Modular High Temperature Gas-cooled Reactor: Safety Design Approach

Advanced Reactor Technologies

Idaho National Laboratory

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ADVANCED REACTOR TECHNOLOGIES

Modular HTGR Safety Design Objectives and Requirements

Deployment Objectives

- Flexibly co-locate with new industry users of nuclear energy
- Steam and electric cogeneration applications
- Direct process heat with temperature ranges from 700°C to 950°C

Enabling Requirements

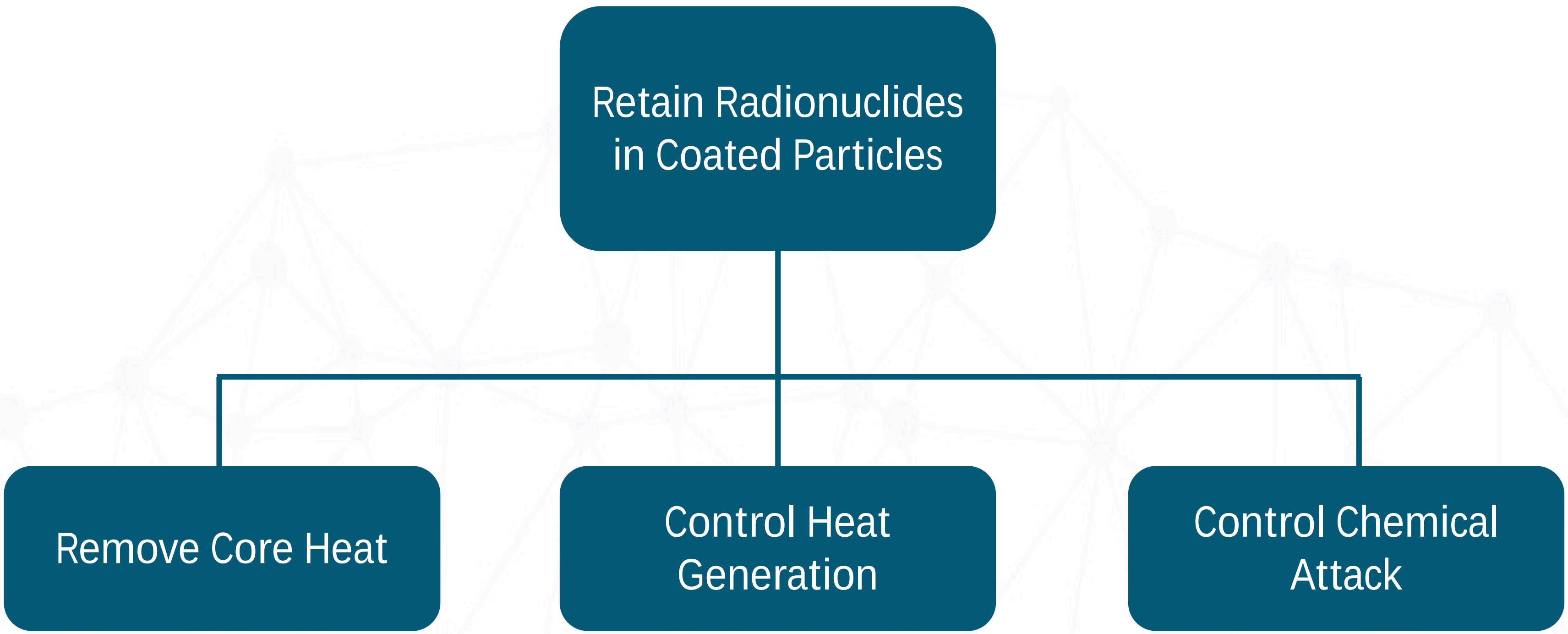
- Meet regulatory dose limits at the Exclusion Area Boundary (EAB)
  - 25 rem Total Effective Dose Equivalent (TEDE) for duration of the release from 10 CFR 50.34 (10 CFR 52.79) at Exclusion Area Boundary (EAB) for design basis accidents
  - EAB is estimated approximately 400 meters from the modular HTGR plant (to support co-location with industrial facilities)
- Meet safety goals for cumulative individual risk for normal and off-normal operation
- Design goal: meet EPA Protective Action Guides (PAGs) at EAB
  - 1 rem TEDE for sheltering
  - Design basis and beyond design basis events are considered
  - Realistically evaluated at the EAB
  - Emergency planning and protection

