Securing the future of Nuclear Energy

HTGR Development, Benchmarking, & Validation

2024 European MELCOR Users' Group Meeting

April 15th-18th, 2024

SAND2024-03575PE

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Overview

History of HTGRs in MELCOR

Early applications and user experiences

- PBMR-400 public workshop (NRC source term demonstration)
- External users

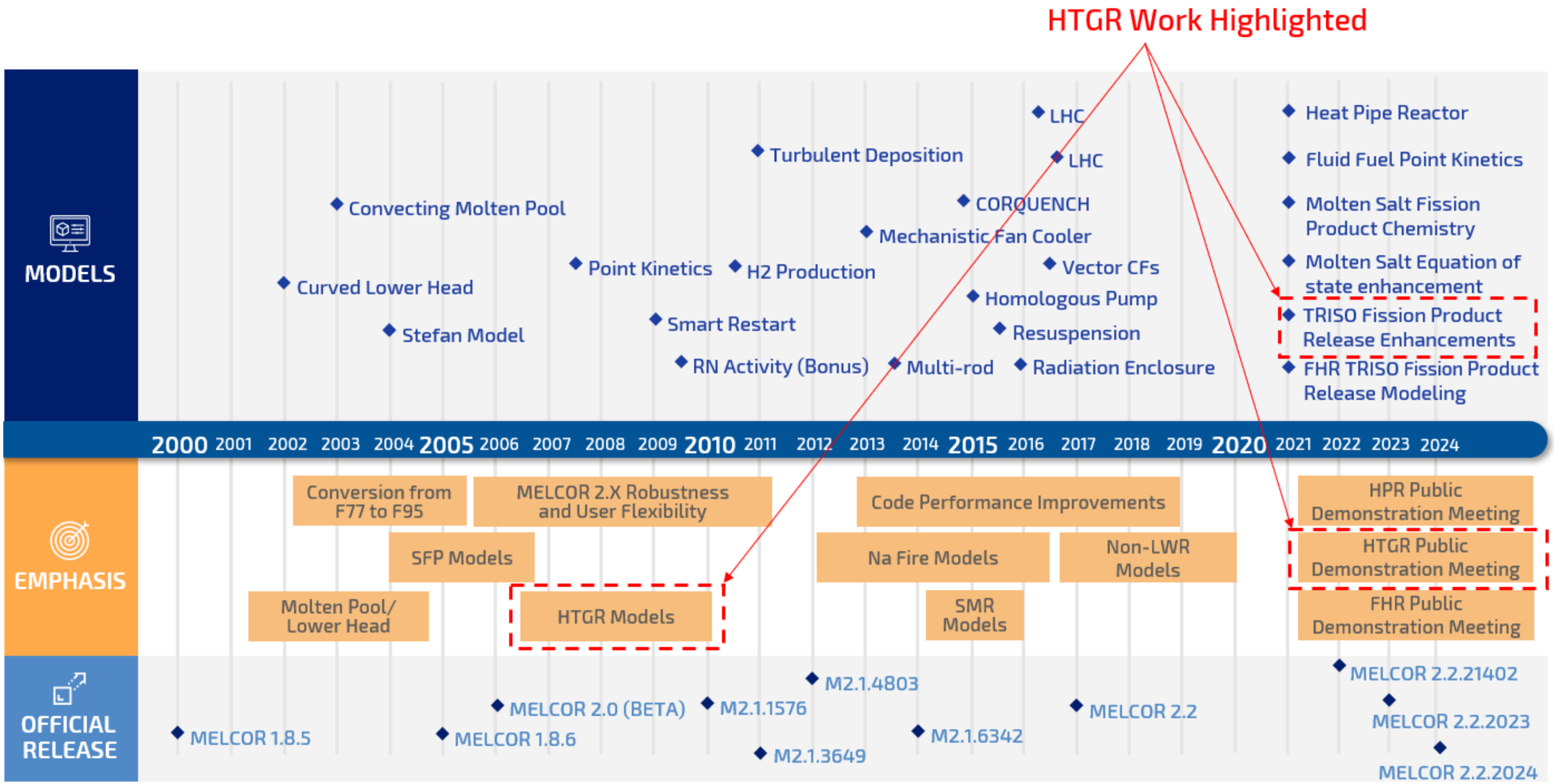
Describe conduction physics models and development(s)/improvement(s)

- Intracell and intercell conduction
- Effective conductivity models by reactor type
- Development(s)/improvement(s) stemming from benchmarks/validations

Benchmarking and validation

- Heat transfer test unit pebble bed gas reactor test facility - HTTU
- GEMINI prismatic high-temperature gas reactor (steady-state)
- For both, discuss:
  - MELCOR results/observations
  - Comparisons (experimental data, other codes)
- PBMR-400 (IAEA TECDOC-1694) revisited

HTGR Historical Development



HTGR Historical Development

Prior to 2008 – Few provisions for PMR/PBR (adapt LWRs)

2008 – CSARP presentation outlined initial plans/efforts
- New reactor types, components, conduction/convection models
- Updated CVH/NCG capabilities (e.g. helium properties)
- Beginnings of:
  - Diffusional fission product release model(s)
  - Graphite oxidation models
  - Point reactor kinetics model

2009-2010 – Miscellaneous improvements

2011-2017 – Limited development activity

2018-2023 – Non-LWR modeling initiative
- Revamped/streamlined FP release model
- Revisited many methods/strategies
- Added new physics models, heavily modified existing models
- Built on PBMR-400 for NRC source term demonstration

Early Applications: PBMR-400

MELCOR

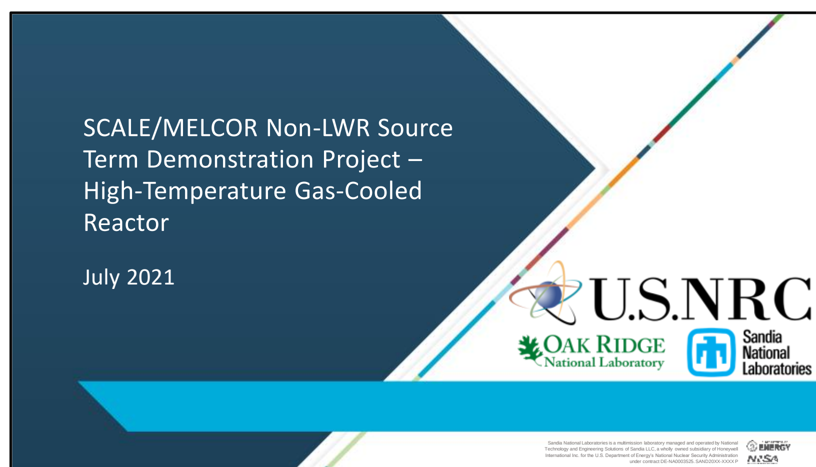
SNL/MELCOR involvement dates back to early 2000's

NRC source term demonstration workshop – May '21

- One of five public workshops to support NRC technical readiness and strategy for non-LWR accident analyses
- Based on PBMR-400 model developed at TAMU (~ 2009)
  - TAMU research based on preliminary OECD benchmark
  - DOE-funded work to support NGNP licensing
  - Developed in consultation with SNL
- Updated from TAMU model for NRC public workshop
  - Incorporated new features developed since 2018
  - Updated the calculation strategy (adhered to NRC evaluation model)
  - Same vessel and core as TAMU model
  - Added reactor building
- Primary means of testing and characterizing the diffusional fission product release model

