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

<u>CONTRACT N°</u>
FIKI-CT-2000-00032

Materials selection for HTR Vessel

By

M. T. Cabrillat
CEA

France

Dissemination level : CO
Document Number: HTR-M-01/11-D-1.1.18

DIRECTION DE L'ENERGIE NUCLEAIRE
DEPARTEMENT D'ETUDES DES REACTEURS
SERVICE D'ETUDES DES REACTEURS INNOVANTS
LABORATOIRE DE CONCEPTION DES SYSTEMES INNOVANTS

CEA/CADARACHE

NT	SERI	LCSI	01/4044	0	H0 - 200 – 5H60 - 5442	N114	DDIN/SF/P5	1/16
NATURE	SERVICE ou CELLULE	LABORATOIRE	N° CHRONO	INDICE	FICHE ACTION - CEA	AFFAIRE	CLASSEMENT UNITE	PAGE

Note Technique

TITRE : European Project for the Development of HTR Technology – Materials for the HTR
HTR-M Project – WP1 Task 1.4 : Damage Mechanisms

AUTEUR(S) : M.T. CABRILLAT

RESUME :

The development of advanced HTR concepts requires material data information and an understanding of material behaviour under reactor operating conditions.
In the framework of HTR-M, WP1 is devoted to the study of the RPV (Reactor Pressure Vessel) material. Improvements are necessary in the areas of design analysis, structural integrity analysis and material properties data. The aim of this WP is to confirm the choice of a material for the RPV of different HTR concepts.
Several tasks have been identified. The aim of task 1.4 is to make a review of the different damage mechanisms which must be considered in order to perform validated design analyses. This document is the contribution of CEA/DER/SERI to this task. It will be completed by EA (Empresarios Agrupados), FRAMATOME and NNC.

MOTS CLES : HTR – Pressure Vessel – Design Rules – Damage Mechanisms

(07/99 - Document2)

	Rédacteur	Vérificateur	A.Q.	Emetteur
Nom et visa	M.T. CABRILLAT	Y. LEJEAIL	C. RENAULT	Chef du DER/SERI/LCSI M. DELPECH
Date	14/12/01	07/01/02	7/02/2002	28.01.02

Cadre de réalisation du document.
Contrat européen 5eme PCRD – HTR-M

CLASSIFICATION				
DR	CC	CD	SD	sans
				X

Indice	OBJET DES REVISIONS	DATE	N° CHRONO
0	Emission initiale	11/10/2004	01/4044

Indice

Table of Contents

1. INTRODUCTION

The development of advanced HTR concepts requires material data information and an understanding of material behaviour under reactor operating conditions. Specific studies are undertaken to identify suitable materials for the different components of the reactor and mainly for the RPV (Reactor Pressure Vessel), the internal structures and the turbine.
In the framework of HTR-M, WP1 is devoted to the study of the RPV material. Improvements are necessary in the areas of design analysis, structural integrity analysis and materials properties data. Complementary informations are also needed on manufacturing of products and parts, influence of environment (neutron-irradiation fluence, temperature, helium) and welding.
This last point is particularly important and must be studied very carefully.

The purpose of WP1 is to investigate all these points. The final objective is to confirm the choice of a material for the RPV of different HTR concepts, taking account of normal and accidental conditions but also of environmental conditions, and to compile the design properties, including the presence of weld joints.

To reach this objective, different tasks have been defined. Task 1.4 is related to the design rules applicable for the RPV, and more precisely it consists in a review of the different damage mechanisms which must be considered in order to perform validated analyses.

2. SPECIFITIES OF THE RPV

In the first concepts of HTR, large size reactors were considered, leading to the use of concrete pressure vessel.
In the last 20 years, studies were undertaken to optimise the design of this kind of reactor and one of the objectives was to reach passive safety characteristics. Different ways were developed for that. There was a reduction of the reactor power which allowed also a reduction of the size of the reactor and the use of a metallic vessel.
This point is very important. The metallic vessel is not thermally insulated and consequently contributes to the heat transfer from the core to the outside of the vessel.

The main characteristics concerning the loadings of the RPV are as follows:

* The thermal conditions of the RPV depend on the gas temperature but also on the conception of the internals.
  For HTTR, for instance, the helium temperature at the core inlet is equal to 395°C in normal conditions, and the mean temperature of the RPV is about 400°C.

  For GT-MHR, the helium temperature at the core inlet is equal to 490°C, but the mean temperature of the RPV is about 440°C. This difference is due to the fact that the cold helium which comes from the PCS vessel (Power Conversion System Vessel) is not in contact with the RPV. It flows in an annular space between the “Core Barrel Shell” (which surrounds the core) and the “Gas Duct Shell” (which is a shell concentrical to the RPV, inside the RPV – The annular space between RPV and the Gas Duct Shell is about 90mm).
  Moreover, the RPV is located in a cavity (the Reactor cavity) which is cooled. Due to the heat transfer through the vessel, there is a thermal radial gradient which reaches 60°C. This loading will contribute to the presence of additive thermal stresses which will have to be taken into account in the analyses.
  Concerning the thermal loading, another aspect must be considered and will have to be analysed. There is only one “hot duct” connecting the two vessels. Thus, the alimentation in gas is not axisymetrical. That can lead to non axisymetrical thermal fields on the RPV in normal conditions and consequently to local thermal stresses. That problem may become more important in transient situations.

