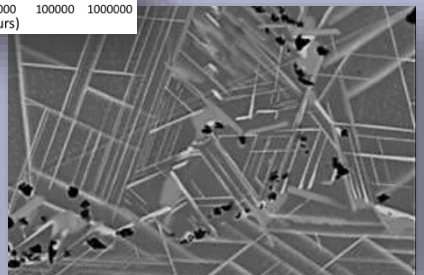
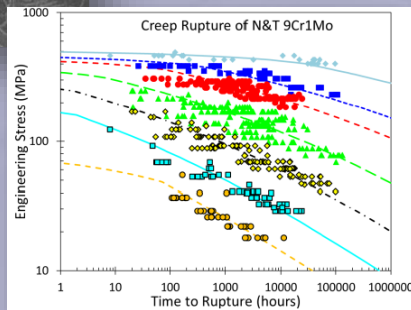
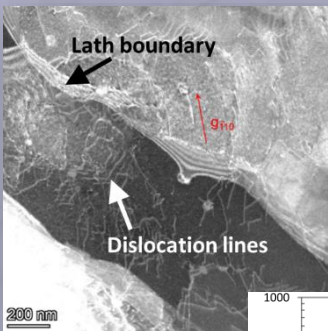


# ECCC 2026 Creep and Fracture

## Aix-en Provence, 18-20 May 2026

### Book of Abstracts



Pictures on front page:

Eurofer97 microstructure, courtesy of Dmitry Terentiev (SCK-CEN)

Creep rupture curves of T9, courtesy of Mike Spindler (EDF Energy)

IN718 creep damaged microstructure, courtesy of Augusto Di Gianfrancesco (Compusystem)

# ECCC 2026 Creep and Fracture

## Aix-en Provence, 18-20 May 2026

### Book of Abstracts

The present book of abstracts contains the abstracts and key words of all oral and poster presentations given during ECCC2026 conference at Aix en Provence (France), from 18 to 20 May 2026.

It is intended to be used in conjunction with the conference program, which can also be downloaded from the conference website, to provide a quick overview of each presentation's content and to help attendees prioritize the presentations they wish to attend. For a more in-depth look at the details of the work being presented, the conference proceedings, containing the complete Full Papers or Extended Abstracts, will also be available for registered attendees via their profile page.

In the conference program, all communications are assigned a paper number as PXXX, which is referenced and used here to order the abstracts in ascending order. These original numbers have been assigned to all announced papers after the official paper call for ECCC2026 and are not in full order caused by paper duplicates, declines or withdrawals.

To quickly access a specific "PXXX" paper or a paper by an author named "YYY", simply use the search tool of your pdf browser (Ctrl + F) and enter the paper number or the author's name.

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# **P011: Very long-term creep behaviour and microstructural evolution of IN718 with modified heat treatment**

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## **Summary**

*The 718 is a very well-known superalloy developed in the years '60 and worldwide used as cast, forged and tubular components, for aircraft engine, petrochemical plants, oil and gas applications, with a very wide operating temperatures spectrum from cryogenic temperature up to 650°C.*

*This work summarizes the 25 years of work done, started in the frame of Thermie Advanced (700°C) Pulverised Fuel Power European Project, to improve the creep behaviours of a trial rotor mock-up disk forged by Società delle Fucine (Italy) using a billet produced by AOD + double VAR remelting at Foroni Metals (Italy).*

*The initial target was 100kh rupture time at 100MPa/700°C for components to be use in the Advanced Ultrasupercritical power plants, seemed impossible reached by this alloy respect to other candidate superalloys, but a new heat treatment was developed by RINA-Consulting – Centro Sviluppo Materiali to improve the microstructural stability in the range of 650-750°C and as consequence to increase the IN718 creep behaviours. Now the longest creep tests have reached about 200.000 hours, and a creep data assessment shows an increase of more than 50°C respect to the standard UNS718 material.*

## **Key Words**

*IN718, forged rotor, heat treatment, microstructural evolution, long term creep assessment*

# P013: Serration Effect in IN718 LCF test carried out at 600°C: metallurgy and reduction

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## Abstract

*The IN718 is the most worldwide produced superalloy for cast, forged and tubular components, operating in a very wide operating temperatures spectrum from cryogenic temperature up to 650°C, with industrial application for aircraft engine, petrochemical plants, oil and gas applications. In particular, applying high levels of cyclic strain the alloy shows a strong irregularity of the stress-strain hysteresis loop. Further, in LCF tests, high stress values are found when these are carried out with a strain ratio  $R_\epsilon = \epsilon_{\min}/\epsilon_{\max} \approx 0$ , rather than  $R_\epsilon = \epsilon_{\min}/\epsilon_{\max} \approx -1$ , alternating-symmetric one as these types of tests are usually performed.*

*This peculiarity has been observed in LCF tests carried out in strain control at  $R_\epsilon=0$ , showing severe oscillation in the stress. The phenomenon was significantly reduced after the application of some stress-strain cycles.*

*Naturally this peculiarity/anomaly is not well regarded by the client, also because it can be interpreted, at first misinterpretation, as an anomaly of the testing system.*

*After researching and identifying the test conditions that would highlight the serrated flow, a targeted experimental effort was conducted to determine the conditions that would at least minimize it.*

*The effect arises during the first LCF cycle at a temperature of 600°C with strain ratio  $R_\epsilon \approx 0$  it was found an anomalous shape of the typical stress-strain curve. This phenomenon called "Serrated Flow" caused by a softening and subsequent hardening due to the interaction between diffusivity of atoms in solid solution and dislocations movements in the IN718 under this testing condition: this effect it also known as Portevin-Le Chatelier effect.*

*The serration shape of the curve is due to the strain level and strain rate during the application of the tensile and compression stress. This paper shows the experimental activity conducted to obtain the first testing cycle free or with limited effect the mechanisms that generated the serration.*

## Key Words

*IN718, Low Cycle Fatigue, Serrated flow mechanism, Software development*

# **P014: Interests to introduce a material in a nuclear code for innovative reactors operating at high temperature**

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## **Summary**

*Standardisation is a powerful tool to make available a content to a community. It is especially the case for mechanical components in the nuclear industry, which is used to rely on codes and standards. Standardisation of a process or a material can take a very long time if developments to bring process or material to maturity don't include standardisation as one of the target.*

*For innovative reactors (Advanced Modular Reactors, Generation IV reactors, fusion reactors, experimental reactors), the RCC-MRx code has been developed since 1985 by afcn. As a specificity, a nuclear code is not dedicated to one component, but covers several applications and thus, it induced wild range of materials that need to be standardized. Moreover, in the RCC-MRx case, it covers also a wild range of operating conditions (temperature up to creep domain, significant irradiation and several coolants such as water, sodium, molten salt, lead/lead bismuth, ...)*

*With the renewal of the nuclear, numerous challenges regarding the standardisation of innovative process or material are bring on the table of the standardisation bodies, we are going to detail a possible way to connect material developments and their industrial use through a standardisation process (RCC-MRx example). We will especially highlight the challenges specific to materials used for components operating at high temperature. We will detailed how we have implemented tools to facilitate standardisation through a Guideline. Firstly edited in 2017, the guideline has been updated in 2025 to implement specificities linked to welded joints.*

## **Key Words**

*Design rules, creep material qualification.*

# P017: Evaluation of Plastic Flow Behavior of Zr-2.5%Nb Pressure Tube Material Using Ring Tensile Test for IPHWR Reactors

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## Summary

*The mechanical strength and deformation behaviour of Zr-2.5%Nb pressure tubes are very important for the safe and reliable operation of Indian Pressurized Heavy Water Reactors (IPHWRs). Traditional tensile testing methods often involve flattening the curved tube samples, which may not represent their actual behaviour under operating conditions at temperature 266°C -310°C and accidental condition where temperature raises from 800°C - 1000°C. To overcome this issue, the present study uses a ring tensile test, which allows the study of material deformation in the hoop (circumferential) direction without altering the natural curvature of the tube. In this work, ring-shaped samples of Zr-2.5%Nb pressure tubes used in 700 MWe IPHWRs are investigated for deformation under tensile loading with strain measured using DIC. The experiments were carried out using specially designed three-mandrel fixture which helped in reducing bending and ensured that the loading remained predominantly in the hoop direction. The loading scheme, however, does not produce a pure radial loading and causes bending due to mandrel separation. To correct this bending effect, Finite Element (FE) analysis has been reported. Since Zr-2.5Nb shows plastic anisotropy due to the orientation of HCP crystals along different directions, the FE analysis incorporates Hill's anisotropic yield model to represent direction-dependent plastic behaviour. For the validation of the ring tensile with experiment, room temperature flat tensile data is used whereas for a higher temperature flat tensile data at 100°C and 200°C is used as in simulation. This methodology can also be extended to elevated temperatures, enabling the evaluation of temperature-dependent tensile and flow behaviour under operational temperature (266°C -310°C) and accident-relevant conditions. The combined experimental and computational approach provides a more realistic understanding of the plastic flow and tensile properties of Zr-2.5%Nb pressure tubes, which is important for the design and safety assessment of IPHWRs.*

## Key Words

Zr-2.5Nb alloy, Pressure Tube, Ring Tensile, Anisotropy

# **P018 - ECCC 35 years of activities for development and introduction of newer materials for power generation plants**

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## **Summary**

*ECCC is a voluntary grouping formed in 1991 to co-ordinate Europe-wide development of creep data to be used to design components for high temperature plants, bases on a Memorandum of Understanding, signed by all partners.*

*The ECCC is deeply involved in EU coordination for the development of knowledge on the damage caused by the creep phenomenon and the consequent reliability assessment activities. Strong links exist with the technical committees of the European Standard organizations, giving an efficient network to mutually exchange of technical information relating to current/future activities for the improvement or development of new materials.*

*For several years ECCC (1991-2005) concentrated efforts by EU support. Nevertheless, revitalization of ECCC has been generated by definition of 3 years Joint Industrial Project (JIP), first started in 2011, and still running (JIP5 2024-2027).*

*ECCC has a very strong link to industrial applications and it is presently organized in four Work Packages: WG1 on common procedures, data generation/assessment and three material specific Working groups: ferritic steels, austenitic steels, nickel-based alloys. Two main outputs are ECCC data sheets and ECCC Recommendation Volumes. The ECCC activities are almost completely carried out by members' contribution-in-kind.*

*The ECCC plays a part of its role, in term of generation of design properties for new materials introduction into fossil fuel power plant and related applications. It therefore engages a crucial role in assessing and realising the potential of new developments. Recently, with the aim of decarbonization, activities for materials for GEN-IV and SMR nuclear plants have intensified,*

## **Key Words**

*European Creep Collaborative Committee, high temperature materials, creep data assessment, energy production*

# **P019: EUROFER 97 creep models for strain and failure, in support of European nuclear design codes**

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## **Summary**

*This paper reviews the ECCC creep property characterization program for EUROFER-97, a reduced activation ferritic-martensitic steel for fusion applications such as ITER and DEMO. The paper includes the SCK CEN efforts for the ECCC WG3A assignment, the utilization of models and methods refined during open-access collaboration with JRC Petten as well with the CEN TC54 (WG59) working group studying negligible creep temperature limits.*

*The first part addresses challenges in creating an ECCC creep strength property sheet from the available dataset, including a 1% creep strain strength table. It presents SCK CEN's proposed models, focusing on two rupture models—the Modified Larson-Miller (MLM) and Wilshire Equation (WE)—both adjusted for batch-to-batch tensile strength variations. Additionally, a comprehensive creep strain model using the LCSP approach is introduced, covering the full stress and temperature range relevant for design.*

*The second part examines methods to enhance limited datasets through tensile strength normalization, time-to-strain data, and creep strain models. These techniques enable the generation of “constructed data” for specific conditions, such as long-term failure or negligible creep thresholds. While enhanced datasets improve coverage, they also pose challenges for benchmarking model performance against predictions based solely on original raw data.*

## **Key Words**

*EUROFER-97, creep, modeling*

# **P020: Comparative creep behaviour of welded and diffusion-bonded joints in oxide dispersion strengthened platinum alloys for high-temperature glass industry applications (Extended abstract)**

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## **Summary**

*Oxide dispersion strengthened (ODS) platinum alloys are widely used in glass manufacturing due to their excellent creep resistance, oxidation, and corrosion resistance at high temperatures. Due to the complexity of glass manufacturing components which are typically assembled through joining processes, the mechanical integrity of joints is a critical factor in ensuring the long-term performance and reliability of ODS platinum components. This study compared the creep performance of welded joints and diffusion-bonded joints in ODS platinum-10% rhodium alloy, (nanoplat®R, Tanaka Kikinzoku Kogyo, Japan). To evaluate the joint strength, creep tests were conducted at 1400 °C across a range of applied stresses including low-stress regime. Specimens were fabricated such that the gauge section consisted exclusively of the joint, enabling the determination of creep properties specific to the joint. Diffusion-bonded joints showed over 2.5 times higher rupture strength than welded joints, resulting in an increase in rupture time by more than 50 times. The superior creep strength of diffusion-bonded joints arises from their thermally stable, fine-grained microstructure, which increases grain-boundary area and, together with dispersed zirconia particles, provides effective dislocation-pinning barriers that suppress dislocation mobility, lower dislocation-creep rate, and extend rupture life. In contrast, welded joints exhibit grain coarsening that reduces grain-boundary area and the depletion of zirconia dispersoids in the heat-affected zone further diminishes dislocation-pinning sites allowing dislocations to move freely and thereby accelerating dislocation-controlled creep and lowering creep strength. The findings demonstrate that diffusion bonding of platinum components substantially extends service life, enhancing operational reliability and cost efficiency in demanding glass production environments.*

## **Key Words**

*Welded joints, diffusion-bonded joints, creep rate, creep rupture strength, dislocation creep*

# P021: Influence of Nb addition on creep behaviour and damage evolution of AISI 316L(N)

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## Summary

*Creep behaviour of 316L(N) stainless steel with small addition of niobium (Nb) was studied at 575 °C – 310 MPa and 600 °C – 200 MPa and compared to the creep properties of a typical 316L(N) steel. For both cases, the Nb-enriched material exhibited lower minimum creep rates and longer times to rupture compared to its conventional counterpart. This minimum creep rate reduction a priori resulted from fine intragranular precipitation strengthening of Nb-rich phases during creep. An increase of ductility was observed at 600 °C – 200 MPa compared to 575 °C – 310 MPa creep condition for the Nb-enriched steel, suggesting a competition between matrix and grain boundary precipitation strengthening. At 575 °C – 310 MPa, creep damage of the Nb-enriched steel was governed by grain boundary cracking resulting in small creep ductility. This mechanism was drastically reduced when coarsened intragranular and intergranular phases were formed during longer creep duration at 600 °C – 200 MPa.*

## Key Words

*Creep, minimum creep rate, ductility, 316L(N) stainless steel, niobium, precipitation strengthening.*

## **P023: High temperature creep tests on additively manufactured AISI 316L**

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### **Summary**

*Small Modular Reactors (SMRs) represent a class of nuclear power plants characterized by reduced electrical output and a highly modular design. Globally, numerous development initiatives are investigating different SMR-concepts. In some concepts heat pipes are used for passive heat transfer from the reactor core. Due to the complex internal geometry of highly efficient, high-temperature heat pipes are particularly well suited for additive manufacturing. As working fluids sodium and potassium are considered promising, with potassium exhibiting more favourable thermophysical properties. At the University of Stuttgart, the Materials Testing Institute (MPA) and the Institute of Nuclear Technology and Energy Systems (IKE) are collaborating on the SiFeKo project (English title: "Critical assessment of the security of innovative, future-proof manufacturing processes for internationally relevant SMR concepts"). The project focuses on the evaluation of additively manufactured materials for application in SMRs, using additive manufactured heat pipes as a representative use case. Prospective materials must be resistant to mechanical and thermal loads, as well as to liquid metal corrosion. This paper will outline the creep and tensile testing methodology applied in the project, and present first experimental results on additively manufactured AISI 316L.*

### **Key Words**

*AISI 316L; long-term creep tests; tensile tests; additive manufacturing; small modular reactors; heat pipes*

# **P024: ECCC Creep Rupture Data Assessment Optimisation and Qualification (Extended Abstract)**

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## **Summary**

*The “Post-Assessment Tests” (PATs) have been central to ECCC creep rupture data assessment (CRDA) for three decades. By providing an independent, consistent framework against which to judge the respective merits of alternative assessments, the PATs have played a key role in promoting consensus and enabling the production of design Data Sheets for major high temperature materials. However, it is widely agreed that whilst the PATs may disqualify poor assessments, they cannot be relied upon to identify the best assessment.*

*Current work within ECCC (Working Group 1, Action Unit 1.6) seeks to improve post-assessment testing, develop a stronger basis for the optimisation and qualification of ECCC CRDAs, and hence maximise confidence in long term design strength data. A broad consensus has been reached that a primary basis for CRDA selection, optimisation and qualification should be that the CRDA successfully predicts, to a reasonable and achievable extent, the average longer-term values and the longer-term trend of the assessed creep rupture life data set.*

*In this paper, the author addresses some key reasons why creep rupture data assessment has proved so challenging. The post-assessment criteria adopted thirty years ago are then critically reviewed, indicating that major changes can be recommended. In parallel, recent re-examinations of selected ECCC creep rupture data assessment exercises are described, and the inherent limitations of many current standard modelling approaches are clarified.*

*The paper also describes the development of improved post-assessment methodologies, and shows that some novel approaches are promising. However, characterising how well a model predicts the longest-term data has proved to be rather complex. Commonly, lowest-stress testing provides failure data on only the weakest heats. Whilst analytical and statistical approaches have been developed to counteract this bias, neither is yet fully proven.*

*It is therefore proposed that, to establish baseline confidence, “scientifically valid” CRDA exercises should be carried out, including only those stress-temperature conditions for which the data set contains little or no significant long-term unfailed data. In parallel, priority should now be given to developing post-assessment techniques which can reject models which do not adequately address the separate effects of stress and temperature on creep rupture behaviour.*

*Finally, novel CRDA methodologies which could overcome the limitations of current “one size fits all” models are reviewed. These include multi-region analysis, higher-flexibility modelling methodologies, and potentially machine learning.*

## **Key Words**

*Creep rupture data assessment (CRDA), post-assessment evaluation, CRDA optimisation and qualification, design strength data.*

# **P025: Fundamental study on a non-destructive method for evaluating three-dimensional creep strain using surface displacement**

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## **Summary**

*Operations at elevated temperatures and under increased loads are crucial to improve the efficiency of thermal power generation. However, the risk of turbine blade failure is relatively high. Therefore, it is crucial to ensure safety. Currently, various methods have been proposed to predict the remaining service life of gas turbine blades used in power generation. However, the estimation accuracy of numerical simulation based on thermal elastic–plastic finite element analysis is relatively low because temperature distributions of actual turbine blades are difficult to measure. Non-destructive methods have been developed to assess damage levels via microcrack examination and hardness measurements; however, these methods can only evaluate the surface of the component. Therefore, the authors propose a method for estimating three-dimensional creep strain using surface displacement observed on turbine blades during regular inspections. In this method, the relationship between creep strain and displacement is first established using elastic calculations based on the finite element method. The three-dimensional creep strain is estimated via an inverse analysis using the relationship and non-destructively measured surface displacements. However, it becomes a large-deformation problem in which the creep strains and displacements become non-linear in actual turbine blade because relatively large creep strains are generated. Therefore, a repetitive calculation method that can estimate creep strain with relatively high accuracy even in such non-linear cases is described. Additionally, the estimation accuracy of this method, considering measurement errors, is evaluated through numerical analysis for its practical application. This study examined the estimation accuracy resulting from differences in the random number and standard deviation of the measurement errors. When measurement errors are relatively large, iterative calculations may diverge rather than converge. However, the relatively significant variations in the estimated creep strain make it possible to discern that convergence has not been achieved.*

## **Key Words**

*Creep strain, Turbine, Non-destructive, Displacement, Inverse problem, Non-linear, FEM.*

# P026: Creep and Fatigue Related Failures in Gas Turbine Components

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## Summary

*Gas turbines operate at high temperatures, subjecting their components to severe thermal and mechanical stresses during service. Rotating parts, such as turbine blades, experience high centrifugal stresses at elevated temperatures. Stationary components, on the other hand, are exposed not only to high temperatures and aggressive environments but also to thermal and mechanical cycling associated with repeated start-ups and shutdowns. Rotating components are typically made from nickel-based superalloys due to their superior hightemperature strength and oxidation resistance. Stationary components are commonly made from either nickel-based or cobalt-based superalloys. While many of these parts are protected with thermal or environmental coatings, they still undergo service-related degradation and, at times, failure. Typical damage mechanisms include fatigue, creep, oxidation, embrittlement, stress corrosion cracking, and general corrosion. Creep-related microstructural damage is a time-dependent phenomenon that develops under prolonged exposure to high temperatures and stress. Timely in-service metallurgical evaluations using minimally invasive test coupons can help assess the extent of such damage in critical components. In some cases, rejuvenation heat treatments may reverse microstructural degradation and extend component life. However, even with recommended periodic evaluations and rejuvenation efforts, creep-related failures continue to occur in various gas turbine components. This paper presents examples of failures associated with creep and fatigue in several key parts of gas turbines, including turbine blades, transition pieces, combustion chambers, fuel nozzle tips, and fasteners.*

