EUROPEAN COMMISSION

Community Research

SEVENTH FRAMEWORK PROGRAMME

ARCHER

Collaborative Project (CP)

Co-funded by the European Commission under the Euratom Research and Training Programme on Nuclear Energy within the Seventh Framework Programme

Grant Agreement Number : 269892

Start date : 01/02/2011 Duration : 48 Months
www.archer-project.eu

Archer
Advanced Reactor
for Cogeneration of
Heat & Electricity-R&D

Final report describing concept of damage characterization and implementation for condition monitori

Authors : BUCKTHORPE Derek (UNIMAN) , J Berka (CRez), M Pouchon (PSI)

ARCHER - Contract Number: 269892
Advanced High-Temperature Reactors for Cogeneration of Heat and Electricity R&D
EC Scientific Officer: Dr. Panagiotis Manolatos

Document title	Final report describing concept of damage characterization and implementation for condition monitori
Author(s)	BUCKTHORPE Derek , J Berka (CRez), M Pouchon (PSI)
Number of pages	17
Document type	Deliverable
Work Package	WP 42
Document number	D42.24
Issued by	UNIMAN
Date of completion	28/01/2015
Dissemination level	Confidential, only for members of the consortium (including the Commission Services).

Summary

This document contains the results from the ARCHER SP4 Workpackage 2 activity on Task 2 including information and aspects associated with the concept of Damage Characterisation implementation for Condition Monitoring. The scope of work is to provide some initial information that would allow development and consideration for HTR Application. . The report summarises the results from investigations performed on corrosion studies and experiments within ARCHER which cover tests on materials such as P91, 316SS and Alloy 800H in helium atmospheres and results from Damage related information contained in small voulumes for condition Monitoring of a Pressure Vessel Steel. The results from these three investigations are reported in ARCHER Deliverables D42-21, D42-22 and D42-23 and their findings considered in the development and findings of this report. A review of Plant Condition Monitoring approaches for active and passive components and systems has been carried out. The current state-of-the-art for online monitoring of component condition includes systems that measure reactor noise, acoustic signals and vibration in various forms and that are part of condition-based maintenance programs that mostly focus on active components. For the the acceptability of and extended longer-term operation of nuclear plant and those of the Advanced reactor systems such as the VHTR/HTR the need for managing the passive components within the Condition Monitoring Systems will be much more likely. The use of Micrometer sized samples could also offer a possibility for advanced condition based monitoring. Investigations within ARCHER have shown that further work is necessary to understand the discrepancy between the yield stress measured with micro-pillars and the ones determined with conventional samples for annealed material. This conclusion fits in with the current understanding and development of the approach generally and supports the recommendation to investigate this type of damage condition monitoring further before it can be considered an alternative approach to the currently developed methods

Approval

Date	By
29/01/2015	Derek BUCKTHORPE
29/01/2015	Derek BUCKTHORPE
29/01/2015	Steven KNOL

Distribution list

Name	Organisation	Comments
P. Manolatos	EC DG RTD	Through the EC participant portal
All beneficiaries	ARCHER	Through the private online workspace

Table of contents

1.Introduction

Investigations on materials for HTR's mainly concern metallic materials, graphite and ceramics & composites. The work on High temperature metallic materials within ARCHER is addressed within Work Package (WP)42 of the project and covers material selection for the high temperature components such as the heat exchangers with particular emphasis on Alloy 800H material behaviour and property development. Specific tests on Alloy 800H have also been carried out within WP3 for the development of the Compact IHX Mock-up and tests. The activities covered within WP42 include a review and data collection activity, corrosion tests and investigation of material condition using micro-pillar testing. This report has been compiled to provide a synthesis of the results from Task 2 activities which can be used as a basis for relevant sections of the SP4 contributions to the Final Report and to address Damage Characterisation and Condition Monitoring issues arising from these tasks and the work of SP4 for the HTR development.

2.Summary of Results of Task 2

2.1 Survey of the materials and data generated in previous HTR and related programmes

The available materials and their limits within the helium cooled environment is an important issue for the key high temperature components of the HTR which has been addressed in past programmes and investigations [see Table 2-1]. Ferritic materials (such as Mod 9Cr 1Mo steel) have been extended through alloying and other improvements to permit operation to temperatures of 650°C. Nickel -Chrome solid solution alloys such as IN 617, Haynes 230, Hastelloy X, Alloy 800H are the most promising candidate materials for the HTR and its Internals, Hot Gas Duct and Intermediate Heat exchanger above this temperature (750 >850°C). Other alloys such as ODS alloys are also being considered due to their high thermal stability and creep strength. Materials data development for Alloy 617 has been addressed within activities of the Generation IV (GIF) Project Management board (PMB) and for the ASME Code Development and it already has a very large database with numerous mechanical properties and creep data measured in air and a helium atmosphere. A draft code case for this material within the ASME Code was developed in the early 1980's but then work stopped as the need for the code case disappeared. This has since been resumed and a code case on this material is soon to be issued.

Within the ARCHER Project the material investigations have been aimed primarily at Alloy 800H properties and behavior at elevated temperature. Tests have been carried out within WP42 to provide information on Alloy 800H parent plate and weld [2]. The scope includes tensile tests at room temperature, 700°C and 800°C in air to address monotonic behaviour; low cycle fatigue tests (with and without tensile hold times at four different strain ranges) on parent plate material to investigate cyclic behaviour and influence of hold time on strain-life behaviour; and their reference micro-structural investigations. The tensile results show a significant reduction in strength properties between 700 and 800°C. Fatigue life is substantially affected by tensile hold time with the maximum reduction occurring at the lowest strain range and micro-structural studies on the parent plate and weld show a high concentration of small spheroidal inclusions (mainly Nb-Ti) in the weld consistent with an effective shielding of the weld pool (from oxygen) during the GTAW process. For the tensile results a good agreement is seen with recent published results from the ASME LLC on the development of Allowable Stresses in ASME Section III NH for Alloy 800H and which indicates that in all cases the weld strength is better than that of the parent plate. Other material tests have been carried out with WP43 addressing base material and welded material properties but using the same material data source [3].

