

Design Code Development in EERA JPNM: work done and future needs

MatISSE/JPNM workshop on cross-cutting issues in structural materials R&D
for future energy systems **25-26 November 2015, Petten, NL**

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www.eera-set.eu



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<http://setis.ec.europa.eu/>

- EERA JPNM support ESNII reactors
 - Objectives
 - General requirements
 - Materials
- Design Code related Work 2011-2015
 - Priorities
 - Work done and achievements
- Design Code related Work 2016 - 2020
 - Priorities
 - Planned Activities (Pilot Projects)
- Conclusions

- **Support Design, Licensing and Construction of ESNII prototypes and demonstrators**
 - MYRRHA, ASTRID, ALFRED and ALLEGRO ←
- **Commercially available nuclear materials whose safe performance needs demonstration for the harsh Gen IV conditions**
 - austenitic and ferritic-martensitic steels
 - nickel-based super alloys

Short-term perspective!
2025-2030

Work Programme is based on engineering priorities from reactor designers and developers

Why and how?

- **Why use "commercial" nuclear materials?**
 - Industrial experience and qualified for nuclear applications
 - Cost low and predictable;
- **But we need to demonstrate that these materials and components operate safely in harsher environment**
 - Resist higher temperature;
 - Resist higher irradiation levels;
 - Resistant to degradation from coolant;
 - Design life > 60 years
 - Load-following.

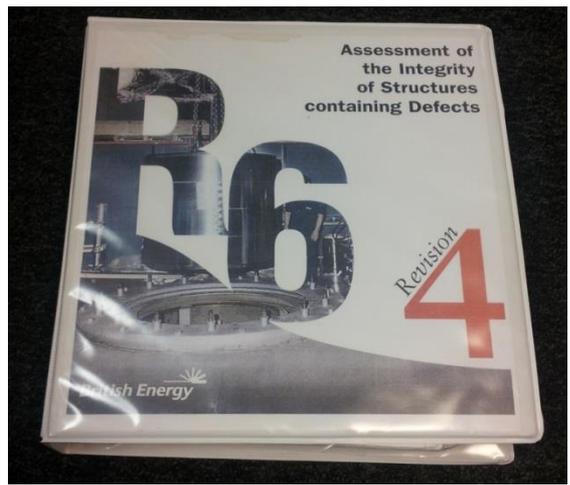
Why and how?

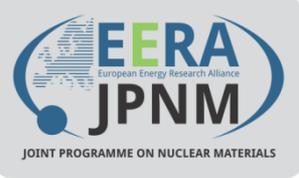
- **Work is primarily pre-normative research:**
 - Screening of candidate materials;
 - **Updated Design Rules and Codes.**
 - Development Test Procedures;

AFCEN RCC-MRx Design Code and R5/R6 Assessment Code



- **RCC-MRx is the selected Design Code for the ESNII reactors**
- **RCC-MRx developed for SFR and Experimental Reactors**
- **R5/R6 Assessment Code developed in the UK**





General Requirements supported by Design Codes

- **Reactor safety**
 - at least same level as Gen III+
 - Post-Fukushima: Increased demand to demonstrate safety under accident conditions
- **Overall Cost**
 - Efficient licensing
 - Components (material, size, design, fabrication)
 - Maintenance
 - Reduce undue conservatism
 - Operational life

Pillars of Design Code

Return-of-Experience

Pre-normative Research

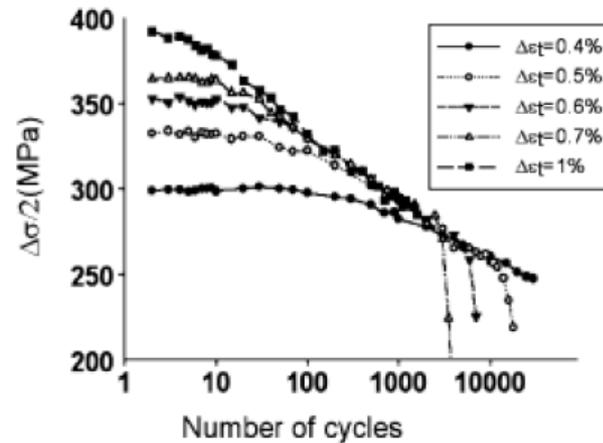
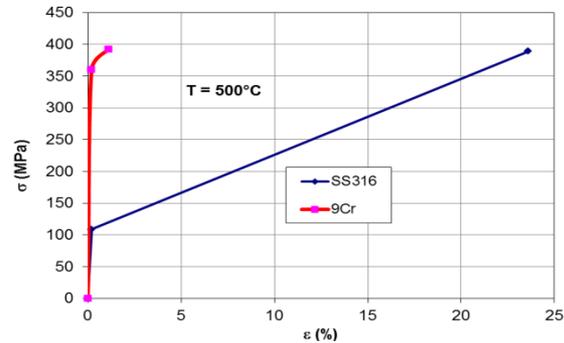
Robust Engineering

IAEA Safety Standards Safety of Nuclear Power Plants: Design Specific Safety Requirements No. SSR-2/1

4.16. Where an unproven design or feature is introduced or where there is a departure from an established engineering practice, safety shall be demonstrated by means of appropriate supporting research programmes, performance tests with specific acceptance criteria or the examination of operating experience from other relevant applications.

