*2-day **On-Line** International Conference*

MIMA-2 *(2nd MIMA Conference)*

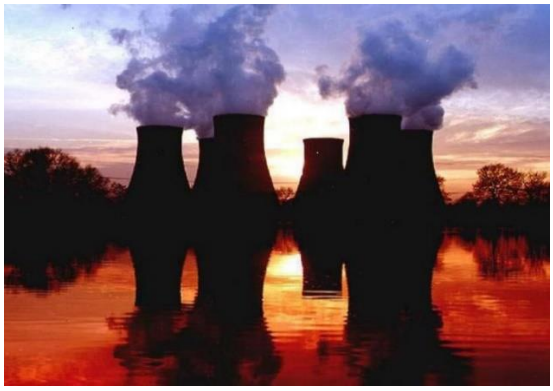
High Temperature Plant

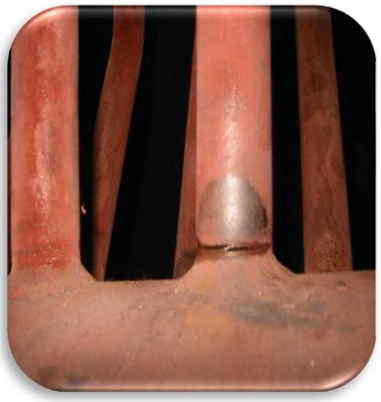
Materials, Inspection, Monitoring & Assessment

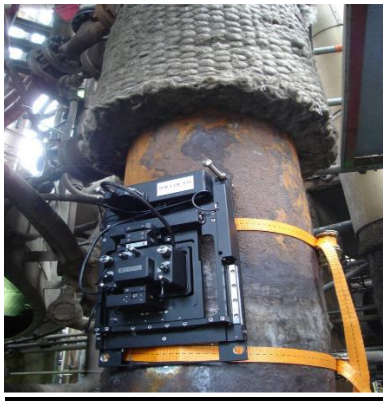
Conference Acronym: **MIMA-2**

Venue: On-Line (from London) *Dates:* 11 – 13 October 2022

ABSTRACTS of the Presentations offered are shown below







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ABSTRACTS

SESSION 1: HIGH TEMPERATURE MATERIALS ISSUES

Paper 1-1

Role of inclusions on degradation in creep life and rupture ductility of ferritic power plant steels

Fujio Abe, National Institute for Materials Science (NIMS), Tsukuba, ***Japan***

Coal-fired power plants will be operated in flexible mode involving frequent start-up and shut-down, because renewable power supply will increase. The thermal cycling capabilities of thick components would be severely restricted by creep-fatigue damage. The creep-fatigue life of 9 to 12Cr steels is proportional to the reduction of area (RA) in creep rupture testing but not to the creep strength.

The role of inclusions, such as boron nitride (BN), aluminum nitride (AlN) and manganese sulphide (MnS) particles, on degradation in creep life and rupture ductility has been investigated for 9 to 12Cr martensitic steels and 1Cr-1Mo-0.25V bainitic steel for power plants mainly at 550 to 650 ºC with emphasis on long-term behavior.

The BN particles form in 9 to 12Cr steels, such as Gr.92 (9Cr-0.4Mo-1.8W-VNb with 0.002B and 0.0462N) and Gr.122 (11Cr-0.5Mo-2W-1CuVNb with 0.0024 to 0.0039B and 0.0540 to 0.0720N), during normalizing heat treatment at around 1100 ºC, suggesting no change in the amount of BN particles during creep. On the other hand, the AlN particles gradually precipitate in high-Al heats (0.035 to 0.039% Al) of 12Cr-1Mo-1W-0.3V steel (JIS SUH 616) for turbine blades during creep, consuming dissolved nitrogen and fine vanadium nitrides. The degradation in creep life takes place in the high-Al heats of 12Cr-1Mo-1W-0.3V steel at long times, while no degradation in creep life is observed in Gr.92, which contained the BN particles. The degradation in RA is more significant in Gr.92 and Gr.122, which contained the BN particle, than in Gr.91 (9Cr-1Mo-VNb) and MARBN (9Cr-3W-3Co-0.2V-0.05Nb steel with 0.0130B and 0.0080N), which contained no BN particle, at long times. The degradation in RA is also more significant in the high-Al heats than in the low-Al heats of 12Cr-1Mo-1W-0.3V steel. The BN and AlN particles are responsible for the degradation in RA at low stresses and long times by accelerating the formation of creep voids at interfaces between the BN and AlN particles and alloy matrix. The shape of creep rate versus strain curves is quite different between the specimens of 9Cr steel with and without the BN particles in the later stage of accelerating creep region at low stresses and long times. The RA of 1Cr-1Mo-0.25V steel (ASTM A470-8) for turbine rotors is lower in a high-sulfur heat (0.015% S) than in other 8 heats with low-sulfur at 550 ºC and long times, indicating that the MnS particles degrade the RA. The creep life is roughly the same among the 9 heats with different sulfur concentrations, indicating no influence of the MnS particles on creep life, similar as the BN particles. To ensure reasonable values of RA in the ferritic power plant steels for up to long times, the formation of not only BN particles but also AlN and MnS particles should be suppressed.

Paper 1-2

Development and Manufacture of IBN1 MarBN Steel Wrought Pipe for Advanced High Temperature Application

Steve Roberts, Goodwin Steel Castings; Steve McCoy, Special Metals Wiggin; Martin Strangwood, Uni. of Birmingham; Mark Jepson, Loughborough Uni.; Paul Robb, Doosan Babcock; Scott Lockyer, Uniper Technologies Limited; Zhuyao Zhang, Lincoln Electric Europe; and David Allen, European Technology Development, ***UK***

Extensive research and development has been undertaken in the UK on MarBN steels. These were first proposed by Professor Fujio Abe from NIMS in Japan. Within the UK, progress has been made towards commercialisation of MarBN-type steel through a series of Government funded industrial collaborative projects (IMPACT, IMPEL, INMAP and IMPULSE). As part of the IMPACT project a cast MarBN steel, IBN1, was developed which demonstrated a consistent 25-30% increase in creep strength over Grade 92 steel. Further development on IBN1 steel took place within IMPULSE project where matching welding consumables were developed and large ingots (3-8 tonnes) were successfully forged and extruded producing four 6m x 330mm OD x 50 mm wt pipes. Subsequent creep testing of the pipe material has demonstrated similar, if not better, increases in creep strength wrt to Grade 92 steel. This paper details the work undertaken to produce the pipes, results to date and outlines future work including pipe to pipe and pipe to casting welds.

