-R5'  NO   'FLDIRCH'  'FLDIRBY'  0.931
   6  1.85   'TOP-PLATE-R6'  NO   'FLDIRCH'  'FLDIRBY'  0.965
   7  2.436  'TOP-PLATE-R7'  NO   'FLDIRHR'  'FLDIRHR'  0.0
   8  2.606  'TOP-PLATE-R8'  NO   'FLDIRHR'  'FLDIRHR'  0.0
```

```
! Core material input
COR_FUM 'GRAPH'
COR_RFM 'GRAPH'
COR_MXM PBRG   ! COR-USER-METAL (UDM3) in MP
```

```
COR_TKE NO
```

```
!        ICBCD  MATMCD    DXBCD  CDFBCD
COR_BCP  4      GRAPHITE  0.01   2.0e-4
```

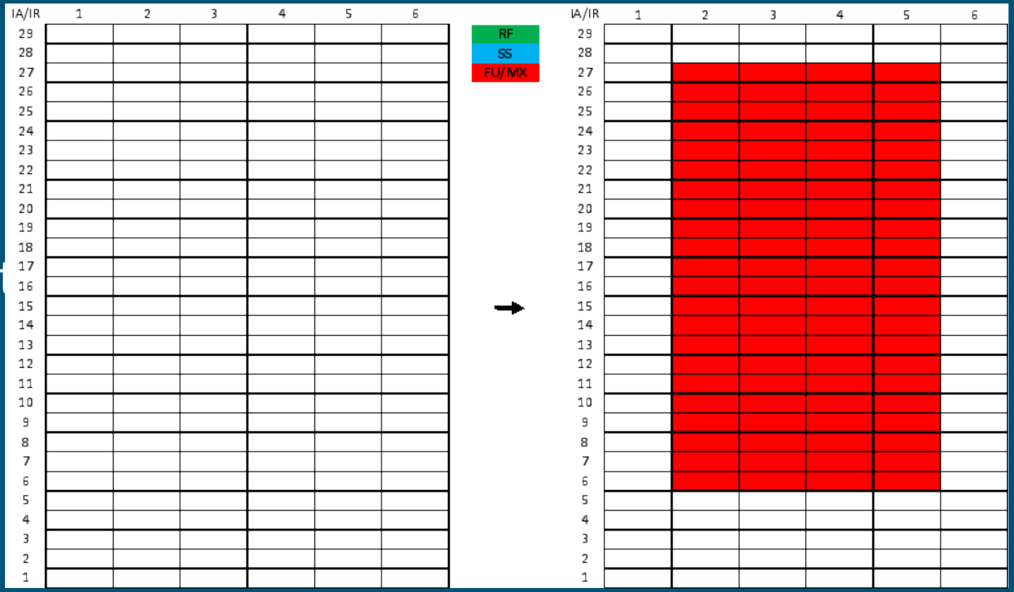


Exercise 1 – COR Nodalization

FU/FUXM and MX situation in nodalization

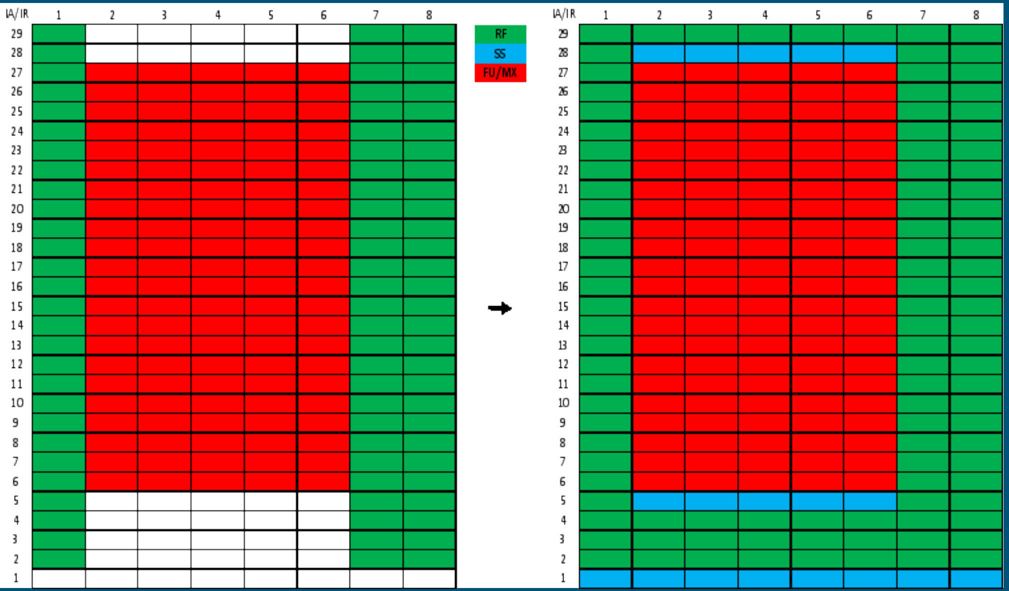
- FU/FUXM and MX in same cells of the active core only
- MX does not appear in rings reserved for inner/outer reflect
- Fuel element radii on COR_GP

