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Summary

The different grades of steels which are of interest for the HTR vessels can be separated in four different groups of ferritic steels :

- high chromium group of steels which comprises Russian grade (10Cr9MoVNb), American ASTM/ASME grade 91 and its equivalent European grade called modified 9Cr1Mo or Z10CDVNbV9-1,

- medium chromium group of steels which comprises Russian grade (15CrNiMoV), European grades (2¼ Cr1Mo or 7CD9-10 ; 10CD9-10) and American ASTM/ASME grade 22,

- LWR low alloy group which includes the different grades used for Light Water Reactor (French 16MND5, ASME/ASTM A533 gr B Cl 1 and ASME/ASTM A508 Cl 2),

- Carbon Manganese group from which typical grades are French grades A48 or A42 and ASME/ASTM A516 grade 70.

The corresponding chemical compositions were identified and given (table 1).

The status of the American materials in the ASME Code is clarified (table 2). The domain of temperature where this code provides the design material properties is explicitly given. The information about the material properties of other materials provided by Russian code and French codes (RCC-MR and RCC-M) was also clarified with the associated temperature range.

Finally the documents which can be used to extend the tensile properties of the different candidate materials up to high temperature (500-650 °C) and those which permit an evaluation of the creep properties were listed.

For a candidate material listed above, table 3 provides the appropriate document to determine the design material properties at a given temperature. Derivation and comparison of these design properties, implications for the selection of vessel materials will be the purpose of a future document.

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(1) International GT-MHR Project :
Preliminary design working Group on Vessel Design and PCU. Meeting at Framatome Chalon and Paris La Défense. November 6-10, 2000.

(2) International GT-MHR Project : Conceptual Design Report Int. GT-MHR 100 025 prepared by OK BM. March 1998.

(3) ASME Nuclear and Pressure Vessel Code 2001.

(4) RCC-MR Design and Construction Rules for Mechanical Components of FBR Nuclear Islands. AFCEN. Mai 1993.

(5) RCC-M Design and Construction Rules for Mechanical Components of PWR Nuclear Islands. AFCEN 2000.

(6) Norms for the calculation of strength of the Equipment and Pipelines of Nuclear Power Units PNAE G7 002 86. 1989

(7) Addendum n° FM 155 to RCC-MR 1993 edition to be included in 2001 edition.

(8) AFNOR Standard NFA 49-213 mars 1990. Steel tubes. Seamless unalloyed and Mo and CrMo alloyed steel tubes for use at high temperatures. Dimensions (with normal tolerances). Technical delivery conditions.

(9) Addendum n° FM 150 and FM 151 to RCC-MR 1993 edition : to be included in 2001 edition.

(10) Letter from C.R. Brinkmann (Oak Ridge) to C. Hoffmann ABB Combustion Engineering August 23 1994.

(11) Evaluation of the elevated temperature properties and creep rupture of C-Mo, Mn-Mo and Mn-Mo-Ni steels ASTM data Series Publication DS 47. November 1971.

(12) Design properties of carbon steels : tensile and creep data EFR-DCRC-Report n° 26. 30/09/1996.

(13) An evaluation of the elevated tensile and creep rupture properties of wrought Carbon Steel. ASTM Data Series DS 11 S1. January 1970.

1. Introduction

The different projects of High Temperature Reactor as the GT-MHR (Gas-Turbine Modular Helium Reactor) or PBMR design two or three pressure vessels :

- Reactor Vessel (with a thickness of 180 to 270 mm in the case of GT-MHR Reactor Vessel),
- Power Conversion Vessel (with a thickness of 100 to 285 mm in the case of GT-MHR PCV),
- Cross vessel which is a cylindric pipe connecting the PCV to the Reactor (100 mm thick in the case cf GT-MHR).

