Safe Cracking: Monte Carlo Nonlinear Coupled Analysis of Nuclear Reactor Bricks

Quintessa support to EDF Energy

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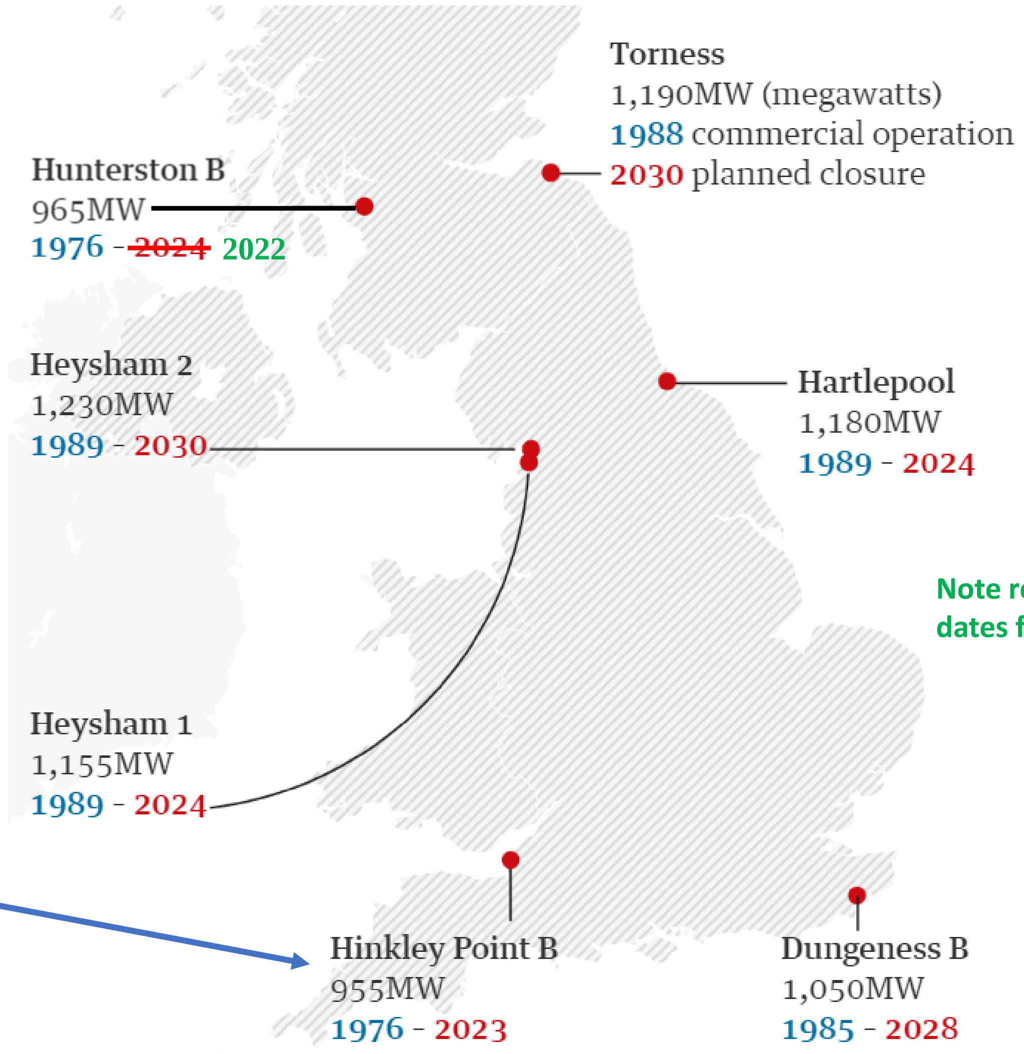
Advanced Gas-cooled Reactors (AGRs)

- AGRs provide around 15% of UK power
  - Owned and operated by EDF Energy
- All are expected to reach end of life over the next decade or so
  - New builds not generating until ~2025
- Quintessa provides modelling support to help understand and predict the behaviour of bricks in the reactors



Torness
1,190MW (megawatts)
1988 commercial operation
2030 planned closure

Hunterston B
965MW
1976 - ~~2024~~ 2022

Heysham 2
1,230MW
1989 - 2030

Hartlepool
1,180MW
1989 - 2024

Heysham 1
1,155MW
1989 - 2024

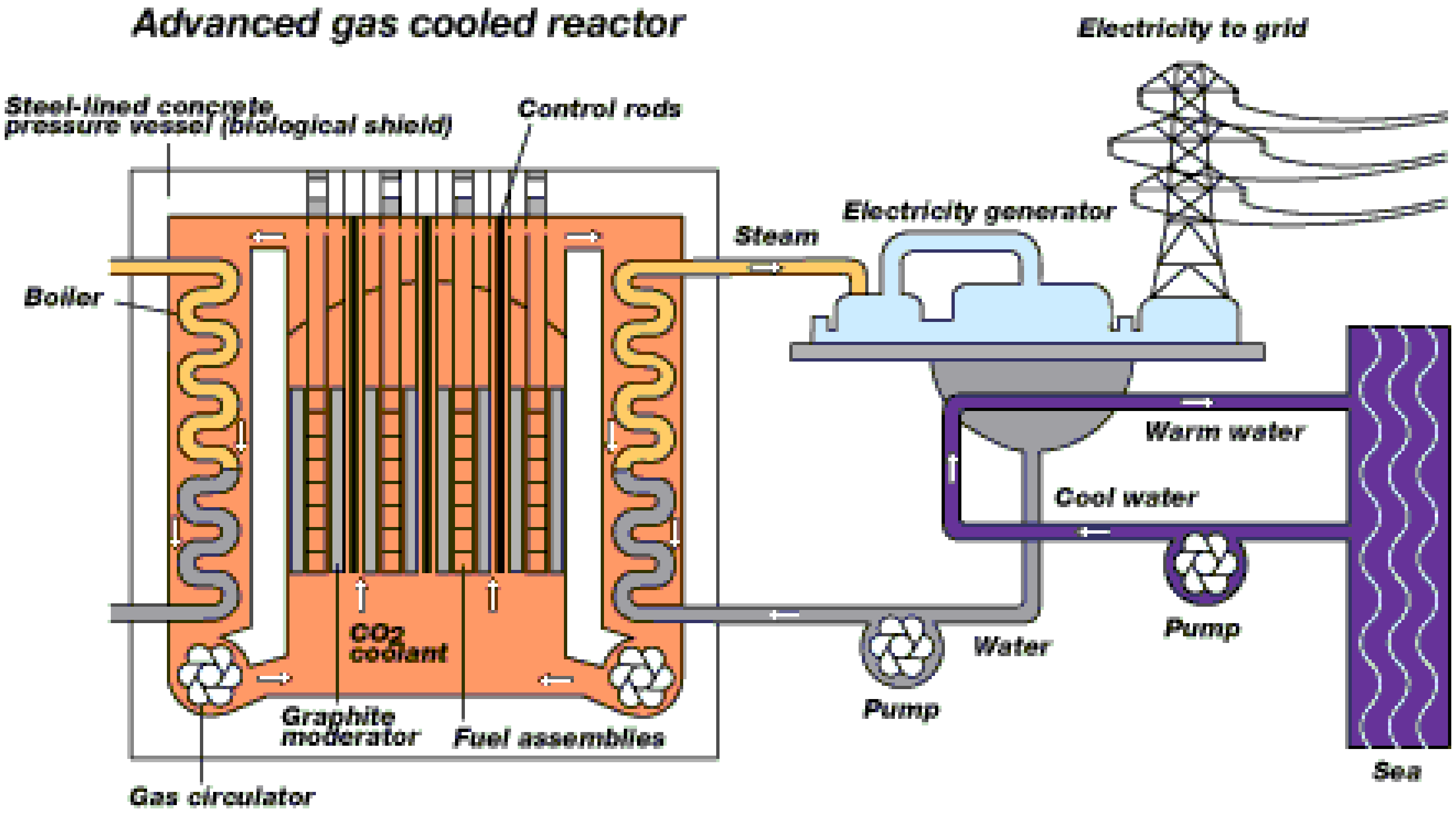
Hinkley Point B
955MW
1976 - 2023

Dungeness B
1,050MW
1985 - 2028

Note recently updated dates for Hunterston B

AGR Design

- Nuclear fuel rods are suspended in channels of graphite bricks, which provide moderation
- Gas-cooled (40 bar CO_2 at ~450 °C)
- Graphite bricks are expected to be the limiting factor in the lifespan of most AGRs

