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HTR compared properties of Pressure Vessel Steels

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Summary

The design material properties of the Pressure Vessel Candidate materials are gathered and compared.

This comparison includes the following materials :

- ASME grade 91 and RCC-MR modified 9Cr1MoVNb
- Different grade of 2.25Cr1Mo steel (ASME grade 22 class 1, normalised or quenched and tempered grade of RCC-MR),
- Manganese-Nickel-Molybdenum steel (PWR grades).

The comparison indicates mainly the needs of long term creep data at moderate temperature (425 °C-500 °C) to confirm long term design values of stress to rupture (RCC-MR A3.18S as compared to ASME grade 91 and quenched and tempered 2.25Cr1Mo as compared to grade 22 class1).

For Mn – Mo - Ni steel, the data are provided by code case N 499 (Réf. 10) with associated restriction on the number and duration of transients at temperatures exceeding 371 °C.

The design implication of the mechanical properties of the different materials properties are the following.

1). It is desirable for acceptance and design of the grades as Pressure Vessel Reactor Material to have a normal service temperature lower than :
435 °C for modified 9Cr1Mo VNb grade
420 °C for 2.25CrMo grade 22 class1
410 °C for normalised or quenched and tempered grade of 2.25Cr1Mo.
371 °C for Mn – Mo - Ni grades.

2). The order of magnitude of the increased thickness of the other grades as compared to modified 9Cr1Mo grade are the following for the same pressure in normal service conditions.

- 1.25 for quenched and tempered 2.25Cr1Mo grade
- 1.5 for 2.25Cr1Mo grade 22 Class1.

In the case of selection of Mn – Mo - Ni steel, there is no increase in thickness but only limitation of normal service temperature and transient required by code case N 499.

Fatigue and creep-fatigue properties do not appear to be important criteria for the selection of pressure vessel candidate materials.

Good toughness values can be obtained in the product of the different grades but the files necessary to build a convincing method of prevention of non ductile failure are in different states :

- quite complete of course for Mn - Mo - Ni PWR steel grade,
- very limited for 9Cr1MoVNb and for 2.25Cr1Mo grade 22 class 1,
- In an intermediate situation for the particular quenched and tempered grade SAS41 grade 22 class3 developed in France as alternative material for PWR.

Degradations of toughness by aging or by irradiation do not seem to be a serious problem for normal service temperatures limited as indicated above and for irradiation dose expected for HTR

vessel. But the information necessary to include aging and irradiation effect in the prevention of non ductile failure has to be obtained and compiled for grades other than Mn - Mo - Ni steel.

Fabrication difficulties are growing up from Mn - Mo - Ni steel to modified 9Cr1MoVNb grade. The different 2.25Cr1Mo grades being in an intermediate situation. A particular problem is the connection of HTR Vessel to PCS through the Cross Vessel which can influence the choice of the material of the PCS depending on the development of a satisfactory welded joint with local post weld heat treatment or with a nickel alloy filler materiel.

Some difficulties have been found in optimisation of filler material for modified 9Cr1MoVNb grade (hot cracking cases or low impact toughness of weld metal).

Creep strength of the weld does not seem to involve very penalising stress reduction factor for a design for normal service temperature limited as indicated above but the long term data to confirm this point have to be obtained.

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1. Introduction

The different grades of steel which are of interest for application in the vessels of high temperature reactor as GTMHR (Gas Turbine Modular Helium Reactor) or PBMR (Peeble Modular Reactor) have been identified in the document in reference 1 which provides their chemical analysis and their code status.

The purpose of the present document is to review the main points of comparison of these materials for use as HT reactor vessel :

- comparison of mechanical properties including fatigue
- design implication of the compared material properties
- toughness properties and prevention of non ductile failure
- degradation of toughness by thermal aging and by irradiation
- manufacturing and welding abilities
- properties of welded joints.

2. Design materiel properties of HTR vessel candidate steel grades

2.1 Design material properties of high chromium alloyed steels

The design material properties of ASTM/ASME grade 91 defined by standards SA 182, SA 213, SA 335 and SA 387 for different types of product (forged fittings, pipe, forgings, plates) are given by reference 2. The design material properties of European modified 9Cr1MoVNb steel are given by RCC-M reference 3. The corresponding products which were for use in steam generators of liquid metal fast reactor (EFR) are defined by specifications RM 2422, RM 2431 and RC 2432.

The design properties of grade 91 and of RCC-MR modified 9Cr1MoVNb grade are summarised in appendix 1 which provides at different temperatures :

- minimum yield strength values $R_{p0,2}$,
- minimum tensile strength, values R_m,
- allowable time independent stress limit S_m,
- expected minimum values of the stress to rupture S_r,
- allowable time dependent stress limit S_t.

The tensile properties and the time independent stress limit S_m given by references 2 and 3 are quite similar. The long term creep properties given by reference 3 are significantly lower (- 22 %). The derivation of the minimum values of the stress to rupture S_r in reference 3 takes into account the creep properties of a thicks (300 mm) forged and rolled plate at 500 °C-550 °C and 600 °C. These S_r values are more pessimistic and probably more realistic for thick products at elevated temperature (500-650 °C). At moderate temperature (375-475 °C) which is the temperature long term range of interest for long term service of HTR vessel, the RCC-MR A3.18S values long term (Ref.3) are probably under estimated due to the lack of long term data at such temperatures.

2.2 2.25 chromium steel grades : ASME/ASTM grade 22, class 1

There is a large number of 2.25Cr1Mo steel grades with differences in the required tensile strength at room temperature. The different levels of yield and ultimate strength are obtained by different heat treatments and particularly by different tempering temperatures.

The ASME/ASTM grade for use at elevated temperature following the previous code Case N47 which is to the subsection NH of the edition 2001 of the code, is grade 22 class 1 of standards SA 182, SA 213, SA 335, SA 336 and SA 387. The tensile properties required at room temperature are the following :

$$R_{p0.2} \geq 205 \text{ MPa} \quad 415 \text{ MPa} \leq R_m \leq 585 \text{ MPa}$$

Fully annealed 2.25Cr1Mo steel products slowly cooled for austenisation temperature to 700 °C can meet these requirement their designation being class 1. Their design material properties are given by ASME code Section NH (Ref.4). They are summarised in appendix 2 which provides at different temperatures :

- minimum yield strength values,
- minimum tensile strength values,
- allowable time independent stress limit S_m,
- expected minimum values of the stress to rupture S_r,
- allowable time dependent stress limit S_t.

2.3 2.25 chromium molybdenum steel grade : RCC-MR 10CD9-10 and 7CD9-10

The RCC-MR covers a normalised and tempered grade which come from the French standard for seamless pipe for pressure vessel NFA 49-213 (Ref.5) and quenched and tempered grade as allowed by the French standard NFA 36-602 (Ref.6). For normalised and tempered grades and for quenched and tempered grades (Q & T or N & T 2.25Cr1Mo), the required tensile properties at room temperature are :

$$R_{p0.2} \geq 320 \text{ MPa} \quad 490 \leq R_m \leq 640 \text{ MPa}$$

These properties are obtained with a tempering temperature around 725 °C.

For forgings, the tensile requirement are those of AFNOR standard in reference 6 :

$$R_{p0.2} \geq 310 \text{ MPa} \quad 520 \leq R_m \leq 670 \text{ MPa}$$

For very thick tube sheet of LMFBR steam generator, the range of tensile strength is reduced to 520-620 MPa.

The design material properties of these products (RM 2421, RM 2423, RM 2424, RM 2441 and RM 2442) are given in appendix A3.16S of RCC-MR (Ref.7). They are summarised in appendix 2.

As shown by figure 1, the yield strength of the normalised/quenched and tempered grade is higher than the yield strength of ASME/ASTM grade 22, class 1 for the temperatures between 20 °C and 400 °C. For temperatures between 400 °C and 550 °C, the difference is less important.

The same remarks can be made for the minimum values of the ultimate tensile strength R_m (Fig. 2). The S_m values (Fig.3) are 24 MPa higher for the quenched/normalised and tempered grade at 350 °C. At 550 °C the advantage of the quenched/normalised and tempered grade on the ASME/ASTM grade 22 class 1 is only 7 MPa.

The creep properties of quenched/normalised and tempered grade were chosen equal to those of ASME/ASTM grade 22 class 1 because it was considered that the improvement of mechanical properties gained by the heat treatment cannot be extended to long term creep data.

The room temperature tensile properties of RCC-MR quenched/normalised and tempered grades are similar to those of ASME/ASTM grade 22, class 3 for forgings and to grade SA 387 F2 class 2 for plates :

$$R_{p0.2} \geq 310 \text{ MPa} \quad 515 \text{ MPa} \leq R_m \leq 690 \text{ MPa}$$

2.4 Other grades of 2.25Cr1Mo alloy steels

Other grades and classes of 2.25Cr1Mo steels are defined by ASME/ASTM standards :

- SA 541 grade 22 class 3 for forgings and SA 542 type B class 4 for plates ($R_{p0.2} \geq 380$ MPa ; 585 MPa $\leq R_m \leq$ 760 MPa),
- SA 541 grade 22 class 4 for forgings ($R_{p0.2} \geq 590$ MPa ; 720 MPa $\leq R_m \leq$ 900 MPa),

These grades are obtained by reduction of the minimum specified temperature for tempering from 675 °C for grades F22 class 2 to 650 °C for grade 22 class 3 and 595 °C for grade 22 class 4.

The recent harmonised European standard for forgings NFEN 1022-2 (Ref.8) defines the grade X11CrMo9-10 with tensile properties similar to those of RCC-MR quenched/normalised and tempered grade :

$$R_{p0.2} \geq 310 \text{ MPa} \quad 520 \text{ MPa} \leq R_m \leq 670 \text{ MPa}$$

For thickness exceeding 200 mm however, the specified tensile properties are reduced :

$$R_{p0.2} \geq 265 \text{ MPa} \quad 450 \text{ MPa} \leq R_m \leq 600 \text{ MPa}$$

This grade is also delivered in normalised and tempered conditions or in quenched and tempered conditions with a tempering temperature between 670 °C and 770 °C.

