Unit 6: Nuclear Fuels

ME 5203 – Nuclear Materials

P. Sharma, Ph.D.

Department of Mechanical Engineering
School of Energy Resources
University of Wyoming

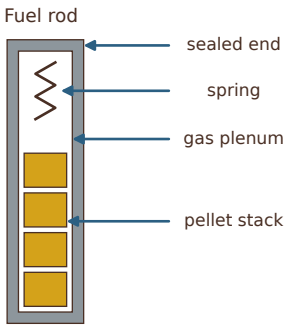
Fall 2026

Fuel must produce heat and keep a stable barrier system

- Fission deposits energy inside the fuel.
- Heat must reach the coolant.
- Fuel and cladding retain radioactive products.
- Their properties change throughout irradiation.

Unit 6 question

How do structure, transport, mechanics and chemistry combine to control fuel performance?



Unit 6: Outline

Part	Main questions
1. Oxide fuel	Why UO_2? How do defects and pores affect it?
2. Heat and mechanics	What controls temperature, cracking and contact?
3. Irradiation history	How do burnup, gas and restructuring change fuel?
4. Alternative fuels	What do MOX, ThO_2, UC, UN and metals offer?
5. Barrier systems	How do TRISO and ATF concepts work?

By the end

Calculate simple performance measures and justify a fuel-system comparison.

Distinguish pellet, rod and assembly

Pellet

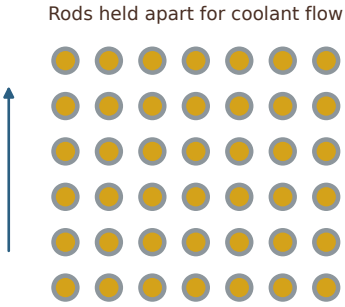
A small fuel body, commonly a sintered ceramic cylinder.

Rod / pin

Fuel inside a sealed cladding tube, with free volume for gas.

Assembly

A supported group of rods with coolant passages.

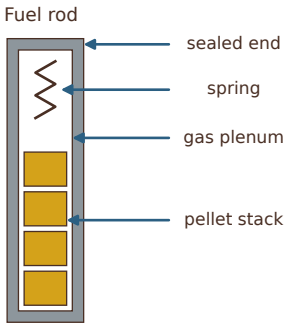


Assembly cross section; schematic

A fuel rod contains more than pellets

- A stack of pellets provides the heat-producing region.
- Cladding separates the fuel from coolant.
- An initial gap allows fabrication tolerances and dimensional change.
- A plenum provides gas volume; a spring holds the stack.

The sketch shows a generic oxide-fuel rod, not a fabrication drawing.



Fuel selection is a system problem

Requirement	Why it matters
Fissile inventory and neutron behavior	Sustain the required power history
Thermal transport and phase stability	Remove heat while maintaining margin
Dimensional response	Manage swelling, cracking and contact
Chemical compatibility	Limit reaction with cladding and coolant
Fabrication and qualification	Achieve a reproducible, predictable fuel

Fuel families solve different parts of the problem

Family	Examples	Main attraction
Oxides	UO_2, MOX, ThO_2	Established ceramic-fuel basis
Carbide / nitride	UC, UN	High density and conductivity
Metallic	U–Zr, U–Pu–Zr	High conductivity and alloy design
Coated particles	TRISO	Barriers around each small kernel
Dispersion	Fuel particles in a matrix	Combine fuel with a supporting phase

The form, matrix and cladding are part of the fuel concept.

Why UO_2 remains a useful reference fuel

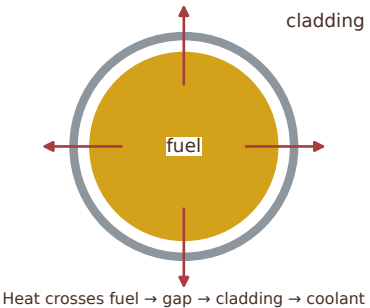
Useful combination

High melting temperature, established fabrication, and extensive oxide-fuel experience.

Limitations

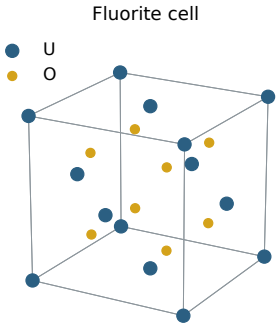
Relatively low conductivity, brittle fracture, evolving defects, swelling and gas release.

Its useful properties do not make its behavior independent of temperature or burnup.



UO_2: connect fluorite structure to Unit 2

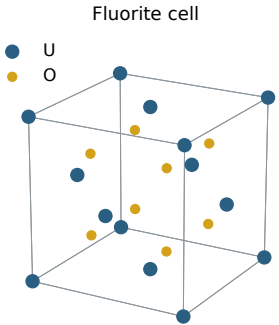
- U occupies an FCC sublattice.
- O occupies all eight tetrahedral sites in the conventional cell.
- Four U and eight O atoms give four formula units.
- Nearest-neighbour coordination: U has 8 O; O has 4 U.



Calculate theoretical density from the cell

Question

Use four UO_2 units per cell, $M = 270$ g/mol and $a = 5.47$ Å. Find the ideal density.

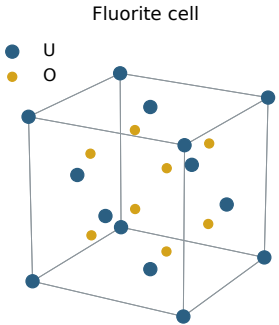


Calculate theoretical density from the cell

Question

Use four UO_2 units per cell, $M = 270$ g/mol and $a = 5.47$ Å. Find the ideal density.

$$\rho = \frac{4M}{N_A a^3}, \quad N_A = 6.022 \times 10^{23} \text{ mol}^{-1}$$



Calculate theoretical density from the cell

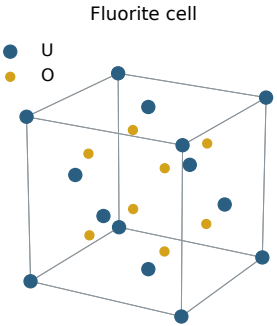
Question

Use four UO_2 units per cell, $M = 270$ g/mol and $a = 5.47$ Å. Find the ideal density.

$$\rho = \frac{4M}{N_A a^3}, \quad N_A = 6.022 \times 10^{23} \text{ mol}^{-1}$$

Answer

$\rho \approx 10.96$ g/cm^3. This excludes porosity.

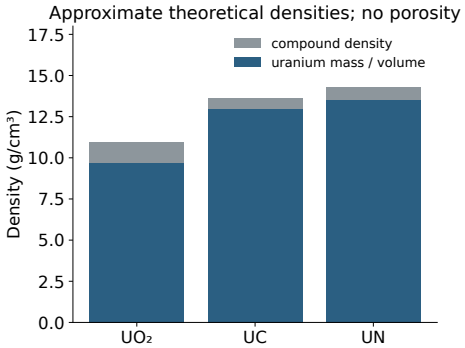


Compound density and uranium density are different

$$\rho_U = \rho_{\text{fuel}}\, w_U$$

- ρ_U: uranium mass per fuel volume.
- w_U: uranium mass fraction.
- For UO_2, $w_U \approx 238/270$.

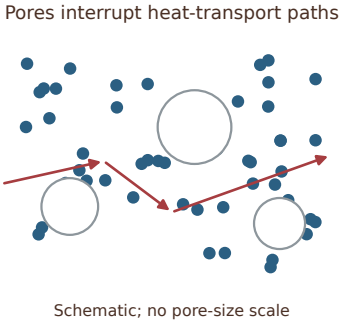
Use the actual pellet density, including porosity, for inventory calculations.



Uranium density in a porous pellet

Question

An illustrative UO_2 pellet is 95% of theoretical density. Use $\rho_{TD} = 10.96$ g/cm^3. Find ρ_U.

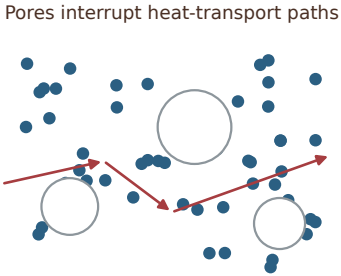


Uranium density in a porous pellet

Question

An illustrative UO_2 pellet is 95% of theoretical density. Use $\rho_{TD} = 10.96$ g/cm^3. Find ρ_U.

First reduce the compound density for pores; then multiply by uranium mass fraction.



Uranium density in a porous pellet

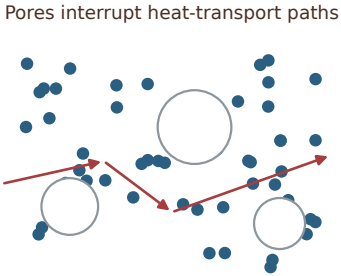
Question

An illustrative UO_2 pellet is 95% of theoretical density. Use $\rho_{TD} = 10.96$ g/cm^3. Find ρ_U.

First reduce the compound density for pores; then multiply by uranium mass fraction.

Answer

$\rho_U = 0.95(10.96)(238/270) \approx 9.18$ g/cm^3.

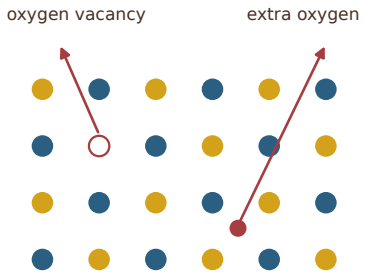


Stoichiometry changes the defect population

$$UO_{2+x} \quad \text{or} \quad UO_{2-x}$$

- Excess or deficient oxygen requires defect and charge compensation.
- Uranium valence and defect clustering can change.
- The accessible state depends on temperature and oxygen potential.

The drawing marks defects conceptually, not a specific fluorite plane.



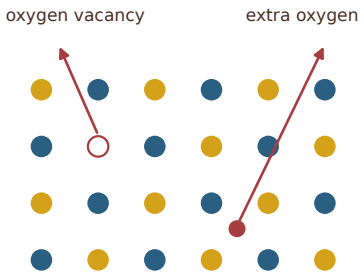
Defect sketch, not a fluorite plane

Oxygen content affects transport and compatibility

- Defects scatter heat-carrying excitations.
- Oxygen chemical potential controls exchange with surrounding materials.
- Changes in composition can affect phase stability and fuel–cladding reactions.

