INL/MIS-21-62885-Revision-0

Modular High Temperature Gas-Cooled Reactor: Severe Accident Phenomena and Safety Criteria

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Changing the World's Energy Future

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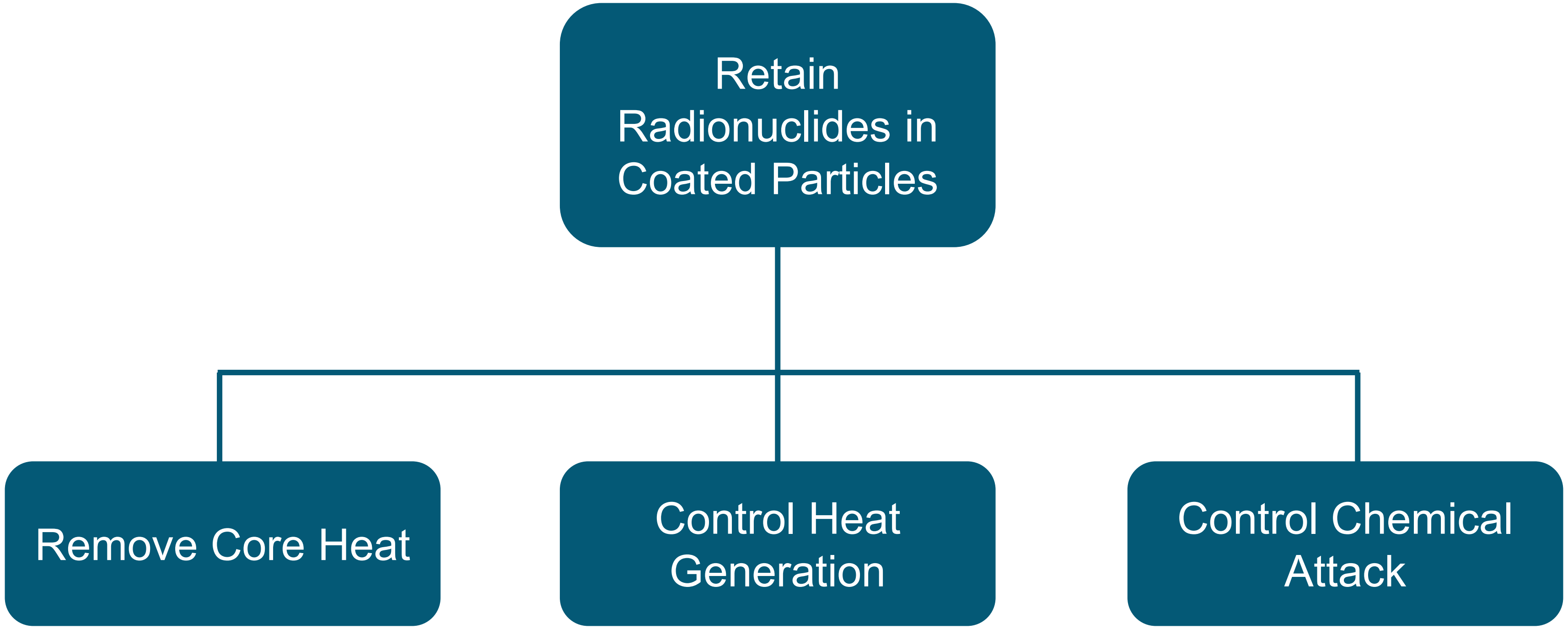
Severe Accident Phenomena and Safety Criteria