Modular HTGR Safety Design Approach

- Utilize inherent material properties as basis for safety
  - Helium coolant – neutronically transparent, chemically inert, low heat capacity, single phase
  - Ceramic coated (TRISO) particle fuel – high temperature capability, high radionuclide retention
  - Graphite moderator – high temperature stability, large heat capacity, long thermal response times
- Simple reactor design with inherent and passive safety features
  - Retain most radionuclides at source (i.e., within fuel)
  - Shape and size reactor to allow passive heat removal from reactor core using uninsulated reactor vessel
    - Heat is still removed if system is depressurized due to breach in reactor helium pressure boundary (HPB)
    - Heat is radiated from reactor vessel to RCCS panels
  - Large negative temperature coefficient supports intrinsic reactor shutdown
  - No reliance on AC-power to perform required safety functions
  - No reliance on operator intervention; insensitive to incorrect operator actions or inactions

Modular HTGR Safety Basis and Approach paper submitted Sept 2011 to NRC for information (INL/EXT-11-22708)

Radionuclide Retention within Modular HTGR Fuel Depends on Three Functions



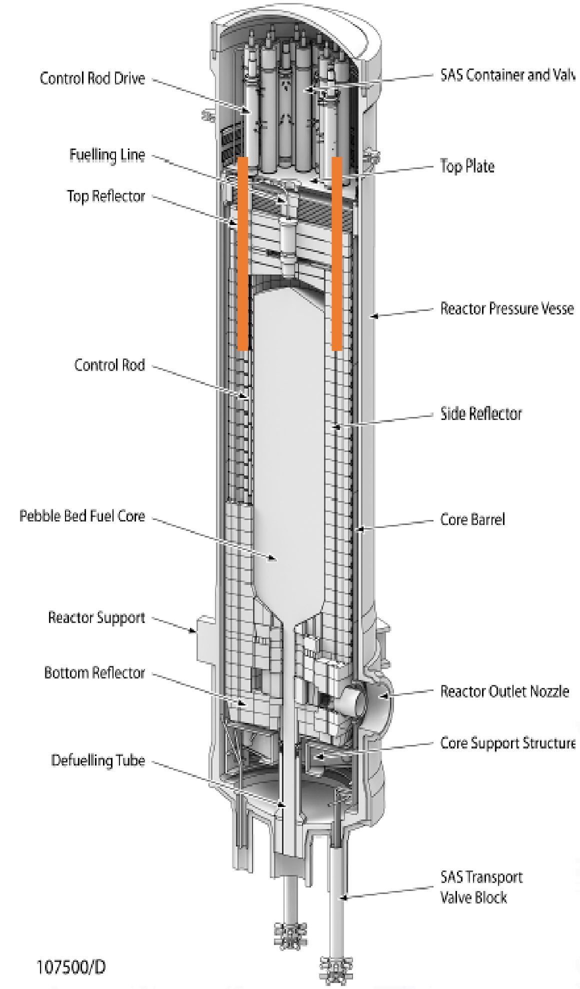
Control Heat Generation

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 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