```
COR_FUM 'GRAPH'
COR_RFM 'GRAPH'
COR_MXM PBRG   !
```



RF situation in nodalization

- Ring 1 reserved for inner reflector
  - Cylindrical and “inner” for COR_RFG input
  - Thickness and radius corresponds to ring 1
- Rings 7 and 8 for outer reflector
  - Cylindrical and “outer” for COR_RFG input
  - Thickness and radius corresponds to rings 7 and 8
- If upper/lower reflectors exists, use RF, SS, or a combo



SS situation in nodalization

Exercise 1 – MX Component and Materials

MP input defines a new generic oxidizable COR material
- Material name ‘MATC’
- Type COR-USER-METAL
- Short name ‘PBRG’
- Templated to MELCOR built-in graphite (material properties + oxidatio

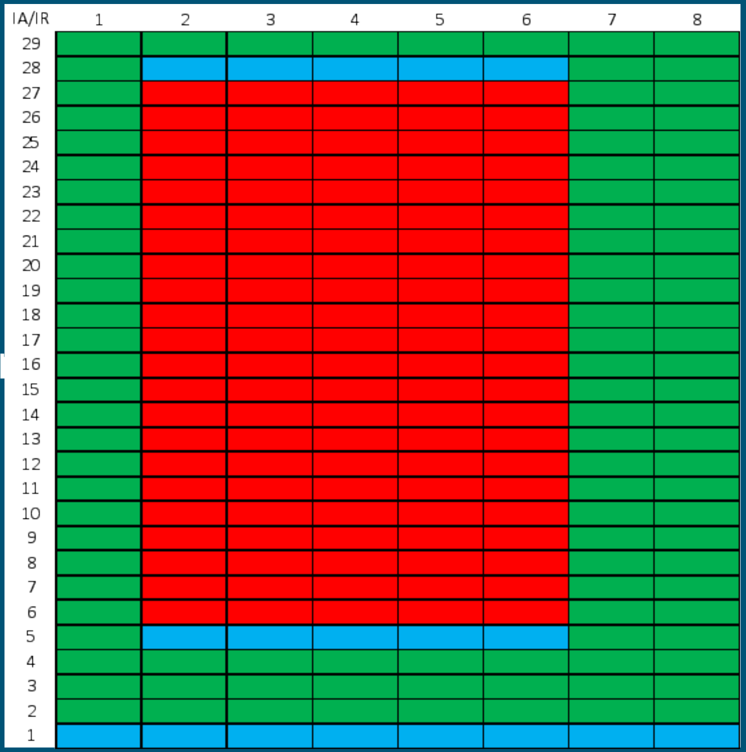
```
MP_ID MATC COR-USER-METAL PBRG
MP_BHVR GRAPHITE
```

COR leverages MP definition for MX primary mate