Work programme 2011-15

- **Emphasis on P91 Ferritic-Martensitic Steel**
 - **Good thermal fatigue resistance (low thermal expansion and high heat conductivity)**
 - **But low ductility, limited hardening and cyclic softening, weldability?**

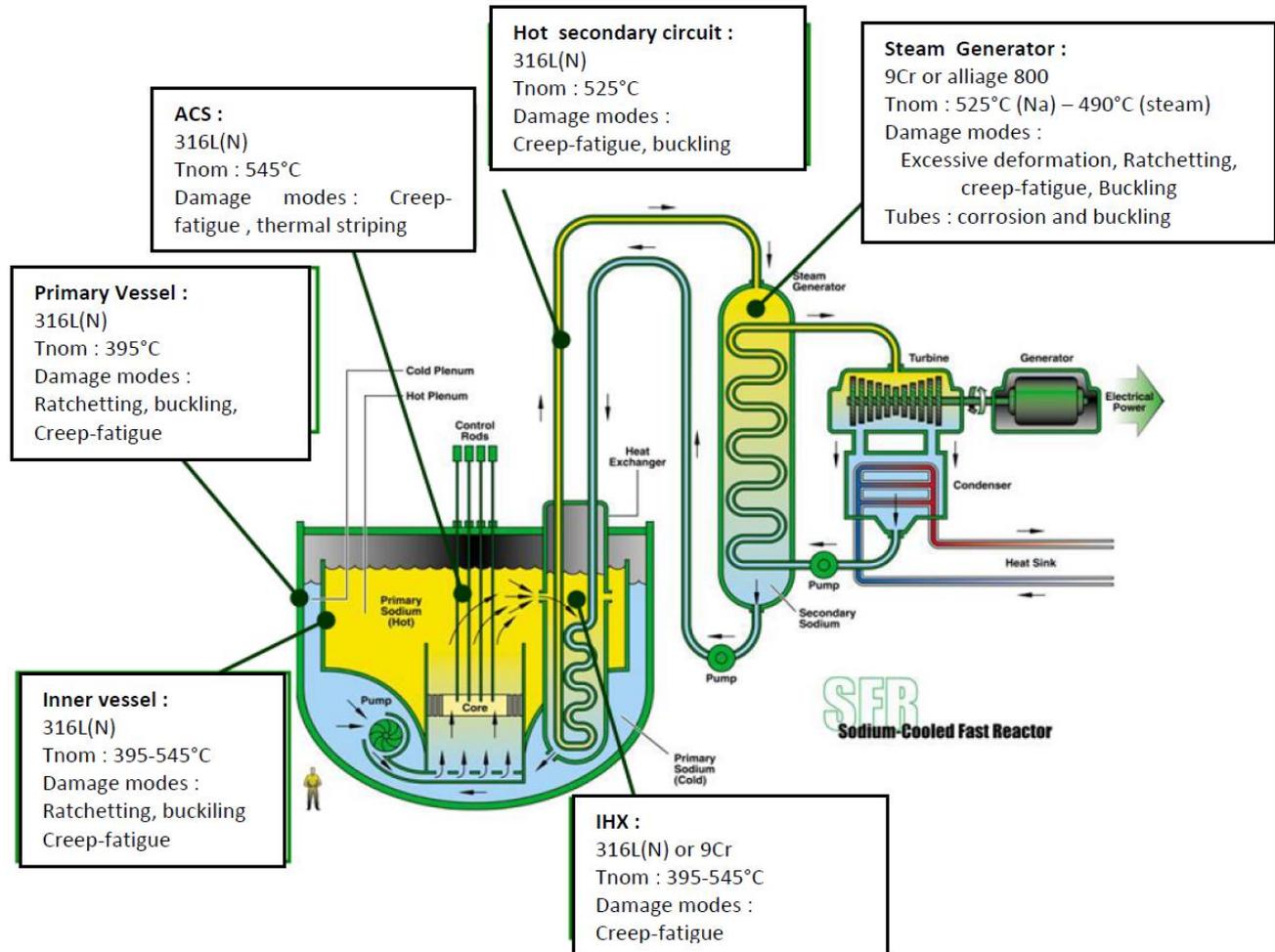


- **Design Code Areas:**

- High Temperature (ratcheting, creep-fatigue, negligible creep) ratcheting)
- Weld procedures and coefficients
- 60-years design life (thermal ageing)

