



Fuel behaviour: can we model it properly and does it matter?

Glyn Rossiter

The Nuclear Institute Modelling in Nuclear Science and
Engineering Seminar 2020

Online

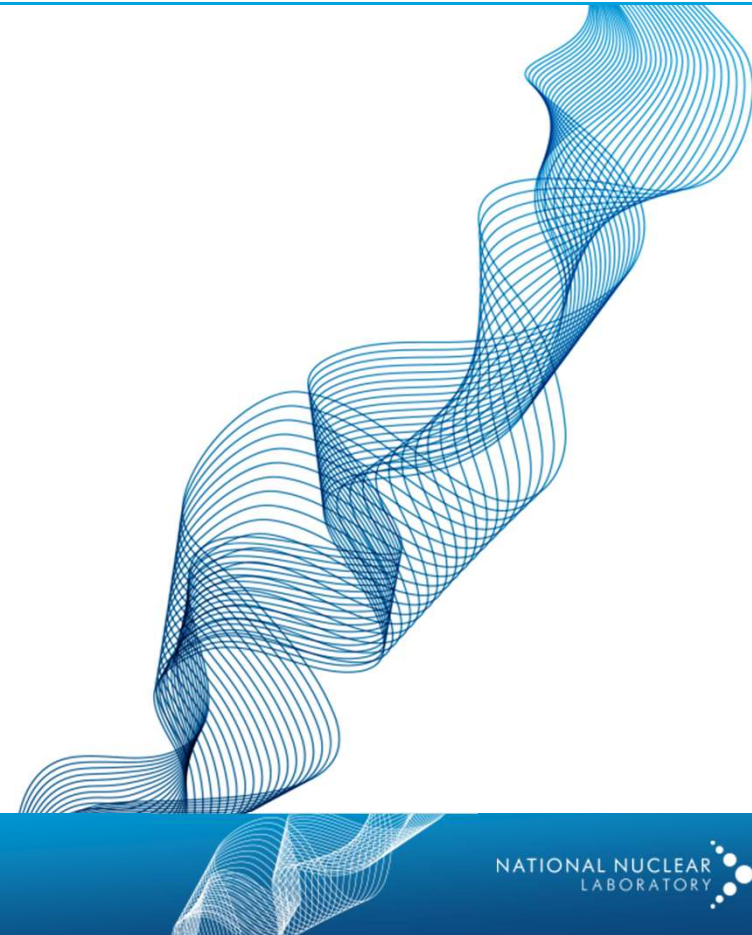
4-5 November 2020

NATIONAL NUCLEAR
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Overview

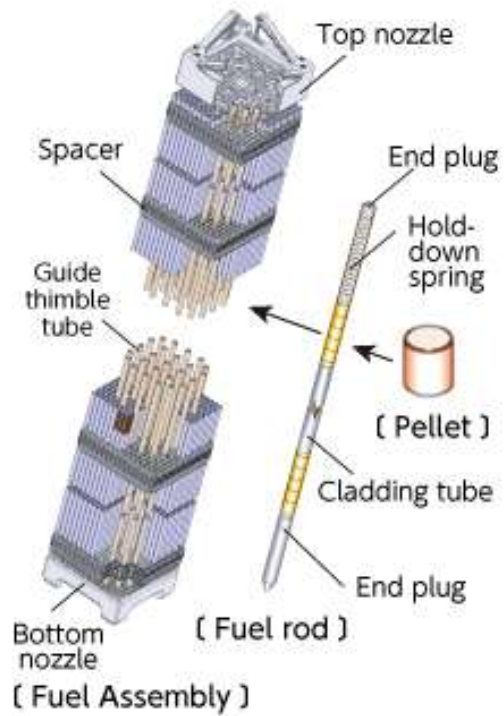
Fuel behaviour: can we model it properly and does it matter?

- Fuel design
 - ... focussed on PWR fuel
- Fuel behaviour
 - again, focussed on PWR fuel
 - can we model it properly?
- Challenges in fuel performance modelling
 - ... and do they matter?
- Conclusions



Fuel design (PWR)

Fuel behaviour: can we model it properly and does it matter?

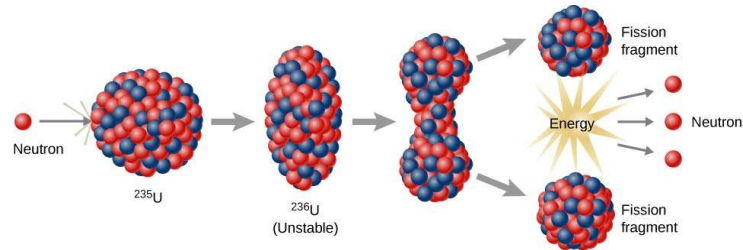


Source: Mitsubishi Nuclear Fuel (<http://www.mnf.co.jp/en/business/process.html>)

