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Integrity concept: Methods for safety assessment

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Summary

This document contains the outline of necessary elements of an integrity concept for high temperature reactors (HTR) and describes currently available sources which may be used. Beside existing approaches in different codes and draft codes recent advances in the assessment of advanced ultra-supercritical high efficiency fossil fired plants are highlighted with respect to their use in an integrity concept for HTRs.

Approval

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1 Introduction

The safety and structural integrity of pressurized components of nuclear power plants must be guaranteed under all operational and accidental conditions. One key element to achieve this is the proof of the integrity of the primary pressure boundary (PPB) components enclosing the primary coolant medium. To rule out a catastrophic failure (large break) of the PPB components in LWR technology the so called Basis Safety Concept (BSC) was developed. The BSC was further extended to the Integrity Concept (IC) that includes possible operational degradation mechanisms into the assessment procedure to exclude catastrophic failure for the whole lifetime of the component.

In the ARCHER-Deliverable D25.21 [1] the LWR BSC/IC was described and the possibility of transferring the IC to PPB of HTRs investigated. A gap analysis was elaborated, which identified the additional steps that are necessary for the application of the existing LWR IC to HTR pressure boundaries. The description of the different HTR concepts given in D25.11 [2] revealed that there will be a so called "cold" pressure boundary (operational temperatures as LWR or lower, low alloy ferritic fine-grained steel as 20 MnMoNi 5 5 or similar; HTR-Modul, HTR-PM, PBMR) and a "warm" pressure boundary (operational temperatures at or in the creep range, e.g. high alloy creep resistant martensitic steel as Mod 9Cr 1 Mo; NGNP designs by AREVA and GA, also cross-cutting to GFR).

For those PPB components that operate at temperatures below the creep range the LWR IC can be used taking into account the damage mechanisms irradiation (RPV only) and corrosion in HTR-helium environment if applicable.

For components operating at temperatures in the creep range of the material time dependent effects must be taken into account and the LWR IC must be extended to assure that the causes of possible operational damage mechanisms (creep and/or creep-fatigue processes) do not impact the component integrity.

Driven by the aim to increase the operating parameters (temperature/pressure) of conventional power plant components extensive R&D was performed during the last decade to improve the materials behaviour and the assessment methods. A description of these approaches will be given and it will be shown how to use the results of the conventional R&D to further improve the assessment procedures for HTR components and thus extending the IC to temperature range where creep effects are relevant.

The following remarks must be seen in the context of the procedures used in the technical codes and standards for the design and operation of high temperature HTR-components. Therefore the procedure used in the nuclear codes and standards like ASME and KTA (draft version) to consider also time dependent materials behaviour in the assessment of HTR-PPB components will be outlined briefly.

2 Integrity Assessment for Pressurized High Temperature Components in Nuclear Codes

2.1 Draft of German Nuclear Safety Standard for Metallic HTR Components

In 1987 work was started for a German Nuclear Safety Standard (KTA-rule) for HTR Components (KTA 3221). The background of this work comprised the experiences with AVR, THTR-300, LWR and the results of two research projects specially related to HTR-code development:

- Formulation of basic principles for a guideline for the design of HTR-components at service temperature above 800℃ (Erarbeitung von Grundlagen zu einem Regelwerk über Auslegung von HTR-Komponenten für Anwendungstemperaturen oberhalb von 800℃, BMU) [3]
- Design criteria for metallic and ceramic high temperature components and the pretensioned concrete reactor pressure vessels of future HTR-plants (Auslegungskriterien für hochtemperaturbelastete metallische und keramische Komponenten sowie des Spannbeton-Reaktordruckbehälters zukünftiger HTR-Anlagen, BMFT) [4]

In 1992 the code work resulted in a proposal for a draft Safety Standard for Metallic HTR Components (KTA 3221) [5], [6], [7], but was terminated in 1993 due to the lack of a perspective of further HTR development in Germany.
In the pre code work [4] a "Concept to assure the integrity of the enclosure of the reactor cooling medium" was elaborated. Treating this item it appeared that:

- The BSC developed for LWR could not be directly transferred to the HTR components for the cooling medium, because the LWR BSC is closely related to metallic components at temperatures below 400°C. This means that important non-metallic components and components at temperatures above 400°C are not covered.
- In case of HTR the restriction of the IC to the PPB would not consider other safety relevant HTR components.

Altough the integrity for HTR not only means integrity of PPB but must be extended to:

- Components with barrier function.
- Component whose failure adversely affects the barrier function.
- Components whose failure leads to an infiltration of other media into the PPB.

Within this WP only the integrity of the PPB is treated.

KTA 3221 (Draft)
The development of KTA 3221 in different parts corresponds to the approach used in KTA 3201 for LWRs:

- Part 1 Materials and product forms (Draft) [5]
- Part 2 Design, Construction and Evaluation (Draft) [6]
- Part 3 Manufacture (Preliminary draft) [7]
- Part 4 In-service inspections and operational monitoring (not yet available)
- Part 5 Additional requirements for Reactor pressure vessels from steel designed and manufactured according to KTA 3201 (not yet available).

For part 1 and 2 drafts of a KTA safety standard were elaborated and for part 3 a preliminary draft exists. For Part 4 there was no adequate experience from HTRs under operation for reliable based safety standards and for part 5 no appropriate basic knowledge was available concerning the influence of HTR typical irradiation and failure temperatures on the RPV material.

For those components operating in the creep regime also time dependent material properties must be determined and used for the design.

Part 2 of KTA 3221 *Design, Construction and Evaluation* is structured as follows [6]:

1. Scope
2. Definitions
3. Fundamentals
4. Load cases and load case classes
5. Actions on components
6. Engineering design
7. Dimensioning
8. Analysis of mechanical behaviour
9. Load limits
10. Proof of integrity with fracture mechanics methods

Due to the wide temperature range of metallic HTR-components time independent and time dependent failure modes must be considered. According to sect.3.2 of [6] the following failure modes must be excluded by design:

- Ductile failure
- Brittle failure
- Ductile creep rupture

- Fatigue due to load changes
- Creep fatigue due to load changes with hold time
- Loss of stability due to short term loading
- Loss of stability due to creep under long term loading
- Gross deformation due to ratcheting
- Gross deformation due to creep ratcheting
- Loss of functionality due to gross deformation
- Environmental damage
- Tribological damage

The mechanical analysis to show that the components withstand the specified loadings is described in Sect. 8. For the analysis of the mechanical behaviour the following regions can be defined that depend on temperature and the duration of the load case:

- Low temperature region (I)
- High temperature region without significant creep (II)
- High temperature region with significant creep (III)

The regions are to be defined due to the specific material.

In region I the loads are evaluated with the methods given in KTA 3201.2 [8] and 3211.2 [9] (test group A1).
In region II no time dependent material behaviour must be considered. In region III time dependent material properties must be used. A graded verification is necessary. The available procedures are:

- elastic procedures
- simplified inelastic procedures
- inelastic procedures.