CNS Annual Conference

Radionuclide Retention within Modular HTGR Fuel Depends on Three Functions



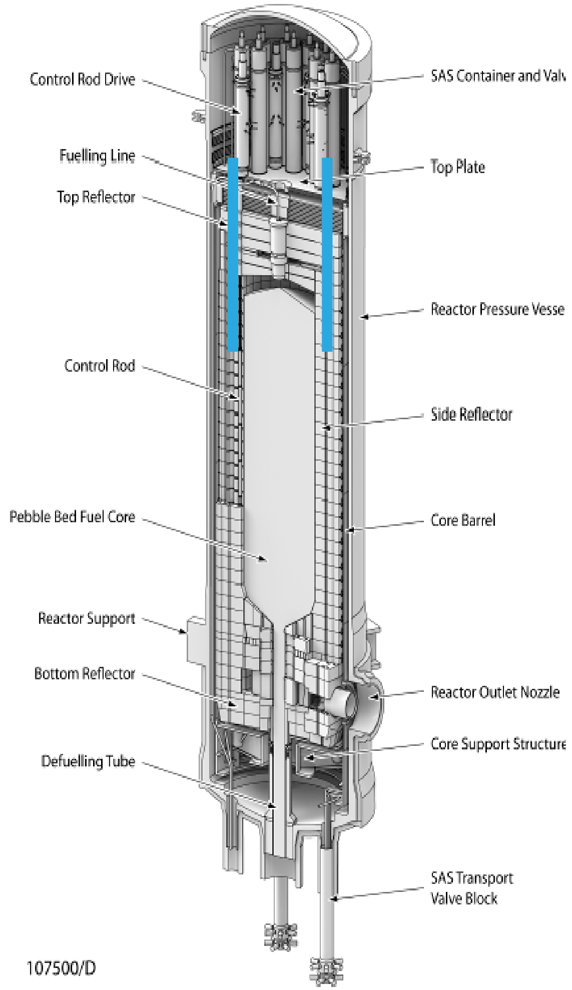
Control Heat Generation

Accomplished by Intrinsic Shutdown and Reliable Control Material Insertion

- Large negative temperature coefficient intrinsically shuts reactor down
- Two independent and diverse systems of reactivity control for reactor shutdown; drop by gravity on loss of power
  - Control rods
  - Reserve shutdown system
- Each system capable of maintaining subcriticality
- One system capable of maintaining cold shutdown during refueling
- Neutron control system measurement and alarms

Typical Reactivity Control

- Two independent rod banks
- Articulated rods suspended from drives by chains to be lowered into the radial reflector
- Bypass flow cools the rods
- Rods may be partially inserted during power operation to provide Xe restart/load follow capability
- Prismatic – Shutdown rods can be inserted into fuel blocks
- PBR – Small absorber spheres have been used in past designs (not in X-energy XE-100)
- Stronger negative fuel temperature feedback
  - HTGR: -7 pcm/K
  - PWR: -1 to -4 pcm/K

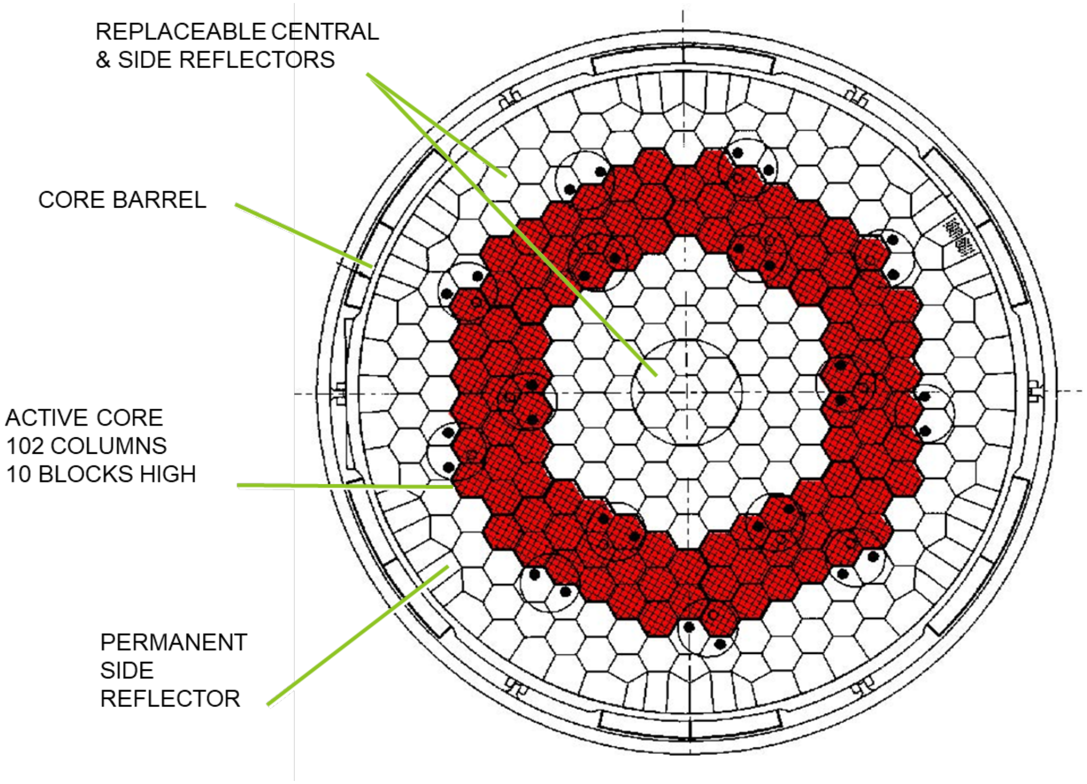


Both AVR and HTR-10 can be shut down without rods – circulators are stopped to affect a core heatup and Doppler shutdown.

