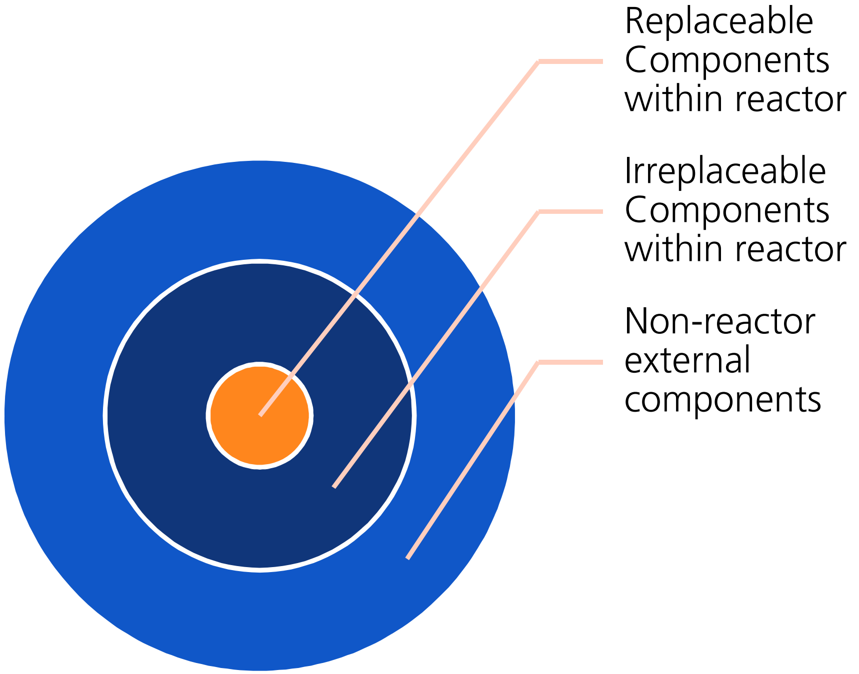
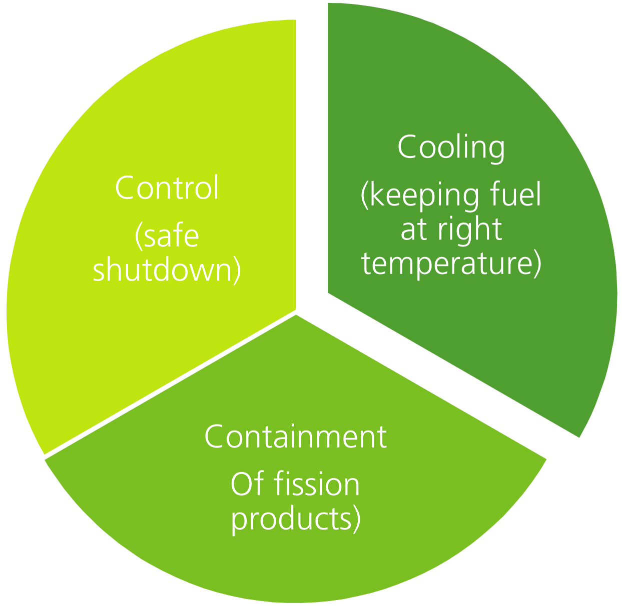
Nuclear Innovation Conference

What are the key lessons to be carried across from AGRs to AMRs?