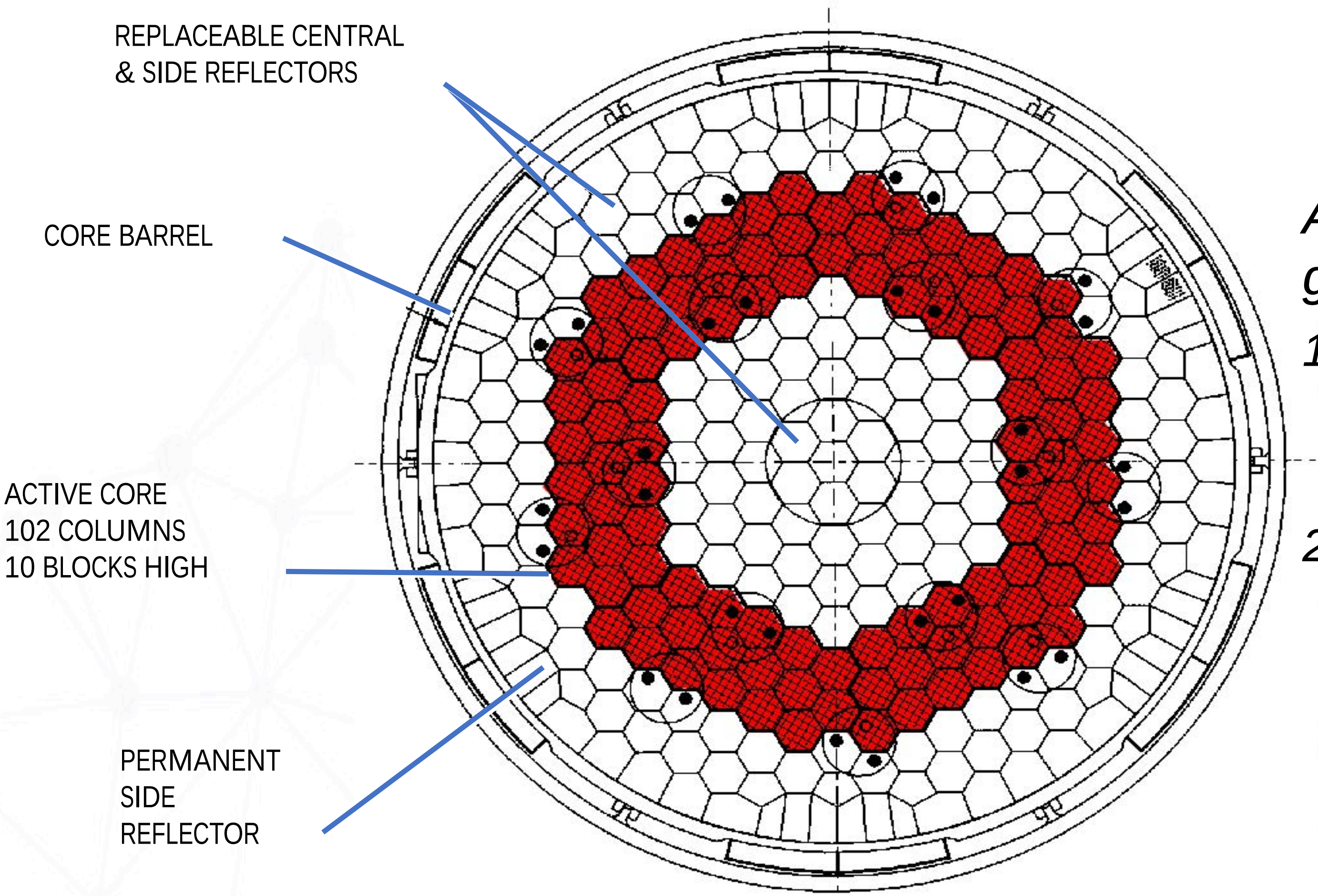
Both AVR and HTR-10 can be shut down without rods – circulators are stopped to affect a core heatup and Doppler shutdown.

Remove Residual Core Heat

Accomplished by Passive Design Safety Features

- Small thermal rating/low core power density
- 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

