EUROPEAN COMMISSION
5th EURATOM FRAMEWORK PROGRAMME 1998-2002
KEY ACTION : NUCLEAR FISSION

HTR-M

European Project for the development of HTR Technology - Materials for the HTR

CONTRACT N°
FIKI-CT-2000-00032
&
FIKI-CT-2001-00135

High Temperature Reactor Pressure Vessel Materials

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Dissemination level : PU
Document Number: HTR-M-03/04-D-0.0.65

Proceedings of ICAPP ’03
Córdoba, Spain, May 4-7, 2003
Paper 3355

High Temperature Reactor Pressure Vessel Materials

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Abstract – *Within the 5th Euratom Framework Programme, a big effort is being made to promote and consolidate the development of High Temperature Reactor (HTR). Empresarios Agrupados is participating in this project and, among others, also forms part of the HTR-M project “Materials for HTRs”. This paper summarises the work carried out by Empresarios Agrupados regarding the material selection of the HTR reactor pressure vessel (RPV). The possible candidate materials and the most promising ones are discussed. Design aspects such as the RPV sensitive zones and material damage mechanisms are considered. Finally the applicability of the existing Design Codes and Standards for the design of the HTR RPV is also discussed.*

I. INTRODUCTION

Gas-cooled HTRs have been under development in Europe for several decades. The current trend in HTRs is towards the design of low or medium power direct circuit modular reactors. This HTR design is held to be one of the most promising options for supplying electricity in the decade to come given the high output (40-50%) resulting from its elevated working temperatures.

HTRs are also thought of as a possible transmutation or “burning” system for plutonium and the other trans-uranic actinides found in waste from fuel used in nuclear power plants. They also provide the possibility of using nuclear power in combined heat and power generation systems (CHP) by supplying the heat needed for various industrial processes which require high temperatures, such as ethane, propane or methane production, the production of hydrogen and aluminium oxide or carbon gasification.

In order to promote and consolidate the development of the HTR, the European Union has formed the High Temperature Reactor Technology Network, HTR-TN, and, through the 5th Euratom Framework Programme, is funding various projects for the purpose of developing fuel (HTR-F), materials (HTR-M&M1), nuclear physics (HTR-N&N1), components (HTR-E) and licensing (HTR-L).

Empresarios Agrupados forms part of HTR-TN and participates in the HTR-M&M1, HTR-E and HTR-L projects. The HTR-M project “Materials for the HTR” commenced at the end of 2000 and is expected to last for four years. The scope of the project focuses on three aspects:

- Finding and selecting suitable materials for the RPV taking into consideration the operating conditions of the HTR. Determining their properties and characteristics under operating conditions, including weld filler metal
- Research into material behaviour simulating local operating conditions on selected parts of the HTR such as the reactor internals, the turbine blades, etc (high temperatures, neutron flux, mechanical loads)
- Research into the use of graphite and carbon based materials. Research into the effects and consequences of graphite oxidation due to air ingress into the cycle

This paper addresses the work that Empresarios Agrupados has performed to date on the first of the three aspects of the project — finding and selecting materials for the RPV.

II. MATERIAL SELECTION FOR THE RPV

The possible candidate materials for the HTR RPV must satisfy technical and economic requirements, guaranteeing the safety and feasibility of the nuclear power plant. Therefore, when selecting a material, consideration must be given to the working environment and operating conditions (possible material damage mechanisms and sensitive RPV zones which may be more affected) as well as to construction aspects.

Two possible concepts –the “cold” and the “warm” vessel options- are currently being considered for the HTR RPV. In the “cold” vessel option –like the South African PBMR (see Figure 1)– an operating temperature under 350ºC is envisaged. In the case of the “warm” RPV option –noninsulated vessel like the Russian GT-MHR (see Figure 2)– the design temperature will increase to a value of at least 450ºC.

