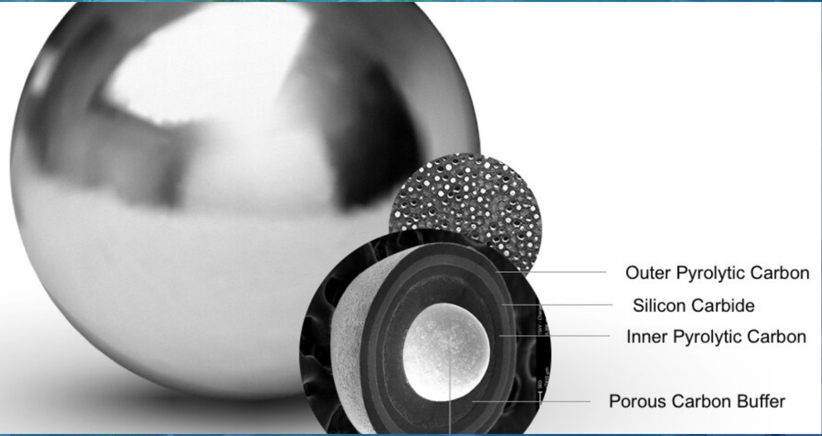
HIGH TEMPERATURE REACTOR TECHNOLOGY AND SAFETY



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OUTLINE

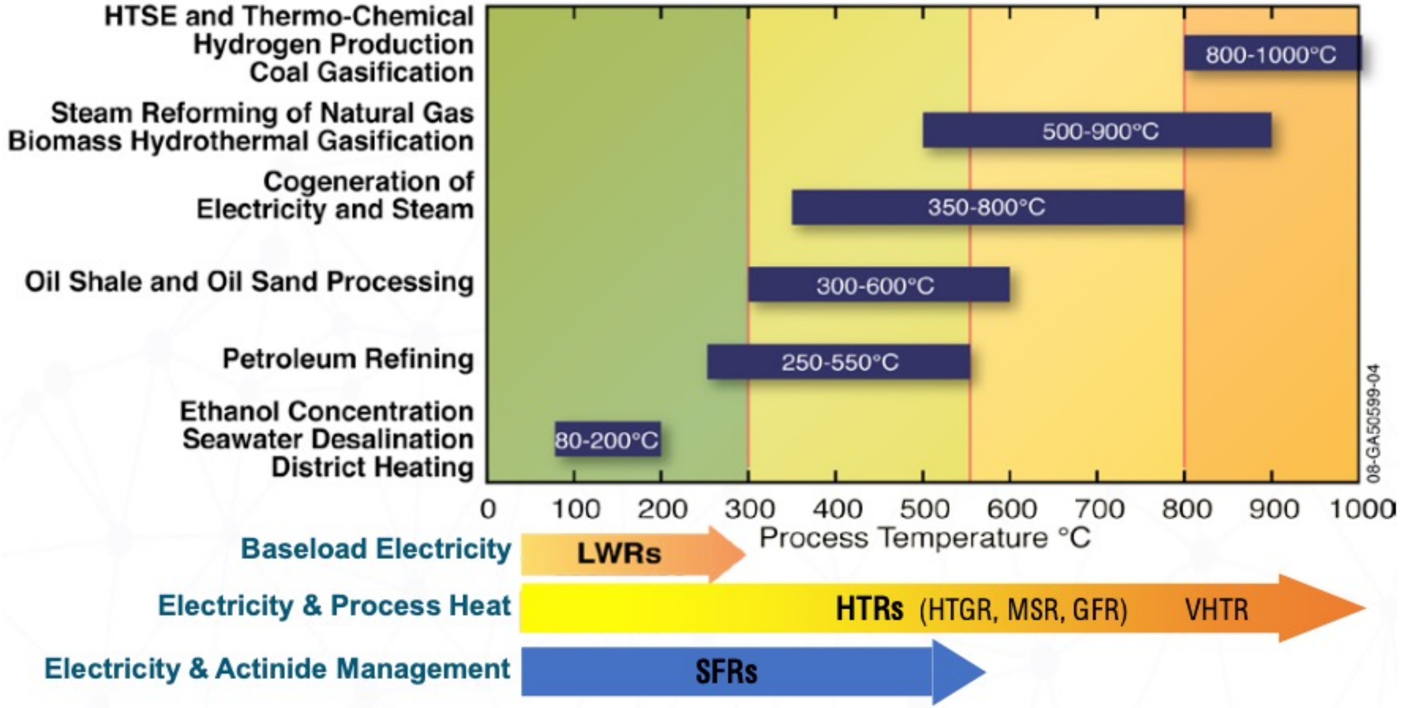
- Introduction: What are HTRs?
  - Basic characteristics, design variants, past and ongoing experience
- Key safety features
  - Reactivity control
  - Air and water ingress
  - Core heat removal
  - Confinement of radioactive materials
- Defense-in-depth strategy
- Summary