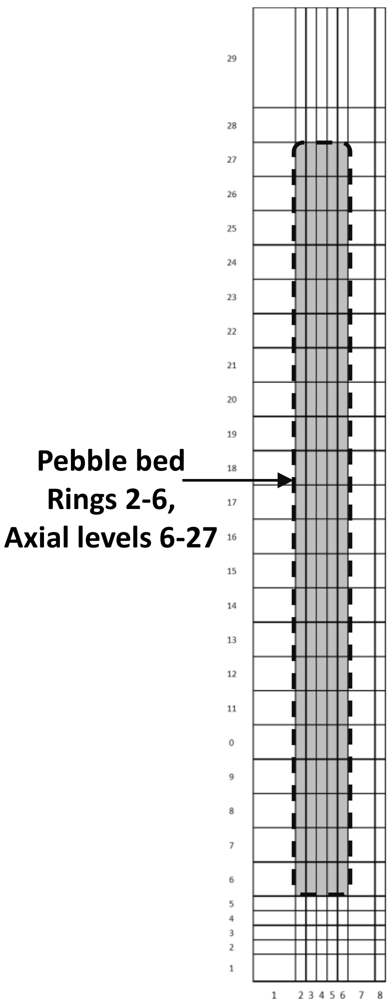
NRC non-LWR website for

- **Reports**
- **Slides**
- **Recordings**

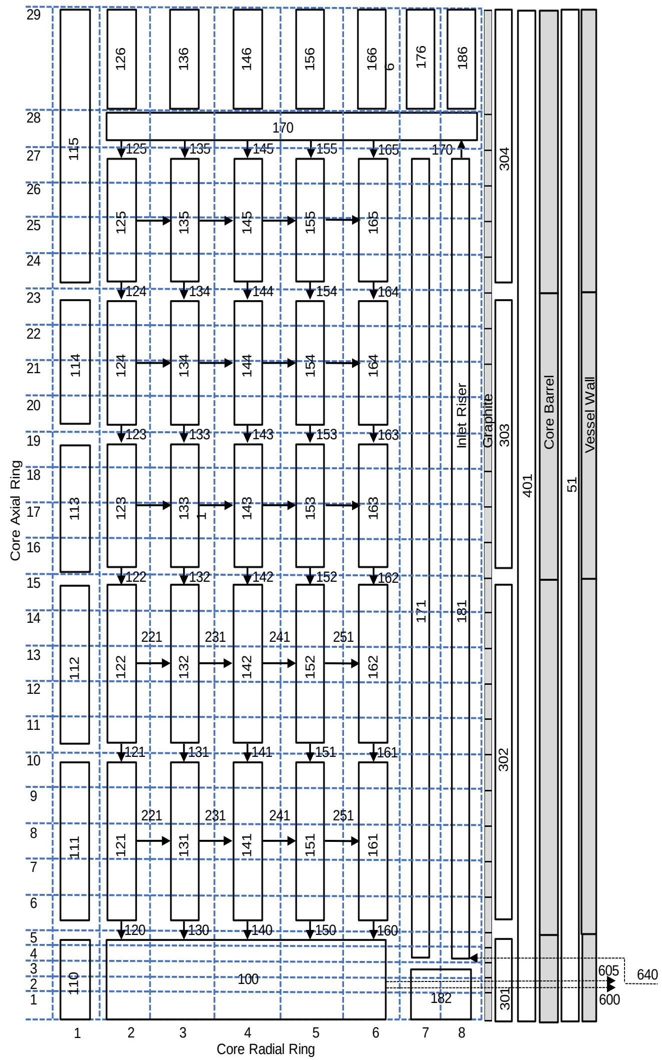


Early Applications: PBMR-400

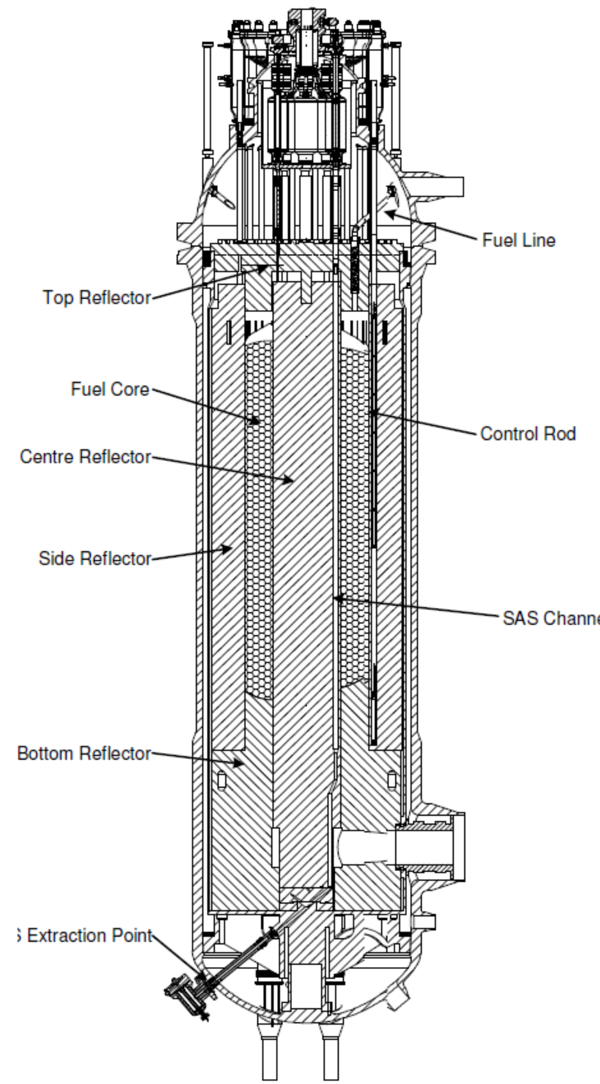
MELCOR



Vessel core package nodalization (8 rings x 29 axial levels) Correct aspect ratio



Vessel control volume, flow path, and heat structure nodalization with core package boundaries in blue



[P.J. Venter, M.N. Mitchell, F. Fortier, PBMR reactor design and development, in: Proceedings from the 18th International Conference on Structural Mechanics in Reactor Technology (SMiRT 18), Beijing, China, Aug. 2005]

Early Applications: PBMR-400 Demo

Single-parameter sensitivity results

Sensitivity parameters sampled at maximum and minimum values to illustrate impacts

Graphite conductivity has large PFT impact

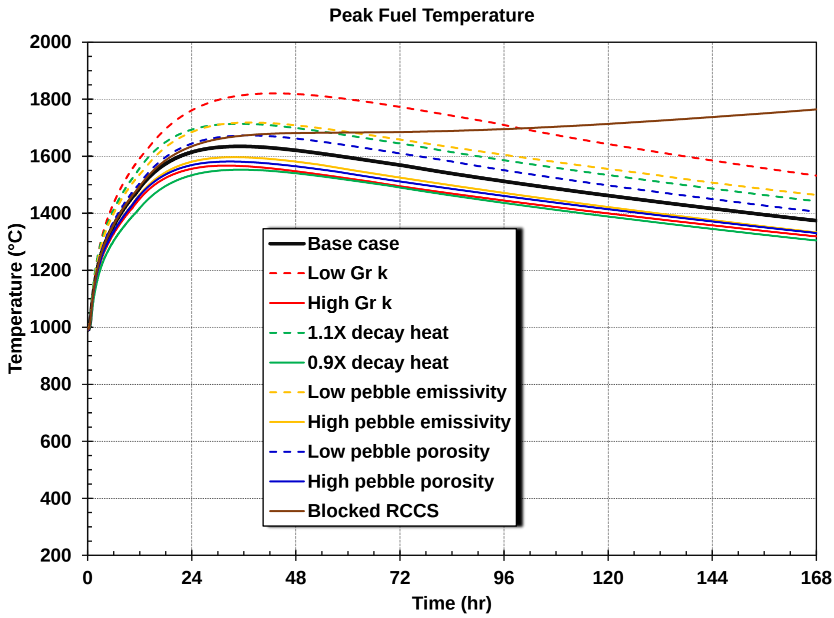
- Temperature variation
- Irradiation variation (> 10x)

Decay heat (+/- 10%) has next largest impact

Emissivity – next largest impact – speaks to relative importance of radiation

Debris bed porosity had a small PFT impact

Heat dissipation limits the magnitude of initial PFT for a blocked reactor cavity cooling system



User Experience

TAMU and limited user engagement on HTGR/non-LWR in early 2000's

- Limitations encountered and worked through with SNL developers
- Capabilities demonstrated to an extent (mostly thermal hydraulics)
- Tailed off as NGNP went by the wayside

SNL in-house experience with HTGR/non-LWR is well documented

- First-of-a-kind efforts (NRC source term demonstrations)
- Models built from scratch
  - HPR based on INL HPR Design A
  - FHR based on UC Berkley Mark-I
  - MSR (fluid-fueled) based on ORNL molten salt reactor experiment (MSRE)
  - SFR (metal fuel, pool type) based on ANL advanced breeder test reactor (ABTR)
- Tight development/applications loop
- NRC demonstration objectives met across the board (though work is not done)

External (and internal NRC/SNL) users had mixed experiences with HTGR models

- Still developing and learning best modeling practices (unlike LWR modeling experience)
- Urgent need to expand benchmarking/validation to prove best practices
- PMR input modeling/experience lagging behind PBR

User Experience

Multiple US/international users started HTGR benchmarking efforts with MELCOR

- PBMR-400, HTR-10, X-Energy, HTR-PM, GEMINI
- Includes helical coil SGs in some cases – complex secondary side

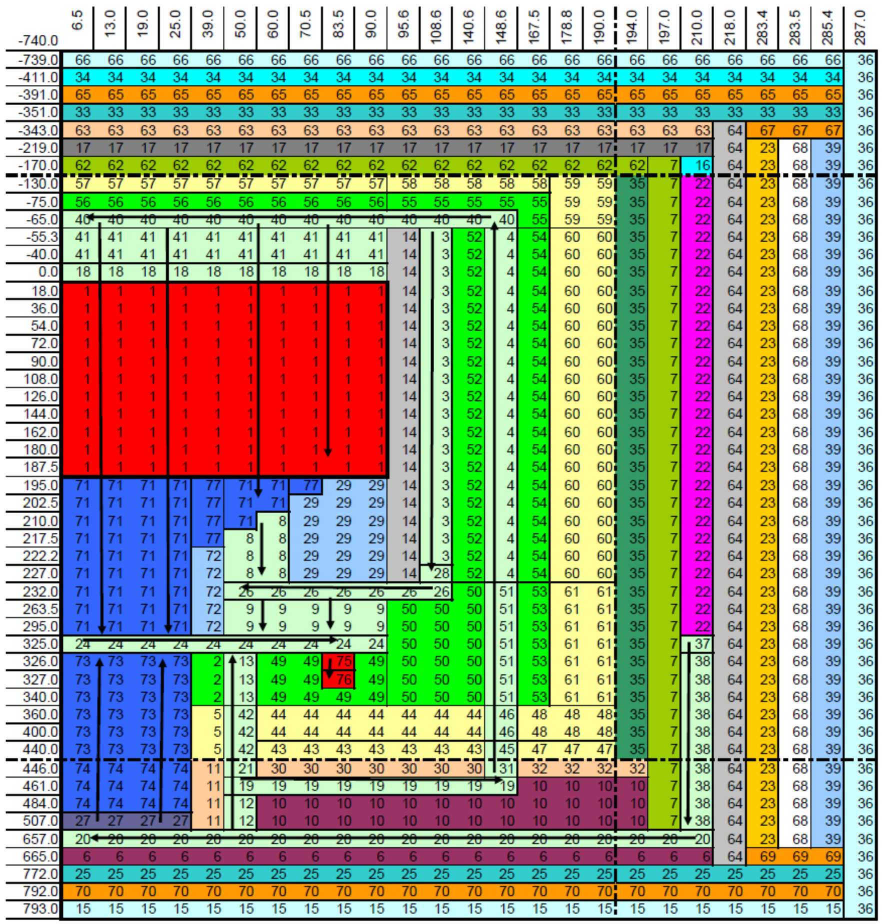
Complex systems/nodalizations are challenging