Paper 1-3

Project HOWEFLEX- MarBN Rotor Qualification for Load Flexible Application

T.-U. Kern, Siemens Energy GmbH*
B. Donth, Saarschmiede GmbH
U. Langer, GE Power
G. Maier, Fraunhofer Institute for Mechanics of Materials, IWM Freiburg
M. Schwienheer, Institute of Materials Technology, TU Darmstadt
Germany

The German funded project HOWEFLEX performed by a consortium of two turbine manufacturer, a forge master, and two research organizations, is dealing with the upscaling of trial melt results of MarBN family alloys to large rotor forgings with diameters of up to 1,200mm and typical weights representative for e.g. IP rotor forgings.
The aim is to confirm the manufacturability and applicability of suitable quality assurance measures, and to determine the achieved material properties allowing for design with this material class.
The results obtained so far indicate auspicious properties regarding the achievable forging quality and short- and long-term material behavior.
The chosen approach is comparable to the activities within the COST projects of the 1990's and 2000 years to implement the options for new material application by non-destructive and destructive testing of real size demonstration components.

Paper 1-4

Multi-component Alloying Element Effects on Solidification Segregation in Cast IBN1-based CSEF Steels

*M Strangwood, University of Birmingham, **UK***

The CSEF steel IBN1 has been developed from a series of 9 Cr steels with controlled additions of B, N, Co, W, Mo and Nb, paralleling other MarBN systems. Although almost all of the alloying elements segregate to the liquid during solidification, their partition ratios show a wide range of values that are dependent on the both the solid phase and on the segregation behaviour of other alloying elements. For example, austenite-stabilisers, such as Co and N, partition less when austenite is the solid phase compared with delta-ferrite as the solid phase. Strong carbide forming elements, such as Nb, Mo and Cr, have their tendency to segregate to the liquid enhanced by segregation of carbon to the liquid phase.

Segregation occurs during solidification either to ingots or final components; for ingots, subsequent thermo-mechanical deformation accomplishes considerable homogenisation reducing the microstructure and property scatter that results from chemical heterogeneity. For shaped castings, homogenisation is only possible through heat treatment, which, for slowly diffusing elements such as Nb, Mo and W, occurs very slowly, so that minimisation of segregation on casting is needed.

Segregation, segregation spacing and back-diffusion values depend on cooling rates and, hence, on casting section sizes so that a trial-and-error approach to assessing and minimising segregation is not feasible. To this end, multi-component thermodynamic and kinetic modelling has been applied to a range of IBN1-type castings and verified by micro-XRF and SEM-EDS measurements. This presentation will describe the modelling approach, verification and rationalise the susceptibility of IBN1-based alloys to solidification segregation.

Paper 1-5

Normalising temperature selection for creep performance of advanced high temperature alloy IBN1

W Philpott, M A E Jepson, R Maclachlan, Loughborough University, UK

IBN1 is an advanced high temperature MarBN steel developed over the past decade in a number of UK-based collaborative projects funded by InnovateUK: IMPACT, IMPULSE and IMPLANT, to meet the demands of increasing efficiency, and therefore increasing temperatures, and/or cyclic operation of thermal power generation applications. IBN1 was developed to exceed the properties of other casting steel alloys such as CB2, in terms of creep strength and ductility. The alloy achieves this heightened performance through additions of boron and nitrogen to the alloy. Boron stabilises $M_{23}C_6$ carbides in the microstructure and inhibits their coarsening during high temperature service, which preserves their grain boundary pinning effect. Nitrogen improves the strength of the material by formation of MX carbonitrides which also have a grain boundary pinning effect. However, there can be a tendency for boron nitride (BN) particles to form in the alloy, which removes the boron and nitrogen from solution and therefore prevents the beneficial effects of these elements when they are in the desired locations. These improvements in performance can mean greater operating efficiency, but also mean that thinner walled sections can be used so that they are more tolerant to fatigue, making this alloy a potential candidate for use in heat recovery steam generators.

If present, BN precipitates can be removed during high temperature normalising of the material,

which is also necessary to homogenise (to an extent) the segregation present from solidification of the material. However, the high temperature exposure also initiates grain growth in the material which can rapidly become excessive as MX precipitates pinning the prior austenite grain boundaries (PAGBs)are dissolved. The grain size of the alloy is inversely proportional to the creep ductility of the material, and there is also an optimum grain size range for creep strength, beyond-which the creep strength of the alloy is reduced. Therefore, there is a balance to be achieved with the normalising heat treatment, as the heat treatment temperature needs to be high enough to sufficiently remove the boron nitride precipitates from the material and reduce the segregation present, while also not being high enough to cause excessive grain growth.

In this paper, samples of IBN1 steel were normalised for a range of temperatures from 1050°C to 1200°C for 8 hours. The prior austenite grain structure of the samples was analysed using EBSD mapping and HKL Tango processing software to detect the PAGBs, and then ImageJ was used to measure the grain size. The BN within the material was detected and quantified using EDS Feature software.

Paper 1-6

Experience of P93 manifold welding under real fabrication conditions

P de Smet, K Tang and M Bok, Siemens Energy Heat Transfer Technology B.V., ***The Netherlands***

A test manifold of Gr. P93 is welded under shop fabrication conditions. Raw materials include pipe and forgings. Welding processes used are GTAW and SMAW. Weld joints involve heavy wall butt welds and branch joints. Welded joints are subjected to different heat treatment cycles to test the effect on weld joint properties. This presentation will share our welding experiences and show mechanical test results for weld metal in relation to PWHT.

