INL/CON-22-69965-Revision-0

Assessing the Impact of Effective Thermal Conductivity on Gas-cooled Reactor Transients in RELAP5-3D

November 2022

Changing the World's Energy Future

Robert Forrester Kile, Aaron S Epiney, Nicholas R. Brown

Idaho National Laboratory

INL/CON-22-69965-Revision-0

Assessing the Impact of Effective Thermal Conductivity on Gas-cooled Reactor Transients in RELAP5-3D

Robert Forrester Kile, Aaron S Epiney, Nicholas R. Brown

November 2022

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

ANS Winter Meeting & Expo
2022

Assessing the Impact of Effective Thermal Conductivity on Gas-Cooled Reactor Transients in RELAP5-3D

Robert F. Kile
Aaron S. Epiney*
Nicholas R. Brown

THE UNIVERSITY OF TENNESSEE KNOXVILLE
INL Idaho National Laboratory

*Affiliated with Idaho National Laboratory

Overview

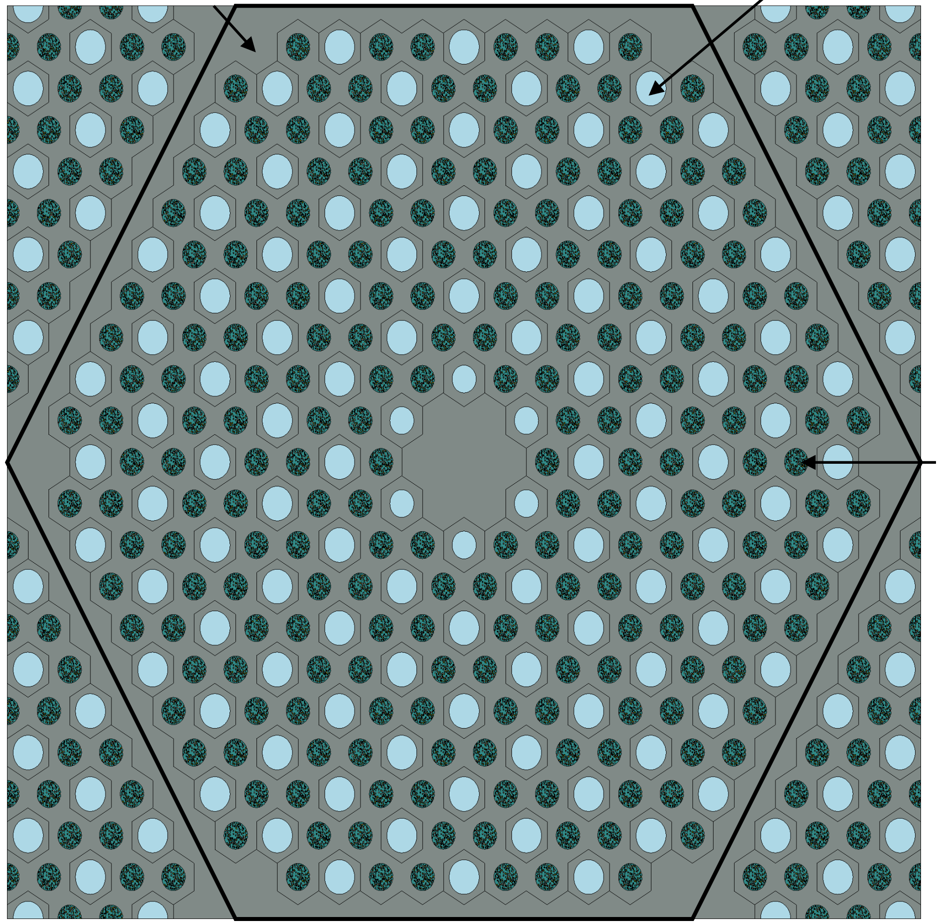
- Motivation
- Effective Thermal Conductivity (ETC)
  - ETC Relationships
- Modular high-temperature gas-cooled reactor (mHTGR)-350
- Impact of ETC in mHTGR-350
  - Steady State
  - Pressurized conduction cooldown (PCC)
  - Depressurized conduction cooldown (DCC)
- High Temperature Test Facility (HTTF)
- Impact of ETC in HTTF
- Conclusions

