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

00-Y-X-10302-F3 Issue 1 I

CONTRACT N°
FIKI-CT-2000-00032

HTR RPV Materials Damage Mechanisms

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Dissemination level : CO
Document Number: HTR-M-02/02-D-1.4.27

EUROPEAN COMMISSION

Project:
EUROPEAN PROJECT FOR THE DEVELOPMENT OF HTR TECHNOLOGY - MATERIALS FOR THE HTR

Title:
HTR RPV Materials Damage Mechanisms

Document No: **092-089-E-M-00003**	Issue: **1**
Purpose of issue: Information and comments	Date: 21/01/2002

Prepared: ABP

Reviewed: AOM

Approved: MDB

092.089-Y-X-10302-F8 Issue 1 I

092-089-E-M-00003-01

1031769 047387

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CLASSIFICATION

Contains information for the design of structures, systems or components: Yes ☐ No ☒

Design verification : Not applicable ☐ Head of OU/Supervisor ☒ Verifier Level 1 ☐ Level 2 ☐

CONTROL OF MODIFICATIONS

Issue	Modifications
1	N/A

PRELIMINARY OR PENDING INFORMATION

Issue	Paragraphs	Subject	Status

DISTRIBUTION

External	Internal	No. copies/Format
	MDB	1 Hardcopy
	FAZ	1 Hardcopy
	AOM	1 Hardcopy
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	AGD	1 Hardcopy

CONTENTS

1. OBJECTIVES AND SCOPE

The aim of this document is to analyse the design and materials of the Reactor Pressure Vessel (RPV) of the European High Temperature Reactor (HTR) in order to contribute to the assessment of the Materials Damage Mechanisms.

2. HTR RPV

2.1 DESCRIPTION

The HTR is a helium-cooled, graphite-moderated, high temperature reactor using coated uranium fuel granules. The design features would be a thermal power between 250 and 600 MW with the corresponding net electric power in the range of 100 to 300 MWe.

The HTR RPV would approximately be of 6 to 7 m diameter and about 20 m high. It is likely it would be lined inside with a 1 m thick layer of graphite bricks serving as a reflector and passive heat transfer medium. This graphite layer would be drilled vertically to house the control rods and will enclose the reactor core, which would be about 3.5 m in diameter and 8.5 m high.

Helium would enter the RPV at a temperature of about 500°C and 7 MPa and leave at a temperature of the order of 900 °C, after removing the heat generated in the core fuel.

Two possible RPV options are being considered for the HTR design:

- The 'cold' vessel option, like the South African PBMR, where the RPV temperature is limited to 350°C. Coolant, leaving the HP compressor at about 100°C and 7 MPa and before entering the recuperator, flows between the graphite reflector and the RPV limiting the RPV wall temperatures
- The 'warm' vessel option, like the Russian GT-MHR, where the RPV temperatures are limited to a higher temperature value of 440°C

The selection of one or the other of the vessel options will have a direct impact on the RPV design, materials and thicknesses. The design pressure will probably be between 7 and 8 MPa and vessel thicknesses of the order of 200 mm are foreseen.

2.2 MATERIALS

The material selection for the HTR RPV was previously analysed [1] and the materials proposed were as follows:

- Low alloy steels like SA 508 for the 'cold' vessel option which have been tried and tested in existing nuclear power plants

- Chrome and molybdenum alloy steels, such as Modified 9 Cr – 1 Mo, for the 'warm' vessel option

The RPV would probably have some areas manufactured using moulding techniques and others would be forged. The number of welds would be reduced if the vessel were manufactured with forged rings (without longitudinal welds) of great height (smaller number of circumferential welds). However, this manufacturing procedure involves greater costs than does building the vessel from moulded shells. Reducing the number of welds is important as will be seen in Chapter 3 of this document.

2.3 OPERATING CONDITIONS

This data is not yet available for the European HTR project. However, some estimates can be made taking into account the information available from other HTR projects being developed in other countries and in accordance with the best engineering knowledge available at the time.

The operating conditions will define the cycles to which the HTR RPV will be subjected during its design life. The selected materials for the RPV should ensure good mechanical behaviour under these cyclic loads.

2.3.1 Steady-State Conditions

The different steady-state power levels desired will be obtained by adjusting the pressure and helium inventory at the HTR manifold (corresponding to the HP turbo compressor outlet temperature). The RPV wall temperature will be controlled by means of a helium flow in the reactor outside cavity, that is, between the reactor graphite reflector and the RPV, as described in the previous chapter. Table 1 shows a first estimate of the steady-state parameters for the HTR RPV, depending on the vessel option. Pressure and temperature estimates are for the reactor outside cavity.

Table 1: HTR RPV Estimated Steady-State Operating Conditions

Power Level (%)	HTR 'Cold' Vessel Option		HTR 'Warm' Vessel Option	
	Pressure (MPa)	Temp. (°C)	Pressure (MPa)	Temp. (°C)
100	7.0 – 8.0	300 – 350	7.0 – 8.0	400 – 450
40	3.0 – 3.5	300 – 350	3.0 – 3.5	400 – 450
10	1.2	300 – 350	1.2	400 – 450

2.3.2 Transient Conditions

A list of possible transient events –and their expected frequencies– that can be expected for the HTR plant during its design life of 60 years is given in Table 2 [1].