The values of $R_{p0,2}$ provided by the European standard are reported in appendix 2. The values for thick forgings (250 mm < t ≤ 500 mm) are lower than those of RCC-MR quenched/normalised and tempered grade and even lower than those of ASME/ASTM grade 22 class 1 for temperature exceeding 350 °C.

Mean values of the stress to rupture are also provided by reference 8 for 10^4 h and 10^5 h. The indicated values are greater at 450 °C and 550 °C than the minimum values of ASME/ASTM grade 22 class 1 by a factor exceeding 1.25.

Finally there is also a modified grade of 2.25Cr1Mo steel : its designation is grade 22V which indicates an addition of vanadium ($\simeq$ 0,3 %). This grade has high specified tensile properties : $R_{p0.2} \geq 415$ MPa, 585 MPa $\leq R_m \leq$ 760 MPa with a tempering temperature equal or greater than 675 °C. This grade is not permitted by ASME code for nuclear applications.

2.5 Manganese - nickel - molybdenum alloy steels

The French grade of forged parts for Pressurised Water Reactor (PWR) vessel is named 16MND5. It is a manganese nickel molybdenum low alloy steel.

The corresponding ASME/ASTM grade is A508 grade 3 class 1 (formerly A508 cl.3). The design material properties are the same in RCC-M for 16MND5 (Ref.9) and in ASME code for A508 grade 3 class 1 and also for the grade A533 grade B class 1 (formerly A533 grade B class 1). Some tensile properties and short and medium term creep properties are provided by the Code Case in reference 10. They are reported in appendix 3. When compared to some experimental data at 500 °C on French 16MND5 (Fig. 4) , the minimum stress to rupture S_r of reference 10 is confirmed to be a lower bound the S_r curve being lower than experimental data.

3. Comparison of the mechanical properties of the different candidate materials

3.1 Tensile properties

The comparison of the tensile properties of the different grades is presented in figure 1 and 2, for the yield strength and for the tensile strength respectively. The different heat treatments and chromium addition produce important differences in the yield strengths at 350 °C from 186 MPa for ASME/ASTM grade 22 class 1 to 356 MPa for ASME/ASTM grade 91 with the following intermediate levels :

- 225 MPa for for RCC-MR Q & T or N & T 2.25Cr1Mo,
- 299 MPa for A508 grade 3 class 1.

The differences of the tensile strength are lower going from 401 MPa for ASME/ASTM grade 22 class 1 to 552 MPa for A508 grade 3 class 1 with intermediate values of 468 MPa for quenched and tempered or normalised and tempered 2.25Cr1Mo and of 493 MPa for modified 9Cr1Mo (examples given also at 350 °C).

The time independent allowable stress limit S_m which is derived from tensile properties is show in figure 3.

The S_m values of modified 9Cr1Mo and SA 508 grade 3 class 1 are very similar up to 350 °C (184 MPa). The S_m values of ASME/ASTM are significantly lower (123 MPa). The S_m values of quenched/normalised and tempered 10CD9-10 are intermediate (147 MPa).

3.2 Creep properties and time dependent allowable stress limit S_t

The minimum expected stresses to rupture S_r at different temperatures and for 100 h, 1000 h and 10000 h are compared in figures 5 to 7.

The slopes of S_r against temperature curves are similar for the chromium alloyed steels (grade 22, grade 91). This slope is steeper for grade A508, grade 3 class 1 and the S_r values of this grade be come lower than S_r values of grade 22 at 560 °C for 100 h, 540 °C for 1000 h and 510 °C for 10^4 h. The corresponding temperatures obtained when A508 grade 3 class 1 are compared to grade 91, are 445 °C, 400 °C and 370 °C.

The S_r values of grade 22 (and RCC-MR 7CD9-10/10CD9-10) are always lower than S_r values of ASME/ASTM grade 91 and RCC-MR modified 9Cr1MoVNb. At temperatures equal or greater than 400 °C, the difference increase with time, the S_r values of grade 22 being approximatively 80 % of grade 91 S_r values at short time and 40 % for long term data as compared to grade 91 or 50 % for long term data as compared to RCC-MR modified 9Cr1MoVNb.

As A508 grade 3 class 1 is not allowed by ASME for permanent use at temperatures higher than 371 °C, no long term date are given for this grade.

The difference between long term data of ASME/ASTM grade 91 and long term data of RCC-MR modified 9Cr1MoVNb has been commented in paragraph 2.1.

Figures 8 and 9 show the expected stress to rupture values for a service life of 40 and 60 years with a plant availability of 80 %. For these long terms, the difference between ASME/ASTM grade 91 and RCC-MR modified 9Cr1MoVNb exceeds 20 % and is of importance for the design (see paragraph 4.1). Long term tests to rupture at temperatures in the range 450 °C-500 °C are necessary to confirm the design.

The time dependent allowable stress limit S_t for 60 years (availability of the reactor 80 %) is shown in figure 10. The conclusions drawn from the comparison of S_t values of the different grades are the same as the conclusions drawn from the comparison of long term stress to rupture S_r.

For grade A508 grade 3 class 1, the available values of S_t are limited to 3000 h.

4. Design implications of the mechanical properties of HTR vessel candidate materials

4.1 Maximum temperature for normal service conditions

When time independent allowable stress limit S_m and time dependent allowable stress limit S_t are involved in the rules of the design code as it is the case for ASME III subsection NH and RCC-MR, there is for each service life duration t a cross over temperature θ_{co} such that :

- if $\theta_{service} \leq \theta_{co}$, the allowable stress limit and as a consequence the thickness of the current part of the cylindrical shell are governed by S_m and therefore by the tensile properties,

- if $\theta_{service} > \theta_{co}$, the allowable stress limit and the thickness of the current part of the cylindrical shell are governed by S_t and therefore by the creep properties.

The long term creep properties are quantitatively uncertain due to the types of main products considered in the data bank, to the extrapolation technique for long term data and to the definition of expected minimum values. It has been shown that the uncertainty can be as high as 20 % when ASME/ASTM grade 91 and RCC-MR modified 9Cr1MoVNb data are compared.

An uncertainty of 20 % can be expected also for the creep weld factor to be considered in the design. It is therefore highly desirable that the thickness of the cylindrical shell evaluated during the preliminary design works should not be affected by such an uncertainty. In other words, it is highly desirable that the thickness should be governed by S_m or that the normal service temperature should be lower than the cross-over temperature θ_{co}.

Table 1 gives the values of the cross-over temperatures θ_{co} for 40 and 60 years of service life and for the different steel grades candidate as HTR vessel material. Grade A508 grade 3 class 1 is not considered in this table as its temperature limit for long term service is 700 °F in ASME code Case N 499-1 (transferred to 375 °C in RCC-M/RCC-MR practices). The following conclusions can be drawn from table 1 :

- the grades come in the following order for increasing service temperature : A508 grade 3 class 1, RCC-MR quenched/normalised and tempered 2.25Cr1Mo, ASME/ASTM grade 22 class 1, RCC-MR modified 9Cr1MoVNb and ASME/ASTM grade 91,

- improving the tensile properties without improving the creep properties is detrimental for the maximum normal service temperature,

- cross-over temperatures given in table 1 are strongly dependent on long term creep properties as it is indicated by the difference of 60 °C in θ_{co} values between RCC-MR modified 9Cr1MoVNb and ASME/ASTM grade 91. The values of table 1 need to be confirmed by validation of long form creep data on representative product at moderate temperatures (400 °C-500 °C),

- the difference in maximum temperature between service life of 40 years and service life of 60 years appears to be small when compared with the uncertainty due to long term creep data.

The conclusion is that a good evaluation of long term creep data is of prime importance even for the choice of the service temperature in order to avoid the situation where the thickness of the shell is governed by creep data.

4.2 Shell thicknesses with the different HTR vessel candidate materials

Considering the temperature limit of paragraph 4.1, table 2 gives the thicknesses evaluated for different HTR vessel candidate materials, at different service temperature for a cylindrical shell of 7300 mm of internal diameter and for internal pressure of 8 MPa (80 bar).

For a given grade, the thickness of the shell is not strongly dependent on service temperature at least when the limit of paragraph 4.1 are observed.

For grade 91, increasing the service temperature from 350 °C to 450 °C results in 22 mm increased thickness.

At lower temperatures (350-375 °C) ASME/ASTM grade 91 and A508 grade 3 class 1 give similar thicknesses. ASME/ASTM grade 22 needs a thickness increased by a factor of the order of 1.5 for temperature of 350 °C to 405 °C. RCC-MR quenched/normalised and tempered 2.25Cr1Mo needs an intermediate thickness 1.2 to 1.25 the thickness for grade 91.

Such thickness evaluations are of course only for comparison purpose and the complete design will result in some thicker parts in order to bear stress concentrations and thermal stresses in nozzle and flanges. Nevertheless the order of magnitude of 1.5 and 1.25 for increased thickness of a vessel in grade 22 class 1 and in quenched/normalised and tempered 2.25Cr1Mo as compared with grade 91 can be kept in mind.

4.3 HTR vessel candidate material : behaviour during thermal transients

The choice of the material for the HTR vessel can be dependent of the resistance to transients if it is hot transient at temperature higher than normal service temperature with in some area of the vessel significant stresses : this situation implies probably that the pressure is kept on. Let us consider for comparison purpose a stress level of 250 MPa. For different transient duration (100 h, 300 h, 1000 h and 3000 h), table 3 give the maximum temperature for a part of HTR vessel under a stress of 250 MPa.

The comparison of ASME/ASTM grade 91 with ASME/ASTM grade 22 class 1 or RCC-MR quenched/normalised and tempered 2.25Cr1Mo indicates an increasing differences in the maximum acceptable transient temperature as the transient duration increases from 58 °C for 30 h to 87 °C for 3000 h of transient duration.

