

Integrated Reactor Physics and Thermal-Fluid Dynamics in HTRs

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Overview

- Motivation & Scope
- Reactor Physics
- Thermal-Fluid Dynamics
- Multiphysics Coupling and Design Implications
- Conclusion

- **Motivation**

- Reactor behavior is governed by power generation and heat removal
 - Neutronics defines heat source
 - Thermal-fluid dynamics determines heat removal capability
 - Their interaction forms a strongly coupled system.

- **Scope**

- Reactor physics characteristics
- Thermal-fluid dynamics behavior in the core
- Multiphysics coupling
- Implications for design and safety

HTR vs LWR: Key Differences

Some important aspects and parameter of modular HTR compared to PWR

| Parameter/aspect | Dimension | Modular HTR | PWR |
|------------------------------------------|-------------------|------------------|-----------------|
| Spectrum | – | Thermal | Thermal |
| Moderator | – | Graphite | Water/liquid |
| Fuel | – | UO ₂ | UO ₂ |
| Enrichment | % | 8–9 | 3–4.5 |
| Coolant | – | Helium | Water/liquid |
| Arrangement of fuel | – | Quasi-homogenous | Heterogeneous |
| Form of fuel | – | Coated particles | Pellets |
| Characteristic dimensions of fuel | cm | 0.05 | 1 |
| Enclosure of fuel | – | C/SiC/C | Zircaloy |
| Form of fuel elements | – | Pebbles | Rods |
| Diameter of fuel elements | cm | 6 | – |
| Length of fuel elements | cm | – | 400 |
| Characteristic burnup | MWd/t | 100,000 | 45,000 |
| Average core power density | MW/m ³ | 3–4 | 100 |
| Average power density in UO ₂ | MW/m ³ | ~ 700 | ~ 300 |

Source: Kugeler, K., & Zhang, Z. (2018). Modular high-temperature gas-cooled reactor power plant. Springer.

HTR vs LWR: Key Differences

Comparison of some core data of a modular HTR and a large LWR (PWR)

| Parameter | Dimension | HTR-PM | LWR (PWR) |
|---------------------------------------------------|-------------------|-----------------------------------|--------------------------------|
| Thermal power | MW | 250 | 3800 |
| Average core power density | MW/m ³ | 3.2 | 100 |
| Core diameter | m | 3.1 | ~3.6 |
| Core height | m | 11 | ~4 |
| Coolant | – | Helium | Pressurized water |
| Coolant heatup | °C | 250 → 750 | 290 → 325 |
| Coolant pressure | MPa | 7 | 16 |
| Moderator | – | Graphite | Water (liquid) |
| Fuel | – | UO ₂ —coated particles | UO ₂ —pellets |
| Enrichment | % | 8.5 | 4.2 |
| Burnup | MWd/t | 90,000 | 45,000 |
| Arrangement of fuel | – | Quasi-homogenous | Heterogeneous |
| Dimension of characteristic fuel zones (diameter) | mm | 0.5 UO ₂ kernel of CP | 10 UO ₂ rods |
| Form of fuel elements | – | Spheres | Example: 16 × 16 rods |
| Characteristic dimension of fuel element | cm | 6.0 diam. | 25 × 25 cm × cm |
| Length of fuel elements | m | – | ~4 |
| Loading of fuel | – | Continuous | Discontinuous, yearly |
| Discharging of fuel | – | Continuous | Discontinuous, yearly |
| Excess reactivity for burnup | % | 0 | till 10 |
| Compensation of excess reactivity | – | – | Burnable poison Boron in water |
| Max. fuel temp. in operation | °C | <1200 | <2300 |
| Position of shutdown elements | – | All in reflector | All in core area |

Source: Kugeler, K., & Zhang, Z. (2018). Modular high-temperature gas-cooled reactor power plant. Springer.

Key characteristics of HTRs:

- Moderator: graphite
- Coolant: helium (neutronic transparency)
- Fuel: TRISO particles (coated fuel) embedded in graphite matrix
- Power density: low ($\sim 3\text{--}4 \text{ MW/m}^3$)
- Temperature: high (up to 950°C)
- High burnup capability ($\sim 10 \text{ GWd/t}$)
- Continuous fueling possible (pebble bed)

These characteristics determine physical behavior:

- Moderator and coolant define the **neutron spectrum**
- Core geometry affects **leakage and flux shape**
- Fuel form affects **heterogeneity and local power distribution**
- Material properties determine **temperature feedback characteristics**

Why is HTR physics special?

