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Nuclear Graphite Research
A UK Regulatory Perspective

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Topics

- Background
- Regulatory regime
- Regulatory challenges and strategy
- Regulatory guidance relating to graphite
- Safety case improvements
- Graphite nuclear safety research
  - Research arrangements
  - Graphite research strategy
  - Current graphite research programme

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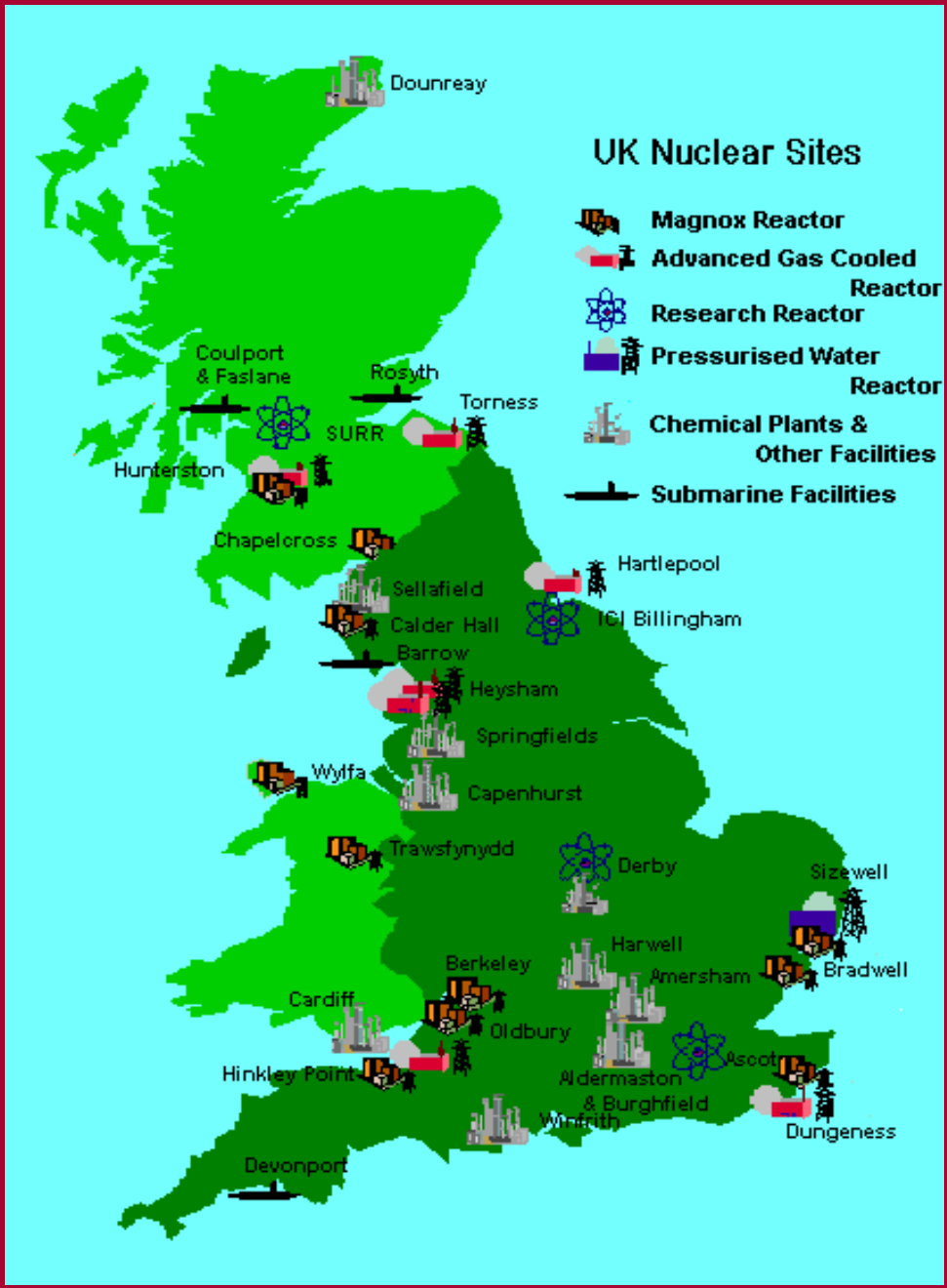
Background

Background

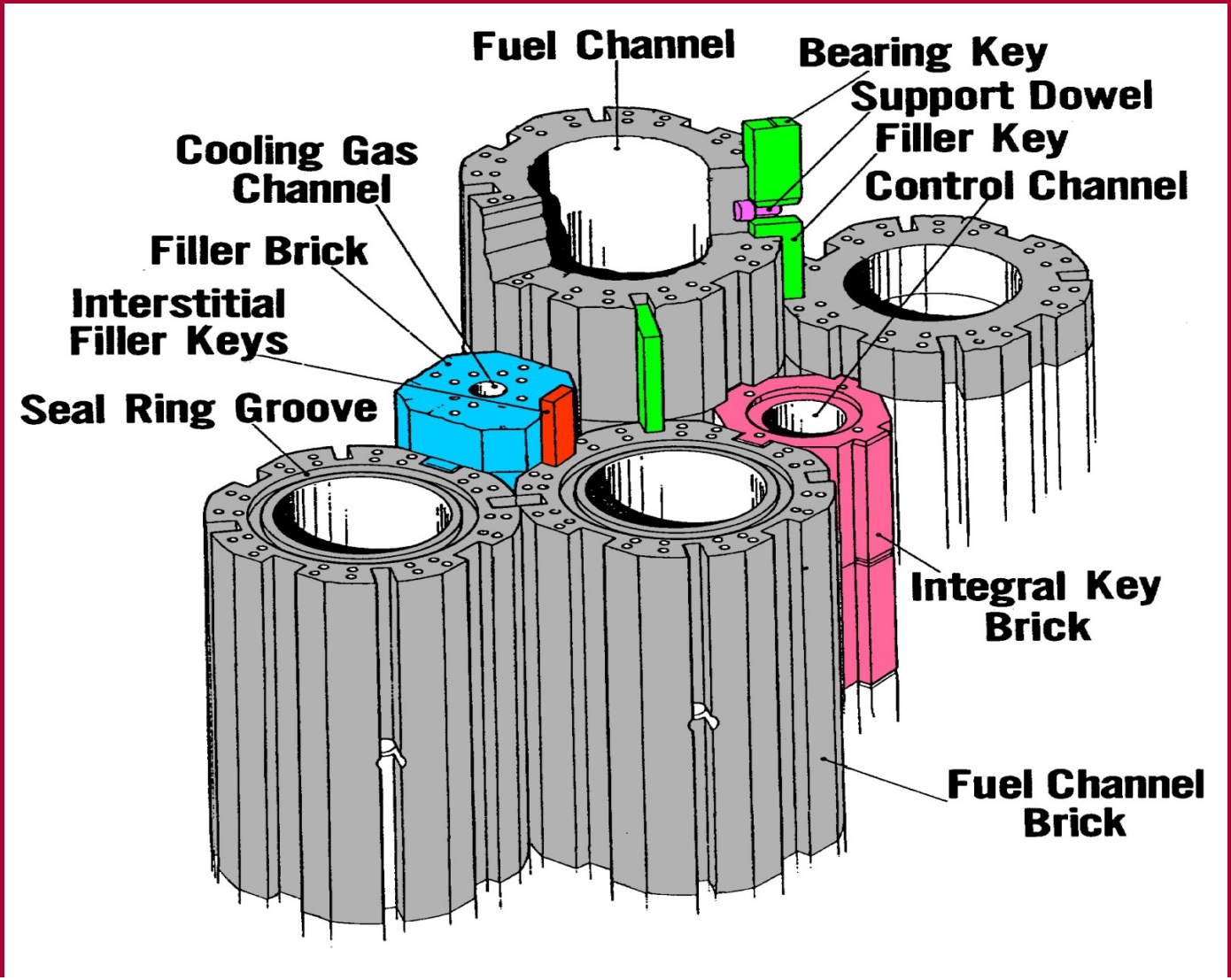
- Around 20% of UK electrical power supply comes from:
  - 14 Advanced Gas Cooled Reactors
  - 4 Magnox reactors
  - 1 PWR
- 18 of these reactors are graphite moderated
- Current planned closure dates for AGRs between 2016 and 2023
- Last of Magnox reactors due to cease generation in 2012