In the case of A508 grade 3 class 1, the code case in reference 10 limit the cumulated duration of transients above 438 °C to 3000 h and to a number of 3 and a total duration of 1000 h the transients between 425 °C and 538 °C. Those limitations do not depend on the stress level. If the number of transient met the requirement of code case N499, table 3 shows that the maximum temperature for transient of 100 h, 300 h and 1000 h between 427 and 538 °C are less sever than in the case of ASME/ASTM grade 22.

5. Comparison of fatigue properties of HTR vessel candidate materials

5.1 Comparison of fatigue design curves

The fatigue design curves given for ASME/ASTM grade 91 at 538 °C maximum temperature and for ASME/ASTM grade 22 at 427 °C and at temperatures between 482 and 593 °C are shown in figure 11. For number of cycles between 100 and 2.10^5, the curve of grade 91 is between the two curves of grade 22. As usual the endurance fatigue curves in the low cycle regime of the different grades are not a powerful criterion for the selection of candidate materials.

It seems that the high cycle fatigue endurance of grade 22 is lower than that of grade 91 : but as it will be discussed here after, this point needs confirmation.

The fatigue design curve of ASME/ASTM grade 91 and that of RCC-MR modified 9CrMoVNb are compared in figure 12. Between 100 and 40000 cycles the difference are small and can be due to the formulation of the mean curves and to the details of the derivation of the design curve (RCC-MR data are mainly low cycle fatigue data at 525°C and 550 °C). At higher number of cycles no correction using high cycle result was applied in the case of RCC-MR design curve and it falls under the curve of ASME/ASTM grade 91. High cycle fatigue data are desirable to produce design curves with better validation in the domain of high cycle fatigue which can be used for design against vibrations or thermal fluctuations.

5.2 Creep fatigue behaviour

There are difficulties in the validation of the creep fatigue interaction diagram for ASME/ASTM grade 91 and RCC-MR modified 9Cr1MoVNb steels :

- following fraction rule, it is difficult to produce significant creep damage in strain controlled fatigue with hold time experiments, this is due to the cycle behaviour of the material with a trend to cyclic softening which is enhanced by relaxations during hold times,

- the hold time in compression appears to be as detrimental or more detrimental than the tensile hold time for the cyclic endurance,

- oxidation which increases when the duration of the elevated temperature fatigue test can play an important role in the reduction with hold time of number of cycles to failure.

Waiting for a more complete understanding of creep fatigue interaction in modified 9Cr1MoVNb grades (as in fact in other ferritic steel grades) it was decided in Europe (Ref.11) as in USA (Ref.2) to use the same creep fatigue interaction diagram for modified 9Cr1MoVNb and for 2.25Cr1Mo grades (Fig.13). As a consequence, resistance to creep-fatigue is not an important criterion for the selection of the material for HTR vessel.

6. Toughness of HTR vessel candidate materials

6.1 Protection against non ductile failure

The ASME method of protection against non ductile failure (Ref.12) is to be used with the impact, drop weight, static fracture, dynamic fracture and crack arrest toughness properties of A533 type B class 1 and A508 grade 3 class 1 materials.

In principle the same method can be used for other ferritic materials if the following data are available :

- reference transition temperature,
- reference curve in the transition temperature range for stress intensity factor,
- stress intensity factor against temperature in the upper shelf domain,
- influence of irradiation on transition temperature,
- influence of irradiation on the upper shelf stress intensity factor.

In the case of elevated temperature service complementary informations are needed on :

- influence of thermal aging on the transition temperature,
- influence of thermal aging on the upper shelf stress intensity factor.

6.2 Toughness data of 2.25Cr1Mo steel grades

Toughness characterisation have been performed for two grades of 2.25Cr1Mo steel :

- the Japanese grade similar to SA 387 grade 22 class 2 in reference 13,
- the French grade similar to SA 541 grade 22 class 3 developed for PWR vessel in place of present A508 grade 3 class 1 (16MND5) steel.

With low impurity levels of the Japanese grade (P and S), high toughness was obtained in both cases :

- low transition temperature
- high upper shelf toughness.

The important difference from A508 grade 3 class 1 type of materials is in the transition temperatures : in the case of 2.25Cr1Mo grades the Charpy V transition temperature for 68J is lower than the NDT temperature measured by Pellini drop weight test.

This trend is confirmed by the data of reference 14 on as received and post weld heat treated product : - 55 °C ≤ NDT ≤ - 15 °C ≤ ; - 80 °C ≤ T_{68J} ≤ - 55 °C. In this case the reference transition curve RT_{NDT} as defined in ASME III is governed by the drop weight test.

The upper shelf toughness data are of the order of 300 MPa√m and higher than the 220 MPa√m of the ASME K_{IR} reference curve.

In the case of annealed grade 22 materials of reference 16, the RT_{NDT} is governed by the Pellini drop weight test but the 68J Charpy V transition temperature (T_{68J}) is higher than the Pellini NDT (with one exception).

The difference between NDT and T_{68J} is smaller and some data for upper shelf toughness fall under the ASME level of 220 MPa√m. This is not the result of annealing treatment but is due to the sulfur level of samples tested in reference 14 (0,016 to 0,026 %).

Taking these results into account, the references 14 and 15 propose to use the reference curve of ASME III appendix G (12) but to modify the reference temperature T_{us} used for temperature scaling :

- T_{us} = FATT if FATT ≥ - 20 °C,
- T_{us} = - 20 °C if FATT ≤ - 20 °C,

FATT is the fracture appearance transition temperature (50 % ductile and 50 % brittle appearance) of the Charpy V transition data.

6.3 Toughness of modified 9Cr1Mo grade

The development of modified 9Cr1Mo grade for LMFBR steam generator was initially for use as tube sheet in order to keep the thickness acceptable and to have high toughness properties everywhere through the perforated plate. This was obtained with the fully martensitic structure of modified 9Cr1Mo which is tougher than the bainitic 2.25Cr1Mo grades.

Impact values required by RCC-MR are higher than those required for grade 2.25Cr1Mo. But in both cases the obtained values are higher than minimum specified values.

There was no extensive study of the transition temperature of modified 9Cr1Mo products using Charpy V test and drop weight tests. There was no clear proposal for reference temperature determination. These is also no conclusion about the validity of K_{IC} or K_{IR} reference curve in the transition range.

The integral J data at 500 °C of reference 17 indicate an upper shelf toughness higher than the ASME level of 220 MPa√m.

6.4 Toughness after aging

6.4.1 Toughness of aged 2.25Cr1Mo grades

Temper embrittlement is an old problem encountered by 2.25Cr1Mo grades of steel : the susceptibility to temper embrittlement is detected by the reduction of Charpy impact values after step cooling in the temperature range 600 – 450 °C. This temper embrittlement susceptibility has been related to parameters depending on the chemical composition (P, Sn for a given level of Mn and Si). When low level of phosphorus and low level of P + Sn are specified the temper embrittlement is suppressed or greatly limited (Ref.16).

For temperatures below the domain of step cooling (< 450 °C) it is considered that aging produce a shift of the transition temperature lower than step cooling and that this shift is limited when P + Sn level is low. The effect of aging on the upper shelf toughness needs further evaluations but it seems that the lower toughness are obtained in the weld metal (Ref.17).

6.4.2 Aging embrittlement of modified 9Cr1MoVNb steel

The effect of aging at temperatures of 482 °C and 538 °C (Ref.18) produces little change in tensile properties but increase the transition temperature which seems to be maximum after 25000 h. The transition temperature as measured by Charpy V level of 68J remains lower than + 50 °C indicating that the service temperature will be in the upper shelf domain. But this point needs confirmation using the reference transition temperature of paragraph 6.3 in order to build a coherent method of prevention of non ductile failure.

Reference 18 indicates that the upper shelf energy is not greatly affected by aging up to 50000 h at 482 and 538 °C but the study was performed using Charpy V and the corresponding levels of K_{IC}, K_{IR} and K_{Id} toughness need to be evaluated. It is noticeable that ageing up to 50000 h seems to produce some recovery of the upper shelf energy.

Test results reported in reference 19 indicate that with chromium content limited to 9 % there is no formation of alpha prime in the steel by aging at 471 °C or 454 °C, in opposition to the case of chromium content exceeding 10 % which is detrimental for the shift of transition temperature due to aging.

6.5 Toughness after irradiation

In principle the effect of irradiation on transition temperature is smaller in the case of Cr Mo alloy steel as grade 91 and grade 22 than in the case of Mn - Mo - Ni steel as A508 grade 3 class 1 : this is attributed to the effect of nickel which is limited to 0.30 and 0.20 in the grades 2.25Cr1Mo and modified 9Cr1MoVNb of RCC-MR.

The expected better resistance of the different grades of 2.25Cr1Mo to radiation embrittlement was the main reason of the development of the SA 541 grade 22 class 3 in place of Mn - Mo - Ni steel for PWR.

This has been verified in the case of 2.25Cr1Mo grade (SA 541 grade 22 class 3) after irradiation at 290 °C up to 3.5×10^{19} n/cm^2 : the shift in transition temperature is lower than 20 °C. The upper shelf KV values remain high (> 250J) but there is no corresponding upper shift K_{IC} data (Ref.20).

In the case of modified 9Cr1MoVNb steel, the available results after irradiation at 300 – 400 °C indicate that the shift in the transition temperature is moderate :

- less than in the case of grades with 12 % Cr (Ref.21),
- less than in the case of grade with 17 % Cr (Ref.22),
- less than in the case of grades with 2.25 and 5 % Cr (Ref.20).

The available data indicate also low upper shelf toughness after irradiation (30 dpa at J_{IC} = 30 k J/m2 according reference). But the irradiation level 30 dpa is more than 100 times those of the HTR vessel 8.10^{18} N/cm^2 E > 1 MeV or 0,25 dpa, using for sake of comparison the fact that end of life for PWR wall corresponds to 5.6 10^{19} n/cm^2 or 1,74 dpa.

