Ray NICHOLSON

HSE - Grande Bretagne

UK Regulatory Perspective on Materials Ageing Issues in Nuclear Reactor Components

R D Nicholson
H M Nuclear Installations Inspectorate
Health and Safety Executive
UK

Scope of talk

- UK Regulatory organisation and process
  - Nuclear Site Licences
  - Periodic Safety Reviews
- Safety Assessment Principles
- Materials degradation issues
  - Irradiation embrittlement of Magnox Reactor Pressure Vessels
  - Reheat cracking of stainless steel welds in Advanced Gas Cooled Reactors
- Conclusions

UK Regulatory Organisation and Process

HSE

- UK law requires any operator of a nuclear installation to be licensed
- Health and Safety Executive (HSE) is UK nuclear regulator
- Nuclear site licences granted by HSE
- HSE has the powers to attach conditions to the licence that are necessary or desirable for safety
- Nuclear Installations Inspectorate (part of HSE) administers licensing function

UK Regulatory Organisation and Process (contin)

- HSE sets safety goals – does not specify how they should be achieved (non-prescriptive regime)
- Licensee is responsible for safety
- Licence conditions require Licensee to have safety cases
- Safety cases are required to demonstrate that safety controlled throughout all stages of plant's life
- Safety cases identify operating conditions and limits necessary for safety

Periodic Safety Reviews

HSE

- Licence condition requires licensee to review and re-assess safety periodically and systematically – Periodic Safety Review (PSR)
- PSR carried out every 10 years
- Objectives of PSR:
  - review current safety case
  - compare with modern standards
  - identify ageing processes
  - revalidate safety case until next PSR

Periodic Safety Reviews (contin)

HSE

- HSE agreement needed for continued operation
- To confirm long term predictions, some areas will be subject to regular reviews throughout future operation
- These reviews include plant surveillance programmes, additional assessment and research
- Between PSRs, maintenance activities and periodic shutdown inspections

  - satisfactory completion required before NII issue a Consent to restart after shutdown

Safety Assessment Principles

- Regulatory process requires safety cases to be submitted to NII for assessment
- Framework for technical judgements provided by NII Safety Assessment Principles (SAPs)
- For structural components important to nuclear safety:
  - should be as defect free as possible
  - should be defect tolerant – critical defect sizes should be large compared with capability of inspection technique

Safety Assessment Principles (contin)

- To achieve this, NII expects several related but independent arguments leading to a multi-legged safety case:

  - use of sound design concepts
  - stress and fracture analysis to demonstrate capability to withstand normal and fault loads
  - use of proven materials
  - quantitative understanding of in-service degradation processes

Safety Assessment Principles (contin)

- high standards of manufacture
- high standards of quality assurance
- pre-service and in-service inspections to detect defects at sizes below those that could cause failure
- provision of in-service plant and materials monitoring
- leak detection – existence of leak before break case

Materials Degradation Issue 1- Irradiation embrittlement of Magnox Reactor Pressure Vessels

HSE

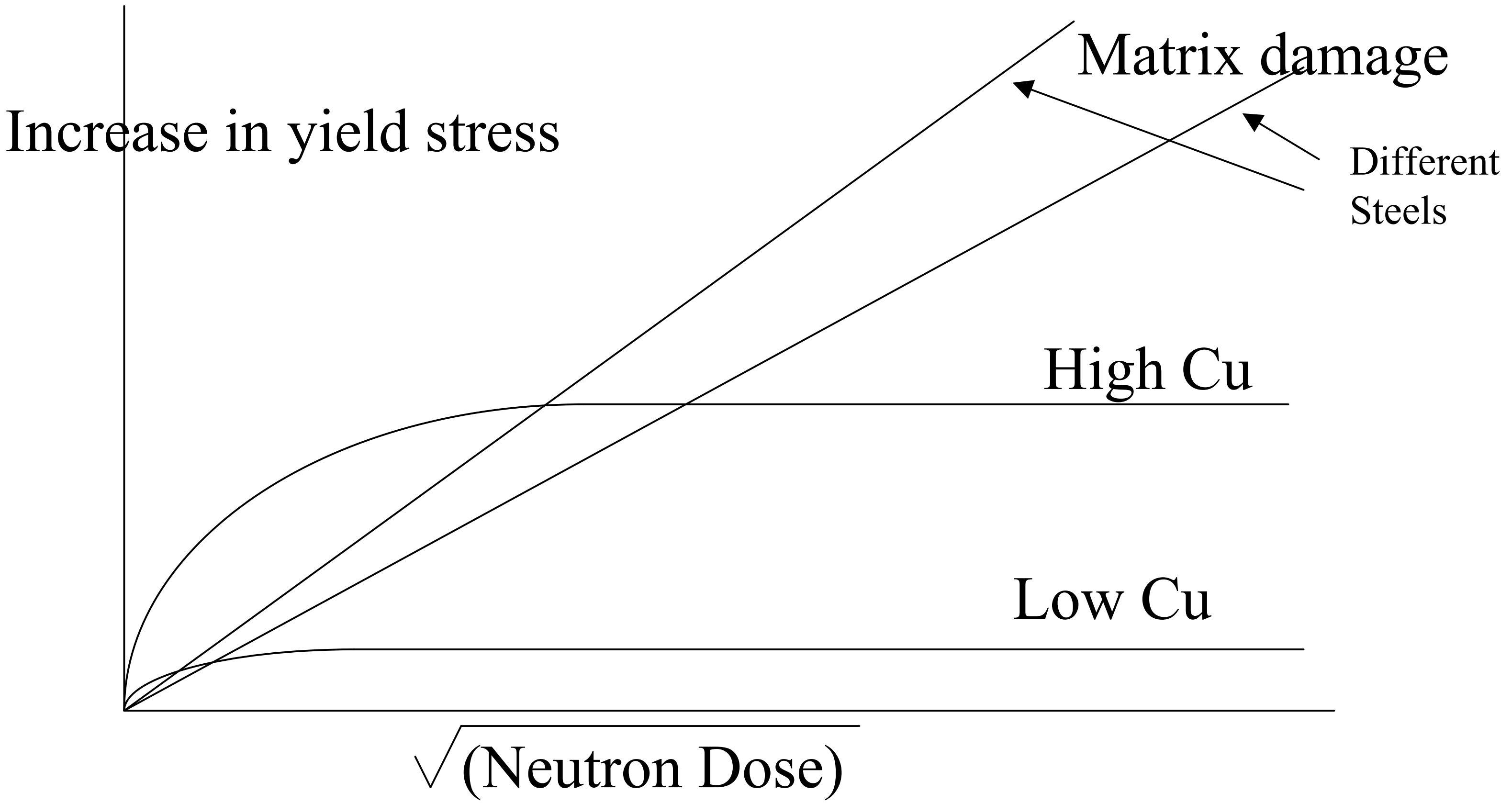
- Five Magnox plants have steel RPVs. Two still operating
- RPVs made from C-Mn steel plates and forgings, welded with submerged arc and manual metal arc welds
- RPVs experience a wide range of irradiation temperatures, neutron doses and neutron energy spectra
- Neutron irradiation causes hardening (change in tensile properties) and embrittlement (change in ductile-brittle transition temperature)