Paper 1-7

Development of INCONEL alloy 740H and its application to supercritical CO2 power plant

Steve McCoy, Special Metals Wiggin, ***UK***

Nickel-base alloys are required for many of the components in advanced supercritical steam and CO2 power systems operating at temperatures and pressures exceeding 650°C and 25 MPa. Age-hardened alloys offer an advantage over traditional solid solution strengthened alloys by virtue of their significantly higher creep strength. This makes it possible to reduce wall thickness and, thereby minimize total construction cost. INCONEL alloy 740H (UNS N07740) is an age-hardened alloy that was developed and extensively characterized for Advanced Ultra-supercritical steam boilers. Material testing by the AUSC Consortium and US Department of Energy led to ASME Code Case 2702 covering UNS N07740. More recent development work on the alloy has focused on applications for supercritical CO_2 systems. This paper focuses on the manufacturing and properties of piping and fittings that are being applied for the various advanced supercritical steam and $uSCO_2$ projects now planned or underway. As many of the structures are constructed by welding, a review of welding practices is presented with emphasis on dissimilar welds and their properties.

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SESSION 2: **PLANT LIFE ASSESSMENT**

Paper 2-1

Prediction of long-term creep life based on short-term data of used Grade 91 steels

M Yaguchi, CRIEPI, ***Japan***

A destructive testing method is the most appropriate way to assess remaining creep lives of materials used in high temperature components. However, in the case of Grade 91 steel, there is an issue that we have to judge the creep life based on relatively short-term creep data of the material, while it is well known that it is difficult to estimate creep rupture property of Grade 91 steel appropriately without long-term data. The present work focuses on the issue. Creep tests were conducted on base metal and welded joint of the long-term used Grade 91 steels which were taken from many USC power plants, and large data scatter bands or heat-to-heat variations of creep lives were recognized for the base metal and welded joint of the materials. An author analyzed the data using Larson-Miller parameter and found out that a master rupture curve of a heat of the base metal is parallel in horizontal direction to that of other heat of the base metals. The same thing holds true for the data of the welded joint, i.e., master rupture curve of the heat of each welded joint is parallel in horizontal direction. Based on the feature, it is possible to estimate the master rupture curve of arbitrary heats of the materials with only one datum in short-term region because a shape of the master rupture curve of the materials is already known and what to be decided is a position of the master rupture curve of the heat of the materials, which can be determined with the short-term creep datum. The estimation method was applied to data set obtained for lots of the heats of the base metal and the welded joint of the long-term used Grade 91 steels, and validity was examined. It was confirmed that the creep rupture property of the materials can be adequately estimated with short-term creep datum. The reason of the successful estimation is discussed in terms of variation of constant C in the Larson-Miller parameter for the long-term used materials.

Paper 2-2

The new Italian standard about the life assessment of martensitic steels - first results of the experimental validation activity of XRD by testing P91 and P92 samples from interrupted uniaxial creep tests

Andrea Tonti, Pietro De Blasi, INAIL, ***Italy***

The Italian Thermotechnical Committee is drafting a new standard for the life assessment of creep operated pressure equipment, including modern steam boilers. For the evaluation of the spent life ratio several methods are available, even if each of them is not exhaustive.
It should be noted that the methods described must be considered in combination with the NDEs and the hardness tests. X-ray diffraction (XRD) is one of the method that could be used to assess the material evolution under creep conditions. The method allows the study of phase transitions involving structural variations. It is possible to operate both on massive samples and on powders. INAIL is currently performing an 8 years research program about the martensitic steels, in order to develop a microstructure atlas. The activity is split in seven projects, including thermal ageing and creep tests with steel grades P91 and P92. These tests are regularly interrupted and X diffraction of the crystal lattice is also performed. Some of the main results obtained by XRD, in comparison with TEM analysis, are showed in this paper.

Paper 2-3

Residual Life Assessment of Critical Piping Systems

Bhaskara Santosh Kumar Pudipeddi, PE - Mechanical, NTPC, ***India***
Vineet Kumar – Manager, PE- Mechanical, NTPC, ***India***

NTPC is India's largest energy conglomerate established in 1975 to accelerate power development in India. NTPC placed itself as the dominant power major with presence in the entire value chain of the power generation business. NTPC has an installed capacity of 67,907.5 MW (including JVs), plans to become a 130 GW company by 2032. From fossil fuels it has forayed into generating electricity via hydro, nuclear and renewable energy sources and aims to be the world's largest and best power major, by lowering its carbon footprint by reducing greenhouse gas emissions. It has 40+ years of Engineering, O&M experience of thermal power plants.

With a population of 1.4 billion and one of the world's fastest-growing major economies, India will be vital for the future of the global energy markets. India, home to 18% of the world's population, uses only 6% of the world's primary energy. As pledged in COP 26, Energy Landscape in India will change by providing sustainable ease of living and access of power to all its people across various living standards with its future growth supported by Renewables, targeting Net Zero by 2070.

Penetration of renewables increased flexible operations, emerging fuel constraints, implementation of new environmental norms necessitate the Generation Companies to operate the low-cost plants longer than their original design life by improving their efficiencies. Further, to ensure safe operation of these plants, it necessitates us to assess the degradation of thermal plants operating nearing completion of intended life based on economic interest from all stake holders. RLA (Residual Life assessment) & LE (Life Extension) of the old thermal power units is carried out with an aim to assess the present remaining useful life and set up an input base for extending their useful life 15 to 20 years beyond the original design economical life.

Critical Piping Systems are those operating in High Temperature and Creep Range. Periodic monitoring and life assessment of these Critical Pipes is necessary, to ascertain the R&M requirement. RLA (Residual Life assessment) is to be carried out to assess the remaining life of Piping systems and their components, thereby making recommendations for replacement of existing components, if required, to enhance the overall life for reliable & safe operation. RLA reports forms the basic input for R&M activities. This paper specifically focusses on the RLA Approach taken in NTPC for Various Critical Piping Systems in our 8 stations comprising 33 units (200/210 MW & 500 MW fleet). The requirement of RLA Study, Covered Piping Systems in each station, Number of Stations / units covered, Criteria of selection, adapted methodology for RLA study, results of various stations have been discussed in this present paper.