Key degradation mechanisms

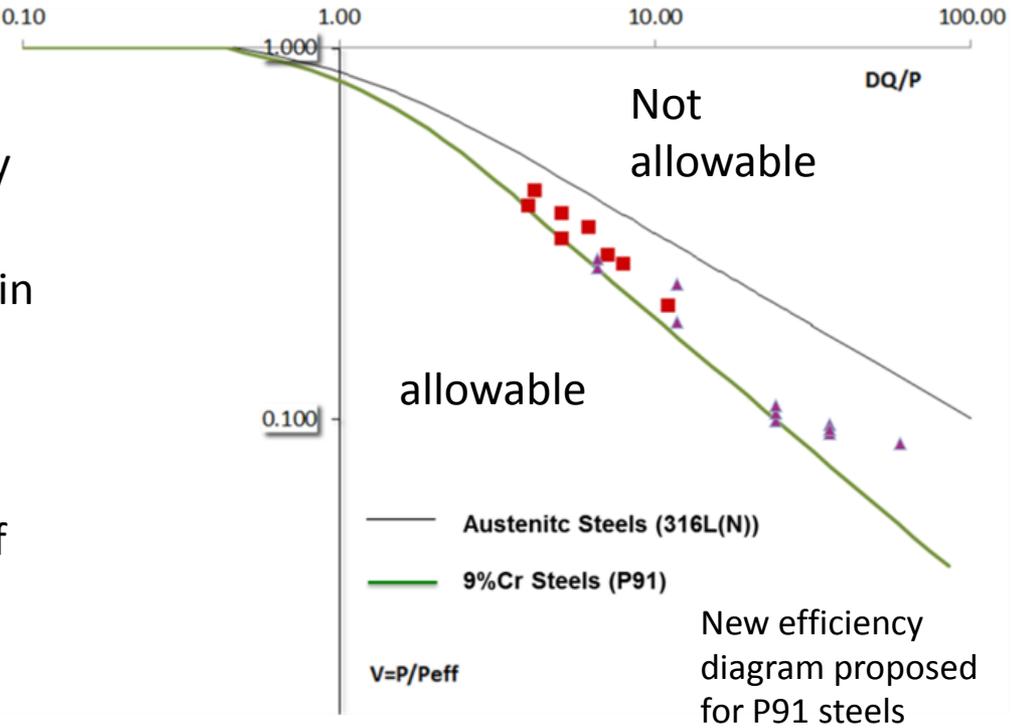
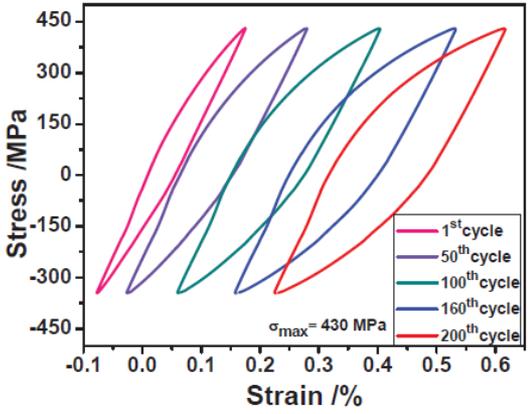
- High temperature degradation (ratcheting, creep, creep-fatigue) limit the life of nuclear components
- We need models for basic understanding as well as engineering models



Ratcheting P91

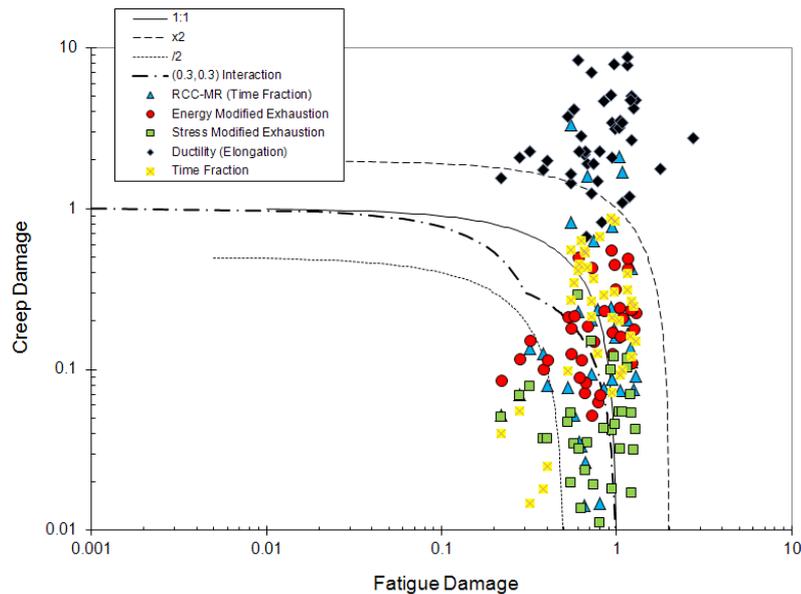
- Ratcheting is accumulated plastic (and creep) cyclic deformation