Table2.1: Heat Exchanger materials and their limits

Material	Temp Limit °C	Limiting Factor	Further Development	Issues for HTR
Mod 9Cr 1Mo steel	**Operating: 550°C**	Long term Creep strength	ODS version capable of 100°C Higher temperatures – developed for Fusion development	Established material information for Gas cooled systems—moderate temperatures
	Max: 650°C			
Austenitic Stainless Steel	**Operating: 550 - 650°C**	Long term Creep strength	Investigations on effects of Corrosion IN Helium atmospheres within ARCHER	Established material information for Gas cooled systems—moderate temperatures
	Max: 750°C			
Alloy 800 Alloy 800H	**Operating: 650-750°C**	Long term Creep strength	Developments within ARCHER to establish capability for IHX & SGU applications. Extension of properties at higher temperature within ASME.	Used in gas cooled and Sodium cooled systems. Considered for the Compact Intermediate Heat Exchanger Application within ARCHER
	Max: 920-980°C	Corrosion		
Alloy 617	**Operating: 750-850°C**	Long term Creep strength <10Mpa @ 100,000h	ODS version possible for Higher temperatures Effect of cold work (forming) on creep strength - limit of 5%	Established in German HTR Programme - KTA Rules developed For ODS version Micro-structural development required as a first step -
	Max: 920-980°C	Corrosion; Cr2O3 evaporation		
Alloy 230	**Operating: 750-850°C**	Long term Creep strength <10Mpa @ 100,000h	ODS version possible for Higher temperatures Effect of cold work (forming) on creep strength investigated in RAPHAEL	Selected as industrially developed alternative to IN 617 – for corrosion resistance For ODS version Micro-structural development required Data base expansion to ;level of IN 617, cold work & ageing
	Max: 920-980°C	Corrosion; Cr_2O_3 evaporation		
Alloy XR	**Operating: 750-850°C**	Long term Creep strength <10Mpa @ 100,000h	Effect of cold work (manufacturing) on creep strength - limit of up to 10% Tests 800-1000°C	Established for HTTR Operation at 750°C
	Max: 920-980°C	Corrosion; Cr_2O_3 evaporation		
ODS - Ferritic	**Operating: 550°C**		Manufacturing development required. Investigated in projects such as EXTREMAT, MATTER	Not developed sufficiently for heat exchanger application – significant programme required on joining/forming involving manufacturer
	Max: 650°C			
ODS - Austenitic	**Operating: >550°C**		Manufacturing development required. Investigated in former projects such as EXTREMAT, MATTER	Not developed for heat exchanger application – significant programme required on joining/forming involving manufacturer
	Max: >650°C			

Within Task 2 of WP42 a survey of the data generated in previous HTR and related programmes associated with degradation of material properties in the HTR helium coolant has been carried out. With regard to past experimental programs corrosion tests that simulate HTR helium coolant conditions have been carried out to determine the influence of the corrosion on mechanical properties. Results of tests of high temperature alloys within previous HTR programs are summarized and the properties of selected alloys (e.g.800H, Hestelloy X, Alloy 617, Haynes 230) are specified in detail [1]. High temperature alloys experience carburisation, oxidation and/or decarburisation depending on the gas atmosphere composition (the carbon activity and oxygen partial pressure in gas atmosphere), exposure temperature and the alloy composition. The specific influence of helium atmospheres (in contrast to other gaseous atmospheres or vacuum) on the mechanical properties of alloys are not necessarily of a low order and the investigations on the effect of the impurities in the helium on the alloy behaviour can be selective and not systematic. With regard to environmental tests in impure helium most have been carried out at parameters near the chemical equilibrium conditions, that is under low total gas pressure and low flow rate. Under this condition the corrosion behavior of the alloys could be different compared to that at high pressure and high gas flow rate (at the same temperature and gas atmosphere composition). Within ARCHER corrosion investigations have been undertaken on a specific material being considered for the heat exchanger application the results of which are discussed in the next section.

2.2 Complementary environmental tests performed within ARCHER

Within the ARCHER Project several high temperature metallic materials for the HTR and heat exchange circuit were investigated [4]. The materials investigated include P91, 316 stainless steel and Alloy 800 H, including welded Alloy 800H. Specimens from these alloys were exposed to a helium atmosphere that contained defined concentrations of selected impurities (CO, H_2, CH_4, CO_2) and residual moisture (H_2O). The temperature was held between 750 – 760°C and the duration of the tests was up to 1500 hours. Two types of facilities were used for the material testing, the High Temperature Furnace (HTF) featuring a low gas pressure and a low gas flow, and the High Temperature Helium Loop (HTHL) which has a high gas pressure and high gas flow. High temperature corrosion (HTC) tests were performed in both facilities in order to compare various conditions (static and dynamic) simulating the HTR He coolant conditions. After exposure the specimens were subjected to several analyses and investigations to assess the effect of the environment on their condition: gravimetry, SEM/EDX, GD-OES, hardness, micro-hardness and fracture toughness investigations were carried out.