Annular Core Optimizes Passive Heat Removal

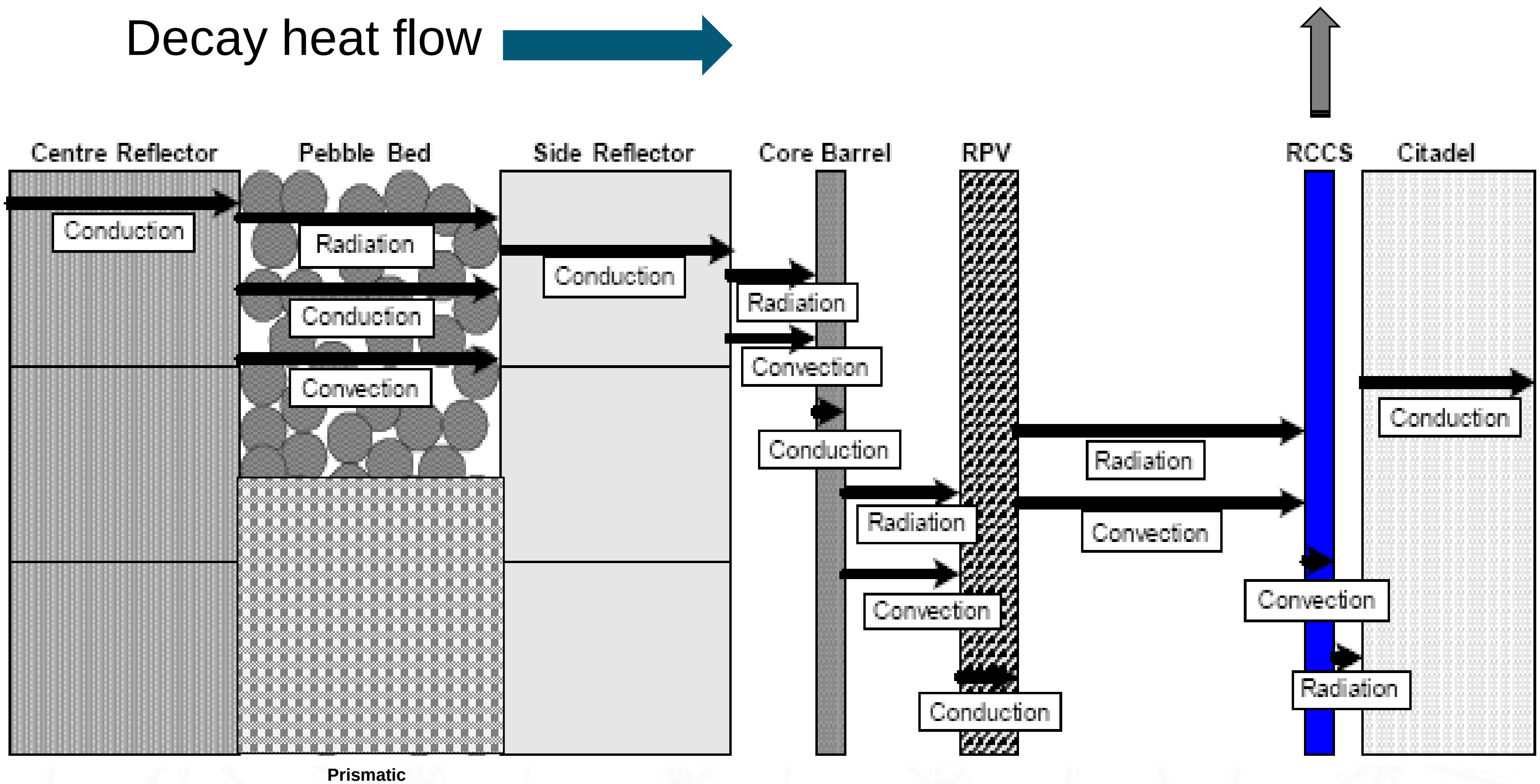


Annular core geometry:

1) Shortens heat conduction pathway

2) Enhances surface to volume ratio

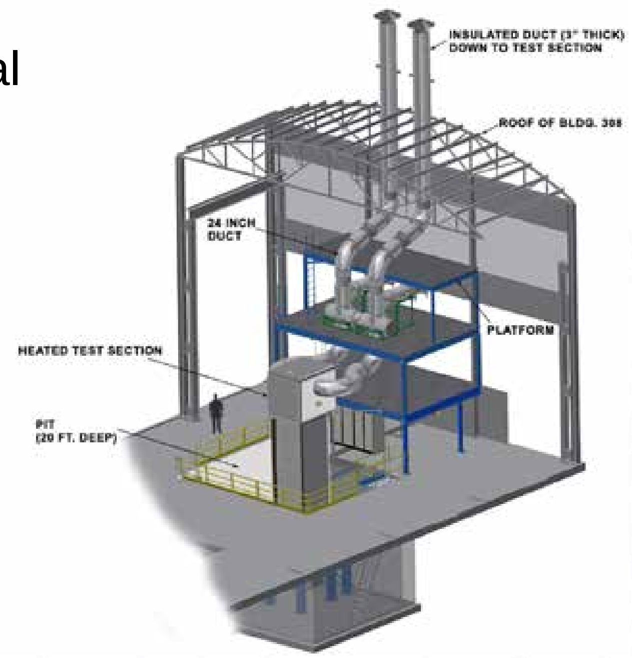
Passive Heat Transfer Path



Example: Annular Core Pebble Bed

Reactor Cavity Cooling System (RCCS)