- New Proposed Design Rules for ratchetting for P91
 - P: primary load with resulting force that can give plastic collapse
 - DQ: cyclic secondary stress (typically thermal)
 - Peff: load related to cumulative strain
 - Efficiency diagram shows the allowable loads
 - The higher ratcheting of P91 than 316L is manifested by a reduction of the efficiency diagramme

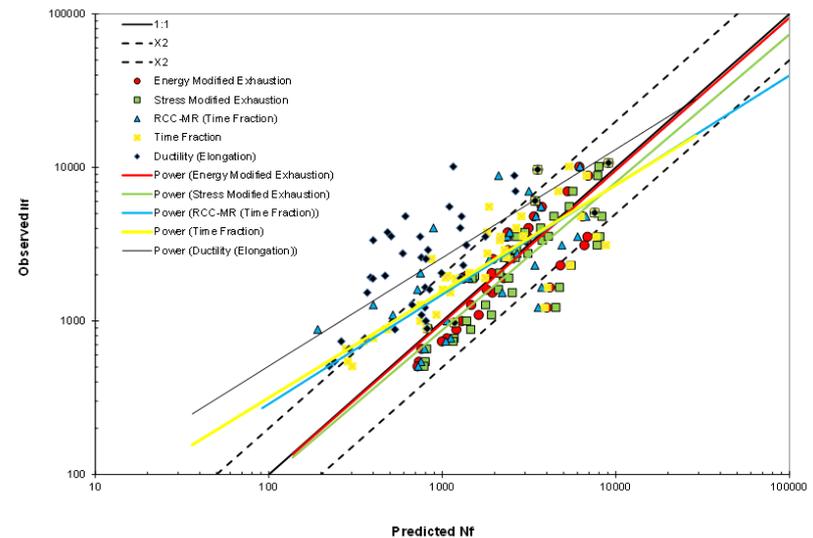


Creep-fatigue and negligible creep

- Creep-fatigue
 - Interaction Diagramme in RCC-MRX provides sufficient but overly conservatism and low accuracy
 - Alternative simplified methods proposed (see S. Holmström)