- COR DT/DZ model and logic behind channel/bypass treatment
- Several types of graphite materials
- Flow patterns

External (and internal NRC/SNL) users had mixed experiences with HTGR models

- Still developing and learning best modeling practices (unlike LWR modeling experience)
- Urgent need for benchmarking and validation
- PMR modeling and experience lags behind PBR

PBMR-400 demonstration underestimated radial heat transfer (high peak and average DLOFC temperatures vs. other codes)



HTR-10 THERMIX nodalization [TECDOC-1694]

Conduction Physics – Intracell

MELCOR

Intracell conduction between FU and MX collocated in a core cell

Accounts for

- FU conduction resistance,
- MX conduction resistance (non-negligible as for CL)
- Other serial/parallel resistances

$$q_{FU-to-MX} = h_{FU,MX} A_{FU} (T_{FU} - T_{MX})$$

$$\frac{1}{h_{FU,MX}} = \frac{1}{h_{FU}} + \frac{1}{\frac{1}{\frac{1}{h_{gap}} + \frac{1}{h_{CF}}} + h_{rad}} + \frac{1}{h_{MX}} \quad , \qquad for \quad \frac{1}{h_{MX}} = \begin{cases} {k_{MX} a}/{f R_{MX,i}} & , PMR \\ {k_{MX} a}/{f R_{MX,i}^2} & , PBR \end{cases} \qquad {1}/{h_{FU}} = \begin{cases} \frac{R_{FU}}{4k_{FU}}, PMR \\ \frac{R_{FU}}{5k_{FU}}, \mathrm{PBR} \end{cases}$$

$$a = \begin{cases} \left(\ln\left(\frac{R_{MX,o}}{R_{MX,i}}\right)\right)^{-1} & , PMR \\ \left({1}/{R_{MX,i}} - {1}/{R_{MX,o}} \right)^{-1} & , PBR \end{cases}$$

$$f = \begin{cases} \left(\frac{1}{2}\right) \left(\frac{2R_{MX,o}^2 \ln\left(\frac{R_{MX,o}}{R_{MX,i}}\right) - \left(R_{MX,o}^2 - R_{MX,i}^2\right)}{\left(R_{MX,o}^2 - R_{MX,i}^2\right) \ln\left(\frac{R_{MX,o}}{R_{MX,i}}\right)} \right) & , PMR \\ \frac{{1}/{R_{mx,i}}}{{1}/{R_{mx,i}} - {1}/{R_{mx,o}}} - \left(\frac{{3}/{2}}{{1}/{R_{mx,i}} - {1}/{R_{mx,o}}} \right) \left(\frac{R_{mx,o}^2 - R_{mx,i}^2}{R_{mx,o}^3 - R_{mx,i}^3} \right) & , PBR \end{cases}$$

* See rewritten COR RM 2.2.9 for derivations

Conduction Physics – Intercell

Intercell axial or radial conduction between like or different components

- Particularly important: MX-MX, MX-RF, RF-SS, MX-SS and any of these backwards
- Logically disallowed: FU-FU for PBR

General equation for axial or radial conduction between components of cells i and j

$$q_{i,j} = K_{eff}\left(T_i - T_j\right)$$

An overall effective conductivity is formulated from the participating component effective conductivities on either side

$$K_{eff} = \frac{1}{{}^{1}/_{K_i} + {}^{1}/_{K_j}}$$

Conduction areas and lengths inform component effective conductivities with a directional (axial or radial) dependence

$$K_i = \frac{k_i A_i}{\Delta x_i} \qquad \begin{aligned} &Axial: \quad A_i = \frac{V_{tot,comp,i}}{\Delta z_i} && \Delta x_i = \Delta z_i/2 \\ &Radial: \quad A_i = \left(\frac{V_{comp,i}}{V_{tot,i}}\right) * A_{rad,i} && \Delta x_i = \frac{V_{tot,i}}{2 * A_{rad,i}} \end{aligned}$$

*See COR RM 2.2.4 and. 2.2.5 for discussion

Conduction Physics: PBR k_{eff}

Zehner-Schlunder-Bauer with Breitbach-Barthels modification (see revised COR RM 2.2.6)

Accounts for:

- Conduction through pebbles,
- Conduction through fluid, and
- Pebble-wise radiation

Used in the inter-cell component conduction formulation (MX only)

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

$$k_c = \frac{2}{N}\left\{ \frac{B\left(1 + \frac{1}{\Lambda_s\left(\frac{2}{\varepsilon_r} - 1\right)} - \lambda\right)}{N^2 \frac{1}{k_f}} \ln\left(\frac{\lambda_p + \lambda_r}{B}\right) + \frac{B+1}{2B}\left(\frac{4\sigma T^3 D_p}{\frac{2}{\varepsilon_r} - 1} - Bk_f\right) - \frac{B-1}{N}k_f \right\}$$

$$\lambda = k_f/k_s \qquad \lambda_P = k_s/k_f \qquad \lambda_r = k_r/k_f$$

$$\Lambda_s = \frac{k_s}{4\sigma T^3 D_p}$$

$$k_r = 4\sigma T^3 D_p$$

$$B = C\left(\frac{1-\varepsilon}{\varepsilon}\right)^m$$

$$C = 1.25$$

$$m = 10/9$$

$$N = 1 + \frac{1}{\left(\frac{2}{\varepsilon_r} - 1\right)\Lambda_s} - \lambda B$$

Conduction Physics: PMR k_{eff}

Tanaka-Chisaka (see revised COR RM 2.2.6) accounts for:

- Solid and pore conduction, and
- Pore radiation
- Block-to-block gap conductance in parallel with single hex block conductance

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

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

$$k_{por} = k_{s,por} + k_{rad}$$

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

$$h_{gap} = \frac{k_g}{\Delta r_g} + 4\varepsilon_r \sigma T^3 D$$

$k_{eff} = Effective\ conductivity\ [W/m/K]$

$k_s = Thermal\ conductivity\ of\ solid\ (continuous) material\ [W/m/K]$

$A = 2(1-\varepsilon)/(2+\varepsilon)$

$B = (1-\varepsilon)/3$

$k_{por} = Thermal\ conductivity\ of\ pores\ (discontinuous) material\ [W/m/K]$

$k_{rad} = Radiative\ conductivity\ of\ pores\ (discontinuous) material\ [W/m/K]$

$k_{s,por} = Thermal\ conductivity\ of\ pores\ (discontinuous) material\ [W/m/K]$

$k_{er} = Effective\ radial\ conductivity\ [W/m/K]$

$h_{gap} = Gap\ heat\ transfer\ coefficient\ [W/m^2/K]$

$D_{blk} = Effective\ diameter\ of\ block\ [m]$

$D = Pore\ diameter [m]$

$\varepsilon = Porosity$

$\Delta r_g = Block - to - block\ gap\ thickness$

Development – Intercell Conduction

1507 – Radial Conduction Parameter

This sensitivity coefficient operates on the radial conduction length and/or the radial conduction area in the context of intercell component-wise conduction (see COR RM) for certain components found in PBRs (or FHRs) and PMRs. Alternatives to the default radial conduction area and length formulation that may be more appropriate for these reactor types can be invoked here.

(1) Radial Conduction Length Parameter.
(default = 0.0, units = -, equiv = none)

(a) C1507(1) = 0.0

Default formulation for both radial conduction length and radial conduction area regardless of component or reactor type:

$$A_i = \frac{V_{comp,i}}{V_{tot,i}} A_{rad}$$

$$\Delta x_i = \frac{V_{tot,i}}{2A_{rad}}$$

(b) C1507(1) < 0.0

For both MX and RF and regardless of reactor type (PBR/FHR or PMR), radial conduction area is the full radial boundary surface area, and radial conduction length is calculated from cylindrical coordinate geometry of COR nodalization:

$$A_i = A_{rad}$$

$$\Delta x_i = \frac{R_{o,i}^2 - R_{i,i}^2}{4R_o}$$

Additionally, for MX in the context of a PBR/FHR reactor type, axial conduction area is taken as the full area of the core radial ring annulus in question. Axial conduction length remains half the cell height:

$$A_i = \pi\left(R_{o,i}^2 - R_{i,i}^2\right)$$

$$\Delta x_i = \frac{\Delta z_i}{2}$$

(c) 0.0 < C1507(1) <= 1.0

RF is unchanged from default, MX conduction length is unchanged from default, and MX conduction area is modified such that fuel (FU) component volume is blended with MX component volume to scale radial boundary surface area:

$$A_{MX,i} = \frac{\left(V_{MX,i} + C1507(1) * V_{FU,i}\right)}{V_{tot,i}} A_{rad}$$

$$\Delta x_i = \frac{V_{tot,i}}{2A_{rad}}$$

Benchmarking & Validation: HTTU

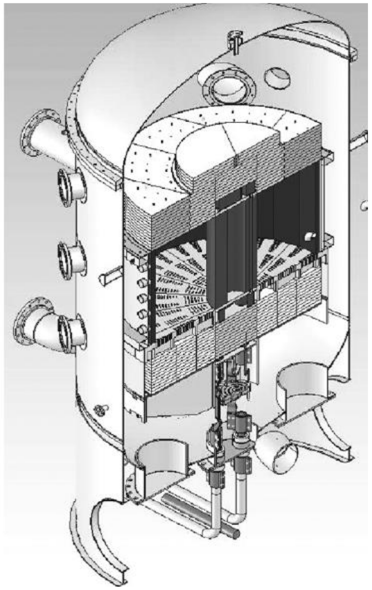
Heat Transfer Test Unit (HTTU)