Motivation

- This work is motivated by an upcoming Organization for Economic Cooperation and Development-Nuclear Energy Agency (OECD-NEA) gas-cooled reactor thermal hydraulics benchmark based on HTTF
- HTTF is a thermal-hydraulics test facility at Oregon State University designed as a ¼-length-scale model the General Atomics Modular High-Temperature Gas-Cooled Reactor (mHTGR)
  - Helium-cooled, electrically heated up to 2.2 MW
  - Prismatic blocks in the core are Al_2O_3 ceramic rather than graphite
- HTTF experiment data are being used to develop an HTGR thermal hydraulics benchmark that can be used for validation exercises
- Further information about the benchmark will be presented on Wednesday in Advanced Reactor Thermal Hydraulics II

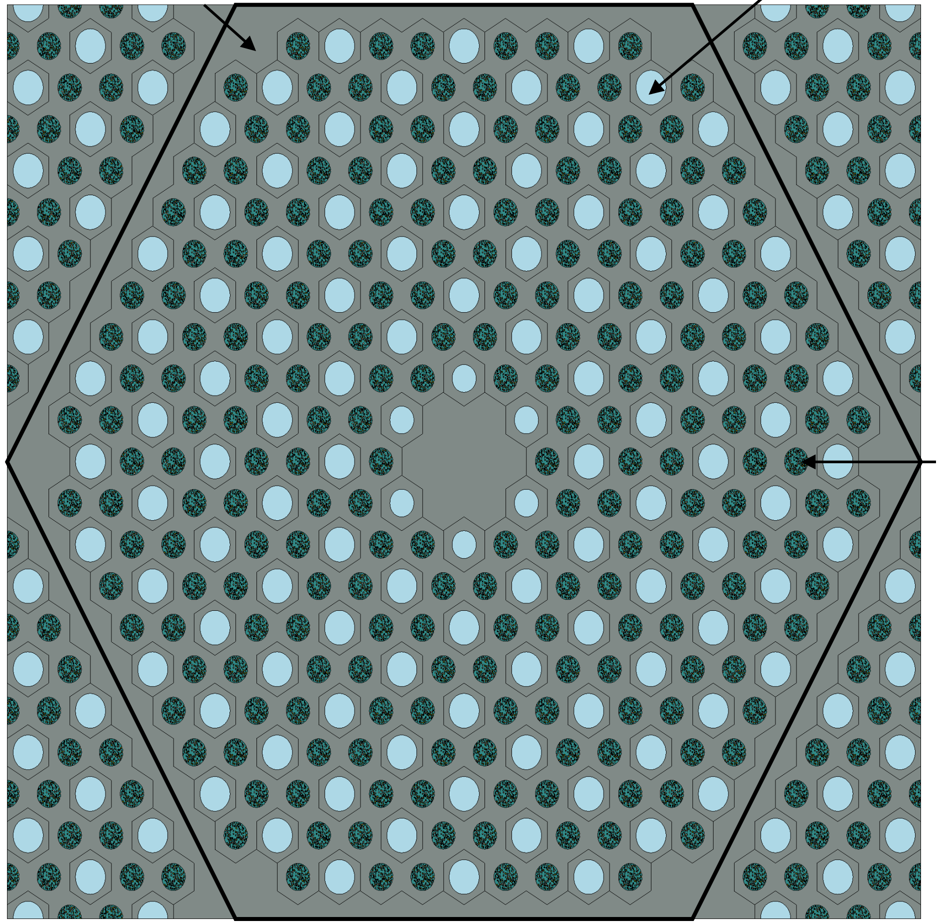
Holes in prismatic blocks impact heat transfer

- Fort St. Vrain blocks contain holes for coolant channels and fuel compacts
- The holes reduce conduction heat transfer compared to a solid block
- Identified relationships in the literature to calculate an ETC for these blocks



GAMMA + ETC relationship

- is coolant channel volume fraction
- is ceramic thermal conductivity
- is helium thermal conductivity



D. H. Shin, S. J. Yoon, N. Il Tak, G. C. Park, and H. K. Cho, "Analytical study on the effective thermal conductivity of vhtr fuel block geometry with multiple cylindrical holes," *Nucl. Technol.*, vol. 191, no. 3, pp. 213–222, 2015, doi: 10.13182/NT14-102.

