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High Temperature Reactor School: Review of Metallic Materials used in HTRs

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HTR MATERIALS & TECHNOLOGIES

" HTR Metallic Materials"

REVIEW OF METALLIC MATERIALS USED IN HTRs

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Abstract

Selection and understanding of material behaviour is a vital part of the development of any advanced nuclear power plant. Not withstanding the economic considerations, there are important technical issues that need to be considered in order to ensure a viable and efficient solution has been obtained. When choosing a material for a particular purpose the designer needs to be confident about its performance and reliability in the environment that it is expected to function and under the loading conditions that are expected to occur. This is especially important for the key components and where safety and feasibility issues are uppermost. Equally critical are issues associated with the performance of the material during manufacture and the need for assurance in consistency and quality following application of the forming and/or fabrication processes used.

This lecture explores some of the important technical issues and problems associated with the "metallic materials" in the High Temperature Reactor. Metals form the majority of the components in the reactor plant (e.g. carbon steels in lightly loaded low temperature areas, low and high strength alloy steels and austenitic steels for the vessel and heat exchangers, super-alloys for the high temperature regions). The topics covered include applications, manufacture, loads, properties, rules and standards and the relative merits of some of the materials available and used in test and industrial projects considered today.

1. Introduction

Gas-cooled reactors (GCR) and especially the HTR have been developed within Europe over many decades and considerable expertise and know-how exists within the European Community countries in this technology.

Renewed interest in HTRs in Europe has returned following the development of the HTR coupled to a gas turbine power conversion system and the recent developments of the industrial prototypes GT-MHR (in Russia) and PBMR (in South Africa) which are supported by International teams with a strong European involvement.

The material selection naturally impinges on design, integrity, manufacturing, metallurgical and chemical factors. To assist in understanding the Reactor Pressure Vessel (RPV), turbine (discs & blades) and control rod have been taken as examples throughout this paper to illustrate some of the arguments and practical issues involved.

2. Issues affecting metallic material selection

This first part looks at issues affecting the selection of metallic materials these main components of the HTR.

Reactor Pressure vessel

The design pressures and internal diameters of the HTR pressure vessels fall within relatively narrow ranges. This is due to the constraints imposed by requirements for passive heat removal under loss of circulation or loss of coolant scenarios and the allowable stress levels in various design codes.

Two types of material are used for RPVs, depending on whether the temperature of the pressure boundary under normal operation or design conditions exceeds the limit for LWR pressure vessels of 370°C.

In China silicon killed C-Mn steel to ASME SA 516-70 has been specified for both the HTR-10 test reactor and a future power reactor. This material is similar to the C-Mn steels used in the UK for the construction of both steel and concrete pressure vessels in CO_2 cooled reactors of the Magnox and AGR types. Long term operating and/or design temperatures are limited to 370°C. Similar limits apply to the SA 508 forgings used widely in LWR pressure vessels and proposed for pebble bed reactors of approximately 300MW_{th} in both South Africa (PBMR) and the Japan (HTR-GT 300). It should be noted that the SA 508 specification covers a number of grades, some of which are not suitable for pressure vessels. In terms of the current designations in ASME specifications 'SA 508 type' material is taken hereafter to mean SA 508 Grade 3 Class 1 or the equivalent material in plate form SA 533 Type B Class 1. Equivalent European designations are 20MnMoNi 5 5 (Germany) and 15MND 5 or 18MND 5 (France). Except for HTR-10 the above systems have core inlet gas temperatures close to 550°C so the integrity of the RPV depends on the performance of insulation in the form of fibre blanket and/or stagnant layers of He.

For the HTTR test reactor and larger power reactors of 450-600 MW_{th} the RPV temperature is close to the core inlet temperature due to the passage of inlet (or intermediate) temperature helium to cool the inside surface of the vessel. Vessel temperatures are in the range 395-460°C under normal operating conditions. The HTTR inlet temperature of 400°C allows the use of 2¼ Cr 1Mo steel with a margin of approximately 25% on allowable stress and approximately 40°C on temperature. Modified 9Cr 1Mo steel has been specified for both large and small reactors with the beltline region of the vessel running at the core inlet temperature. This material is not yet qualified for pressure vessel use according to most design codes. The RCC-MR design rules for steam generator tube material in modified 9Cr 1Mo steel were extended during the European Fast Reactor (EFR) project to cover its use for tube-plates, shells and hemispherical ends in steam generators with outlet steam temperatures near 500°C.

High Tempertaure areas – reactor inernals

For the HTR primary circuit components metallic and ceramic materials are possible. Some data exist on such materials but the information and experience for the HTR environment are not well established. The materials for the control rod for example are required to be stable at very high temperatures and property information is needed (900^{o}C) in the post-irradiated condition and in a helium atmosphere. Loss of creep ductility due to irradiation induced damage in helium is an important property. The current design of control rod in the HTTR uses a metallic design made from Hastalloy 800.

High temperature areas – Turbine

Candidate alloys for the disc must have a sound industrial base and be capable of production of large defect free ingots with good forging properties and proven thermal stability. Ni based super-alloys are often considered for the case of industrial gas turbines. For the turbine blade, failure modes such as creep rupture strength, high cycle fatigue and low cycle fatigue have to be considered. Corrosion can cause a significant shortening of material creep life and acceleration of creep crack growth rates.

For the turbine components, especially the turbine discs and blades, the criteria for material selection are based on a safe operation period of 60,000 h at 3000 r.p.m. (50 Hz), with upper temperature limits in the range 850 to 950^{o}C. The main material considerations are those concerned with creep and environment. Two basic requirements dictate the design of gas turbine blades and discs, the cycle temperature and the maintenance of critical dimensions (clearances) throughout the service life. For turbine discs it is necessary to limit the permanent growth and distortion to within typical design life targets. This is usually achieved by maintaining a greater part of the disc cross section within elastic limits. Critical regions for the disc from the point of view of potential creep and fatigue failure are invariably the hottest parts. These are at the disc neck because of unrelieved high localised stresses giving rise to undetected growth, and at the rim due to the additional geometric effects of the blade root slots and possibly cooling holes. Careful material selection or control of localised stress and temperature conditions can avoid creep-fatigue interaction problems in these areas.

The selection of turbine blade designs is limited by the high temperature creep properties of the material (i.e. non-cooled blade). For the turbine blades gas radial temperature variation often peaks typically in the middle third of the blade with steep temperature gradients across the blade section which vary according to the transient and steady state conditions. All regions of the blade profile therefore undergo complex stress-strain cycling with reversed plasticity in some areas. For material selection a close understanding of some important parameters such as creep rupture, creep ductility and creep rate are needed. Typically for nickel based super-alloys time dependent effects induced by creep and oxidation on cyclic crack growth rates are important for design, and hence an understanding of creep crack growth behaviour and the interaction between creep and fatigue with tensile and compressive dwells is needed. The awareness of the role of grain boundaries in high temperature fracture has also led to significant developments in single crystal super-alloys that can give beneficial an-isotropic material properties. However for the HTR turbine blades such advanced blades are not thought to be necessary.

3. Manufacturing

Manufacturing considerations for steels for reactor applications involves a range of processes and activities. These may include for example:

- casting;
- forging/rolling/extrusion;
- semi-finished products – forgings, plates, tubes/pipes & welding filler metals/electrodes;
- vessel manufacture – cold/hot forming, welding;
- post weld heat treatment;
- inspection & testing;
- pre-service inspection.

In order to provide the necessary assurance and component integrity, manufacturing is usually done in accordance with a recognised and accepted design and construction code that anticipates the rigours of the operational requirements. Such codes and standards require the use of carefully specified and tested best quality materials, fabrication using well tried and tested procedures (such as proven welding practices), a comprehensive quality assurance programme, with an extensive but efficient inspection during fabrication and the effectiveness of any confirmatory testing that may be required.

The following summarises the manufacturing considerations issues for the HTR RPV. The cases for the cooled and the uncooled vessel options are summarised.

Manufacturing considerations for the vessel

Manufacturing standards for pressure vessels cover the following:

base materials;
manufacturing processes other than welding;
rules for welding.

Manufacturing requirements need to include provision of procurement specifications, forming facilities and forming procedures for heavy plates.

The technology developed for building PWR vessels (and materials) from heavy section ring forgings provides a sound basis for ‘cold’ vessel manufacture covering:

- procurement specifications for forgings;

- welding procedures and filler metal selection;
- manufacturing sequences including weld examinations and post weld heat treatment.

HTR vessel wall thicknesses are within the PWR range but the diameters of HTR vessels (6-8.5 m) are much greater than for PWR (up to 4.5m). If the PWR technology is used for HTR there is a need to establish a manufacturing capability able to produce forged parts of the required dimensions and having the required mechanical properties. If this should not be possible, the vessel may have to be manufactured from formed plates, which will have implications for both design and manufacturing, the most important design consideration being the introduction of axial welds with higher cross-weld stresses.

For the HTR there is also a requirement for on-site welding and post weld heat treatment (PWHT) of the Reactor Vessel-Cross Vessel- PCS Vessel assembly (which does not arise in PWR manufacture). For such a need it may be necessary to develop either a validated local heat treatment procedure, or a site heat treatment facility that can accommodate the whole Reactor Vessel-Cross Vessel- PCS Vessel assembly. This consideration also applies to ‘warm’ vessels.

For use of 2 ¼ Cr 1Mo steel, the material used for HTTR, manufacturing experience exists in Europe for one grade and it can be extended to other grades. Appropriate filler metals also exist but the properties of welded joints require evaluation. Russian experience of WWER-1000 vessel manufacture in 2 ¼Cr-Ni-Mo-V steel is also relevant. The PWHT temperature for 2 ¼ Cr 1Mo steel is 630-660°C compared with 620°C for Mn-Ni-Mo steel. This difference may be significant particularly in the case of a site PWHT facility.

