Nuclear fuel behaviour

2.5.2019

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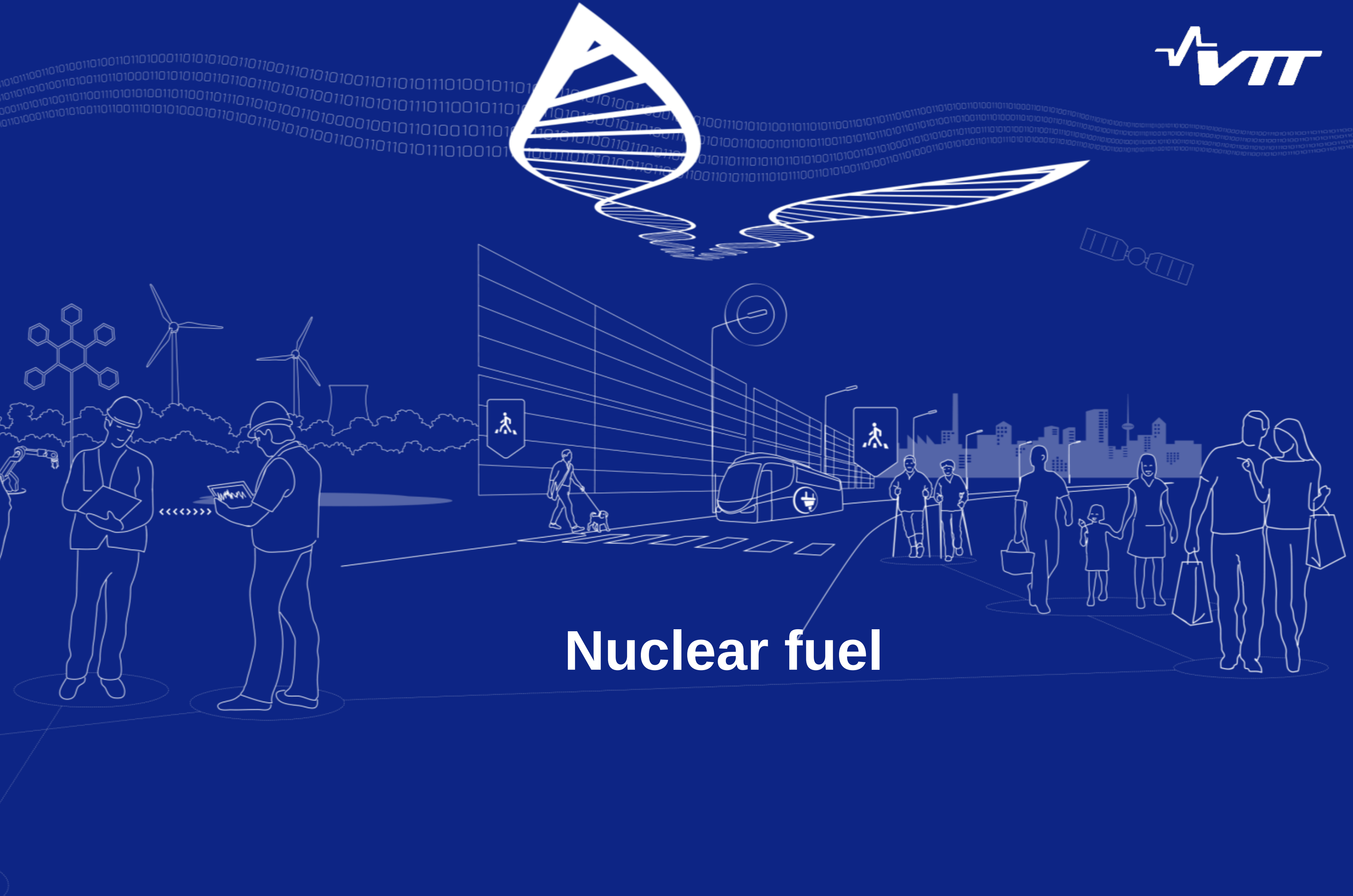
Outline

- Extended introduction
  - Nuclear fuel behaviour in 40 minutes
- Thermomechanic solution (simplified)
- Mechanical and material models
- Fuel in-reactor behaviour
  - Simulation runs and reasons for them



Nuclear fuel

Nuclear fuel

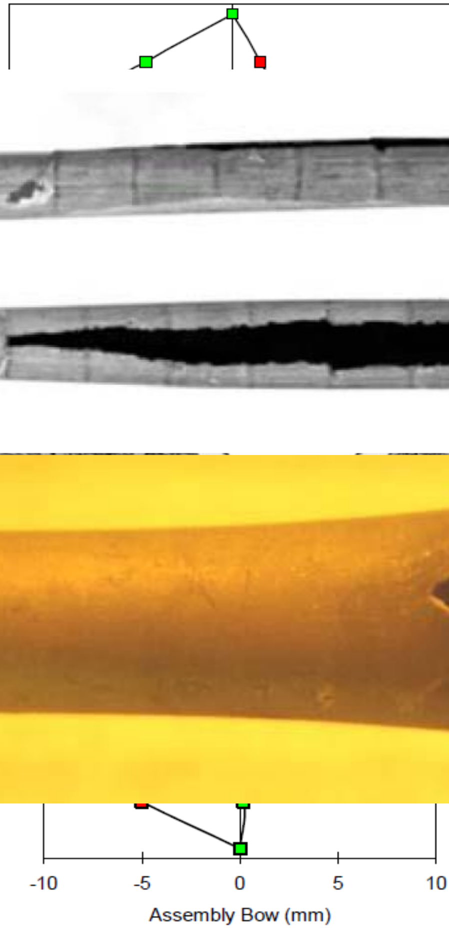
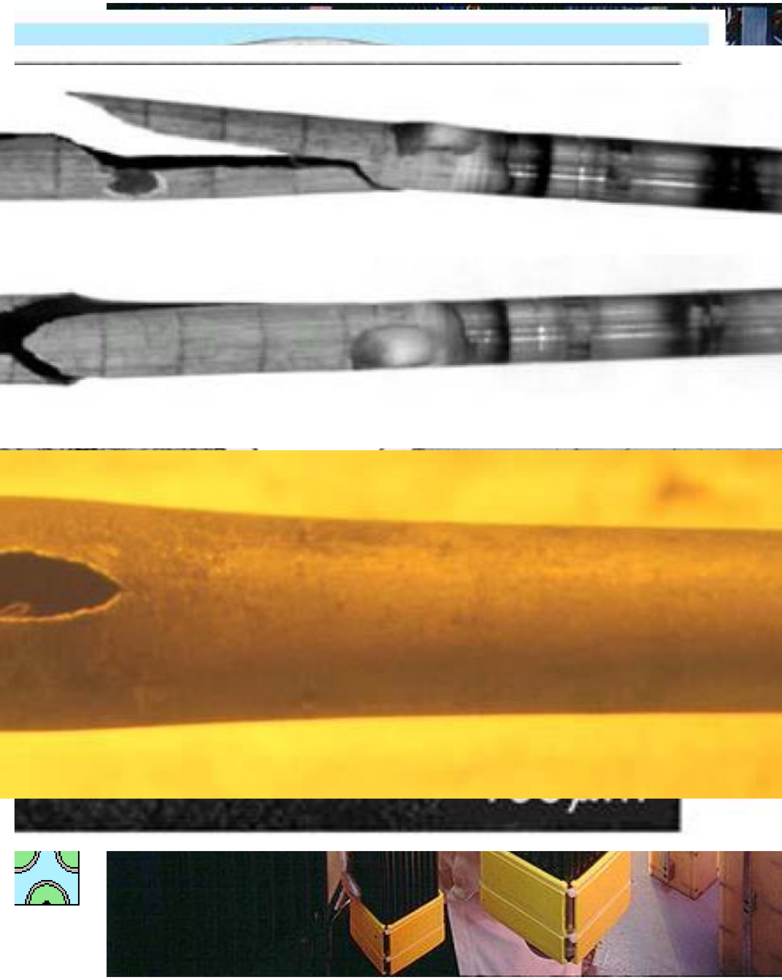
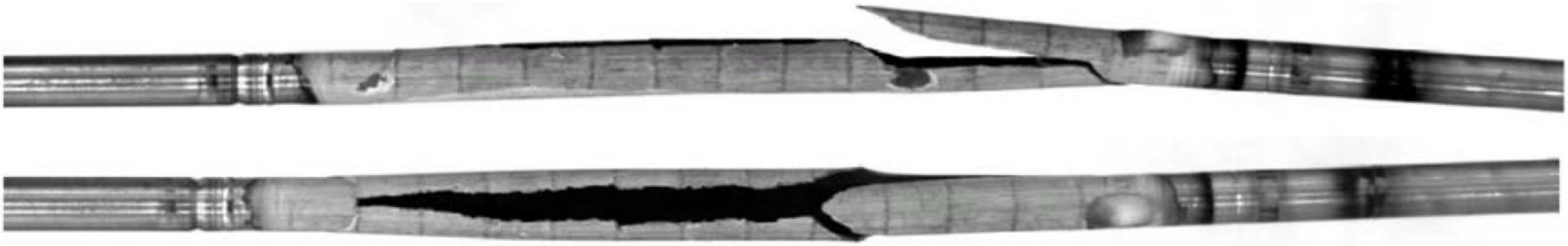
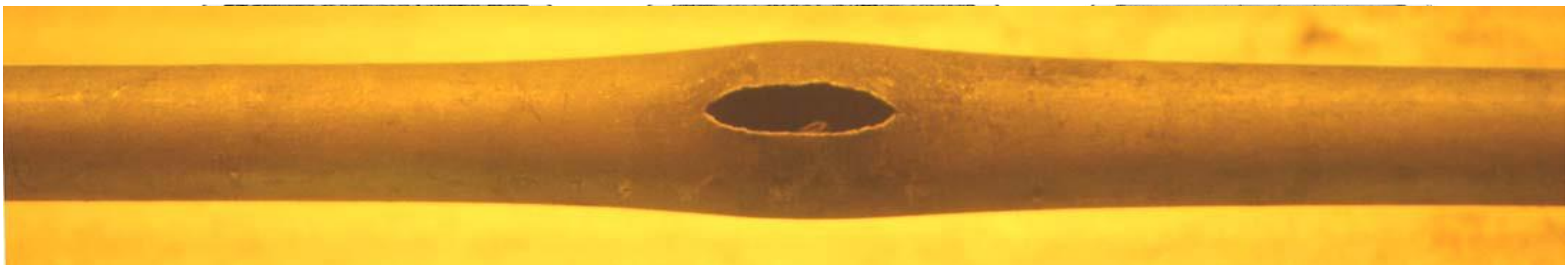


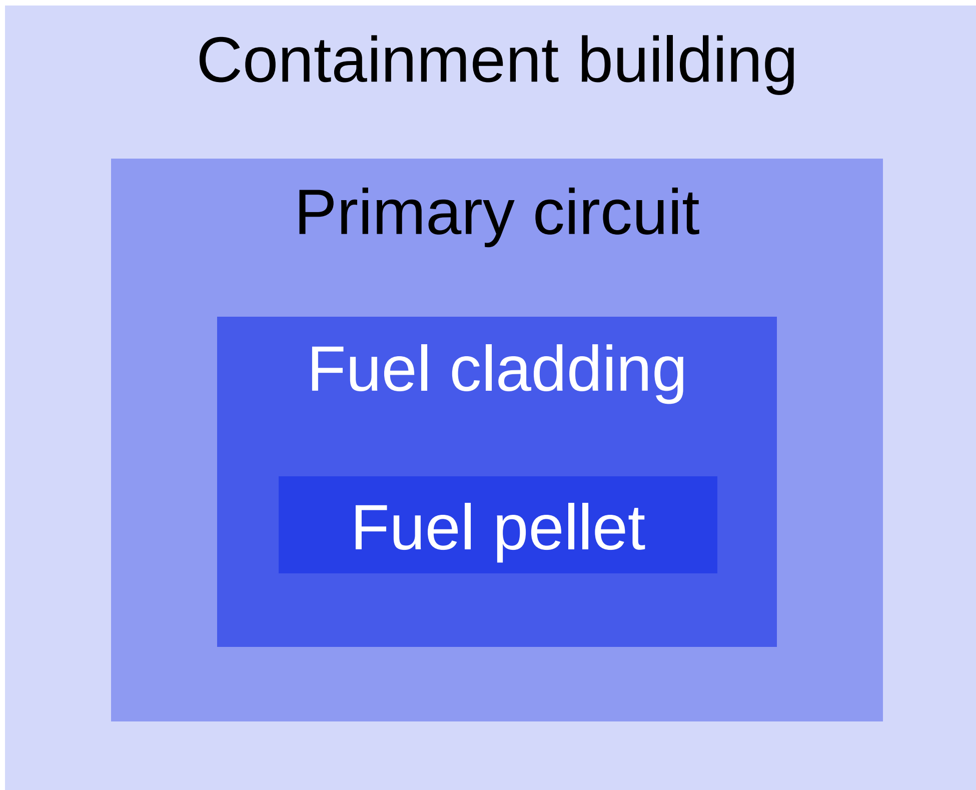
FIG. 4. Ringhals 3 - Example of C-shaped assembly bow.







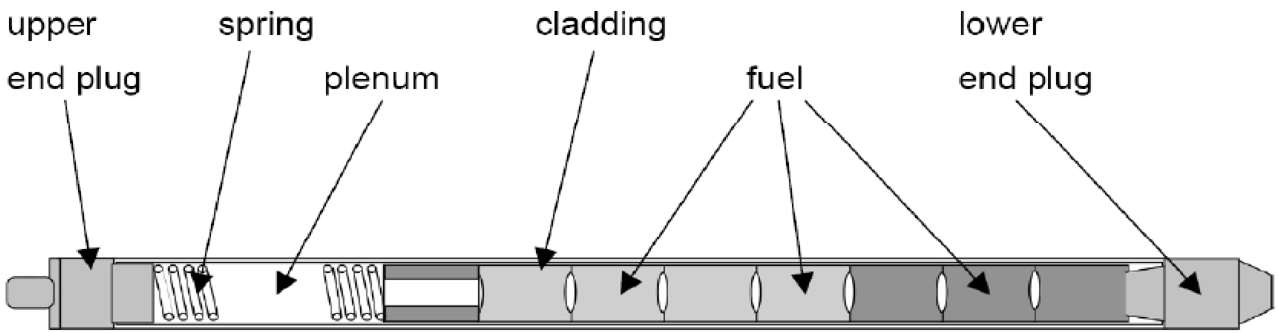
Safety barriers



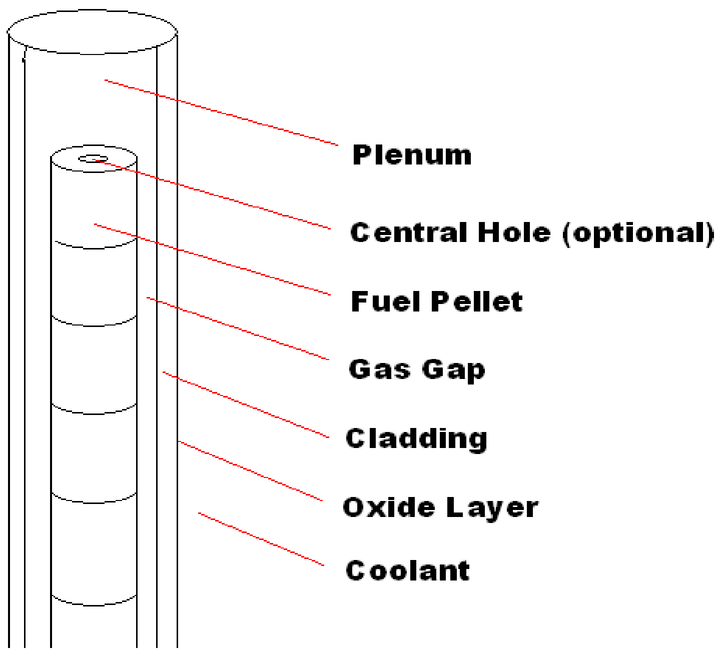
Fuel behaviour

- During irradiation fuel is affected by
  - Neutron flux, pressure differential, high temperature, temperature gradient, chemically aggressive environment
- There are changes in the conditions
  - Operational transients
  - Anticipated operational occurrences
  - Accidents
- These all change fuel composition and properties

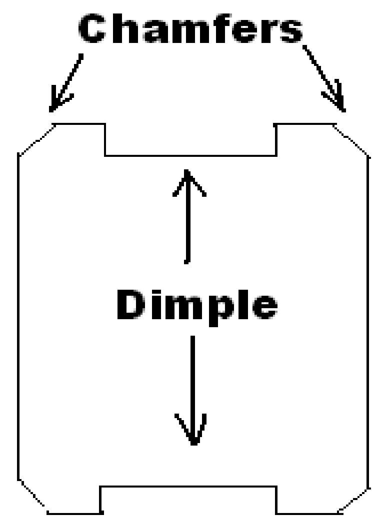
Fuel rod



upper
end plug
spring
plenum
cladding
fuel
lower
end plug

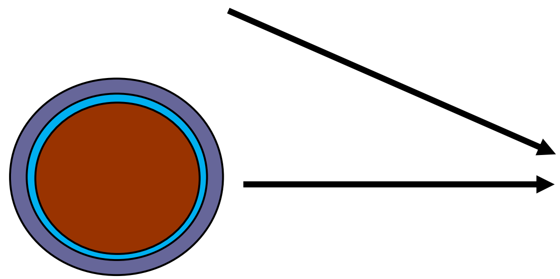


Plenum
Central Hole (optional)
Fuel Pellet
Gas Gap
Cladding
Oxide Layer
Coolant

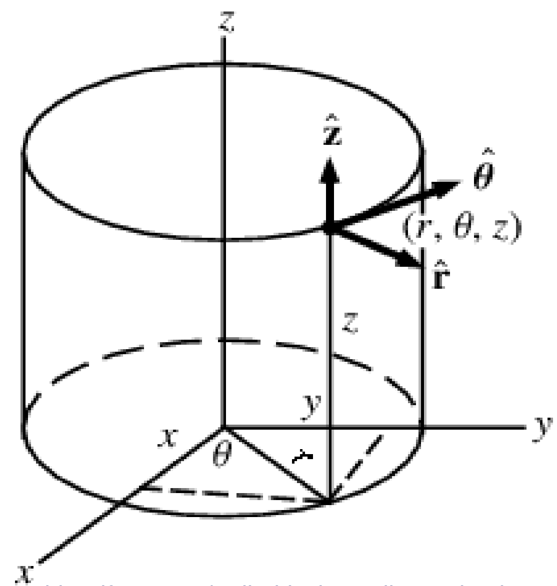


Chamfers
Dimple

Fuel rod



Cylindrical geometry

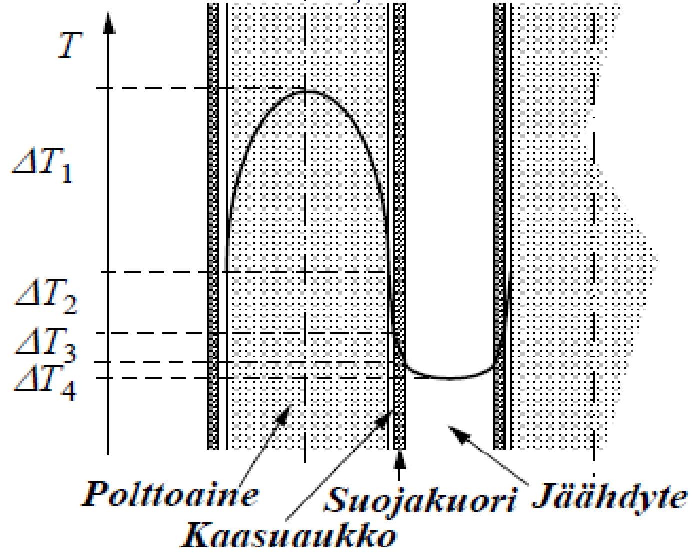


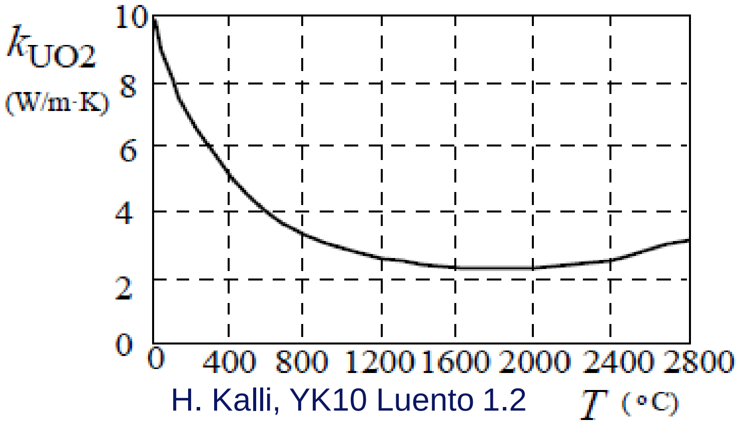
http://mathworld.wolfram.com/CylindricalCoordinates.html

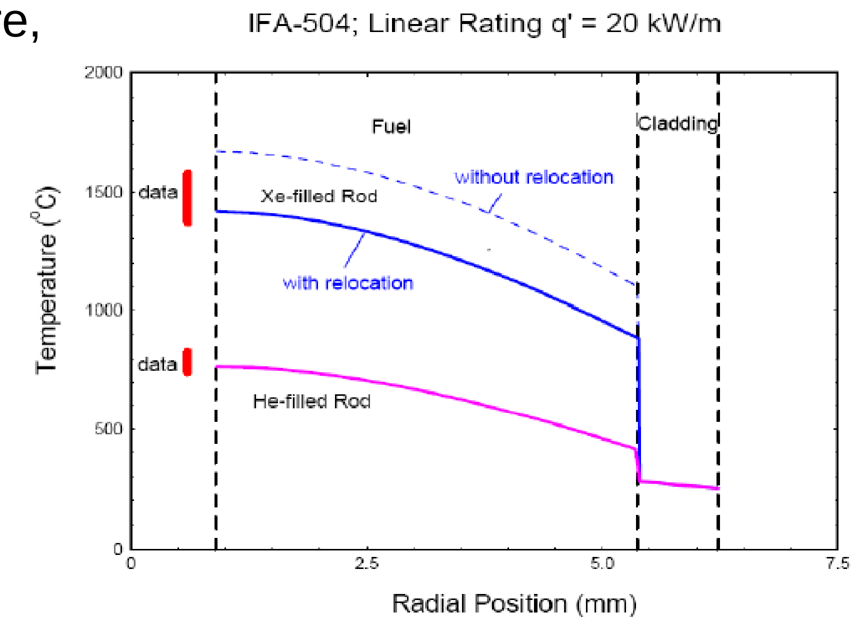
- Diameter approximately 1 cm, length several metres
  - Many of the phenomena are local, the conditions change axially
  - This can be used in problem simplification for analysis

Basic phenomena

- Thermal energy
- Deposited to fuel pellets by fission processes
- Radially conducted to the coolant
  - Material conductivity and gas gap conductance depend on materials, burnup, temperature, fluence et al.
  - We'll get back to this

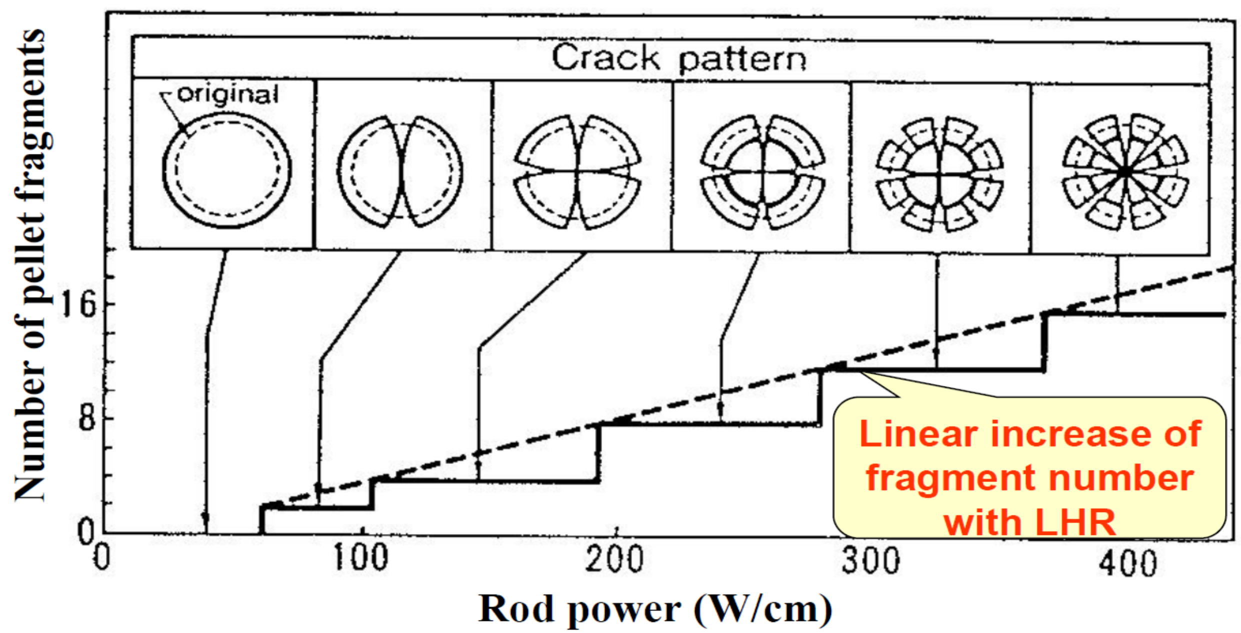






Challenge

- We're attempting to describe complex phenomena on a macroscopic scale
- For instance thermal conduction and mechanical properties depend on, e.g. the cracking of the fuel pellet, which in turn depends on the pellet internal stress state, temperature and other conditions

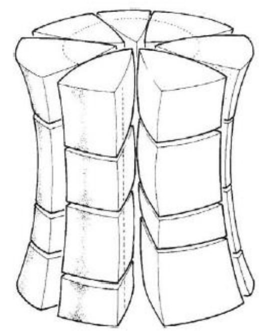


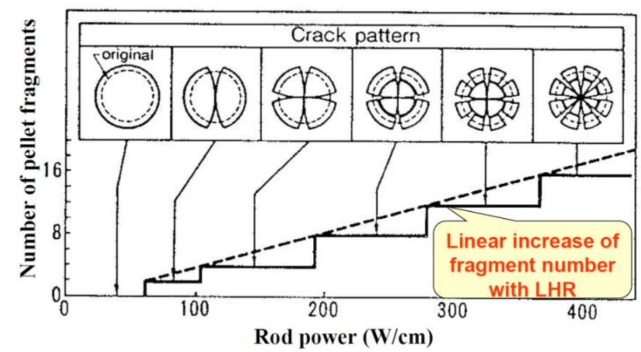
Fuel behaviour analysis

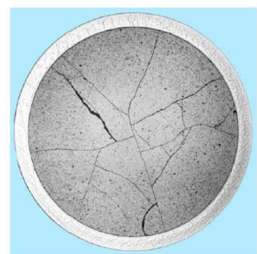
- Fuel behaviour analysis focuses on a single fuel rod
- Phenomena can be divided into two classes
- Steady state / normal operation
    - Effects of accumulating burnup, long-term irradiation and slow changes in the properties of the fuel
    - The production and conduction of thermal energy can be considered to be equal (d/dt=0)
  - Transients and accidents
    - Fast and strong changes in conditions, phenomena not normally encountered
    - No thermal equilibrium
- Specialized codes
  - SS: ENIGMA, FRAPCON, etc
  - Transient: FRAPTRAN, SCANAIR, etc
  - SS-codes often used in the initialization of transient codes

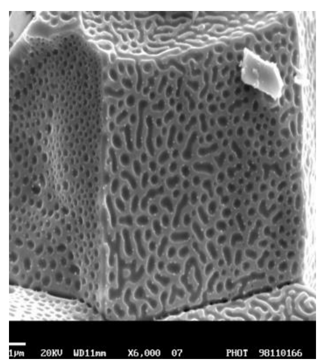
Phenomena in normal operation: pellet

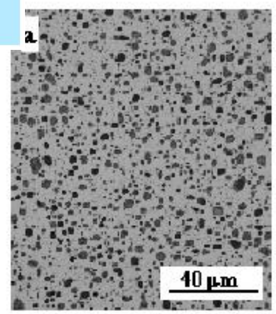
- In normal operation, the fuel…
  - Expands due to thermal expansion
  - Cracks due to thermal stresses
  - Swells due to fission products
  - Releases gaseous products into the gas gap
  - Changes in physical and chemical composition