Irradiation embrittlement of Magnox Reactor Pressure Vessels

HSE

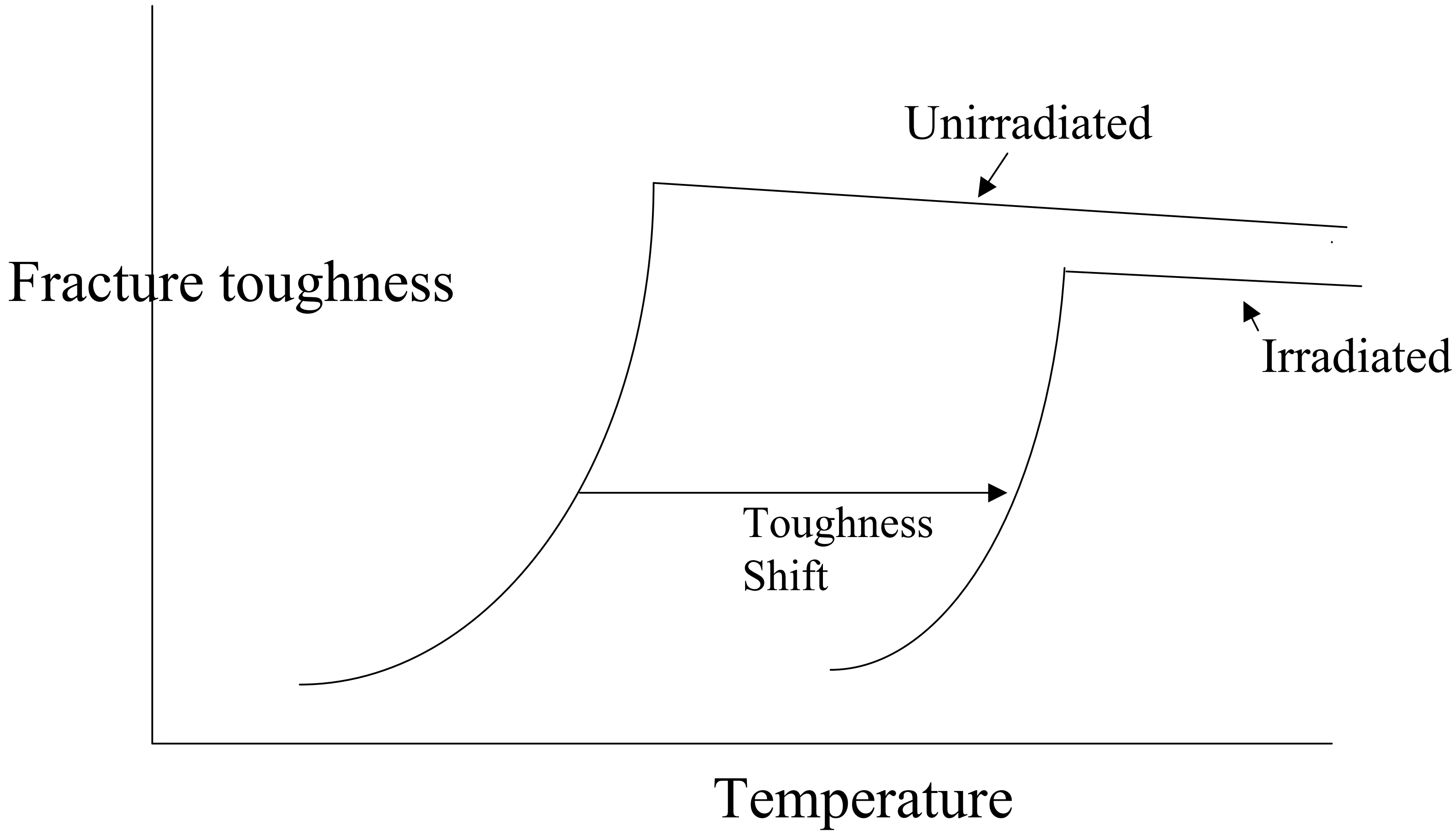
- Three basic mechanisms of irradiation embrittlement
  - irradiation enhanced formation of copper-rich precipitates
  - matrix damage due to radiation produced point defect clusters and dislocation loops
  - irradiation induced/enhanced grain boundary segregation of embrittling specied, eg phosphorus