The limits that must be satisfied are:

- *Low temperature region (I)*
  Stresses, strains and their ranges and number of cycles are limited according to KTA 3201.2

- *High temperature region without significant creep (II)*
  Stresses, their range and number of cycles are limited as in region I. Strains and strain ranges must be evaluated by elasto-plastic materials laws. Limitations with strain controlled fatigue design curves. Accumulation of plastic strain increments has to be excluded.

- *High temperature region with significant creep (III)*
  Stresses and strains are limited by time and temperature dependent limit values.
  Stresses and strains must be limited.

In the annotation to the standard [6] it is stated that for the evaluation of creep-fatigue behaviour an approach is used that is conservative but could be more realistic. In the standard the necessity of inelastic analyses for the high temperature region with significant creep was emphasized. Constitutive equations for these analyses are required.

2.2 American ASME III –BPV Code, Div. 1, NH

Subsection NH of ASME-BPVC Section III, Div. 1 [10] deals with the construction of Class 1 components in elevated temperature service. It must be used for components that experience temperatures above the limits given in subsection NB. For temperature and loading conditions

resulting in significant creep effects time-dependent materials properties must be considered (NH-1110, d).
For all major structural components a detailed stress analysis shall be prepared to show that the rules and limits of NH-3220 and NH-3230 are satisfied (NH-3214). In the high temperature region not only the stress but also the strains must be limited. This may require an inelastic analysis, if thermal and mechanical loadings produce yielding and/or thermal creep processes. A combined analysis of time–independent elastic-plastic and time-dependent creep will be needed in general. For inelastic analysis required by Subsection NH, appropriate multiaxial stress-strain relationships and associated flow rules shall be used to combine multiaxial stresses and strains (NH-3212 (b)). Constitutive equations to describe the inelastic material behaviour should reflect:

- Effect of plastic strain hardening including cyclic loading effects
- Hardening or softening resulting from high temperature exposure
- Primary creep and effects of creep strain hardening or softening
- Effects of prior creep on subsequent plasticity and vice versa.

Such constitutive equations are quite ambitious, especially in the case of 9Cr-1Mo-V steels where unified equations that do distinguish between rate dependent plasticity and time dependent creep are needed (NH-3214.2). A flow diagram for elevated temperature analysis is given in Fig.NH-3221-1 (Design limit and Level A, B, C, D service limits). Appendix T of NH provides rules for the evaluation by analysis of strain, deformation and fatigue limits.

2.3 French Code RCC-MR

The French code RCC-MR goes back on common efforts of Commisariat à l'Energie Atomique (CEA), Electricité de France (EDF) and Novatome in order to gather a complete collection of rules to apply for design of LMFBR components and was published in 1987 [11]. The rule is based on the previous code for light water reactors and covers extensions for the high temperature regime. It deals with nuclear components, materials, NDE methods, welding and fabrication, introduces a level system for the components and is mainly based on experiences with pool type liquid metal fast breeder reactors (i.e. Superphenix) [12]. As far as design rules are concerned it is taken into account that most of the components are operated below the creep regime where existing rules can be applied, furthermore rules for ínsignificant or negligible creep were established and the limits for the application of rules which are based on the assumption of negligible creep were defined. For components operated under high temperatures in a first stage extensions were made using Neuber approach to evaluate actual strains based on elastic calculations to allow for the use of linear damage accumulation rules of creep and fatigue damage similar to ASME code regulations. Complete elasto-visco-plastic calculations are also described in the appendices. This field was followed up in numerous developed covering the viscoplastic behaviour including ratcheting effects.

3 Integrity Concept for HTR Pressure Boundary Components

3.1 Application of LWR Integrity Concept

In all approaches for the assessment of components operated at temperatures below creep regime described in the previous sections existing rules for conventional nuclear plant components are used. Thus, for all components the basic principles that are given in the following may be applied and additions covering the high temperature loading of some components have to be made.
To rule out catastrophic failure (large break) of safety relevant components of LWR´s PPB an integrity concept (IC) was developed. This LWR IC is described in detail in D25.21 [1]. The main features are given here.
The IC is based on the Basis Safety Concept, **Figure 1** consisting of the Basis Safety (BS) and the Independent Redundancies.

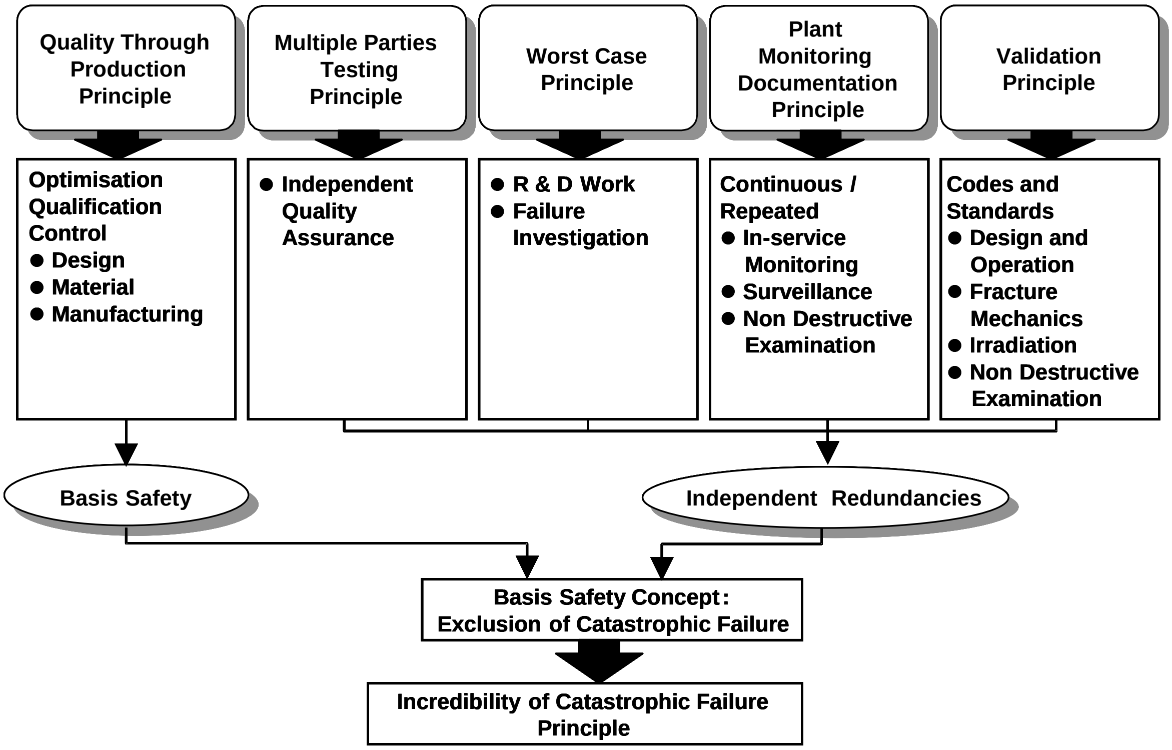

Figure 1 : Summary of the “Basis Safety Concept” (BSC), schematic, [13] - [15]

The BS is the realization of the “quality through production principle”, this means optimization, control and qualification of

- Design
- Material
- Manufacturing.