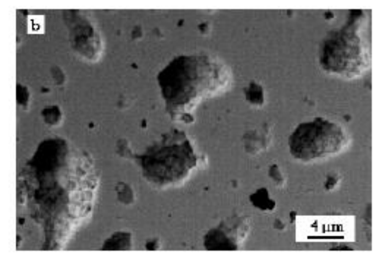


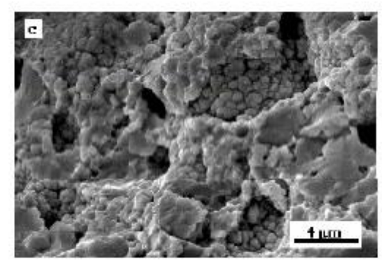








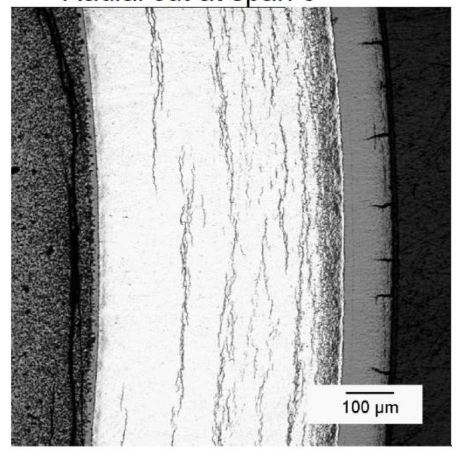




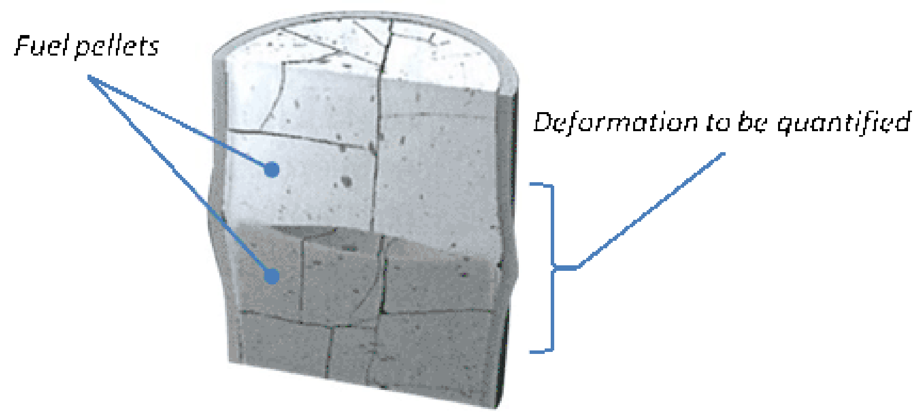
Phenomena in normal operation: cladding

- In normal operation, the cladding…
  - Is oxidized by water from outer surface
  - Creeps inward due to pressure difference
  - Takes in hydrogen, changing in properties
  - Elongates due to irradiation growth

Radial cut at span 6



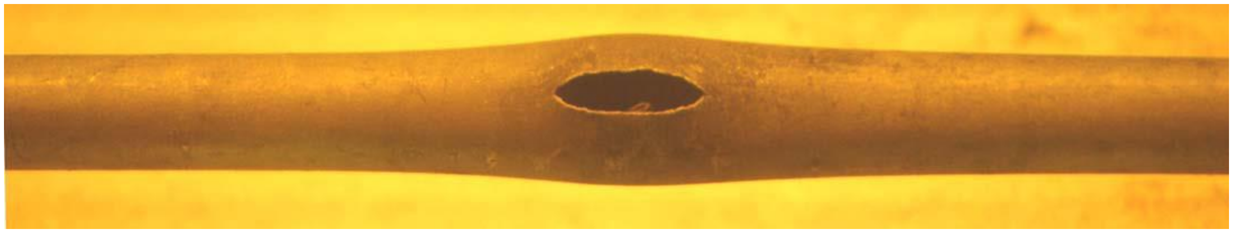
- And, at high enough burnup…
  - Comes into contact with the pellet
  - Creeps outward with the pellet
  - Bonds chemically with the pellet



Fuel pellets after irradiation

Accidents: LOCA

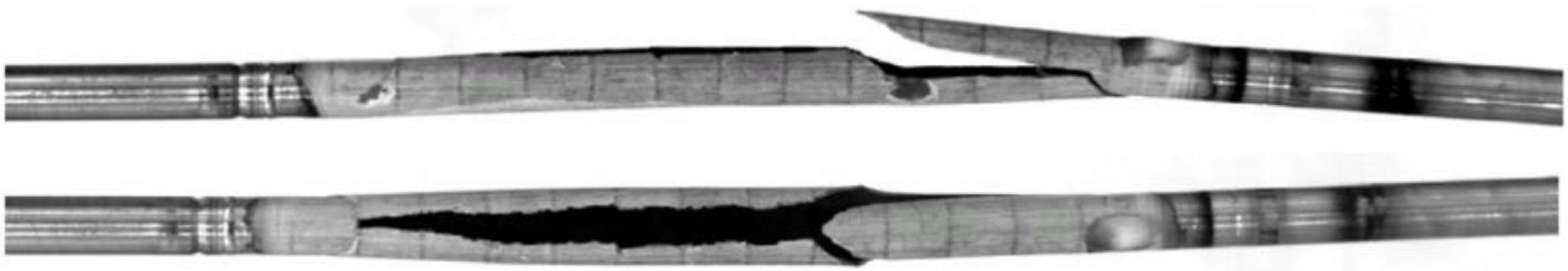
- In a loss-of-coolant-accident…
  - Heat transfer is blocked and temperature in fuel and cladding rise
  - Internal pressure builds up, cladding deforms plastically, balloons, fails (> 650 °C)



  - The cladding oxidizes rapidly (> 1200 °C)
    - The oxide is brittle, shatters easily
    - Zircaloy reacts with water exothermically to produce heat and hydrogen
  - The pellet shatters and may be dispersed into the primary loop
  - The fuel melts (> 2800 °C)

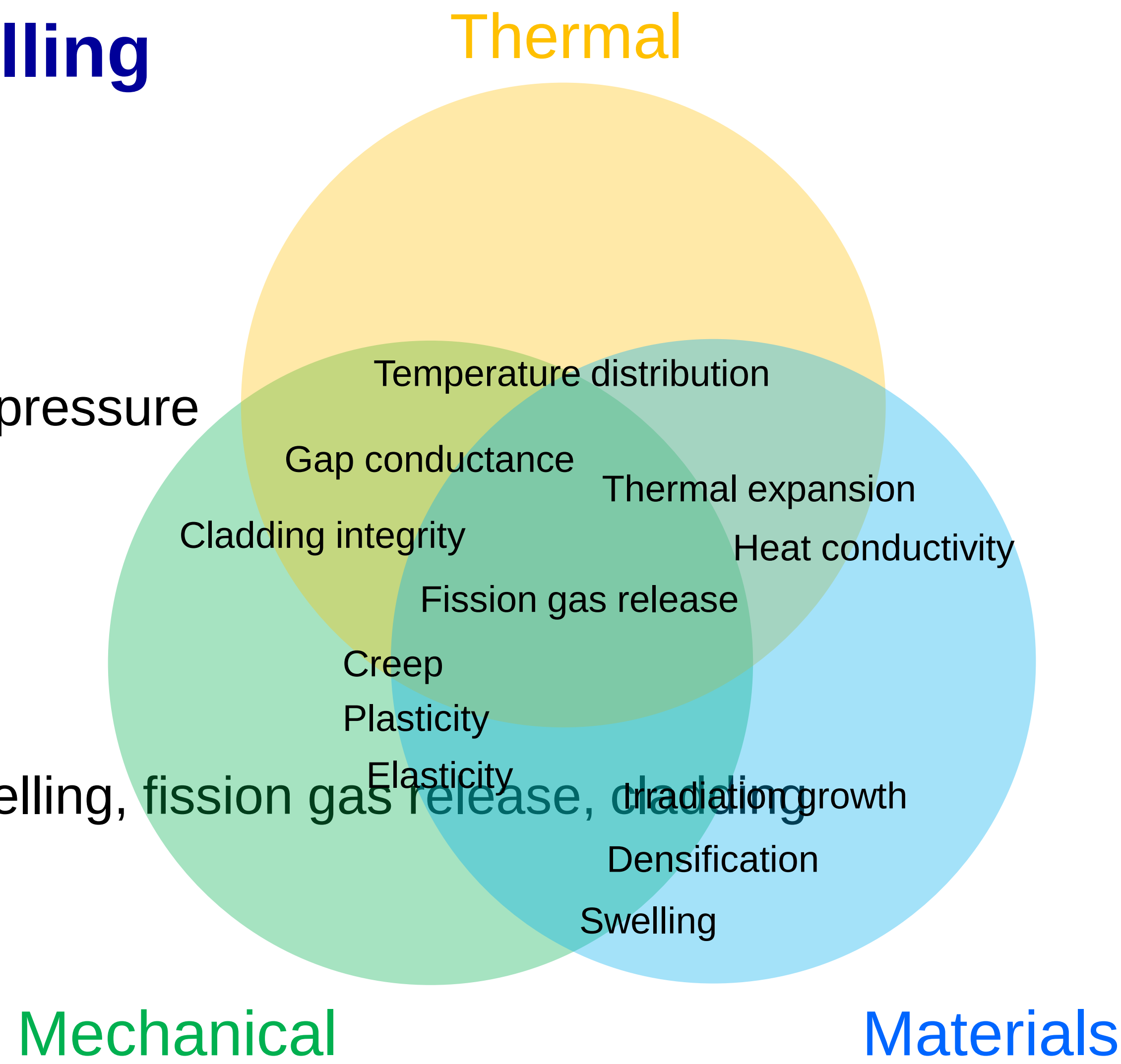
Accidents: RIA

- In a reactivity accident…
  - Sudden spike in reactivity deposits energy into the fuel extremely fast (tens of milliseconds)
  - The pellet expands rapidly due to thermal expansion, may lead to cladding failure
  - The outcome of the accident is greatly dependent on the initial state of the fuel rod (gap width, etc.)

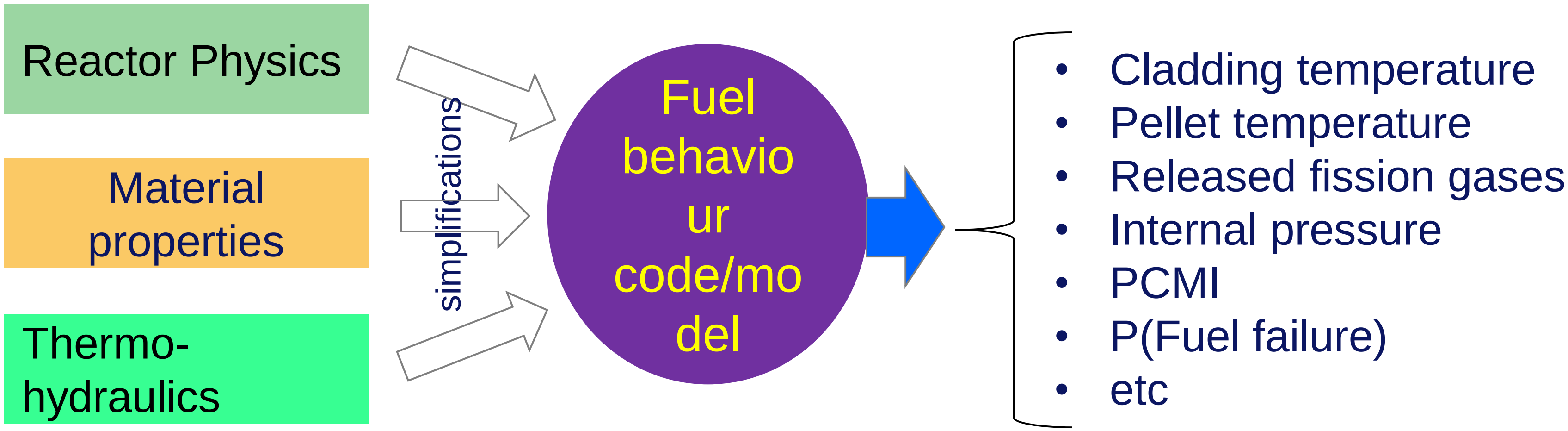


Fuel behaviour modelling

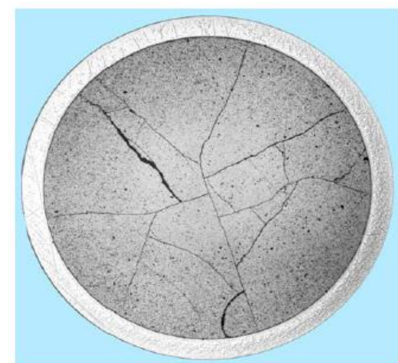
- Boundary conditions
  - Power distribution
  - Coolant temperature and pressure
- Solve
  - Temperature distribution
  - Mechanical deformations
  - Heat flux to coolant
  - Effects of burnup (fuel swelling, fission gas release, cladding creep, etc.)



Modelling nuclear fuel behaviour

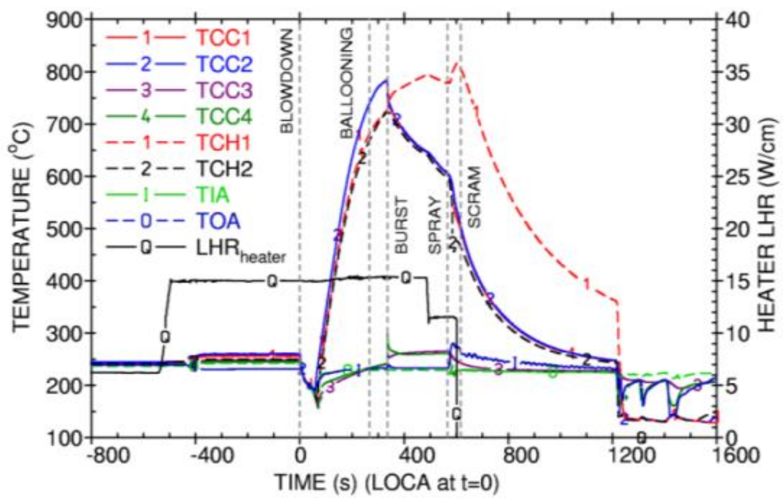


- Models have been developed to describe the macroscopic effect of microscopic statistical phenomena
  - Not necessarily directly measureable
  - Models based on partially theory, partially on parameters fitted to experimental results (correlations)
- Application range and validity of the modelsi
  - Range of validity (e.g. <45 MWd/kgU), new materials, new fuel designs



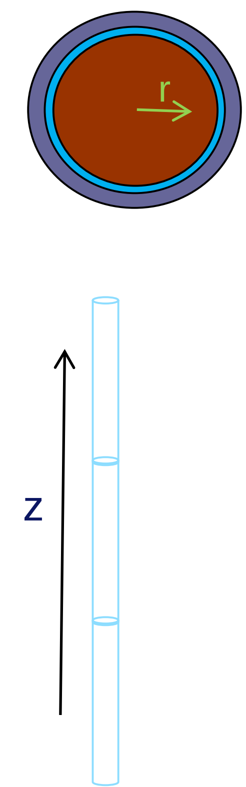
Where to get information from

- No room for fuel on-line instrumentation in power reactors, but fuel behaviour in NPPs is the reason for the studies
  - Pool inspections during annual maintenance shutdowns
  - Post irradiation examinations after the irradiation
- Experimental reactors feature space for instrumentations, but do not necessarily match power reactor size or conditions (flux, temperature, pressure)
  - Several ways to compensate
  - Use of rod segments
  - Possibility for on-line instrumentation
  - Experiment to fuel damaging



Modelling fuel: 1½D-fuel codes

- Fuel rod is described as concentric cylinders, divided into simulation nodes (finite element or finite difference)
  - Axial nodalization ~10 – 50 cm
  - Radial nodalization ~10 – 100 µm
- Fuel thermomechanical modelling radially, axial coupling via free volume gases
- Whole time in reactor modelled
  - Previous power history affects the current fuel state
- Phenomena are described by models and correlations
  - Models fitted to various conditions (normal use, LOCA, RIA)
- Simulations take seconds or minutes
- In common use in fuel behaviour modelling



Safety analyses

- Safety limits obtained primarily from experiments
- Modelling assists in evaluation and interpretation of the results
  - All things cannot be measured

- Choice of models to be used depends on
  - Resources
  - Available information
  - Application
- Conservative assumptions
  - If the models cannot describe a phenomenon (e.g. cladding ballooning during LOCA), a conservative limit is set (ballooning won't happen below 650 °C)
  - What's conservative? And when do we get too much conservatism?

Summary

- The purpose of the fuel rod is to produce thermal energy and transport it to the coolant, and to contain the radioactive substances produced in nuclear reactions

- Understanding the fuel rod performance requires knowledge on thermal, mechanical and materials behavior

- Fuel rod modeling is done with specialized computer codes that simulate thermal, mechanical and materials properties on various levels of detail

Modelling fuel behaviour
Thermomechanic solution

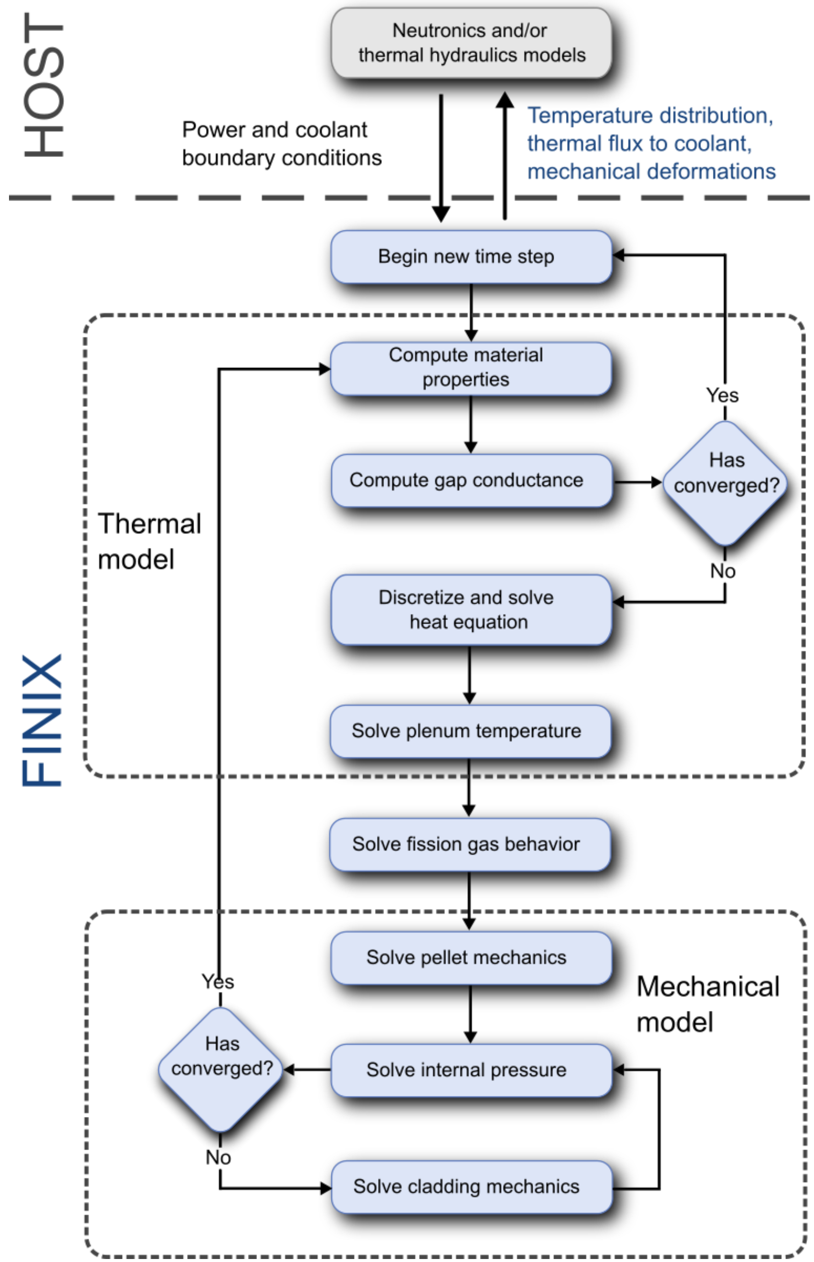
Contents

- Description of solution to the thermomechanical state of the fuel rod
    - Iterative solution required
- Solving the heat equation
- Solving the mechanical state

The aim is to present the general solution scheme to the coupled problem of fuel thermal and mechanical state

Iterative solution

- Solving the thermomechanical state of the fuel
  - Linear phenomena such as thermal expansion, elastic loads
  - Non-linearity in creep, swelling, fission gas release
- Time discretized into time steps during the fuel state solved iteratively
- In practice, iterative solution of thermal and mechanical model has proven to be robust
  - Some exceptions

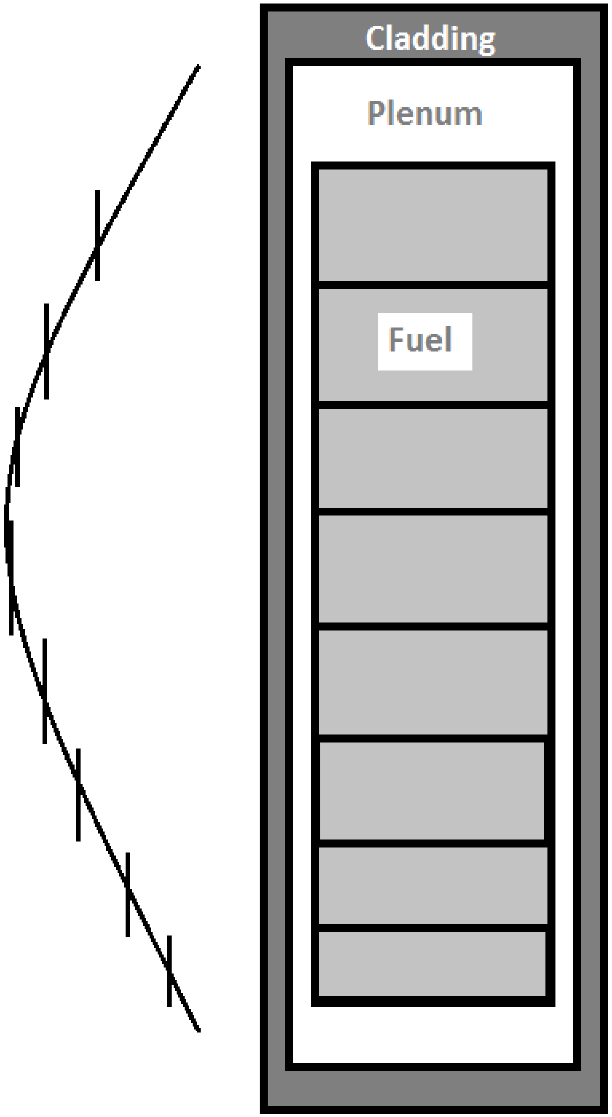


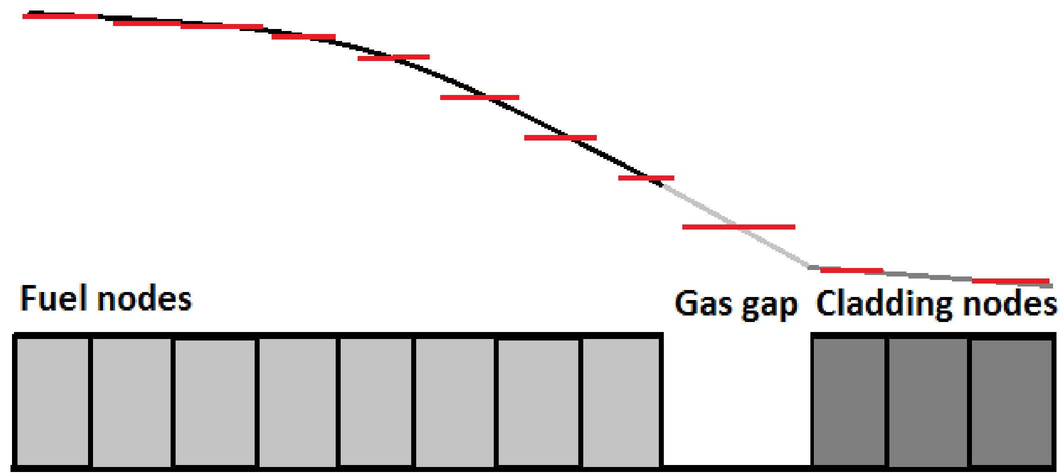
Spatial discretization

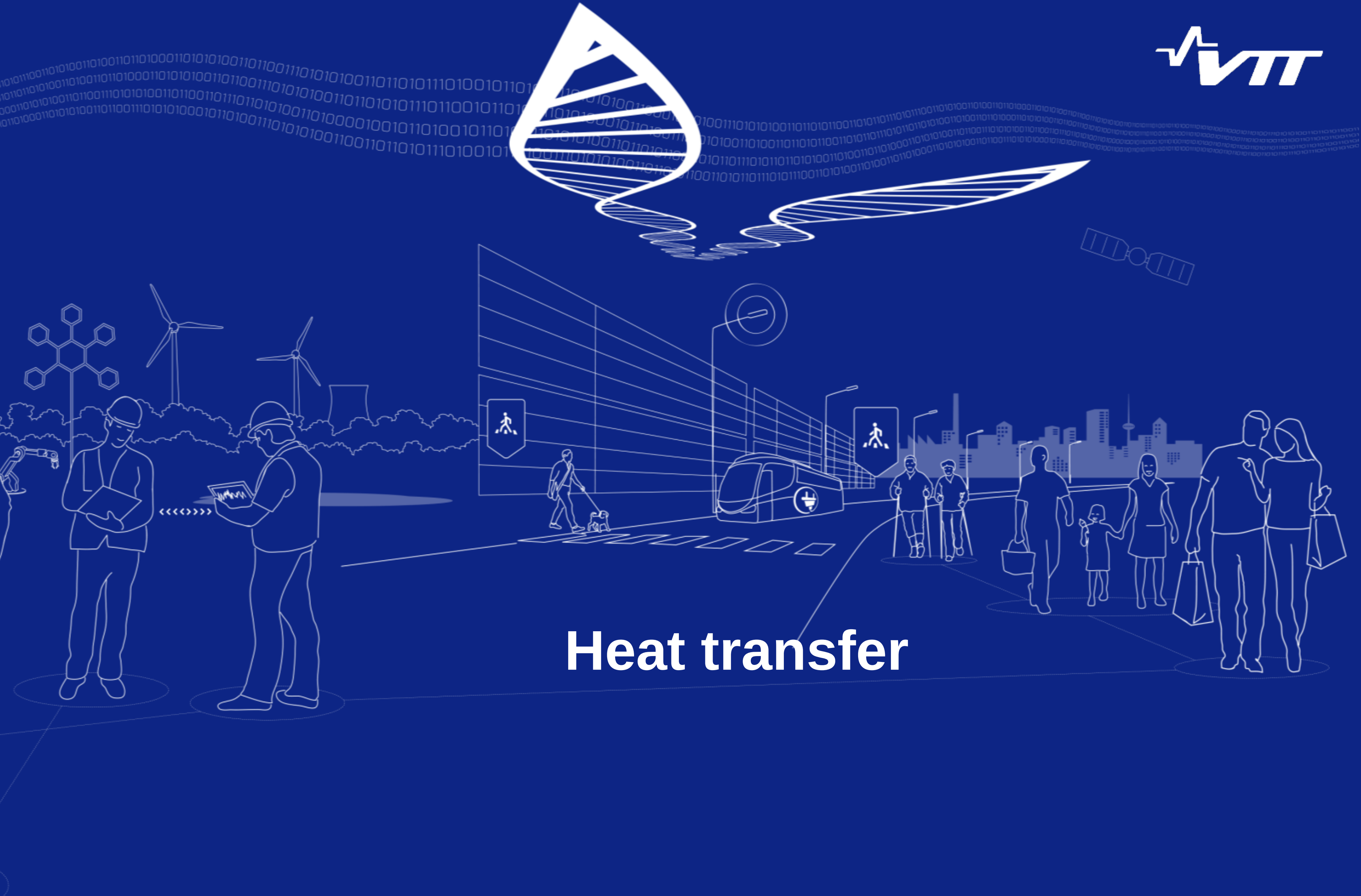
- Discretization depends on chosen approach
  - 1½-D, axisymmetry assumed, r and z modelled separately
    - Plane strain, often isotropic properties
  - 2D, either looking at slice cut axially or radially
  - 3D, minimum of two pellet-halves
    - Pellet edges places of interest
- For 1½-D, the solution sought is essentially 1D radial solution in each axial slice of the fuel rod
  - Solution by Finite Element Method, finite difference method, etc
  - Simulation nodes usually by equal volume or equal radius
  - Properties stay constant within a simulation node (ring)

1½-D solution

- Thermomechanic state of each axial slice is solved individually
- Plenum pressure combines the thermomechanic solution across axial slices
- Fuel stack growth, cladding axial elongation