Adapted Methodology for Residual Life Assessment Study of Piping has been developed jointly by NTPC Piping Engineering Team & NETRA (NTPC Energy Technology Research Alliance) based on various codal requirements. This wholistic approach is a cocktail of Advanced NDT & Metallographic Techniques supported by the Computer Based As-is-Where-is / As Recommended Stress & FEM Analysis of the Piping Systems. Combining and Validating the NDT & Metallographic results along with the Stress/FEM Analysis resulted in comprehensive recommendations, by implementing which, the Life of the Piping System can be extended by another 10 years safely. All these requirements are elaborated along with a brief glance of the results obtained in certain stations. Results of the completed Stations are assorted and presented for various activities taken up in RLA study and presented to get the glimpse / overview of the RLA outcomes for our base load operating Stations viz. like Singrauli, Korba & Ramagundam.

Paper 2-4

Real-time creep remnant life prediction for fired heaters

H Othman, H Chik, NH Kamaruzaman, PETRONAS Group Technical Solutions, ***Malaysia***

Creep monitoring is crucial for fired heater equipment that is operating at extreme creep regime. It becomes significant when it involves catalyst regeneration cycle in the system as furnace's tube materials temperature is expected to become higher when the catalyst gets towards the end of the cycle. During this period, creep assessment is performed to determine current creep damage accumulation and projected remnant life based on the recorded tube metal temperature. However, creep assessment becomes conservative as most of the engineers will use the recorded high tube metal temperature in their creep remnant life calculations.

This paper presents real-time creep monitoring program on fired heater equipment using available online monitoring and established creep modelling to provide dynamic creep damage accumulation and remnant life prediction. This program is also able to analyse and provide notification to the plant operator in the event of online monitoring parameters deviating from the preset integrity operating window parameters. By having real-time prediction, it empowers plant operator ~~for~~ to evaluate multiple scenarios feeding into plant operation for optimum planned maintenance and shutdown windows.

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SESSION 3: PLANT INSPECTION AND MAINTENANCE

Paper 3-1

DX (digital transformation) of boiler maintenance

Shigemitsu Kihara and Toshiaki Yoshida, Best Materia Co., Tokyo, ***Japan***

The tools, AI for prediction of degradation mechanisms and software for calculation of risk were developed for DX of boiler maintenance. The AI was created by rule base and machine learning using data of degradation experienced. The software of risk evaluation is based on HPIS (High Pressure Institute Standard) Z-107; RBM handbook.
DX of boiler maintenance can be realized by cloud using of the AI and software in cyber-area.

[BACKGROUND PROJECT]
[Collaboration to build first-ever AI and DLT (distributed ledger technology) - based Predictive Maintenance System for critical infrastructure in Japan and Abroad. The project will develop a cloud-based SaaS software with the following capabilities:
● A decentralized database using IOTA's distributed ledger technology. Centralized databases are vulnerable to accidents, tampering and leakage. RBM system built by using IOTA is able to provide a solution to infrastructure partners that is resistant to cyber attacks while protecting sensitive data.
● Artificial Intelligence (AI) system developed. With current RBM systems, individuals are dependent on the knowledge of skilled technicians making standardization difficult. Due to Japan's aging population, there is a serious risk of information loss when current employees retire. By creating an artificial intelligence system, information can be captured, shared, and acted upon by distributed teams across the world.
● Digitizing and sharing infrastructure data right now, data for various plants across Japan are stored manually and not digitized. This can cause a host of issues when it comes to the integrity and sharing capabilities of data. Digitization of Infrastructure Data can make it easier for partners across the plant owners to collaborate and share data in a safe, efficient way.]

Paper 3-2

Risk-based maintenance for steam turbines and generators

Pascal Decoussemaeker, GE, ***Switzerland***

Use of condition monitoring, operational data analysis and a risk-based method to improve outage planning and lifetime management for steam turbines and generators in an uncertain market environment

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Paper 3-3

Evaluation of various risk-based maintenance procedures and recommendations for best practices

Feroza Akther, European Technology Development, Leatherhead, Surrey, ***UK***

In recent years, power plant operation has changed significantly due to increasing competition in the market, obligation to meet increasingly stringent statutory requirements and environmental regulations. There has been a shift in the operation mode from base to cyclic load and this has led to increased numbers of plant failures. Therefore, it resulted in an increased interest in a 'risk-

based maintenance (RBM)' approach to address these challenges and avoid market penalties. API 580 and API 581 provide procedures using risk assessment in managing inspection/ maintenance (time interval) considering failure or damage factor and financial implications. However, due to further developments in the RBM field, currently different types of standards/ codes for risk assessment exist in the market. Recently, ETD has completed a large study on the review of various types of RBM standards/ codes/ procedures and compiled a review/ analysis as a large comprehensive report.

This presentation is based on the outcome of this study. The study covers a review of various existing codes/ standards for risk assessment, provide critical assessment of the RBM methodologies including case studies, identify gaps and provide recommendations for best practices. It also discusses the types of risk maintenance such as predictive, reactive and so on. Furthermore, the review also describes ETD's RBM procedure 'RiskFit', especially prepared for power plants, which consists of four levels of risk assessment each of which can be carried out independently or together.

The Review Report concluded that a well-developed RBM program should include important steps such as specifying business goals and objectives, identifying all potential risks, categorising and analysing risk, evaluating and mitigating risk and monitoring the performance of the RBM program.

Paper 3-4

Risk Based Inspection and Integrity Management of HRSG Headers and Manifolds

*David Tuey, RWE, **UK***

The application of Risk Based Inspection (RBI) on piping and vessels is now well established throughout power generation and process industries and is based around guidance from the Health and Safety Executive, American Petroleum Institute, and other Industry Bodies. Integrity management for high pressure steam boiler headers and manifolds differs from pipework systems in that, by their nature, all failures are likely to result in high consequence events in terms of process safety or commercial impact due to loss of asset availability. Historically in the UK there was the requirement to carry out periodic, systematic inspection of headers of large utility boilers and HRSG's to satisfy the requirements of the Competent Person for Examination under the Pressure System Safety Regulations. Modern designs of HRSGs can feature many hundreds of collector headers and manifolds located on the steam/water circuits and it would not be practical to carry out widespread inspection of all locations during the operational life of a normal site. GENSIP member organisations in collaboration have created a documented process to define best practice in the application of Risk Based Inspection techniques to the inspection of HRSG headers. The document provides specific information on targeted inspection locations, appropriateness of specific inspection and NDT techniques, inferred condition on a hierarchical assessment of risk, sample sizes, consideration of wider fleet experience and optimised record keeping ensuring the maximum benefit and technical value is delivered when defining periodic inspection programmes.