Conductivity consequence

Excess oxygen does not generally improve UO_2 conductivity.



Defect sketch, not a fluorite plane

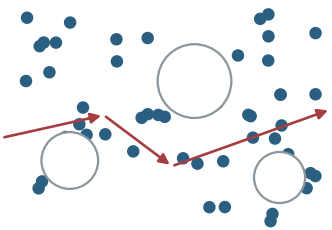
Pores change both inventory and heat transport

- Pores reduce heavy-metal mass per pellet volume.
- They interrupt heat-flow paths.
- Their size and connectivity influence later densification and gas behavior.

A design balance

Specify density together with pore distribution and grain size.

Pores interrupt heat-transport paths



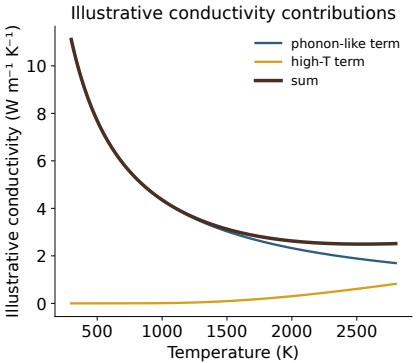
Schematic; no pore-size scale

Heat transport in UO_2 changes with temperature

- Phonon scattering strongly affects the lower-temperature contribution.
- Higher-temperature contributions can alter the trend.
- Defects, porosity and irradiation shift the conductivity.

Plot interpretation

The curve illustrates competing terms. It is not a UO_2 property correlation.



Use property values with their conditions

Property value needs	Example of the missing condition
Temperature	Conductivity at room temperature is insufficient
Composition	O/U ratio, dopants and fuel mixture
Density / microstructure	Pores, grains and cracks
Irradiation history	Burnup and defect accumulation
Model validity range	Do not extrapolate through a phase change

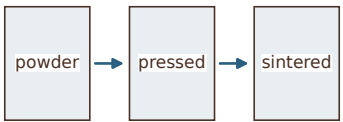
An unqualified single number can give a misleading ranking.

Fabrication establishes the initial material state

- Condition powder and form a green body.
- Sinter to develop density and grain structure.
- Finish dimensions and inspect.
- Load and seal the qualified fuel form.

Each stage helps set the initial pores, grain size and chemistry.

Processing sets pores, grain size and chemistry



Then finish dimensions and inspect

Initial inspection links processing to performance

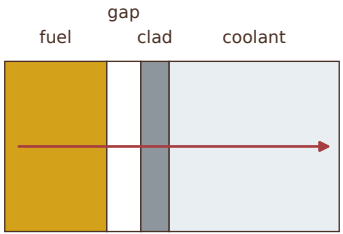
Measure	Performance connection
Pellet dimensions and surface quality	Initial gap and local contact
Density and pore distribution	Heat transport and densification
Grain size	Diffusion distance and gas behavior
Composition and impurities	Defects, phases and compatibility
Rod integrity	Containment and dimensional control

Start thermal analysis with the heat path

- Heat is generated inside the pellet.
- It conducts toward the outer surface.
- It then crosses the gap, cladding and coolant film.

Four distinct drops

A fuel-centre calculation requires the boundary temperature or all the outer resistances.



Heat flow across the rod wall

Three heat-generation quantities

Symbol	Meaning	Units
q'''	Power per fuel volume	$\mathrm{W/m^3}$
q'	Power per rod length	$\mathrm{W/m}$
$q''(r)$	Outward power per cylindrical area	$\mathrm{W/m^2}$

$$q' = \pi R^2 q'''$$

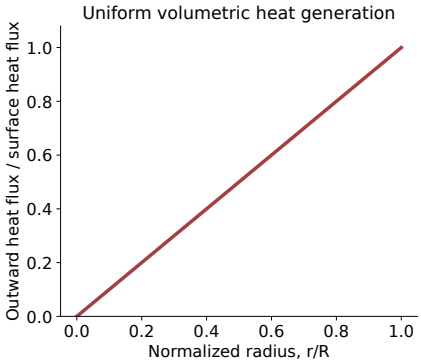
R: pellet radius. This relation assumes uniform volumetric heating.

The centre is hottest even though its radial flux is zero

$$q''(r) = \frac{q'''r}{2}$$

- At the centre, symmetry gives no preferred radial direction.
- More heat is enclosed as radius increases.
- All generated heat crosses the pellet surface.

The heat flux rises linearly for uniform volumetric heating.

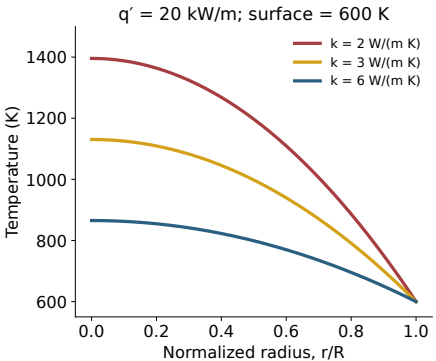


The simple cylindrical temperature profile

$$T(r) - T_s = \frac{q'}{4\pi k}\left(1 - \frac{r^2}{R^2}\right)$$

- T_s: pellet surface temperature; k: conductivity.
- r: radial position; R: pellet radius.
- Steady state, uniform heating, constant k, no axial heat flow.

This is the temperature drop within the fuel only.

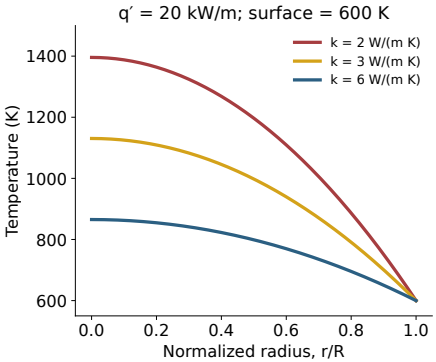


Read the radial temperature curves

- All curves use the same linear power and surface temperature.
- Lower conductivity gives a larger internal temperature rise.
- The slope is zero at the centre and steepest at the surface.

Do not confuse boundaries

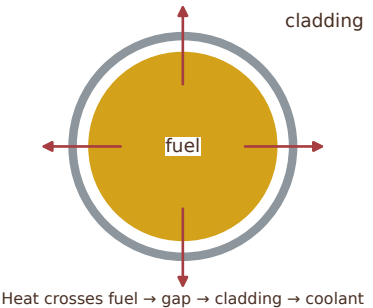
The common 600 K value is the assumed fuel surface, not automatically the coolant temperature.



Worked example: centre-to-surface rise

Question

Use $q' = 20$ kW/m and $k = 3$ W m^{-1} K^{-1}.
Find $T_c - T_s$.

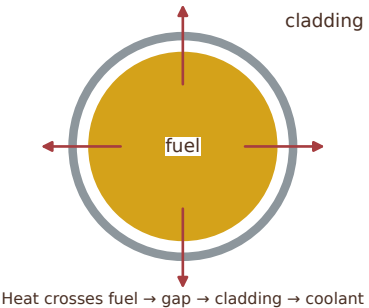


Worked example: centre-to-surface rise

Question

Use $q' = 20$ kW/m and $k = 3$ W m^{-1} K^{-1}. Find $T_c - T_s$.

$$T_c - T_s = \frac{20{,}000}{4\pi(3)}$$



Worked example: centre-to-surface rise

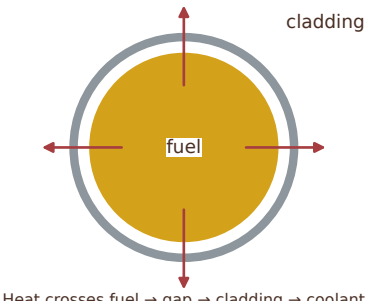
Question

Use $q' = 20$ kW/m and $k = 3$ W m^{-1} K^{-1}. Find $T_c - T_s$.

$$T_c - T_s = \frac{20{,}000}{4\pi(3)}$$

Answer

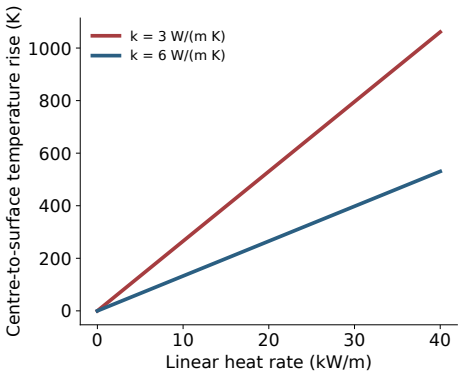
$T_c - T_s \approx 531$ K. If $T_s = 600$ K, then $T_c \approx 1131$ K.



What happens if conductivity doubles?

Question

At the same q' and T_s, conductivity changes from 3 to 6 W m^{-1} K^{-1}. What changes?

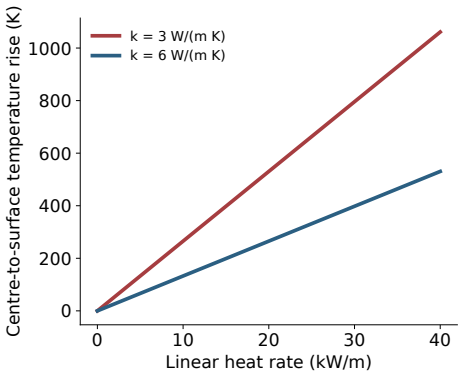


What happens if conductivity doubles?

Question

At the same q' and T_s, conductivity changes from 3 to 6 W m^{-1} K^{-1}. What changes?

$$T_c - T_s \propto 1/k$$



What happens if conductivity doubles?

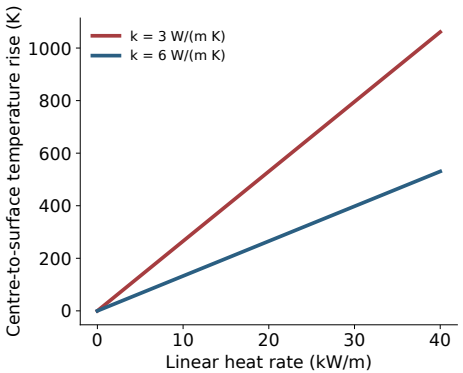
Question

At the same q' and T_s, conductivity changes from 3 to 6 W m^{-1} K^{-1}. What changes?

$$T_c - T_s \propto 1/k$$

Answer

The internal rise halves, from about 531 to 265 K. The absolute centre temperature does not halve.