## Key Words

*Failures, Creep, Fatigue, Gas Turbines, Superalloys*

# P027: An investigation on the driving force for creep crack growth

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## Summary

*The physical meanings of the conventional creep crack growth parameters, e.g. the  $C^*$ -integral,  $C^*$ , the experimental  $C^*$ -integral,  $C^*_{exp}$ , or the experimental  $C$ -integral,  $C_{t,ssc}$ , are not fully clear. Therefore, this paper presents a comprehensive numerical study where these conventional creep crack growth parameters are compared to several  $J$ -integral related parameters and the crack driving force (CDF), which has been used in linear elastic and elastic-plastic fracture mechanics. Hereby, the CDF is derived from basic thermodynamic principles and by applying the concept of configurational forces (CFs). This analysis shows that the CDF is given by the  $J$ -integral for elastic-plastic, creeping materials,  $J_{epc}$ , evaluated for contours,  $\Gamma_{acZ}$ , around the active creep zone. This CF-based type of  $J$ -integral,  $J_{epc}$ , has been introduced in preceding papers. In the numerical study, crack propagation is modelled by alternating creep and crack extension steps at constant loads in a compact tension specimen made of the nickel-base superalloy Waspaloy at a temperature of 700°C. The CDF is evaluated by a CF-based post-processing procedure after a conventional finite element (FE) computation using the FE program ABAQUS. This procedure is applicable for small-scale creep (ssc-), transition creep (tc-) and "moderate" extensive creep (ec-) conditions. The results show that  $C^*_{exp}$  and  $C_{t,ssc}$  reflect the time derivative of the CDF during the creep stages. The CDF-values come close to the far-field value of the computational  $J$ -integral of ABAQUS,  $J_{farVCE}$ , and for ssc- and tc-conditions also to the elastic component of the experimental  $J$ -integral,  $J_e$ . For extensive ec-conditions, the CDF-evaluation procedure must be modified, which is the topic of a future paper.*

## Key Words

*Creep crack growth, Crack driving force,  $C^*$ -integral,  $J$ -integral, Configurational force concept, Finite element method.*

# **P029: Effect of microstructure on creep strength of modified 9Cr-1Mo steels manufactured via laser powder bed fusion**

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## **Summary**

*Creep strength of mod. 9Cr-1Mo steels manufactured via laser powder bed fusion (LPBF) was investigated at 923 K up to approximately 20,000 h. LPBF resulted in the duplex microstructure formation consisting of  $\delta$ -ferrite and martensite.  $\delta$ -ferrite is a unique phase frozen by the rapid cooling during LPBF. Martensite is formed by the solid-state phase transformation of once solidified  $\delta$ -ferrite at the heat-affected zone. Four samples with  $\delta$ -ferrite area fractions ranging from 35% to 66% were fabricated by varying the LPBF conditions to investigate the influence of microstructure on the long-term creep strength. The as-built samples exhibited significantly higher creep strength than the conventional steels. Creep strength was increased with the area fraction of  $\delta$ -ferrite. These results provide the microstructure control strategy of mod. 9Cr-1Mo steels through LPBF to maximize the creep strength.*

## **Key Words**

*Modified 9Cr-1Mo steel, Laser powder bed fusion, Microstructure, Creep*

# P031: Effect of Fabrication Conditions on Creep Properties of Modified 9Cr-1MoVNb Steel.

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## Summary

*This study examines whether differences in fabrication conditions between pipe (KA-STPA28) and plate (KA-SCMV28) products of modified 9Cr-1MoVNb steel can explain the discrepancy in Japan's 2019 creep life assessment equations. Although pipe materials appear to show longer creep life in long-term, low-stress regions, the underlying datasets differ, raising the question of whether fabrication conditions inherently enhance creep strength. To investigate this, seven laboratory-melted steels were produced by varying heating temperature, hot-working temperature, and post-working cooling rate, based on differences identified in industrial manufacturing processes. A standard condition simulated pipe-material processing, while other specimens varied one parameter at a time. After normalizing and tempering, all materials showed similar chemical composition, prior-austenite grain size, and mechanical properties, indicating that final heat treatment eliminated differences in precipitation behaviour. Creep tests at 650 °C were conducted under stresses of 100, 80, 50, and 40 MPa. Rupture occurred only at higher stresses, and rupture times showed no systematic dependence on fabrication conditions. At 50 and 40 MPa, tests exceeded 18000 h without rupture. Minimum creep rates were determined, but no trend was observed in which conditions resembling pipe manufacturing (higher temperatures, slower cooling) produced lower minimum creep rates. Using the extended Monkman–Grant law, rupture times for unbroken tests were estimated and found to align with plate-material behaviour, not pipe-material assessment curves. STEM/EDX observations revealed MX and  $M_{23}C_6$  precipitates before testing, with Cr-V-Nb precipitates appearing after long-term creep. All materials showed similar MX coarsening, and no fabrication-condition-dependent differences in particle-size distribution were detected. Overall, the study concludes that variations in heating temperature, hot-working temperature, and cooling rate do not significantly influence long-term creep properties. Thus, the superior long-term creep life suggested for pipe materials is not supported by fabrication-condition effects*

## Key Words

*Modified 9Cr-1MoVNb steel, Creep, Minimum creep rate, Microstructural evolution, Transmission electron microscopy, MX-type precipitate, particle distribution, Modified Monkman-Grant relationship.*

# P032 - Preliminary Development of the Structural Safety Assessment Criteria for In-Vessel Components for Fusion Device (Extended Abstract)

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## Summary

*A relatively suitable method to assess the structural safety is significant and necessary in the road to develop a reliable and robust in-vessel components for magnetic confinement fusion reactor. Up to now, many standards and design criteria from fission reactor, such as ASME and RCC-MR, and several other methodologies are not intended to cover fusion applications, but they have been used to form corresponding design criteria for fusion devices, including RCC-MRx and SDC-IC.*

*However, the in-vessel components, especially the plasma facing components, will suffer a unique load history in the fusion device. The characteristics includes: (1) heat loads from one-side, which will induce an uneven temperature distribution in the structural; (2) very high transient heat loads ( $\sim 1\text{-}10\text{ GW/m}^2$ ,  $\sim 0.2\text{-}0.5\text{ ms}$ ), which will induce a large temperature gradient ( $\sim 1000\text{ }^\circ\text{C/mm}$ ) in a thin layer of the plasma facing surface; (3) irregular cyclic loads from the plasma, (4) dominated by secondary stress induced by heat loads; (5) very high loads induced by the electromagnetic fields. These special characteristics brought a new challenge to assess the structural safety in the design for in-vessel components. In the structural design criteria for ITER in-vessel components, the high heat flux test is applied as the final acceptance criteria for the plasma facing components, which has the disadvantage of high cost and long cycle. It is not conducive to the development and promotion of fusion reactor in the future.*

*Therefore, it is essential to develop an applicable structural safety assessment criterion for in-vessel components of fusion reactor. This part of work will provide an evaluation of those characteristics and adapt appropriate assessment methods, and ultimately form applicable structural safety assessment criteria for in-vessel components of magnetic confinement fusion reactor via elastic analysis method.*

## Keywords:

*Fusion, Plasma facing components, Design code, Elastic analysis.*

# P034: Efficient Prediction Method of Creep Fracture Life Based on the QL\* Concept Using Various Specimen Shapes

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## Summary

*Mechanical performance evaluation by creep testing is essential for the heat-resistant materials used in the thermal power generation equipment such as steam turbines and boiler piping. However, since creep testing takes significant time and financial costs, the number of institutions capable of conducting creep testing is becoming limited. Therefore, it is required to develop the estimation method that can predict long-term creep life efficiently from a small-number of short-term creep testing. In order to achieve the above objective, creep life prediction method based on the QL\* concept has been proposed. On the basis of the QL\* concept, relationship between steady-state creep strain rate and creep rupture life can be represented by a linear correlation in log-log scale. This method was shown to be applicable not only to smooth specimen but also to notched specimen for steels.*

*In this study, creep tests have been conducted for simple material, pure Ni, to investigate the applicability of the creep life prediction method based on the QL\* concept. In addition, based on the new concept of converted stress proposed for steels, a quantitative estimation method of mechanical performance on creep strength was discussed with various specimen shapes. As a result, in creep testing using pure Ni, a linear relationship between the steady-state creep strain rate and creep life in log-log scale was obtained, and the same trend was obtained for steels. Therefore, the validity of the creep life prediction method based on the QL\* concept for pure Ni was verified. Furthermore, although QL\* line was found to shift due to the difference of creep ductility depending on the specimen shape, that is, the structural brittleness, the slope of the QL\* line remained parallel. Therefore, creep life for various specimen shapes was found to be able to predict based on the QL\* concept and the converted stress using the data of the standard specimen.*

## Key Words

*Creep life prediction, QL\* concept, Converted stress, Quantitative estimation of mechanical performance on creep*

# P035: Effects of Localized Lattice Contraction on Stress Relaxation Cracking (Extended Abstract)

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## Summary

*Localized lattice contraction arising from solid-state reactions, such as  $M_{23}C_6$  carbide precipitation or gamma prime precipitation, can generate significant hydrostatic tensile stresses in welds and cold-worked regions. When contraction is spatially non-uniform, these stresses may reach several hundred megapascals and contribute directly to stress relaxation cracking. This extended abstract presents a comprehensive literature review of phase transformation-induced contraction in metallic alloys. A physical contraction model is formulated and integrated into a finite element simulation to demonstrate that transformation-induced shrinkage is a credible, previously overlooked driving force for high-temperature brittle failure.*

## Key Words

*Lattice contraction, volumetric shrinkage,  $M_{23}C_6$  precipitation, hydrostatic stress, stress relaxation cracking (SRC), precipitation kinetics, austenitic stainless steels, nickel base alloys.*

# **P036: Fabrication and creep rupture strength of Alloy 617 welds**

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## **Summary**

*The allowable and mean stresses for the 100,000-hour creep-rupture strength of Alloy 617 welds were*

*determined from long-term tests conducted between 600 °C and 1000 °C, with individual test durations of up to 86,000 hours. These extensive test campaigns provide a robust database for assessing the long-term reliability of welded joints.*

*Optimization of matching filler metals introduced since the late 1990s has markedly increased weld creep strength, narrowing the gap to base-material performance. Depending on temperature and fabrication practice—particularly the application of post-weld heat treatment (PWHT)—failures occur either in the weld metal or in the base material. Modern welds exhibit a scatter of approximately  $\pm 20\%$  in stress ( $\pm 30\%$  at 1000 °C). Stabilization annealing at 980 °C for 3 h shifts creep rupture toward the upper scatter range and improves creep ductility, thereby extending the preferred operating window. Above 800 °C, the resulting weld strength reduction relative to the base material does not exceed about 10%.*

*Applying best practices can significantly reduce the risk of hot cracking, relaxation cracking, and other weld seam irregularities while improving the service life of Alloy 617 welded components. Key factors influencing weld quality include precise control of welding parameters, temperature management, layer build-up, and PWHT.*

## **Key Words**

*Alloy 617, Creep Rupture Strength, Welded Joints, Fabrication*

## **P037: Microstructural evolution in T24 homogeneous welds during long-term service exposure of the waterwall**

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### **Summary**

*This contribution deals with the results of a study on crack formation in single-pass T24 homogeneous fin to tube welds of the waterwall during long-term operational exposure of a coal fired boiler. PWHT of welds could not be performed. Hardness testing of TIG and SAW welds revealed that long-term service exposure at 494 °C and steam pressure of 295.1 bar resulted in very high hardness values in both the CG HAZ and the WM. Prolongation of the service exposure from 22,000 to 31,000 hours had only minor effect on hardness in these critical parts of welds. The hardness values in these parts of welds were higher than those in the as-welded state. This indicates that microstructural evolution in welds during operational exposure resulted in precipitation hardening. Cracks were observed mostly in TIG assembly welds and were initiated in the weld toe on the flue gas side. They propagated mainly in the HAZ. Attention has been paid to the study of precipitation processes during operational exposure. Changes of microstructure towards thermodynamic equilibrium took part very slowly. Very fine precipitates in the CG HAZ and the WM slowed down recovery processes in the metallic matrix. The experimental heat treatment simulation for field made repairs by welding was carried out in the temperature interval of 660-760 °C. The effect of heat treatment parameters on the hardness and microstructure evolution in critical parts of the fin to tube welds after operational exposure was studied. The experimental heat treatment simulation results have been verified on field weld repairs of the waterwall.*

### **Key Words**

*T24 homogeneous welds, fin to tube welds, hardness, microstructural evolution, minor phases, heat treatment.*

# **P038: Influence of Post Weld Heat Treatment Temperature and Holding Time on the Creep Properties of B91-Type Welds in ASME Grade 91 Steel**

## **(Extended Abstract)**

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### **Summary**

*This study investigates the influence of post-weld heat treatment (PWHT) conditions—namely temperature and holding time—on the creep properties of ASME Grade 91 steel welds using B91-type welding consumables, which feature restricted Mn+Ni content. B91-type consumables are known to provide weld metals with higher creep strength than conventional high Mn+Ni consumables; however, they exhibit lower toughness. To secure adequate toughness in practice, PWHT temperatures higher than those typically applied to high Mn+Ni content welds are often required, with current industrial practice adopting maximum temperatures around 760 °C. Nevertheless, the effect of elevated PWHT temperature on creep strength— particularly for welded joints where damage frequently localizes in the heat-affected zone (HAZ)—has not been sufficiently clarified by experimental studies. To address this issue, a systematic investigation was carried out, focusing on both weld metals and welded joints fabricated with B91-type consumables. Creep rupture tests were first performed on B91-type weld metals subjected to PWHT at 745–775 °C with a holding time of 4 h. The results revealed no significant reduction in creep life with increasing PWHT temperature within this range. The weld metals maintained creep lives equivalent to or longer than the mean property line of the Grade 91 weld joint life assessment equation, which is widely applied in the Japanese thermal power industry for life assessment of high-temperature components. To further clarify the effects of PWHT conditions, additional creep tests were conducted on Grade 91 welded joints fabricated with B91-type consumables and subjected to PWHT at 745–775 °C for holding times ranging from 4 to 100 h. Even under extended PWHT conditions, the creep rupture lives of the welded joints were at least equivalent to the mean life curve of the Grade 91 weld joint assessment equation, including the shortest-time data obtained in this study. These results demonstrate that, within the studied PWHT range, neither temperature nor holding time critically degrades the creep strength of B91-type weld metals or welded joints. Considering the practical margin required for actual field operations, the findings suggest that adopting a PWHT target temperature of 760 °C for B91-type welds does not pose a concern for creep life performance.*

### **Key Words**

*B91-type welding consumables, Grade 91 steel, post weld heat treatment (PWHT), creep rupture, weld metal, welded joints, long-term creep strength, life assessment*

# **P039: Influence of Welding Process, Deposit Geometry, and Specimen Orientation on the Creep Properties of ASME Grade 91 Weld Metals (Extended Abstract)**

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## **Summary**

*This study investigates the factors affecting the creep properties of weld metals produced with 9Cb-type consumables widely used for ASME Grade 91 steel joints. Traditionally, creep damage in Grade 91 welded joints has been recognized to occur mainly in the heat-affected zone (HAZ). However, long-term creep rupture in weld metals has also been reported, and examinations of service-exposed components revealed significant softening of weld metals, indicating that rupture may occur in the weld metal rather than the HAZ. Therefore, it is essential to consider both HAZ and weld metal degradation in life assessment. To clarify the key factors governing the creep performance of weld metals, systematic experiments were conducted. The parameters studied included deposit thickness (thin  $\approx$  2.5 mm vs. thick  $\approx$  5 mm), number of passes per layer (1 vs. 2), specimen extraction direction relative to the weld line (parallel vs. perpendicular), and welding processes, namely gas tungsten arc welding (TIG), submerged arc welding (SAW), and shielded metal arc welding (SMAW). Weld metals were subjected to post-weld heat treatment at 745°C for 4 h. Creep rupture and deformation tests were performed at 600–700°C under stresses ranging from 40 to 100 MPa. The results showed that creep life strongly depends on the welding process and geometry. Thin one-layer one-pass TIG weld metal exhibited creep lives significantly longer than the standard weld joint assessment curve, but at long-term conditions, TIG weld metals tended to show pronounced strength reduction. In contrast, SAW weld metals demonstrated longer creep lives at lower stresses. The results also revealed that the relative ranking of welding processes depends on the applied stress and temperature, with TIG being most durable in the short-term region but likely to become the weakest in the long-term region. The temperature dependence of creep life varied with welding process and geometry. For instance, some weld metals showed a characteristic “knee” behavior around 650°C at 50–60 MPa. Creep rupture ductility generally decreased with increasing rupture time up to  $\sim$ 10,000 h, followed by partial recovery in certain cases. Furthermore, the relationship between minimum creep strain rate and rupture time followed a power-law form, similar to base metal behavior, and was independent of welding process. In conclusion, the creep properties of Grade 91 weld metals are influenced by deposit thickness, pass number, specimen orientation, and welding process. Reliable long-term creep data are indispensable, since short-term data alone cannot adequately represent actual service conditions.*

## **Key Words**

*Grade 91 steel, weld metal, creep rupture, welding process, deposit geometry, long-term creep behavior.*

# P040: Study on creep rupture property and mechanism of TP347H stainless steel pipes at high temperature

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## Summary

*In response to temperature fluctuations during the actual service of TP347H stainless steel pipes, creep rupture tests were conducted at temperatures of 480°C, 585°C and 700°C under various stress conditions. The creep rupture specimens were examined by SEM and TEM. The effects of different temperatures, stresses and creep rupture test duration on the microstructure as well as the macro and microfracture surfaces of TP347H stainless steel pipes were analyzed. At 585°C and 700°C, traces of Cr-rich phases were observed, which are distributed along grain boundaries around Nb-rich phases.  $M_{23}C_6$  precipitate was not detected at 480°C. However, numerous  $M_{23}C_6$  precipitates were found at the grain boundaries of samples tested at 585°C under low stress and long life conditions (230 MPa, 8535 h). At 700°C, under high stress and short life conditions (150 MPa 335 h), coarse  $M_{23}C_6$  and MX precipitates precipitated at the grain boundaries. Observations of the macro and micro morphology of the fracture surfaces of creep rupture specimens revealed that, under high stress, the specimens exhibited trans-granular creep fracture, with dimple-dominated fracture surfaces and significant necking, which was strongly influenced by the quantity and distribution of inclusions. As the stress decreased, the fracture mechanism transitioned from transgranular creep fracture to intergranular fracture and the fracture surface changed from dimple to rock candy character.*

## Key words

*TP347H stainless steel pipe, creep rupture strength, fracture morphology, microstructure, MX precipitate,  $M_{23}C_6$*

# P042: Effect of Residual Vanadium on the Thermal Stability of Modified Z-phase in Advanced Austenitic Steels

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## Summary

*The long-term creep resistance of advanced austenitic heat-resistant steels strongly depends on the thermal stability of their secondary phases. Among these, the modified Z-phase (Cr(Nb,V)N) plays a key role as a strengthening nitride in alloys designed for high-temperature applications. However, its stability during extended service remains insufficiently understood, particularly in relation to the presence of residual elements such as vanadium.*

*This study investigates the microstructural evolution of selected advanced steels after long-term annealing at elevated temperatures, with a specific focus on the transformation behaviour of the modified Z-phase. A combined experimental and computational methodology was applied. Specimens were systematically analysed using advanced electron microscopy and diffraction techniques to characterize the morphology, distribution, and thermal stability of nitride precipitates. Complementary thermodynamic modelling was employed to predict precipitation behaviour and solvus temperatures of strengthening phases, providing deeper insight into their long-term evolution. The results indicate that even minor variations in residual vanadium content can influence the precipitation stability of the modified Z-phase, which in turn affects the creep performance of the studied alloys. These findings highlight the complex relationship between microalloying elements and phase stability, demonstrating that seemingly negligible compositional differences may lead to significant changes in stability of minor phases.*

*Overall, this work enhances the current understanding of phase evolution in advanced austenitic steels and underlines the importance of considering residual elements during alloy design and service-life prediction. The insights obtained contribute to optimizing the balance between composition, microstructure, and performance, supporting the development of next-generation heat-resistant steels with improved creep resistance and structural stability.*

## Key Words

*Z-phase; modified Z-phase; austenitic heat-resistant steels; residual vanadium; microstructural stability; high-temperature annealing; precipitation behaviour*

# P043: Predictive Modelling of Creep-Fatigue Phenomena in polycrystalline Nickel-base Superalloys with Kitagawa-Takahashi and a Creep Pore Model

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## Summary

*In the transforming energy market gas turbines are faced with challenges due to the rising demand for efficiency and operational flexibility. As a result, turbine blades designed for extended service life, are subjected to a combination of increasing constant and cyclic stresses as well as elevated homologous temperatures. Conventionally cast (CC) nickel-base superalloy are widely used blade materials and are prone to creep cavitation, which promotes fatigue cracking and leads to failure.*

*This work introduces a physics-based framework to characterize creep-fatigue interactions on grain boundaries of polycrystalline nickel-base superalloys. To address creep damage, a diffusive creep pore model was developed, incorporating the mechanisms of pore nucleation, growth, and coalescence of multiple pores on grain boundaries. The creep pore model was calibrated with analysis of sectioned pre-creep damaged fatigue specimens with scanning electron microscopy (SEM), electron backscatter diffraction (EBSD), and computed tomography (CT) imaging. On the other hand, the influence of high-cycle fatigue (HCF) on fatigue crack initiation is described by the Kitagawa-Takahashi approach. Through the proposed Kitagawa-Takahashi with creep (KTC) method, modified Wöhler and Haigh diagrams for creep-fatigue interactions across various temperatures from 750°C to 900°C are presented. In comparison with experimental data of Alloy 247 LC CC the model predictions show good agreement.*

## Key Words

*Creep-Fatigue, Creep Cavitation, Fatigue Crack, nickel-base superalloy.*

# P044: Assessment of the earthquake impact on the creep rupture life of Grade 91 steels

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## Summary

*On March 11, 2011, when the Great East Japan Earthquake occurred, strong shaking from the earthquake was observed at the NIMS testing facility. At the time, 238 creep test specimens were in progress in the creep testing laboratories. With the exception of one specimen that ruptured approximately 22 hours after the Great Earthquake, creep tests were suspended either immediately after the earthquake (suspended due to a power outage) or three days later, on March 14, 2011, but most of the specimens were subsequently resumed. The effects of seismic motion on creep rupture time were examined using creep test data for Grade 91 steel, for which 72 creep tests were being conducted at the time of the Earthquake, the largest number for a single steel type. The creep testing time when the tests were suspended due to the earthquake ranged from 1,464 hours to 100,422 hours. After the tests resumed, 57 of the 72 specimens had creep ruptured (as of the end of March 2025). The longest creep rupture life of the 57 ruptured specimens was 121,972 hours, and the shortest was 12,690 hours. The longest creep test time from the Earthquake to rupture was 83,387 hours. The life consumption ratio at the time of the Earthquake ranged from 0.223 to 0.987. The creep rupture lives were compared with predicted values interpolated from the creep rupture lives of specimens with the same heat and test temperature but not affected by the Earthquake. As a result of that no effect of the Earthquake on the creep rupture life was observed. The creep rupture lives of a total of 452 specimens, including the 57 specimens that were in testing at the time of the Earthquake, were analysed using the Larson-Miller parameter, and the measured rupture times were compared with the predicted values. As a result, the creep test data for the specimens in testing at the time of the Earthquake were all within the range of variation of the data plots, confirming that the seismic motion caused by the Great East Japan Earthquake did not affect the creep rupture time.*