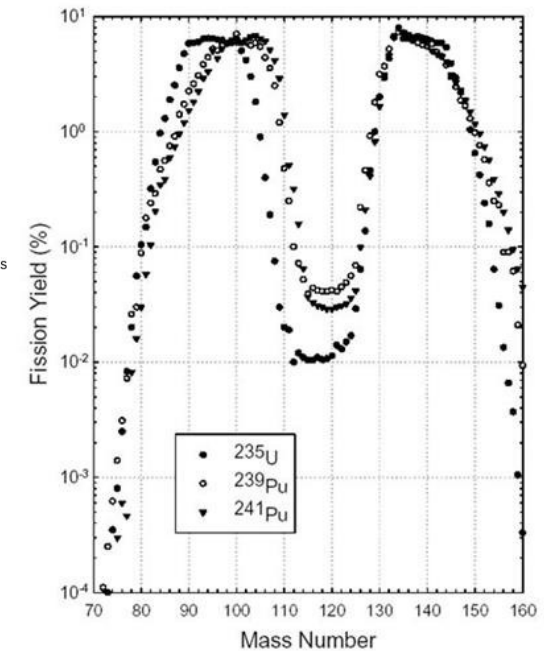
Fuel behaviour (PWR)

Fuel behaviour: can we model it properly and does it matter?

- **Fissions take place**
- Fuel gets hot
- Fuel expands & cracks
- Fuel densifies & swells
- Clad creeps down
- Cladding contact
 - **mechanical interaction**
 - **chemical reaction**
- Clad oxidation & hydriding
- Fission gas release / rod pressurisation
- Fuel temperatures, stresses and strains change



Source: BC Open Textbooks,
<https://opentextbc.ca/universityphysicsv3openstax/chapter/fission/>

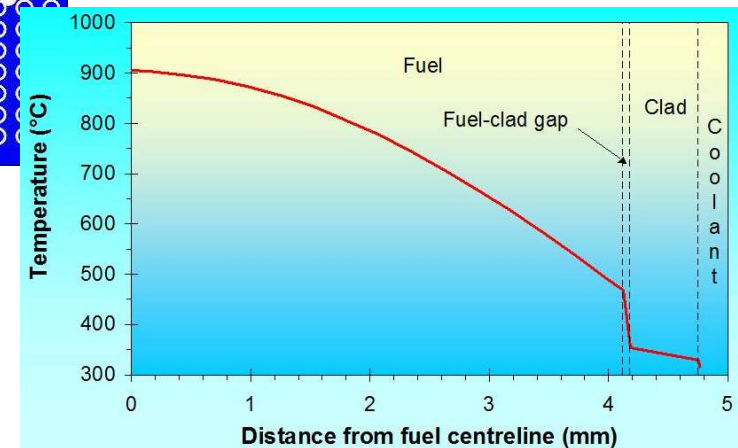
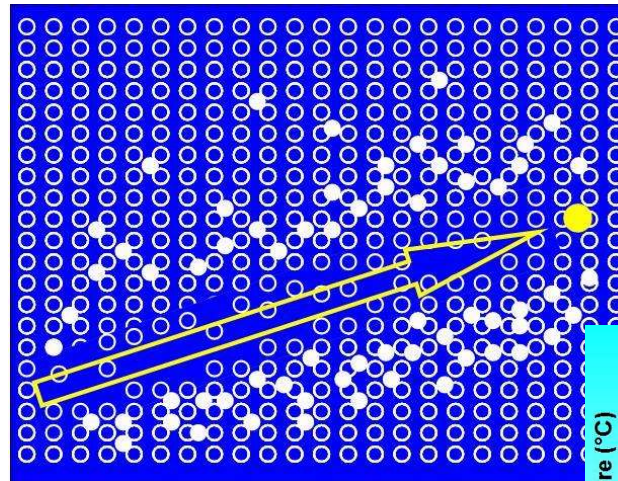


Source: White, HWR-632, 2000

Fuel behaviour (PWR)

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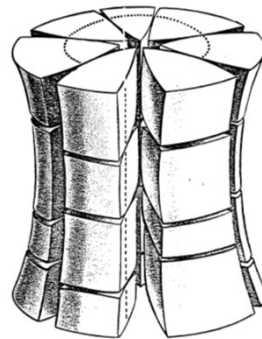
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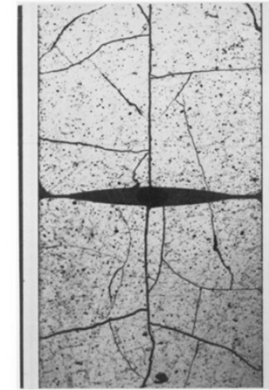
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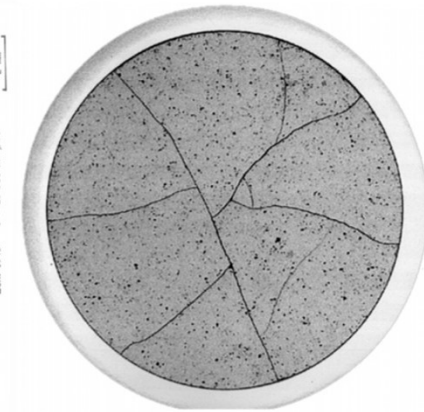
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Source: Gittus, Nuclear Engineering and Design 18 (1972) 69-82