* The pressure is high. It represents the main loading.
  For HTTR, the internal pressure is equal to 40 bar.
  For GT-MHR the design pressure is equal to 80 bar.

* A characteristic which will be important for the RPV design is the fact that the thickness is high: 120mm for HTTR, 190mm for GT-MHR. There is a risk of heterogeneities of microstructures in the thickness and consequently of mechanical characteristics. This kind of problem would be probably increased in the vicinity of weld joints. Investigations will have to be performed in order to evaluate the potential consequences.

* Incidental and accidental conditions will have to be analysed. The corresponding loadings are not clearly identified at the moment.

* Neutron irradiation effect. The expected cumulated fluence on the RPV for the whole life will have to be evaluated in order to estimate if it is necessary to take it into account in the design.

3. DESIGN OF THE RPV

For the design of the RPV, we have to consider different damage mechanisms.

3.1 IDENTIFICATION OF DAMAGE MECHANISMS

* The nominal pressure is high. The first verifications will concern:
  - o the instantaneous excessive deformation and the instantaneous plastic instability
  - o the delayed excessive deformation, the delayed plastic instability and the delayed rupture (influence of time if the structure works in the creep range)
* The RPV will be submitted to different loading cycles: normal situations and incidental or accidental situations. Due to cycling loadings the following rules will have to be checked:
  - o ratchetting
  - o fatigue
  - o creep-fatigue
* In addition, defect nocivity and Leak Before Break (LBB) analyses may be used to justify the RPV design.

It is important to keep in mind that, for all theses analyses, we'll have to take account of the presence of weld joints.

3.2 IDENTIFICATION OF DESIGN RULES

Design codes such as ASME [1] or RCC-MR [2] can be used for RPV design.
In RCC-MR, data concerning 2¼Cr and 9Cr1Mo mod are tabulated respectively in A3-16S and A3-18S.
Some data are available for 16MND5 steel (or A533B), coming from PWR experience.
It is possible to perform a first pre-design using these values.

3.2.1 Limitation of primary stresses

In RCC-MR, the limitation on primary membrane stresses P_m is:

$$P_m < S_m(\theta_m)$$

and: $U(P_m) < 1$ if creep is not negligible

When the primary stress is constant during the whole time, the last equation is equivalent to:

$$P_m < S_t(\theta_m)$$

where θ_m is the maximal value of the mean temperature in the thickness
S_m allowable stress, independent of time
S_t allowable stress depending of time

In presence of weld joints these rules become:

$$P_m < nJ_m S_m(\theta_m)$$

and $P_m < nJ_t S_t(\theta_m)$

where n is a coefficient which depends on the controls performed on the weld during and after realisation and J_m and J_t are joint coefficients introduced to take account of the difference of behaviour between base metal and weld metal.
For 2¼Cr et 9Cr1Momod, the values of J_m and J_t are not documented in RCC-MR.

For the 3 steels considered, the values of S_m and S_t with the temperature are given in figures 1 and 2, for the parent metal.

Concerning the SA533B, we observe that S_m value is almost constant up to 400°C, and then decreases very rapidly. Very few data are available to derive S_t value. But the effect of creep is very significant at 450°C and probably at lower temperatures. So to avoid creep influence it will be necessary to limit the use of this steel at low temperatures (lower than 350°C).

2¼Cr steel can be used up to 400°C. But above this temperature, the admissible stress S_t decreases very rapidly.
For instance, at 425°C, S_t is equal to 114 MPa for 3.10^5h (i.e. about 34 years), and equal to 88 MPa at 450°C.

For 9Cr1Momod, the S_t value (for $t=3.10^5$h) is greater than the S_m value up to 440°C. Then the S_t value decreases and must be taken into account in the analyses.
For instance, at 450°C, S_t is equal to 153 MPa for 3.10^5h, and equal to 107 MPa at 500°C.

On figure 1a and 1b, we have indicated the point (primary membrane stress due to pressure, temperature) corresponding respectively to the 2 reactors GT-MHR and HTTR. We observe that there is margin for HTTR, but not for GT-MHR, although no allowance is made for the presence of weld joints.

In order to clearly point out the influence of the material choice on the RPV design and mainly on the RPV thickness, a parametric study has been performed with these 3 steels. For a given RPV diameter, we determine the minimal thickness value which allows to respect the RCC-MR rules on the primary stresses limitation, for a life of 60 years.
The pressure varies between 10 and 110 bar, the temperature between 200 and 500°C, and the diameter is fixed to 6m. Other value can be tested very easily.
The results are presented on figures 3 and 4.
Concerning A533B, S_t values are available only for temperatures greater than 450°C, it's why there is a discontinuity in the curves. The thickness value is underestimated in the temperature range 350-450°C.
Hence again, we conclude that 2¼Cr steel is interesting for temperatures lower than 400°C, and 9Cr1Momod can be used up to 440°C without influence of time.

