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

Best-practice proposal for in-service inspection concept

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Summary

This document contains the results from the ARCHER SP4 Workpackage 2 activity on Task 3 including information and issues associated with the development of the best practice proposal for In-service Inspection. The scope of work is to provide some initial information that would allow development for HTR Application. Conclusions are made concerning the ISI and NDE examination of the IHX including the Compact IHX. The tube and shell IHX provides the best opportunity to perform ISI and repairs since it uses proven technology. For the compact IHX ISI this more problematical and inspection and repair of individual channels while installed is currently considered impossible. However failure of a compact IHX module would not result in fluid release to the atmosphere as the design of the HTR provides for minimal ammounts of contamination of the cooling fluid. It is considered that leak testing of individual modules should be performed and when the system is found to be leaking beyond acceptable limits as monitored by plant operation indicators repair or replacement should be considered. The report has summarised the findings from Task 3 Work Package 42 investigations performed on the IHX material Alloy 800H within ARCHER which covers a literature review and data collection on the effect of microstructure, heat treatment, welding process and welding parameters on various types of cracking (solidification cracking, liquidation cracking and/or ductility dip cracking, relaxation cracking) experienced in Alloy 800H. Results from the development of a Visco-plastic Creep-Fatigue Constitutive Model for Alloy 800H are also given and included as Appendix A of this report. The Visco-plastic Creep-Fatigue Constitutive Model has been developed specifically for the design, manufacture and testing of the mock-up investigations on the Compact IHX investigated in WP43. Thermal transients and gradients in the major components of the steam cycle lead to thermal induced str

Approval

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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 behavior and property development. Specific tests on Alloy 800H have also been carried out within WP43 for the development of the Compact IHX Mock-up and tests. The activities covered under Task 3 of WP42 include a review and data collection activity and tests and evaluations for the development of a visco-plastic creep fatigue constitutive equation for Alloy 800Hwhich was used for the IHX mock-up investigations of WP43. The tests were performed on the material provided by Thyssen-Krupp VDM. This report has been compiled to provide a synthesis of the results from Task 3 activities which can be used as a basis for relevant sections of the SP4 contributions to the Final Report and to address a best practice proposal for In-service Inspection arising from these tasks and the work of SP4 for the HTR development. Since the latter work was to be carried out by FZJ and they withdrew from the project at the outset, it was not possible to perform any substantial developments in this area. This part of the work could therefore only be answered by the completion of a short review using the findings and information in [1] and [2].

2 Summary of Results of Task 3

2.1 Review and Data Collection

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 have 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 which operate 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 Alloy 617 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. Alongside this, further developments for Alloy 800H have also been made which address the available design material properties in terms of temperature and operating duration (creep properties). These have been reported in specific ASME LCC Documents [3], [4], [5].

Within the ARCHER Project the material investigations have been aimed primarily at Alloy 800H properties and behavior at elevated temperature. A literature review on the effect of microstructure, heat treatment, welding process and welding parameters on various types of cracks (solidification cracking, liquidation cracking and/or ductility dip cracking, relaxation cracking) in Alloy 800H has been carried out [6]. Alloy 800H is a solid solution strengthening Ni-Fe-Cr alloy with a face centred cubic lattice structure, and a grain size between 70 to 180 µm with twin grains present in the microstructure. The austenitic matrix includes mainly titanium carbonitrides (TI (C, N)), chromium-rich mixed carbides ($M_{23}C_6$) and γ'-phase (Ni_3 (TI, Al)). The precipitation of the $M_{23}C_6$ carbide occurs in along the grain boundaries in the temperature range 550-1100℃. TiC carbides precipitate at temperatures above 700℃ and mostly within the grain. A precipitation of γ'-phase occurs at a temperature range of 440 to 650 ℃. Some mechanical properties for the material are shown in Figure 2-1. The welding processes for the production of similar and dissimilar weld joints have been discussed along with recommended welding parameters used in the literature. The filler materials, their microstructure and the influence on crack formation has been reviewed. The filler metal 2.4806 has been mainly recommended in standards and from manufacturers of semi-finished products. The creep rupture weld strength factors for Alloy 800H for temperatures of 600 to 1000 °C has been reviewed, finding from some creep relaxation tests results performed at MPA Stuttgart are presented in Figure 2-2.

With regard to crack susceptibility of Alloy 800H a critical strain rate v_{kr} could be demonstrated as a criterion for the formation of hot cracks. The critical temperature interval of brittleness and the nil-strength temperature can be determined and the behaviour of the material, the formation of thin films and cavities along the grain boundaries described. For hot cracks type I the influence of the accompanying elements and the need for compliance with the total content of P+S < 0.01 % to prevent solidification cracks have been presented. The cause of the cracks of hot type II (DDC) was shown, the context with the grain boundary types present explained and the influence of impurities and the pinning effect of carbides demonstrated. Thus the occurrence of DCC is not expected in a temperature range above 600 °C by use of filler material 2.4806 and a maximum strain of 4 %. No damage due to relaxation cracks is expected at temperatures above 788° C.

Of the possible factors influencing the formation of cracks, which can be divided into metallurgical-related and process-related mechanisms, an intermediate stabilising annealing for 3 hours at 980 °C is required to avoid relaxation cracks due to intense welding. To reduce residual stresses a stress relief heat treatment can be carried out, however a full removal can only be achieved by means of soft annealing at 750 to 960 °C, at which attention must be paid to high cooling rates due to a susceptibility of the alloy. As a result of this detailed literature review, a comprehensive overview of published articles, research reports and manufacturer's specifications and recommendations, standards and guidelines for the nickel base alloy Alloy 800 H is given. It also provides a comprehensive overview of the possibilities for welded structures made of Alloy 800H.

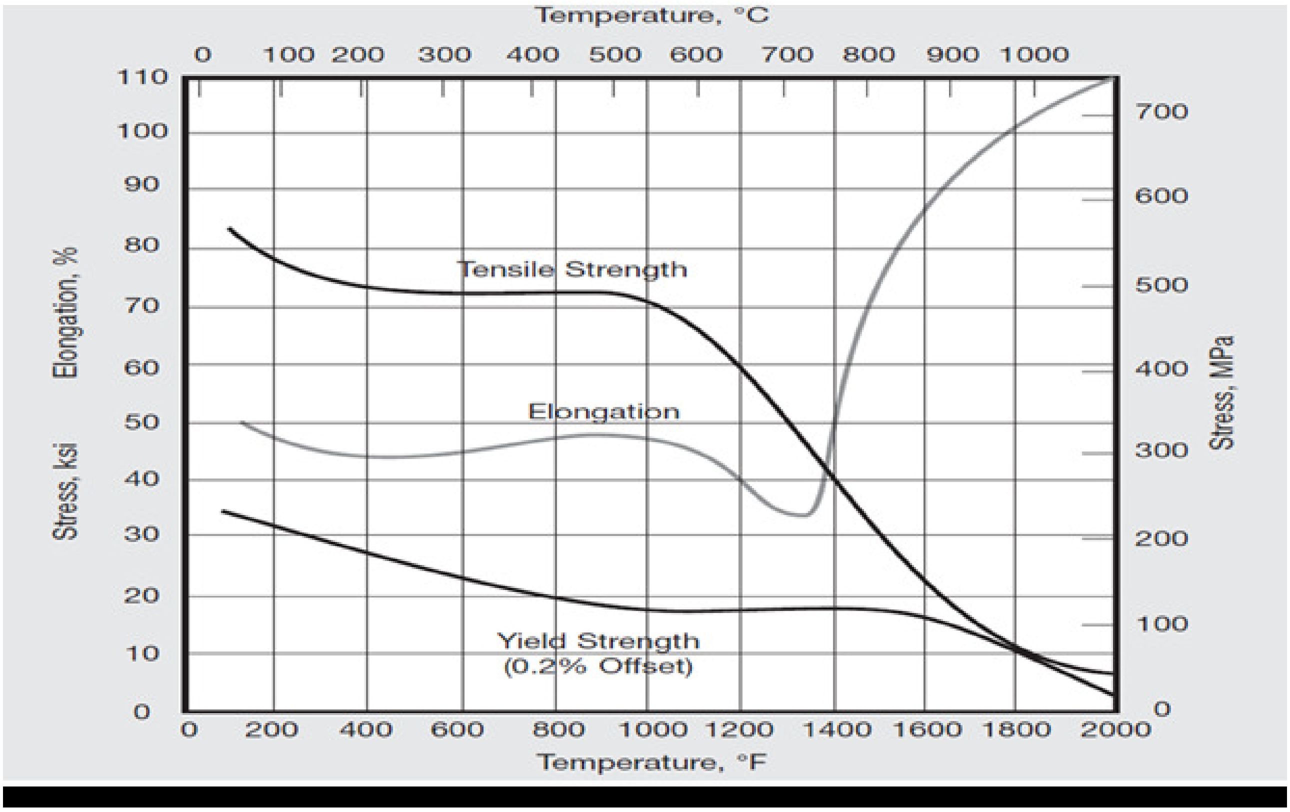

Figure 2.1 Mechanical Properties of Alloy 800H [x]

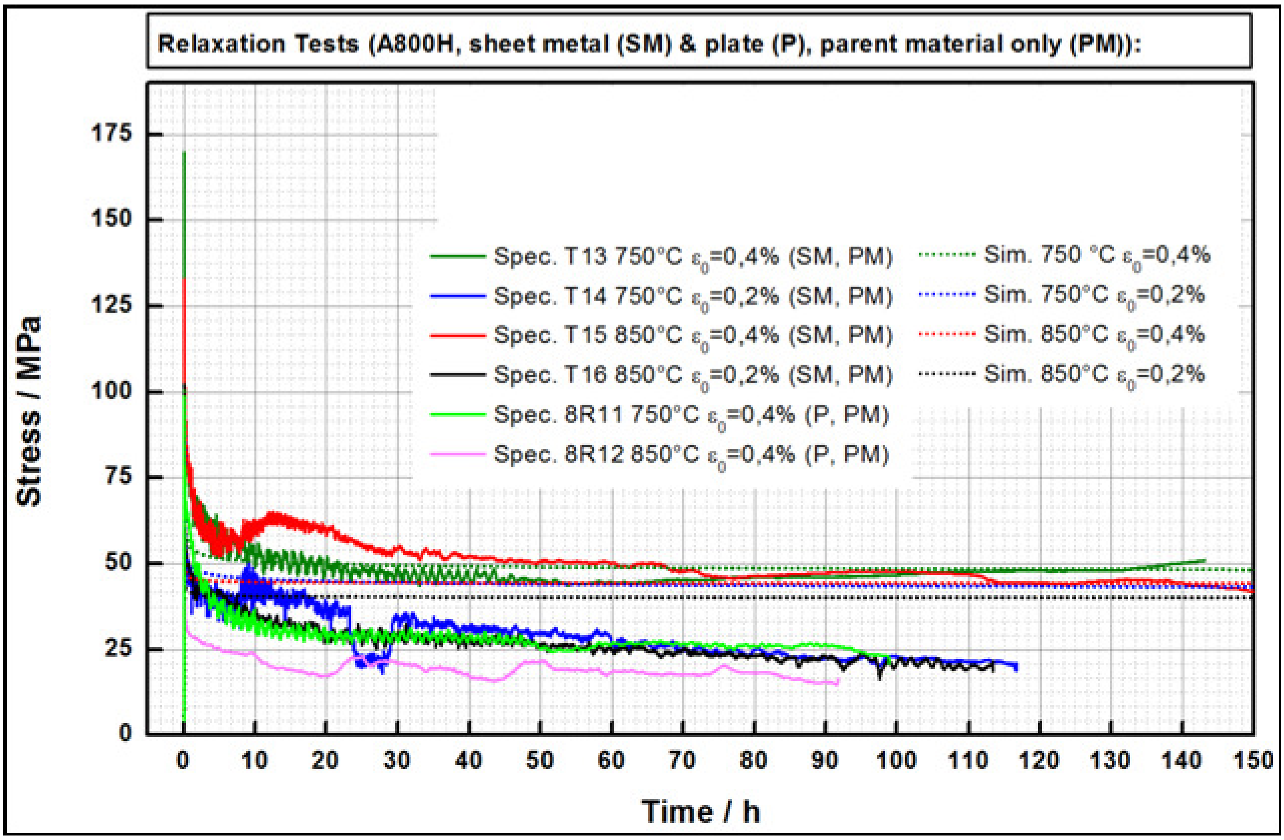

Figure 2-2 Creep relaxation test results (MPA Stuttgart)

2.2 Visco-plastic Creep-Fatigue Constitutive Model for Alloy 800H

Within the ARCHER Project to properly describe the time-dependent deformation behaviour of the material at elevated temperatures, constitutive equations need to be developed for application in Finite-Element simulations during the design phase of the intermediate heat exchanger (IHX) or steam generator unit (SGU) to optimize the components lifetime. Low cycle fatigue tests at various temperatures were carried out to measure the material response in terms of stress-strain hysteresis loops. This data is subsequently processed to identify material parameters for a Chaboche type visco-plastic material model for A800H ranging from room temperature up to 850℃.

Strain-controlled LCF tests were carried out on a servo-hydraulic machine with Zwick® controller system. To cover all influencing quantities on the visco-plastic deformation of Alloy 800H (e.g. temperature, strain range and strain rate influence), it was decided to add a pre-program to the standard periodic LCF test which consists of three major blocks with different strain ranges. Within each block the strain rate varies from $1E^{-3}$ 1/s to $1E^{-5}$ 1/s to investigate the influence of strain rate. Two additional dwell times of 30 mins at the maximum and minimum strains were applied to record the stress relaxation during the tensile and compression dwell period. All tests were carried out with symmetric strain limits ($R\varepsilon$=-1), respectively with no mean strain. The test results shows initial cyclic hardening behaviour, which reaches a stable plateau after only a few cycles. The peak stresses remain stable after the initial hardening for temperatures below 650℃. The tests at higher temperature (≥650℃) show a steady softening until macroscopic failure with a significant load drop occurs.

The parameter identification for the Visco-plastic Creep-Fatigue Constitutive Model was carried out in three steps. The first included establishing the hardening parameters for the kinematic hardening, the second, the identification of the isotropic hardening parameters, and the third the static recovery parameters. It was very important to improve the material model for long-term relaxation behaviour to properly predict the remaining stresses for stationary loads and longer dwell periods. The presented steps of parameter identification were repeated in an iterative manner to provide a sound parameter set. Finally a steady nature of the parameters with increasing temperature was fulfilled to provide good interpolation performance in transient FE simulations. A good agreement between the experimental and material model predictions for relaxation tests on thin sheet metal for 100 hours was obtained. It should be noted that the model is not capable of describing the long-term response of a creep-loaded structure especially at low stresses, because the simplified Chaboche model is not suitable for covering relaxation and creep sufficiently at the same time.