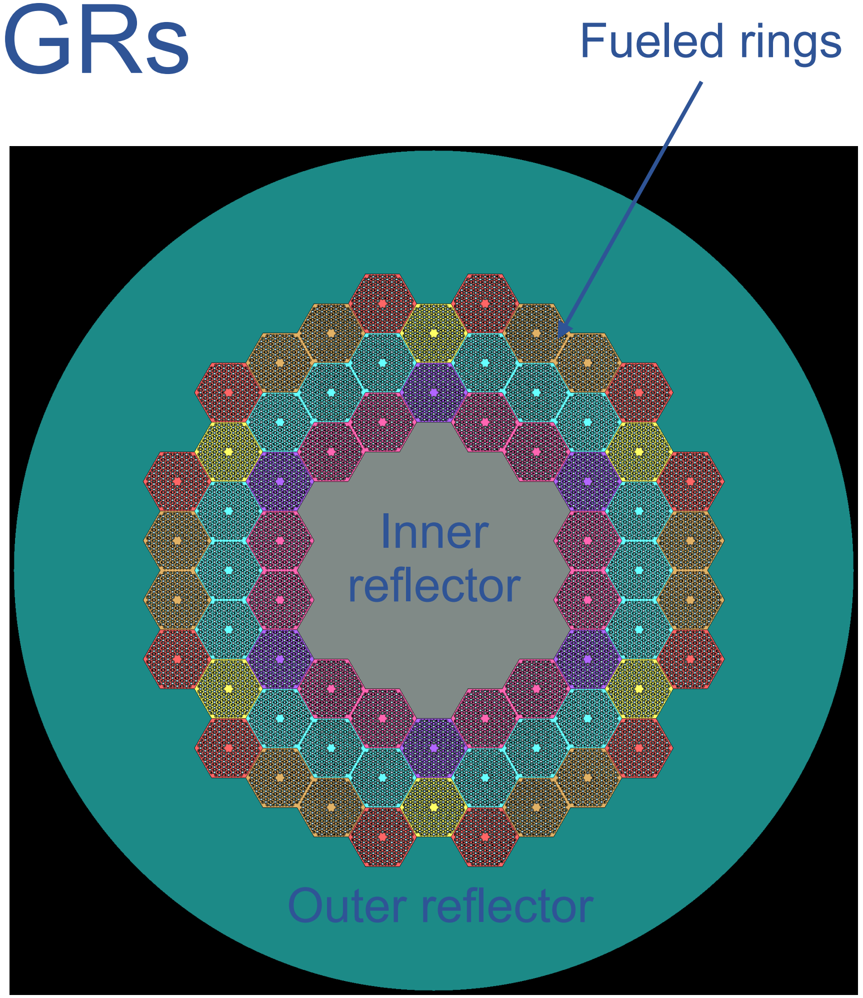
Rayleigh ETC relationship

- is coolant channel volume fraction
- ceramic thermal conductivity value
- is helium thermal conductivity
- Must define thermal conductivity in parallel and perpendicular directions to coolant holes
- Denominator of second term on right-hand side of perpendicular term contains a truncated series expansion

K. Pietrak and T. Wiśniewski, "A review of models for effective thermal conductivity of composite materials," *J. Power Technol.*, vol. 95, no. 1, pp. 14–24, 2015.

mHTGR-350 is an OECD/NEA computational multiphysics benchmark for HTGRs

- 350 MW_t prismatic block-type HTGR
- Blocks are made of H-451 graphite
- Inlet/Outlet temperature 532/960 K
- Coolant flow rate 157 kg/s
- Pressure 6.39 MPa
- Using ring model developed at Idaho National Laboratory



