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Structural Performance of next-generation nuclear components: lessons from the UK's R5 and R6 structural integrity assessment procedures

MATISSE Workshop on cross-cutting issues in structural materials R&D for future energy systems

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(with thanks to Dave Dean and Julian Johns, EDF Energy Nuclear Generation)

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UK Civil Nuclear Regulatory Environment

- The Office of Nuclear Regulation license and regulate nuclear operators
  - Regulation is non-prescriptive
  - ONR define Nuclear Safety Principles
  - The licensee must demonstrate how they meet those principles
- This places a considerable technical responsibility on the licensee
  - They must first satisfy themselves that the plant is safe to operate
  - They must then convince the regulator
  - This is especially true if the reactor design is unique
- R5 and R6 have been developed in this environment

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Design codes and fitness for service assessment procedures

- Design codes (eg ASME Boiler and Pressure Vessel Codes) typically assume a structure is defect-free
  - Design calculations cover ultimate failure by plastic collapse, with appropriate safety factors, and known degradation mechanisms such as fatigue – welds are not generally analysed separately
  - Time-dependent failure in the creep regime is historically handled using stress-rupture approaches
  - Weld quality is assured by use of qualified joint designs, materials and procedures, with appropriate inspection – traditional welding engineering to ensure welds are no worse than the material being joined
- Fitness for service assessment procedures such as R5 and R6 deal with structures that may generate or contain crack-like defects
  - They need to consider weld behaviour explicitly (including residual stresses)
  - They are used when defects are found in service, or to provide increased confidence in the structural integrity of safety-critical plant
  - They tend to evolve relatively quickly as new in-service problems are found and understood/solved

R6: Assessment of the integrity of structures containing defects

- ***Or: "It operates outside the creep regime, and it may contain a crack-like defect – how fast / how much will it grow? How big can it get before it fails? Will it go Bang or Squish?"***

- Maintained by a consortium of users: EDF Energy Nuclear Generation, Amec Foster Wheeler, Rolls-Royce, TWI, Frazer-Nash and NRG.
- Influenced other Codes and Standards worldwide (BS7910, API579, SINTAP, SKIFS:1994 …)
- Based on the Failure Assessment Diagram (FAD)
- Basic and alternative approaches (***quick, cheap and conservative versus slow, expensive and accurate***)

R6: Assessment of the integrity of structures containing defects

Layout of R6:

I - Overview (Basic Procedure)

II - Inputs to Basic Procedures

III - Alternative Approaches (more sophisticated analysis)

IV - Compendia

V - Validation and Worked Examples

Example: handling of residual stresses

Section II.6 – Treatment of combined primary and secondary stresses

Section II.7 – Treatment of weld residual stresses

Section III.15 – Finite element prediction of residual stresses in weldments

Section IV.4 – As-welded residual stress distributions

Section V – validation benchmarks for FE simulation

R5: An assessment procedure for the high temperature response of structures

Or: "It operates within the creep regime, and it may (or may not) contain a crack-like defect – how fast will crack-like defects form, and what will they do then?"

R5 deals with the following degradation mechanisms

- Excessive plastic deformation due to single application of a loading system.
- Incremental collapse due to a loading sequence.
- Excessive creep deformation or stress rupture.
- The initiation of cracks in initially defect-free material by creep and creep-fatigue mechanisms.
- The growth of cracks by creep and creep-fatigue mechanisms.
- Failure of dissimilar metal welds by creep and creep-fatigue mechanisms.

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R5: An assessment procedure for the high temperature response of structures

Layout of R5

Volume 1: Overview

Volume 2/3: Creep-Fatigue Crack Initiation Procedure for Defect-Free Structures

Volume 4/5: Procedure for Assessing Defects under Creep and Creep-Fatigue Loading

Volume 6: Assessment Procedure for Dissimilar Metal Welds

Volume 7: Behaviour of Similar Weldments - Guidance for Steady Creep Loading of Ferritic Pipework Components.