## Key Words

*Long-term creep test, creep rupture life, earthquake, Grade 91*

## **P045: Influence of microstructure and secondary phases on creep damage tolerance of Grade 91 Type 2 material**

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### **Summary**

*Over thirty years after the introduction of Grade 91 material to the market, the specification for Type 2 material was formulated to address the poor tolerance to cavitation and creep damage observed in some serviced components. This specification mostly enforces restrictions on the content of impurities, aiming to limit the availability of elements known to segregate at grain and secondary phase boundaries. Further research was performed in recent years to better evaluate the effects of heat treatment, microstructure and manufacturing parameters. One such exercise, specifically, presented results from extensive creep testing on Grade T91 material manufactured at the same mill from two different melts sourced from different suppliers. Despite both products being fully compliant with the Type 2 specification, significant differences were observed in the failure mode, with either heat exhibiting a consistently creep-ductile or creep-brittle behaviour. Advanced scanning electron microscopy was performed to identify the fine microstructural features including secondary precipitate phases such as carbides and nitrides, non-metallic inclusions, and laves phase and assess each phase's association with creep damage. This work presents a summary of most relevant observations and considerations.*

### **Key Words**

*Grade 91, Creep, Damage, Tolerance, Ductile, Brittle, phases, inclusions.*

# **P047: Creep damage and fracture in metal and metamaterial structures subjected to cyclic loading and heating**

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## **Summary**

*The approach to numerical modelling of creep–damage processes in structural elements using the Finite Element Method is presented. Various phenomena, such as non-uniform temperature fields, cyclic loading, irradiation creep, irradiation swelling, and hydrogen embrittlement, are considered using both classical and newly developed constitutive and evolution equations. The growth of macroscopic defects arising after the completion of hidden damage accumulation is simulated using proposed Finite Element Method algorithms based on a reformulated boundary-initial value creep–damage problem, with the exclusion of finite elements in which the damage parameter has reached its critical value. Cyclic creep–damage processes are modelled using a proposed method for obtaining averaged boundary-initial value problems based on the method of asymptotic expansions. The developed method and software for analysing creep, damage, and fracture of structural elements are demonstrated through examples of numerical modelling of a notched plate and an inner cell of a three-layered metamaterial plate. The influence of various phenomena on creep, damage, and macroscopic defect growth is demonstrated, and the contribution of each factor is discussed.*

## **Key Words**

*Creep, damage, fracture, boundary-initial value problem, cyclic loading, irradiation, metal, metamaterial.*

## **P048: Analysis of precipitation processes in the microstructure of Thor®115 martensitic steel after aging at 650°C.**

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### **Summary**

*THOR®115 (Tenaris High Oxidation Resistance Steel) is a new martensitic steel with increased creep resistance, developed by the Italian company Tenaris. The increased chromium content (11%) provides better oxidation resistance at high temperatures and ensures a fully martensitic microstructure and the stability of strengthening precipitates. However, to prevent the formation of undesirable secondary phases that appear after long-term aging, such as the Laves phase and the Z phase, the Mo and Nb content has been reduced. This steel has been developed as an improvement on the popular T/P91 grade. This article presents the results of metallographic studies and an analysis of the precipitation process in THOR®115 steel in the as-received condition and after long-term aging at 650°C for 3,000 and 10,000 hours. An aging led to intensified precipitation. The effects of aging time on microstructural changes and the precipitation process in the tested steel were described. The tests included detailed microstructure analysis using scanning electron microscopy (SEM) and transmission electron microscopy (TEM). Examination of the material in the as-received condition revealed a martensitic structure typical of this steel. In the microstructure of the tested steel in the as-received condition, primary MX phases and primary M<sub>23</sub>C<sub>6</sub> carbide precipitates were identified.*

### **Key Words**

*THOR®115 steel, martensitic steel, precipitation process, microstructure, aging*

# P049: Rupture Strength Prediction of Austenitic Stainless Steels – Extended Abstract

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## Summary

*The creep resistance of austenitic stainless steels depends strongly on the dispersions of precipitates formed during tempering or ageing. Conventional life prediction methods (e.g. Larson-Miller or Manson-Haferd) often fail to account for microstructural evolution, leading to unreliable long-term rupture strength extrapolations from short-term tests. To address this, we previously developed a microstructure-based model for predicting rupture strength in martensitic/ferritic steels and Ni-based superalloys. This study extends this methodology to austenitic stainless steels. The material model firstly describes the simultaneous precipitation kinetics (including nucleation, growth and coarsening) during tempering based on an extended CALPHAD framework. The resulting microstructural output - precipitate type, size and amount - is then coupled with precipitation hardening theories, enabling the calculation of yield strength and hardness evolution. The secondary creep rate is formulated to incorporate a back stress term linked to precipitate hardening contributions. As the microstructure evolves with time at a given temperature, so does the secondary creep rate. This time-dependent creep rate is used to compute an instantaneous rupture life at each time step. Creep rupture is predicted via a damage accumulation integral, where failure is reached at the point when the sum of the ratios of time-increment to instantaneous rupture life equals unity. The model has been extensively validated against experimental creep rupture data for a wide range of austenitic stainless steels across temperatures from 600°C to 800°C, showing excellent agreement with experimental data. This microstructure-based approach quantifies the effect of the initial material state (e.g., compositional variation, solution annealing temperature) on long-term rupture strength, rationalising the observed scatter in experimental data from different sources. It can serve as a powerful tool for designing new creep-resistant alloys as well as assessing the remnant life of operating power plant components.*

## Key Words

*Rupture strength, austenitic stainless steels, precipitation, creep, materials modelling.*

# **P050: Boron effect on creep properties of austenitic stainless steel 316L(N)**

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## **Summary**

*In the scope of GENIV International Forum, the Sodium Fast Reactor (SFR) is one of the concepts selected by France, building on its experience with previous SFRs such as Rapsodie, Phenix and Superphenix.*

*The assessment of structural materials behavior up to 60 years is a subject of interest in the scope of collaborative work between CEA, Framatome and EDF R&D. It mainly concerns studies on 316L(N) stainless steel as referenced in RCC-MRx code which is used at elevated temperature (up to 550 °C) for many components in primary circuit and in heat exchanger.*

*The austenitic stainless steels 316L(N) may contain small additions of boron to enhance creep resistance and forgeability. However, boron negatively affects hot cracking during welding, particularly when present as boride precipitates, which necessitates keeping its concentration as low concentration. In 316L(N) stainless steel, boron is typically limited to 20 ppm, with some products containing as little as 3–8 ppm. Studies show no significant impact of boron content on tensile and impact properties. Creep tests conducted at EDF R&D on three plates with only varying boron levels (7, 20, and 37 ppm) confirm improved creep resistance with higher boron content.*

## **Key Words**

*Stainless steel, boron, creep*

# P051: Creep Behaviour of novel High-Entropy Alloys using Small Punch Creep testing

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## Summary

*The creep and tensile behaviour of HEA-1 (CrFeMnNi) alloy using Small Punch Tensile (SPT) and Small Punch Creep (SPC) tests at 550°C and 700°C is studied. This alloy is being investigated within the HORIZON EUROPE INNUMAT research project to support nuclear-application material development and put it on track towards qualification for fission lead-cooled and molten salt fast reactors as well as the fusion demonstrator DEMO. Small Punch testing is used here due to only a small amount of available material. Initial results show the expected decrease in Small Punch Tensile maximum force with temperature, though anomalously high initial stiffness at 550°C-likely due to oxidation and friction at the pin/test piece assembly interface-indicates some test issues. SPC testing at 550°C demonstrated that rupture times are highly sensitive to applied load and exhibit substantial scatter. Fractography indicates predominantly brittle failure modes in the ruptured test pieces, with microstructural differences correlating to large lifetime variation among nominally identical tests. At 700°C the scatter in rupture times decreased substantially, possibly indicating a different failure mechanism.*

## Key Words

*High Entropy Alloys, Creep, Small Punch Test, Structural Materials.*

## P052: Creep Behaviour of 316L(N) weld materials

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### Summary

*The study investigates the creep behaviour of welds and base metal for the development of an innovative Advanced Sodium Technological Reactor for Industrial Demonstration (ASTRID) by EDF, CEA and FRAMATOME, although the ASTRID project has since been cancelled. Nevertheless, the selection of material was done in 2015 as 19-12-2 for SMAW (Shielded Metal Arc Welding) used for Superphénix (SPX), followed by its optimisation for TIG (Tungsten Inert Gaz) welding, called 18-12-2 TIG, both variants of 316L(N). In the reactor concept, creep of 316L(N) is an issue in the upper core structures at the operating temperature of 550°C. Components like the reactor pressure vessel and core support structures work at lower temperatures around 400°C where the negligible creep limits may need closer investigation. Long term creep data are still needed to justify 60 years lifetime of structure components, especially concerning welded assemblies. Weld creep testing roadmap was proposed for ECCC WG3B in 2018 for a narrow gap TIG weld of 316L(N) plate. Long term creep tests results from base metal, weld metal and cross-welds at temperature ranges from 550 to 675°C and initial stress ranges from 120 to 350MPa are reported in this work. Times to 0.2, 1, 2, 5 and 10% creep strains have been measured as well as times to rupture. In two cases, uniaxial creep tests of a weld metal at 575°C and 190MPa, and a cross weld at 550°C and 230MPa are still running without rupture of the test pieces after more than 50 000 hours (five years+).*

### Key Words

*Stainless steel, welds, base metal, long term creep.*

# P053: Validation of a micromechanical model for UO<sub>2</sub> creep behaviour

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## Summary

*Modelling of viscoplastic behaviour of UO<sub>2</sub> nuclear fuel at high temperature is of major interest to have a deeper understanding of the cladding loading in power transient condition where pellet to cladding mechanical interaction occurs. In this work, a micromechanical model, based on a crystal plasticity formulation including climbing mechanism, is used to study the fuel viscoplastic behaviour at the polycrystalline scale. The objective is to validate the simulation results in comparison with the experimental stress-strain curves depending on the temperature, the strain rate and the stoichiometry deviation.*

*Experimental creep compression tests are simulated through a single representative volume element of the polycrystalline microstructure. The nonlinear mechanical problem is solved with the AMITEX code, using the FFT method with periodic boundary conditions and a finite strain formulation implementation of the single crystal law through the MFront tool.*

*The validation of temperature and strain rate sensitivity is achieved with the analysis of the apparent thermal activation energy. Thanks to the FFT simulation, the respective contributions of the dislocation gliding and climbing can be analysed as a function of the temperature and of the type of gliding systems activated in the grains. The results show that in the case of UO<sub>2</sub> the transition between low and high temperature regimes is controlled simultaneously by thermally activated plasticity and dislocation density recovery induced by vacancy diffusion. The physics-based formulation of the model enables also a complementary validation analysing the effect of the stoichiometry deviation. The latter is introduced in the simulation through the variation of the self-diffusion coefficient. A comparison with experimental strain-stress curve of reference shows that the significant flow stress decrease of hyper stoichiometric UO<sub>2</sub> is well predicted by the model.*

## Key Words

*UO<sub>2</sub> micromechanical modelling, crystal plasticity, dislocation climbing, creep compression test validation, polycrystalline microstructure.*

# **P054: Effect of abnormal prior austenite grain on creep behavior of Grade 91 steel**

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## **Summary**

*The effect of the presence of coarse prior austenite grains (PAG) on creep properties was investigated in Grade P91 steels. The MGS heat consisted of normal and coarse PAGs, while normal PAGs were homogeneously distributed in the MGQ heat. The creep strength of the MGS heat was similar to that of the MGQ heat at 550°C to 650°C. On the other hand, at 600°C to 650°C, the creep ductility of the MGS heat was smaller than that of the MGQ heat in the long term. For the MGS heat, a large number of creep voids were observed in the normal PAG area in between coarse PAGs. The concentration of creep voids in the normal PAG area can reduce the creep ductility in the MGS heat. Precipitation strengthening in the normal PAG area was smaller than that in the coarse PAG area because the number density of precipitates was lower in the normal PAG area than in the coarse PAG area. The decrease in precipitation strengthening can promote the formation of creep voids in the normal PAG area for the MGS heat.*

## **Key Words**

*Grade 91 steel, abnormal prior austenite grain, creep ductility, heterogeneous deformation*

# **P055: Cyclic Properties of Normalised and Tempered 9Cr1Mo Steel**

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## **Summary**

*The steel Normalised and Tempered 9Cr1Mo (Grade 9) has been used as tubes and supports in the secondary economiser and primary superheater portions of the boilers used in electricity generation. This paper reviews all the materials properties that are required for an R5 creep-fatigue crack initiation assessment (R5 Volume 2/3) of N&T 9Cr1Mo. Including the cyclic stress strain properties at room temperature, 360°C and 525°C; the fatigue endurance, the creep deformation (as used to predict stress relaxation), creep rupture and creep ductility (which are used to calculate creep damage). A model for cyclic stress strain was developed that includes the effect of creep dwell on cyclic softening. Different methods for calculating creep damage were considered, including time fraction and the stress modified ductility exhaustion method. Validation of the R5 Volume 2/3 assessment method for use with N&T 9Cr1Mo is then provided by applying the complete model set to predict the creep-fatigue endurance at 525°C of N&T 9Cr1Mo with tensile creep dwells of up to 5 hours. It was found that the stress modified ductility exhaustion method gave the most accurate predictions of creep damage and therefore the most accurate predictions of creep-fatigue endurance. In addition, methods for predicting the effect of compressive creep dwells on fatigue endurance were applied to cyclic tests at 525°C with compressive dwells of up to 2 hours.*

## **Key Words**

*Grade 9, Cyclic Stress Strain, Creep-Fatigue, Cyclic Relaxation, Ductility Exhaustion.*

# P056: A Creep Ductility Model for Grades 9, 91 and 92

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## Summary

*ECCC datasets have previously been collated and analysed to produce creep rupture data assessments. These creep rupture data assessments provide a model for time to rupture as a function of stress and temperature, which are used to calculate rupture strength tables for the calculation of allowable stresses for use in design codes that address primary stresses. Time to rupture models are also frequently used in conjunction with the time fraction (otherwise known as life fraction or Robinson's rule) to calculate remnant life, for life assessments and to calculate creep damage during a creep-fatigue cycle. However, comparisons with laboratory test data with stress changes, with post exposure creep test data and with creep-fatigue test data have consistently shown that time fraction is a poor predictor of creep fracture under conditions of changing stress. The alternative to time fraction is to use ductility exhaustion. Unfortunately, models for creep ductility are not freely available in the literature. Hence, this paper has developed a model for the creep ductility of 9Cr steels including Grades 9, 91 and 92 using those ECCC datasets. This model for creep ductility can be used to calculate creep damage using ductility exhaustion methods. However, this paper does not provide details of the creep deformation or stress relaxation models that must be used in conjunction with ductility exhaustion methods. The surprising outcome of this study is that a single model for creep ductility, which is a function of stress, strain rate and temperature, accurately predicts creep ductility in all three grades of 9Cr1Mo steel, Gr.9, Gr.91 and Gr.92 even though the creep strength of three grades varies considerably. Indeed, the combined effects of temperature, strain rate, and stress indicate that, for any given stress and temperature, a material with higher strength will inevitably exhibit lower creep ductility.*

## Key Words

*Grade 9, Grade 91, Grade 92, Creep-Ductility.*

# **P057: Implications of creep damage and creep crack growth on serviceability assessments of creep strength enhanced ferritic steels**

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## **Summary**

*Creep strength enhanced ferritic (CSEF) steels such as Grades 91 and 92 are commonly used in power plant components that operate at elevated temperature. Metallurgical risk factors can impart significant creep cavitation susceptibility which can be evident at typical service conditions. In laboratory tests, this creep damage susceptibility may manifest as low creep ductility or notch sensitivity. Creep crack growth is often assumed to be a particular concern for creep cavitation susceptible materials since classical models suggest enhanced crack growth rates for low creep ductility. However, reviews of testing and field experience show that at typical service stress levels, creep cavitation blunts crack-like features and consequently creep damage in the ligament ahead of the crack controls rupture. These characteristics pose challenges for integrity assessment of components which are explored, including practicality of nondestructive examination and shortcomings of remaining life estimates based on creep crack growth. Practical approaches for life assessment of components fabricated from such creep damage susceptible steels are explained through analyses of circumferentially notched bars, compact tension specimens and ex-service components. The stationary state, creep redistributed, maximum principal stress is shown to provide excellent correlation of creep damage distribution and creep rupture time. For components with stress singularities (cracks) the skeletal stress, or analysis of the uncracked ligament, can provide an acceptable basis for lifetime prediction. In all cases, the short time between initiation of a crack detectable by advanced nondestructive examination methods and a through-wall leak poses a significant challenge to inspection programs and highlights the need for integrated life management plans based on metallurgical risk and stationary state, creep redistributed, stresses*

## **Key Words**

*CSEF, creep, multiaxiality, crack growth, stress analysis, life prediction*

# P058: Breakthroughs and Challenges in Applying AFA Steels to Energy Equipment for Net Zero Realization

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## Summary

*The global transition toward carbon neutrality has intensified the need for non-fossil energy carriers, such as hydrogen and ammonia, which are expected to enable deep decarbonization across industrial and power-generation sectors. Components operating in hydrogen and ammonia environments must satisfy demanding requirements related to mechanical strength, environmental resistance, and long-term structural reliability. Among the various degradation mechanisms, hydrogen embrittlement (HE)—which typically manifests in low- to intermediate-temperature regimes—remains a critical concern for many Fe based alloys used in hydrogen systems. These considerations have highlighted the importance of materials capable of maintaining mechanical integrity while resisting complex degradation modes. In this context, alumina-forming austenitic (AFA) steels have attracted attention due to their ability to form stable Al<sub>2</sub>O<sub>3</sub> protective scales while preserving austenitic mechanical properties.*

*In the present study, a 15Cr-25Ni-4Al-2Mo-CuNb AFA steel was investigated as a candidate for use in hydrogen - and ammonia - related energy systems. To assess its resistance to HE-sensitive strength degradation, tensile tests were conducted after aging treatment. The alloy exhibited a yield strength of approximately 1 GPa at room temperature and retained mechanical strength comparable to Ni-based alloys up to 500 °C. High-temperature creep tests performed at 700–800 °C further demonstrated that the alloy possesses creep strength equivalent to that of SUPER304H, a representative advanced heat-resistant austenitic steel. These mechanical properties are attributed to precipitation strengthening from intermetallic phases such as B2 and L12 compounds formed during aging.*

*The alloy's environmental resistance was evaluated using high-temperature oxidation and nitridation tests. In steam oxidation at 800 °C, the AFA steel exhibited a mass gain less than one-tenth that of type 310 stainless steel and less than half that of a Ni-based alloy, confirming the effectiveness of the alumina scale in suppressing oxidation. Nitridation behavior was examined at 500 °C to reflect ammonia-rich environments. The mass gain of the AFA steel was approximately one-third that of stainless steel. Furthermore, when a pre-formed Al<sub>2</sub>O<sub>3</sub> layer was introduced by controlled pre-oxidation, nitridation was significantly suppressed. The mass gain decreased markedly with increasing Al<sub>2</sub>O<sub>3</sub> scale thickness and approached nearly zero when the layer exceeded approximately 2 μm.*

*Overall, the combination of HE-tolerant mechanical performance in the low - to intermediate - temperature regime, high-temperature creep strength, superior oxidation resistance, and excellent nitridation tolerance positions the investigated AFA steel as a promising candidate for components in future hydrogen - and ammonia - based energy infrastructures. Its ability to form a robust Al<sub>2</sub>O<sub>3</sub> protective scale provides advantages over conventional stainless steels and even certain Ni-based alloys, enabling long-term durability in demanding clean-energy environments.*

## Key Words

*Alumina-Forming Austenitic (AFA) steel, High-temperature creep strength, Nitridation corrosion, Al<sub>2</sub>O<sub>3</sub> protective scale, Steam oxidation resistance*

# **P059: A physics-based mean-field model for dislocation creep: Application to different martensitic 9-10 % Cr steels**

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## **Summary**

*Creep deformation continues to be a decisive factor limiting the long-term performance and influencing the design of components in high-temperature applications. Martensitic 9-10% Cr steels, such as Grade 91 (9Cr-1Mo), Grade 92 (9Cr-2W-Mo), and X12 (10Cr-1Mo-1W) rotor steel, developed in European COST 501 project), represent key materials due to their balanced combination of creep resistance, weldability, and cost-effective manufacturability. At JKU Linz, a physics-based mean-field creep model has been developed to provide a predictive and broadly applicable framework for describing dislocation creep in these martensitic steels. The model was initially calibrated and validated for P91 at 650°C and 70 MPa specifically, and was later extended to P92 and X12 rotor steel, while also being adapted to cover a much wider range of stresses and temperatures relevant for service conditions.*

*The model links microstructural evolution - for example subgrain coarsening and recovery mechanisms - to macroscopic creep behaviour. As a result, the model not only reproduces experimental creep curves with high accuracy, but also simulates the underlying microstructural changes observed during creep exposure. This capability allows for a comprehensive assessment of both mechanical and microstructural performance over service-relevant timescales.*

*A particular strength of the framework lies in its predictive capacity. By being grounded in physical mechanisms, the model enables extrapolation to very long times. It provides access to characteristic creep properties such as time-to-rupture (TTR) and times to specific creep strains (TTx%), across a wide stress and temperature range. This makes the framework particularly valuable for lifetime assessment and component design under service-relevant conditions.*