Irradiation embrittlement: effect of irradiation on yield stress



Irradiation embrittlement: effect of irradiation on fracture toughness

HSE



Irradiation embrittlement – trend curves

- Trend curves combine contributions to hardening and embrittlement so that changes to yield stress (?s) and DBTT shift (??) may be calculated:

  - $\Delta s(\text{Total}) = \Delta s(\text{Cu}) + \Delta s(\text{Matrix})$

  - $\Delta T(\text{Total}) = \Delta T(\text{Cu}) + \Delta T(\text{Matrix}) + \Delta T(\text{Gb})$

Irradiation embrittlement – NII Position Statement on Operation of ferritic steel RPVs

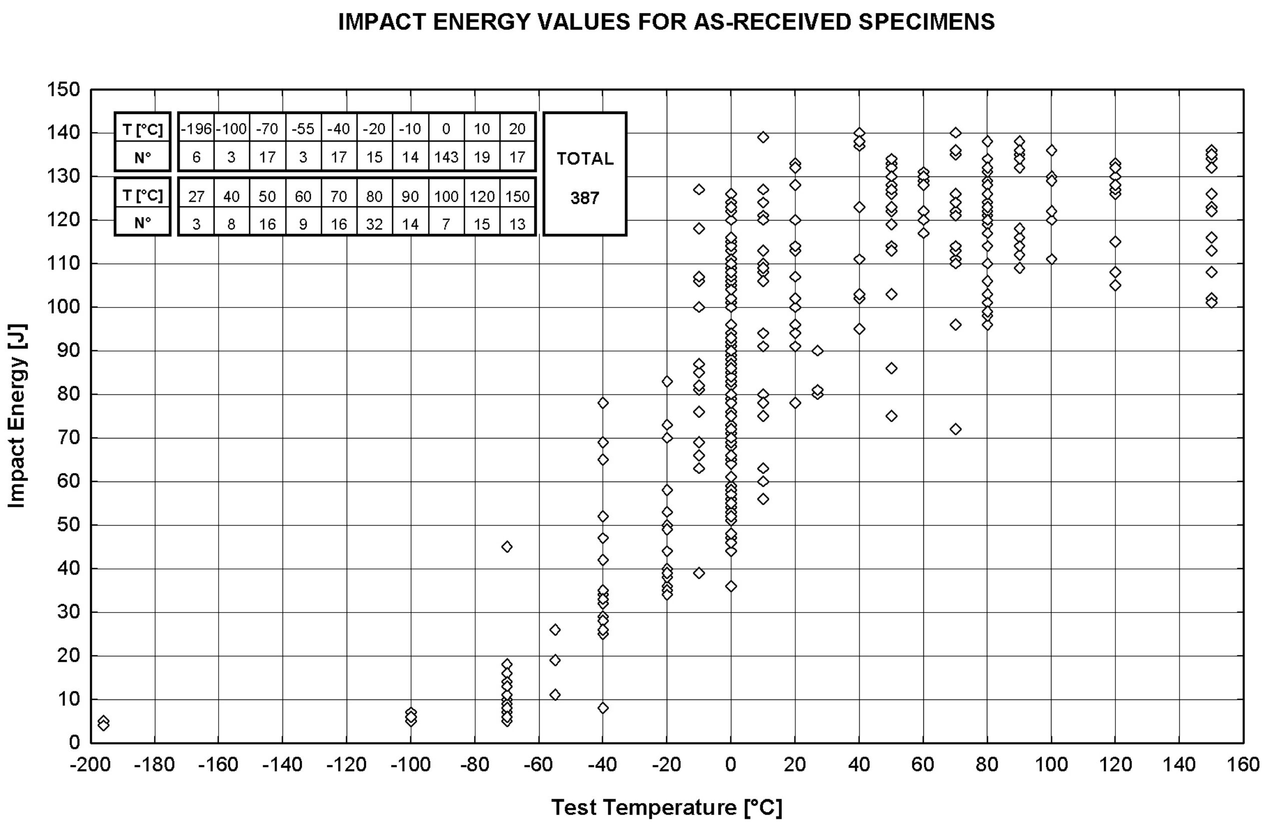
HSE

- In 1995, NII published Position Statement, based on SAPs – still NII's position
- NII requires steel RPVs to operate on the upper shelf for normal steady state operation – in ductile state
- For other conditions, RPVs should be on the upper shelf whenever possible
- Shutdown, start up or limited duration transients, uncertainties and conditions to be considered – adequate toughness margins to be shown