Paper 3-5

Inspection of pipelines with varying cross sections using a combined multidisciplinary and robotized solution.

Alfredo LAMBERTI, ENGIE Laborelec, ***Belgium***

The Venturi systems are convergent-divergent piping components which can be used in many power plants as flowmeters for controlling the amount of produced power.

In 2020, the I&C monitoring of some Venturi flowmeters in use on the secondary circuits of some nuclear sites showed some flow disturbances associated to a drift of the measured pressure difference. Two potential root causes were identified: i) a wall thickness reduction caused by internal erosion phenomena; ii) the presence of a leak in the I&C tubes causing an unwanted water flow in the dead-zone of the Venturi systems and thus explaining the pressure drift. To confirm these hypotheses, in 2021 Engie Laborelec started the development of a combined multidisciplinary inspection solution consisting of three main parts: i) a robotic solution able to perform the internal inspection of such Venturi components by means of laser profilometry and indirect High Definition Visual Testing (HDVT); ii) a leak test solution for the I&C small tubes encircling the Venturi; iii) a borescope inspection through the spindle of the sliding valve of the I&C tubes to check for anomalies like obstructions, material deposit, surface irregularities.
The development of the combined inspection solution was performed using a step-by-step approach. First a market research was done to select the most suitable available systems. Then, mechanical adaptation of the selected systems was performed in order to comply with the range of ID for the intervention (valve access, pipe ID and Venturi convergent-divergent section). Successively, a representative mock-up of the pipeline including the Venturi tube was 3D printed and used for the development tests. At the end of the development, a procedure for the onsite inspection was prepared. Finally, the developed combined robotized solution was used for onsite inspection.

The post-inspection root cause analyses showed the absence of significant erosion of the Venturi ID capable of justifying the observed pressure drift. The comparison of the collected laser profiles with the original as built CAD showed an erosion lower than 500µm in correspondence of the Venturi midsection. Moreover, the presence of a leak path was identified. The boroscopic I&C tube inspection showed that the leakage was in the pressure tube accessible through the spindle of the sliding valve.

Paper 3-6

Possible microstructural resistant factors in P91 steel to the magnetic domain wall motion of electro-magnetic inspection method

Yasushi Hasegawa[1], Noriyuki Ishii[1], Masayuki Kodama[2],
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3: Iwate University, ***Japan***

9% Cr containing high strength creep resistant steels are the already common in high temperature pressure vessel application, and its modified steels, ASME Gr.91 and 92, are expected to increase the energy conversion efficiency and refining process in power plant and oil refining system. Such modern materials potentially decrease a CO_2 emission of plants and contribute to solution of a climate change problem. In order to maintain the safe operation and increase the conversion

efficiency of plants for long term, the new exact inspection technology must be developed and newly introduced for the accurate remnant life estimation.

A magnetic inspection method is adequate to detect the microstructure degradation by measuring its magnetization process. Its modification of sensitivity and actual application technology are now under development. However, the relation between measured magnetic data and the microstructure development is not yet precisely studied well.

In ferromagnetic material, steels and its alloys, a magnetic domain wall motion is the decisive factor of the magnetic characteristics. In this study, the possible domain wall motion obstacles of microstructure, precipitates and grain boundary migration during the creep deformation, were carefully analyzed concerning the size, structures, and distribution status. These obstacles are also the decisive factors of creep deformation resistance. Those microstructural changes were related to the magnetic characters of the 9 % Cr steel, permeability, initial and maximum permeability, and coercivity by the magnetic inspection test on the creep specimens.

The comparison of microstructure analysis and magnetic characters transition resulted in that an initial magnetic domain wall motion was supposedly restricted by the dislocation density. On the other hand, in long term, magnetic domain wall motion was restricted by the grain boundary precipitates and boundary character. Long term creep deformation resistance is supposedly maintained by the coarse precipitates on the grain boundary, $M_{23}C_6$ type carbide in transition creep period, and Fe_2Mo, intermetallic compound, in acceleration creep period according to the SEI and BEI analyzation by using SEM and EBSD. The magnetic inspection method possibly detected such factors as a change in magnetization process.

Paper 3-7

Inspecting the un-inspectable – A review of a project delivering a new Inspection Techniques on complex geometries

John Trelawny – Technical Lead Specialist Inspections – Uniper Technologies Limited, Integrity and Inspection Solutions Department, Uniper, ***UK***

Uniper Technologies (UTG) is one of the foremost energy sector consultancies providing specialist engineering and technical services in every aspect of power plant development, operation and maintenance. Our abilities, backed by experience in competitive electricity markets, are concentrated on helping customers to operate and maintain plant safely, efficiently and effectively with maximum benefit from the latest technologies.

As part of the Integrity and Inspection Solution Department, the Inspection Management Team are responsible for developing Inspections, using current and new technologies, on components not previously inspected or on those that have been considered un-inspectable. With the advent of newer power producing technologies like Wind Turbines, Energy from Waste and Biomass to name a few, inspection needs are often becoming more complex. Many simply can’t be resolved, some give really good and unexpected results.

With the advent of 3D Full Matrix Capture inspection capabilities, it is possible to get a more comprehensive coverage and easier interpretation of results. The Integrity and Inspection Solutions Department has therefore begun using this technology to assist in the visualisation and characterisation of flaws.

The following project has been used as a test bed for this technology. As a recent failure of a

socket weld at an external power plant, concerns have been raised about the reliability of these small fillet welds, as currently the weld body cannot be fully inspected and relies solely on surface inspection. It is acknowledged that many of the potential degradation mechanisms develop sub-surface, so current practice is less than ideal. The Uniper CCGT fleet contains vast quantities of socket welds within the HRSG drains, vents and interconnecting small bore pipework. 25% of steam leaks documented by UTG in the previous 2 years at one of the Uniper CCGT units have been from failed socket welds. The Inspection Management Team were therefore asked if a technique could be developed to locate these sub-surface flaws. This presentation details the work undertaken and the outcomes of that development.