Remove Residual Core Heat

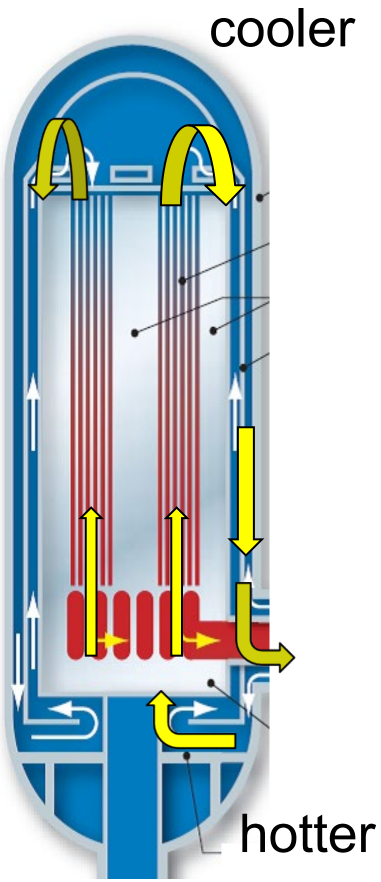
Accomplished by Passive Design Safety Features

- Small thermal rating/low core power density
  - Limit's amount of decay heat
  - Low linear heat rate
- Core geometry
  - Long, slender or annular cylindrical geometry
  - Heat removal by passive conduction and radiation
  - High heat capacity graphite
  - Slow heat up of massive graphite core
- Uninsulated reactor vessel
- Reactor Cavity Cooling System (RCCS)
  - Separate and distinct from reactor vessel system
  - Natural convective circulation of air or water during accident conditions
- Atmosphere is ultimate heat sink

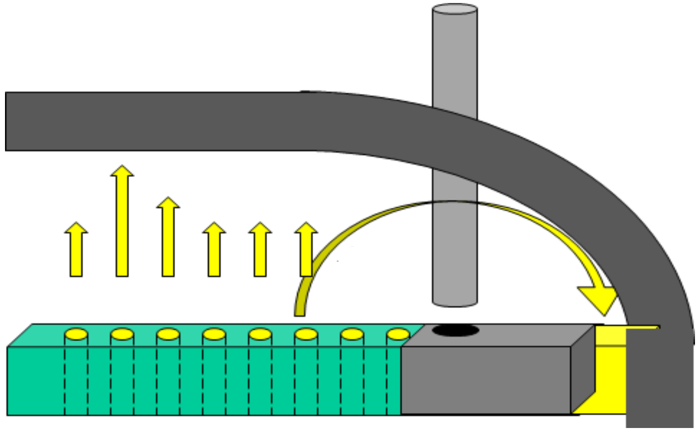


Pressurized Loss of Forced Cooling (PLOFC)

aka Pressurized Conduction Cooldown



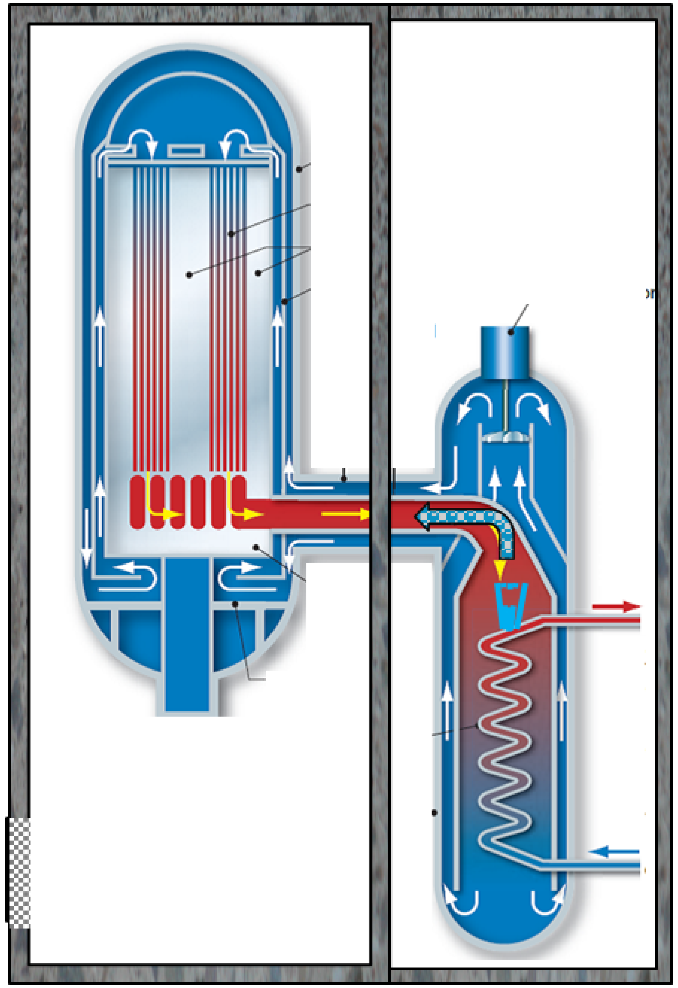
- Blower trip leads to loss of forced flow through core. Doppler shuts down fission within first few seconds.
- Forced downflow quickly yields to gravity-driven upflow through channels (or bed) - the transition flow is complex
- Core increases in temperature over many hours, then cools
- The hotter lower vessel structures drive ‘plenum-to-plenum’ currents and complex recirculation patterns
- RCCS pulls off heat from RPV
- If unmitigated (e.g., shutdown cooler), hot plumes impinging on upper plenum structures may damage CR guide tubes and the RPV head