UK Nuclear Sites
Magnox Reactor
Advanced Gas Cooled Reactor
Research Reactor
Pressurised Water Reactor
Chemical Plants & Other Facilities
Submarine Facilities
Dounreay
Coulport & Faslane
Rosyth
Torness
SURR
Hunterston
Chapelcross
Hartlepool
Sellafield
Calder Hall
ICI Billingham
Barrow
Heysham
Springfields
Wylfa
Capenhurst
Trawsfynydd
Derby
Sizewell
Harwell
Berkeley
Amersham
Bradwell
Cardiff
Oldbury
Ascot
Hinkley Point
Aldermaston & Burghfield
Winfrith
Dungeness
Devonport

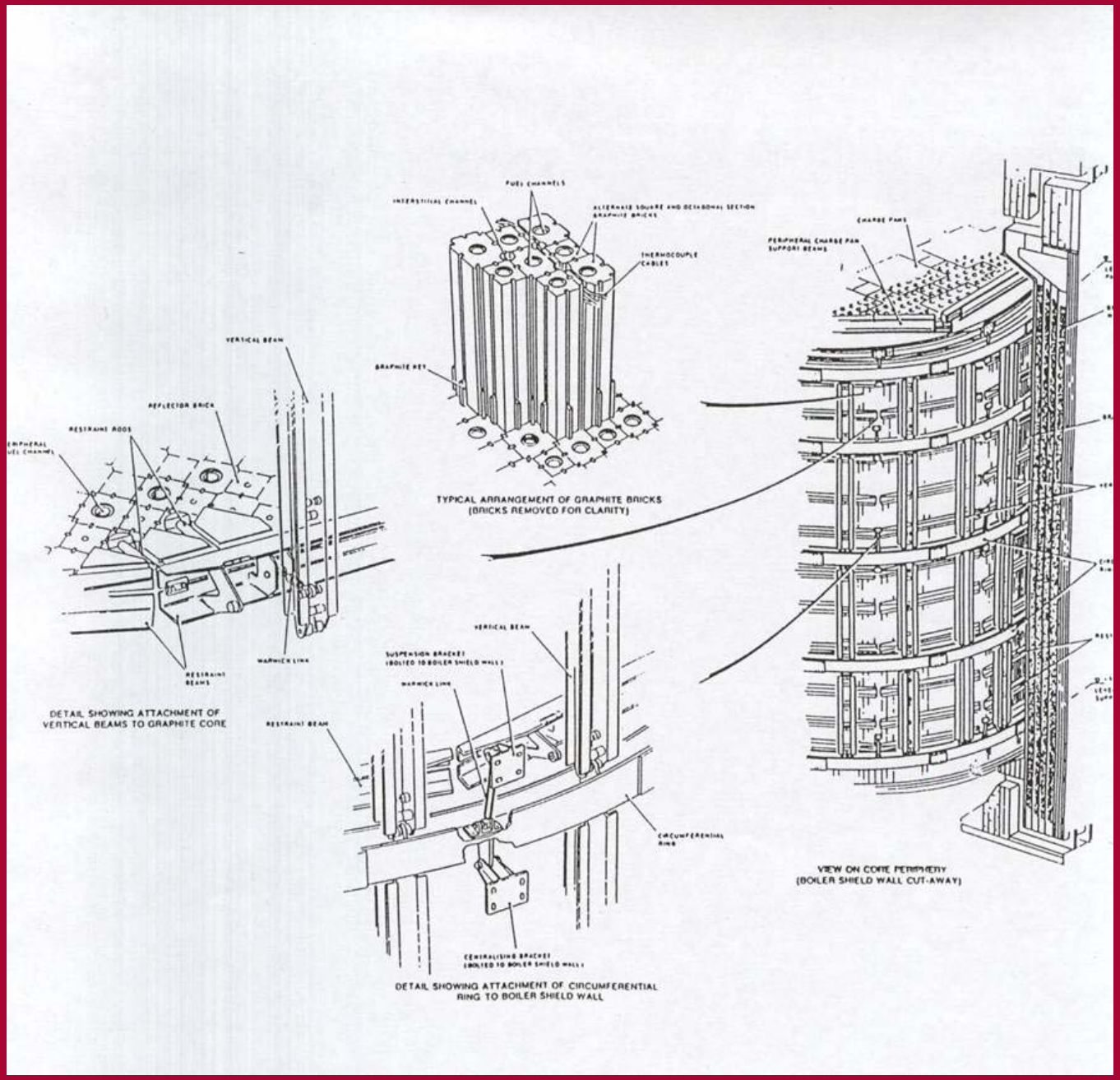
AGR Core

AGR Core

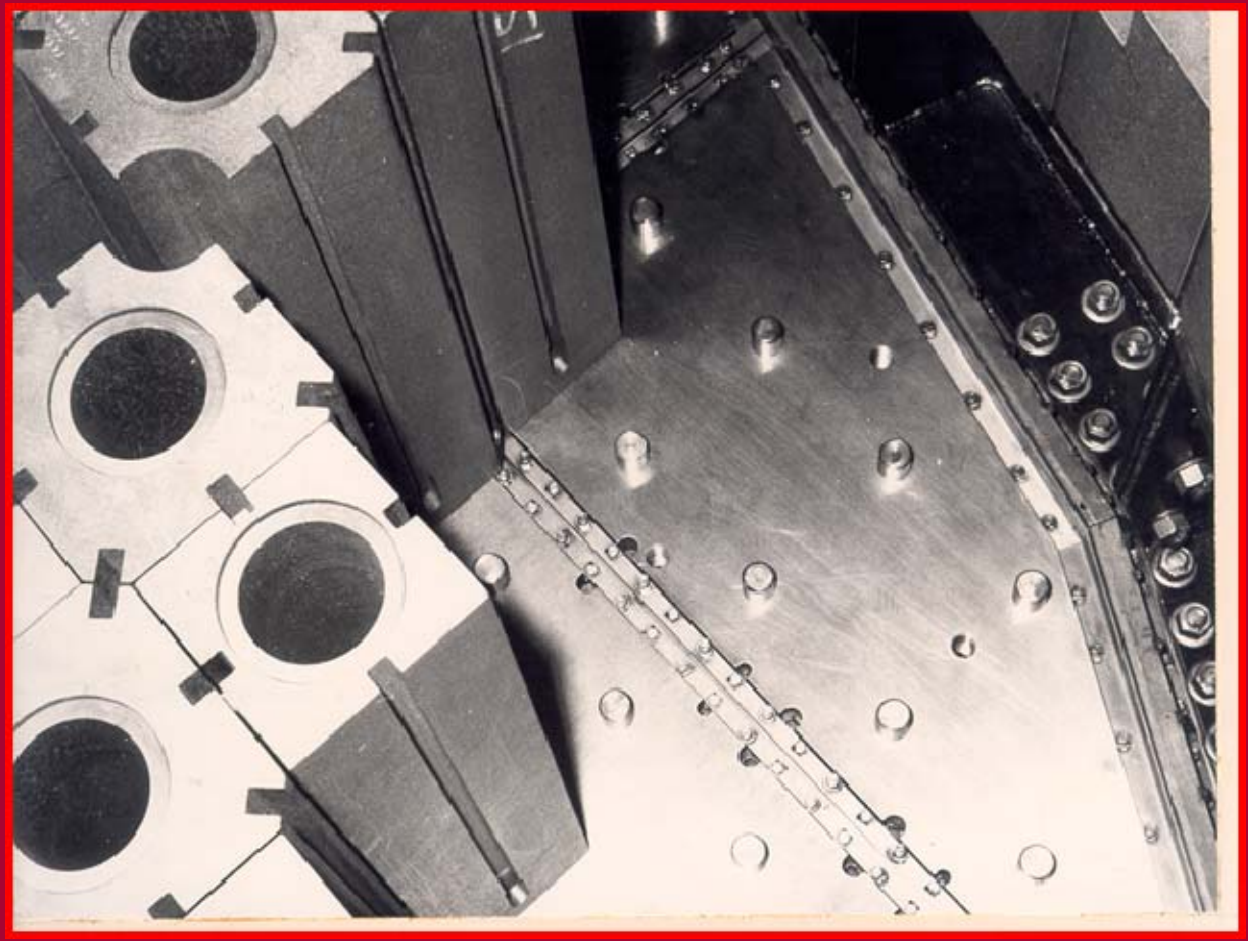
AGR brick design

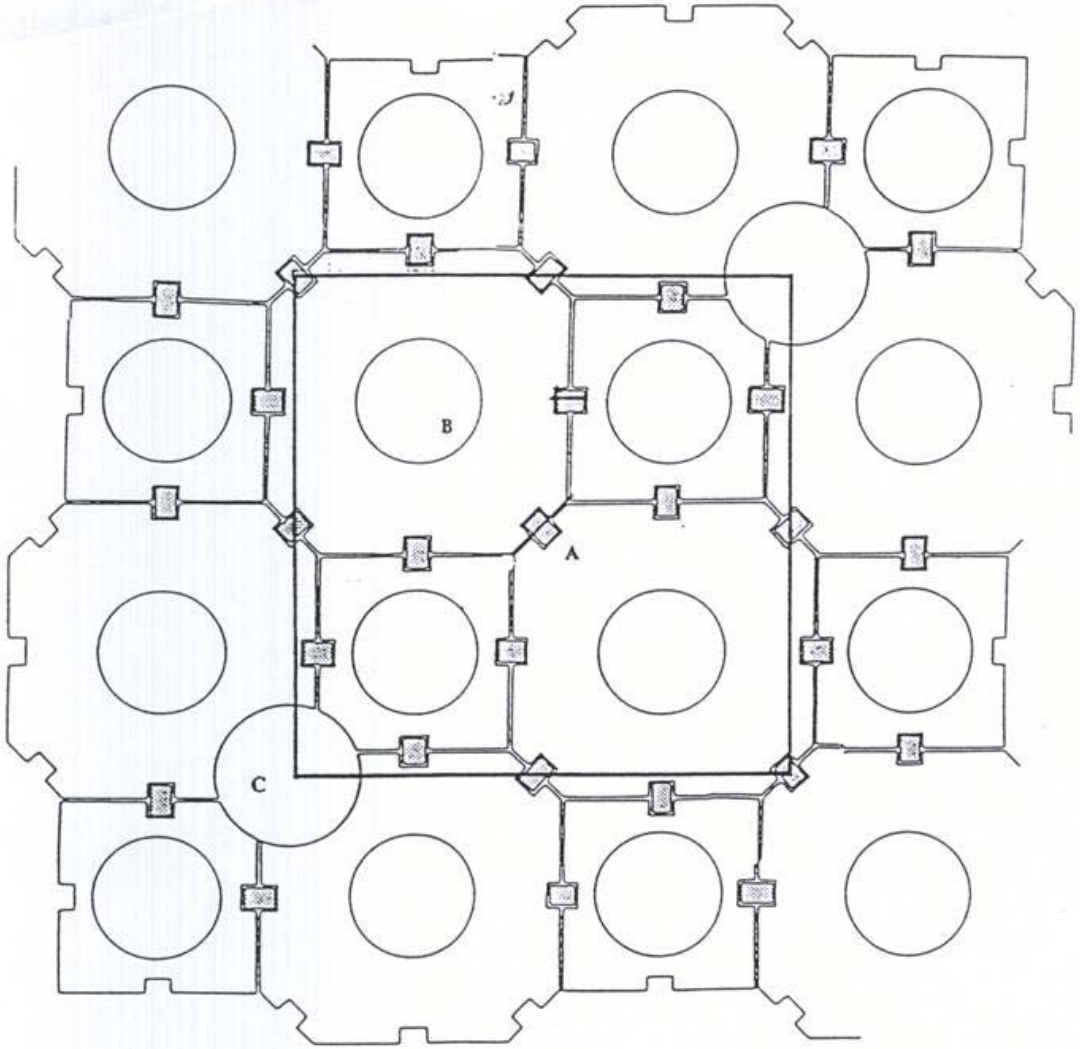


Magnox core


FUEL CHANNELS
INTERSTITIAL CHANNEL
ALTERNATE SQUARE AND OCTAGONAL SECTION GRAPHITE BRICKS
THERMOCOUPLE CABLES
GRAPHITE KEY
TYPICAL ARRANGEMENT OF GRAPHITE BRICKS (BRICKS REMOVED FOR CLARITY)
CHARGE PANS
PERIPHERAL CHARGE PAN SUPPORT BEAMS
VIEW ON CORE PERIPHERY (BOILER SHIELD WALL CUT-AWAY)
VERTICAL BEAM
REFLECTOR BRICK
RESTRAINT RODS
PERIPHERAL FUEL CHANNEL
WARWICK LINK
RESTRAINT BEAMS
DETAIL SHOWING ATTACHMENT OF VERTICAL BEAMS TO GRAPHITE CORE
VERTICAL BEAM
SUSPENSION BRACKET (BOLTED TO BOILER SHIELD WALL)
WARWICK LINK
RESTRAINT BEAM
CIRCUMFERENTIAL RING
CENTRALISING BRACKET (BOLTED TO BOILER SHIELD WALL)
DETAIL SHOWING ATTACHMENT OF CIRCUMFERENTIAL RING TO BOILER SHIELD WALL

Magnox core





A Octagonal Corner Keyway

B Fuel Channel

C Interstitial Channel

Unit Cell bounded by heavy box

Magnox core plan view

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Regulatory Regime

Regulatory Regime

- Health and Safety at Work Act (1974)
  - Health and safety of employees and public
  - Non-prescriptive, goal setting regime
  - Duties on employers and employees
- Nuclear Installations Act 1965 as amended
  - Act established licensing system
  - NII can attach conditions to the site licence in the interest of safety (without recourse to parliament or ministers)
- Conditions attached to nuclear site licence
  - Licence issued by NII to individual sites
  - Compliance with licence conditions is mandatory
  - Safety of an activity should be demonstrated before the activity is undertaken - permissioning
  - Licensee must be in adequate control of safety related activities and an intelligent customer for services provided
  - Licensees set their own design safety standards and criteria