System design – where are the risks due to incomplete knowledge

Maintenance & Inspection



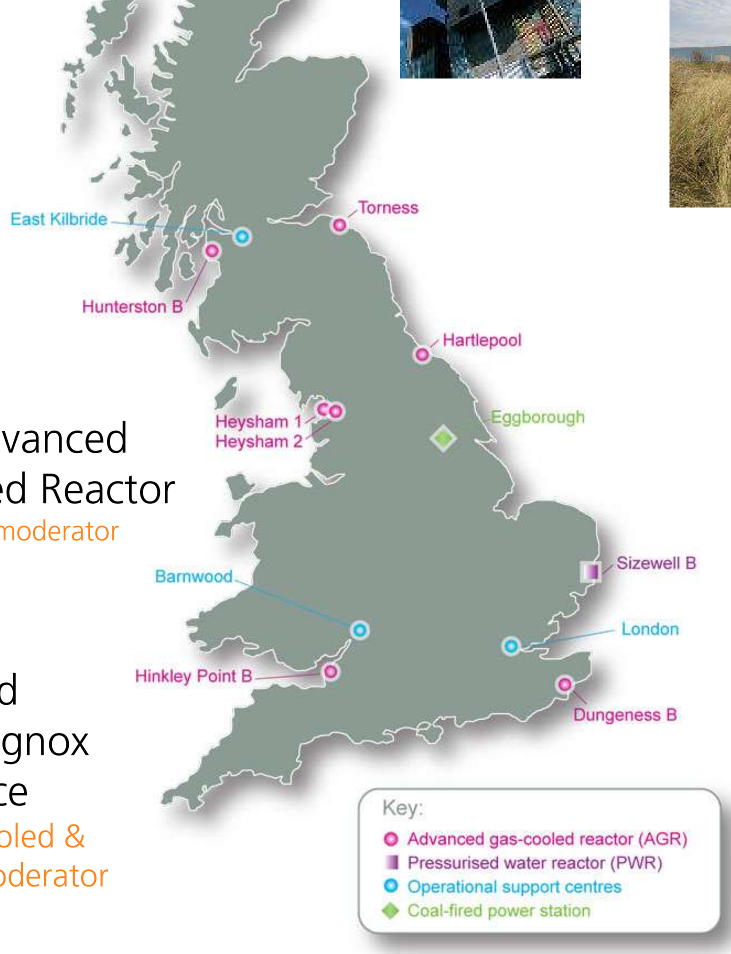
Nuclear Safety – where is the balance in protection, prevention or mitigation?

AGR = Advanced Gas Cooled Reactor

With graphite moderator

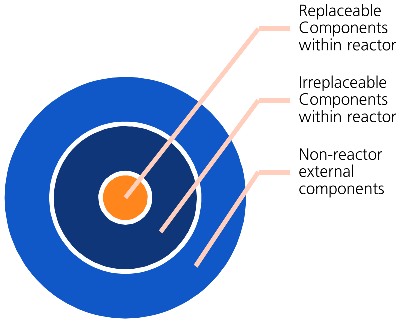
AGR build upon Magnox experience

Also gas cooled & graphite moderator



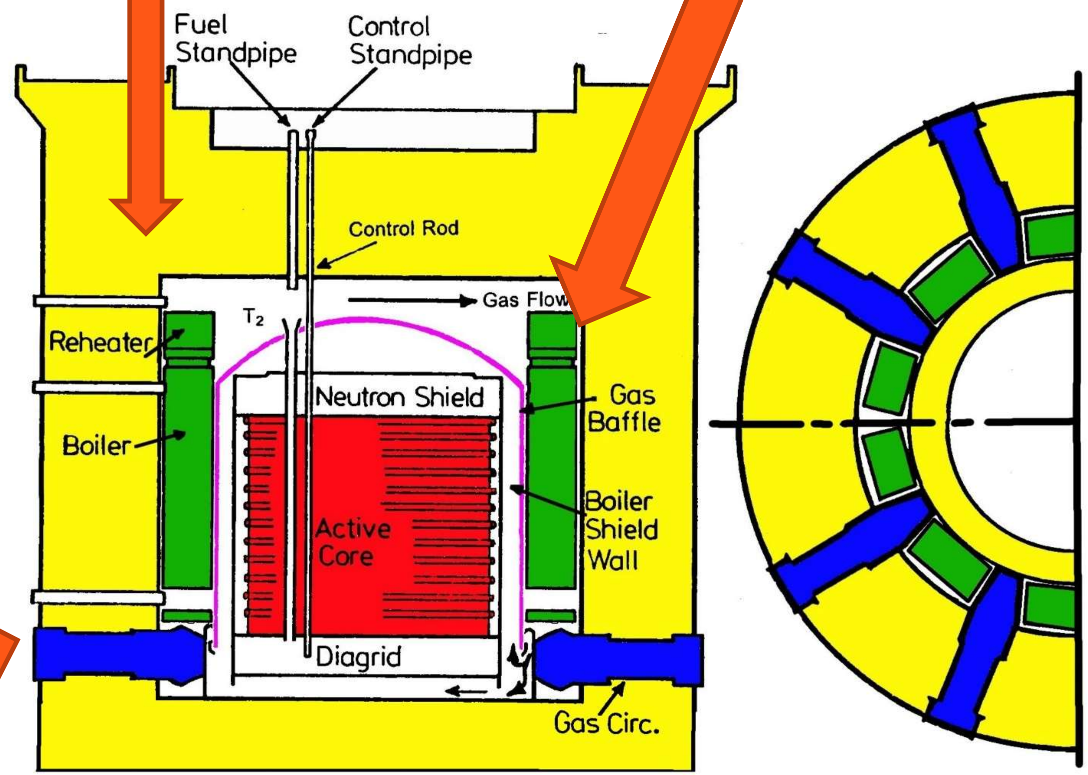
- Operating these reactors as been a success for UK
- Designed later 1960s
- Built late 1970s-early 1980s
- Only in 2021 have the first of these stopped generation
- But there are some lessons to learn for the next generation of reactors