- Typically safety-related in modular HTGR applications
- Consists of cooling panel structures that surround the reactor vessel
- Removes heat transmitted from vessel via radiation and convection
- Always operates to remove heat during both normal and off-normal operations
- All RCCS designs passively remove heat during all off-normal events via natural convection air or natural circulation water flow
- A simple and reliable means of residual heat removal
- Meets all requirements with ample margin and redundancy
- Natural convection Shutdown heat removal Test Facility (NSTF) at Argonne National Laboratory



Key RCCS Design Considerations

- RCCS maintains concrete cavity wall and reactor vessel temperatures
  - Concrete cavity temperatures are strongly related to RCCS performance
- RCCS operation is not typically 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

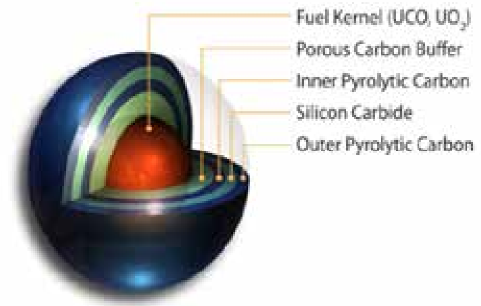
- Modular HTGRs employ "functional containment" for radionuclide control
- Eliminates need for "traditional" pressure retaining containment structure
- Functional containment is a collection of design choices that, when operated together, ensure that:
  - Radionuclides are retained within an independent 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

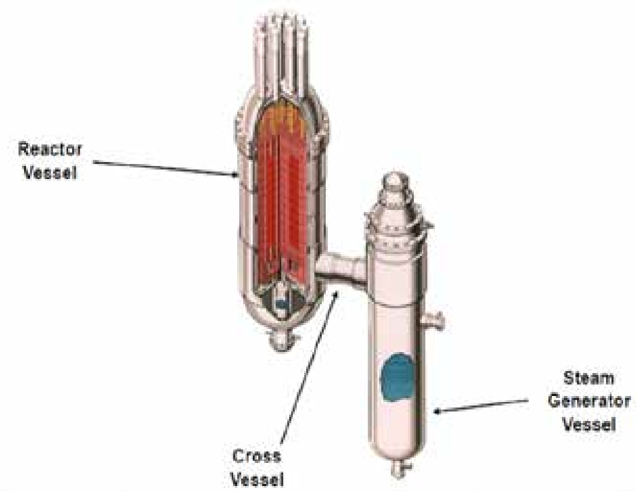
Modular HTGR Functional Containment

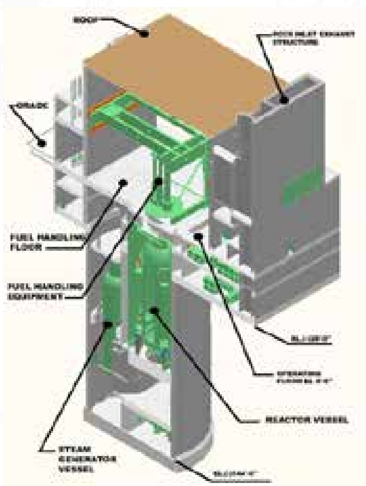
5 Radiological Release Barriers

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

(Fuel Kernel, Fuel Particle Coatings, Matrix/Graphite: Fuel Element)