The requirements of BS will provide the pressure-retaining boundary with a basic safety that will preclude any disastrous failure of a plant component as a result of manufacturing defects, [13] - [15].

Furthermore the **“Basis Safety Concept” (BSC)** requires the existence of redundancies to ensure that any possible deviation from optimization is sufficiently unimportant and unlikely for catastrophic failure. One redundancy of considerable importance relies on the verification and validation of calculation codes and fracture mechanics as well as the verification and qualification of non-destructive testing technologies and in-service monitoring. Therefore, now as before validation work is indispensable to provide the knowledge for the validation of codes and standards and a reliable in-service monitoring of operational parameters. The validation work was done mainly based on the results of uniquely large full scale quasi-static and dynamic testing of components without and with degraded sections to demonstrate their load bearing capacity and their failure behaviour under light water reactor (LWR) conditions, e.g. [16] to [21]. Furthermore for a safe operation and to prove and maintain high quality plant in-service monitoring and recurrent examinations are of indispensable importance. For the practical application of the BSC under operational conditions, the existence of the independent redundancies is demanded, but their application has to be balanced in a way case by case. This makes evident that BS ("quality through production" principle) exclusively cannot ensure the integrity of components for operation and the entire lifetime. Therefore the independent redundancies are demanded in a balanced way.

To apply break preclusion to mechanical components (piping and vessels) and to meet the concerns of operational terms and conditions for the total lifetime the **“Integrity Concept” (IC)** was developed. The IC emerged from the fundamentals of the BS, considering plant specific terms and conditions. Consequently, the “independent redundancies” of the BSC will be effective to consider operational terms and conditions as well as the operational experience and results from R&D, **Figure 2**. As a premise for a systematically approach to ensure the integrity of components based on IC it is indispensable to show that the as-built status of quality (design, construction, material) is according to the required quality given in the guidelines, codes and standards, to demonstrate that sufficient knowledge of possible operational degradation mechanisms is available (e.g. no inadmissible cyclic and/or dynamic mechanical and/or thermal loading, no corrosion) to prevent the causes of possible operational damage mechanisms and to show that the required quality can be guaranteed for the on-going operation. In amplification of the BSC the IC is a proactive approach to ensure the required quality for break preclusion during operation for the total lifetime, e.g. [22] and [23]

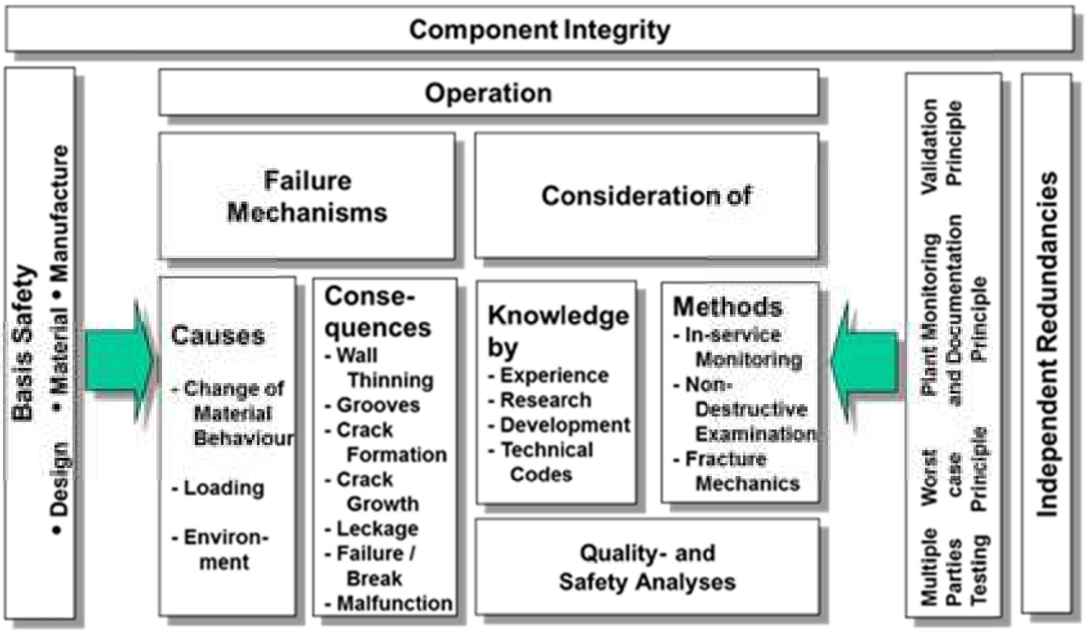

Figure 2: Concept to prove the integrity of components

3.2 Extension of the LWR Integrity Concept to HTR Pressure Boundary Components

The approach of the LWR IC can be adapted to assure the integrity of HTR PPB components taking into account the differences in the reactor types.

Materials: The application of the BSC needs a reliable database that has been elaborated for the materials used for PPB of LWR (acc. to KTA 3201.1). As far as other materials are used for the construction of HTR PPB the available database it must be carefully checked and supplemented if necessary.

Operational Temperature: Depending on the specific HTR type some PPB components will be operated at high temperatures where time dependent materials behaviour (creep and/or creep fatigue) occur. This time dependent behaviour results in possible additional degradation mechanisms that must be taken into account. The knowledge gained in conventional power plant technology will give valuable support to the assessment of the component behaviour, see chapter 4.

Cooling medium: The primary cooling medium of HTRs is helium, being an inert gas in itself. Due to the small amount of impurities oxidation or carburisation cannot be ruled out. Here further investigations may be needed [1].

4 New Approaches Developed for Fossil Fired Power Plant Components

4.1 Developments towards Advanced Ultra-supercritical High Efficiency Power Plants

For fossil fired power plants regulations of the European Pressure Equipment Directive (PED) and subsequent standards e.g. DIN EN 13445 or DIN EN 12952 as well as other regulations, e.g. "AD Merkblätter" are used for design and lifetime assessments. In the framework of the development of CO_2-reduction technologies a demand for high efficiency fossil fired power plants was identified in recent years and development programs for high efficiency plants with service temperatures operating at temperatures as high as 700℃ or 750℃ have been established. Within the Cooretec initiative of the German Federal Ministry for Economy and Technology (BMWi) research on advanced ultra super critical plants was put forward. To reach the high efficiency goals, high steam parameters (700℃ and 350 bars) are used and the qualification and development of new materials such as Nickel based alloys are needed. Previous investigations show that above 650℃ Nickel based alloys are required to ensure sufficient high-temperature creep resistance, **Figure 3**. These materials are nevertheless very costly to produce and also difficult to manufacture and weld.