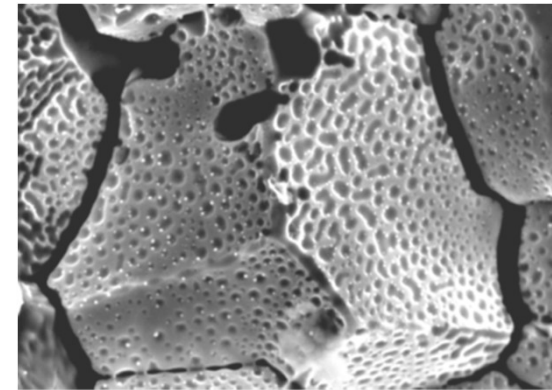
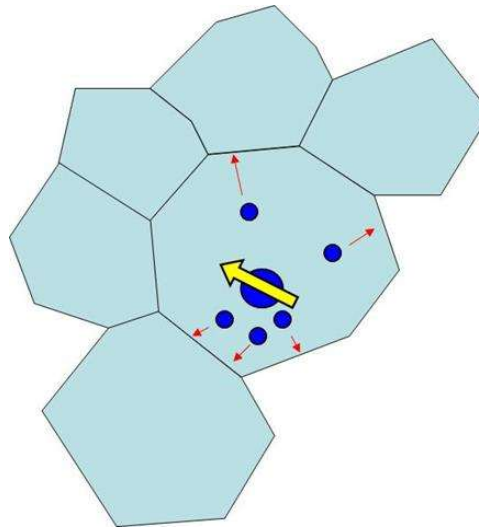
Source: Michel *et al*, Engineering Fracture Mechanics, vol. 75, pp. 3581–3598, 2008



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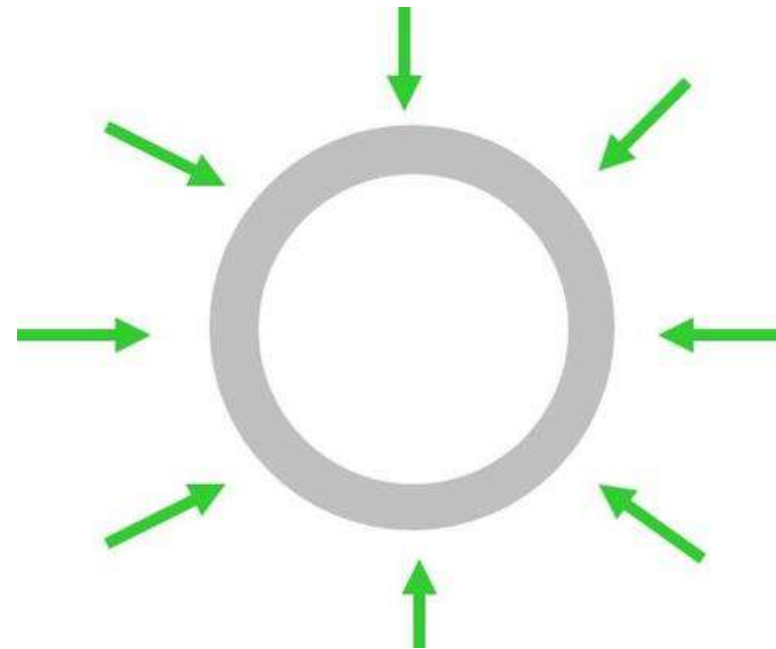


Source: White, OECD/CEA seminar on pellet-clad interaction in water reactor fuels, Cadarache, March 2004

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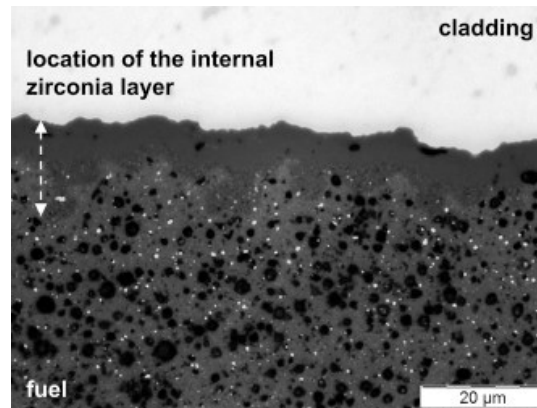
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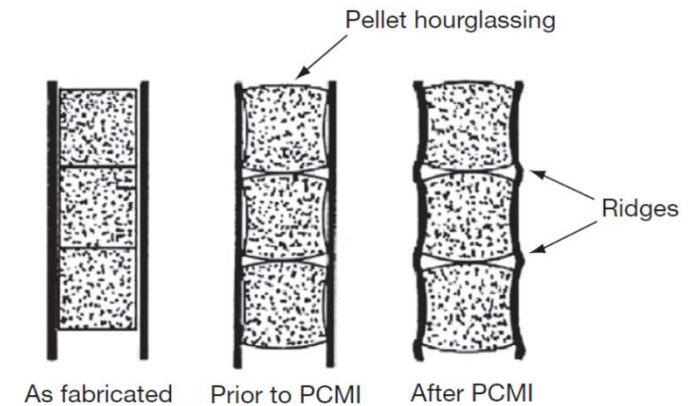
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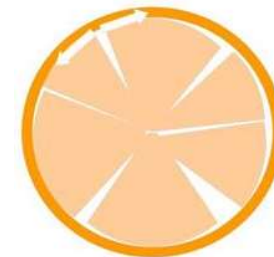
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Source: Cizak *et al.*, Journal of Nuclear Materials 520 (2019) 110-120