- Graphite moderator → efficient moderation with low energy loss per collision
- Helium coolant → neutronically transparent, enables high-temperature operation
- TRISO fuel → quasi-homogeneous neutronics with localized heat generation

Key Neutronic Quantities

- Neutron flux: determines reaction rates and power distribution → **where power is generated**
- Multiplication factor: defines criticality condition and neutron balance → **whether the reactor is stable**
- Reactivity: quantifies system response to perturbations → **how the reactor responds to changes**

$$\rho = \frac{k_{eff} - 1}{k_{eff}}$$

Power Generation from Neutronics

- Heat is produced by nuclear fission reactions
- Fission reaction rate is proportional to neutron flux
- Power distribution can be estimated by:

$$P = R \cdot E_f = \int_0^{\infty} \Sigma(E)\phi(E)dE \cdot E_f$$

Reaction rate

energy released per fission

- Neutron flux \rightarrow Power distribution \rightarrow Temperature field

Temperature Feedback Mechanisms

- Nuclear cross sections depend on temperature
- Changes in temperature affect neutron spectrum → neutron flux

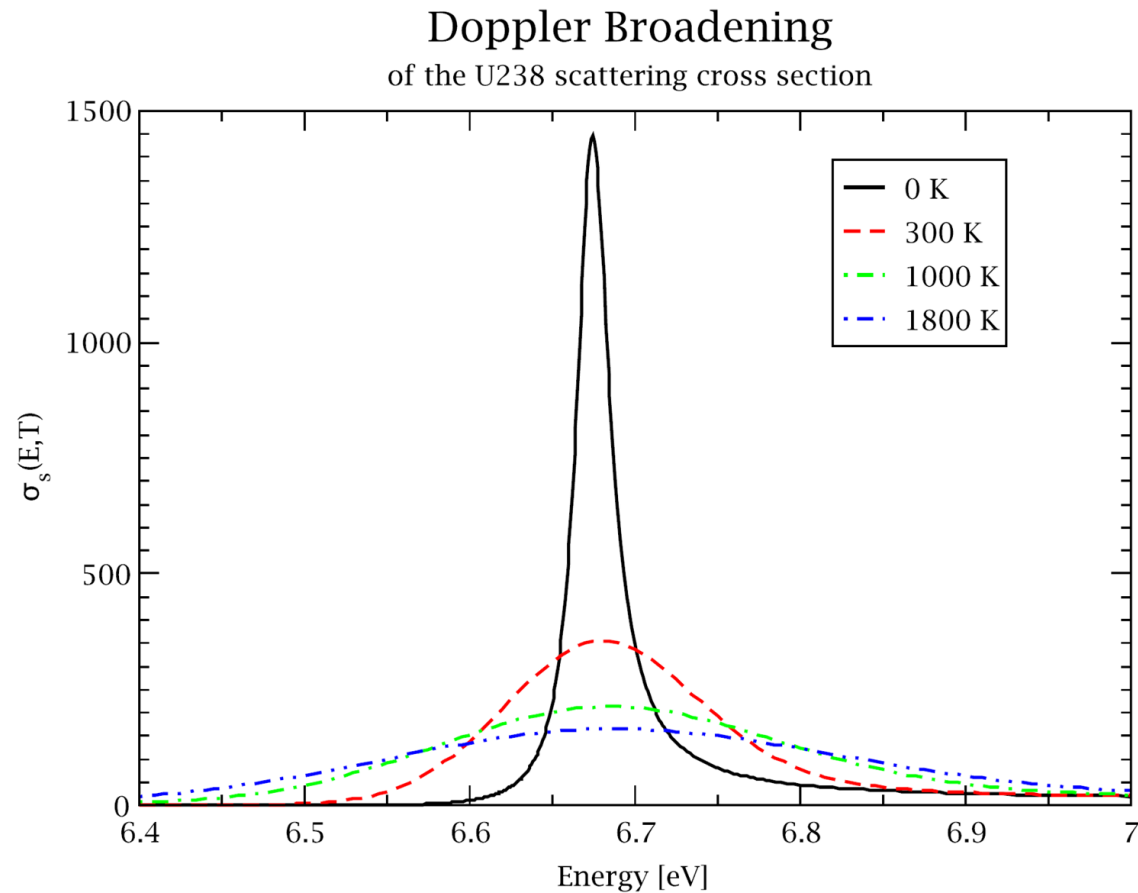
Key Feedback Effects

- Doppler effect: resonance broadening and increased resonance absorption at high temperature
- Density effect: reduced atom density and weaker moderation at high temperature