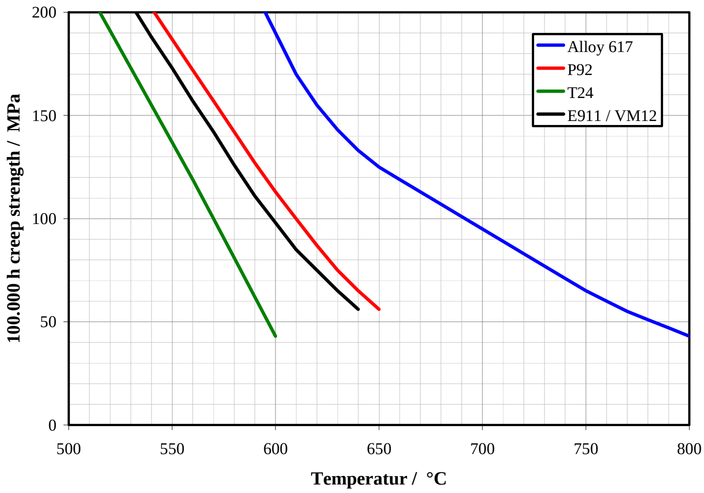

Figure 3 : 100.000 h creep rupture strength for candidate materials of P92, E911/VM12, T24 and Alloy 617 at different temperatures

Since the use of Nickel based alloys for the application in the boiler and for piping systems is an innovation manufacturing problems have to be solved and qualification and assessments have to take into account the properties of the materials in the as built state. Up to now, components are being designed with the help of codes and standards mentioned above combined with empirical knowledge. In order to reduce the cost related to the new nickel based alloys and an economic and efficient use of other materials, a Taylor-made design of components is required. Extended steam conditions would also yield high wall thickness and thick-walled components and piping if they are designed according to currently existing codes and standards. However, in some cases these requirements are contrary to the possibilities of manufacturing. Furthermore high thermal stresses during start-up and shut-down would be taken into account in such components due to high wall thickness. Actual codes and standards and standards do not take into account the inelastic material response (for example the relaxation of secondary stresses). One way to improve the design of new high temperature components consists in the use of modern constitutive equations. The European Pressure Equipment Directive (PED) allows for example the use of Design By Analysis (DBA). Consequently, Finite Element Method (FEM) can be used to predict the creep and relaxation behavior of boiler components for 700℃ fossil power plants. Since these models are mostly phenomenological, a detailed experimental database is necessary to fit simulation parameters [24].

Altogether this demands for detailed research work concerned with both material development and component design. Results from such research work are necessary to face the challenge of building safe, energy efficient fossil plants. In the following a summary of already existing efforts is given. An outline of a concept to improve design of components and enhance assessments with regard to safety and reliability of high temperature power plants is presented.

4.2 Assessment Concept for New Fossil Power Plants up to 700℃

In the design of high-temperature components for the development of 700℃ plants, a lot of aspects still require research efforts, **Figure 4**. In order to use Design by Analysis, appropriate constitutive equations need firstly to be derived from a large and reliable experimental database to describe the thermo-mechanical behavior of the investigated materials. Besides a reliable database determined by uniaxial tests experiments under multiaxial conditions such as hollow cylinders are required to quantify the influence of multiaxiality, since these equations have to describe the behavior in multiaxial conditions. In the last few years, a lot of efforts have also been consented to combine physical aspects of damage with phenomenological constitutive equations. The analysis of the evolution of the microstructure during creep, fatigue or creep-fatigue tests with help of Transmission Electron or Scanning Electron Microscopy gives hints (f.i. dislocation density, creep pores) for the implementation of mechanistic based damage evolution laws into materials equations.

Component qualification must cover several aspects. First the manufacturability and weldability must be demonstrated. The influence of manufacturing on the material properties must be considered especially in the case of weldments. For design it must be ensured, that the used material property data are valid for the state of the material in the component. This may be validated by feature and component tests which on the other hand can be used to validate the above mentioned simulation models. The principles given in the BSC must be applied for component qualification and manufacturing.

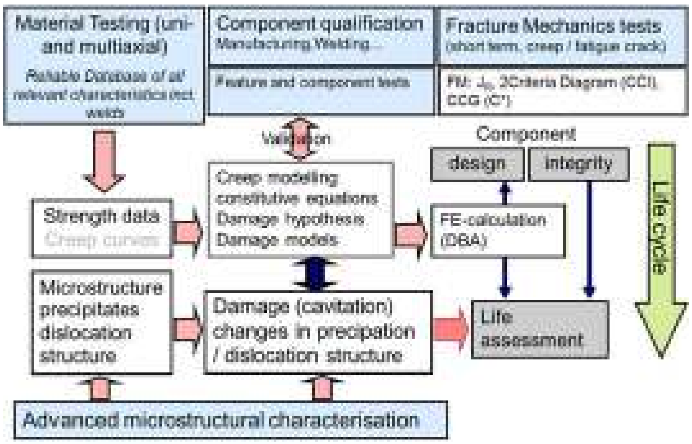

Figure 4 : Scheme of a design and assessment concept for new fossil power plants

In case of weldments two main aspects have to be considered. Firstly, residual stresses coming from the welding process could influence the behavior. Secondly, heat affected zones need to be taken into account because of their different mechanical behavior in comparison to the base material.

Since Ni based alloys and advanced martensitic steels are quite complex in terms of precipitation and changes in microstructure, for the assurance of safety and reliability the tools for advanced considerations like assumptions of defects and cracks must be available. Especially for Nickel based alloys precipitation states after long term exposure may cause a reduction in ductility. In this case the resistance against initiation and growth of cracks should be known. Creep crack initiation (CCI) and creep crack growth (CCG) assessments need to be quantified both in base materials and welded structures to guaranty the components reliability. Fracture mechanics tests are then required for the determination of fracture parameters such as the J-Integral (strain energy release rate) and the creep crack parameter C*. In the following sections, this global concept is illustrated by examples covering some of the aspects shown in **Figure 4**.