"Generic" Design



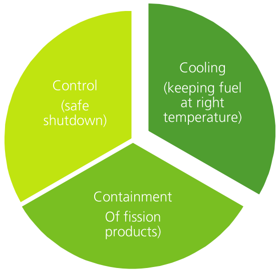
Concrete pressure vessel & graphite core - irreplaceable

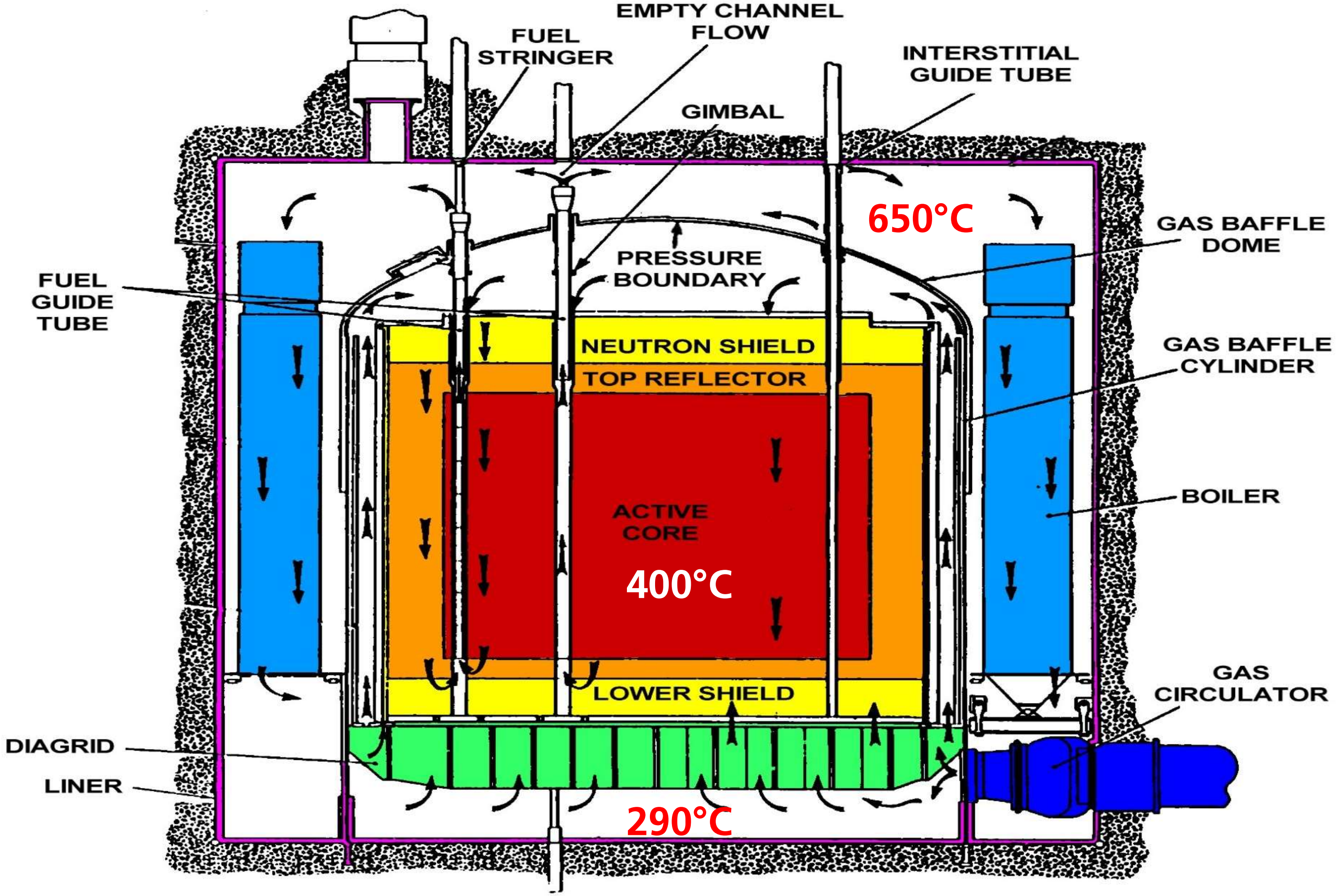
Repair boiler tube leaks
Replaceable at HRA/HRA – but never completed