*Overall, the presented work highlights the robustness, transferability, and predictive capabilities of the physics-based mean-field approach. It demonstrates how the model can be applied to different martensitic 9-10% Cr steels and extended stress-temperature regimes, advancing the understanding of creep mechanisms and supporting lifetime assessment, alloy optimization, and material design for high-temperature applications.*

## **Key Words**

*creep, martensitic 9-10% Cr-steel, P91, modelling, dislocation creep, dislocation climb, rupture time, microstructure*

# P060: Data-Driven Alloy Design for Petrochemical Applications Using Gaussian Process Models

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## Summary

*The development of high-performance alloys for the petrochemical industry necessitates a careful balance between mechanical reliability, high-temperature stability, oxidation resistance, and cost-effectiveness. Conventional trial-and-error alloy design methodologies are time-consuming and resource-intensive. To overcome these limitations, we present a computational framework that combines machine learning and thermodynamic modelling to accelerate alloy design, with a particular emphasis on creep life prediction.*

*The methodology is based on a Gaussian Process (GP)-based algorithm trained on a proprietary creep life database of high-temperature alloys. The model delivers accurate, uncertainty-aware predictions of creep performance under petrochemical operating conditions. To broaden its utility, the GP model is embedded into a bimodal optimization pipeline that incorporates creep lifetime predictions and cost estimations.*

*This integration of statistical learning with domain-specific criteria enables rapid screening of candidate compositions while ensuring compliance with application-specific constraints. The approach not only predicts long-term material performance but also supports informed decision-making in alloy design, making it highly suitable for the stringent requirements of petrochemical components.*

*To validate the predictive capability of the framework, creep tests are being conducted on the selected alloy candidate under representative service conditions. The experimental outcomes will be directly compared with model predictions, providing a benchmark for accuracy and guiding further refinement of the algorithm. This combination of computational and experimental insights underscores the framework's potential as a practical tool for the accelerated discovery and deployment of next-generation petrochemical alloys.*

## Key Words

*Machine Learning, Multi Objective Optimization, Creep, Gaussian Processes.*

# P061: Effect of $\sigma$ phase on creep rupture strength of 18Cr–9Ni–3Cu–Nb–N Steel (Extended Abstract)

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## Summary

*In order to clarify the effect of chemical composition on the creep rupture strength of 18Cr–9Ni–3Cu–Nb–N steel, creep rupture tests were conducted using three different heats, and the microstructure was investigated. Comparison of the microstructures of the creep-ruptured specimens with different creep strength revealed that the lower strength heats exhibited a greater amount of  $\sigma$  phase precipitation at the same time, and the precipitation of the  $\sigma$  phase started at shorter time. Additionally, since creep voids were mainly observed at the matrix/ $\sigma$  phase interface, it was found that creep degradation is related to  $\sigma$  phase precipitation. To clarify the differences in the equilibrium volume fraction of  $\sigma$  phase, aging tests were performed using specimens subjected to cold working. Evaluation of  $\sigma$  phase volume fraction in cold worked specimens after aging showed that the lower strength heats exhibited larger equilibrium volume fractions. Therefore, it was clarified that in lower strength heats,  $\sigma$  phase precipitation starts earlier and the equilibrium volume fraction is larger. It is considered that this  $\sigma$  phase precipitation is the main factor controlling the creep rupture strength. Furthermore, to clarify the effect of chemical composition on  $\sigma$  phase precipitation, the compositions were evaluated using the d-electron theory. As a result, it was found that the larger the Md value, the larger the equilibrium volume fraction of  $\sigma$  phase. Based on the above, a relationship between Md value (chemical composition) and creep rupture strength was identified, and it was concluded that the differences in strength are due to differences in the onset of  $\sigma$  phase precipitation and the equilibrium volume fraction, both of which are caused by the phase stability of the austenite phase.*

## Key Words

*18Cr–9Ni–3Cu–Nb–N Steel, creep rupture strength, heat-to-heat variation,  $\sigma$  phase, phase stability, d-electron theory, Md value, equilibrium volume fraction.*

# P063: Extended Abstract: Micromechanical behavior of microcell UO<sub>2</sub> pellets

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## Summary

*This work examines the effect of chromium (Cr) grain-boundary engineering on the high-temperature mechanical response of microcell (CERMET-type) UO<sub>2</sub> fuel at 1000 K and 1600 K using a dislocation density-based crystal plasticity model. Polycrystalline UO<sub>2</sub> was modelled with physically motivated hardening laws, while thin Cr layers at grain boundaries were represented with an isotropic elastic-plastic formulation reflecting thermal softening and limited strain hardening. Comparative simulations of pure UO<sub>2</sub> and Cr-modified microstructures under compressive loading (10<sup>-4</sup> s<sup>-1</sup>, up to 5% strain) show that the CERMET configuration has lower yield stress and reduced post-yield hardening. In addition, the presence of Cr redistributes stresses at the grain scale and lowers peak von Mises stresses within UO<sub>2</sub> grains. These results indicate that chromium grain-boundary networks softens the material at the onset of plasticity and potentially improves damage tolerance through stress relaxation mechanisms at elevated temperature.*

## Key Words

*Uranium dioxide, Crystal plasticity, Microcell fuel, Accident tolerant fuel, Chromium.*

# P064: Alternative Weld Repair Research and Industry Case Studies in Grade 91 and 92 Steel

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## Summary

*Over the last 15-years, an extensive body of research has been developed to support the introduction of alternative weld repairs in creep strength enhanced ferritic (CSEF) steels like Grade 91 or 92 that do not require the use of post-weld heat treatment (PWHT). To date, 1,000s of such repairs have been executed across the USA thermal fleet. The longest in-service repairs are now exceeding 60,000 hours of operation and awarded the industry significant resiliency allowing plants during critical portions of the year to return to normal operation.*

*This manuscript will review the codification of alternative repair procedures in the National Board Inspection Code (NBIC) for CSEF steels, and highlight critical outcomes from a sustained research effort that has developed >700,000 hours of creep testing to date including novel pressure vessel tests that include the application of end load. These findings will be complimented by a selected set of industry case studies that EPRI continues to track as a key task to validate the repair approaches.*

## Key Words

*CSEF, repair, creep, PWHT, Grade 91, Grade 92.*

# **P065: Load and Temperature Dependence of Load/Stress Conversion Coefficient in SP Creep Test and Creep Remaining-Life Assessment of Gr.91 Steel**

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## **Summary**

*This study investigated the applicability of the SP creep test to the remaining-life assessment of 9Cr steel boiler piping. SP creep tests were conducted using a Mod. 9Cr-1Mo steel (Gr. 91) that had been in long-term service in an actual plant. The effects of the test load and temperature on the  $F/\sigma$  value were also examined. Based on the obtained SP creep data, the long-term rupture curve reference method proposed by Yaguchi et al. was used to evaluate the creep remaining-life assessment. It was found that the  $F/\sigma$  value determined by comparing SP creep and conventional uniaxial creep rupture data was approximately 2.6 and largely independent of SP creep test conditions (i.e., load and temperature). Additionally, applying the master rupture curve reference method to SP creep rupture data (16 data points) predicted 10 points within a factor of 1.2 and 15 points within a factor of 1.5 for rupture time at 625°C/45.4 MPa.*

## **Key Words**

*Small Sample Testing Technique, Creep, Small Punch Test, Remaining-Life Assessment, Mod. 9Cr-1Mo Steel, Master Rupture Curve Reference Method*

# **P066: Establishing Extrapolation Credibility for Long-Term Creep: A Physically Traceable TTS-Based Reform of Dyson's Damage Framework in Creep-Resistant Steels**

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## **Summary**

*Reliable prediction of long-term creep deformation and rupture in high temperature steels requires constitutive frameworks that remain valid beyond the specific test conditions used for calibration. It is well established that creep rupture evolves from ductile to brittle with decreasing stress, that the minimum creep strain rate decreases systematically with stress, and that creep cavitation is the dominant rupture mechanism in the long-term regime. Dyson's approach, while widely regarded as mechanism inspired and influential in shaping modern creep damage modelling, does not provide the structural capabilities needed to represent stress range transitions or multi axial cavitation behaviour.*

*This paper reconstructs and formalises the research programme that originated in the 2013 HIDA (High-temperature Defect Assessment)-6 keynote, which motivated the development of the TTS (time-temperature-stress)-Mechanism and TTS-Integrate frameworks. Building on established understanding of creep deformation, minimum creep rate behaviour, cavitation characteristics, and ductile–brittle transitions in high Cr steels, the programme pursued three objectives: (1) to establish a minimum creep strain rate function applicable across a wide stress range; (2) to develop a cavitation evolution model grounded in available cavity density and growth data and embedded within a TTS consistent mechanistic structure; and (3) to formulate a coupled cavitation–deformation relationship capable of reproducing the observed transition from ductile to brittle rupture.*

*These developments collectively provide a constitutive architecture that is mechanism resolved, transformation aware, and structurally accountable. A P91 case study demonstrates how independent calibration of each mechanism, explicit treatment of transitions, and physically motivated coupling yield mechanistically credible predictions across stress–temperature–time fields. The paper also presents the theoretical justification for the TTS and TTS Integrate formulations and explains why a TTS based structure is required to achieve predictability.*

*The resulting 2026 constitutive model represents the first full implementation of this architecture. The work provides both a practical example of TTS based modelling and a theoretical foundation intended to support future developments in creep damage constitutive modelling.*

## **Key Words**

*Time–temperature–stress framework, Cavitation kinetics, Minimum creep strain rate, Ductile–brittle transition, Mechanism-resolved constitutive equations, P91 creep behaviour, TTS-Mechanism/TTS-Integrate*

# **P067: Stress relaxation tests applied to martensitic steel and to aluminum: new findings from microstructurally based modeling and from experimental investigations**

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## **Summary**

*This work explores the close relationship between stress relaxation and creep, focusing on two distinct materials: a martensitic 9% Cr-steel and a cast aluminum alloy. Repeated (stepped) stress relaxation tests in compression mode were conducted for both materials using a deformation dilatometer. The activation volume, a critical parameter influencing dislocation glide and common to both creep and relaxation phenomena, was determined from stress decay data for both materials.*

*The relaxation behavior of both 9% Cr-steel and aluminum was modeled by a phenomenological approach, namely the logarithmic stress relaxation law. In addition, a physically based stress relaxation law was developed and employed. This new law was obtained from combining the Orowan equation and Hooke's law.*

*Finally, the microstructural evolution in the course of the stress relaxation process was simulated. Special focus was set on understanding the increase in the plateaus of the saturation stress at the end of the relaxation cycles. For the 9% Cr-steel, transmission electron microscopy (TEM) figures are presented and compared to predictions for the dislocation density from the microstructure simulation.*

*The study highlights the distinct mechanisms governing stress relaxation in different materials. For the 9% Cr-steel, the findings provide valuable insights into the microstructural evolution and its impact on high-temperature creep resistance. For aluminum, the results are particularly relevant for understanding residual stress reduction in lightweight structural applications.*

*By bridging phenomenological and physically based models, this work contributes to the development of predictive tools for stress relaxation and creep, tailored to the specific requirements of diverse materials and applications.*

## **Key Words**

*Stress Relaxation, Creep, Modeling, Dilatometry, Martensitic Steel, Aluminum*

# P068: Long-term creep ductility of Grade 92 – Why the $\lambda$ -parameter is not helpful

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## Summary

*Grade 92 steel is used for many components in modern power plants. In the recent ASME Code Case 3048, creep strength enhanced ferritic (CSEF) steels are classified based on their creep tolerance. This classification is derived from the creep damage tolerance parameter  $\lambda$  ( $\lambda$ -factor), which theoretically links creep damage and strain. Using this  $\lambda$ -parameter required as  $\lambda > 5$ , the ASME code case classifies not only Grade 92 but also many materials within the heat-resistant martensitic family as 'creep intolerant', which fundamentally contradicts many years of positive service experience with components made of Grade 92 in European power plants. The German vgb technical association of energy plant operators has therefore launched a project to reassess this classification.*

*Extensive evaluation work was carried out on creep behaviour, fracture deformation parameters, and the  $\lambda$ -parameter, in the temperature range of 550 to 750 °C including times exceeding 100,000 hours. The analysis was based on a dataset comprising over 380 creep tests from more than 30 heats of Grade 92 steel, including both component and test heats. Numerous microstructural investigations were also carried out on creep specimens.*

*No systematic dependence of the  $\lambda$ -parameter or on loading conditions such as stress, temperature, or time to rupture, could be identified. Furthermore, no systematic correlation could be established between the  $\lambda$ -parameter and service life consumption up to a design-relevant elongation, such as the 1% creep strain limit, the 2% creep strain limit, or the Monkman-Grant elongation. Moreover, variations in the methods used to evaluate minimum creep rates lead to significant differences in the resulting  $\lambda$ -parameter values.*

*The investigations therefore demonstrate that the  $\lambda$ -parameter is not suitable for evaluating a material type with regard to its suitability for the design, operation, and monitoring of components. However, the investigations also show that individual heats of Grade 92 steel reach the creep strain limits relevant to construction significantly faster than other heats. This is believed to be caused by complex interaction between the steel's composition and the applied manufacturing process. The question will be investigated further in a future vgb project.*

## Key Words

*Grade 92, lambda-parameter, creep ductility, creep damage, life time consumption*

## **P069: Alloy content, heat treatment and creep performance in martensitic steels for fossil and fusion plant**

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### **Summary**

*Key concepts from high temperature fossil plant martensitic steel R&D, in particular controlled boron-nitrogen alloying, offer potential advantages when adapted for nuclear fusion alloy development. However, as important strengthening elements including niobium, molybdenum and cobalt must be excluded for radiological reasons, fundamental alloy redesign is required. This paper describes a review and analysis of published creep data to derive semi-quantitative estimates of the individual strengthening effects of each of the major elements available for fossil and fusion martensitic steel applications. As an essential factor, the major influence of heat treatment conditions, especially normalising temperature and time, is also addressed. A main conclusion is that tantalum, when introduced to replace niobium on a simple equal-atomic-percentage basis, is a much less effective strengthener.*

*Alongside these data analysis activities, our practical collaborative materials R&D has aimed to develop a more robust next-generation "BRAFM" (boronated reduced activation ferritic-martensitic) steel for heat transfer applications in fusion power plant. Multiple alloy variants have been formulated, cast, rolled, characterised, and creep tested. Modelling and experiment have established how BRAFM alloy composition may be varied to enable successful high temperature normalising at 1200°C, and the resulting benefits have been confirmed by creep testing.*

*Lessons learned from projects examining novel "double normalising" heat treatment procedures are also critically reviewed. Whilst this approach has proved to be markedly unsuccessful, the work has nevertheless generated some very helpful insights. Creep data analysis has clarified how heat treatment affects the location and distribution of submicron-scale precipitation, and can thereby optimise – or indeed, impair – creep strength.*

*A further series of experimental alloys has then been produced to examine how changes in tantalum content, and compositional variations including zirconium additions, can best be formulated to optimise creep strength. Microstructural characterisation has provided useful indications of which variations show the greatest promise, and creep tests have been planned.*

### **Key Words**

*Creep performance, composition, heat treatment, nuclear fusion.*

## **P070: Modeling of cross slip of the screw dislocation in UO<sub>2</sub>**

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### **Summary**

*Understanding the high-temperature mechanical behavior of uranium dioxide (UO<sub>2</sub>) is critical for evaluating the structural integrity of nuclear fuel. UO<sub>2</sub> exhibits strong plastic anisotropy, which has long been hypothesized to be related to the complex behavior of 1/2 (110) screw dislocations and their ability to cross-slip between multiple slip systems of the fluorite structure, as proposed by Sawbridge and Sykes. However, the microscopic origin of this mechanism has remained unclear due to the lack of direct microscopic or atomistic evidence. In this work, a multiscale approach combining molecular dynamics, theoretical modeling, and discrete dislocation dynamics is used to investigate dislocation mobility as a function of temperature, stress, and orientation. Atomistic simulations show that above ~1500 K, screw dislocations progressively transition from planar glide in {001} and {110} systems to frequent cross-slip in {111} planes, leading to a full slip-system transition near 1700 K. This evolution is linked to a temperature-induced transformation of the dislocation core, driven by disordering of the oxygen sublattice. An atomistically-informed stochastic cross-slip model is developed and implemented in dislocation dynamics simulations, successfully reproducing atomistic results, experimental observations, and the plastic anisotropy of UO<sub>2</sub>.*

### **Key Words**

*Cross-slip, nuclear fuel, plasticity, slip systems, dislocation dynamics, simulation.*

# P072: Strain-rate asymmetry effects on high-temperature low-cycle fatigue of 316H stainless steel at 550 °C

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## Summary

*Type 316H austenitic stainless steel is widely used in high-temperature structural components where cyclic loading with non-uniform strain-rate histories may occur due to thermal transients or mechanical constraints. In this study, the low-cycle fatigue behaviour of 316H stainless steel was investigated at 550 °C under strain-controlled loading with different tensile–compressive strain-rate waveforms, including fast–fast (FF), slow–slow (SS), fast tension–slow compression (FS) and slow tension–fast compression (SF). The influence of strain-rate asymmetry on cyclic stress response, fatigue life, deformation localisation and fracture behaviour was systematically examined. The results reveal a pronounced dependence of fatigue behaviour on strain-rate distribution within the loading cycle. A clear fatigue life ranking of  $FF > FS > SS > SF$  was observed, which cannot be explained solely by peak stress levels. Stabilised hysteresis loops show stress serrations during slow straining, indicating dynamic strain ageing; however, the presence of serrations does not directly correlate with fatigue life. EBSD and kernel average misorientation analyses demonstrate that slow tensile straining promotes strong localisation of plastic deformation near grain boundaries, while slow straining in compression is significantly less detrimental. Fracture surface observations further confirm distinct crack propagation characteristics associated with different strain-rate waveforms. These findings indicate that tensile–compressive strain-rate asymmetry plays a critical role in fatigue damage accumulation of 316H stainless steel at elevated temperature, with slow tensile straining being particularly damaging. The results provide experimental insight into rate-sensitive fatigue mechanisms and highlight the importance of considering strain-rate distribution within loading cycles for creep–fatigue assessment of high-temperature structural components.*

## Key Words

*316H stainless steel, low-cycle fatigue, strain-rate asymmetry*

# P073: More than 30 years of online creep strain measurements in power plants – from sensor technology to creep modelling

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## Summary

*Components under creep deformation must be analysed periodically during the operating time with regard to the degree of damage. On the one hand, the "degree of fatigue" for "critical components" is calculated from the pressure and temperature recordings for creep and fatigue and compared with a limit value from the codes and standards. Secondly, these components are analysed during shutdowns. Non-destructive tests (crack analyses, determination of wall thicknesses) are carried out and the microstructure is analysed using replica technology. The latter method is used to classify the current degree of damage (void density, microcracks) and the remaining service life is derived from "experience" with these materials. Furthermore, the macroscopic geometry (circumference, diameter) is checked in the shutdowns using simple measuring equipment and the "permanent strain" is determined from this according to the regulations. A more precise method for analysing the remaining service life is to measure strain during operation at high temperatures using capacitive strain sensors. The recorded strain data can be used to determine both creep strains under constant load and strain amplitudes during start-ups and shutdowns. For creep, for example, the creep rate can be observed in the safety-relevant transition from secondary to tertiary creep. Capacitive strain sensors are designed for a service life of several decades. Their drift is extremely low at temperatures above 600 °C, which makes them ideal for long-term monitoring of creep deformations on thick-walled components. The technology has been continuously further developed and, in addition to the methods mentioned above, is increasingly becoming a further basis for assessing service life. In documents such as VGB-S-509, the use of capacitive high-temperature strain sensors is therefore recommended as a local measurement method. In practice, the technology is used when there are uncertainties and deviations from the design that are not captured by a recalculation using the measured temperatures and pressures, e.g.: (i) uncertainty about the scatter band position of the material batches used, (ii) multi-axial stresses from the component geometry (ovality, notches, ...), (iii) additional stresses from external forces and moments, (iv) additional thermal stresses. In addition to optimising the capacitive sensor, TÜV Rheinland has further developed the industrial suitability of the entire monitoring concept in recent years, so that in newer power plants a large number of capacitive sensors are fed to a central monitoring system via decentralised data processing (near the component), thus enabling the monitoring of HP steam pipes or larger thick-walled components such as headers. The operation of conventional power plants is now determined by the volatile feed-in from renewable energy. The components are stressed by more load changes and higher load gradients. As a result, the interaction of creep and fatigue damage is becoming the determining factor. TÜV Rheinland uses the BOLTON creep model for the relevant materials of low-alloy steels and 9-12% Cr steels. With this model, the critical components can now also be evaluated economically on a recurring basis using the published ECCC material parameters.*

## Key words

*Capacitive creep strain measurement, component deformation, tertiary creep, creep simulation, power plant technology, 9-12% Cr steels, plant safety*

# **P074: Capabilities and limitations of short-term creep testing with a quenching and deformation dilatometer**

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## **Summary**

*Short-term creep testing utilizing a quenching and deformation dilatometer offers an efficient alternative for rapid evaluation of the creep resistance of engineering materials. Unlike conventional long-duration creep furnace testing, this method subjects specimens to tensile loading at controlled temperatures and stresses directly within the dilatometer. The investigation is carried out up to the time of the minimum creep rate, recognizing the inherent limitations of the dilatometer for long-term creep studies.*

*Compared to standardized uniaxial steady-state creep testing, additional factors are present that may restrict quantitative classification of creep properties. Nevertheless, this approach enables a rapid and straightforward qualitative comparison of the creep resistance across varying alloy compositions or heat treatment conditions.*

*In this study, initial tests were conducted on the established 9% Cr steel P91 (X10CrMoVNb9-1), which provides an extensive basis for experimental validation. The advantages and challenges associated with the experimental setup are critically evaluated, including the significant temperature gradients identified within the sample as a result of inductive heating. These gradients are attributed to the interplay between specimen geometry and heating methodology. Moreover, systematic errors in strain measurement were observed due to the susceptibility of the LVDT measurement aperture to radiant heat.*