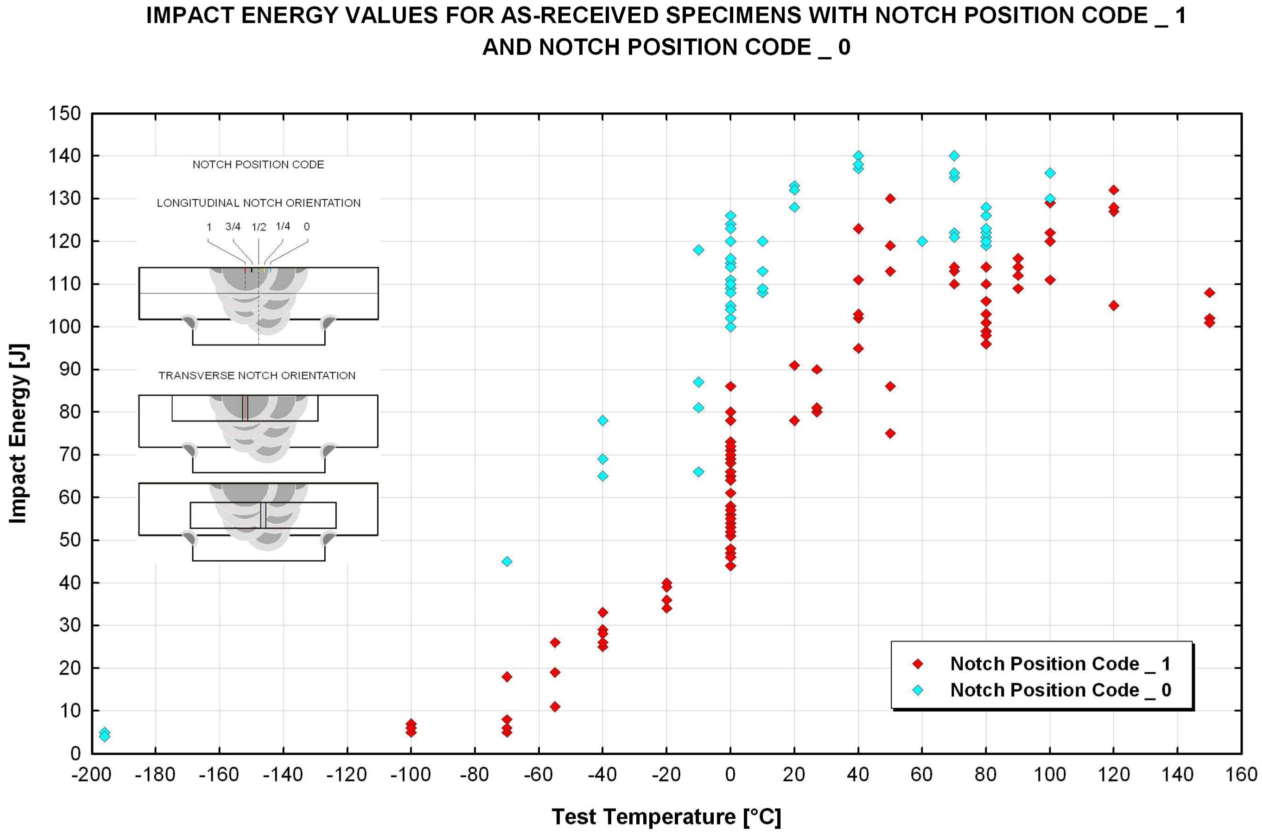
Irradiation embrittlement – Sources of scatter

- Irradiation embrittlement data (??, ?s) can show significant scatter
- Limited amounts of irradiated data available
- Many possible sources of scatter:
  - variability in start of life properties
  - variability in irradiation conditions
  - variability in embrittling species
  - experimental errors

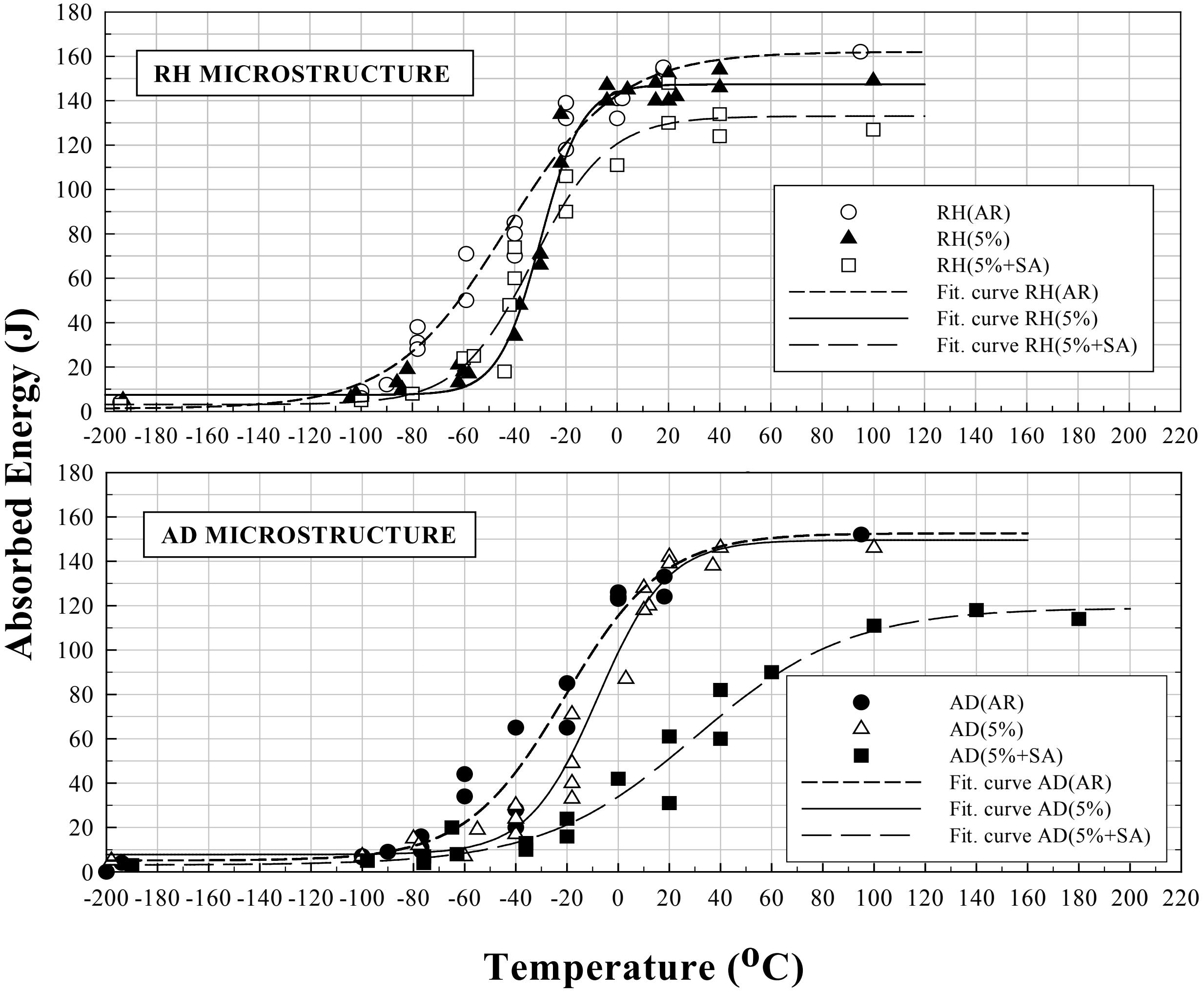
Irradiation embrittlement – Sources of scatter – start of life charpy impact energies (C-Mn)