4.3 Material Testing and Component Qualification

Beside pedigree data as short term strength properties, Charpy energy and metallographic characterisation the knowledge of reliable material properties is necessary for design and lifetime analysis. Various research projects, e.g. [25] to [29] resulted in a good database for all materials used in advanced ultra supercritical plants. The material knowledge comprises beside the materials known from previous projects, the materials T24, T/P 92, VM12, Alloy 617mod and Alloy 263. Parallel to the qualification tests on base material welded joints taken from representative welds and the manufacturability has to be ensured. All material data should be obtained from specimens taken from component like specimens in order to represent the material state with regard to ageing history.
So as to guarantee the transferability of results gained by uniaxial creep tests to real components, the multiaxial state of stress must be taken into account. Components in service are indeed exposed to multiaxial loadings. Under such loadings, these elements show shorter times to failure for comparable equivalent stresses (Von Mises criterion). **Figure 5** is representing the influence of multiaxiality on the creep strain and creep damage. This effect has been already investigated for martensitic steels “P91” and “E911” [30], [31] . The physical basis is the formation and growth of cavities during the creep tests. Because nickel alloys are of high interests in new fossil plants, the influence of multiaxiality on the creep behavior of Alloy 617 will be reported in this paper. An adequate test to investigate multiaxiality consists in the hollow cylinder creep measurement under a static pressurized loading.
During creep tests involving Alloy 617 cylinders, axial and hoop strains were measured by capacitive high temperature strain gauges [29], [32]. By using finite element simulations using an incremental creep equation including a damage parameter with an evolution equation which is dependent on the stress state, a comparison with experimental results could be done. This constitutive law describes primary and secondary creep using a Graham Walles type creep equation and tertiary creep with the damage parameter. The description of primary creep (decreasing creep rate at the beginning as illustrated in Figure 5 left) and secondary stationary creep is not affected by the damage parameter and hence not affected by the multiaxiality of stress state. The equations are outlined in more detail in section 4.5. Simulation results for an internal pressure of 490 bars and temperature of 700℃ are presented in Figure 5 (right). The blue line shows the experimental hoop strains. The black line presents the results of the simulation without considering the quotient of multiaxiality q. The red line is finally the representation of the simulation with consideration of the quotient of multiaxiality q. As expected, the first calculation is well defining the primary and secondary creep stages. In order to describe the global behavior, i.e. all three creep domains, the introduction of the quotient of multiaxiality was finally required. The red line shows the good fit in the tertiary domain by imposing q to 0.3.

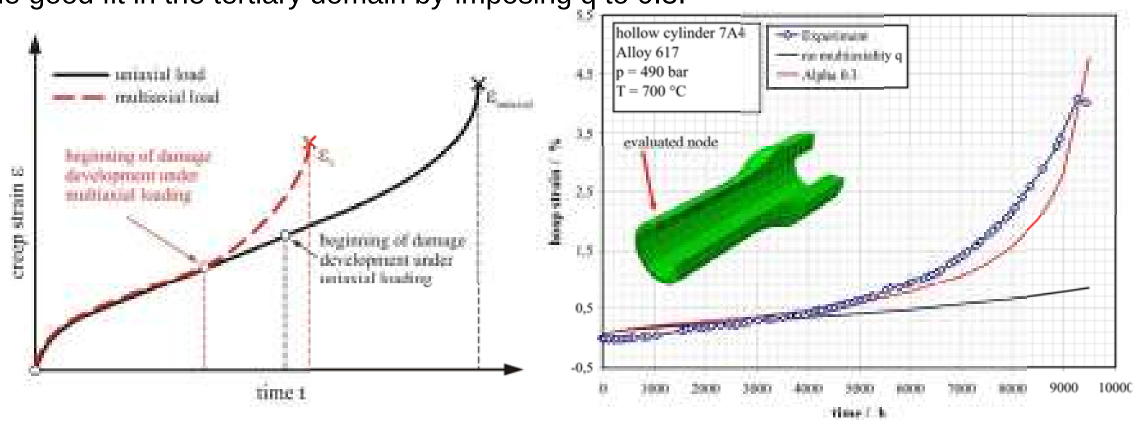

Figure 5 : Effect of a multiaxial state of stress on the creep behaviour (Left), Measured hoop strains of an Alloy 617 hollow cylinder compared with simulated results (Right) [29]

In a former project, a correlation between cavity density measured in a hollow cylinder specimen made of “P91” after creep testing and the distribution of the damage parameter D of a simulated hollow cylinder was found [31]. In **Figure 6** (left), the distribution of the damage parameter D after 9.500 hours of creep in the mentioned P91 specimen is presented. Metallographic investigations were enhanced on spots of highest damage. These areas show the highest cavity density as well, Figure 6 (right).

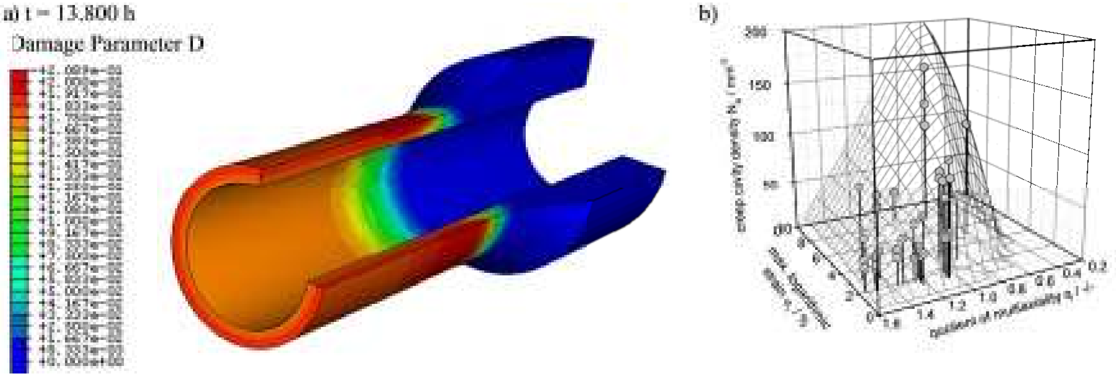

Figure 6 : Distribution of the damage parameter in a hollow cylinder test at 600°C (Left), cavity density of a P91 hollow cylinder (Right)

Similar investigations on damage characterization based on conventional damage characterization by optical micrography and investigations are under way for nickel based alloys. Such mechanistic parameters are planned to be implemented in phenomenological laws. Microstructural analyses are finally nowadays being conducted to evaluate the influence of microstructural parameters on the creep but also fatigue behavior of new materials. This aspect is picked up in section 4.7.

4.4 Investigations on Crack Resistance

Integrity and remaining lifetime of high temperature components are influenced in many cases by defects which are often unavoidable in real manufacturing processes. Depending on the loading conditions creep or fatigue cracks can thereby occur and grow. Due to this reason, it is necessary that in addition to non-destructive testing methods for the reliable proof of failures, methods are available for the evaluation of detected failures under consideration of service loading. Particularly the crack initiation and propagation at imperfections of long-term loaded components deserve a reliable quantitative description. Furthermore an integrity analysis should comprise all stages of lifetime including consideration of growing cracks.
In order to determine crack resistance curves (JR-curves) tests with compact tension specimens at high temperatures have been performed for different materials. Using crack resistance curves initiation under static conditions can be assessed. Two examples of crack resistance curves are given in **Figure 7**.