For the HTF the corrosion tests can be performed in a gaseous atmosphere at atmospheric pressure and gas flows of up to 1l/min to a maximum temperature of 900°C. The oven temperature can be programmed for the duration of the experiments. The space used for testing at constant temperature has a diameter of 40mm, length of approx. 15cm and is arranged in the middle of the oven. The source of the gas atmosphere is a pressurized gas bottle containing a gas mixture of defined composition. The gas bottle is connected to the oven with flexible tubes. For several experiments the gas is dehumidified before entering the oven using a molecular sieve (gas dryer) [TAMIS 5A]. The humidity of the entering gas is controlled with an optical hygrometer [BARTEC 5673]. The gas passes through the system and is eventually released into the environment (once through system).

The High Temperature helium loop (HTHL) is a device which is equipped with an individual circuit for cleaning, dosage, and control of the purity of the helium. For the control of gaseous impurity an optical hygrometer BARTEC and a gas chromatograph with HID detector (GC-HID) was used. The testing space for the samples is approximately 30 x 500 mm in size. The main testing parameters for the HTHL are:

- Pressure of gaseous media: max. 7 MPa
- Max. temperature (only in the region of the sample): 900°C
- Max. main gas flow in the main circuit: 38 kg h^{-1}

For tests in the HTHL the temperature and pressure in the loop were kept at 760-800℃, and 3.5MPa. During the exposure gas impurities were added, 10 ppm H_2 + 10 ppm CH_4 + 50 ppm CO. Impurity levels in the flowing helium were controlled through a feedback mechanism based on gas chromatography with HID detector (GC-HID) measurements of the gas chemistry at the inlet from a HTHL-1 containing the test materials. The tests in the HTHL were originally planned for 1000h duration at a temperature of 760℃ and minimum pressure of 3 MPa. The gas concentration, its contaminants and other parameter were monitored during the whole period of the experiment. After approximately 160 hours of operation of the HTHL (109 hour at 760℃) a serious failure of the device occurred. The test had to therefore be interrupted and the device completely dismantled. After dismantling 2 specimens were taken out for evaluation. The rest of the specimens were retained for continuation of exposure after repair of the device.

For P91 and 316 steels, tests were carried out in the HTF for up to 1000h. Gas flow in the retort was approx. 0.1 l /min-. The nominal parameters for the helium atmosphere in terms of its partial pressure and composition are shown in Table 2-2. The results from the tests show a decrease in fracture toughness for 316SS of up to 67% compared with the initial state. The reduction in fracture toughness in the case of P91 steel was only moderate. The reduction in hardness after exposure of 100h was approx. uniform for P91 but for 316SS it was fluctuating. The change in mechanical properties was mainly influenced by the temperature rather than the composition of the gaseous atmosphere. The corrosion layer was made up of chrome and manganese oxides. After exposure an under-surface zone depleted of chromium was observed which for P91 steel was considered to be a decarburization zone. The corrosion layer thickness was in the range of approx. 2 to 12µm, the thicker corrosion layer was found in the samples of P91 steel. Also the weight increase after exposure was greater for steel P91. Although the gaseous atmosphere was slightly reductive, it is considered that there was a small amount of air in the apparatus during the testing since it was not possible to remove all the air completely. The gas also contained a residual humidity of approx. 10vppm.

Table 2-2: Chemical composition of HTF gaseous atmosphere during the endurance tests of P91 and 316 stainless steels

Component	Concentration [vppm]	Partial pressure [Pa]
CO_2	1	0.1
O_2	2	0.2
CH_4	35	3.5
CO	250	25
H_2	400	40
Helium	Bal.	Bal.

The results for Alloy 800H and its weld in the HTF are for a temperature of 750°C and duration of up to 1500h. The humidity of the gases was controlled before entering the oven, the optical hygrometer and molecular sieve were installed. For tests in the HTHL a special holder was developed in which several Alloy 800H samples could be placed. The highest mass gain of the tested materials after exposure was given for the Alloy 800 H material. For the Alloy 800H heat affected zone and weld metal a spalling of the corrosive layer after exposure was observed. The hardness of base metal and heat affected zone increased after exposure, the hardness of Alloy 800 H weld metal decreased. The highest change in hardness was observed for the case of Alloy 800 H base metal (increased by ca. 19%). The micro hardness of all the tested materials decreased after exposure, the highest decrease being recorded for Alloy 800 H base metal (ca. 17 %).

2.3 Damage related information contained in small voulumes for condition Monitoring

Micrometer sized samples could offer a means of advanced condition based monitoring in nuclear plants. Miniature test procedures for material characterization are being considered for Condition Monitoring and feedback of service performance from long term operating tests and components. Examples where this type of approach could be used includes: irradiated materials, welds and in-situ materials. Tiny sample volumes can be removed either directly from a component or from test coupons for mechanical and micro-structural analyses. Modern micro-sample preparation techniques (e.g. focused ion beam) together with micro-deformation machines (nano-indenter) allow both, the preparation of small thin foils for micro-structural analyses and the testing of micrometer sized samples.

The influence of specimen size on impact testing has been extensively studied [1] with respect to analysis of surveillance samples however, these samples are still in the milli-meter range. Small punch test were also investigated for toughness testing and ball indentation tests were also considered for toughness monitoring in nuclear environments. Nano-indentation and micro-pillar testing for components exposed to nuclear environments offers a further solution.