Valentin, F. I., N. Artoun, M. KawaJI and D. M. McEligot, 2018. Forced and mixed convection heat transfer at high pressure and high temperature in a graphite flow channel. J. Heat Transfer, 140, pp. 122502-1 to -10

Steam Generator Tube Rupture

- SG rupture sends water/steam into the RPV. Rupture may cause surrounding tubes to fail
- Reactivity insertion event (extra moderator)
- Moisture penetrates and oxidizes graphite surfaces. It picks up residual fission products normally trapped there. CO and volatile hydrocarbons formed
- Primary pressure relief valve opens, releasing circulating and leached FP into the building
- Relief valve closes but may reopen if more water enters and flashes. After 2-3 valve cycles, it is assumed to fail open
- Event is classified as a DLOFC with additional FP release

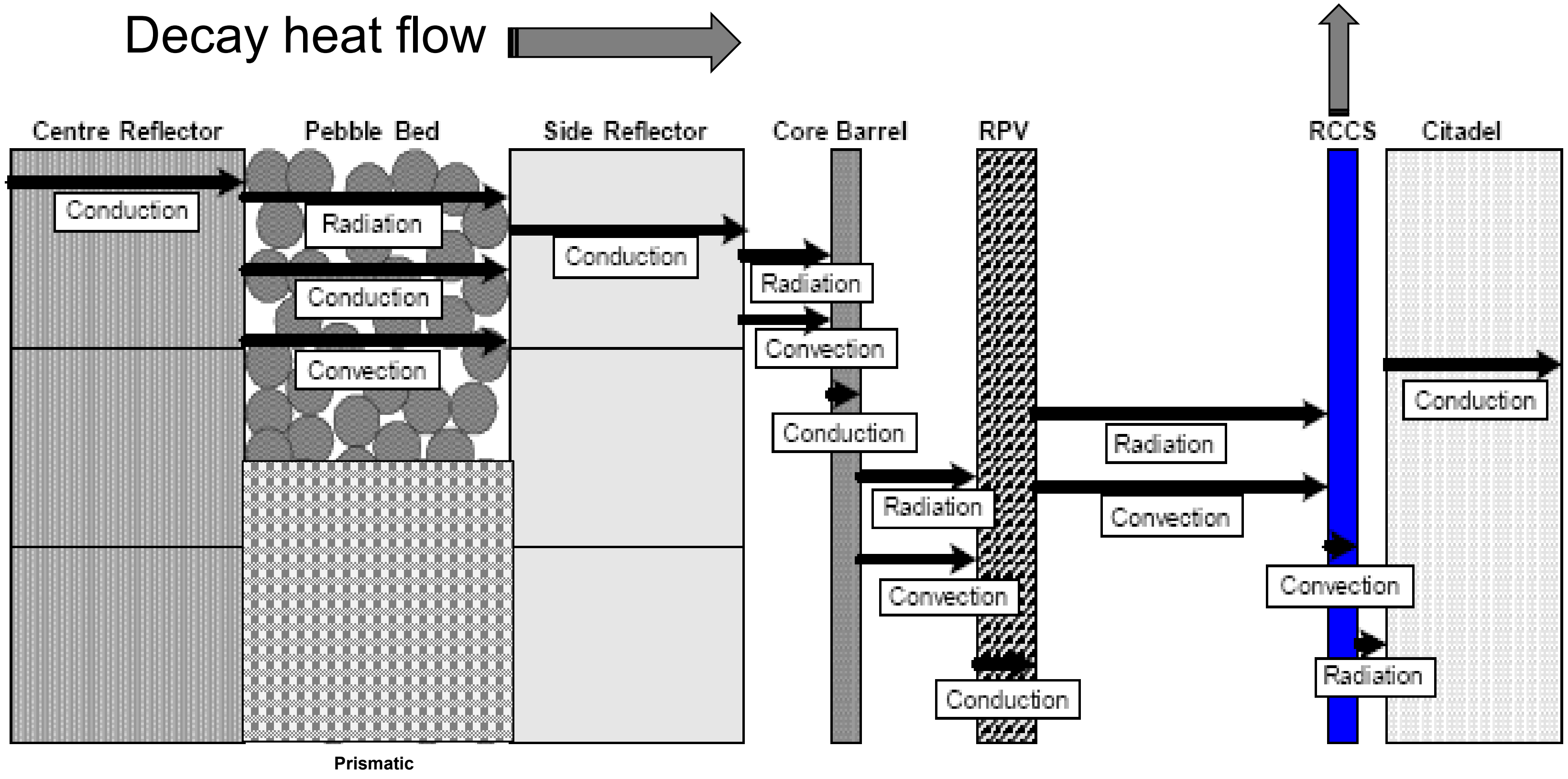


Issue: Amount (and phase) of water entering the core depends upon location of break. Fun multiphysics problem.