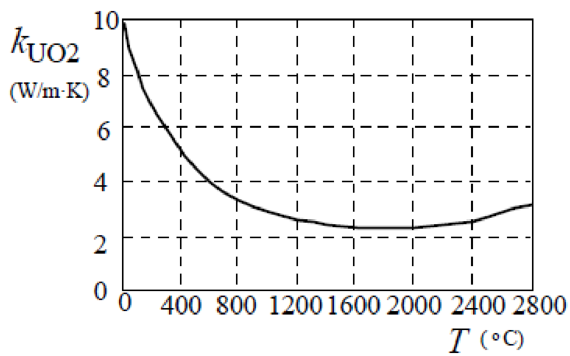
Heat transfer

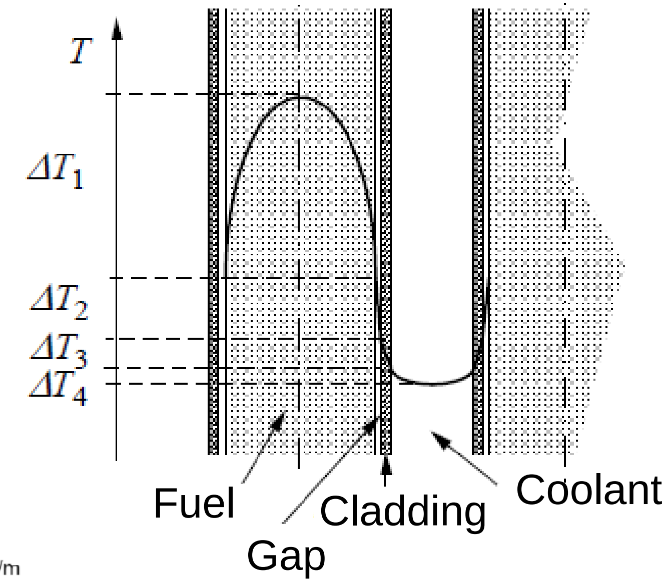
Heat transfer equation

- Numerical solution of the heat transfer equation depends on the chosen solution method and application
- For instance, FINIX was first written with transient heat equation solver with an assumption that steady state could be easily modelled using long time steps
  - In practice, issues with convergence of the solution during the steady state
  - We ended up creating a parallel steady state solver
- What follows is the conceptual overview of the solution

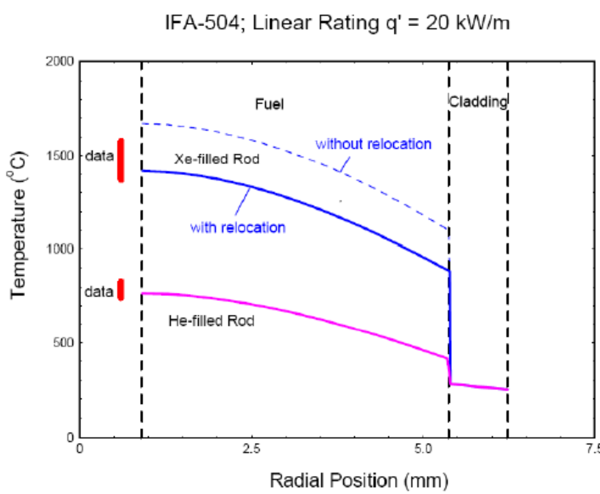
Normal operation: heat transfer to coolant

- Thermal conductivity of UO2
  - Temperature
  - Burnup
  - Cracking
  - Porosity





- Gap conductance
  - Gap width
  - Gas composition
  - Temperature



- Cladding conductivity
  - Oxide, CRUD

Solving the heat equation

$$P_v + \nabla(\lambda \nabla T) = c_p \rho \frac{dT}{dt}$$

In steady state situation:

$$\frac{dT}{dt} = 0$$

In cylinder coordinates, assuming no gradient over z or aximuthal

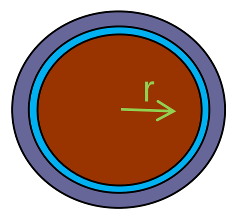
$$P_v + \nabla(\lambda \nabla T) = P_v + \frac{1}{r}\frac{r}{dr}\left(\lambda r \frac{dT}{dr}\right)$$

Ergo:

$$P_v + \frac{1}{r}\frac{r}{dr}\left(\lambda r \frac{dT}{dr}\right) = 0$$

Solving steady state heat

- Divergence theorem
  - Flux over a given volume's surface is a sum of sinks and sources in the volume
- In steady state we know the amount of heat produced
- No longitudal or angular gradient
- Solve the heat equations from outside in
  - Heat sources only in pellet
  - Pellet discritization



- Solution to heat exchange from cladding surface to the pellet center (cladding-coolant heat transfer part of thermal hydraulics)

Cladding temperature

- Assuming one cladding node and that we can determine T_{co} from coolant temperature and steady state assumptions (yes we can)
- Cladding heat equation:

$$\frac{d^2T}{dr^2} + \frac{1}{r}\frac{dT}{dr} = 0 \qquad \Rightarrow \frac{dT}{dr} = \frac{a}{r}$$

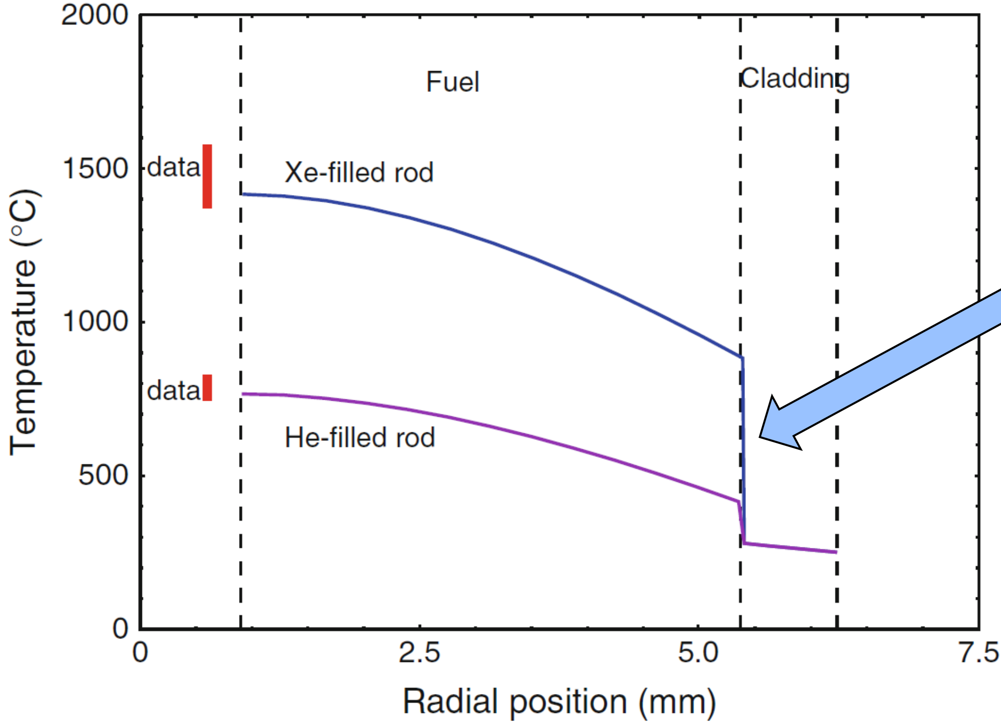
$$\Rightarrow T(r) = a\ln(r) + b$$

- Fourier equation & power from pellet

$$q = \left(\lambda \frac{dT}{dr}\right)_{r_i} = \frac{P}{2\pi r_i}$$

$$\Delta T = T_{ci} - T_{co} = \frac{P}{2\pi\lambda}\ln(\frac{r_o}{r_i})$$

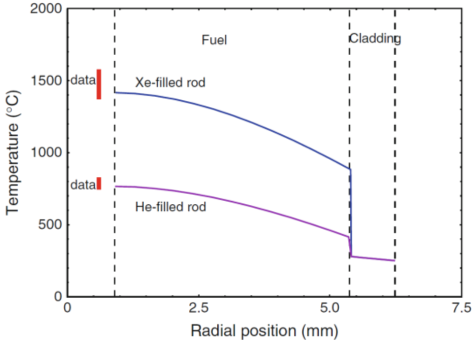
Gap conductance



$$\Delta T_{gap} = \frac{q''}{h}$$

Gap conductance

$$\boxed{h = h_{\text{cond}} + h_{\text{rad}} + h_{\text{contact}}}$$



$$h_{\text{cond}} = \frac{\lambda_{\text{eff}}}{d_{\text{eff}}}$$

$$\lambda_{\text{eff}} = \sum_{i}^{n} \frac{\lambda_i x_i}{x_i + \sum_j (1 - \delta_{ij}) \Psi_{ij} x_j}$$

$$d_{\text{eff}} = e^{-0.00125 P_{\text{contact}}} (\rho_f + \rho_c) + 0.0316 (g_f + g_c) + d$$

$$h_{\text{rad}} = \frac{\sigma_{SB}}{\frac{1}{\epsilon_f} + \frac{R_f}{R_{ci}} \left(\frac{1}{\epsilon_c} - 1 \right)} \frac{T_f^4 - T_{ci}^4}{T_f - T_{ci}}$$

$$h_{\text{contact}} = \begin{cases} 13.740 \dfrac{\lambda_m P_{\text{rel}}^{1/2}}{\rho_f^{-0.528} \sqrt{\rho_f^2 + \rho_c^2}}, & \text{for } P_{\text{rel}} \le 9 \cdot 10^{-6}, \\ 0.041226 \dfrac{\lambda_m}{\rho_f^{-0.528} \sqrt{\rho_f^2 + \rho_c^2}}, & \text{for } 9 \cdot 10^{-6} < P_{\text{rel}} \le 0.003, \\ 4579.5 \dfrac{\lambda_m P_{\text{rel}}^2}{\rho_f^{-0.528} \sqrt{\rho_f^2 + \rho_c^2}}, & \text{for } 0.003 < P_{\text{rel}} \le 0.0087, \\ 39.846 \dfrac{\lambda_m P_{\text{rel}}}{\rho_f^{-0.528} \sqrt{\rho_f^2 + \rho_c^2}}, & \text{for } P_{\text{rel}} > 0.0087, \end{cases}$$

Temperature distribution in fuel

- This time P_v cannot be ignored

$$P_v + \frac{1}{r}\frac{r}{dr}\left(\lambda r \frac{dT}{dr}\right) = 0$$

- Assuming constant P_v and λ

$$T(r) = -\frac{P}{4\lambda} r^2 + a \ln(r) + b$$

- Remember, P_v and λ are not constants
  - Solved in small radial nodes where they can be assumed constant
  - Linearization of the source and conductivity leads to a bit more complex equations as dλ/dr and dP_v/dr are not zeroes

Solving the heat equation

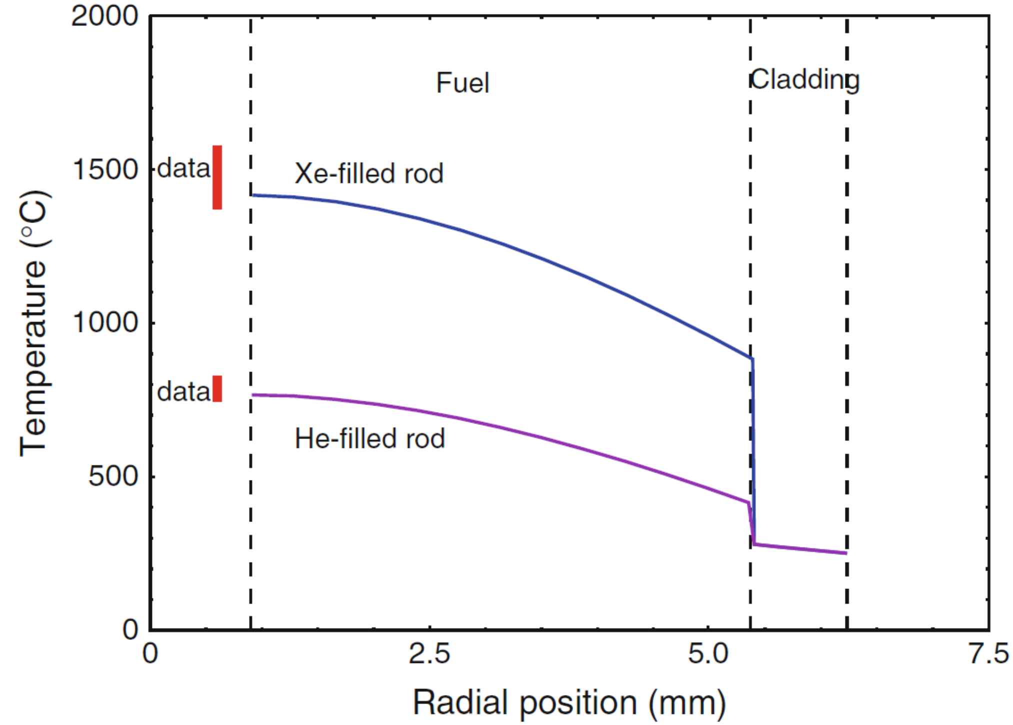
- In practice, we will have a solvable matrix of the form

$$\begin{bmatrix} 1 & -1 & 0 & 0 & \dots & 0 & 0 \\ 0 & 1 & -1 & 0 & \dots & 0 & 0 \\ 0 & 0 & 1 & -1 & \dots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \dots & 1 & -1 \\ 0 & 0 & 0 & 0 & \dots & 0 & 1 \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ \vdots \\ T_{n_f+n_c-1} \\ T_{n_f+n_c} \end{bmatrix} = \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ \vdots \\ I_{n_f+n_c-1} \\ I_{n_f+n_c} \end{bmatrix}$$

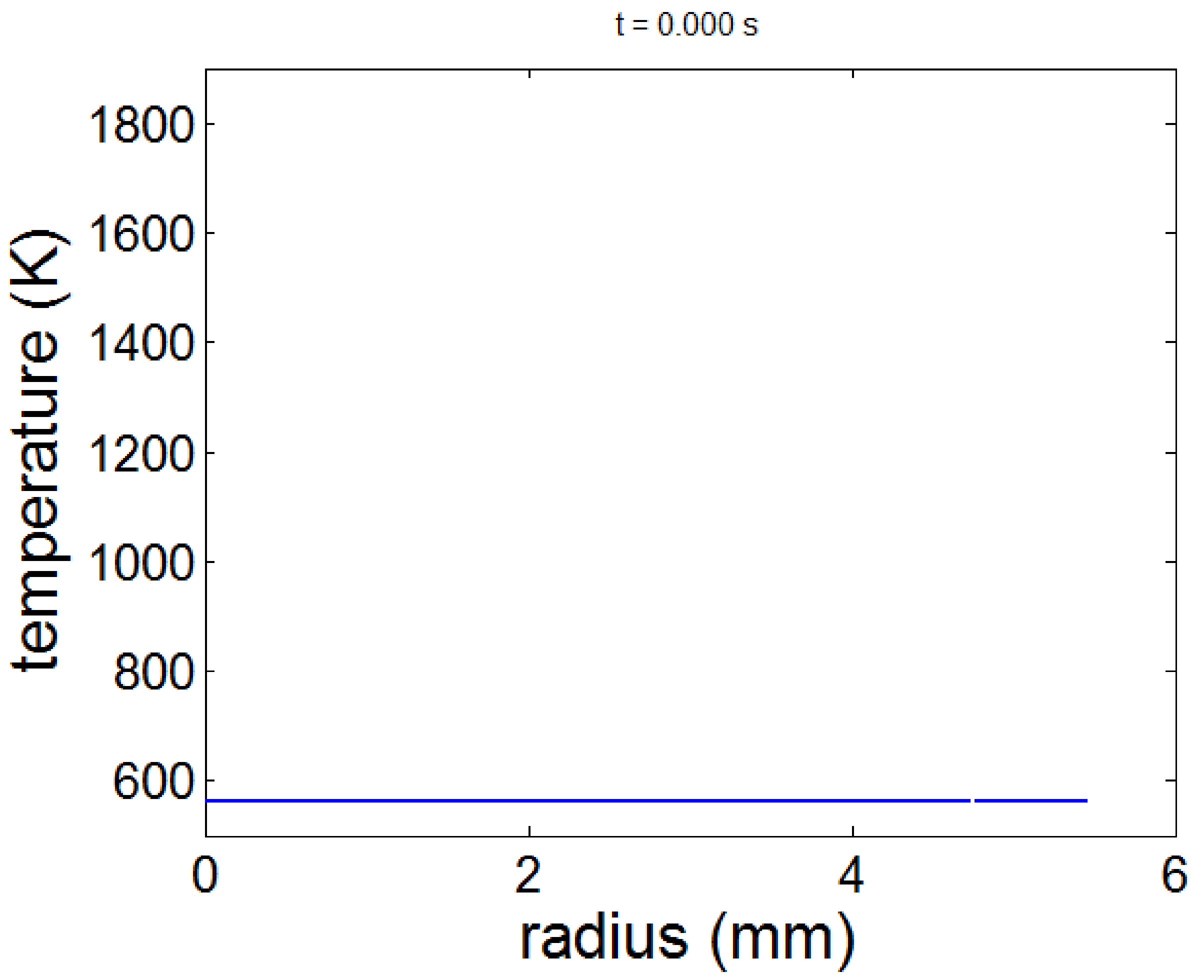
- Here index goes from the pellet centre to the outermost cladding node
- Can be solved through backwards substitution

Transient heat transfer

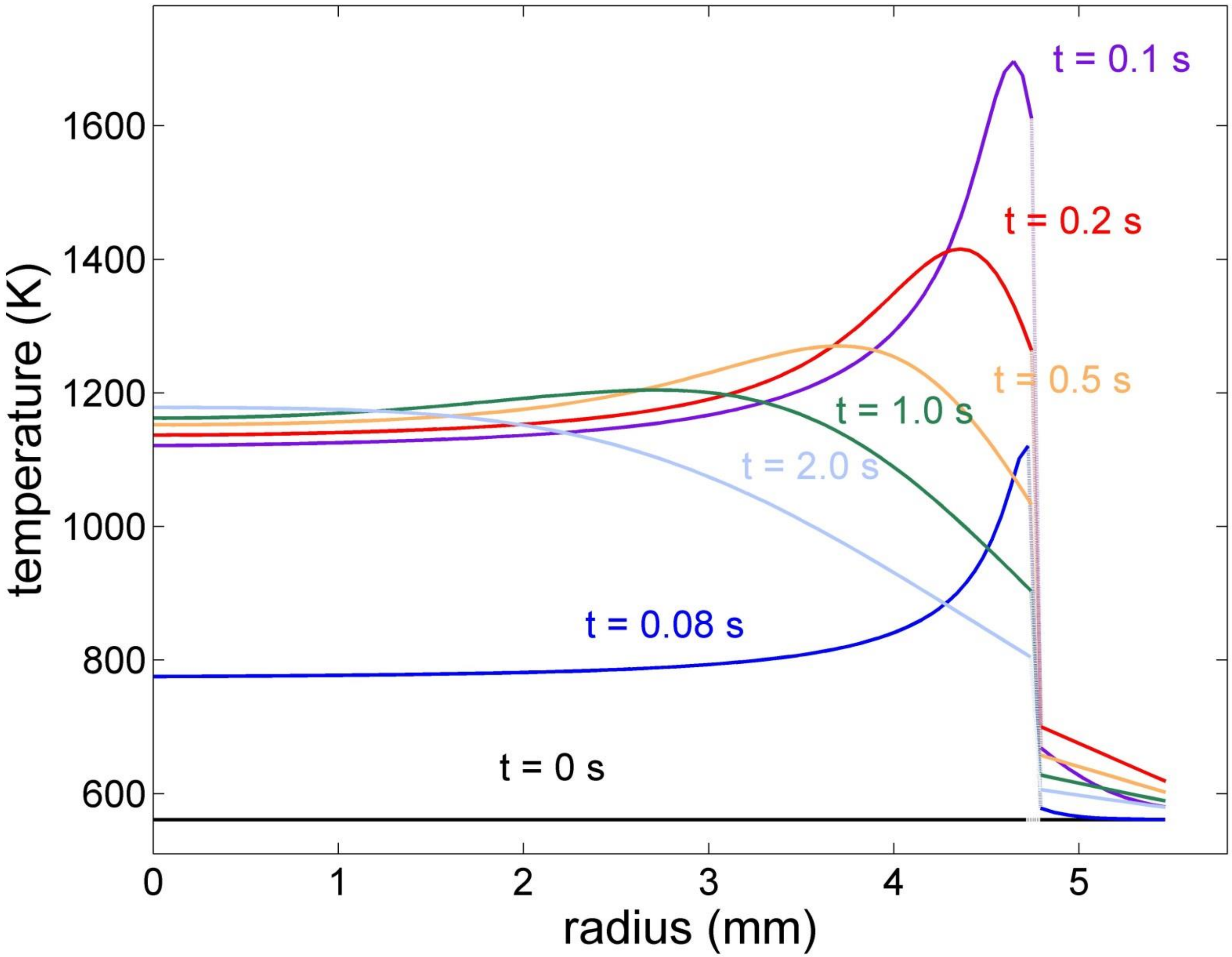
- Steady state yields near-parabolic temperature profile in fuel
- Transient cases where no equilibrium is a bit different

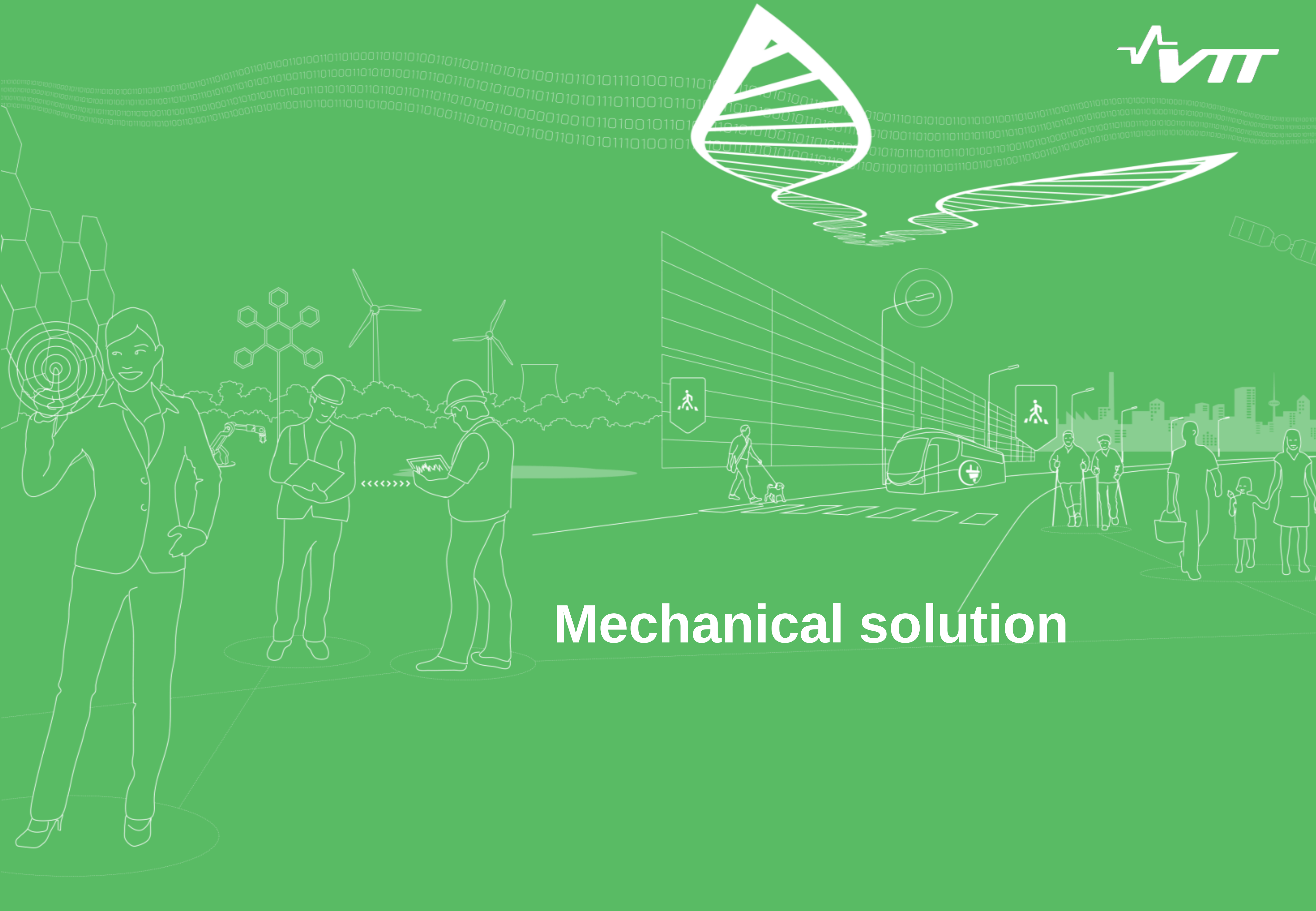


Radial temperature distribution during RIA, according to the FINIX fuel behaviour model



Radial temperature distribution during RIA, according to the FINIX fuel behaviour model





Mechanical solution

Main equations

- The displacement in axisymmetric case

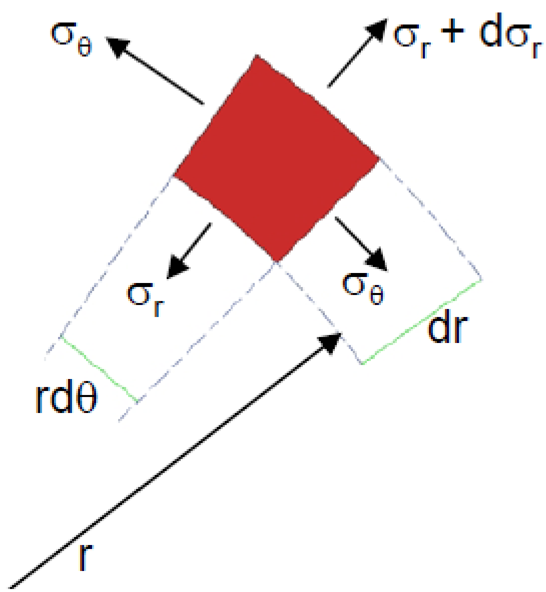
$$(\sigma_r + d\sigma_r)(r + dr)d\theta = \sigma_r r d\theta + \sigma_\theta d\theta dr$$
$$\rightarrow \frac{d\sigma_r}{dr} + \frac{\sigma_r + \sigma_\theta}{r} = 0$$
$$\varepsilon_r = \frac{du}{dr}, \qquad \varepsilon_\theta = \frac{u}{r}, \qquad \varepsilon_z = C$$

- Basic stress-strain relationship comes from Hooke's law

$$\epsilon_\theta = \frac{1}{E}(\sigma_\theta - \nu\sigma_z)$$

$$\epsilon_z = \frac{1}{E}(\sigma_z - \nu\sigma_\theta)$$

$$\epsilon_r = -\frac{\nu}{E}(\sigma_\theta + \sigma_z)$$



Assumption of small deformations!