For modified 9Cr 1Mo steel the above noted manufacturing problems introduce greater difficulties.

- A lower limit on the mass of single cast or ingot for high Cr steel compared with 2 ¼ Cr 1Mo steel.
- Difficulties in selecting filler metals to achieve the required levels of resistance to cracking, high toughness at 0°C and creep strength.
- A much higher PWHT temperature (>750°C) compared with 2 ¼ Cr 1Mo steel (630-660°C). Local heat treatment at >750°C of welds in the RPV/cross vessel assembly would be particularly difficult to validate.
- The design temperature of the PCS vessel for GT-MHR is 150°C compared with 440°C for the RPV and cross-vessel. It is possible therefore to specify C-Mn, Mn-Ni-Mo or 2 ¼ Cr 1Mo steel for the PCS vessel. A transition joint between modified 9Cr 1Mo steel and any one of the other candidate material types would involve a mismatch of 100-150°C in their PWHT temperatures.

Properties of vessel welded joints

For the Mn-Ni-Mo steel welds in ‘cold’ vessels, PWR experience provides filler metals and welding procedures giving toughness properties well matched to the base material. Because some transients may involve temperatures in the creep regime, cross weld creep tests may be required to determine whether reduction factors need to be applied to the relatively short time-high temperature design data appropriate to the assessment of transients.

For ‘warm’ vessels, the start of life toughness of the 2 ¼ Cr 1Mo steel HAZ and weld metal match that of the base material. The same is true for the HAZ of modified 9Cr 1Mo steel but adequate weld metal toughness depends on filler metal selection.

Values of strength reduction factor for welds for modified 9Cr 1Mo steel with matching filler metal are controlled by the strength of the HAZ. In tensile and short term cross weld creep tests at lower temperatures the coarse grained HAZ controls failure. In long term tests at higher temperatures cross weld strength is limited by higher creep rates in the fine grained ‘intercritically annealed’ HAZ leading to cavitation and ‘Type IV ‘ cracking. Such cracking has been observed at 600°C and 650°C but not in tests at 550°C extending to 20000h.

A large programme of short and long term cross weld tests would be required to provide full coverage in design codes at temperatures of 400-550°C for both 2 ¼ Cr 1Mo and modified 9Cr 1Mo steel. A set of more restricted requirements for ‘warm’ HTR vessels is also possible incorporating cross weld creep tests at 400-450°C, long-term creep tests at 400-500°C on modified 9Cr 1Mo steel and assessment of collected data to establish short-term values, at temperatures up to 550°C.

Manufacturing considerations for higher temperature areas (e.g turbine, control rod)

Components such as Turbine discs and blades require the use of Ni or Fe based super alloys in order to have adequate operating integrity. The Manufacturing processes for such specialised materials requires the use of different manufacturing techniques and approaches compared with those of the majority of the steel structures. These may include for example:

- casting;
- directionally solidified products;
- single crystals;
- oxide dispersion strengthened products;
- powder metallurgy;
- Hot Isostatic Pressing of Cast alloy.

The manufacturing route and capability has a direct bearing on the material selection and strength. For the turbine disc for example there is a requirement to produce large ingots without porosity and segregation. Such a process requires the production of around 10 ton ingots with subsequent forging. For aero-engines the manufacturing route includes re-melting technology (vacuum induction melting, vacuum arc re-melting, electro-slag re-melting) in order to produce large diameters however current alloys discs produced in this way have reached the limit of their performance.

Powder metallurgy offers a route for high quality ingots to be produced. The possibility of producing near-shaped large diameter discs using Hot Isostatic Pressing (HIPping) seems more promising, following the availability of large diameter hipping furnaces. Subsequent heat treatments are shown to have a significant effect on the high temperature strength properties. The future possibility of a bonded disc produced in this way should also not be discounted. HIPping produces materials with design properties different from those of the corresponding forged or cast alloy.

With respect to the manufacture of blades, single crystals offer the highest creep properties but their cost is high, properties can be an-isotropic and they cannot be easily repaired if damaged. Directionally solidified blades are good candidates for non-cooled blades. They offer improved creep properties compared with conventionally cast versions, better repair possibilities and their experience in industrial land-based gas turbines is more extensive. Conventionally cast grades are easy to procure, have extensive industrial experience and the fabrication of HTR blades should be possible. However, the major limitation is the modest creep strength at 850°C.

For the manufacture of a component using an ODS alloy, active co-operation with a producer of the alloy is necessary. It is possible to produce a material that has design material properties quite different from those of the matrix alloy.

Use of Intermetallics offers a further potential process for turbine blade manufacture. Such materials (e.g. NiAl) look promising for very high temperatures. They surpass superalloys in terms of melting temperatures, density, thermal conductivity and oxidation resistance but their ductility, shear strength and hot corrosion resistance is low. The strength potential is still unclear. Other potential materials and processes include thermal barrier coatings, Ceramics (Silicon Nitrite and Silicon Carbide) and fibre reinforced ceramics. Ceramics seem to be limited to temperatures of 1300^{o}C because of oxidation resistance and strength. Fibre reinforced ceramics offer an improved toughness (e.g in the case of SiC) but the temperature capability is not extended.

The application of processes proven to be sound in many industrial applications, e.g. industrial gas turbines, may not be subject to the same controls and specification restrictions associated with nuclear applications. Hence there are often no established design code practice or approved code manufacturing specifications from which to base an assurance of integrity and quality of the finished product or part. Such processes therefore will probably require additional considerations when applied in nuclear plant (e.g. gas turbine within a direct cycle HTR).

4. Loads

The Loads considered for assessment and evaluation of materials for HTR application are those for normal operation (steady state & transient), emergency loads (events not expected within the component lifetime) for which the component will need to retain its function during and after the event (e.g seismic) and beyond design events. This latter category is to provide assurance of retention of structure against low probability events.

Such loads when applied to materials give rise to stresses and strains at every point in the components. Distributions of stress and strain are often complex and are simplified for analysis purposes into (sectional) parts, i.e membrane (average through section), bending (through a section) and peak (reminder - local stress at a point). These terms sectional stresses are interpreted from component disrtibutions or equivant (von mises or Tresca) distributions.

Loads are interpreted for materials and assessment either as having a primary or secondary nature i.e having stress dependent or displacement dependent behaviour. Applying and removing a primary load, will increase the stress level up to a cetain value and then return it to its starting level. Primary loads can be caused by pressure, weight, force, moment. For secondary loads which are displacement dependent (e.g temperature, residual stresses) their application and removal results in a change in the displacement to a particular value before returning the displacement back to its starting valiue. Application and removal of a secondary load can therefore result in a change in stress from its starting point, which is often referred to as a residual stress. Application and removal of a primary load can result in a change in extension (if above the yield stress).

Depending on the level of load applied, the material response can either be elastic or inelastic. An elastic response occurs when the resulting stresses are below the yield stress of the material at all times. For displacement controlled loadings the yield limit for the material extends over twice the material yield stress (i.e.the elastic shakedown area). An inelastic response occurs when the level of stress exceeds the material yield stress. Stress-strain material curves with cyclic hardening or cyclic softening characteristics are considered for different materials in order to assess material behaviour when this occurs.

Applied loads are often cyclic, they are usually applied and then removed some time later, and invariably result from reactor load or power changes, start-up, shut down, load following, etc. Certain loads are time-independent (the time duration over which they occur has a negligible affect on the material behaviour). Other loads are time-dependent, i.e, the time duration over which the load has been applied causes a redistribution of stresses. Time dependent loads are usually those which cause creep deformation and often result from temperature changes. Depending on the material, creep strains can occur at high temperature and/or at low temperature (cold creep).

Cyclic loads give rise to changes in stress levels that can result in premature cracking due to fatigue (see under section on design codes). Assessment of these requires interpretation of loads in terms of stress ranges. Premature fracture can also occur if a stress at a notched (or crack) exceeds the material toughness. This involves use of fracture mechanics terms and quantities.

Pressure vessels

The main concerns for the vessel are expected to be at the welds. The welds of the HTR vessel carry an additional requirement to satisfy the safety analysis methodology and safety studies (defect location and defect size) and have to be assessed from the point of view of non-destructive examination and potential for failure or leakage.

The main damage mechanisms to be addressed are fracture, fatigue and creep-fatigue. These have to be evaluated from an initiation aspect and for crack growth of defects under fluctuating thermal and mechanical loads. The potential effects of environment (temperature, irradiation, ageing) all have to be taken into account. The important issues to address are toughness and creep behaviour under as-fabricated and simulated end-of-life conditions. This is to provide an understanding of the welding processes, weld metals and post-weld heat treatment required for thick welds and weld factors to be applied on the base material properties.

Other sensitive zones that are important are areas that feature thicker sections (potential for reduced properties and strength), hot spots and regions important from a functionality point of view. This includes the flange area and belt line which have to satisfy primary and secondary stress limit requirements and progressive deformation mechanisms.

Reactor Internal structures / turbines

For the high temperature regions of the HTR the main structural integrity issues are the consequences of creep and the influence of the environment. For turbine discs there is a requirement to limit the permanent growth and distortion to within typical design life targets. For the turbine blades failure modes such as creep, high cycle fatigue and low cycle fatigue have to be taken into account.

Corrosion can cause a significant shortening of the material creep life and acceleration of creep crack growth rates. Application of suitable coatings can arrest creep reduction tendencies, however their use requires an understanding of the potential for interfacial cracking at the coating layer to avoid the development of more significant cracking from the interface.

Thermal-mechanical assessments need to take account of rotational speeds, vibration, temperature gradients and where applicable, consider the effects of geometric concentrations and localised temperature gradients. For the discs 2-D investigations can be sufficient whereas significant stresses in the transverse plane can necessitate 3-D studies for blades.