WHAT ARE HIGH-TEMPERATURE REACTORS?

- Thermal reactors with coated particle fuel forms
- They use graphite as the moderator
- Most use pressurized helium gas as chemically inert coolant (no boiling concern), one design variant with molten-salt coolant (not pressurized)
- Known for ability to achieve much higher operating temperatures than traditional water-cooled reactors
  - Greater thermal efficiency for electricity conversion
- Inherent safety for reactivity control
- Passive safety for decay heat removal
- No risk of core melt

POTENTIAL FOR NON-ELECTRIC APPLICATIONS

Suitable for process heat and hydrogen production



DESIGN VARIANTS

Types of HTRs

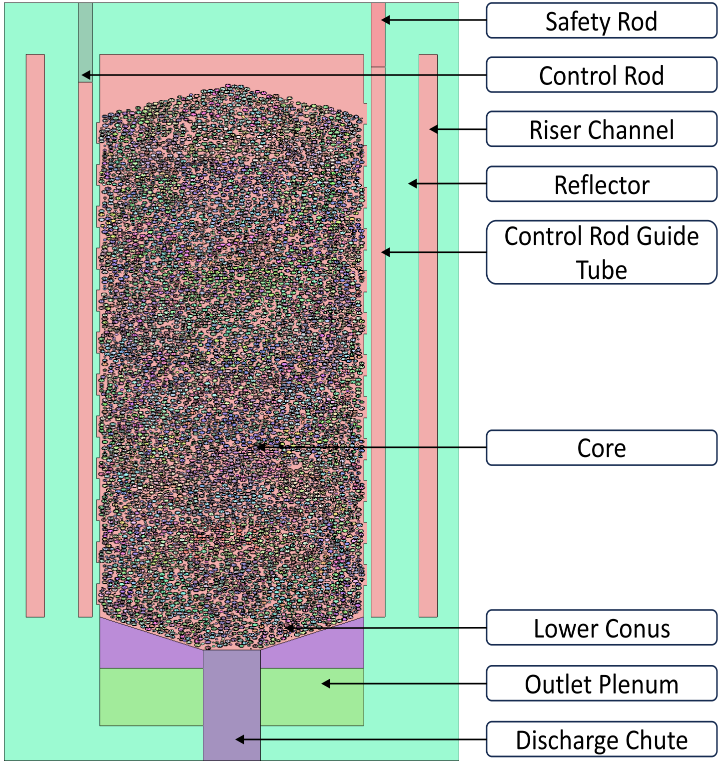
- Prismatic block pressurized gas-cooled reactors: Reactor core consists of hexagonal graphite blocks containing fuel and coolant channels
- Pebble-bed pressurized gas-cooled reactors: Reactor core is filled with spherical fuel elements (pebbles) made of graphite and uranium particles
- Molten-salt-cooled fluidized-bed reactor:
  - Fuel form and graphite moderation are like pebble-bed gas-cooled reactors, but with smaller pebbles (half in diameter)
  - Higher power density than gas systems (20 W/cc vs. 5 W/cc)
  - Coolant is not pressurized

PAST AND ONGOING EXPERIENCE

- Dragon (U.K.): 20 MW-th (1964-1975)
- Peach Bottom (U.S.A.): 115 MW-th (1967-1974)
- AVR (Germany): 46 MW-th (1967-1988)
- Fort St. Vrain (U.S.A.): 842 MW-th (1976-1989)
- THTR (Germany): 750 MW-th (1986-1989)
- HTTR (Japan): 30 MW-th (1999-present)
- HTR-10 (China): 10 MW-th (2000-present)