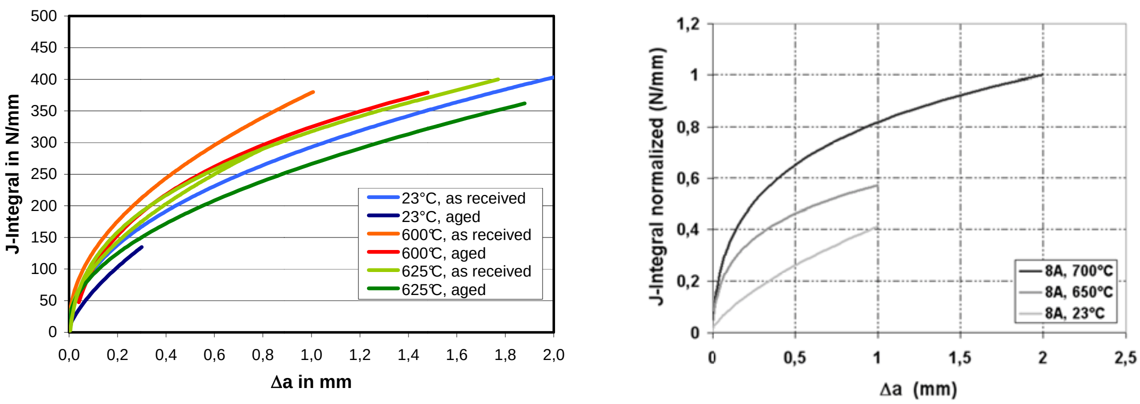

Figure 7 : Crack resistance curves for P92 in virgin and aged condition [33] and a Nickel based cast material for turbine casings [33]

Since a change in ductility behaviour during service due to ageing effects has to be expected, tests on aged materials are planned as shown in the example for the martensitic steel [33]. It is obvious that there is a reduction for the aged materials, but the crack resistance curve shows that ductile behaviour ensures sufficient crack resistance during stable crack growth. For new materials as Nickel based alloys the knowledge about crack resistance is essential. Therefore the crack initiation and crack propagation behaviour under elevated temperatures and creep, fatigue and creep-fatigue loading conditions for turbine materials [33] as well as piping and boiler materials [28],[29],[34] were investigated as shown exemplarily in **Figure 8**. The results must be considered in advanced integrity analyses. Data especially for materials with a limited ductility are required for such analyses.

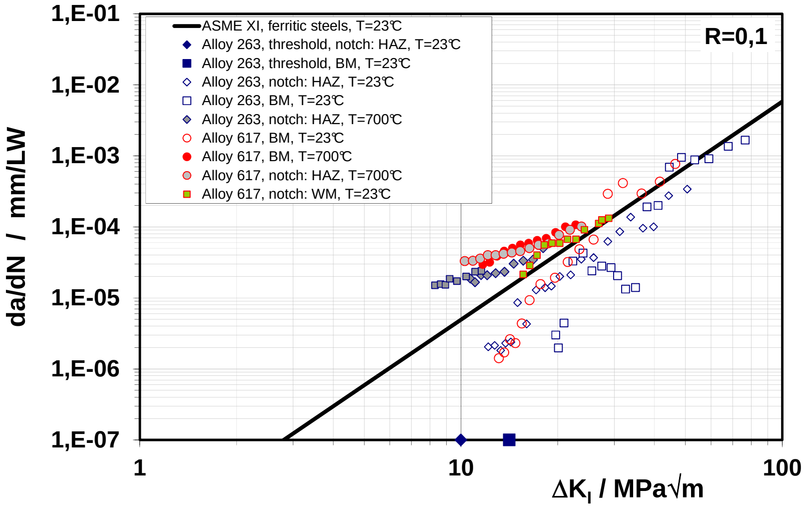

Figure 8: Cyclic crack growth for Alloy 617 and Alloy 263 at RT and 700°C [28].

4.5 Simulation of Material and Component Behaviour

Constitutive equations are an essential part of any structural calculations. Depending on the load type and complexity, they differ in their complexity. Whereas in monotonic and low cycle fatigue, some standards based on rate independent models are widely used in the industry, modeling the creep behavior of materials needs the introduction of rate dependent laws. Unified viscoplastic equations are combining, if enough complex, the global behavior of a material under a wide range of load type. Nevertheless, such unified models require a huge and precise database to describe the complete behavior of a material accurately. Most of the time, this amount of information is not available and the complexity for the model calibration is so high that most authors limit their investigation to a defined purpose. In order to assess the lifetime of components submitted to creep, an incremental constitutive equation covering all creep stages is required. The models must be based on sufficient data available also considering the specific demands of parameter approximation. A sufficient data base especially on the creep fatigue behavior of the relevant materials are the basis for the constitutive equations [35], [36], [37].

Exemplarily two approaches are given briefly in the next paragraph. Under creep conditions the time dependent viscoplastic behavior can be described by an incremental constitutive equation covering all creep stages is required. The basic creep equation was formulated in the fifties by Graham and Walles [38]. This creep law was modified at MPA Stuttgart [39] and has been successfully used in many R&D projects. In the original formulation, the third creep stage is modeled by introducing a third term. Through the deletion of this third component and the introduction of an effective stress concept with damage evolution $\dot{D}$, a good description of the global creep behavior is ensured:

$$\frac{d\varepsilon}{dt} = 10^{A1} \cdot \left[\frac{\sigma}{1-D}\right]^{n1} \cdot \varepsilon^{m1} + 10^{A2} \cdot \left[\frac{\sigma}{1-D}\right]^{n2} \cdot \varepsilon^{m2} \quad (1)$$

It presents the advantage to introduce a parameter being able to reproduce the multiaxial stress state. A power law of the quotient of multiaxiality q is then introduced in the modified Graham-Walles creep law. The damage evolution is defined as follows:

$$\dot{D} = 10^{AD1} \cdot \left(\left(\frac{\sqrt{3}}{q}\right)^{\alpha} \cdot \sigma_{vm}\right)^{nD1} \cdot \tilde{\varepsilon}^{mD1} + 10^{AD2} \cdot \left(\left(\frac{\sqrt{3}}{q}\right)^{\alpha} \cdot \sigma_{vm}\right)^{nD2} \cdot \tilde{\varepsilon}^{mD2} \quad (2)$$

where: $\tilde{\varepsilon} = \sqrt{\langle\varepsilon_1\rangle^2 + \langle\varepsilon_2\rangle^2 + \langle\varepsilon_3\rangle^2}\,;\, q = \sqrt{\frac{3}{2}} \cdot \frac{\tau_{okt}}{\sigma_{okt}} = \frac{1}{\sqrt{3}} \cdot \frac{\sigma_{vm}}{\sigma_{hyd}}\,;\, \sigma_{hyd} = \frac{1}{3} \cdot (\sigma_1 + \sigma_2 + \sigma_3)$