Advanced Gas-Cooled Reactor (AGR)

- **Unique: high temperature civil nuclear plant operated commercially over significant timescales (14 reactors operated for >250kh)**
- Graphite core/moderator
- CO_2 primary coolant
- Key metallic boiler, reactor and fuel route components operate in the creep range (480-650^{o}C)
- Components within concrete pressure vessel difficult to inspect/repair/replace
- Primary focus on austenitic components – range of product forms, grades, casts + wide range of loading conditions
- Significant number of welds received no PWHT – welding residual stresses are important

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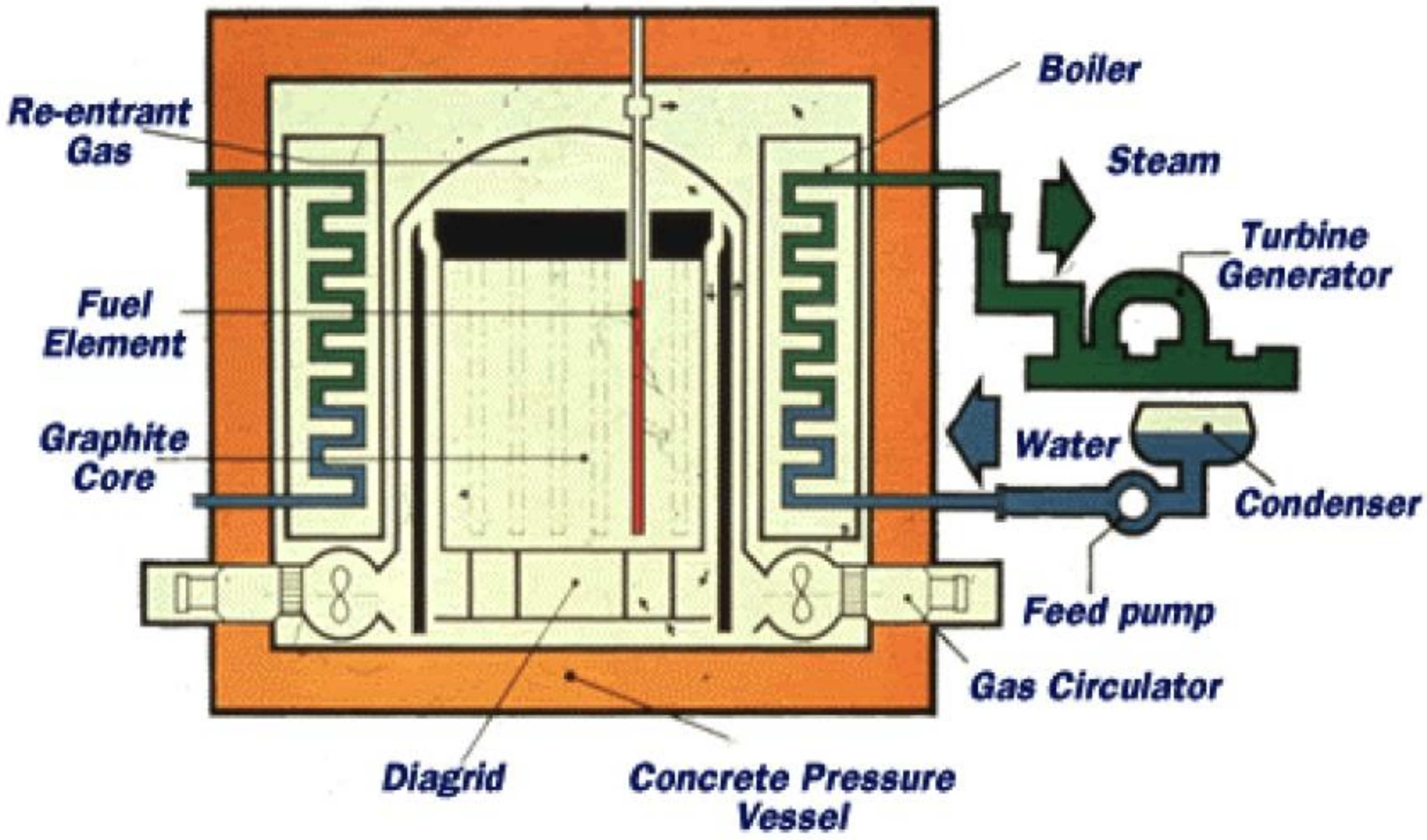
Internals of an Advanced Gas Cooled Reactor