Paper 3-8

High-temperature corrosion data and mechanism of T122, Super 304H and HR3C in a 1000MW ultra-supercritical power plant

Haomin Wu(a), Shuo Wang(a,b), Qinxin Zhao(a), Zhiyuan Liang(a)

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High-temperature corrosion of heat-resistant steels T122, Super304H and HR3C used as the inlet of header in a 1000MW ultra-supercritical power plant for 15 years was investigated. The steam temperature and pressure were about 610 ℃ and 28 MPa, respectively. The morphology and phase compositions of the corrosion products formed on steam-side and fireside of the investigated tube were analyzed using the X-ray diffraction and the scanning electron microscope with an energy disperse spectroscopy. The results showed that the thickness of the corrosion products on tube fireside was larger than that on the steam-side of the investigated tube, which was due to the sulfur in the flue gas. The oxide scales of the investigated steels on steam-side was more uniform than that on fireside. The thickness rank of the corrosion products on investigated steel was T122 > Super304H > HR3C. The internal sulfidation was the main reason for the severer fireside oxidation of T122 and Super304H. Defects including micro-cracks and voids were found in the corrosion products on both side of three tubes, which led to the breakaway of the corrosion products.

Paper 3-9

COMBINED AC & DC ELECTRICAL POTENTIAL DROP AS AN ON AND OFF-LINE NDT METHOD FOR CREEP LIFE MONITORING OF PRESSURE VESSELS

Adam Wojcik, Matthew Waitt, Alberto Santos, Matelect Ltd UK
Ahmed Shibli, European Technology Developments Ltd UK

The authors have previously developed a method and presented promising results using a combination of AC and DC electrical potential drop (EPD) techniques to help determine remaining lifetime of steel pressure vessels under field conditions that encourage creep, detecting both final cracking as well as incipient creep damage in on-line tests at high temperature and pressure. The incipient changes were tentatively ascribed to the development of cavitation damage, but recent modelling has shown that cavitation is unlikely to provide enough of a change in electrical properties to explain all of the variations observed in EPD in the field trials. Here we report on the modelling, and on a large "off-line" study using laboratory specimens in a more controlled set of creep experiments. Here, we analyse all three studies together to hopefully generate a greater insight into the mechanisms at play. Whilst changes in both AC and DC-EPD

have been observed off-line that largely accord with the in-field testing, the modelling has shown that the changes seen in the on-line work cannot be fully explained by cavitation development, and that local strain effects must play a large part, as could other microstructural effects such as phase or grain size changes. Deconvoluting these is not straightforward and may not even be possible, and the implications of this are discussed in the context of using EPD for remaining lifetime determination in both continuously monitored (HT) and spot-checked NDT/NDE (RT) contexts.

Paper 3-10

Robotics applied to inspection of infrastructure - examples of internal and external pipe inspection

Paulo Debenest, HiBot, ***Japan***

Petrochemical and power plants are vital elements of infrastructure. To ensure their safe operation, the pipes used in boilers, heat exchangers and pipelines in general must be maintained regularly. Any defects in the pipes, such as corrosion or cracks, must be repaired properly to avoid accidents with potentially fatal consequences.

This requires frequent inspection of such pipes. However, the inspection works are sometimes hampered by difficult access (too high, too narrow), presence of insulation (hides defects), geometry (pipes too complex or too small to inspect), schedule (downtime must be kept to a minimum), and others. In addition, it is not rare for inspectors to have to risk their lives inspecting pipes in high, hazardous or confined environments.

For 20 years, the authors have been working with robotic solutions to make inspection missions safer, faster and more reliable. This paper presents some of the recent solutions, currently in operation, used for inspection of pipes from inside (boiler water pipes, cooling water pipes) and from outside (pipe racks).

The challenges unique to each of the applications will be presented, followed by a description of the concepts used to automate the inspection tasks. Results from field missions will be mentioned to prove the feasibility of the solutions, from economical, technical and operational standpoints.

Paper 3-11

Paper replaced with the sponsors' and other introductory presentations.

SESSION 4: COMPONENT CRACKING & FAILURE

Paper 4-1

Real Time Damage Monitoring Software (RTDMS)

Aron Abolis, Greg Fletcher, ALS Global, ***Australia***

Real Time Damage Monitoring Software (RTDMS) supports day to day operation inclusive of flexible operation and ultra-low load running. This level of understanding is required in order to determine the viable frequency response rate that can capitalise on future energy market flexibility without impacting the plant's strategic life.

Today's environmental commitments coupled with the integration of renewable energies into the energy market has left both combined cycle and coal fired power generators with the commercial challenge of shifting from baseload to flexible operation to respond to fluctuating renewable generation supply. RTDMS is the solution to support this transition to flexible operation.

RTDMS enables the operator and plant engineers to link transient operation and associated operator induced actions to potential damage of critical components. RTDMS is based on an advanced real time modified rain flow algorithm that decouples the local cyclic creep damage due to relaxation from a creep fatigue cycle while the cycle counting continues and additional fatigue damage may be occurring independently of creep. The software couples and then decouples when a cycle occurs where creep-fatigue damage would be significant

As a result, the software accounts for different damage types simultaneously and in real time, which includes the primary creep rupture life, high cycle fatigue damage, low cycle fatigue damage and coupled creep fatigue damage. This allows for an increased level of accuracy and confidence in predicting asset life.

Paper 4-2

CrackFit: A software for crack assessment in pressure vessels and turbines

David Robertson, European Technology Development, Leatherhead, Surrey, ***UK***
Stuart Holdsworth, EMPA, ***Switzerland***

Defect assessment procedures aim to avoid component failure during service and too early a replacement that can incur unnecessary capital costs. Once a crack is found then it is important to understand how long the crack/ defect containing component can remain safely in service.
ETD, initially as a part of the European Commission project HIDA (High-temp. Defect Assessment) and later as a joint-industry project, has brought together various recognized national and international defect assessment codes and practices and developed a practical defect assessment tool named 'CrackFit'. This tool is designed to help and assist engineers perform crack stability checks and defect/crack assessment of Pressure Vessels, Piping and Turbine components operating both at *low* and *high* temperatures. Crack initiation and growth for a host of components (pressure vessels, turbine rotors, plate and laboratory specimens) and commonly occurring crack geometries (embedded cracks, surface emerging cracks, various crack front shapes etc.) found in industrial plant are incorporated in this software. Crackfit functioning has been checked and verified by independent experts against hand calculations and other in-house procedures.
CrackFit is also unique in that it contains a large material and creep and fatigue (representing various operation modes of a flexible operation power plant/HRSG) crack growth database.