Within the ARCHER project investigations on samples from well characterized irradiated reactor pressure vessel materials were tested with nano-indentation and micro-pillars to obtain information on irradiation effects on mechanical properties [5]. Sample material exists for pressure vessel steel ASTM A533 grade B class 1 steel that was designated as ‘JRQ reference steel’ from surveillance investigations. This was used for many years as a radiation/mechanical property correlation monitor in a number of international and national studies of irradiation embrittlement of reactor pressure vessel steel. The A533 B class 1 plate of 225 mm thickness, was heat treated and stress relieved at 620°C for 40 hours with irradiations carried out at different neutron flux levels by PSI in the 10 MW (t) SAPHIR reactor at 290°C. Additional specimens were thermally annealed at 460°C for 18 h when 50 % of the target fluence was reached, followed by re-irradiation (IAR). The detailed irradiation/annealing procedures of the samples investigated are summarized in Table 2-3 (extracted from Ref [5]). In this table “I” means irradiated, “A” means annealed, “R” means re-irradiated. The set of samples has been well characterized in the literature. Not only mechanical data (yield stress, rupture stress, Brittle ductile transition temperature, KI_C) are available but also microstructural investigations with an atom probe and Seebeck effect measurements.

Table 2-3: Summary of exposure conditions for the investigated ASTM A533 grade B class 1 pressure vessel steel Micro-pillar samples

Secimen designation	Fluence 1 (cm^{-2})	Annealing 1 T (K)	Annealing 1 t (h)	Fluence 2 (cm^{-2})	Annealing 2 T (K)	Annealing 2 t (h)
Ref.						
I	$5.0x10^{19}$	-	-	-	-	-
IA	$5.0x10^{19}$	735	168	-	-	-
IAR	$0.85x10^{19}$	735	18	$0.85x10^{19}$	-	-
IARA	$0.85x10^{19}$	735	18	$0.85x10^{19}$	735	168

Qualitatively, the results from the micro-samples compared well with expectations. For the annealed conditions the yield stress measured with micro-pillars was below the expectations whereas for irradiated samples a quite good agreement was obtained. A quantitative assessment of the shift in KI_C from the shifts in yield stress was difficult, since the influence of a pronounced yield stress on the results of the micro-sample tests was not fully understood. Relating these to the observed differences in yield stress indicates that the differences between irradiated and non-irradiated material are higher for the micro-samples. This suggests that the expected KI_C-shift would be higher and it is at least on the conservative side. For large samples a pronounced yield stress is expected for the annealed condition which is no longer present in the irradiated samples.

Other conclusions drawn from the micro-sample tests were consistent with Atom probe analyses. The applied heat treatment recovers the radiation damage but not to a full 100 percent. After the irradiation, annealing and re-irradiation (IAR) treatment, a high number density of small copper-enriched precipitates was observed. The presence of these small precipitates correlates with the re-hardening and consequently re-embrittlement of the steel. A significantly lower number density of ultrafine copper-enriched precipitates was observed after the second annealing treatment (IARA). However, some larger copper-rich precipitates were also observed after this treatment. These results indicate that the ultrafine precipitates did not re-dissolve into the matrix but coarsened.

The results encourage the use of micro-sample test for condition based monitoring of components in current and particularly in advanced nuclear plants. For the particular case of the Pressure Vessel Material investigated further work is considered necessary to understand the discrepancy between the yield stress measured with micro-pillars and the ones determined with conventional samples for annealed material.

3.Condition based Monitoring at Nuclear Power Plants

Safe, secure, and economic operation of nuclear power plants will remain of strategic importance and new and improved monitoring methods and requirements will have increased significance for the next generation plant developments. Condition monitoring is a means to improve both the safety and economics of extending the operating lifetimes of nuclear power plants, enabling adoption of proactive ageing management. It is the management of materials issues that will ultimately determine the safe operating life limits for a nuclear power plant.

The components, systems, and structures in NPPs are in general categorized in two classes: active or passive. Active components are managed under a maintenance rule, and this covers items such as pumps, motors, valves, and compressors. Passive components, which include the reactor pressure vessel, piping, core internal components, the containment structure, and cables, are managed using in-service inspections (ISI) performed in the context of an ageing management plan (AMP). Degradation found under an ISI program is managed through mitigative actions, changes in designs, and repair or replacement of degraded components. This reactive, find and fix, approach has maintained the safety of operating reactors but it is becoming increasingly expensive as plants age. Attention is now moving to consider the potential for more proactive management of both active and passive components

This sections discusses the general approach to Reactor Plant Condition Monitoring and is aimed at describing some of the technologies involved for both passive and active components. . A further section will discuss the specific case of new methods being developed for advanced reactors such as the use of Micro-pillars investigated and reported in ARCHER Deliverable D42-23 which are aimed at Passive components. The information for this section has been taken from the Condition Monitoring approaches and techniques given in an IAEA Document [6].

Condition Monitoring and Maintenace should not be considered as a substitute for the more traditional monitoring and maintenance management methods used in Nuclear Power Plant but a valuable addition that can provide a comprehensive, total plant approach to ensure effective plant operation and control. Condition based monitoring is a condition-driven preventive maintenance programme involving regular monitoring of the actual mechanical condition of the equipment and the operating efficiency of systems. The process schedules specific tasks as and when they are required by the plant and equipment in order to ensure a fast and effective response to the many differing and influencing situations that can occur. Its application ensures the maximum interval between repairs; minimizes the number and cost of unscheduled outages created by failures and improves the overall availability of operating the plants. By providing condition based monitoring and maintenance as a total plant management programme it is possible to optimize the availability of equipment and components and greatly reduce the cost of maintenance and problem solving.