Overall Impact

- Negative reactivity feedback in HTR → inherent safety feature

Doppler Broadening: Increase in resonance absorption with temperature



Source: Becker, Bjorn. (2010). On the influence of the resonance scattering treatment in Monte Carlo codes on high temperature reactor characteristics.

Reactivity Control

Passive Reactivity Control (temperature feedback)

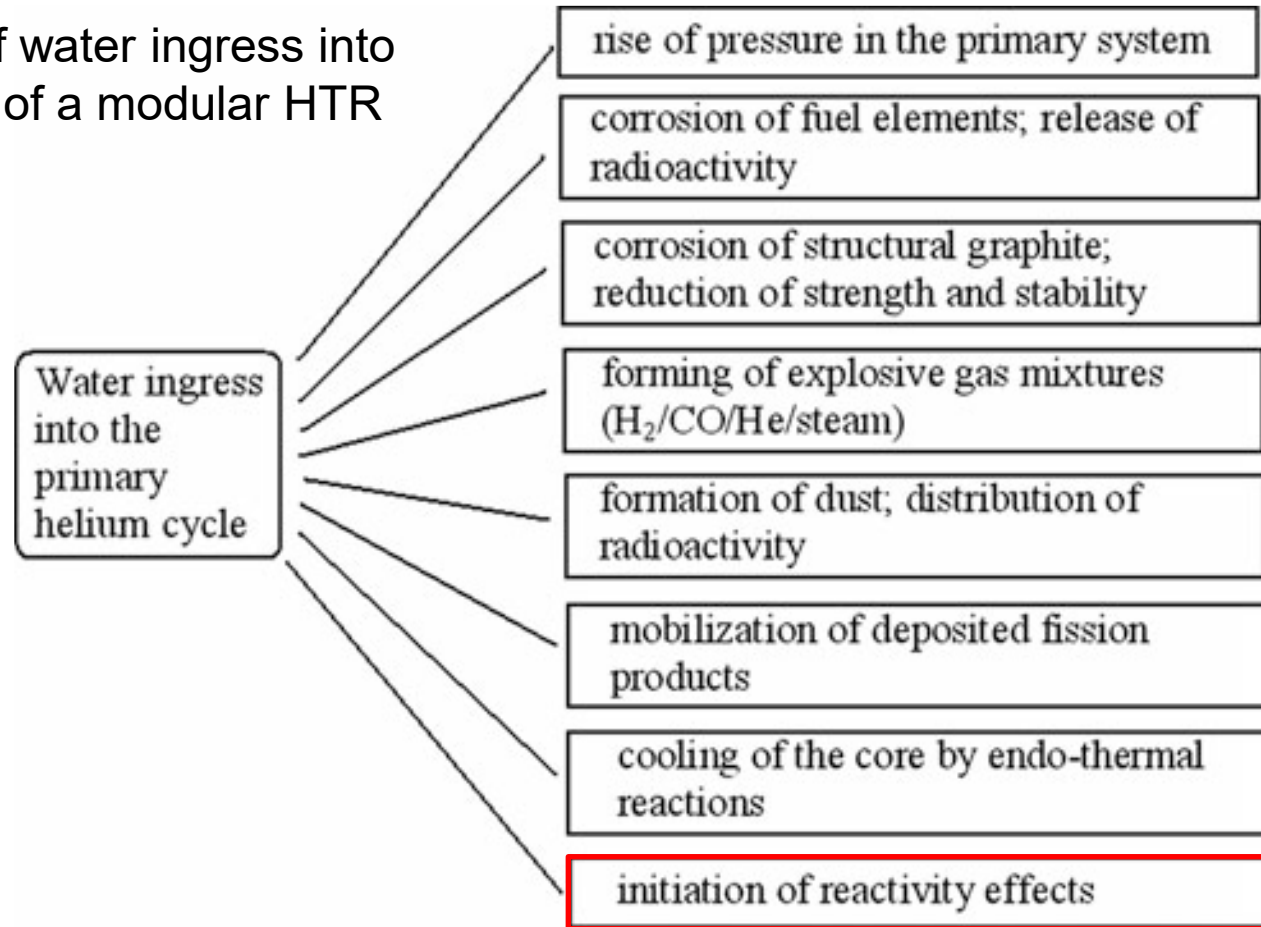
- Negative temperature coefficient
- Increase in temperature \rightarrow negative reactivity \rightarrow inherent safety feature

