HTGR Technology Course for the Nuclear Regulatory Commission

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Module 3

Industry Proposed Modular HTGR Safety Design Approach and Safety Systems

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General Atomics

Outline

- **Safety in top-down design process**
  - Passive safety
  - Prevention vs. mitigation
- **Barriers to radionuclide release**
  - Fuel elements
  - Helium coolant pressure boundary
  - Reactor Building
- **Residual heat removal**
- **Control of heat generation (reactivity)**
- **Control of chemical attack**
- **Summary**

Modular HTGR Safety Design Philosophy

Top-level Requirement

- **Worker doses within 20% of 10CFR20**
- **Accident doses at exclusion area boundary within EPA PAGs precludes need for public**
  - Drills
  - Sheltering
  - Evacuation

Design Solution

- **Control radionuclides primarily at their source (within fuel particles)**
- **Without reliance on**
  - Active design features
  - Operator actions

NRC Advanced Reactor Policy Statement (1/2)

“Among the attributes which could assist in establishing the acceptability or licensability of a proposed advanced reactor design, and which therefore should be considered in advanced designs, are:

- **Highly reliable and less complex shutdown and decay heat removal systems.** The use of inherent or passive means to accomplish this objective is encouraged (negative temperature coefficient, natural circulation).
- **Longer time constants** and sufficient instrumentation to allow for more diagnosis and management prior to reaching safety system challenge and/or exposure of vital equipment to adverse conditions.
- **Simplified safety systems** which, where possible, reduce required operator actions, equipment subjected to severe environmental conditions, and components needed for maintaining safe shutdown conditions. Such simplified systems should facilitate operator comprehension, reliable system function, and **more straight-forward engineering analysis**.

NRC Advanced Reactor Policy Statement (2/2)

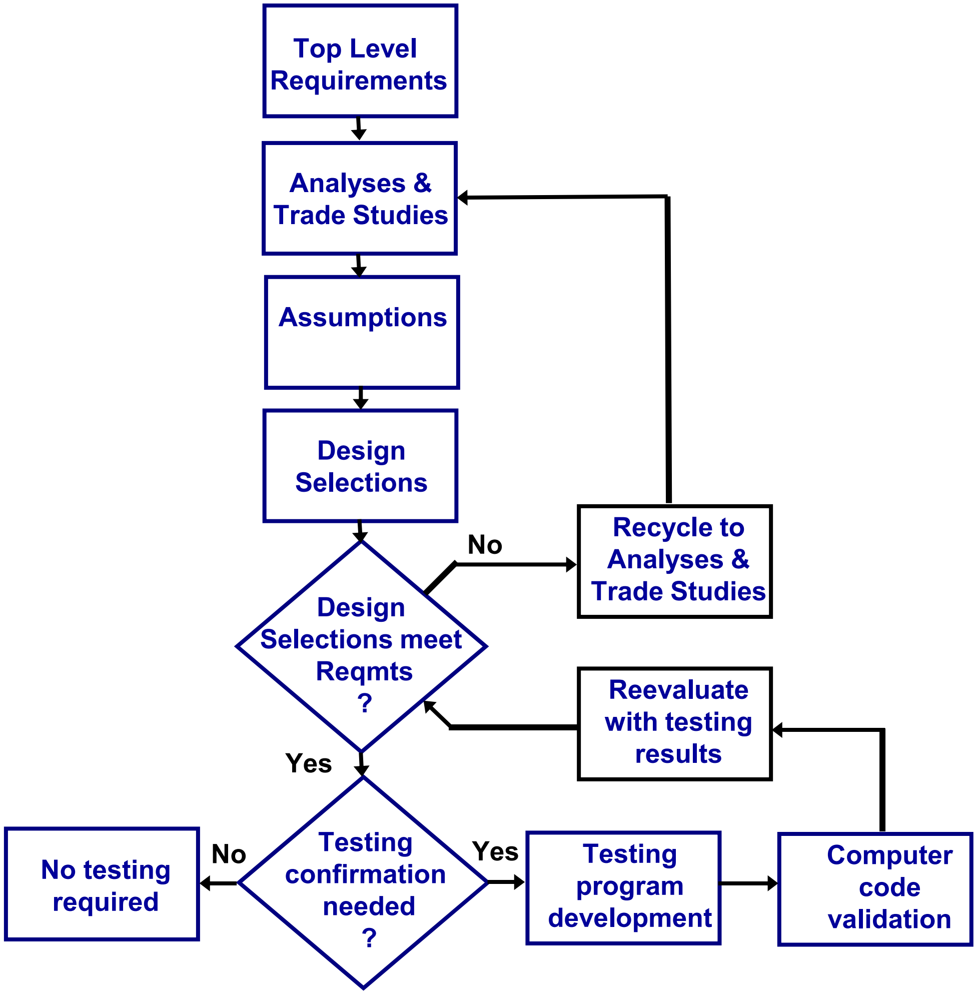
- Designs which **minimize the potential for severe accidents and their consequences** by providing sufficient inherent safety, reliability, redundancy, diversity, and independence in safety systems.
- Designs that provide reliable equipment in the balance of plant, (or **safety-system independence from balance of plant**) to reduce the number of challenges to safety systems.
- Designs that provide easily maintainable equipment and components.
- Designs that **reduce radiation exposure to plant personnel.**
- Designs that incorporate defense-in-depth philosophy by maintaining **multiple barriers against radiation release,** and by **reducing the potential for consequences of severe accidents.**
- Design features that can be proven by citation of **existing technology** or which can be satisfactorily established by commitment to a **suitable technology development** program."