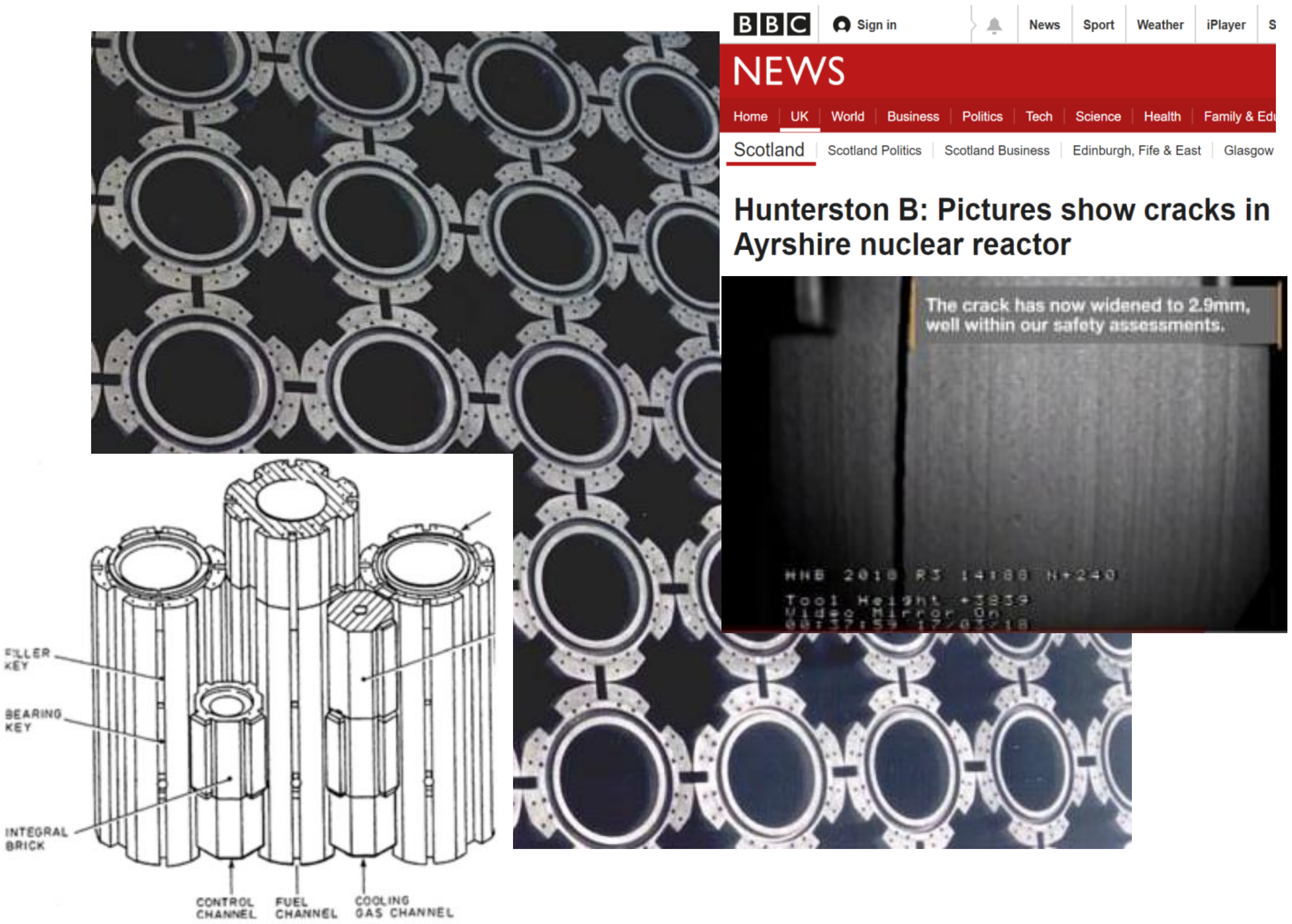


What is the issue?

- Reactors are expected to operate until 2022-2030 (depending on the individual reactor)
- Some already had a lifetime extension for safe operation
- New nuclear build (e.g. Hinkley C) not expected to start providing electricity until ~2025
- Keeping these reactors running is important to maintain UK energy mix (nuclear provides valuable 'base-load')
- Reactors continue to age. Main area of challenge is on the distortion and geometry of the graphite core
- Continued safe operation is kept under constant review and scrutiny by ONR. EDF Energy delivers regular safety cases to demonstrate sufficient understanding of the core state to permit continued safe operation

Graphite Bricks

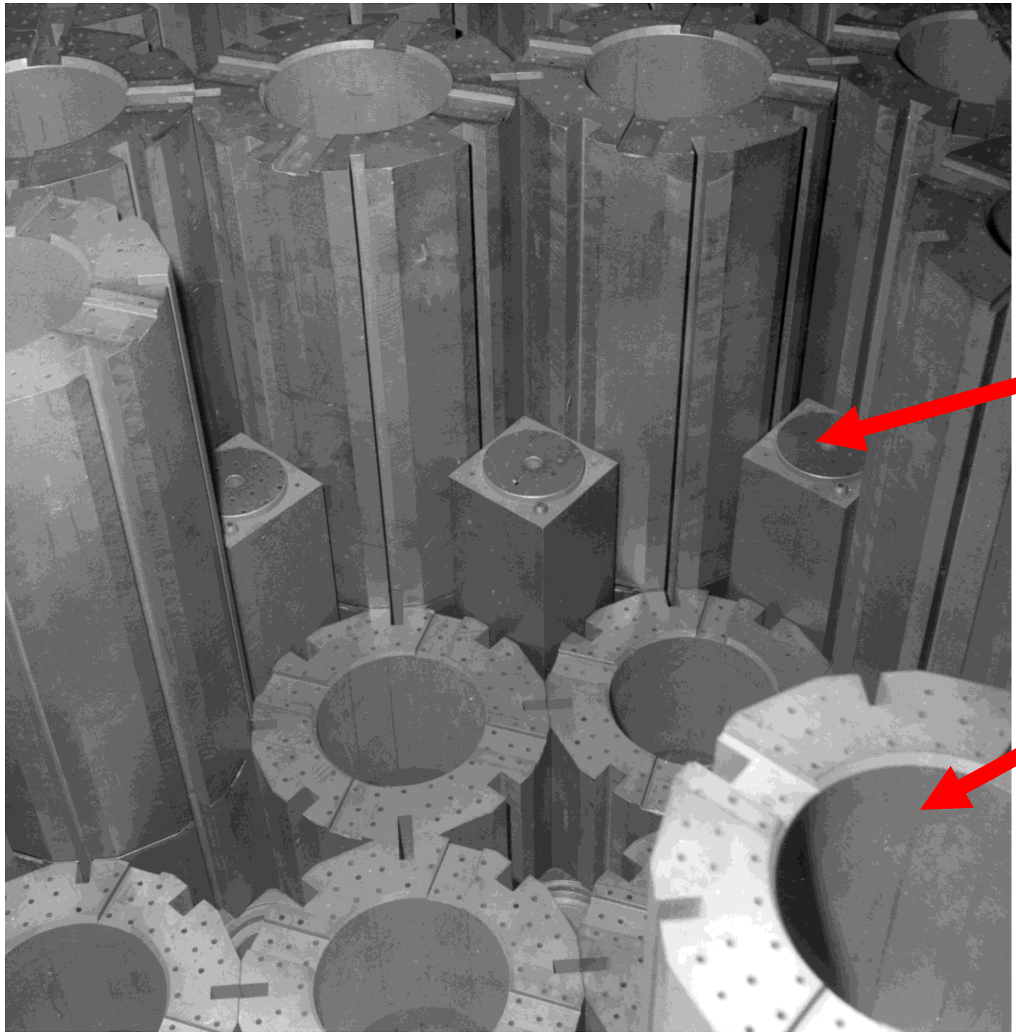
- Graphite makes up the bulk of the core
- Conditions for the bricks are incredibly hostile
  - High temperatures (~400+ °C) – **thermal expansion**
  - High flux of neutrons – causes graphite atoms to be knocked out of place – **changes to material properties**
  - High pressure and temperature CO_2 – chemical changes resulting in **loss of graphite** as the reactor ages



Hunterston B: Pictures show cracks in Ayrshire nuclear reactor

The crack has now widened to 2.9mm, well within our safety assessments.