Paper 4-3

Developing reliability framework for power plants - Integrated RCM IV Generation implementation

Nadeem Ahmed, ETD Consultant, ***UK***

Power Generations Assets operations and Maintenance are paramount to overall effectiveness of business objectives ensuring minimum downtimes and maintenance cost optimization. The variety of Power Generation Equipment such as Gas Turbines, HRSGs, Boilers, Steam Turbines, Generators, Boilers, Control System and Distribution Grids brings certain complexities when identifying problems and conducting the specific maintenance requirements.

This paper/ presentation will focus on understanding the Reliability Frame-Work development and Implementation with an Integrated RCM- IVth Generation and Asset Performance Management System.

Operations, Maintenance and Reliability Team Understanding is very important in identifying the Performance degradation of Equipment, Criticalities and Failure Modes, Causes, consequences and desired mitigation characteristics. These should be compared to the standard Performance over the whole life cycle of the Power Generation Plants.

Specific focus in discussion on New, Medium Aged and Aged Power Generation Assets will help in developing a Proactive Maintenance and Reliability program with embedded RCM-IV methodology. & implementing for the Critical Assets with Specific Equipment plans. RRM - Risk and Reliability Management Approach for optimizing the Power Generation Assets Maintenance schedule.

Power Generation Assets Bad actors management programs with emphasis on Maintenance costs, Trips, Performance variations, Load Cycling its effects, Forced Outages, Turn Around Work-Scopes Optimization techniques, Equipment Repair and Replacement decision will supplement the discussion.

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SESSION 5: POWER PLANT FLEXIBILITY ISSUES

Paper 5-1

Predicting high temperature component integrity in turbines required for flexible operation - evaluating assessment effectiveness

Stuart Holdsworth, Empa: Swiss Federal Laboratories for Materials Science & Technology, ***Switzerland***

For many years, the metallurgy of the materials used to manufacture critical high temperature turbine components evolved relatively slowly, primarily because the demands of turbine operators remained relatively constant. Towards the end of the last century, technological advances, an increasing demand for energy, at lower cost, and an increasing awareness of the detrimental environmental effects of carbonaceous and NOx emissions led to changes in the way fossil turbines in particular were operated. Traditionally, the effectiveness of assessment procedures used to predict component integrity was established on the basis of service experience. As new materials were adopted after increasingly shorter development periods, and more efficient and flexible operation to complement the availability of renewable energies became the norm, it was no longer possible to evaluate assessment effectiveness on the basis of prior operating experience, since it did not exist. The solution was to use the results of component-feature specimen tests. Initially, these were isothermal tests conducted at the

maximum operating temperature. More recently, the use of component-feature thermo-mechanical fatigue tests has become more common.
In practice, laboratory component-feature specimen testing can be more revealing. Not only, can the applied boundary conditions be more closely controlled, but the testpieces used can be more amenable to continuous instrumentation monitoring and post-test examination. Importantly, in such tests, the effectiveness of defect-free and defect assessment procedures can be evaluated, with the main constraint being time. The evidence is reviewed.

Paper 5-2
Cavitation during creep-fatigue loading
Rolf Sandström, Materials Science and Engineering, KTH Royal Institute of Technology, Stockholm, ***Sweden***

It is well established that cavitation plays an important role during creep-fatigue conditions. It is controlling both the crack initiation and propagation in many cases. The situation for fossil fired power plants has changed in recent years due to the use of solar and wind power in many countries. This implies that a transfer from base power to standby has taken place with many more start-ups with creep-fatigue cycles as a consequence. In spite of this, the number of studies of cavitation during cyclic loading is quite limited. Significant progress concerning basic modelling of cavitation during monotonous loading has been achieved. Models for both nucleation and growth of creep cavities can now be described with fair accuracy without involving adjustable parameters [1]. Initial attempts have also been made to apply these models to creep-fatigue cases [2]. In the present paper some of the major difficulties involved will be attacked.
For monotonous loading diffusion controlled cavity growth has successfully been applied. But due to the short times in particular in laboratory tests, diffusion controlled growth has limited impact during cyclic loading. The common models for strain controlled growth are quite sensitive to the assumption about the initial cavity size and there is no obvious way of selecting the value. A model based on grain boundary sliding has recently been proposed [2] that eliminates the problem and the use of this model will be discussed. An import aspect that will also be covered is the shrinkage of cavities during reversed loading. The modelling result will be compared with the limited sets of experimental data for cavitation during cyclic loading that are available.

Paper 5-3
Use of filming chemistry to improve corrosion protection of flexible operated power plants
Manfred Jansen, Anodamine, ***The Netherlands***
Adrian Baily, VPI, ***UK***

Anodamine (a filming chemical that has proven case studies of successfully mitigating FAC and other internal corrosion threats) dosing at a FFR 2+1 CCGT was commenced in February 2019. As detailed in the Technical Review, the 2021 inspections were tailored to further check the efficacy of Anodamine following positive initial results from the 2019 and 2020 interim and steam turbine outages.

Overall, the 2021 inspection results are considered to indicate that Anodamine is providing good levels of protection against FAC (both single and two-phase) and have indicated that a benefit to corrosion fatigue and offload corrosion mitigation is also likely to be realised. Internal visual and RVI have shown build-up of protective Anodamine film in areas susceptible to both single phase (i.e. condensate, feedwater and the economiser circuits) and two phase (i.e. evaporators, steam

drums, deaerator, blowdown / drains and steam turbine exhaust circuits) FAC. Furthermore, repeat UTh inspection of critical areas (i.e. HP and LP evaporator risers) shows a general reduction in thinning rates compared to pre-2019 levels. As a result of the good performance observed, it is judged that credit can now start to be taken via a reduction (gradual reduction of sample size rather than complete removal) of inspection scope for FAC damage at future outages.

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SESSION 6: **PLENARY SESSION**

Paper 6-1

Life assessment of high temperature plant – The role of materials design data

*David J Allen, European Technology Development, Leatherhead, Surrey, **UK***

Assessment of the remaining life of high temperature pressure plant components may be required to underwrite their safe ongoing operation in the medium and longer term. Initially, the emphasis is generally on components at greatest risk, such as damaged, degraded or non-conforming items. In the longer term, especially beyond the design life, emphasis may shift toward the more generic concern that complete pressure systems based on a specific material could approach "end of life", and require urgent wholesale replacement before the failure risks become unacceptable.