Rod Bank Withdrawal and Seismic Events

- Both are part of the reactivity insertion event class
- These events are challenging for modelers because the reactor may stay critical if not scrammed. Coupled neutronic/thermal-fluid simulations are computational demanding for anything but simple point kinetics/homogenized core models
- Control rods in HTGRs are generally ‘banked’ (grouped). A spurious control signal may cause uncontrolled withdrawal, the rate of which determines rate of energy deposition and ultimate temperature increase (Rod ‘ejection’ is prevented by core design)
- If rapid, the heat surge will shut down the reactor (Doppler) before particle failure conditions are attained
- Explicit modeling of kernel energy deposition indicates that the lower-order (smeared) fuel models over-predict power and fuel temperature
- Likewise, seismically-induced pebble bed settling is computed to result in relatively small but positive reactivity insertion
- Earthquake effects on other plant structures would need to be evaluated

Passive Heat Transfer Path



Example: Annular Core Pebble Bed

Key RCCS Design Considerations

- RCCS maintains concrete cavity wall and reactor vessel temperatures
  - Consists of cooling panel structures that surround the reactor vessel
  - Concrete cavity temperatures are strongly related to RCCS performance
- RCCS operation is not required to protect fuel
- Heat removal rates are similar during normal operations and accident conditions
- RCCS is a simple system that functions passively when required during off-normal conditions
- Various air- or water-cooled RCCS configurations are possible
- Normal plant operation provides ongoing confirmation of RCCS system status

Control of Chemical Attack – Air

Assured by Passive Design Features and Inherent Characteristics

- Inert coolant (helium)
- High integrity nuclear grade pressure vessels make large breaks exceedingly unlikely
- Air ingress limited by core flow area and friction losses
- Reactor embedment and building vents close after venting, thereby limiting potential air in-leakage
- Graphite fuel form, fuel compact matrix, and ceramic coatings protect fuel particles
- Graphite exhibits slow oxidation rate (high purity nuclear grade graphite will not “burn”)

Control of Chemical Attack – Moisture

Assured by Passive Design Features and Inherent Characteristics

- Non-reacting coolant (helium)
- Limited sources of water in steam cycle plants
  - Moisture monitors
  - Steam generator isolation (does not require AC power)
  - Steam generator dump system
- Water-graphite reaction:
  - Endothermic
  - Requires temperatures > normal operation
  - Slow reaction rate
- Graphite fuel form, fuel compact matrix, and ceramic coatings protect fuel particles

Functional Radionuclide Containment

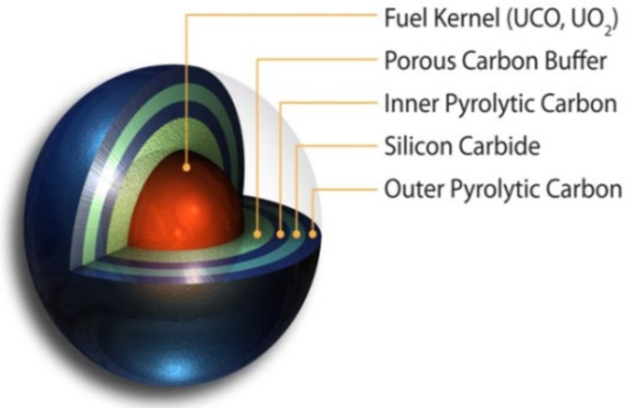
- Modular HTGRs employ “functional containment” for radionuclide control
- Eliminates need for “traditional” pressure retaining containment structure
- Functional containment is a collection of design choices that, when operated together, ensure that:
  - Radionuclides are retained within an independent multi-barrier system
  - Emphasis is on radionuclide retention at source (i.e., in the fuel)
  - NRC regulatory requirements (10 CFR 50.34/10 CFR 52.79) and plant design goals (PAGs) for release of radionuclides are met at the EAB
- See SECY-18-0096 and RG 1.232 for further information on functional containment performance criteria for non-LWRs