Figures 5a and 5b present the same analysis for the geometries of GT-MHR and HTTR respectively. We have a direct indication of the influence of the temperature on the minimal thickness required.

3.2.2 Limitation of cyclic stresses

3.2.2.1 Ratchetting

Due to the internal pressure, the primary stress will be relatively high.
In fact, for the 2 steels considered: 2¼Cr and 9Cr1Momod, the values of S_m or S_t are low when compared to the yield stress $R_{p0.2\%}$ at the same temperature.
For instance we have:

	2¼Cr	9Cr1Momod
Temperature °C	400	450
$R_{p0.2\%}$ MPa	216	320
R_m MPa	468	439
S_m MPa	144	163
S_t (3.10^5h) MPa	156	153
$Min(S_m,S_t)/R_{p0.2\%}$	0.67	0.48

In the situations of HTTR or GT-MHR, using the design conditions, the primary stress value due to pressure is about the half value of the yield stress.
The superposition of this constant primary loading and of the cyclic secondary loading may induce ratchetting. We'll have to check the absence of ratchetting before evaluating the fatigue damage.
For nominal situations, the secondary stress range will be probably rather low, and consequently the limitations concerning this rule will be easily respected.
The situation of incidental or accidental conditions will have to be analysed. Are there situations where there is a possibility of ratchetting?

In a next document, we'll analyse the available ratchetting rules and evaluate if they are suitable for the RPV design.
Nevertheless, we must keep in mind that 9Cr1Momod steel is a steel which softens in cyclic solicitations. We can suspect that this point is unfavourable for ratchetting. Experimental results would be necessary to clear up this point. Unfortunately, very few results are available in this field.

3.2.2.2 Fatigue

We must check that cyclic loading don't induce fatigue damage. Hence again, normal situations will probably cause low damage fatigue on the vessel. But we'll have to analyse incidental and accidental situations.
A point which can become important for the fatigue damage evaluation is the fact that there will be a constant primary stress and we'll have to evaluate if there is an influence of the mean stress on the fatigue life. Experimental results will be necessary to solve this problem.

3.2.2.3 Creep-fatigue

In nominal situations, the RPV will probably be at a temperature where creep is not significant or very low. In incidental or accidental conditions, the temperature of the RPV can increase, leading to situations where creep will have to be considered.
Consequently, it may be necessary to perform creep-fatigue analyses.

Concerning 9Cr1Momod steel, most of the data necessary for these analyses are available in RCC-MR. The data missing are: the negligible creep curve and the joint coefficients.
For 2¼Cr steel, more data are missing in RCC-MR: negligible creep curve, creep-fatigue interaction diagram, creep strain laws, joint coefficients. May be some of them are available in other codes or documents. A research will be necessary to complete the data.

For creep damage, the presence of weldments is an important point which has to be evaluated very carefully.

3.2.3 Irradiation effect

It will be necessary to estimate the cumulated fluence on the RPV during the whole life in order to be able to evaluate if it is necessary to take account of its influence on the material behaviour.
Due to the irradiation, the material becomes more brittle: the yield stress and the tensile stress to rupture increase, but at the same time the ductility decreases.
In such a case, the design rules are modified. In the framework of studies on FBR, specific rules had been developed in CEA for structures which are brittled, either by irradiation or due to the presence of Hydrogen or Helium [3].
These rules will be examined and presented in a next document.

3.3 OTHER POINTS TO CONSIDER

* In relation to the creep analysis, and due to the fact that the vessel thickness is high, we'll have to examine if there is a potential risk of Reheat Cracking of Heat Affected Zone. This problem is well known on austenitic steels, and mainly on stabilised ones, but also on 316H and 304H for instance. We'll have to check if the steels considered are susceptible to this type of cracking.

* Structural integrity analyses.
  - The Leak Before Break (LBB) analyses can be used in the RPV design, for instance to take account of the defects due to fabrication. For that it is necessary to check if the methods developed for FBR or for PWR components are available.
    The aim of this approach is to check if a through wall defect will be detected before it becomes unstable under accidental conditions. For this evaluation, it is necessary to know the fatigue propagation curve and the creep propagation curve if necessary, for the base metal but also for the weld metal.
    Some preliminary studies have been made. They allow to identify the points to improve such as:
    - toughness values for the different steels
    - influence of temperature, of thermal aging, of fluence on toughness values
    - creep propagation curve
    - gas leak detection methods, identification of the detectable leak
    - identification of accidental situations to consider
    - influence of thermal radial gradient in the thickness leading to defect closure
    - influence of the welds
    - …

  - In addition, it will be also possible to perform defect nocivity evaluations in order to verify the integrity of the RPV. In these cases, we postulate the presence of a realistic defect and we evaluate the crack initiation and propagation during the reactor operation, taking into account the different loading situations. The same data as before are necessary.

4. CONCLUSIONS

A review of the damage mechanisms that we'll have to consider for the RPV design has been proposed.
Some preliminary studies are presented showing that, if we consider only the limitation of primary stresses, A533B steel can be used for low temperatures (lower than 350°C), 2¼Cr steel can be used up to 400°C and 9Cr1Momod is the better candidate for temperatures higher than 400°C. Nevertheless, it will be necessary to take account of creep influence when temperatures exceed 440°C.