A full parameter set for the presented model was therefore developed and provided to the partners of work package WP43 IHX for code assessment and design optimization of the intermediate heat exchanger and as material input data for WP44 Steam generator unit (SGU).

3 Non-destructive Examination and In-Service Inspection Technology for HTR's

This section provides a brief review of Non-destructive Examination and In-Service Inspection Technology for HTR's. Since this work was to be done by FZJ and they withdrew from the project at the outset, it was not possible to carry out any substantial work in this area and this part of the work could only be answered by the completion of a short review. The contents of this section have largely been taken from the findings and information given in [1] and [2].

3.1 HTR Past Reactor Experience

A review and assessment of past reactor experience is included in [x] in terms of HTGR NDE Methods and ISI Strategy. The operating and maintenance environments for HTGRs are not considered significantly different to those of LWRs. Much of the past HTR experience is considered of limited value since today's proposed reactor configurations should be designed to accommodate both outage-based and on-line monitoring and examination. Summaries for specific reactors are reproduced below:

3.1.1 Dragon (U.K.) (1964–1977)

The Dragon reactor was built to fulfil a research and development role. The Dragon was used to develop and qualify the BISO and TRISO fuels used in today's HTRs. The Dragon reactor had a steel pressure vessel enclosed by a concrete confinement building. Periodic inspections of the Pressure Containment System were executed as part of an integrated inspection program and included pressure testing, remote visual inspections and helium leak monitoring on a continuous basis via the double containment and leak detection interspaces. A similar approach is now being proposed for next generation of HTRs.

3.1.2 Thorium Hochtemperatur Reaktor (THTR) (Federal Republic of Germany) (1985–1989)

The THTR was constructed with a PCRV vessel, the design of which is not considered relevant for today's advanced reactors. The THTR was an indirect cycle reactor, consisting of a reactor vessel, six helical coil steam generators and helium circulators all enclosed by the PCRV. There is a large body of documents (in German) which includes information on operational experience, NDE and monitoring techniques. The following NDE techniques were used: visual inspection, leak testing, pressure test and weld inspection using X-ray or ultrasound for wall thickness measurements.

The THTR had videos of inspections carried out in the hot gas duct, steam generator structural support and the hot gas duct to core lower plenum interface. The THTR also conducted video inspection of some areas in the fuel handling system such as the core unloading device pebble collection box and associated piping. The THTR continuously monitored the helium leakage via a leak detection system. The THTR had double penetration closures and the interspace volumes were monitored for pressure build up over time. The system had a very low helium leakage/consumption in contrast for example to the Fort Saint Vrain reactor. Data on the exact helium quantities ordered for THTR and the amount of helium consumed due to charging and discharging of fuel pebbles and quantities vented for maintenance are available. The THTR steam generator tubes were monitored continuously via the moisture monitoring and reheat steam activity. The THTR did not have any steam generator tube leaks during the three years of operation.

3.1.3 Fort Saint Vrain (FSV) (U.S.) (1974–1989)

There is a considerable body of documented experience relating to the operation and decommissioning of FSV [NUREG/CR-6839] [3]. FSV had two steam generator leaks in 13 years of operation (the first occurred one year after the plant began generating power). In the context of monitoring, diagnostics and prognostics, the following operational experience may be relevant to the monitoring of advanced reactors:

- water incursion events or failures of moisture detection systems
- air or other unwanted gas incursion events and failures of gas detection systems.

A similar approach is now being considered for the next generation of HTRs.

3.1.4 Other Gas-cooled Reactors

Limited public information on in-service inspection and monitoring of some of the other past reactor systems is available (Magnox, AGRs, HTTR and HTR-10 reactors). Information available in the public domain is largely related to reported operational experience and shows different types of monitoring techniques were successfully applied. Also since most of these plants had PCRVs, access was severely restricted. This is in contrast to LWRs where discrete examinations are mandated and monitoring techniques receive less emphasis. An increasing emphasis on the use of monitoring techniques, as a valid ISI technique, is anticipated for HTRs, to demonstrate the ongoing safety of the plant, which is the ultimate objective of ISI.

3.2 HTR Examination Methods and ISI Strategy

Rules for in-service inspection (ISI), examination and testing of the nuclear reactor plant are presented in a number of different Codes and Standards [7], [8]. Such rules also address repair and replacement activities and provide for a mandatory program of examination, testing and inspection to establish evidence of adequate safety and to manage deterioration and aging effects. An In-service Inspection program constitutes all the requirements both administrative and technical necessary to perform the ISI of systems and components important to safety. They provide the requirements and practices needed to maintain original and / or sufficient margins in the Nuclear Plant and its components and to return it to service in a safe manner following plant outages that can involve refueling, maintenance, repairs, replacements, inspections of welds, valves, etc..

The basic standards are the government standards, i.e. Regulations or Orders, which are published by the legal bodies of the different governments and compliance is mandatory. Industry standards are also provided and written in compliance with these regulations, to give input in the form of actual practices and lessons learned in performing ISI's. ASME Section X1 for example has been prepared through the voluntary participation of knowledge from nuclear utilities, NSSS vendors, architect engineers, nuclear consultants, insurance companies and regulatory personnel. For such methods extensive experience has been accumulated from numerous commercial LWRs operating around the world and has contributed to a continuous improvement of plant operations and in-service inspection, examination and testing requirements to address the current state of the art developments in non destructive examination and inspection methods.

It is considered that the examination and inspection issues for the HTR will not be significantly different to those of the LWR apart from issues that result from their environmental differences. There are also potential differences that could be introduced as a result of longer operating periods between maintenance outages with a recommendation made in [1] to use the RIM methodology (reports are referenced in section 2.2 of [1]) that applies combinations of strategies for the reliability and integrity management of passive components to achieve reliability goals. It is suggested that HTRs should be designed to accommodate both outage based and on-line monitoring and examination and identify and detect in-service degradation not only using the traditional in-service inspection methods but a combination of strategies including plant and component design elements, on-line in-service monitoring and non destructive examinations. The selection of specific strategies should be based on the degradation mechanism assessment and the level of reliability required.

Non Destructive Examination and testing (NDE) techniques which form the basis of in-service inspection programs are used to interrogate the possible effects of the material degradation mechanisms on critical locations of the pressure boundary. These techniques have been proven to have no harmful effects on the components being inspected. Currently NDE is used as a diagnostic tool to detect and size the geometry of degradation effects such as, wear scars, cracks, corrosions, deformations, etc. More recently work has been carried out on developing prognostic tools that could define other material properties (preconditions to physical degradation effects) conventionally obtained through destructive testing (residual stresses, susceptibility to stress corrosion cracking (SCC) and mechanical property changes). These methodologies exist in laboratory research programs and in some instances are finding practical application in the field. These are some of the areas that should be targeted for further development in this area. Based on existing empirical observations in operating light water nuclear power plants (LWRs), methods involving ultrasound and eddy current are also recommended as priority for future developments.

3.2.1 Available Non Destructive Examination Techniques

An extensive list of NDE Techniques has been developed as a result of the past LWR Reactor experience and operation. Table 3-1 provides a list of NDE/NDM techniques applicable for use on LWR components and some new techniques along with existing applicable code and standards for specific technique applications. Prognostic methods are identified as Material Property Condition Monitoring techniques given in Table 3-2. Due to the similarity of pressure boundary components and inspection acceptance standards between LWR and HTRs the techniques of Table 3 are considered to applicable techniques that could be applied to the HTGR pressure boundary components. Selection would be made based on the specific environmental conditions both during operation and maintenance intervals and the degradation mechanisms involved, as well as readiness with regard to development within the reactor construction timeframe. The need for new techniques and further development can be decided once specific designs and the inspection criteria for specific components and environmental conditions as well as the planned inspection outage durations have been finalized.

The following sections discuss the current experience in certain areas:

a) Flaw Acceptance Resolution

Experience with LWRs for applicable and approved volumetric and surface inspection methods has demonstrated the adequacy of the existing techniques to comply with structurally defined acceptable flaw sizes (ASME IWB-3000). Since a similar concept for defining these criteria will be implemented on pressure boundary components for the HTR, the existing experience from LWR inspection resolution criteria (detection of minimal size acceptable flaws) could also be credited for NDE/NDM methods approved for use on the HTR. If more stringent acceptance criteria are required, further qualification will be needed to demonstrate that applicable NDE/NDM methods will be in compliance.

b) Degradation Mechanisms and NDE/NDM Techniques

Table 3-2 lists possible NDE/NDM techniques that may be suitable for the detection of the HTR degradation mechanisms. Damage mechanisms have been highlighted below (with their ancronyms) to support the table proposals. The issues associated with Damage Characterisation implementation for Condition Monitoring have also been discussed in ARCHER Deliverable D42-24 [9].

High Energy Radiation Embrittlement (RE)

Current experience with monitoring this degradation in LWRs is accomplished through sacrificial test samples installed in the operating reactor vessel and exposed to the high energy radiation field. These samples are removed from the operating reactor at appropriate time intervals to undergo destructive testing and to provide information on material mechanical property changes. Similar approach could be used for the HTR, provided that the RPV design allows for positioning of test samples inside it. These would normally be positioned adjacent to the beltline surface to simulate similar temperature and fast neutron flux exposure.

Material condition monitoring techniques could be an alternative way to monitor this degradation. Recent experimental applications (material manufacturing) have shown that non destructive monitoring using acoustic and electromagnetic techniques can be used to predict changes in material mechanical properties. Recent results from Idaho National Laboratory on characterization of material microstructure with laser based resonant ultrasound spectroscopy and from the Fraunhofer Institute for Non Destructive Testing with micromagnetic, multiple parameter, microstructure and stress analysis on neutron irradiated samples have produced encouraging results. These techniques are considered Long Term.

Table 3-1 NDE/NDM Techniques Applicable to HTGR

Item	Type of Inspection	NDE / NDM Method	Existing Applicable ASME Codes and Standards	Comments	Applicability to HTR ISI Programme
1.1	Volumetric	Radiography: Film Recording Digital Recording	ASME B&PVC: 1) Section V, Subsection A, Article 2 2) Section XI IWA-2231	Primarily a manufacturing inspection. Limited for ISI use due to access restrictions.	Primarily a manufacturing inspection. Current.
1.2	Volumetric	Ultrasonic	ASME B&PVC: 1) Section V, Subsection A, Articles 4 and 5 2) Section XI IWA-2232	Most preferable technique for LWR. (temp < 50℃).	Improvements needed in sensors and robotics for high temperature application. Short term.
1.3	Volumetric	Ultrasonic TOFD (Time of Flight Diffraction)	ASME B&PVC: 1) Section V, Subsection A, Article 4 Appendix III	Wide applications in LWR for sizing. (temp < 50℃).	Improvements needed in sensors and robotics for high temperature application. Short term.
1.4	Volumetric	Ultrasonic Phased Array	ASME B&PVC: 1) Section V, Subsection A, Article 4 Appendix IV	Recently deployed in LWR. (temp < 50℃).	Improvements needed in sensors and robotics for high temperature application. Short term.
1.5	Volumetric	Ultrasonic Non-Contact Laser UT	No applicable standards	Limited experience in other industries	Further development required. Long term.
1.6	Volumetric	Ultrasonic Non-Contact EMAT (Electro Magnetic Acoustic Transducers)	ASTM E-1774 Standard guide for EMAT	Limited experience in LWR.	Further development required. Long term.
1.7	Volumetric	Eddy Current	ASME B&PVC: 1) Section V, Subsection A, Article 8 2) Section XI IWA-2233	Most preferable technique for thin wall tubular products (heat exchanger) in LWR. (temp < 50℃).	Improvements needed in sensors and robotics for high temperature application (50℃ and above) Short term.
1.8	Volumetric	Remote Field Eddy Current	ASME B&PVC: 1) Section V, Subsection A, Article 17 2) Section XI IWA-2233	Limited use in LWR. (temp < 50℃). Thin wall tubular products. Thin wall plates. Ferromagnetic materials	Improvements needed in sensors and robotics for high temperature application (50℃ and above) Long term.
1.9	Volumetric	Magnetic Flux Leakage	ASME B&PVC: 1) Section V, Subsection A, Article 16	Limited use in LWR. (temp < 50℃). Limited to ferromagnetic materials.	Improvements needed in sensors and robotics for high temperature application (50℃ and above) Long term.
2.1	Surface	Magnetic Particle	ASME B&PVC: 1) Section V, Subsection A, Article 7 2) Section XI IWA-2221	Manufacturing inspection. Limited for ISI use (loose particles). Class 2 & 3 components in LWR. (temp < 50℃). Limited to ferromagnetic materials.	Manufacturing inspection. Current.
2.2	Surface	Liquid Penetrant	ASME B&PVC: 1) Section V, Subsection A, Article 6 2) Section XI IWA-2222	Manufacturing inspection. Limited for ISI use (loose particles). (temp < 50℃).	Manufacturing inspection. Current.
2.3	Surface	Eddy current	ASME B&PVC: 1) Section V, Subsection A, Article 8 2) Section XI IWA-2223	Recently expanded use in LWR. Suitable for remote applications. (temp < 50℃).	Improvements needed in sensors and robotics for high temperature application (50℃ and above) Short term.