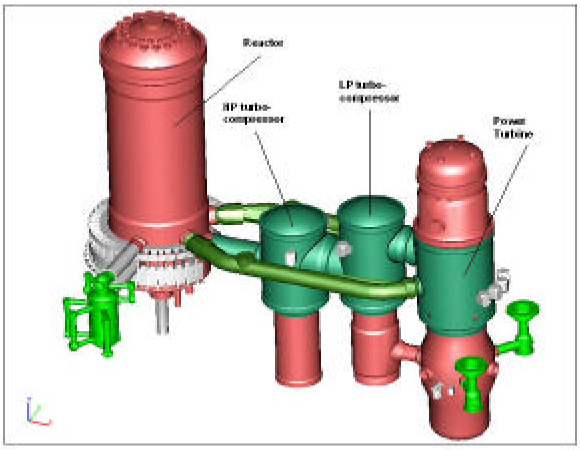

Fig 1: PBMR

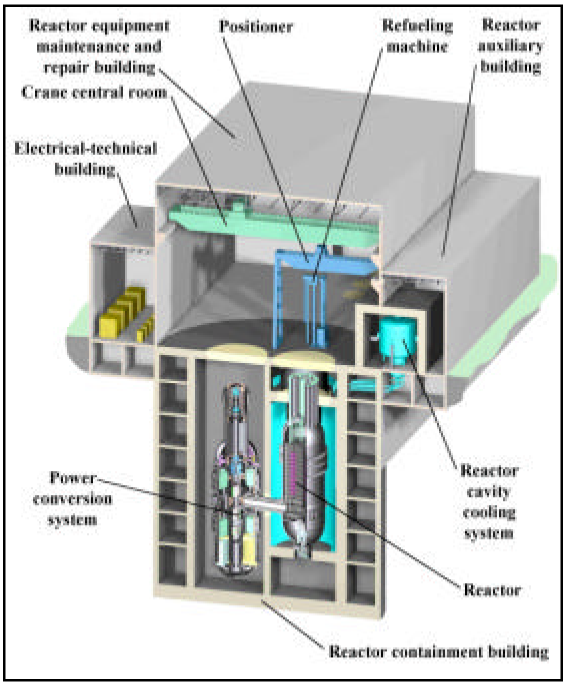

Fig 2: GT-MHR

II.A. Working Environment and Operating Conditions

Given the working conditions of HTRs, the technical requirements for reactor materials are very strict.

First of all, they must withstand high neutron irradiation environments. In this environment the RPV material will suffer the collision of the fast neutrons with the atomic lattice and will develop microstructural defects that would increase the yield strength (hardening) and the ductile-to-brittle transition temperature of the material. Embrittlement is one manifestation of material damage due to neutron irradiation. Others include the formation of internal voids or bubbles, which result in material accelerated creep, changes in material composition, unexpected internal segregation and the presence of phases not expected on the basis of chemical equilibrium. Welded joints are sensitive to neutron irradiation and special attention should be given to the selection of additional welding material, avoiding all those that may have a Cu or P content and any other component that may be affected by irradiation. Reducing the number of welds in the RPV zone opposite the reactor core should be favoured as much as possible.

The materials to be used must also have good mechanical resistance to withstand the HTR reactor vessel pressure (about 70 bar) and temperature (around 450ºC). Thermal ageing of the RPV material might occur due to high working temperature for long periods of time. This temperature and time age-related material degradation mechanism causes a change in the nonductile fracture mode from being completely transgranular in nature to being completely intergranular. This change in the nonductile fracture mode results from precipitation hardening. This effect leads to an increase in ductile-to-brittle transition temperature.

On top of that, temperature transients during operating incidents and accident conditions must also be considered. Under these conditions, one of the several forms of embrittlement due to thermal ageing that have to be evaluated is temper embrittlement. It occurs when impurities such as P, Sn, Sb and arsenic segregate at grain boundaries. Temper embrittlement is not a significant degradation mechanism for low alloy pressure vessel steels (“cold” vessel option). However, abnormal temperature variations (thermal shocks) are known to cause temper embrittlement.

Moreover, thermal ageing and its combined effect with irradiation embrittlement should be evaluated for the RPV material.

The combination of constant primary stresses due to the RPV internal pressure and cyclical stresses due to normal operating transients and accidental conditions could lead to fatigue damage. The vessel wall thicknesses should be designed to prevent fatigue or in such a way that this develops to an insignificant extent during RPV lifetime.

Ratchetting phenomena may also appear because of the superposition of constant primary stress due to internal pressure and the cyclic secondary loading. However, the pressure and temperature transients during specific operating conditions are relatively gentle for the RPV and only accident conditions could present a danger.