Other damage mechanisms have also to be considered. It will be important to obtain rapidly informations on the RPV thermal conditions during the transients and the different incidental or accidental situations, in order to be able to evaluate which design rules and consequently which material data are necessary: for instance, will creep be significant or not?
Another point which is important is the evaluation of the cumulated fluence. If it is significant, specific rules will have to be used to take account of the brittleness of the steel.

The presence of welds must be taken into account. Design rules must include this aspect.

Defect nocivity and Leak Before Break Analyses may be used for the RPV design. For these applications, some improvements are necessary, concerning either the steels data or the loading conditions or the calculation methodology.

5. REFERENCES

[1] ASME Boiler and Pressure Vessel Code, The American Society of mechanical Engineers

[2] RCC-MR code Règles de Conception et Construction des Matériels mécaniques des Ilôts Nucléaires RNR - AFCEN issue May 1993

[3] Règles d'Analyse Mécanique des Structures Irradiées par le Groupe de Travail RAMSES II. Rapport CEA-R-5618

FIGURE 1 S_m and S_t values

Figure 1a: 9Cr1Momod

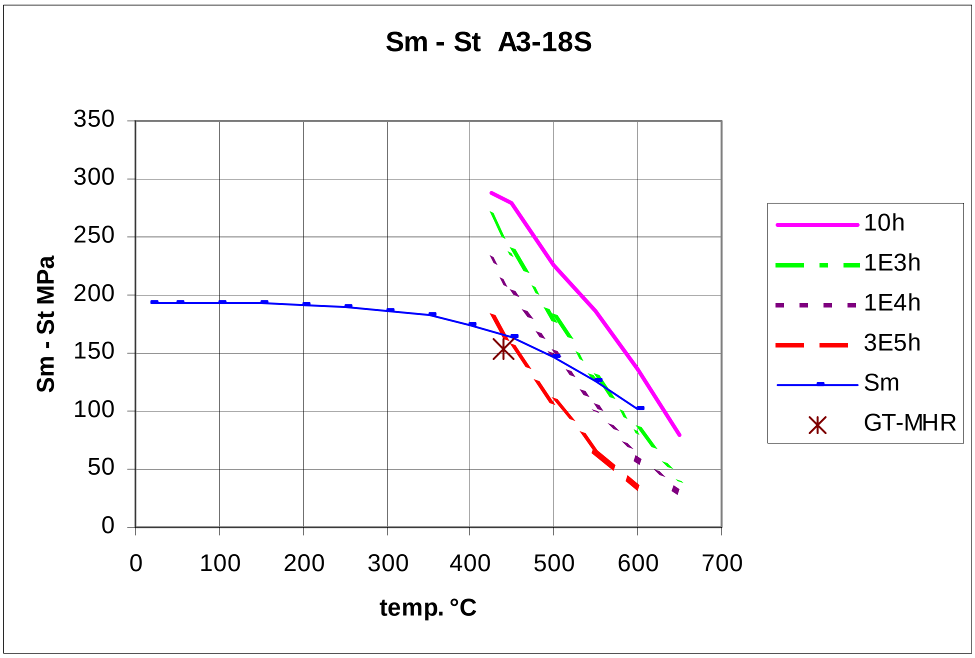


Figure 1b: 2¼Cr

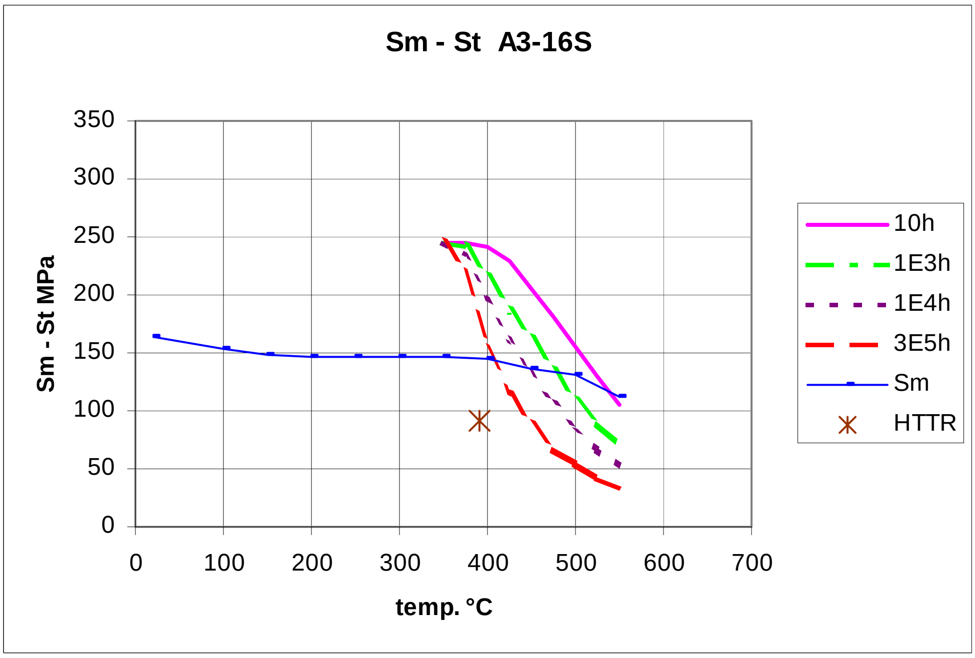
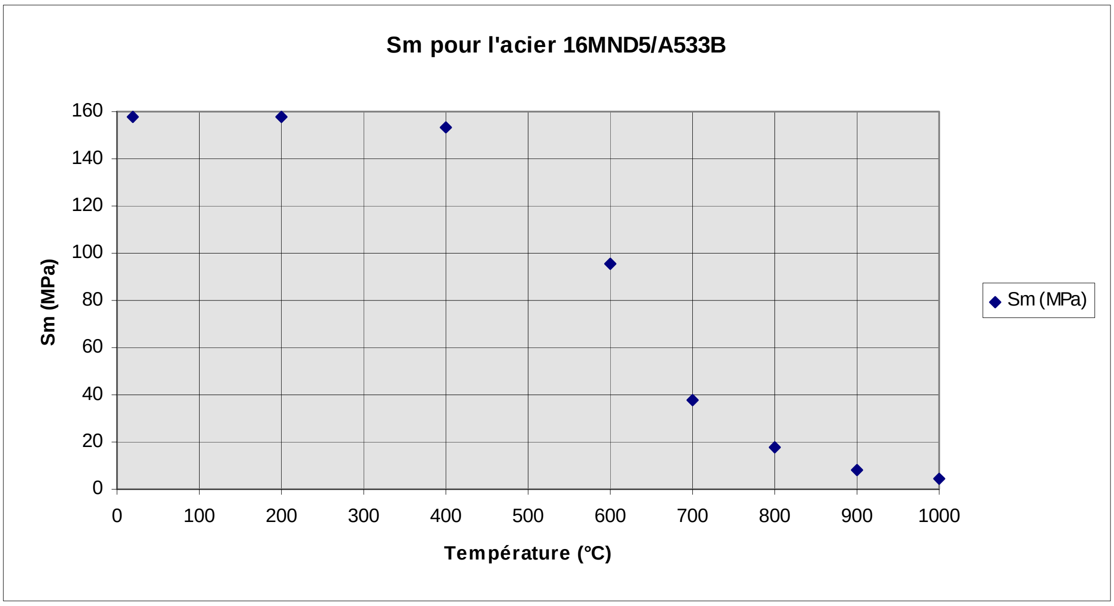


FIGURE 2 S_m and S_t values A533B steel



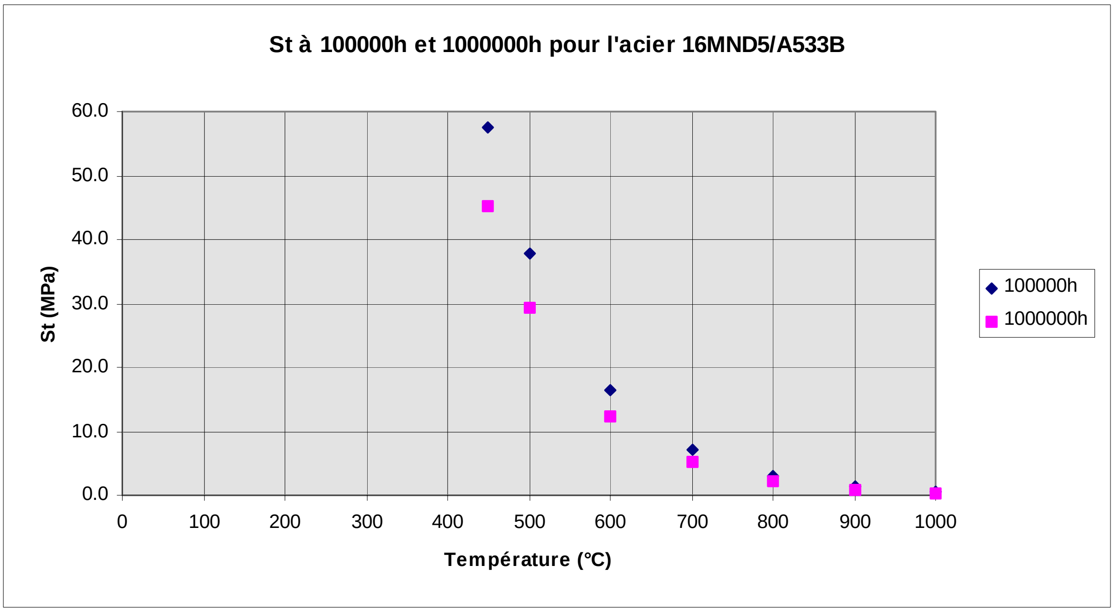


FIGURE 3: minimal thickness required to respect design rules on primary stresses Diameter=6m – Life=60 years