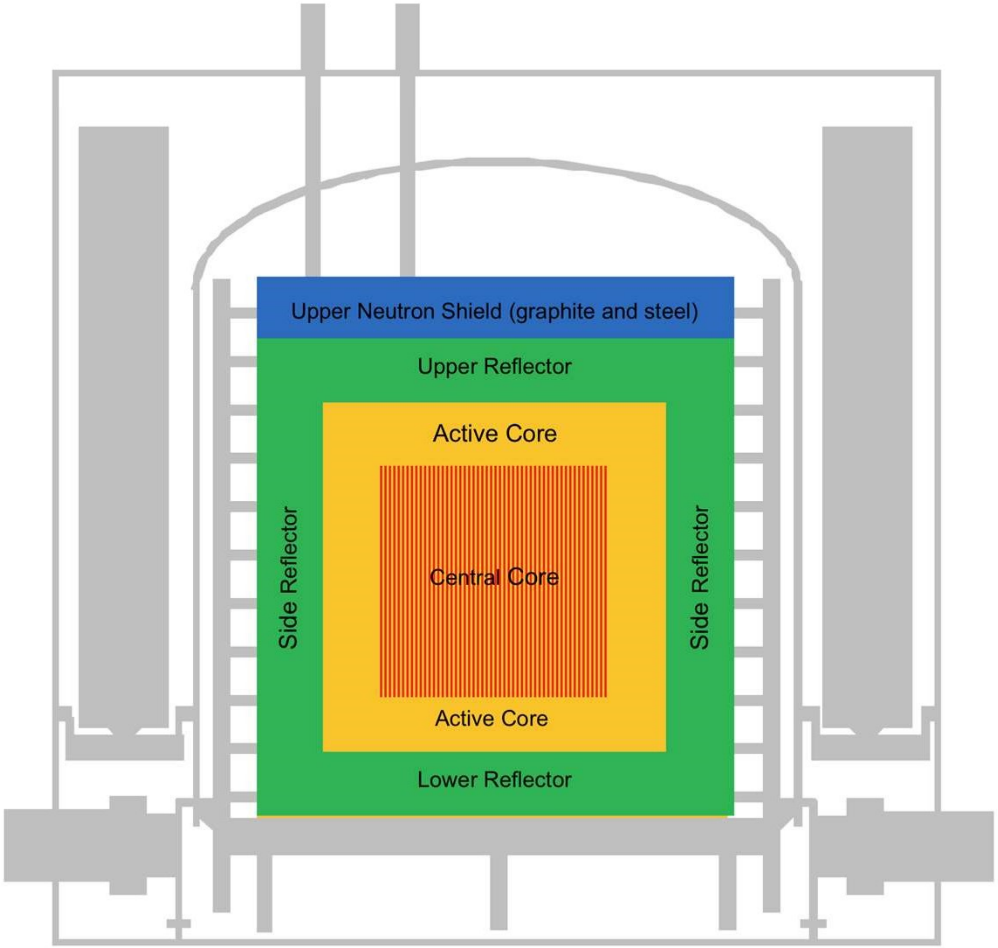
Maintenance & Replacement

Temperature Control





Graphite Core – The Challenge



AGR Core Schematic Diagram

Safety Requirement

- Free movement of fuel
- Free movement of control rods
- Provide Fast neutron moderation

The graphite core cannot be repaired or replaced

Ageing and degradation due to fast neutron irradiation and radiolytic oxidation leads to a potential challenge to the safety requirements