Reheat cracking of the heat affected zones due to pre- and post-welding thermal treatments may appear since large vessel wall thicknesses are foreseen (200 mm).

Although the coolant will be 99.9% helium, some active corrosion impurities will probably pollute the helium during plant operation. Therefore, corrosion at high temperatures of the RPV material should be considered. Moreover, special attention shall be given to accident conditions where air ingress may occur with the RPV at high temperature.

Creep damage could appear if RPV temperatures rise to high values over a period of time and in the presence of stresses due to design loads. Creep is typically considered if foreseen temperatures are over 1/3 of the absolute melting point. Considering that the design temperatures of the RPV are 350ºC and 450ºC for the 'cold' and 'warm' vessel options, respectively, creep damage will probably be insignificant. However, during accident conditions RPV temperatures will have higher values over significant periods of time and creep damage should be evaluated. It should also be considered that creep is often intensified by exposure to neutron irradiation.

Moreover, the combined creep-fatigue effect has to be evaluated. Whether it will be a question of creep intensified by the fatigue environment or vice versa will depend on load conditions. When the cyclical stress amplitude is small in comparison with the mean stress, or the applied frequency is low and/or the temperature high, the phenomenon should be regarded as one of creep perturbed by fatigue

II.B. Construction Aspects

Manufacturing considerations and their cost are decisive. The first factor to be taken into account is the suitability of the material for welding, guaranteeing the resistance, ductility, fatigue and weld joint creep requirements. Special attention must be paid to the selection of filler material, avoiding those that might contain Cu, P and other impurities that might be affected by irradiation. The large wall thicknesses of the HTR make pre- and post-welding thermal treatments necessary, bearing in mind that owing to the size of the vessel some of these welds have to be carried out in situ.

The second factor to be taken into account is whether the vessel is to be forged or shaped. Either choice directly affects the number of welds. The advantage is greater if the number of welds is reduced since, on the one hand, it reduces the risk of embrittlement due to material irradiation in the welded areas and, on the other, it reduces the costs of welding, thermal treatment and inspection. Manufacturing the vessel with forged rings reduces the number of longitudinal welds. However, the cost of manufacturing forged rings is greater than that of shaped plates. In any case, the manufacturing process can be decided based on the expected radiation dose at least in the RPV zone facing the reactor core.

III. CANDIDATE MATERIALS

Table 1 lists the materials proposed for reactor vessels in other HTR programmes and projects under way [1], [2].

HTR Project	**Country**	**Power**	**Reactor Material**
HTTR	Japan	30 MWt Block	2¼ Cr – 1 Mo
MSF-HTR	Japan	450-600 MWt Block	mod 9 Cr – 1 Mo
MSF-HTR	Japan	50 MWt Block	mod 9 Cr – 1 Mo
HTR-GT 300	Japan	300 MWt Pebble bed	SA 508
HTR-GT 600	Japan	600 MWt Block	mod 9 Cr – 1 Mo
PBMR	S Africa	265 MWt Pebble bed	SA 508
GT-MHR	Russia	600 MWt Block	mod 9 Cr – 1 Mo
MHGTR-1GT	China	200 MWt Pebble bed	SA 516-70
HTR10	China	10 MWt Pebble bed	SA 516-70

Table 1: Proposed materials for HTR vessels in other projects in progress

Figure 3 below shows the mechanical behaviour of these materials at different temperatures [1], [2].

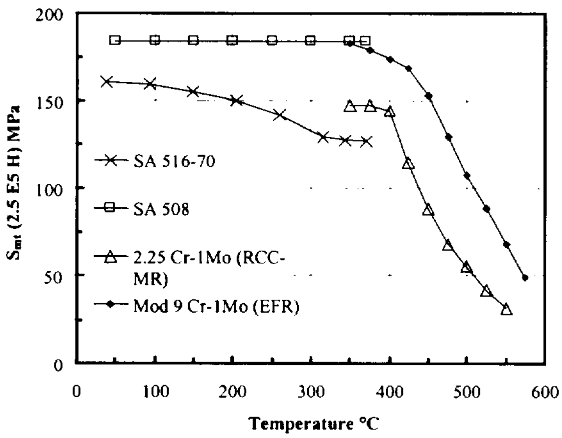

Fig 3: Allowable material stress intensity depending on temperature

Low allow steels such as SA 508 and SA 533 have been commonly used in reactor vessels for many years. They behave well vis-à-vis neutron irradiation and there is ample information on their behaviour and mechanical properties, as well as wide experience in their use. However, they have only been used for design temperatures below 400°C. There is very little information on their behaviour at higher temperatures and under the operating conditions of the HTR.