```
COR_MXM PBRG
```

Define mass of UDM primary in MX according to COR_NMAT:
- MX specified
- Cell-by-cell
- 3rd slot mass

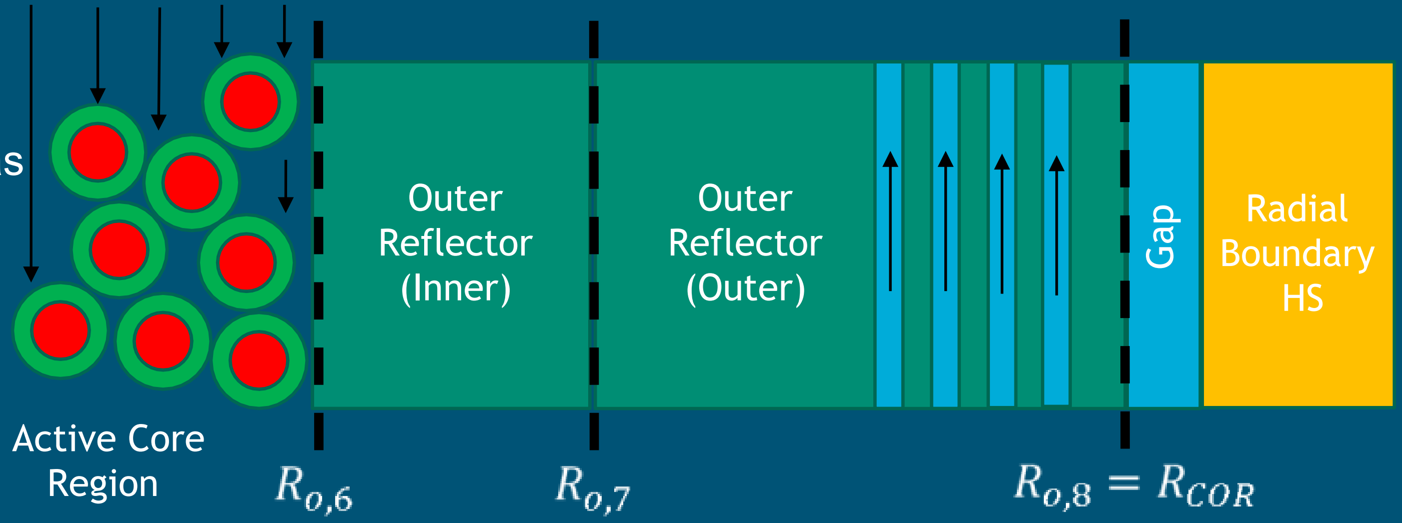
```
COR_NMAT 9
     1  1-5    1-6  MX  0.0    0.0      0.0    0.0
     2  6-27   1    MX  0.0    0.0      0.0    0.0
     3  6-27   2    MX  0.0    0.0    265.073  0.0
     4  6-27   3    MX  0.0    0.0    306.606  0.0
     5  6-27   4    MX  0.0    0.0    348.138  0.0
     6  6-27   5    MX  0.0    0.0    389.670  0.0
     7  6-27   6    MX  0.0    0.0    431.202  0.0
     8  28         1-6  MX  0.0    0.0      0.0    0.0
     9    ALL  7-8  MX  0.0    0.0      0.0    0.0
```



Exercise 1 – RF Component Configuration

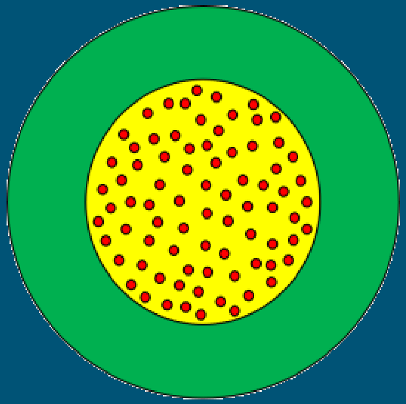
Special concern that may arise in certain PBR/PMR designs…worth thinking through as an exercise

- Outer reflectors may double as coolant risers
- Coolant entering vessel travels upward in riser before turning downward through upper plenum/core
- How could this be modeled assuming COR RF component comprises the entire outer reflector?
  - Use one or two rings at core periphery
  - Use COR_RBV to specify CV's in CH/BY
  - Use COR_BFA to apportion coolant flow areas
    - AFLOWC in ring 6 decremented somewhat