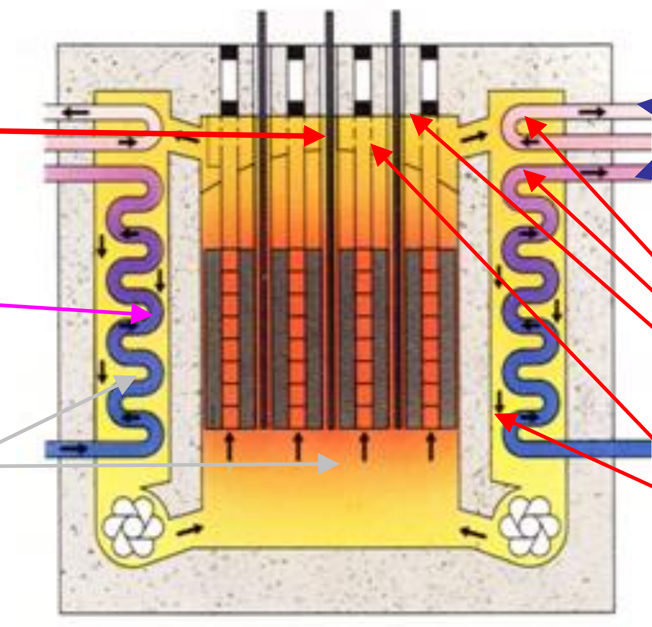


AGR Plant: Schematic Layout

CO_2 coolant gas at 650°C

Boiler evaporator / superheater 9Cr1Mo steel

Boiler economiser, Gas baffle, Core support Carbon steel <350°C



Steam at boiler outlet ~540°C
External steam pipework

Boiler secondary superheater / reheater and casing;
Pressure vessel penetrations;
Insulation covering and retention;
Fuel guide tubes, nozzles, fuel plug units.
Stainless steel 480 to 650°C:
Type 304, 316H, 321, 347, Esshete.

A generation 4 reactor from the 1970's

AGR Degradation Issues

- Many components subjected to creep-fatigue loading
- Recent work has highlighted potentially detrimental effect of AGR CO_2 coolant environment
- Degradation mechanisms:-
  - creep or creep-fatigue (including reheat cracking)
  - oxidation (metal loss)
  - carburisation (hardening/embrittlement of surface layer)
  - corrosion (including SCC)
  - fretting
  - high cycle fatigue
  - thermal ageing
- Potential for synergistic effects – particular concern is effect of surface carburisation on development of creep and creep-fatigue damage

Component Life Assessment (CLA) Process

- CLA is used to monitor creep-fatigue life usage of AGR boiler and reactor internal components
- Set of representative components defined for each AGR
  - components likely to have high damage whose failure has nuclear safety or commercial significance
  - components with high sensitivity to gas pressure, pressure differentials or gas temperatures
  - components of particular importance, interest or vulnerability
  - components of particular lifetime significance
- Most components are assessed using R5 Volume 2/3, using bounding deterministic material properties and assumptions
- Probabilistic R5 Volume 2/3 approaches are being developed to address large populations of components where small numbers of failures are tolerable