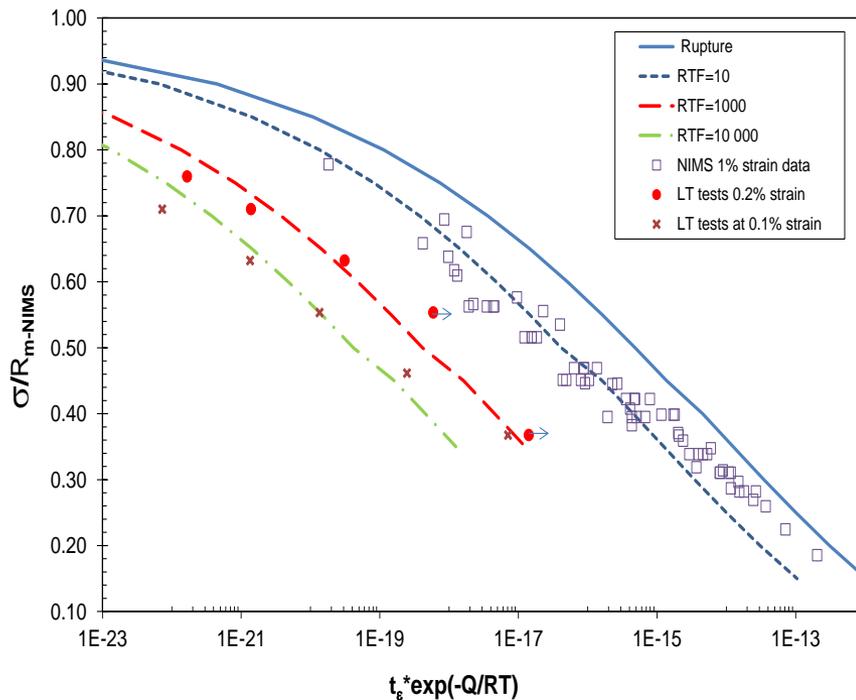


Experimental points creep-fatigue interaction diagramme

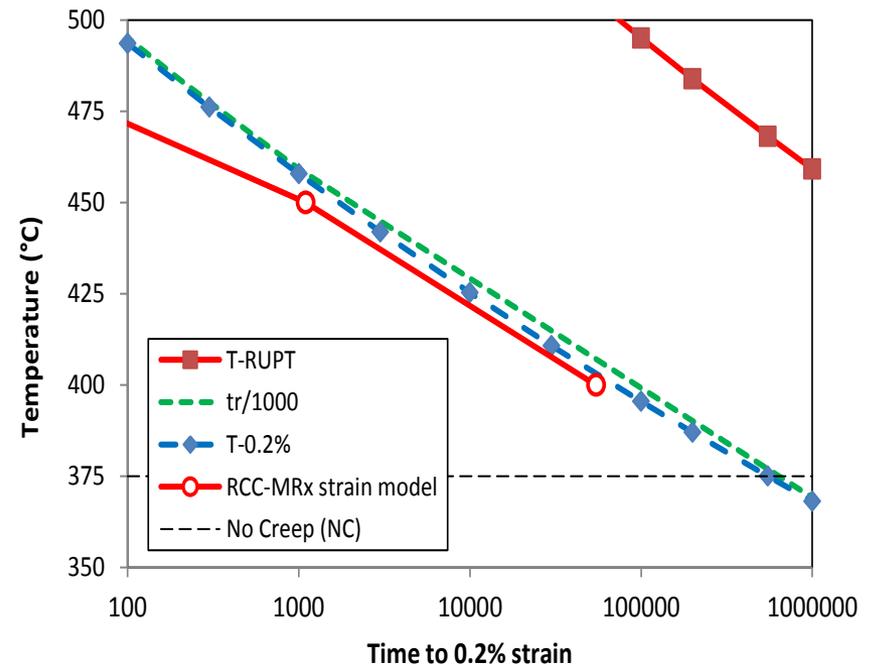


Predicted vs. measured creep-fatigue life

- Negligible creep
 - Updated proposal based on Wilshire model
 - Can be adjusted to different values of acceptable strain

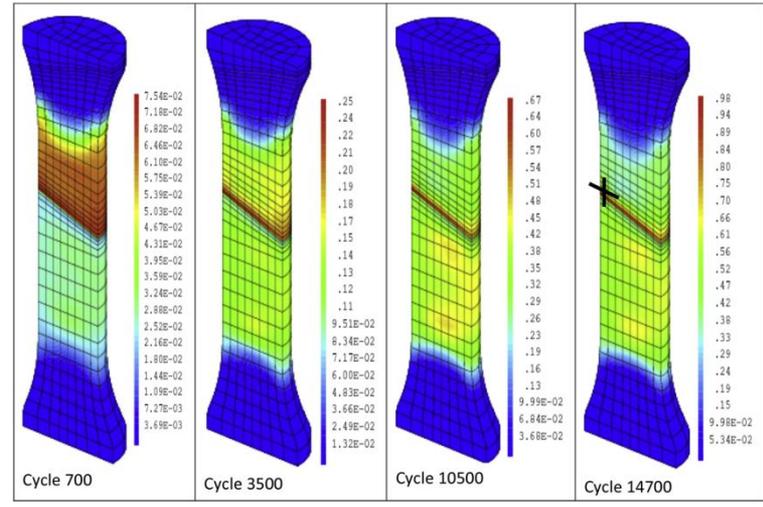
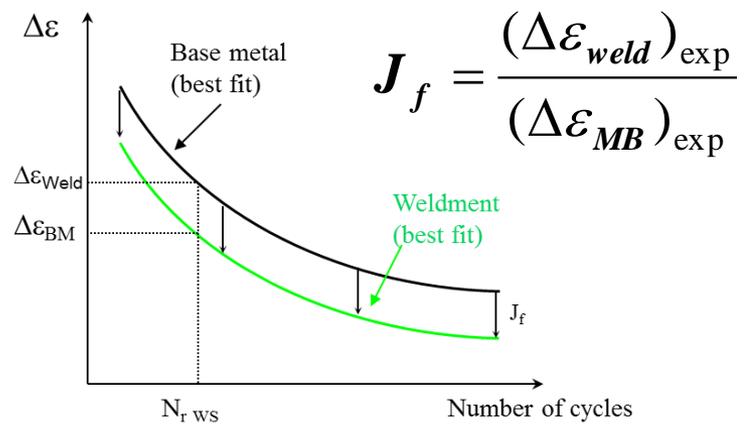