Why did pellet radius disappear from the centre-rise equation?

Question

Does $T_c - T_s = q'/(4\pi k)$ mean pellet size never matters?

Why did pellet radius disappear from the centre-rise equation?

Question

Does $T_c - T_s = q'/(4\pi k)$ mean pellet size never matters?

$$q' = \pi R^2 q'''$$

Why did pellet radius disappear from the centre-rise equation?

Question

Does $T_c - T_s = q'/(4\pi k)$ mean pellet size never matters?

$$q' = \pi R^2 q'''$$

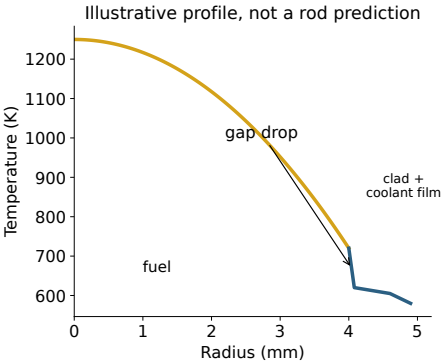
Answer

No. It is independent of radius only at fixed linear power and the stated assumptions. At fixed volumetric heating, $T_c - T_s = q''' R^2/(4k)$.

Temperature falls across the whole rod

- Fuel conduction gives the curved inner profile.
- The gap can add a substantial temperature difference.
- Cladding conduction and the coolant film add further drops.

The temperature profile is schematic.

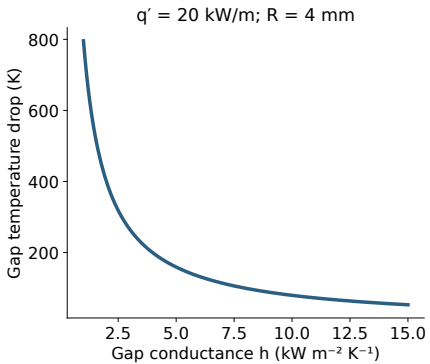


Gap conductance turns heat flux into a temperature drop

$$\Delta T_{\text{gap}} \approx \frac{q'}{2\pi R h_g}$$

- h_g: effective gap conductance, W m^{-2} K^{-1}.
- Gap size, gas composition, pressure and contact matter.
- Radiation and solid contact may also contribute.

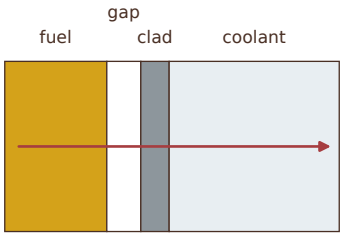
This formula uses a thin-gap area approximation.



Worked example: gap temperature drop

Question

Assume $q' = 20$ kW/m, $R = 4$ mm and $h_g = 5000$ W m^{-2} K^{-1}. Find ΔT_{gap}.



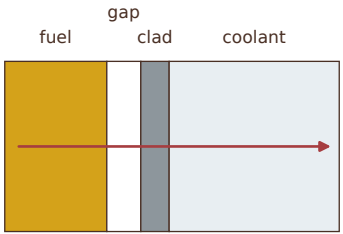
Heat flow across the rod wall

Worked example: gap temperature drop

Question

Assume $q' = 20$ kW/m, $R = 4$ mm and $h_g = 5000$ W m^{-2} K^{-1}. Find ΔT_{gap}.

$$\Delta T_{\text{gap}} = \frac{20{,}000}{2\pi(0.004)(5000)}$$



Heat flow across the rod wall

Worked example: gap temperature drop

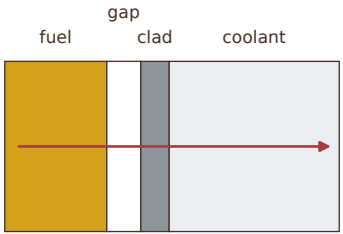
Question

Assume $q' = 20$ kW/m, $R = 4$ mm and $h_g = 5000$ W m^{-2} K^{-1}. Find ΔT_{gap}.

$$\Delta T_{\text{gap}} = \frac{20{,}000}{2\pi(0.004)(5000)}$$

Answer

$\Delta T_{\text{gap}} \approx 159$ K. Doubling h_g halves this drop under the same assumptions.



Heat flow across the rod wall

Add temperature drops from coolant to centre

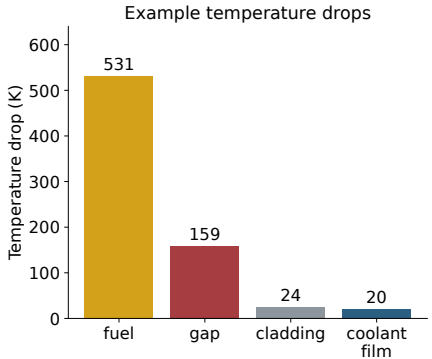
$$T_c = T_\infty + \Delta T_{\text{film}} + \Delta T_{\text{clad}} + \Delta T_{\text{gap}} + \Delta T_{\text{fuel}}$$

Example

$T_\infty = 580$ K; drops: 20 K, 24 K, 159 K and 531 K.

$$T_c \approx 1314 \text{ K}$$

T_∞: bulk coolant temperature. The backup gives the full parameter set.

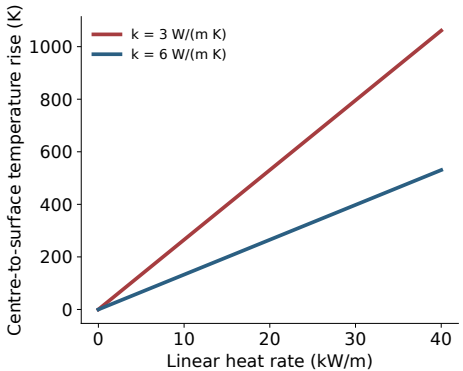


Thermal margin is more than the melting temperature

- Estimate the operating temperature with condition-dependent properties.
- Compare it with the relevant phase or degradation limits.
- Include uncertainties and changes during irradiation.

A fair comparison

A higher melting temperature alone does not establish a larger operating margin.



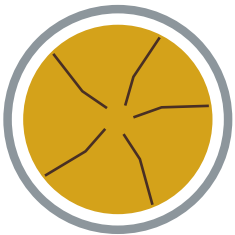
Thermal gradients create mechanical mismatch

$$\epsilon_{\text{th}} \approx \alpha \Delta T$$

- α: linear thermal-expansion coefficient.
- Hotter regions would expand more if unconstrained.
- Surrounding material and cladding resist that free expansion.

The strain expression is not a complete stress solution.

Thermal gradients can crack brittle fuel



Cladding can remain intact

An expansion scale estimate

Question

Assume $\alpha = 10^{-5}\ \mathrm{K}^{-1}$ and a uniform 500 K rise. What free linear strain is predicted?

An expansion scale estimate

Question

Assume $\alpha = 10^{-5}\ \mathrm{K}^{-1}$ and a uniform 500 K rise. What free linear strain is predicted?

$$\epsilon_{\mathrm{th}} = \alpha \Delta T; \qquad \Delta R = R\epsilon_{\mathrm{th}}$$

An expansion scale estimate

Question

Assume $\alpha = 10^{-5}$ K^{-1} and a uniform 500 K rise. What free linear strain is predicted?

$$\epsilon_{\text{th}} = \alpha \Delta T; \qquad \Delta R = R\epsilon_{\text{th}}$$

Answer

$\epsilon_{\text{th}} = 0.005 = 0.5\%$. A freely expanding 4 mm radius would increase by 20 μm.

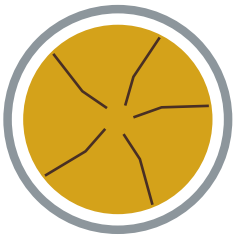
Pellet cracking and cladding failure are different

- Brittle fuel can form radial and circumferential cracks.
- Cracking redistributes stress and divides the pellet into fragments.
- The cladding may remain intact around those fragments.

Heat-transfer consequence

Cracks within fuel and changes in the outer gap affect heat flow differently.

Thermal gradients can crack brittle fuel

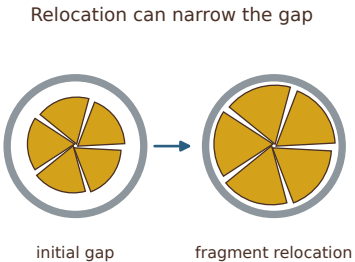


Cladding can remain intact

Relocation changes the pellet–cladding gap

- Cracked fragments can move outward.
- The effective gap can shrink, increasing gap conductance.
- Fragment geometry can also produce uneven contact stresses.

Cracking does not guarantee a lower total thermal resistance.



Densification and swelling can compete

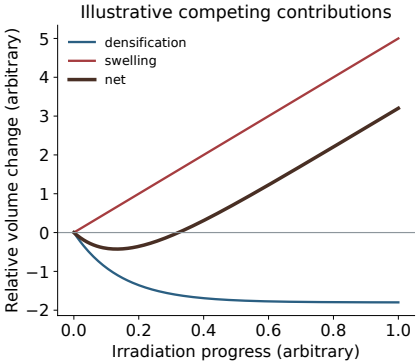
Densification

Shrinkage as some fabrication pores are removed or evolve.

Swelling

Volume increase from solid fission products and retained gas bubbles.

Net dimensions depend on the balance, together with temperature and mechanical constraint.



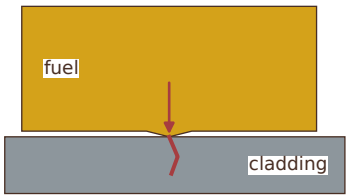
Mechanical contact is one part of PCI

- Expansion, relocation and swelling can close the gap.
- Contact loads the cladding.
- Pellet edges and cracks can produce local stress concentrations.

Terminology

PCMI emphasizes mechanical interaction; PCI can also involve chemical effects.

Local contact + tensile stress + chemistry



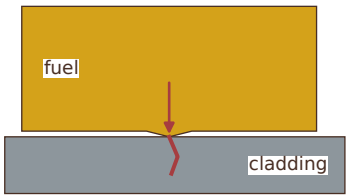
PCI schematic; not a crack-growth model

Chemical conditions can turn contact into a failure mechanism

- A susceptible cladding state, tensile stress and aggressive species can act together.
- Iodine-assisted stress corrosion is a concern in oxide-fuel systems.
- Power history changes both stress and fuel temperature.