FR Vol. 73, No. 199, pg. 60612-60616, Oct. 14, 2008

HTGR Requirements Driven Approach

- Objective: Provide safe, economic reliable process heat & power
- Select compatible fuel, moderator, & coolant with inherent characteristics
- Design reactor with passive safety features *sufficient to meet safety requirements*
- *Supplement with active features for investment protection and defense-in-depth*
- Utilize proven technologies

Iterative, Requirements Driven Design Approach



Top Level Requirements

Analyses & Trade Studies

Assumptions

Design Selections

Design Selections meet Reqmts ?

No

Recycle to Analyses & Trade Studies

Yes

Testing confirmation needed ?

No

No testing required

Yes

Testing program development

Computer code validation

Reevaluate with testing results

Modular HTGR Safety Design Approach Emphasizes Prevention vs. Mitigation

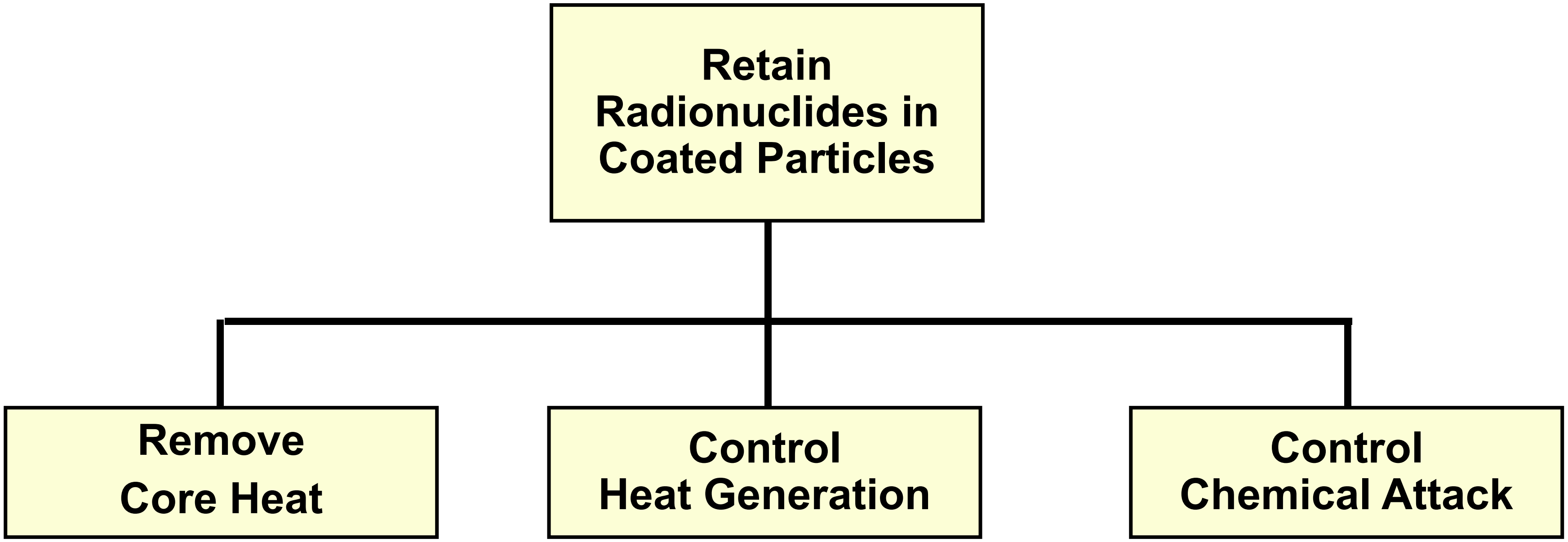
- **Utilize inherent materials characteristics**
  - Helium coolant – neutronically transparent, inert, low heat capacity, single phase
  - Refractory coated fuel - high temp capability, low release
  - Graphite moderator - high temp stability, long response times, large heat capacity
- **Develop simple modular design**
  - Small unit power rating per module
  - Embedded installation
- **Maximize passive accomplishment of safety functions**
  - Large negative temperature coefficient
  - Passive decay heat removal system *independent of coolant*
  - No AC powered safety-related systems
  - No operator action required
  - Insensitive to incorrect operator action

Two Major Design Impacts of Safety Philosophy

- **Emphasis on retention of radionuclides at source (within fuel particles) means**
  - Manufacturing process must lead to high quality fuel
  - Normal operation fuel performance limits potential for immediate release during off-normal conditions
  - Fuel is continuously monitored during operation
- **Safety-related SSCs* not reliant on AC powered systems or operator intervention means safety based on:**
  - Inherent characteristics of structures, system, & components
  - Natural processes (e.g., conduction & radiation)
  - Integrity of passive design features

**Additional SSCs relying on AC power or operator actions provide further defense-in-depth*

Modular HTGR Safety Philosophy Based on Three Functions



Retain Radionuclides in Coated Particles

Remove Core Heat

Control Heat Generation

Control Chemical Attack

High fuel manufacturing quality and performance aim at ensuring MHTGR

- *Can release activity outside of fuel during normal operation (e.g., circulating) & stay within offsite accident dose limits*
- *Thus safety focus on avoiding incremental releases from fuel*