3.1 Condition based Monitoring Technologies

A variety of technologies can be used as part of a comprehensive condition based maintenance programme. Since mechanical systems or machines account for the majority of the plant equipment, vibration monitoring is generally the key component of most condition based maintenance programmes. However, vibration monitoring alone cannot provide all of the information that will be required on such equipment for a successful condition based maintenance programme since it is limited to monitoring the mechanical condition and not other critical aspects and parameters that are required for maintaining reliability and efficiency of the equipment. A comprehensive condition based maintenance programme must also include other monitoring and diagnostic techniques such as those listed below :

- Vibration monitoring.
- Acoustic analysis.
- Motor analysis technique.
- Motor operated valve testing.
- Thermal measurements.
- Tribology.
- Process parameter monitoring.
- Visual inspections.
- Other non-destructive testing techniques.

3.1.1 Vibration Monitoring

Vibration monitoring can be used to detect repetitive motion of a surface within a rotating or oscillating piece of equipment. The repetitive motion may be caused by unbalance, misalignment, resonance, electrical effects, rolling element bearing faults, or other problems. The various vibration frequencies in a rotating machine are directly related to the geometry and the operating speed and by knowing the relationship between the frequencies and the types of defects, vibration analysts can determine the cause and severity of faults or problem conditions. The history of the component or equipment and its previous degradation pattern are important in determining the current and future operating condition.

Vibration analysis can monitor many things on rotating and moving equipment: cracks, pits, and roughness, unbalance, misalignment, coupling problems, bends, bows, and cracks in shafts, excess wear, loose parts, misalignment, deterioration, effects of erosion and corrosion, resonance and electrical effects. Detecting the faults is the first step in the diagnostic process and certain faults or problem conditions are more easily detected because of the type of equipment or components the faults occur in, for example, bearings. Thermal measurements can also be used to verify vibration analysis as this can detect any overheating due to insufficient lubrication, misalignment, or other causes.

3.1.2 Thermal Measurements

Thermal measurements are used to monitor absolute or relative temperatures of key equipment parts or areas being monitored. Abnormal temperatures indicate developing problems. Temperature and thermal behaviour of plant components are the most critical factors in the maintenance of the plant and for this reason, temperature is frequently considered the key to successful plant maintenance and is the most measured quantity. Contact and non-contact. methods of temperature measurement can be used: thermometers and thermocouples for the former and non infrared sensors etc. for the latter.

The most commonly stated advantages of non-contact thermal measurement over contact measurement are that they are non-intrusive, remote, faster and provide a thermal distribution of the object surface. Some basic concepts that are used for non-contact thermal measurement include:

- Electromagnetic spectrum.
- Infrared energy.
- Infrared thermal measurement.
- Infrared image.
- Emissivity.
- Blackbody, graybody, and realbody.

3.1.3 Tribology

One of the basic technologies of condition based monitoring and maintenance is lubricating oil analysis. This is very effective for providing early warning of potential equipment problem. Oil analysis can involve the assessment of lubricant quality, particle contamination, wear particle analysis, oil sampling and testing. Its main aims are to ensure that bearings are being properly lubricated. Some utilities and operators maintain their own oil analysis laboratories and chemists. however, most send the samples to a recognized laboratory. Lube oil sampling intervals are based on operating history, operating time, oil condition, etc.. A key element in determining the root cause of oil-related problems, is the ability to classify the types of wear and contaminants present (both chemical and particulate) and their potential source(s). This requires an understanding of chemical properties of the lubricants being used, the metallurgy of the internal components within the bearing reservoir, and the sources of contamination that could affect the system.

3.1.4 Acoustics & Acoustic Leak detection

Acoustic systems can detect anomalies, either structural or airborne and provide a digital indication of the sound intensity level and can locate the source of the sound. For monitoring critical equipment on a continuous basis, the sensors are permanently attached to the equipment and the signals are transmitted to an on-line acoustic monitoring system.

Long term ultrasonic analysis can identify poor maintenance practices such as improper bearing installation or lubrication, poor steam trap maintenance, and improper hydraulic seal or gasket installation. It can also identify machines that are being operated beyond their original design limitations, inadequately designed machines, or consistently poor quality replacement parts.

Periodic monitoring can provide an indication of seal or packing wear, steam trap contamination or deterioration, or cracks in tanks or piping. They can be detected when they are minor, and less expensive to repair and an advance notice of problems means that they can be repaired during normal shutdown, rather than have a catastrophic failure cause unscheduled down time. Long term ultrasonic analysis can identify improper maintenance practices, including poor seal or packing installation, improper steam trap maintenance, poor welding or pressure vessel maintenance. Long term trends can also identify improper operating conditions, such as running equipment beyond design specifications. They can be used to compare similar equipment from different manufacturers to determine if there are design benefits that will be reflected in increased service life; and they can identify consistently poor quality replacement parts.

Ultrasonic analysis is one of the less complex and less expensive predictive techniques. Its simplicity is directly related to the size and ease of use of handheld detectors, and the relatively straightforward presentation of measurement data on meters or digital readouts. The cost of the equipment is moderate, as is the amount of training required for its use. The technique is limited to applications which produce measurable ultrasounds: hydraulic, compressed air, steam or vacuum systems.

Acoustic monitoring devices have been applied in several different areas including leak detection for feedwater heaters, valve internals, valve externals, and boiler tubes. Feedwater heater tube leaks are commonly detected by changes in heater water level, flow rate, or water chemistry. Because of the large total fluid volume, all of these methods require large leaks in order for the change to be noticeable, and it may be hours or days before the leak is discovered which can reduce plant efficiency through thermal efficiency losses. When a feedwater leak is detected early, it is possible that the leaking heater can be taken of-line for repair while the other heaters remain in service which avoids a complete shutdown and minimizes the performance efficiency degradation.