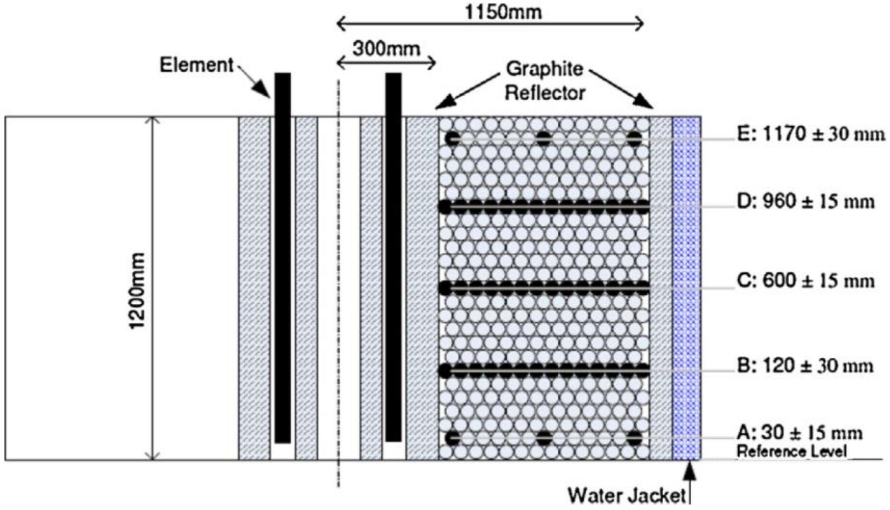
Separate effects testing captures effective (radial) conductivity in pebble bed

Developed by PBMR (Pty) Ltd for purposes of PBMR-400 design validation

Measure effective thermal conductivity across the pebble bed

- Heater rod in the inner reflector
- Heavily insulated at axial boundaries
- Heat transfer radially to outer reflector
- External boundary condition
  - Water jacket
  - Flowing water at T_{inlet} = 30 °C
- Redundant thermocouple strings
- Statistical processing for $k_{effective}$



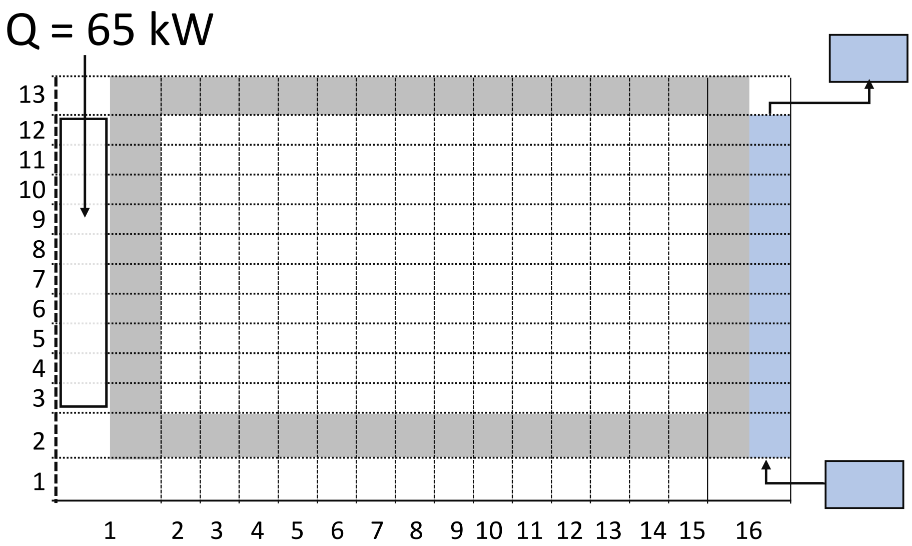


[P.G. Rousseaua, et al., "Separate effects tests to determine the effective thermal conductivity in the PBMR HTTU test facility," Nuclear Engineering and Design 271 (2014) pp. 444-458**]**

Benchmarking & Validation: HTTU

MELCOR model sought to test alternate modeling approaches vs PBMR-400 demo

- COR Nodalization to the boundary
  - PBMR-400 COR went to middle of outer RF
  - High resolution (13 levels, 16 rings)
- 1 CV per core cell
- No fictitious/non-participating CVs
  - PBMR-400 had non-participating CVs in inner and outer reflectors
  - Eliminate any inner/outer RF convective coupling to the pebble bed
  - AFLOWB = ASRFB = 0 in most core cells
- Tested and implemented up to 3 different RF materials
- Approximated experimental conditions
  - Inner RF at outer radius of heater rods
  - Specified heat source on inside of inner RF
  - Water flow outside outer RF
  - Eliminate any extraneous heat transfer (conduction) pathway through lower head
  - Axial boundaries effectively insulated via alternate RF materials with low conductivity



Benchmarking & Validation: HTTU

Compared this "pure radial conduction" COR with a 65 kW heat source and a ***specified*** effective conductivity to:

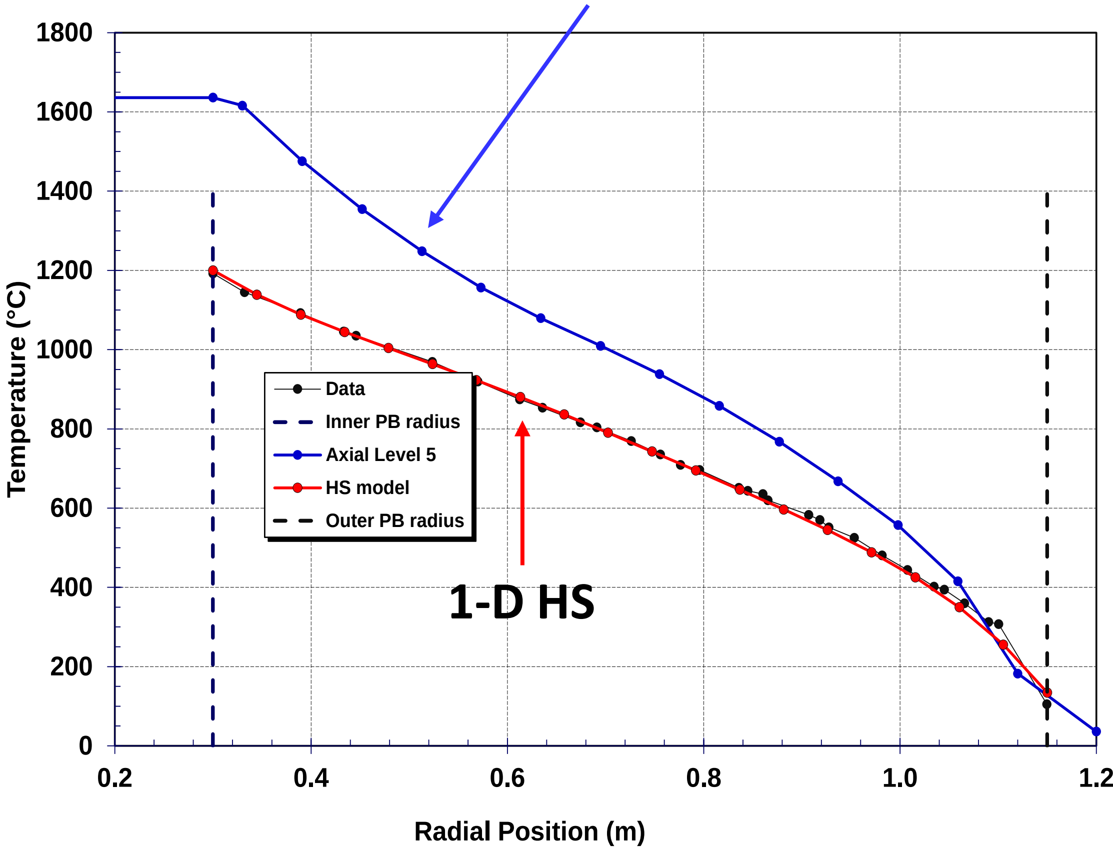
- HTTU experimental data
- MELCOR 1-D HS calculation

1-D HS compares well to data

COR struggles

- Radial conduction seems off
- No Zehner-Schlunder-Bauer
- Off-the-shelf componentwise inter-cell radial conduction apparently the culprit
- Geometry of COR nodalization properly matches HS