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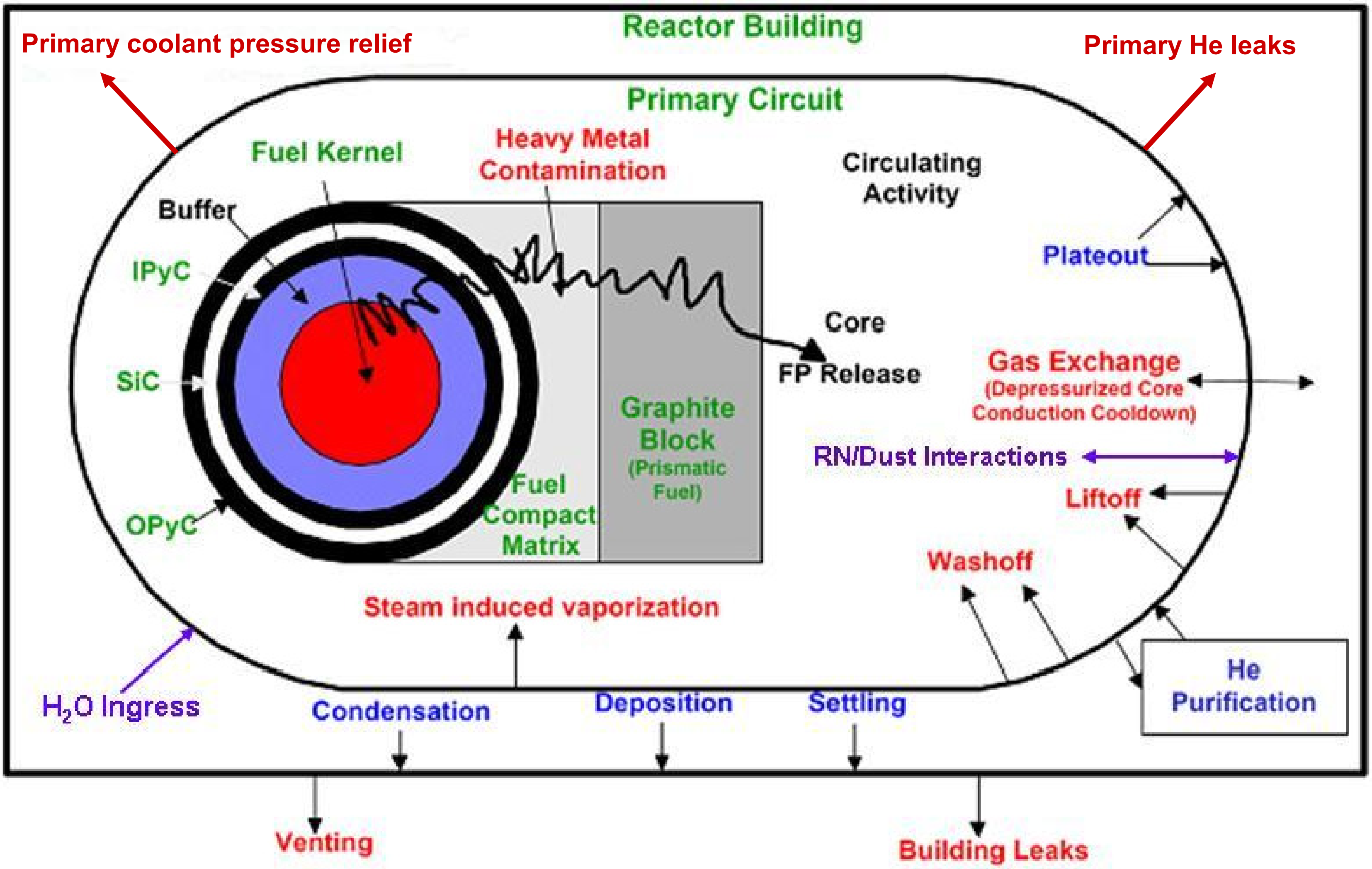
Radionuclide Containment Function

- **Modular HTGR designs employ multiple barriers to meet radionuclide retention requirements**
  - **Fuel Elements**
    - **Fuel kernels**
    - **Particle coatings (most important barrier)**
    - **Compact or pebble matrix/graphite**
  - **Helium coolant pressure boundary**
  - **Reactor building**
- **Performance criteria for each barrier derived using a top-down allocation process**

Modular HTGR Radionuclide Containment Function



Primary coolant pressure relief

Reactor Building

Primary He leaks

Primary Circuit

Fuel Kernel

Heavy Metal Contamination

Circulating Activity

Buffer

IPyC

SiC

OPyC

Plateout

Core FP Release

Gas Exchange (Depressurized Core Conduction Cooldown)

Graphite Block (Prismatic Fuel)