This example shows that using such formulation it is also possible not only to describe the deformation behavior and determine stresses for further assessments but also assess damage mechanisms and phenomenological or mechanism based approaches in order to describe the failure behavior of components. To describe the deformation and damage behaviour under creep-fatigue-loading, the viscoplastic CNOW-model was implemented based on [40], [41], [42] and used in various research projects. For low stresses, creep is dominated by diffusion mechanism, whereas for high stresses, creep is controlled by dislocation mechanism. To enable a more accurate description of the creep behavior, two inelastic strain rates were used. The sum of the two inelastic strain rates equals overall creep rate. By using kinematic and isotropic variables, both the static and the cyclic hardening or softening behavior was reflected in the model. Two damage parameters D_c and D_f were included to describe the damage caused by creep or fatigue.
Using this kind of material models inelastic analyses may be sufficiently provided for components operated at high temperatures. These approaches are already used in the ARCHER framework. Data and models are provided for example in WP4 e.g. [43]. The model parameters were in a first step derived from a plate in order to get reasonably thick specimens. It could be shown that the model and the parameters determined are applicable to thin walled structures as well.

4.6 Component and Feature Tests and their Simulation - Examples

The inelastic models do not only demand for an appropriate data base. It is also necessary to sufficiently validate the models and the parameter approximations. Component and feature tests are an essential tool to verify the models under multiaxial service-like conditions. This may be illustrated by the following examples.
Membran wall sections representing a boiler component were tested at MPA Stuttgart within the research project MARCKO 700 [26], [27]. Sections from waterwalls of ferritic and martensitic steels T24, T92, VM12 and the nickel base material Alloy 617 were investigated. They were tested under realistic boiler conditions unter steam conditions. The above mentioned tests allow for a simulation of component-like conditions. In order to verify the transferability of the results gained in such tests as a final step of qualification, tests on tubes are carried out in a project for the development of high temperature tubes and valves made of nickel based alloys and other materials used in a ultra supercritical plant. In Mannheim, a test rig operated at 725℃ has been put in place directly in a derived circuit of the GKM power plant to investigate the damage under creep load and real steam conditions [44]. One challenge is to forecast the life cycle of such tubes and to optimise their thickness for a given expected life by means of inelastic calculations.
Welds are critical parts in the global construction of fossil power plants. The heat input of the welding process affects the microstructure of the welding zone. The deformation and damage of welded joints is then resulting from the interaction of different parameters such as for instance residual stresses upcoming from the welding process or the structure dissimilarity along the weld. Under service conditions, for a number of heat resistant materials e.g. new martensitic steels like “P91”, “E911” and “P92”, the fine grained, coarse grained and intercritical heat affected zone have

different properties, fine grained or intercritical heat affected zones have poor creep strength in comparison to the base materials. For a detailed description of the creep behavior, the material properties of all interacting elements (Base Material (BM), Weld Material (WM) and Heat Affected Zones (HAZ)) are therefore required. In a lot of applications, these properties are nevertheless not accessible. That's the reason why welds are, in most industrial applications, modeled without heat affected zones. The introduction of Weld Strength Factors (WSF) is then giving the possibility to link simple calculations to real welds [45][46].
Research and qualification work done in various projects is aimed to provide long term data on weld strength reduction for ferritic and martensitic steels as well as Nickel based alloys [47]. These factors are established thanks to creep experiments on base material and creep experiments on welded elements. However, weld strength factors obtained by long term tests on crossweld specimens do not reflect the behavior of welded components in all cases. Therefore, inelastic calculations taking care of heat affected zones are nowadays promoted for an exact description of damage.
In order to model the creep behavior of a weld, material data must first be collected for all components involved. Secondly, the microstructure has to be metallographically analyzed so as to get some information on the size and position of the heat affected zones. Creep calculations can then be used to determine the location of maximum strain. Stress redistribution during the creep test lead to different strain accumulation. In this case the change in fracture location which can be usually observed in martensitic and ferritic materials can be explained by the different strain distribution of two specimens, one fractured in the base metal after 3000 h, the other one fractured in the heat affected zone after 10,000 h. This could also be verified by metallographic investigations of the tested specimen.

4.7 Influence of the Microstructure on the Creep Damage Evolution

Microstructural changes during the creep process are giving information about the situation regarding precipitation and evolution of dislocation structure. These data can be correlated to actual material properties and therefore give a piece of information which can be used for determination of long term behaviour and damage evolution in new materials. This microstructural evolution of materials is determined using SEM and TEM analyses. As an example the change of microstructure of the nickel based alloy 617 is shown. For three states of a thick walled pipe precipitation characteristics and dislocation density has been determined. The first two states, i.e. the initial state and a creep state after around 10.000 hours for a stress of 110 MPa and a temperature of 750℃ were investigated within the MARCKO-DE2 project [25]. The third state is resulting from a creep test of 26.700 hours at 700℃ for a stress level of 140 MPa within the MARCKO-700 project [26]. The initial state is presenting an average grain size of 51 µm. Precipitates of $M_{23}C_6$ were detected (**Figure 9**) inside the grain but also at the grain boundary. They just differ by their average size (50 nm inside the grain and 250nm at the boundary).
In the received state, no γ' phase (Ni_3Al or Ni_3Ti) could be detected. For the creep damaged specimen, a rise of the number of dislocations and subgrains is present. The average grain size is for instance growing from 50 µm (as received state) through 75 µm (after 10.000 hours) to end at a 90 µm level (after 26700 hours). The dislocation density is also rising from 4.10^9 cm^{-2} in the initial state to $6.1.10^9$ cm^{-2} after 10.000 hours to end finally at $8.2.10^9$ cm^{-2} after 26,700 hours of creep test. By systematically analysing the microstructure, some other parameters like precipitation size and number can be extracted.
A future challenge will be to correlate these findings with quantitative measures with regard to material behavior and damage development, **Figure 10**. Such investigations deliver information on the physical mechanisms of creep deformation and damage. Multi scale modeling approaches and thermodynamical calculations will be used in a near future to determine the macroscopic behavior on the basis of microstructural findings.