5. Properties

The need for reliable material data and properties is a key issue in the development of HTR technology. In addition to applied load, information on material behaviour is needed in order to make reliable judgements on the suitability of a particular steel for a specific application or situation. The propety data needed includes physical as well as strength properties and where applicable certain analysis properties which often closely relate to specific codes and standards procedures. For the HTR key components therefore a materials database of properties are required that covers information on manufacturing provisions, products & parts, test data information and design properties.

Typical properties needed for investigation and confirmation of material suitability in an HTR application are given in Table 1. For the reactor components such properties are often obtainable from appendices or specific volumes of Design Codes (e.g ASME, RCC-MR). Where information is lacking, this can be requested through specialist material organisations or obtained from specific R & D actions. For the Power Conversion Unit materials, especially the turbine and its related components, (e.g Ni based or Fe based superalloys) material property information can be obtained from open literature or specialist component organisations or in some cases directly from turbine materials organisations or manufacturers.

Table 1. List of typical material property data

Physical properties
Thermal expansion coefficient
Youngs' Modulus
Thermal conductivity, etc….
Strength properties - Base Material (Sheets, Forgings, ..)
Yield Strength 0.2% Offset
Tensile Strength
Elongation after fracture (A5)
Reduction of Area after Fracture

Design Stress Limit Sy
Design Stress Limit Su
....
Creep Strength 10 000 h, 100,000h
Low cycle Fatigue (10^4 cyc)
High cycle Fatigue (10^9 cyc)
....
Impact Toughness (Charpy-V-Specimen)
Fracture Mechanic Properties
K1c (specimen, conditions etc....)
Analysis properties
Symmetrisation coefficient
Factors relating to cyclic curves
Factors for welds
Creep strain law
Properties under environmental condition
Creep-fatigue interaction diagram
Factors for irradiation, for corrosion
Impact Toughness (Charpy-V-Specimen)
Fracture Mechanic Properties

6. Codes & Standards

Codes & Standards play a major role in ensuring a consistent engineering approach and quality during the design and construction of phases of power plant. They provide the design criteria and design procedures necessary for performing structural integrity assessments and meeting licensing requirements. The procedures have been developed from insight into the different failure processes, past experience in plant operation and reliability and applicable research and development on the materials, environments and loading being considered. The Design Codes are supported by analysis and experience in the areas they apply and are used to demonstrate the quality of design, manufacture, inspection and construction. In principle codes from any source can be used however it is usually easier to justify those that are familiar to the host licensing authority and directly relevant to the reactor type or situation. Figure 1 lists some of the design codes used and their temperature of application.

Design Codes provide a link between safety class and design class and provide a framework through which different operating conditions and occurrences can be assessed against recognised failure criteria. Four relevant failure mechanisms for HTR are summarised below. These are not exhaustive but provide an indication of some of the structural integrity issues that need to be considered.

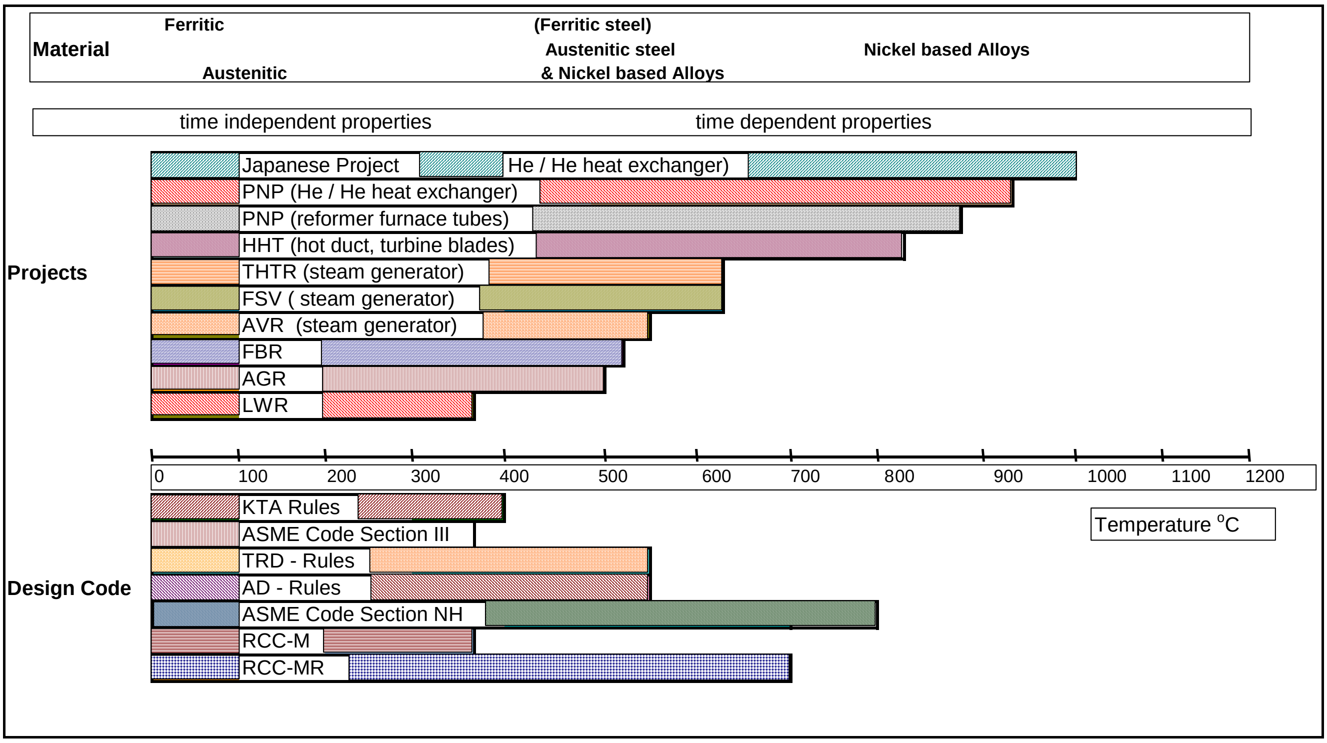


Figure 1 Materials Temperature Versus Design Code Temperatures

Excessive deformation and plastic instability

Excessive deformation and plastic instability are local effects that can occur under single or repeated loading causing irreversible permanent deformation of the structure. Retention or confinement of the plasticity by elastic regions is not achieved and the overall permanent deformation exceeds the deformation that would occur under purely elastic behaviour. The deformation or instability can occur instantaneously or in a more gradual manner (time-independent and time dependent manner).

The basic stress limits are derived using perfect plasticity with no material strain hardening. Allowable values are chosen in terms of yield stress for general primary membrane stress and membrane plus bending stress. Protection against the failure mechanisms for elastic analysis for non-creep temperatures are achieved by limiting stresses to the allowable design values within the design code used as primary stress limits with coefficients that depend upon the service level.

For ASME for example, the primary stress limits for level C and Level D service conditions are higher than the design or level A limit on the basis that some damage is acceptable against lower probability loads. Level C limits are 20% higher than level A and are chosen to allow a reduced margin but without resulting in gross loss of structural integrity. The Level C limit restricts the stresses to those that the vessel would be subjected to under hydrostatic pressure testing without significant deformation. Level D limits permit the loads to reach 70% of those that would result in gross failure. In the ASME Code the non-mandatory Appendix F provides the rules for evaluation of service loads with level D service limits. Special stress limits are also provided (NB-3227) to cover special service loads or configurations (bearing loads, pure shear, transitions between nozzle and piping, etc.) which are more or less restrictive than the basic limits.

In addition to elastic analysis the acceptance criteria at levels A,C & D can be met using limit analysis, experimental analysis and plastic analysis.

Ratcheting

Under certain combinations of steady and cyclic primary and secondary (i.e. pressure and thermal) loads there is a possibility of large distortions developing as a result of a ratchet action. Ratcheting or progressive deformation occurs when there is a continued repeated accumulation of plastic strains per cycle and the loading does not settle down into elastic action. The result is the structure becoming dimensionally unstable. Ratcheting can be avoided by ensuring an absence of cyclic plasticity after the first few cycles. This is achieved by limiting the combination of primary and secondary stresses and ensuring the structure shakes down.

Theoretically the shakedown limit can be predicted by application of Melan's shakedown theorem but this is seldom used in design. A simplified approach is to allow a primary plus secondary stress intensity up to twice the yield stress. Such an approach is used in the ASME Code where prevention of ratcheting is in the form of a $3S_m$ check and an interaction diagram.

If this limit is exceeded because of thermal bending the analysis may be continued based on a simplified elastic-plastic method provided in the form of an interaction (BREE) diagram developed for the case of a cylindrical shell subject to pressure and superimposed cyclic through wall temperature gradient. The diagram is used in conjunction with judgements on stress classification and provides a check on the deformation behaviour by categorising it into one of four types of behaviour: elastic regime, shakedown regime, cyclic plasticity regime and ratcheting regime. The boundaries for each one of these regimes are defined according to the ratios of primary and secondary load to the material yield stress.

The code also recommends the use of the fatigue endurance limit (i.e 2x limit at 10^6 cycles) where this is lower than the yield stress, if there are large numbers of cycles involved, to guard against the onset of strain softening.

Other procedures exist for example in the UK, developed for prevention of ratcheting due to accumulation of plasticity and creep that allow the use of simplified tools. These consist of the "shakedown method" and interaction diagram method. The latter is similar in form to the ASME interaction diagram approach and covers specific geometries and a wider range of loads (axisymmetric with both through wall and axial temperature gradients). The Shakedown Method is a general purpose tool covering all loads and has been applied to a wide range of geometries including structures with geometric features, piping and tube plates. This method is used as a design tool and employed within the UK R5 assessment code for application to UK Advance Gas Cooled Reactors.