Fuel Compact Matrix

RN/Dust Interactions

Liftoff

Washoff

Steam induced vaporization

He Purification

H_2O Ingress

Condensation

Deposition

Settling

Venting

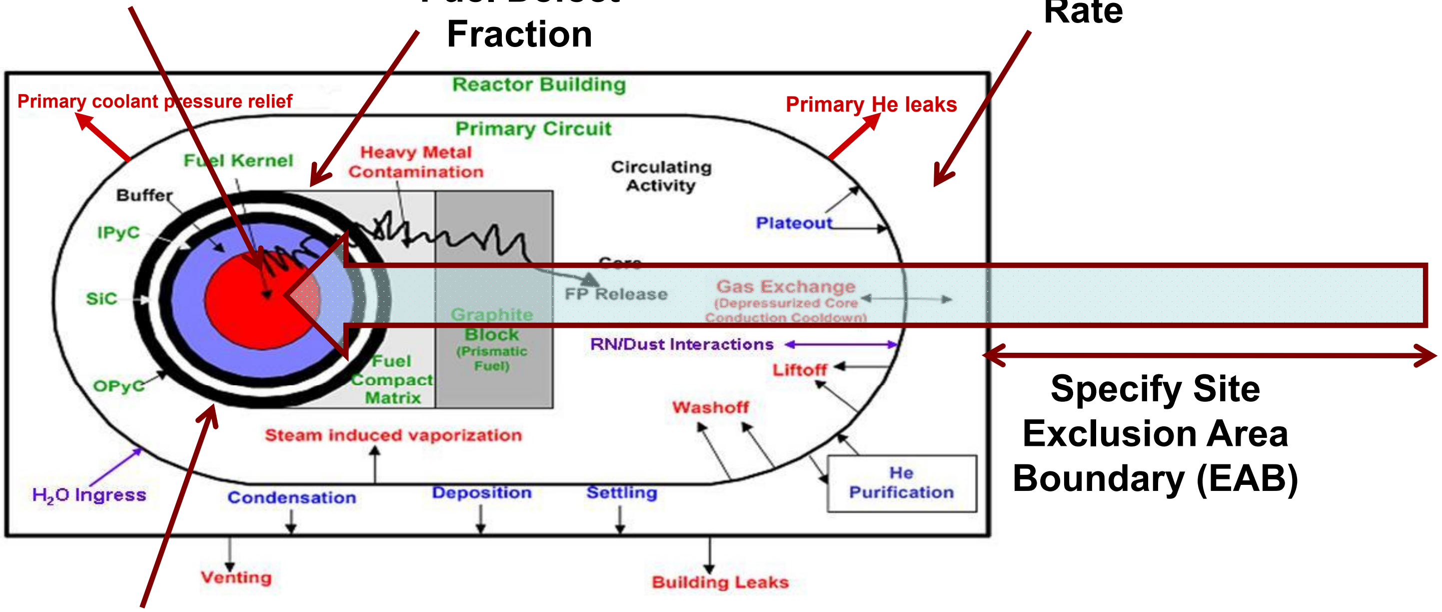
Building Leaks

Radionuclide Control Requirements Derived From Top-Level Regulatory Criteria

Specify
Max power
(initial inventory)

Specify
Fuel Defect
Fraction

Specify or Allow
for Building Leak
Rate



Specify Site
Exclusion Area
Boundary (EAB)

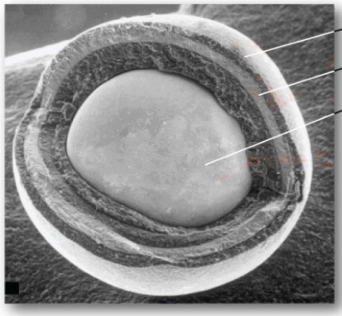
<u>Max Allowed Exposure</u>

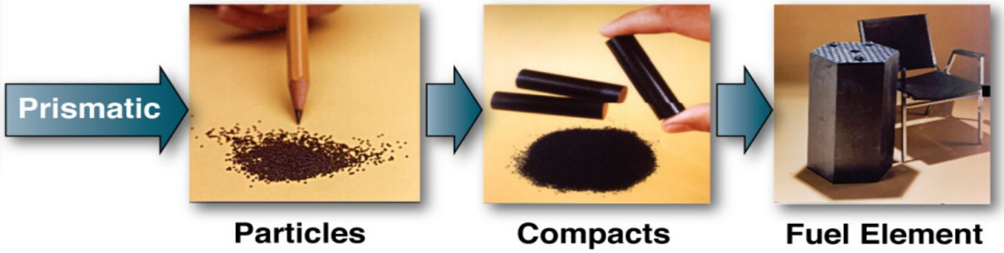
- 10CFR20
- 10CFR50.34
- PAG
- Safety Goals

Specify
Fuel Element
Performance

Illustrative outside-in, barrier requirements specification

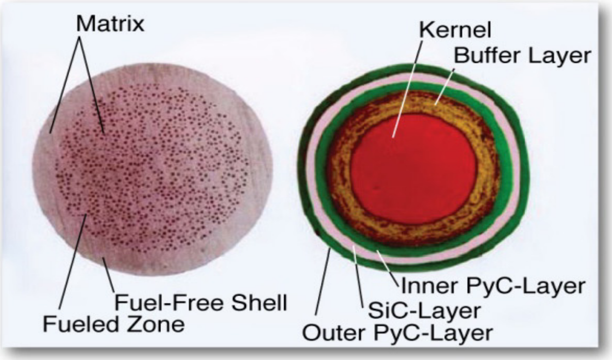
TRISO Particles Make Modular HTGR Top-Level Requirements Achievable



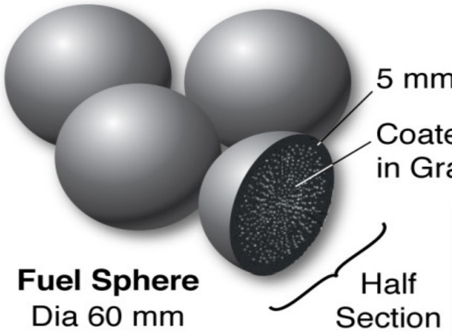


TRISO-coated fuel particles (left) are formed into fuel compacts (center) and inserted into graphite fuel elements (right) for the prismatic reactor