Sources of strain

- Various sources of strain (i=radial, axial, tangential)
  - These are solved for both fuel and cladding (material dependent variables)

$$\varepsilon_i^{tot} = \varepsilon_i^{el} + \varepsilon_i^{th} + \varepsilon_i^{s} + \varepsilon_i^{vp}$$

- Elastic strains
- Thermal strain
- Swelling
- Viscoplastic flow

Instantaneous processes

- Instantenous reversible deformations
  - Elastic deformation depends on the stress state
    - Material-dependant poisson ratio
  - Thermal expansion isotropic

The hoop, axial and radial strains are connected to the stresses through relations

$$\epsilon_\theta = \frac{1}{E}(\sigma_\theta - \nu\sigma_z) + \epsilon_{\mathrm{th}}, \tag{29}$$

$$\epsilon_z = \frac{1}{E}(\sigma_z - \nu\sigma_\theta) + \epsilon_{\mathrm{th}}^{\mathrm{z}}, \tag{30}$$

$$\epsilon_r = -\frac{\nu}{E}(\sigma_\theta + \sigma_z) + \epsilon_{\mathrm{th}}, \tag{31}$$

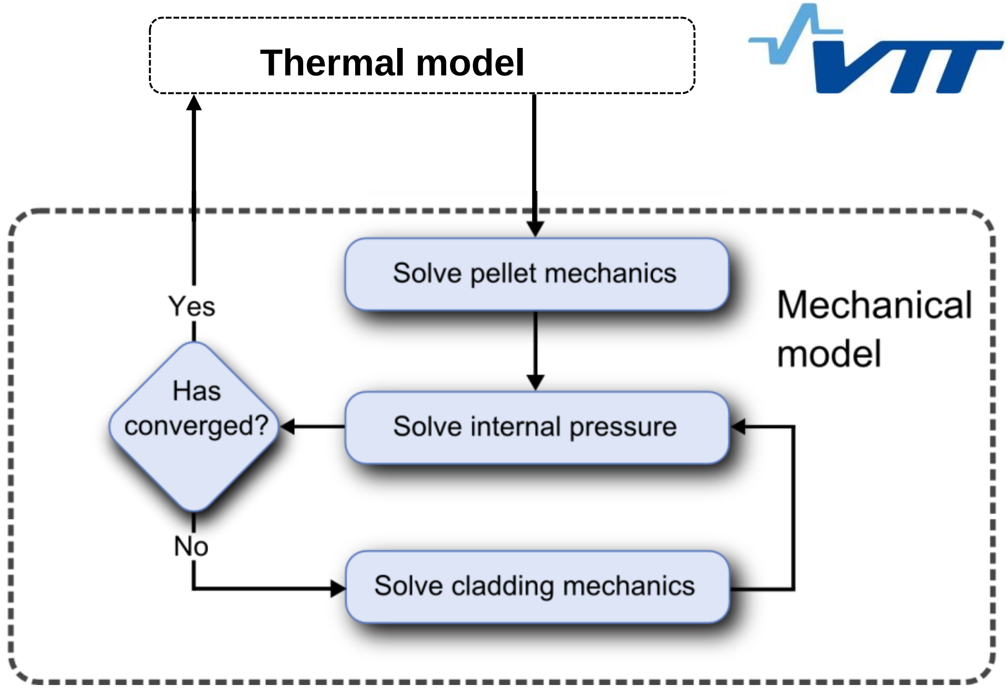
- Plastic deformation instantenous permanent deformation
  - Usually considered after yield stress exceeded

Time-dependent processes

- In fuel
  - Densification, swelling, fission gas release, changes to properties, cracking
- In cladding
  - Creep, oxide layer formation, hydrogen pickup
- Some create additional strains, some alter material properties
  - In effect, many are modelling solutions and conventions
- With small enough time steps these can be assumed to be linearized
  - Driving forces constant during the time step
  - If not, decrease in time step length

Mechanical solution

- Pellet quite rigid
  - Some codes assume fully rigid (infinite Young's modulus)
- Internal pressure from fill gas, released fission gases
  - Ideal gas law
  - Instant mixing or diffusion between nodes
- Internal and external pressure provide the solution to free standing cladding
  - Should the pellet expand beyond free standing cladding, a contact
  - Hard or soft contact possible



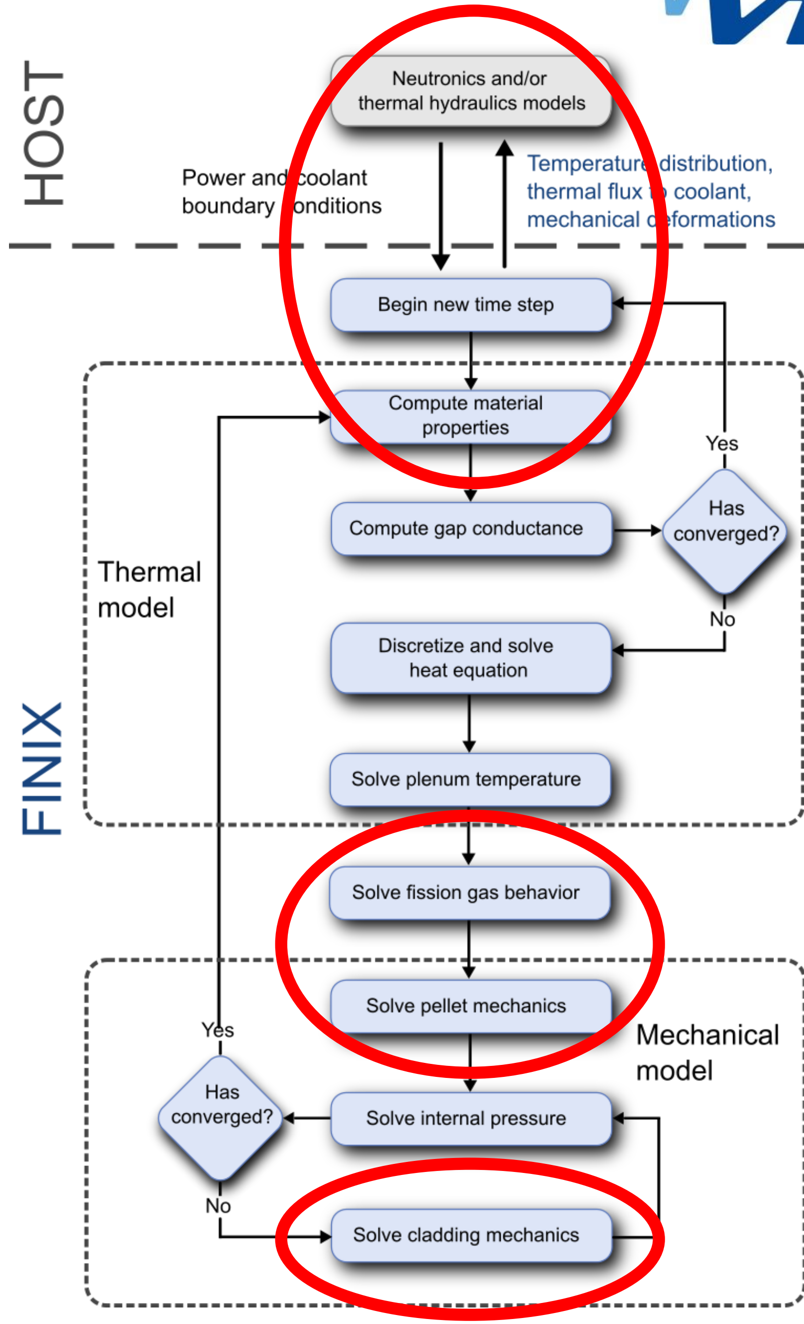
$$P = \frac{nR}{V_{\text{plen}}/T_{\text{plen}} + \sum_k \left(V_{\text{cent},k}/T_{\text{cent},k} + V_{\text{gap},k}/T_{\text{gap},k}\right)}$$

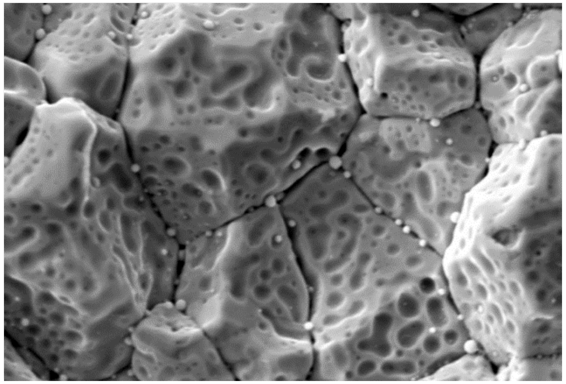
Bridging the gap

- Open gap
  - Pellet and cladding mechanical solutions independent
  - Gas gap width a strong influence to thermal solution
- Closed gap
  - Contact pressure
  - Pellet/cladding friction
    - No slip / slip / friction?
  - Rigid pellet model relatively easy to solve, yielding pellet may have better results
  - Cladding mechanical state, potential for plastic deformation if stresses high
  - Contact pressure a strong influence for contact conduction

To summarize

- Update material properties
    - End of time step, previous iteration
- Solve heat equation
- Solve FGR, pellet mechanics, internal pressure
- Solve cladding state
    - Open/closed gap
    - Stress state
- Check for convergence
    - Iterate

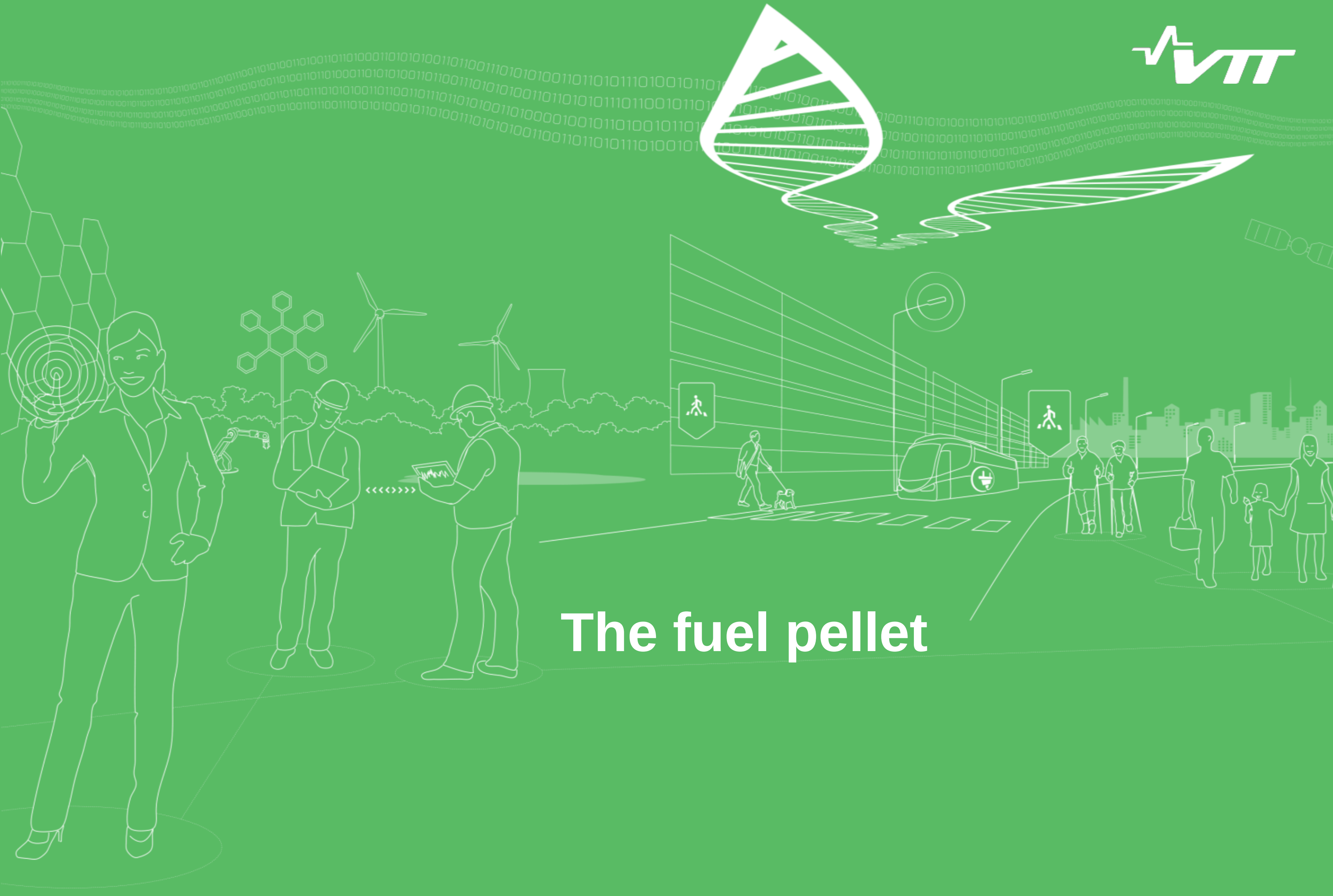




Phenomena in the fuel pellet

Overview

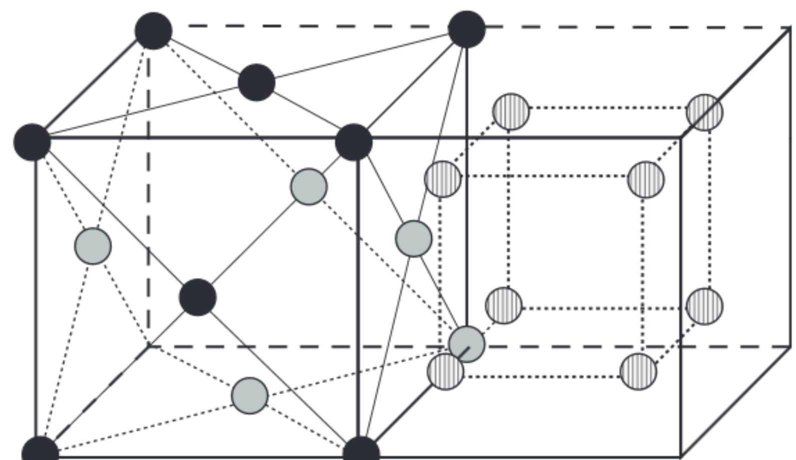
- General considerations
- Thermal properties: thermal conductivity and heat capacity
- Mechanical properties: Elastic and plastic deformation, thermal expansion, density and swelling, pellet cracking
- Fission gas behavior: intra- and intergranular behavior, fission gas release, grain size development
- Special topics: Pellet-cladding interaction, high burnup structure, mixed-oxide fuel, fuels with dopants



The fuel pellet

The fuel pellet

- Typical LWR fuel pellets are cylindrical and made of uranium oxide (UO_2) or uranium-plutonium oxide (MOX)
- Density about 95 % of theoretical, porosity to accommodate fission product formation
- Uranium oxide has a fluorite-type structure
- In reality, the structure contains defects:
  - Interstitials: excess atoms
  - Vacancies: missing atoms
- Typical fresh LWR fuel has oxygen interstitials (UO_2) or vacancies (MOX)



Fluorite structure (3D)

Upper figure: AREVA
Bottom figure: Guéneau, Chartier & van Brutzel, Ch. 2.02, Comprehensive Nuclear Materials (2012)

Environment of the fuel pellet

- Three main factors have an effect on fuel pellet properties during irradiation in a nuclear reactor:

1. Change of composition
2. Irradiation
3. Changes in temperature and the temperature gradient
4. Interaction with the surroundings (mostly cladding)

- Effects from 1 and 2 often grouped together as the burnup, amount of power produced per amount of material
  - Correlations often based on burnup, which is a gross simplification

Change of composition

- Fission typically produces two (rarely three) fission products and a number of neutrons
- Neutron activation forms higher actinides (Np, Pu, Am, Cm…)
  - For example:

    $^{238}U + n \rightarrow {}^{239}U \rightarrow {}^{239}Np + \beta \rightarrow {}^{239}Pu + \beta$
- Chemical differences result in defects in uranium oxide and precipitation of secondary phases

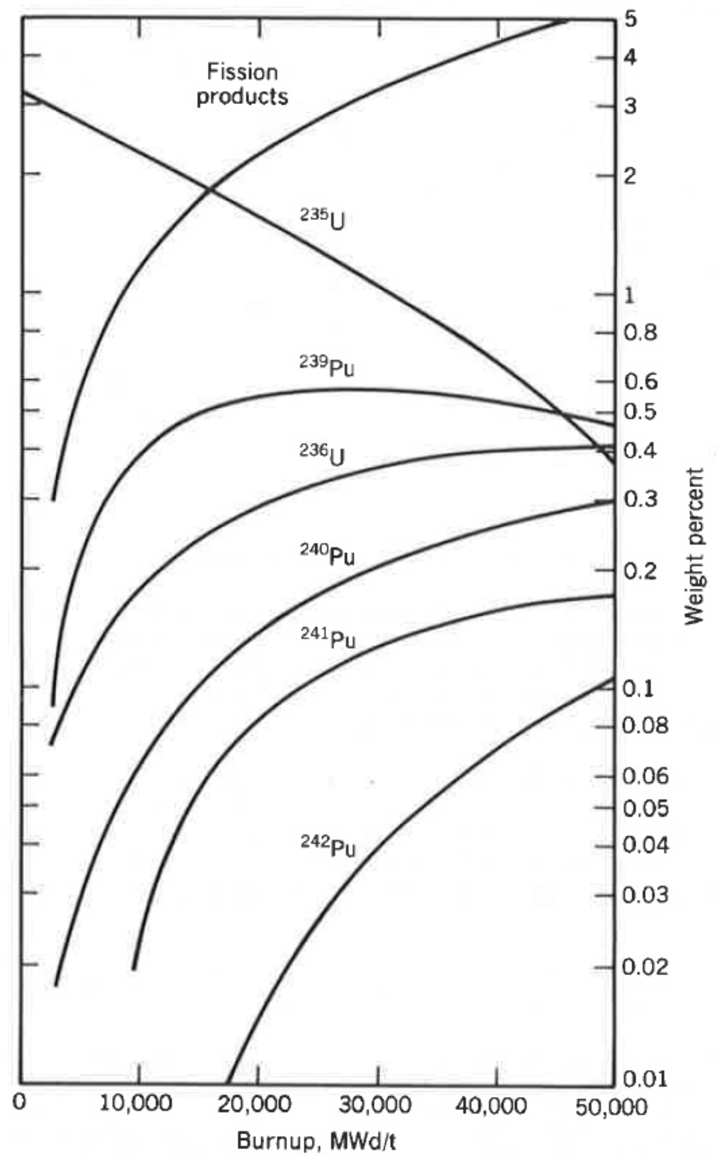


Figure: Rahn et al. A Guide to Nuclear Power Technology, 1984.

Changes in temperature and the temperature gradient

- Practically all material properties are temperature-dependent in some way

- Changes in temperature result in strains in the pellet
- Steep temperature gradient across a short distance results in tensile stresses on pellet outer rim
  - Inside of the pellet expands more than the outer part

Irradiation

- Irradiation produces damage cascades in solids
- Two sources are prominent: fission fragments and neutrons
- Fission product kinetic energy is dissipated as heat
  - Basis of nuclear power production
  - Heavy ions produce heavy damage
- Neutrons produce less but significant damage

Fission track on fuel surface:

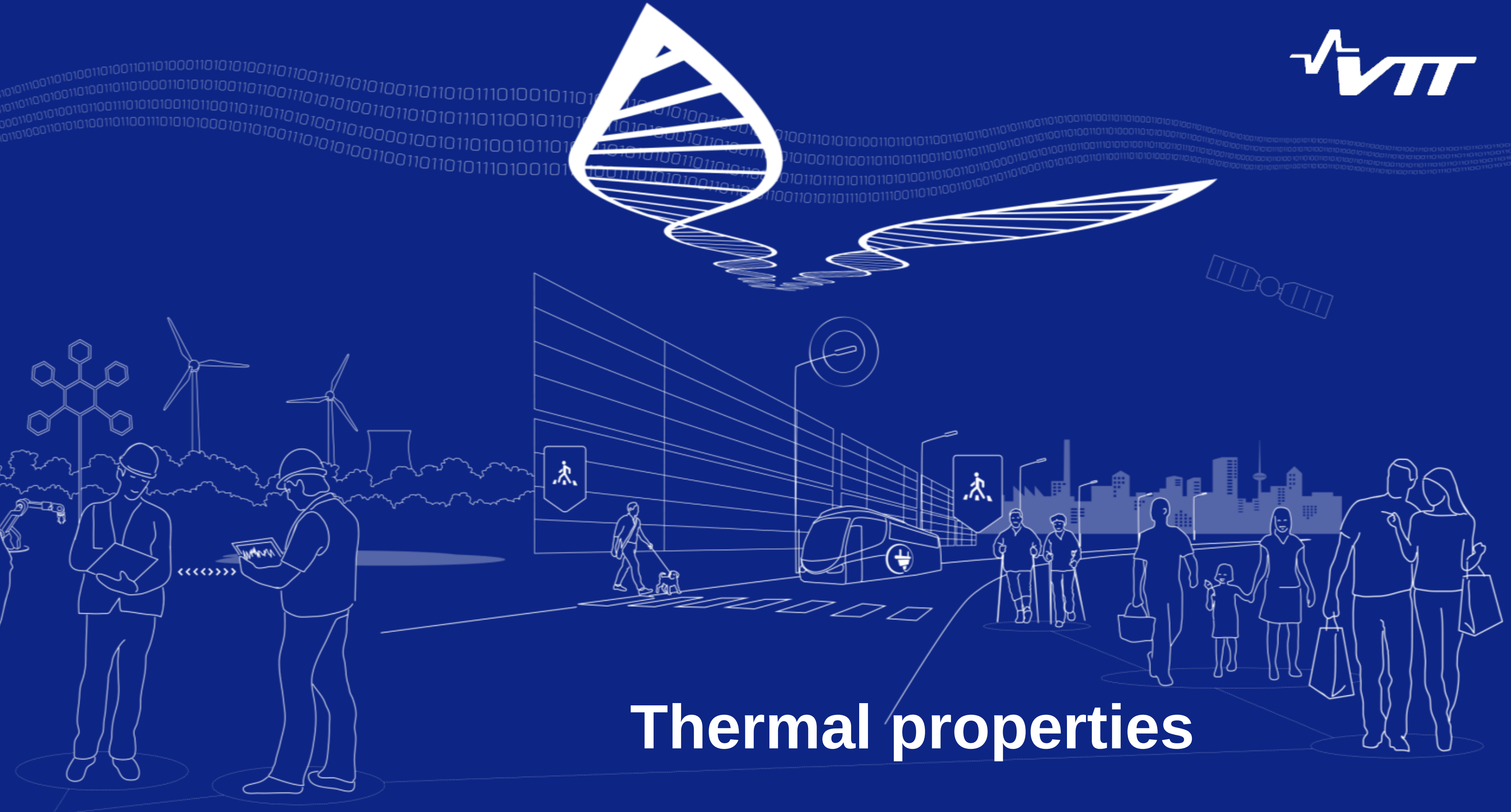
Collision cascade video (PSI)

Picture: C. Ronchi, J. Appl. Phys. 44 (1973) 3575

Interaction with surroundings

- In intact fuel: cladding
  - Mechanical interaction: pellet pushes on the cladding
  - Chemical interaction: chemical species from the pellet react with the cladding
- In breached fuel: coolant
  - Oxidation of fuel by reaction with water

Picture: C. Ronchi, J. Appl. Phys. 44 (1973) 3575



Thermal properties

Thermal conductivity (1/2)

- Thermal conductivity of uranium oxide is poor
  - Uranium oxide: 3.5
  - Zircaloy: 21.5

  $W \cdot m^{-1} \cdot K^{-1}$ @ 1000 K

- Conduction of heat (movement of phonons) is more efficient through a perfect crystal

- Defects lower the thermal conductivity
  - Higher burnup lowers th. cond. → more defects
  - Higher porosity lowers th. cond. → more insulating gas
  - Deviation from stoichiometry lowers th. cond. → more defects

Thermal conductivity (2/2)

- Example: NFI thermal conductivity model for 95 % dense fuel (Ohira & Itagaki, 1997)

$$k = \frac{1}{a + bx_{Gd} + cT + f(Bu) + \left(1 - 0.9e^{-0.04Bu}\right)g(Bu)h(T)} + \frac{d}{T^2}e^{\left(-\frac{f}{T}\right)}$$

  - T = temperature
  - Bu = burnup
  - x_{Gd} = weight fraction of gadolinia
  - f(Bu) = effect of fission product defects
  - g(Bu) = effect of irradiation defects
  - h(T) = irradiation defect annealing term
  - a,b,c,d,f = constants

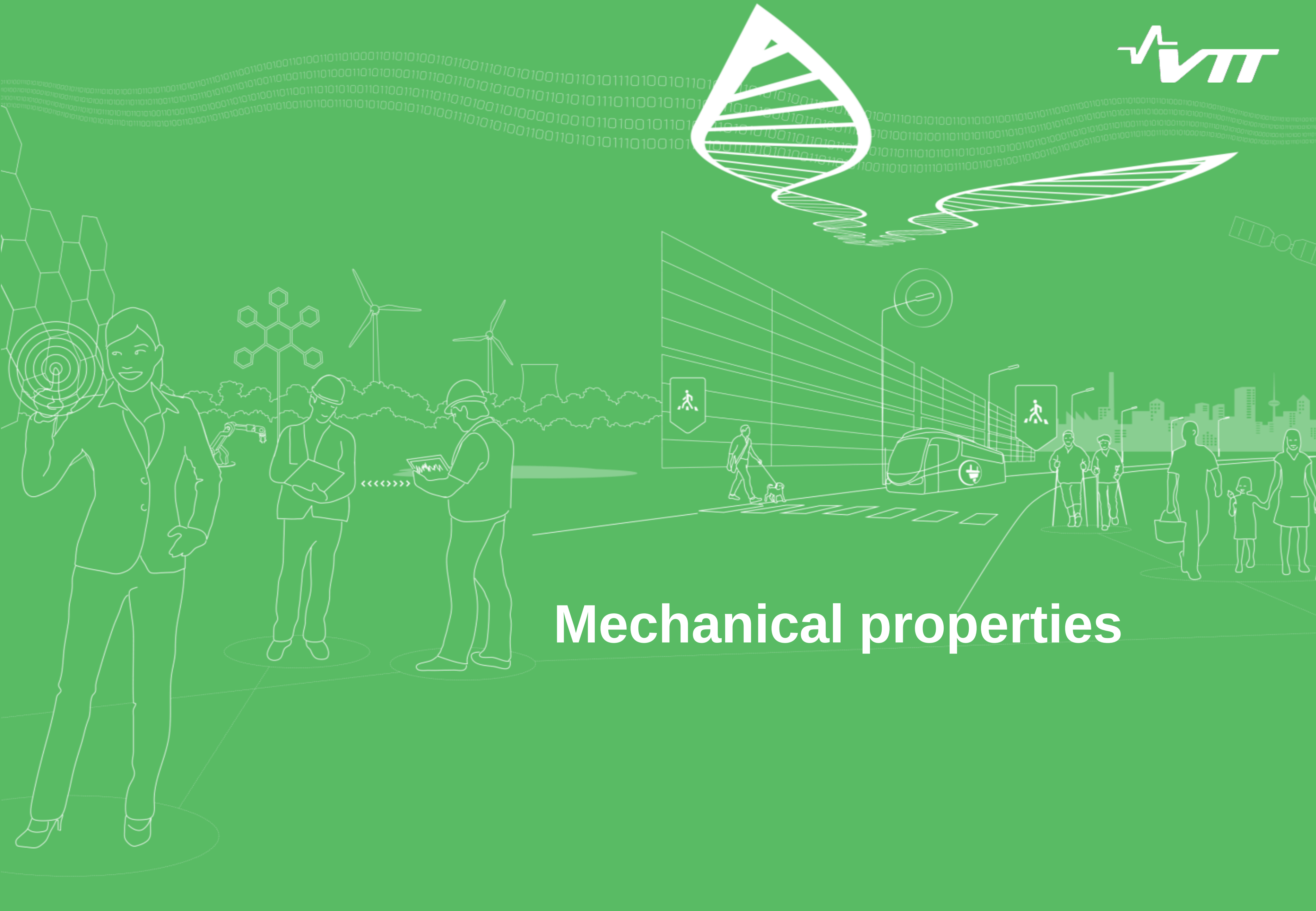
Ohira & Itagaki, Proc. ANS Int. Meet. LWR Fuel Perf. 1997, p. 541-549.

Heat capacity

- Amount of heat added to/removed from the fuel per unit temperature
- Dependent on temperature

- Heat capacity does not affect the fuel temperature distribution in steady-state conditions
- Important in transient conditions

- Discontinuous behavior (λ-transition) for UO_2 at 2670 K



Mechanical properties

Elastic deformation

- To some extent, the fuel pellet responds elastically to applied stress
- Compressive stress through contact with the cladding
- Many fuel performance codes use the rigid-pellet approximation, e.g. no elastic deformation of the pellet

- If taken into account, Hooke's law can be thought to be valid, so strains and stresses are related by

$$\varepsilon_{ij} = \frac{1}{E}\left(\sigma_{ij} - v\left(\sigma_{kk}\delta_{ij} - \sigma_{ij}\right)\right), \text{ where}$$

  - E = Young's modulus (dependent on temperature)
  - v = Poisson's ratio
  - ε = strains
  - σ = stresses

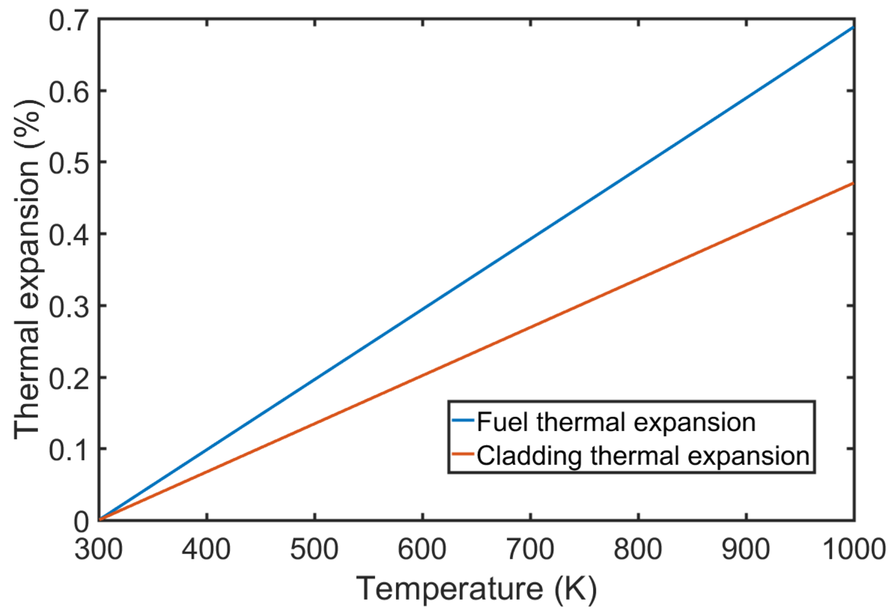
Permanent deformation

- No consistent nomenclature, but permanent (non-reversible) deformation can be classified to at least two types:
  - Time-independent plastic deformation
  - Time-dependent plastic deformation (creep)
- Due to the rigid-pellet approximation, plastic behavior of the pellet is often neglected
  - Can happen during power ramps, at pellet ends (stress concentrations – need 3D modelling)
- Deformation due to thermal expansion and fission product accumulation is treated separately (next)
- Cracking of fuel is treated implicitly in 1.5D fuel performance codes (later)

Thermal expansion

- UO_2 lattice expands to accommodate more thermal vibration when temperature rises

- Cladding expands less than fuel with rising temperature
- This leads to eventual contact between fuel and cladding



- Typically modelled with a polynomial temperature dependence
- Thermal strain is set to zero at some reference temperature

Densification

- Fuel density initially typically around 95 % of theoretical density
    - The rest are pores between fuel grains
- At the start of operation (below 10 MWd/kgU), fuel density increases typically to around 96 to 97% of TD
    - Temperature-dependent process

- In-reactor densification and ex-reactor sintering are related but not the same
    - Point defects from irradiation accelerate fuel densification
- Increases gap size, so decreases thermal conduction through the gap

See, for example, Paraschiv et al. JNM 302 (2002) 109-124 and Olander, Fundamental Aspects of Nuclear Reactor Fuel Elements, 1976.