The conclusion for this low dose level is that the service temperature 400 – 450 °C will remain the upper shelf domain during full life. This point will be rationalised when the question of relevant reference transition temperature for modified 9Cr1MoVNb grade will be solved. But the effect of low dose on upper shelf toughness needs also to be clarified.

7. Manufacturing of the pressure vessels

7.1 Pressure vessel in manganese – nickel – molybdenum steel

If manganese – nickel – molybdenum steel is used, the reference for manufacturing the vessel would be the main vessel of Pressurised Water Reactor for :

- procurement specification of forged parts,
- welding procedure and filler metal selection,
- manufacturing scenario inducting examinations of welds and post weld heat treatments.

The main differences are due to the size of the vessel :

- extension of the experience of the producers of forged parts to diameter up to 8500 mm,
- bending of heavy plates if the vessel cannot be entirely made with forged parts,
- need for a welding workshop on site to join different packages which have to be transported from factory workshop to the site.

If the first action failed, there can be important consequences :

- need for procurement specification of heavy plates,
- facility for bending of heavy plates,
- existence of axial welds in the vessel.

The last point implies that there are more stressed welds than the circumferential welds and that the surveillance program to propose for the reactor vessel must take into account this type of welds.

Welding on site implies that a post weld heat treatment facility able to encompass the greater package of reactor vessel and power conversion system (PCS) will be built on site.

In fact local post weld heat treatments do not enter in the practice of reactor vessel manufacturing.

The connection of PCS to reactor vessel through the cross vessel needs to be post weld heat treated.

This means one of the following alternatives :

- a local heat treatment for Mn Ni Mo alloy steel is validated with its main requirements (width of the treated area, temperature gradients),
- the heat treatment facility on site can encompass the cross vessel and the package of reactor vessel and PCS connected to it.

7.2 Pressure vessel in one of the grades of 2.25Cr1Mo type

As there is some experience in France in producing and welding heavy forged parts in a grade near to SA 541 grade 22 class 3 and as this manufacturing experience can be extended to other grades of 2.25Cr1Mo type, the manufacturing problems and solution are the same as for Mn - Ni - Mo grade. No differences are expected in the production of large parts. Convenient filler materials exist but the properties of the weld joints must be evaluated (see paragraph 8). The difference which can be important for the cost is the required temperature for heat treatments and particularly for post weld heat treatments 630 – 660 °C for 2.25Cr1Mo type of steels and 620 °C for Mn - Ni - Mo grade.

7.3 Pressure vessel in modified 9CrMoVNb steel

The difficulties to over come in order to built an HTR vessel in modified 9Cr1MoVNb steel are the same as in the case of 2.25Cr1Mo grades but the solutions are more difficult or costly to optimise :

- for the producer of forgings the limit of the mass of individual cast or ingot is lower for high chromium alloy steel than for 2.25 Cr alloy steel,
- filler metals producing a weld metal of high toughness are difficult to select,
- post weld heat treatment would be performed at significantly higher temperature (near 750 °C),
- local heat treatment to apply to the weld connecting the reactor vessel and the PCS through the cross vessel seems move difficult to define and validate in the case of modified 9Cr1MoVNb steel.

7.4 Connection by welding of PCS to HTR vessel

The choice of the material of the Power Conversion System (PCS) implies several options for the connection by welding of the PCS vessel to the reactor vessel :

- the grade of the PCS (at least the package connected to the reactor vessel through the cross vessel) is the same as the grade of the HTR vessel,
- the grade of the PCS is a lower alloyed steel (2.25Cr1Mo or SA 508 grade 3 class 1) and there is a welded joint in the cross vessel with mixed materials.

In the first case, the fabrication problem is the local post weld heat treatment with associated thermal requirement which are to settle and can be more sever than those of the SA 508 grade 3 class 1 material.

In the second case the post weld heat treatment if adapted to modified 9Cr1MoVNb material will be overheating and overaging for the other grade. The properties of the welded joint with overheated heat affected zone would need characterisation by tensile, creep, fatigue and fracture mechanics tests in order to validate the solution.

An alternative solution is the use of alloy 82 as filler material for this welded joint. The filler material is compatible with both of the parent materials.

Buttered layers can be heat treated with each of the parent materiel parts. The final weld does not need post weld heat treatment of buttered layers if they are thick enough to prevent heat reaffectation of the parent materials. As for the preceding solution, the alloy 82 welded joint need characterisation taking into account the service temperature expected at the precise location of the weld : less will be this temperature, easier will be the validation of the joint by mechanical testing.

8. Welding and properties of welded joint of HTR vessel candidate materials

8.1 Selection of optimised filler materials

There are commercial available consumables for the different types of 2.25Cr1Mo steels and for 16MND5 or A508 grade 3 class 1 for shielded metal arc welding (SMAW) submerged arc welding (SAW) and gas tungsten arc welding (GTAW). The selection will be based on the tensile and creep properties at temperature relevant to the service conditions including creep testing on cross weld specimen in order to include the heat affected zone and to evaluate the risk of premature type IV cracking in service.

In the case of modified 9Cr1MoVNb grade, several filler metal composition for SAW, SMAW and GTAW have been tested and reported. These reports indicate two problems which complicate the selection of filler materials :

- hot cracking in the weld metal (Ref.23),
- low impact toughness at 0 °C in some of the weld metals, at least for SMAW and SAW (Ref.24) even after post weld heat treatment at 750 °C or 760 °C.

Reduction of niobium content improve the filler materials for both problem. Increasing nickel content improve toughness properties of the weld metal. But the optimisation of the filler material is difficult when creep strength of the welded joints must be taken into account because niobium is known to improve tensile and short and long term creep strength. On the other hand nickel has a clear although not explained detrimental effect on the creep strength of 9 – 12 % chromium alloy steels.

8.2 Properties of the welded joints

8.2.1 Modified 9Cr1MoVNb welds

Concerning toughness, there seems to be no problem for the heat affected zone : if high enough (≥ 740 °C) the post weld heat treatment result in a toughness level as high as in the parent material. The selection of filler material to obtain an acceptable toughness in the weld and after post weld heat treatment has been discussed in paragraph 8.1. It should be noted that there is an optimum for toughness properties in temperature and duration of the post weld heat treatment : if longer the heat treatment is detrimental to the toughness for parent material as well as for the weld metal. The effect of ageing which can be different in the parent material and in the weld metal has to be tested for the second.

Creep strength of the welded joint is another important property. It is the creep strength of the weld metal which has been taken into account in the filler material optimisation reported in reference 24. But when the creep strength of the weld metal is satisfactory, the weak zone in creep is located in the heat affected zone (HAZ). This is due to the microstructures produced by the thermal cycles during welding and to post weld heat treatment. In the case of cross weld tensile and short term creep tests, the softened zone is the coarse grain part of the HAZ. In the case of long term cross weld creep tests, work on other ferritic steels has shown that weldments may fail prematurely by what has been called Type IV cracking under certain temperature/stress conditions. These failures are associated with a very fine grained microstructure which forms part of the HAZ. This fine grain zone will allow cavitation and failure to occur in this region provided that the temperature is sufficiently high or the strain rate sufficiently low at an adequate temperature such that grain boundary movements are significant.

In principle this long term cracking mechanisms is more efficient when the service temperature is higher and the data of reference 24 confirm clearly that the deviation of cross weld creep stress to rupture from base material stress to rupture appears for shorter times at 650 °C than at 600 °C. At 550 °C no deviation is detected before 20 000 h.

This trend is taken into account in the creep strength weld factor J_r proposed in reference 2 and reported in Table 4 : J_r decreases when temperature increases form 482 °C (J_r = 0,93) to 649°C (J_r = 0,76).

Long term cross weld creep tests at relatively low temperature (400 °C – 500 °C) are necessary to check whether or not the proposed values for J_r are unduly pessimistic for a service temperature limited to 435 or 495 °C as explained in paragraph 4.1.

8.2.2 Welds of 2.25Cr1Mo grades

Concerning toughness there seems to be no problem in the HAZ and the weld metal with the commercial available consumables. HAZ and weld metal appear to as tough as the base metal.

For creep properties of the welded joint, the situation is similar to the case of 9Cr1Mo steel. Values of creep strength reduction factor J_r are given in reference 4 for grade 22 and for selected filler material following American welding society (AWS) standards : there is no reduction for temperature up to 454 °C (J_r = 1) and a very small reduction at 482 °C (J_r = 0,99 for 3.10^5 h).

For other grades of 2.25Cr1Mo steel, cross weld creep test at 400 – 450 °C are necessary to justify the use of J_r = 1 for service temperature limited to 410 °C or 420 °C.

8.2.3 Welds of manganese-nickel-molybdenum steel

The toughness properties of Mn – Mo - Ni steel welds are well known from the PWR experience with the use of the corresponding filler materials and welding procedures.

For creep properties which can be of interest for the transients allowed by the code case in reference 10, some cross weld creep tests would be of interest in order to conclude that there is no reduction factor to consider for the temperature time conditions of the table giving S_t values in appendix 3.

9. Conclusion

The design material properties of the Pressure Vessel Candidate materials are gathered and compared.

This comparison includes the following materials :

– ASME grade 91 and RCC-MR modified 9Cr1MoVNb

– Different grade of 2.25Cr1Mo steel (ASME grade 22 class 1, normalised or quenched and tempered grade of RCC-MR),

– Manganese-Nickel-Molybdenum steel (PWR grades).

The comparison indicates mainly the needs of long term creep data at moderate temperature (425 °C-500 °C) to confirm long term design values of stress to rupture (RCC-MR A3.18S as compared to ASME grade 91 and quenched and tempered 2.25 Cr1Mo as compared to grade 22 class1).