A contact sketch alone cannot predict crack growth or failure.

Local contact + tensile stress + chemistry



PCI schematic; not a crack-growth model

Design and operating choices address different causes

Choice	Mechanism addressed
Pellet edge geometry	Reduce local loading at edges
Suitable cladding / liner	Change susceptibility and mechanical response
Power-history control	Limit rapid changes in temperature and contact
Qualified gap and dimensions	Manage thermal and mechanical evolution

The appropriate combination depends on the fuel system.

Burnup measures energy extracted per initial heavy-metal mass

$$B = \frac{E_{\text{thermal}}}{m_{\text{HM},0}}$$

- $m_{\text{HM},0}$: initial heavy-metal mass, excluding oxygen or other light elements.
- Use thermal energy, not net electrical output.
- Local, rod-average and inventory-average burnup are different.

$$1 \text{ MWd/kgHM} = 1 \text{ GWd/tHM}$$

Worked burnup example

Question

A 1 tHM inventory produces 30 MW thermal for 100 effective full-power days. Find its average burnup.

Worked burnup example

Question

A 1 tHM inventory produces 30 MW thermal for 100 effective full-power days. Find its average burnup.

$$B = \frac{30(100)}{1} \text{ MWd/tHM}$$

Worked burnup example

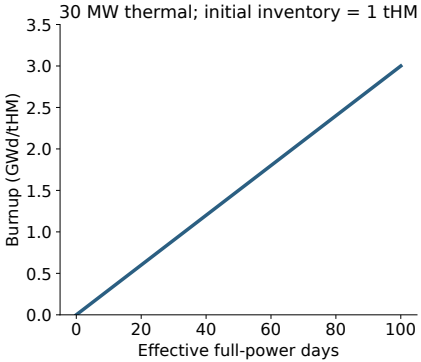
Question

A 1 tHM inventory produces 30 MW thermal for 100 effective full-power days. Find its average burnup.

$$B = \frac{30(100)}{1} \text{ MWd/tHM}$$

Answer

$B = 3000$ MWd/tHM $= 3$ GWd/tHM $= 3$ MWd/kgHM.

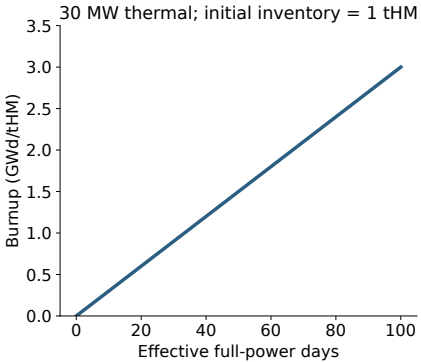


Effective full-power days account for power history

$$t_{\mathrm{EFPD}} = \frac{\int P(t)\,dt}{P_{\mathrm{reference}}}$$

- A day at half reference power counts as half an EFPD.
- An outage contributes no full-power operating time.
- Calendar time alone is insufficient for burnup.

Use the same reference power and inventory basis throughout.



FIMA counts fissions relative to initial heavy-metal atoms

$$\mathrm{FIMA} = \frac{N_{\mathrm{fission}}}{N_{\mathrm{HM},0}}$$

- Often reported as a percentage.
- It is distinct from enrichment and from dpa.
- Converting energy-based burnup requires an energy per fission and an initial atom inventory.

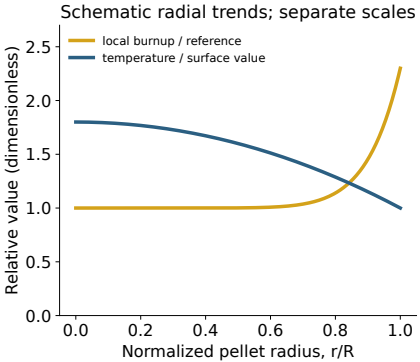
Example of the definition

5% FIMA means five fissions per 100 initial heavy-metal atoms.

Why the pellet rim can have higher local burnup

- Neutron absorption and isotope evolution vary with radius.
- In UO_2 fuel, plutonium buildup can increase rim power and burnup.
- The rim also stays cooler than the centre.

The plot shows relative trends with separate normalizations, not a measured rod profile.

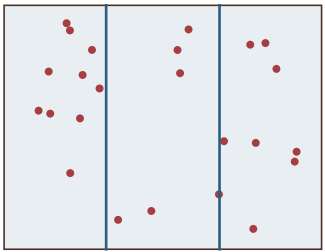


Fission creates gas as well as solid products

- Xenon and krypton are important fission gases.
- Gas can remain in the lattice or collect in bubbles.
- Solid fission products also affect swelling, phases and thermal transport.

Track an inventory

Gas production, retention and release are different quantities.

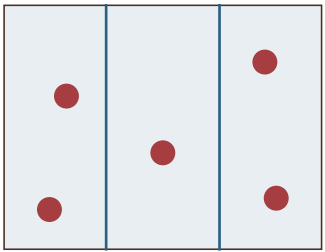


Gas atoms in the lattice

Intragranular gas: inside the grains

- Gas atoms migrate and become trapped.
- Small bubbles can form within a grain.
- Bubble populations evolve under irradiation and temperature.

Intragranular means inside a grain; intergranular means at grain boundaries.

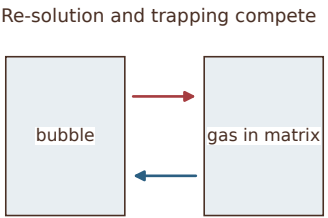


Bubbles inside grains

Trapping and re-solution compete

- Trapping transfers gas from the matrix into bubbles.
- Energetic fission fragments can return gas to solution.
- The balance affects the mobile gas population.

A pure thermal-diffusion picture is incomplete under irradiation.

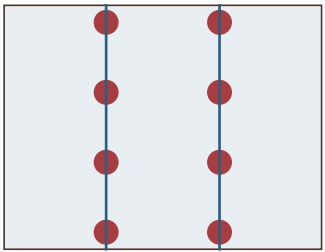


Grain boundaries collect gas

- Gas reaching a boundary can join intergranular bubbles.
- Boundary bubbles grow and can coalesce.
- An isolated boundary bubble still retains gas.

A necessary distinction

Reaching a boundary is not the same as reaching the rod plenum.

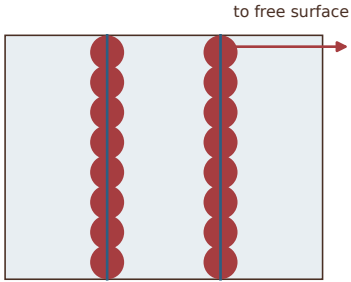


Bubbles on grain boundaries

Release requires a route to a free surface

- Boundary networks, connected pores or cracks can create pathways.
- Gas may then enter the gap and rod free volume.
- Pathway opening depends on thermal and mechanical history.

The drawing illustrates connectivity; it is not a predicted microstructure.



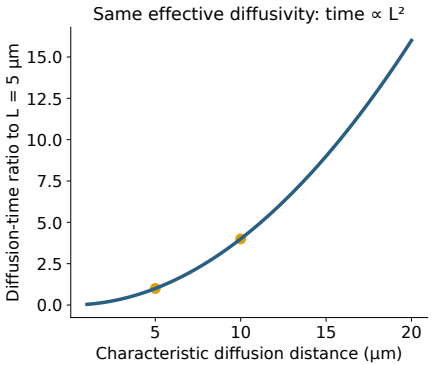
A connected release path

Grain size enters through diffusion distance

$$t_{\text{diff}} \sim \frac{L^2}{D_g}$$

- L: characteristic distance to a grain boundary.
- D_g: effective gas diffusivity.
- Larger grains increase diffusion time if all other inputs are fixed.

Trapping, irradiation and cracks can change this simple scaling.



Compare diffusion times in two grain sizes

Question

The characteristic distance grows from 5 to 10 μm at the same diffusivity. How does the diffusion time change?

Compare diffusion times in two grain sizes

Question

The characteristic distance grows from 5 to 10 μm at the same diffusivity. How does the diffusion time change?

$$\frac{t_2}{t_1} = \left(\frac{10}{5}\right)^2 = 4$$

Compare diffusion times in two grain sizes

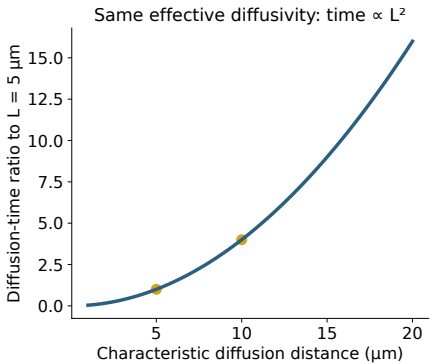
Question

The characteristic distance grows from 5 to 10 μm at the same diffusivity. How does the diffusion time change?

$$\frac{t_2}{t_1} = \left(\frac{10}{5}\right)^2 = 4$$

Answer

It increases by a factor of four. This does not mean measured release must decrease by exactly four.

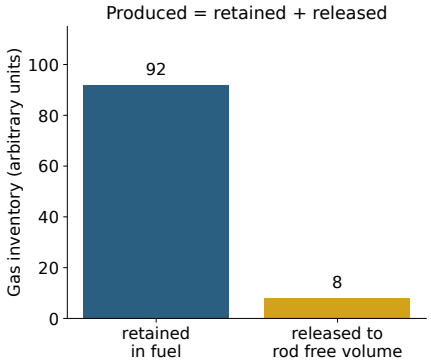


Define the fission-gas release fraction

$$F_{\mathrm{rel}} = \frac{N_{\mathrm{gas,released}}}{N_{\mathrm{gas,produced}}}$$

- Define the species and counting interval.
- For stable-gas bookkeeping, produced = retained + released.
- Radioactive species can also require decay and transmutation terms.

Release from fuel into an intact rod is not release to the environment.



Gas inventory bookkeeping

Question

An illustrative stable-gas inventory contains 100 units produced and 92 retained in fuel. What is the release fraction?

Gas inventory bookkeeping

Question

An illustrative stable-gas inventory contains 100 units produced and 92 retained in fuel. What is the release fraction?

Released = produced − retained = 8 units.