KEY SAFETY FEATURES

- Low power density (large volume)
- High core heat capacity
- Strongly negative temperature coefficient of reactivity
- Large height-to-diameter ratio of the core for effective vessel cooling (via natural circulation of air)
- Coated fuel particles as the primary barrier to radionuclide release



SAFETY DESIGN APPROACH

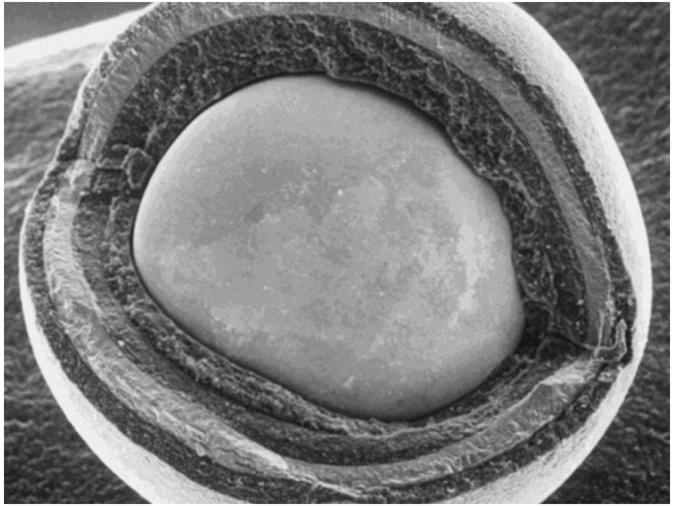
- Design using chemically stable materials that can retain their integrity at high temperatures
  - Coolant choices
    - Pressurized helium (~7 Mpa) as inert single-phase coolant with negligible neutron absorption
    - Unpressurized molten-salt as corrosive but practically single-phase coolant with moderate neutron absorption
  - Ceramic coated particle fuel
    - High temperature capability, high radionuclide retention characteristics
  - Graphite as structural material and moderator
    - High temperature stability, large heat capacity, long thermal response times

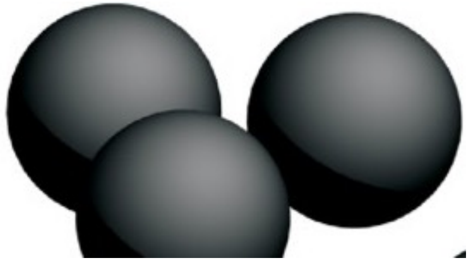
SAFETY DESIGN APPROACH (CONT.)

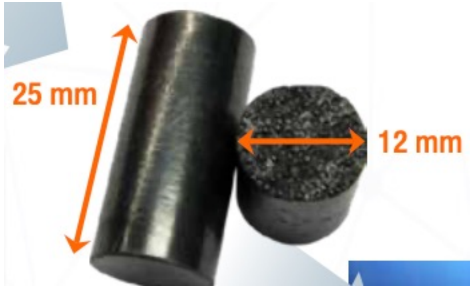
- Designs with inherent and passive safety features
  - Large negative temperature coefficient for inherent reactivity control
  - Shape and size of the reactor allows for passive decay heat removal from the reactor core through the reactor vessel
    - Decay heat is removed passively even with a pressure boundary breach through conduction and radiation in the core
  - No reliance on power or actuation signal to perform necessary safety functions
- Low power density and slow thermal response during accidents (high heat capacity)
  - Little or no reliance on operator action, insensitive to incorrect actions
- Retain radionuclides at the source (mostly within coated fuel particles)

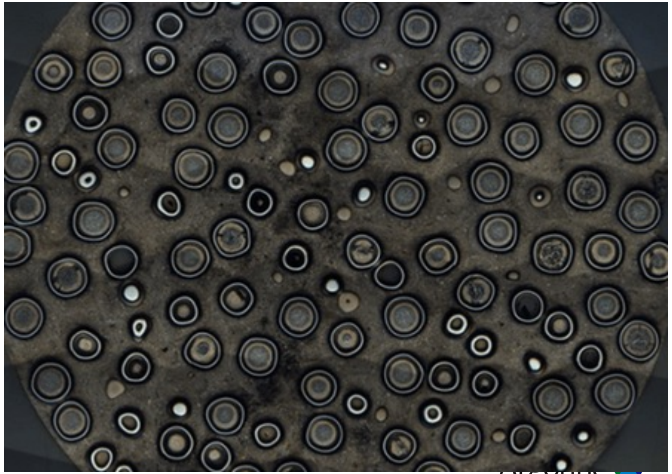
COATED PARTICLE FUEL

- UO_2 or UCO fuel kernels (fraction of a mm in diameter, size of a poppy seed)
- Several layers of protective ceramic coating around the kernels
  - These layers serve as initial barriers against release of fission products
- Coated particles pressed into graphite matrix and shaped into pebbles or pellets
- Large margin to particle failure (>1800^{o}C)