For Mn – Mo - Ni steel, the data are provided by code case N 499 (Réf. 10) with associated restriction on the number and duration of transients at temperatures exceeding 371 °C.

The design implication of the mechanical properties of the different materials properties are the following.

3). It is desirable for acceptance and design of the grades as Pressure Vessel Reactor Material to have a normal service temperature lower than :
435 °C for modified 9Cr1Mo VNb grade
420 °C for 2.25CrMo grade 22 class1
410 °C for normalised or quenched and tempered grade of 2.25Cr1Mo.
371 °C for Mn – Mo - Ni grades.

4). The order of magnitude of the increased thickness of the other grades as compared to modified 9Cr1Mo grade are the following for the same pressure in normal service conditions.

- 1.25 for quenched and tempered 2.25Cr1Mo grade
- 1.5 for 2.25Cr1Mo grade 22 Class1.

In the case of selection of Mn – Mo - Ni steel, there is no increase in thickness but only limitation of normal service temperature and transient required by code case N 499.

Fatigue and creep-fatigue properties do not appear to be important criteria for the selection of pressure vessel candidate materials.

Good toughness values can be obtained in the product of the different grades but the files necessary to build a convincing method of prevention of non ductile failure are in different states :

– quite complete of course for Mn - Mo - Ni PWR steel grade,

– very limited for 9Cr1MoVNb and for 2.25Cr1Mo grade 22 class 1,

– In an intermediate situation for the particular quenched and tempered grade SAS41 grade 22 class3 developed in France as alternative material for PWR.

Degradations of toughness by aging or by irradiation do not seem to be a serious problem for normal service temperatures limited as indicated above and for irradiation dose expected for HTR vessel. But the information necessary to include aging and irradiation effect in the prevention of non ductile failure has to be obtained and compiled for grades other than Mn - Mo - Ni steel.

Fabrication difficulties are growing up from Mn - Mo - Ni steel to modified 9Cr1MoVNb grade. The different 2.25Cr1Mo grades being in an intermediate situation. A particular problem is the connection of HTR Vessel to PCS through the Cross Vessel which can influence the choice of the material of the PCS depending on the development of a satisfactory welded joint with local post weld heat treatment or with a nickel alloy filler materiel.

Some difficulties have been found in optimisation of filler material for modified 9Cr1MoVNb grade (hot cracking cases or low impact toughness of weld metal).

Creep strength of the weld does not seem to involve very penalising stress reduction factor for a design for normal service temperature limited as indicated above but the long term data to confirm this point have to be obtained.

Table 1

Cross over temperature θ_{co} (°C)

	Grade			
Service life	**ASME/ASTM Grade 91**	**RCC-MR A3.18S Modified. 9Cr1MoVNb**	**RCC-MR A3.16S Q & T or N & T 2.25Cr1Mo**	**ASTM/ASME Grade 22 – Class 1**
40 years	499 °C	439 °C	410 °C	421 °C
60 years	494 °C	434 °C	406 °C	417 °C

Table 2

Thickness in mm for a cylindrical shell of internal diameter 7300 mm for internal pressure of 8 MPa (80 bar)

Service Temperature (°C)	ASME/ASTM Grade 91	RCC-MR A3.18S Mod.9Cr1MoVNb	ASME/ASTM Grade 22 class 1	RCC-MR A3.16S Q & T or N & T 2.25Cr1Mo	ASME/ASTM SA 508 Grade 3 class 1
350	160	161	238	199	159
375	164	165	238	201	159
400	168	168	238	203	
405	169	169	238	204	
415	172	172		.	
425	175	174			
435	178	177			
450	182				
490	199				

Table 3

Maximum transient temperature under 250 MPa for the different HTR vessel candidate materials

Transient duration	ASME/ASTM Grade 91	RCC-MR Mod. 9Cr1MoVNb	RCC-MR Q and T or N and T 2.25Cr1Mo	ASME/ASTM Grade 22 class 1	ASME/ASTM SA 508 Grade 3 class 1
30 h	562 °C	554 °C	503 °C	504 °C	538 °C (1)
100 h	550 °C	539 °C	483 °C	484 °C	(521 °C)
300 h	540 °C	525 °C	468 °C	468 °C	(504 °C)
1000 h	529 °C	511 °C	450 °C	450°°C	(487 °C)
3000 h	520 °C	498 °C	438 °C	433 °C	427 °C (1)

(1) limit due to the requirements of code Case N499-1

Table 4
9Cr1MoVNb welds : proposed values for creep stress to rupture reduction factor J_r

Temperature °F	900	1000	1100	1200
Temperature °C	482	538	593	649
J_r	0,93	0,90	0,85	0,76