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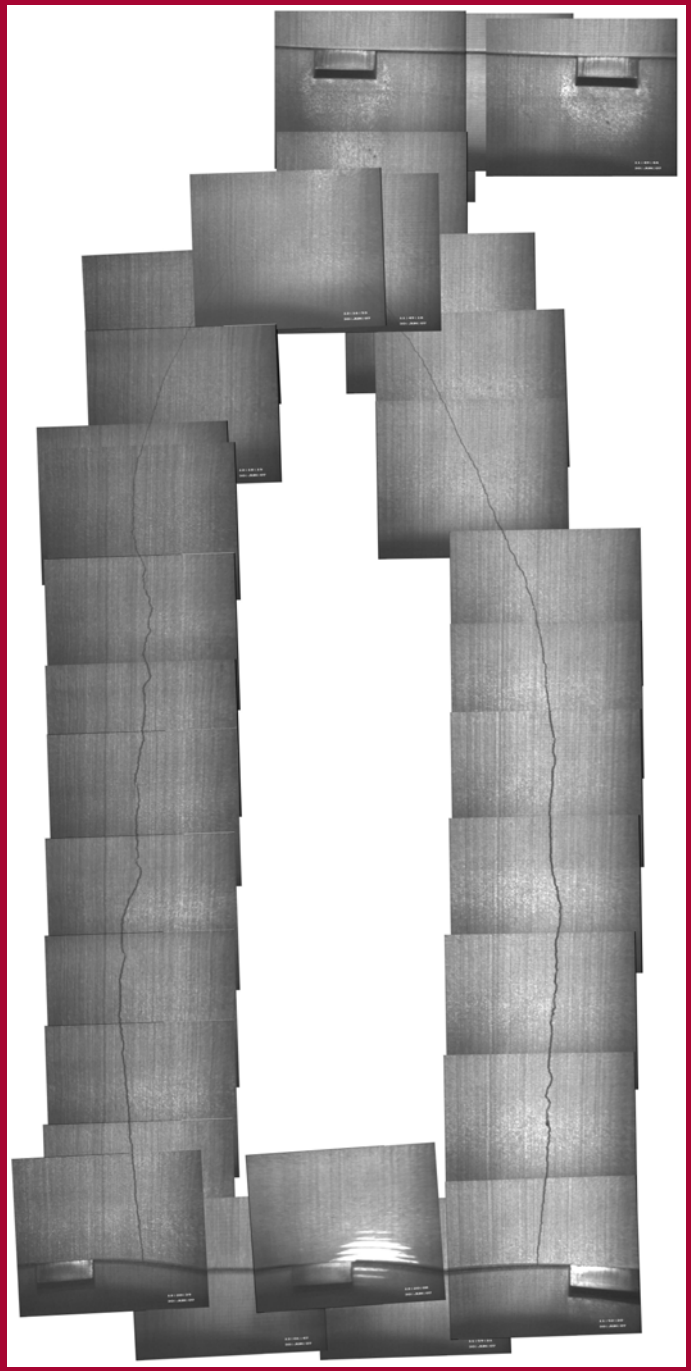