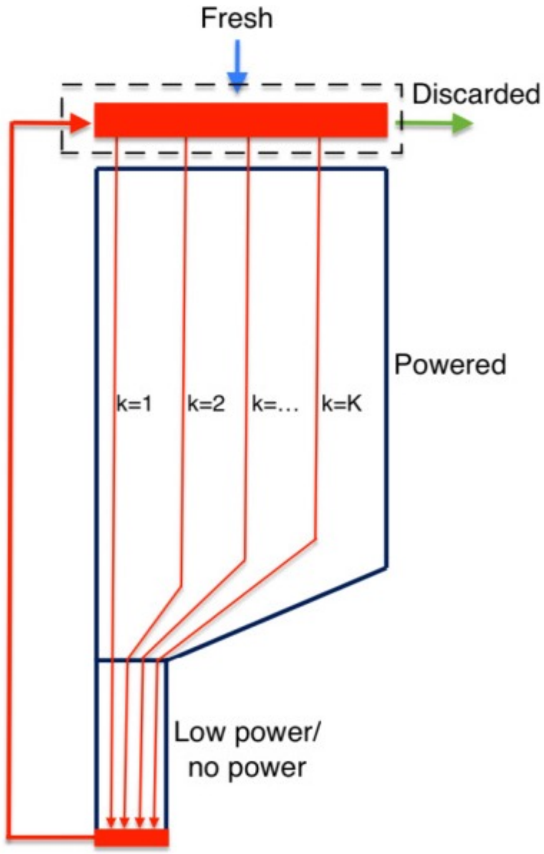






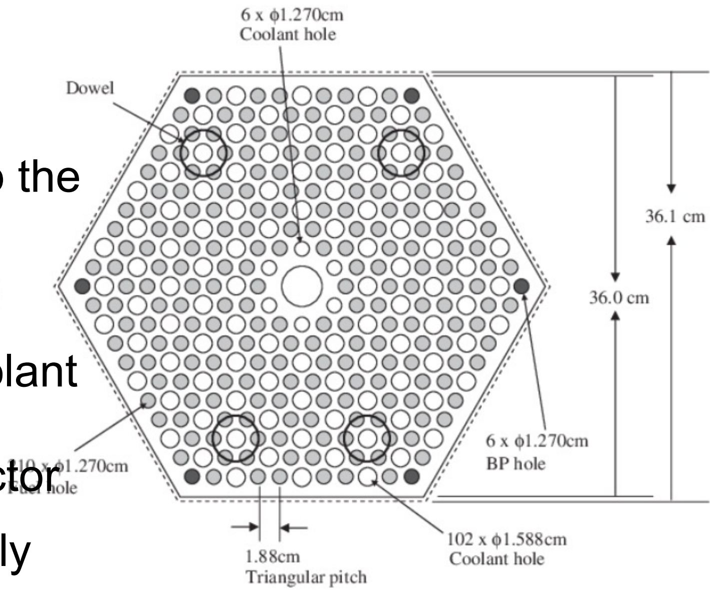
PEBBLE-BED DESIGN CONSIDERATIONS

- Pebbles are loaded from top and collected at the bottom
  - Downward coolant flow, resulting flow reversal during loss of forced cooling event
- In gas-cooled reactors, pebbles move slowly at different speed along streamlines
- Partially burnt pebbles are sent back to the top after an online burnup measurement
  - Reactor core eventually reaches an equilibrium burnup profile (can take up to a year or more)
- This online fueling allows for a very low excess reactivity