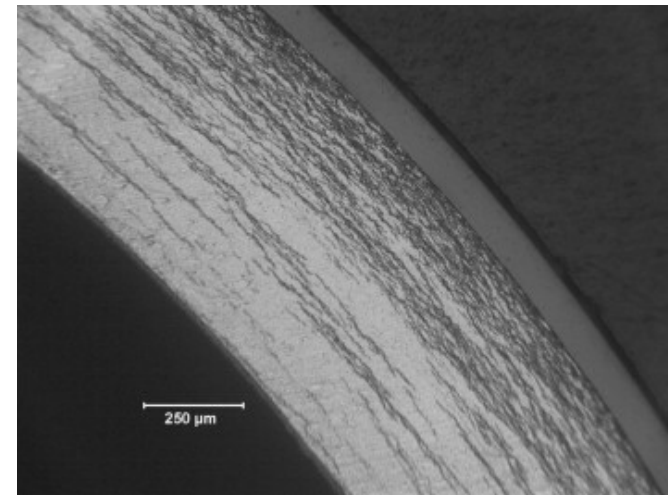
Source: Van Uffelen & Suzuki, in Konings (Ed.), "Comprehensive nuclear materials", Elsevier Ltd, 2012



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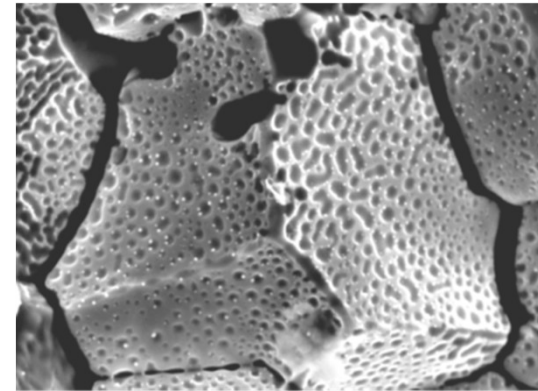


Source: Billone, Burtseva & Einziger, Journal of Nuclear Materials 433 (2013) 431-448

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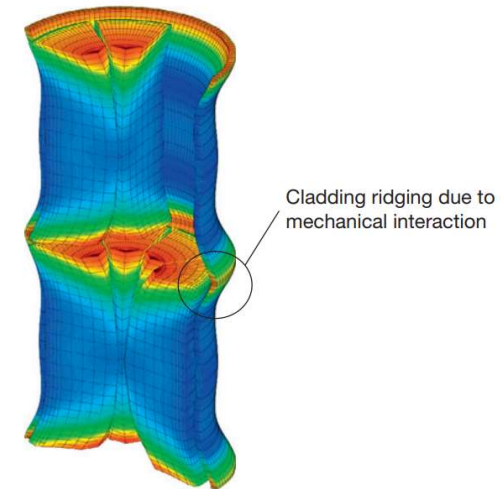


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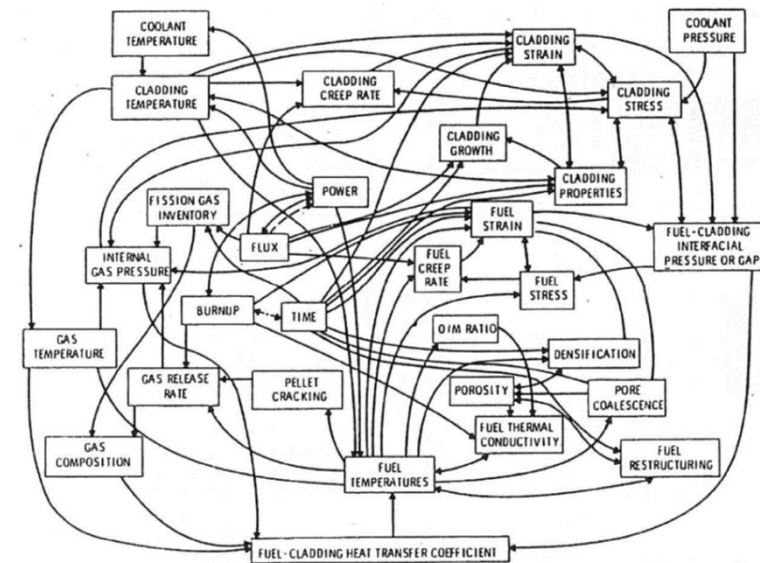
Source: Michel *et al*, in Konings (Ed.), "Comprehensive nuclear materials", Elsevier Ltd, 2012

Fuel performance modelling

Fuel behaviour: can we model it properly and does it matter?