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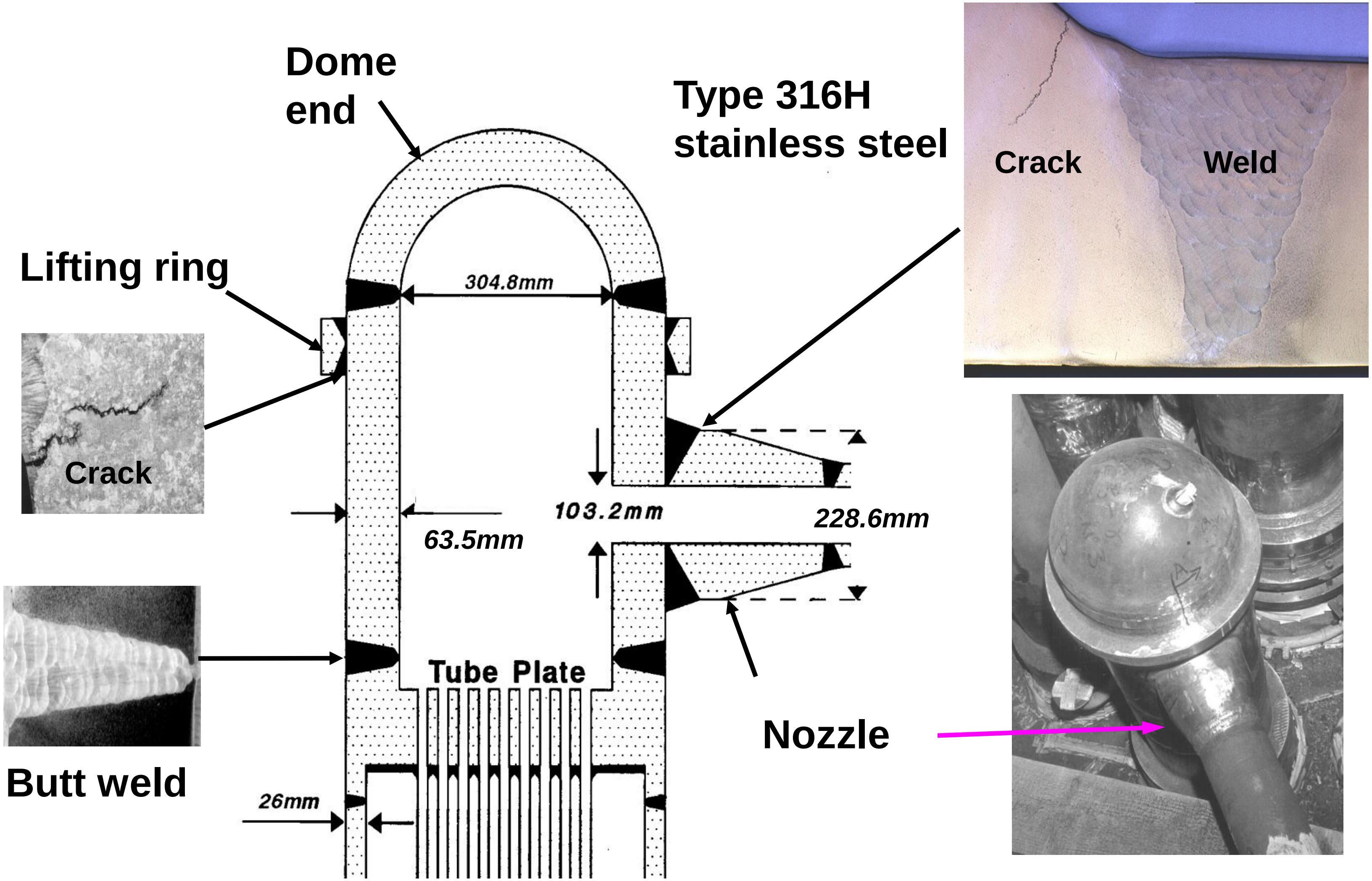
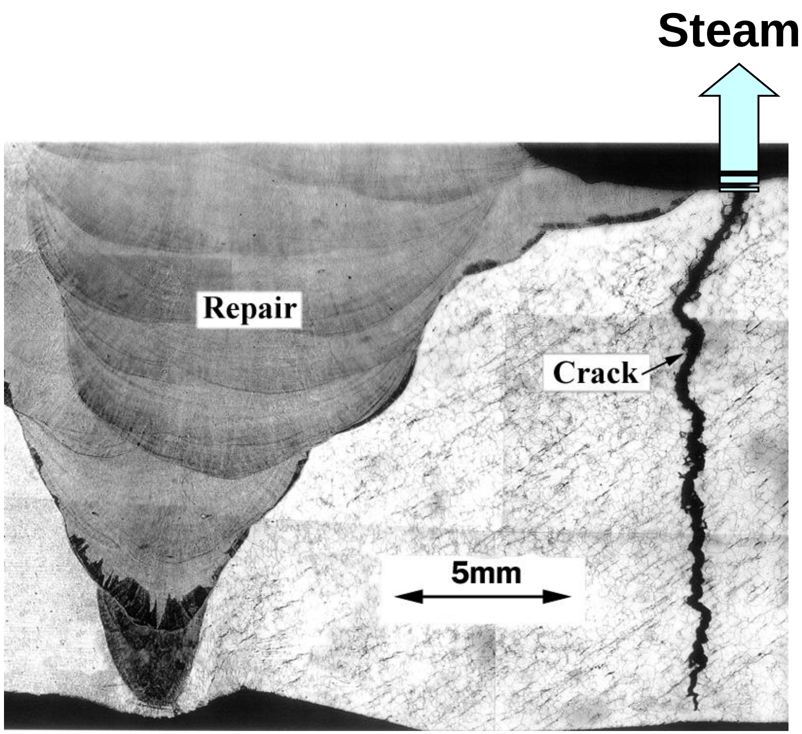
High Temperature Structural Integrity Issues: Reheat Cracking in Superheater Header Welds