Active Reactivity Control

- Control rods, absorber balls in the reflector
- Adjustment of neutron absorption
- Used for startup, shutdown, and power regulation

Water Ingress into the Primary System

Consequences of water ingress into the helium cycle of a modular HTR



Source: Kugeler, K., & Zhang, Z. (2018). Modular high-temperature gas-cooled reactor power plant. Springer.

Water Ingress as a Reactivity Control Challenge

- Steam ingress increases moderation and shifts the neutron spectrum
- Results in positive reactivity insertion

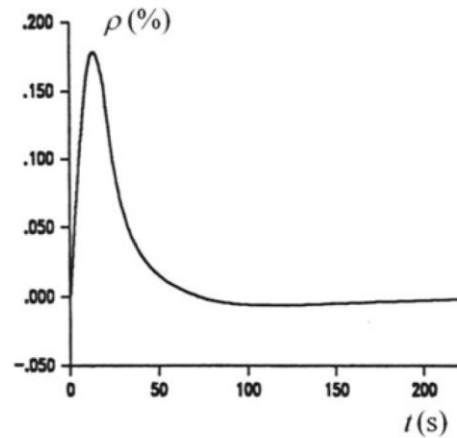
Competing Effects

- Positive effect: enhanced moderation → positive reactivity
- Negative effect: Doppler feedback at rising temperature

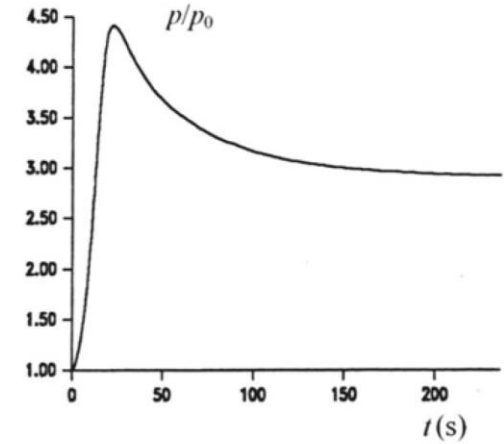
Requires careful transient and safety analysis.

Water Ingress into the Primary System

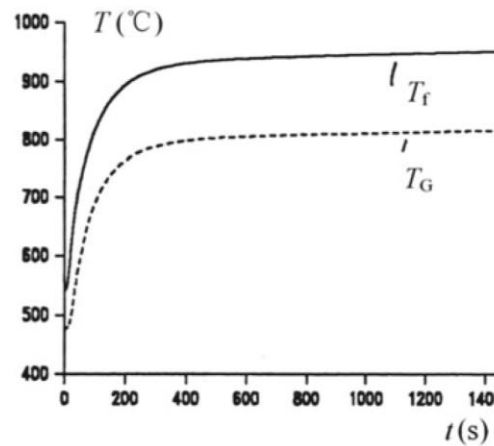
Consequences of ingress water into the primary circuit of a modular HTR (200 MWth) (rate H₂O: 50 kg/s; total H₂O in primary circuit: 2000 kg; in core: 60 kg) (corresponding to BDBA)