Densification correlations

- FRAPCON model:

$$\frac{\Delta L}{L} = \left(\frac{\Delta L}{L}\right)_{max} + \exp\left(-3(B+b)\right) + 2\exp\left(-35(B+b)\right),$$

where B = fuel burnup, b = a constant, $\left(\frac{\Delta L}{L}\right)_{max}$ = maximum densification

- Maximum densification can be calculated based on, for example (FRAPCON & MATPRO):
  - Experimental resintering tests and the measured densification
  - Based on the initial density of the fuel pellet and sintering temperature

Fuel swelling

- As fission products form in the fuel, the pellet swells
- Two main processes working concurrently
  - Swelling due to solid fission products
  - Swelling due to gaseous fission products
- Decreases the gap size with burnup, so thermal conduction through the gap increases

More information in Olander, Fundamental Aspects of Nuclear Reactor Fuel Elements, 1976.

Solid fission product swelling

- Solid swelling is caused by the solution of solid fission products into the uranium oxide lattice and their different molar volumes

- Example correlation by Anselin:

$$\frac{\Delta V}{V} = \left(\sum Y_i \frac{V_{m,i}}{V_{m,UO2}} - 1 \right) B$$

Where Y_i are the cumulative fission yields of fission products, $V_{m,i}$ the partial molar volumes of fission products and $V_{m,UO2}$ the partial molar volume of UO_2 and B the burnup

- For example, FRAPCON simplifies the burnup multiplier to $6.2 \cdot 10^{-4}$ at 6 to 80 MWd/kgU, and $8.6 \cdot 10^{-4}$ at over 80 MWd/kgU

Anselin, GEAP-5583, 1969.

Gaseous fission product swelling

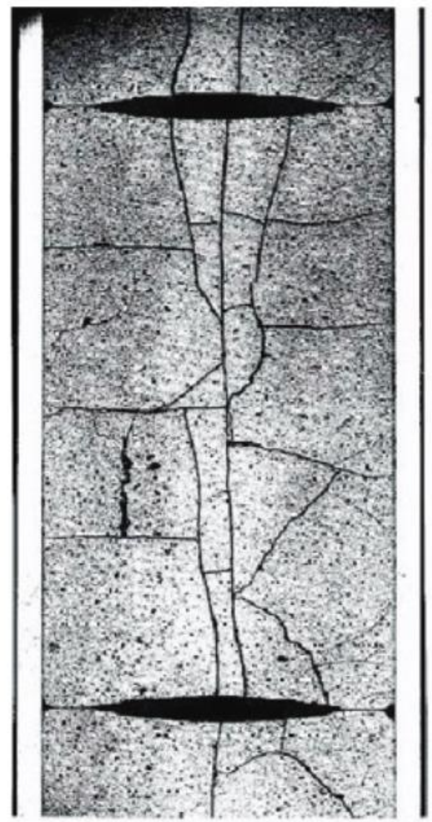
- Gaseous fission products form bubbles both within grains and on the grain boundaries
- Highly dependent on behaviour of fission gases (later)

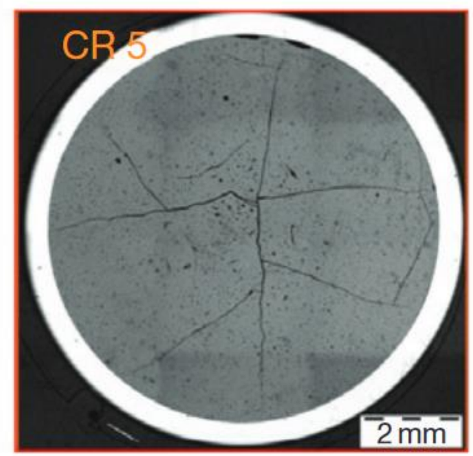
- Number density of bubbles and average volume can be calculated both within grains and on grain boundaries
  - With molar volumes of gas atoms, the increase in fuel volume can be calculated

- Also simpler models with just a temperature dependence are used (FRAPCON)

Pellet cracking (1/3)

- Strains due to thermal expansion cause the pellet to crack
- Higher power and higher temperature leads to more cracks
- Highly stochastic process
- Detailed analysis requires 2D or 3D modeling





Pellet cracking (2/3)

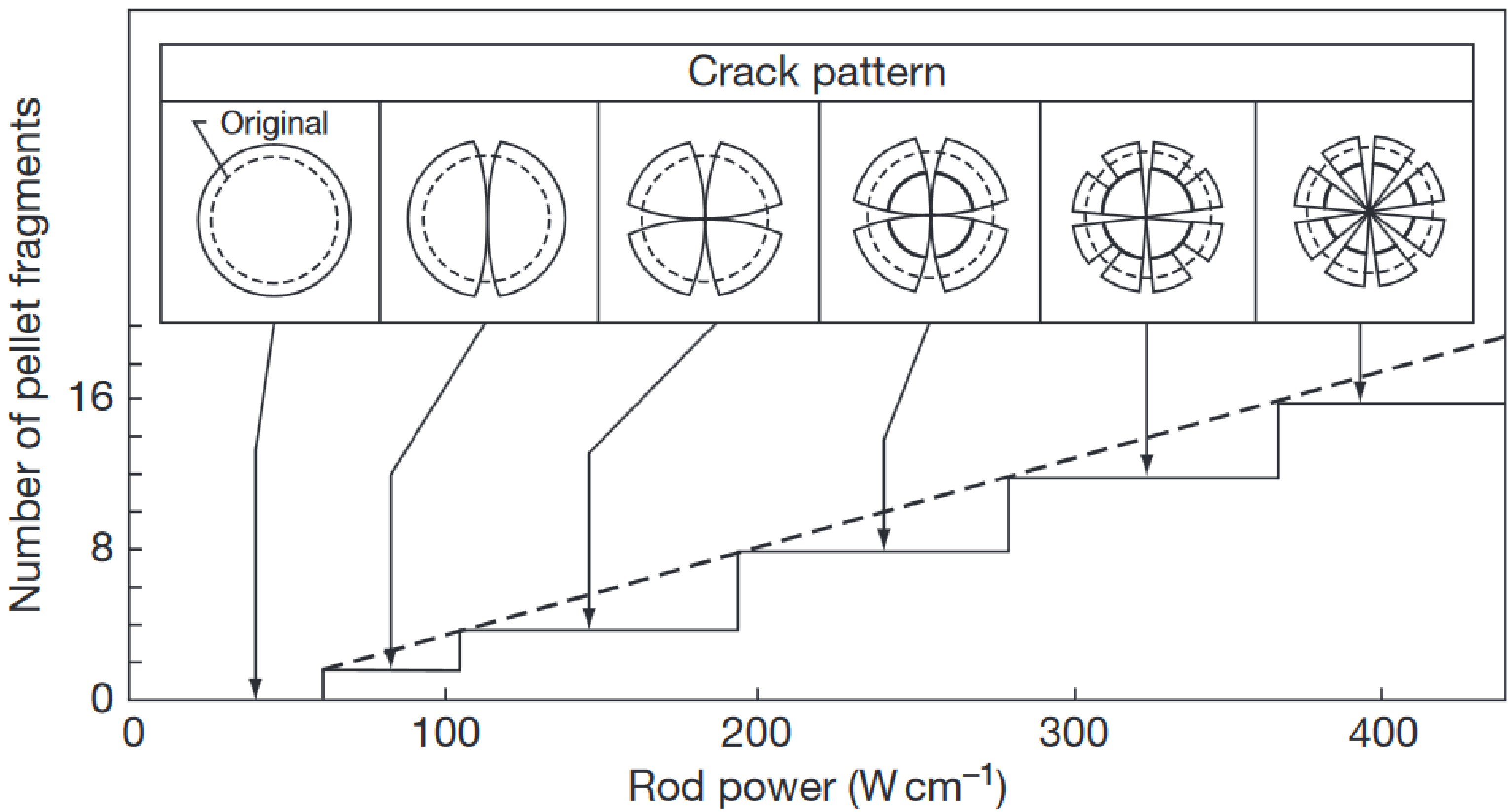


Figure: van Uffelen et al., Chapter 13, pp 1520-1627, in Handbook of Nuclear Engineering, 2010.

Pellet cracking (3/3)

- Thermal properties
- In effect, radial cracks reduce the gap
- Azimuthal cracks create thermal resistance inside the pellet – only small effect to centreline temperature

$$\sigma_{\theta,\max} = \frac{E_\alpha}{2(1-\upsilon)}(T_c - T_S)$$

$$T_c - T_S = 2\frac{1-\upsilon}{E_\alpha}\sigma_{\text{frac}}$$

- Mechanical properties
- Some ignore
  - e.g. rigid pellet model FRACAS
- Affect the pellet properties
  - Calculate pellet stresses, crack if stress over boundary value
  - Number of cracks affects pellet elastic properties
  - Model the pellet expansion due to cracks
- Direct simulation
  - Requires 3D
  - Much information

Pellet relocation

- In a 1.5D fuel performance code, the effect of pellet cracking is often taken into account through pellet relocation
- The pellet fragments are thought to move towards the cladding, decreasing gap size
- Decrease in gap size leads to better thermal conduction through the gap

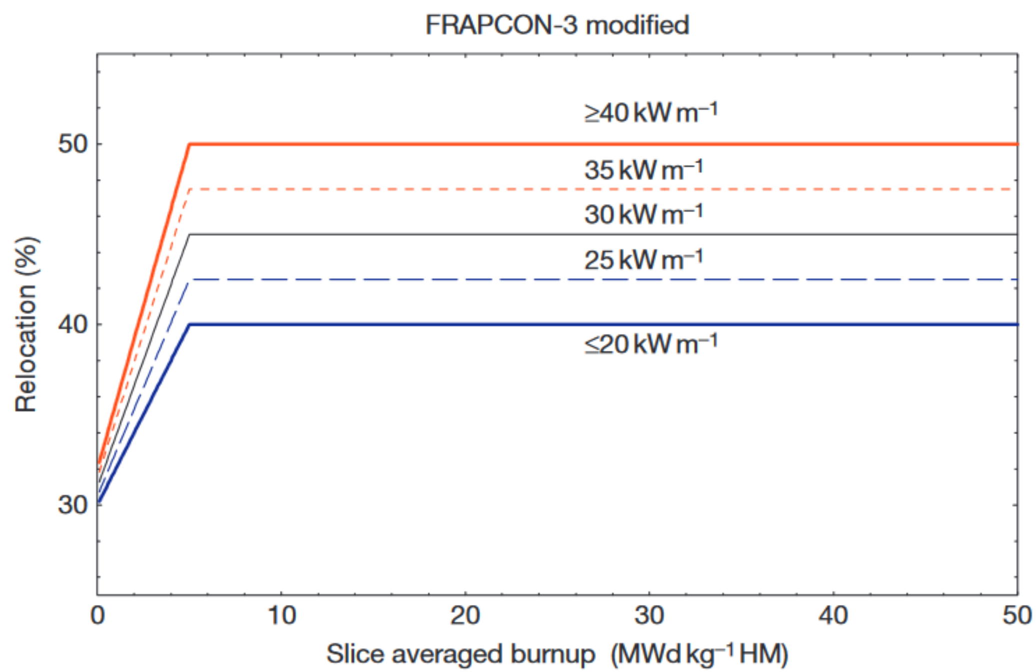


Figure: van Uffelen et al., Chapter 13, pp 1520-1627, in Handbook of Nuclear Engineering, 2010.

Fission gas behavior

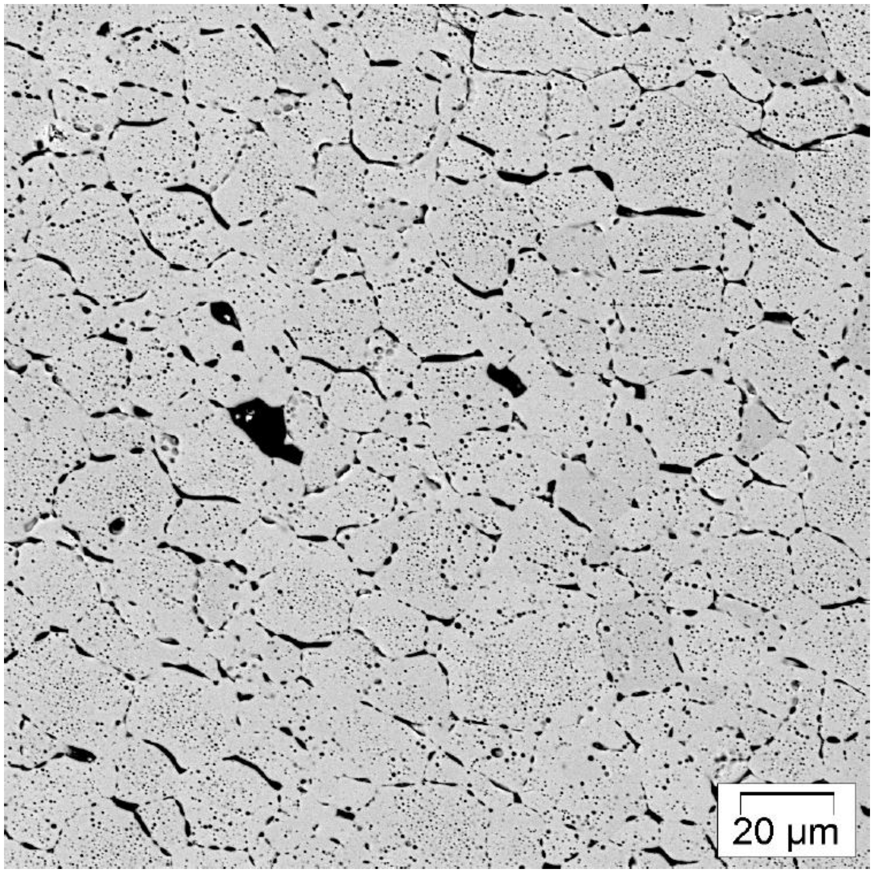
Fission gas behavior in general

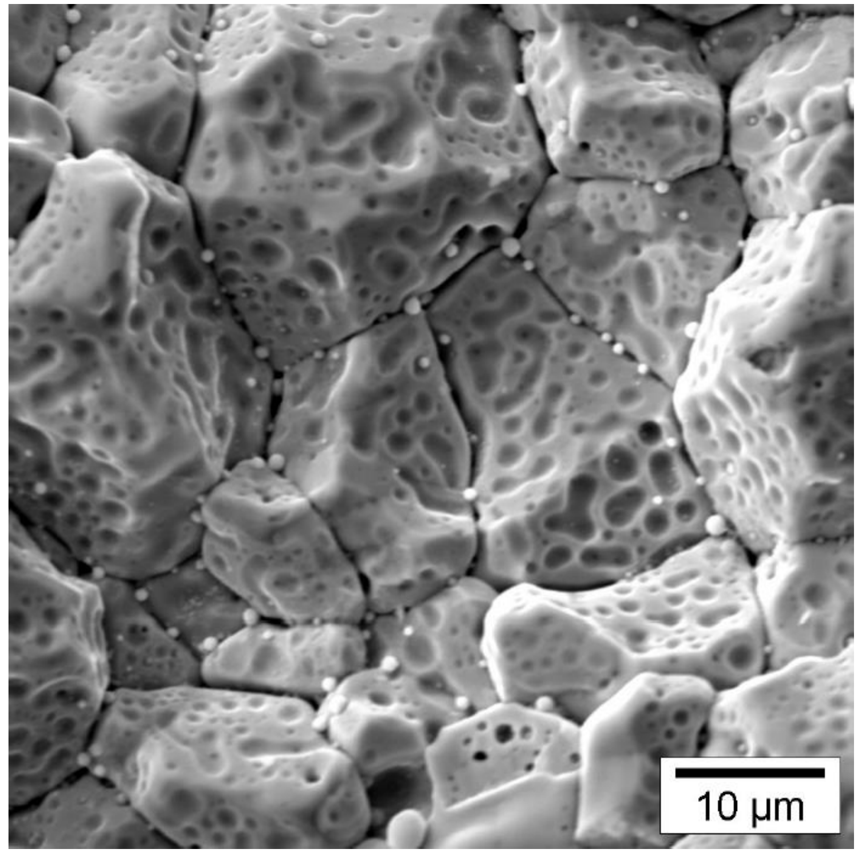
- On average, about 3 gas atoms (xenon and krypton) are produced with every 10 fissions

- Gas atoms form inside the fuel grains
- Gas atoms are insoluble and form bubbles within grains
- Gas atoms diffuse to grain boundaries and form bubbles between grains

- With a sufficient bubble coverage of grain boundaries, gases are thought to escape to free volume of the fuel rod (interconnection of bubbles)
- Increase in gas mole amount increases the internal pressure of the rod

Intra- and intergranular bubbles





Pictures: J. Noirot, IAEA-TECDOC-1635 (2009)

Important phenomena in fission gas behavior

- Production of fission gas
- Recoil and knockout
- Irradiation-induced resolution
- Intragranular diffusion
- Intragranular bubble formation
- Intragranular bubble growth, destruction and diffusion
- Grain boundary bubble formation
- Grain boundary bubble growth and coalescence

Intragranular behavior (1/3)

- The classic description is **the Booth model**, where gas is created uniformly in a spherical grain of radius a and time evolution is governed by

$$\frac{\partial C}{\partial t} = D\nabla^2 C + \beta,$$

where D is the diffusion coefficient and β the gas generation rate.

- Diffusion coefficient for xenon and krypton is often assumed to be the same, classic model is that of Turnbull:

$$D = a \exp\left(\frac{-E_1}{kT}\right) + b\,\dot{F} \exp\left(\frac{-E_2}{kT}\right)$$

where a, b, E_1 and E_2 are constants and $\dot{F}$ is the fission rate.

Booth, AECL 496 (1957)

Intragranular behavior (2/3)

- Turnbull later redefined the diffusion coefficients:

$$D = 7.6 \times 10^{-10} \exp\left(\frac{-35000}{T}\right) + 5.64 \times 10^{-25} \sqrt{\dot{F}} \exp\left(\frac{-13800}{T}\right) + 8 \times 10^{-40}\, \dot{F}$$

- First term being the temperature driven diffusion
- Middle term diffusion through thermal and and irradiation induced vacancies
- Last term the athermal term dominating at low temperatures

Intragranular behavior (3/3)

- Booth assumes that the fission gases move through the fuel lattice and do not react with traps
  - Traps include bubbles, dislocations, impurities, vacancy clusters…
- Speight included the presence of trapping sites for the gas atoms implicitly by defining an effective diffusion coefficient

$$D_{\text{eff}} = \frac{b}{b+g} D$$

where b is the rate of irradiation-induced resolution back into the grains from bubbles and g the rate of trapping of gas into bubbles from the grains

- The movement of bubbles can also be implicitly taken into account in the diffusion coefficient

Speight, Nucl. Sci. Eng. 37 (1969) 180-185,
Van Uffelen et al., Nucl. Eng. Tech. 43 (2011) 477-488

Irradiation-induced processes

- Irradiation-induced resolution
  - Irradiation, mainly by energetic fission products, is thought to collapse fission gas bubbles
  - Fission gases dissolve back into the fuel lattice

- Recoil and knockout
  - Recoil means the ejection of a fission gas atom from the fuel with the energy it has gained from fission (a fission fragment)
  - Knockout means the ejection of a fission gas atom from the fuel by having been knocked out by a fission fragment (gaseous or not)

Grain size development

- At high temperatures, grains in the fuel grow to minimize grain boundary area and the associated surface energy
- Grain growth occurs by movement of the grain boundary, which then traps fission gases from the grain (sweeping)
  - Increases gas release
- Larger grain size increases the diffusion path to the grain boundary, reducing the rate of arrival of fission gas to the boundary
  - Decreases gas release

Grain boundary behavior (1/2)

- Eventually the gas atoms diffuse from inside the grain into a sink, e.g. the grain boundary
- Original Booth model treats the sink as perfect, later models (for example, Forsberg-Massih) consider irradiation-induced resolution from the grain boundary
    - If resolution from the grain boundary is neglected, the intra- and intergranular models can be solved independently
- Gas bubbles formed in the grain boundary take a lenticular shape
- With a larger number of gas atoms, the bubbles grow and then coalesce

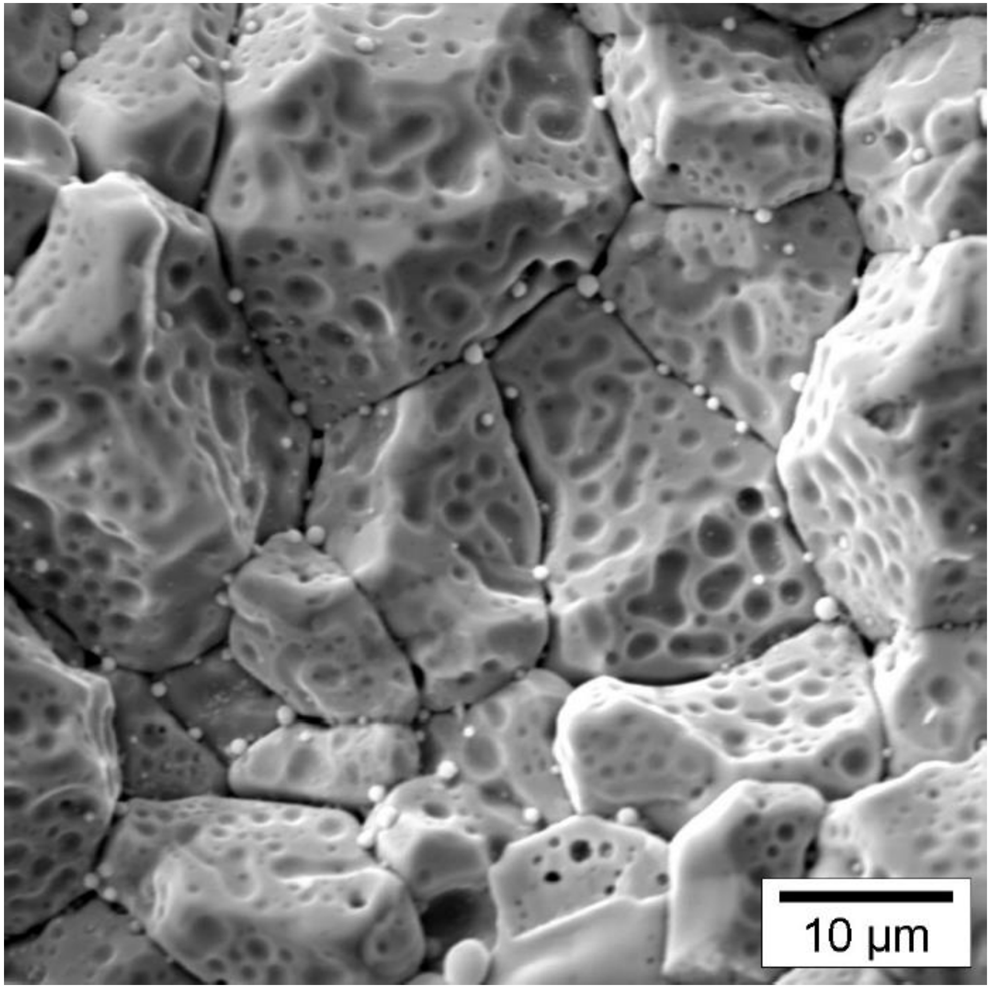
Forsberg & Massih, JNM 135 (1985) 140-148

Grain boundary behavior (2/2)

- Models can be classified into three types (van Uffelen 2012):
  1. Models that do not treat kinetics at the grain boundaries directly
  2. Models that do consider kinetics directly
  3. Complex models in which intra- and intergranular models are solved simultaneously

- Category 1 includes the default model of FRAPCON, where a saturated gas concentration at the grain boundary determines gas release
- Category 2 includes the model used in FINIX, where the development of intragranular bubble growth and coalescence is modeled

Intergranular bubbles



Pictures: J. Noirot, IAEA-TECDOC-1635 (2009)

Bubble growth

- The average volume of a grain boundary bubble is

$$V_{gb} = n_g V_g + n_v V_v$$

where n_i are the numbers of gas atoms or vacancies per bubble and V_i the volumes of a gas atom or vacancy

- The numbers of gas atoms and vacancies vary with time
  - Gas atoms increase the pressure of bubbles when they diffuse into them from the grain
  - Vacancies are absorbed/emitted into/from a bubble to attain mechanical equilibrium

More information from White, JNM 325 (2004) 61-77.

Bubble coalescence

- Growth of bubbles eventually lead to coalescence of bubbles to larger bubbles
  - White (2004) estimates this happens when 19.6 % of the grain boundary surface is covered in bubbles
- Number of bubbles decreases as the average area ($V_{gb} \approx A_{gb}^{\frac{3}{2}}$) of bubbles increase
- The change in the number of grain boundary bubbles due to change of bubble area can be calculated as (White (2004))

$$N_i = \frac{N_{i-1}}{1+2N_{i-1}dA_{gb}}$$

Fission gas release (1/2)

- With a certain number density and size of the bubbles, they are thought to interconnect and release their contents into the rod free volume

- Depending on the type of the fission gas release model, different criteria can be used
  - Saturation concentration, fractional coverage

- Fractional coverage is defined as the product of the number density and average area of bubbles, $N_{gb}A_{gb}$
  - Experiment has shown that fractional coverage saturates at about 50 % → release

Pastore et al., Nucl. Eng. Des. 256 (2013) 75-86
White, JNM 325 (2004) 61-77.