Pebble



TRISO-coated fuel particles are formed into fuel spheres for pebble bed reactor



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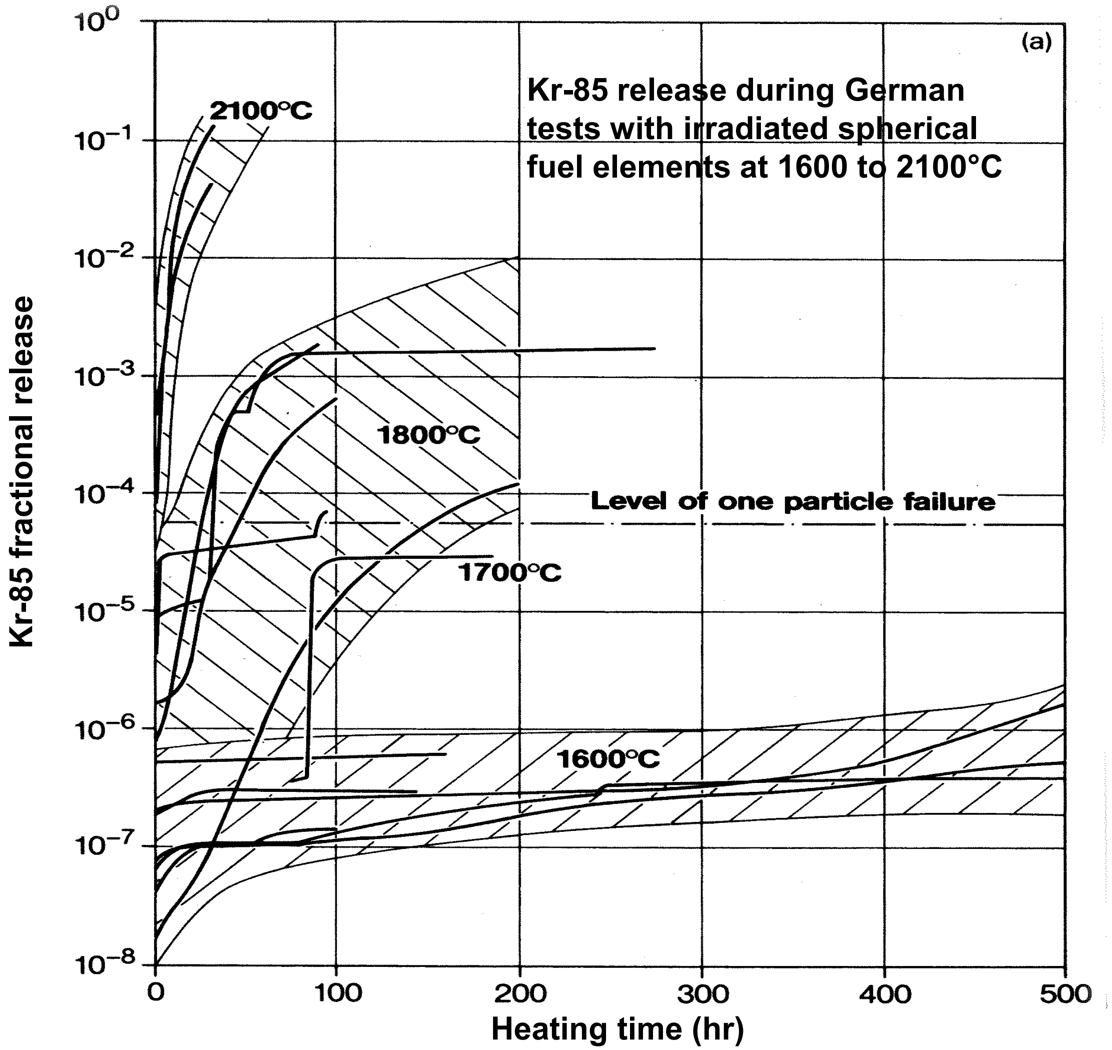
TRISO Particle Release Is Slow Even 100s of Degrees Above Normal Operating Temperatures



Normal operating peak fuel temperature less than 1250°C

Large temperature margins enable:

- **Passive heat removal independent of coolant**
- **Greater use of negative temperature coefficient**

Helium Pressure Boundary Barrier

- Composed of three nuclear quality pressure vessels surrounding fuel barriers
- Higher pressure colder helium in contact with vessels
- Higher location of reactor pressure vessel with ceramics and high temperature materials limits natural convection during passive cooling to lower steam generation vessel containing metallic materials
- Loss of helium pressure does not cause loss of cooling ---no scenarios of loss of coolant leading to core melt

Reactor Building Barrier

- **Structurally protects helium pressure vessels and RCCS from external hazards**
- **Surrounds helium pressure boundary**
- **Vented rather than pressure retaining building provides safer design solution for non-condensable helium**
  - Pressure opening and closing vent
  - Eliminates transport mechanism for delayed release from fuel for significant off normal events
- **Less challenged by release of low heat capacity (lower energy) coolant**

Vented Building Addresses Several Modular HTGR Specific Design Issues

- **Matched to non-condensing helium coolant**
- **Matched to modular HTGR accident behavior**
  - Vented early in transient when radionuclides released are low
  - Closed later in transient when fuel sees maximum temperatures
- **More benign environment for passive Reactor Cavity Cooling System designs**