Figure 1

Materials candidate for HTR vessel : yield strength

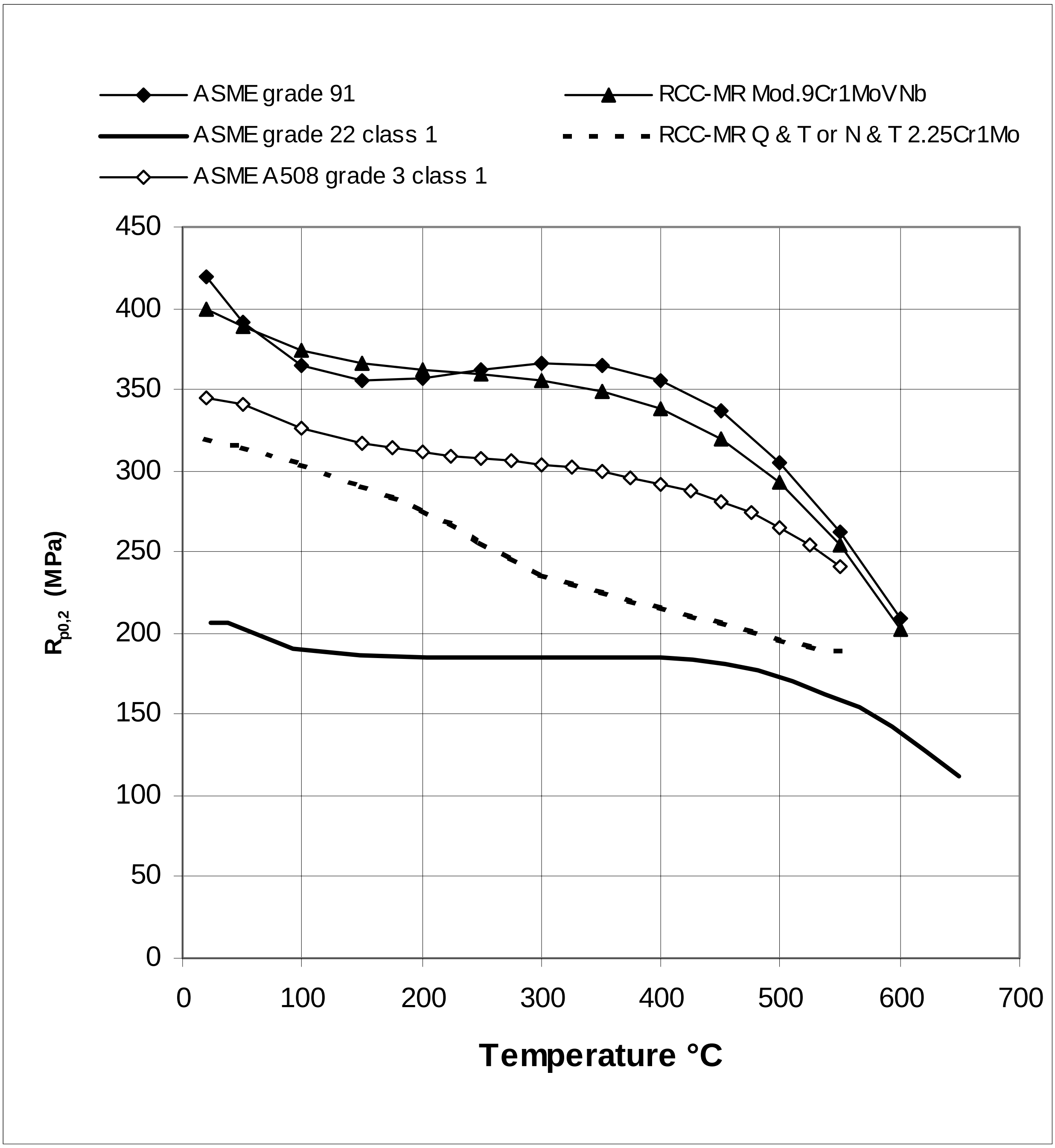


Figure 2

Materials candidate for HTR vessel : ultimate tensile strength

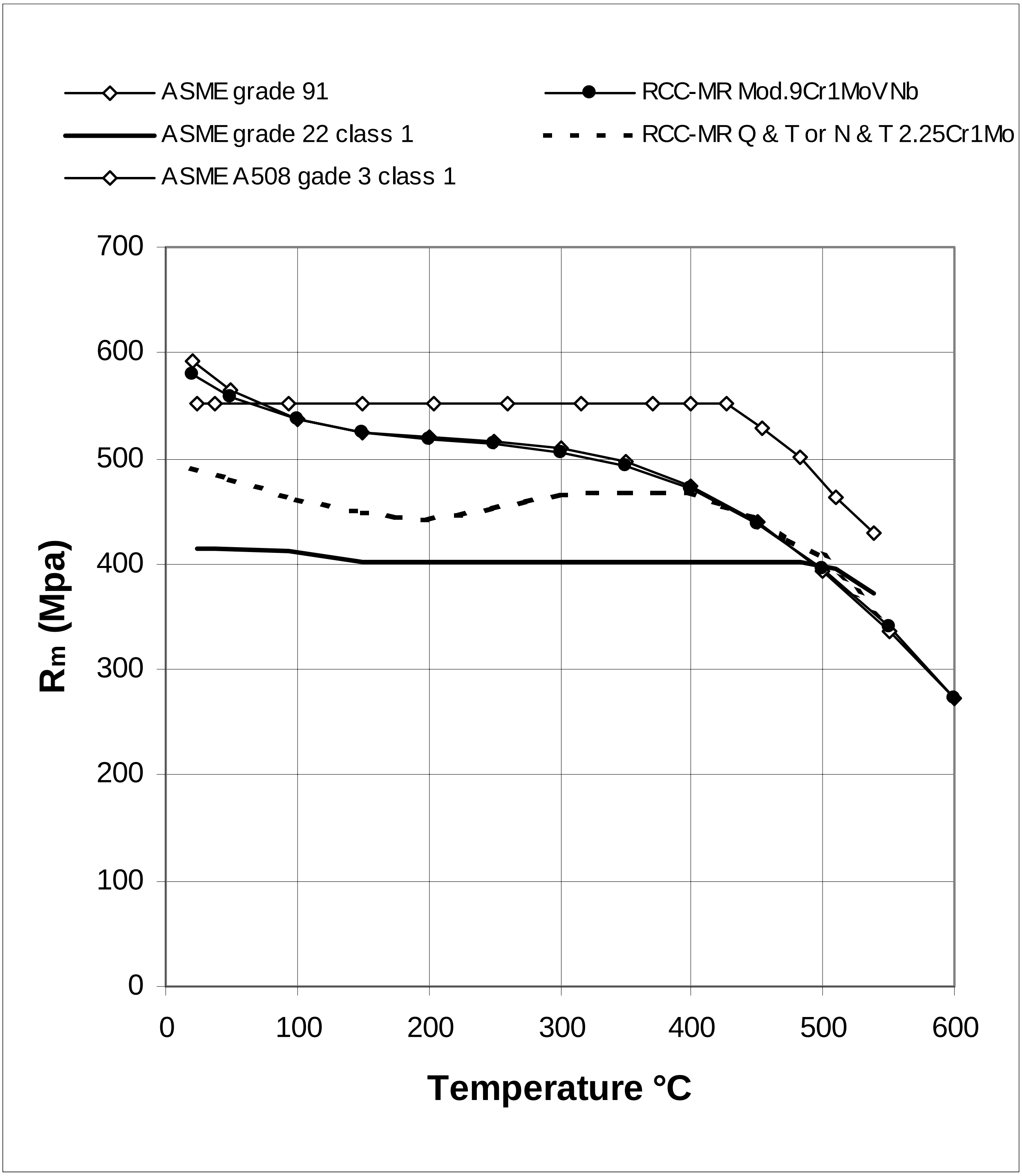


Figure 3

S_m values

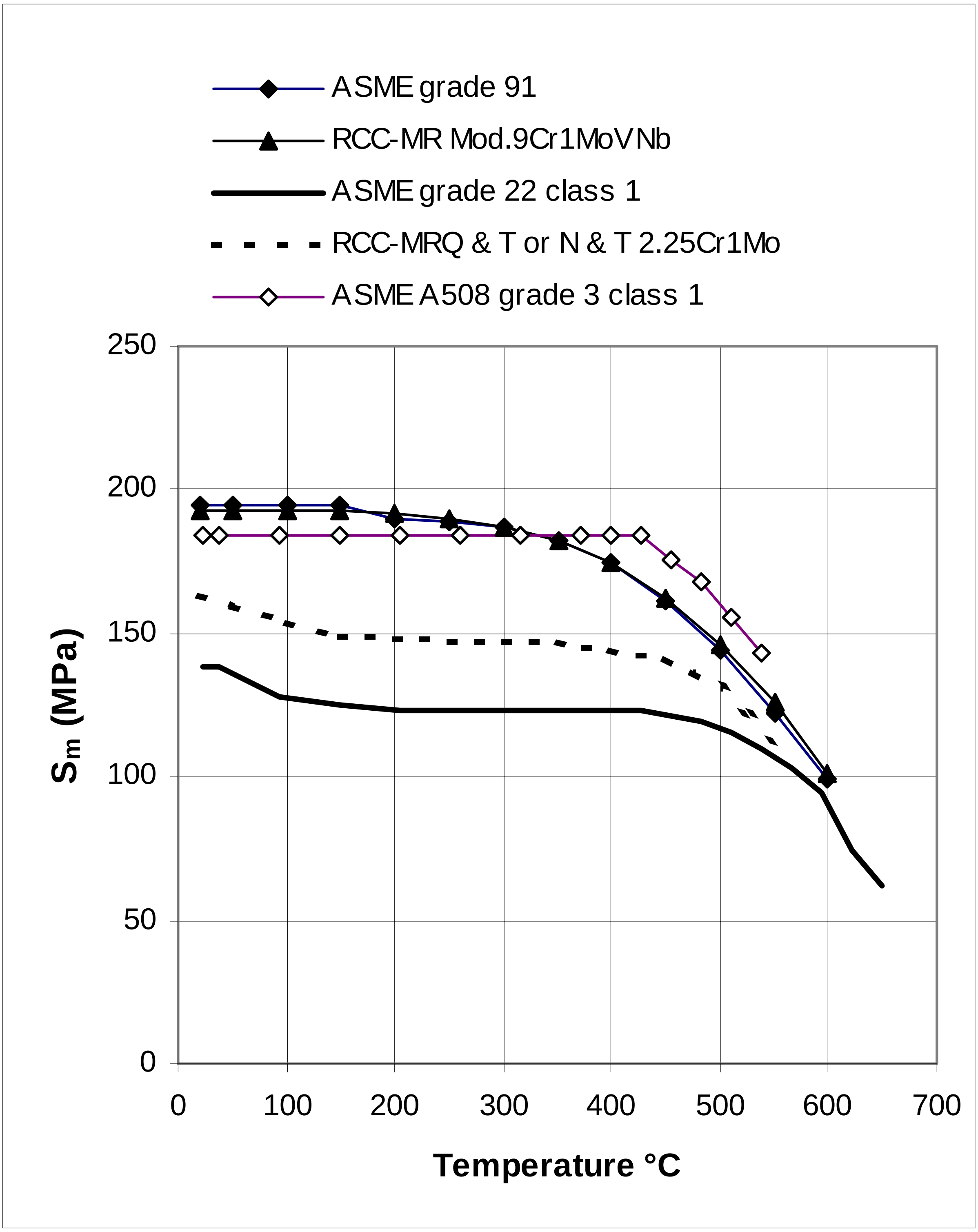


Figure 4