Normalized creep rupture curves



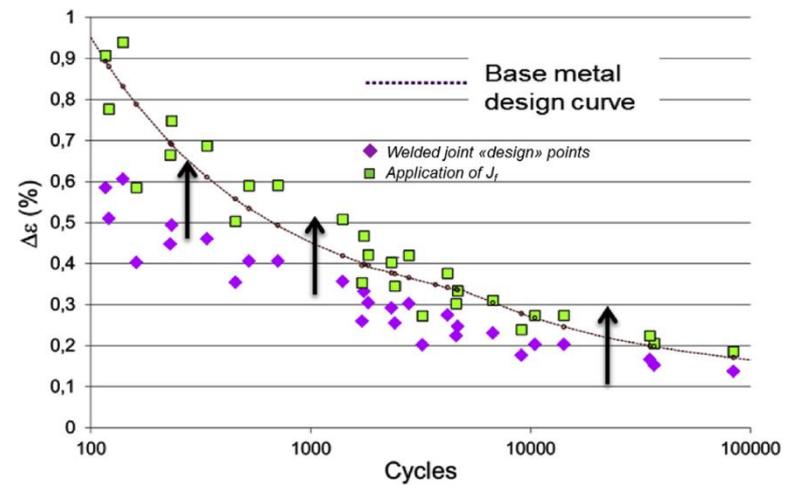
Negligible creep and creep rupture curves P91

Weld fatigue factors for P91



Computed strain evolution in weld

- $\Delta \epsilon \leq 0.25 \Rightarrow J_f = 1,35$
 (failure in BM)
- $0.25 \leq \Delta \epsilon \leq 0.55 \Rightarrow J_f = 1.35 + \frac{2}{3}(\Delta \epsilon - 0.25)$
 (transition zone)
- $0.55 < \Delta \epsilon \Rightarrow J_f = 1,55$
 (failure in HAZ)



Fatigue curves weld and base material

Directions for Work Programme 2016 -

- **Emphasis on austenitic steels: 316L(N), 316L;**
- **Methodology* to predict and mitigate material degradation in lead and lead-bismuth**
 - Corrosion, liquid-metal embrittlement, material data
- **Methodology 60 years Design-Life**
- **Methodology life assessment welded components, e.g type IV cracking**
 - Residual stresses, material properties of welds, weld defects, weld procedures,

* Methodology = Design Codes, Assessment Codes and Test Procedures

Directions for Work Programme 2016 -

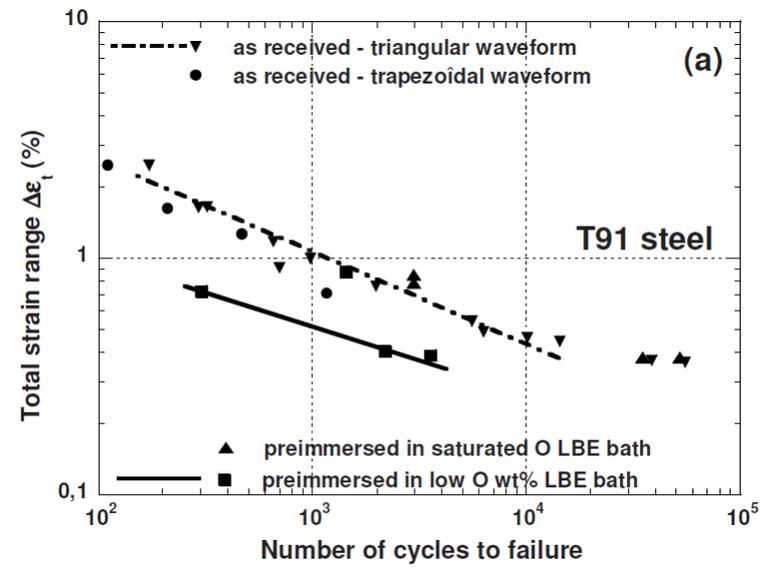
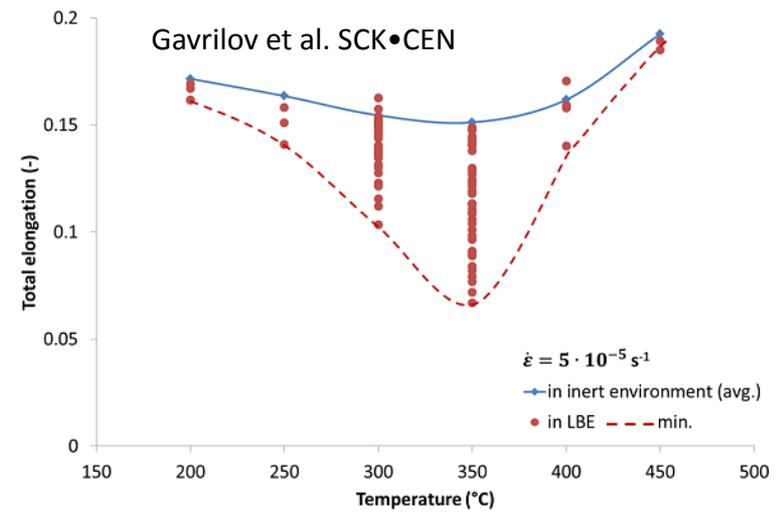
- **High-temperature: degradation and life assessment**
 - Creep-fatigue, thermal fatigue, thermal buckling (MATTER iso-thermal conditions), long-term material data, non-isothermal
- **Development of innovative miniature tests for material characterization**
 - Small Punch Test, nano-indentation,
- **Safety margins beyond design cases**
 - High temperature material properties, Dynamic loads, nonlinear deformation, rate effects, material data, fuel-pin