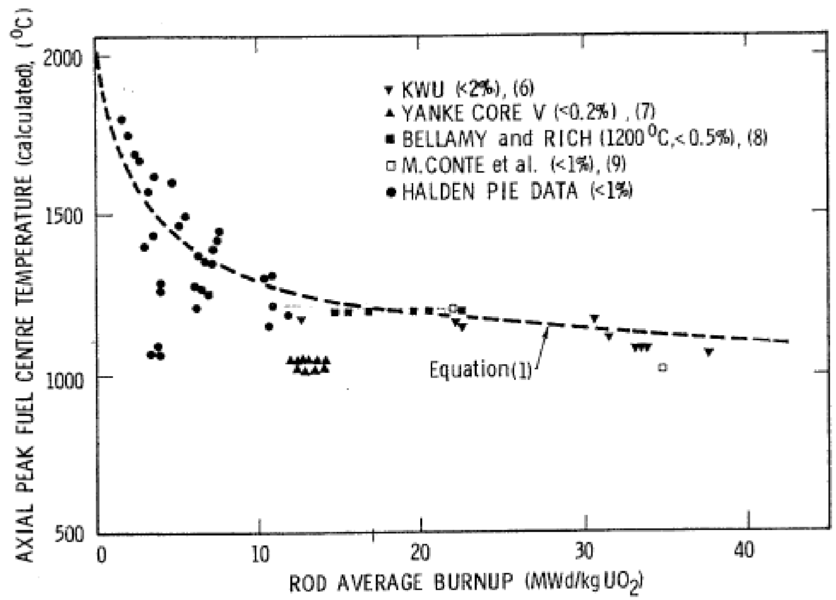
Fission gas release (2/2)

- The experimental Vitanza curve (a.k.a Halden 1% limit) seems to describe fission gas release quite well

$$T_{f,c} = \frac{9800}{\ln(200B)}$$

where $T_{f,c}$ is the fuel centreline temperature and B the burnup in MWd/kg_{UO2}

- Recently new criteria for different fuels have been suggested



Vitanza et al., LWR Fuel Performance Meeting, Portland, Oregon (1979)

Uncertainties in the models

- Large uncertainties in the parameters: for example the uncertainty in the diffusion coefficient of fission gases is at least *one order of magnitude*
- The assumptions of the models may not reflect reality: for example, the effective diffusion coefficient is dependent on the gas concentration
- Transient fission gas release is not understood well

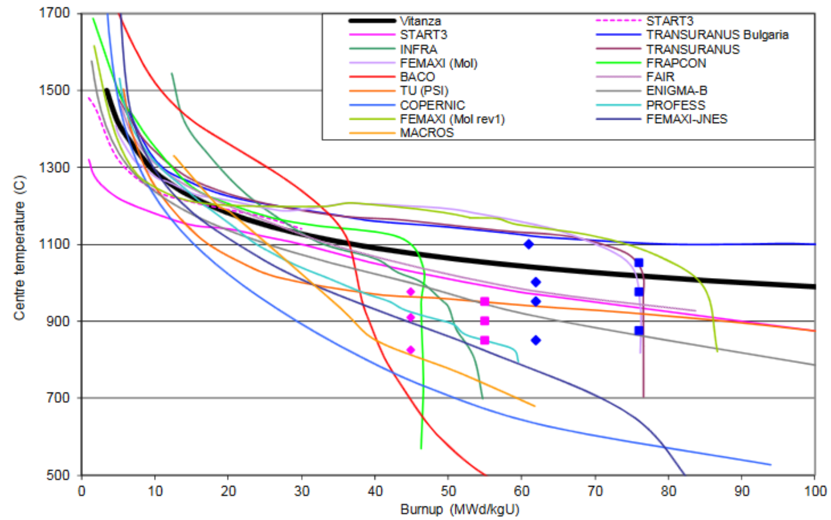


Figure: Modeling in different codes compared to the Vitanza curve from the FUMEX II project

Cladding performance

Cladding deformation

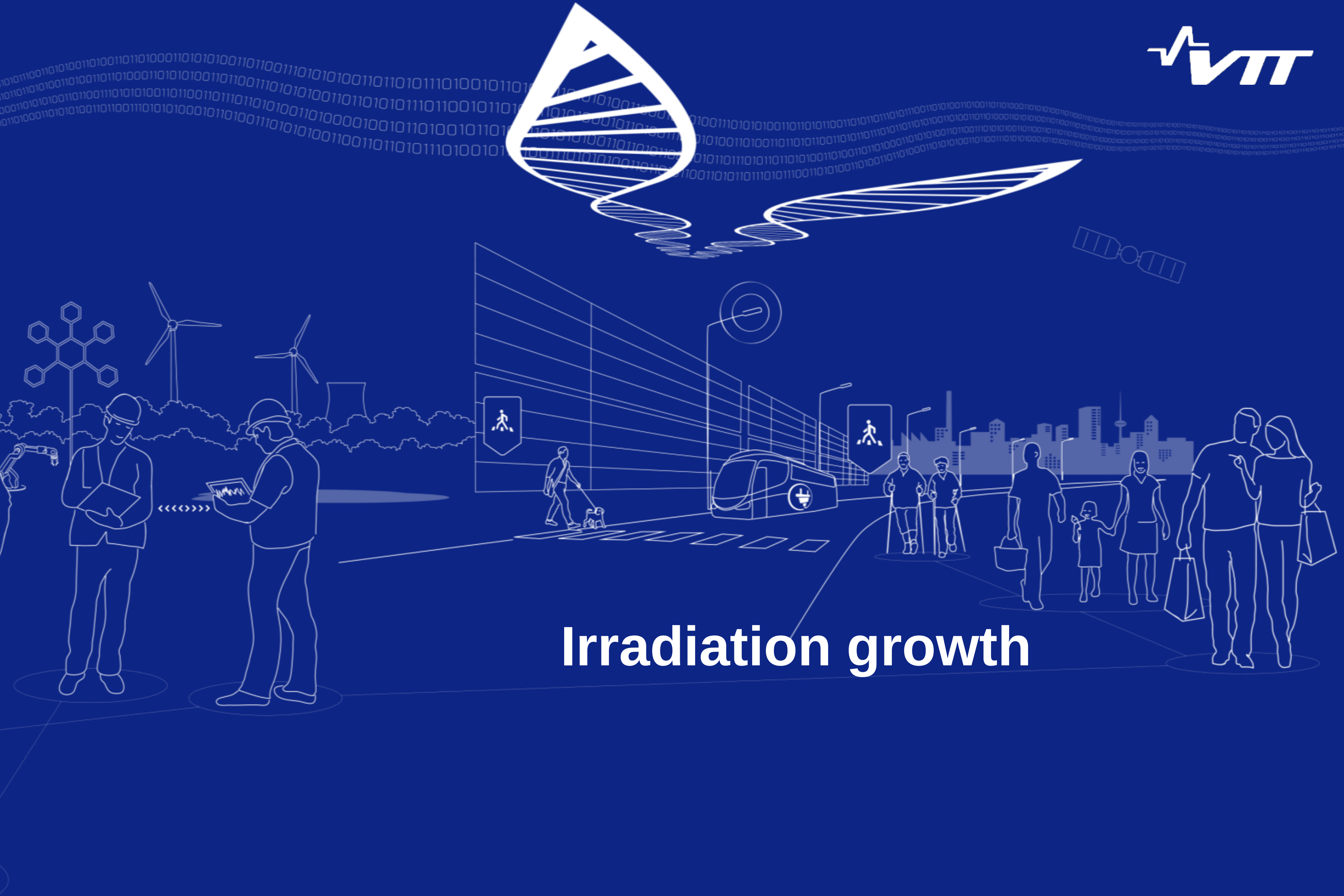
- Instantaneous deformation
  - Elastic and thermal response are assumed to be reversible
  - Plastic deformation happens when the stress exceeds material-depending yield stress
- Creep is
  - Slow deformation under elevated temperatures driven by stress
  - Volume-conserving
- Growth is
  - Deformation of cladding crystal structure under irradiation
  - Volume-conserving

- Also swelling, but
  - It applies mainly to steel claddings and we focus here to zirconium based alloys

Contents

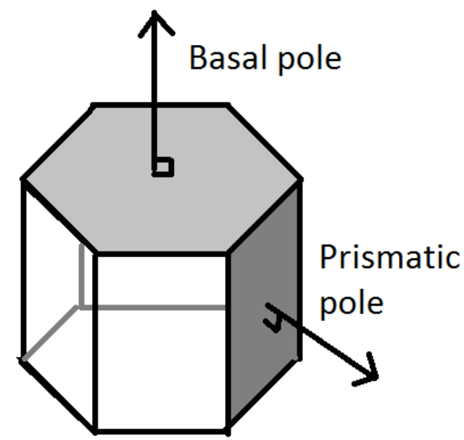
- Growth
  - What it is
  - How and why it shows up
- Stress driven deformation
  - What creep is
  - Mechanisms
  - Engineering approach to creep

Irradiation growth



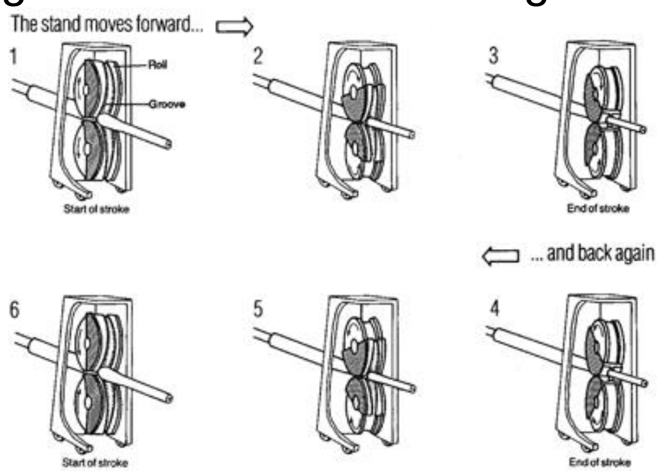
Irradiation growth, simplified version

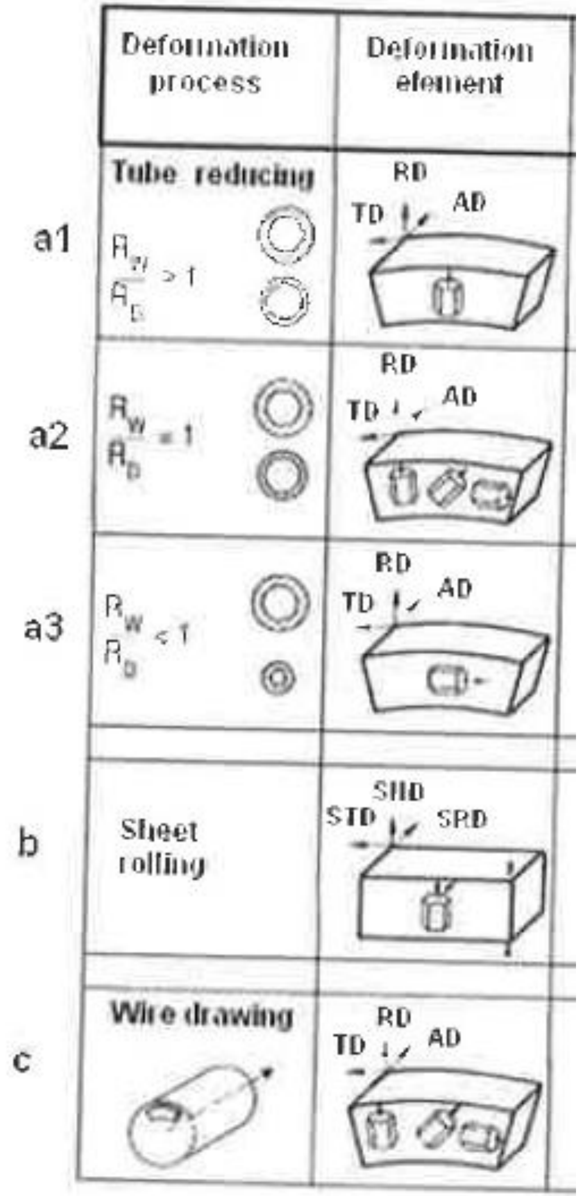
- Irradiation growth is volume-conserving deformation that happens under irradiation to materials with hexagonal close packed crystal structure
  - No stress needed
  - Assumed to be additive to creep
- Decreases the hcp structure in basal pole direction, increases in prismatic pole direction
  - If the grains in the cladding were randomly oriented, the net sum would be negligible



Irradiation growth

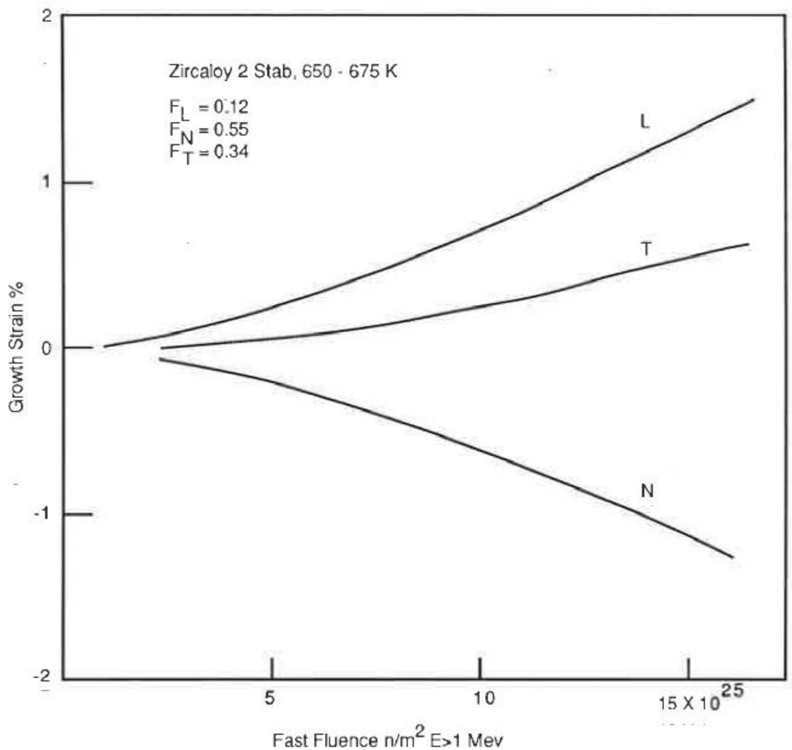
- The irradiation growth is observed macroscopically because the way crystals are oriented
- Cladding tubes are manufactured by pilgering process
  - Crystal preferential orientation depends on ratio of OD and wall thicknes reduction
  - Radially oriented crystals preferred
  - Irradiation growth increases rod length

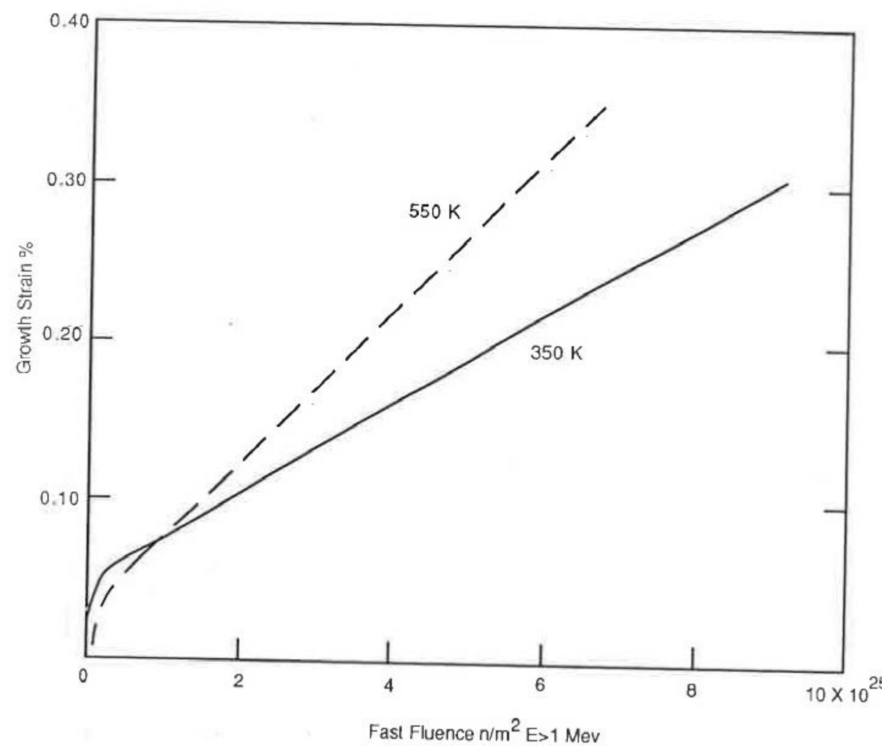




Irradiation growth

- Growth is volume-conserving and approximately linear in relevant conditions

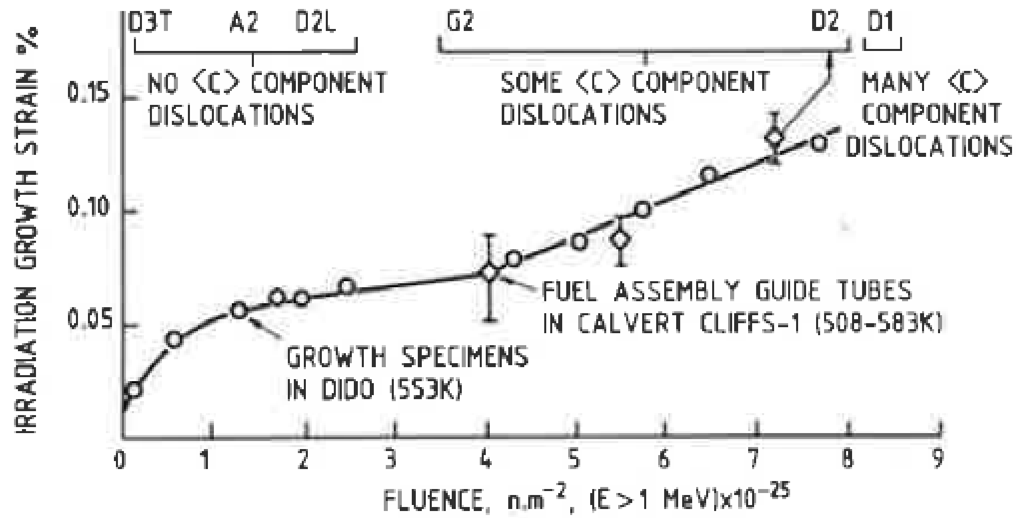


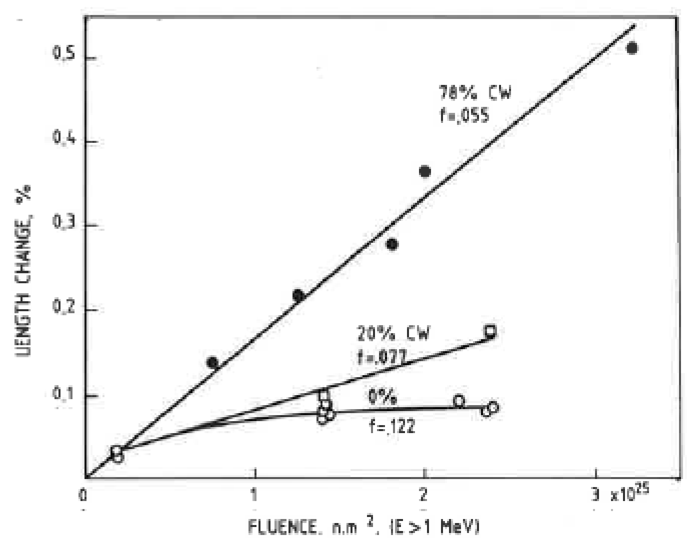


From R.A. Holt, Mechanisms of irradiation growth of alpha-zirconium alloys JNM **159** (1988) 310-338

Complications

- There is an increase in the growth rate for some cladding types at high fluence
- Also cladding with a high cold work ratio grows faster than ones with a low cold work ratio
  - Cold work ratio depends on the final heat treatment



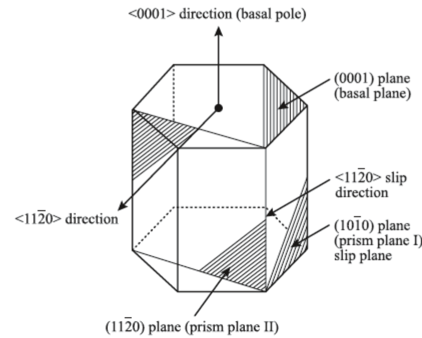


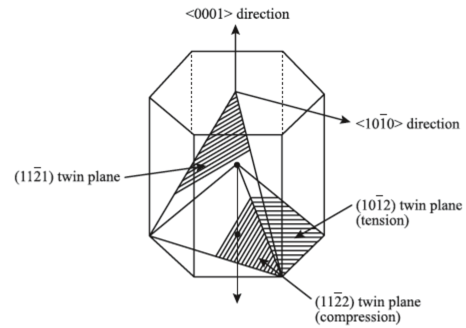
Figures from V. Fidleris, The irradiation creep and growth phenomena, JNM **159** (1988) 22-42

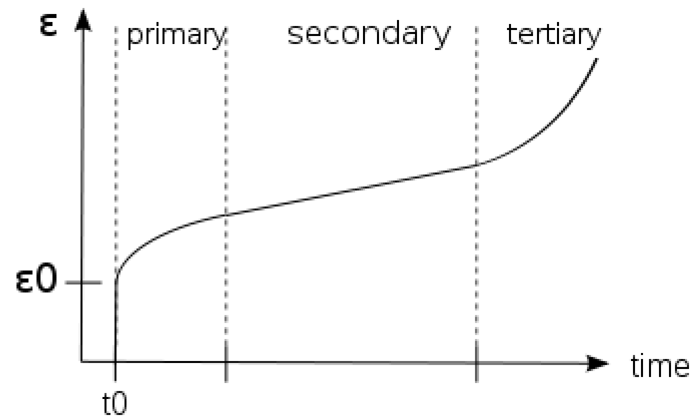
Stress driven cladding deformation

Stress-driven deformations

- Material response commonly assumed to consist of
  - Elastic response
  - Instantaneous plastic response
  - Creep response
- Creep is slow permanent deformation happening below yield stress and at elevated temperatures
  - Three stages
  - Enhanced by irradiation
- Creep is the macroscopic effect of movement of the lattice defects and the grain boundaries
- Driven by stress







"3StageCreep" by Strafpeloton2 - Own work. Licensed under CC0 via Wikimedia Commons - http://commons.wikimedia.org/wiki/File:3StageCreep.svg#/media/File:3StageCreep.svg

On determination of the stress state of the cladding wall

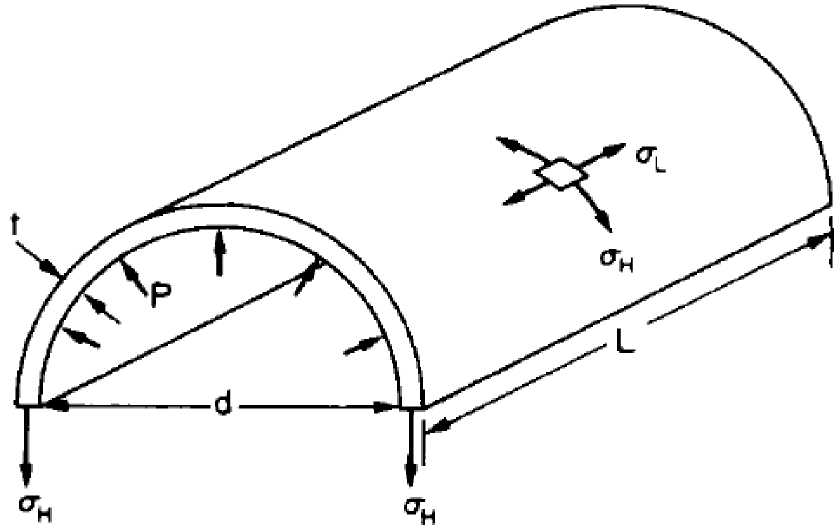
- Local stress state drives the elastic, the plastic and the creep response
  - Hence, we start by determining the stress
- For cladding without hard contact to pellets the stress is determined by the pressure differential across the cladding wall
  - Stress is given and strain changes -> creep
- If pellet pushes the cladding the strain is given and stress changes
  - Stress relaxation
- Well developed approaches using e.g. FEM
- Short detour on determining the stress analytically
  - Assume perfect geometry, isotropic properties

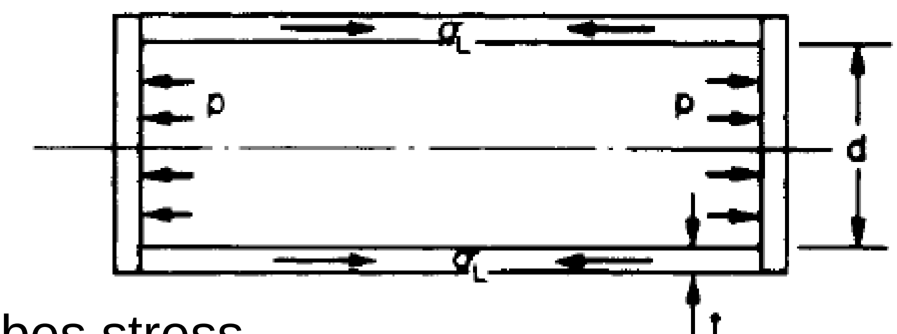
Stress to the cladding wall

- For a thin-walled tube

$$\sigma_h = \frac{Force}{area} = \frac{\Delta P dL}{2dLt} = \frac{\Delta P r}{t}$$

$$\sigma_z = \frac{Force}{Area} = \frac{\Delta P \pi r^2}{2\pi rt} = \frac{\Delta P r}{2t}$$





For thin-walled internally pressurized tubes stress in hoop direction is twice the stress in longitunal direction

Deviatoric stress

- Part of the stress is always hydrostatic
  - In principle, the average of the stress components is just compressive and is not assumed to cause any creep

$$\sigma_{i,dev} = \sigma_i - \sigma_{hydr} = \sigma_i - \left(\sigma_h + \sigma_z + \sigma_r\right)/3$$

$$\sigma_{h,dev} = \sigma_h - \left(\sigma_h + 0.5\sigma_h\right)/3 = 0.5\sigma_h$$

$$\sigma_{z,dev} = \sigma_z - \left(2\sigma_z + \sigma_z\right)/3 = 0$$

- No creep in axial direction!
  - This is why usually irradiation growth is noted only in axial direction
- But, this treatment for thin tubes (wall thickness less than tenth of diameter

Thick walled tube

- Stress distribution (inside the wall) must also taken into account
  - Also radial stresses
  - Often mid-wall stresses calculated

$$\sigma_h = A + \frac{B}{r^2} \qquad A = \frac{r_i^2 P_i - r_o^2 P_o}{r_o^2 - r_i^2}$$

$$\sigma_z = A$$

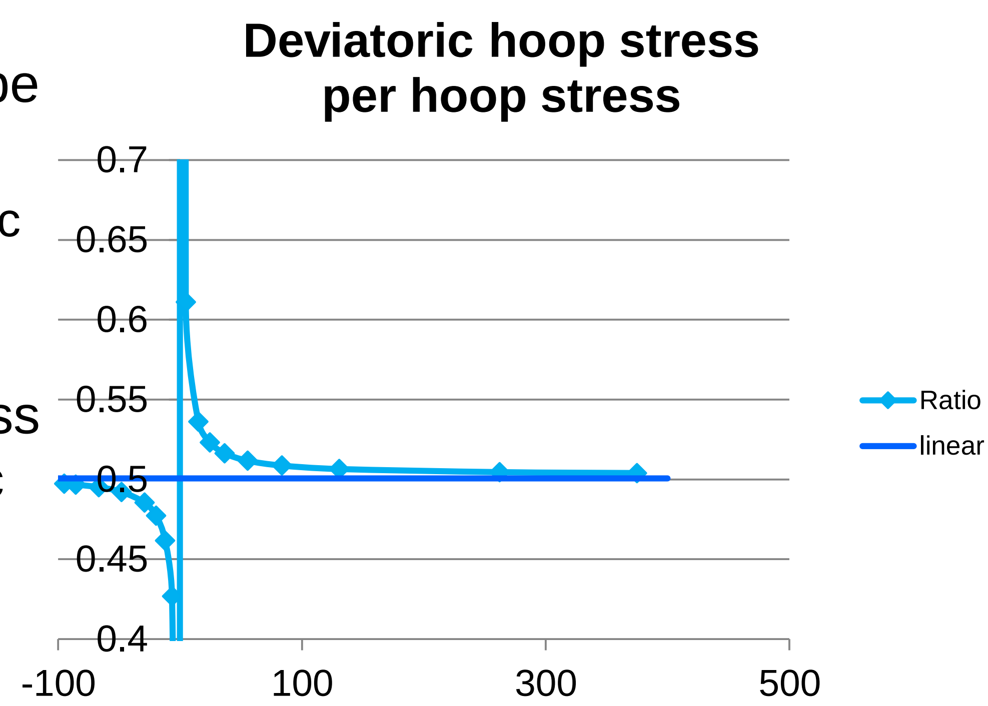
$$\sigma_r = A - \frac{B}{r^2} \qquad B = \frac{(P_i - P_o) r_o r_i}{r_o^2 - r_i^2}$$

- Main conclusions the same, no creep in axial direction
- BUT, hoop stress and deviatoric hoop stress are not zero at the same pressure differential!

Deviatoric hoop stress versus hoop stress

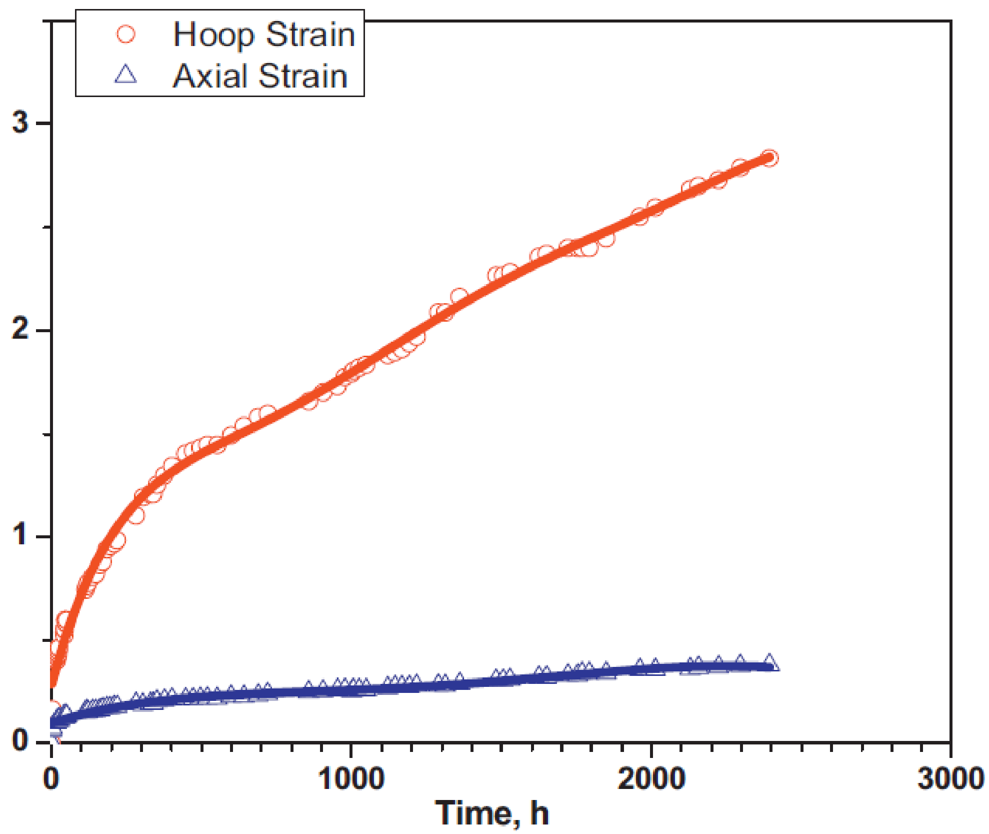
P_o	r_i	r_o	P_i	Ax	hoop	rad		hydr
1	4,7	4,75	1	-1	-1	-1		-1

- If internal and external pressures are the same, mid-wall there will be hoop stress
  - However, it is equal to hydrostatic stress, ergo no creep
- However we see that, using thick wall approximation, the hoop stress is not linearly relative to deviatoric hoop stress at low stresses!