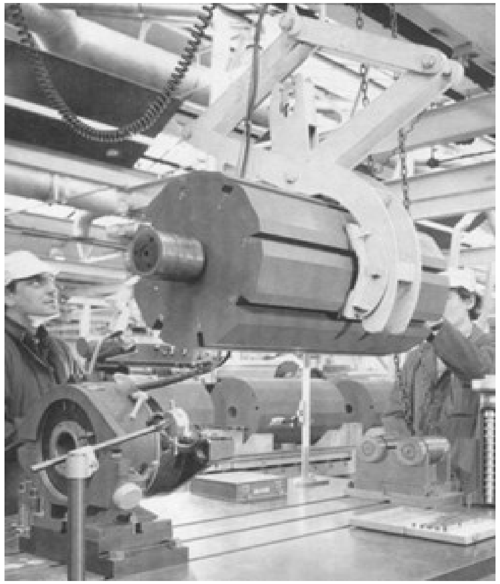
Graphite Core is one of lifetime limiting factors for AGRs

There is limited world-wide experience

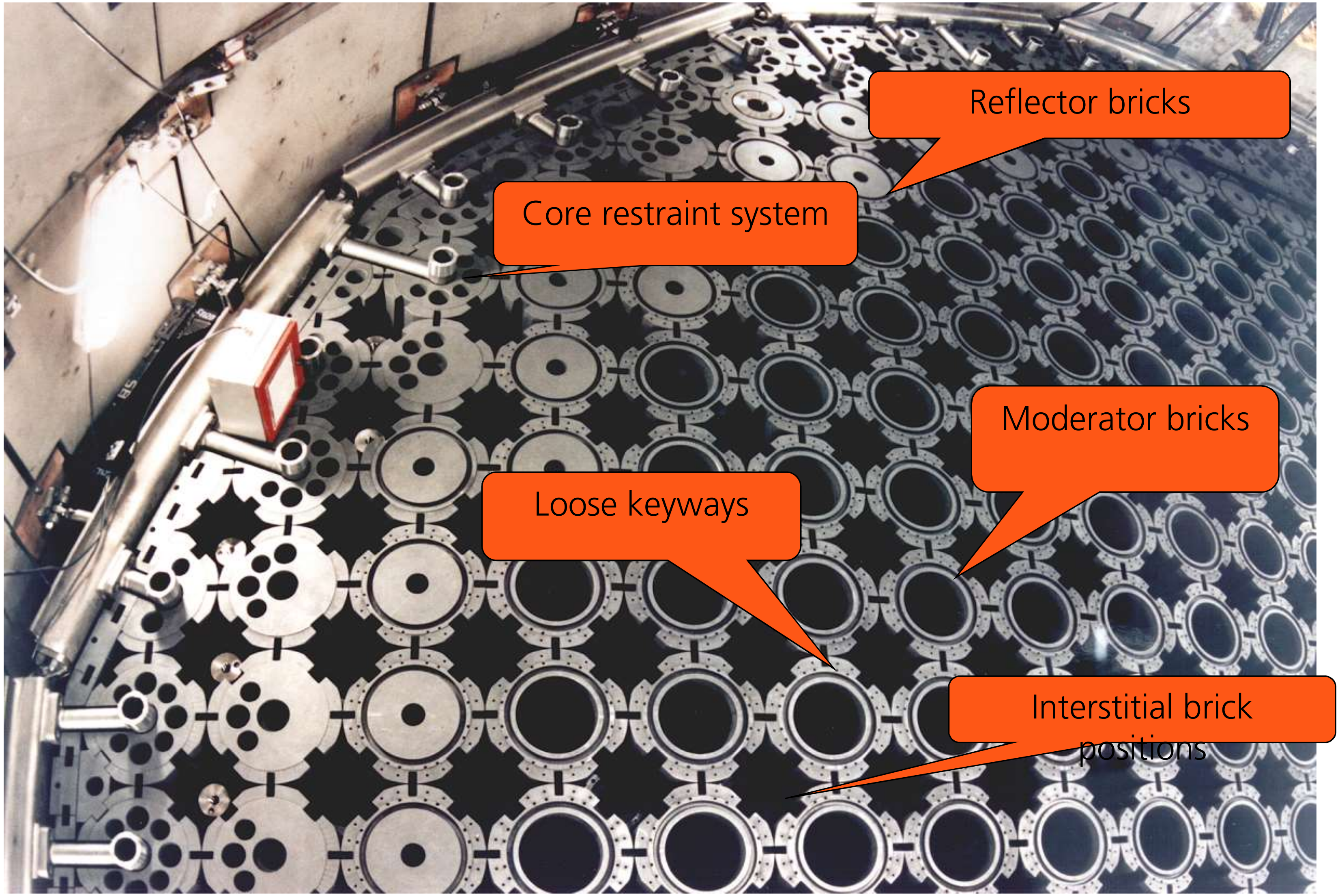
Graphite - How it is made and why it is unique

A view along the auxiliary Polygonal Brick Line.