PRISMATIC FUEL DESIGN CONSIDERATIONS

- Pellets in graphite blocks with embedded coolant channels
- Pellets are batch-loaded and reshuffled during core reloading
- Burnable poison is used to flatten the power and keep the reactor critical without excess reactivity
- Shutdown rods are inserted into the blocks
- Dimensional changes in graphite lead to alternate coolant pathways (bypass flow)
  - Alters the temperature profile in the core and reflector
- When the blowers stop, forced convection stalls quickly and natural convection (driven by buoyancy) picks up
  - If there are significant bypass gaps, radiation across the gaps becomes a dominant heat transfer mechanism



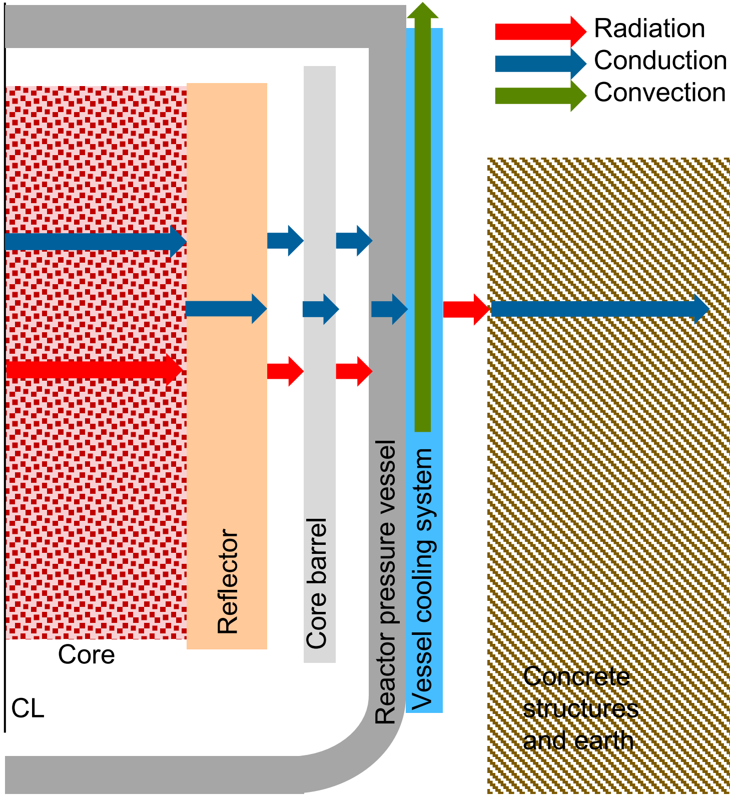
REACTIVITY CONTROL

- Mechanisms for reactivity control include:
  — Absorber pebbles (in pebble bed concepts)
  — Burnable poison (in prismatic fuel concepts)
- Subcriticality is achieved via
  — Inherent safety (strong Doppler feedback)
  — Control rods
- These mechanisms ensure that the reactor can be safely shut down and maintained in a subcritical state

PASSIVE DECAY HEAT REMOVAL

Vessel cooling system

- Removal of heat from the core to reactor vessel via conduction and radiation alone is sufficient
  - — Convective core cooling is not needed to keep the core temperatures below the design limits (during unpressurized events)
- Core heat is then dumped to atmosphere (ultimate heat sink) via radiation and natural convection in the coolant panels surrounding the reactor pressure vessel



PASSIVE DECAY HEAT REMOVAL (CONT.)

Vessel cooling system

- A simple, always on system (during both operational states and off-normal events)
  - Does not need power or an actuation signal
- Its main function is to maintain reactor pressure vessel and concrete cavity wall temperatures below design limits
  - Does not impact core temperatures significantly if not functional (not needed to protect the fuel)
- Heat removal rates are similar during normal operations and accident conditions
- Various air-cooled or water-cooled configurations are possible

AIR INGRESS

- Helium is inert, but air and water ingress into the HTGR system can pose significant safety risks
- Design measures to prevent or mitigate these events include:
  - Preventing pressure boundary breach (rapid depressurization)
  - Limiting water ingress in case of steam generator tube rupture
- Nuclear grade steel pressure vessel makes large breaks highly unlikely
  - Air ingress is limited by core flow area and friction losses
  - High-purity, nuclear-grade graphite does not “burn” but it can oxidize at a slow rate at temperatures above critical point
    - Oxidation rate is limited by availability of oxygen near the break point
- Fuel compact matrix and ceramic coatings protect fuel particles