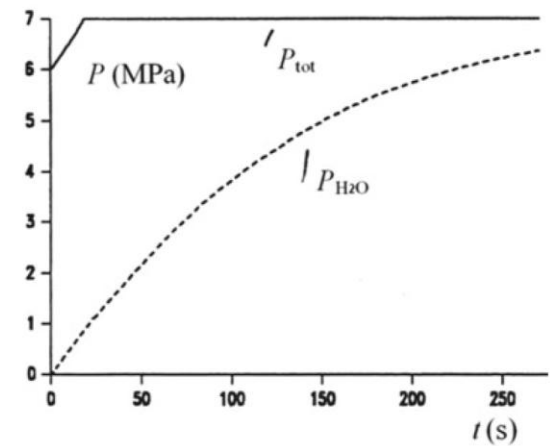
(a) reactivity



(b) relative power



(c) fuel and gas temperature



(d) pressure

Source: Hübel, H.; Lohnert, G., The safety concept of HTR-Modul, explained on the example of the water ingress into the primary circuit, KTG-Fachtagung; Safety of high temperature reactors, Jülich, March 1985

From Neutronics to Thermal-Fluid Dynamics

- Neutronics determines power generation and spatial distribution
- Power density acts as the thermal source term
- Heat must be removed to maintain fuel temperature limits

Role of Thermal-Fluid Dynamics

- Governs temperature and flow fields in the core
- Determines heat removal capability
- Directly linked to fuel integrity and safety margins

Heat Removal Mechanism

- Helium coolant flows through the core
- Heat transfer from fuel → graphite → coolant
- Convective heat removal dominates during operation

Relation

- Heat removal governed by:

$$P = \dot{m}c_p(T_{out} - T_{in})$$

- Controlled by:
 - Mass flow rate
 - Temperature rise

Temperature Distribution

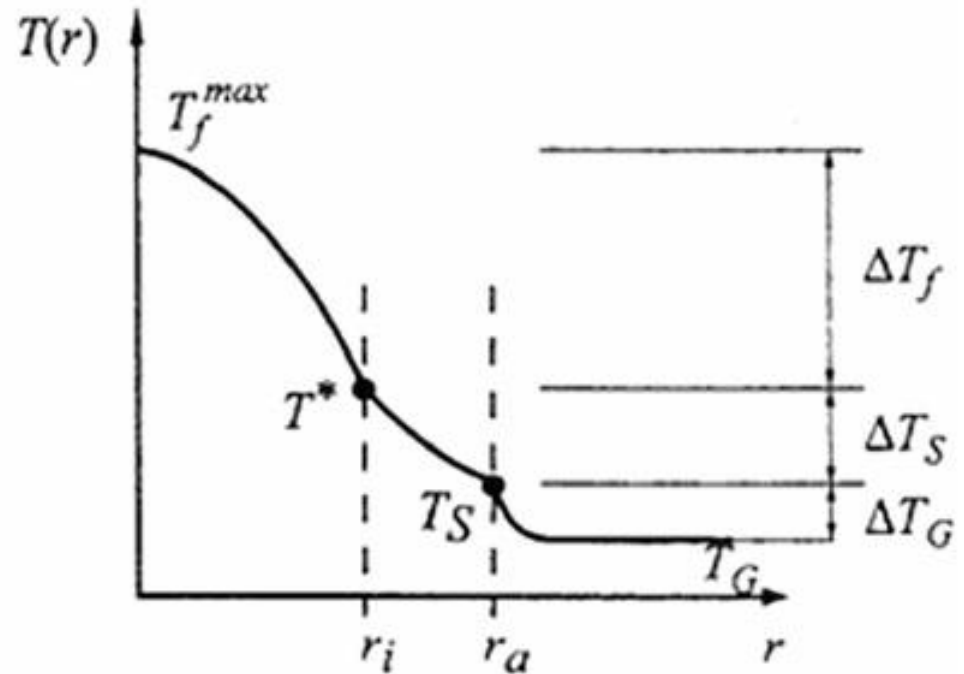
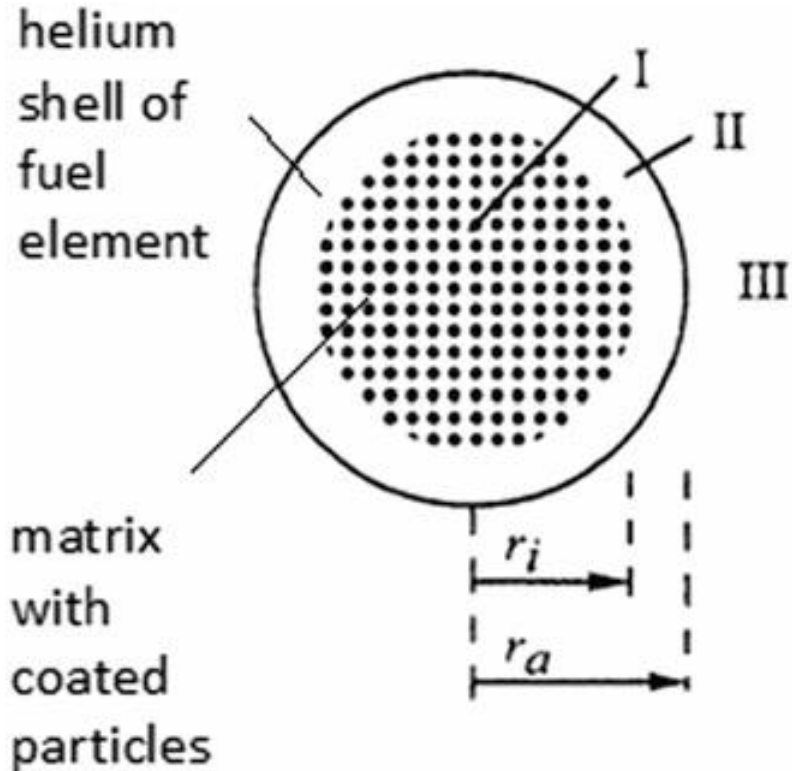
- Temperature field is determined by the combined effect of heat generation and heat removal
- Local temperature depends on:
 - power density
 - coolant temperature
 - mass flow distribution
 - heat transfer conditions