    - AFLOWC in ring 7 incremented correspondingly
    - AFLOWB in ring 8 represents riser flow
  - Use COR_RFA to ensure RF has CH/BY SA
  - Conduction is on by default between:
    - Ring 6 MX and ring 7 RF
    - Ring 7 RF and ring 8 RF
    - Given COR_BFA and COR_RFA, ring 7 RF (CH) gets some convection cooling from core flow
    - Given COR_BFA and COR_RFA, ring 8 RF (BY) gets some convection cooling from riser flow
  - Use COR_BCP for boundary conduction, ring 8 RF conducts to the radial boundary HS across gap

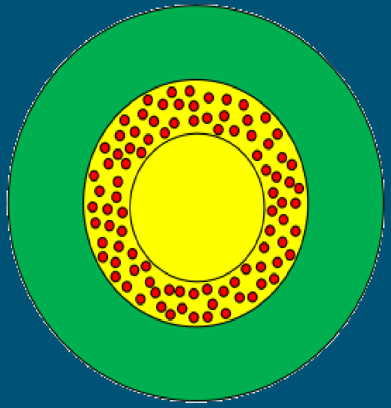


…Exercise 2 – PRKE Step Reactivity Insertion…

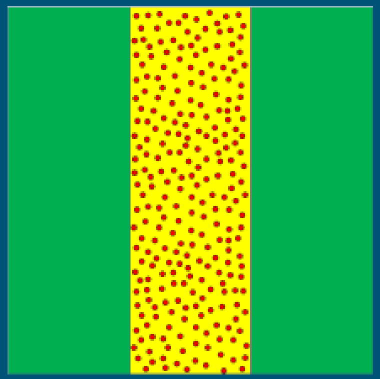
Conventional Pebble Fuel Element (HTGR/PBR)



Annular Pebble Fuel Element (FHR)



Prismatic Fuel Element (HTGR/PMR)



TRISO	Fuel (FU)
GRAPHITE	Fuel Extra Material (FUXM)
GRAPHITE	Matrix (MX)

Exercise 2 – Point Reactor Kinetics Step Reactivity Insertion

COR_PKM01, COR_PKM02, and COR_PKM03 added to PBR COR TH demo to illustrate point kinetics

- Default kinetics data and delayed neutron group parameters
- 400 MW power level at criticality
- External CF does a step reactivity insertion of $0.5 and holds
- Invoke Doppler, fuel temperature, and moderator temperature feedback with whole-core component average temperatures