In order to prepare a detailed comparison of the different grades and the discussion for the selection of the grades appropriate to the different service conditions, the purpose of this note is to identify the different candidates grades and to indicate their code status i.e. the code which consider them and the range of temperature where their design properties can be found. This note covers the Pressure Vessel grades from plain carbon steel to high chromium grades.

2. Chemical analyses of the different grades

The different grades of steels which are of interest for the HTR vessels can be separated in four different groups of ferritic steels :

- high chromium group of steels which comprises Russian grade (10Cr9MoVNb), American ASTM/ASME grade 91 and its equivalent European grade called modified 9Cr1Mo or Z10CDNbV9-1,
- medium chromium group of steels which comprises Russian grade (15 Cr2NiMo V), European grades (2¼ Cr1Mo or 7CD9-10 ; 10CD9-10) and American ASTM/ASME grade 22 Cl 1,
- LWR low alloy group which includes the different grades used for Light Water Reactor (French 16MND5, ASME/ASTM A533 gr B Cl 1 and ASME/ASTM A508 Cl 2,
- Carbon manganese group from which typical grades are French grades A48 or A42 and ASME/ASTM A516 grade 70.

The chemical analyses of these grades are given in table 1. For Russian grades, the analyses were given during the meeting in reference 1 : this information corrects the Mo content level of the 10Cr9MoVNb grade which is 0,60-0,80 instead of 0,06-0,08 as written in IAEA document.

The chemical analyses of ASTM/ASME grades 91 and 22 are given in section II A of ASME code (3) (see specification SA 182, SA 213, SA 335 and SA 387 for grades 91 and 22 SA 336 for grade 22 only). Some small differences can exist in the specified chemical composition in these different specifications but they are not considered to be important for the material properties.

The chemical composition of grades Z10CDVNb9-1 and 7CD9-10 are given in the specifications included in the RCC-MR (4) (RM 2422, RM 2431 and 2432 for Z10CDVNb9-1, RM 2423 and 2424 for 7CD9-10). It can be noted that Z10CDVNb9-1 and 7CD9-10 are old AFNOR designations, the foot note of table 1 gives the corresponding designation following the recent European designation system.

The chemical composition of 16MND5 is given in RCC-M (5) (M 2111, M 2112, M 2113 and M 2114) : some differences are found in the maximum specified content of phosphorus, sulfur and copper in order to improve the toughness of the parts which are concerned by irradiation effects.

The chemical compositions of A533 grade B class 1 and A508 Cl 2 are given by the section II of ASME Code (3). It should be noted that A533 grade B Class 1 is a grade for plates and A508 Cl 2 is a grade for forgings. In addition the chemical analysis of A508 Cl 2 is different from the chemical analysis of A533 gr B Cl 1 (no chromium in A533 g B Cl 1 and a minimum of 0,25 % for Cr in A508 Cl 3).

For plain carbon steels, the specified chemical analyses of A 48 and A 42 are given by the RCC-MR specifications available for plates or forgings (RM 1122 and RM 1133 for A 42, RM 1132 for A 48). It can be noted that specifications RM 1122 and RM 1133 cover thick products in A 42. Theve is no available specifications for thick products in A 48.

A 516 grade 60 and 70 were selected in ASME Code as a carbon manganese grades with a specification covering thick plates and requiring mechanical properties not far from A 48 and A 42 respectively.

3. Codes and documents providing design properties of candidate materials for Pressure Vessels

3.1 Status of the candidate materials in Codes and Standards

3.1.1 Russian grade 15Cr2NiMoV

The grade is mentioned in the Russian Code in reference 6 Design tensile properties (minimum yield strength $R_{p0,2}$ or S_y minimum tensile strength R_m and ductility data) are given from 20 °C to 350 °C (table P1.1 of reference 6).

The thermal expansion coefficient and the elastic modulus are given up to 600 °C (Tables P 1.2 and P 1.3 of reference 6). But no creep data are included for the grade 15Cr2NiMoV in tables P 1.4 and P 6.1 of the same document.