Graphite Core Detail

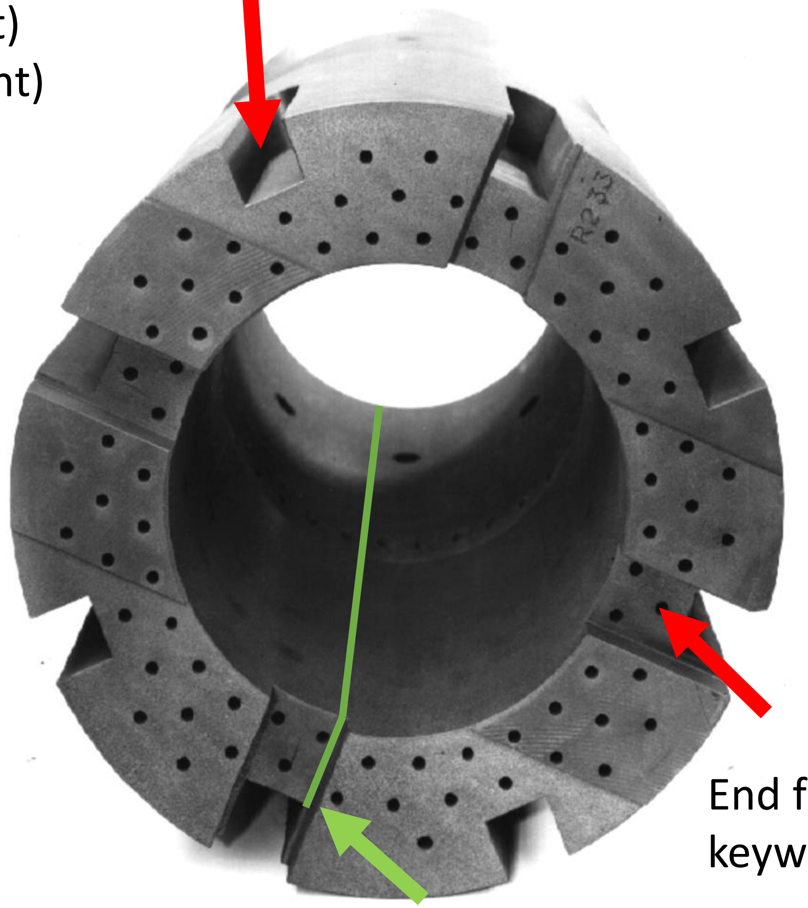


Details vary between stations
Hinkley/Hunterston (left)
Hartlepool/Heysham (right)

Interstitial Brick

Fuel Brick

Brick Height: ~830-900mm
Brick Radius: ~230mm



Radial keyway

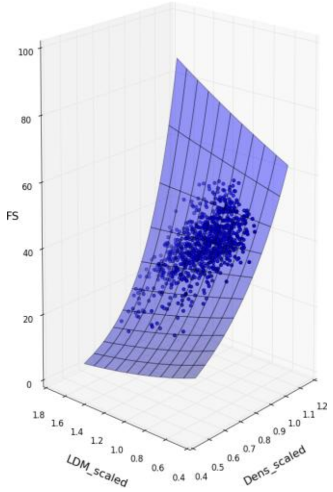
End face keyway

Keyway root and illustrative crack to brick bore

Modelling Overview

COMSOL is at the centre of a ‘diverse’ modelling route used by Quintessa to predict brick cracking rates, accounting for variability between bricks

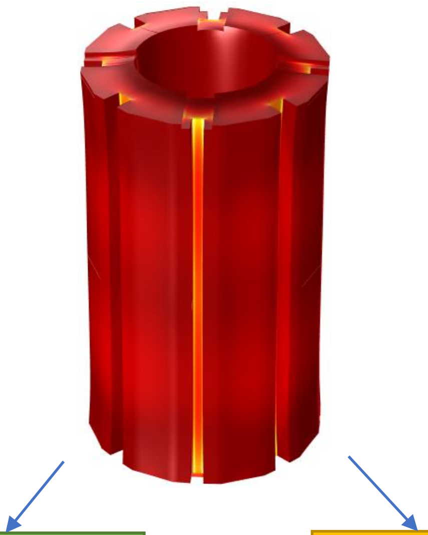
Data analysis (inc. central trends and variability)



Conceptual & mathematical model development

$$\boldsymbol{\varepsilon}_c = \int_o^t \frac{1}{y}\left(\alpha \frac{\boldsymbol{\sigma} P}{\boldsymbol{S}} - \boldsymbol{\varepsilon}_{pc}\right)\frac{d\gamma}{dt}$$