Irradiation embrittlement – Sources of scatter – start of life charpy impact energies (C-Mn)



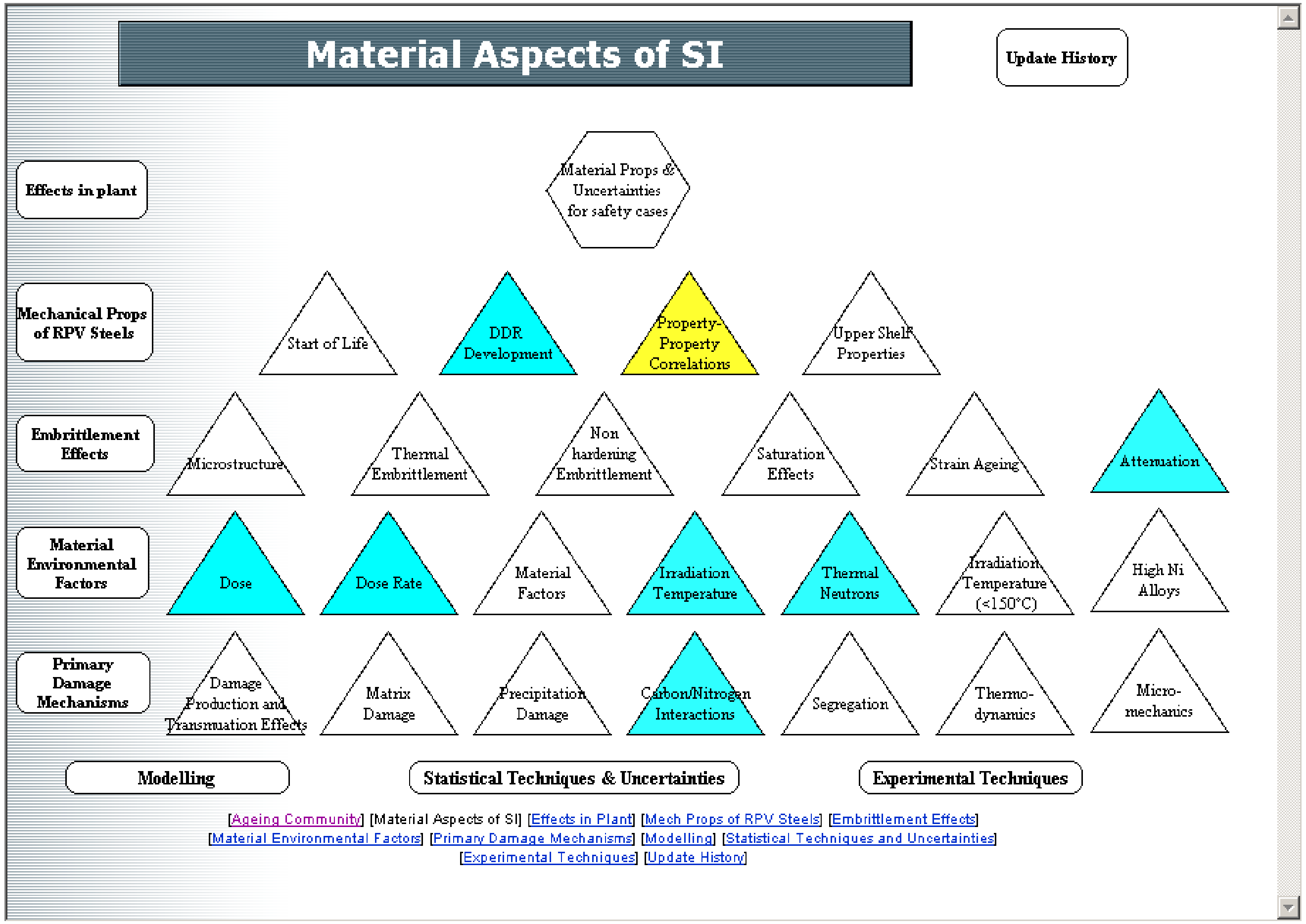
Sources of scatter – effects of microstructure, pre-strain and strain ageing on charpy impact energies (MnMoNi weld metal)