The available data mean that the grade 15Cr2NiMoVNb can be used out of the creep range that is up to 350 °C.

3.1.2 European and French grades

The grade Z10CDVNb9-1 (modified 9Cr1Mo) is covered by RCC-MR (4) in appendix A3.18S.

The design properties are given up to 600 °C. They have been reviewed during the European Fast Reactor (E.F.R.) project studies and the revised evaluation of design properties are given in (reference 7) to be included in the next 2001 edition of RCC-MR. In the reference (7) the majority of design properties is still limited to 600 °C but some creep properties are provided up to 650 °C and 675 °C.

The grade 7CD9-10 (or 2¼Cr1Mo) which is delivered after normalisation and tempering or after quenching and tempering is covered by appendix A3.16S of RCC-MR (4). The design properties including creep data are provided up to 550 °C.

For tubes the RCC-MR covers also the mill annealed grade of 10CD9-10 (or 2¼ CrMo) following AFNOR standard NFA 49-213 (8). The design properties of this grade are provided in appendix A3.14S of RCC-MR (4).

The grade 16MND5 is covered by section Z appendix ZI of RCC-M (5) which provides design properties including yield strength, tensile strength and time independent allowable stress limit S_m or S up to 370 °C. Thermal Expansion coefficients are provided up to 450 °C and Young modulus up to 600 °C.

The design data for carbon manganese grade A42 and A48 are provided by RCC-MR (4) respectively in appendix A3.11S and A3.12S. These appendices were reviewed during the EFR project and revised design properties are given in reference 9.

3.1.3 American grades

In order to clarity the status of steel grades in ASME Code (3) it is necessary to take into account the ASME class of the components (class 1, 2 or 3) and the design rules (set of rules using allowable stress limit S_m or set of rules using allowable stress limit S). As shown in table 2 for each grade and each design situation (class and set of rules) the code indicates a maximum limit temperature. In principle the temperature limits for nuclear components are those given for section III class 1 or section III classes 2 and 3 : these temperature limits are given in table 2.

The status of the candidate pressure vessel materials in non nuclear parts of the code (section VIII-1 and VIII-2) are also given for information : when a given material is permitted by VIII-2 division using S_m design rules up to a temperature θ higher than 371 °C, the subsection II D of the code provide S_m S_y and S_u values up to θ. (S_y is the minimum yield strength, S_u is related to the tensile strength but at elevated temperature can be 10 % than the evaluated lower bound of the tensile strength).

3.2 Other documents providing design material properties for Pressure Vessel steels

3.2.1 Russian grades 10Cr9MoVNb and 15Cr2NiMoV

As this grade is not included in the Russian code (Ref. 6), the document giving the material properties is the GT-MHR design document (Ref. 2).

In the Russian contributions to references 1 and 2, there are no material properties for 15Cr2NiMoV at temperatures above 350 °C.

3.2.2 American grade T91

Design data have been prepared in the appropriate form for inclusion in code case N47 (now subsection NH of section III) of the ASME-Code. In consequence material design properties such as minimum yield strength, tensile strength (lower bound and lower bound + 10 %), allowable stress limit S_m, minimum creep rupture strength S_r and allowable stress limit S_t are given in the meetings of ASME Subgroups for elevated temperature design are reported in reference 10 for temperatures beetween 371 °C and 649 °C.

3.2.3 French grade 16MND5 and American grade A533 grade B class 1

For light water applications, the design material properties are provided up to 371 °C (or 370 °C) by RCC-M and ASME Codes. It is interesting to extend the design tensile properties above 370 °C and to have an evaluation of creep properties in order :

- to perform evaluation of maximum temperature in normal service conditions acceptable for the different grades using the same criterion for all,

- to evaluate the acceptable transient hold times at elevated temperature for the different grades.

This can be done for Mn-Ni-Mo alloyed steel grades as 16MND5 and A533 grade B class 1, using the information and the data of reference 11 up to 600 °C : evaluations of minimum values of the yield strength and of the tensile strength, of S_m and of the minimum creep stress to rupture S_r are possible.