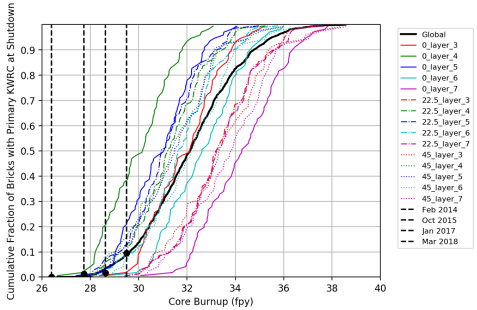
COMSOL



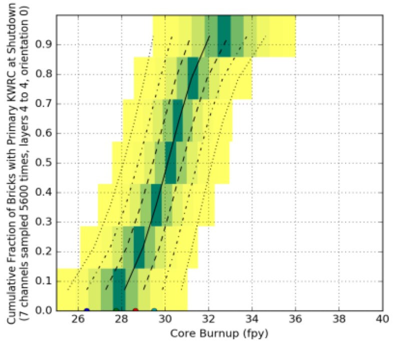
Brick shape

Stress

Analysis of stochastic batch sweep outputs

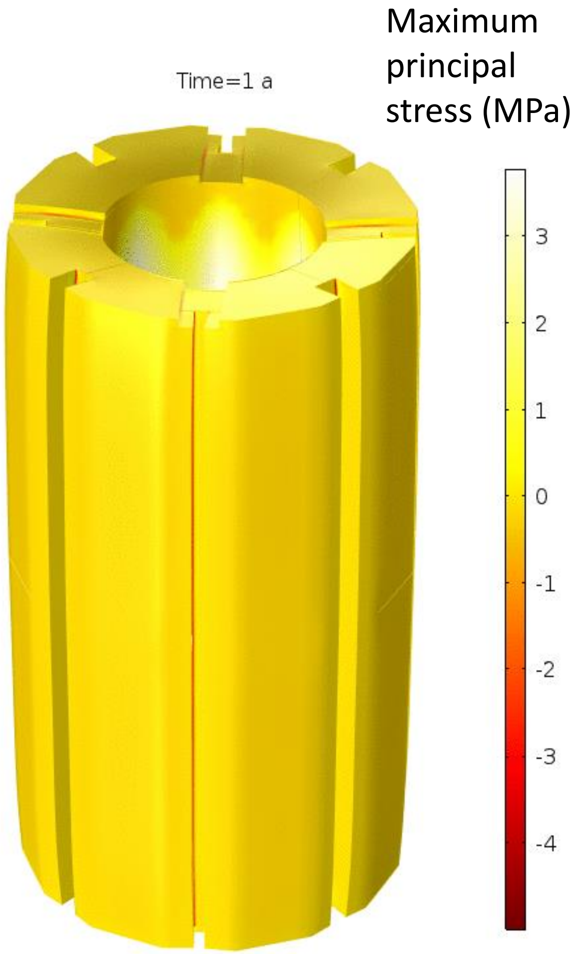


Response surfaces, calibration and further analysis



Quintessa

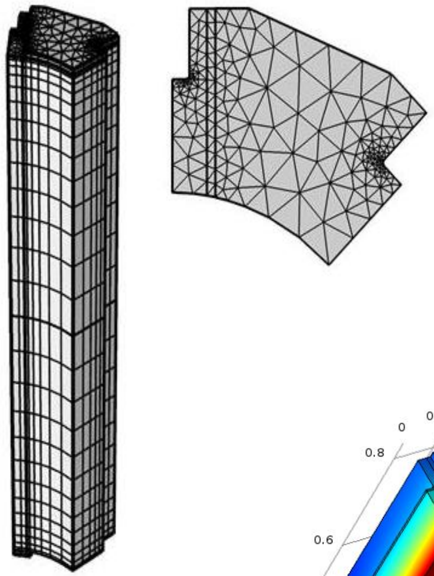
COMSOL Simulation



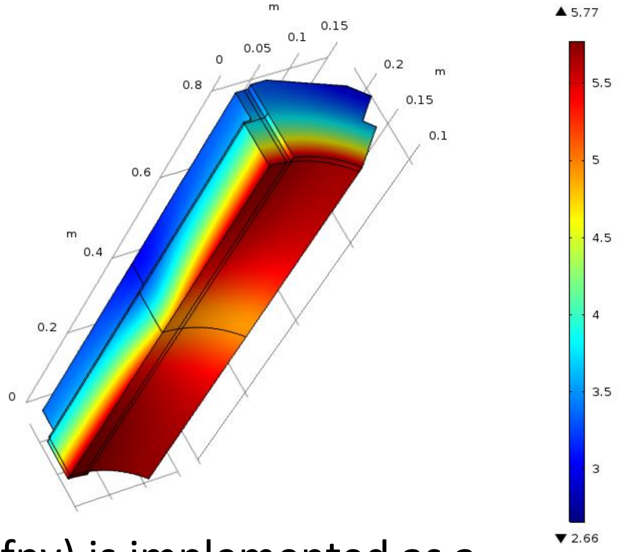
- Each brick is simulated over 40 full power years (fpy)
- Brick shape evolves due to ‘dimensional change’ process driven by neutron dose (shape goes from barrel → wheatsheaf)
- In later life, stresses concentrate in keyways, which can lead to keyway root cracking (KWRC)

COMSOL Implementation

- Custom physics coupled with **Structural Mechanics** module using ODE interfaces
- **Batch Sweep** Monte Carlo simulation accounts for brick variability in physical properties
    - Dimensional Change (DC), Creep, Dose, Weight Loss, Dynamic Young's Modulus, Flexural Strength (FS), Coefficient of Thermal Expansion
- 256 bricks simulated per layer using independently sampled parameters, 'at power' and 'at shutdown'
- Run time of ~1 hr per case



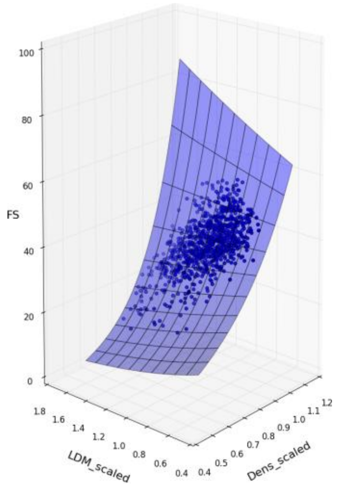
Prism mesh, exploiting brick symmetry

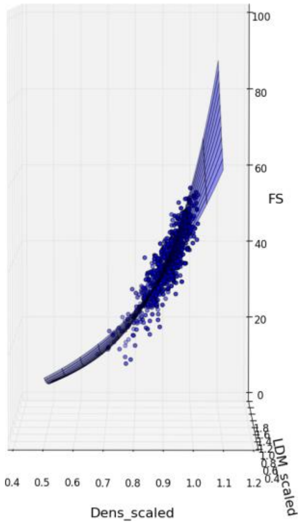


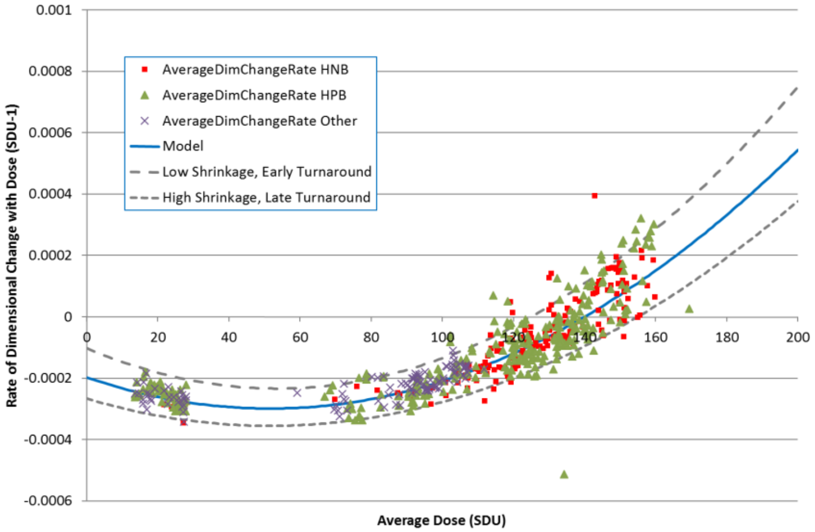
Dose rate (SDU/fpy) is implemented as a field variable, similarly to temperature

Underlying Statistical Modelling

- AGR-specific data collected every ~12 months (at reactor shutdowns)
  - Trepan data (small-scale boring of graphite bricks)
  - Bore shape data (diameter measurements)
  - Camera inspection data (identifies keyway root cracks)
- Also have material test reactor MTR data for dimensional change
  - Small samples not in true AGR conditions, so considerable uncertainty
- These data are used to construct statistical models of graphite properties
  - Model forms are constrained to be physically plausible
  - Allows brick-to-brick variability to be characterised quantitatively
  - Easier to implement and validate than mechanistic models