Table 3-1 NDE/NDM Techniques Applicable to HTGR (CONT)

2.4	Surface	Magnetic Flux Leakage	ASME B&PVC: 1) Section V, Subsection A, Article 16	Limited application in LWR. (temp < 50℃). Ferritic materials	Improvements needed in sensors and robotics for high temperature application (50℃ and above) Long term.
2.5	Surface	Giant Magneto Resistors	No applicable standards	No production experience with LWR	Further development required. Long term.
2.6	Surface	Laser UT Rayleigh waves	No applicable standards	No production experience with LWR	Further development required. Long term.
2.7	Surface	EMAT Rayleigh waves	ASTM E-1774 Standard guide for EMAT	No production experience with LWR.	Further development required. Long term.
3.1	Visual	Direct, Fiber Optics and Remote TV	ASME B&PVC: 1) Section V, Subsection A, Article 9 2) Section XI IWA-2210	Extensive experience with LWR	Further development in high temperature ranges. Short term.
4.1	Visual surface	Pattern Image Correlation Analysis	No applicable standards	Creep monitoring in high temperature components in fossil plants.	Further development required. Long term
5.1	Visual Thermo Graphics	Infrared Monitoring	Further development required.	Limited experience with LWR.	Further development required. Long term.
6.1	Volumetric Monitoring	Acoustic Emission	ASME B&PVC: 1) Section V, Subsection A, Article 12 & 13 2) Section XI IWA-2234 The Section V Working Group Acoustic Emissions is currently working on revising standards for online flaw detection/monitoring.	Limited experience with LWR. Focused on the monitoring of known crack propagation	Further development required. Short term.
7.1	Vibration and Loose Part Monitoring		No applicable standards	Extensive empirical experience at LWR and conventional power plants.	Further development in application of methods and identification of areas of use. Long term.
8.1	Leak test	Helium Leak Test	ASME B&PVC: 1) Section V, Subsection A, Article 10.	Used in LWR as a confirmatory test.	Further development in application of methods and identification of areas of use. Long term.
8.2	Leak Monitoring	On-Line Helium Leak Detection Acoustic Emission	No applicable standards	No production experience with LWR	Further development required. Short term.
9.1	Material Characterisation (NDC) used for Material Property Condition Monitoring	Detecting Electro Magnetic Micro Property Changes as result of microstructure states	No applicable standards	Some experimental experience in LWR and other industries	Further development required. Long term.
9.2	Material Characterisation (NDC) used for Material Property Condition Monitoring	Measuring Variation in Acoustic Velocity and Acoustic Attenuation	No applicable standards	Mechanical property (elasticity)	Further development required. Long term.
10.1	Displacement Measurement	Laser profiling. Eddy current gap measurement. Capacitive strain gauges	No applicable standards	Creep or radiation induced strains (deformations).	Further development required. Long term

Table 3-1 NDE/NDM Technique Applicability to HTGR Components for ISI / Monitoring

	Surface		Surface & Subsurface		Volumetric					Strains & Deformations			Material Property Condition Monitoring			Surface Temp. Monitoring
DM	VT	PT	MT	ET	RT	UTA	UTS	AE	UTT	VT	Laser gap	ET gap	UT Sound Velocity Change	UT Sound Attenuation Change	ET Electrical Conductivity & Magnetic Permeability Change	IR Cameras
RE							A		C				C	C	C	
TT	B			B		A				B	A	A				A
TASCS	B			B		A				B	A	A				A
FIV	A			A	A	A	A		A							
SF	A						C		C							
MF	A	A	A	A	A	A	A	C					C	C	C	
SCC		A	A	A	A	A	C	C					C	C	C	
CF						A		C		B	C	C	C	C	C	

<u>Acronyms and Definitions for Table 3-2</u>
DM - Degradation Mechanism (*Physical Manifestation):*
RE - Radiation Embrittlement, Material *(reduced material elasticity and possible swelling)*
TT - Thermal Transients *(local shape deformation, buckling, surface cracking)*
TASCS - Thermal Stratification Cycling and Striping *(local distortions, surface cracking)*
FIV - Flow Induced Vibrations *(localized wear against support structures, distortions, surface fatigue cracking)*
SF - Self Welding and Fretting Fatigue *(localized fusion, increased surface roughness, metal transfer, deformations and fatigue cracking)*
MF - Mechanical Fatigue *(fatigue cracking, surface initiated micro-cracks, develops into deeper cycle progressive cracks)*
SCC - Stress Corrosion Cracking *(high stressed area exposed to corrosive environment, surface initiated cracking)*
CF - Creep and Creep Fatigue *(distortions, elongations, with plastic deformations, reduced elasticity, surface cracking progressing with loads and time)*

<u>NDE Techniques</u>:
VT - Visual Techniques
PT - Liquid Penetrant Techniques
MT - Magnetic Particle Technique
ET - Eddy Current Technique
RT - Radiographic Techniques
IR - Infrared Monitoring
UTA - Ultrasonic Angle Beam, Including TOFD and Phased Array
UTS - Ultrasonic Straight Beam
UTT - Ultrasonic Thickness Measurement
AE - Acoustic Emission
UT - Ultrasonic Technique
NDE Technique Applicability:

A- All or most standard techniques will detect this imperfection under all or most conditions.

B - One or more standard technique(s) will detect this imperfection under certain conditions.

C - Special technique, conditions and /or personnel qualification are required to detect this imperfection.

Electromagnetic property changes are limited to surface or relatively shallow subsurface zones, and require direct access to the altered material surface. An alternate approach by monitoring acoustic parameter changes (sound velocity, attenuation) could provide a method for extracting information on mechanical property characteristics for embrittled material. This Long Term concept will require proper investigation and efforts could be coordinated with the present practice of destructively examining test samples, and further basic non destructive material characterization research.

An alternative to non destructive material condition monitoring approach is to follow existing practice used in LWRs with deploying volumetric inspection techniques that will interrogate possible degradations. Ultrasonic inspection from the outside surface provides the most practical approach for inspecting RPV zones exposed to this phenomenon. Current techniques that are regulated within the ASME Section XI code (UTA, including TOFD, and Phased Array) provide adequate bases for inspection. Short Term development will be needed on the Phased Array approach since only initial technical regulations exist in the ASME Section XI code.

Thermal Transients and Thermal Stratification Cycling and Striping (TT & TASCS)
The results from this type of damage are shape distortion and local cracking, buckling and distortion or movement at support structures and surface cracking and to monitor these effects the techniques identified in Table 3-2 are appropriate:

- Visual and eddy current for surface cracking;
- Visual, laser gap and eddy current gap for local geometry change measurement;
- Infrared camera monitoring for unexpected temperature field distributions during plant operation.

For surface inspection, visual and eddy current techniques are recommended since these techniques could be deployed remotely with robotic tooling. Current regulations in the code provide an adequate basis to implement these techniques. Some further short term development is required to provide proper guidelines for implementation of deformation measurements with visual, laser gap, eddy current gap techniques and infrared monitoring.

Flow Induced Vibrations (FIV)
To monitor effects that results from this degradation mechanism (i.e., localized wear) visual, eddy current (from the affected surface side only) and volumetric inspection with ultrasonic techniques could be applied with remote robotic tooling. Radiography will have very restricted application due to limited access for the source and sensor (film or digital receptor).
For the detection of possible surface cracking, eddy current could be applied if the critical surface is accessible, otherwise volumetric inspection with ultrasonic angle beam (including TOFD and Phased Array) techniques should be used.
Current techniques that are regulated within the code (VT, ET, UTA, including TOFD, and Phased Array) provide an adequate bases for implementing these inspections. Some further Long Term development should be needed on the Phased Array approach since only initial technical regulation exists in the code.

Self Welding and Fretting Fatigue (SF)
The effects from these mechanism are surface roughness and metal transfer and, in severe cases of adhesive wear and cracking at contact surfaces. For detection of self welding and fretting fatigue, visual and volumetric with straight beam UT methods should be applied. Current code requirements are sufficient for VT. Further long term guidelines for volumetric (UTS) could be required to properly characterize these effects, since access to the interfaces is difficult and damage at the interface likely to be very irregular.

Mechanical Fatigue (MF)
For fatigue cracking detection the preferable surface inspections will be visual (VT) and eddy current (ET) since these two methods could be deployed with remotely operated robotic tooling.

Magnetic particle (MT) and liquid penetrant (PT) could also be used in isolated cases where human access is practical. For detailed characterization of fatigue cracking, volumetric inspection will be required. Radiography will have very restricted application due to its limited ability to allow proper access for source and sensor (film or digital receptor). Volumetric with ultrasound is a method of choice that allows deployment with remote robotic manipulators. Acoustic emission monitoring could be used to monitor crack progression. This will require on-line monitoring and existing transducers operating at temperatures up to 400℃ as used in LWRs. Further sensor temperature hardening or alternative methods of inducing the ultrasound energy with laser or electromagnetic principles (Laser UT or EMAT) will be required (Short Term) for the higher operating temperature.

Current ASME code regulations provide an adequate basis for implementation of all of these techniques. However some further long term development should be considered for UT Phased Array, Laser UT and EMAT approaches since these have only limited technical regulation in the code. In addition to characterizing developed degradation (fatigue cracking), it could also be possible to implement early detection with material monitoring by interrogating local material fatigue induced hardening by monitoring sound velocity changes, sound energy attenuations and/or by monitoring local material micro structure electromagnetic property changes. These material condition monitoring techniques have shown some positive results in material manufacturing fields and a laboratory environment. Further long term development is needed to bring these material condition monitoring processes to practical applications. Concepts based on monitoring sound energy responses and electromagnetic changes will allow these processes to be remotely deployable by robotic manipulators for interrogations in high radiation areas.

Stress Corrosion Cracking (SCC)

If exposed surfaces subjected to this mechanism are accessible for inspection, surface techniques like LP, MT and ET could be applied. The preferable surface inspection technique is ET since it could be deployed remotely with operated robotic tooling. For inaccessible surfaces and more detailed crack sizing, the volumetric methods are preferred. Volumetric with ultrasound is a method of choice that allows deployment with remote robotic manipulators. Acoustic emission monitoring could also be used to monitor crack progression however this requires on-line monitoring. Within LWR's existing transducers operate at temperatures up to 400℃. For higher temperatures some further short term sensor temperature hardening or alternative methods of inducing the ultrasound energy with laser or electromagnetic principles (Laser UT or EMAT) will be required.

Current code regulations provide an adequate basis for implementation of all of these techniques. Some further long erm development could be needed on UT Phased Array, Laser UT and the EMAT approach since only limited initial technical regulation exists in the code. Material property condition monitoring techniques measuring electromagnetic property changes and acoustic characteristics have shown some initial positive results in LWRs (permeability changes due to increased residual stresses or deformed microstructure in austenitic steels and nickel based alloys). Further long term development will be required with these techniques to interrogate and quantify essential preconditions that lead to SCC degradations.

Creep and Creep Fatigue (CF)

For observing the effects of creep fatigue damage, visual monitoring, combined with more accurate local deformation measurements (through the use of laser, eddy current gap measurements and/or capacitive strain-gauges), could be applied. Further investigation of changes in material properties that affect sound velocity and energy attenuation, combined with possible alterations in microstructure resulting with local changes of electromagnetic properties could also be used. Further temperature hardening could be required for situations that experience higher operating temperatures. These methods are considered long term.

c) Advanced Material Characterization

Operating LWRs currently use NDE as a testing technology to detect, characterize and size physical imperfections (material defects, geometrical deviation, etc.). There is also the prospect of using NDE sensing parameters to detect material lattice defects, and in-homogeneous effects in material microstructure which are precursors for material degradation (defects) that directly impede on originally designed structural integrity. These changes or alterations can be detected and measured with non destructive testing techniques. Ultrasonic and electromagnetic techniques have shown that it is possible to detect early stages of material changes that lead to degradations influenced by thermal, mechanical or chemically induced microstructure alterations. Improperly conducted thermal treatments, inhomogeneous physical properties, creep and residual stresses have been detected by changes in the acoustic and electromagnetic property of the materials.

Non Destructive Characterization

Further long term evaluation and development of the following NDC (Non Destructive Characterization) techniques may advance early detection and allow for the proper mitigation actions to increase component reliability:

<u>Magnetic Barkhausen Noise:</u>

The magnetic Barkhausen effect is observed as transient pulses induced across a search coil placed near or around the ferromagnetic material undergoing a change in magnetization. These pulses can either be observed individually by counting and amplitude sorting or as an RMS signal as a function of the applied magnetic field. The BE signal arises from irreversible magnetic domain wall movements as domain walls become successively pinned and jump over obstacles in the material. The obstacles are typically dislocation defects, second phases or grain boundaries and consequently the technique is particularly sensitive to the microstructure and mechanical properties of the component. The technique is sensitive to the internal stress state because of the partial domain alignment along the maximum principal stress axis. Tensile and compressive stresses usually increase and decrease the BE signal respectively. The application of this method shows promise for qualitative evaluation of irradiation damage, but it is questionable with regard to its capability with regard to fracture toughness.

<u>Micro-Magnetic Measurements:</u>

The 3MA analyzer system (Micro-magnetic, Multi-parameter, Microstructure and Stress Analysis) has been developed by the Fraunhofer Institute for Non Destructive Testing in Germany. The instrument measures a combination of different magnetic parameters, enabling some degree of separation between variations in the stress and microstructure states. The 3MA analyzer employs the techniques of magnetic Barkhausen, conductivity (derived from Barkhausen profiles) and magnetic field frequency harmonics. The instrument is designed for use in a wide range of applications including detection of different heat treatments, residual stresses, hardness gradients and parameters loosely related to strength and toughness.

To achieve some quantitative measurement, the 3MA analyzer is calibrated against samples containing the variations of interest. Researchers have investigated a large range of materials and heat treatment conditions. Also new approaches have been developed which concentrate on using linear multiple regression or neural network algorithms to calibrate the system for limited, well-defined sets of specimen or component conditions. These calibrations rely on a detailed mathematical variation formalism that notably does not involve any empirical or fundamental understanding of the physical principles of the magnetic techniques. This technique is not considered mature and would require a large database of test results to benchmark against for determining irradiation embrittlement.

<u>Nonlinear Harmonic Analysis of Eddy Current Signals:</u>

This technique utilizes the complete magnetic hysteresis loop and the way in which it is influenced by the micro-structural changes due to degradation. An oscillating sinusoidal magnetic field is applied to the material, which is modified by the material that acts as a transfer function, so that a detector coil picks up a distorted signal, which is then analyzed for amplitude and phase of different harmonics of the original signal frequency. When calibrating the variation of these parameters is fitted using a "multidimensional regression analysis" to provide the best correlation with the material property. This technique is not considered mature enough and its sensitivity to toughness variation is also considered questionable.

Laser Ultrasonic:
Laser induced ultrasound and electromagnetically induced ultrasound does not require direct coupling with the inspected surface and a media capable of transmitting the mechanical pulses is applied (e.g. liquid couplant with piezoelectric transducers). Laser induced ultrasound relies on local thermal expansion of the inspected material by laser energy. Ultrasonic waves within inspected material produce reflections which are observed. Laser ultrasonic uses two lasers, one with a short pulse for generation of ultrasound and the other, long pulse or continuous, coupled to an optical interferometer for detection. Laser ultrasonic allows for testing at long distances and inspection of parts without any coupling liquid. The technique also features a large detection bandwidth, which is important for different applications, particularly those involving small crack detection, sizing and material characterization. The ability to perform testing at distance allows inspections on components with high surface temperatures. Several practical applications have shown positive results in the nuclear industry. Further advancement of this technique could have possible application to material property characterization of components operating in a high temperature environment.

EMAT (Electro Magnetic Acoustic Transducers):
This approach generates acoustic waves within the inspected materials and relies on electromotive forces created by inducing an electrical current within inspected material with an oscillating magnetic field (similar to eddy current technique). At the same time an outside static magnetic field is applied through the material's interaction with the induced current which results in a Lorentz force that becomes a source of mechanical pulsing and creates ultrasonic vibration within the inspected materials. Reflected ultrasonic vibrations are sensed using proximity coils that monitor the inspected surface. There is no direct contact so this concept can be applied on surfaces with elevated temperatures. Some experience of this has been seen in the ship-building industry for monitoring integrity on high temperature components during the welding process. Further advancement of this technique to material property characterization of HTR operating components at high temperature is suggested.