For boiler tube leak detection high temperature sensors, mounted onto waveguides that couple the acoustic pressure waves in the boiler to the sensor, are installed in locations of the boiler that have had a history of failures. Acoustic pressure waves generated in the boiler from a tube leak are detected by the sensors and converted to an electrical signal. The signal indicates the size of the leak and the relative magnitude of the various sensor readings allows approximation of the leak location.

A further advantage of acoustic emission is that very early crack growth can be detected well before a highly stressed component may fail. This type of technology can also provide analysts with early indication of the onset of degraded strength in metal components such as pressure vessels. By trending the acoustic emission event occurrence, analysts can track and project the progression of grain structure breakdown. With this information, the plant can remove the metal component from service before total loss of function occurs. Acoustic emission technology has been successively used on Reactor vessels and related piping, Control rod housings, Main steam lines, Transformers and Fossil high energy piping. In such applications, the sensors can be monitored continuously during all levels of plant operations and analysts can then trend this data.

3.1.5 Other techniques

Numerous other non-destructive techniques can be used to identify incipient problems in plant equipment or systems. These can be used as the means of confirming failure modes identified by the condition based maintenance techniques discussed above or to support condition based maintenance. Such methods include acoustic emissions, eddy-current, magnetic particle, residual stress and most of the traditional non-destructive methods. A set of handbooks produced by the American Society of Non-destructive Testing (ANST) provides a comprehensive database for most non-destructive testing techniques.

4. Damage Characterisation and Condition Monitoring for Passive Components

Within a nuclear power plant, the reactor instrumentation and control system provides the online monitoring of various process and environmental parameters, including temperatures, pressures, flows, and neutron flux, at a range of locations. Such information is not however generally related to the effects of environmental conditions or to show the life time utilization of a plant system or components The current state-of-the-art for online monitoring of component condition, as opposed to process parameters in NPPs includes systems that measure reactor noise, acoustic signals and vibration in various forms (as discussed in the previous section) and has been part of condition-based maintenance programs that mostly focus on active components. It is increasingly expected however that the management of the passive components in such systems will determine the acceptability of and extended longer-term operation of nuclear plant [7] and those of the advanced reactor systems such as the VHTR.

Components and passive systems of particular interest to Condition Monitoring include the pressure vessel, Class 1 piping, concrete structures in the form of those which support and surround the nuclear island and the containment, buried piping, core-internals and cables. Passive components can also include some of the structural components that are related to active components such as large pump or valve cases. In addition to those systems that are effective in detecting and characterizing large cracks and other degradation/corrosion/erosion, there is also an interest in those methods capable of detecting and monitoring early degradation.

Within the Division 1 of Section XI of the ASME Boiler and Pressure Vessel Code [8], Inspection and examination methods are classified in Article IWA-2000 as visual, surface, or volumetric examination methods. Specific nondestructive technologies are used for surface and volumetric examination which are shown below in Table 4-1. Generally, a “phased” approach is applied to examinations, with a specification that all required examinations for a given category be distributed over three inspection periods within a 10-year inspection interval. The Code establishes a hierarchal and layered sampling strategy for the inspection of components based on their perceived importance to safety. Systems in direct contact with reactor coolant (Class 1) receive the most stringent and numberous inspections because it is important to maintain the coolant inventory and contain radioactivity.

Table 4-1:Summary of NDE techniques given in Section XI of the ASME Boiler and Pressure Vessel Code

Surface Examination	Volumetric Examination
Magnetic Particle	Radiographic
Liquid Penetrant	Ultrasonic
Eddy Current	Eddy Current
Ultrasonic	Acoustic Emission
Visual	

Many operating plant have adopted a risk-informed inservice inspection (RI-ISI) programs to define the locations and sample size for ISI of safety-related (Class 1, 2, and 3) piping welds at their plants. The concept behind RI-ISI is to use insights from a plant risk analysis to develop a ranked order of components and apply ISI resources to those contributing the higher risk. The RI-ISI approach provides a more meaningful basis for selecting the specific components to be inspected than was originally developed by the Code. Currently, only acoustic emission (AE) is sanctioned by the ASME Code for performing online monitoring of passivestructural components. Research is continuing to investigate the use of modern AE systems with digital signal processing, Guided ultrasonic wave (GUW) technology is also receiving serious consideration as a crack detection and degradation monitoring tool for piping inspection. A further monitoring technology that has potential for field deployment is based on low-frequency ultrasonic phased arrays (PAUT) [9]. Applications of such methods include examination of degradation in coarse grain materials (such as cast austenitic stainless steels), dissimilar welds, surge line piping welds and the interference fits of control rod drive mechanism (CRDM) penetrations.

Degradation in metal components in its early stage is characterized by the development of crack nucleation sites which can lead to small cracks, which are below the size that current NDT is sensitive. Laboratory techniques, including optical methods and those using potential drop, can be used to study crack initiation. The stages in the evolution of ageing degradation in passive components involves microscopic and macroscopic crack development and nucleation and the linking of small cracks that can lead to the growth of large cracks and leakage or failure. Traditional NDE technologies are only sensitive to the most severe (later) stages of degradation. Several NDE technologies are emerging as potential candidates to meet early degradation measurement needs and these include micromagnetic techniques, magnetic Barkhausen noise (MBN) and B-H curve analysis. Nonlinear acoustic/ultrasonic techniques are also promising with research indicating that nonlinear techniques are more sensitive to micro-damage than conventional linear ultrasonic techniques.