```
! PKM
COR_PKM01  10.0 400.0e+6  ! start PKM at time 10.0 s, before that a 400 MW power level
COR_PKM02  'CFStepRx'      ! CF furnishes external reactivity in reactivity units of $
COR_PKM03  3
           1 RDOPF   1    ! TAVG #1 (over FU, see below) , Doppler feedback
           2 RFUF    2    ! TAVG #2 (over MX, see below),  Fuel density feedback
           3 RMODF  2    ! TAVG #2 (over MX, see below) , Moderator density feedback
!
COR_TAVG 2
         1  ALL ALL FU  UO2                    ! pull FU component T's averaged over whole
core
         2  ALL ALL MX  COR-USER-METAL     ! pull MX component T's averaged over whole-
core
CF_ID 'CFStepRx'     607  L-A-IFTE
CF_SAI    1.0    0.0   0.0
CF_ARG    3 ! NARG CHARG             ARSCAL            ARADCN
             1 CF-VALU('TimeOverTrip')  ! L-GT type, goes T for time > 0
             2 CF-CONST 0.5                  ! $0.5 insertion
             3 CF-CONST 0.0           ! $0 otherwise (criticality)
```

Exercise 2 – Output Processing

```
============================
  POINT KINETICS MODEL DATA
============================

     ******************************
     *    TIME-INDEPENDENT DATA    *
     ******************************

     TIME OF MODEL ACTIVATION (S)    = +1.60000E+004
     TIME OF MODEL DEACTIVATION (S)  = +1.79769E+308

     REACTOR DATA
     ==========================================================
     INITIAL CORE POWER (W)                         = +4.00000E+008