- We can model all these phenomena
- ... to determine temperatures, stresses and strains (fuel performance)
- ... and we can verify and validate these models
- ... so we can model fuel 'properly' right?
- ... even though it's quite complex
- Yes
 - ... but with some challenges!

to be able to
license fuel for
use in a reactor



Source: Lassmann, Nuclear Engineering and Design 57 (1980) 17-39

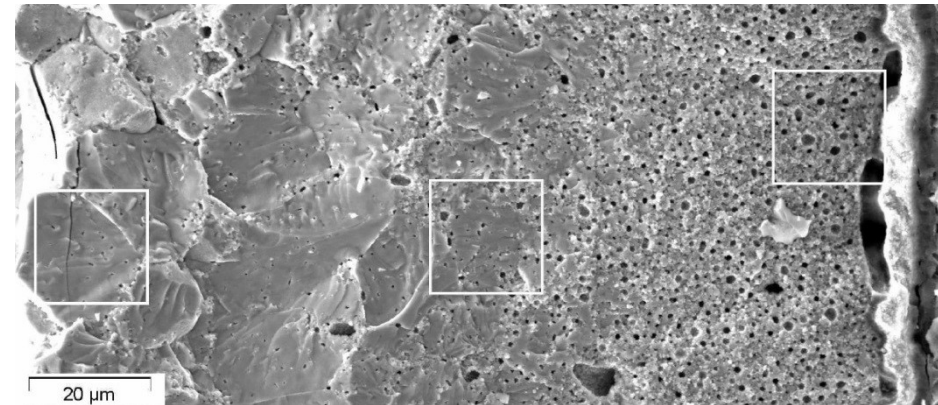
Challenges in fuel performance modelling: higher duty

Fuel behaviour: can we model it properly and does it matter?

- Need to extend ranges of validity for models
 - ... with corresponding validation data
- Emergent phenomena
 - thermal conductivity degradation
 - high burnup structure formation
 - outside-in cracking (BWRs)

Does it matter?

Yes: models must be applicable throughout operation space



Source: Noirot *et al*, 2008 Water Reactor Fuel Performance Meeting, Seoul, South Korea, October 2008

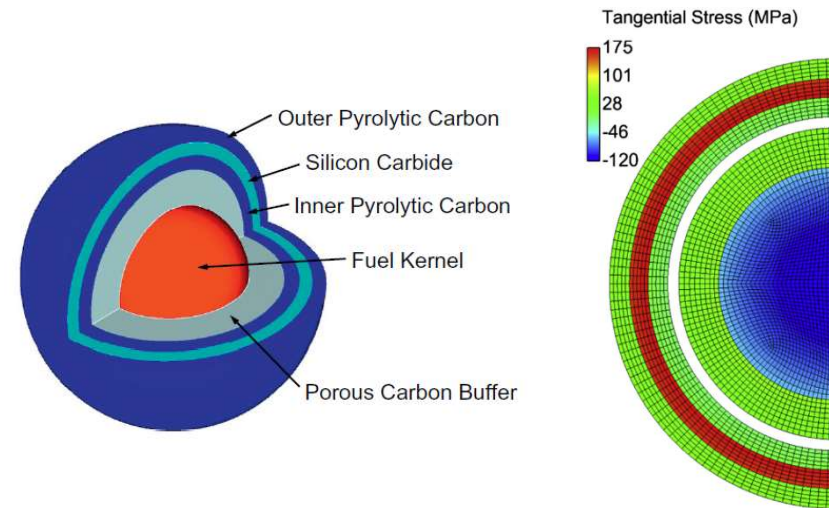
Challenges in fuel performance modelling: new fuels

Fuel behaviour: can we model it properly and does it matter?

- Property correlations/models for new materials
 - **fuel and clad**
 - **irradiated**
- New fuel types
 - **different geometry**
 - **different phenomenology**
 - **e.g. phase changes, thermal dissociation, amorphisation**
- Towards multi-use codes?

Does it matter?

Yes: modelling new fuels underpins their licensing



Source: Hales et al, Journal of Nuclear Materials 443 (2013) 531-543

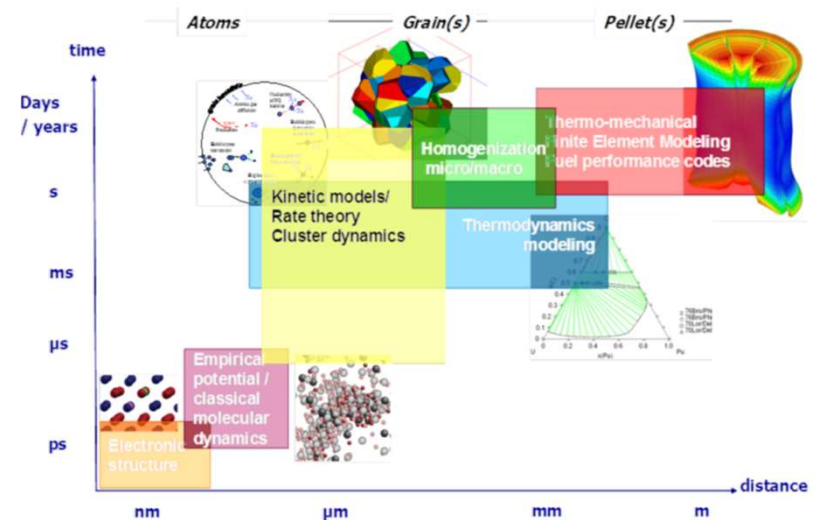
Challenges in fuel performance modelling: multi-scale

Fuel behaviour: can we model it properly and does it matter?