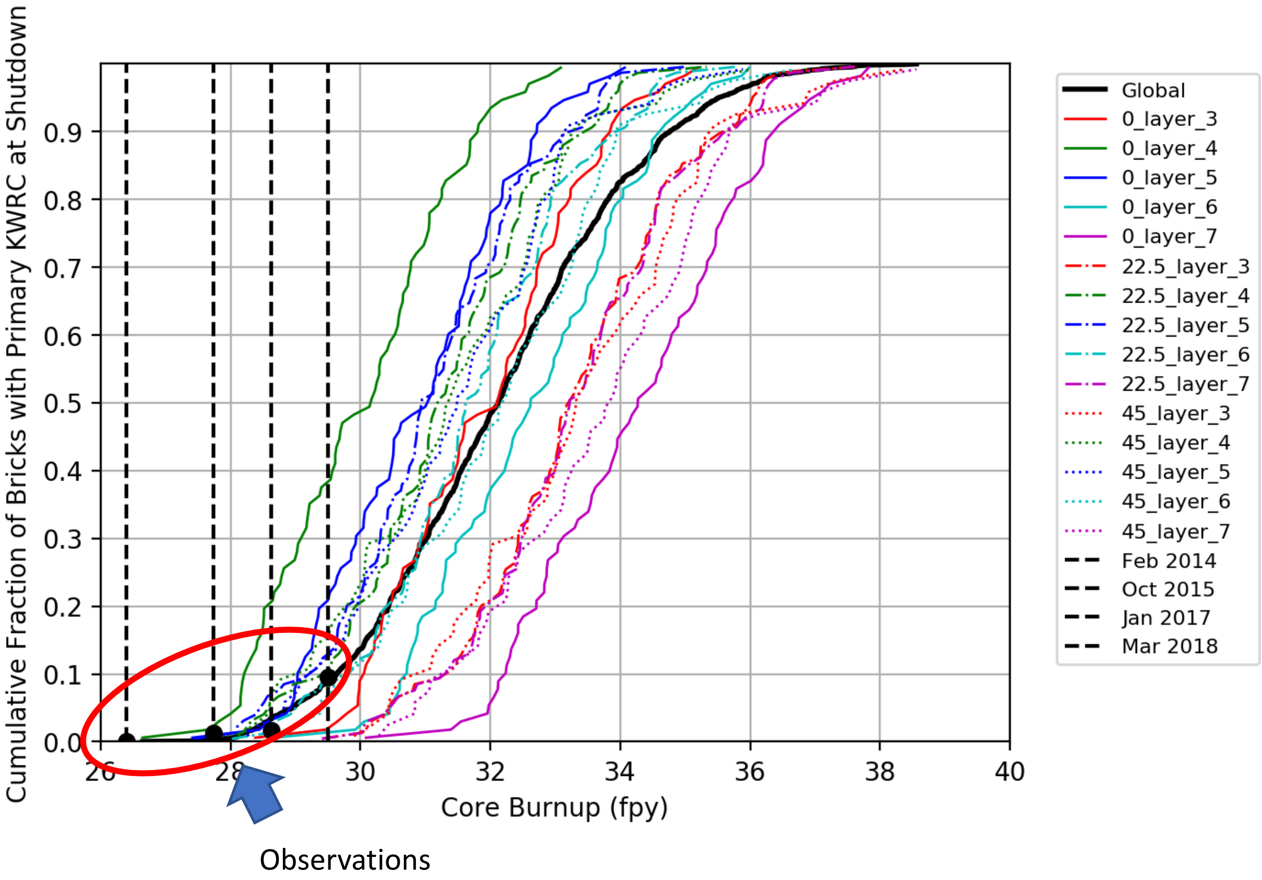






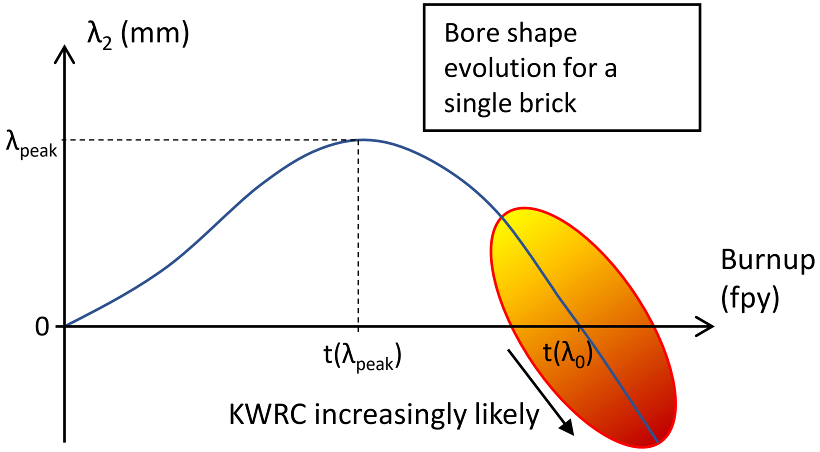
Uncalibrated KWRC Rates

- KWRC times are calculated from the ratio of maximum in-plane principal (MIPP) stress relative to FS
  - Threshold of 1.5 from lab tests but with considerable uncertainty
- All cracks are predicted to occur when the reactor has been cooled for inspection (noting that any cracking caused by brick interaction is not modelled here)
- Predictions in good agreement with observations
  - No global calibration has been performed here – only fitting of each property to AGR data (MTR for DC)



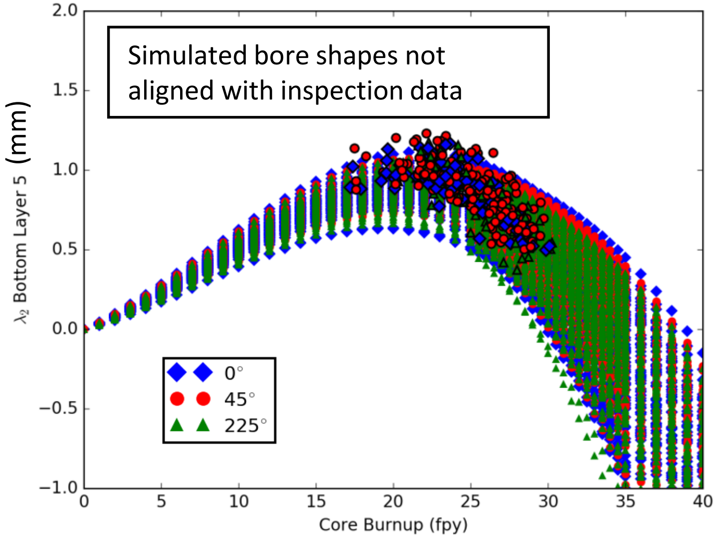
Bore Shapes

- Bore shape is characterised by λ_2 measurement
  - Bore radius difference: $\lambda_2 = r_{\mathrm{mid}} - r_{\mathrm{end}}$
- Bricks bulge out early in life before contracting later (barrel → wheatsheaf)
  - KWRC more likely as λ_2 decreases
- There is an offset apparent between predictions and observations
  - Suggests DC parameter distributions are not quite right (noting use of MTR not AGR data)
- Therefore need to calibrate the model as a whole, not just to individual properties
  - But COMSOL model slow to run



Bore shape evolution for a single brick

KWRC increasingly likely



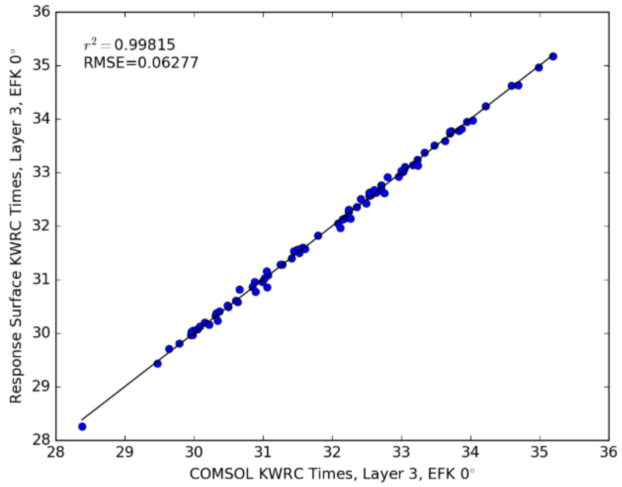
Simulated bore shapes not aligned with inspection data