There is no data concerning the grade A508 Cl 2 in reference 11.

3.2.4 Carbon manganese steel grades A42 and A48

For the same reasons as in the case of 16MND5 and A533 gr B Cl 1, it is interesting to extend the design data of carbon manganese steel grades above 370 °C and to evaluate their creep properties.

This has been done during EFR project and is reported in reference 12 which gives minimum values of the yield stress and tensile strength and values of S_m up to 600 °C and long term creep properties S_r and S_t up to 500 °C.

3.2.5 American carbon manganese steel grades

For the same purpose as for 16MND5, A 533 gr B Cl 1, A 42 and A 48, the data of reference 13 can be used for American grades of carbon manganese steel grades including A 516 grade 60 and grade 70. The extension of tensile properties up to 538 °C and the creep data up to 566 °C which can be performed and compared to the result of the same exercise made for A 48 and A 42.

4. Conclusion

For the four categories of materials which are candidate for the vessels of HTR, the specifications and the corresponding chemical compositions were identified and given (table 1).

The status of the American materials in the ASME Code is clarified (table 2). The domain of temperature where this code provides the design material properties is explicity given.

The information about the material properties of other materials provided by Russian code and French codes (RCC-MR and RCC-M) was also clarified with the associated temperature range.

Finally the documents which can be used to extend the tensile properties of the different candidate materials up to high temperature (500-650 °C) and those which permit an evaluation of the creep properties were listed. For a candidate material listed in paragraphe 2, table 3 provides the appropriate document to determine the design material properties at a given temperature.

Derivation, comparison of these design properties and implications for the selection of Vessel materials will be the purpose of a future document.

Table 1

HTR Vessel Candidate Materials Chemical Compositions

	C	Si	Mn	P	S	Cr	Mo	Ni	V	Nb	N	Al	Cu
10Cr9MoVNb	0,08		0,30			8,6	0,6		0,15	0,10	?		
Russian grade	0,12	0,50	0,60	0,030	0,025	10	0,8	0,50	0,25	0,20			
Z10CDVNb9-1	0,08	0,20	0,30			8,0	0,85		0,18	0,06	0,030		
RCC-MR	0,12	0,50	0,50	0,020	0,010	9,0	1,05	0,20	0,25	0,10	0,070	0,040	0,10
Grade 91	0,08	0,20	0,30			8,0	0,85		0,18	0,06	0,030		
ASME/ASTM	0,12	0,50	0,60	0,025	0,025	9,5	1,05	0,40	0,25	0,10	0,070	0,040	
15Cr2NiMoV	0,12	0,17	0,30			2,20	0,50	0,80	0,08				
Russian grade	0,16	0,37	0,60	0,020	0,020	2,70	0,80	1,30	0,15				
2¼CrMo (7CD9-10)	0,07	0,15	0,30			2,00	0,90						
RCC-MR	0,11	0,35	0,70	0,020	0,015	2,50	1,10	0,30				0,020	0,20
10CD9-10		0,10	0,30			2,00	0,90						
AFNOR	0,15	0,50	0,60	0,030	0,035	2,50	1,10	0,30				0,025	0,25
Grade 22 Cl 1			0,30			2,00	0,90						
ASME/ASTM	0,15	0,50	0,60	0,025	0,025	2,50	1,10						
16MND5		0,10	1,15				0,45	0,50					
RCC-M	0,20	0,30	1,55	0,012	0,012	0,25	0,55	0,80	0,01			0,04	0,20
A533 gr B Cl 1		0,15	1,15				0,45	0,40					
ASME/ASTM	0,25	0,40	1,50	0,035	0,040		0,60	0,70					
A508 Cl 2		0,15	0,50			0,25	0,55	0,50					
ASME/ASTM	0,27	0,40	1,00	0,025	0,025	0,45	0,70	1,00	0,05				
A42													
RCC-MR	0,18	0,25	0,60	0,030	0,008	0,25	0,07	0,30					0,30
A48			0,80										
RCC-MR	0,20	0,35	1,50	0,030	0,008	0,20	0,10	0,30	0,05				0,025
A516 gr 60		0,15	0,85										
ASME/ASTM	0,27	0,40	1,20	0,035	0,040								
A516 gr 70		0,15	0,85										
ASME/ASTM	0,31	0,40	1,20	0,035	0,040								