*The findings highlight both the capabilities and the limitations of short-term creep testing with a quenching and deformation dilatometer. The implications for the qualitative assessment of creep resistance and the influence of extraneous factors on measurement accuracy are discussed, providing guidance for the broader application and further refinement of this methodology.*

## **Key Words**

*Dilatometer, Creep test, Induction heating, Temperature deviation, P91 (X10CrMoVNb9-1)*

# P076: Prediction Thermo-Mechanical Fatigue Behavior of 316 Stainless Steel from Isothermal Properties

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## Summary

*This study presents a constitutive model for accurately predicting the thermo-mechanical fatigue (TMF) behavior of 316 stainless steel, a material widely used in power and chemical plants. Isothermal fatigue, creep-fatigue, and TMF tests with and without dwell periods were conducted at temperatures ranging from 300°C to 700°C. The experimental results revealed the presence of two distinct creep exponents during dwell periods, corresponding to high- and low-stress regimes. Material constants for the constitutive equation were derived from isothermal fatigue data, and the model was extended to TMF conditions. Comparison between experimental and simulated stress-strain responses demonstrated excellent agreement, confirming the model's capability to accurately reproduce cyclic hardening and stress relaxation behavior under thermal loading. These findings contribute to improved life prediction and integrity assessment of high-temperature components in industrial applications. This extended abstract presents a representative example of the key results. Comprehensive results and detailed discussion will be provided in the full paper.*

## Key Words

*thermo-mechanical fatigue, constitutive equation, viscoplasticity, creep, cyclic hardening, thermal recovery*

# P077: From Microstructural Evolution to Creep Behaviour: Effect of Long-Term Thermal Aging in Stabilized Ferritic Stainless Steels

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## Summary

*Stabilised ferritic stainless steels are designed for high-temperature applications, such as solid oxide fuel cell components, where deformation under constant load must be taken into account. Prolonged exposure to high temperatures can lead to microstructural changes that affect phase stability and mechanical properties. This study therefore examines how long-term aging influences microstructural evolution and creep resistance.*

*The work focuses on K44M (AISI 444), a stabilised ferritic stainless steel. Some samples were aged for up to 10,000 hours. Creep tests were carried out at 650 °C and 850 °C following different aging durations. Within the tested range, aging induces significant microstructural changes, with an increase in precipitation. The chemical composition of the matrix (between the precipitates) is modified. Despite an increase in precipitate density, a very significant increase in the creep strain rate was measured. The microstructural changes observed during the creep tests on the unaged sample lead to a change in creep behaviour during the tests.*

## Key Words

*Microstructural changes, precipitates, Laves phases, solid solution hardening*

# P078: Dependence of creep model parameters on the degree of fatigue damage

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## Summary

*Turbine components operating at high temperatures are exposed to combined loading from low-cycle fatigue (LCF) and creep. These two mechanisms interact and affect both the deformation behaviour and service life. However, modelling approaches often treat fatigue and creep separately, which prevents consideration of fatigue damage in creep deformation. To investigate this interaction, stress relaxation phases were extracted from creep-fatigue experiments and analysed as a function of the cycle number. The study focuses on the wrought alloy MarBN and the cast alloys GX12CrMoVNbN9-1 and G17CrMoV5-10 in the service-relevant temperature range of 550–650 °C. Creep behaviour was modelled using the phenomenological Norton-Bailey approach, whose parameters are typically derived from constant-load creep tests. Moreover, this creep model also allows the representation of stress relaxation phases in strain-controlled fatigue tests with dwell times. In the present work, model parameters were defined either as constants or as functions of the lifetime-ratio. Predictive accuracy of the calculated stress relaxation curves was evaluated using parameter optimization, cross-validation, and statistical criteria. The quality of fit was found to potentially depend on the degree of fatigue damage, quantified by the lifetime-ratio.*

*The results show that lifetime-ratio parameters quantify the influence of fatigue damage on creep deformation. Compared with constant parameters, predictive accuracy improved for all materials considered. At 600°C, GX12CrMoVNbN9-1 only showed a little change, whereas MarBN and G17CrMoV5-10 exhibited marked improvements in statistical evaluation criteria. Furthermore, comparison of calculated stress relaxation curves across different lifetime-ratios revealed that creep-induced stress relaxation increases with the number of LCF cycles. For MarBN, this cycle-dependent effect became more pronounced at higher temperatures.*

## Key Words

*stress relaxation, creep-fatigue interaction, low-cycle fatigue, high-temperature materials, lifetime-ratio, martensitic steels, creep modelling, cross-validation*

## **P080: Live presentation of CreeSo - Creep Software**

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### **Summary**

*“CreeSo” is short for “Creep Software”. This application is currently in development at the Institute for Engineering Materials – Metals and Alloys at the JKU Linz, Austria. The live presentation uses practical examples to demonstrate the functionality and features of the application.*

*The institute works on different models for the simulation of creep and other material properties utilizing descriptions of the microstructure for the materials in question. Most models deal with the mechanics of dislocation creep for martensitic 9-12% Cr steels. The resulting systems of differential equations cannot be solved analytically and numerical methods have to be applied.*

*CreeSo provides a GUI (Graphical User Interface) for the creation of the model and the simulations. It enhances the speed of the simulation by a factor of approximately 10 compared to MatLab. CreeSo also contains a variety of tools for e.g. creation of time to rupture (TTR) diagrams, comparison to creep curves, parameter finding, and data export.*

*Although the application still is a prototype, CreeSo is built as a desktop and online version so that researchers outside our institute can also access our models and carry out simulations. The program is written in C++ for Windows 11 (desktop version) and Linux (online version). A small subset of the functionality can even be tried out publicly under <https://imk.jku.at/creeso>.*

### **Key words**

*Software, Online, Desktop, Creep, Simulation, Modelling, Martensitic Steel, Live Presentation*

# **P081: Micromechanical behaviour and modeling of irradiated UO<sub>2</sub>: strain gradient plasticity and cleavage damage approach**

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## **Summary**

*Understanding plastic deformation, strain hardening and damage of uranium dioxide (UO<sub>2</sub>) is important for reducing uncertainties related to its mechanical behavior in reactor conditions. Especially, modelling of UO<sub>2</sub> mechanical behaviour at higher temperatures and creep rates is critical for estimations of cladding integrity in transient conditions of a nuclear reactor. In this work, we utilize a crystal plasticity (CP) model coupled with cleavage damage mechanisms. Material's strain localization behavior is analyzed with strain gradient enriched model with and without irradiation effects. Strain localization is important for understanding creep and damage behavior in UO<sub>2</sub>. Irradiation induced hardening in the fuel is introduced via dislocation loop interactions with dislocations informed by dislocation dynamics simulations. It is demonstrated how modeling choices influence strain localization and therefore ultimately have an effect on damage behavior at high temperatures. Thus, the new correlations for the irradiation induced mechanical properties give directions for fuel pellet microstructural behaviour. The micromechanical properties could be applied in more physics-based description of the fuel safety estimations.*

## **Key Words**

*Crystal plasticity, Uranium dioxide, Dislocation loops, Irradiation, Damage, Strain localization*

# P082: High-Temperature Mechanical and Impact Behaviour of UK-RAFM Steel for Fusion Applications

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## Summary

*Fusion DEMO-class components demand structural materials that retain strength and creep resistance at elevated temperature under neutron irradiation while limiting long-lived activation. Within Europe, EUROFER97 is the reference reduced-activation ferritic martensitic (RAFM) steel, but the strength and creep lifetimes are poor above 550 °C and established production routes are not readily scalable to the tonnages required for blanket structures. In response, the NEUtron iRradiatiOn of advaNced stEels (NEURONE) programme is developing a UK capability and database for qualification of industrially scalable RAFM steels.*

*This work reports the high-temperature tensile, creep and Charpy impact behaviour of UK-RAFM, an electric arc furnace (EAF)-produced, fusion-grade RAFM steel manufactured at industrial scale in the UK and processed into a 14 mm normalised-and-tempered plate. Tensile tests at 550 °C and 600 °C show UK-RAFM provides improved strength retention relative to EUROFER97 (most clearly in UTS), with ductility assessed via uniform and total elongation. Total elongation comparisons are interpreted with care due to differing gauge lengths between datasets of EUROFER97 and UK-RAFM. Creep testing conducted at 550 °C and 200 MPa, and 650 °C at 90 MPa demonstrates an approximately five-fold increase in rupture life for UK-RAFM versus EUROFER97 under matched conditions. Charpy testing indicates a reduced upper-shelf energy and a higher DBTT than EUROFER97, motivating further work, particularly irradiation testing to quantify operational implications.*

## Key Words

*EUROFER97, UK-RAFM, tensile properties, creep, Charpy impact, high-temperature materials, nuclear fusion, NEURONE.*

# P084: Microstructural modelling of low cycle fatigue in Copper

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## Summary

*Oxygen free phosphorous (OFP) copper is chosen as outer shell material to protect the spent fuel canisters in the underground repository. The copper shell is subject to internal heating by residual activity of the contents and external loading by ground water and swelling of bentonite surrounding the shell, as well as geological activity. We present a crystal plasticity model approach for simulating low cycle fatigue and monotonic tensile behaviour. Key aim is to introduce sufficient plastic deformation mechanisms to be able to capture the monotonic (tensile and creep) and cyclic (LCF and cyclic relaxation) behaviour with reasonable accuracy with the same model parametrization. A dislocation density based model is used for the investigated copper material and local slip band development. In detail, the basis of work is a crystal plasticity material modelling including grain orientation and size distribution from electron backscatter diffraction (EBSD) imaging and low cycle fatigue and cyclic relaxation tests experimental results along with creep and small scale testing methods to gain more insight how the different regions (e.g. friction stir weld between lid and cylindrical part of the canister) of the copper shell behaves. Local material behaviour has been investigated with small-scale tensile tests conducted in SEM and analysed with digital image correlation method. Electron microscopy characterization including SEM-EBSD is performed both to undeformed material and also to deformed material. Existing crystal plasticity framework is extended to be compatible with the OFP copper microstructure that is the focus of this study. Synthetic models are based on EBSD characterization (i.e. grain orientation, size and shape distribution are stochastic variables) in order to provide more realistic material description.*

## Key Words

*OFP Copper, Crystal Plasticity.*

# P085: Microstructural insights of how normalising temperature and MX dissolution affect creep strength in tempered-martensitic-steels for fusion devices (extended abstract)

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## Summary

*Creep-strength-enhanced Reduced Activation Ferritic–Martensitic (RAFM) steels are being pursued as candidate structural materials for future fusion reactor systems [1–10]. Conventional RAFM grades such as Eurofer-97 [11] and F82H [12] exhibit limited creep resistance at elevated temperatures, restricting their deployment to below roughly 550°C [13, 14]. At the same time, ferritic–martensitic steels suffer from pronounced embrittlement and loss of ductility under neutron irradiation at temperatures below about 350°C [15], leaving only a narrow operational window for fusion blanket components. Enhancing the high-temperature creep strength of RAFM alloys therefore represents a key route to widening this usable temperature range and improving the thermal efficiency of breeder blanket designs.*

*One established approach to improving creep performance in ferritic–martensitic steels is high-temperature normalising, typically in the range of 1100–1200°C. Such treatments dissolve existing precipitates and generate very coarse prior-austenite grains [16]. While beneficial for creep strength, these microstructures can be detrimental for applications requiring good fracture toughness and resistance to creep–fatigue damage [15, 17]. High-temperature normalising is nevertheless important for achieving full dissolution of MX-type carbonitrides and, in boron-containing alloys, for removing undesirable boron-nitride phases [2, 18]. This creates an inherent conflict in RAFM alloy design: the heat treatments that maximise creep strength [19] tend also to degrade toughness [16].*

*Two-stage normalising treatments, in which a second lower-temperature austenitisation step is introduced, have been explored as a means of refining the austenite structure and improving toughness [16]. Although such treatments can produce finer prior-austenite grains, they have been associated with reductions in creep strength [20]. Since smaller grain sizes might actually enhance creep resistance of these steels [21, 22], the origin of this degradation must lie in other microstructural factors.*

*A second effect of high temperature normalising is the complete dissolution of MX carbides during at the normalising temperature. RAFM steels are strengthened typically by V(C,N) and TaC [23], and/or TiC. Dissolving the coarse MX particles formed during casting and thermomechanical processing is considered essential for achieving a uniform distribution of solute and promoting fine, homogeneous precipitation during tempering. A dense population of MX particles within subgrain interiors is thought to be important for stabilising the high dislocation density of the martensitic substructure by suppressing recovery [24]. Increasing the normalising temperature should therefore increase the number density of these strengthening precipitates by maximising the solute available for re-precipitation.*

*In two-stage normalised Grade 91 steel, reductions in creep strength have been reported [20] and attributed to coarsening and incomplete dissolution of MX precipitates during the lower-temperature normalising step, although this mechanism has not been directly verified. The present study*

*examines RAFM alloys subjected to either single-step high-temperature normalising or two-stage normalising treatments. The objective is to characterise the resulting microstructures, particularly grain structures and precipitate populations, and to relate these features to the observed differences in creep behaviour.*

# **P086: Increasing the heat: Developing next-generation high-temperature steels to deliver commercial fusion energy**

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## **Summary**

*As the UK nuclear 'renaissance' continues apace, steels continue to demonstrate incredible versatility and performance, particularly as we consider next-generation structural materials to use in the most demanding environments ever developed. Proposed commercial fusion powerplants contain plasmas ten times hotter than the sun, with materials witnessing extreme levels of radiation damage. This is coupled with challenging mechanical loads, and other environmental factors such as corrosion. Yet nano-structuring and carefully designed steel microstructures can be tuned to manage these effects.*

*A UK consortium, NEURONE (Neutron Irradiation of Advanced Steels), operating across academia, national labs and industry are tackling the challenge of developing steels to use in fusion plants, and utilising existing national infrastructure to deliver the tonnages of material required by the end of the decade. This talk will explore some of the key challenges we face within this programme, as well as the science behind the steels being developed. Importantly, the immediate opportunities for wider industry engagement in this emerging sector will be outlined.*

# P087: Damage kinetics of anisotropic material for nuclear application

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## Summary

*Zr2.5Nb is the material of choice for pressure tubes in Pressurized Heavy Water Reactors (IPHWRs) owing to its low neutron absorption, high corrosion resistance and adequate strength. Since the structural integrity of pressure tubes is critical for reactor safety, the lifetime assessment of Zr2.5Nb pressure tubes, requires clear understanding of not only of their deformation but also of their damage mechanism leading to fracture. Present work aims at investigation of damage evolution in Zr2.5Nb using combination of experimental testing and post-fracture image analysis. Uniaxial tensile test was performed on Zr2.5Nb specimens and DIC (Digital Image Correlation) was employed to capture local strain evolution. To quantify damage kinetics, fractured specimens were examined under a field emission scanning electron microscope (FESEM) to capture high resolution images of fracture surface. The FESEM micrographs were processed using image analysis techniques, where the grayscale images were converted to binary (black-and-white) form to clearly distinguish voids from the matrix. Quantitative analysis of FESEM micrographs allowed measurement of void nucleation, growth, and coalescence, enabling the construction of a void volume fraction–strain relationship. Although the current study was performed at only 100°C temperature, the developed experimental framework and analysis methodology are applicable to elevated temperatures of more than 100°C conditions, enabling future studies to find temperature-dependent damage evolution in Zr2.5Nb.*

## Key Words

*Zr-2.5Nb alloy, Pressure Tube, Anisotropy, Ductile Fracture*

# **P088: Creep of irradiated fuel - addressing technological challenges to succeed in the thermomechanical experiments at high temperature at millimetric scale**

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## **Summary**

*These studies are conducted in the framework of safety analyses involving Pellet Cladding Mechanical Interactions (PCMI) in nuclear fuel rods of Light Water Reactors (LWRs). The mechanical stresses induced in the cladding, the first safety barrier, under PCMI depend on the viscoplastic properties of the fuel pellet. For the validation of the Fuel Performance Codes (FPCs), used in the safety analyses, it is therefore necessary to understand and to characterize these properties and their evolution in operation. While existing studies have extensively investigated the fuel viscoplastic behaviour through mechanical tests on fresh materials, conducting similar tests on irradiated fuel pellets poses significant challenges.*

*This work, part of the EURATOM OperaHPC Project co-funded by the European Union, aims to demonstrate the feasibility of mechanical testing on irradiated ceramics.*

*One major challenge is to perform a creep experiment on a millimetric sample in a high temperature furnace in a hot cell, including controlled atmosphere, fluid circulation, fission gas release analysis, and complete load lines to accurately replicate representative conditions. Fuel creep compression calculations were used to specify all the thermomechanical conditions needed for the validation of FPCs. The new experimental mechanical setup was designed and simulated in a numerical twin to ensure optimal thermomechanical performances. The device is linked to a dedicated furnace that controls the temperature as well as the gas composition. Creep compression tests were performed on alumina and fresh fuel under 100 MPa stress at temperatures up to 1500 °C.*

*By overcoming these technical challenges, this research aims to pave the way for the world's first creep experiment on irradiated fuel within a hot cell environment at millimetric scale, thus contributing to our understanding of the mechanical behaviour of irradiated ceramics and enhancing the safety and efficiency of nuclear fuel elements.*

## **Key Words**

*Mechanics, Experimental device, Viscoplasticity, Irradiated fuel, Creep compression, High temperature*

# P089: Creep-resistant 3Cr-3WVTa Bainitic Ferritic Steels with PWHT-free Design

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## Summary

*A compositional modification of a reduced activation bainitic ferritic steel based on Fe-3Cr-3W-0.2V-0.1Ta-Mn-Si-C in weight percent, developed at Oak Ridge National Laboratory in 2007, was proposed which targeted eliminating the requirement of post-weld heat treatment (PWHT) while preserving the advantage of mechanical properties in the original steel. The alloy design includes reducing the hardness in the as-welded condition for minimizing property inhomogeneity across the weldment as well as improving toughness, while increasing the hardenability for preserving the high-temperature mechanical performance such as creep-rupture resistance in the original steel. A composition range with a reduced C content combining with an increased Mn content, so-called "modified" steel, successfully achieved relatively low hardness, less hardness variation across the weldments, together with an improved impact toughness in the as-welded condition, compared to those of the original steel. The creep-rupture performance across the weldments without PWHT demonstrated the improved creep strength in a temperature range of 500 to 550°C and a stress range from 275 to 500 MPa, with maximum testing time of 21,299h, with significantly higher creep strength than that of the original steel weldment after PWHT when compared using Larson-Miller Parameter. All specimens were ruptured at the heat-affected zone adjacent to the weld metal. By combining with the improved impact toughness, the present results demonstrated a proof of alloy design eligibility to develop PWHT-free bainitic ferritic steels.*

## Key Words

*Bainitic ferritic steels, PWHT, fusion reactor, reduced activation*

# P090: A physics-based mean-field model for dislocation creep in 9-12% Cr steels: Fundamentals, predictivity and extended applications

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## Summary

*In this work, we present a creep model which has predominantly been developed for martensitic 9-12% Cr steels under loading conditions typical for thermal power plants. Industrial benefit is a prediction of creep rates, accumulated creep deformation and time to x% deformation depending on the specific material, and the external parameters stress and temperature. Academic benefit is the identification of the crucial creep mechanisms which contribute to the overall damage.*

*The creep model is based on a quantitative representation of the relevant microstructural constituents (subgrain boundaries, dislocations, precipitates of various kinds) and the respective interactions between them, which are based on physical models. The results of the calculations are the microstructural evolution at a given stress and temperature, as well as the deformation rate stemming from dislocation motion. This approach holds 2 advantages: (i) the model can be second-checked not only by a creep experiment, but also by microstructural investigations from samples at different stages during their creep life and (ii) the input into the model is not a specific material type, but rather a starting microstructure at the beginning of the investigated creep exposure. This feature opens the opportunity to compare different material badges from the same material type, which may have been exposed to different heat treatments or have different chemical compositions – resulting in different starting microstructures. In addition, the model is capable of rating which specific microstructural feature(s) is/are crucial for improved creep properties, and which other features might also be beneficial, but have little impact.*

*We have extensively tested the model on P91 due to the amount of available experimental data on both creep rates and microstructure. We have also tested the model on various other 9-12% Cr steels with good results.*

*One further advantage of the model is its time resolution – we calculate the evolution of the material state progressively with small timesteps. In each timestep, stress and temperature can be changed (within reasonable boundaries). Consequently, the system stress and temperature do not have to be constant in time, but change in any given manner, e.g. for simulating load changes of a power plant. Although a realistic test of this feature is yet to be carried out (the test has not been set up yet, due to the lack of experimental data to compare with), we are able to demonstrate how fluctuating stresses let the material age at a different rate compared to constant stresses.*

## Key Words

*Creep, modelling, microstructure, 9-12% Cr steels, P91, sensitivity analysis, material recovery*

# P091: The application of a tapered specimen geometry to accelerate creep testing

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## Summary

*Creep testing using full-field metrology and complex stress-state specimens has been proposed as an accelerated, data-rich alternative to conventional methods for evaluating creep response. Despite clear advantages, widespread adoption remains limited due to the increased complexity of data interpretation, challenges in validating full-field measurements, the need to establish reproducible methodologies, and a lack of clarity regarding integration within existing standardised creep qualification frameworks.*

*The primary objective of the study is to directly compare conventional uniaxial creep testing to a full-field approach using a tapered geometry specimen. This will allow the establishment of a clear methodology for extracting relevant creep evaluation metrics from full-field data and validating the approach against standard creep qualification practices. This work forms part of a broader effort to quantify the uncertainty of using full-field measurement for long-term, high-temperature testing, using inverse identification to determine creep model parameters, and optimisation of the specimen geometry.*

*In the work reported here, conventional ISO 204 creep tests were conducted at 250 °C on ISO 6892 tensile specimens of Al 1050 at five applied loads. A tapered geometry specimen was subsequently tested under a single load. For these specimens, stereo Digital Image Correlation (DIC) was used to obtain full-field surface strain measurements, from which spatially resolved strain-time data were calculated.*