Machining the flats on the sides of the Polygonal Bricks on a Duplex machine.

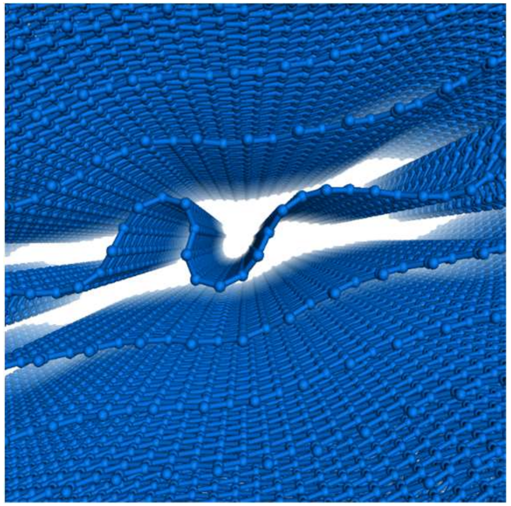


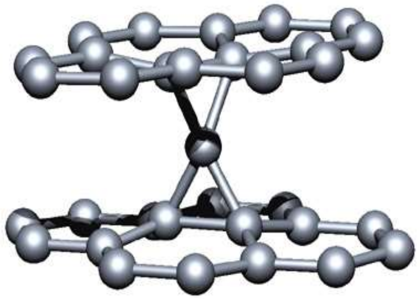
Putting the Keyways into the faces of a Polygonal Brick.



Construction of Torness Core

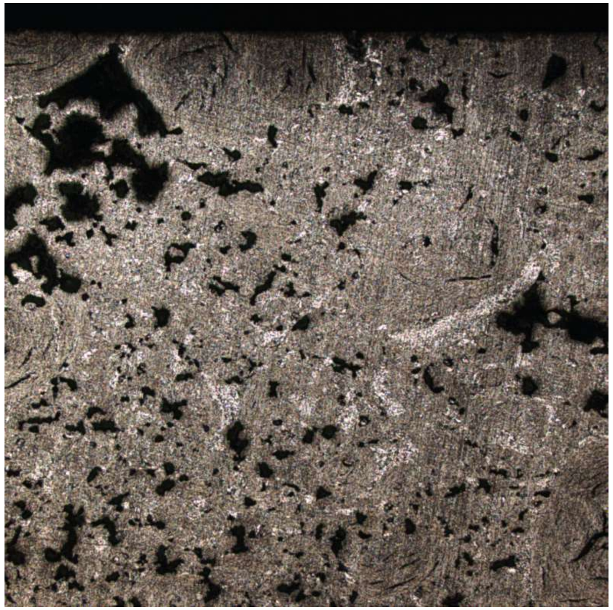
Irradiation Dose





- Each carbon atom is displaced 26 times
- The change in graphite properties is complex and hard to predict from first principles.
- There was only limited data during design & early years of operation

Radiolytic Oxidation



- CO2 coolant was know to ionize and cause oxidation of the graphite
- Original intent was to add methane which acts as an inhibitor to keep weight loss low

Graphite Ageing & degradation

- Irradiation and oxidation were known about however insufficient information at design stage
  - Carbon deposition – this was cause by too much methane and led to deposition of fuel and deposition on boilers.
  - Deposition on fuel could lead to inappropriate fuel temperatures
  - Reduced methane (needed some O_2 injection to remove deposits) but net result is graphite weight loss locally ~40%+
  - Graphite Strength decrease exponentially – leading to low seismic tolerance of the core

Graphite Ageing & degradation

- Irradiation and oxidation were known about however insufficient information at design stage
  - Irradiation caused dimensional change which was successfully accounted for (i.e. the channel size is within acceptable dimension)
  - But differential shrinkage and thermal stress we not successfully accounted for.
  - Net result was that stresses set up with bricks were sufficient to cause cracking
  - And cracking leads to a potential weakening of the keying system which leads to potential challenge during seismic event of inability for control rods to enter the core (challenge to control)

Two other key design issues missed

- AGRs were intended to refuel during full power
- However during early operation it was found that the gas loads & buffeting cracked the fuel sleeve (temperature control)
- Low power refuelling was instigated