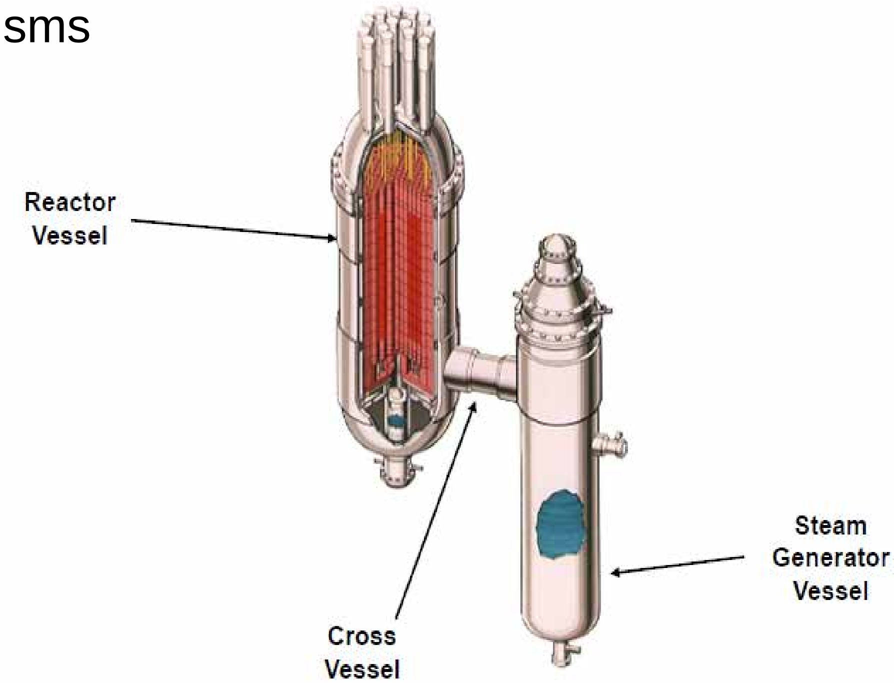


Fuel Particles Retain Radionuclides Well Above Normal Operation Temperatures

- Normal operating peak fuel temperature is <1250°C. Testing shows RN retention for hundreds of hours at >1600°C without fuel particle failure
- Large temperature margins enable:
  - Passive heat removal independent of coolant pressurization
  - Greater use of negative temperature coefficient for intrinsic reactor shutdown
- Most radionuclides reach steady state concentration/distribution in primary circuit
  - Exceptions are long lived isotopes (i.e., Cs-137 and Sr-90) where plateout inventory builds over time
- Concentration and distribution are affected by:
  - Radionuclide half-life
  - Initial fuel quality
  - Incremental fuel failures during normal operation
  - Fission product fractional release from fuel kernel
  - Transport of fission products through particle coatings, matrix, and graphite
  - Fission product sorptivity on fuel matrix and graphite materials
  - Fission product sorptivity on primary circuit surfaces (i.e., plateout)
  - Helium purification system performance