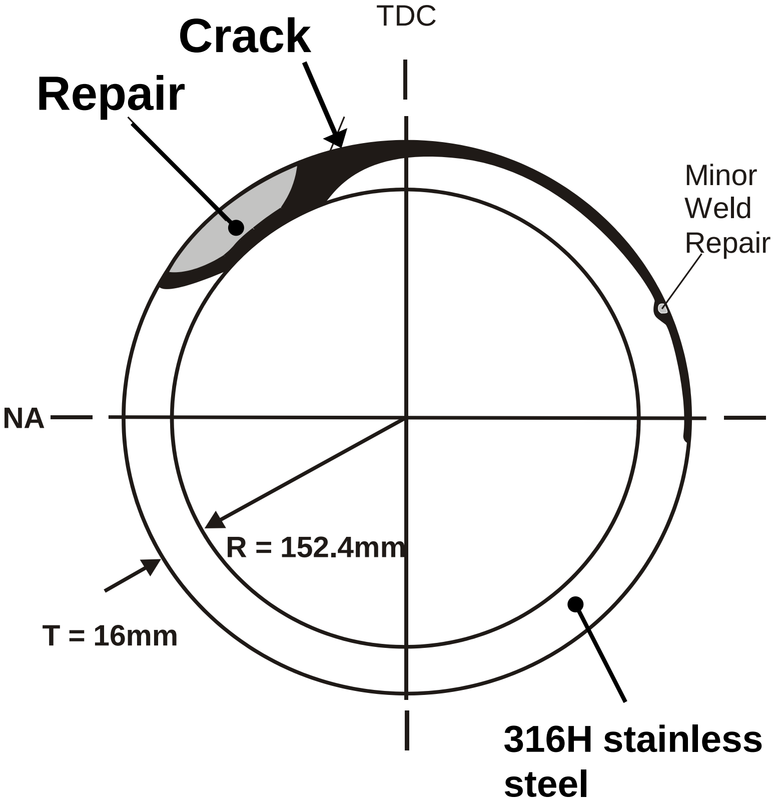


High Temperature Structural Integrity Issues: Reheat Cracking in Superheater Header Welds