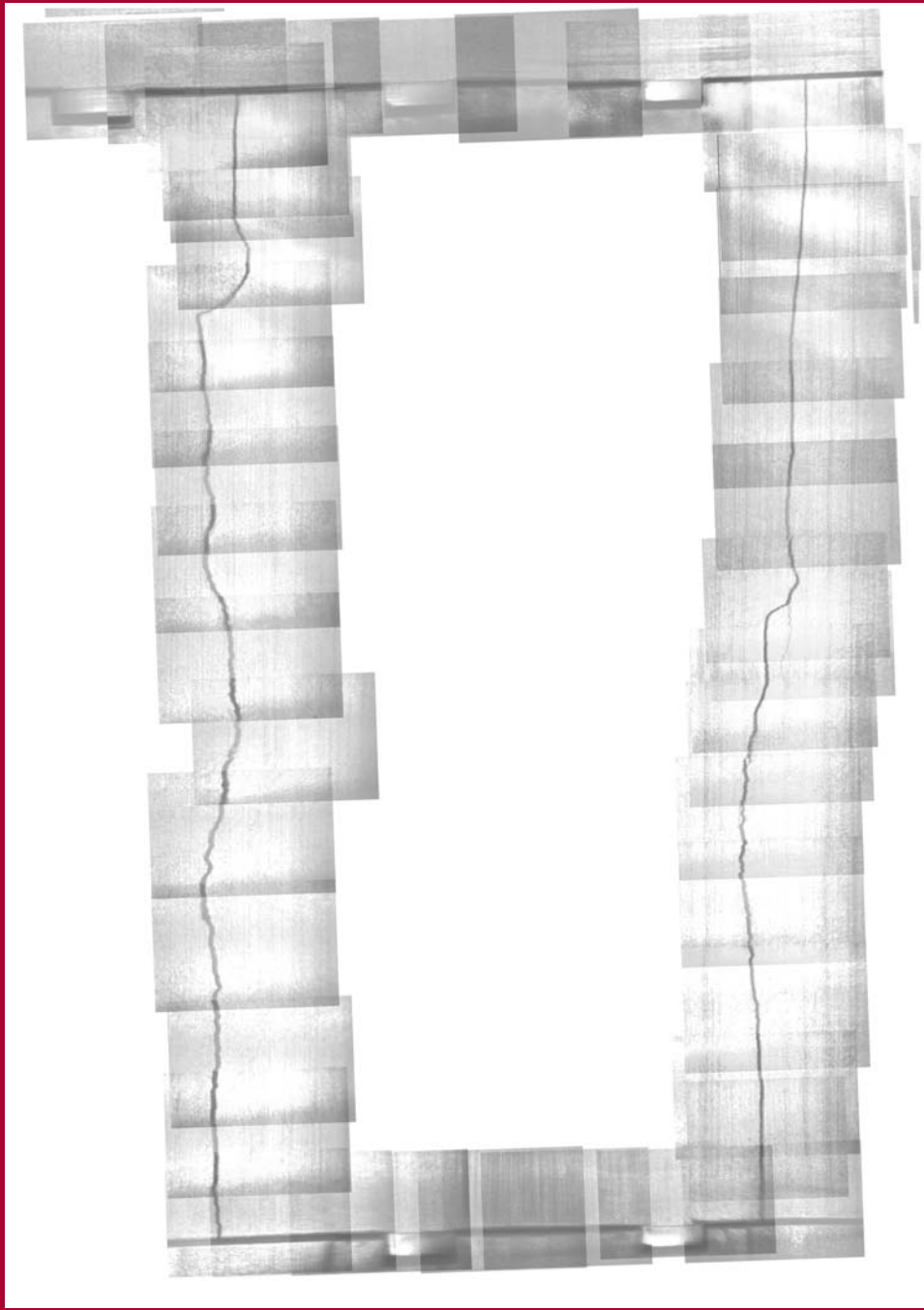
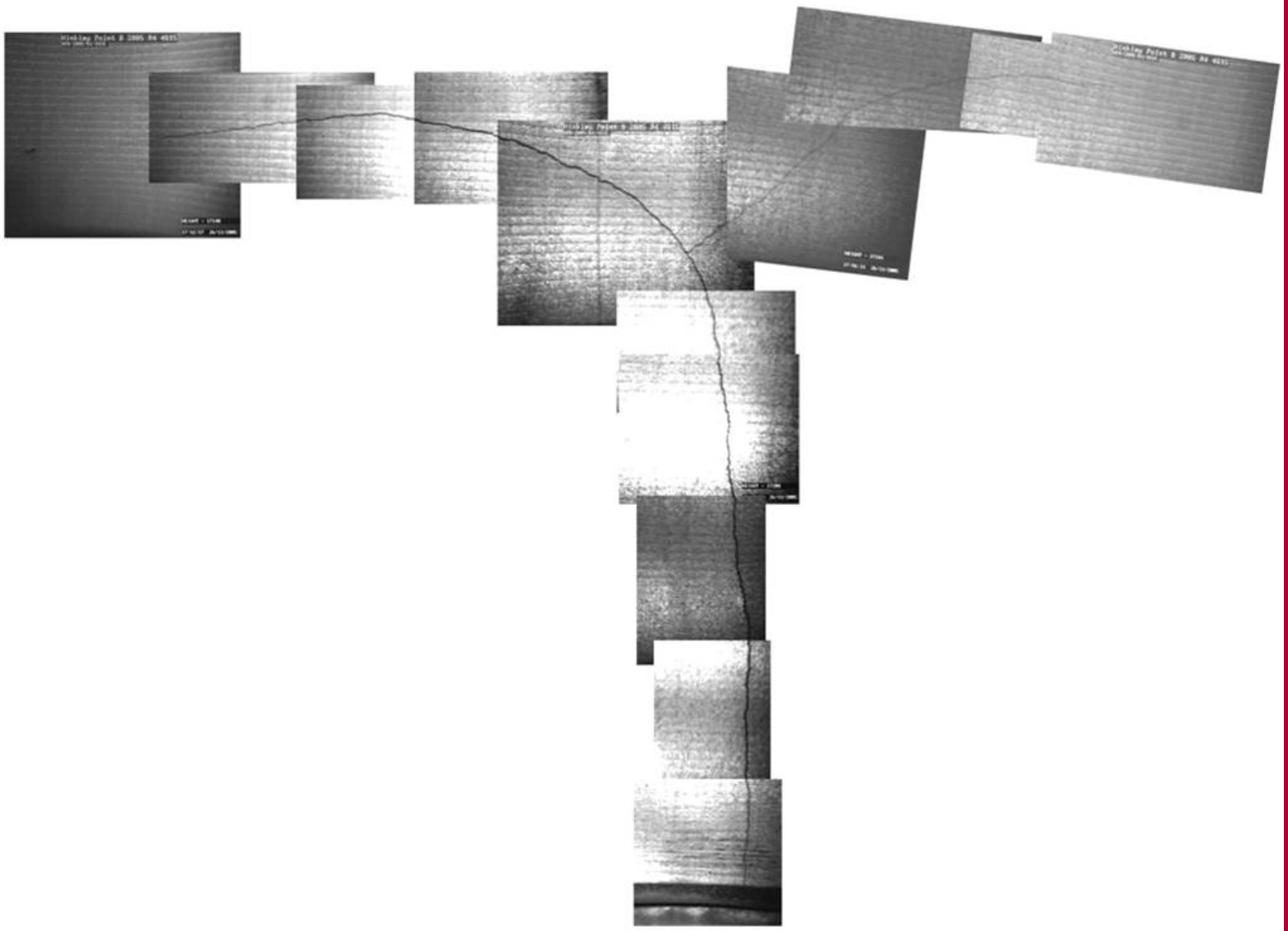
Regulatory Challenges and Strategy