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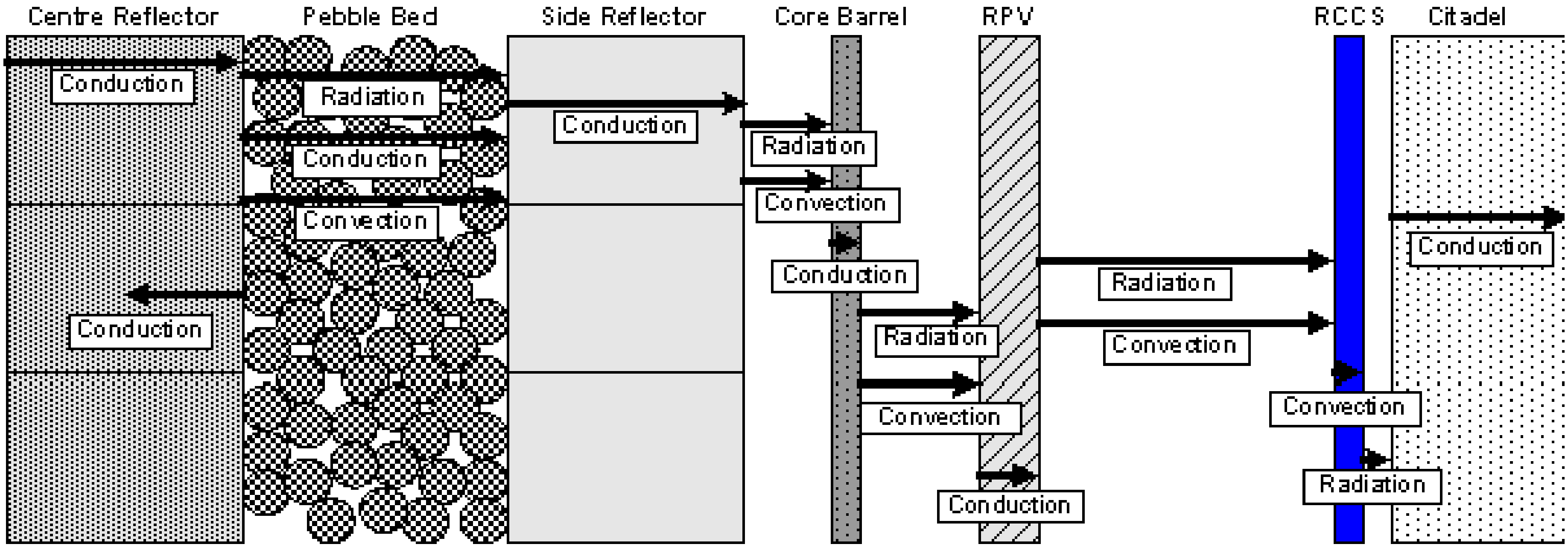
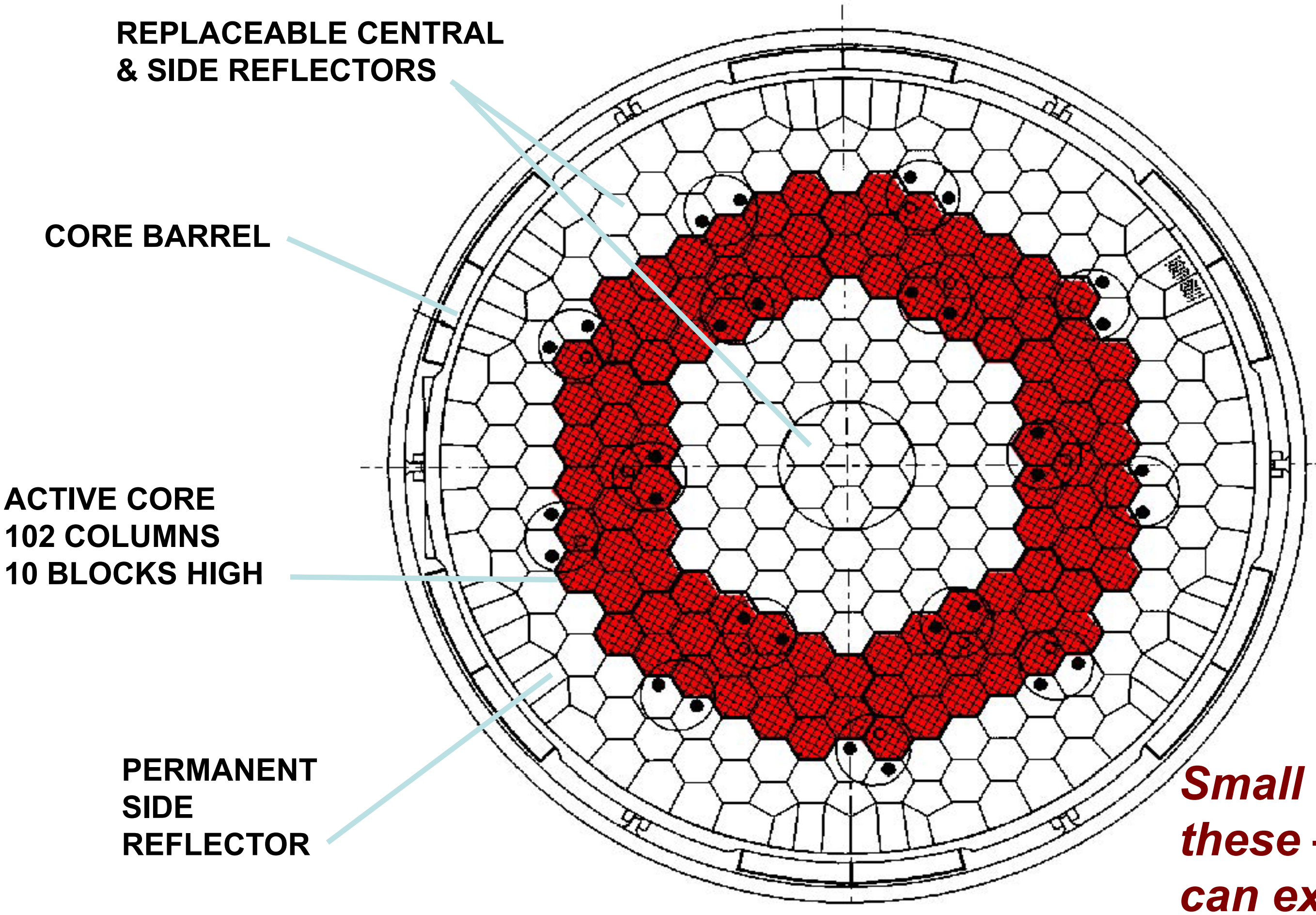
Removal of Core Heat Accomplished by Passive Safety Features