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



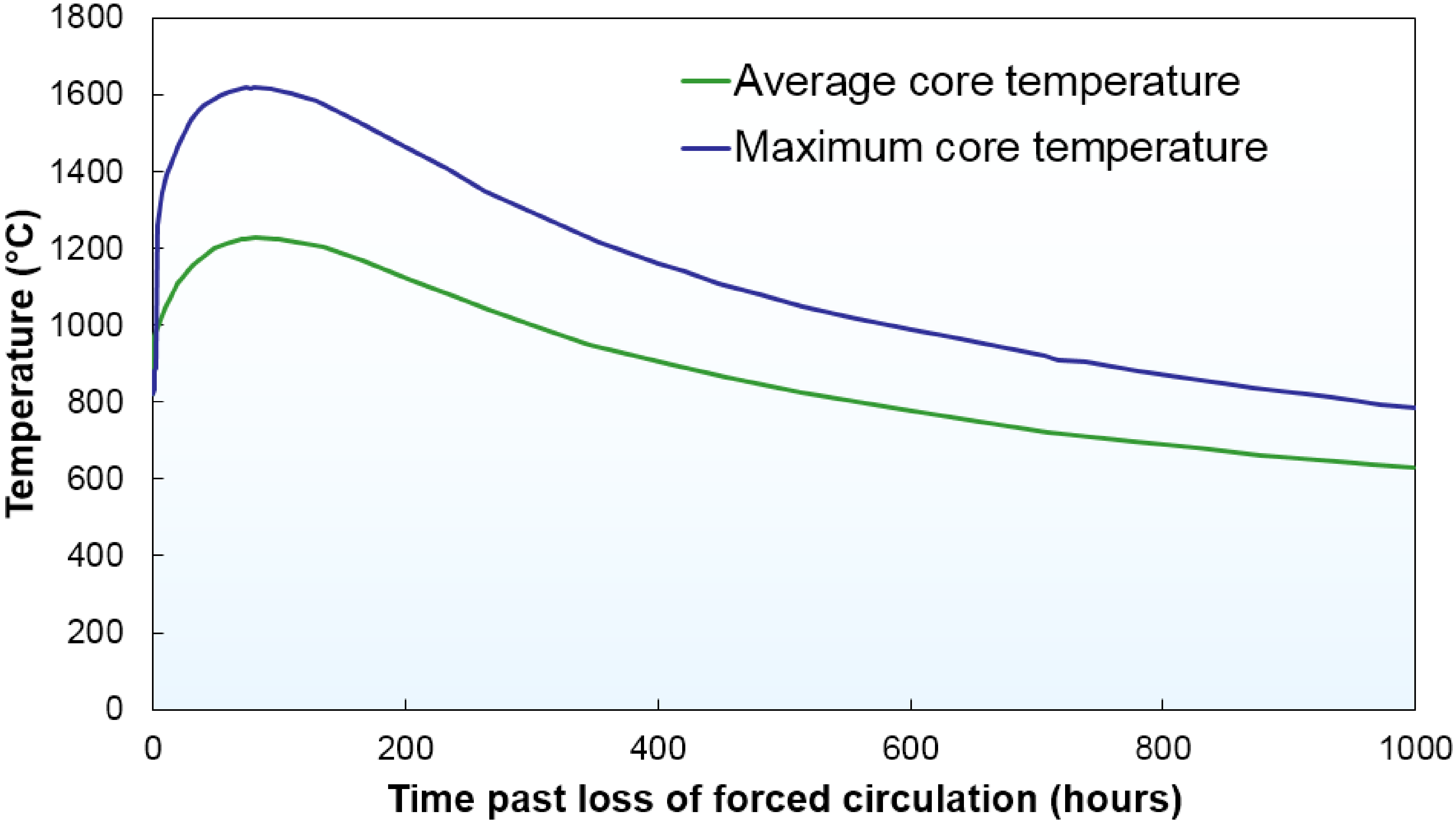
Initial RN Release Mechanisms for HPB Sources

- 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 may be 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

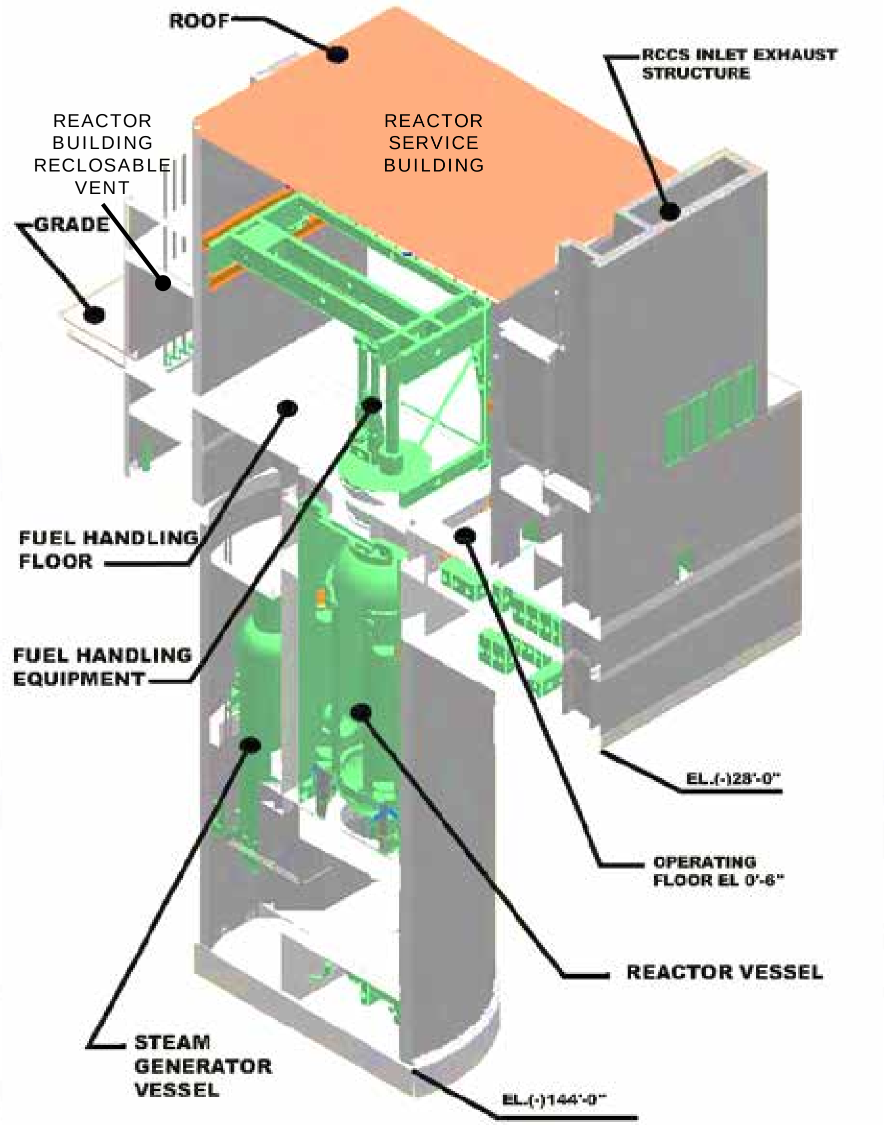
Typical Core Temperatures Following Depressurized Loss of Forced Cooling