Nota :

AFNOR Z10CDVNb91 is X10CrMoVNb9-1 in EN designation

AFNOR 7CD9-10 is 7CrMo9-10 in EN designation

AFNOR 10CD9-10 is 10CrMo9-10 in EN designation

(Numbers 7 and 10 are selected to identify the 2 grades differing from their specified carbon content)

AFNOR 16MND5 is 16MnNiMo5 in EN designation

Table 2

ASME Status of the Pressure Vessel Candidate materials : maximum temperature limits

	Design rules using S_m		Design rules using S	
	Nuclear Section III Cl 1	**Non Nuclear Section VIII - 2**	**Nuclear Section III Cl 2-3**	**Non Nuclear Section VIII - 1**
grade 91	371 °C	not permitted	371 °C(1)	649 °C
grade 22	371 °C(2)	482 °C	371 °C	649 °C
A533 grade B Class 1	371 °C	371 °C	371 °C	428 °C
A508 Class 2	371 °C	371 °C	371 °C	428 °C
A516 grade 60	371 °C	371 °C	371 °C	538 °C
A516 grade 70	371 °C	371 °C	371 °C	538 °C

(1) permitted only for thickness < 76 mm (3 inches)

(2) can be used up to 649 °C if the rules of subsection NH (formerly code case N 47) are used

Table 3

References giving the design material data or useful to derive them : HTR Vessel candidate materials

10Cr9MoVNb	**tensile**	(2)	→ **600 °C**
	creep	(1)	→ **600 °C**
Z10CDVNb9-1	**tensile**	(4 - Appendix A3-18S) + (7)	→ **600 °C**
	creep	(7)	→ **650 °C**
grade 91	**tensile**	(3) or (10) → **538 °C**	(10) → **649 °C**
	creep	(10)	→ **649 °C**
15Cr2NiMoV	**tensile**	(6) → **350 °C**	
	creep	(?)	
7CD9-10	**tensile**	(4 – Appendix A3-16S)	→ **550 °C**
	creep	(4 – Appendix A3-16S)	→ **550 °C**
10CD910	**tensile**	(4 – Appendix A3-14S)	→ **550 °C**
	creep	(4 – Appendix A3-14S)	→ **550 °C**
grade 22	**tensile**	(3 Section II – D) → **482 °C**	(3 Subsection NH) → **649 °C**
	creep	(3 Subsection NH)	→ **649 °C**
16MND5	**tensile**	(5) → **370 °C**	(12)→ **600 °C**
	creep	(11)	→ **600 °C**
A533 grade B Cl 1	**tensile**	(3 Section II – D) → **371 °C**	(11)→ **600 °C**
	creep	(11)	→ **600 °C**
A508 Cl 2	**tensile**	(3 Section II – D) → **371 °C**	
	creep	no data	
A42	**tensile**	(4 – Appendix A3-11S) → **350 °C**	(12) → **600 °C**
	creep	(12)	→ **500 °C**
A48	**tensile**	(4 – Appendix A3-12S) → **350 °C**	(12) → **600 °C**
	creep	(12)	→ **500 °C**
A516 gr 60	**tensile**	(3 Section II – D) → **371 °C**	(13) → **538 °C**
	creep	(13)	→ **566 °C**
A516 gr 70	**tensile**	(3 Section II – D) → **371 °C**	(13) → **538 °C**
	creep	(13)	→ **566 °C**