- **Small thermal rating/low core power density**
  - Limits amount of decay heat
  - Low linear heat rate
- **Core geometry**
  - Long, slender or annular cylindrical geometry
  - Heat removal by passive conduction & radiation
  - High heat capacity graphite
  - Slow heat up of massive graphite core
- **Uninsulated reactor vessel**
- **Reactor Cavity Cooling System (RCCS)**
  - Natural convection of air or water

Pebble Bed Passive Heat Transfer Path for Annular Core Design



Annular Core Can Extend Passive Cooling To Larger Core Sizes



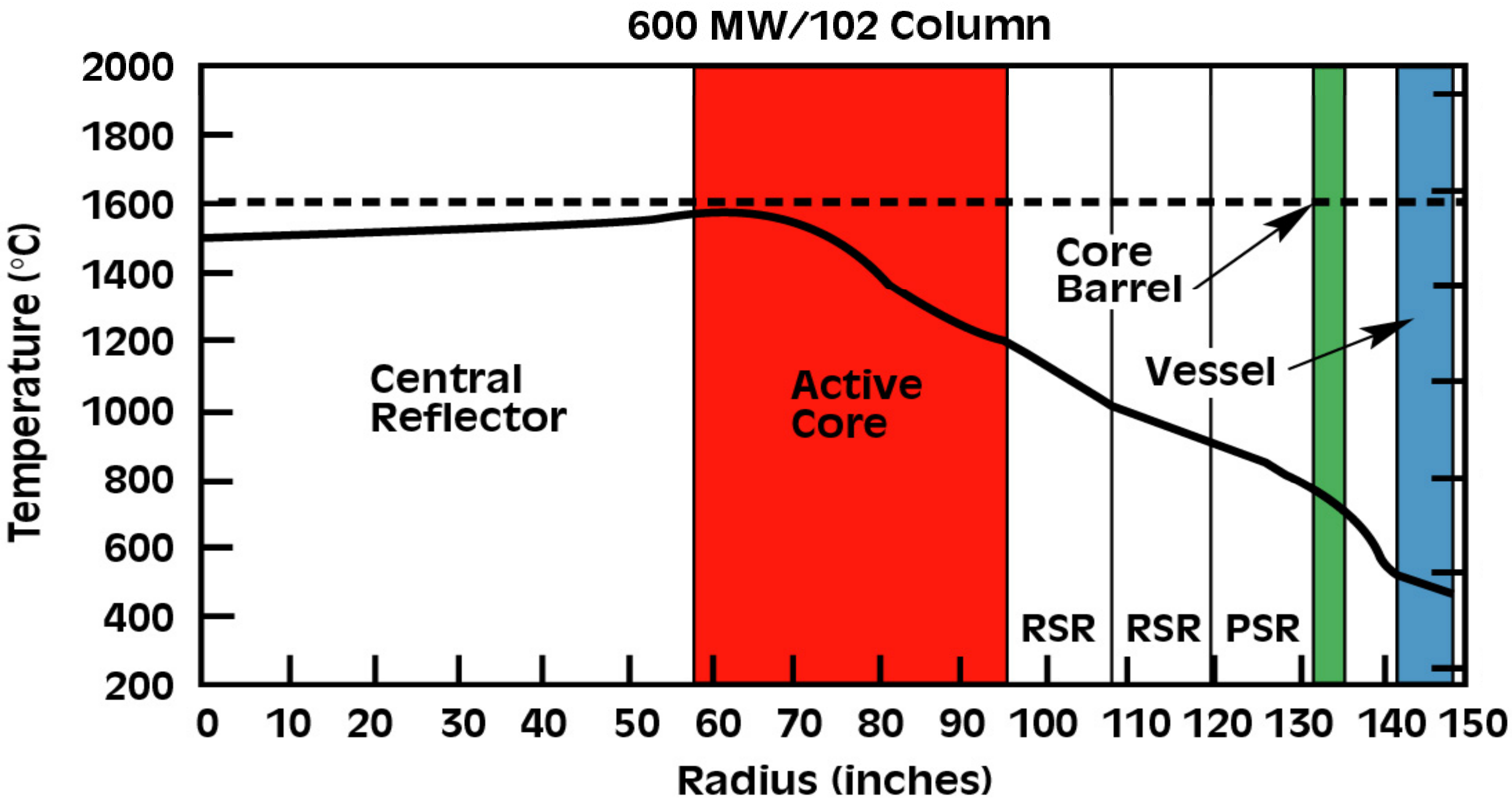
All Modular HTGR design teams emphasize geometries that can…