Irradiation embrittlement – Ageing Community Project

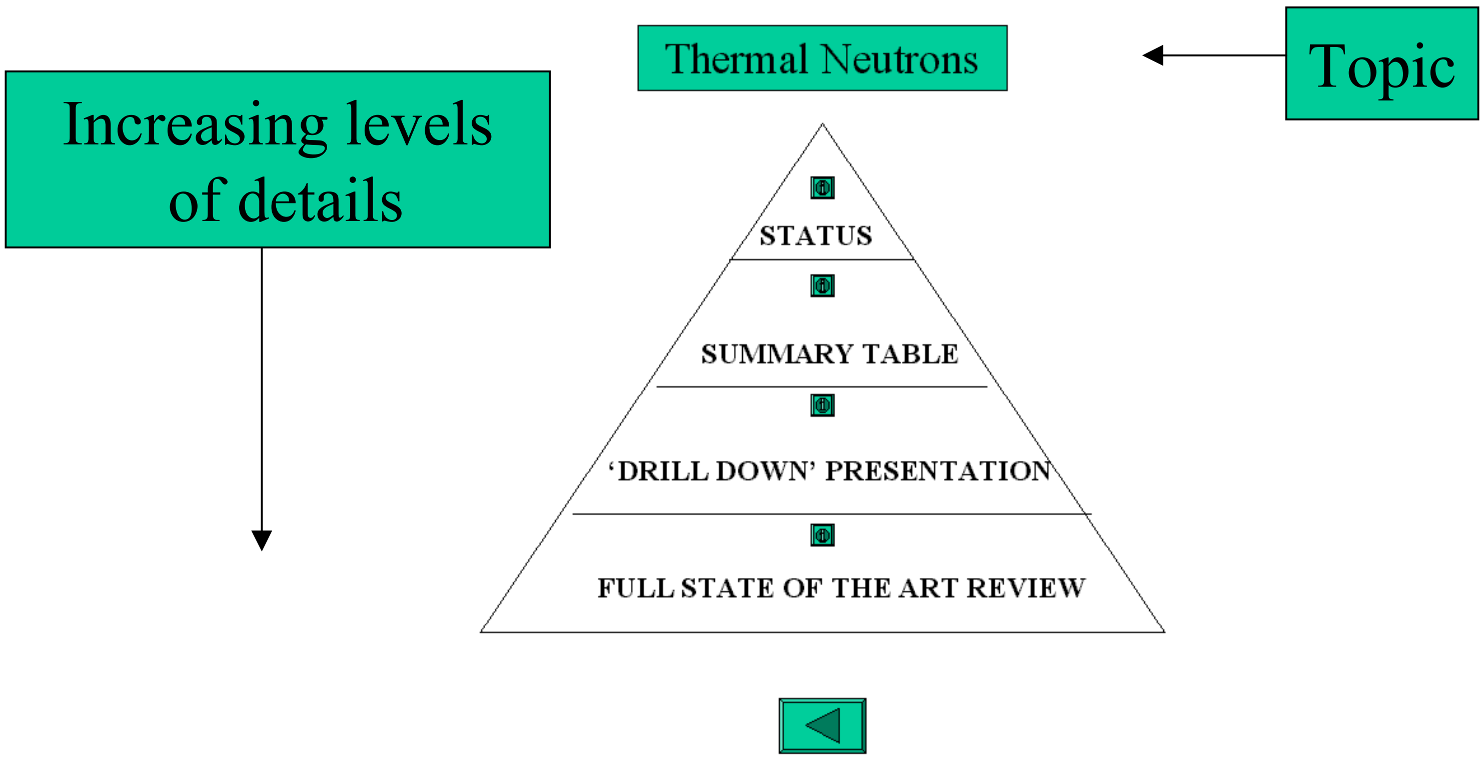
- Important aspect of defining and managing long term ageing is to ensure that key information and knowledge are not lost
- Knowledge lost as people retire or move to different jobs
- Ageing Community Project objectives:
  - develop and maintain knowledge system
  - state of the art knowledge/expert judgement
  - easily accessible knowledge base

Irradiation embrittlement – Structure of Ageing Community Project



Irradiation embrittlement – Ageing Community Project – “knowledge triangle”

HSE



Materials Degradation Issue 2 – Reheat cracking in stainless steel welds in AGRs

HSE

- Cracking during service observed in HAZ of thick section or repaired Type 316H stainless steel welds
- Welds were not post weld heat treated
- Operating temperature of AGRs sufficient for creep deformation
- Extensive research programme carried out by licensee to identify key factors for cracking

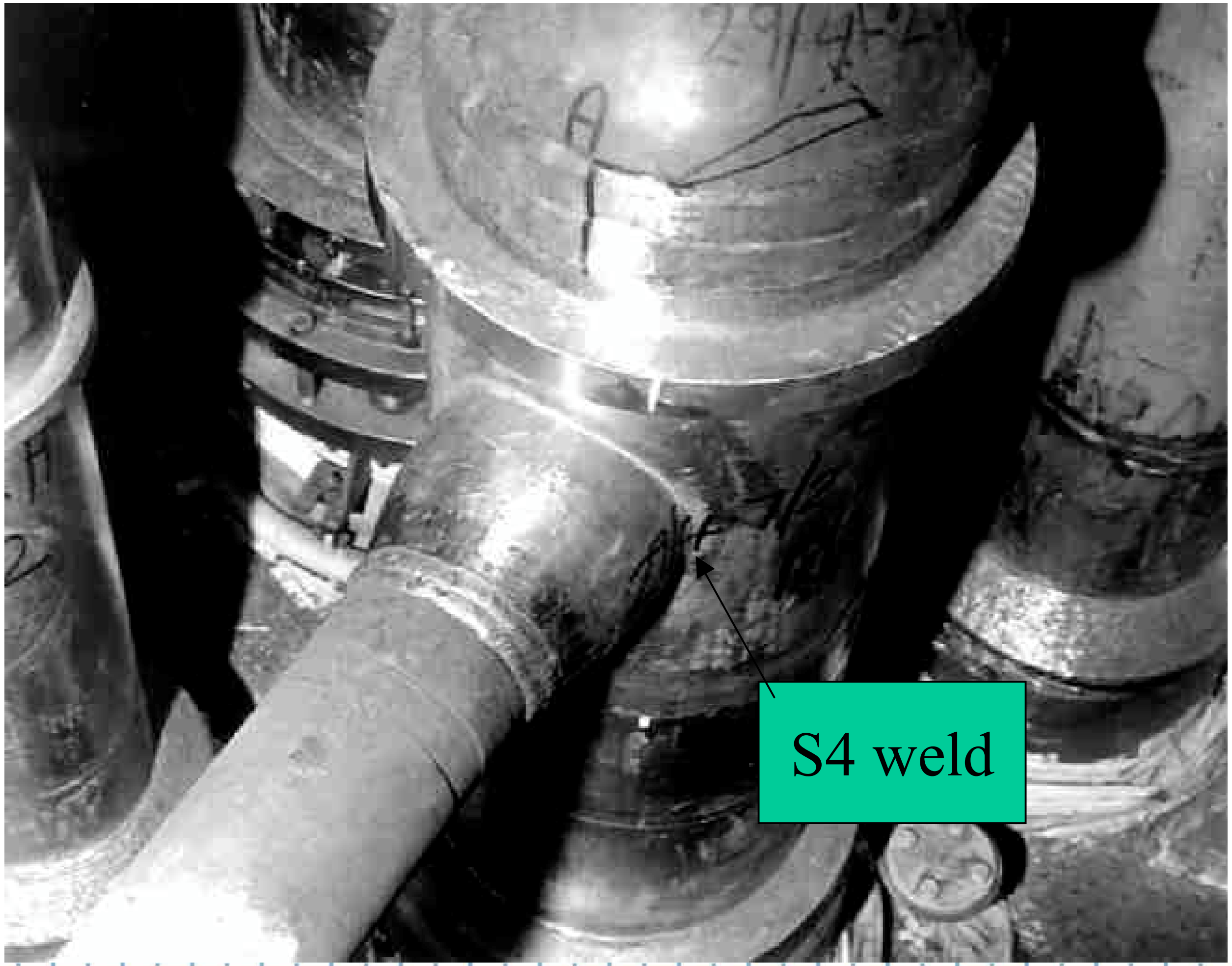
Reheat cracking in stainless steel welds in AGRs