* Methodology = Design Codes, Assessment Codes and Test Procedures

Compatibility HLM coolant & structure

- Lead, as opposed to sodium, induces strong environmental effects (embrittlement, corrosion, erosion);
- The chemical composition of the coolant has a large impact;
- Limited feedback experience of HLM coolants.

- **Implicit Code Assumptions**
 - The chosen material has the same behaviour as air, except for depletion of corrosion allowance;
 - ISI will detect degradation when it becomes critical;
 - Composition stays within allowable range in the entire system.



Jean-Bernard Vogt and Ingrid Proriol-Serre / Procedia Engineering 55 (2013) 812 – 818

Compatibility HLM coolant & structure

Approach 1: Immunity

- Demonstrate "immunity" and Implicit Code Assumptions
 - P91 ruled out due to LME
 - 316L OK?, welds?
- Requires extensive qualification programme

Approach 2: Degradation allowance

- Accept some degradation effects but ensure sufficient margins through reduction factors, inspection programmes
- Requires substantial associated pre-normative R&D

General problem: lack of long-term data at operational conditions

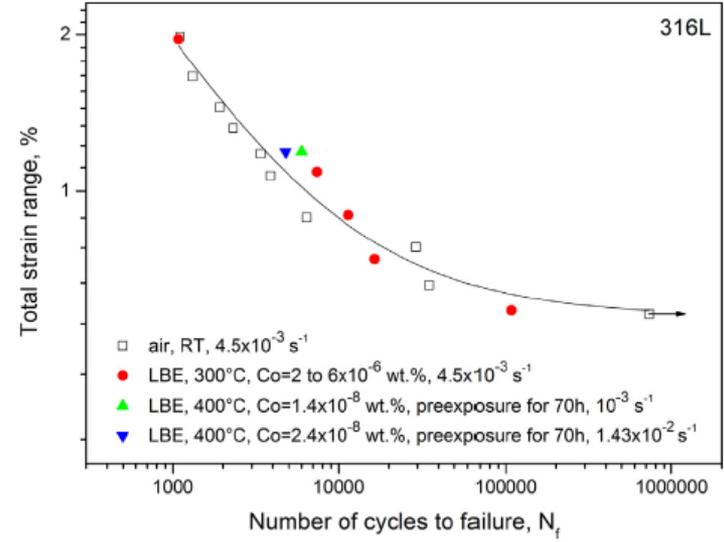


Fig. 6. Fatigue endurance of 316L tested in LBE at 300 and 400 °C, compared to air tests conducted at RT. Pierre Marmy^{a,*}, Xing Gong^{a,b}

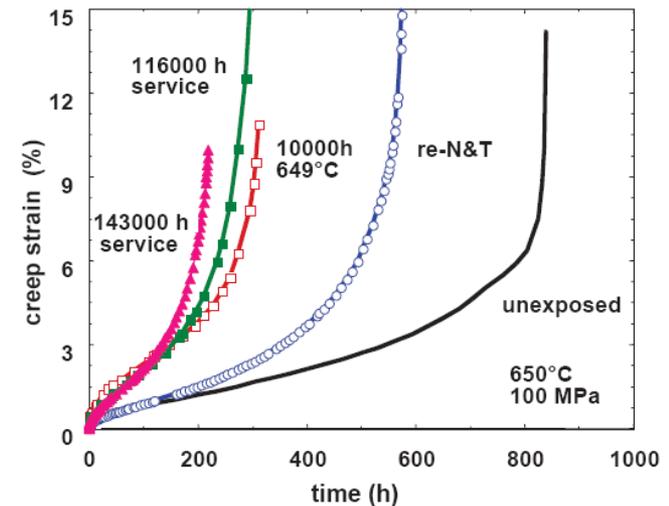
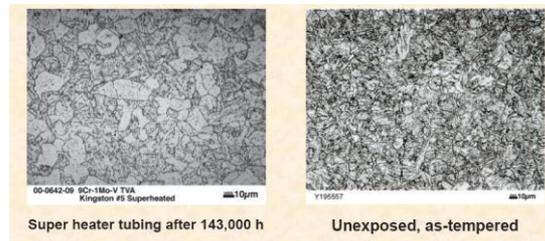
Journal of Nuclear Materials 450 (2014) 256–261