1) shorten conduction path,
2) enhance surface to volume ratio

Small core size provides these – annular geometry can extend to higher pwr

600 MW(t) core cross-section shown here.

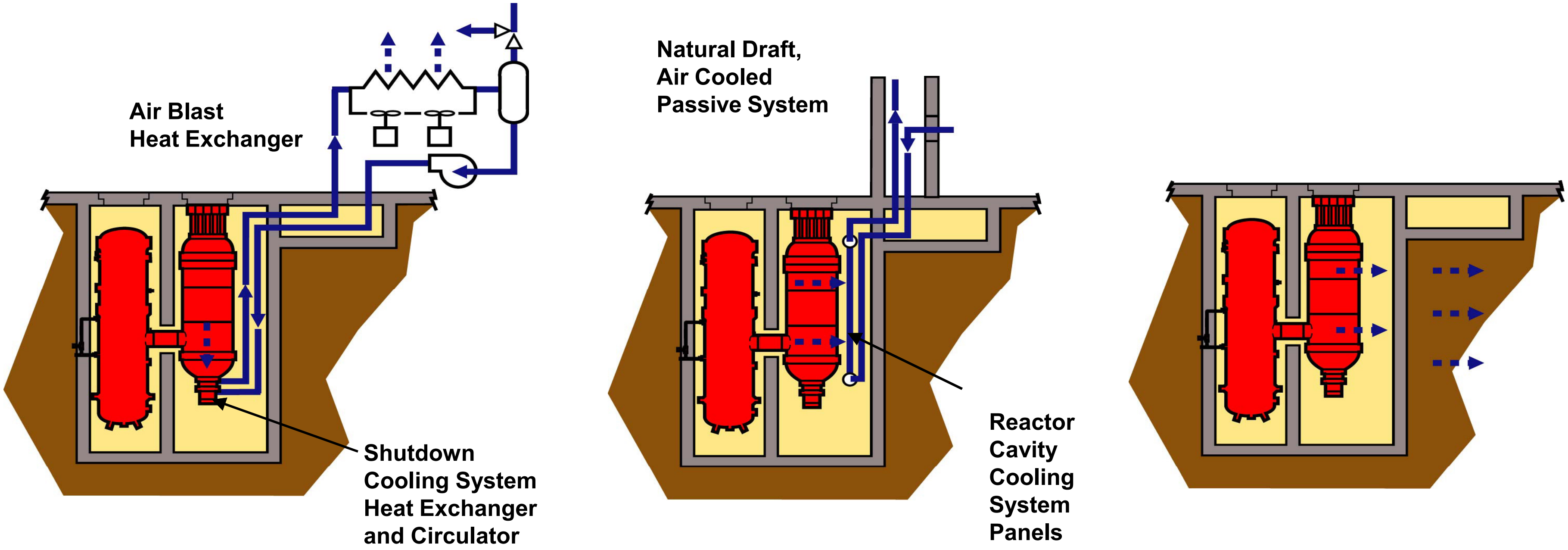
Peak Fuel Temperatures Limited to <1600 °C in Prismatic 600 MW(t)/102 Column Core Design



Reactor Cavity Cooling System

- Consists of cooling structures surrounding reactor vessel
- Removes heat transmitted from the vessel by radiation and convection
- Removes heat by forced and/or natural convection air or water flow
- Provides simple and reliable means of decay heat removal
- Meets all requirements with ample margin and redundancy
- Passive mode sufficient for accident safety

Possible Residual Heat Removal Paths When Main Cooling System Is Unavailable



A) Active Shutdown Cooling System

B) Passive Reactor Cavity Cooling System

C) Passive radiation and conduction of residual heat to reactor building (Beyond Design Basis Event)

Defense-in-Depth buttressed by inherent characteristics

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Control of Heat Generation Accomplished by Reliable Control Material Insertion and Inherent Shutdown

- **Large negative temperature coefficient intrinsically shuts reactor down**
- **Two independent and diverse systems of reactivity control for reactor shutdown**
  - Control rods
  - Reserve shutdown system
- **Each system capable of maintaining subcriticality**
- **One system capable of maintaining cold shutdown during prismatic refueling**
- **Neutron control system measurement and alarms**

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Control of Water Attack Assured by Combination of Design Features & Inherent Characteristics

- **Non-reacting coolant (helium)**
- **Limited source of water**
  - Moisture monitors
  - Steam generator isolation
  - Steam generator dump system
- **Water-graphite reaction:**
  - Endothermic
  - Requires temperatures > normal operation
  - Slow reaction rate
- **Graphite and particle coatings protect fuel**

Control of Air Attack Assured by Passive Design Features & Inherent Characteristics

- Non-reacting coolant (helium)
- Slow oxidation rate (nuclear grade graphite)
- Limited by core flow area and friction losses
- Embedded ceramic coated particles
- High integrity nuclear grade pressure vessels make large break exceedingly unlikely
- Reactor building embedment and vents that close after venting limit potential air in-leakage

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Summary

- **Top-down safety design approach emphasizes prevention versus mitigation by retaining radionuclides at the source within high quality TRISO fuel particles**
- **Multiple barriers provide defense-in-depth to limit radionuclide release**
- **System designed to protect fuel particles**
  - Heat removal by passive means
  - Reactivity control
    - Large negative temperature coefficients
    - Shutdown without rod motion
  - Plant designed to limit air/water ingress

Suggested Reading

“Preliminary Safety Information Document for the Standard MHTGR,” HTGR-86024, Rev. 13, Stone & Webster Engineering Corp., September 1992

“Probabilistic Risk Assessment for the Standard Modular High Temperature Gas-Cooled Reactor,” DOE-HTGR-8601, Rev. 5, General Atomics, April 1988