- Lower length scale models
 - predictive material properties
 - effects of microstructural phenomena / features
 - coupled or 'ported'
- Capable of extrapolation beyond validation space
- Need for lower length scale validation data?

Does it matter?

Yes: drive for more mechanistic basis to modelling; particularly important for new fuels



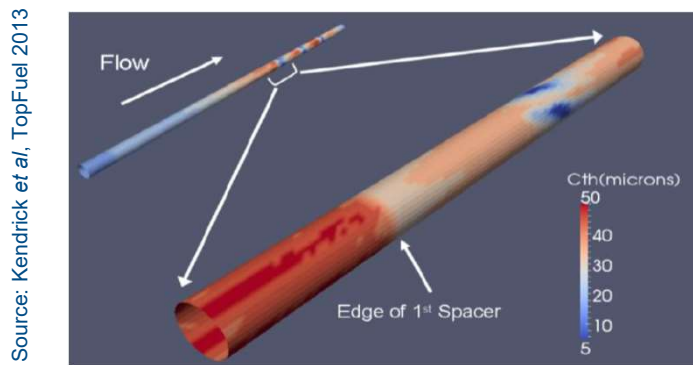
Source: NEA/NSC/R(2015)5

Challenges in fuel performance modelling: multi-physics

Fuel behaviour: can we model it properly and does it matter?

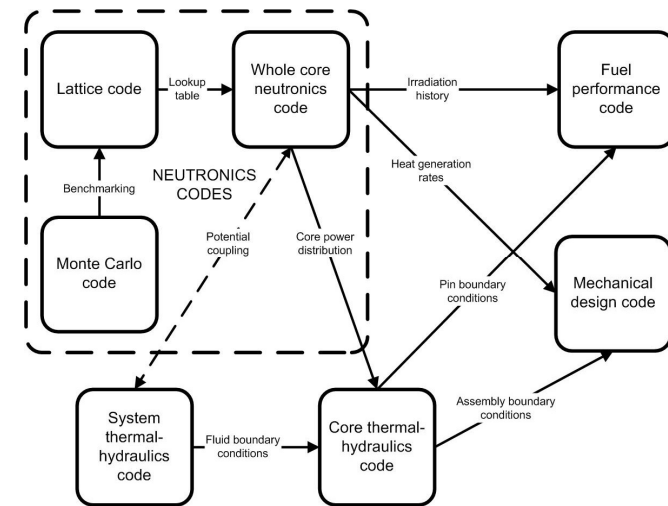
- Combining physics (and chemistry!) modelling of different phenomena
 - towards true code coupling (where necessary: significant feedback)
- Towards 'push-button' fuel licensing assessment

Example: CIPS prediction



Source: Kendrick et al, TopFuel 2013

Does it matter?
 Yes: simplify design & licensing methods;
 increase accuracy



Source: Rossiter, in Crossland (Ed.), "Nuclear fuel cycle science and engineering", Woodhead Publishing Ltd, 2012

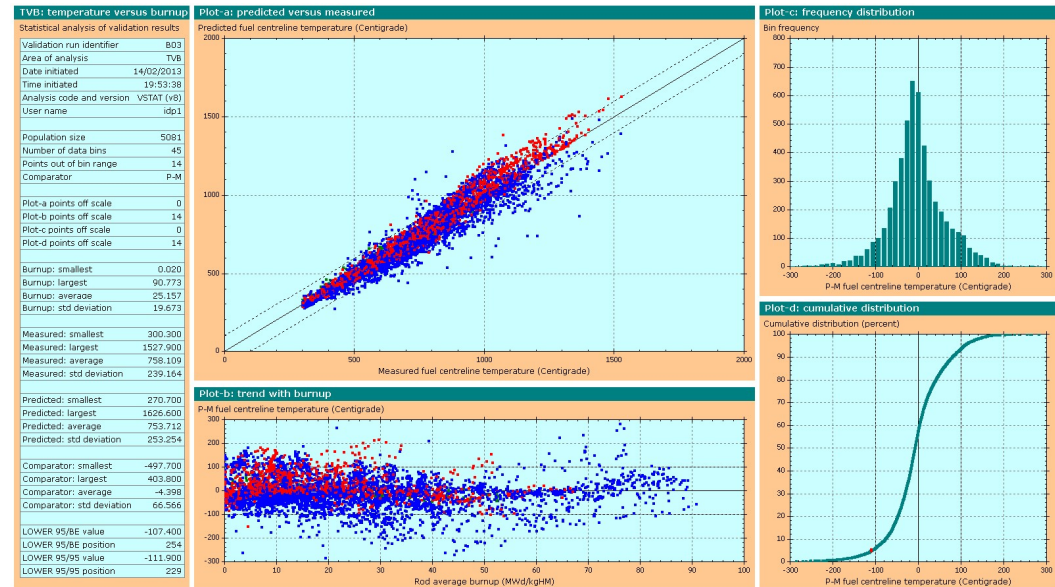
Challenges in fuel performance modelling: uncertainty quantification

Fuel behaviour: can we model it properly and does it matter?