- AISI 316 welds in 63.5mmm thick 316H header, no PWHT
- Operated at ~510-550^{o}C
- Air environment on outer surface
- Modest mechanical (pressure and system) stresses but high welding residual stresses
- Reheat cracking occurred in the outer surface HAZ of many of these welds after ~10-80kh operation
- Reheat cracking is predicted using the **ductility exhaustion** approach in R5 Volume 2/3, which accounts for the effect of the multiaxial stress state on creep ductility
- External to concrete pressure vessel (inspectable!) so managed by replacement with an improved header design manufactured using a higher ductility, lower carbon 316 steel

Reheat cracking at a repair weld in thin-section pipe



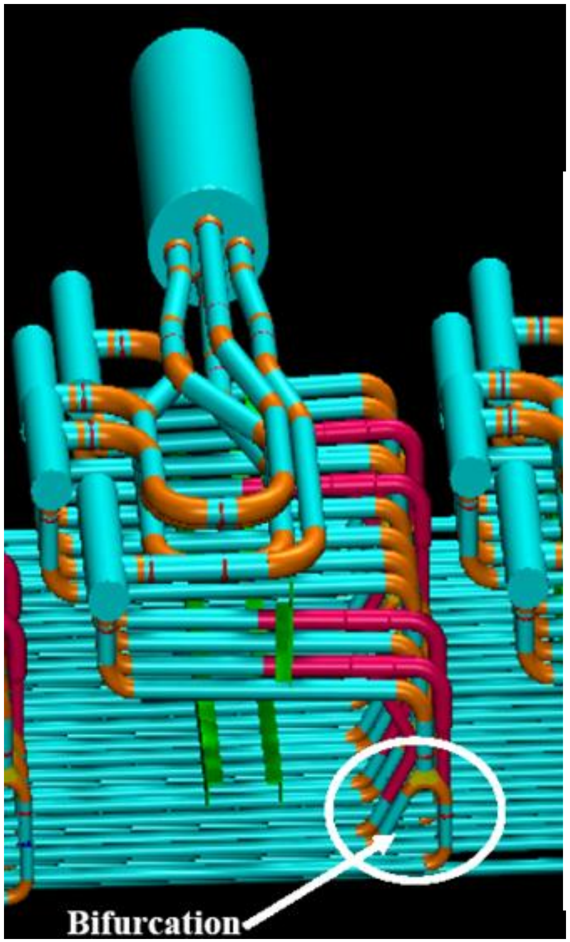


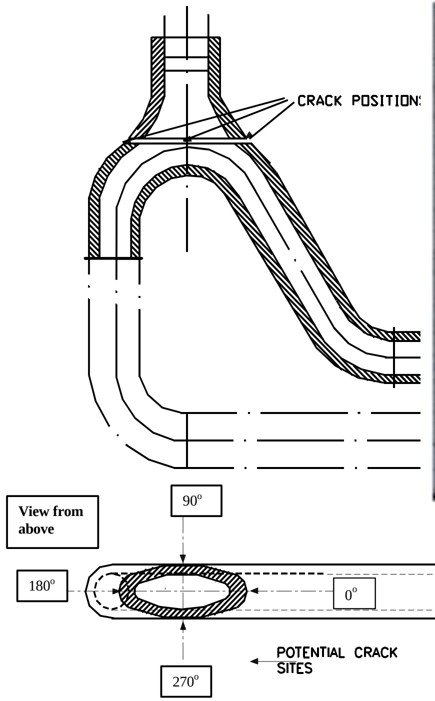
Hunterston 'B' developed a steam leak in 1997
Repair weld residual stress + plant loads at high temperature (>500ºC),
Creep cavitation » microcracking » crack growth » through-wall crack » steam leak