Chromium molybdenum steels such as 2¼ Cr – 1 Mo are characterised by their good behaviour at high temperatures when high resistance to creep is required. 2¼ Cr – 1 Mo has been used for years in steam generators where temperatures reach 600°C, as well as in pressure vessels in the petrochemical industry.

As seen in Figure 3, modified 9 Cr – 1 Mo has good resistance properties to creep and cracking at high temperatures and they are superior to those of 2¼ Cr – 1 Mo. However, there is little information on its behaviour and properties and less experience in its use, especially with regard to its welding and under operating conditions like those of the HTR.

SA 508 welds very well, better than 2¼ Cr – 1 Mo which, in turn, welds better than modified 9 Cr – 1 Mo. SA 508 requires lower temperatures and less time for the different pre- and post-welding thermal treatments than the other two materials.

The cost of the material and the weld is less for SA 508 than for 2¼ Cr – 1 Mo and modified 9 Cr – 1 Mo.

Based on the foregoing considerations, two candidate materials have been selected for the HTR vessels:

- Low alloy steels like SA 508, because of the wide experience gained from their traditional use in the nuclear sector. There is little information on their behaviour at temperatures above 400°C and under the operation conditions of the HTR. This material would probably be more suitable for the "cold" vessel option
- Chromium molybdenum steels like modified 9 Cr – 1 Mo, because of their mechanical properties at high temperatures. This material would be suitable for the "warm" vessel option. Again there is little information on its behaviour under the operating conditions of the HTR

The feasibility of these two candidate materials will be verified by a test campaign covering all possible aspects during the HTR vessel lifetime. The campaign will include tests on the materials and their welded joints to determine their mechanical properties, thermal ageing, creep, behaviour vis-à-vis thermal shocks, embrittlement due to irradiation, ductility, corrosion at high temperatures in an He environment with a certain amount of impurities, etc, considering both normal operating conditions of the HTR and accident conditions.

IV. DESIGN CODES FOR THE HTR RPV

Different design codes can be used for RPV design, mainly ASME or RCC-MR. These two codes have been examined in order to assess their applicability to the design of the HTR RPV.

ASME Code, Section III, Division 1, Subsection NB is fully applicable for the design of the HTR "cold" RPV. For the "warm" RPV option, Subsection NH "Class 1 Components in Elevated Temperature Service" shall be applied. The Code contains all data for 2¼ Cr – 1 Mo. However, none has yet been codified for the other two "warm" RPV option candidate materials, modified 9 Cr – 1 Mo and 12 Cr MoV.

RCC-MR design rules are applicable for the HTR RPV design, but some improvements and verifications are necessary and some material data are missing or not yet codified. For modified 9 Cr – 1 Mo, the ratcheting rule has to be validated with experimental results. For both 2¼ Cr – 1 Mo and modified 9 Cr – 1 Mo, some creep-fatigue data is missing, welded joint coefficients are not available and the verification procedure against fast rupture has to be validated.

V. CONCLUSIONS

Considering the HTR RPV working environment and operating conditions, possible material damage mechanisms, RPV sensitive zones and some construction aspects, the following have been proposed as the most promising candidate materials for the HTR RPV:

- Low alloy steels like SA 508 for the “cold” vessel option
- Chromium molybdenum steels like modified 9 Cr – 1 Mo for the “warm” vessel option

The applicability of ASME and RCC-M codes to the design of the HTR RPV has been studied. In the case of low alloy steels like SA 508 both codes are fully applicable and there is wide experience in their use. However, with regard to chromium molybdenum steels like modified 9 Cr – 1 Mo, no material data is available in ASME at the moment, and in RCC-M some improvements and verifications are necessary and some material data are missing or not yet codified.

ACKNOWLEDGEMENTS

The HTR project, and in particular the HTR-M project, is being co-sponsored under the Fifth Euratom Framework Programme. The information provided herein 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.

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