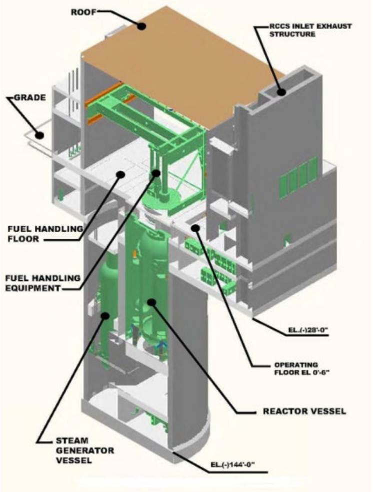
Modular HTGR Functional Containment

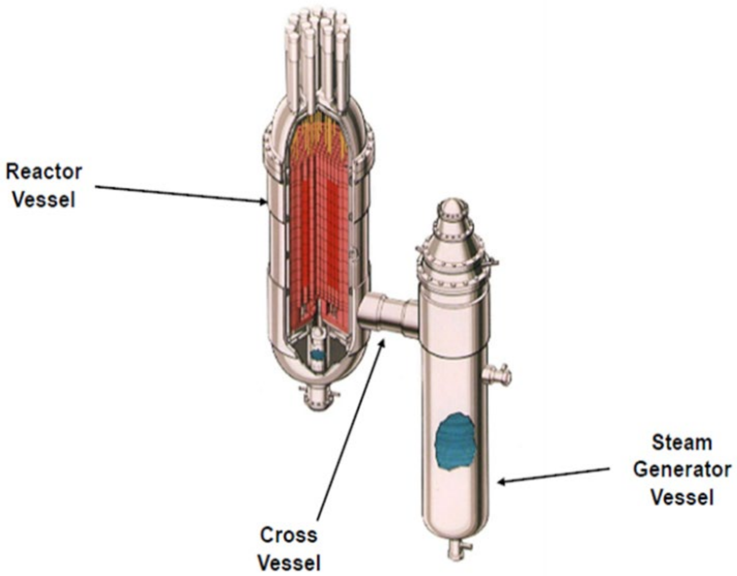
5 Radiological Release Barriers

- Fuel Kernel (TRISO)
- Fuel Particle Coatings (TRISO)
- Matrix/Graphite
- Helium Pressure Boundary
- Reactor Building

Fuel Element

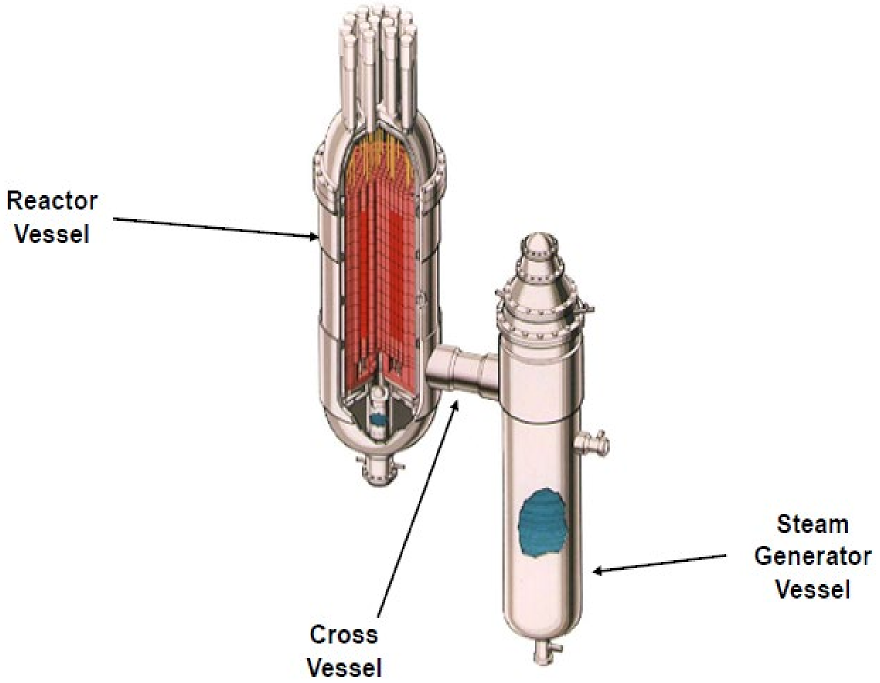






Helium Pressure Boundary (HPB) Releases

- Potential radionuclide release mechanisms
  - Primary coolant leaks
  - Liftoff (mechanical reentrainment)
  - Steam-Induced vaporization
  - Washoff (removal by liquid H_2O)
  - Primary coolant pressure relief
- Controlling parameters
  - Size/location of coolant leaks/breaks
  - Temperatures
  - Particulate matter
  - Steam/liquid H_2O ingress and egress
- Barrier performance
  - Condensable radionuclides (RNs) plate out during normal operation
  - Circulating Kr and Xe limited by Helium Purification System (HPS)
  - Plateout retained during leaks and largely retained during rapid depressurizations
  - RN holdup after core heatup due to thermal contraction of gas