By meeting the code requirements, the following are assured:

- satisfaction of the shakedown or elastic regime to ensure an absence of cyclic plasticity after the first few cycles;
- applicability of conventional fatigue data;

- that the structure remains dimensionally stable.

Fatigue

Structures that are subject to cyclic loads may be prone to damage due to fatigue leading to cracking from a localised point. Assessment of the stresses at all points in the structure is therefore required to ensure cracking does not occur. This is done using the fatigue assessment procedures in design codes and may be carried out using elastic or inelastic methods. Procedures can differ within codes and between codes, they can either be based localised elastic stress quantities (e.g. ASME, RCC-M, KTA) or localised strain quantities (e.g. RCC-MR). They also may differ within a particular design code depending for example on whether the temperature is below or within the creep regime (e.g. ASME section NB, ASME Section NH).

The procedure of the ASME Code section NB uses the localised elastic stresses to calculate alternating stress intensity differences based on the Tresca failure criterion between two extremes in the loading cycle. The alternating stress intensity S_{alt} is one half of the largest magnitude of the stress differences. This is then used against the design fatigue curve for the material to obtain an allowable number of cycles for comparison with the design requirement to assess the margin. The number of cycles divided by the allowable number of cycles from the design fatigue curve should be less than unity. In many cases the point on the structure will be subjected to a variety of stress cycles during its lifetime, having amplitudes of varying magnitude. The cumulative effect of these variations is evaluated using a linear damage relationship (Miner's Rule) in which the cumulative fractions of numbers of cycles divided by allowable number of cycles from the design fatigue curve should not exceed unity. The procedures include design fatigue curves for Carbon and low alloy steels, austenitic steels and nickel alloys. The design fatigue curves allow for assessment beyond 10^6 cycles (up to 10^{11} cycles) and include adjustment for mean stress effects. These adjustments can also be used to assess the effects of the presence of a localised residual stress such as occurs in a weld.

For cases where the $3S_m$ limitation on primary plus secondary stress is exceeded a procedure is given for adjusting the elastic stress intensity range by a peak strain concentration factor K_e defined according to the magnitude of the range and material parameters. Use of the K_e factor drastically reduces the allowable number fatigue cycles, when it is used. There are differences in the derivation of this factor between ASME and other European codes (RCC-M, KTA) where justification for a less conservative K_e factors derived using alternative procedures have been made.

RCC-MR uses a procedure based on strain quantities. A usage fraction is determined from the elastic-plastic Von Mises equivalent strain range $\overline{\Delta\varepsilon_{ep}}$ and from the allowable number of cycles N_f which is obtained from the continuous design fatigue curves. For evaluation using elastic analysis the response of the structure is elastic and linear and a correction is needed to allow for the effects of plasticity in order to estimate the elastic-plastic equivalent strain range which is evaluated from the range of the elastically calculated local stress. The main parts of the procedure include:

- calculation of $\overline{\Delta\varepsilon_1}$ the elastically calculated strain range taking account of any local stress concentrating event;

- calculation of the plastic increase in strain due to an applied primary stress range at the point being examined;

- calculation of the plastic increase in strains due to triaxiality and from the intersection of the cyclic curve and the hyperbolic $\overline{\Delta\sigma}\,.\,\overline{\Delta\varepsilon_3} = \text{constant},$ curve.

In the case of assessment of fatigue damage using elastic-plastic analysis, the fatigue usage fraction for a complete load cycle is determined from the variation of strain components deduced from an elastic-plastic calculation of the load cycle. A value of $\overline{\Delta\varepsilon}$ is obtained from each of the strain sub-cycles, which combine together to form the complete load cycle. The fatigue usage fraction is deduced for each sub-cycle from the design fatigue curves and summed together for the complete fatigue usage fraction.

For a fuller description of these procedures see the relevant Design Code documents.

Creep

Structural components in high temperature plant are subjected to thermal cycling under normal operating conditions. These thermal transients can lead to cyclic loading by direct thermal shock and displacement controlled bending produced by constrained differential expansion. This can occur during heat up and cool down cycles (fatigue) with creep occurring during steady state operation. The requirement is that the structures should be designed against the possibility of either mechanism or both. The above section deals with the procedures for fatigue. This section considers the additional procedures for creep and creep-fatigue (fatigue with hold time effects).

Creep is a time dependent damage mechanism imposed on the material usually as a result of temperature. It can occur at elevated temperatures (typically above 370^{o}C for ferritic steels) or low temperature (below 150^{o}C for austenitic steels) when it is known as cold creep. Creep can cause creep deformation (strain) and creep rupture (failure). It is usually assumed to be associated with the formation and linkage of cavities or voids which form on the grain boundaries of some materials. There is some considerable scientific evidence to relate the growth of cavities to the accumulated strain in the material for the strain rates that occur in high temperature plant.

For some materials, e.g. stainless steels, the formation and growth of cavities is assisted by the presence of helium formed during neutron irradiation. The presence of the helium in the irradiated steel is taken into account by its effect in reducing the minimum ductility. For other materials, UK 9Cr 1 Mo steel for example, experimental evidence suggests that this material does not cavitate.

Many design codes use a time fraction approach to evaluate creep damage and procedures for preventing significant creep damage or interaction are introduced either as an extension (e.g. significant creep part in RCC-MR) or as a completely separate section or Code case (Section NH in ASME). Where applicable, additional checks are made against effects of creep for all the considered damage mechanisms (i.e. excessive deformation, ratcheting, creep-fatigue) and can involve the use of an interaction diagram (e.g. significant creep diagram, Creep Fatigue Interaction diagram of RCC-MR) to assess its significance.

As an example the following summarises the additional provisions used to allow for the effects of creep on fatigue damage within the RCC-MR Code.

For loading cycles at elevated temperatures where the effects of creep are significant, time effects are included by:

- the addition of a creep strain term $\overline{\Delta\varepsilon_c}$ to the equivalent elasto-plastic strain range $\overline{\Delta\varepsilon_{ep}}$ to evaluate the fatigue usage fraction, i.e.: $\overline{\Delta\varepsilon} = \overline{\Delta\varepsilon_{ep}} + \Delta\varepsilon_c$ - (creep/fatigue);

- considering the creep rupture usage fraction W derived from the minimum stress to rupture curves (denoted S_r) versus time to rupture T_r and a stress $\frac{\sigma_k}{0.9}$ - (creep rupture).

Buckling

Buckling or structural instability under compressive loads induces damage such as elastic-plastic instability or excessive deformation and can result in increased risks of fatigue damage or progressive deformation. Buckling may be accelerated or amplified due to the presence of geometrical imperfections permitted within manufacturing tolerances. Load controlled buckling occurs when the imposed loads are not reduced by the resulting deformations and continued application leads to failure or collapse. Strain controlled buckling occurs when the loads are insufficient by themselves to produce the buckling deformation and the load reduces upon initiation of buckling. Even though strain controlled buckling is self limiting it must be avoided to guard against fatigue failure, excessive strain and interaction with load-controlled instability. Buckling analysis requires the consideration of the large displacement response (elastic and elastic-plastic) of the structure and material behaviour. Important considerations are the use of unfavourable assumptions concerning geometric imperfections, determination of bi-furcation modes, use of parametric studies to test sensitivities, superposition of and realistic assumptions for loads and boundary conditions (dynamic and static loads). Buckling is a potential failure mode for components that feature thin walled sections.

Rules for the prevention of buckling are provided in the design codes in terms of acceptance criteria and design by analysis (elastic and in-elastic) rules for monotonic and cyclic loads.

The rules and limits provided in the ASME Code for example are conservative but applicable to specific geometrical configurations under specified loading conditions. (i.e. column mode buckling). ASME provides charts for determining allowable stresses for design for spherical and cylindrical shells and tubes with and without stiffeners loaded by external pressure. The charts include the effects of initial imperfections where appropriate and the effects of temperature on the short-time stress strain curve. Level C limits allow the permissible external pressure to be increased by a factor of 1.2 and testing limits by a factor of 1.35. Level D criteria limits use a factor of 1.5 or limit the maximum compressive load (or stress) to: 2/3rds of the buckling load (or stress) obtained by detailed analysis (i.e. including the effects of geometric imperfections, other loads, residual stresses, etc.) or testing on representative models.

More detailed criteria are contained in ASME Code Section NH applicable to time-independent and time dependent buckling, the latter referring to elevated temperature operation. The factors are provided for load controlled and strain controlled buckling. Where elastic follow-up is possible the load controlled factors are also used for strain controlled behaviour. For load controlled buckling the effects of initial geometry imperfections should be taken into account, whether present initially or induced in service. For strain controlled buckling they need not be considered except where creep is present. In some codes, procedures replace the charts. For example German procedures applied in the early stages of design requires calculation of the elastic bi-furcation buckling load that take into account plastic material behaviour and use knock-down factors dependent on geometry and type of loading (including imperfections). The procedures when applied to shells (vessel) are consistent with section NF of the ASME Code.

Welds

Welds are a major concern in structures because:

- they are frequently the site of damage found in plant;
- they are often associated with geometrical discontinuities;
- they can result in a 'metallurgical notch' or strain concentration due to discontinuities in the properties of the weld;
- at elevated temperature stainless steel welds often have a lower creep ductility in comparison with the parent steel;
- and they frequently have to be made without stress relief, thus containing significant residual stress.