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

In addition to non destructive material condition monitoring, it is also suggested to consider newly developed mechanical testing with micro samples. Direct mechanical testing is recommended on sacrificial test coupons or surveillance samples and possible micro material samples from operating components. A further approach is to take samples directly from the point of interest in the component for damage monitoring. Such samples would contain information just from the point of interest. Such a method, however, can only be successful when the remaining damage from sample removal does not weaken or damage the structure.

Until recently, it was necessary to use relatively large samples for testing, even when they were called miniaturized samples and for component based monitoring, only local hardness tests and replica-techniques could be used. With the advent of focused ion beam equipment and micro-machines for controlled deformation (Nano-indenter), more extensive mechanical testing is possible. The below table provides the most important methods for testing and analysis of sub-sized and micro/ nano samples. Items 1 through 5 refer to mechanical tests. Items 6 through to 10 refer to analytical methods and material modelling for understanding and quantitatively interpreting the experimental results.

Table 3-3 - Micro Sample Techniques

Item No.	Method	Comments
1	Minature Samples	Typically specimens for Charpy Impact, J_{IC}, stress-strain, creep testing - in dimensions of a few mm.
2	Ball/shear punch	Small discs, stress-strain behavior, finite element analysis required.
3	Thin strip	100-200 μm thin strips, irradiation creep, creep, stress-strain behavior.
4	Nano indenter	Instrumented hardness testing, hardness profiles, stress-strain behavior, finite element analysis required; cylindrical indenters for creep deformation.
5	Micro-samples	FIB machined micro/nano-pillars, bend-bars etc., stress-strain behavior and deformation in SEM or beamline possible.
6	Surface replica	Corrosion, surface microstructure.
7	Transmission Electron Microscope (TEM)	Heating and deformation stages, EELS and other analysis techniques, micro-and nanostructure, precipitates, irradiation defects.
8	Atom probe	Cluster formation.
9	Advanced neutron/X-ray techniques	Coordination chemistry, magnetic effects, micro- and nano-structure, complementary to TEM techniques.
10	Materials modelling	Relate the cast microstructure to stress-strain relationships, toughness and/or residual life.

For the HTR application the following steps of development have been proposed.
For coupons/surveillance samples:
• Address components to be monitored;

• Define relevant damage mechanisms;
• Quantify expected damage in terms of changes of mechanical properties and microstructure.

For material taken from components directly:

• Define tools for sample extraction;
• Define and foresee locations for extraction of sample material from the component;
• Study safety aspects for component and sample removal;
• Develop a sound testing concept for an HTGR.

Considerable progress in the development of micro- and nano-sensors and micro-monitoring devices (smart materials, MEMS) have been made. These developments should be matched with possible work on sensors to facilitate the on-line monitoring of quantities such as stress or strain or damage.

3.3 Suggestions for future Development

3.3.1 In the Short Term

Helium Leak Monitoring

Current practice is given in ASME B&PV Section V and further development of the techniques is considered unnecessary. Development of the requirements for application as continuous monitoring is however needed. IGA-5000 provides draft rules for on-line leakage monitoring as an element of the RIM Program. A more detailed evaluation of existing experience from experimental and similar helium reactors and the development of proper design dependent strategies are suggested.

Development of Non-Contact UT with Laser UT and EMAT

Development of non-contact UT techniques with laser UT and EMAT technology is required to support several examination requirements in high temperature environments for volumetric inspection and monitoring (acoustic emission, loose part and leak monitoring, volumetric inspections and surface =inspection) based on ultrasound:

Acoustic Emission

For continuous monitoring during the operation further development will be needed to establish code qualified techniques that will address:

- detection of crack initiation;
- crack growth progression/growth – already addressed by the code;
- crack location via multiple sensors.

Present equipment with temperature hardened transducers and stand-off mounting concepts from the LWR could be directly applied to the HTR steel vessel. For other higher temperature components options of using non-contact UT transducers, such as laser UT or EMAT transducers, will need further investigation.

Loose Part Monitoring

Current experience in LWRs with AE for loose part monitoring and leak detection should be investigated and guidelines developed for application in HTRs. Additional investigation for non-contact transducers with laser UT or an EMAT transducer will be required for application with high temperature surfaces.

Volumetric Inspection

Current techniques (UTA, UTS, AE and TOFD), which are used in LWRs, are also available for use in HTRs during scheduled maintenance outages. If such techniques are to be deployed at elevated temperatures, further development will be required on ultrasonic sensors. This will require use of non-contact approaches with laser UT and/or EMAT transducers that have been used on high temperature components in other industries. The introduction of Phased Array UT for the LWR has shown advantages with this approach with more accurate sizing and improved understandings on degradation spatial characteristics. It is recommended that detection and sizing limits with Phased Array combined with contact and non-contact transducers are investigated.

Surface Inspections

Environmental conditions involving higher temperature non-contact techniques using UT surface waves (Rayleigh waves) with laser UT and/or EMAT need to be further investigated and properly qualified for use as ISI techniques.

Infrared Monitoring
This concept is used in other industries, and the development of guidelines for application in HTRs should focus on surface temperature monitoring with infrared thermo imaging systems for thermal transients and stratification. Experience from monitoring fossil boiler, gas and steam turbines and electric power components (transformers and generators) should provide adequate references for the application developments.

Thin Wall Inspection Techniques
Eddy current and giant magneto resistors are techniques for thin walled tubing that would need further development and qualification for high temperature applications. Applicability would be for steam generator use for the HTGR producing process steam.

Remote Delivery Robotics
Current experience at LWRs uses robotic manipulators for inspection technique delivery along critical locations (welds) on inspected components. These manipulators in LWRs are commonly used at temperatures between ambient and 50°C. For application in HTRs where higher temperatures could be encountered, further temperature hardening will be required in order to withstand higher temperatures.

3.3.1 In the Long Term

Non destructive monitoring concepts selected through a reliability and integrity management (RIM) program require complex non destructive monitoring (NDM) techniques to observe initiation and progression of damage mechanisms during the operating period between scheduled maintenance intervals. A pilot study for the RIM strategy applied to pressure vessel components was made for the PBMR. To accomplish the expectation of this advanced degradation mechanisms monitoring and inspection program, further development of non destructive monitoring and material characterization will be required:

Creep Monitoring
Current experience with high temperature creep monitoring can be found in fossil power plants and the petro-chemical industries. Recent investigation with on-line monitoring for creep in high temperature piping with non-contact strain measurements and local optical surface pattern monitoring have shown positive results when detecting early stages of creep damage. The early detection approach allows preventive maintenance measures to be deployed to avoid unwanted compromises of component integrity. These monitoring methods should be further investigated and guidelines developed for implementation on HTR components.

Continuous Material Monitoring
Further development is required in the field of micro monitoring techniques that have shown potential in estimating material property changes by observing local electro-magnetic or acoustic characteristics. This research should be coordinated with material property verifications through mechanical testing on samples removed from operating components due to the demanded repairs and/or micro sampling processes and localized micro mechanical testing. The outcome of this development should establish qualified techniques for non destructive material characterization to potentially determine the following properties:

- Extent of neutron embrittlement – other than coupons (destructive techniques);
- Changes in fracture toughness – automated ball indentation (stress strain microprobe);
- Changes in tensile properties;
- Changes in electromagnetic properties as a result of changes in material structure induced by a specific damage mechanism;
- Changes in acoustic properties as a result of changes in material structure induced by a specific damage mechanism.

For HTRs, this will provide a real time view of the material condition as it is not possible to place representative material test coupons at lead locations for the RPV. Also, the amount of embrittlement is expected to be low and difficult to measure with coupons. Another advantage of this approach is the measurement of the actual material properties rather than deduced properties via coupon testing. The technique is generally applicable to any RPV where the external wall surface is accessible.

4 Considerations for Alloy 800H Components

4.1 Intermediate Heat Exchanger (IHX)

There are currently no inspection guideline available in ASME directly applicable to the IHX. Guidelines such as those available in ASME Section XI for light water reactors will need to be established for the IHX component. The IHX is not considered to be a safety related component since it is not required for the safe shutdown of the plant. For both the tubes of the tube and shell design and the stacked plate compact IHX, the leak path is from one contained system to another. The HTR design concept allows for very low contamination levels in the primary coolant loop such that a small leak should not transfer significant amounts of contaminants and depending on the secondary side coolant chosen, there may be little concern over small transfers of fluid between the two loops.

Leakage could be detected by the coolant “make-up” system as it attempts to maintain proper pressure differential between the primary and secondary loops or by detecting trace elements in the helium purification train. Nonetheless, catastrophic failure of a large number of tubes or passages could cause unwanted thermal transients and any leakage may affect the plant efficiency. Consequently, from an investment safeguard point of view, it is envisioned that in-service inspections would be desired where practical.

Two IHX designs discussed below are the tubular design and the compact heat exchanger. The issues affecting the compact (stacked plate) heat exchanger apply equally to each of the designs The compact IHX will be in modular units arranged inside of a pressure vessel. The tubular IHX concept will be produced as a stand-alone unit and NDE comments for this design could also be considered for the Steam Generator.

4.2 NDE for the Shell and Tube design

It is expected that all welds of the shell should be inspected by conventional “ultrasonic” means. The heat transfer tubes should be capable of examination by eddy current means provided this is accounted for in the design. Eddy current inspection of the KVK IHX tubes has en successfully performed and there is much eddy current inspection experience available from LWR steam generators. The Inspection frequency and survey size should be developed by performing a degradation assessment of the design. If a tube is found to be defective it can be plugged. Tube plugging techniques are well established from LWR and other reactor steam generator experience. As with LWR steam generators, the inspection program and criteria for the heat transfer surfaces can be provided in a plant technical specification.

4.2.1 Examination of Joints (NDE) - Welds of Helical Tube design

Suitable examination methods are required for:
• Tube-to-tube sheet welds taking into account the geometry of the welded joints
• Tube-to-tube butt welds as the length of helical tube of the IHX is likely to exceed the length of tubes as fabricated. In both cases, volumetric examination methods have been developed for steam generators of fast neutron reactors and could be applied.

4.3 Compact Intermediate Heat Exchanger

The main concern with regard to the ISI of a plate type IHX is that the individual coolant passages cannot easily be inspected. The most reasonable way to inspect a compact heat exchanger is possibly through a leak test. Inspection of individual primary/secondary boundary joints is considered impossible. If leaks are found, repair is normally done in a “shop” environment after removal which again may not be a practical situation. For this reason it is considered that the compact IHXs should be replaced at a predetermined “end of life” position for the product. A system check as described above can be performed and if a leak is found to be beyond predetermined limits, efforts should be made to isolate the location of the leak. Once found, the IHX module could be isolated from the system. As with the tubular IHX, the inspection program and criteria can be provided in a plant technical specification.

4.3.1 Examination of Joints (NDE) - Joints of Plate IHX

Provisions for non-destructive volumetric examination of welds of headers need to be made in the design of the headers. In the case of plate assembly by different processes such as brazing, diffusion bonding or laser welding, there are as yet no available volumetric examination practices, plus, the geometry frequently precludes examination of each individual joint. As a minimum, a pressure/leak test should be performed. Dye penetrant and visual examination should be performed where practical. It would be beneficial to develop non-destructive methods to check the effective joined area of IHX plates.

4.4 Conclusions on ISI Requirements

The tube and shell IHX provides the best opportunity to perform ISI and repairs since it uses proven technology in both regards and the tubes and vessel should be inspected at prescribed intervals as part of an ISI and NDE inspection programme.

For the compact IHX ISI is more problematical and inspection and repair of individual channels while installed is considered impossible. Failure of a compact IHX module would not result in fluid release to the atmosphere and the design of the HTR provides for minimal amounts of contamination of the cooling fluid, hence prevention of primary/secondary fluid mix is not as critical an issue as with the LWR, provided that the two fluids are compatible. It is considered that leak testing of individual modules should be performed and only when the system is found to be leaking beyond acceptable limits as monitored by plant operation indicators should repair or replacement be considered. Acoustic sensors placed along the outer surface of the containment vessel might be possible for this and monitoring of the IHX modules and headers within would provide the general location of the leak. The main issue with this approach would be the noise generated by the circulators. The repair procedure for an individual compact IHX would be to cap off the header pipes entering and exiting the IHX, and thereby isolating and removing the module from service.

It is suggested that Rules governing the ISI of the HTR IHX should be added to Codes and Standards and for the ASME Code to Section XI, Division 2. The surveillance/replacement plan for the IHX could be established through a plant technical specification (as with current LWRs) to allow for timely adjustments (as necessary) by the most current operating experience. In addition the criteria for inspection could be included the plant technical specification.

5 Conclusions

In-service inspection (ISI), examination and testing of the nuclear reactor plant are presented in a number of different Codes and Standards and such rules also address repair and replacement activities and provide for a mandatory program of examination, testing and inspection to establish evidence of adequate safety and to manage deterioration and aging effects. An In-service Inspection program constitutes all the requirements both administrative and technical necessary to perform the ISI of systems and components important to safety. This report has been compiled to provide a synthesis of the results from Task 3 activities which can be used as a basis for relevant sections of the SP4 contributions to the Final Report and to address a best practice proposal for In-service Inspection arising from a review of available literature relevant to HTRs. The documents reviewed were produced in support of ASME Code developments on this topic.

Conclusions are made concerning the ISI and NDE examination of the IHX including the Compact IHX. The tube and shell IHX provides the best opportunity to perform ISI and repairs since it uses proven technology in both regards and the tubes and vessel should be inspected at prescribed intervals as part of an ISI and NDE inspection programme. For the compact IHX ISI is more problematical and inspection and repair of individual channels while installed is currently considered impossible. However failure of a compact IHX module would not result in fluid release to the atmosphere as the design of the HTR provides for minimal ammounts of contamination of the cooling fluid. It is considered that leak testing of individual modules should be performed and when the system is found to be leaking beyond acceptable limits as monitored by plant operation indicators repair or replacement should be considered.

The report has summarised the findings from Task 3 Work Package 42 investigations performed on the IHX material Alloy 800H within ARCHER which covers a literature review and data collection on the effect of microstructure, heat treatment, welding process and welding parameters on various types of cracking (solidification cracking, liquidation cracking and/or ductility dip cracking, relaxation cracking) experienced in Alloy 800H. Results from the development of a Visco-plastic Creep-Fatigue Constitutive Model for Alloy 800H are also given and included as Appendix A of this report. The Visco-plastic Creep-Fatigue Constitutive Model has been developed specifically for the design, manufacture and testing of Mock-up investigations on the Compact IHX investigated in WP43.