60+-Years Design Life

- Design Codes assumes 40 years Design Life but future reactors should operate for at least 60 years
- 60-years operation life must be based on "60 years Design" and Plant Life Management

- For the 60+ year Design Life all relevant slow processes and their interactions need to be taken into account

- Creep,
- Fatigue,
- Irradiation,
- Thermal ageing,
- Environmental



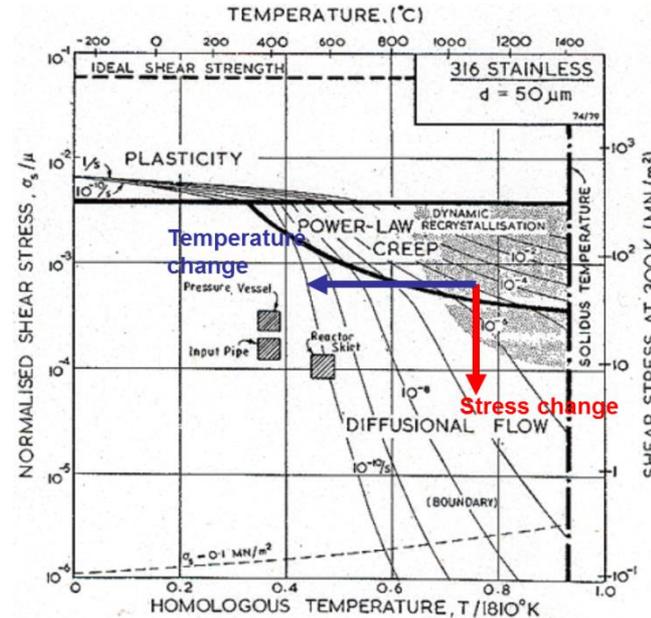
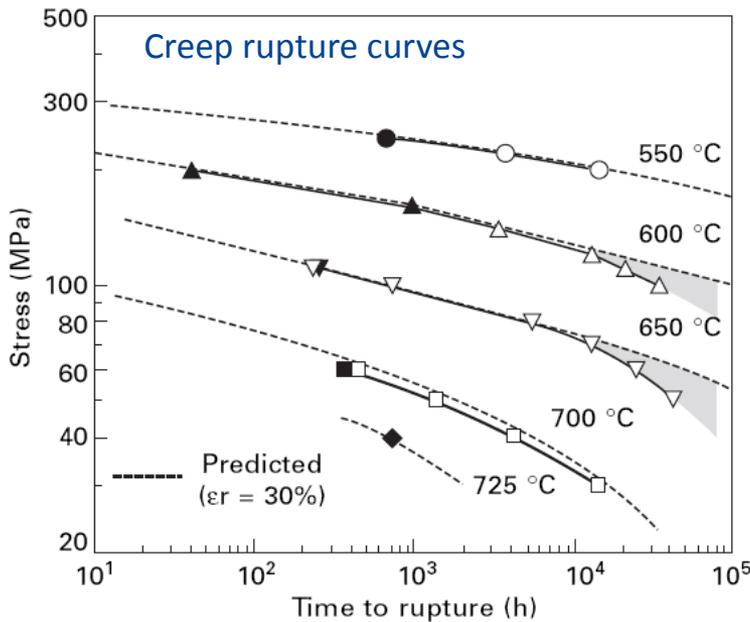
Creep strain for unexposed and aged P91 steel (Swindemann)

- The main issue is long-term material properties. The "rule of thumb" is that an acceleration factor of 3 is acceptable → 20 years test needed for 60 years design life!

60+ Years Design Life

How get relevant material data for 60+ design life?

- Testing of materials exposed to long-term operational conditions
- Extrapolation of accelerated tests. This requires that:
 - The deformation mechanism and microstructural evolution is the same in the accelerated test as the operational conditions, or at least
 - We can predict the change in deformation mechanism and microstructural evolution
 - Integration of physics-based models at different and time scales



Creep Deformation maps

- **The development of Design Codes and Assessment is essential for the Design of new reactors and hence key objective for EERA JPNM**
- **The future European innovative reactors will use RCC-MRx as their design code**
- **The design codes need to be further developed to address the harsher conditions, stricter safety requirements and cost reduction**

- **The Work Programme from 2016 is an evolution of the previous work.**
- **Key areas are:**
 - **HLM degradation and life assessment**
 - **60-years Design-life**
 - **Welded components**
- **Other areas include:**
 - **Miniature specimens**
 - **High temperature life assessment**
- **The concrete work plans for most of the areas have been worked out as Pilot Projects**

Thank you for listening
Any question?