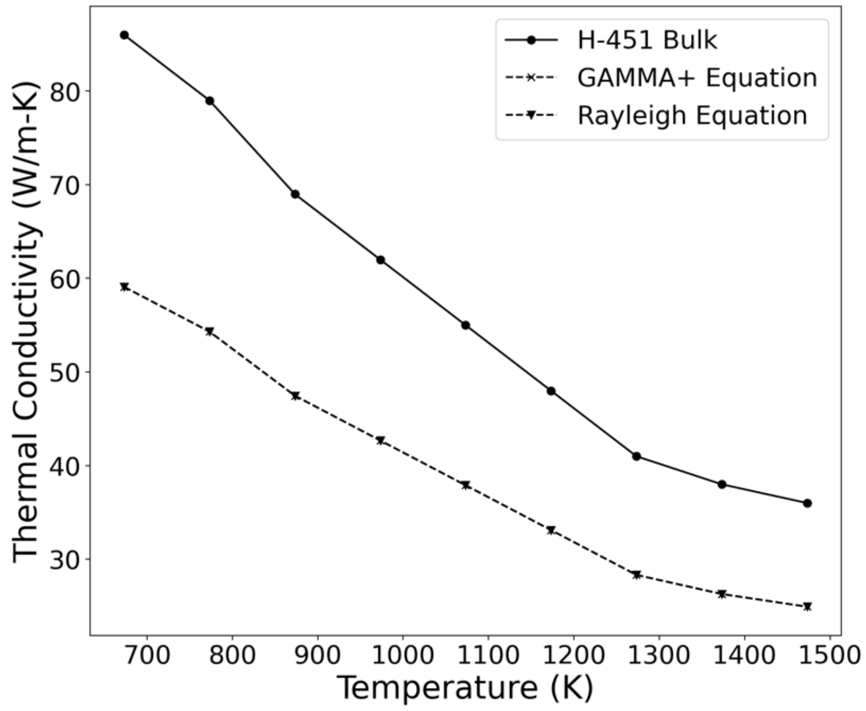
THE UNIVERSITY OF TENNESSEE KNOXVILLE

Idaho National Laboratory

ANS

Benchmark mHTGR-350 RELAP5-3D model used bulk graphite thermal conductivity, not ETC

- ETC is about 69% of bulk thermal conductivity
- GAMMA+ and Rayleigh relationships provide excellent agreement
  - Indistinguishable on graph
- Selected GAMMA+ relationship for RELAP model
- Only changed graphite in fueled blocks, not reflectors
- Changed thermal conductivity but not conductance between the blocks
- Reactor is modeled as a series of concentric rings, with rings 4, 5, and 6 representing the fueled region of the core

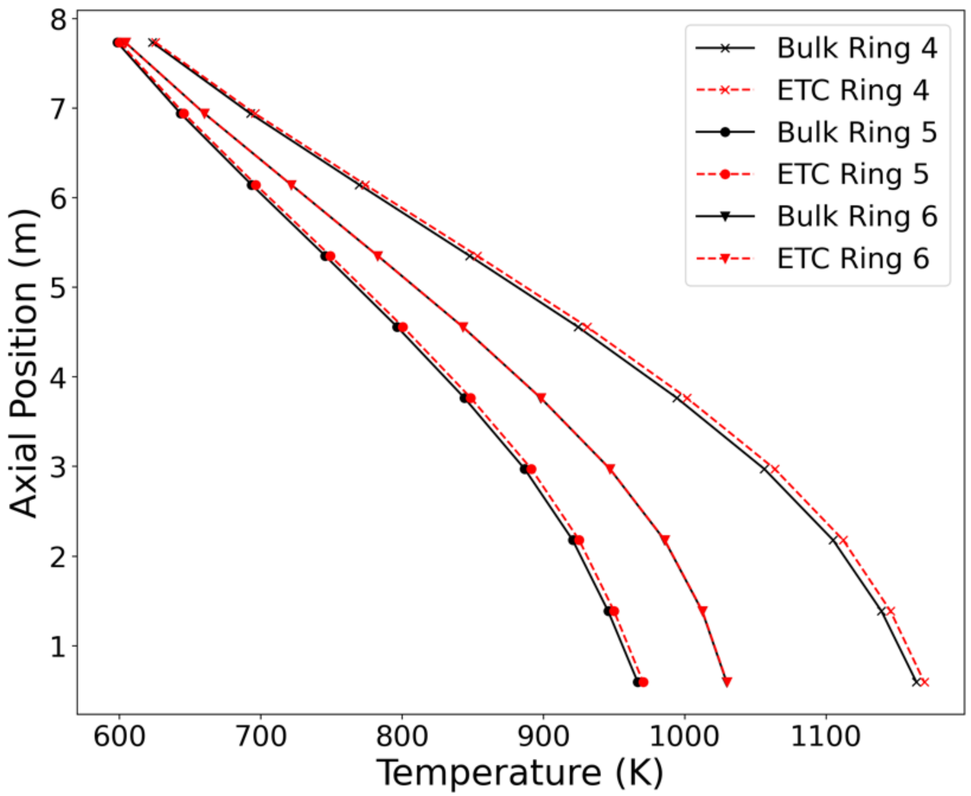


H-451 thermal conductivity includes effects of irradiation

Strydom, G., Epiney, A. S., Alfonsi, A., & Rabiti, C. (2016). Comparison of the PHISICS/RELAP5-3D ring and block model results for phase I of the OECD/NEA MHTGR-350 benchmark. *Nuclear Technology*, *193*(1), 15–35. https://doi.org/10.13182/NT14-146.