HSE

- Reheat cracking caused by conversion of elastic strains to creep strains as welding residual stresses relax
- Exhaustion of creep ductility causes cracking
- Low creep ductility due to;

  - susceptible materials
  - operation in a susceptible temperature range
  - presence of multiaxial stresses from constraint or local stress concentrations

Reheat cracking – view of superheater header



Reheat cracking – schematic diagram of superheater header

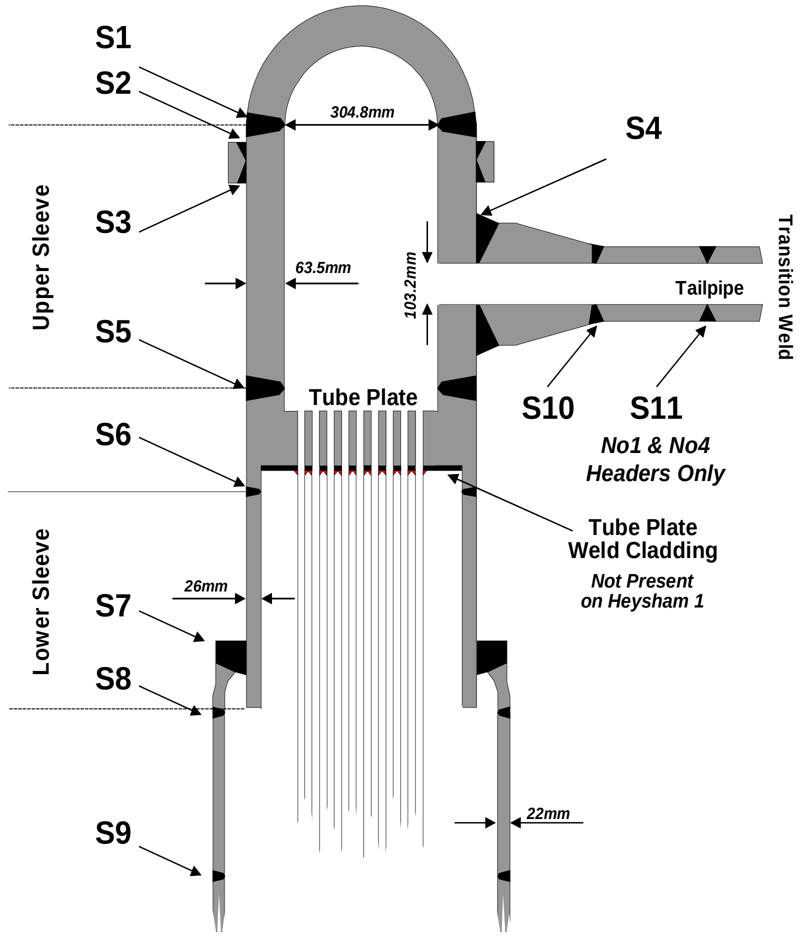
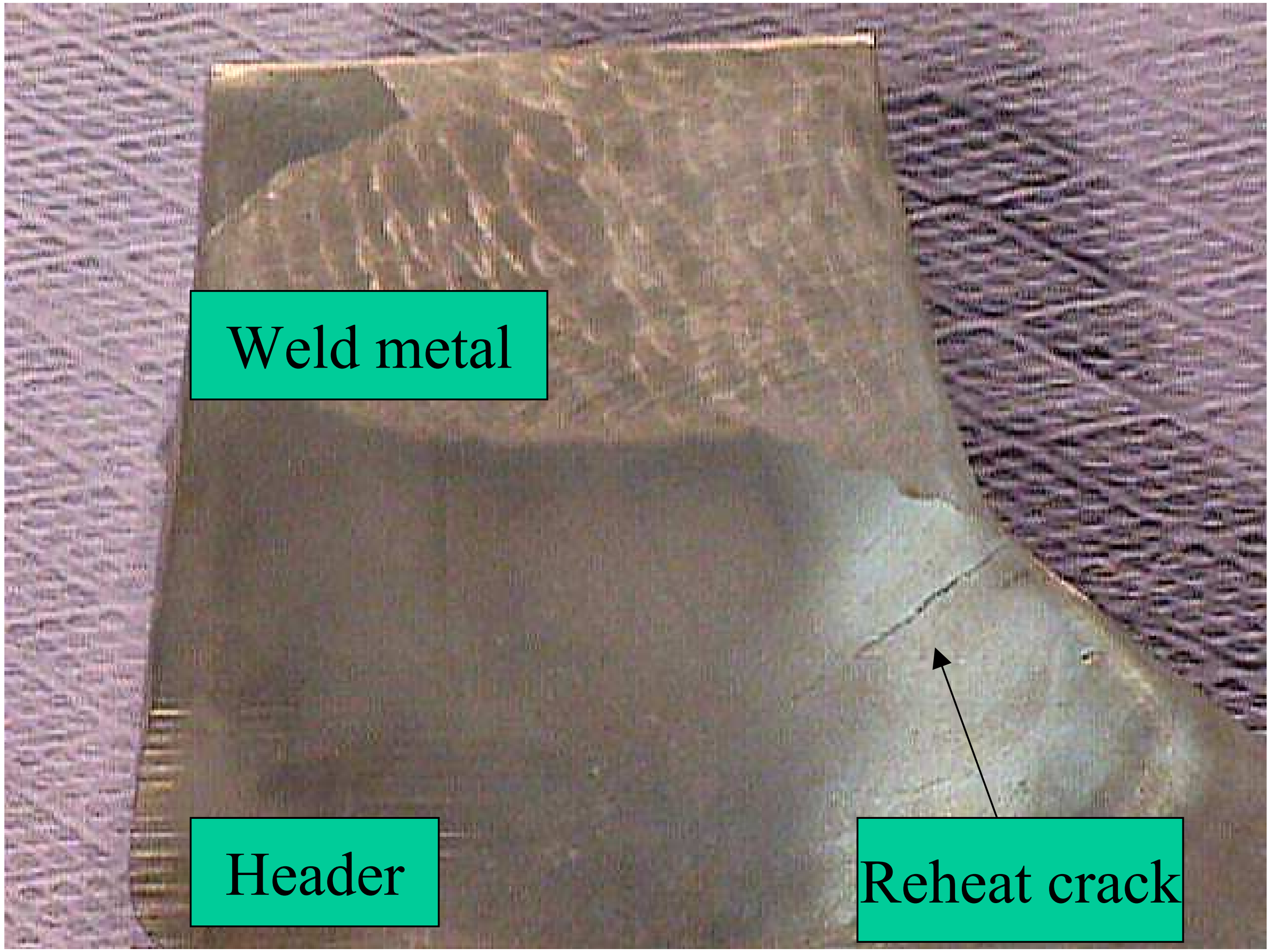