- Important outcome of validation
 - used in fuel licensing calculations
- Linked to models used
- Linked to fuel qualification approach
 - deterministic vs. probabilistic

Does it matter?

Yes: determines margin to limits in operation; particularly important for new fuels



Source: NNL

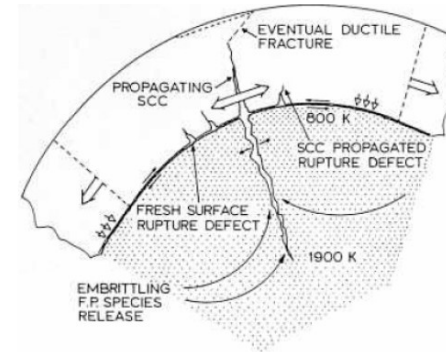
Challenges in fuel performance modelling: fracture

Fuel behaviour: can we model it properly and does it matter?

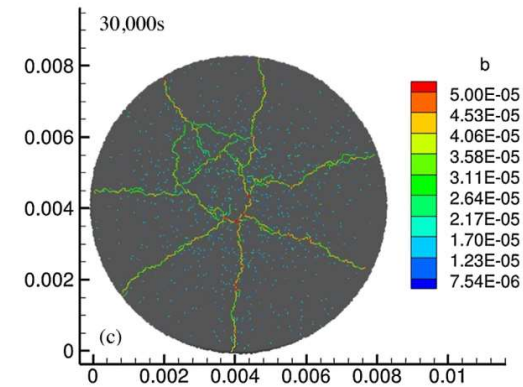
- Fracture mechanics is its whole own discipline!
- Use emerging macroscale modelling techniques?
 - e.g. XFEM, discrete element method, peridynamics, SPAM
 - enabled by advances in computational power
- PCI and fuel fragmentation & relocation are of particular importance

Does it matter?

Yes: move away from reliance on empirical data; particularly important for new fuels



Source: Yagnik, Cheng & Sunderland, NEA seminar on PCI, Cadarache, March 2004



Source: Huang, Spencer & Hales, Nuclear Engineering and Design 278 (2014) 515-528

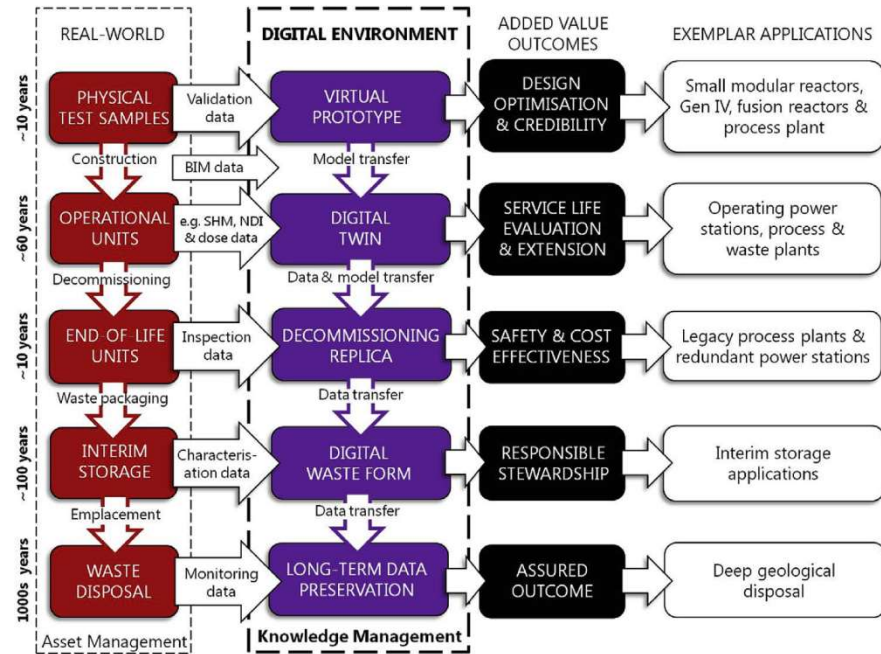
Challenges in fuel performance modelling: full lifecycle

- Towards consistent modelling across fuel lifecycle
 - irradiation
 - post-irradiation storage
 - final disposal
 - reduce conservatism in safety case assessments
- 'Digital twins' for fuel assemblies?
- Towards 'push-button' fuel lifetime assessment?

Does it matter?

Yes: prevent over-engineering;
reduce limitations in storage/disposal

Fuel behaviour: can we model it properly and does it matter?