     PROMPT NEUTRON GENERATION TIME (S)             = +1.00000E-002
     TOTAL EFFECTIVE DELAYED NEUTRON YIELD (-)      = +6.50000E-003
     AVERAGE NEUTRONS PER FISSION (NEUT/FISS)       = +2.43200E+000
     ENERGY RELEASE PER FISSION (J)                 = +3.04400E-011
     EFFECTIVE DELAYED NEUTRON LIFETIME (S)         = +8.50000E-002
     PROMPT NEUTRON LIFETIME (S)                    = +1.00000E-004


     DELAYED NEUTRON GROUP DATA
     ======================================================
     INDEX  DECAY CONSTANT (1/S)  RELATIVE ABUNDABNCE (-)
     -----  --------------------  -----------------------
       1        +1.24000E-002           +3.30000E-002
       2        +3.05000E-002           +2.19000E-001
       3        +1.11000E-001           +1.96000E-001
       4        +3.01000E-001           +3.95000E-001
       5        +1.14000E+000           +1.15000E-001
       6        +3.01000E+000           +4.20000E-002
```

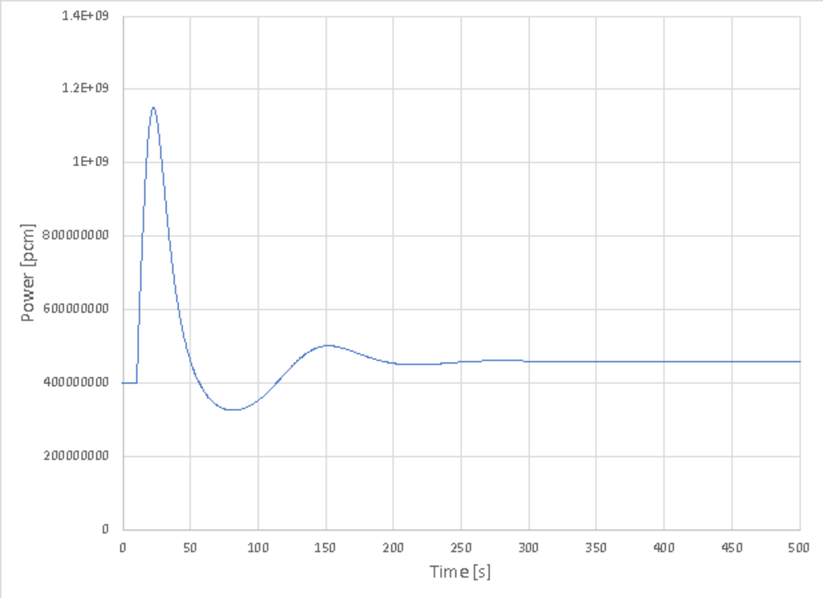
MELGEN/MELCOR Text Output

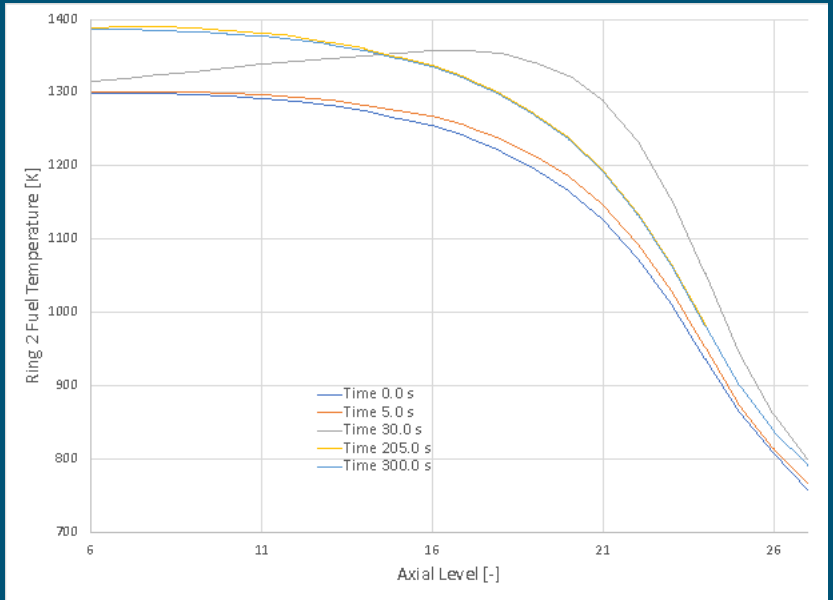
```
FEEDBACK MODEL DATA
=========================================
DOPPLER COEFFICIENT (-) = -2.20000E-002
FUEL DENSITY COEFFICIENTS:
    LINEAR     (1/K)     = -4.78000E-005
    QUADRATIC  (1/K**2)  = +6.75000E-009
MODERATOR DENSITY COEFFICIENTS:
    LINEAR     (1/K)     = +1.48340E-004
    QUADRATIC  (1/K**2)  = -1.60250E-007
    CUBIC      (1/K**3)  = +6.99000E-011
    QUARTIC    (1/K**4)  = -1.11140E-014
```