FIGURE 1 - SCHEMATIC DIAGRAM OF THE SUPERHEATER HEADER

Reheat cracking – transverse section through header at S4 weld



Reheat cracking – CDM model of S4 weld

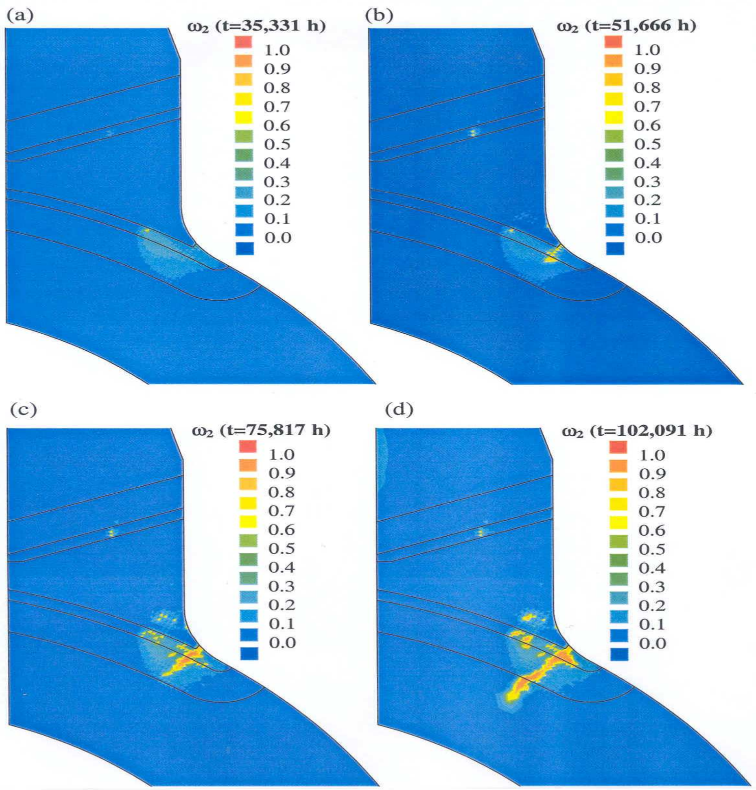


FIGURE 7: CDM model showing the change in creep damage with time for superheater header nozzle weld

Conclusions

HSE

- UK law requires nuclear installations to be licensed
- Licence conditions provides strong regulatory oversight of the nuclear industry through a non-prescriptive regime
- Specific licence conditions require safety cases to substantiate safety through all stages of the plant's life
- The licensing regime requires 10 yearly Periodic Safety Reviews that include reviews of age-related degradation processes

Conclusions (contin)

- For components important to nuclear safety, structural integrity safety case should demonstrate that component is as defect free as possible and is defect tolerant
- A key input to a structural integrity safety case is a quantitative understanding of materials degradation and the effects on material mechanical properties
- Examples of materials degradation issues relevant to UK reactors are irradiation embrittlement of Magnox RPVs and reheat cracking of stainless steel welds in AGRs