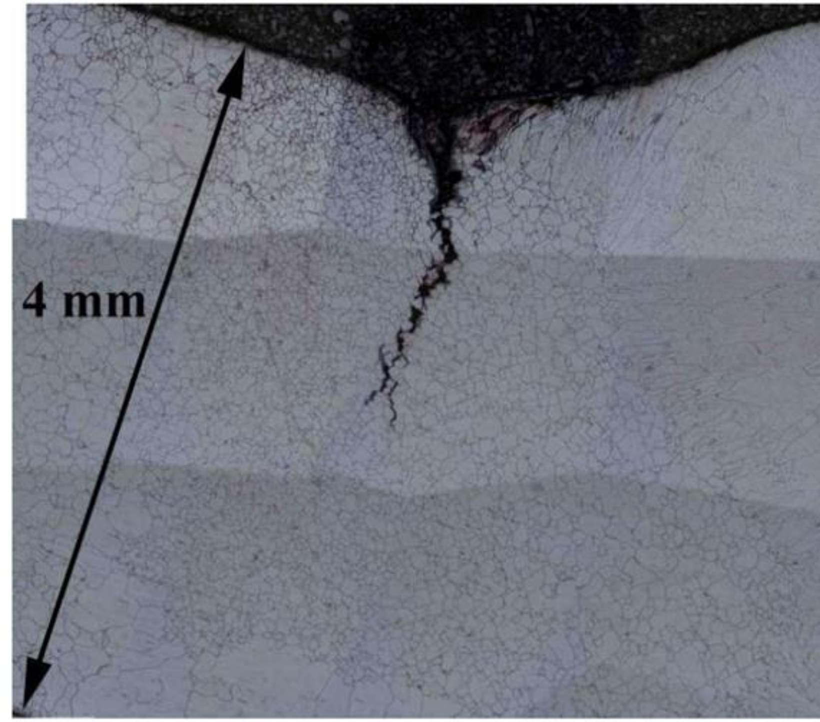
High Temperature Structural Integrity Issues: Bifurcation and Tailpipe-Pintle weld Cracking

- Welds in AISI 316H boiler tubing
  - bifurcation welds ~4mm thick,
  - tailpipe-pintle welds ~7mm thick, no PWHT
- Operated at 500-525^{o}C
- CO_2 reactor gas on outer surface
- Significant pressure and system stresses
- Cracking occurred in HAZ on the outer surface
- Managed by down rating to 80% power
- Creep dominated growth mechanism but initiation mechanism less clear
- Here inspection requires man-access inside the concrete pressure vessel

High Temperature Structural Integrity Issues: Bifurcation and Tailpipe-Pintle weld Cracking (2)

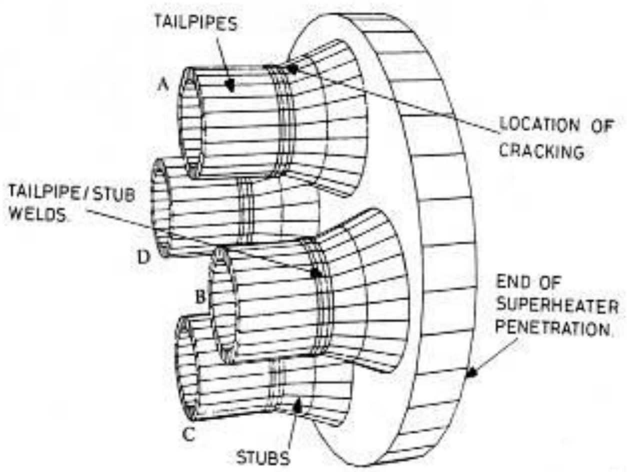






Creep-Fatigue Cracking in Bifurcation Welds

High Temperature Structural Integrity Issues: Bifurcation and Tailpipe-Pintle weld Cracking (3)