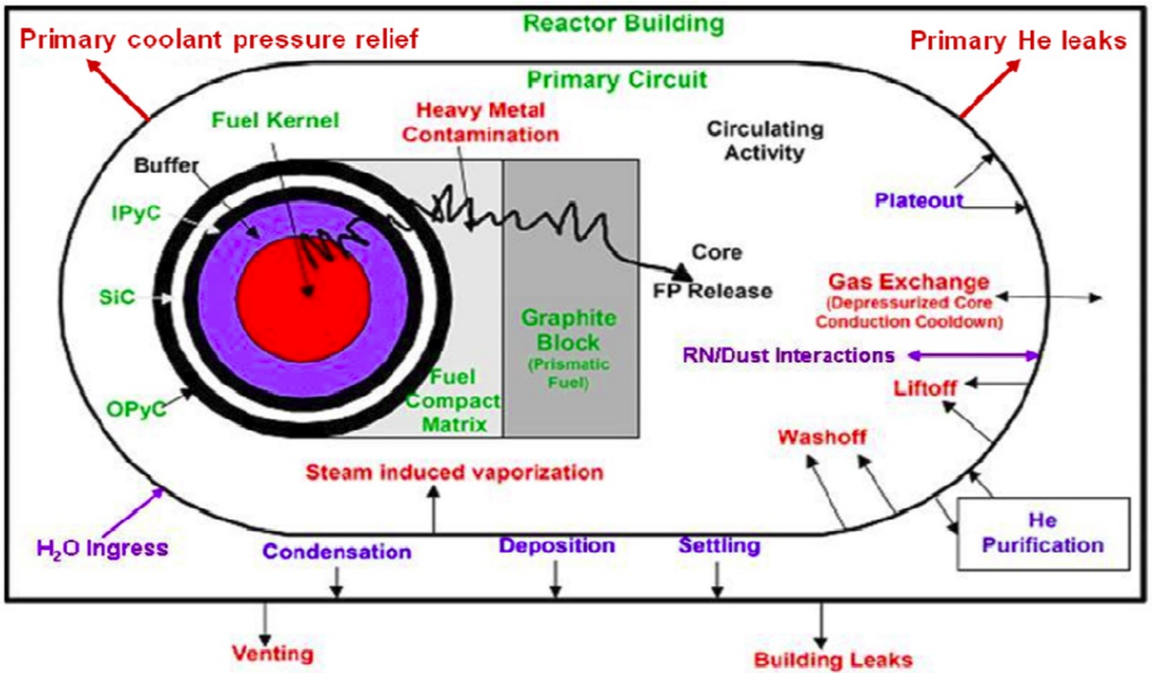
WATER/STEAM INGRESS

- Limited sources of water in steam cycle plants
- Ingress is monitored and limited by
  - Moisture monitors
  - Steam generator isolation (does not require power)
  - Steam generator dump system
- Water-graphite reaction:
  - Endothermic
  - Requires temperatures above normal operation
  - Slow reaction rate
- Fuel compact matrix and ceramic coatings protect fuel particles

CONFINEMENT OF RADIOACTIVE MATERIALS

Functional containment

- Multiple barriers to confine radioactive materials:
  - — Coated fuel particles
  - — Graphite matrix
  - — Coolant
    - Helium purification system
    - Molten salt with high retention rate
  - — Coolant boundary
  - — Reactor building



CONFINEMENT OF RADIOACTIVE MATERIALS

Functional containment (cont.)

- Emphasis is on radionuclide retention at source:
  - Coated fuel particles act as the primary barriers, effectively retaining fission products
  - Normal operating peak fuel temperature is <1250°C and tests show high retention for hundreds of hours at >1600°C without fuel particle failure
- Potential release mechanisms:
  - Primary coolant leaks
  - Liftoff (mechanical re-entrainment)
  - Steam-induced vaporization
  - Wash-off (removal by liquid H2O)
  - Primary coolant pressure relief
- Barrier performance:
  - Condensable radionuclides plate out during normal operation
  - Graphite absorption
  - Circulating activity is limited by helium purification system
- This sequence of multiple barriers eliminates the need for traditional pressure-retaining containment structure