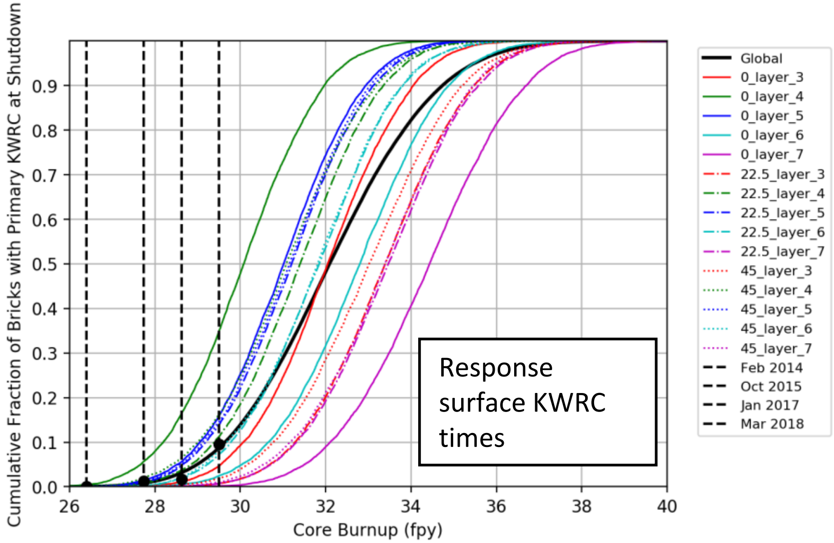
Response Surface (Surrogate model)

- Low-order polynomial is used to approximate COMSOL results, with parameters grouped by property

$$\begin{aligned} R = {} & (c_0 + c_{\mathrm{FS}} S_{\mathrm{FS}} + c_{\mathrm{DYM}} S_{\mathrm{DYM}} + c_{\mathrm{WL}} S_{\mathrm{WL}} + c_{\alpha X} \alpha_{\mathrm{DC}}) \\ & \times (1 + c_\alpha \alpha_{\mathrm{DC}} + c_\beta \beta_{\mathrm{DC}} + c_{\alpha\beta} \alpha_{\mathrm{DC}} \beta_{\mathrm{DC}}) \\ & \times (1 + c_{\mathrm{C}} F_{\mathrm{C}}) \times (1 + c_{\mathrm{CTE}} S_{\mathrm{CTE}}) \\ & \times (1 + c_{\mathrm{D_{self}}} S_{\mathrm{D_{self}}} + c_{\mathrm{D_{side}}} S_{\mathrm{D_{side}}} + c_{\mathrm{D_{corner}}} S_{\mathrm{D_{corner}}}) \end{aligned}$$

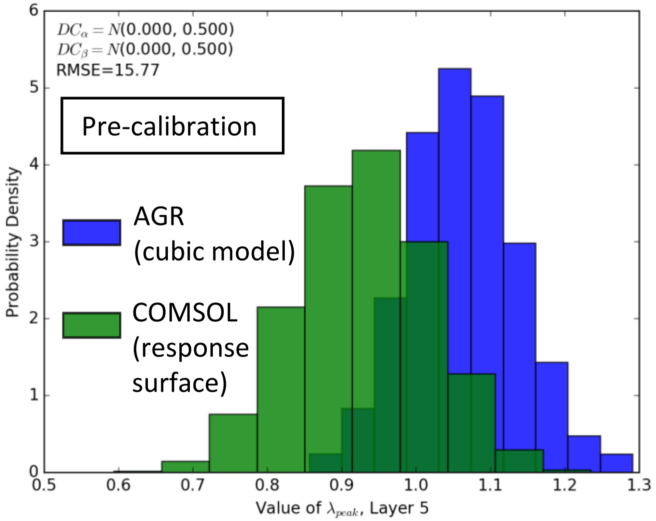
- Coefficients *c* are fitted to variable *R* from COMSOL outputs
  - Originally developed to model time of KWRC
  - Also predicts other variables well, e.g. λ_2, t(λ_2)
- Far greater sample sizes can be used than with COMSOL

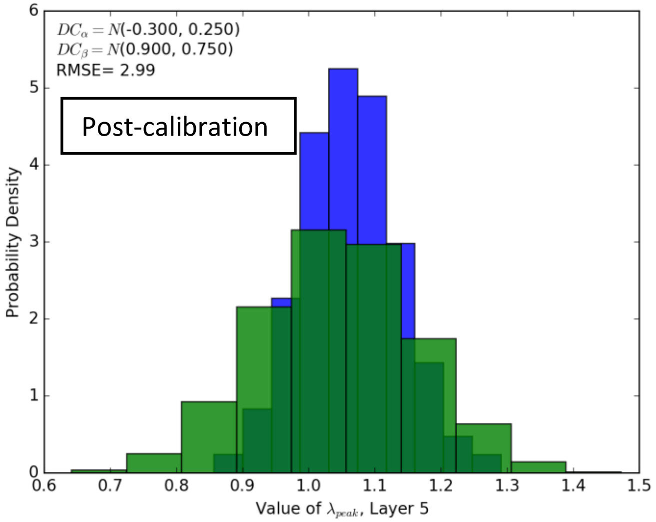




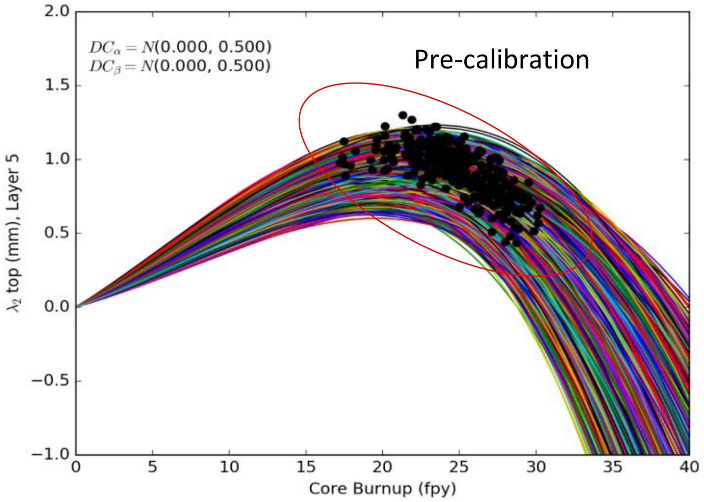
Calibrating to Bore Shape

- The response surface is fitted to bore shape features of λ_{peak}, $t(\lambda_{peak})$ and $t(\lambda_0)$
  - These features are then predicted using multiple brick samples
- The same bore shape features are estimated using a cubic model fitted to inspection data for individual bricks
- Distributions of the features are compared between the cubic model and response surface
  - By varying DC parameter distributions used in the response surface, differences in features are minimised by optimisation
- Calibrated parameter distributions are required to be consistent across layers and features