Gas inventory bookkeeping

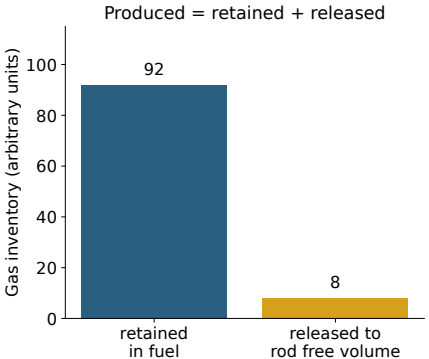
Question

An illustrative stable-gas inventory contains 100 units produced and 92 retained in fuel. What is the release fraction?

Released = produced − retained = 8 units.

Answer

$F_{\mathrm{rel}} = 8/100 = 0.08 = 8\%$. The eight units are in the rod free volume if the rod remains sealed.



Retained and released gas cause different problems

Gas location	Main consequence
Retained in bubbles	Fuel swelling and local stresses
Released into free volume	Changes gas inventory and pressure
Xe/Kr mixed into the gap gas	Can reduce conductance relative to helium-rich gas
Connected boundary porosity	Provides potential transport paths

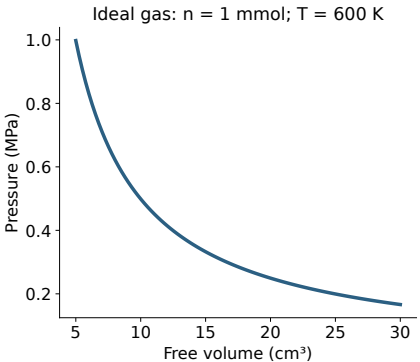
A fuel-performance model must couple these effects.

Plenum pressure: begin with a simple gas law

$$P = \frac{nR_gT_g}{V_g}$$

- n: total gas amount; $R_g = 8.314$ J mol^{-1} K^{-1}.
- T_g: absolute gas temperature; V_g: free volume.
- Include the original fill gas as well as released gas.

An actual rod has a nonuniform gas temperature and changing free volume.



Worked example: gas pressure scale

Question

Assume 1 mmol total gas at 600 K in 10 cm^3. Estimate pressure with the ideal-gas law.

Worked example: gas pressure scale

Question

Assume 1 mmol total gas at 600 K in 10 cm^3. Estimate pressure with the ideal-gas law.

$$P = \frac{(10^{-3})(8.314)(600)}{10 \times 10^{-6}}$$

Worked example: gas pressure scale

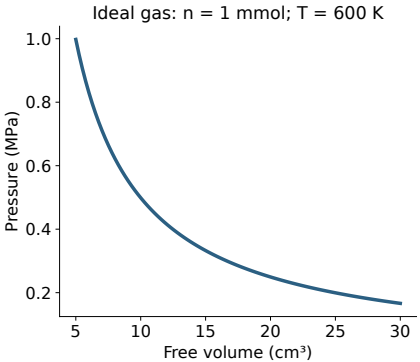
Question

Assume 1 mmol total gas at 600 K in 10 cm^3. Estimate pressure with the ideal-gas law.

$$P = \frac{(10^{-3})(8.314)(600)}{10 \times 10^{-6}}$$

Answer

$P \approx 4.99 \times 10^5$ Pa $= 0.499$ MPa.

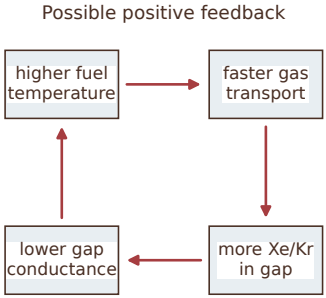


Gas behavior can feed back into temperature

- Higher temperature often increases gas transport.
- Released Xe/Kr can lower gap gas conductivity relative to He.
- Lower gap conductance can raise fuel temperature.

A coupled response

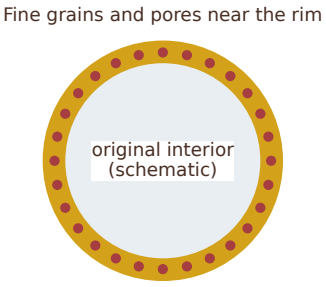
Other changes, especially gap closure, may counteract this feedback.



High-burnup structure changes the pellet rim

- Original grains subdivide into much finer structures.
- Gas redistributes into a changed pore population.
- High local burnup and relatively low local temperature favor the rim structure.

There is no universal single burnup threshold for every fuel and history.



Recognize the HBS microstructural changes

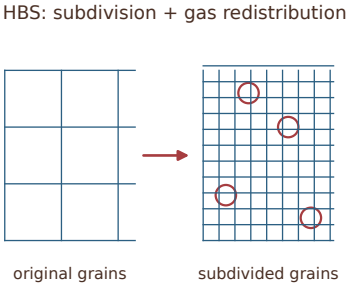
Before

Larger original grains and fabrication porosity.

After restructuring

Fine subdivisions with a redistributed gas and pore population.

Grain subdivision and pore formation change the local mechanical and thermal response.

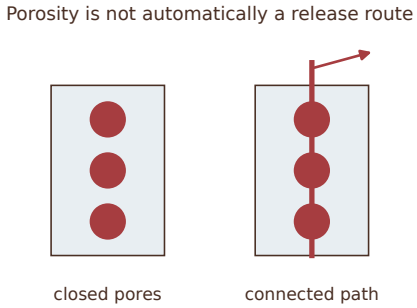


Closed rim pores can retain gas

- A pore can store gas while remaining isolated.
- Connectivity changes the ability to release that gas.
- Heating and mechanical changes can alter the pathways.

Useful question

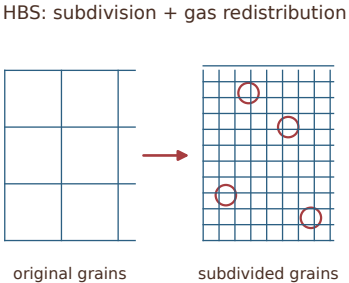
> Is the gas merely at a boundary, or does it have a connected route out?



HBS affects more than gas release

- Pores, subdivisions and defects change thermal transport.
- Swelling and mechanical response change with structure.
- Transient fragmentation and release depend on the pre-existing state.

Do not assign one universal beneficial or harmful effect to the entire rim structure.



Fragmentation and dispersal are separate events

Fragmentation

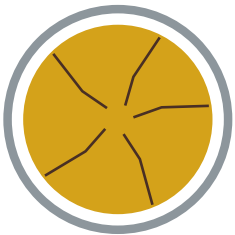
> Fuel breaks into smaller pieces under a given transient.

Dispersal

> Fragments leave their original containment region through a release path.

Fragmentation alone does not establish how much material escapes; cladding condition and flow also matter.

Thermal gradients can crack brittle fuel



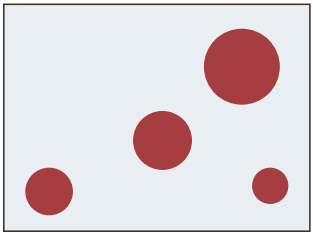
Cladding can remain intact

MOX changes the actinide mixture in an oxide matrix

- Mixed oxide commonly combines UO_2 and PuO_2.
- The matrix is related to the fluorite structure.
- Composition, porosity and oxygen content influence properties.
- Using recovered plutonium is one fuel-cycle motivation.

Fuel-cycle benefits depend on the full system and accounting basis.

Illustrative Pu-rich regions in an oxide matrix



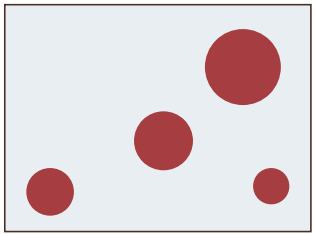
Fabrication controls the spatial distribution

MOX heterogeneity matters locally

- Pu-rich regions can have different local fission rates.
- Gas generation and burnup can vary within the pellet.
- The fabrication route controls the composition distribution.

The sketch illustrates heterogeneity; it does not predict isolated thermal spikes.

Illustrative Pu-rich regions in an oxide matrix



Fabrication controls the spatial distribution

Compare MOX with UO_2 at matched conditions

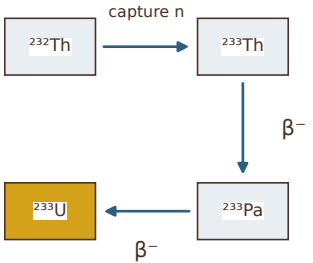
Match or state	Why
Temperature and density	Separate composition effects from thermal / pore effects
Pu fraction and distribution	Set local inventory and irradiation response
Oxygen stoichiometry	Affects defects and chemical potential
Power and burnup history	Controls microstructure and gas transport

A single MOX conductivity or release factor is not universal.

Thorium is fertile and needs a fissile driver

- ^{232}Th can capture a neutron and eventually produce fissile ^{233}U.
- Two beta decays connect the capture product to uranium.
- An initial fissile inventory is still required.

The diagram shows the breeding route conceptually, not a fuel-cycle design.



ThO_2 offers a different property and fuel-cycle balance

- It has the fluorite structure and high thermal stability.
- Mixed fuels and irradiation conditions alter its properties.
- Fabrication, handling and fuel-cycle infrastructure affect practicality.

Fuel-cycle considerations

Thorium fuel is not automatically waste-free or free of proliferation concerns.

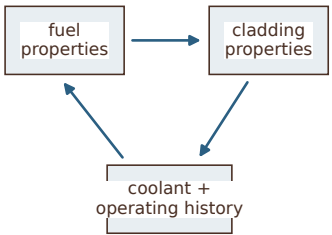
Alternative fuels target several limitations at once

- Higher conductivity can reduce the internal temperature gradient.
- Higher heavy-metal density can change the inventory per volume.
- Chemistry, swelling and phase stability can introduce new limits.

Comparison rule

Compare complete fuel–cladding–coolant combinations.

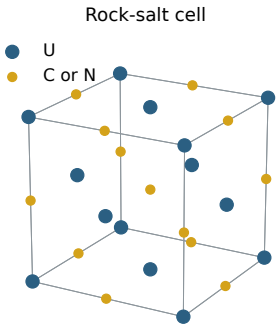
Qualification evaluates the coupled system



UC and UN have the rock-salt structure

- The U sublattice is FCC.
- C or N occupies the octahedral sublattice.
- Each species has six nearest neighbours of the other species.

Compare this with the 8:4 coordination of fluorite UO_2.