Initial RN Release Mechanisms for HPB Sources

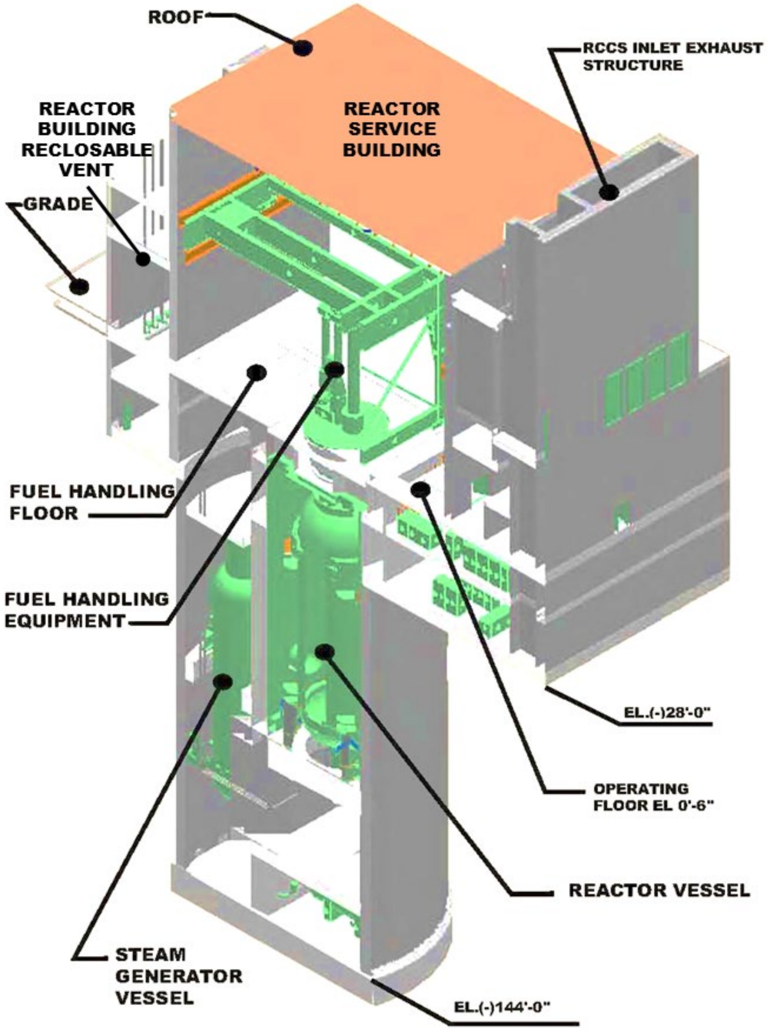
- Circulating activity
  - Released from HPB with helium in minutes to days as a result of HPB leak/break
  - Amount of release depends on location of leak/break and any operator actions to isolate and/or intentionally depressurize
- Liftoff of plateout and resuspension of dust
  - For large breaks, fractional radionuclide amounts released from HPB with helium relatively quickly (minutes)
  - Amount of release depends on HPB break size and location
  - Surface shear forces must exceed those for normal operation to obtain liftoff or resuspension

Delayed RN Release Mechanisms From Core

- Delayed releases occur only for accidents involving a core heatup
- Partial release from contamination, initially failed/defective particles when temps exceed normal levels, and particle failures during event
- Timing of release is tens of hours to days
- Delayed inventory is larger than circulating activity and liftoff mechanisms
- Releases from fuel depend on fraction of core above normal operation temperatures for a given time and on associated radionuclide volatility
  - Governed by amount of forced cooling
  - Dependent on size of leak or break
- Delayed releases from HPB depends on location/size of leak/break and timing relative to HPB gas expansion and contraction during core transient
  - Small leaks can potentially lead to a greater HPB RN release
  - Releases cease when internal HPB temps decrease due to core cooldown

Role of Reactor Building in Safety Design

- Structurally protects pressure vessels and RCCS from internal and external hazards
- RB limits air available for ingress after HPB depressurization
  - Vents open and close at certain times to retain radionuclides
- Provides structural support for RCCS and helium depressurization pathway
- Provides additional radionuclide retention opportunity
- Is not relied upon for radionuclide retention to meet off-site dose regulatory requirements



The Modular HTGR Safety Approach

- Functional containment employs multiple independent and diverse barriers that work together to negate the need for a single-walled pressure-retaining structure
- Fuel has very large temperature margin in both normal and accident conditions
- TRISO fuel failure is function of time at temperature; no cliff-edge effects
- Fuel, helium, and graphite moderator are chemically compatible under all licensing basis conditions
- Safety is independent of primary circuit circulation or pressure; helium pressure loss does not transfer large energy load to reactor building
- Reactor response times are very long (i.e., days, not seconds or minutes)
- No inherent mechanism exists for runaway reactivity or power excursions