As part of the lifetime assessment and design optimization for components in the steam cycle of power plants it is necessary to accurately describe the time-dependent deformation and stresses resulting from thermal gradients and pressure loads. Within the ARCHER project additional LCF test for Alloy 800H with a complex pre-program were carried out ranging from room temperature to 850°C. This data was processed for material model parameter identification. A minimum material model of type “Chaboche” was committed within the working group which is capable of describing the time-dependent deformation of A800 H. The unified model consists of terms for kinematic and isotropic hardening and a Norton power law to describe the strain rate dependency. The stress-strain data of the complex pre-program was used to calibrate the kinematic hardening parameters, initial yield stress and the parameters for strain rate dependency. The cyclic hardening of the material is described with the help of an isotropic hardening term and was calibrated by the periodic part of the LCF test. The remaining parameters for static recovery were optimised with relaxation test data of sheet metal specimens. As a consequence of this approach the model is suitable for describing the stress relaxation conditions with temperature and load changes, but is not suited to simulate the long-term response of a creep-loaded structure. A full parameter set for the presented model was developed and provided to the partners of work package WP43 IHX for code assessment and design optimization of the intermediate heat exchanger and as material input data for WP44 Steam generator unit (SGU).

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7 Appendix A: MPA Report on Visco-plastic Creep-Fatigue Constitutive Model for Alloy 800H

ARCHER

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Appendix A to Deliverable D42.32: Best-practice proposal for in-service inspection concept

Andreas Klenk, Patrick Buhl (MPA Stuttgart)

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Summary

Thermal transients and gradients in the major components of the steam cycle lead to thermal induced stresses, resulting in repeated visco-plastic deformations at elevated temperatures. Therefore low cycle fatigue tests are necessary to investigate the stress-strain behaviour of Alloy 800H. LCF tests with a specific pre-program containing strain range and strain rate variations were carried out with round bar specimens ranging from room temperature to 850°C. This experimental data was subsequently processed to identify material parameters for a Chaboche type visco-plastic material model which can be used for design optimization and code assessment of components made of Alloy 800H operating at elevated temperatures.

Approval

Rev.	Short description	First author	WP Leader	SP leader	Coordinator
0	First issue	Buhl, P.(MPA), Klenk, A (MPA)		Buckthorpe, D.	Name (org)

Distribution list

Name	Organisation	Comments
P. Manolatos	EC DG RTD	
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Abbreviations and Symbols

CNOW	Chaboche Nouialhas Ohno Wang
(C)LCF	Complex Low-cycle fatigue
HT	Hold time
FE	Finite-Element
IHX	Intermediate heat exchanger
RT	Room temperature
SGU	Steam generator unit

Symbols

D_f	Fatigue damage
K, n	Visco-plastic parameters (Norton power law)
k	Initial yield stress
p	Accumulated plastic strain
R	Isotropic hardening variable
X	Kinematic hardening variable
σ_{vis}	Over-stress, visco stress

1. Introduction

Thermal transients and temperature gradients in the major components of the power plant lead in conjunction with complex shaped geometry to thermal induced stresses, resulting in repeated visco-plastic deformations by creep and relaxation at elevated temperatures during operation of the component. As a consequence fatigue and creep damage is induced in specific regions of the intermediate heat exchanger mock-up and needs to be addressed for code assessment. To properly describe the time-dependent deformation behaviour of material at elevated temperatures, constitutive equations need to be developed for application in Finite-Element simulations during the design phase of the intermediate heat exchanger (IHX) or steam generator unit (SGU) to optimize the components lifetime. Low cycle fatigue tests at various temperatures were carried out to measure the material response in terms of stress-strain hysteresis loops. This data is subsequently processed to identify material parameters for a Chaboche type visco-plastic material model for A800H ranging from room temperature up to 850°C.

2. Low-cycle fatigue tests

The specimens were extracted at the edge of a welded plate section of A800H (plate thickness: ~15,8 mm) which was provided by ThyssenKrupp VDM and fully consist of parent material. The material specifications are given by ThyssenKrupp VDM in material data sheet No. 4029 [1]. The manufacturing was performed in the workshop of MPA Stuttgart according to the drawing of the LCF test specimen given in Fig. 2-1.

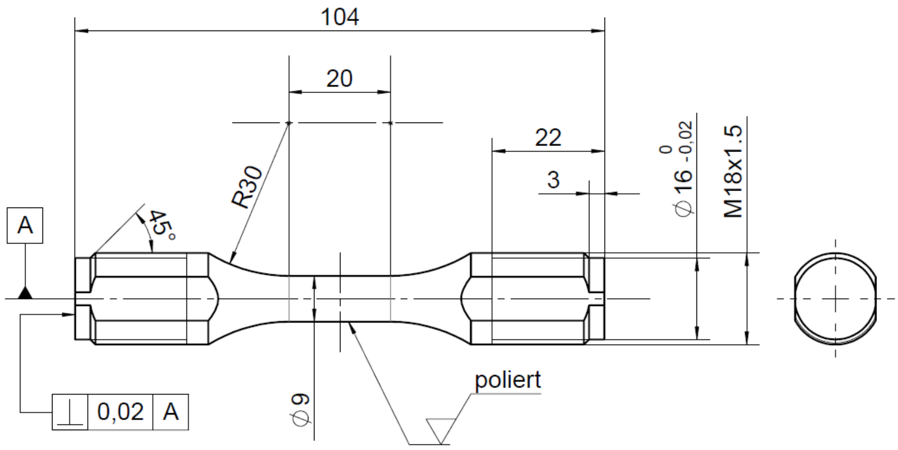

Figure 2-1: Drawing of LCF test round bar specimen used in ARCHER project

The strain-controlled LCF tests were carried out on a servo-hydraulic machine with Zwick® controller system. The elongation is measured and controlled with a high temperature axial extensometer attached with ceramic rods to the specimen surface. The whole assembly consisting of specimen and clamping is completely surrounded by the resistance-heated furnace to maintain a uniform temperature. To cover all influence quantities on the visco-plastic deformation of A800 H like temperature, strain range and strain rate influence, it was decided to add a pre-program to the standard periodic LCF test similar to the ones proposed in literature [2]. This pre-program consists of three major blocks with different strain ranges. Within each block the strain rate varies from 1E-3 1/s to 1E-5 1/s to investigate the influence of strain rate. Two additional dwell times of 30 mins at the strain maximum and minimum were applied to record the stress relaxation during tensile and compression dwell period. A schematic composition of the LCF test is given in Fig. 2-2. All tests were carried out with symmetric strain limits (R_ε=-1), respectively no mean strain.

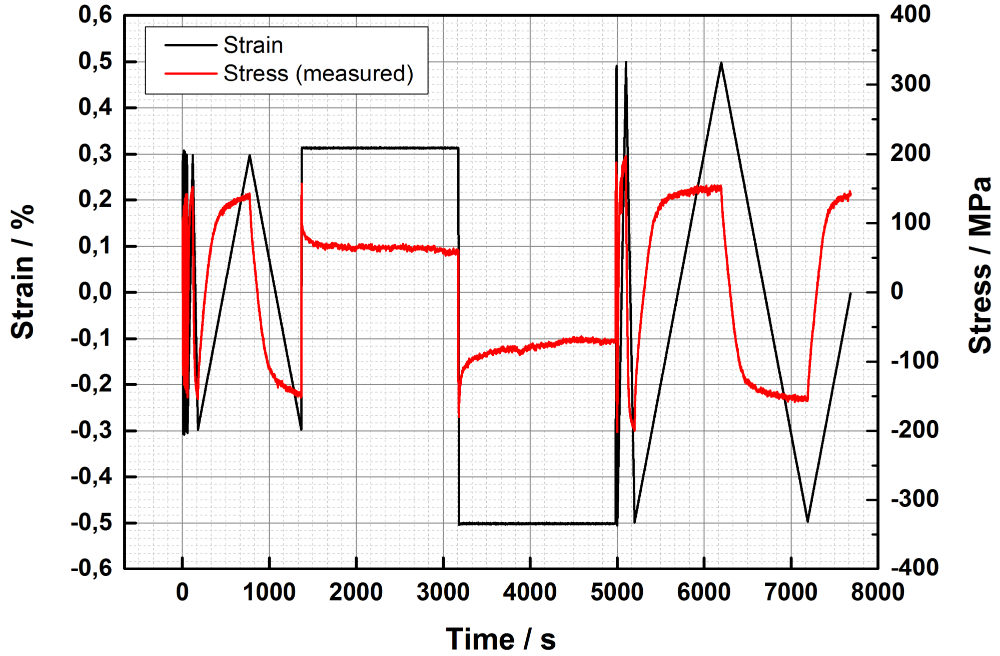

Figure 2-2: Pre-program of (C)LCF test with strain range (0,6%, 1,0%) and strain rate variations (1E-3, 1E-4, 1E-5 1/s)

All test conditions of (C)LCF tests are summarized in Table 2-1. The total number of cycles N_t and the number of cycles $N_{f,5\%}$ to reach 5 % load drop, derived as offset from the stable slope of the maximum stress curve of the LCF test is given also in Table 2-1.

Spec Nr.	Temp.	Strain rate (period.)	Strain ampl.	Strain ratio	Pre-program Strain rate	Pre-program Dwell time compr.	Pre-program Dwell time tension	Total number of cycles	Cycles to 5% load drop
	T	$\dot{\varepsilon}$	$\Delta\varepsilon$	R_ε	$\dot{\varepsilon}$	t_c	t_t	N_t	$N_{f,5\%}$
	[°C]	[1/s]	[%]	[-]	[-/s]	[min]	[min]	[-]	[-]
A8H2	RT	10^{-3}	0,6/1,0	-1	10^{-5}, 10^{-4}, 10^{-3}	30	30	5547	5131
A8H7	300		0,6/1,0	-1				5361	5207
A8H5	550		0,6/1,0	-1				1599	-
A8H1	650		0,6/1,0	-1				1189	958
A8H6	750		0,6/1,0	-1				755	611
A8H3	750		0,3/0,6	-1				2281	1850
A8H8	850		0,6/1,0	-1				426	-

Table 2-1: (C)LCF test matrix for Alloy 800 H

The test results of stress and strain for all temperatures ranging from room temperature to 850°C are shown for the complex pre-program in Annex I (Fig. A-1 to Fig. A-6). Results of the peak stresses (min/max) in the periodic part of the LCF tests are given in Fig. 2-3. The material shows initial cyclic hardening behaviour, which reaches a stable plateau after only a few cycles. The peak stresses remain stable after the initial hardening for temperatures below 650°C. The tests at higher temperature (≥650°C) show a steady softening until macroscopic failure with a significant load drop occurs.

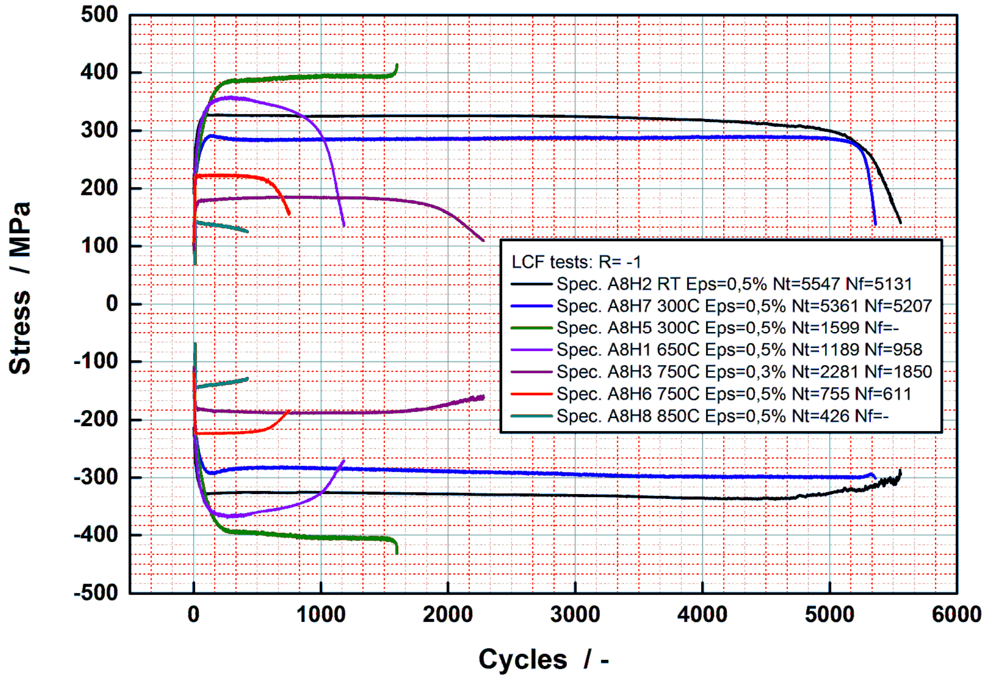

Figure 2-3: Peak values for Alloy 800 H

3. Material modelling by constitutive equations

In the last thirty years a large number of constitutive equations with different model complexities have been developed to describe the relationship between stress and strain [3], [4]. In the high temperature regime it is necessary to consider the time-dependent inelastic material deformation, which is known as creep for constant loads or as stress relaxation for constant deformations. A common type of material model is the so called “uniform model” which forms the total strain as sum of elastic, thermal and visco-plastic (irreversible) strain. With increasing computer performance, these models are ready to use within FE codes to simulate time-dependent deformation with transient temperature distributions and load conditions. To achieve the best benefit for all partners within the ARCHER project a collation of available material models in the different FE codes (MSC.Marc, Systus, Ansys) was started. It was committed to use a common “minimum” model which was chosen to be a Chaboche type model consisting of kinematic and isotropic hardening terms to describe the cyclic deformation and the strain rate dependency covered by the Norton power law. This type of model with extensions for ratcheting under multiaxial stress states is also available as user subroutine for ABAQUS at the MPA Stuttgart and was used to compare the results to the experiments. This model is called CNOW (Chaboche-Nouialhas-Ohno-Wang, [5], [6], [7]) model and can be reduced to a simpler Chaboche model with Norton power law term by a clever choice of redundant model parameters. The remaining equations for the simplified model are shown in Table 3-1. The fatigue damage variable D_f was neglected, because of its unavailability in the FE codes of the project partners and the limited number of cycles that can be simulated using such a complex material model.