Creep-Fatigue Cracking in Tailpipe-Pintle Welds

High Temperature Structural Integrity Issues: Bifurcation and Tailpipe-Pintle weld Cracking (4)

- Observed crack creep-fatigue crack growth rates broadly consistent with R5 Volume 4/5 predictions **but R5 Volume 2/3 did not predict creep-fatigue crack initiation in the bifurcation welds**
- Probabilistic R5 Volume 4/5 assessments that accounted for uncertainties in crack growth predictions and in the inspection process gave predictions consistent with observed crack growth behaviour
- Hypothesis that surface carburisation plays a significant role in creep-fatigue crack initiation – supported by results of probabilistic R5 Volume 2/3 assessments

Material Effects on Cracking in AGR 316H Components (1)

- Wide range of chemical compositions used in AGR AISI 316H components
  - different steelmakers
  - wide range of manufacturing processes
  - wide range of section thicknesses
- Likely to be significant scatter in creep properties
- For the boiler superheater bifurcation components there were 3 distinct sources of material manufactured by different steelmakers

Material Effects on Cracking in AGR 316H Components (2)

- The material most susceptible to developing creep damage and cracking in the boiler bifurcation components was manufactured by the same steelmaker and had similar chemical compositions to the superheater headers that suffered extensive reheat cracking
- Susceptibility to creep damage and cracking is influenced by the steelmaking process and chemical composition

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Implications for Future High Temperature Reactor Designs – Lessons from AGR Operation (1)

- Creep or creep-fatigue cracking **invariably** occurs in weldment HAZ (SAZ)
  - all relevant austenitic grades,
  - range of thicknesses,
  - with and without PWHT
- Cracking often associated with high secondary stresses
  - thermal transients
  - welding residual stresses
- Cracking tends to occur in low creep ductility materials (e.g. HAZ (SAZ) of thick section 316H weldments)
- Carburisation at the surface of components during high temperature exposure in a pressurised AGR CO_2 reactor gas environment can affect creep-fatigue crack initiation

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Implications for Future High Temperature Reactor Designs – Lessons from AGR Operation (2)

- Probabilistic approaches are useful for managing lifetime for large populations of components after some cracking or failures have occurred
- The operational feedback from the UK AGR fleet provides key drivers for ongoing development of EDF Energy's R5 high temperature assessment procedure
- **However many of the issues identified are not currently addressed in high temperature design codes**

Implications for Future High Temperature Reactor Designs – Surveillance Schemes

- The Oxidation Monitoring Scheme (OMS) set up for AGRs exposed materials and components to pressurised AGR CO_2 reactor gas at a range of relevant temperatures
- The AGR OMS gives valuable information on long-term oxidation behaviour – it has also been used to investigate carburisation
- Major shortfall of AGR OMS is that samples are not loaded
- **Surveillance schemes for future high temperature reactors should consider exposing samples in a relevant reactor environment and subjecting them to loadings experienced by typical plant components**

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Summary of AGR experience

- Susceptibility to creep and creep-fatigue damage and cracking is influenced by the steelmaking process and chemical composition
- Common features of AGR creep and creep-fatigue cracking:-
  - invariably occurs in weldment HAZ(SAZ)
  - is often associated with high secondary stresses (thermal transient stresses and/or welding residual stresses)
  - tends to occur in low creep ductility materials
- **AGR experience can be used to inform design and operation of future high temperature reactors**

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Some final thoughts on welds

- Welding is a fundamental joining technology in nuclear power generation plant
- In-service structural performance issues tend to centre around welds
- Degradation and failure are controlled by the interaction between microstructure, environment and loading at the **worst** welds
- Optimised parent material properties and microstructure can be irrelevant
- Neglect weld residual stresses at your peril
- Fixing weld structural performance issues after they arise in service is a complex and expensive process
- **Make sure your structures are both inspectable and repairable/replaceable – there are always "unknown unknowns"**

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