Actual experimental results may differ

We must remember the previous discussion is theoretical



[Mathew, M.D., Ravi, S., Vijayanand, V.D., Latha, S., Dasgupta, A., Laha, K., 2014. Biaxial creep deformation behavior of Fe–14Cr–15Ni–Ti modified austenitic stainless steel fuel cladding tube for sodium cooled fast reactor. Nucl. Eng. Des. 275, 17-22].

Instantenous reversible deformation (elastic and thermal)

Given the internal pressure P, the outside (coolant) pressure P_o, and the cladding inner and outer radii, R_{ci} and R_{co}, the hoop stress σ_θ and the axial stress σ_z are obtained as

$$\sigma_\theta = \frac{R_{ci}P - R_{co}P_o}{R_{co} - R_{ci}}, \tag{27}$$

$$\sigma_z = \frac{R_{ci}^2 P - R_{co}^2 P_o}{R_{co}^2 - R_{ci}^2}. \tag{28}$$

The hoop, axial and radial strains are connected to the stresses through relations

$$\epsilon_\theta = \frac{1}{E}(\sigma_\theta - \nu\sigma_z) + \epsilon_{\text{th}}, \tag{29}$$

$$\epsilon_z = \frac{1}{E}(\sigma_z - \nu\sigma_\theta) + \epsilon_{\text{th}}^{\text{z}}, \tag{30}$$

$$\epsilon_r = -\frac{\nu}{E}(\sigma_\theta + \sigma_z) + \epsilon_{\text{th}}, \tag{31}$$

Plastic deformation

- Often used (simplified) assumption is that below yield stress there is only elastic strain, above it (rate dependent) plastic strain
- Above yield stress, rate-dependant strain curve

$$f_{vM} = \sigma_e - \sigma_Y(\epsilon_e)$$

- Plastic deformation is increased as much as is needed for the stress to return to yield surface f_{vM}=0
- Effective plastic strain remains

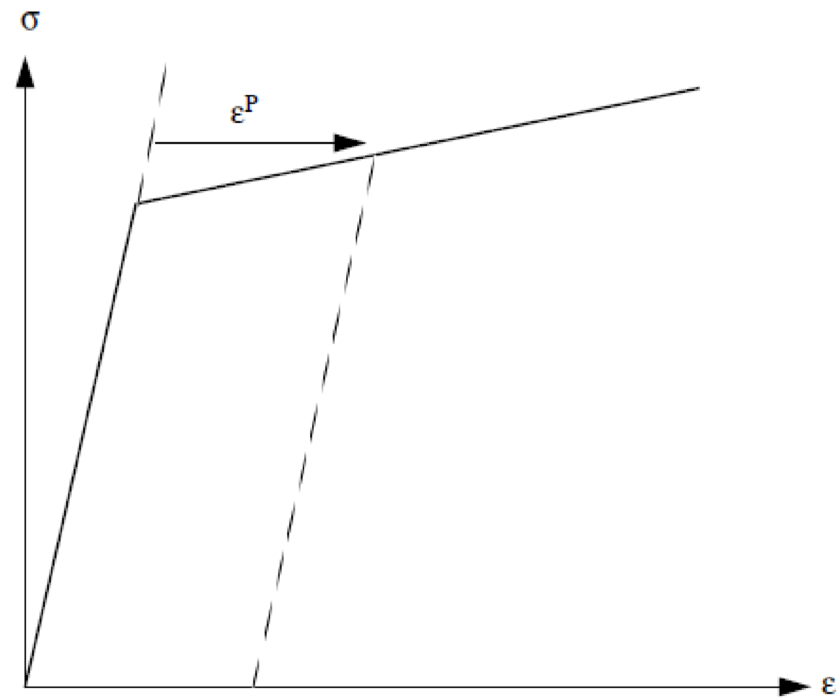


Figure 2.7 Typical Isothermal Stress-Strain Curve

Creep

- Experimental observations
- Mechanisms behind creep deformation
- Modelling of creep

Experimental observations

- Thermal creep in three stages
  - Primary creep with diminishing creep rate
  - Secondary creep with stationary creep rate
  - Tertiary creep with increasing creep rate ending in a break
- Irradiation increases the numbers of various defects
  - Accelerated creep
  - Accelerated material hardening
- At high temperature thermal creep dominates

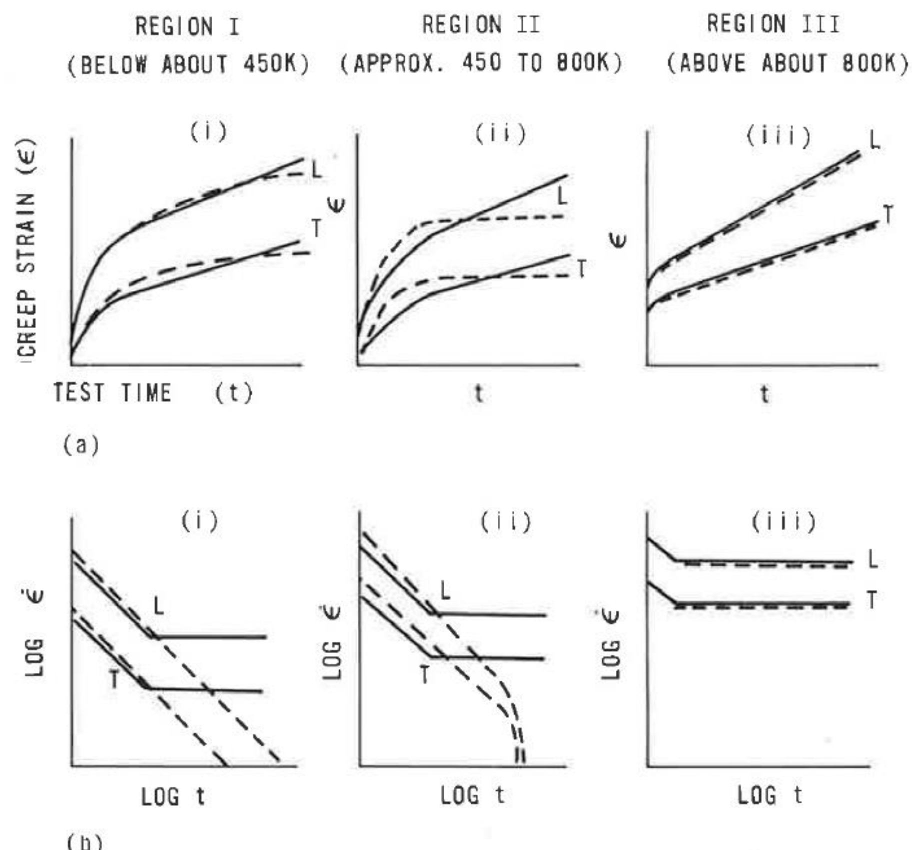


Figure from V. Fidleris, The irradiation creep and growth phenomena, JNM **159** (1988) 22-42

Experimental observations

- At low stress creep rate is relative to the stress
- At medium stress creep rate is approx stress to power of 5
- At high stress the relation is exponential
  - ”Power law breakdown”

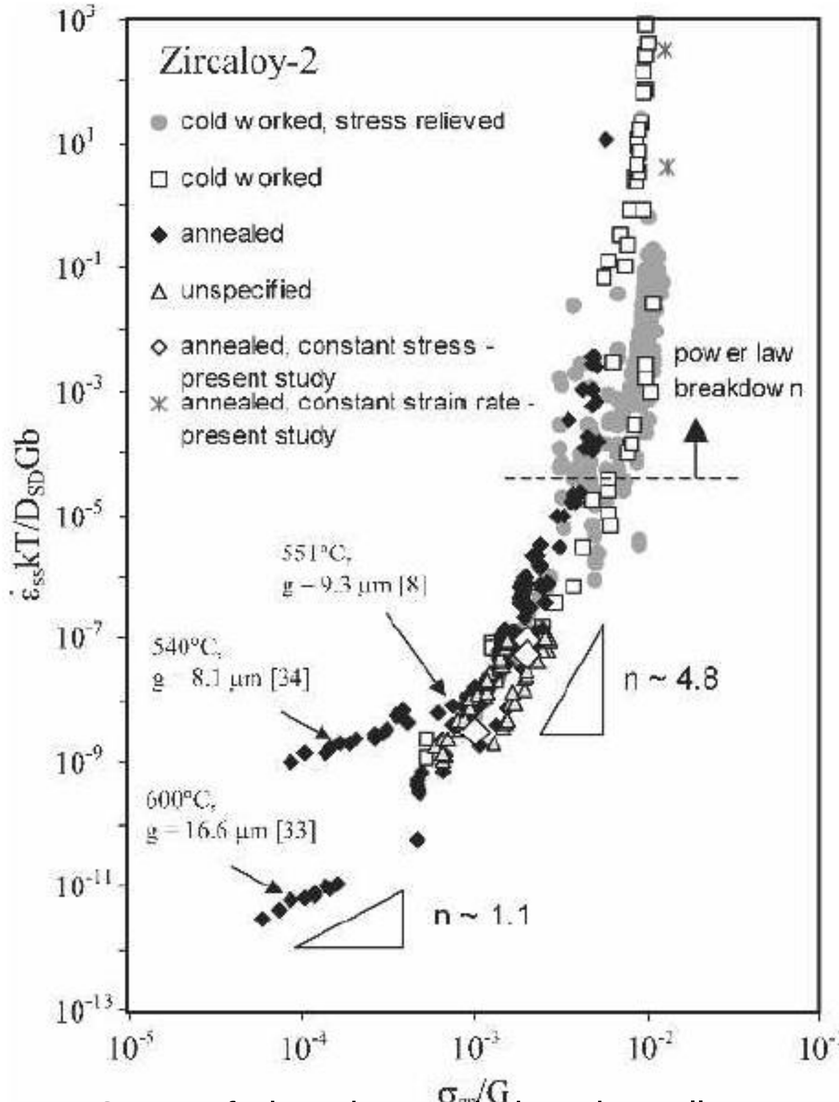


Figure from T.A. Hayes and M.E. Kassner, Creep of Zirconium and Zirconium Alloys, Metallurgical and Materials Transactions A **37A** (2006) 2389-2396

Mechanisms of creep

- Thermal creep
  - Dislocation creep (or climb and glide)
  - Diffusional creep
    - Nabarro-Herring and Coble creep
- Irradiation creep
  - Stress-induced preferential nucleation of loops (SIPN)
  - Stress-induced preferential absorption (SIPA)
  - Climb and glide assisted by irradiation defect formation
- Different mechanisms work at parallel
  - Creep rate determined by the fastest mechanism

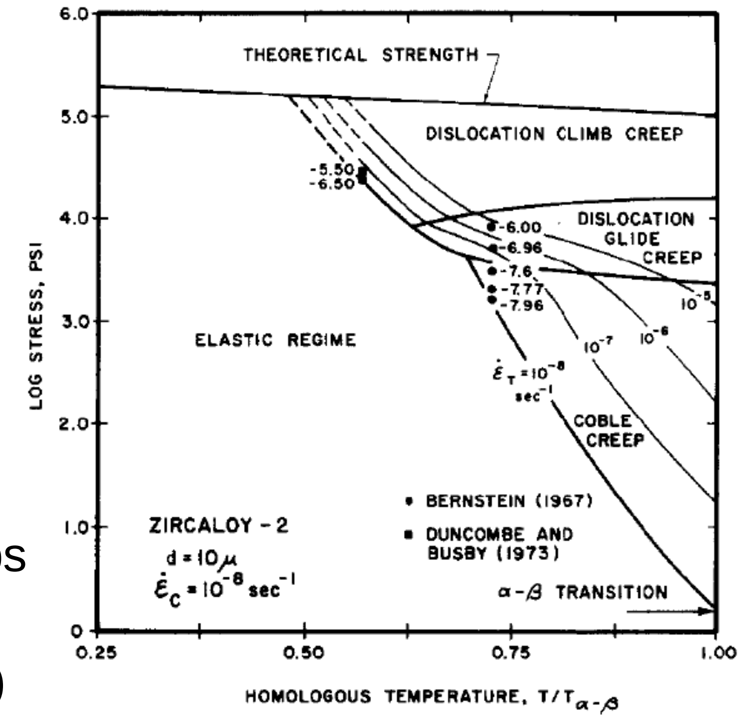
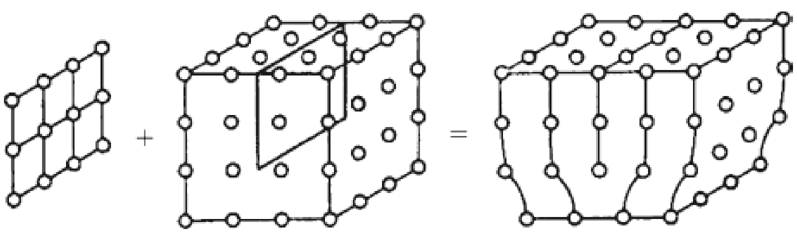
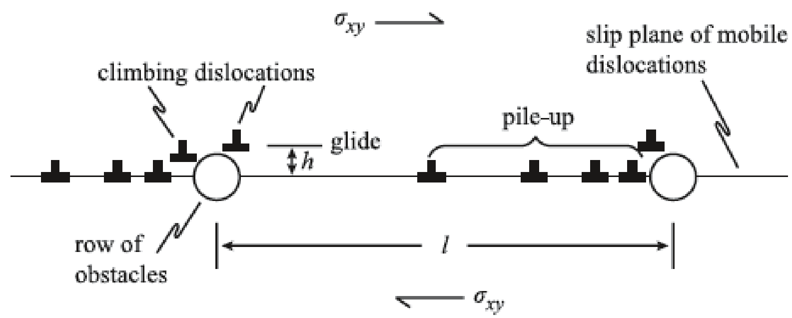


Figure from D. Knorr and M. Notis, Deformation mechanism mapping of alpha-Zr and Zircaloy-2, JNM **56** (1975) 18

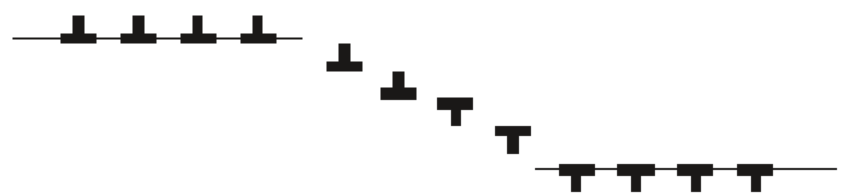
Mechanisms of creep
Thermal creep: Dislocation creep

- Dislocations (deviation from a perfect lattice structure) either exist or are created by the stress
- Dislocations glide through a lattice plane driven through stress
- Glide is arrested by an obstacle
  - Climbing over obstacle takes time / energy
  - Pile-up of dislocations





- Also opposite dislocations attract each other
  - Dislocation annihilation



Figures from G. Was, Fundamentals of Radiation Materials Science, 2007

Mechanisms of creep
Thermal creep: Diffusional creep

- At high temperature and low stresses atom diffusion by way of vacancies a rate determining mechanism
  - Vacancies flow from one grain face to other changing the form of the grain
  - Nabarro-Herring creep
- At lower temperatures grain boundary diffusion dominates
  - Coble creep
- Creep rate relative to stress, depends on grain size

Mechanisms of creep
Irradiation creep

- Stress-Induced Preferential Nucleation of Loops
  - Loops nucleate on preferred planes depending on stress
  - Basically deforms to the direction to tensile stress
- Stress-Induced Preferential Absorption and Preferred Absorption Glide
  - Atoms are transferred from one plane to another due to stress (SIPA)
  - Dislocations glide (PAG)
- …there are several other possible mechanisms also
  - See e.g. G. Was, Fundamentals of Radiation Materials Sceince 2007

Can known mechanisms be attributed to the experimental observations?

- SIPN accounts best the primary creep behaviour
  - Cannot explain steady state creep
- SIPA most likely explanation for in-reactor creep
  - Very little thermal creep at reactor temperatures and stresses

Phenomenological models

- Various formulations for in-reactor creep exists
- In general phenomenological
  - Correlations derived from experiments
  - Information from mechanistic understanding of creep necessarily partially lost
  - Parameters fitted to particular cladding types
  - In general vendors have more data (and thus better predictions) for their own cladding types even if the models may be quite simple

Creep models

- Phenomenological creep models
  - May separate thermal and irradition creep OR just assume in-reactor conditions
  - Usually separate the effects of stress, temperature, flux and fluence as well as material parameters
  - Primary creep may or may not be taken explicitly into account

$$\dot{\varepsilon} = f(\sigma)f(T)f(\phi)f(t)f(\chi)$$

- Some examples to follow

MATPRO creep model

$$\dot{\varepsilon} = K(\sigma + Be^{C\sigma})\phi t^{-0.5} e^{-\frac{Q}{RT}}$$

- Creep rate for in-reactor creep
- Low and high stress responses
- Linear flux dependence
- Constantly lowering creep rate
    - ”Primary creep” and radiation hardening taken into account by it
- Arrhenius function for temperature dependence

Model evolution: Creep model by Matsuo 1987

- For the thermal creep of Zircaloy-4
- Separates primary and secondary creep
- Primary creep magnitude and rate relative to secondary creep rate
- Hyperbolic sin used to model both low and high stress regions
    - *n*=2 has no physical explanation but improves the fitting
- E is the elastic modulus

$$\varepsilon_{tot} = \varepsilon_p^s\left(1 - e^{-C\sqrt{\dot{\varepsilon}_{sec}\cdot t}}\right) + \dot{\varepsilon}_{sec}\cdot t$$

$$\varepsilon_p^s = B(\dot{\varepsilon}_{sec})^b$$

$$\dot{\varepsilon}_{th} = A\left(\frac{E}{T}\right)\left[\sinh\left(\frac{a\cdot\sigma}{E}\right)\right]^n e^{-\frac{Q}{RT}}$$

Model evolution:
Creep model by Limbäck and Andersson 1996

$$\varepsilon_{tot} = \varepsilon_p^s\left(1 - e^{-52\sqrt{\dot{\varepsilon}_{sec}\cdot t}}\right) + \dot{\varepsilon}_{sec}\cdot t$$

$$\varepsilon_p^s = B(\dot{\varepsilon}_{sec})^b[2 - \tanh(D\dot{\varepsilon}_{sec})]^d$$

$$\dot{\varepsilon}_{sec} = \dot{\varepsilon}_{th} + \dot{\varepsilon}_{irr}$$

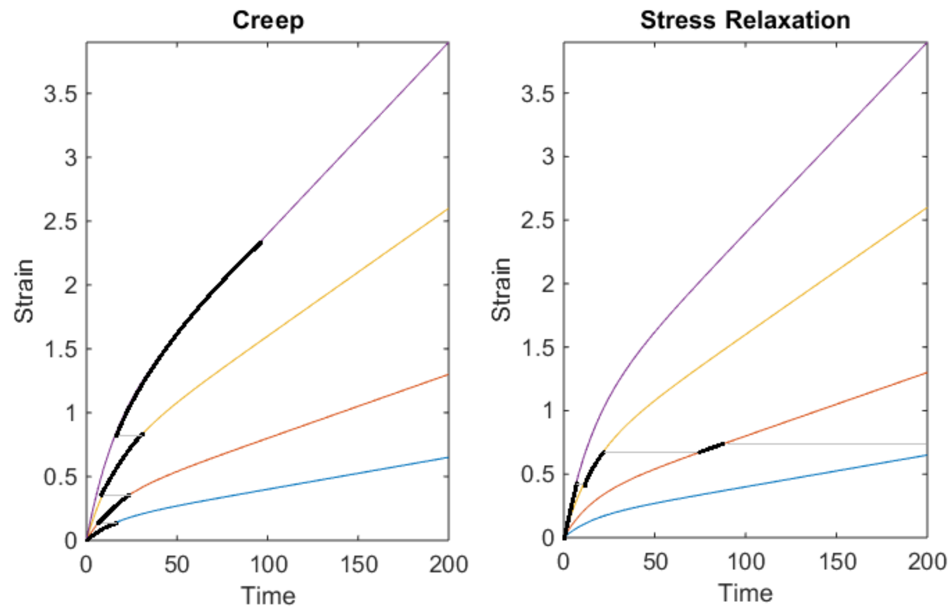
$$\dot{\varepsilon}_{th} = A\left(\frac{E}{T}\right)\left[\sinh\left(\frac{a\sigma}{E}\right)\right]^n e^{-\frac{Q}{RT}}$$

$$a = a_1\{1 - a_2[1 - e^{-a_3(\phi t)^{a_4}}]\}$$

$$\dot{\varepsilon}_{irr} = C(10^4\phi)^{c_1}\sigma^{c_2}$$

Creep in changing conditions
Strain hardening

- Creep curves determined from single stress experiments used
  - In transient cases assume that the strain is invariable
- Lucas and Pelloux showed in 1981 that strain hardening applies to Zirc alloys in some conditions
  - Adopted to most integral fuel codes
- More complex models do not need such approximations
  - Not adopted in practice



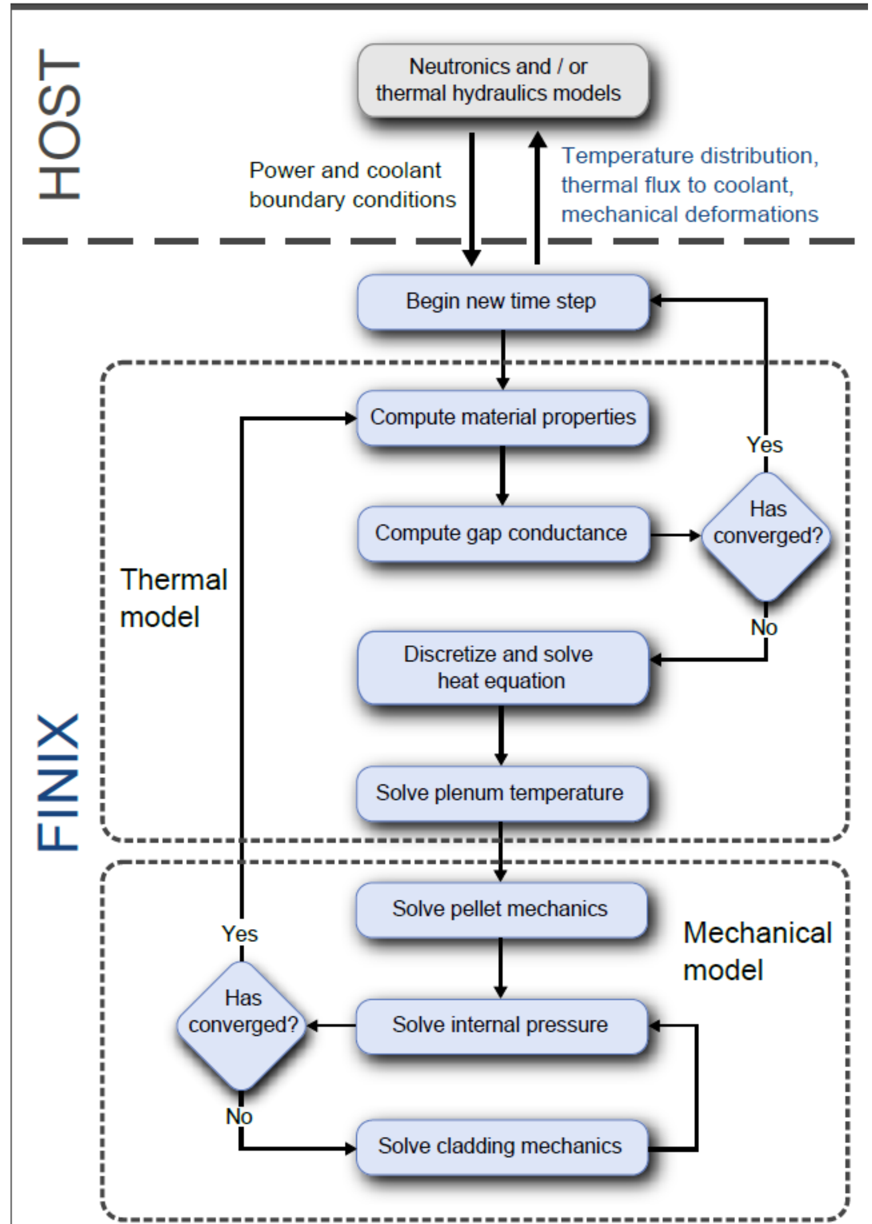
Fuel behaviour

Fuel behaviour

- Fuel behaviour code
  - Common solution scheme
- Applications
  - Ensuring safe use of fuel
  - Coupled safety analysis

Fuel behaviour code: FINIX as an example

- Thermomechanically coupled solution
- Models and correlations validated
- Whole time in reactor simulated



YVL B.4.1 & B.4.2 (general)

401. The integrity of nuclear fuel shall be ensured during its operation, handling, transport, long-term storage and final disposal.

406. In determining the design criteria for nuclear fuel, the physical, chemical and mechanical phenomena that affect the durability of the nuclear fuel during operational and accident conditions shall be comprehensively analysed. The analyses shall cover all design basis scenarios.

409. Irradiation-induced changes that affect nuclear fuel properties shall be taken into account in determining the limits for safe use of the fuel, including the effects on the final disposal of spent nuclear fuel. Burn-up limits to be applied to nuclear fuel shall be presented, and they shall be based on experimental data.

YVL B.4.3 (normal operation)

412. In normal operational conditions, the nuclear fuel shall fulfil the following conditions:

- No melting shall occur in fuel pellets.
- Cladding temperature shall not substantially exceed coolant temperature.
- Fuel rod cladding shall not collapse.
- The internal pressure of a fuel rod shall not increase to the extent that cladding deformations caused by it would negatively affect the heat transfer between fuel pellets and coolant (no lift-off occurs).

413. Deformations in the fuel assembly and control rod components shall remain minor

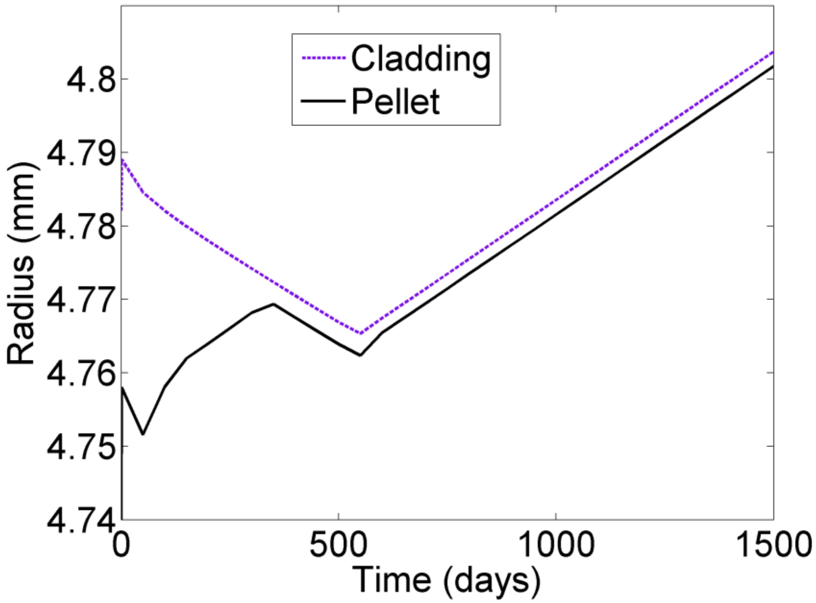
Assembly level is not considered in this lecture.