Steady-state temperature differences with and without ETC are small

- Difference in peak fuel temperature is 5 K
- Largest difference in fuel temperature ~10 K
- In outermost ring, difference in temperatures is negligible
- Given that heat is generated in fuel and not blocks, the small impact of ETC is not surprising



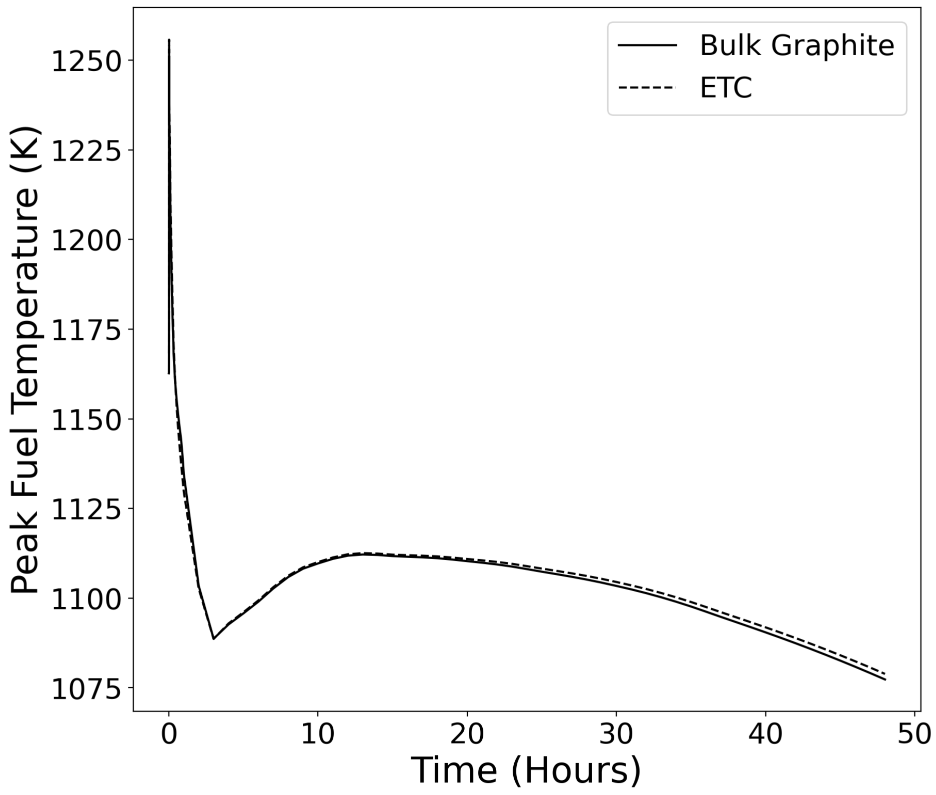
THE UNIVERSITY OF TENNESSEE KNOXVILLE

Idaho National Laboratory

ANS

Temperature differences in PCC are also very small in mHTGR-350

- PCC occurs when forced circulation stops but coolant pressure boundary remains intact
- Maximum difference in temperature is about 6 K
- ETC model remains at elevated temperatures for longer times
- ETC model has lower temperatures at a few times
  - Natural circulation rates differ slightly between the two models