In the past, many high temperature materials have been deployed under conservative design conditions, and have commonly exceeded their design lives without serious performance problems. However, current martensitic alloys such as P91 and P92 are often used under more aggressive design conditions. As plant ages, therefore, there may be increasing concern that "end of life" could be approaching.

This presentation will discuss how the generic "end of life" risk may be characterised and quantified. It will review the materials characterisation methodologies which may be pursued to assess this risk, and evaluate their capabilities and shortcomings.

Reference will be made to past UK experience with CrMoV steel steam pipework. This low alloy steel has experienced long term service under moderately onerous design conditions at 568ºC, and whilst the design life has generally been successfully surpassed, the UK power industry has found it necessary to replace many CrMoV pipework systems before the plant reached the end of its operational life. The UK experience may therefore provide a useful background to help consider the comparable issues which may arise with P91 and P92.

The high temperature testing of as-manufactured materials is often considered as relevant only to the initial plant design process. A common view is that when life assessment of service-aged materials is required, testing must instead be carried out on aged materials. This presentation will argue that, on the contrary, the value of testing aged materials is often seriously limited, because neither the extent of ageing and degradation, nor the properties of the selected heat relative to other heats of the alloy involved, are likely to be well established. By contrast, it may be shown that a reassessment of the as-manufactured materials design data may provide very useful guidance on when the approach toward "end of life" should trigger wholesale materials replacement.

Paper 6-2

Life evaluation and research subjects for safe service of 9Cr steels used in UCS power plants

Koichi Yagi, Meilin Wang and Yonghao Lu;
National Center for Materials Service Safety, University of Science & Technology Beijing, ***China***

The USC coal-fired power plants are an important source of electric energy generation in China and in the world. The first USC coal fired power plant in China was operated in 2006, and after that, about 150 units have been operated. China has about 80% USC power plants in the world. P92 steel is used as high-temperature structural components (main steam pipes, hot reheat pipes, etc.) of USC coal-fired power plants in China.

Recently, the long-term plans to reduce greenhouse gases in response to global warming was announced in China as follows; to achieve a "peak out" emission in 2030 and to achieve real zero up to 2060. From this reason, the coal-fired power generation will be shifted from a main power source to an adjustment power source. But the coal-fired power plants will be used in harmony with clean energy source, because these plants can supply the stable electric energy for safe society and civil life. Therefore, the plants will be used under more sever conditions, so the plants must be the reliable power generation source that can always respond when needed.
Therefore, it is important to maintain the structural components suitably in order to operate the power plants safely, and it is needed to evaluate accurately the remaining life of high temperature structural components in USC boilers. Although 9Cr steels have been used for the principal structural components in USC boilers, the high temperature long-term performance of these steels has not yet been understood perfectly because of the complicated micro-structural changes. We think that there are two procedures for life evaluation of structural components. One procedure is to evaluate the damage from many data of real component which is operated, and another procedure is to evaluate the remaining life from the basic research of material. Of course, both procedures are not independent and have the close relation to each other. Many USC power plants are operated in China and in the world, and we can get many experiences and data from the service of plants, and the information of metallurgical change and mechanical properties will be accumulated from the practical experiences. We think that the practical life evaluation method can be developed by using such practical information on the basis of the basic research. Of course, this trial should be started from the structural components with low risk. On the other hand, although the second procedure is orthodox, it is important to understand the material properties used in the plants and to develop the techniques for evaluating the time-dependent damage and predicting the remaining life.

The material research subjects which should be studied will be discussed in this presentation, and the research viewpoints will be pointed out based on the examination of various research results which have been conducted on not only P92 steel but also other heat-resistant steels. It is important to reduce uncertainty as much as possible by accumulating basic research to reduce risk.

NCMS (National Center for Materials Service Safety) will contribute this trial from the viewpoint of basic research. NCMS is planning to do the long-term creep tests of the steels (P92 and so on) for USC boilers, and to do the following research from the viewpoint of metallurgical science:

(1) understanding the long-term creep behavior of steels for USC boilers, and
(2) investigating the relationships between micro-structural changes and long-term creep behavior, and evaluating the creep damage based on micro-structural changes, etc.

Paper 6-3

HRSG Design Challenges: Materials and Mechanical Integrity

*Ian J. Perrin, Triaxis Power Consulting, LLC., **USA***

Heat Recovery Steam Generators (HRSGs) to be paired with next-generation Gas Turbines are larger and required to operate at higher pressures and temperatures. This is accompanied by increasing demands for rapid start and flexible operation. This places significant demands on material selection, which must consider fabrication practicality alongside durability. This presentation highlights some of the key challenges encountered in modern HRSG designs including use of stainless steels for tubing and headers, dissimilar metal welds, and large bore piping. Examples are provided to illustrate challenges and identify where detailed analysis can help optimize designs. Also discussed are some of the challenges related to Codes and Standards which are struggling to keep pace with design demands. The needs for future materials and integrity assessment methods are also discussed.

Paper 6-4

Activities to advance residual life evaluation techniques for highly aged power plant boiler materials in Japan

*Isamu Nonaka, Tohoku University, **Japan***

In Japan, a national guideline for residual life evaluation techniques of aged power boiler components was issued in 1999. In order to revise the guideline to suit highly aged power boiler, the working group was formed in the Society of Materials Science, Japan. The following issues were addressed and discussed there.

Location and mode of creep damage in piping system based on damage case observation
Effect of system stress on Gr.22 and Gr.91 circumferential welds
Creep void nucleation time in Gr.22 steel under very long-time loading
Comparison of stress triaxiality factor in uniaxial creep specimen and internal pressure piping
Mechanism of Type IV damage in Gr.22 welded joint and its evaluation parameter
Sensitivity of Type IV damage detection by ultrasonic phased array method
Creep-fatigue damage caused by variable load operation in piping system
Problems of destructive test method and application of miniature creep test to the field
Online creep damage monitoring methods in piping system
Manual on transcription of creep damage by replication method in the field

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