A significant proportion of the design rules are concerned with weld materials, design at welds, fabrication of welds and inspection of welds. However the analysis requirements for weld regions are minimal and the weld region is modelled as an extension of the base material with identical properties. The Attitude of the Code Rules towards weldments stems from the belief that although weld regions are not the same as base material, they can be made as strong as a base metal by means of proper control of fabrication, materials and processes and that bend tests will assure that the actual welds will have the necessary ductility in the weld region. With these controls on fabrication and materials, weld regions have been considered at least as strong as the base metal in some codes (e.g. ASME, RCC-M), and can therefore be conservatively modelled as extensions of the base material. In other codes (e.g RCC-MR) a reduction factor is used to allow for effects of material discontinuity which are dependent on the material, type of weld and the welding procedures used. In general the treatment of welds in design codes under fatigue and creep loading is usually done by conservatively ignoring the beneficial increase in some properties (e.g. yield strength) and adjusting the parent plate design curves of others by a strength reduction factor (SRF) treating all other properties as if they were base material. For some codes the factor of unity is used (i.e. FSRF = 1.0 for ASME, RCC-M) for the reasons given above. For others factors to reduce allowable stress and strain quantities are used (e.g. Jf, Jr, Jt in RCC-MR).

As mentioned above the presence of welds can lead to the introduction of residual stresses, which contribute to the overall stress system. Residual stresses remain in a structure after removal of all loads and they arise because of the need for compatibility between the total strain field and the displacement field. This compatibility is achieved by additional elastic strains that result in elastic stresses. Residual stresses are often difficult to evaluate analytically because of the lack of precise information on the stress cycles imposed. Residual stresses in welds may in some cases reach yield stress and can result in a reduction in fatigue strength and premature failure of a structural part. A typical residual stress field for thin plates with a weld longer than 450 mm is shown in Fig 2. For low carbon steels the maximum tensile stress is often of the order of yield stress of the weld metal but for high strength steels such as austenitic steels stresses can be considerably lower than the yield stress.

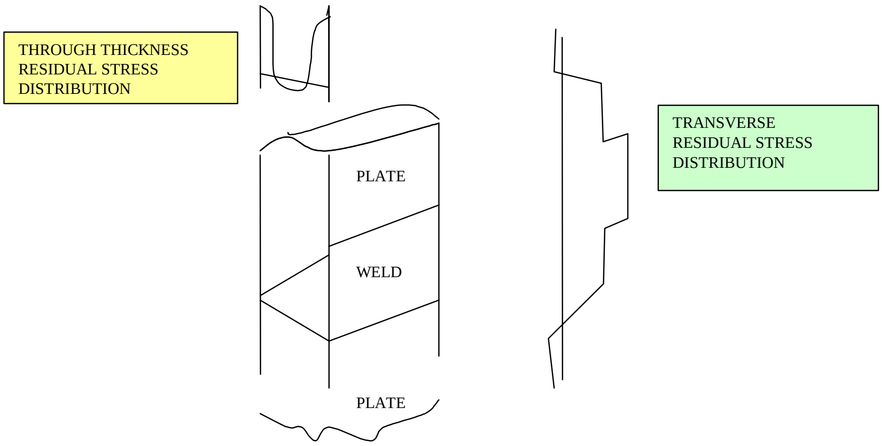


FIGURE 2 TYPICAL RESIDUAL STRESS DISTRIBUTION

Design Margins

Design margins are introduced on material property parameters in order to ensure as far as practical that there are no unforeseen failures due to foreseen or unforeseen events. The ASME fatigue design curves, for example, uses best fit failure fatigue curves derived from low cycle fatigue tests. The design curves were obtained by lowering the adjusted best-fit curves by a factor of 2 on stress or 20 on cycles, whichever gives the lower curve. The design factor of 20 was intended to cover data scatter (x 2) size effects (x 2.5) and surface finish/atmosphere etc. (x 4). Size effect can occur because of loading configuration (e.g. stress variation can be more important for small thickness than larger ones), a statistical effect caused by the probability of the presence of a defect and/or a technological effect (differences in manufacture between large and small components). Poor surface finish also leads to early crack initiation as can environmental effects (stress corrosion) which can also produce accelerated crack growth. Investigations on the suitability of the design factors have been made with a view to reducing them where they appear over conservative. In Western codes so far changes to these design margins have been resisted. In Russian codes lower margins are used where safety considerations are less important. The equivalent Russian margins on fatigue curves are 2 on stress and 10 on cycles. However for cases where thermal loads prevail, for example, strains are restricted by the elastic parts, loss of reactor coolant cannot occur and the factors are reduced to 1.5 on stress and 3 on cycles.

Piping

Procedures are available to determine permissible levels of internal pressure for different service levels and allowable stresses for straight pipes and elbows based on the combined membrane plus bending stress levels. Limits are also given for external pressure, ratcheting and fatigue. The criteria for progressive deformation limits the primary plus secondary stress intensity range to 3 Sm and provides for elastic and simplified elastic plastic analysis using primary and secondary stress indices. The rules for prevention of fatigue damage consider the combined mechanical plus thermal stresses including the non linear through wall gradient.

Curved pipes or elbows in bending are more flexible than the equivalent solid curved beams due to ovalisation of the cross section (Von Karman effect) hence additional flexibility factors are included in the analysis of the piping system. These flexibility factors are derived from more detailed analysis. The extra flexibility is gained at the expense of higher stress therefore appropriate stress intensification factors or stress indices are also used.

For some codes the treatment of thermal effects is included in the formulations for progressive deformation and fatigue. Axial temperature changes are considered for structural or material discontinuities over a distance.

Elastic follow-up is of special concern where this can cause premature failure. This is when thermal loads and geometry are such that they cause the pipe to behave as if the load was applied as a primary load.

In-service inspection

Some countries inspection programs (Spain, India, Italy) are based on those of the NSSS supplier whereas others (Belgium, Finland, Switzerland, Sweden) who are also importers, have formulated their own regulatory requirements but are largely based on those existing in vendors countries. Countries such as France and Germany in the EU and Japan have developed their own ISI standards. They share common points with the US Standards but are sufficiently distinct to be treated separately. The way in which they are applied can also vary from country to country. In many countries however the ASME Section XI is used as a guideline. Note that it is left to the discretion of the Regulatory Authority to choose the code on a case by case basis and the extent to which the ASME Section XI should be followed.

The following section summarises some of the guidelines available in the ASME XI code.

The requirements of ASME Section XI place the responsibility for component categorisation for ISI/IST on the owner of the plant. Components are generally categorised for ISI/IST on the basis of the Section III Code Class for their construction.

Examinations are performed on a sampling basis and usually limited to areas of weldments. The exceptions to this are the Reactor Pressure Vessel and some acknowledged problem areas such as nozzle corners. Consideration is given to the practicality of including the required examinations and exposure to radiation within the time available during the normal refueling shutdown periods plus a major shutdown inspection every 10 years.

Components are placed in one or more of seven categories. Pre-service inspection requires 100% inspection of pressure retaining welds in all class 1 components (not exempt by the rules). Shop and field examinations may serve in lieu of the on-site pre-inspection provided that for vessels, the examination is performed after the hydrostatic test (of section III) and such examinations are carried out under conditions equivalent to those expected to be employed under subsequent ISI examinations.

For Class 1 pressure retaining components the inspection schedule may be to either of two inspection programs and the inspection intervals may be increased or decreased by as much as a year to enable an inspection to coincide with a plant outage. Examination sequences established in the first inspection are repeated in subsequent ones where practical and where a component has been accepted for continued service by analytical evaluation, the area containing the flaws must be re-examined during the next three inspection periods. When examinations reveal flaws in excess of the acceptance standards, the inspections during outages are extended to cover an additional number of welds and areas equal to the number scheduled in the current inspection (i.e. 100% increase). The additional examinations are selected from similar welds and areas in the component. If these reveal flaws, then the inspection is extended further to cover all the remaining similar areas or welds.

Acceptance standards for pre-service examinations are evaluated by comparison with tabulated code quantities, except where flaws meet the non-destructive examination requirements. For cases of repair, the repaired flaw must meet acceptance standards prior to its placement in service.

The recommended procedures for analytical evaluation of flaws is expressed in terms of stress intensity factor or fracture toughness for normal, faulted and Emergency conditions. For the vessel the margins on flaw size and toughness under normal operation are 10 (on K_{1c},fracture toughness based on crack initiation) and $\sqrt{10}$ (on K_{1a},fracture toughness based on crack arrest). A safety factor of 3 is used for material toughness and LEFM (Linear Elastic Fracture Mechanics) principles are used to determine an equivalent safety factor on flaw size.

Future developments on ISI procedures in Europe are aimed at flaw evaluation procedures (i.e. use of elastic-plastic fracture mechanics procedures) and establishing a consistency across Europe following the CEN and European directives.

Environment

Protection against the effect of the environment (e.g. corrosion and irradiation) is usually the responsibility of the designer, but often there are no formal provisions given to show the designer how it should be done. Fatigue curves for example are usually derived in air but often there are no additional rules or guidance on how to compensate for the effect of a different environment (e.g helium). Certain procedures are available in Russian Codes which do allow designers to incorporate certain environmental effects into their fatigue curves (water corrosion, irradiation), but these are new and not generally available in other codes. The next section deals with the environmental issues with respect to HTR in more detail.

7. Environment

Helium

Design codes usually instruct the designer to take into consideration the effects of corrosion without specifying in detail how this should be done.

In practice two measures are usually adopted:

- an allowance for metal losses over its lifetime is added to the minimum design thickness of a pressure vessel;
- fatigue and creep-fatigue damage calculations made with design data include allowances for data scatter, ‘mild’ (oxidising) environments and the characteristics of typical pressure vessel surfaces. Additional margins are necessary only where the environment has different and/or more severe effects on fatigue and creep e.g. by carburising exposed surfaces or by producing intergranular oxidation to a significant depth.

The helium coolant gas used in an HTR contains small levels of impurities (H_2, H_2O, CO, CO_2) at low partial pressures that can interact with the core graphite and metallic components and cause some loss or damage to their properties. Low concentrations of H_2O and H_2 are produced by leakage and/or desorption from both metal surfaces and graphite. CO, CO_2, and CH_4 may be produced by coolant/graphite reactions at high temperatures. Three factors are considered to influence and control the He impurity levels.