Figure 3a: 9Cr1Momod

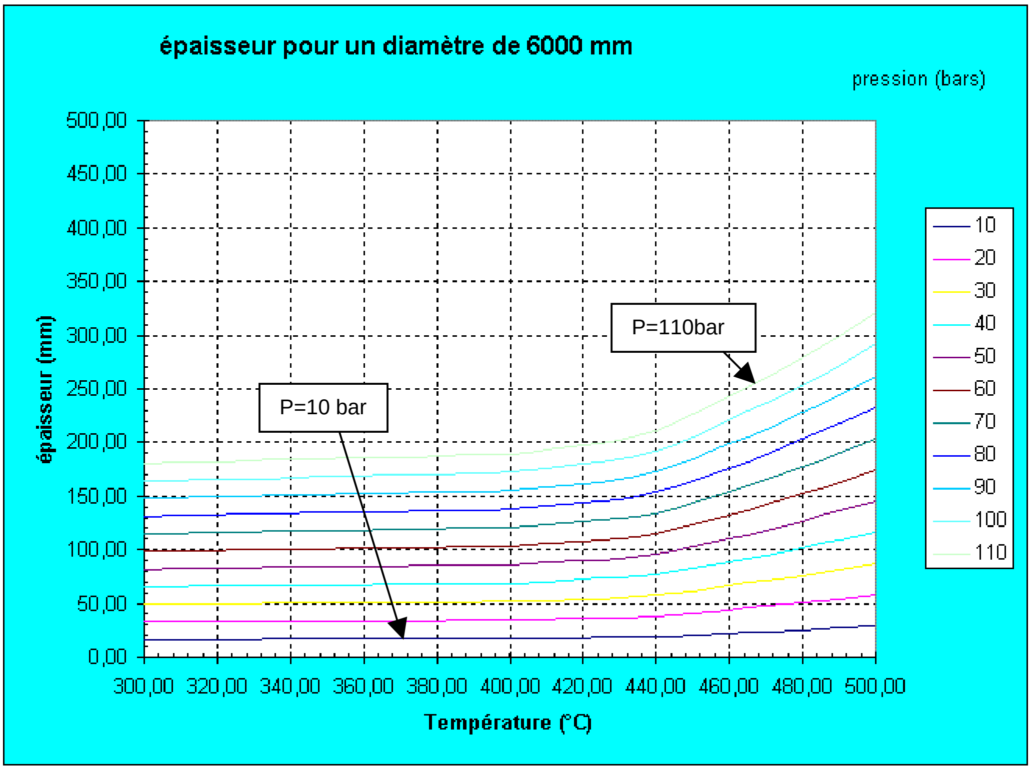


Figure 3b: 2¼Cr

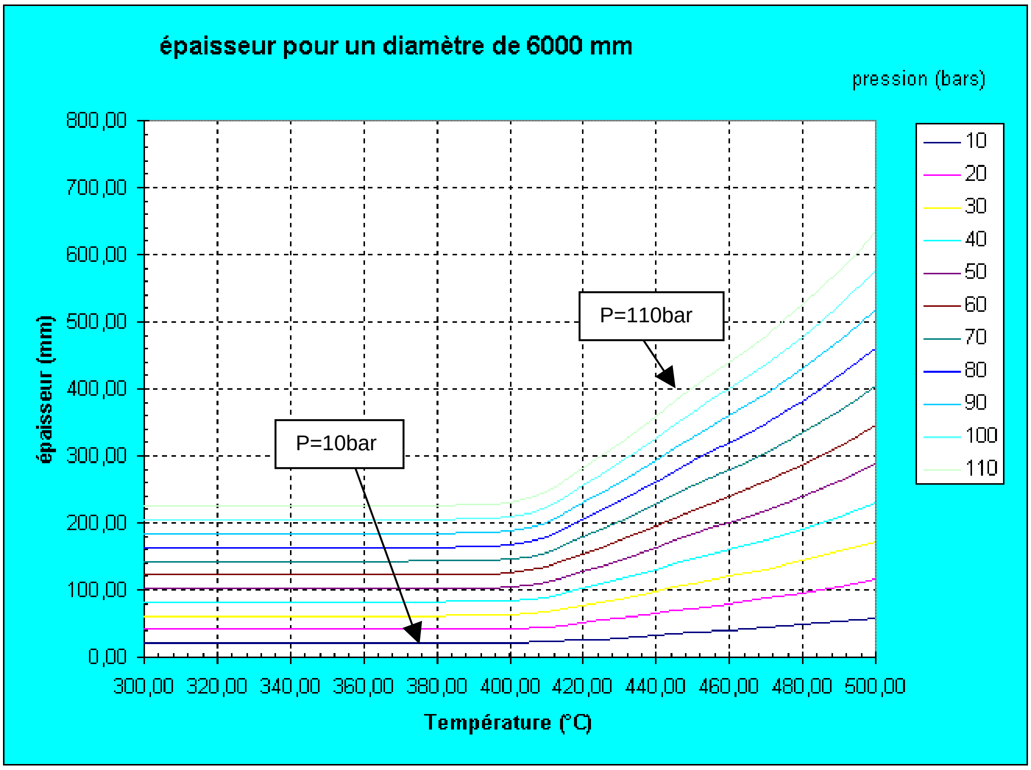


FIGURE 4: minimal thickness required to respect design rules on primary stresses Diameter=6m – Life=60 years