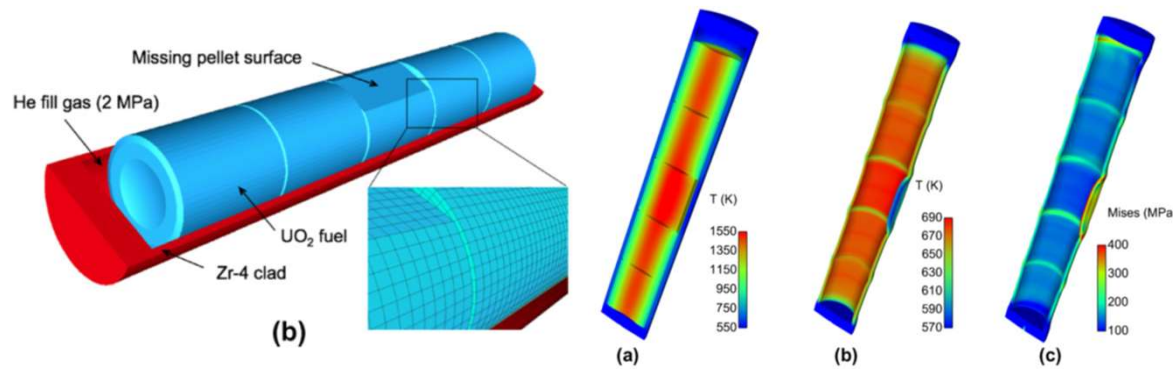


Source: Patterson, Taylor & Bankhead, Progress in Nuclear Energy 87 (2016) 97-103

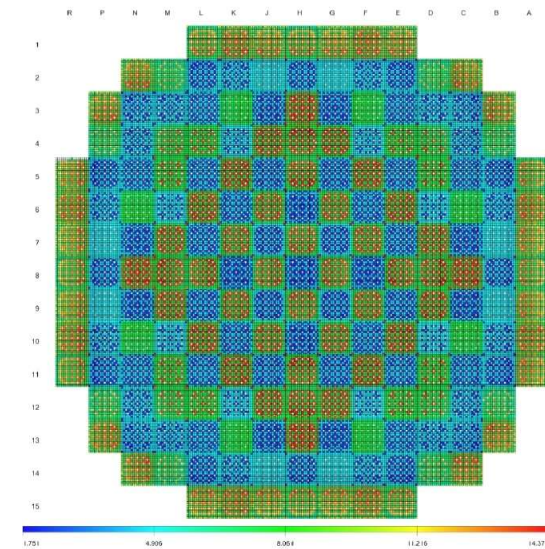
Challenges in fuel performance modelling: high fidelity

Fuel behaviour: can we model it properly and does it matter?

- Integrated whole core modelling
- Effects where 3-D geometry important
 - e.g. pellet chips, asymmetric clad ballooning in a LOCA



Source: Williamson *et al*, Journal of Nuclear Materials 423 (2012) 149-163



Source: NNL

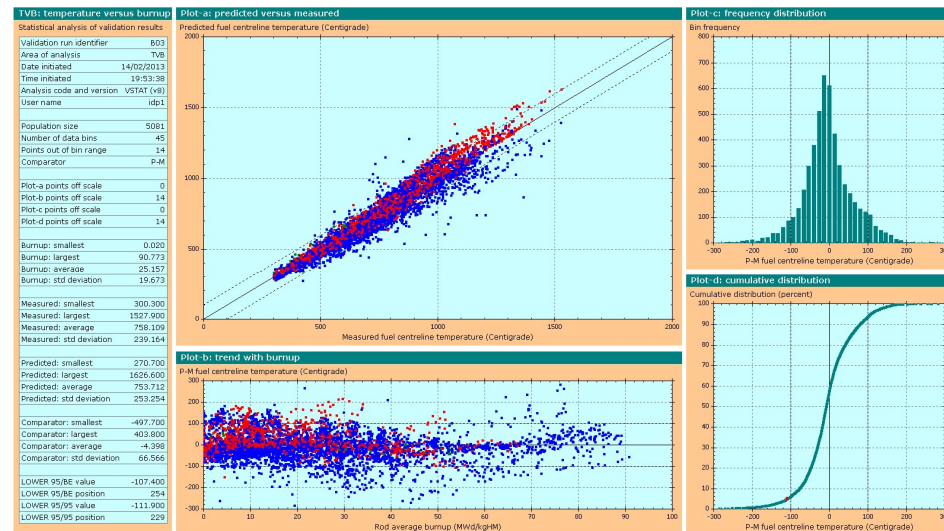
Does it matter?

Yes: increased accuracy/reduced conservatism;
more generic application

Conclusions

Fuel behaviour: can we model it properly and does it matter?

- Fuel can be modelled ‘properly’ ... with some challenges
- The challenges matter
- especially for new fuels
- ... but they don’t preclude the need for validation data
- ... and modelling can never give the full picture of fuel behaviour
 - especially for stochastic phenomena
 - need experimental testing, OPEX and PIE
- Finally, ‘how good is good enough?’ comes into play
 - advanced modelling can always help elucidate phenomenological behaviour
 - ... but won’t necessarily make the models more accurate!



Source:>NNL