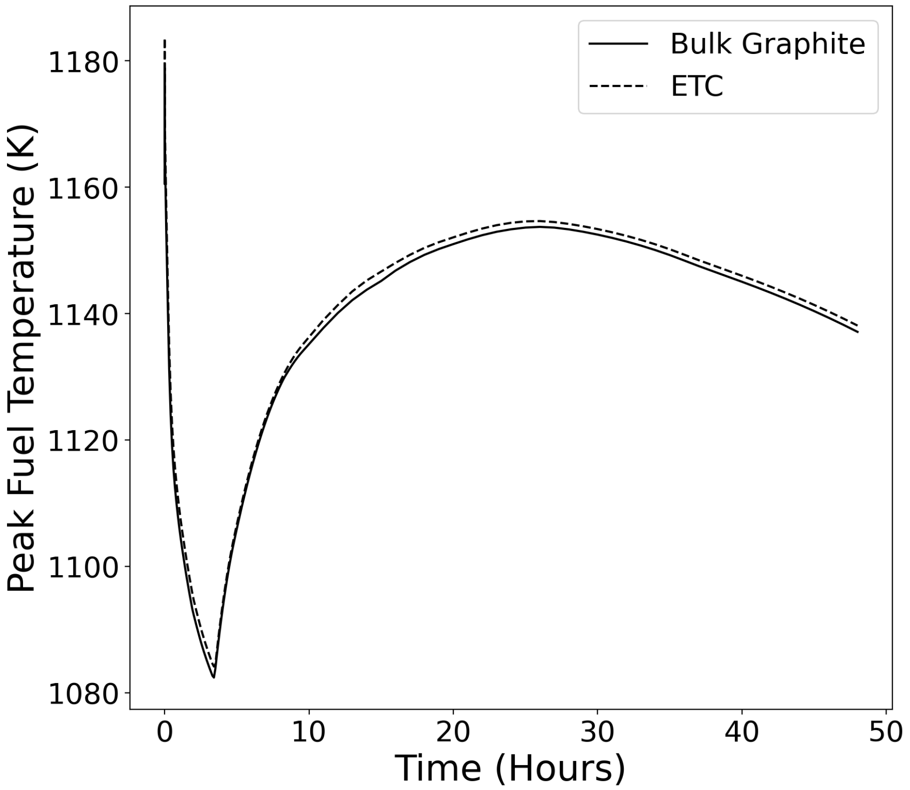
THE UNIVERSITY OF TENNESSEE KNOXVILLE

Idaho National Laboratory

ANS

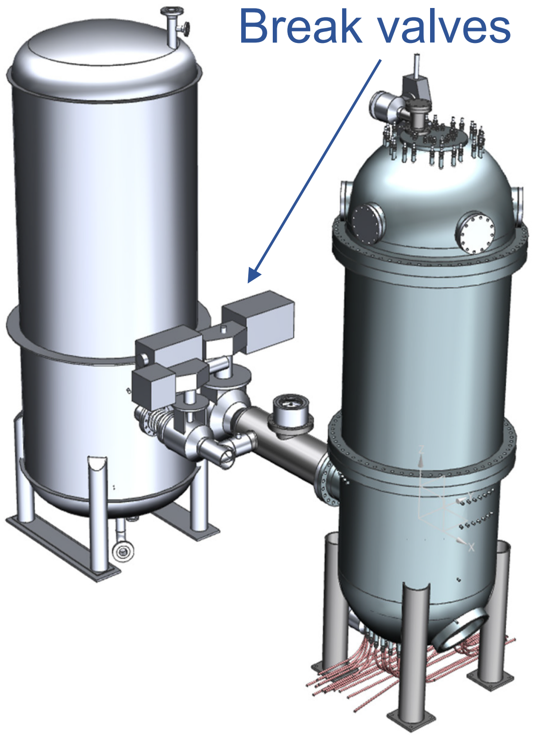
DCC temperature differences are also small

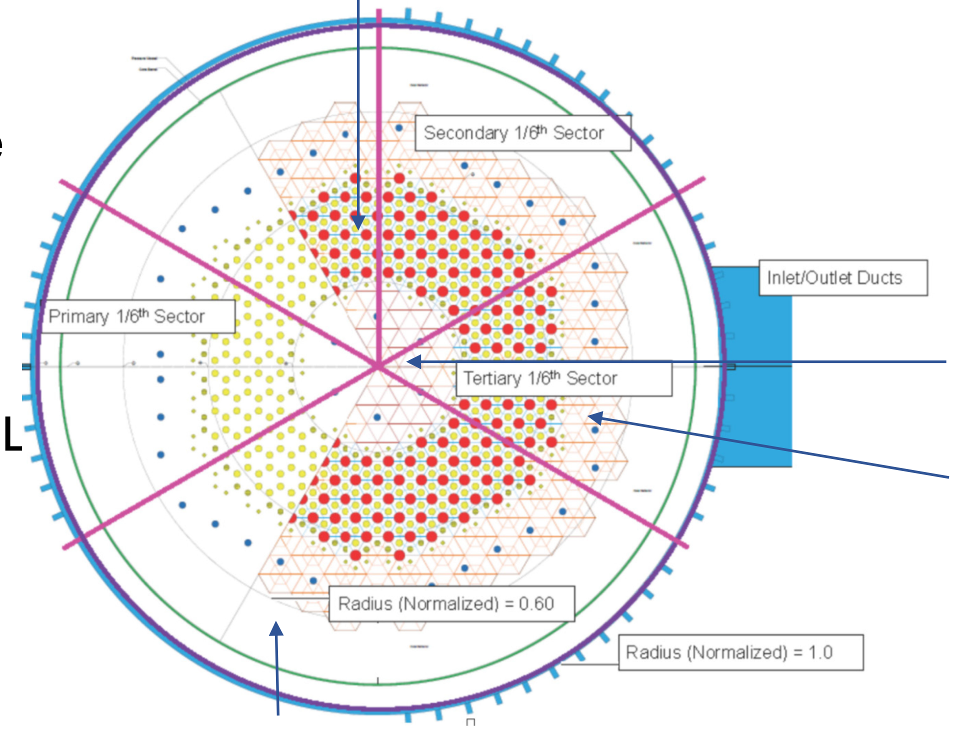
- DCC occurs when coolant pressure boundary is ruptured
- Maximum temperature difference about 7 K
- ETC temperature always higher than bulk graphite
- Once again, no meaningful difference in performance
- Differences in temperature are small for first 10 hours, but temperatures diverge at longer times due to reduced conduction heat transfer
- Shape of PCC and DCC peak temperature vs. time curves arise due to bottom of core cooling down while top of the core heats up