*Norton's law creep parameters were identified from each approach, demonstrating the advantage of the more information-rich dataset provided by the tapered geometry and full-field measurement in enabling more robust and accelerated parameter identification.*

*In future work, the methodology will be extended to incorporate a digital twin, enabling systematic assessment of the sensitivity of the extracted creep parameters to experimental uncertainties such as image noise, as well as to the effects of inhomogeneous stress fields within the specimen. This will allow the robustness of the full-field parameter identification approach to be evaluated under realistic experimental conditions.*

## Key Words

*Accelerated Creep Testing (ACT), Digital Image Correlation (DIC).*

# P092: Microstructural Tailoring of Modified IN738LC Manufactured via PBF-LB/M

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## Summary

*In this study, the microstructural tailoring of a modified Inconel 738LC (IN738LC) superalloy (MetcoAdd 738LC-A) manufactured by powder bed fusion of metals using a laser beam was investigated. In particular, the influence of post-processing heat treatments on grain size,  $\gamma'$ -precipitate morphology, and hardness was studied. Due to the fine columnar grains and suppressed  $\gamma'$ -precipitation in the as-built condition, hot isostatic pressing and subsequent grain-coarsening heat treatments were applied to achieve grain diameters favourable for high-temperature performance. Grain growth above the  $\gamma'$ -solvus temperature produced equiaxed grains of a diameter of approximately 107  $\mu\text{m}$ , while subsequent partial solution and aging treatments enabled systematic control of bimodal or monomodal precipitate morphology. Hardness strongly correlates with the presence of fine spherical  $\gamma'$ -precipitates and decreases with precipitate coarsening during aging. In this study, it was demonstrated that tailored heat-treatment strategies can effectively modify the microstructure and mechanical response of additively manufactured modified IN738LC.*

## Key Words

*Additive manufacturing, LBPF, Inconel 738LC, gamma-prime precipitates, heat treatment, grain growth, microstructural tailoring, high-temperature properties*

# P093: 3D ANALYSIS OF INCLUSIONS AND CAVITIES IN THE HAZ OF A WELD IN GRADE 92 STEEL

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## Summary

*Grade 92 is an important creep strength enhanced ferritic steel (CSEF) for the power generation industry. The composition of the steel results in it being susceptible to large BN precipitate (or inclusion) formation during the steel fabrication process. These BN inclusions are known to be a primary nucleation site for creep cavities, which reduce the ductility of the material. Conventional 2D analysis is unable to provide a clear unambiguous link between the inclusions present and the cavities that form. The two main reasons for this include preparation artefacts from metallographic sample preparation (e.g. contamination from consumables and potential pullout out of inclusions that are surrounded by a cavity) and sectioning effects due to the cavities usually being much larger than the inclusion at the point of rupture.*

*To overcome these inherent issues 3D analysis was performed on an extracted macro-volume (400  $\mu\text{m}$  x 400  $\mu\text{m}$  x 400  $\mu\text{m}$ ) from a site-specific location in the heat affected zone (HAZ) of a P92 weld where significant creep damage was present. A system combining a Plasma Focused Ion Beam (PFIB) for the sectioning with an SEM for data acquisition was used. The system was also equipped with Electron Backscatter Diffraction (EBSD) and Energy Dispersive Spectroscopy (EDS) detectors that provided quantitative crystallographic and chemical data for each of the >200 serial sections collected. This allowed the size, shape, chemistry and position of inclusions and cavities to be unambiguously determined without mechanical preparation induced artefacts. The inclusion contents observed in the 3D analysis were then related to those measured using automated SEM-based inclusion analysis performed in the parent a large distance from the weld (>10 mm) where there is no damage to avoid the complexities introduced when creep cavities are present. This comparison allowed the features responsible for creep ductility reduction to be identified.*

## Key Words

*Inclusions, Boron Nitride, 3D Analysis, PFIB, Grade 92, Cavity-inclusion association.*

# P094: Accelerated Creep Testing of Laser Powder Bed Fusion Ti6Al4V (Extended Abstract)

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## Summary

*Reliable characterisation of high-temperature creep behaviour is essential for the development and calibration of constitutive models used in thermo-mechanical simulations of structural components. Conventional constant-load creep testing is time-intensive, motivating the use of accelerated methods capable of rapidly assessing creep properties, which can accurately reflect the findings of longer-term tests.*

*In this study, the high-temperature uniaxial creep response of laser powder bed fusion (LPBF) Ti6Al4V (Ti64) at 800 °C is examined using displacement-controlled stress relaxation tests and stepped creep experiments. The aim is to evaluate the ability of these techniques to extract meaningful creep parameters, identify stress-dependent deformation regimes, and assess consistency between accelerated and conventional testing approaches.*

*Stress relaxation tests were conducted under displacement control. All experiments exhibited a two-stage relaxation response, characterised by an initial rapid stress decay followed by a slower, quasi-steady regime. Differentiation of the stress relaxation data enabled the extraction of strain-rate evolution as a function of stress. The resulting effective stress exponents exhibit a pronounced stress dependence, increasing from values close to unity at low stresses (< 10 MPa) to values exceeding four at higher stresses. This transition is consistent with a change in the dominant deformation mechanism from diffusion-controlled creep at low stresses to dislocation-controlled processes such as climb and glide at higher stresses.*

*Stepped creep tests were performed to efficiently generate creep strain-rate data over a wide stress range within a single specimen. These tests produced steady-state creep rates in a fraction of the time required for individual constant-load creep experiments. Comparison of stepped creep results with stress relaxation-derived strain rates and available uniaxial creep data shows good agreement in both absolute values and stress exponent trends, supporting the validity of accelerated testing methodologies for constitutive parameter identification.*

*Pre-test microstructural characterisation using scanning electron microscopy (SEM) and electron backscatter diffraction (EBSD) was undertaken on heat-treated material to provide context for the observed deformation behaviour. Overall, the results demonstrate that stress relaxation and stepped creep methods provide a robust and time-efficient framework for characterising the high-temperature creep response of LPBF Ti64, with relevance to constitutive modelling and long-term performance assessment.*

## Key Words

*Laser powder bed fusion, accelerated creep, stress relaxation, stepped creep, EBSD, constitutive modelling*

# P095: Coarsening kinetics for $M_{23}C_6$ carbide in a 12% Cr steel: Modelling and experimental validation

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## Summary

*In context to powerplant applications, 12% Cr tempered martensitic steels are the cheaper alternatives to austenitic steels and nickel-based alloys, when the exposure temperature is about 650 °C. The strength of these steel class degrades with exposure time due to increase in the size of carbide and carbonitrides precipitates, hence kinetics should be looked upon. In this work, presence of MX,  $M_{23}C_6$ , and Laves phase precipitates was confirmed through TEM investigations with the mean radius of approximately 11, 41, and 37 nm, respectively, for investigated 12% Cr tempered martensitic steel. Coarsening kinetics of  $M_{23}C_6$  ( $M = Cr, W, Fe$ ) carbide has been studied at the aging temperature of 650 °C, employing DICTRA simulations. The prediction in terms of precipitate size is substantiated with the TEM investigation. The effect of interfacial energy, alloying elements, temperature, and the formation of Laves phase on the coarsening kinetics of  $M_{23}C_6$  has been investigated. Combination of TEM investigations and precipitation kinetic simulations suggest that interfacial energy of carbide and tempered martensitic matrix lies in the range of 0.5-0.7 Jm<sup>-2</sup>. Simulation results suggests that, the addition of Mn increases the coarsening rate coefficient of the carbide, while the addition of Co decreases it, which could be explained by their effect on the diffusion coefficients of Cr in the matrix. Higher temperature results in an increase in the diffusion coefficient of Cr in the matrix which thereby leads to increase in coarsening rate of the carbide. Further it was observed that, formation of Laves phase ( $Fe_2W$ ) leads to slight increase in the coarsening rate coefficient of  $M_{23}C_6$  carbide.*

## Key Words

12% Cr steel,  $M_{23}C_6$  carbide, Coarsening, TEM, DICTRA simulations.

# P096: Application of an Integrated Approach for Lifecycle Management of High-Temperature Components in Steam Methane Reformer Furnaces

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## Summary

*This study presents a comprehensive metallurgical and mechanical integrity assessment of pigtail tubes from a steam methane reformer (SMR) furnace, including Omega creep testing, finite element analysis (FEA), and remaining life assessment (RLA). Both damaged and reference tubes were subjected to a comprehensive destructive testing comprised of: visual inspection, dimensional analysis, compositional verification, dye penetrant testing, microstructural examination, hardness profiling, and grain size distribution analysis. Notable findings include significant vertical deflection in the bottom arms of damaged pigtails—up to 30 mm—and outer diameter growth exceeding 2.5% in some cases. These deformations correlated with observed creep voiding, particularly around the extrados of bends and manifold ends. Omega creep testing was performed on specimens from the most and least damaged tubes, yielding strain rate and Omega parameter data that informed the creep degradation model. Finite element simulations captured creep relaxation of the system stress due to thermal expansion with respect to support constraints. This integrated approach combining metallurgical characterization, advanced creep modelling, and FEA provides a robust framework for lifecycle management of SMR components. The findings support proactive maintenance planning and demonstrate the value of strain-based assessments in high-temperature service environments.*

## Key Words

*pigtail tubes, Omega creep, effective tube metal temperatures, strain-based assessments, finite element analysis, tube life predictions, lifecycle management.*

# **P097: A numerical analysis of component tests on a model of a power plant flange under steady state and transient loads**

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## **Summary**

*With the growing share of renewable energy, the flexible operation of thermal power plants has become increasingly important. Warm and hot starts now occur far more often than in the past, significantly raising the frequency of thermal stresses caused by temperature gradients within plant components. The investigations presented in this paper focus on flange connections, particularly those used between pipes and turbine housings. For reliable operation and leak tightness, it is essential that these connections maintain sufficient long-term contact pressure provided by the bolted joint. In this context, experiments were carried out on a model of a scaled intermediate pressure turbine flange in order to investigate the influences of different bolt materials, the reuse of bolts, sleeves and nuts, transient temperatures and temperature gradients within the components. Tests on this model flange were carried out under near-service loads, involving internal heating and pressurisation of the flange. In order to investigate the influence of the bolt material, experiments were conducted on two distinct bolted joints. Initially, experiments were carried out on a X12CrMoWVNbN10-1-1 bolted joint at 600°C, followed by a Nimonic 80A bolted joint at 625°C. To gain further insights, a numerical model was created using a modified Graham-Walles creep model. Model parameters were fitted using data from dedicated creep and stress-relaxation tests. Subsequent simulations were performed to assess the effects of bolt material, thread representation, prior loading history and the temperature distributions. The experimental results reveal contrasting deformation behaviours for the two bolt materials, a trend that is reproduced in the simulations. Furthermore, the numerical analyses demonstrate that prior loading history must be taken into account to achieve more accurate predictions of the residual bolt stress.*

## **Key Words**

*Stress relaxation, creep, turbine flange, transient loads, retightening of bolts, simulation, modelling*

# P098: High-Temperature Materials in the Energy Transition: Addressing Complex Degradation in Next-Generation Power Systems

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## Summary

*The global shift toward low-carbon energy systems is driving the deployment of technologies that operate under increasingly severe thermal and chemical conditions. As coal-fired power plants are phased out and gas turbines are relegated to peaking roles with limited operational hours, the demand for materials capable of withstanding flexible and transient thermal cycles is intensifying. Concurrently, advanced nuclear systems—including Generation IV reactors and advanced modular reactors (AMRs)—are being designed for elevated operating temperatures and exposure to aggressive coolants such as molten salts and liquid metals. Gas turbines are transitioning to alternative fuels like hydrogen and ammonia, while oxy-fuel combustion and concentrated solar power (CSP) systems further push the thermal envelope.*

*These developments necessitate a paradigm shift in high-temperature materials engineering. Traditional creep-dominated degradation is giving way to complex, synergistic mechanisms involving creep-fatigue interaction, oxidation, and corrosion. The accurate prediction of component life under such mixed-mode degradation regimes is a critical challenge to ensure the structural integrity and reliability of materials in future energy systems.*

## Key Words

*Mixed-mode degradation, hydrogen, advanced modular reactors, oxy-fuel combustion.*

# P099: Improved Residual Life Assessment by Identifying the Actual Creep Scatter Band of Power Plant Components During Operation

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## Summary

*The following describes a method to enhance the assessment of service life or residual service life of power plant components by accounting for the material specific creep scatter band factor. The approach assumes that the creep scatter band factor can be accurately determined well before fracture by comparing measured deformation under real, non-isothermal operation with corresponding simulated deformation.*

*To describe creep deformation, a modification of the well-known 'Logistic Creep Strain Prediction' (LCSP) model was used. The modification incorporates a scatter band concept, allowing for the derivation of a model adjustment that reflects the hypothetical mean batch deformation behaviour of a specific material when creep deformation curves from different batches are used, and their scatter band factors are known. Also, an additional creep term was introduced to enable a unified description of both dislocation and diffusion creep within a single model framework.*

*The predictive accuracy of the underlying creep deformation model was quantified based on the standard Post Assessment Tests (PATs) of the European Collaborative Creep Committee (ECCC). In addition, a concept for service life predictions based on creep deformation was developed and extended for the evaluation of the scatter band position. Recommendations for applying the method were developed with the help of evaluations of the predicted scatter band of different casts and the results of the post-assessment-tests adapted for this purpose. These support the user in estimating and extrapolating design-relevant creep strength values based on measured component deformations.*

*Within this work, the modified LCSP model has been adjusted on a large set of creep deformation curves from different batches of the martensitic steel Grade 91. The application of the proposed concepts to the available Grade 91 dataset shows that the introduction of an additional term for diffusion creep into the LCSP model significantly improves the extrapolation of creep deformation and creep rupture strength in the operationally relevant range of low stresses and long durations. A prerequisite for this is the availability of creep deformation curves in the diffusion creep regime. Finally, a demonstration conducted on a component operating in a real power plant highlights both the prerequisites and potential of the method.*

## Key Words

*Creep deformation modelling, Post Assessment Tests, creep scatter band factor, diffusion creep, Grade 91*

# P102: Current status of the Indian AUSC power plant initiative

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## Summary

*The Indian Advanced Ultra Supercritical (AUSC) power plant project started with an objective to reduce CO<sub>2</sub> emissions. It is a landmark national program marking India's arrival at the forefront of coal-based power generation technology. The development of AUSC power plant in India is a government–industry consortium which includes Bharat Heavy Electricals Limited, National Thermal Power Corporation and included in Phase 1 Indira Gandhi Centre of Atomic Research for the development of materials which can help power plant components operate at high temperatures and pressure. The initiative aims to demonstrate and commercialize an 800 MW AUSC power plant with indigenous technology.*

*The demonstration plant includes steam temperatures of 710–720°C, main steam pressure of 310 bar, and a projected gross plant efficiency of 46%—a step change from the 38–42% efficiency of conventional and supercritical units. These targets will enable a reduction in coal consumption and specific CO<sub>2</sub> emissions by approximately 11% per unit of power generated, supporting India's climate commitments and energy security.*

*The AUSC R& D phase, completed in December 2020, established a domestic supply chain for advanced ferritic and nickel-based superalloys, validated through long-term creep, fatigue, and oxidation testing under near-operational conditions. The plant's core components—boilers, steam turbines, and high-temperature piping—will utilize these indigenous materials, certified for prolonged operation at extreme parameters.*

*Site selection for the 800 MW demonstration plant has been finalized at NTPC's complex in Chhattisgarh. Following central government approval and fiscal closure, the construction phase is slated for completion within 4.5 years, on top of the already finished 2.5-year R&D phase, targeting full commissioning by 2030. This project, once operational, will set a new global benchmark for advanced coal-fired power, firmly establishing India as a leader in sustainable, high-efficiency thermal technology.*

*The work here reviews the developments of Indian AUSC power plant in different stages, environmental effects, operational challenges, safety, water requirement, environmental factors and technological developments.*

## Key Words

*AUSC, power plant, materials for power plant*

# P104: A review of stable models to reliably extrapolate creep rupture strength values (Extended Abstract)

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## Summary

*Ever since Larson and Miller published in 1952 a method of collapsing creep rupture test data at different temperatures and stresses onto a single curve, numerous mathematical models have been developed to describe the time-dependent failure behaviour of materials in creep. Such models are widely used to determine the strength values recorded in standards and design codes to permit the safe and efficient operation of high temperature plant. Typically, 200kh lifetimes are declared for fossil power plant. More recently, however, it has been the stated objective for nuclear plant to design for a 60 year minimum life (~500kh). However, a 60 year life implies a test programme running for 20 years before materials and their properties can be used. It would be difficult to develop new plant for a 60 year life on such a basis.*

*It is desirable, nevertheless, to use stable models that can be extrapolated to provide realistic estimates of long-term life (and hence strength values) and can form the basis for lifetime estimation more reliably than the potentially less stable polynomial forms used for decades [1]. These traditional polynomial forms, and several intrinsically stable models designed to replace them are compared using a trial dataset (NIMS datasheet 3A on 10CrMo 9 10 Normalised and Tempered steel). The questions addressed are: 1) how to use creep rupture test data to understand the changing failure mechanisms over ranges of temperature and stress; 2) how best to develop, categorise, and judge stable models; and 2) is there a risk that stable models are also inflexible, and therefore unable to represent well the material properties at very long times?*

*In discussion, the paper seeks to identify general criteria for stable and accurate models, and how they might be applied flexibly to adapt to, for example: different dominant deformation and failure modes; the enhancement of creep deformation by oxidation and other surface effects. Such criteria could provide a benchmark and framework to not only review current models, but also to identify future development activities.*

## Key Words

*Creep, Time-Temperature-Parameters, LOESS, Datum Temperature*

# **P106: Creep Damage Evaluation of Super 304H Steel Boiler Tube under Internal Pressure**

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## **Summary**

*This paper presents the creep damage evaluation of Super 304H steel under internal pressure. Internal pressure creep tests were performed at 700 °C and interrupted at specific life fraction to obtain pre-damaged tube specimen. Miniature specimens were extracted from the pre-damaged tube specimen and creep damage undergone in the pre-damaged specimen were measured through the uniaxial creep rupture lifetimes of the miniature specimens. Miniature specimens were extracted from the inner surface, mid-thickness and outer surface of the tube wall. Miniature specimens extracted from the mid-thickness overestimated the creep damage at the accelerated stress condition but estimated appropriately at the same maximum principal stress condition as that of the pre-damaged internal pressure creep test. There was a little effect of sampling orientation of specimen on the creep property of pre-damaged specimen under the internal pressure, indicating that creep damage accumulated isotropically under internal pressure. The creep damage in the mid-thickness region was slightly greater than that of the inner and outer surfaces of the pre-damaged specimen under the internal pressure.*

## **Key Words**

*Creep, Damage, Evaluation, Miniature Specimen, Super 304H, Internal Pressure.*

# P107: Effect of Periodic Additional Loading on the Creep Life of Grade 91 Steel

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## Summary

*This study investigated the effect of periodic additional loading superimposed on a base load on the creep life of Grade 91 steel. Creep specimens were machined from a normalized, tempered, and simulated-PWHT pipe, with the circumferential direction aligned parallel to the loading axis. Creep tests were conducted at 650 °C with a base stress of 70 MPa, and additional stresses of 50 MPa or 30 MPa were applied for 1 h every 24 h.*

*Under the 50 MPa additional loading, rupture occurred at approximately 2100 h, whereas the test with 30 MPa additional loading was interrupted at approximately 8200 h without clear acceleration. The 50 MPa additional loading significantly reduced the creep life compared with that predicted by the linear rule based on constant-load data at 70 MPa and 120 MPa, whereas the 30 MPa additional loading showed little deviation from the linear rule prediction.*

*Microstructural observations revealed pronounced subgrain development in the mid-gauge section of the specimen tested with 50 MPa additional loading, including regions far from the fracture surface. In contrast, the tempered lath martensitic structure was largely retained in the specimen tested with 30 MPa additional loading. Analysis of creep-rate–time curves indicated that, under 50 MPa additional loading, the creep rate gradually increased with time during both the additional loading periods and the base stress periods, which is attributed to enhanced microstructural recovery. In contrast, under 30 MPa additional loading, the creep rate remained close to the minimum creep rate obtained under constant-load conditions throughout the test duration.*

*These results suggest that the applicability of the linear rule under periodic additional loading depends on the level of additional stress.*

## Key Words

*Periodic additional loading, creep life, Grade 91 steel, microstructural recovery, linear rule*

# P111: Mean-field modeling of the creep deformation response of alloy 1.4959 addressing precipitate kinetics

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## Summary

*High temperature creep deformation of austenitic steel alloys is accompanied by a complex process of microstructure evolution induced by internal and environmental factors. Processes such as aging and corrosion (i.e., ripening and precipitation of primary and secondary precipitates) result in non-conventional creep hardening and softening trends that are found beyond the limitations of conventional creep models. In this work, a mean-field creep model adapted to recover the non-classical creep response of austenitic steel 1.4959 alloy is formulated, implemented and validated. The microstructure evolution is considered in terms of precipitate kinetics, and is evaluated by means of ex-situ CALPHAD simulations conducted in ThermoCalc TC-PRISMA. This approach allows to recover the creep hardening and softening effects attributed to phenomena such as solid-solution hardening, precipitate strengthening and precipitate damage accumulation. The numerical implementation of the model follows a fully-implicit 1-level Newton-Raphson resolution algorithm. Physical parameters are obtained from either literature or in-house experiments, whereas fitting parameters are optimized to fit the creep response observed during our creep experimental campaign. Creep curves obtained using the validated set of parameters show reasonable accuracy with experiments. Further extrapolation of results is physically consistent, and reliability is limited to loading regimes sharing the same creep mechanisms. An additional phenomenological cavitation damage formulation is implemented to achieve accurate fracture prediction.*

## Key Words

*Dislocation forest density, Dislocation creep, Solid-solution hardening, Non-classical creep behavior, Incoloy 800H, Thermo-Calc PRISMA*