For Primary Containment structures such as the pressure vessel the ASME Code Section XI specifies general visual inspections for all surfaces accessible to inspection. For Concrete Structures assessments of concrete containments are normally performed through NDE and destructive mechanical and chemical analysis of core samples. The heterogeneous nature of concrete containments and variety of degradation mechanisms requires the application of diverse techniques to obtain a more complete assessment of structural integrity. For new plants, there is increased interest in the use of embedded optical fibers to continuously monitor the condition of concrete structures. Guided ultrasonic waves (GUW) and Acoustic Emissions (AE) are used to monitor strain in prestressed tendons as well as reinforcing steel for signs of corrosion and delamination. For monitoring and evaluation of metallic vessels and structures this makes use of measurements of levels of irradiation in damage assessment methods for the forward evaluation of the condition and performance of the vessels and its health management.

The traditional approach to determining NDE applicability to detection of embrittlement in PV steels has been mainly experimental, with measurements on samples with varying degrees of embrittlement taken to see if there is any correlation to the fracture toughness of the steel. In many cases, these measurements have been made on surrogate specimens (i.e., specimens with varying hardness levels but not necessarily the same microstructure that is indicative of irradiation embrittlement). To improve things it is important to expand upon this experimental work to include modeling efforts that assist in the understanding of the NDE measurements versus the changes in steel physical properties, as well as approaches to determine the correlation of that measurement with any crack propagation during accident conditions. The development of the NDE methods themselves needs to assist in the determination of current RPV fracture toughness as well as in prediction of fracture toughness with further ageing of the vessel (particularly in the presence of microcracks or other stress concentrators). The NDE measurements and the corresponding models that can verify their applicability to the problem, the sensitivity to embrittlement and microcracking, and the accuracy in characterizing physical properties of RPV steel to establish correlations with RPV fracture toughness are all important inputs for providing information to the overall Condition Monitoring approach and program. Some emerging NDE techniques also appear to show promise for detecting and characterizing microstructural changes in RPV steels. These techniques include nonlinear ultrasonic, micromagnetic measurements and Seebeck-effect-based techniques. These techniques may offer a method for nondestructive characterization of RPV steel which can then possibly be correlated to its fracture toughness. Soome established techniques for addressing irradiation damage monitoring in REACTOR Pressuer Vessels are as follows :

NDE Techniques for Fast Neutron Embrittlement of RPV Steels

Various non destructive testing methods have been used to measure the degree of irradiation embrittlement, which can lead to an increase in yield and tensile strength, and a decrease in toughness (shift in the Ductile-to-Brittle Transition Temperature (DBTT)). These techniques are in various stages of development and maturity. The most mature methods are as follows:

Automated Ball Indentation:
The Automated Ball Indentation (ABI) is a system that converts instrumented hardness testing to tensile and fracture toughness data. The method is considered to be non destructive as it only produces shallow indentations. It is claimed that this method of fracture toughness testing can produce results conforming to the Master Curve requirements in accordance with ASTM E1921-97. The technique has been fully qualified and is commercially available as laboratory equipment, and possibly in-field equipment. The application of this method in the field and in an irradiation environment should be investigated.

Thermo-power Measurements:
This system is based on the Seebeck effect, which leads to thermoelectric power in metals. Currently two devices have been developed, the first by Electricite de France (EdF) together with the Technical University INSA de Lyon, and the second by the Joint Research Council (JRC). Laboratory measurements have established the variation of voltage generated when a temperature gradient is applied to the metal, which varies with hardness, toughness and with the Cu content of reactor pressure vessel steels. The generated voltage drop, DV, is measured to give the coefficient DV/DT = DTEP. EdF have built a portable Thermo-Electric Power (TEP) system, which can be used on large components after some surface preparation. It has been demonstrated by the measurement of damage on a cast duplex steel elbow. The JRC device has shown its capability to detect material damage induced by irradiation. This technique has reached a high level of maturity and developments regarding sensitivity and portability are recommended.

Magnetic Interrogation Method:
This method relies on a good correlation between the degrees of radiation-induced hardening and magnetic coercivity change in the steel of nuclear reactor pressure vessels. The part of the pressure vessel to be inspected is magnetized with a two-pole magnetic yoke and the magnetic field distributions on the surface are measured. Through magnetostatic field analysis, the coercivity distribution through the thickness of the RPV is determined, which could be correlated with the degree of irradiation embrittlement. The level of maturity of this technique is not known and developments should be monitored.

Advanced Mechanical Testing with Micro Samples
The use of Micrometer sized samples could also offer a possibility for advanced condition based monitoring. Tiny sample volumes can be removed either directly from a component or from test coupons for mechanical and microstructural analyses. Modern micro-sample preparation techniques (e.g. focused ion beam) together with micro-deformation machines (nano-indenter) allow both, the preparation of small thin foils for microstructural analyses and the testing of micrometer sized samples. Micromechanical testing methods have been developed in various geometries for bending, compression and tensile testing. A simple, and now widely used, test geometry is a compression pillar, which gives the advantage of a simple stress state compared to the more complex stress states found in bending. However, research on pillar compression at the micron scale has shown very strong size effects on the yield stresses (smaller pillars being stronger) and on the shape of the stress–strain curves (smaller pillars giving a step-like, behaviour). This has been attributed to both dislocation starvation and to the statistics of a limited number of small dislocation sources. This has so far limited the applications of such tests to understanding the underlying physical processes that govern the dislocation motion in the pillars; and only a limited amount of work has focused on using them to try and understand the properties of bulk materials.