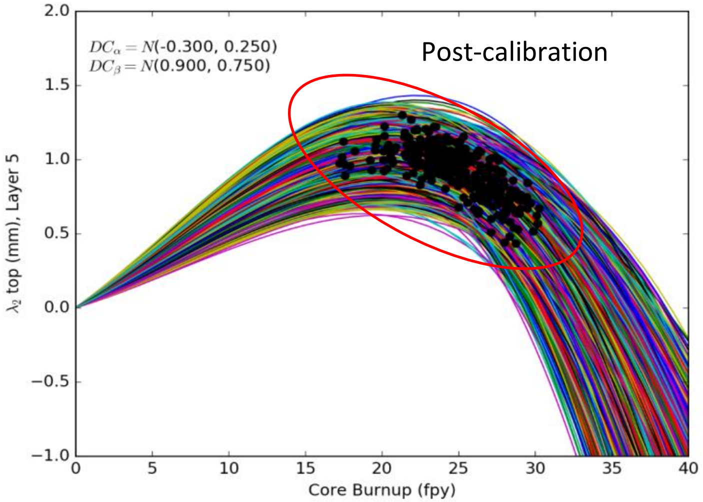




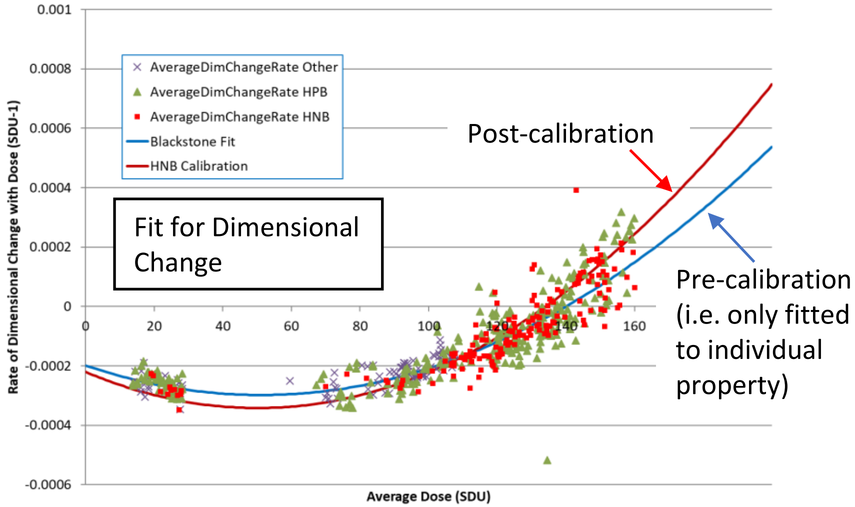
Calibration Result



Pre-calibration



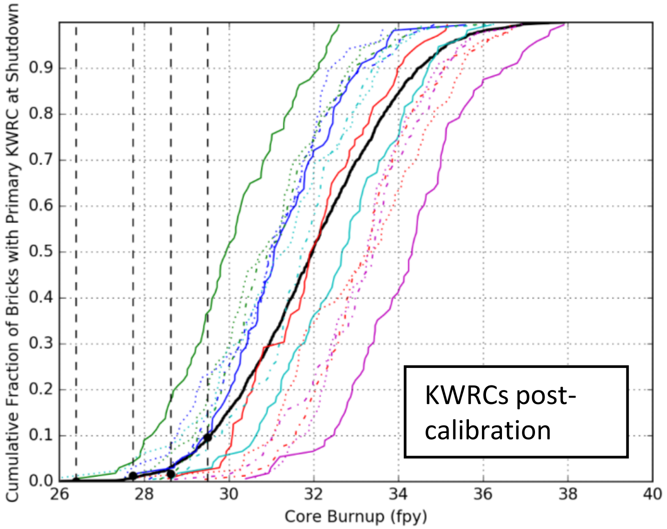
Post-calibration



Fit for Dimensional Change

Post-calibration

Pre-calibration (i.e. only fitted to individual property)

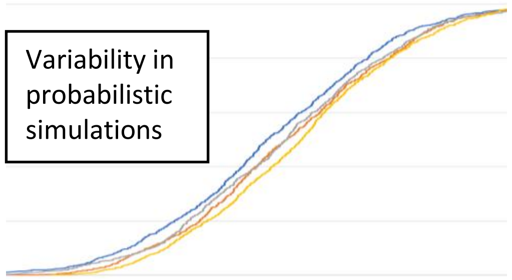


KWRCs post-calibration

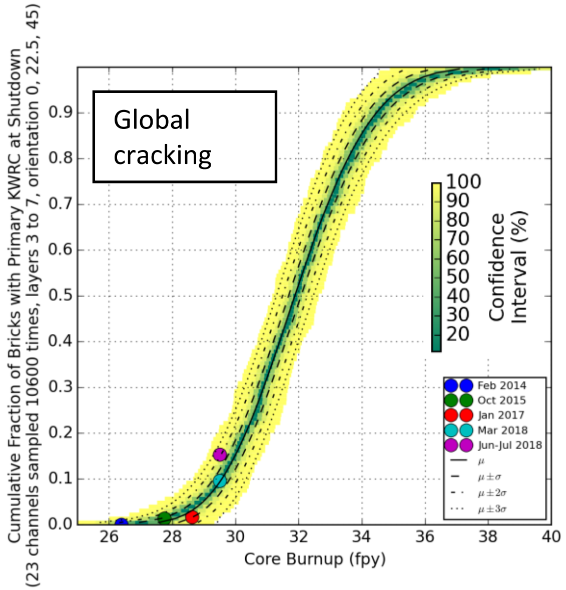
- The new parameter distributions improve agreement with bore shape evolution data
  - Fits for individual physical properties also remain good
- Small adjustment to failure model on keyway root to recalibrate
  - This is well within its uncertainty, and also accounts for differences in modelled temperatures
- Transparent calibration process
  - Builds confidence in model
  - Allows further analysis using response surface

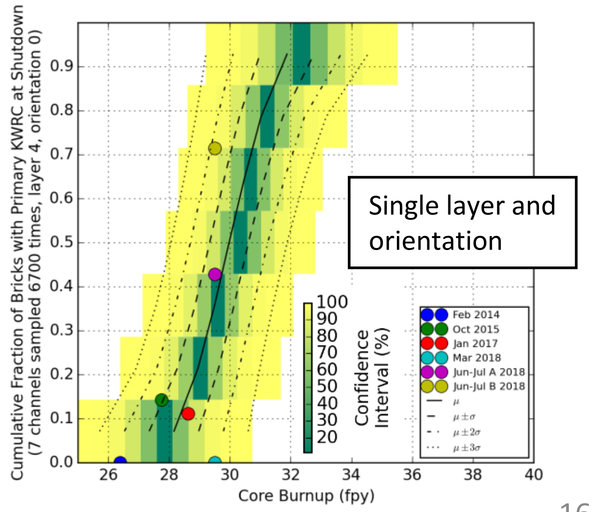
Comparison with Observed KWRCs

- The response surface can also be used to estimate KWRC uncertainties
  - Each Monte Carlo simulation gives slightly different results, so repetition captures inherent variability
  - The calibrated DC parameters (using AGR data) help to support predictions of variability


Variability in probabilistic simulations

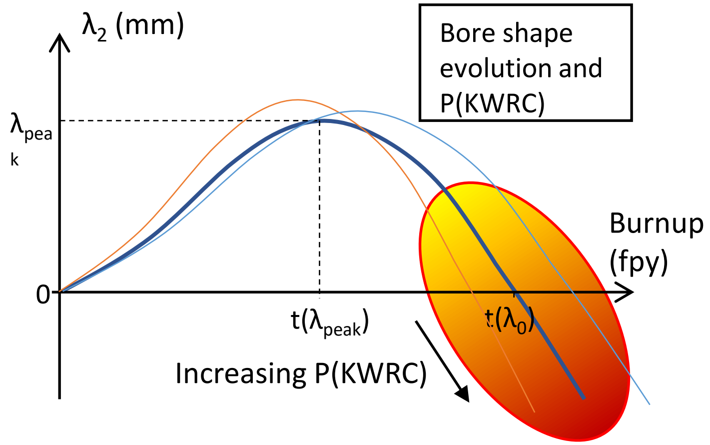
- The sample size can be fixed to match the number of inspection channels
  - Confidence intervals are estimated by repeated simulation using the fixed sample size
  - Large uncertainties exist with limited channels and layers – important to note for comparison with observations