COR with nodalization improvement but *before* conduction model updates

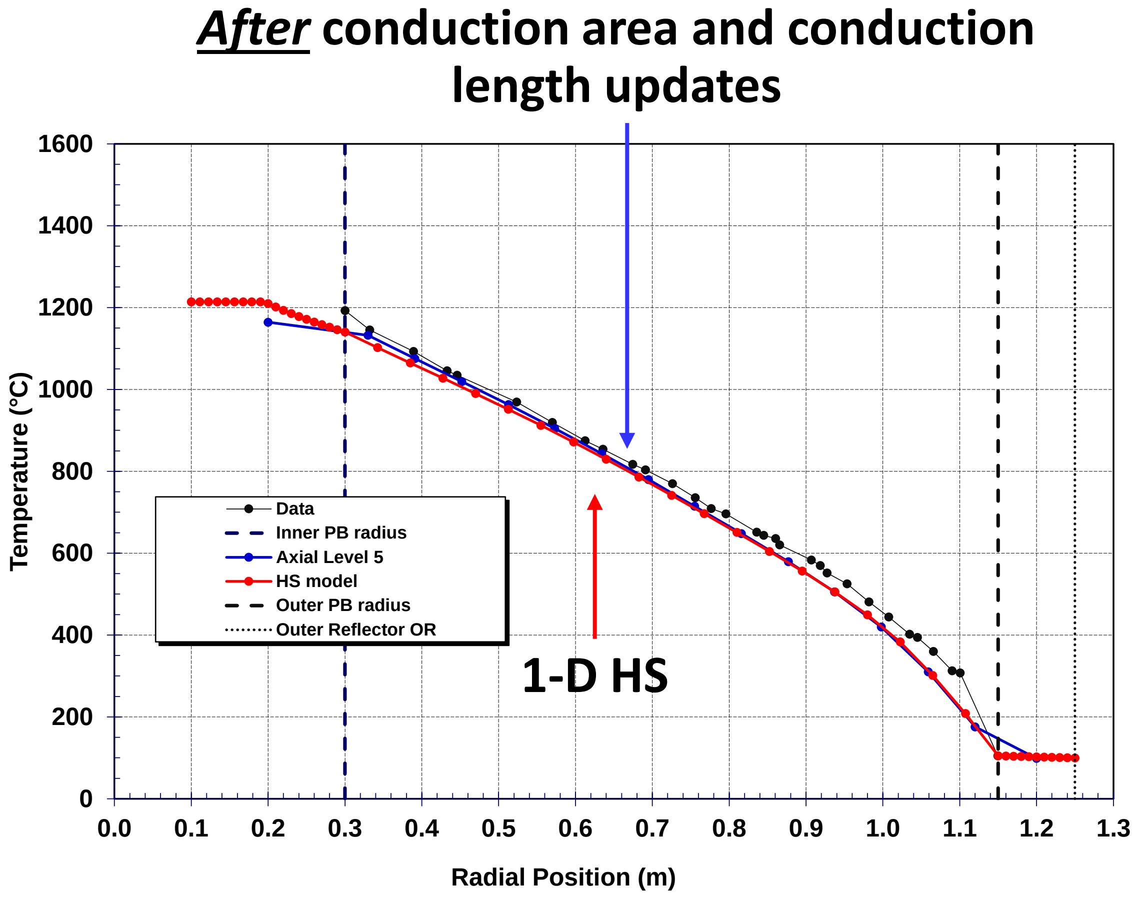


Benchmarking & Validation: HTTU

Keep the "pure radial conduction" COR with a 65 kW heat source and a ***<u>specified</u>*** effective conductivity, but reinterpret the component-wise conduction area and length terms in a physically appropriate manner

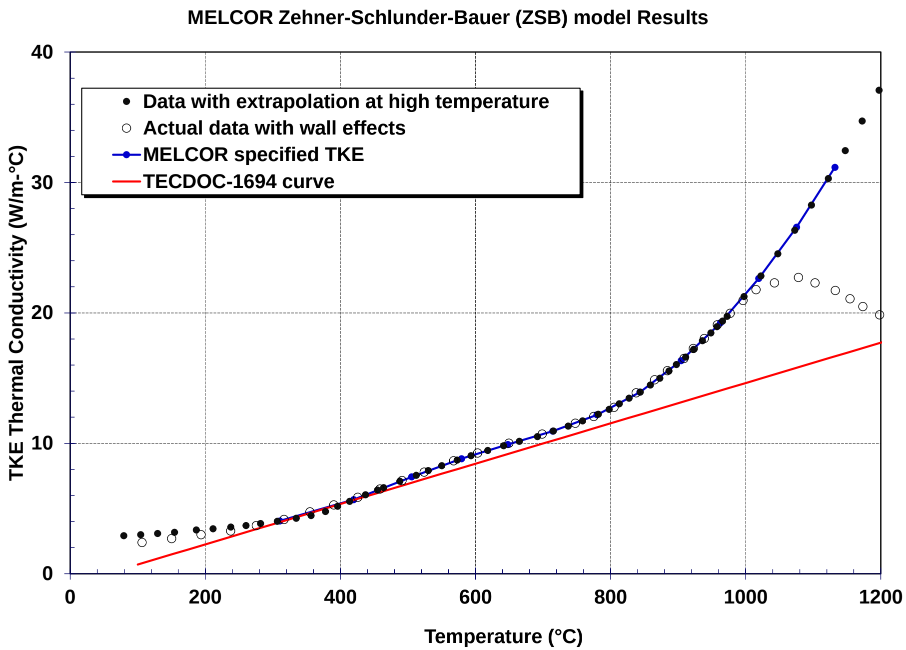
COR does much better

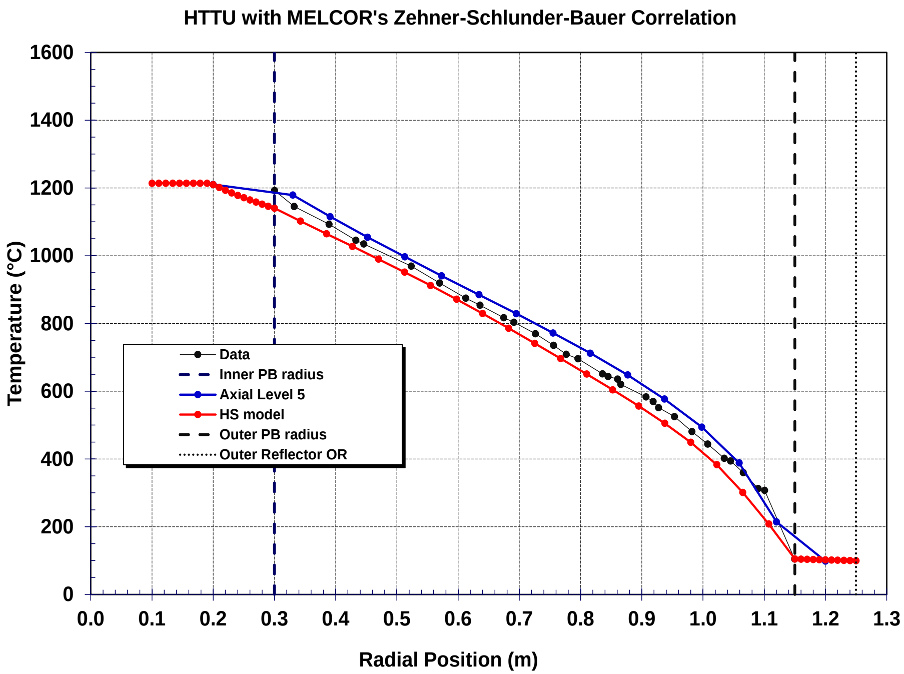
- Reconciles to 1D-HS and data
- Same component-wise inter-cell radial conduction model, but with alternative interpretations of:
  - Radial conduction area
  - Radial conduction length



Benchmarking & Validation: HTTU

Keep the “pure radial conduction” COR with a 65 kW heat source and alternative prescriptions for radial conduction area and length, but introduce the Zehner-Schlunder-Bauer effective conductivity model





Experiment had some wall effects

MELCOR correlation for effective conductivity shows good agreement with data

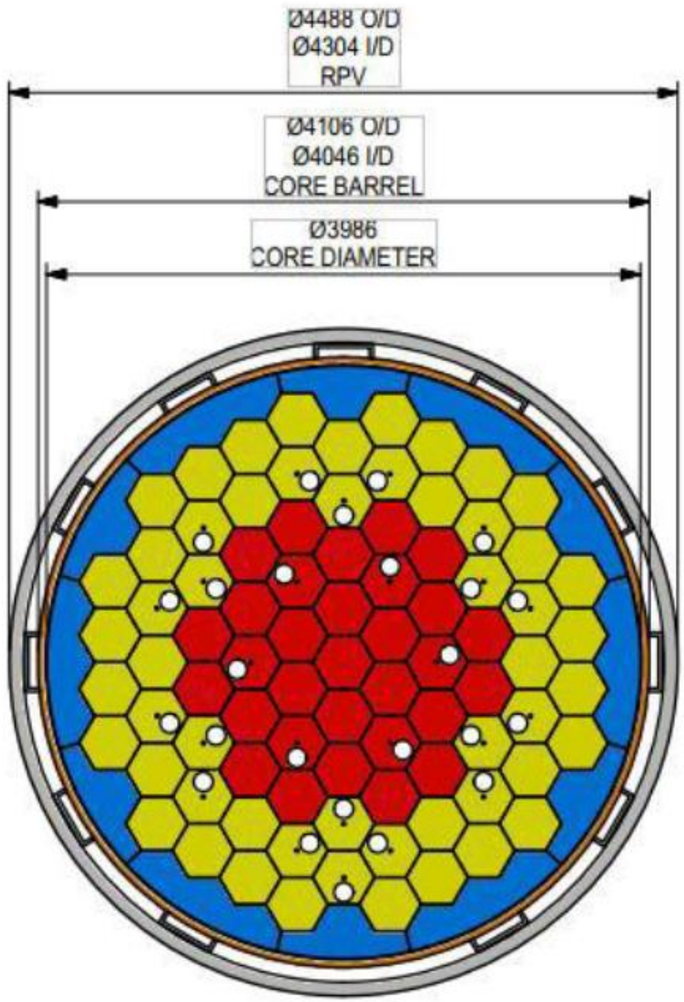
Radial conduction with ZSB model still shows good agreement with data

Benchmarking & Validation: GEMINI

"The Euratom Horizon 2020 project GEMINI+ is aiming at the (preliminary) design of a reactor system with a net power output of 165 MWth (gross power of 180 MWth including house load)"

MELCOR code benchmark exercise

- SPECTRA using GEMINI full-power, mid-plane, steady-state calculation
- MELCOR to SPECTRA to hand calculations
- Tanaka-Chisaka effective conductivity model