Mn – Ni – Mo alloy steel : creep stress to rupture

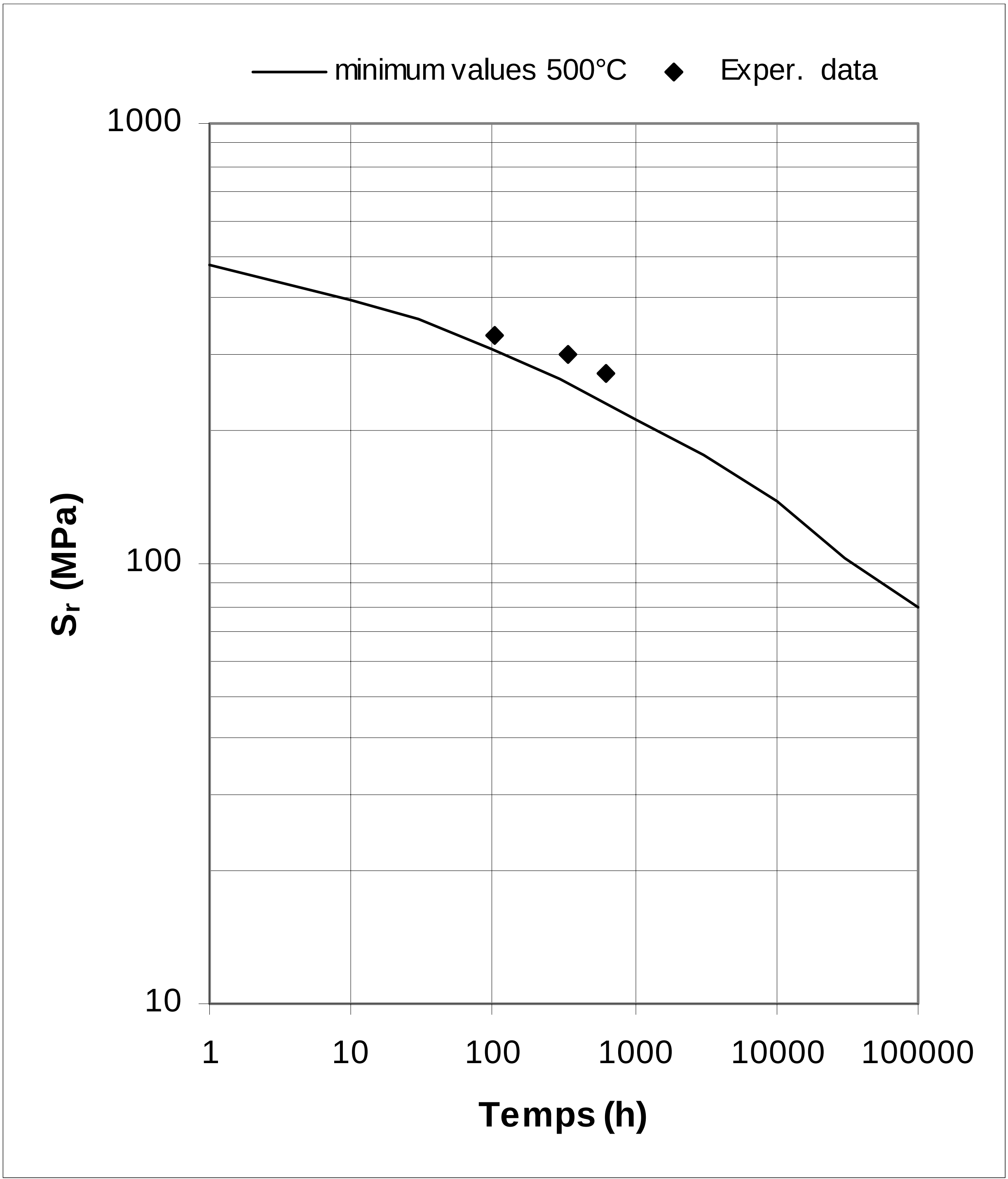


Figure 5

Minimum 100 h stress to rupture S_r values

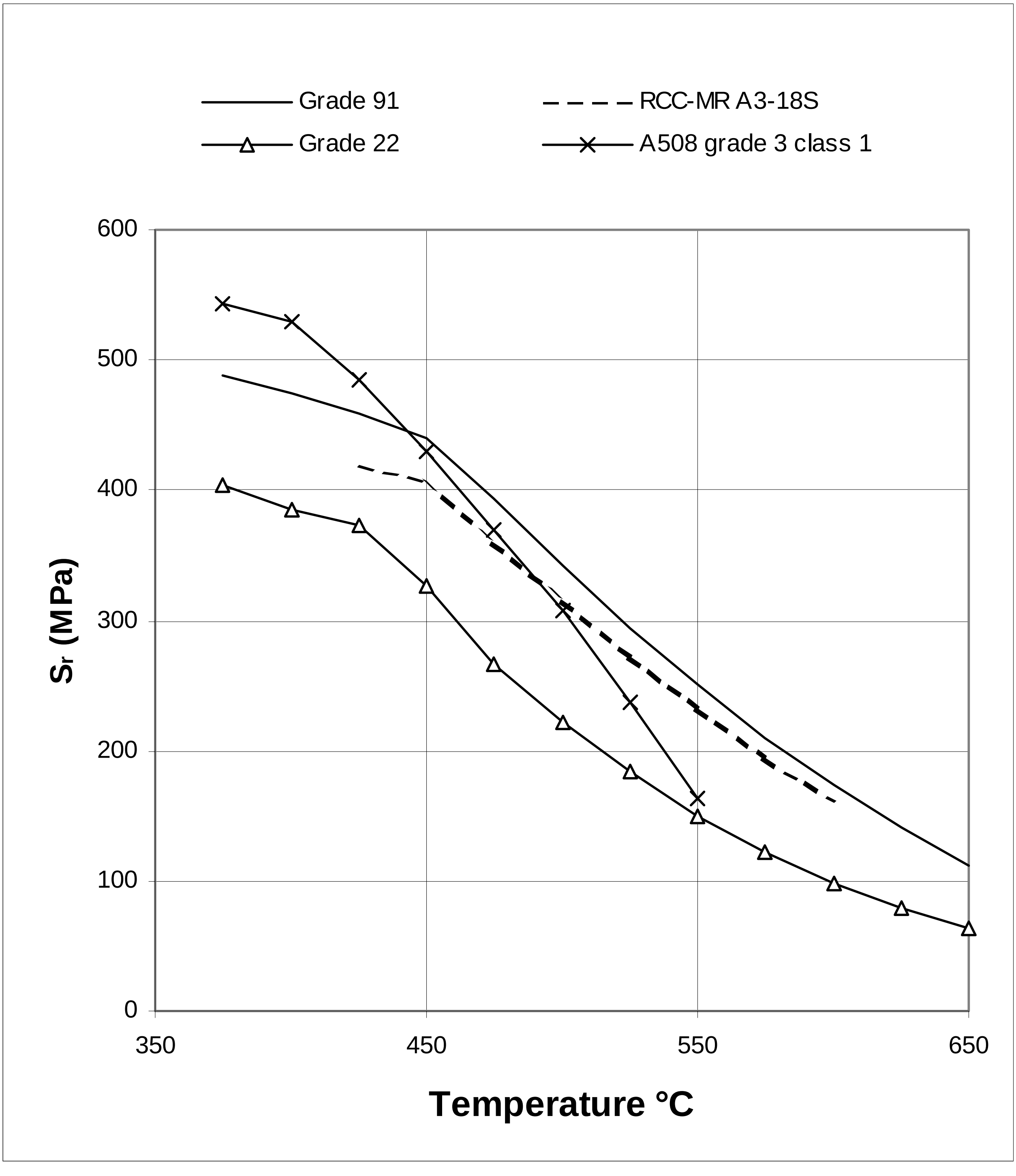


Figure 6

Minimum 10^3 h stress to rupture S_r values

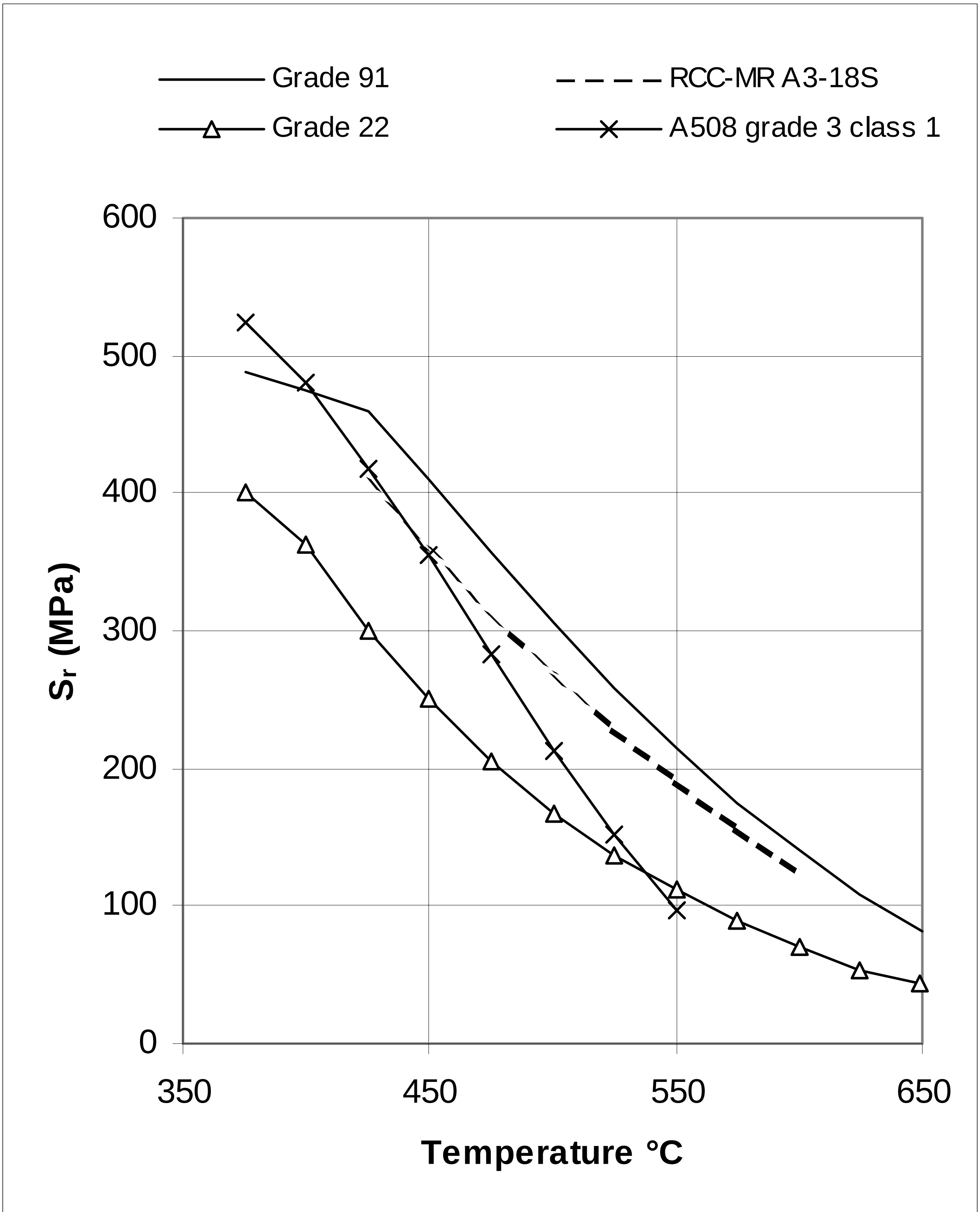


Figure 7