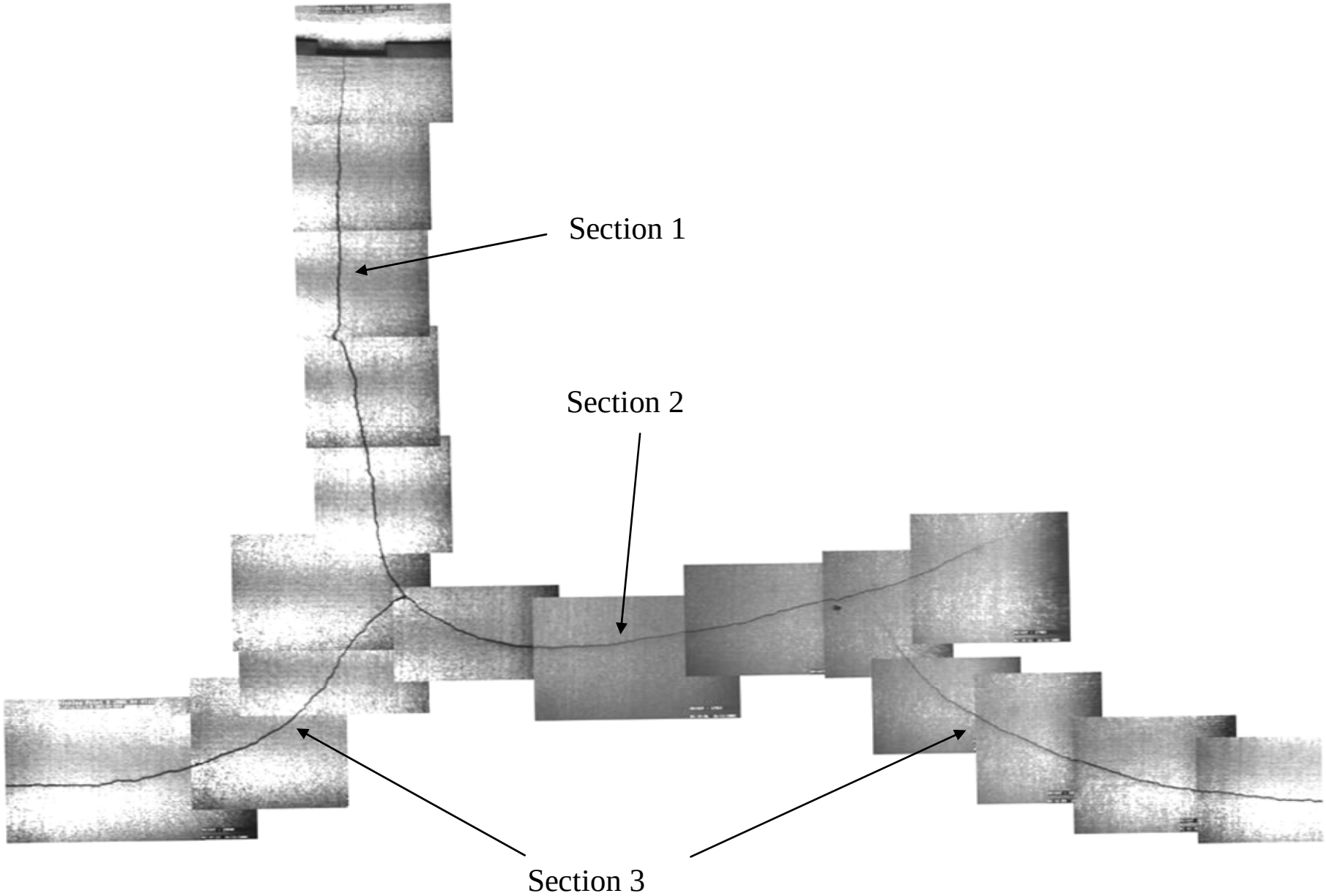
Regulatory Challenges

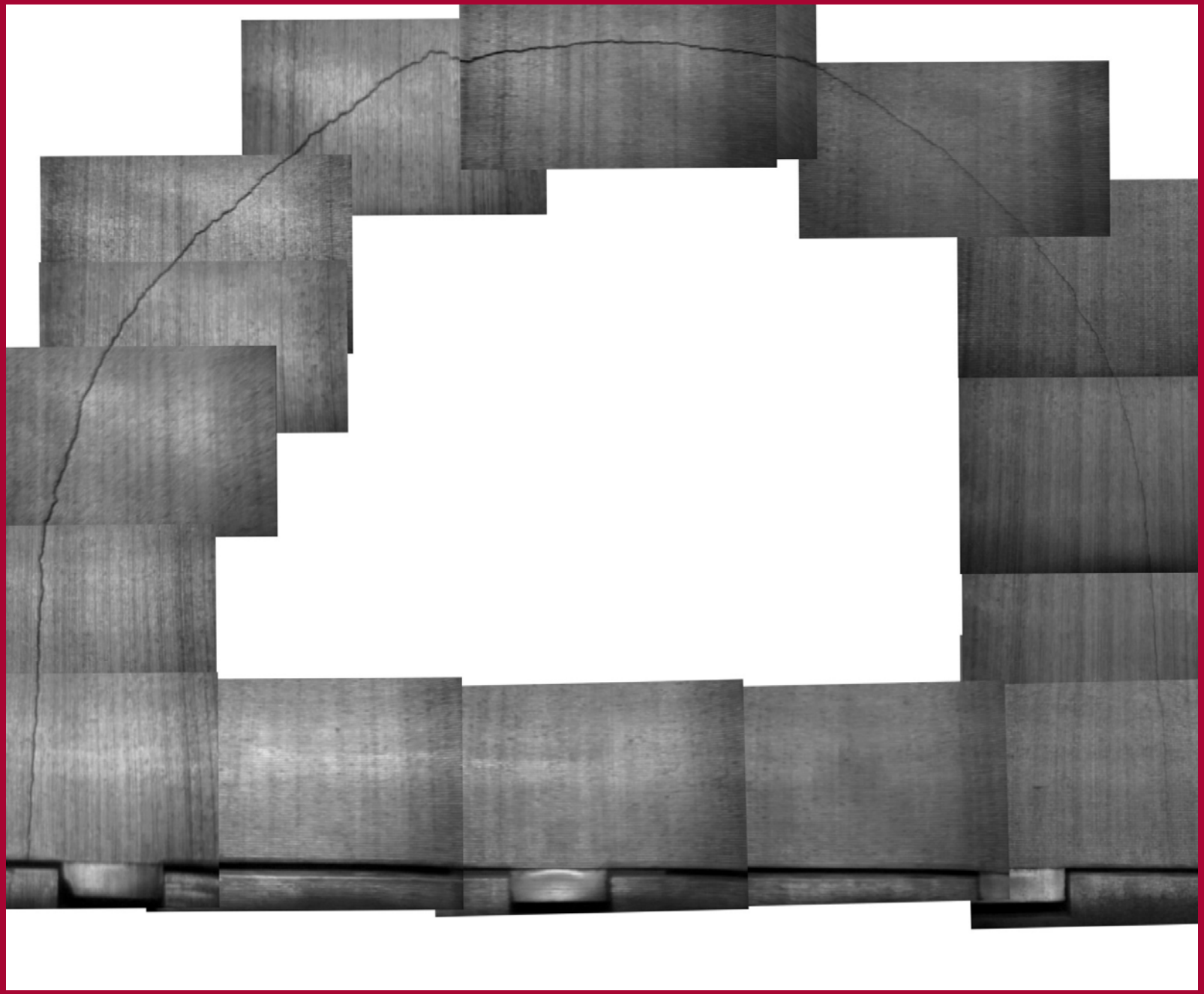
- Graphite core safety functions:
  - Shutdown and reactivity control post shutdown
  - Fuel cooling
  - Fuel integrity and unimpaired refuelling
- Challenges to core safety functions arising from:
  - Observations of unpredicted graphite moderator brick cracking in AGRs, pre stress reversal
  - Predictions of cracking in AGRs, post stress reversal
  - High radiolytic weight loss








Section 1
Section 2
Section 3



2002/04 Strategic Technology Review

- Onerous material duty, ~20dpa, >40w/o
- Established engineering practice:
  - Licensee bespoke
  - Empirical , lacks in-depth understanding
  - Limited validation
  - Need for bounding data
  - Highly complex
  - Limited user group
- Data scatter
- Significant uncertainty
- High complexity - many inputs, interactions & iterative loops

Handling Uncertainty

- Reducing Risks, Protecting People (R2P2)
- Precautionary Principle:
  - Rules out lack of scientific certainty as a reason for not taking preventive action
- Types of uncertainty:
  - Knowledge - sensitivity studies
  - Modelling – expert judgement, alternative hypotheses
  - Limited predictability or unpredictably – initial and current state

2004/05 Graphite Strategic Objectives

1. Develop revised assessment guidance
   - SAPs and TAGs revised
2. Secure maintenance and improvement of graphite core safety cases
   - Significant progress made
3. Develop credible and cost effective graphite research programme
   - Improved research programme in place
4. Provision of independent advice
   - Graphite Technical Advisory Committee (GTAC) established 2004 – contract in place to 2011

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Regulatory Guidance

Regulatory Guidance

- Safety Assessment Principles for Nuclear Facilities, 2006, SAPs
  - "Safety cases for graphite components and structures are expected to present a multi-legged approach, based upon independent and diverse arguments. The rigour of application and robustness of the supporting data and information should be based upon the safety classification of the graphite components and structures. The multi-legged arguments, when taken together with the various elements of established engineering practice, should provide defence in depth."

Regulatory Guidance continued

- The safety case should develop multi-legged arguments based upon the following:

  a) design;

  b) manufacture, construction and commissioning;

  c) component and structure condition assessment (CSCA);

  d) defect tolerance assessment;

  e) analysis of radiological consequences of defectiveness;

  f) monitoring; and

  g) examination, inspection, surveillance, sampling and testing.

- Technical Assessment Guide – “Graphite Reactor Cores”