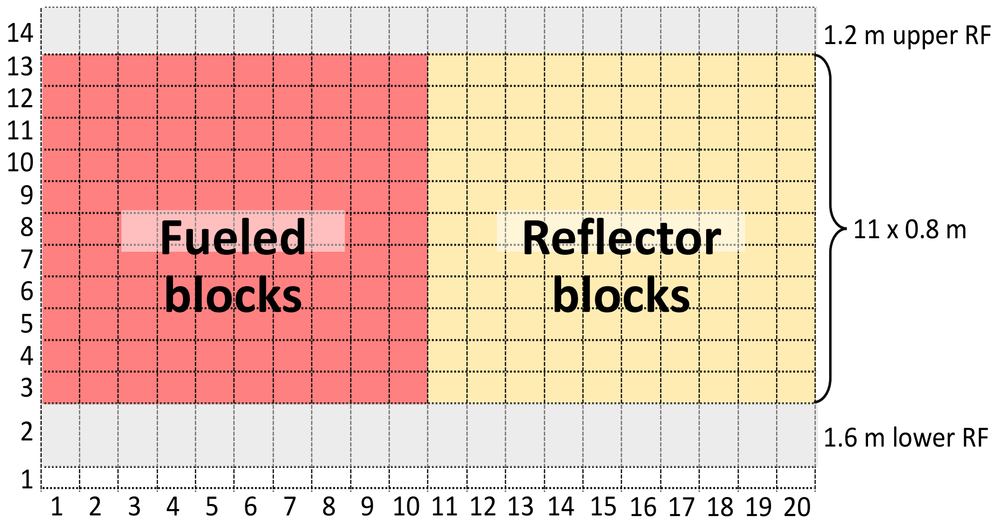
GEMINI core design

Provided courtesy of Marek M. Stempniewicz, SPECTRA lead code developer and GEMINI Safety Analyst, Nuclear Research and Consultancy Group (NRG), Arnhem, The Netherlands.
[GEMINI Results of DLOFC and PLOFC, 88 (D1-10), Appendix A]

Benchmarking & Validation: GEMINI

MELCOR input model

- Detailed COR (ia=14, ir=20)
- Include RF prismatic blocks
- Extend COR to barrel
- 10 rings in active fuel
- 10 rings in RF blocks
- 11 axial nodes (0.8 m) in active core
- Uniform power (match benchmark)
- Eliminate lower head conduction
- Decay heat at 100,000 s
- Adiabatic upper/lower RF
- 500 K at outer RF surface



Benchmark specifications in GEMINI:

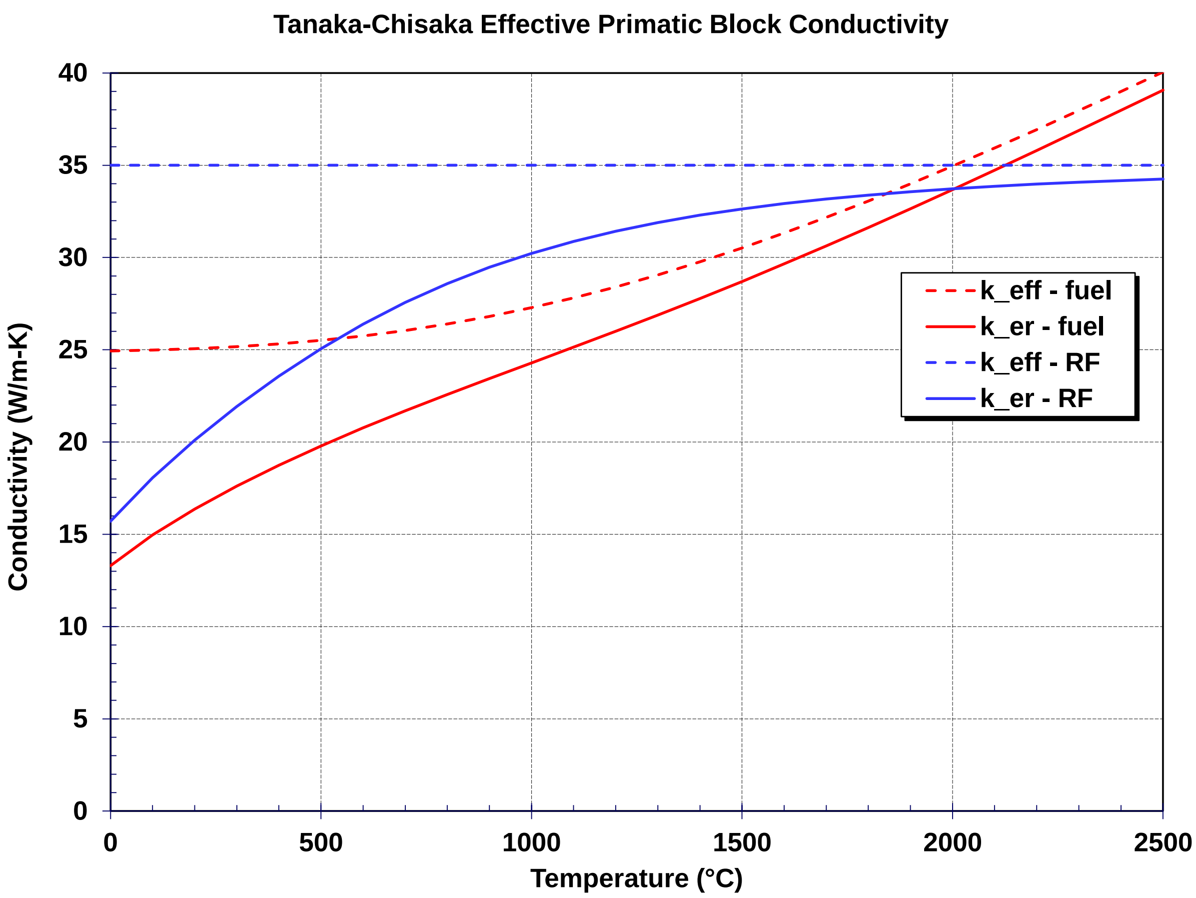
k_s = 35 W/m/K

ε_{fuel} = 0.214

ε_{ref} = 0.0

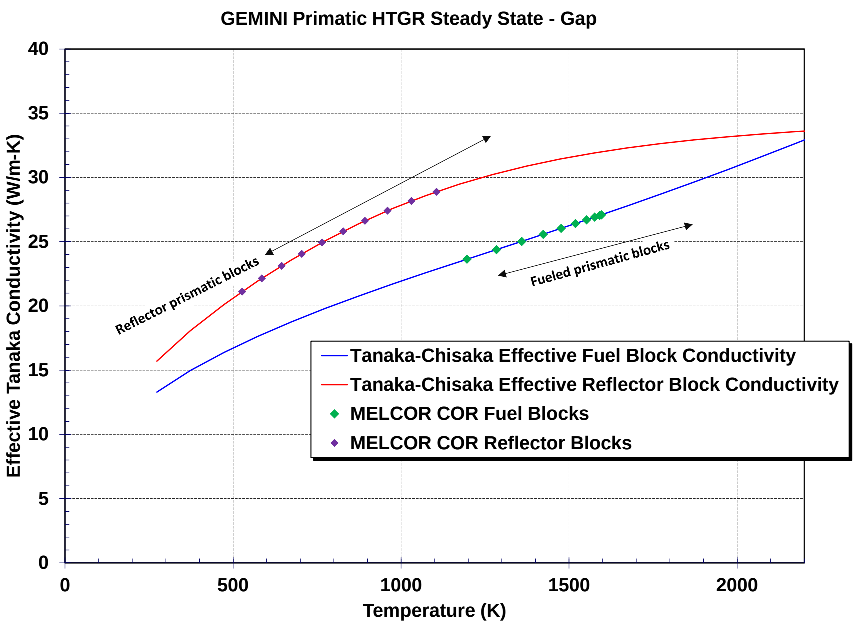
D = 0.08 m ; ε_r = 0.8 ; Δr_g = 0.002 m

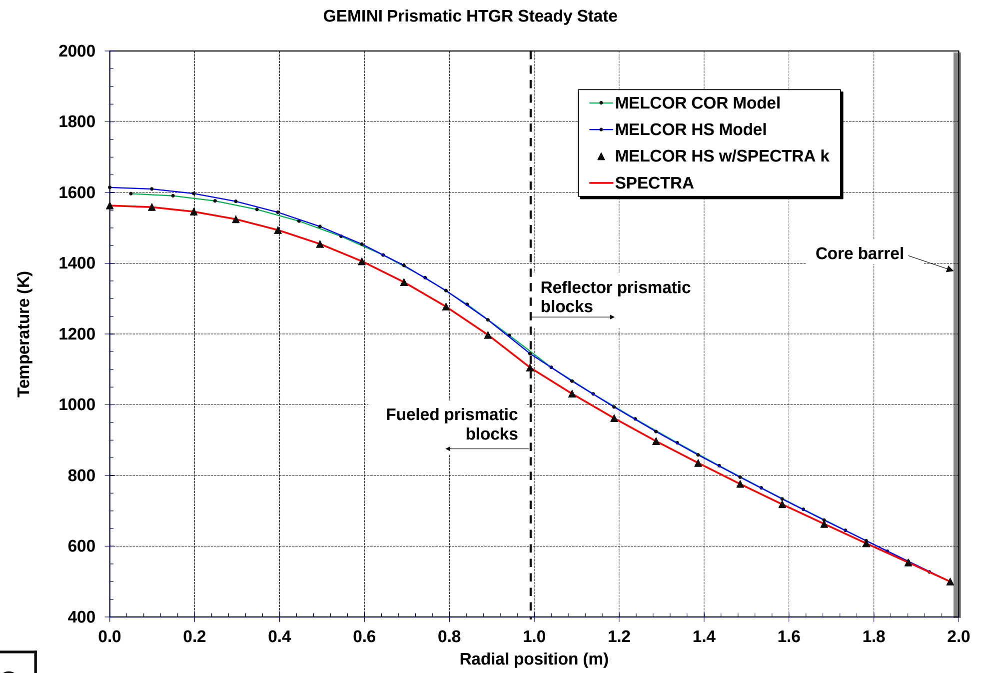
Benchmarking & Validation: GEMINI



Code predictions verified with hand calculations

Benchmarking & Validation: GEMINI





Location	MELCOR COR	MELCOR HS	SPECTRA	MELCOR HS SPECTRA k
r = 0.05 m	1596 K	1612 K	1561 K	1561 K
r = 0.94 m	1196 K	1192 k	1151 K	1151 K
r = 1.93 m	527 K	529 K	527 K	527 K
Heat flow	59.5 kW	59.5 kW	59.5 kW	59.5 kW