A533B (16MND5)

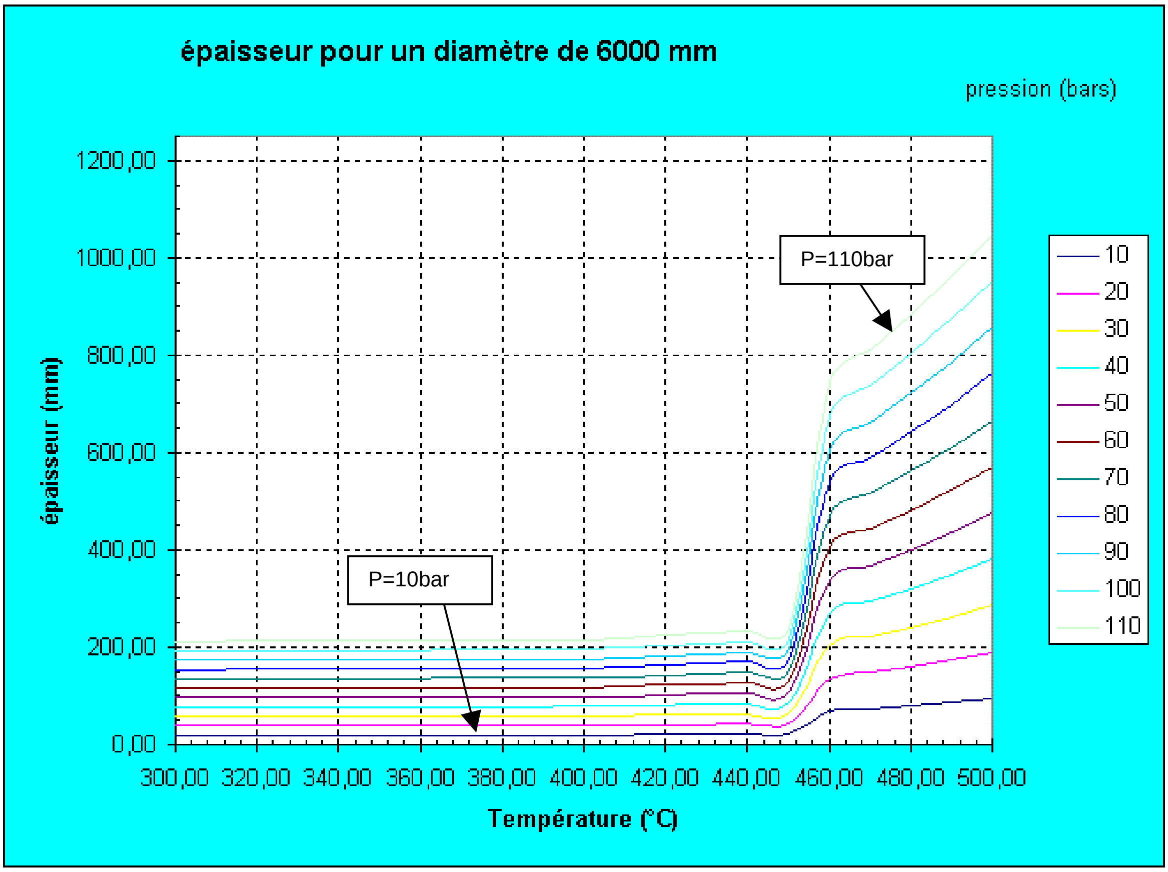


FIGURE 5: minimal thickness required to respect design rules on primary stresses Life=60 years