```
******************************
*         DYNAMIC DATA        *
******************************

POWERS (W)
=========================
PROMPT + DELAYED = +4.00000E+008
GROUP  1         = +0.00000E+000
GROUP  2         = +0.00000E+000
GROUP  3         = +0.00000E+000
GROUP  4         = +0.00000E+000
GROUP  5         = +0.00000E+000
GROUP  6         = +0.00000E+000

NO NEUTRON SOURCE SPECIFIED.
```

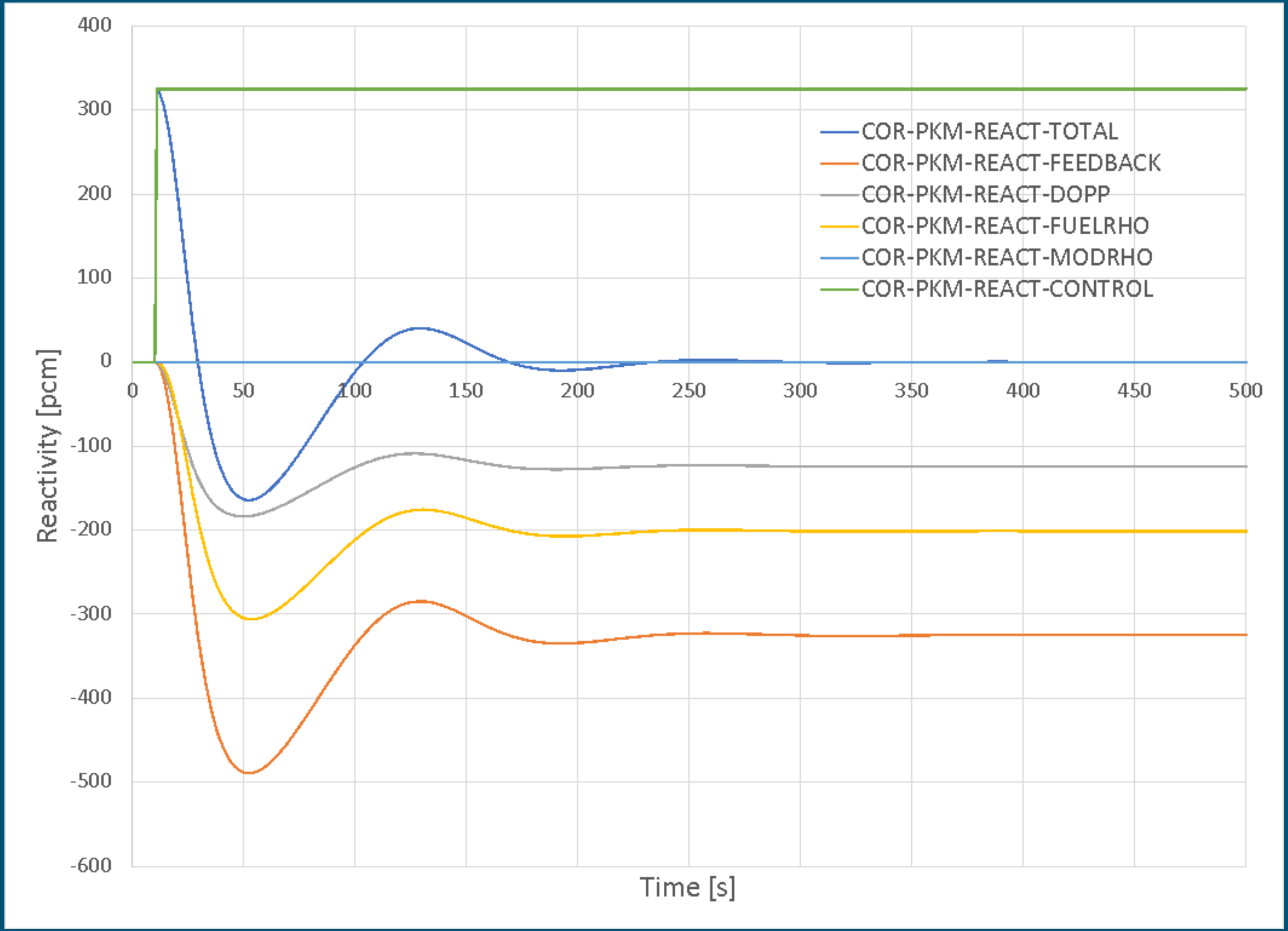
```
TEMPERATURES (K)
===============================================
    FEEDBACK           CURRENT       EQUILIBRIUM
-----------------  -------------  -------------
DOPPLER            +0.00000E+000  +0.00000E+000
FUEL DENSITY       +0.00000E+000  +0.00000E+000
MODERATOR DENSITY  +0.00000E+000  +0.00000E+000


REACTIVITIES (- / $)
================================================
DOPPLER            = +0.00000E+000 / +0.00000E+000
FUEL DENSITY       = +0.00000E+000 / +0.00000E+000
MODERATOR DENSITY  = +0.00000E+000 / +0.00000E+000
TOTAL FEEDBACK     = +0.00000E+000 / +0.00000E+000
EXTERNAL/CONTROL   = +0.00000E+000 / +0.00000E+000  (VALUE OF CF CFStepRx)
TOTAL              = +0.00000E+000 / +0.00000E+000
```

Exercise 2 – Output Processing





MELCOR Plot Variables



Conclusions

Reviewed some user input structures and best practice guidelines for PBR/FHR and PMR COR modeling

Talked through construction of a COR PBR nodalization and population with properly defined components

Performed a step reactivity insertion point kinetics exercise with that COR PBR nodalization