Some averaging of HS & SPECTRA node results to MELCOR lumped parameter T's

- **Comparison between MELCOR COR and HS models is good**
- **SPECTRA uses slightly different formulation for gap resistance**

Benchmarking & Validation: GEMINI

MELCOR

SPECTRA gap formulation vs MELCOR…slight unresolved difference

- $4\varepsilon_r(2\sigma)T^3$ vs $4\varepsilon_r\sigma T^3$
- Importance of gap radiation
- Impacts conductivity across core
- Requires more research and thought

$$k_{er} = \frac{1}{\frac{1}{h_{gap}D_{blk}} + \frac{1}{k_{eff}}} = \frac{1}{\frac{1}{\left(\frac{k_g}{\Delta r_{gap}} + \boxed{4\varepsilon_r\sigma T^3}\right)D_{blk}} + \frac{1}{k_{eff}}}$$

where

k_{er}	=	Final effective conductivity (W/m-K)
h_{gap}	=	Gap conductance (W/m^2-K)
D_{blk}	=	Effective radial diameter of a block (m)
Δr_{gap}	=	Block-to-block gap thickness (m)

Key PMR-related improvements

- Updated UG/RM
- Cell-by-cell porosity used in effective conductivity model (COR_CPOR)
- Prismatic block gap temperature aligned to MX component (not CV helium)
- More specifically to facilitate the GEMINI benchmark:
  - Some SC controls related to RF component heat transfer coefficients (allow water)
  - COR_QHS heat source extended to RF component

Very appreciative of the SPECTRA GEMINI benchmark from Marek M. Stempniewicz, NRG

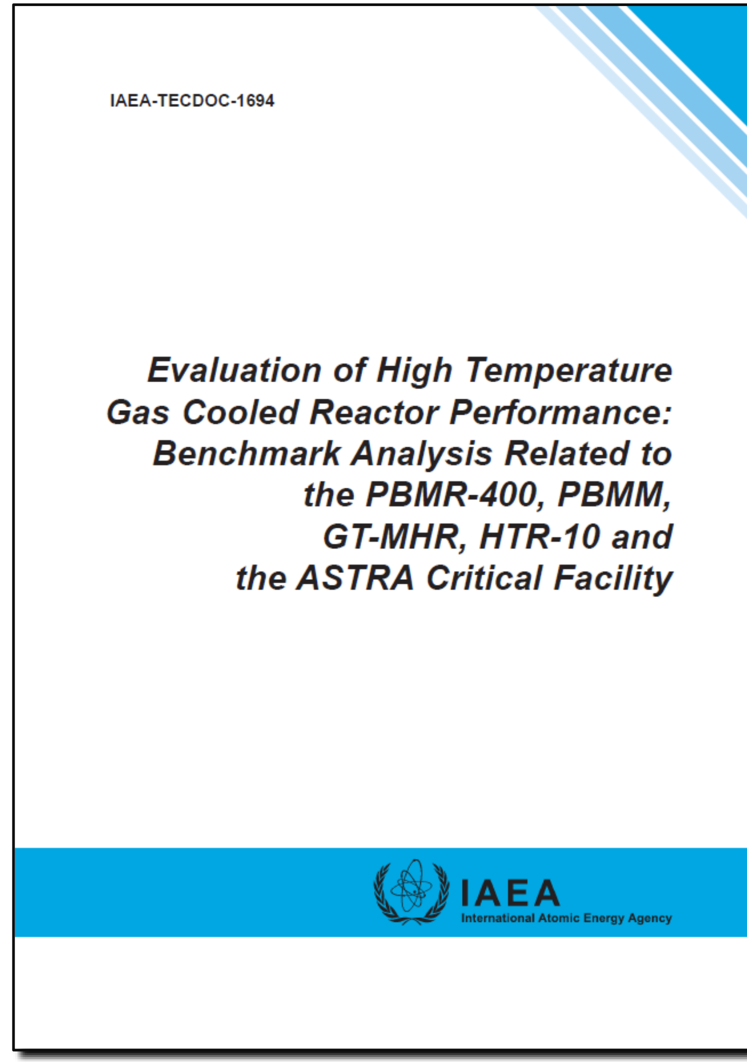
Revisiting the PBMR-400 DLOFC

PBMR-400 comparisons are complicated with many different benchmarks done over time

Lack of publicly available set of results

IAEA TECDOC-1694 a good source for input specifications and detailed code predictions

- Several participants' results provided
- Focus on PBMR Company VSOP-99 and TINTE multi-dimensional thermal-hydraulics and reactor kinetics specifications/results
- Significant differences (relative to TAMU model)
  - Geometry
  - Material properties
  - Initial conditions
  - Power distribution
- Draw upon best practice lessons from HTTU validation and GEMINI SPECTRE benchmark


IAEA-TECDOC-1694

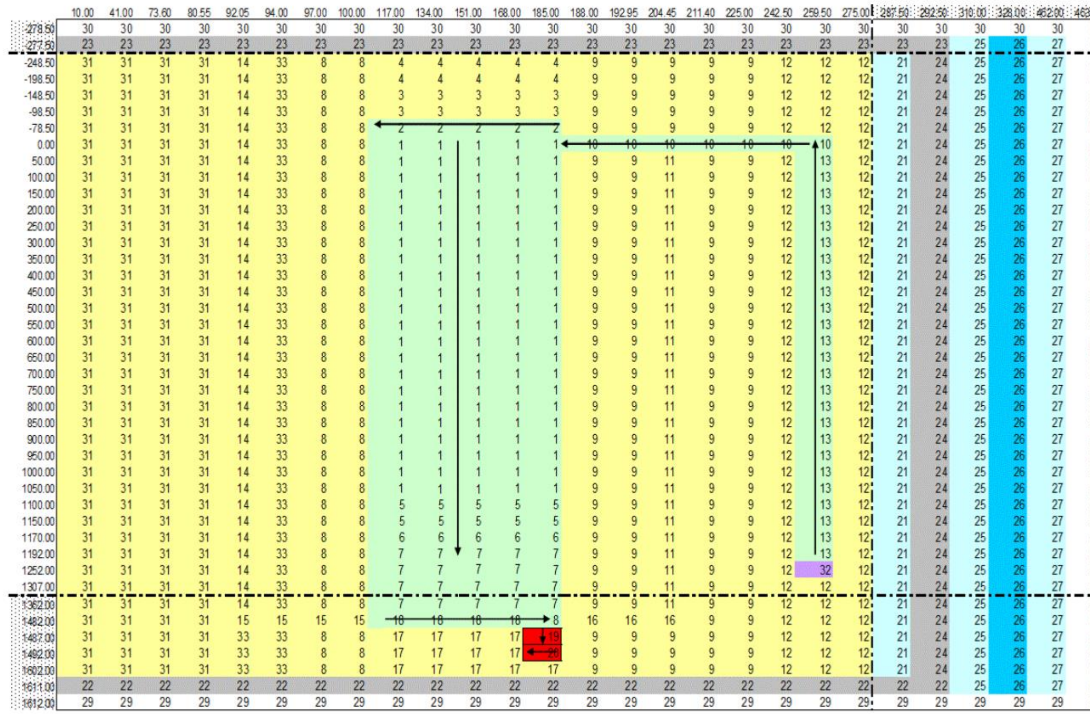
Evaluation of High Temperature Gas Cooled Reactor Performance: Benchmark Analysis Related to the PBMR-400, PBMM, GT-MHR, HTR-10 and the ASTRA Critical Facility

IAEA
International Atomic Energy Agency

Revisiting the PBMR-400 DLOFC

Recalculated vessel parameters based on VSOP-99 volumes, material masses, surface areas, 2-D power profile, and thermo-physical properties

- Eliminate dummy CVs in inner and outer RF regions
- Revise porosity input by region
- Redevelop RF input
- Include RF convection on the surface facing pebble bed
- Conduction developments stemming from HTTU