- The hydrogen and oxygen supply rates.
- The core temperature and gas residence time, the latter is usually considered to be sufficient for equilibrium to be achieved at 850 - 1000°C.
- The capacity of the gas clean-up plant.

Table 2 below gives some information on He impurity levels from various sources.

Description	Pressures in Pa				
	H_2	CO	H_2O	CO_2	CH_4
Dragon Normal maximum	1.5	0.8	0.015	0.08	0.15
Realistic Direct Cycle	3	2	0.5	-	-
Oldbury B boiler leak	50	50	5	-	5
JAERI Type B	20	10	0.1	0.2	0.5
GT-MHR normal	<35	<42	<14	<1	-
AGR	800	$4x10^4$	$1.7x10^4$	$4x10^6$	800

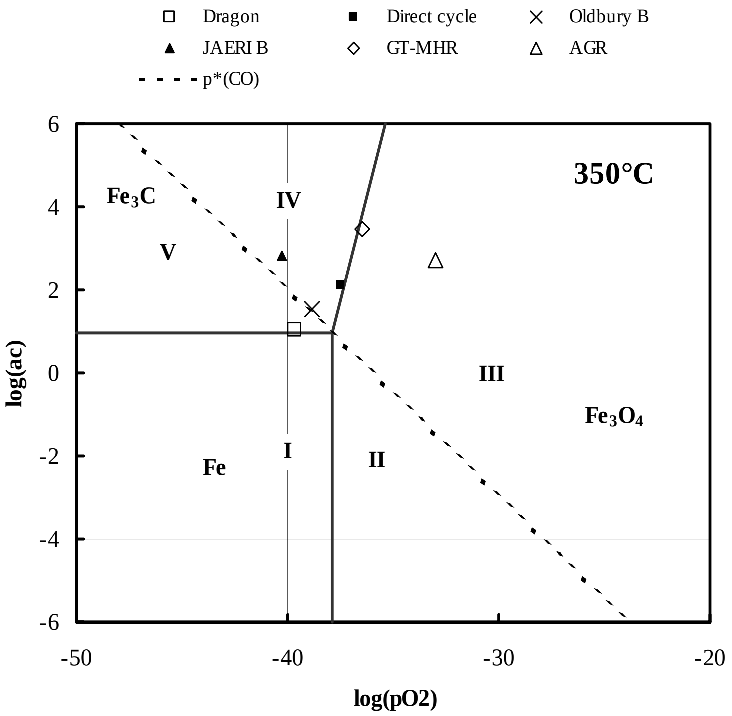
Water can oxidise some metals and in certain situations help to produce a protective layer which decreases the degradation of the underlying metal. The higher the temperature and the higher the hydrogen content, the less oxidising is the water.

Methane can decompose on metal surfaces and lead to the formation of carbides. The higher the temperature, the lower the stability of methane and the greater the carburising potential.

Carbon monoxide can decompose to cause metal oxidation and the formation of carbides and result in non-protective surface layers on the metals. The higher the temperature, the more stable the carbon monoxide and the less prone the material is to oxidise and carburise. Carbon dioxide can also be oxidising, however when the temperature exceeds 750/800°C its content becomes negligible.

Depending on the partial pressure of the impurities the resulting atmosphere can either be oxidising (high P_{o2}, low a_c) or carburising (low P_{o2}, high a_c) for the materials selected. Damage to the metallic materials may be either at the surface (formation of surface films involving oxides or carbides) or diffuse to significant depths into the metallic matrices (internal oxidation or carburisation or decarburisation) resulting in loss of mechanical properties over a significant thickness of the material. This can lead to either loss of strength or local embrittlement and favour the initiation of cracks.

For assessing the effects of environment on the structural metals, phase diagrams are used to determine the neutrality of the chemical activity and to determine whether compatibility issues are likely to have a strong impact on materials selection

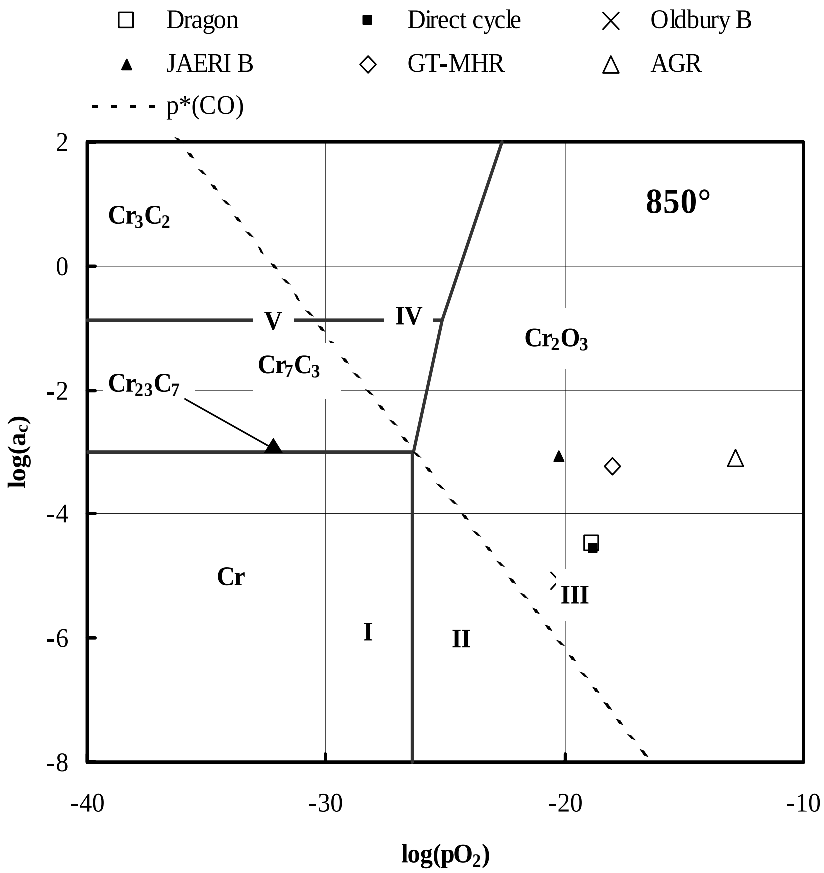


Regions I and II: Severe decarburisation
Region III: Protective oxidation plus slight carburisation
Region IV: Carburisation
Region V: Severe carburisation

Figure 3 Phase diagrams for Fe at 350°C in atmospheres containing H_2, H_2O, CO_2 and CO

As an example figure 3 above shows the stability daiagram after Quadakkers and Schuster for 350°C in atmospheres containing H_2, H_2O, CO_2 and CO applicable to the vessel steels. It should be noted that the GT-MHR composition is an upper bound to both the range of compositions allowed in the plant and the selected He compositions from Table 2. The selected He compositions are either neutral with respect to the equilibria between Fe, Fe_3C and Fe_3O_4 or well within the field where Fe is the stable phase.

For Ni based alloys such as used in turbine blades or discs a similar diagram can be constructed based on Cr. The zones for carburisation and de-carburisation and formation of protective oxidation are identified below for temperatures of 850°C (figure 4).



Regions I and II: Severe decarburisation
Region III: Protective oxidation plus slight carburisation
Region IV: Carburisation
Region V: Severe carburisation

Figure 4 Phase diagrams for Cr at 850°C in atmospheres containing H_2, H_2O, CO_2 and CO

Irradiation

Neutron irradiation can degrade the mechanical properties of metallic materials. The extent of the degradation is determined by a number of factors such as neutron fluence, irradiation temperature, neutron flux and the concentration of deleterious elements in the steel. (i.e. P, Cu in th case of a RPV steel). For certain components such as the RPV there are a number of sensitive locations (i.e. the belt-line region) where the irradiation damage could be of partticular concern. Welds too are especially important since these are potential sites for cracks or defects.

For the HTR RPV cold vessel concept such as adopted for the PBMR, material grades can be used that can take full advantage of LWR RPV technology and design rules. The effects of irradiation on the toughness of these LWR steels have been studied extensively and reviews have been undertaken as part of the work programme of the CEC supported AMES network (**A**geing, **M**aterials **E**valuation and **S**tudies). The major effect is on fracture toughness properties and an increase in the ductile brittle transition temperature DBTT (ΔDBTT) due to the combined effects of matrix hardening and grain boundary weakening associated mainly with the residual elements P and Cu. Neutron irradiation has the effect of displacing the Charpy toughness curve to higher temperatures, and by specifying the transition temperature at a given energy level, the 'shift in transition temperature' for a given neutron fluence can be established. Values of 'shift' can be plotted against neutron fluence to establish the trend curve of shift with fluence for specific materials. A further effect (shown schematically in Figure 5a) is on the upper 'shelf' value which decreases with increase in neutron fluence.

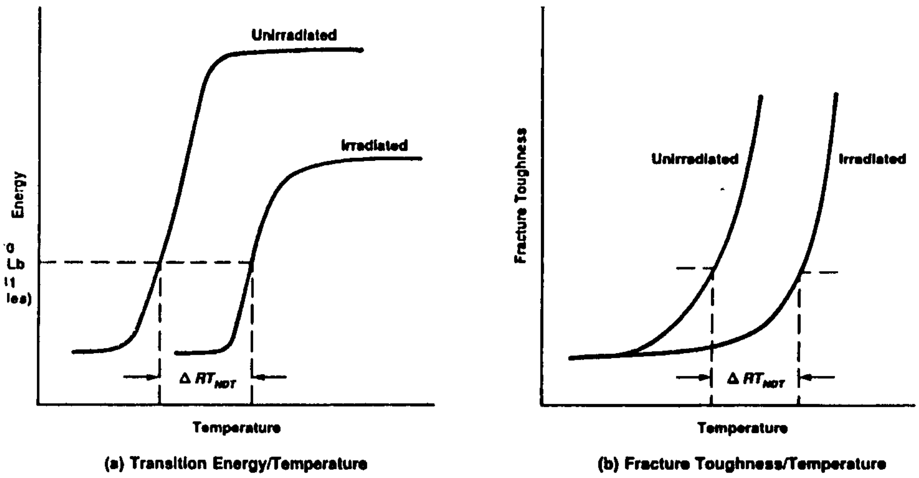


Figure 5a and 5b. *Effect of neutron irradiation on the transition temperature and fracture toughness properties.*

With regard to other properties the following approach is adopted for RPV applications.