350 MWt Prismatic Core Design

Role of Reactor Building in Safety Design

- Structurally protects pressure vessels and RCCS from internal and external hazards
- Limits air available for ingress after HPB depressurization
- 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



Design Issues for Vented Reactor Building

- Matched to modular HTGR accident behavior
  - Reactor building is vented early in a helium pressure boundary break scenario (when the helium circulating activity is low)
  - The reactor building vent is closed later in the transient (when the particle fuel experiences maximum temperatures)
  - Prevents reactor building overpressure from release of non-condensing helium coolant
- Provides a more benign environment for the passive Reactor Cavity Cooling System (RCCS)
  - Heat
  - Pressure

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

Key mHTGR Design Criteria

- MHTGR-DC 10
  - Specified acceptable fuel design limit (SAFDL) does not align with the mHTGR safety design approach
  - Replace with specified acceptable system radionuclide release design limits (SARRDL); to be defined by applicant to protect fuel during AOOs
- MHTGR-DC 16
  - Allows use of “functional containment” by multiple barriers
  - Eliminates need for pressure-retaining containment structure requirements
- MHTGR-DC 17
  - All SR power needs must be met for all applicable plant conditions
  - Battery power may be required for certain mHTGR event conditions
- MHTGR-DC 34
  - RCCS (passively) removes residual heat under off-normal conditions.
  - Provides for eliminating emergency core cooling system (ECCS)

Other mHTGR Design Criteria Considerations

- Reactor coolant makeup: helium pressure is not needed to remove heat from core (passive heat removal is used)
- Containment heat removal/atmospheric cleanup/cooling systems: mHTGRs do not employ LWR-style containment; heat removal is assured by other design criterion applicable to modular HTGRs
- Containment design/leak rate testing/containment isolation: functional containment design is addressed by the full range of mHTGR design criteria and includes new reactor building requirements
- New mHTGR reactor building design requirements
  - MHTGR-DC 70: Reactor vessel and reactor system structural design – maintain core integrity
  - MHTGR-DC 71: Reactor building design basis – protect and maintain passive cooling geometry and provide helium vent path
  - MHTGR-DC 72: Reactor building inspection – assure reactor building will perform required safety function

Major Take-Aways in Safety Design Approach

- Top-down mHTGR safety design emphasizes retention of radionuclides within very high quality TRISO fuel particles
- Independent barriers provide defense-in-depth that limit and attenuate radionuclide releases under all LBE conditions
- Residual core heat removal by passive means
- Large negative temperature coefficients
  - Shutdown without rod motion
- Overall plant design limits air/water ingress

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

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