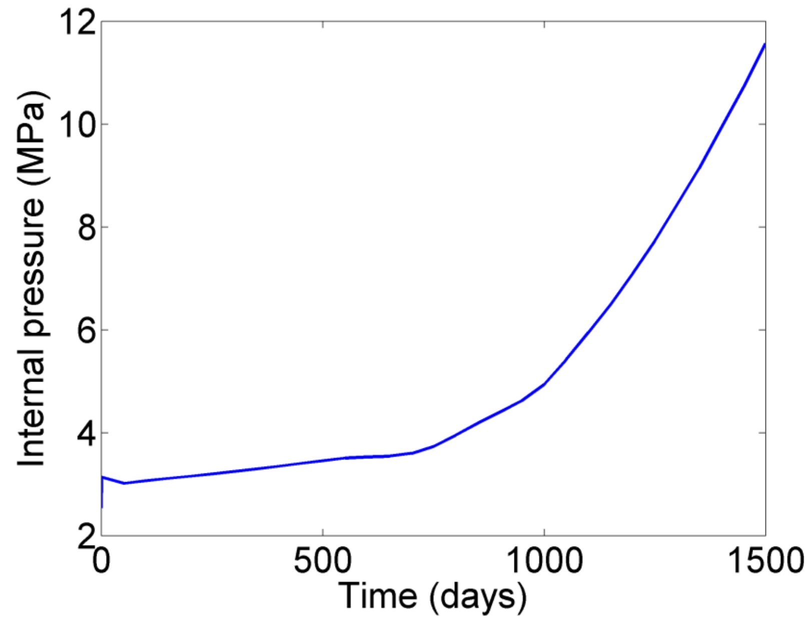
414. The probability of a fuel failure caused by mechanical interaction between fuel pellet and cladding shall be extremely low.

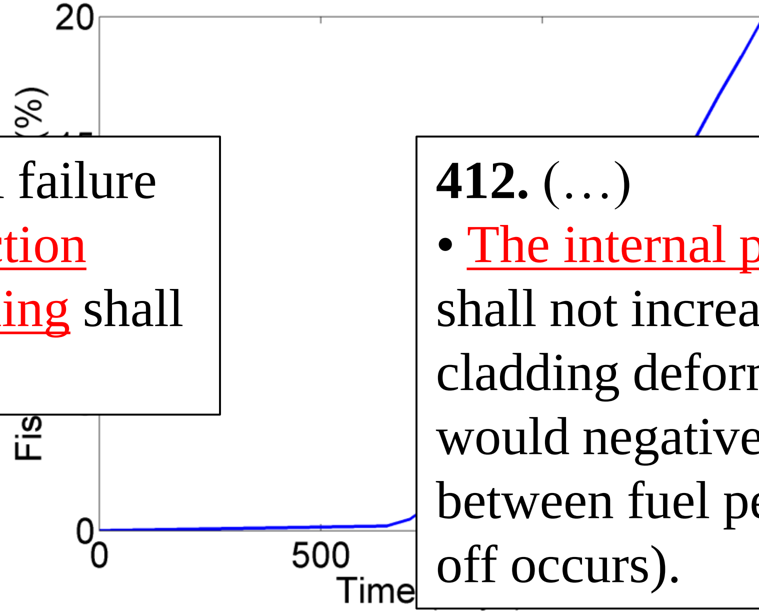
YVL B.4.4 (anticipated operational occurrences)

415. In anticipated operational occurrences:

- No melting shall occur in fuel pellets.
- Adequate cooling of the cladding shall be ensured. (…) Thermal hydraulic analyses not considered in this lecture.
- The probability of fuel failure caused by mechanical interaction between fuel and cladding shall be extremely low.



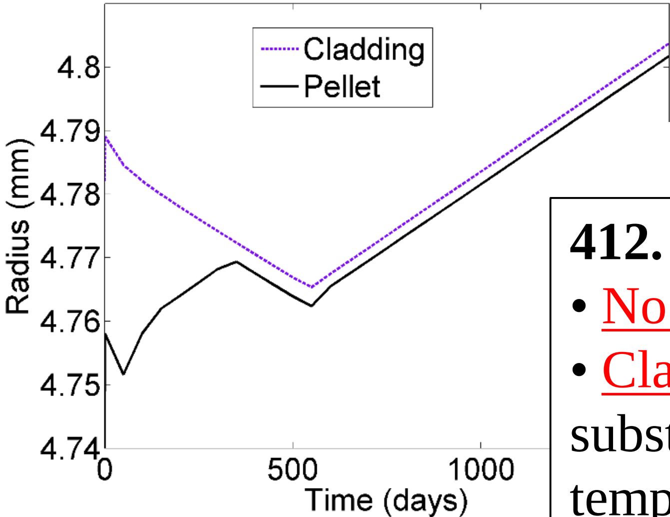


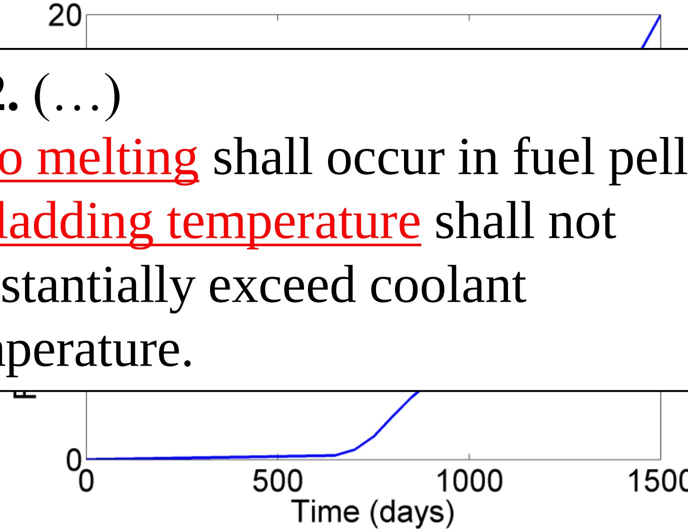


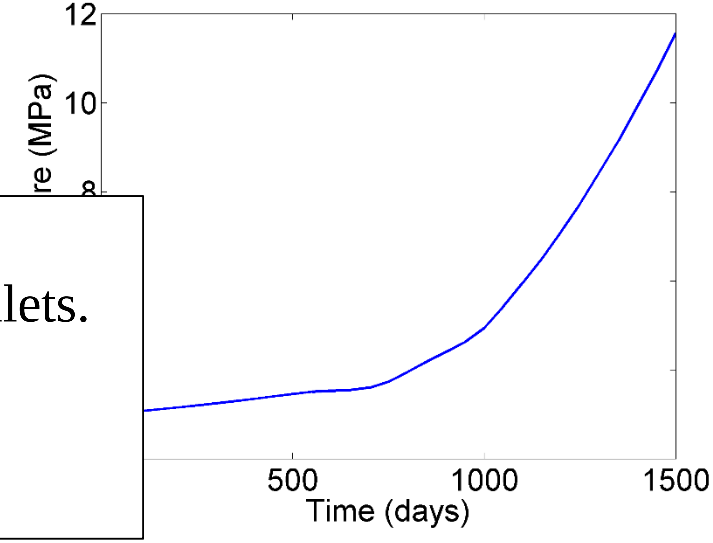
414. The probability of a fuel failure caused by <u>mechanical interaction between fuel pellet and cladding</u> shall be extremely low.

412. (…)

• <u>The internal pressure</u> of a fuel rod shall not increase to the extent that cladding deformations caused by it would negatively affect the heat transfer between fuel pellets and coolant (no lift-off occurs).







412. (…)

- No melting shall occur in fuel pellets.
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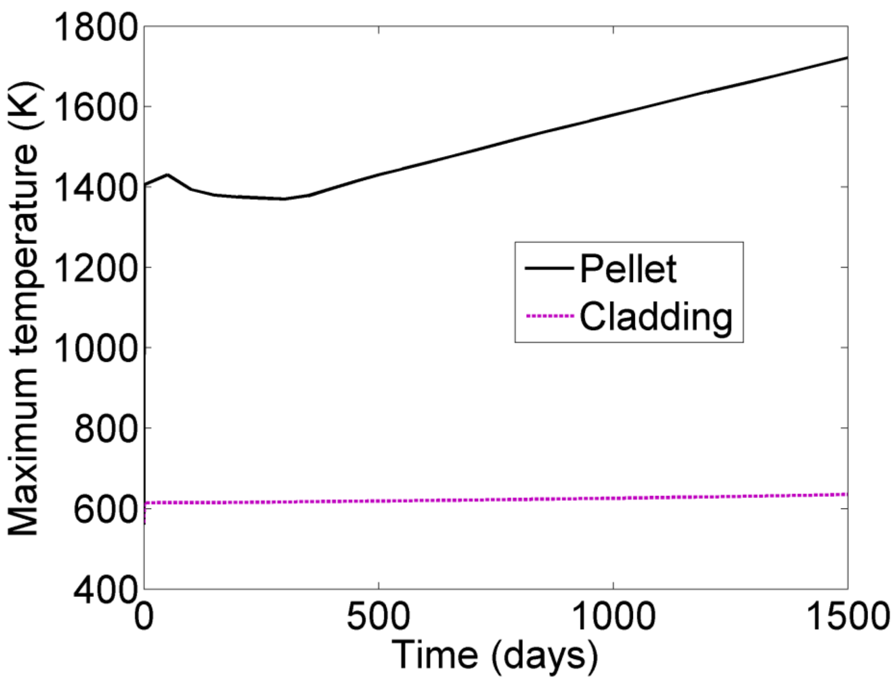
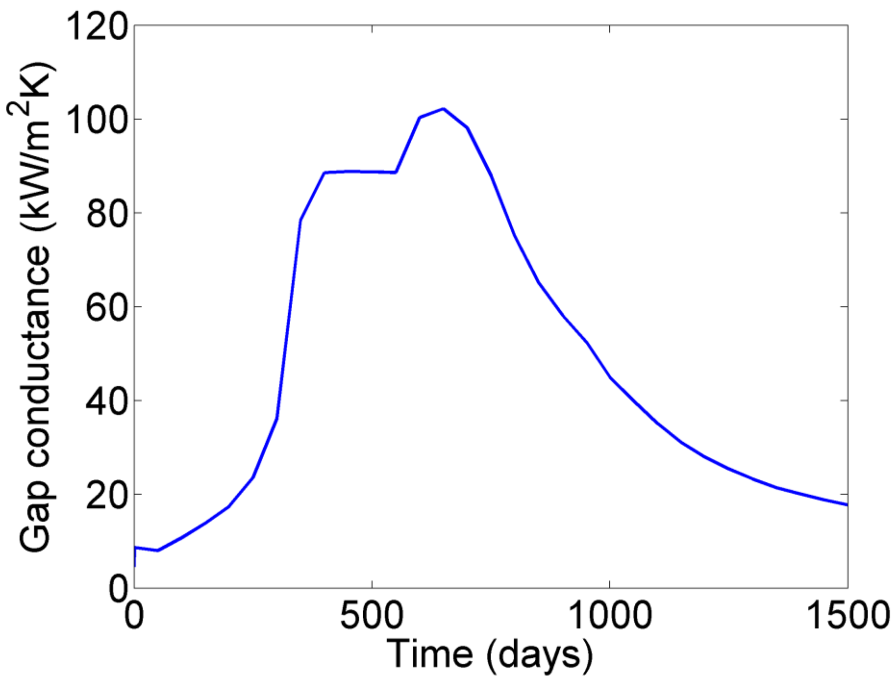




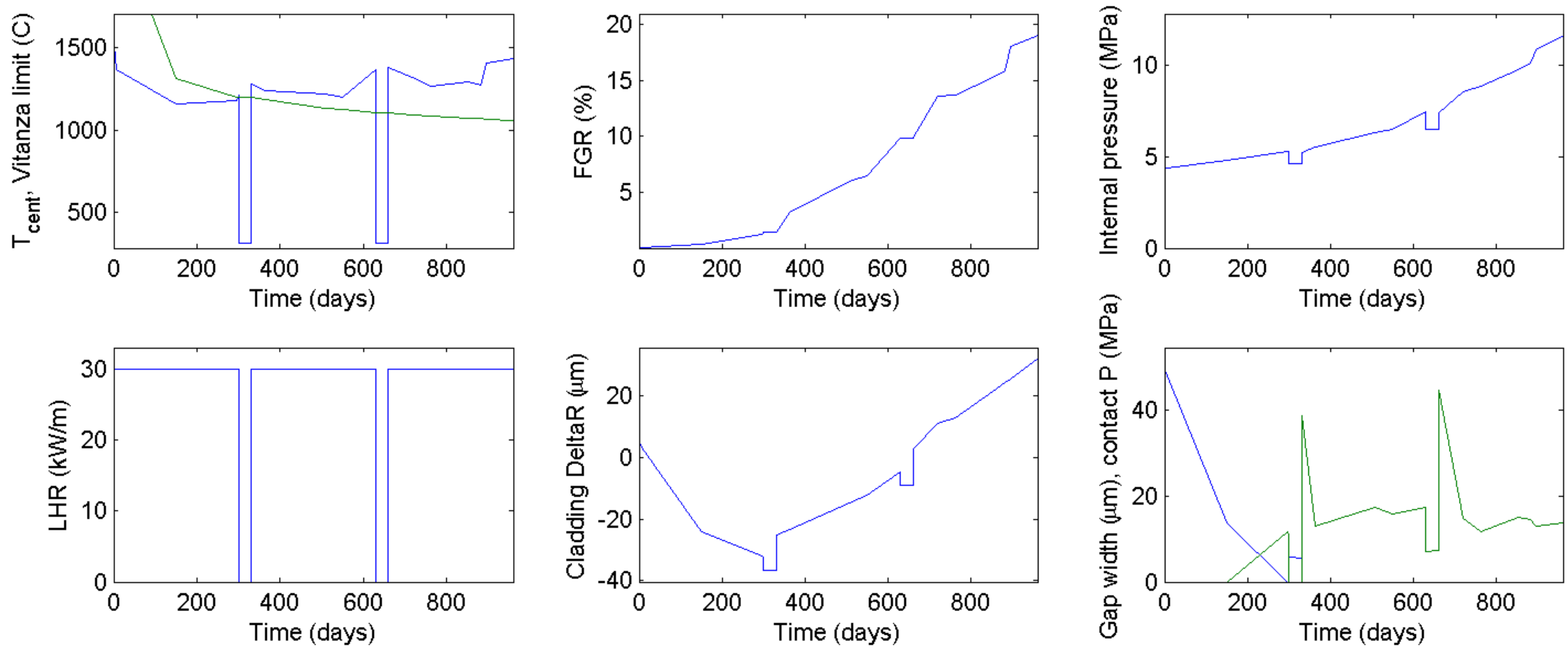
Normal operation, effect of linear heat rate

- Burnup of nuclear fuel is limited by the degradation of cladding material properties (oxidation, hydriding), pellet swelling, fission gas release, formation of high burnup structure in the pellet, enrichment
- Performance in transients

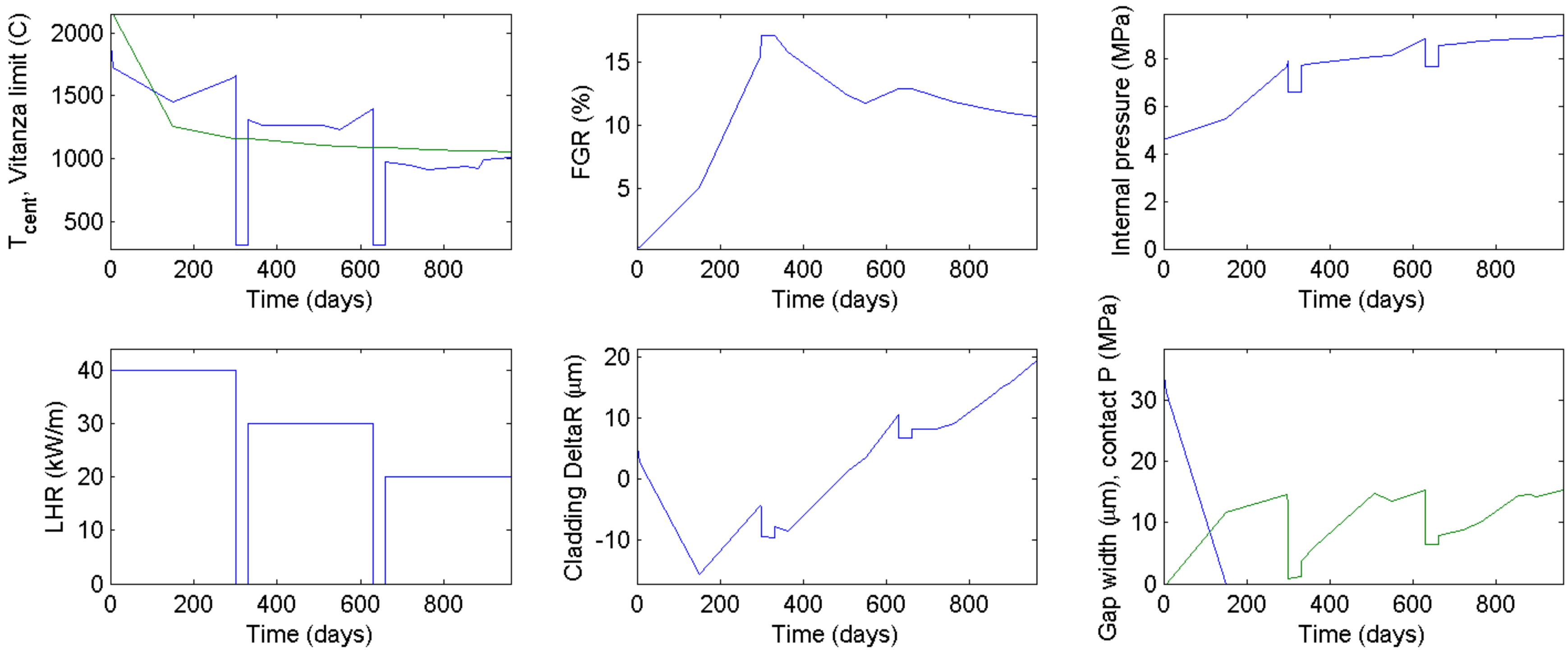
- To reach a certain burnup safely, how to distribute the linear heat rate between cycles?

409. Irradiation-induced changes that affect nuclear fuel properties shall be taken into account in determining the limits for safe use of the fuel, including the effects on the final disposal of spent nuclear fuel. Burn-up limits to be applied to nuclear fuel shall be presented, and they shall be based on experimental data.

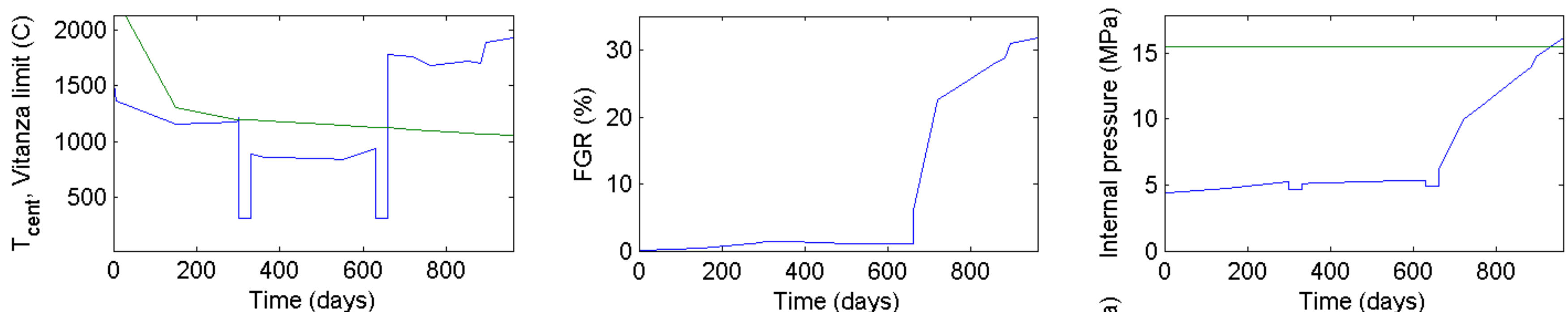
Case 1: constant LHR

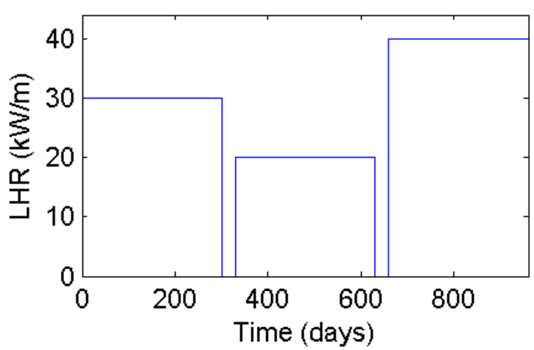


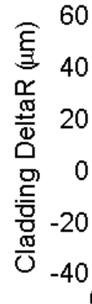
Case 2: low LHR for 3rd cycle

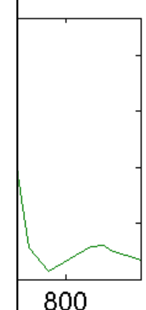


Case 3: high LHR for 3rd cycle





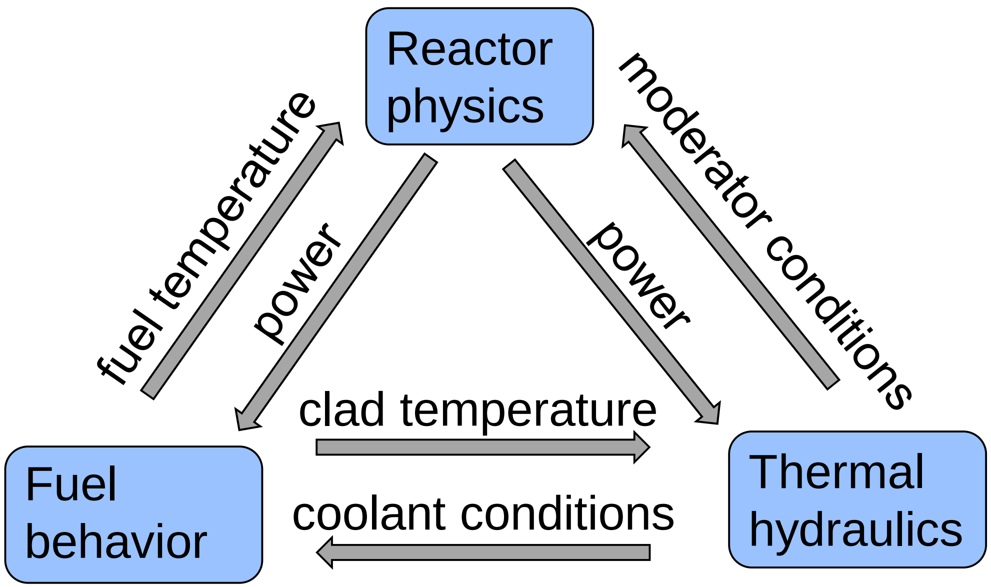


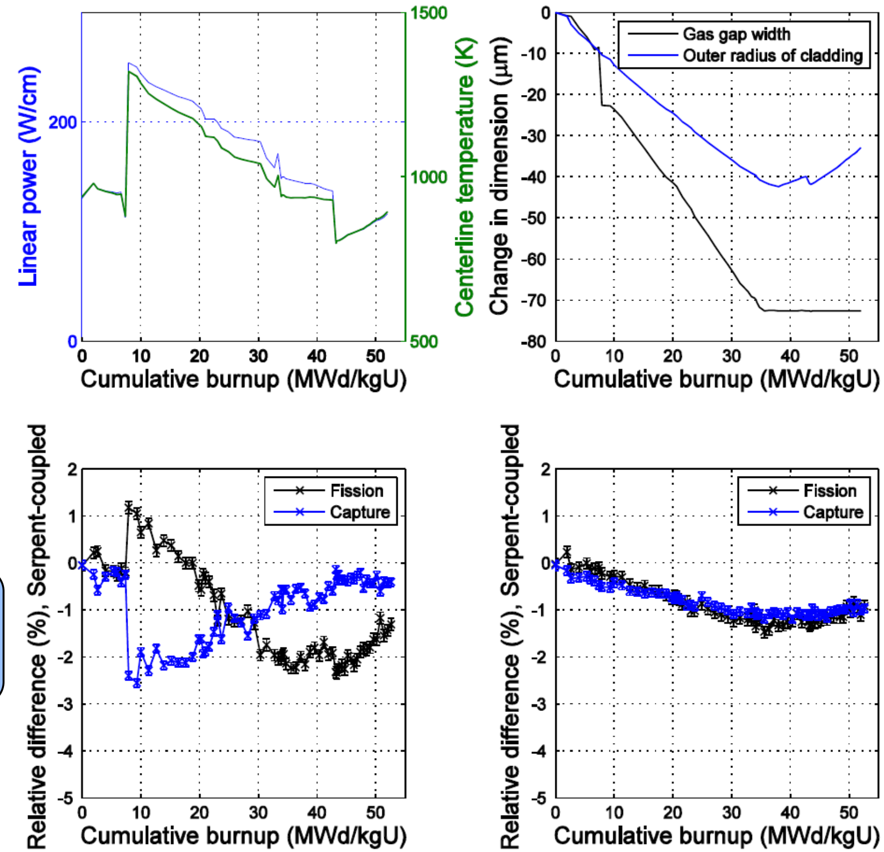


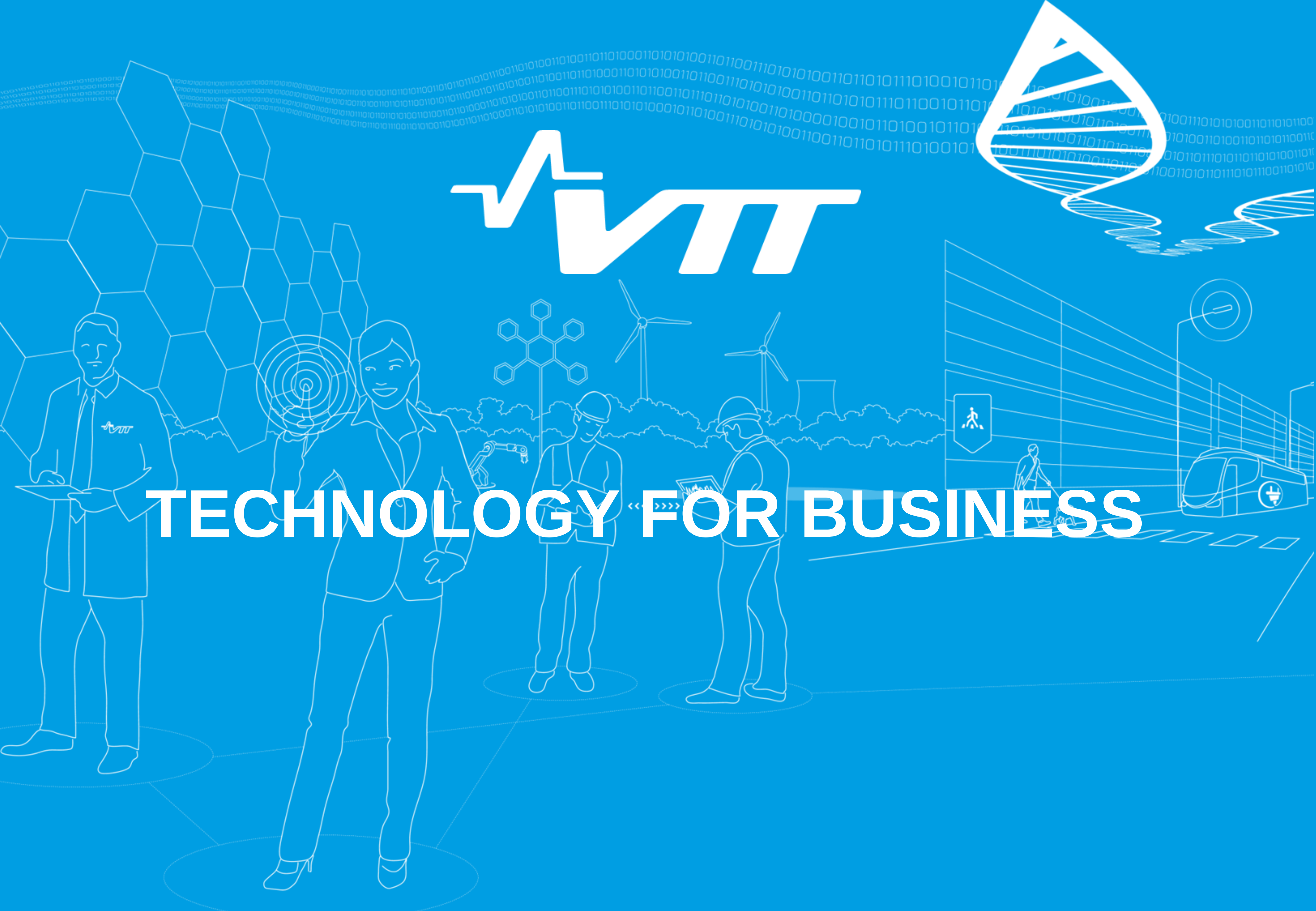
412. (…)

- <u>The internal pressure</u> of a fuel rod shall not increase to the extent that cladding deformations caused by it would negatively affect the heat transfer between fuel pellets and coolant (no lift-off occurs).

Multiphysics applications






TECHNOLOGY FOR BUSINESS