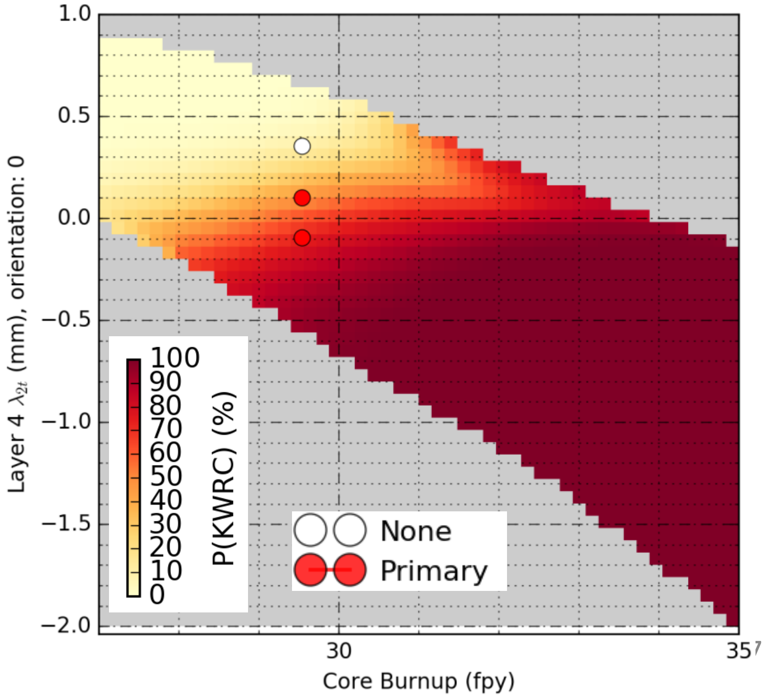

Global cracking


Single layer and orientation

Understanding Data, Building Confidence

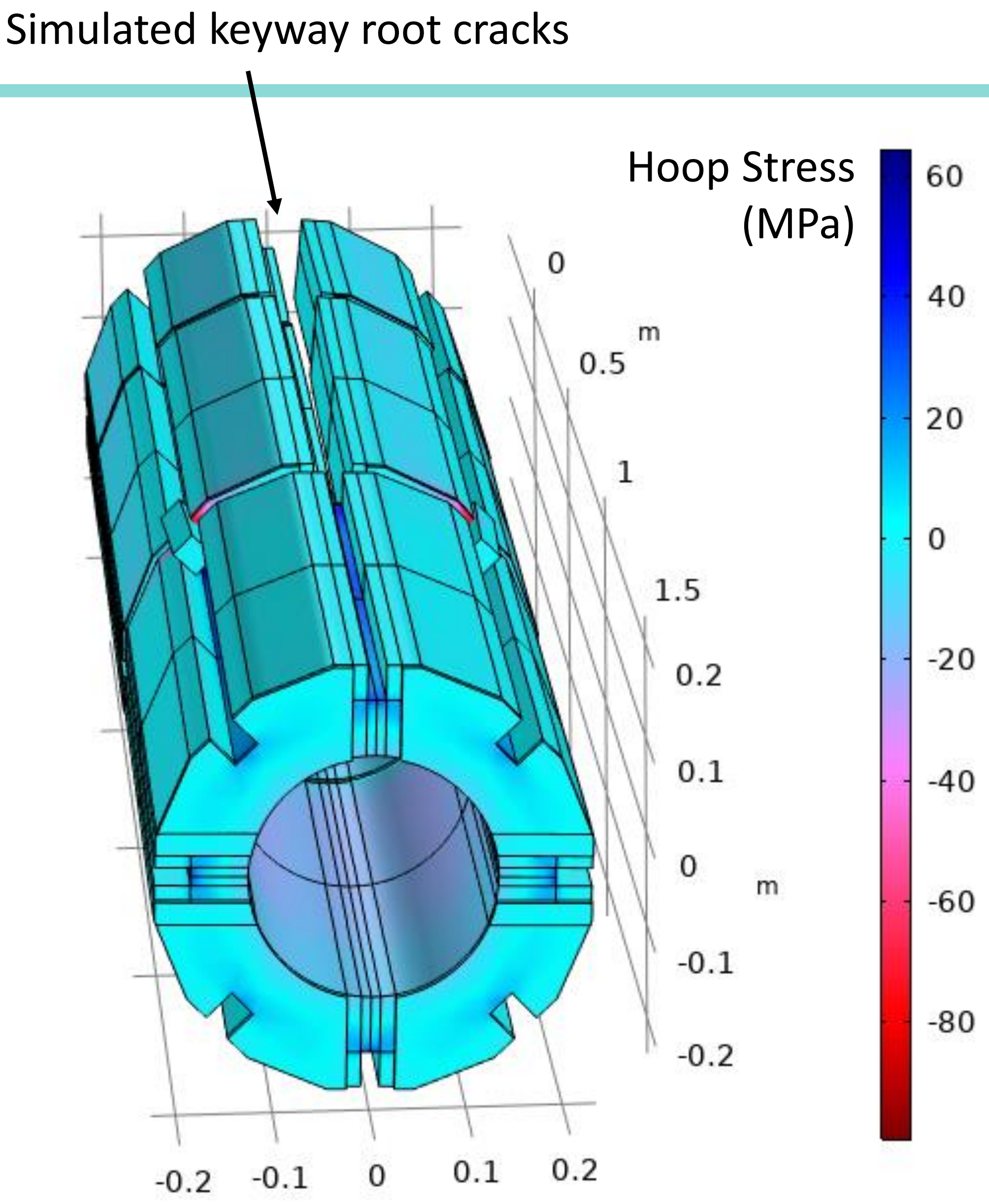
- Multiple types of cracks expected to be seen in reactor, not just ‘primary’ keyway root cracks.
- Method can be used to say how likely we expect a crack is to be a primary keyway root crack given the reactor age and bore shape
- Can also be used to build confidence in the modelling method





Multiple Bricks

- Currently investigating multiple bricks interacting
- Having cracked, can get significant interaction via the keying system, accelerating cracking in adjacent bricks
- Initial work matches with observations


Simulated keyway root cracks

Quintessa

Modelling Overview (revisited)

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Conceptual & mathematical model development

COMSOL

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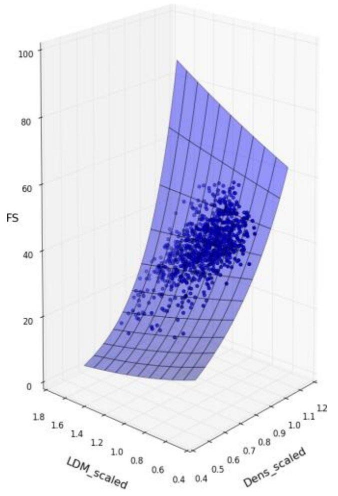

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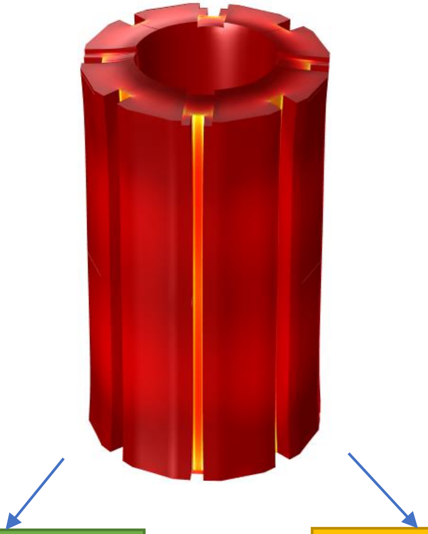
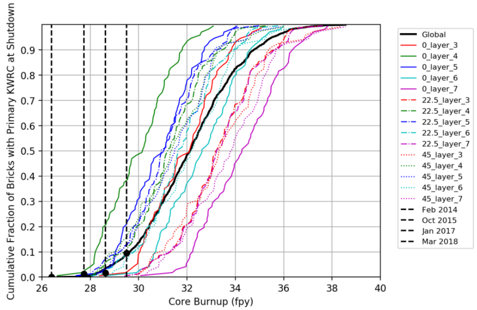
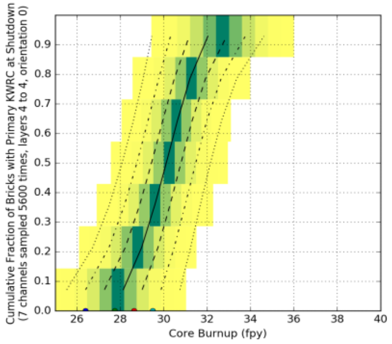


Brick shape

Stress





Quintessa

Summary

- Understanding the state of the graphite core of AGRs is a key component in their continued safe operation
- COMSOL is being used as an ‘engine’ in a statistical and stochastic modelling approach by Quintessa to help understand the core state
- Sincere thanks to all in the EDF Energy Graphite Branch, especially Mark Bradford, Sam Baylis and Jim Reed