HTTF

- 2.2 MW_t integral effects thermal hydraulics test facility
  - Heated with 210 graphite resistive heater rods
- Inlet/Outlet temperature match mHTGR-350
- Mass flow rate at full power ~ 1 kg/s
- 0.7 MPa
- Uses an Al_2O_3 ceramic instead of graphite for inner-outer reflector and heated blocks
- Looking at block temperature because there is no fuel
- Replaced all the Al_2O_3
- Using RELAP5-3D model developed at INL





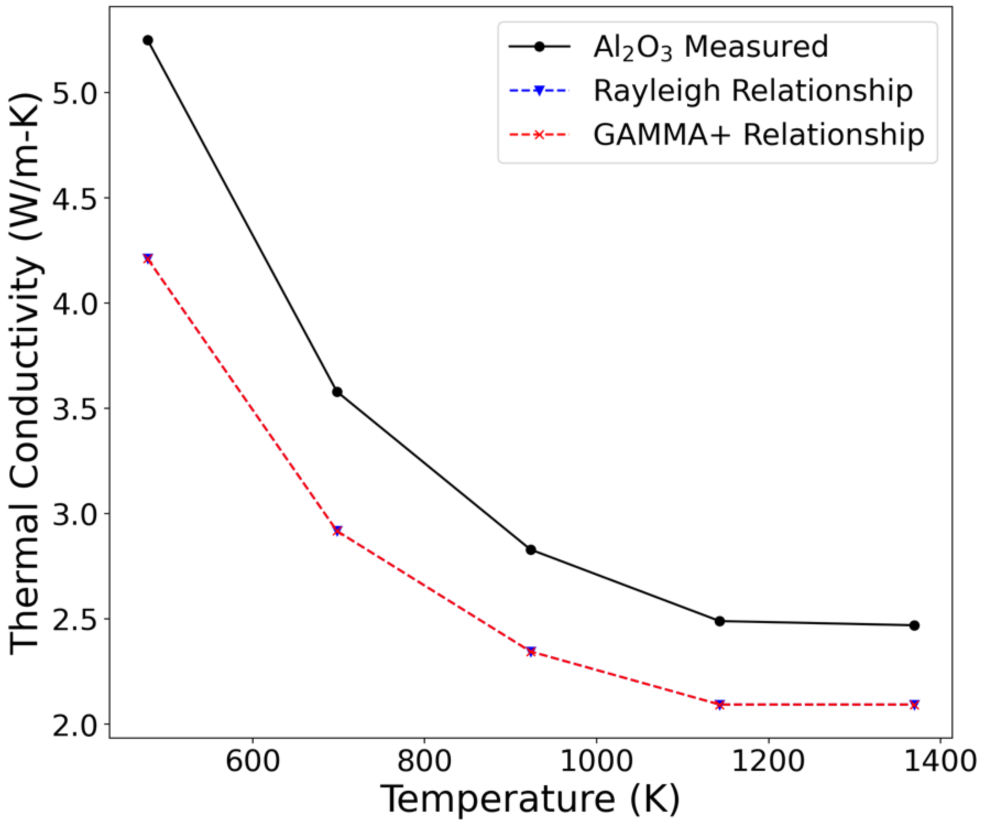
THE UNIVERSITY OF TENNESSEE KNOXVILLE

Idaho National Laboratory

ANS

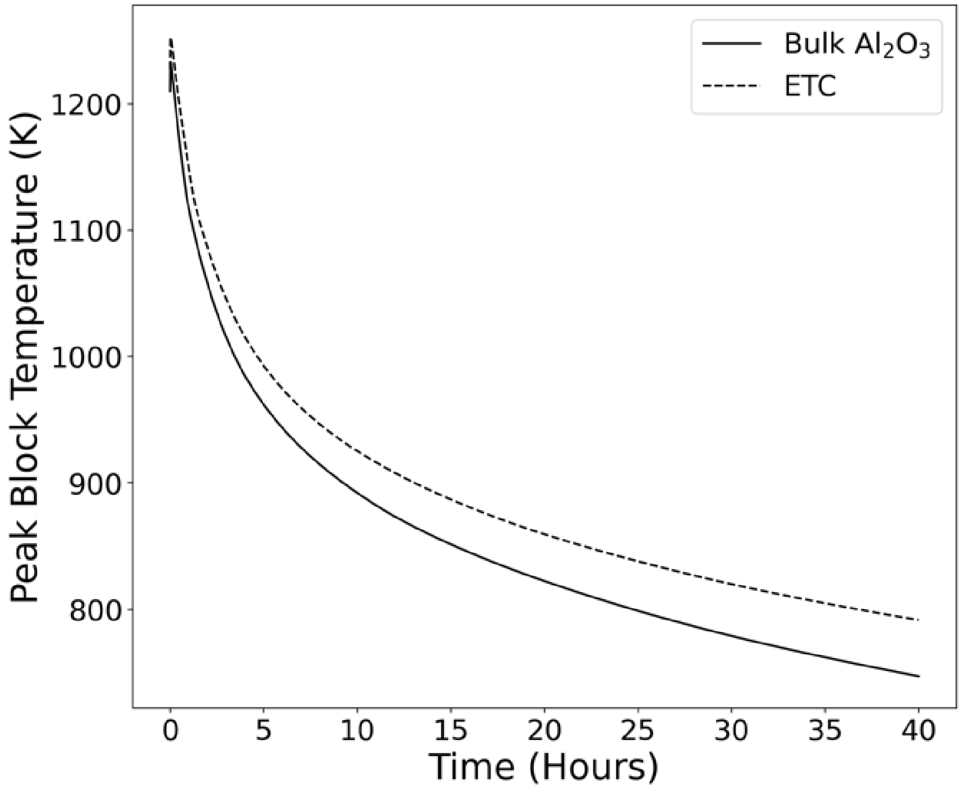
Al_2O_3 thermal conductivity is much lower than that of graphite

- Lower thermal conductivity and lower power lead to comparable temperatures for HTTF and mHTGR-350
- Looking at HTTF also allows us to compare impact of ETC at low thermal conductivity and high thermal conductivity
- ETC is 75–80% of nominal thermal conductivity
- Replaced the thermal conductivity of all Al_2O_3 with an ETC based on the whole-core helium volume fraction.



Peak block temperature in HTTF differs by 19 K for PCC and 20 K for DCC

- Behavior is similar for PCC and DCC in HTTF
- Difference between bulk Al_2O_3 temperature and ETC temperature is larger for DCC than PCC
- In DCC difference reaches 40 K at 17.67 hours, and in PCC it takes 27.15 hours to reach 40 K difference
- Difference is smaller in PCC because natural circulation can redistribute heat in the core



THE UNIVERSITY OF TENNESSEE KNOXVILLE

Idaho National Laboratory

ANS

Conclusions

- ETC reduces the rate of heat removal in HTGRs
- Steady-state temperatures are slightly higher when using ETC instead of thermal conductivity
- Peak temperatures during PCC and DCC are only slightly higher, but no impact on safety performance
- Long-term cooldown is slower with ETC, so temperature difference grows larger with time

Acknowledgements

- This work is supported by the Advanced Reactor Technologies – Gas Cooled Reactor Program (ART-GCR)
- This research made use of the resources of the High-Performance Computing Center at Idaho National Laboratory, which is supported by the Office of Nuclear Energy of the U.S. Department of Energy and the Nuclear Science User Facility under contract number DE-AC07-05ID14157

THE UNIVERSITY OF TENNESSEE KNOXVILLE

Idaho National Laboratory

ANS