Within ARCHER (sees section 2.3), samples from well characterized irradiated reactor pressure vessel materials were tested with nano-indentation and micro-pillars to obtain information on irradiation effects on mechanical properties. The results encourage the use of micro-sample test for condition based monitoring of componentsin current and particularly in advanced nuclear plants. For the particular case of the Pressure Vessel material investigated further work is considered necessary to understand the discrepancy between the yield stress measured with micro-pillars and the ones determined with conventional samples for annealed material. This conclusion fits in with the current understanding and development of the approach and supports the recommendation to investigate this type of damage condition monitoring further before it can be considered an alternative approach to the currently developed methods.

5. Considerations for the HTR

For HTR's it is likely that the latest most developed condition monitoring approach and methods will be applied. The HTR will be designed for long-term operation at temperature in a helium environment and the limited operational experience of some of the materials in such an environment and plant will necessitate a reliable assessment of damage and residual life of components[10]. The use of techniques such as AE currently allowed in Codes such as ASME and other systems developments (highlighted above in section 4) currently being investigated or considered may offer a means of montioring areas of the plant performance and operation that are currently not available.

For monitoring of component life, non-destructive condition monitoring of damage in some materials may be difficult. Periodic investigation of small samples taken from well defined locations in the plant could provide an attractive tool for damage assessments. The possibility of using very small samples taken from plant locations for complementary condition monitoring offers a way forward. Techniques such as micro/nano-indentation, micropillar compression, micro bending, small punch and thin strip testing can be used for the determination of local mechanical properties. Advanced preparation techniques such as focused ion beam (FIB) allow the preparation of samples from these small volumes for micro-structural analyses with transmission electron microscope (TEM) and advanced X-ray synchrotron techniques. Modeling techniques (e.g. dislocation dynamics DD) can provide a quantitative link between microstructure and mechanical properties.

The results from investigations within ARCHER have shown further work is considered necessary to understand the discrepancy between the yield stress measured with micro-pillars and the ones determined with conventional samples for annealed material. This conclusion fits in with the current understanding and development of the approach and supports the recommendation to investigate this type of damage condition monitoring further before it can be considered an alternative approach to the currently developed methods.

6. Conclusions

Condition based monitoring (CBM) monitors the condition or performance of plant equipment through various technologies. The data is obtained and analyzed, and used to predict equipment failures. Condition based monitoring uses various sensors (e.g. pressure, temperature, vibration, flow) and fluid (e.g., oil and air) samples. With these sensors and samples, indications of system and equipment health, performance and integrity (strength) are obtained for scheduling timely correction action. When equipment failure timing is known, then actions to prevent or delay failure will ensure that the reliability of the equipment can remain high.

The results of Task 2 of Workpackage 42 of ARCHER have been summarised and a review carried out of Damage Characterisation and Condition Monitoring issues. The report has summarised the findings from investigations performed on corrosion studies and experiments within ARCHER which cover tests on materials such as P91, 316SS and Alloy 800H in helium atmospheres along with results from damage related information contained in small volumes for Condition Monitoring of a Pressure Vessel steel. This latter method is being considered for development as an attractive tool for condition monitoring damage assessments.

The results from investigations within ARCHER have shown further work is considered necessary to understand the discrepancy between the yield stress measured with micro-pillars and the ones determined with conventional samples for annealed material. This conclusion fits in with the current understanding and development of the approach and supports the recommendation to investigate this type of damage condition monitoring further before it can be considered an alternative approach to the currently developed methods.

7. References

[1] J Berka, CV Rez Ltd: Degradation of metallic materials in HTR helium coolant - survey of the data generated in previous HTR and related programs, Deliverable D42.21, ARCHER Project,

[2] M. Kolluri, NRG: Compilation of reference mechanical and micro-structural data for 800H and weldments, Deliverable D42-12, ARCHER Project,

[3] Dr. Kloewer, ThyssenKrupp AG: Procurement of test material, Deliverable D42-11, ARCHER Project,

[4] Jan Berka, Karin Stehlik, CV Rez Ltd.: Report of complementary environmental test results, Deliverable D42-22, ARCHER Project,

[5] Manuel A: Pouchon, Wolfgang Hoffelner, Jiachao Chen (PSI): Report on pre-damage procedures & characterization of pre-damaged samples using small samples, Deliverable D42-23, ARCHER Project,

[6] I IAEA-TECDOC-1551: Implementation Strategies and Tools for Condition Based Maintenance at Nuclear Power Plants, IAEA International Atomic Agency, 2007

[7] R M Meyer, L J Bond, P Ramuhalli, Applied Physics, Pacific Northwest National Laboratory, USA, Online condition monitoring to enable extended operation of nuclear power plants, Nuclear Safety and Simulation, Vol. 3, Number 1, March 2012.

[8] Division 1 of Section XI of the ASME Boiler and Pressure Vessel Code

[9] G. J. Schuster, S. R.Doctor, L J A Bond, System for High-Resolution, Nondestructive, Ultrasonic Imaging of Weld Grains, IEEE Trans. Instrum. Meas., 2004, 53(6):1526-1532.

[10] Wolfgang Hoffelner; Manuel Pouchon; Maria Samaras; Annick Froideval; Jiachao Chen, (PSI), Condition Monitoring of High Temperature Components With Sub-Sized Samples, Proc. ASME. 48555; Fourth International Topical Meeting on High Temperature Reactor Technology, Volume 2:69-74.January 01, 2008