- Novel Boiler tube technology (heat exchanger) was used in one pair of stations with the idea that the boilers could be replaced
- However inadequate consideration of the practicality and safety implication of such an exchange meant that it was never undertaken
- And the inbuilt design weakness of the boiler closure units resulting in major 2-3 year programme of remedial work

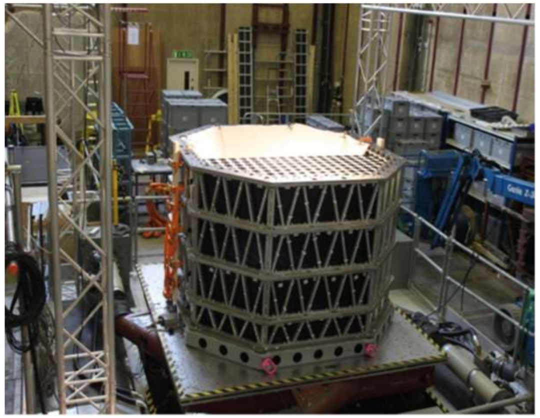
Action to address Graphite Shortfalls

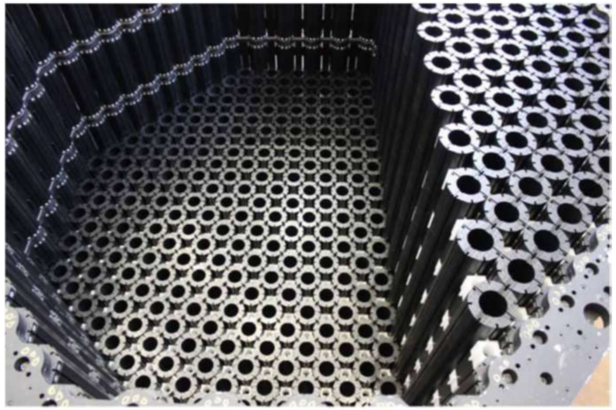
- Development of improved analysis tools to better predict the behaviour of graphite, graphite bricks and the graphite core as an assembly
- Major programme to generate data from experiments and rig testing to support the analysis tools
- Significant increase in inspection programme to understand the state of the core (which has direct impact on generation since reactor needs to be off-line)
- Plant modifications to diverse shutdown and holddown to cover uncertainty in core behaviour

Shaker Table

- To understand how cracked core behaves for channel distortion
- ¼ scale model of plastic bricks
- **300** channels and 8 layers
- **30%** cracked bricks into the array
- **20,000** sensors to measure the seismic experiments

- Collaboration with Bristol University
- 8 year programme
- 15 scientist and engineers



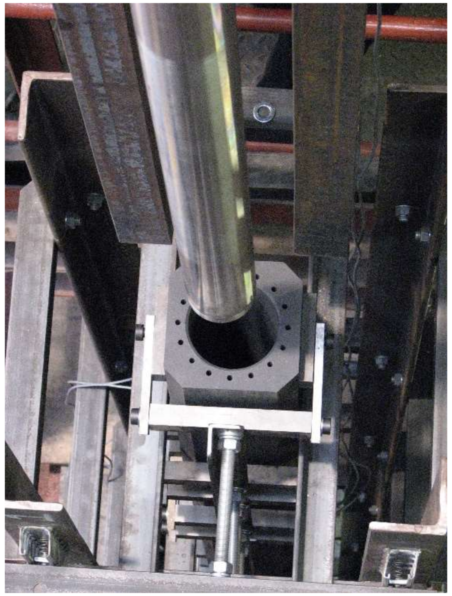


Super articulated control rods & N2 system

- Stringer and Control Rod Channel Rigs
  - To determine the effect of channel geometry on fuel and control rod movement, and gapping of fuel stringers.
  - Installed in HPB/HNB