Uranium carbide: conductivity and chemistry

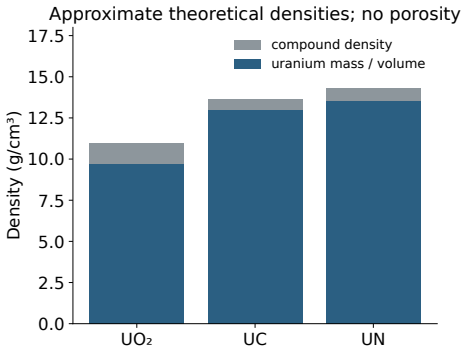
Attraction

High uranium density and useful thermal conductivity.

Challenges

Carbon balance, phase constitution, irradiation response and chemical compatibility.

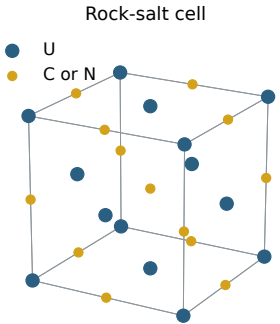
Water contact and oxidation require specific assessment; conductivity alone does not settle suitability.



Uranium nitride: another dense ceramic option

- High uranium density and conductivity motivate interest.
- Nitrogen stoichiometry and high-temperature stability matter.
- Reactivity with surrounding materials must be evaluated.

UN performance depends on temperature, environment, fuel form and cladding integrity.



The nitrogen isotope also enters the materials decision

$$^{14}\mathrm{N}(n,p)^{14}\mathrm{C}$$

- This reaction absorbs a neutron and produces carbon-14.
- Using nitrogen enriched in ^{15}N can reduce this contribution.
- Isotope supply and cost become part of the comparison.

The need and specification depend on the reactor and fuel-cycle design.

Compare ceramic fuels at matched conditions

Fuel	Main attraction	Key constraint
UO_2	Oxide-fuel experience	Low conductivity; evolving gas and cracks
UC	Density and conductivity	Composition and chemical compatibility
UN	Density and conductivity	Nitrogen reactions and compatibility
ThO_2	Thermal / chemical stability	Fissile driver and fuel-cycle infrastructure

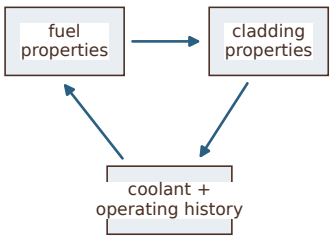
Property values must refer to comparable temperature, density and irradiation state.

Does higher conductivity prove a better fuel?

Question

Fuel A has twice the conductivity of fuel B. Is A automatically the better choice?

Qualification evaluates the coupled system



Does higher conductivity prove a better fuel?

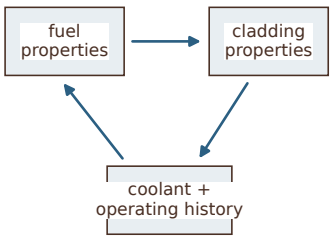
Question

Fuel A has twice the conductivity of fuel B. Is A automatically the better choice?

Answer

No. It reduces one thermal resistance under matched conditions. Phase limits, swelling, gas retention, chemistry and qualification still matter.

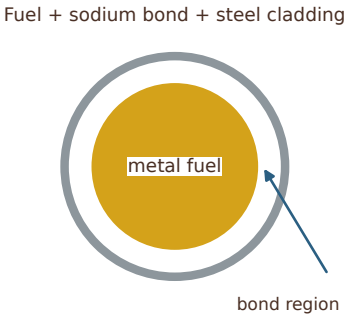
Qualification evaluates the coupled system



Metallic fuels use alloy design as a control

- Examples include U–Zr and U–Pu–Zr.
- Alloying changes phase stability and properties.
- High conductivity reduces internal gradients.
- Swelling and fuel–cladding chemical interaction require accommodation.

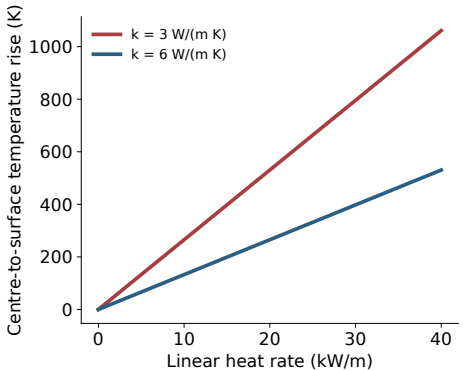
Melting and phase limits are composition dependent.



Metallic fuel temperature and phase margin must be compared together

- A smaller temperature rise is attractive.
- A metallic alloy can also have a lower solidus than oxide fuel.
- Compare the actual operating temperature with the relevant alloy limits.

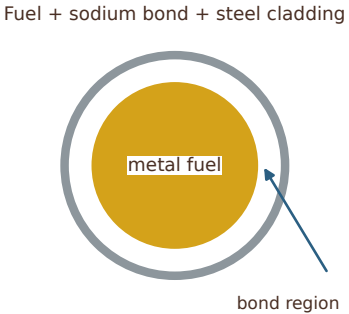
High conductivity does not by itself determine transient performance.



The sodium bond transfers heat across an initial gap

- In suitable metallic-fuel designs, sodium occupies the bond region.
- The bond improves heat transfer relative to a poorly conducting gas gap.
- Fuel swelling changes this geometry during irradiation.

The bond material, cladding and coolant must be compatible with the design.

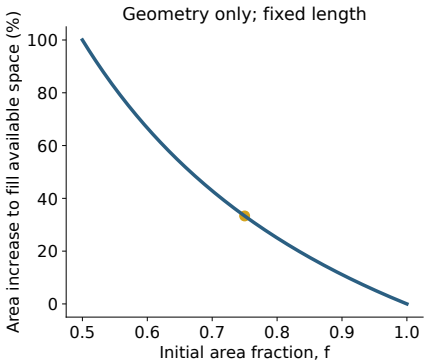


Smear density describes initial fuel loading

$$f_A = \frac{A_{\text{fuel}}}{A_{\text{clad,inside}}}$$

- For a dense circular slug, this area ratio describes geometric loading.
- Space outside the slug accommodates dimensional change.
- If the slug itself is porous, density-based smear includes that porosity.

State the convention and initial fuel density.



A 75% loading leaves how much expansion space?

Question

A dense slug occupies 75% of the available internal area. At fixed length, what relative area increase would fill it?

A 75% loading leaves how much expansion space?

Question

A dense slug occupies 75% of the available internal area. At fixed length, what relative area increase would fill it?

$$A_{\text{available}} = A_0 / f_A$$

A 75% loading leaves how much expansion space?

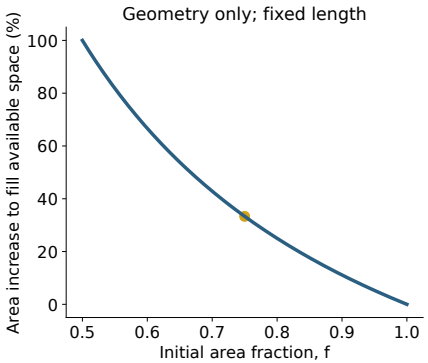
Question

A dense slug occupies 75% of the available internal area. At fixed length, what relative area increase would fill it?

$$A_{\text{available}} = A_0 / f_A$$

Answer

$\Delta A/A_0 = 1/0.75 - 1 = 0.333$, or 33.3%. This is a geometric capacity, not a swelling limit.

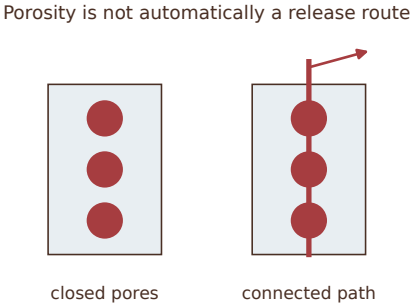


Metallic fuel swelling can create connected porosity

- Fission gas contributes to swelling.
- Bubbles can interconnect and release gas to free volume.
- Contact, axial motion and constraint change the later response.

No universal plateau

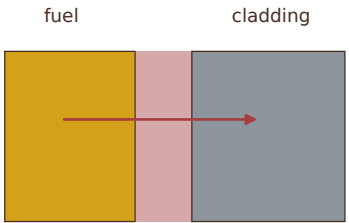
A single 30% saturation curve is not valid for all alloys and histories.



Fuel–cladding chemical interaction consumes margin

- Fuel species and fission products can react with cladding.
- Interdiffusion changes local composition and properties.
- Lanthanide fission products are important in metallic-fuel FCCI.

Interaction layers, barriers and temperature limits must be evaluated for the chosen pair.



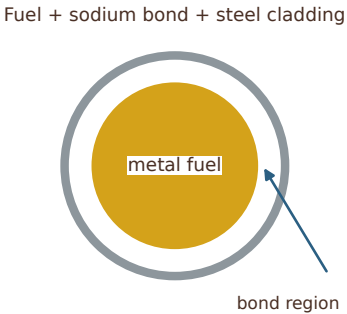
Interdiffusion / reaction zone consumes margin

Constituent redistribution changes the alloy locally

- Temperature and chemical-potential gradients can redistribute alloy constituents.
- Local phases and solidus temperatures can change.
- A uniform starting composition need not remain uniform.

Modeling implication

Track spatial composition as well as temperature and burnup.

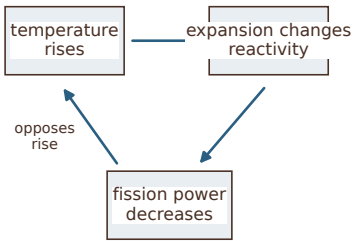


EBR-II demonstrated a system response

- The 1986 tests examined loss-of-flow and loss-of-heat-sink conditions without normal scram action.
- Negative reactivity feedback and heat removal limited the response.
- Metallic fuel was part of the tested reactor configuration.

The demonstration is not a guarantee for every reactor that uses metallic fuel.

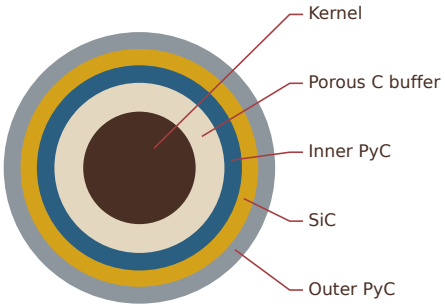
Negative feedback in the tested reactor system



TRISO puts barriers around each small kernel

- A fuel kernel generates heat and fission products.
- A porous buffer surrounds it.
- Dense pyrocarbon and SiC layers provide additional functions.