<table>
<tr><td rowspan="5">CNOW-Model MPA Stuttgart</td><td>Viscoplastic Potential</td><td>$\Omega_p = \sum_{i=1}^{2} \frac{K_i}{n_i+1} \exp(\langle \sigma_{vis,i} / K_i \rangle)^{n_i+1}$</td></tr>
<tr><td>Flow rule</td><td>$f_1 = J_2(\bar{\sigma} - \bar{X}\cdot) - R - k - \sigma_{vis1} = 0$
mit $J_2(\bar{\bar{\sigma}} - \bar{\bar{X}}_{1,2}) = \sqrt{\frac{3}{2}(\bar{\bar{\sigma}}' - \bar{\bar{X}}'_{1,2}) : (\bar{\bar{\sigma}}' - \bar{\bar{X}}'_{1,2})}$</td></tr>
<tr><td>Inelastic strain rate</td><td>$\dot{\bar{\bar{\varepsilon}}}_{in'} = \frac{3}{2} \cdot \frac{1}{1-D_f} \cdot \left\langle \frac{\sigma_{vis1}}{K_1 \cdot (1-D_f)} \right\rangle^{n_1} \cdot \frac{\bar{\bar{\sigma}}' - \bar{\bar{X}}'_1}{J_2(\bar{\bar{\sigma}} - \bar{\bar{X}}_1)} = \frac{3}{2} \dot{p}_1 \frac{\bar{\bar{\sigma}}' - \bar{\bar{X}}'_1}{J_2(\bar{\bar{\sigma}} - \bar{\bar{X}}_1)}$</td></tr>
<tr><td>Isotropic variable</td><td>$\dot{R}_i = b_i(Q_i - R_i)\dot{p}_i(1 - D_f)$</td></tr>
<tr><td>Kinematic variable</td><td>$\mathbf{X}_i = \sum_{j=1}^{M_i} \mathbf{X}_{ij};$
$\dot{\mathbf{X}}_{ij} = \frac{2}{3} c_{ij} a_{ij} \dot{\varepsilon}_i^{in} (1 - D_f) - c_{ij} \Phi_{ij}(p_i) \left(\frac{|\mathbf{X}_{ij}|}{a_{ij}} \right)^{m_{ij}} \mathbf{X}_{ij} \dot{p}_i - \beta_{ij} |\mathbf{X}_{ij}|^{r_{ij}-1} \mathbf{X}_{ij} + \frac{\partial (c_{ij} a_{ij})}{\partial T} \frac{1}{c_{ij} a_{ij}} \mathbf{X}_{ij} \dot{T}$</td></tr>
</table>

Table 3-1: Equations of the simplified CNOW material model [7]

The parameter identification was carried out in three subsequent steps. In the first step the hardening parameters for kinematic hardening with two backstresses c_i, a_i, the initial yield stress k and the Norton power law parameters K, n were identified by using the complex pre-program of available LCF tests. The deviation between experiment and simulation is judged in terms of the sum of the least squares for the whole pre-program and is minimized by a downhill-simplex algorithm to identify the best parameter set for the given material model. Reasonable start values were necessary to succeed with this gradient-based approach. The identification of the isotropic hardening parameters b_i, Q_i is achieved in the second step by comparing the peak stresses of experiment and simulation of the periodic part of the LCF test. This procedure is again supported by the downhill-simplex algorithm to minimize the deviation. Last step is the identification of static recovery parameters β_i, r_i by comparing experiment and simulation of relaxation tests performed on thin sheets (see Deliverable D43.53 - Creep and relaxation test report). It is very important to improve the material model for long-term relaxation behaviour to properly predict the remaining stresses for stationary loads and longer dwell periods. This accuracy can be improved by optimizing the parameters of the static recovery. The knowledge of the redistributed stresses is important to assess the creep damage by comparing the remaining stresses to creep rupture data. The presented steps of parameter identification need to be repeated in an iterative manner to provide a sound parameter set. One further detail needs to be considered. A steady nature of the parameters with increasing temperature should be fulfilled to provide good interpolation performance in transient FE simulations. The evaluated parameters for A800H are compiled in Table 3-2. The progression of parameters with increasing temperature is shown in figure Fig. A-12 in Annex I.

	T [°C]	**20**	**300**	**550**	**650**	**750**	**850**
Elastic constants	**E** [MPa]	194000	177000	160000	153000	145000	137000
	μ [-]	0,288	0,294	0,3	0,304	0,308	0,312
Strain rate dependency	**K** [MPas$^{(1/n)}$]	70,00	100,00	160,00	240,00	330,00	577,00
	n [-]	24,00	20,00	12,00	10,00	8,00	3,51
Elastic limit	**k** [MPa]	35,00	10,00	10,00	10,00	10,00	10,00
Kinematic variables	a_1	85,00	63,36	40,00	35,00	18,00	17,12
	c_1	2000,00	2063,00	2500,00	3000,00	3200,00	3530,00
	a_2	61,00	32,21	21,00	19,50	18,00	17,87
	c_2	380,00	433,00	550,00	650,00	700,00	794,00
Static recovery	β_1	0,00	0,00	0,00	0,00	0,00	1,0E-06
	r_1	2,20	2,20	2,20	2,20	2,20	2,10
	β_2	0,00	0,00	0,00	1,0E-06	2,0E-06	1,0E-06
	r_2	2,20	2,20	2,20	2,20	2,20	2,10
Isotropic variables	**b** [-]	2,00	2,00	1,00	3,00	20,00	0,00
	Q [MPa]	100,00	110,00	235,00	170,00	40,00	0,00

Table 3-2: Parameter for simplified Chaboche model Alloy 800 H

The comparison of experiment and material model predictions for relaxation tests on thin sheet metal specimens is shown in Fig.3-1 for 750°C and 850°C. The model predictions are in good agreement with the relaxation test results in the time span up to 100 hours. Therefore it can be expected that relaxation of secondary thermal induced stresses within the components can be accurately described. It should be remarked that this model is not capable to describe the long-term response of a creep-loaded structure especially at low stresses, because the simplified Chaboche model is not suitable to cover relaxation and creep sufficiently at the same time. Extensions to the model are necessary, for instance a second flow rule as already introduced in the complete CNOW model of MPA Stuttgart.

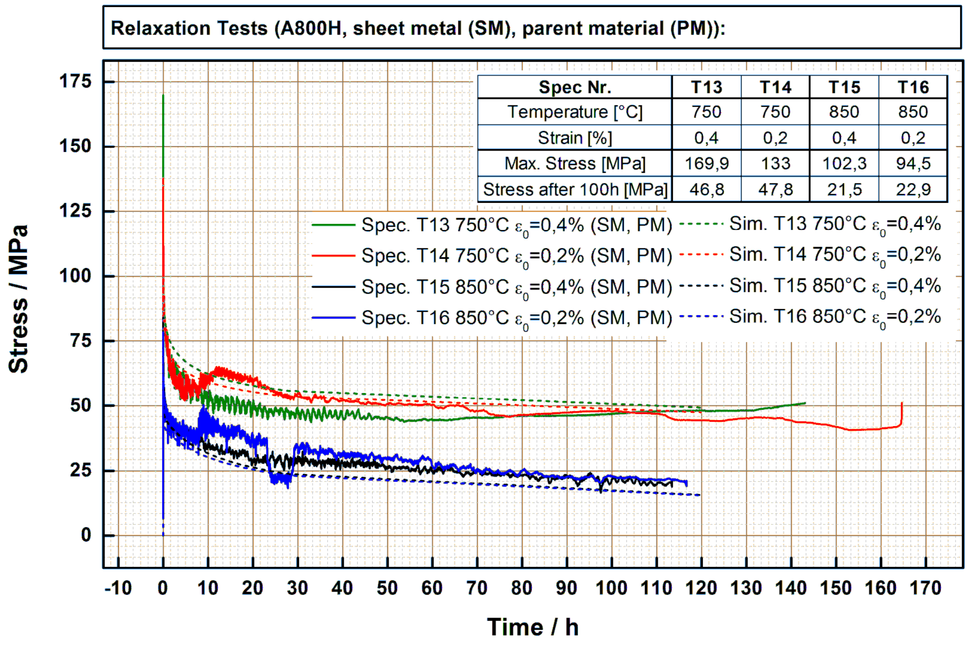

Figure 3-1: Comparison of experiment (solid lines) and material model predictions (dashed lines) for relaxation tests on thin sheets (Alloy 800H)

4. Conclusion

As part of the lifetime assessment and design optimization for components in the steam cycle of power plants it is necessary to accurately describe the time-dependent deformation and stresses resulting from thermal gradients and pressure loads. Within the ARCHER project additional LCF test for Alloy 800H with a complex pre-program were carried out ranging from room temperature to 850℃. This data was processed for material model parameter identification. A minimum material model of type “Chaboche” was committed within the working group which is capable to describe the time-dependent deformation of A800 H. The unified model consists of terms for kinematic and isotropic hardening and a Norton power law to describe the strain rate dependency. The stress-strain data of the complex pre-program was used to calibrate the kinematic hardening parameters, initial yield stress and the parameters for strain rate dependency. The cyclic hardening of the material is described with the help of an isotropic hardening term and was calibrated by the periodic part of the LCF test. The remaining parameters for static recovery were optimised with relaxation test data of sheet metal specimens. As a consequence of this approach the model is suitable for describing the stress relaxation under instationary conditions with temperature and load changes, but is not suited to simulate the long-term response of a creep-loaded structure.
A full parameter set for the presented model has been developed and provided to the partners of work package WP43 IHX for code assessment and design optimization of the intermediate heat exchanger and as material input data for the WP44 Steam generator unit (SGU) investigations as illustrated in Fig.4-1.

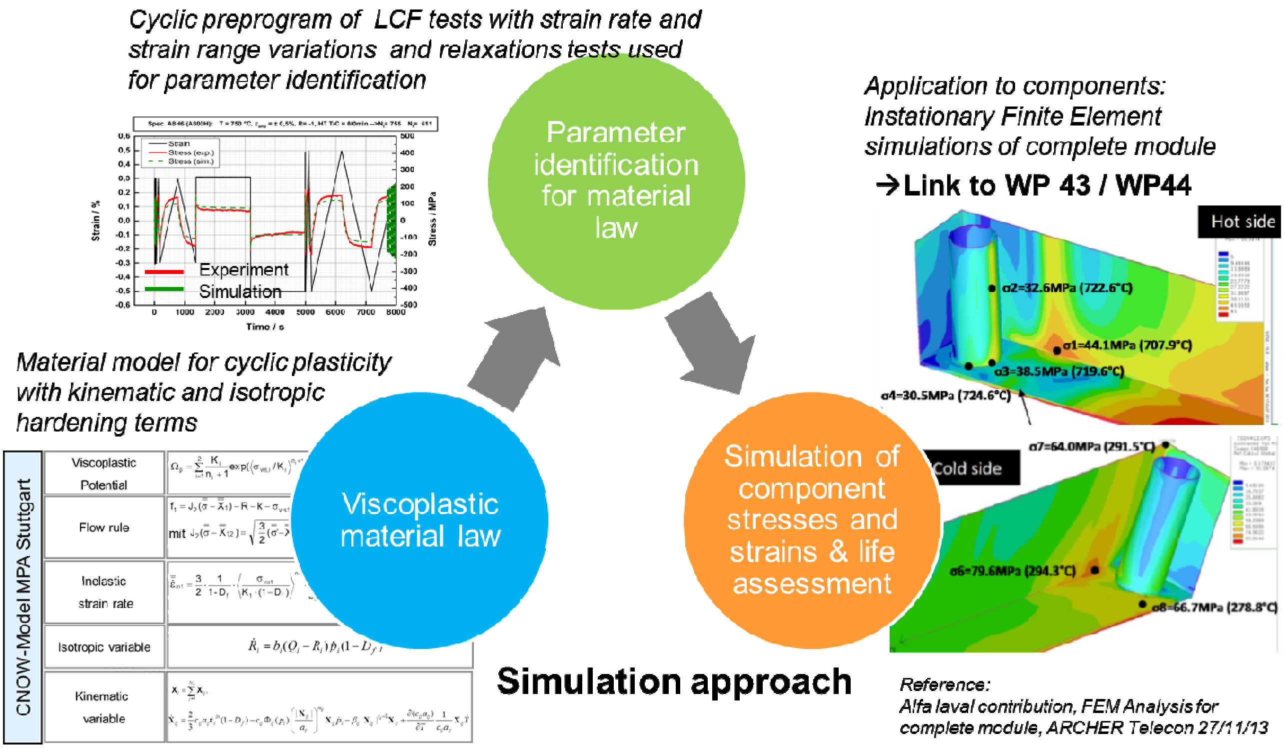

Figure 4-1: Simulation approach for parameter identification of material law

5. References

[1] Material Data Sheet No. 4029: Nicrofer® 3220 H/3220 HP – alloys 800 H/800 HP, high temperature alloys, ThyssenKrupp VDM GmbH, Werdohl, 2002

[2] Seifert, T.: Ein komplexes LCF-Versuchsprogramm zur schnellen und günstigen Werkstoffparameteridentifizierung, Proceedings of Werkstoffprüfung, pp. 409-414, 2006

[3] Chaboche, J.-L.: Constitutive equations for cyclic plasticity and cyclic viscoplasticity, International Journal of Plasticity, Volume 5, pp. 247-302, 1989

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[5] Nouailhas, D.: Unified Modelling of Cyclic Viscoplasticity, Application to Austenitic Stainless Steels, Int. J. of Plasticity, Vol. 5 (1989)

[6] Ohno, N.: Constitutive Modelling of Cyclic Plasticity with Emphasis on Ratchetting, Int. J. Sci. Vol. 40. p. 251/261 (1998)

[7] Roos, E.; M. Ringel, K. Maile and A. Klenk: Constitutive Equations of Adapted Complexity for High Temperature Loading. Proceedings of the ECCC Creep Conference “Creep & Fatigue in High Temperature Components – Design & Life Assessment Issues” (2005)

Annex I:

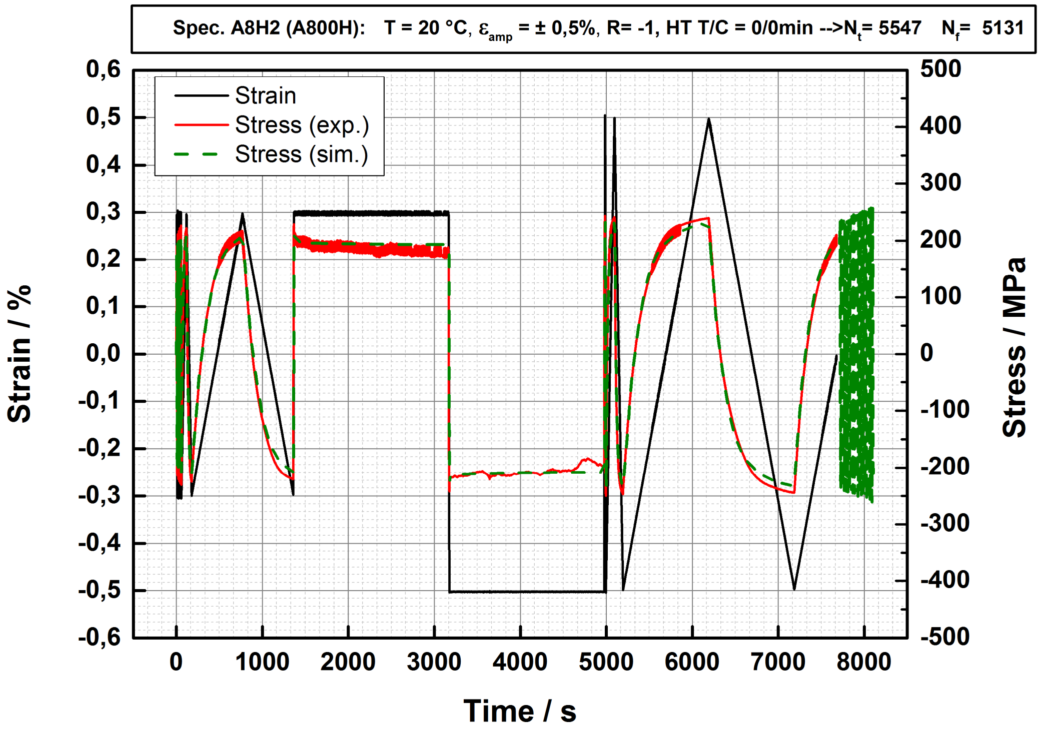

Figure A-1: Complex pre-program for A8H2 (RT)

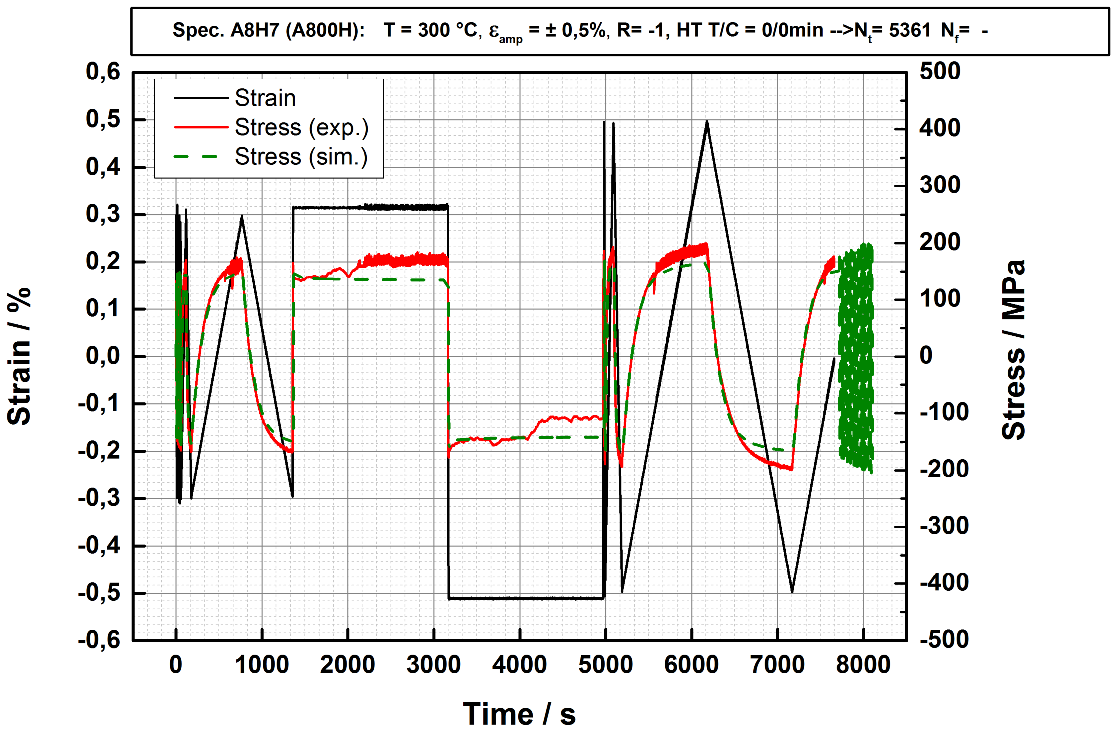

Figure A-2: Complex pre-program for A8H7 (300 °C)

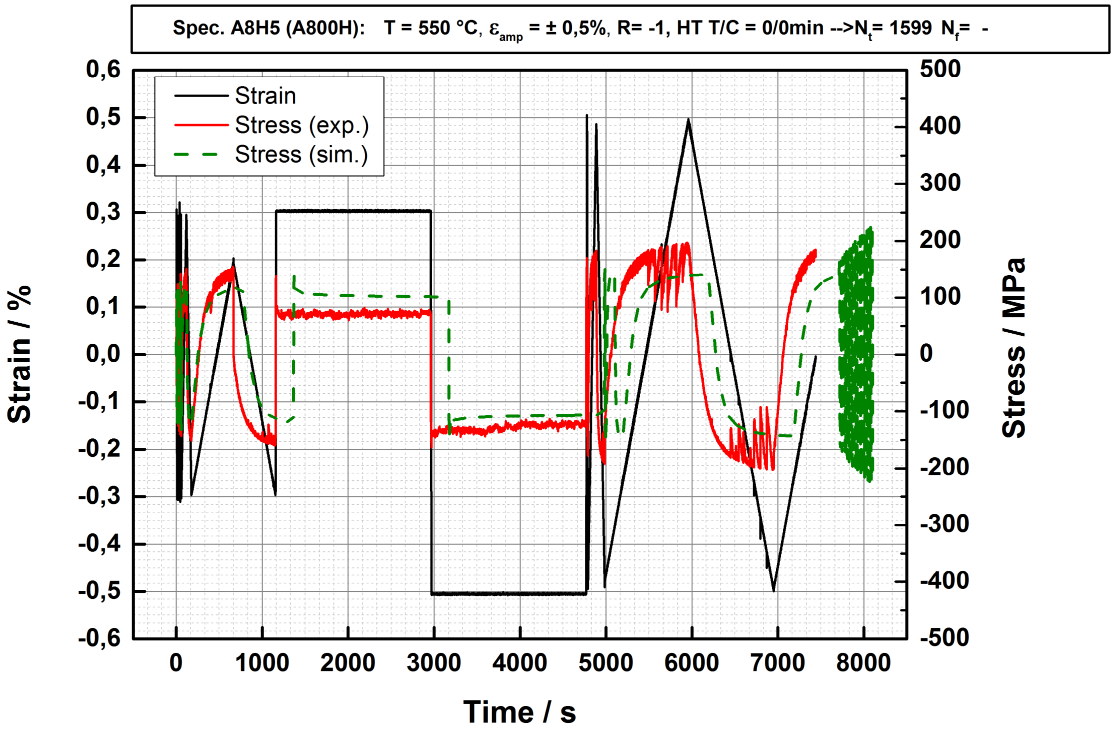

Figure A-3: Complex pre-program for A8H5 (550°C)

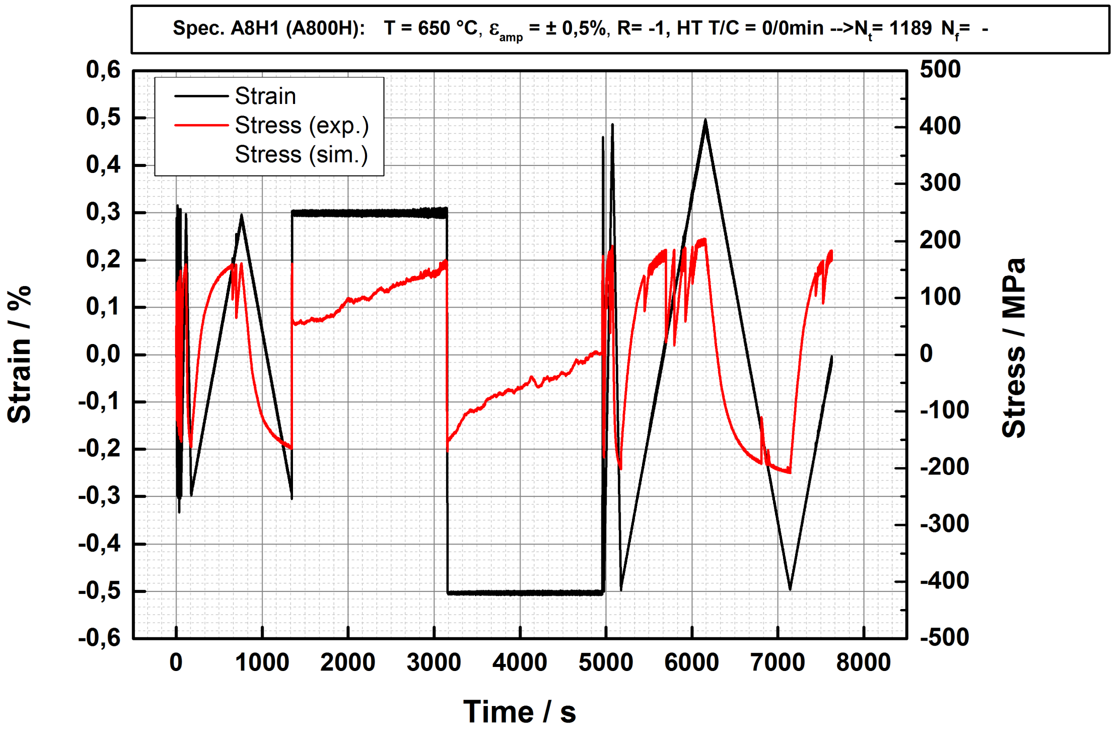

Figure A-4: Complex pre-program for A8H1 (650°C), remark: signal drift in dwell time

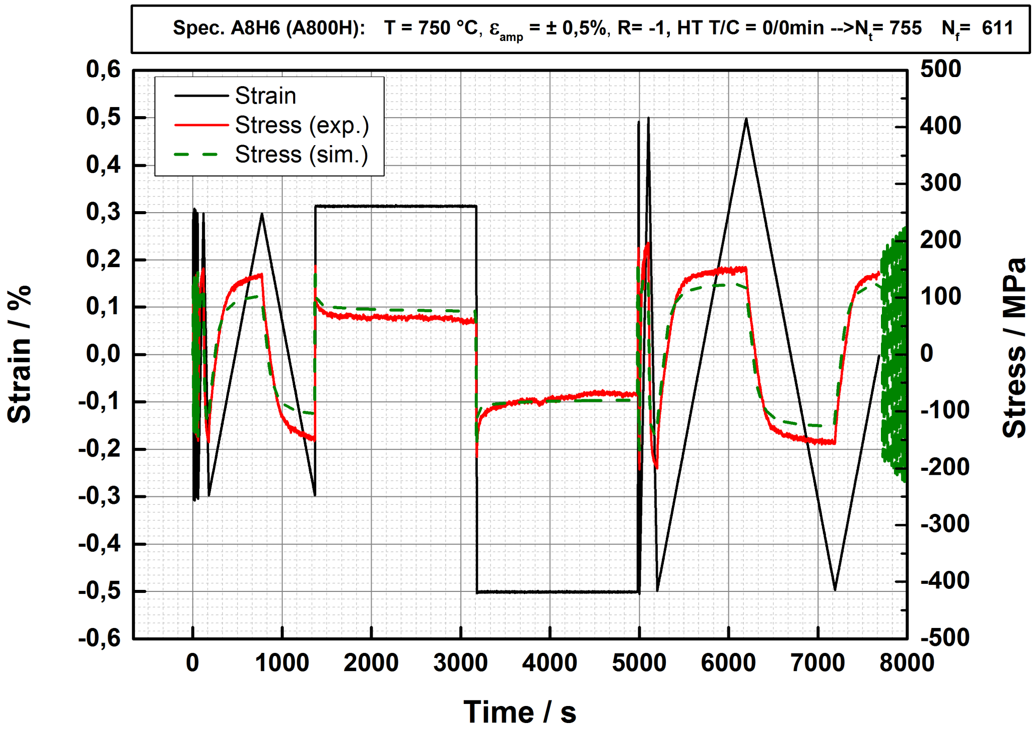

Figure A-5: Complex pre-program for A8H6 (750°C)

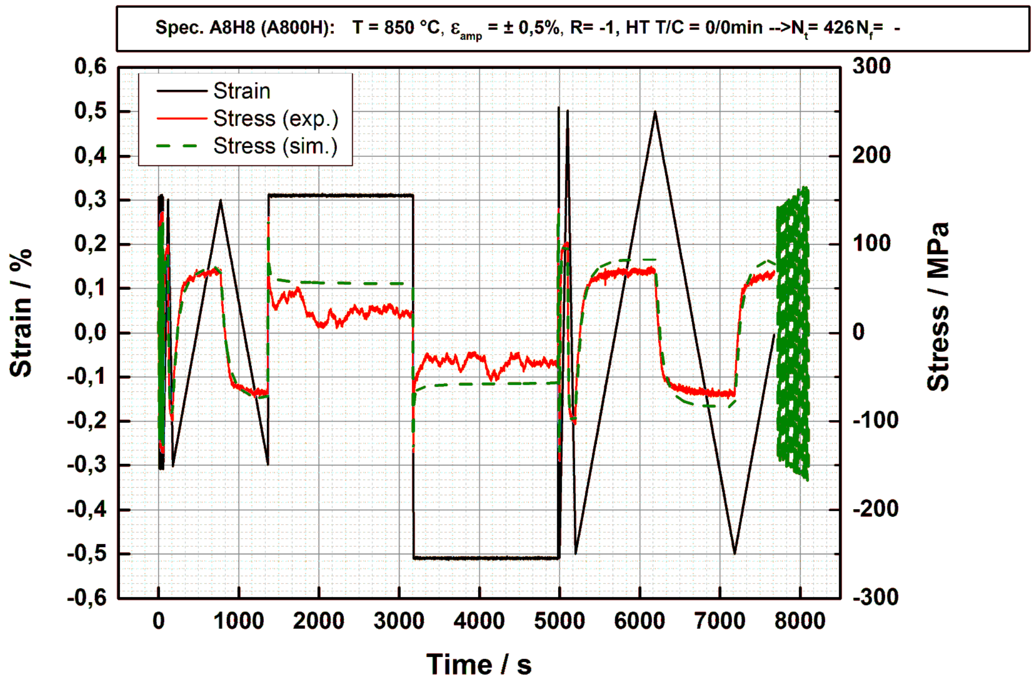

Figure A-6: Complex pre-program for A8H8 (850°C)