- Irradiation induced effects (swelling, irradiation induced creep) are considered to have no significant effect on stress levels or stress distributions.
- Ductility and strain hardening characteristics are not affected significantly.
- The minimum yield and ultimate tensile strength of the as fabricated base material and weld metal provides a lower bound to the values after irradiation. No credit is taken for any increases in yield strength, UTS or S_m due to irradiation.

Irradiation conditions in an HTR vessel wall are broadly similar to those in PWR vessels (neutron energies and fluence damage levels well below 1dpa) and empirical relationships between composition, fluence and ΔDBTT have been proposed on the basis of results from test reactors and LWR surveillance programmes. The range of behaviour predicted for Mn-Ni-Mo, 2 ¾ Cr-Mo-V and 2 ¼Cr-Ni-Mo-V pressure vessel steels for example is shown in Figure 6. The upper bounds correspond to steels used in the 1960's and 1970's which had relatively high levels of either Cu (PWR steels) or P (WWER steels). For modern steels and weld metal special limits on Cu and P for material used in the most highly irradiated (beltline) region of LWRs are used which can be met comfortably using modern steel-making techniques and ensure that the predicted end of life ΔDBTT for a vessel operating at 250-300°C is small in relation to the data scatter.

For steels used in the 'warm' RPV concept such as adopted for the GT-MHR, (i.e Cr-Mo steels with modified 9Cr 1Mo steel grades similar to ASME Grade 91) there is little data available on effects of irradiation with neutron energies and fluence damage levels <1dpa. Data from a recent review of published information on effect of irradiation level on ΔDBTT for steels containing 2 ¼ -12% Cr and irradiation temperatures of 250-500°C (see figure 6) shows a strong effect of irradiation temperature in the range 250-450°C although effects may be small on ΔDBTT at 400-440°C, but measurable at 350°C. There is no information on welds. Limited data on other high Cr steels suggest a similar behaviour to parent metal.

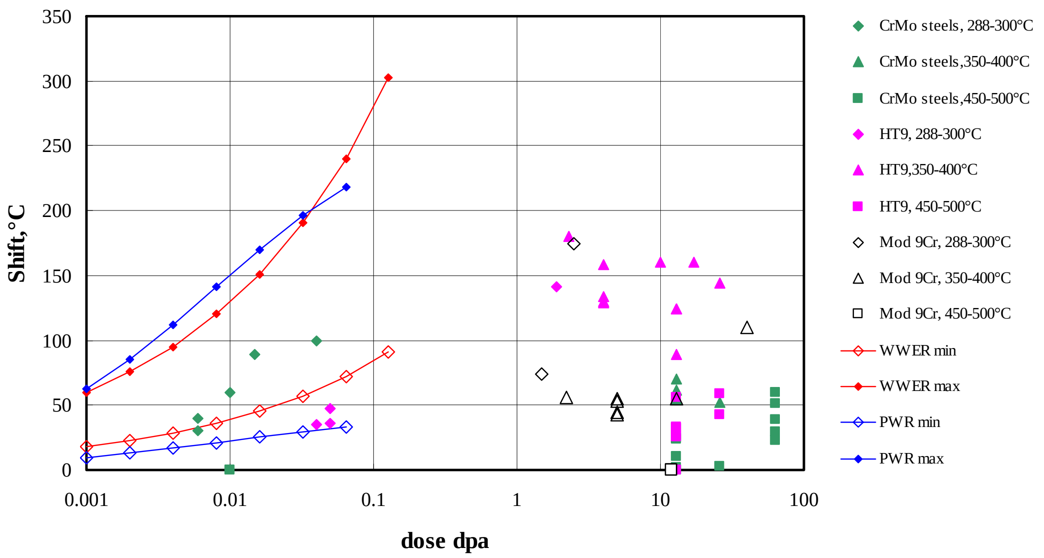


Figure 6 Effect of irradiation on the Ductile to brittle transition temperatures of pressure vessel steels

The only change to the classical design rules for irradiation of metallic materials to less than 1 dpa concerns austenitic stainless steels when creep is significant. Irradiation may produce sufficient He in these materials to reduce creep strength, (S_r and S_t) and increase the creep damage component in creep-fatigue. This effect is not thought to be significant in the ferritic steels under consideration for HTR pressure vessels.

Thermal ageing embrittlement

Ageing describes a continuous time or operational degradation of materials due to operating conditions, which include normal and operating conditions (but excludes 'design' and 'beyond design basis' accidents). As a result of ageing degradation the plant or component state could vary through the operating life.

Thermal ageing embrittlement (TAE), sometimes called temper embrittlement (TE), may involve hardening due to precipitation of carbides and intermetallic compounds along with grain boundary segregation of trace elements (P, Sn, As, Sb). The term temper embrittlement came into use because slow cooling after tempering was sufficient to embrittle steels with relatively high levels of the trace elements. More severe effects could be induced by step cooling from the tempering temperature followed by holding at about 450°C and or slow (furnace) cooling to room temperature.

TE is not usually a problem in modern steels with very low levels of P and the other trace elements. TAE can however occur after long-term service at temperatures in the range 350-550°C. The severity of the effect depends on a number of factors including:

- the prior austenite grain size of the material;
- the concentration and distribution of the trace elements P, Sn, As and Sb;
- the cooling cycle after tempering;
- time at temperature(s) within the critical range;
- the property considered.

The base materials and weld metals of both cold and warm HTR vessel steels normally have very fine grain sizes. The most likely embrittlement location is therefore the coarse grained heat affected zone. This is a narrow region adjacent to the fusion boundary where temperatures of 1100-1300°C are reached during welding.

Cold vessels operate at temperatures below the embrittlement range so TAE can occur only during transients involving exposure to higher temperatures for tens or hundreds of hours. Warm vessels operate in the TAE temperature range throughout their lifetime and the possible effect of TAE of on vessel integrity is of greater concern.

8. Current R & D

There has been an increase in research and development activities in Europe on HTRs in a number of key technical areas including materials. One such programme (HTR-M) is being supported by European Community Framework Programmes and this involves partnerships between principal industrial and research organisations from different countries of the European Union, with the aim to develop and consolidate European expertise and experience in this area. A European HTR Technology Network (HTR-TN) has also been set up to coordinate and encourage work-shared actions within European companies and to serve as a channel for international collaboration. The technological issues important to two recent industrial projects PBMR and GT-MHR are being used as basis for this continuing R &D.

The project on materials (denoted HTR-M) deals with the selection and development of materials for the reactor pressure vessel, high temperature resistant alloys for the internal structures and turbine and graphite for the reactor core. The work started in November 2000 and involves eight partners from five European countries. The key elements of the programme are shown in Figure 7.

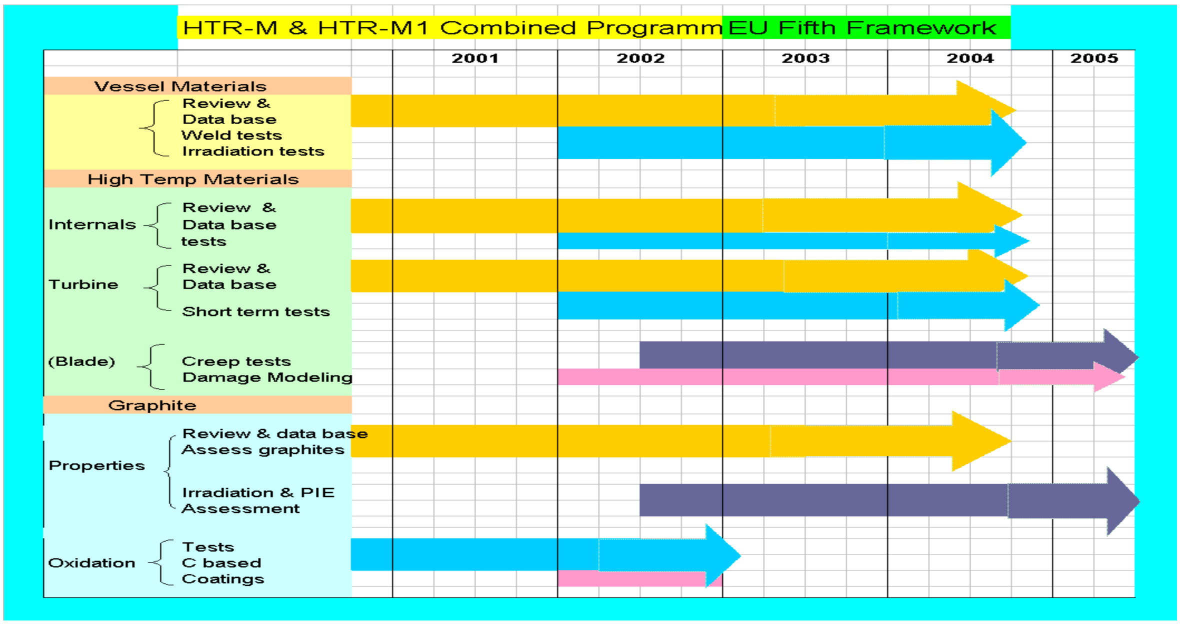


Fig. 7 Description of Overall HTR Materials Programme

HTR M & M1 Projects

The projects involve research into materials technology for three main component areas:
(i) vessel; (ii) turbine (blades & discs) and (iii) graphite (core). The main objectives and activities are as follows.