# P112: Evaluation of the Effect of Hydrogen on Creep Properties Using Hollow Specimens: A Study on SUS316L Steel

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## Summary

*The effect of hydrogen on the creep behavior of SUS316L steel was investigated using hollow specimens. Hollow cylindrical specimens (gauge length 30 mm, outer diameter 6 mm, inner diameter 2 mm) were machined from a commercially available round bar after solution treatment at 1100 °C for 1 h, resulting in an average grain size of approximately 100 μm. Creep tests were conducted at 800 °C and 30 MPa with hydrogen or air introduced into the hollow interior and air on the outer surface, hereafter referred to as H<sub>2</sub>/Air and Air/Air conditions, and were interrupted at 185 h and 1200 h. Creep strain was monitored using extensometers and linear variable differential transducers (LVDTs), and the microstructures of interrupted specimens were examined by field-emission scanning electron microscopy (FE-SEM). Both specimen types exhibited a similar minimum creep rate of approximately  $3 \times 10^{-5} \text{ h}^{-1}$ ; in the Air/Air specimen the creep rate remained nearly constant until interruption, whereas in the H<sub>2</sub>/Air specimen it gradually increased to approximately  $6 \times 10^{-5} \text{ h}^{-1}$  by around 150 h and subsequently stabilized. Microstructural observations revealed comparable precipitation behavior in both specimens, while extensive oxidation developed on the outer surface of the H<sub>2</sub>/Air specimen, with the oxide layer following parabolic growth kinetics. A simple simulation assuming that only the metallic portion of the specimen carried the applied load, with a stress exponent of 5, predicted creep rates 1.6 and 2.9 times higher than those of the Air/Air specimen at 185 h and 1200 h, respectively; however, this prediction did not reproduce the experimentally observed evolution of the creep rate. These results indicate that the higher creep rate under the H<sub>2</sub>/Air condition may not be fully accounted for by precipitation or oxidation effects alone, particularly in terms of the time evolution of the creep rate, suggesting that hydrogen contributes to creep deformation through additional, yet not fully clarified, mechanisms.*

## Key Words

*Creep, high-temperature hydrogen atmosphere, Austenitic stainless steel, Carbon neutrality*

# P114: Grain Size Dependence of Grain-boundary Precipitation Strengthening due to P phase in Creep of Ni-Cr-Mo Alloys at Elevated Temperatures

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## Summary

*This paper investigates whether grain-boundary precipitation strengthening (GBPS) due to TCP phases can function in Ni-based superalloys and examines its relationship with grain size dependence. TCP phases are generally regarded as detrimental phase because creep strength is decreased by their precipitating. Therefore, conventional Ni-based superalloys are designed to suppress their precipitation. On the other hand, since TCP phases are thermodynamically stable, they can be effective strengthening phases if properly controlled. Fe-Cr-Ni-Nb alloys developed by Takeyama et al. have achieved superior creep strength comparable to Ni-based alloys due to GBPS due to TCP/Laves phases. This result suggests that GBPS due to TCP phase could also enhance the creep strength of Ni-based superalloys.*

*Creep tests using Ni-15Cr-15Mo (at.%) model alloy demonstrated that the grain boundary TCP phase reinforce grain boundaries and that GBPS is effective in Ni-based superalloys. Multi-step heat treatment produced a microstructure with TCP P-NiCrMo(oP56) phase at grain boundaries and GCP Ni<sub>2</sub>(Cr, Mo) (oP6) phase within grain interiors. Creep tests under 973 K/300 MPa were conducted on materials, which is conducted multi-step heat treatment, with the grain size (d) of 320 μm and the grain boundary coverage ratio (ρ) ranging from 0.35 to 0.85. The creep strength increased with higher ρ; the specimen with ρ = 0.85 exhibited a rupture time approximately three times longer, and a rupture elongation approximately nine times higher than that with ρ = 0.35. Therefore, GBPS is effective method to enhance creep strength of Ni-based superalloys and that TCP phases, when properly controlled to precipitate at grain boundaries, can function as strengthening phases.*

*Additional creep tests were conducted to examine the effect of grain size on GBPS due to the P phase on heat-treated materials with similar ρ (≈ 0.8) and different grain sizes (d=210 and 320 μm) under 973 K/300 MPa. The fine-grained material exhibited higher ductility, but its rupture time was shorter, and its deformation was faster than the large-grained material. The grain size exponent calculated from the relationship between minimum creep rate and grain size was -0.44, which is lower than the commonly reported value (-1.0), this result suggests that the grain boundary P phase suppressed grain size dependence of creep in Ni-based superalloys. Microstructural observations after fracture revealed that the creep deformation occurred at the bare grain boundaries. Therefore, reducing the area of the bare grain boundaries is essential for improving the creep strength. Since the fine-grained materials have larger bare grain boundaries area even at the same ρ, increasing ρ can further suppressed the grain size dependence and enhance the creep strength.*

## Key Words (using Heading 1 Style)

*TCP phase, Phase diagram, Microstructure control, GBPS, Thermal power plant*

# P115: Philosophy of Grain Boundary Precipitation Strengthening (GBPS) in Creep - Modelling and Experiments

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## Summary

*Objective of this paper is to identify the creep strengthening mechanism, specifically focusing on the role of grain-boundary precipitates in creep deformation. The higher the fraction of grain-boundary coverage ratio ( $r$ ) by the thermodynamically stable phases, the lower the creep rate, along with the following equation:  $\dot{\epsilon} \dot{\epsilon}_1 / = (1 - r)$ , where  $\dot{\epsilon}$  is creep rate of the material with grain-boundary precipitates and  $\dot{\epsilon}_1$  is that of the material with no grain-boundary precipitates. This strengthening method is called "Grain-boundary precipitation strengthening (GBPS)". Based on this strengthening mechanism, together with innovative "inverse" design approach, novel solid solution type Ni-Cr-W alloys with bcc  $\alpha_2$ -W phase at grain boundaries and novel Fe-Cr-Ni-Nb austenitic heat-resistant steels with Fe<sub>2</sub>Nb (C14) Laves phase at grain boundaries have developed. These alloys exhibit creep rupture strengths more than three times superior to those of conventional Hastelloy X at 1273 K and SUS347 type steels at 1073 K, respectively. The microstructure analyses clearly demonstrate that creep deformation preferentially occurs along grain the region near boundaries (mantle region), and the thermodynamically stable phases precipitated at the grain boundaries change the mantle region to core region, suppressing the localized deformation, and this is responsible for improving the long-term creep rupture strengths. The grain-size dependence of GBPS in creep was calculated based on the core-mantle model by introducing the microstructure factors of grain size  $d$  and  $r$  into the equation of creep rate, and the model suggests that, as the grain size becomes smaller, the slope of the grain-size exponent  $p$  becomes shallower from -1 to 0 (no grain-size dependency) with increasing the  $r$  from 0 to 1 (full coverage of GBs). The validity of the grain-size dependency of GBPS was experimentally confirmed under the power low creep conditions.*

## Key Words

*Grain-boundary Precipitation Strengthening (GBPS), Creep deformation, Grain-boundary coverage ratio, Grain size effect, Core-mantle model*

# P116: A quantitative study on microstructures and their boundaries after heat treatments and long-term service exposures of 9Cr steels

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## Summary

*This study quantitatively analyzes the evolution of microstructural parameters in heat-treated states (HT) and service-exposed states (BM and FGHAZ of weld joints) of 9Cr steels (P91, T91 and P92). Parameters investigated include the boundary densities of prior austenite grains and martensite laths, the volume fractions and cluster sizes of  $M_{23}C_6$  carbide, and the EBSD characteristic peak frequencies (especially,  $59.5^\circ/52.5^\circ$  and  $0\sim 5^\circ$ ). Utilizing SEM-EDS/EPMA-WDS, EBSD and AI tool, microstructures resulting from varying austenitization temperatures ( $920^\circ\text{C}$ ,  $1060^\circ\text{C}$  and  $1150^\circ\text{C}$ ) were compared. The lowest austenitization temperature produced the highest boundary densities of prior-austenite grains and martensite laths with a highest absolute value of free energy, producing the highest volume fraction and largest cluster size of  $M_{23}C_6$  precipitates, significant C/Cr depletion in the matrix, and the lowest hardness values. The resulting grain-boundary characteristics closely resemble those observed in FGHAZ regions of service-exposed 9Cr steels where creep void formation and Type-IV cracking occurred. Simulated heat-treatment tests further confirmed that the highest austenitization temperature yields the most stable microstructure, whereas the lowest temperature produces a much less stable one that closely mimics the FGHAZ morphology and boundary misorientation feature. These results validate that the precipitation and coarsening of  $M_{23}C_6$  carbides promoted local Cr and C depletion, which subsequently drove the evolution of HAGB/LAGB distributions and KAM intensities, elevate local stress/strain concentrations, and ultimately accelerated creep-void nucleation and growth. In addition, a pair of EBSD-based quantitative indicators, PCI (Peak Clustering Index) and SI (Structural Index), is introduced to assess the microstructure stability / degradation degree of the 9Cr steels.*

## Key Words

*9Cr steels, Boundary densities of prior austenite grains and martensite laths,  $M_{23}C_6$ , HAGB/LAGB and KAM, Structure stability.*

# **P117: Time dependent deformation and crack behavior of similar/dissimilar weld joints made of ferritic-martensitic 9% Cr steels under creep and creep-fatigue loadings**

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## **Summary**

*Ferritic-martensitic materials are often used in piping systems and complex turbine and valve casings in high temperature power plant applications. Welded joints are indispensable for the manufacture and repair of these components and play a decisive role in determining their long-term performance and reliability. In this paper, two weld joints were investigated: a dissimilar weld joint of CB2 and P92 steel with an additional buttering layer in-between (hereafter referred to as weld CB2/BU/P92) as well as another similar weld joint of P92/P92 steel.*

*Firstly, the microstructure was investigated to characterize the heterogeneous weld structure consisting of weld metal, different heat-affected zones, and base material. To investigate time dependent deformation and strength behavior, creep tests were carried out on both welds and base materials. Especially for the dissimilar weld CB2/BU/P92, creep tests at 600 °C and 625 °C showed different creep rupture positions. Numerical calculations with heterogeneous locally fitted material properties predicted the same rupture positions as observed in the tests.*

*High temperature creep crack growth (CCG) tests were performed on compact tension (CT) specimens of both joints and the corresponding base materials, in order to investigate crack initiation and crack growth behavior of the joints and then compare them with that of base materials. Moreover, systematic creep-fatigue crack growth (CFCG) tests were performed on corner crack (CC) specimens made of these joints. Standard and complex loading cycles were used hereby to investigate the crack behavior under different creep-fatigue conditions.*

*Furthermore, evaluation methods and assessment concepts based on fracture mechanics parameter developed in previous studies for ferritic-martensitic base materials were modified and extended to be applied on ferritic-martensitic welded joints.*

## **Key Words**

*Martensitic and ferritic steels, weld joint, creep-fatigue, crack behavior, finite-element modelling*

# **P120: Stress-rupture of austenitic steel 316L in contact with oxygen-containing liquid lead–bismuth eutectic: An example of superimposition of corrosion and creep**

## **(Extended Abstract)**

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### **Summary**

*Previously published test results obtained for an austenitic steel of type 316L at 550 °C, under 300 MPa static load and simultaneously exposed to oxygen-containing liquid lead–bismuth eutectic (LBE) are re-evaluated in order to solve an apparent contradiction between observed reduction in load-bearing cross section and creep life for two different regimes as to oxygen dissolved in the liquid metal.*

### **Key Words**

*Liquid metal, creep analysis, corrosion scale, selective leaching, oxidation, internal stress*

# **P121: High Frequency Fatigue Behaviour of Ti-6Al-4V Alloy, Effect of Stress Ratio**

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## **Summary**

*Ti-6Al-4V (Ti-64) alloy is widely used in aerospace applications due to its high strength-to-weight ratio and excellent corrosion resistance even at moderate temperatures. The components made of Ti-64 are subjected to different temperatures and stress ratios (R) during service. High Cycle Fatigue (HCF) tests were conducted on Ti-64 specimens for R values of 0.5 and 0.7 and at a frequency of 78 Hz using the RUMUL TESTRONIC 100 kN resonance system. The frequency was determined by the system based on the material's stiffness. Stress levels ranging from 700 to 1350 MPa were used, with increments of almost 50 MPa. SN curves were generated, and Basquin's constants were derived. Results indicated that the fatigue limit at RT and 150 °C increased with an increase in R value. The effect of R on fatigue strength was found to vary with a change in the maximum stress at both temperatures. Above a particular maximum stress value, R=0.5 resulted in improved fatigue strength. In this region, the damage was attributed to the maximum stress. However, below that maximum stress value, R=0.7 resulted in improved fatigue strength. In this region, the damage was attributed to alternating stress. Fractographs confirmed that at higher stresses, the fatigue life was dominated by the mean stress rather than the alternating stress.*

## **Key Words**

*High Cycle Fatigue (HCF), Stress ratio, Moderate temperature, Maximum stress, Fractograph, Ti-6Al-4V alloy, SN curve.*

# P122: Effect of Hot-Isostatic Pressing on High-Temperature Low-Cycle Fatigue and Creep Behavior of Laser Powder Bed Fused Alloy 718 (Extended Abstract)

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## Summary

*This study investigates how hot-isostatic pressing (HIP) influences the high-temperature deformation and damage responses of laser powder bed fused (LPBF) Alloy 718 by comparing a non-HIP condition and a HIP-treated condition under a controlled final heat-treatment schedule. To isolate the intrinsic effects of HIP, both conditions received identical solution treatment and aging. Microstructures were characterized using electron backscatter diffraction (EBSD) and scanning electron microscope (SEM), and mechanical behavior was evaluated via tensile testing, strain-controlled low-cycle fatigue, and creep testing using both smooth and notched specimens. The work is intended to clarify how HIP shifts the balance between cyclic and time-dependent deformation in LPBF Alloy 718 by linking microstructural evolution (recrystallization, grain-size changes, and substructure modification) to observed deformation and damage characteristics.*

## Key Words

*Alloy 718, Laser powder bed fusion, Hot-isostatic pressing, Low-cycle fatigue, Creep, Ductility, Recrystallization*

# P123: Role of Small Punch Creep in assessing the effect of microstructure due to cyclic loading on rupture life in Su-263

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## Summary

*Su-263 is a Ni-based superalloy which is widely used in aerospace applications as well as stationary components of gas turbine because of its good creep resistance, oxidation resistance, and high specific strength at high temperatures. Understanding its behaviour under combined fatigue and creep conditions is crucial for improving its performance and reliability in such high-end applications. Small Punch Creep (SPC) testing has emerged as an effective technique for evaluating the creep properties using miniature specimens, typically 0.5 mm thick, offering valuable insights into material degradation when limited material is available. In this study, the effect of microstructural change due to prior cyclic loading on the creep life of Su-263 was investigated using SPC. Creep life was compared for different locations of two pre-cycled (PC) specimens, one which was exposed to 2,672 cycles at  $\epsilon_{max} = 0.9\%$  and the other to 5,720 cycles at  $\epsilon_{max} = 0.6\%$ , both with a tensile hold of 120 seconds and temperature of 600 °C. The SPC tests were conducted at 650 °C temperature and 700 N load for samples extracted from thread region, near to the fracture, and away from the fracture locations of each of the two pre-cycled (PC) specimens. It was found that the increased severity and the effect of microstructural changes induced by cycling clearly reflected into the creep response. The threaded region specimen was used as the baseline reference for comparison. Specimens tested closer to the fracture location displayed a larger reduction in creep life compared to the ones away from fracture location, indicating progressive material degradation. This accelerated failure was further supported by fractographic observations, highlighting the role of damage accumulation during process. The findings emphasized the critical role of prior cycling influencing the long-term creep performance of Su-263, highlighting the importance of accounting for fatigue history in the design and remaining life assessment of components operating under similar conditions.*

## Key Words

*Rupture life, superalloy, microstructural effect, cyclic loading, SPC*

# P124: Analysis of ex service Thor®115 pipes for refinery applications

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## Summary

*P5 and P9 steel grades are the typical options for fired heaters in refinery furnaces when the design metal temperature is close to 600°C. At such high temperatures, creep and oxidation are the dominant damaging mechanisms but, depending on the processed fluid, other mechanisms may be present, like carburization or coke formation. Thor®115 has been proposed for these applications, due to its better creep and oxidation performances respect to P5 and P9, which give to the plant owner higher safety margins and may allow also higher pipes life with savings in the maintenance operations.*

*By taking into account the above advantages, Tenaris, RINA and ISAB agreed to start a field test in an operating furnace. A Thor®115 pipe was installed in the radiant section of a heating furnace of the ISAB refinery located in Priolo, Italy.*

*The Thor®115 pipe was successfully installed during the 2020 turnaround and the furnace returned to service. During the last turnaround, one section of Thor®115 and one of P9, serviced for about three years, have been removed from the same position in the hot part of the radiant section for metallurgical analysis.*

*The present paper summarizes the laboratory analysis done on the sampled pipe sections. The results on ex-service pipes confirm the good behaviour of Thor®115 and its suitability for refinery applications.*

## Key Words

*THOR 115, furnace heaters, high temperature, oxidation, carburization*

# P125: Biaxial Tension Creep Evaluation with Miniature Cruciform Specimens for Type 304 Steel

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## Summary

*Creep experimental investigations are crucial for the safe design and remaining life evaluation of structural materials used in high-temperature equipment, such as turbine blades and boiler piping for power generation. A multi-axial creep experimental investigation is required because actual structures are subjected to multi-axial stresses. Furthermore, because experimental investigations using samples obtained from actual structures have many advantages, this study conducted multi-axial creep tests using a miniature cruciform specimen of a commonly used austenitic stainless steel. Specifically, the optimal shapes and dimensions of 50 mm x 50 mm cruciform specimens were obtained, and an in-situ observation technique in an electric furnace was developed. The creep rupture lifetime of Type 304 stainless steel was significantly reduced at 650°C under non-equal-biaxial stress conditions that simulated the stress state of a thin-walled pipe subjected to internal pressure. The maximum principal stress parameter is effective for evaluating the creep rupture lifetime.*

## Key Words

*Cruciform specimen, in-situ observation, Miniature specimen, Multi-axial stress*

# P126: Re-evaluation of creep rupture data of Nicrofer 6025 HT using a separated temperature range approach

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## Summary

*The high temperature Ni-based alloy Nicrofer 6025 HT (Alloy 602 CA - UNS N06025) has been designed for application temperatures up to 1200°C. Below 750°C, the main hardening mechanism is via carbides and  $\gamma'$ -particles, beside solid solution strengthening which can be found across the entire temperature range, and above 750 °C mainly via carbide hardening. This could lead to different creep mechanism depending on the temperature range.*

*In a first step, creep data ranging between 500 to 1200 °C, i.e. an extended data set with new results on creep tests compared to the previous analysis, was evaluated with the Larson Miller model with 1st to 3rd order polynomial in log stress, which all reveal systematical deviations. In a second step, the whole data set has been separated into two parts, in order to consider the different hardening mechanisms in the two temperature ranges. As a result, the analysis shows no systematical deviations and using the straight-line equation for log time as a function of log stress, one for each temperature region, leads to the most suitable results.*

*For re-calculating the allowable stresses, the ASME SWI stress rupture package has been used separately for the two parts of the whole data set and a significant increase of the allowable stresses, in particular at lower temperatures, has been achieved and the results are published in the ASME BPVC Section II Part D (2023).*

## Key Words

*Nicrofer 6025 HT, creep, modeling*

# **P127: Design, Development, and Ongoing Experimental Verification of the SPC 1300 DLS System for Very-High-Temperature Creep Testing of Miniature Specimens in Accordance with EN 10371**

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## **Summary**

*The SPC 1300 DLS is a newly developed testing system for small punch and miniature uniaxial creep testing at temperatures up to 1300 °C. This paper presents the design concept, key structural features, and the current stage of experimental verification of the system, developed within a four-year research project. The system enables testing of miniature specimens in accordance with EN 10371:2021 in a protective argon atmosphere, with automated load application and direct measurement of specimen-surface temperature. Long-term thermal stability of  $\pm 0.1$  °C was demonstrated experimentally at 600 °C over 62 h, while additional long-duration and higher-temperature validation tests are still in progress. The results obtained to date confirm the technical feasibility of the proposed concept and identify the key issues requiring further optimisation before full experimental qualification.*

*Testing miniature specimens offers major advantages, including reduced material and energy consumption and the possibility of assessing the remaining life of in-service components without shutdown. The SPC 1300 DLS extends miniature creep testing into the very-high-temperature range and supports the development and qualification of advanced materials for energy and other high-temperature applications. The system was developed within the four-year TREND research programme supported by the Technology Agency of the Czech Republic (TA ČR).*

## **Keywords**

*small punch creep test, miniature specimens, very-high-temperature testing, test equipment, EN 10371, protective atmosphere, SPC 1300 DLS.*

# P128: Creep testing of heat-resistant steels using miniature tensile specimens

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## Summary

*Testing of heat-resistant steels using miniature specimens represents an attractive topic, especially for the remaining life assessment of thermal power plants. In this paper, we summarize the results of uniaxial creep testing of ferritic-martensitic steel P92. Two miniature geometries are compared in this study - a flat sample with a squared section of 2x1 mm and a gauge length of 4 mm, with an overall length of 8 mm, and a round sample with a diameter of 2 mm and a gauge length of 7.6 mm, with M4 threaded heads and an overall length of 27 mm. The comparison of the time to rupture vs. stress on standard and miniature specimens is presented. Also, the minimum creep rate vs. stress has been evaluated. The scatter of the results represented by the squared multiple correlation ( $R^2$ ) is comparable or slightly worse in the case of miniature specimens. The difference in the rupture times between standard and miniature tests has been quantified and discussed to determine if it is acceptable to make a reliable extrapolation of the results to higher rupture times. The paper also looks at the aspects of the manufacturing of such miniature specimens and their possible impact on the creep test results. The results suggest that systematic research followed by possible standardization of miniature specimen geometry for creep testing should be highly desirable.*

## Key Words

*Miniature specimens, creep rupture, creep rate, extrapolation.*

# P129: Creep behaviour and martensite decomposition in additively manufactured Ti64 studied by Small Punch Creep Testing (SPCT)