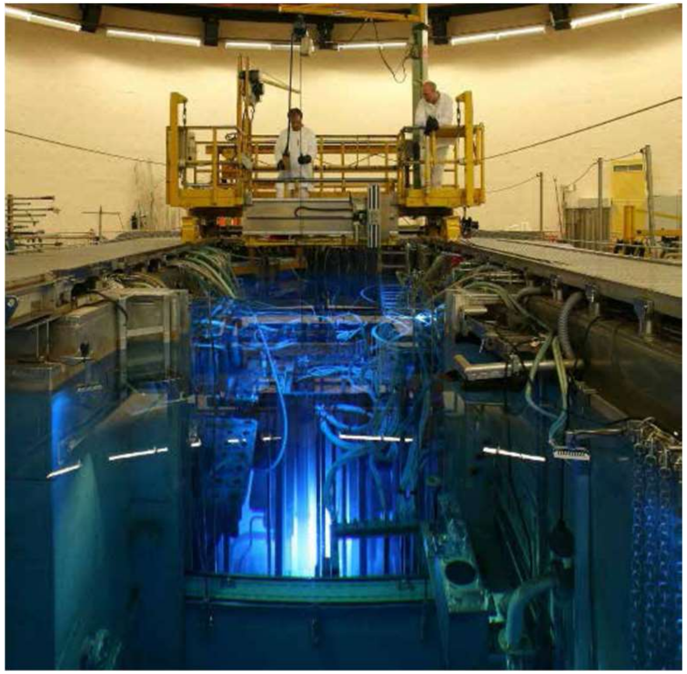
- N2 and boron ball system updates
  - Plant was not seismically designed
  - But major requirement to guard against incorrect graphite core assessment

- Direct station operation.
- 3 year programmes at each station



Graphite Properties data -

- Half way through reactor life realised there was insufficient graphite data
- Material test reactor programme to gather data over the dose temperature and weight loss range
- Comprehensive programme that also included a series of creep experiments
- Pre- and post sample measurements which then needed to apply to brick 100x greater in scale



- Collaboration with NRG and NNL
- 8 year programme
- 30 scientist and engineers

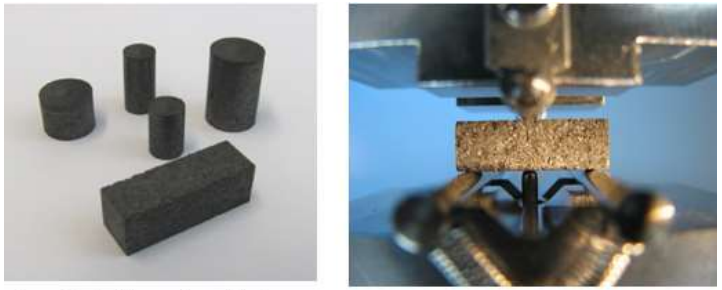


Figure 82: Graphite samples and testing

What have we achieved

- Each reactor nominal design was 25 years operation.
- Early this year Hunterston B closed after reaching 40 years operation
- Graphite was the major contributor to determining the lifetime
- Original design limit of weight loss was passed 25 years ago and first cracked bricks observed 18 years ago – design intent low weight loss and no cracked bricks
- Successful programme of safety case, inspection , modelling and experiments
- And the cost - over 10+ years, over 100+ scientists & engineers with major cost implications

What are the key lessons

- Graphite is a special material with some complex irradiation behaviour which cannot be defined from first principles – need to gather data
- Graphite components will also evolve in may unexpected
  - Magnox core expansion low temperature
  - Magnox core height shrinkage to challenge charge path
  - RBMK brick cracking and core distortion (in excess 100mm)
  - AGR brick cracking & weight loss
- Requirement to get the right property data and put these into the right models to predict component behaviour

What are the key lessons

- Variation may be a friend rather than a foe
- If everything was identical if failure were to occur – all components at risk
- With variability potentially only a few could be at risk and these could be found from inspection programme

What are the key lessons

- Redundancy within design may be useful
- The AGR graphite bricks were connected by 8 keys to the surround neighbours
- So failure of one of these 1 was not catastrophic for core distortion
- And the AGR fuel sleeve protected the fuel from changes in the gas flow
- This was not the case for Magnox reactors where no brick cracking could be tolerated

What are the key lessons

- Independent Peer review
- When tasked with delivery it is too easy to get focussed
- Much of the work is novel and first of a kind – so there is a need to check and review
- Careful use of independent advice is key – they need to know enough and have the right experience but they also need to act as a sounding board

What are the key lessons

- Key skill and competence in organisation to respond to changes
- The ability the write safety cases that responded to the plant evolution needs to be maintained
- The evidence for these cases had to be generated and this was not a trivial undertaking
- Industry and University expertise was combined to address the issues and so relationship and expertise needed to harnessed.
- But beware – some organisations are less competent e.g. some MTR experiments have yielded virtually useless data; some property modelling curve fit MTR data but do not replicate operating reactor data; …….

Conclusion

- For AMRs there will be challenges in their design
- And they will get things wrong – but what can be put in place to minimise these consequences
- Operation Experience is key – and there must be examples from UK AGRs to support the AMR programme