(i) Vessel:

- review existing materials used in gas-cooled reactors and previous high temperature reactors;
- setting up a materials database on design properties (which will lead to identification of data omissions for future R& D testing);
- carrying out of specific tests on welded joints under irradiated and non-irradiated conditions.

(2) Turbine:

- review of existing materials used in gas-cooled reactors and previous high temperature reactors;
- setting up of a materials database on design properties (which will lead to identification of data omissions for future R& D testing);
- specific tests on control rod, turbine disc and blade materials (carbon/carbon (C/C) composites, high alloy steels) at temperature and under short and intermediate times in air, vacuum and helium.

(3) Graphite core:

- review of graphite materials data identifying new graphites suitable for HTR and formulating a database of available information;
- selection of and performing of irradiation testing on new graphites;
- investigate graphite oxidation and the consequences of severe air ingress with core burning including the development of HTR models and data, protective coatings and C-based materials.

The work involves two main areas of investigation.

Review and database

Vessel materials can operate at temperatures as high as 450°C and information is required on manufacturing, environment (neutron-irradiation fluence, operational temperature, and helium environment) and welding. The primary circuit components operate at temperatures of 850-900°C and metals and ceramic materials are being considered for the reactor internals, core support, etc. with high strength alloys for the turbine. Graphite acts as a moderator and structural component and has important safety implications because of structural and other property changes that occur when it is irradiated. Information on all these components is crucial and design and material property data under HTR relevant conditions are to be reviewed and compiled for candidate materials of different HTR concepts, in relation to both normal and accident conditions.

Materials testing

For the vessel some tests on a chosen grade of steel taken from typical welded vessel joints are to be carried out under irradiated and non-irradiated conditions. The test pieces will be irradiated in the Petten High Flux Reactor prior to performing the mechanical testing. For the high temperature control rod and the turbine components some short term and medium term testing of important material options under simulated HTR environments are to be carried out. The tests concern fracture, creep and creep fatigue conditions in air and helium environments. For graphite the tests will be carried out to determine properties and oxidation. Many existing graphites used in previous core designs are no longer manufactured commercially, and currently available grades are limited to a few specific sources of raw materials. Alternative graphite grades with a better combination of desirable properties will therefore be irradiated in the HFR and tested to determine variations in physical and mechanical properties. Test work associated with graphite oxidation on the consequences of severe air ingress with core burning and advanced C-based options is also carried out.

Results

The following provides a brief summary of the status and results obtained to date on the metallic materials investigations.

Vessel Steels

As discussed previously, most designs of future plant make use of the either an LWR type steel or modified 9Cr 1Mo. These materials have similar strength levels at temperatures up to 370°C. Modified 9Cr 1Mo steel allows higher temperatures with only a gradual reduction in design strength at temperatures up to 450°C and above 450°C allowable stresses for all materials fall off rapidly. The main structural integrity concerns are at the vessel welds, at thicker sections, hot spots and regions important to functionality. Fracture, fatigue and creep-fatigue (depending on temperature) are the main damage mechanisms with compatibility aspects (metal loss and carburisation) unlikely to have an impact on material choice. The database is being assembled to include such materials as C-Mn steels (as used in the UK Magnox and AGR types), SA 508 Grade 3 Class 1 (LWR) or its European equivalent, 2¼ Cr 1Mo steel as used on HTTR and modified 9Cr 1Mo. Aspects such as provisions, products & parts, test and design data and environment are covered. Significant amounts of data exist for these steels and the main focus is on comparisons and assembling relevant design data. Modified 9Cr 1Mo steel showed the most uncertainty on data and fabrication experience with respect to HTR characteristics and also potentially has the wider applicability. The test programme for the vessel steel therefore concentrates on qualification of modified 9Cr 1 Mo.

Thick section modified 9Cr 1 Mo steel welded joints are being prepared for the irradiation tests. The tests involve the use of the Lyra rig, giving accurate control of the temperatures and use of a helium atmosphere (Figure. 8). The heaters in the rig are used to correct the temperature levels obtained from gamma heating. Post irradiation tests include tensile, creep, Charpy and CT toughness tests. The fabrication and characterisation of the welded specimens involves tests on 40 and 150mm thick plate. The thinner plate specimens provide a means for trials using different weld bead lengths and different weld parameters before producing the final weld specimens with the thicker plate. The conditions used simulate the accumulated dose at the end of life. For the tests the lowest temperature condition is being considered as higher temperatures are expected to act to anneal out any irradiation damage effects. Work has started in defining the tests for post-irradiation and reference properties and final test selections and boundary conditions. The procurement of the material and fabrication of the thick section welded test pieces is well advanced and tests are to commence following completion of characterisation. The irradiation test programme is expected to start mid 2003.

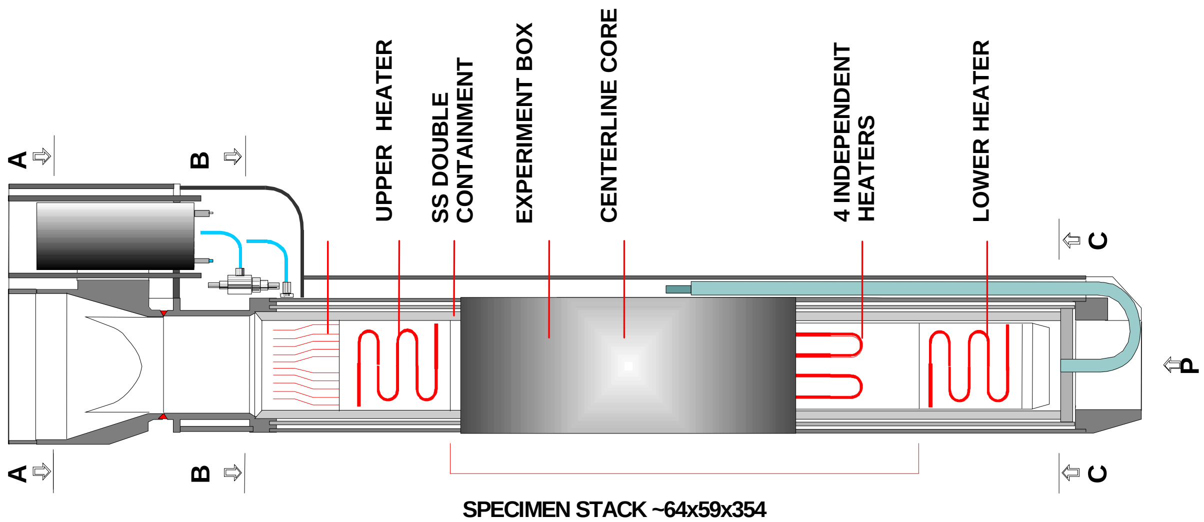


Fig. 2 The Lyra test rig used for irradiation experiments of RPV materials in the High Flux Reactor

High Temperature materials

Materials for both the control rod and turbine (blades and discs) are being investigated. Carbon-carbon composites offer advantages in strength, ductility and increased thermal resistance over metal alloys for the control rod, giving potential for improved reactivity control during shutdown and for allowing the normal operating temperatures of future reactors to be increased. For the turbine high temperatures and long term endurance are key issues. Criteria for material selection are typically to be based on a safe operation period of up to 60,000 h at 3000 rpm (50 Hz), with upper temperature limits in the range 850 to 950°C. The main criteria to be considered are creep and the influence of environment. Manufacturing considerations are also a major factor for the disc. Candidate alloys for the disc must be capable of production of large defect free ingots with good forging properties and proven thermal stability. The need for cooling is another major issue since the review has shown temperature limits for suitable disc materials to be below 750^{o}C. For blades corrosion is a concern. Helium atmospheres from decomposition of methane under extremely low oxygen partial pressures can be heavily carburising and can cause a significant shortening of the material creep life and accelerated creep crack growth rates. The presence of alloying elements such as cobalt (which is in most of the currently available turbine disc and blade materials) may be difficult to avoid. The main issues are the potential for plate out and lift off of particles and their activation and prevention of them flowing through the core. The review and database work has identified a few potential materials and from these specific materials have been chosen for the experiments.

Experiments on the turbine materials include short and intermediate term tests. Short term tensile/creep tests (air, atmosphere) up to 850^{o}C are carried out for the blade materials (2 grades) and fatigue and creep/fatigue tests up to 750^{o}C in air and helium for the disc material (1 grade). The tests under atmosphere conditions cover both carburising and de-carburising cases. The duration of the intermediate creep tests are expected to be around 5000 h. The tests on the blade material includes aged and notched samples and candidate materials selected for the blade and disc tests are CM 247 LC DS and IN792 DS which give a good creep resistance. Discussions are in progress with suppliers to confirm choices and availability. For the disc a large pancake of U720 has been obtained and characterisation tests are underway (on small blocks initially) before commencing the tests.

Concluding remarks

The HTR-M project aims to provide a materials platform on which to develop the future HTR technological basis within Europe and represents a first step towards building an understanding of the behaviour and manufacturing requirements for some of the new materials that will be needed for such developments. The project extends over a period of four years and is being co-sponsored under the Fifth Framework programme of the European Atomic Energy Community (“Euratom”), contracts FIKI-CT-2000-0032 and FIKI-CT-2001-00135. Please note that the information provided herein with regard to these projects is the sole responsibility of the author and does not reflect the Community’s opinion. The Community is not responsible for any use that might be made of the data appearing in this publication.

9. Overall Conclusions

The need for reliable material data and properties is a key issue in the development of HTR technology especially for those areas where safety considerations are important. In this paper attention is paid to some of the important issues that affect the selection of metallic materials for the HTR. Also highlighted are the main areas of Research & Development, and status and progress on a current activity on materials in the 5th Framework Programme.

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