Figure 5a: GT-MHR case - 9Cr1Momod

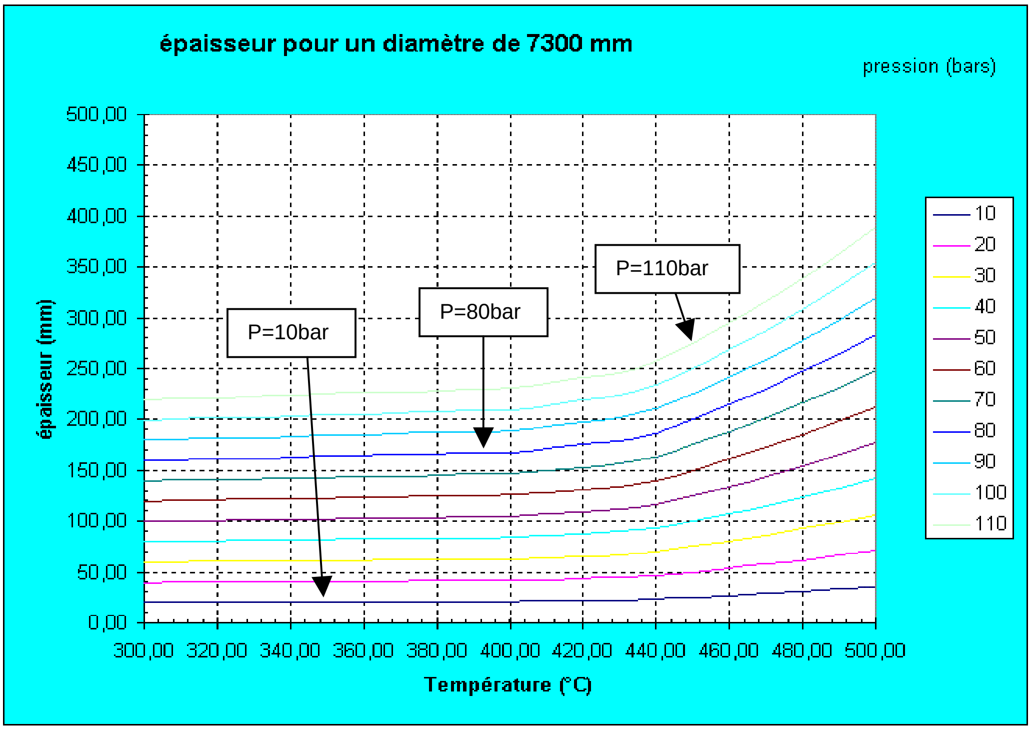
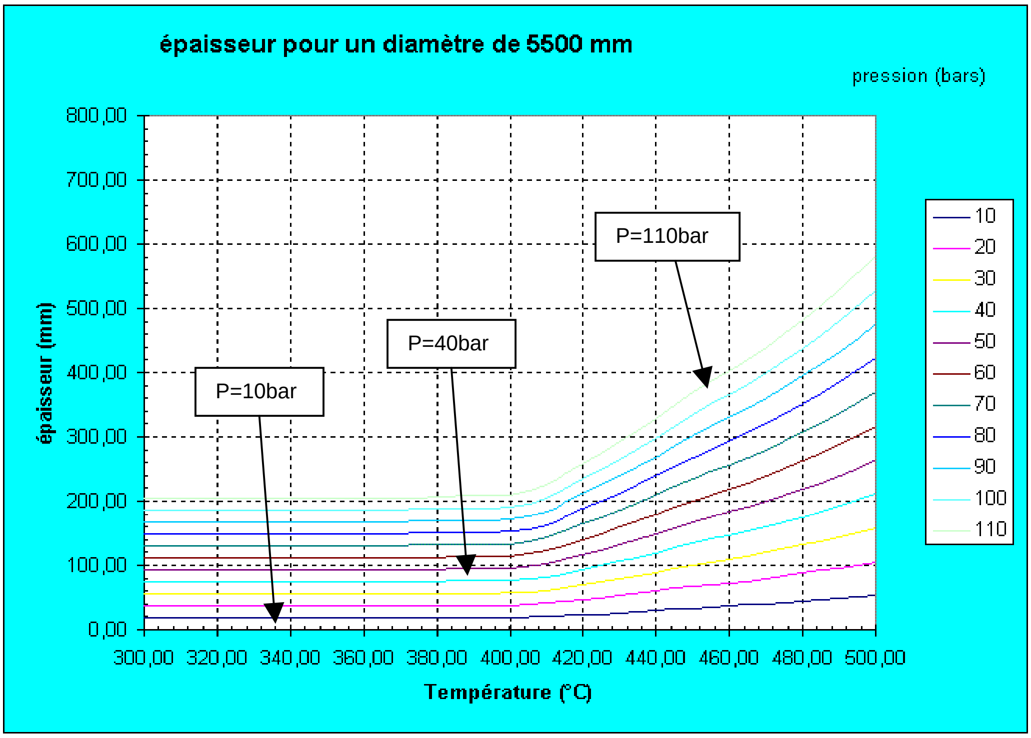


Figure 5b: HTTR case – 2¼Cr



Indice

FICHE DE VERIFICATION DU DOCUMENT

TITRE DU DOCUMENT : European Project for the Development of HTR Technology – Materials for the HTR - HTR-M Project – WP1 Task 1.4 : Damage Mechanisms

Rédacteur : M.T. CABRILLAT

Vérificateur : Y. LEJEAIL Date : Visa :

ACTIONS	SUFFISANT *	
1) Vérification de la forme		
- Résumé	oui	non
- Plan du document	oui	non
- Clarté	oui	non
- Texte	oui	non
- Figures (titres, échelles, légendes)	oui	non
- Tableaux (titres, unités)	oui	non
2) Vérification du fond		
- L'étude s'appuie-t-elle sur une analyse de l'état de l'art ?	oui	non
- Le problème est-il clairement posé ?	oui	non
- Les hypothèses sont-elles clairement définies ?	oui	non
- Les données sont-elles exactes et appropriées ?	oui	non
- Les méthodes employées sont-elles justifiées et validées ?	oui	non
- Les ordres de grandeur sont-ils cohérents ?	oui	non
- Les documents de références et les documents applicables sont-ils mentionnés ?	oui	non
3) Vérification des conclusions		
Les conclusions sont-elles justifiées ?	oui	non
4) Observations		

* Si la rubrique ne s'applique pas, inscrire S.O. (sans objet).