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## Summary

*Titanium alloys are widely used in the aerospace systems due to their excellent mechanical properties and good corrosion resistance. Among them, Ti-6Al-4V (Ti64) is the most widely used, classically exhibiting  $\alpha + \beta$  microstructures. The development of additive manufacturing (AM) technologies, particularly Laser Powder Bed Fusion (L-PBF), has further expanded the use of Ti64. In its as-built state, L-PBF Ti64 exhibits a metastable  $\alpha'$  martensitic microstructure that develops within large prior  $\beta$  grains elongated along the building direction. The fabrication process may induce anisotropic and heterogeneous mechanical behaviour of elaborated parts. The Small Punch Testing techniques constitute a relevant testing method since it allows extracting small specimens (10 mm discs) from different places and orientation within parts elaborated through AM process.*

*In the present study, we examine the creep behaviour of AM Ti64 alloy using small specimen testing techniques, namely Small Punch Creep Tests (SPCT) and uniaxial creep tests on miniature specimens. The present work focuses on the study of the L-PBF Ti-6Al-4V in the as-built state in an intermediate temperature range (400-500°C). Creep parameters are compared using Norton and Monkman-Grant plots, demonstrating the reliability of SPCT for characterizing the creep response of this alloy. Observations of the specimen microstructure after interrupted SPCT at midlife show heterogeneous evolution, with locally complete martensite decomposition and the formation of sub-micron equiaxed grains. Finite element modelling links the microstructure evolution to localized zones of high cumulative plastic and creep strain. A mechanism is proposed for this microstructure evolution in support to the mechanical behaviour of the as-built alloy.*

## Key Words

*Ti-6Al-4V, LPBF, creep*

# P130: Steel Grades 91 and 92 Microstructure and Precipitate Evolution Atlas and life assessment tool (Extended Abstract)

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## Summary

*This paper summarizes the work carried out within Grade 91 and Grade 92 atlas project launched by INAIL jointly with RINA Consulting - Centro Sviluppo Materiali S.p.A (CSM). Result analysis has evidenced microstructural modification and precipitate evolution of steel Grade 91 during isothermal ageing for a total annealing time up to 96,000 hours showing an advanced stage of recovery process of original tempered martensite, combined with the coarsening of  $M_{23}C_6$  carbide, Laves phase formation and coarsening. Long term ageing at 650 °C promotes the destabilization and subsequent dissolution of the Laves phase, which is no longer detected after 87,000 hours. The combined effect of temperature and stress on precipitate evolution of  $M_{23}C_6$  carbide and Laves phase during creep up to 30,000 hours have been also evaluated, which in turn enhances the kinetics of the microstructural constituent evolution.*

## Key Words

*MX,  $M_{23}C_6$ , Laves Phase, Z phase*

# P131: Advanced Remaining Life Estimation for cyclic operation of P92-Components in GKM Unit 9

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## Summary

*Due to the ongoing transition in energy supply the lifetime of existing plants and its determination are affected by changes in operation modes. In the current situation pure flexible operation of plants is often necessary for grid stability and during periods of low renewable energy production. However, most existing plants were originally designed to operate at static or nearly static loading conditions, with creep as dominant damage mechanism. A recent assessment of GKM Unit 9 showed that cyclic contribution to the lifetime consumption is for several components significantly higher than expected in design, or the design limit in terms of allowed cycles will be reached much sooner as expected.*

*To address this issue, a project was initiated by GKM Mannheim, Germany, to achieve a more precise assessment of lifetime consumption for its coal fired Unit 9 (911 MW). The concept involves:*

- *Use of batch specific creep data obtained from long-term creep tests on material which was taken in the manufacturing phase of the plant from the components with the highest expected design life consumption*
- *Analysis of operational data and identification of real load cycles*
- *Lifetime estimation for typical cycles of selected components using advanced FE-based constitutive equations and a fracture mechanics-based lifetime model*
- *Comparison of these results with those obtained by the installed monitoring system that uses standard lifetime calculation according to EN 12952.*
- *Specific consideration of welds in critical components*

*The paper describes the concept in detail and gives an overview on analyses of operational data, material data and numerical calculations. A modified definition of cold, warm and hot starts based on the analysis of operational data is given, representative cycles were derived from these data. In a first step, a main steam line T-piece, which shows the highest increase in life exhaustion in the evaluation of data from the installed monitoring system, was selected for numerical analysis of lifetime. The results provide a more realistic estimation of the actual lifetime consumption and allow to investigate future operation scenarios.*

## Key Words

*Flexible Operation, Lifetime estimation, Operational Data, FE-based lifetime calculation, Grade 92*

# P132: Investigations on creep and microstructure of P93 as next generation high temperature martensitic pipe material

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## Summary

*Different classes of creep resistant, high alloyed martensitic steels are applied in power plants and other applications. Starting from steel P9 with 9% Cr, further alloying elements were added over the last decades to improve long-term stability and creep strength, resulting in Grade 91 and Grade 92 which are in wide use today. The alloy class of MarBN steels developed in Japan, offers further advantages, and was therefore investigated in different product forms in Europe, e.g. castings, forgings, and pipes. Alloy composition adjustments had to be applied to meet the different component requirements and manufacturing routes. Currently a wide commercial use of MarBN steel grades is still outstanding. Components made of the particularly promising MarBN steel Grade 93 were in the meantime standardised in ASTM A182 (forgings), A213 (seamless tubes) and A335 (seamless pipes) and are regulated in ASME code case 2839, stating a 9Cr-3W-3Co-Nd-B material for applications above 600 °C. Grade 93 pipe material from Nippon Steel/Japan has been delivered to Europe to improve and complete knowledge on the expected properties and to perform own investigations. Therefore, ECCC has installed an appropriate working group. Multi-national collaborative actions coordinated and supported by the ECCC within working group WG3A 'Ferritic Steels' started exploring creep tests at 650 °C and 675 °C, now approaching test times of 9,000 h. So far, the test results for durations  $\geq 1,000$  h match the lower bound of the creep scatter band of published Nippon Steel creep data. Microstructural investigations on material in as-received condition and after creep tests were performed. Metallurgical evidence, creep test results, collected data, and further information will be discussed in the light of other published data.*

## Key Words

*Martensitic steels, creep behaviour, microstructure*

# **P133: CEA–JAEA collaborative study on miniature ring creep and fracture toughness characterization of ODS cladding tubes for Fast Reactor (Extended Abstract)**

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## **Summary**

*France and Japan are jointly developing oxide dispersion strengthened (ODS) steel claddings for Generation IV sodium-cooled fast reactors, designed to operate under severe thermo-mechanical conditions at temperatures up to 650-700 °C. ODS ferritic/martensitic steels are among the most promising candidate materials for fast reactor cladding applications due to their excellent high-temperature strength, irradiation resistance, and microstructural stability. Within the framework of a collaborative CEA-JAEA program, the creep and fracture toughness properties of two independently developed cladding grades, a martensitic 9Cr-ODS steel (JAEA) and a ferritic 14Cr-ODS steel (CEA), were investigated using adapted methodologies suitable for thin-walled tubular geometries. A cross-comparison interlaboratory campaign of miniature ring creep tests was conducted at high temperature and complemented by internally pressurized creep tests, considered representative of in-service conditions. The creep behavior was analyzed using classical power-law relationships and time-to-rupture correlations. In parallel, fracture toughness was evaluated using a miniaturized Ring Notched Bend (mRNB) three-point bending configuration specifically developed by CEA for thin cladding tubes. Finite element-derived geometric functions enabled the determination of  $J$ - $\Delta a$  resistance curves through the unloading compliance method. For the JAEA 9Cr-ODS tube,  $J_0.2$  values were assessed and compared with previously reported results for the CEA 14Cr-ODS grade. The objective of this work is to establish a consistent experimental framework enabling reliable interlaboratory comparison while minimizing material consumption. The materials, specimen preparation procedures, testing conditions, and data reduction methodologies are described in detail. This study aims to demonstrate the robustness and reproducibility of miniature ring-based methodologies for the evaluation of both creep and fracture behavior of ODS cladding tubes.*

## **Key Words**

*Sodium Fast Reactor, ODS, fuel cladding tube, ring creep test, creep strength, fracture toughness test.*

# P134: Nuclear Design Code Challenges for Advanced Nuclear Reactors

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## Summary

*Nuclear energy is expected to play a crucial role in achieving a low-carbon energy system in the coming decades. This requires the design, construction, and deployment of advanced Generation III and IV reactors. Generation IV technologies include sodium-cooled fast reactors (SFR), liquid-lead-cooled reactors (LFR), molten-salt-cooled reactors (MSR), very-high-temperature reactors (VHTR), and gas-cooled fast reactors (GFR). These systems operate under harsher conditions, involving more corrosive coolants, higher temperatures, and stronger irradiation.*

*Licensing for construction and operation is governed by national and international regulations. Designers and operators must demonstrate structural integrity and functionality under all service conditions. To support this, nuclear design codes — primarily AFCEN's RCC-MRx (France) and ASME (USA) — provide fabrication procedures, material data, and design rules based on proven engineering, testing, and operational feedback. However, qualifying new materials for slow degradation processes like creep can take decades, leaving few materials formally approved. For unproven designs, safety must be demonstrated through pre-normative research.*

*The development and deployment of advanced reactors face several challenges:*

- Safety must be demonstrated under more severe conditions, including coolant corrosion — particularly critical for MSR and LFR systems.*
- Components must achieve at least 60-year design lifetimes or allow replacement due to high capital costs.*
- Reactor development and code evolution must proceed rapidly to meet deployment timelines.*
- New reactors must be economically competitive with other low-carbon technologies and capable of flexible operation such as load following.*

*In Europe, several Generation IV projects focus on liquid-lead and molten-salt systems, following a staged path from demonstration to deployment. Early demonstration reactors will operate at moderate temperatures using qualified materials—mainly austenitic steels of the 316 family. The primary technical challenge is coolant compatibility, driving the need for standardized tests addressing corrosion, liquid-metal embrittlement, and creep in molten salts and liquid lead.*

*For deployment-ready designs, higher operating temperatures and irradiation levels require additional code-qualified structural materials. Qualification follows RCC-MRx guidelines for introducing new materials, which is easier for commercial alloys than innovative ones. Advanced manufacturing methods could improve cost-effectiveness but must still achieve code qualification or equivalent safety justification.*

*The presentation reviews Generation IV reactor types, deployment challenges, and the RCC-MRx code's approach to material qualification. Special attention is given to LFR and MSR technologies, focusing on coolant compatibility and creep. Related work from EURATOM projects and the GEN WS064 initiative on RCC-MRx code evolution will be discussed, including methods for accelerated material qualification using miniature testing, accelerated degradation studies, and machine learning. A Design Code Qualification Technology Readiness Level (DCQ-TRL) scale from 0 to 5 has been introduced. Some examples:*

- 316L(N) austenitic steel: DCQ-TRL 5 for SFR, 4 for LFR/MSR; temperature limited to 450 °C due to corrosion.*

- *Aluminum-forming austenitic (AFA) steels: improved corrosion resistance up to 550 °C, but corrosion-creep interaction requires study (DCQ-TRL 1–2).*
- *Inconel 625: introduced in RCC-MRx 2025 for non-creep use; reliable creep data still lacking (DCQ-TRL 3).*
- *SiC–SiC composites: excellent corrosion, creep, and irradiation resistance but brittle; each component requires qualification. Almost no nuclear feedback experience (DCQ-TRL 1).*

# **P136: Operator experience with Grade 92 as a material for pressure equipment and monitoring concepts to ensure safe long-term use under creep stress**

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## **Summary**

*With the introduction of live steam temperatures of 600°C and up to 620°C in the intermediate pressure range, Grade 92 is widely used as a pipe and forging material in European power plants. Operating experience to date has not revealed any material-critical damage cases. Nevertheless, a detailed review of the monitoring methods used has been carried out due to the international discussion initiated by ASME on the evaluation of creep rupture ductility of martensitic heat-resistant materials. For the review, the reasoning of ASME CC3048 was evaluated in detail, and a data analysis of Grade 92 was performed based on more than 300 data sets. In a broader context, the material delivery specifications were reviewed and adjusted where necessary based on the findings. All recurring tests for this material were also considered. After weighing up all the available information, it was confirmed that the established national and European assessment methods are valid, and therefore operational safety can be guaranteed. It is further recommended to follow or consider the additional specification notes for materials and recurring testing for inspections provided by the vgb standards. In principle, further investigations are planned to gain a deeper understanding of the long-term deformation behaviour of martensitic heat-resistant grades under creep stress. The current findings and outlook are an important contribution to the energy security in Europe over the next 20-30 years.*

## **Key Words**

*Grade 92, creep ductility, creep damage, lifetime monitoring*

# P137: Creep in Composite Phase Change Materials

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## Summary

*Phase Change Materials (PCMs) are designed to store and release (latent) heat through phase transformations, such as melting and solidification. Composite Phase Change Materials (C-PCMs) combine a phase undergoing transformation with a second phase, which can provide additional functionalities, such as enhanced thermal conductivity or tailored sensible heat contributions for heat storage and release. Furthermore, if properly designed and manufactured, C-PCMs can ensure effective confinement of the PCM phase in the molten state and form stability. Among these materials, the present study focuses on fully metallic C-PCMs based on Al-Sn system. Previous studies have shown that internal stress fields develop during thermal cycling across phase transformation due to volume changes associated with the melting and solidification of the low-melting Sn phase (the PCM phase), combined with the mismatch in thermal expansion between solid Al and Sn. In this paper the analysis of the thermomechanical behavior of a representative Al-Sn C-PCMs is extended to potential service conditions, in which compressive loading is combined with thermal cycles of different duration. Numerical analyses were carried out using an idealized finite element model of the C-PCM, representative of the phase arrangement. The plastic and creep behavior of Sn was experimentally determined and combined with literature data for Al, as well as with thermophysical properties of both phases. The predicted macro- and microscopic thermomechanical response indicates that, at and above an applied stress of 1 MPa, a holding period at 270°C (above the melting temperature of Sn) affects the form stability of the alloy, as well as the residual stress distribution at the microscopic level.*

## Keywords

*Composite phase change material, creep, form stability, Al-Sn, thermos-mechanical behaviour.*

# P138: Mechanical and Creep Properties of Advanced High- and Compositionally Complex Alloys Investigated by Small Punch Techniques

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## Summary

*High-entropy alloys (HEAs) and compositionally complex alloys (CCAs) have attracted increasing attention as potential structural materials for applications operating under demanding thermo-mechanical conditions. Alloys based on the Cr–Fe–Mn–Ni system offer promising combinations of strength, ductility, and thermal stability. However, relatively limited information is available regarding their high-temperature deformation and creep behaviour, which are critical for the reliable application of these materials in advanced energy and structural systems. In the present work, the mechanical and creep responses of three advanced CrFeMnNi-based alloys developed within the INNUMAT project were investigated using small punch testing (SPT) and small punch creep (SPC) techniques. The studied materials included HEA-1 (Ni-rich CrFeMnNi), HEA-3 (CrFeMnNi alloyed with Cu and Mo), and CCA-2 (CrFeMnNi alloyed with Al and Ti). The HEA-1 alloy was examined in both recrystallized (ReX) and as-forged (AsF) conditions, whereas HEA-3 and CCA-2 were examined in the recrystallized state. Both SPT and SPC experiments were performed at room temperature and at 400 °C, 550 °C, and 700 °C, enabling evaluation of the temperature dependence of the deformation behavior of the investigated alloys. The characteristic parameters obtained from the SPT load-displacement curves revealed a strong influence of temperature on the mechanical response of the investigated materials. In general, both the characteristic force ( $F_e$ ) and the maximum force ( $F_m$ ) decreased with increasing temperature, although the extent of degradation varied between alloys. The HEA-1 alloy exhibited relatively stable deformation behavior and good ductility retention at elevated temperatures, consistent with its fine-grained, defect-rich microstructure revealed by EBSD and TEM analyses. The HEA-3 alloy exhibited a more heterogeneous microstructure, which may explain its moderate temperature sensitivity in mechanical response. In contrast, the precipitation-strengthened CCA-2 alloy demonstrated the highest room-temperature strength but also the most pronounced reduction in maximum force and displacement at elevated temperature. Fractographic observations revealed a transition from ductile fracture at room temperature to intergranular fracture at 700 °C, indicating grain boundary weakening at elevated temperature, despite the precipitation-strengthened microstructure responsible for the high room-temperature strength. The combined results demonstrate a strong relationship between microstructural state and mechanical behavior in advanced multi-component alloys and highlight the usefulness of miniature testing techniques for evaluating newly developed high-temperature materials.*

## Key Words

*High-entropy alloys, compositionally complex alloys, small punch testing, small punch creep,*

## **P139: Cyclic creep as an element of service life assessment of steel and alloys operating under creep conditions**

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### **Summary**

*Research on cyclic creep of heat-resistant steels aims to determine the impact of power boiler shutdowns and restarts on the durability of critical components. In real operating conditions, boilers do not work continuously – shutdowns result from planned maintenance, decreased energy demand, or failures. In the face of the development of renewable energy sources and changes in the energy mix in the Polish power system, it is predicted that conventional power boilers will serve as a system reserve, operating in a regulatory (load-following) mode. Each restart of the boiler initiates the primary creep stage in the material, characterised by a rapid increase in permanent deformation. To assess the impact of cyclic shutdowns on service life, creep tests were conducted at cyclically varying temperatures under a constant load, simulating real operating conditions. The research results enable a more precise determination of component durability under regulatory operating conditions, which is crucial to the safety and reliability of power systems. The article presents creep test results for T/P91, VM12-SHC, and 304H steels, which are used, among others, in supercritical boilers.*

### **Key words**

*creep, cyclic creep, steels for the power industry, service life*

## P140: Creep-fatigue interaction behaviour in Sanicro 25

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### Summary

*Sanicro 25 is an advanced heat resistant austenitic stainless steel with good resistances to steam oxidation and flue gas corrosion, and has higher creep rupture strength than other ones available today. It has been used as super-heaters and reheaters in the advanced ultra-super critical power plants where the creep-fatigue interaction is a concern. In this work, the creep-fatigue (CF) interaction tests using Sanicro 25 bar material were performed in strain control mode and five strain ranges up to 2% were used with dwell times 0, 300, 600 and 1800 seconds. The influences of dwell time on the cyclic deformation behaviours and life time have been evaluated. The results show that a longer dwell time results in a lower maximum stress and a shorter creep-fatigue life ( $N_f$ ). However, when the life is calculated in total test time instead of cycles to failure, the tests with longer dwell times have longer lives. A creep-fatigue interaction diagram shows that Sanicro 25 exhibits more creep damage than fatigue damage. Due to stress relaxation, the dwell time will lead to a larger plastic strain range compared to that without dwell time. This leads to more creep damage. Fracture investigations show that dwell times result in more intergranular cracking.*

### Key Words

*Creep, Fatigue, Cyclic plastic deformation, Sanicro 25, Crack propagation*

# P142: A Comparative Study of Data-Driven and Physically-Based Models for Creep Curve Modelling in Austenitic Stainless Steels

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## Summary

*Artificial Intelligence (AI) has emerged as a strong alternative to traditional methods for predicting creep failure. However, most existing studies have primarily focused on rupture life prediction, while modelling the full creep curve evolution in high-temperature alloys remains relatively less explored. The present work develops a hybrid modelling framework that integrates a purely data-driven, Probabilistic Gaussian Process Regressor (GPR) with the physically-based B.J.F model coupled with the Kachanov approach, applied to model the full creep curve behaviour of 316 austenitic stainless steel. A comprehensive dataset comprising both rupture and non-rupture creep curves across multiple heats is employed. The modelling capabilities are evaluated on completely unseen creep conditions. In addition, the GPR model is explicitly extended beyond the training domain to evaluate its behaviour in the extrapolated regime, defining a fundamental part of the present study. This work provides new understandings into purely data-driven models under extrapolated conditions and highlights the need to incorporate physics-based damage mechanisms into purely data-driven machine learning methodologies.*

## Keywords

*Austenitic stainless steel, Artificial Intelligence, Kachanov approach, Creep curve modelling, Optuna.*

# P143: Conceptual Design of an In-Pile Sub-Critical Crack Growth Experiment for Diffusion-Bonded Fusion Window Materials (Extended Abstract)

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## Summary

*Window materials in fusion reactors, including transparent ceramic assemblies used in diagnostic and heating ports, are potentially life-limiting components that form part of the primary confinement boundary and whose behaviour under neutron and gamma irradiation is not well characterised. Sub-critical crack growth (SCCG) in brittle materials is hypothesized to be particularly consequential under certain design conditions, yet existing radiation-effects data are almost exclusively derived from post-irradiation examination of pre-cracked specimens, a method that recovers end-state crack length but not the kinetics of crack propagation during irradiation. In-situ measurement under representative conditions is required to separate the thermal, gamma, and neutron irradiation contributions to SCCG. This paper presents the conceptual design process, with working examples, of an in-pile neutron irradiation experiment to be deployed in the Jules Horowitz Reactor (JHR) reflector position, developed jointly by UKAEA and CEA under the FUSERO-A workstream.*

*The experiment targets fused silica specimens in diffusion-bonded window assemblies produced by UKAEA, loaded pneumatically with pressurised helium. Two in-situ signals are recorded during irradiation: electrical circuit continuity on the specimen surface, which reports on the integrity of the transparent material, and pneumatic pressure across the assembly, which in combination with the circuit signal reports on the integrity of the diffusion-bonded interface. The design process we present includes iterations between design decisions, neutronic calculations, and thermal modelling. A single JHR cycle will not yield enough specimens, so the capsule is intended to be re-run across multiple cycles until the performance metrics are known to a level suitable for qualification. Beyond the scientific measurement, the experiment qualifies a UKAEA-produced diffusion-bonded window assembly as an integrated unit under the coupled thermochemical, mechanical, and irradiation conditions it is expected to experience in service.*

## Keywords

*Sub-critical crack growth; fusion window materials; diffusion bonding; fused silica; in-pile irradiation; Jules Horowitz Reactor; FUSERO.*