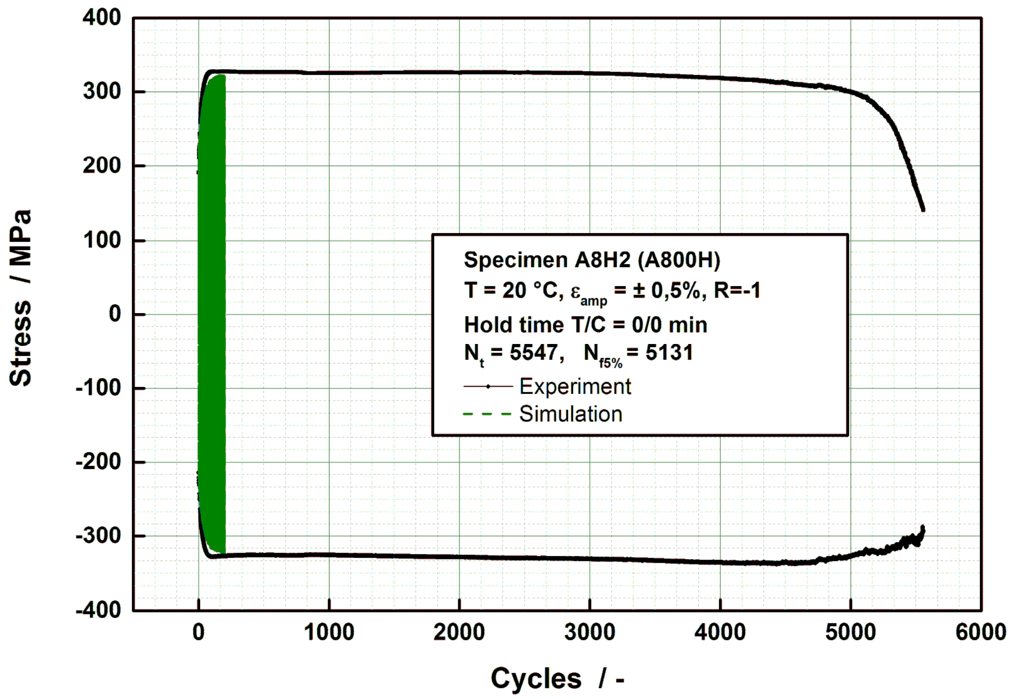

Figure A-7: Peak stresses for A8H2 (RT)

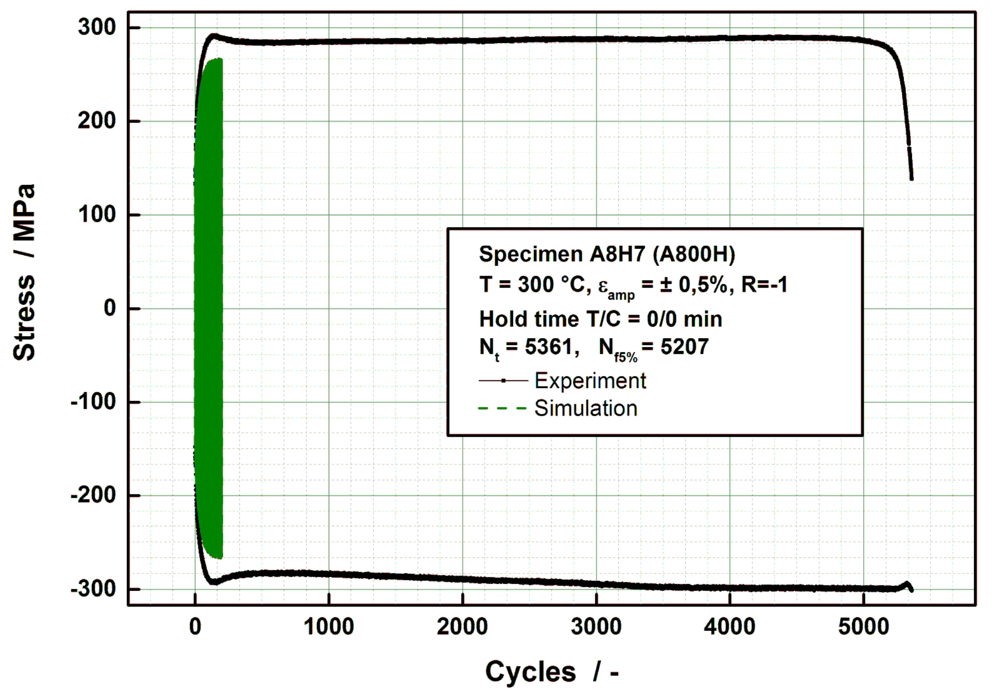

Figure A-8: Peak stresses for A8H7 (300 °C)

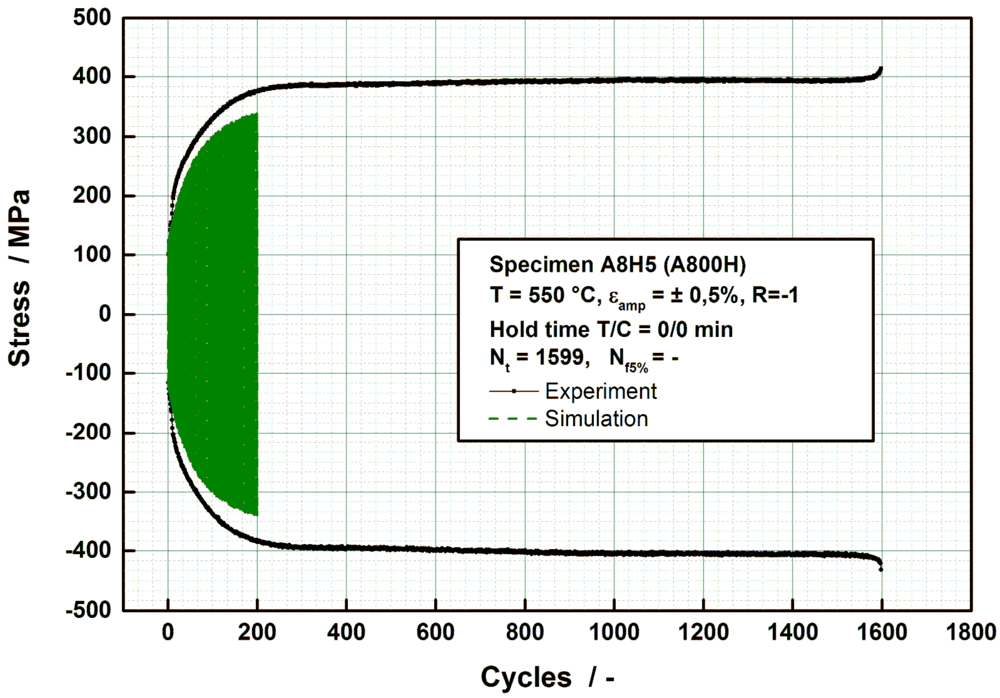

Figure A-9: Peak stresses for A8H5 (550°C)

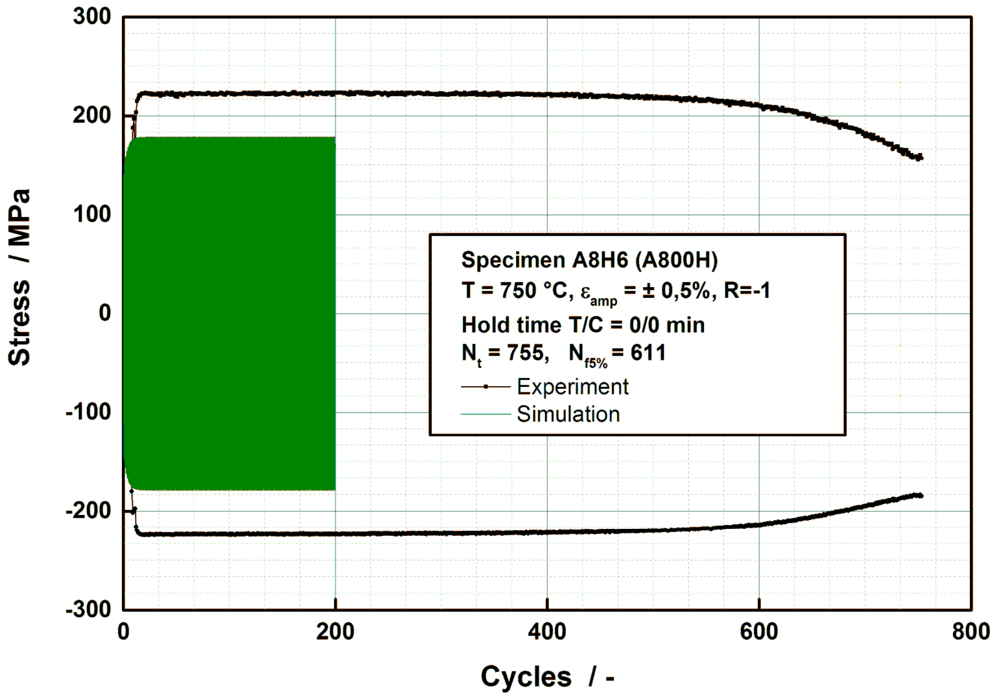

Figure A-10: Peak stresses for A8H6 (750°C)

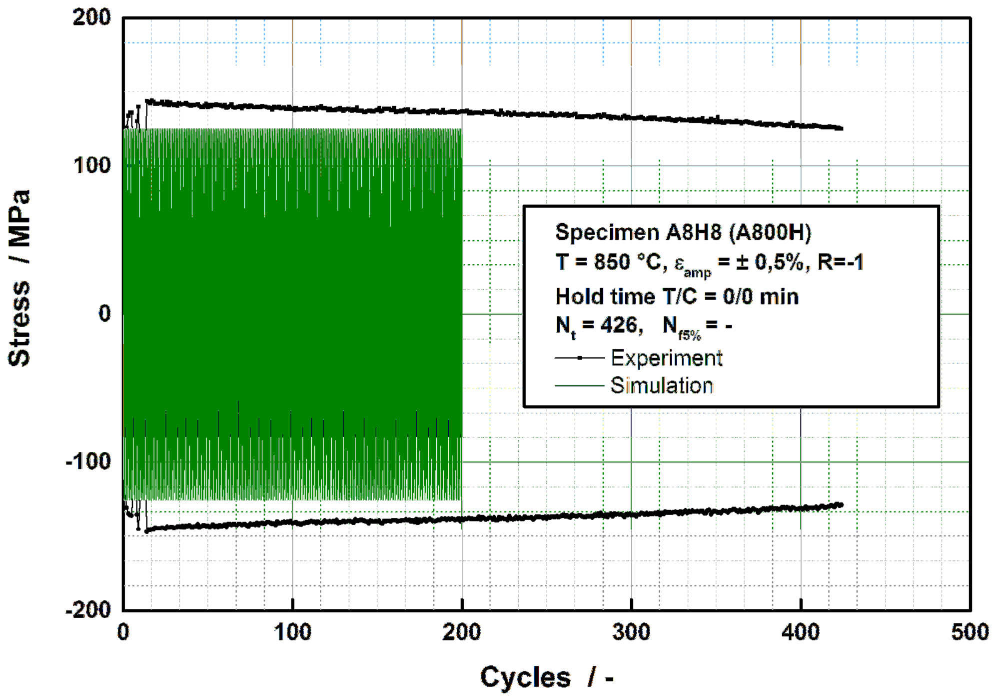

Figure A-11: Peak stresses for A8H8 (850°C)

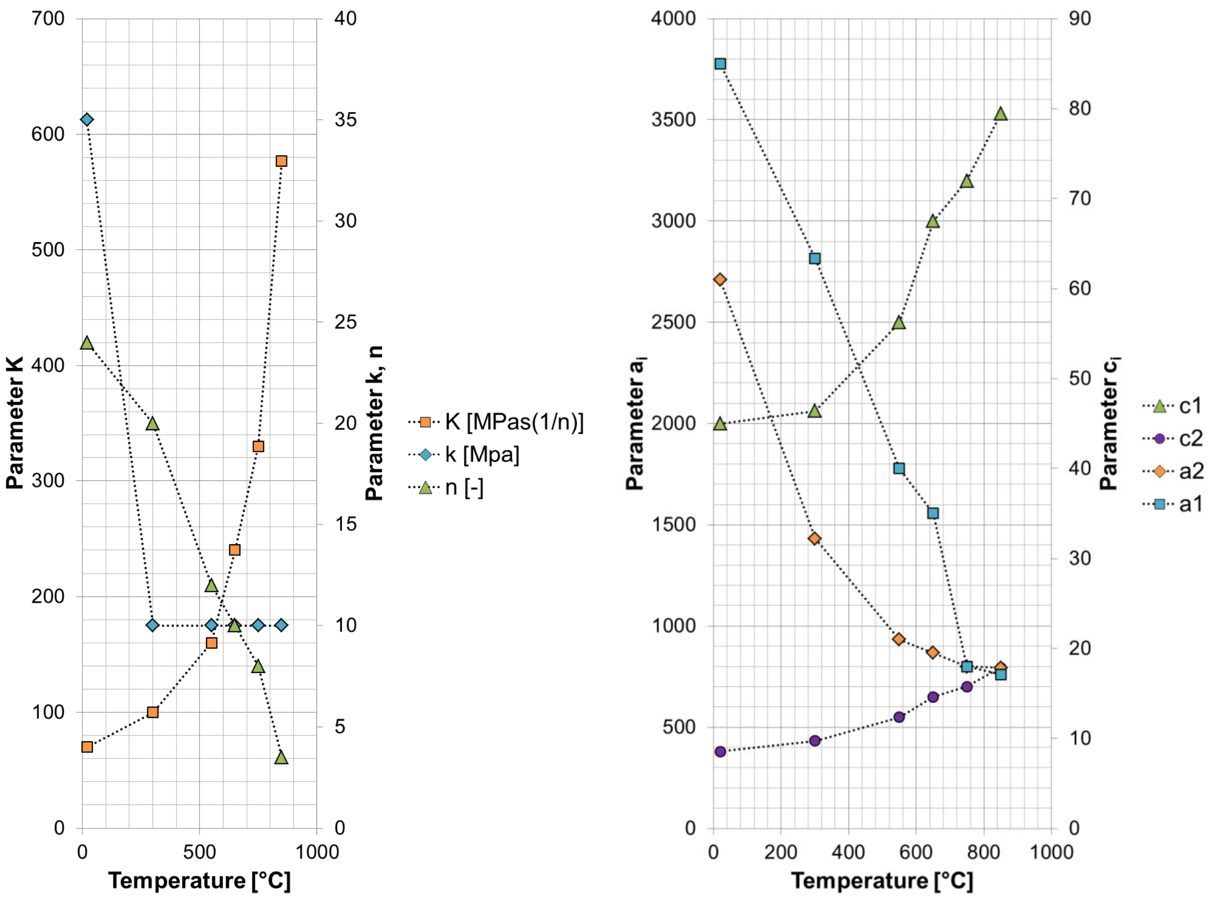

Figure A-12: Parameter progression for viscous (K, n) and hardening parameters (c_i, a_i, k)