Fuel Temperature Characteristics

- Heat is generated inside TRISO particles
- Temperature decreases from fuel → graphite → coolant

Temperature Distribution

Principle temperature distribution in spherical fuel elements



Source: Kugeler, K., & Zhang, Z. (2018). Modular high-temperature gas-cooled reactor power plant. Springer.

Power Peaking and Cooling Non-Uniformity

- Power is non-uniformly distributed in the core
- Cooling conditions are also spatially non-uniform
- Hot spots occur where high power coincides with limited cooling

Power **Peaking Factor**

- Defined as: $\beta = \frac{q'''_{max}}{q'''_{avg}}$
- Typical values in HTRs: 1.7 ~ 2
- Depends on:
 - Fuel management strategy (OTTO, MEDUL)
 - Spatial flux distribution (core design, burn-up)

Flow Distribution and Pressure Drop

- Heat removal depends on local coolant mass flow rate
- Flow distribution in the core is non-uniform
- Flow is influenced by hydraulic resistance (pressure drop)
- Regions with higher resistance receive less coolant flow

Implications

- Reduced local flow → reduced heat removal capability
- Combined with high power → formation of hot spots
- Global flow is limited by system pressure drop constraints (pump capacity, system design)

Multiphysics Coupling in HTR Systems

- Neutronics determines power generation
- Power defines temperature field
- Temperature affects material properties and cross sections

Feedback Loop

- Temperature \uparrow \rightarrow Doppler effect \rightarrow reactivity \downarrow
- Temperature \uparrow \rightarrow density change \rightarrow moderation \downarrow
- Reactivity change \rightarrow power redistribution

Implications for Design and Safety

Coupling Implications

- Power, temperature, and flow are interdependent
- Local perturbations can propagate through the system
- System response is nonlinear and time-dependent

Engineering Challenges

- Accurate prediction requires coupled multiphysics models
- Strong feedback dominates transient behavior
- Simplified or decoupled approaches may be insufficient

Relevance for SMRs

- Smaller cores → **stronger coupling effects**
- Reduced thermal inertia → **faster response**
- Safety analysis relies on correct representation of feedback → **High-fidelity coupled simulation is mandatory**

- HTR-SMR behavior is governed by tightly coupled neutronics–thermal-fluid interactions
- Power, temperature, and coolant flow evolve in a strongly interdependent manner
- Safety margins are controlled by local limiting conditions, not only by core-averaged behavior
- Passive temperature feedback provides inherent stabilization, but can be challenged under strong transients
- Therefore, high-fidelity coupled multiphysics simulation is essential for design and safety analysis