Normal operating load steps, including start-up load steps, have been estimated taking into consideration that the HTR plant will compete in an open electricity market with other generating power plants using other energy sources. The number of loads steps has been selected considering the present electric utility requirements for these types of plants.

Table 2: HTR Transient Events and Expected Frequencies

Transient event	Frequency
Pressure test	2 to 6 times/life
Operation with new core (start up)	5 to 7 times/life
0% – 10 % load step (start up)	3 times/year
Mayor operating load steps	730 times/year
10% –0 % load step	3 times/year
Main circuit trip	3 to 5 times/year
Load rejection	2 to 4 times/year

Transients involving load rejection are considered the most demanding for the HTR plant. A load rejection occurs when there is a loss of electrical load and the system tries to remain connected to the grid. These transients lead to a rapid decrease in fluidic power through the turbine and associated changes in pressure throughout the cooling circuit. The following two transients involving full load rejection have to be analysed:

- Main circuit trip, where the turbine will over-speed and no attempt is made to keep the generation cycle functioning
- Full load rejection, where the generation cycle is kept functioning at a very low load level by controlling the by-pass valves

Moreover, the main circuit trip leads to significant and rapid changes in coolant pressure not experienced during any other normal operating transient. On the other hand, since the main circuit trip is a short transient, the temperature effects are more important for the full load rejection transient. Table 3 shows estimated values for variations of helium pressure and temperature in the reactor outer cavity during these transients.

Table 3: HTR RPV Estimated Transient Operation Conditions

Transient	Pressure Rate (MPa/s)	Temperature Rate (°C/s)
Main circuit trip	0.10 – 0.20	20 – 30
Full load rejection	0.10 – 0.20	30 – 40

3. HTR RPV MATERIALS DAMAGE MECHANISMS

In view of the HTR working environment and operating conditions described in previous chapters of this document, the materials selected for the HTR RPV would potentially be subjected to the following damage mechanisms:

- Irradiation embrittlement, since the expected neutron fluency for the HTR RPV would be high. The upper bound of the accumulated (60 years) high energy (> 1 MeV) neutron irradiation at operating temperature can be estimated in 3×10^{19} neutrons cm^{-2} (TBC) [1]. 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, P content and any other component that may be affected by irradiation. The reduction in the number of welds in the RPV zone in front of the reactor core should be favoured as much as possible

- Thermal ageing of the RPV material 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 form 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. As discussed previously, the vessel wall operating temperature for the 'cold' vessel option would be of 300-350ºC. In the case of the 'warm' vessel option, the operating temperature will be up to 400 – 450ºC.

  On top of that, temperature transitients during operating incidents and accidental conditions should also be considered. Under these conditions, one of the various 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, temperature variations of the abnormal type (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 (studies and tests carried out for PWR component materials could be a good reference)

- Fatigue damage, since there is a combination of constant primary stresses due to the RPV internal pressure and cyclical stresses due to normal operating transients and accidental conditions. 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 accidental conditions could present a danger

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

- Corrosion at high temperatures of the RPV material. The coolant will be 99.9 % helium, however, some active corrosion impurities will probably pollute the helium during plant operation. 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 temperatures of the RPV rise to high values over a period of time and in presence of stresses due to design loading. Creep is typically considered if temperatures foreseen are over 1/3 of the absolute melting point. Considering that the design temperatures of the RPV are 350ºC and 450ºC for 'cold' and 'warm' vessel options respectively, creep damage will probably be insignificant. However, during accidental conditions temperatures of the RPV will rise higher values over significant periods of time and creep damage should be evaluated. It should also be considered that creep is often enhanced by exposure to neutron irradiation, which is the case.

Moreover, the combined effect creep-fatigue has to be evaluated. Whether it will be creep enhanced by the fatigue environment or vice versa will depend on the loading condition. When the cyclical stress amplitude is small in comparison to 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.

4. CONCLUSIONS

The HTR RPV design and operating conditions have been studied. The RPV material damage mechanisms have been analysed based on this study.

The information presented in this document may provide some elements for the selection of the HTR RPV materials.

The materials selected for the RPV should behave well in respect of all presented material damage mechanisms. Moreover, they should ensure good mechanical behaviour for combinations of the damage mechanisms, such us thermal ageing under irradiation embrittlement conditions or creep-fatigue interactions.

An exhaustive test campaign should be addressed to verify the behaviour of the RPV materials selected. A complete test matrix should be proposed in order to make sure that all these material damage mechanisms and their combinations are considered.

5. REFERENCES

1. A. Buenaventura et al, *Materials selection for HTR Reactor Pressure Vessel.* HTR-M 01/10 D.1.0.17, October 2001