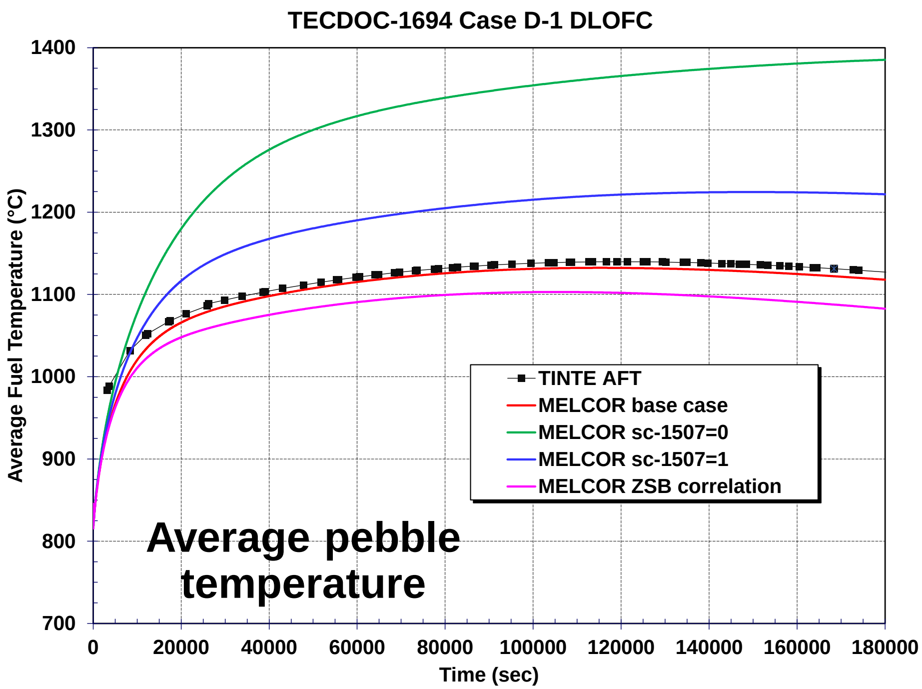


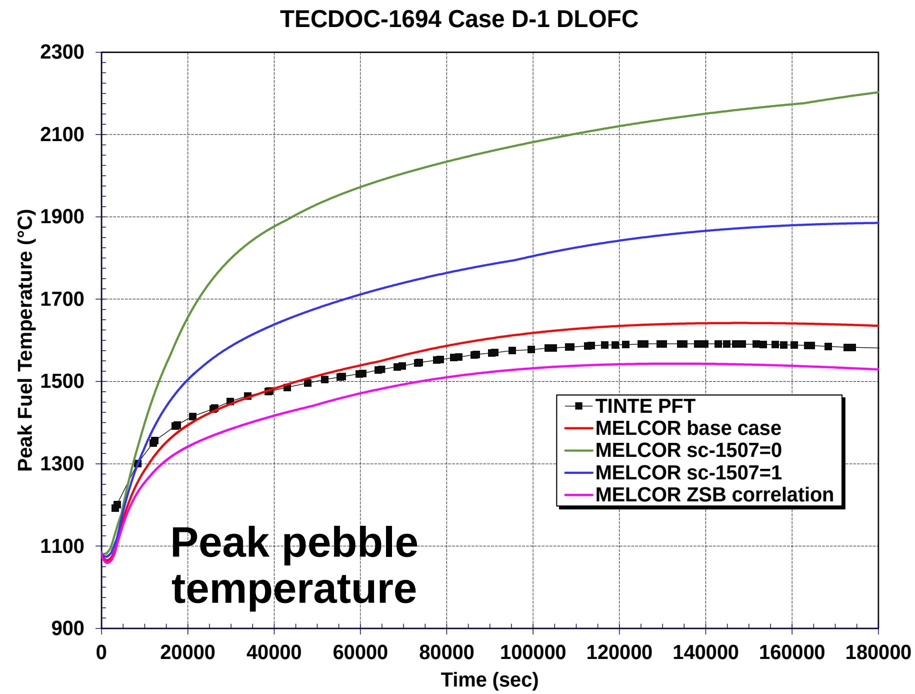
VSOP-99 thermal-hydraulic nodalization for PBMR-400 [IAEA TECDOC-1694]

Vessel radial nodalization not yet changed

- Outer reflector still split between COR and HS
- But with cor_htr conduct-cf option instead of cor_bcp

Revisiting the PBMR-400 DLOFC



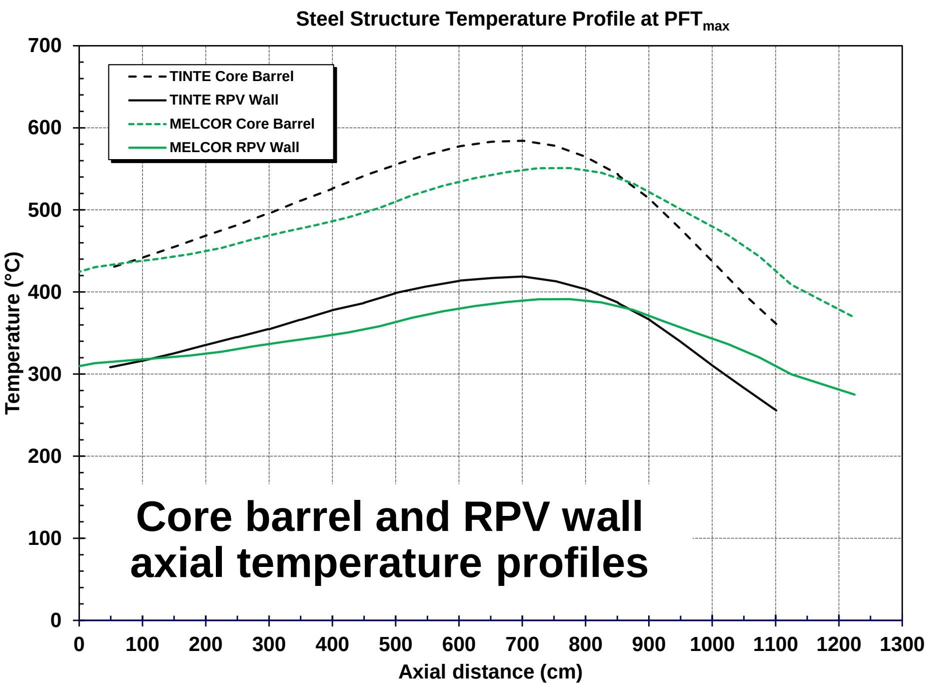


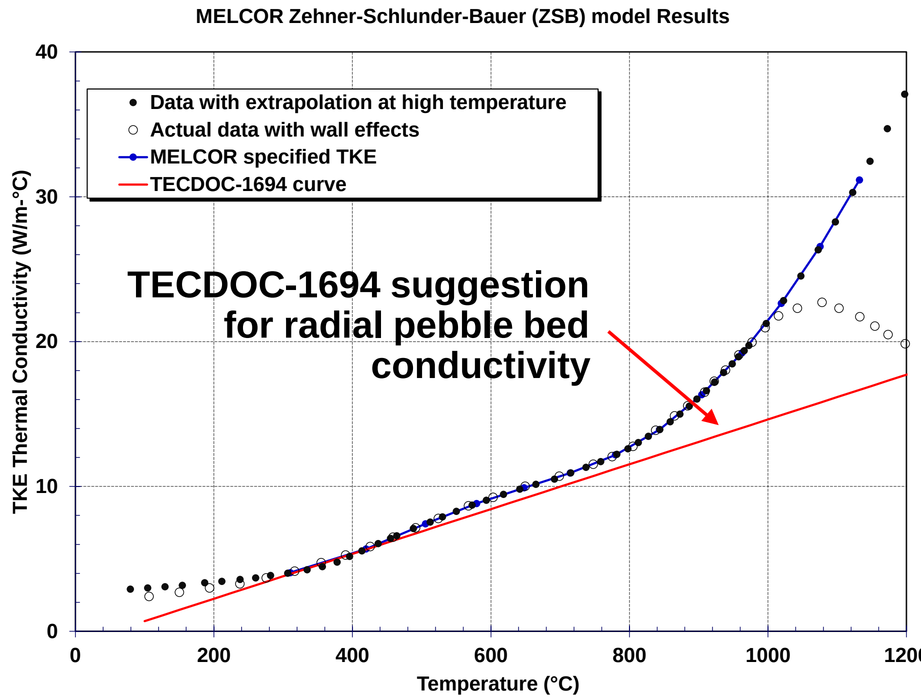
Three cases using TECDOC-specified thermal conductivity:

- COR SC 1507 = [0|1|-1] ; 0 for conventional COR conduction areas and lengths
- 1507 = 1 and -1 introduce alternatives for select conduction areas/lengths
- 1507 = -1 (base case) shows good TINTE T_{avg} agreement and fair TINTE T_{PFT} agreement

Case using ZSB/BB k_{eff} model (1507 = -1) consistently underpredicts TINTE

Revisiting the PBMR-400 DLOFC





Reasonable TINTE/MELCOR comparison of barrel and RPV temperature response

- MELCOR model includes transition from COR RF to 1-D HS within outer reflector
- Future work to extend COR Nodalization further out (through outer reflector to barrel)

TECDOC recommends radial pebble bed conductivity

- Does ***not*** show a non-linear increase in radial heat transfer at high temperature
- Explains MELCOR's underprediction with respect to TINTE when using ZSB/BB

Summary

MELCOR

MELCOR is rapidly developing in the area of non-LWR

- Beyond the NRC source term demonstrations
- Starting to include code benchmarking/validation activities
- MELCOR HTR-10 benchmark to soon be published
    - More to come at CSARP/MCAP '24
    - Main author now on staff at SNL
    - More lessons in the near future

Reviewed benchmark/validation activity

- Invaluable to improving models
- Useful in discovering best-practices
- GEMINI, noteworthy as 1st PMR effort

New models could help even more

- 2D-HS (e.g. for barrel and RPV)
- Generalized COR component work
- Expect updates at CSARP/MCAP '24

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Validation of a MELCOR model of HTR-10 in normal operation and accident conditions

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A B S T R A C T

We apply the thermal-hydraulics accident progression tool, MELCOR, to thermal–hydraulic benchmark problems on the 10 MW High Temperature Gas-cooled Reactor-Test Module (HTR-10) listed in the International Atomic Energy Agency (IAEA) Coordinated Research Project on Evaluation of High Temperature Gas-Cooled Reactor (HTGR) Performance (CRP-5). MELCOR results are compared to other solutions reported in the CRP-5 and compared to experimental data to perform code-to-code verification and code-to-experiment validation. Steady state temperature results calculated by MELCOR for the HTR-10 at initial full power operation show good agreement to experimentally measured values and predict the temperature more accurately than most of the solutions presented in the CRP-5 report. For transient calculations, the MELCOR model predicted the behavior in power during the first few hundred seconds for both types of transient quite well relative to the measured experimental data. This first of a kind work on verification and validation of MELCOR with steady state and transient pebble bed HTGR data highlights the recent and ongoing efforts in developing advanced reactor modeling capabilities with MELCOR and suggests areas for future MELCOR development.