TRISO: tristructural isotropic. The layer drawing is not to scale.



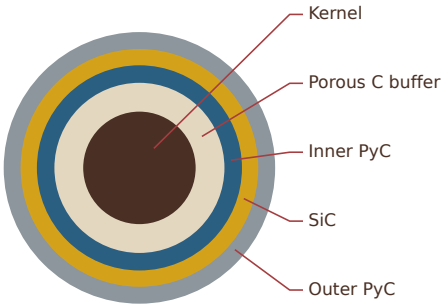
Read the TRISO layers from inside outward

Layer	Main role
Kernel	Fuel inventory and heat generation
Porous carbon buffer	Space for swelling and gas; recoil accommodation
Inner pyrocarbon (IPyC)	Support / gas barrier and interface functions
Silicon carbide (SiC)	Structural and fission-product barrier
Outer pyrocarbon (OPyC)	Support and protection of the coated particle

The buffer makes space for internal change

- The kernel swells and releases gas internally.
- The porous buffer provides accommodation volume.
- Its evolution changes how load reaches outer layers.

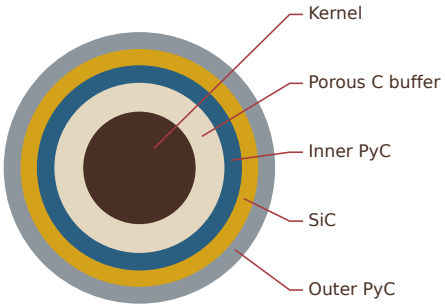
An intact outer coating system can retain products that leave the kernel.



SiC provides strength and a transport barrier

- The layer carries mechanical load as internal conditions evolve.
- Transport differs among fission-product species.
- Coating microstructure, defects and chemical attack affect retention.

An important barrier is not an absolute barrier under every condition.

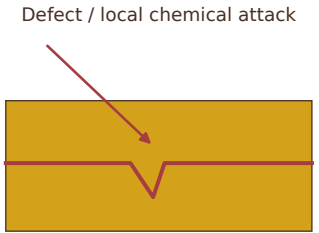


Layer thicknesses not to scale

Pyrocarbon layers affect stress as well as transport

- Their dimensional response under irradiation changes coating stresses.
- Anisotropy and defects influence performance.
- Interfaces can debond or crack and alter load transfer.

Coating quality is a materials variable, not just a layer count.

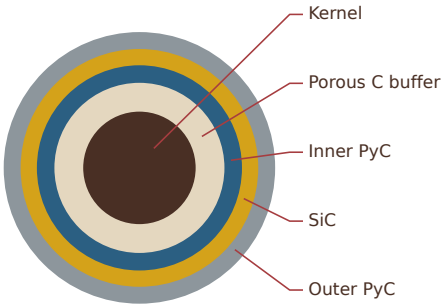


Coating integrity and species transport both matter

Kernel composition affects internal chemistry

- UO_2 and UCO are examples of kernel compositions.
- UCO includes oxide and carbide phases that alter oxygen and carbon chemistry.
- Gas chemistry and kernel evolution affect coating loads.

A kernel composition must be assessed together with its coatings and irradiation history.



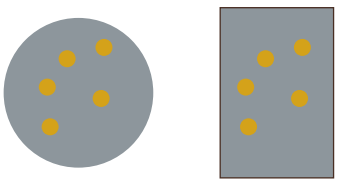
Layer thicknesses not to scale

Coated particles become larger fuel elements

- Particles can be embedded in graphite-based pebbles or compacts.
- The surrounding matrix conducts heat and supports the particles.
- Coolant channels and element geometry set the larger heat-removal problem.

The particle barrier and reactor cooling system do different jobs.

Coated particles embedded in a matrix



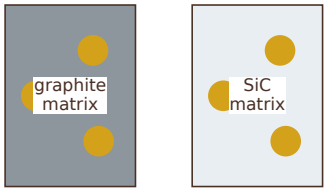
pebble compact

A ceramic matrix is another design choice

- Fully ceramic microencapsulated concepts place coated particles in a ceramic matrix, such as SiC.
- The matrix changes heat flow, mechanics and manufacturing requirements.
- Particle and matrix damage must both be characterized.

Matrix properties and particle loading affect the overall fuel response.

Matrix choice changes heat flow and mechanics



TRISO coating layers remain separate barriers

Distinguish coating failure from species release

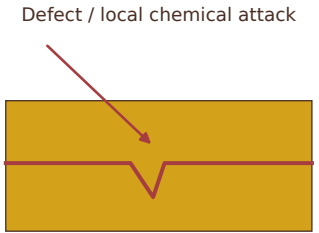
Coating failure fraction

Fraction of particles meeting a defined structural-failure criterion.

Release fraction

Fraction of a specified inventory transported outside a stated boundary.

Some species, including silver in studied TRISO systems, can migrate through nominally intact coatings.

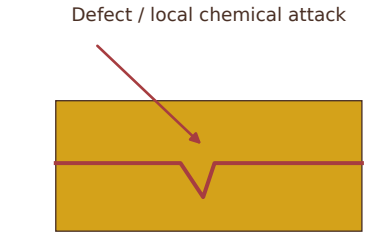


Coating integrity and species transport both matter

Why is a tiny failure fraction not the whole result?

Question

A test reports very few failed particles. Can we conclude that every fission product was fully retained?



Coating integrity and species transport both matter

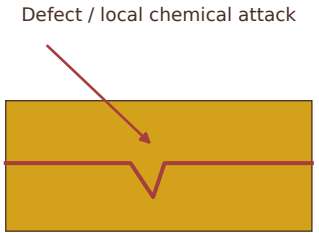
Why is a tiny failure fraction not the whole result?

Question

A test reports very few failed particles. Can we conclude that every fission product was fully retained?

Answer

No. Failure and species-specific transport are different observables. Temperature, time and the release boundary must be stated.

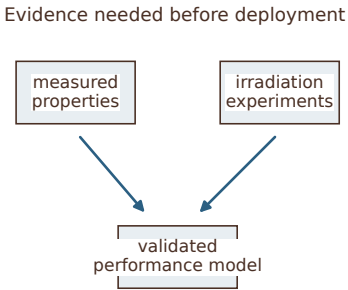


Coating integrity and species transport both matter

TRISO qualification needs a defined test envelope

- Kernel and coating properties must meet controlled specifications.
- Irradiation tests span relevant burnup, temperature and fluence.
- Post-irradiation heating tests measure retention and failure behavior.

A single temperature or failure number cannot represent every particle design.

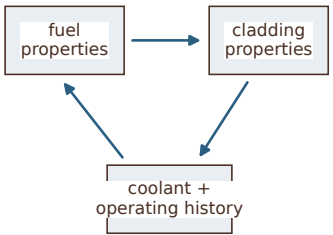


Accident tolerance is a property of the fuel system

- The goal is improved response in specified accident conditions.
- Normal-operation performance must also remain acceptable.
- Fuel, cladding, chemistry and cooling remain coupled.

Accident tolerant does not mean accident proof.

Qualification evaluates the coupled system

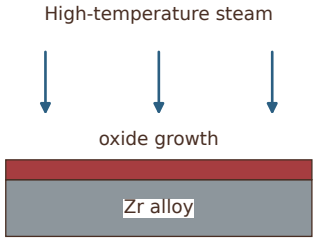


Why high-temperature zirconium–steam reaction matters

$$Zr + 2H_2O \longrightarrow ZrO_2 + 2H_2$$

- The reaction produces hydrogen and releases heat.
- Oxidation changes cladding thickness, chemistry and mechanical response.
- The rate depends strongly on temperature and condition.

The equation gives stoichiometry; it does not give the reaction rate.



Oxidation releases heat and hydrogen

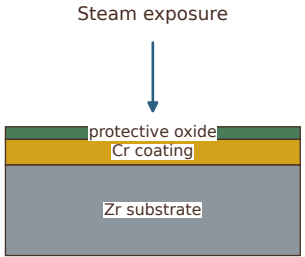
ATF concepts change different parts of the rod

Approach	**Examples**	**Material question**
Coating	Cr on Zr alloy	Can the coating remain protective?
Alternative cladding	FeCrAl; SiC/SiC	What are the new mechanical and chemical limits?
Modified oxide pellet	Doped UO_2	How do grains, creep and gas behavior change?
Alternative fuel	UN; U_3Si_2	Are thermal benefits retained under irradiation?

Cr coatings modify the cladding surface

- A protective surface layer can reduce oxidation in relevant conditions.
- The Zr alloy remains the main substrate.
- Adhesion, cracking, wear and interdiffusion affect protection.

The coating must work through the relevant temperature and deformation history.



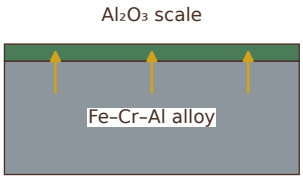
Coating adhesion and continuity matter

FeCrAl uses a protective alumina scale

- Al supply supports formation of an alumina barrier.
- Scale growth can be much slower than unprotected reaction.
- Alloy composition and thermal history determine whether protection persists.

Neutron absorption, strength, irradiation response and tube design also enter the assessment.

Al supply helps sustain the protective scale

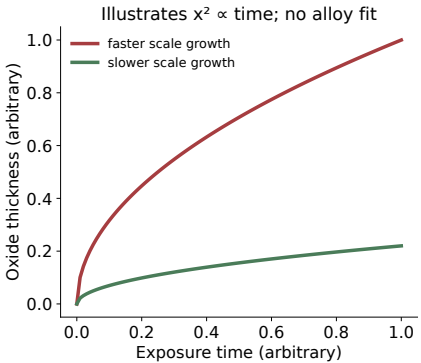


Oxidation resistance is kinetic, not a yes/no label

$$x^2 \approx k_p t$$

- x: scale thickness; k_p: parabolic rate coefficient.
- This describes one ideal diffusion-controlled regime.
- Cracking, scale loss or composition changes can break the assumption.

The curves are illustrative, with no alloy-specific rate constants.