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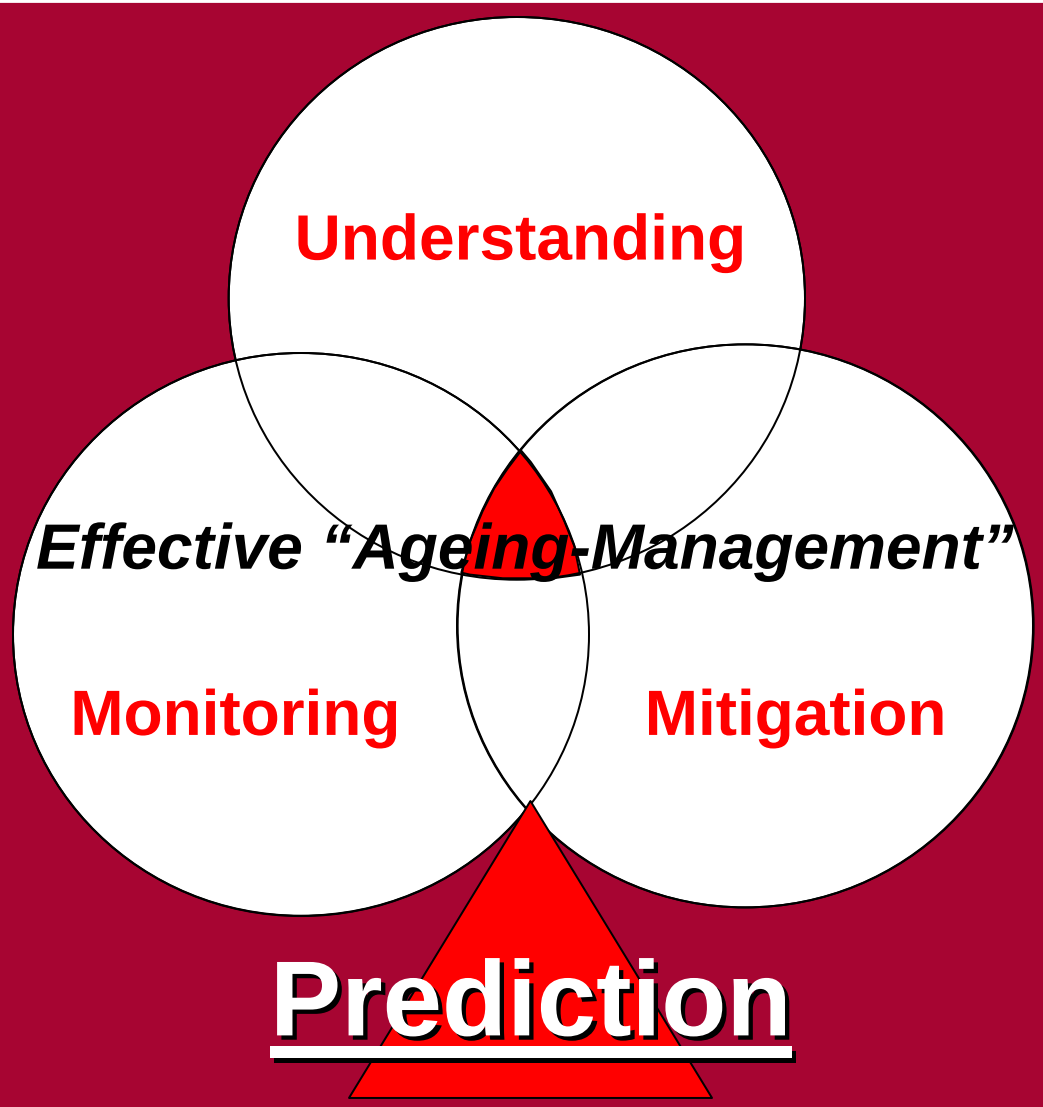
Safety Case Improvements

IAEA "Ageing-Management" Programme



Safety Case Improvements

Understanding

- Improved understanding of materials and component behaviour, further work progressing

Monitoring

- More frequent and extensive inspection, surveillance & sampling
- Enhanced on-line monitoring & trending of core behaviour

Mitigation

- ALARP plant modifications & methods of operation implemented, further work progressing
- Safe limiting conditions established, further work progressing

Prediction

- Progress with validation of predictive methods, further work progressing
- Extensive sensitivity studies and probabilistic analyses undertaken and compared with inspection data, further work progressing
- Progress obtaining bounding materials data, further work in-hand

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Graphite Nuclear Safety Research

Nuclear Research Arrangements

- HSE coordinated nuclear safety research programme. Consists of:
  - Licensee research
  - HSE Levy programme
- Nuclear Safety Studies (NSS)
  - Direct support to safety case assessment
- Process for HSE coordinated research
  - NII writes Nuclear Research Index (NRI) annually
  - Licensee undertakes research in response to NRI and updates this annually

Graphite Nuclear Research Strategy

- Improve fundamental understanding of ageing processes and materials behaviour
- Improve understanding of cracking mechanisms
- Obtain materials data that bounds future operating conditions in relevant environments
- Address data scatter by improved modelling
- Establish limiting component, channel, and core condition or limit of tolerability and associated safety margins
- Validate models
- Improve inspection and monitoring techniques
- Maintenance and development of independent expert advice
- Improve international collaboration on nuclear graphite research

HSE coordinated research Summary of current work undertaken by licensees & NII

- Graphite core material properties
  - MTR experiments investigating:
    - Effect of high radiolytic weight loss
    - Irradiation creep
    - Standardisation of testing procedures
    - Microstructural characterisation
  - Modelling of graphite structure
  - Development of new measurement techniques eg Poisson's ratio
  - Improved dose/damage relationships for irradiated material properties trends

HSE coordinated research
Summary of current work undertaken by licensees & NII

- Core component integrity
  - Fracture behaviour under biaxial loading
  - Fracture modelling
  - Improved spatial and temporal predictive modelling, incorporating:
    - More representative stress analyses
    - Improved probabilistic modelling
    - Prediction and validation of:
      - Brick shape changes
      - Brick cracking rates and morphologies
      - Material properties

HSE coordinated research
Summary of current work undertaken by licensees & NII

- Whole core structural response
  - Development of improved static and dynamic whole core models to assess realistic core driving forces
  - Validation of whole core models
  - Seismic model validation using “shaker” table tests
- Inspection, sampling and monitoring
  - Model based condition monitoring
  - Integrated core inspection in CO_2 - brick dimensions, remote visual, brick internal stress, volumetric inspection
  - Techniques for measurement of core distortion during operation

HSE coordinated research Summary of current work undertaken by licensees & NII

- Regulator access to independent advice
  - Microstructural studies on irradiated graphite
  - Modelling dose/damage development and understanding of irradiated material properties trends
  - AGR Brick Cracking Network – understanding and prediction of cracking
    - Materials resistance parameters
      - Crack initiation, size effects etc
      - Fracture behaviour under biaxial loading
      - Effect of notches on fracture initiation
    - Driving force parameters
      - Stress analysis sensitivity studies
      - Statistical modelling of brick shape changes
      - Convergence of stresses and brick shape using Bayesian framework
  - Whole core modelling using super-elements
  - ASME graphite code development
  - IAEA international graphite database
  - Graphite Technical Advisory Committee (GTAC)

Summary

- Reviewed regulatory challenges on nuclear graphite technology
- Outlined research and regulatory strategy to address safety issues
- Approach to address current challenges faced by UK on graphite creates opportunity for closer international collaboration to achieve benefits for current and future gas-cooled reactors