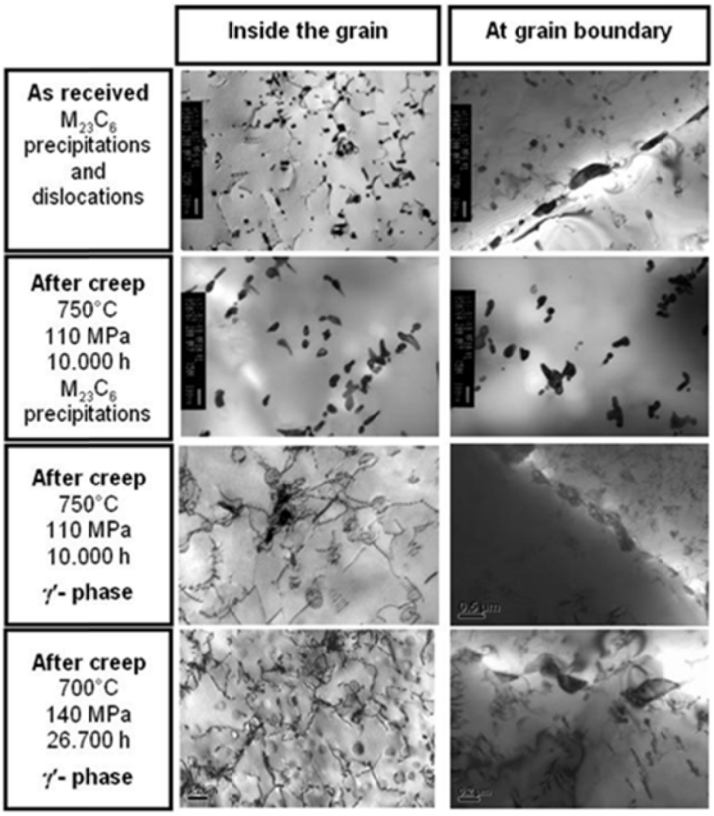

Figure 9 : TEM-Analysis of the evolution of precipitations and dislocations during creep of an Alloy 617 specimen

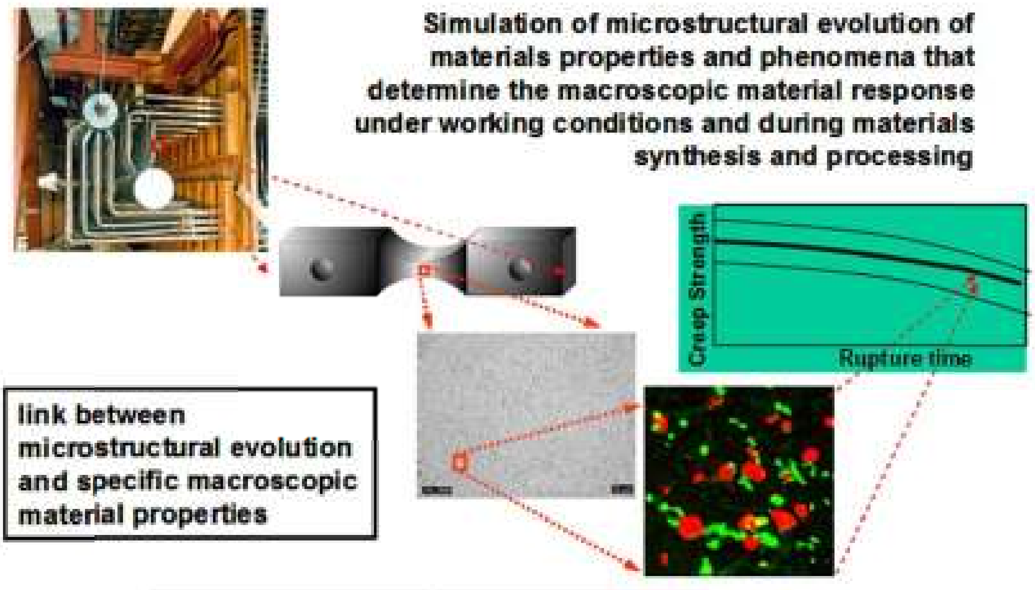

Figure 10 : Link between material properties, simulation and microstructural evolution

5 Conclusions for the Integrity Concept for HTR Components

A concept of design by analysis and a methodology for a holistic approach for the assessment of high temperature components for new fossil fired power plants has been presented in section 4. The inelastic calculations derived from complex constitutive equations presented in this research are a very efficient way to perform state of the art simulations of stress relaxation and creep behavior at high temperature loadings. Uniaxially, as well as multiaxially loaded components could be simulated. Welds were also considered and the geometrical consideration of heat affected zones was reported to be essential for a good forecast of the creep failure zone. In order to get reliable results with these inelastic approaches, a good data basis of uniaxial creep tests at a wide range of stress levels, some multiaxial tests (e.g. hollow cylinders) as well as creep experiments on welds are required. In order to open a new scope of modeling, TEM and SEM analyses were used to evaluate the evolution of damage through microstructural changes. Multi-scale simulations taking as input for example parameters like the dislocation density or precipitates size and number are one way to get rid of phenomenological approaches and to present mechanistic approaches based on physical properties as the future of inelastic modeling. In order to develop such models and get finally access from the microscale to the macro-behavior of a component, further investigations are required and can be used for the development of new material models on a multi-scale basis.

These developments are in line with the demands given in existing drafts and codes for advanced reactor components described in section 3. The concept described in section 4 includes modern inelastic analyses and advanced fracture mechanics assessments for high temperature loading and can thus be combined with the regulations described in section 3.

An integrity concept must take into account the exact boundary conditions of the relevant components. Most important are the temperature which decides on the assessment concept which is dependent on time dependent or time independent deformation and damage behaviour. Furthermore the influence of media and radiation must be incorporated in new approaches for inelastic modelling. For the nuclear steel grades which will be used for the low temperature regime existing regulations are sufficient.

High temperature steel grades like X20 or newer martensitc steels P91, P92, austenitic or Ni based alloys (e.g. Alloy 800 H, Alloy 617) are used dependent on the design principle of the advanced reactors. For these materials data are already available to a wider extent. However, as indicated earlier, the component specific loading conditions has to be considered in the data acquisition and modelling.

Summarizing this, an integrity concept for HTR must include:

- the principles of the basic safety concept (BSC): Quality through production as basic safety and multiple parties testing, worst case, documentation and validation as independent redundancies
- established design rules for components operated at the regime of time independent behaviour
- advanced inelastic analyses, damage and failure assessment for components operated at the high temperature (time dependent) regime.

For the latter methods from the regulation described in section 3 and methods briefly outlined in section 4 can be used as parts of an appropriate concept. For the description of this time dependent behaviour additional measures have to be taken. For these additions a reliable data base on fatigue, creep and creep-fatigue loading must be available.

In this context the effect of additional degradation mechanisms such as radiation and oxidation due to helium impurities must be taken into account.

Experience from developments for fossil plants shows that a reduced ductility and deformation capability has to be taken into account. A high deformation capacity is an additional safety margin and required in the BSC. Hence, the deformation behaviour has to be investigated and taken into account in the assessment procedure. Additional fracture mechanics investigations must be included in the safety concept to ensure sufficient crack resistance in case of reduced deformation capacity of a material.

First results on new materials for HTR e.g. ODS materials investigated in the GETMAT project exhibit very low deformation capacitiy. Although they may not be used for pressure boundaries but for steam generator tubes or fuel rods this aspect has to be taken into account using experiences from investigation on the conventional high efficiency plant. For the primary pressure boundary operated in the creep regime the influence of multiaxiality on the damage development has to be taken into account.

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