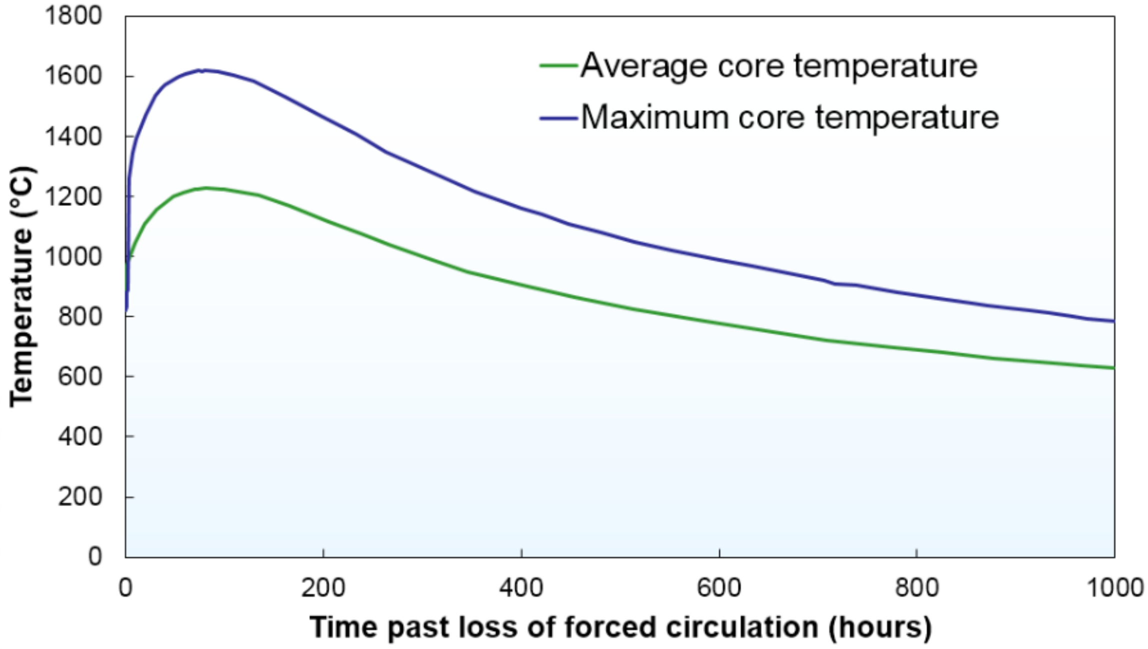
CONFINEMENT OF RADIOACTIVE MATERIALS

Delayed release mechanisms during accidents

- Early (but limited) release of circulating activity in coolant and liftoff mechanisms
  - From defective coated fuel particles
  - Helium purification system to reduce circulating activity from the coolant
- Delayed releases during off-normal events leading to elevated core temperatures
  - Releases from fuel depend on fraction of core above normal operating temperatures and duration of the event
  - Timing of release is from tens of hours to several days
  - Release rate is governed by amount of forced cooling or size of leak/break
    - Small leaks can potentially lead to a greater radionuclide release
    - Releases cease when internal temperatures decrease due to core cooldown

TYPICAL CORE TEMPERATURES

Depressurized loss of forced cooling



350 MWt Prismatic Core Design

ROLE OF VENTED REACTOR BUILDING

- Structurally protects pressure vessels and vessel cooling system from external hazards
- Limits air ingress following helium pressure boundary breaks
- Provides additional radionuclide retention opportunity, but may not be relied on for radionuclide retention to meet off-site dose regulatory requirements
  - Not a conventional pressure-retaining containment structure
- 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 higher temperatures and becomes leakier)
  - Prevents reactor building overpressure from release of non-condensing helium coolant

SUMMARY

- High Temperature Gas-cooled Reactors are a type of Generation-IV reactor system
  - Thermal reactors with coated particle fuels
  - They offer high thermal efficiency and can be used for electricity generation and process heat applications
- Design variants:
  - Pebble bed reactors
  - Prismatic fuel reactors
  - Molten-salt cooled fluidized bed concept
- Characteristics that contribute to inherent/passive safety and accident prevention:
  - Low power density
  - High heat capacity of the core
  - Strongly negative temperature coefficient of reactivity
  - Large height-to-diameter ratio of the core
  - Coated fuel particles as the primary barrier to radionuclide release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