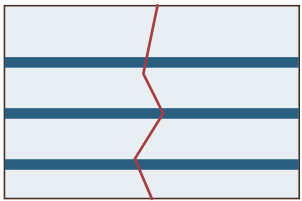


SiC/SiC combines fibres and a ceramic matrix

- Fibres and interfaces can deflect or bridge cracks.
- Composite strength and conductivity can be direction dependent.
- Gas tightness, joining, irradiation and coolant compatibility remain separate questions.

Toughness does not automatically provide a hermetic tube.

Fibres bridge and deflect cracks

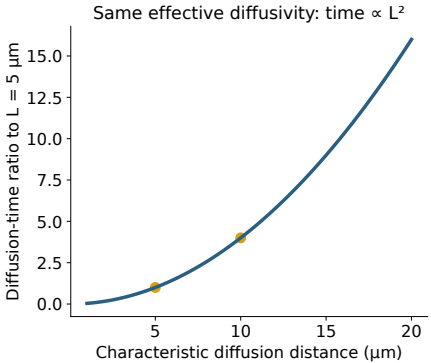


Toughness does not by itself ensure gas tightness

Doped oxide fuel changes the microstructure

- Small additions can change grain growth during fabrication.
- Larger grains change gas-diffusion distances.
- Creep, defects and thermal properties may also change.

Benefits must be demonstrated for the specific dopant and fabrication route.

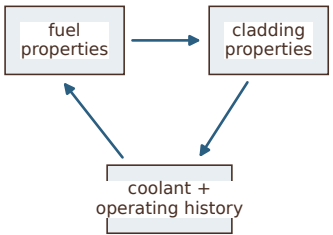


U_3Si_2: thermal benefits do not settle compatibility

- Higher uranium density and conductivity motivate interest.
- Swelling, phase changes and chemical compatibility must be assessed.
- Water and steam studies show that reaction behavior needs specific attention.

Dispersion-fuel experience does not automatically qualify a monolithic LWR pellet.

Qualification evaluates the coupled system



Compare cladding concepts by the limiting mechanism

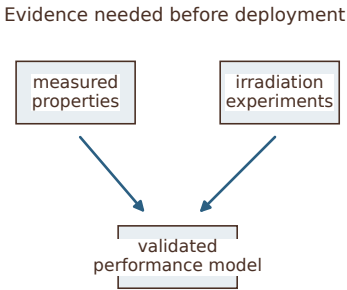
Concept	Main opportunity	Question that remains
Cr-coated Zr	Surface oxidation resistance	Will the coating survive strain and exposure?
FeCrAl	Alumina-forming protection	What are the neutron and mechanical trade-offs?
SiC/SiC	High-temperature ceramic system	Can the tube and joints remain gas tight?

No material can be selected from an oxidation curve alone.

Fuel qualification links measurements, tests and models

- Measure properties and mechanism-specific behavior.
- Test under relevant irradiation conditions.
- Examine fuel after irradiation and during selected transients.
- Validate models against independent measurements.

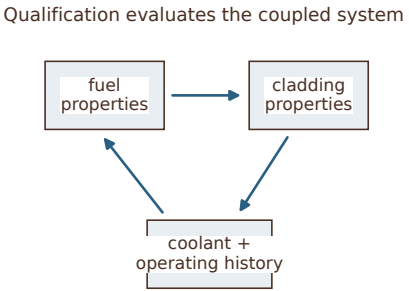
The test conditions must cover the intended operating range.



Selection exercise: a water-cooled fuel system

Question

A new dense ceramic lowers the calculated centre temperature. What evidence is still needed before replacing UO_2?



Selection exercise: a water-cooled fuel system

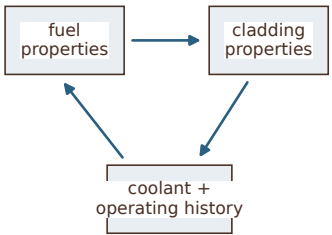
Question

A new dense ceramic lowers the calculated centre temperature. What evidence is still needed before replacing UO_2?

Answer

Compatibility after cladding breach, swelling and gas behavior, phase stability, fabrication consistency, and irradiation / transient evidence.

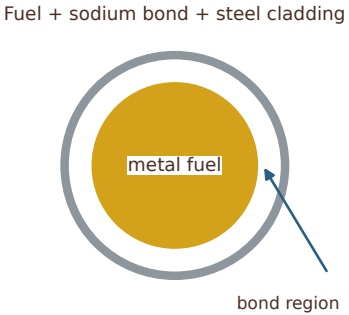
Qualification evaluates the coupled system



Selection exercise: a metallic-fuel pin

Question

Why combine high-conductivity fuel with a bond region and substantial swelling space?



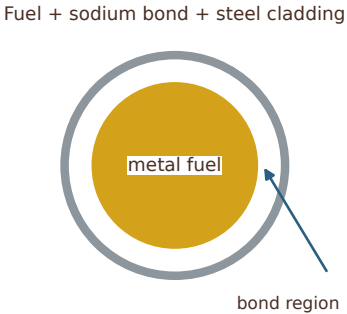
Selection exercise: a metallic-fuel pin

Question

Why combine high-conductivity fuel with a bond region and substantial swelling space?

Answer

The bond transfers heat across the initial separation; free space accommodates dimensional change. Chemical interaction and gas pressure still need assessment.



Integrated practice: temperature and release

Given

$q' = 24$ kW/m, $k = 4$ W m^{-1} K^{-1}, $T_s = 700$ K. Separately, 200 units of stable fission gas are produced and 190 remain in fuel.

Find

The centre temperature and the gas release fraction.

Integrated practice: temperature and release

Given

$q' = 24$ kW/m, $k = 4$ W m^{-1} K^{-1}, $T_s = 700$ K. Separately, 200 units of stable fission gas are produced and 190 remain in fuel.

Find

The centre temperature and the gas release fraction.

$$T_c = 700 + \frac{24{,}000}{4\pi(4)} \approx 1177 \text{ K}$$

Integrated practice: temperature and release

Given

$q' = 24$ kW/m, $k = 4$ W m^{-1} K^{-1}, $T_s = 700$ K. Separately, 200 units of stable fission gas are produced and 190 remain in fuel.

Find

The centre temperature and the gas release fraction.

$$T_c = 700 + \frac{24{,}000}{4\pi(4)} \approx 1177 \text{ K}$$

Gas answer

$F_{\text{rel}} = (200 - 190)/200 = 0.05 = 5\%$. This does not specify release outside an intact rod.

Fuel Performance Assessment

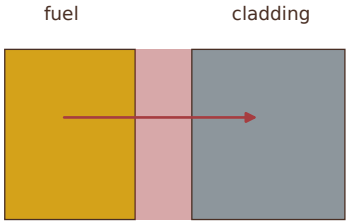
Question	Main quantities
Where is the heat generated and removed?	q', k, gap and coolant conductance
How does the fuel change shape?	Expansion, cracking, densification and swelling
Where are the fission products?	Lattice, bubbles, boundaries and free volume
Which barrier or interface limits performance?	Fuel, coating, cladding, matrix and coolant

Connect Unit 6 to corrosion and compatibility

- Temperature and irradiation change the material state.
- Chemical potential and transport drive interface reactions.
- Protective scales work only while they remain effective.

Carry into Unit 7

Evaluate reaction kinetics, environment and stress together.



Interdiffusion / reaction zone consumes margin

Optional backup: derive the pellet temperature profile

$$\frac{1}{r}\frac{d}{dr}\left(rk\frac{dT}{dr}\right) + q''' = 0$$

For constant k, symmetry requires $dT/dr = 0$ at $r = 0$; set $T(R) = T_s$.

$$\frac{dT}{dr} = -\frac{q'''r}{2k}, \qquad T(r) - T_s = \frac{q'''}{4k}(R^2 - r^2)$$

$$q' = \pi R^2 q''' \;\Rightarrow\; T_c - T_s = \frac{q'}{4\pi k}$$

Assumptions: steady radial conduction in a long solid cylinder; uniform source.

Optional backup: temperature-dependent conductivity

$$\int_{T_s}^{T_c} k(T)\, dT = \frac{q'}{4\pi}$$

- The heat equation can be integrated without forcing one constant conductivity.
- Use a correlation valid for the fuel state and temperature interval.
- Solve for T_c with the stated surface temperature.

Uniform heating, steady radial conduction and a solid cylinder are still assumed.

Optional backup: the outer thermal resistances

$$\Delta T_{\text{clad}} = \frac{q'}{2\pi k_c} \ln \frac{r_o}{r_i}, \qquad \Delta T_{\text{film}} = \frac{q'}{2\pi r_o h_c}$$

- r_i, r_o: inner and outer cladding radii; k_c: cladding conductivity.
- h_c: coolant-film coefficient.
- Constant cladding conductivity and steady cylindrical conduction.

Parameter set for the 1314 K example

$q' = 20$ kW/m; $R = 4$ mm; $h_g = 5000$ W m^{-2}K^{-1}; $k = 3$ W m^{-1}K^{-1}; $r_i = 4.1$ mm; $r_o = 4.6$ mm; $k_c = 15$ W m^{-1}K^{-1}; $h_c = 34{,}270$ W m^{-2}K^{-1}; $T_\infty = 580$ K.

Optional backup: burnup-to-FIMA scale conversion

Assume $M_{\mathrm{HM}} = 238$ g/mol and 200 MeV of thermal energy per fission.

$$1 \text{ GWd/tHM} = 8.64 \times 10^{10} \text{ J/kgHM}$$

$$N_f = \frac{8.64 \times 10^{10}}{200 \times 10^6 (1.602 \times 10^{-19})} \approx 2.70 \times 10^{21} \text{ kg}^{-1}$$

$$N_{\mathrm{HM},0} = \frac{1000}{238} N_A \approx 2.53 \times 10^{24} \text{ kg}^{-1}$$

Thus 1 GWd/tHM is about 0.107% FIMA with these assumptions; 1% FIMA is about 9.38 GWd/tHM.

Optional backup: thin-wall pressure loading

$$\sigma_\theta \approx \frac{(P_i - P_o) r_m}{t_c}$$

- σ_θ: hoop stress; $P_i - P_o$: pressure difference.
- r_m: mean tube radius; t_c: wall thickness.
- Thin-wall, uniform pressure and simple geometry are assumed.

Thermal stress, contact, creep, irradiation and corrosion require additional models.
This is not a cladding-failure criterion.