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Suggested Reading List

- John D. Bess, Leland M. Montierth, Oliver Köberl & Luka Snoj (2014) Benchmark Evaluation of HTR-PROTEUS Pebble Bed Experimental Program, Nuclear Science and Engineering, 178:3, 387-400, DOI: 10.13182/NSE14-13
- Bostelmann,F., Hammer, H. Ortensi, J. Strydom, G. Velkov, K., Zwermann, W., Criticality calculations of the Very High Temperature Reactor Critical Assembly benchmark with Serpent and SCALE/KENO-VI, Annals of Nuclear Energy, Volume 90, 2016,
- Dong-Ho Shin, Chan Soo Kim, Goon-Cherl Park, Hyoung Kyu Cho, Experimental analysis on mixed convection in reactor cavity cooling system of HTGR for hydrogen production, International Journal of Hydrogen Energy, Volume 42, Issue 34, 2017.
- HTGR Technology Course for the Nuclear Regulatory Commission, 2010.
- INTERNATIONAL ATOMIC ENERGY AGENCY, Evaluation of High Temperature Gas Cooled Reactor Performance: Benchmark Analysis Related to Initial Testing of the HTTR and HTR-10, IAEA-TECDOC-1382, IAEA, Vienna (2003).
- INTERNATIONAL ATOMIC ENERGY AGENCY, 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-TECDOC-1694, IAEA, Vienna (2013).
- Lisowski, D.D. et al, Experimental Observations of Natural Circulation Flow in the NSTF, Nuclear Engineering and Design 306, (2016) 124-132.

Suggested Reading List

- Martin, W, Creation of a Full-Core HTR Benchmark with the Fort St. Vrain Initial Core and Assessment of Uncertainties in the FSV Fuel Composition and Geometry, Battelle Memorial Institute United States. Department of Energy. Office of Scientific and Technical Information.
- Moorman, R., “Phenomenology of Graphite Burning in Air Ingress Accidents of HTRs”, 2011.
- Schultz, R.R., Gougar, H., Lommers, L., Identification and Characterization of Thermal Fluid Phenomena Associated with Selected Operating/Accident Scenarios in Modular High Temperature Gas-Cooled Reactors, Paper 2018-0177, Proceedings of HTR 2018, Warsaw, Poland, October 8-10, 2018.
- Strydom G., Bostelmann, F., and Yoon, S. J., 2015, Results for Phase 1 of the IAEA Coordinated Research Project on HTGR Uncertainties, INL/EXT-14-32944, Rev. 2.
- Strydom, G., Uncertainty and Sensitivity Analysis of a Pebble Bed HTGR Loss of Cooling Event, Science and Technology of Nuclear Installations, Volume 2013, Article ID 426356
- Se Ro Yang, Ethan Kappes, Thien Nguyen, Rodolfo Vaghetto, Yassin Hassan, Experimental study on 1/28 scaled NGNP HTGR reactor building test facility response to depressurization event, Annals of Nuclear Energy, Volume 114, 2018.
- Valentin, F. I., N.Artoun, M. KawaJI and D. M. McEligot, 2018. Forced and mixed convection heat transfer at high pressure and high temperature in a graphite flow channel. J. Heat Transfer, 140, pp. 122502-1 to -10
- Windes, W. et al, “Discussion of Nuclear-Grade Graphite Oxidation in Modular High Temperature Gas-Cooled Reactors, 2017.

Suggested Reading

- NGNP White Papers
  - NGNP Fuel Qualification, July 2010 (ML102040261)
  - Mechanistic Source Terms, July 2010 (ML102040260)
- INL/EXT-11-22708, Modular HTGR Safety Basis and Approach, August 2011 (ML11251A169)
- NGNP – Encl. 1, Summary Feedback on Four Key Licensing Issues, July 2014 (ML14174A774)
- INL/EXT-14-31179, Guidance for Developing Principal Design Criteria for Advanced (Non-Light Water) Reactors, Rev 1, December 2014 (ML14353A246, ML14353A248)
- RG-1.232, Guidance for Developing Principal Design Criteria for Non-Light Water Reactors, Appendix C – mHTGR-DC, April 2018 (ML17325A611)
- SECY-18-0096, Functional Containment Performance Criteria for Non-Light Water Reactors, w/ Encl. 1 and Encl. 2, September 28, 2018 (ML18115A157, ML18115A231, ML18115A367)
- ANL-SMR-8, Design Report for the 1/2 Scale Air-Cooled RCCS Tests in the NSTF, June 2014