Minimum 10^4 h stress to rupture S_r values

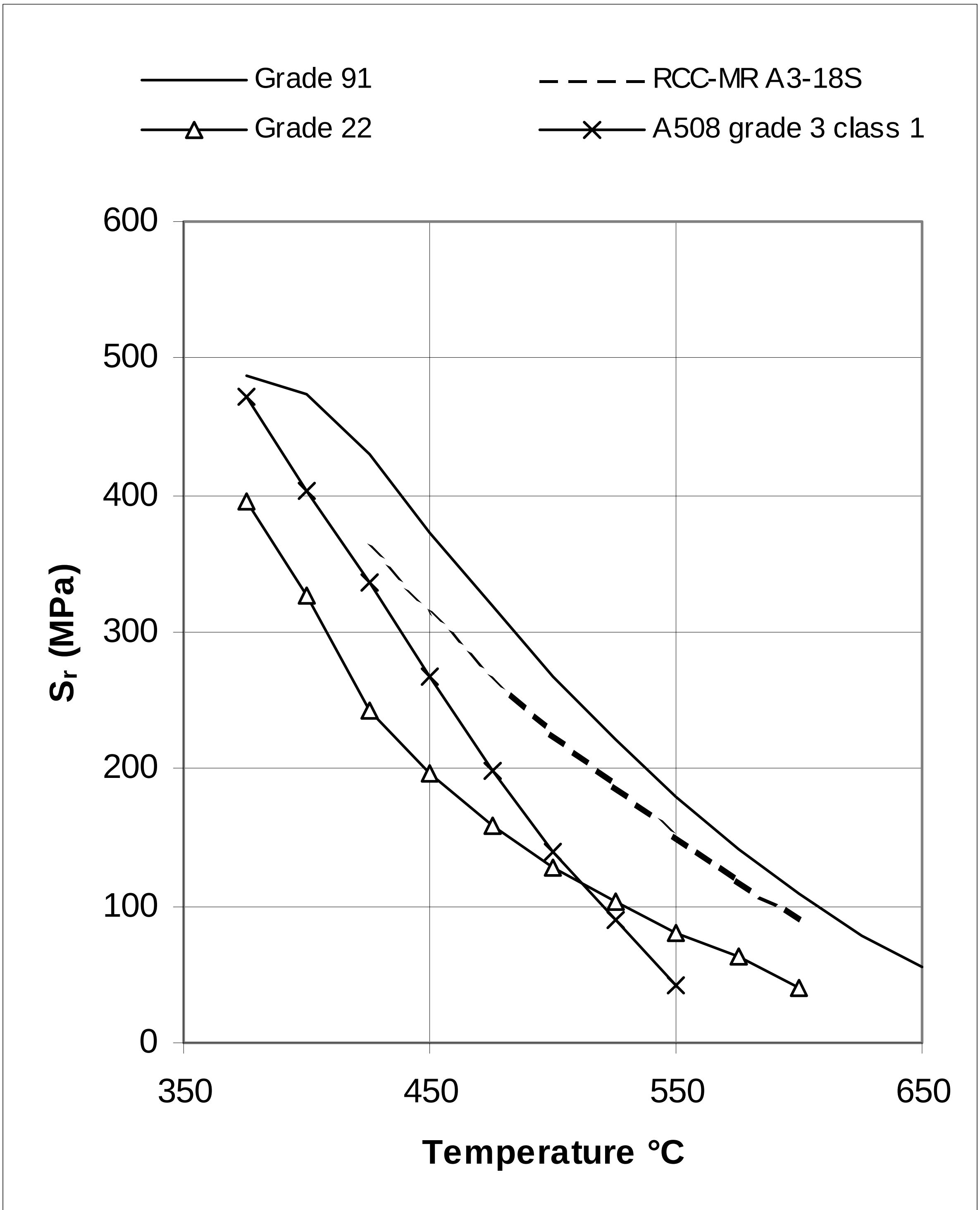


Figure 8

Minimum stress to rupture S_r values for 40 years

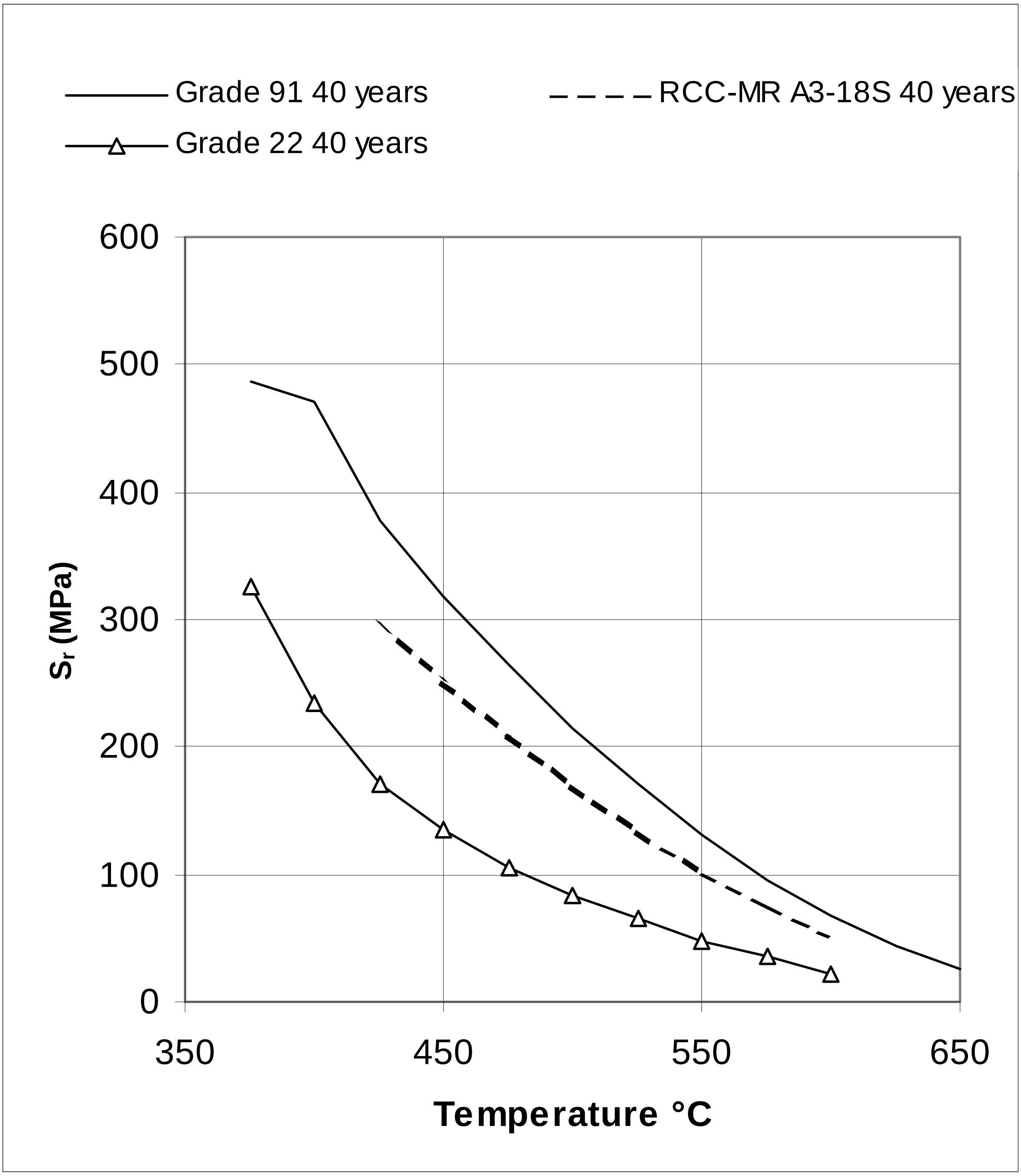


Figure 9

Minimum stress to rupture S_r values for 60 years

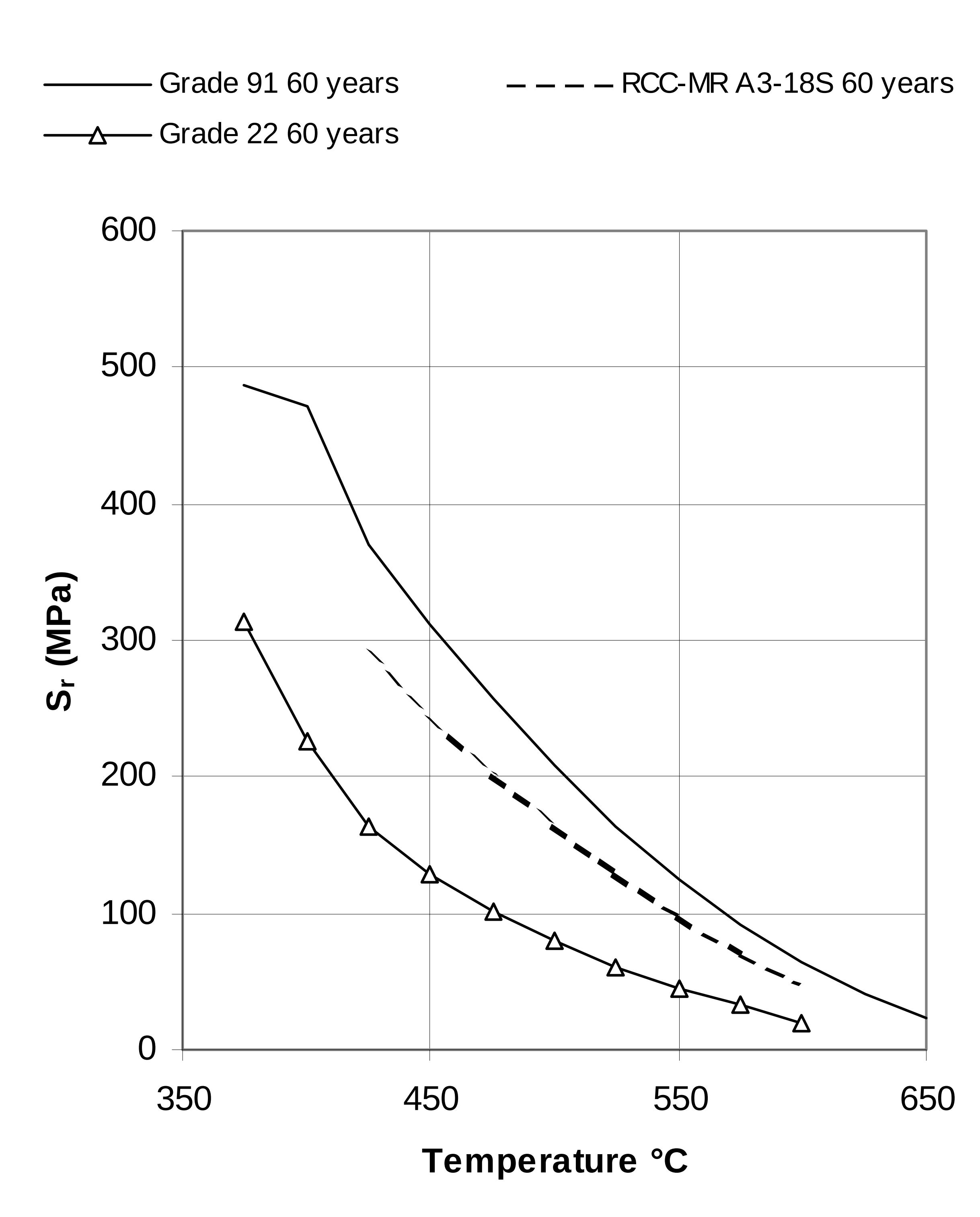


Figure 10

S_t values for 60 years

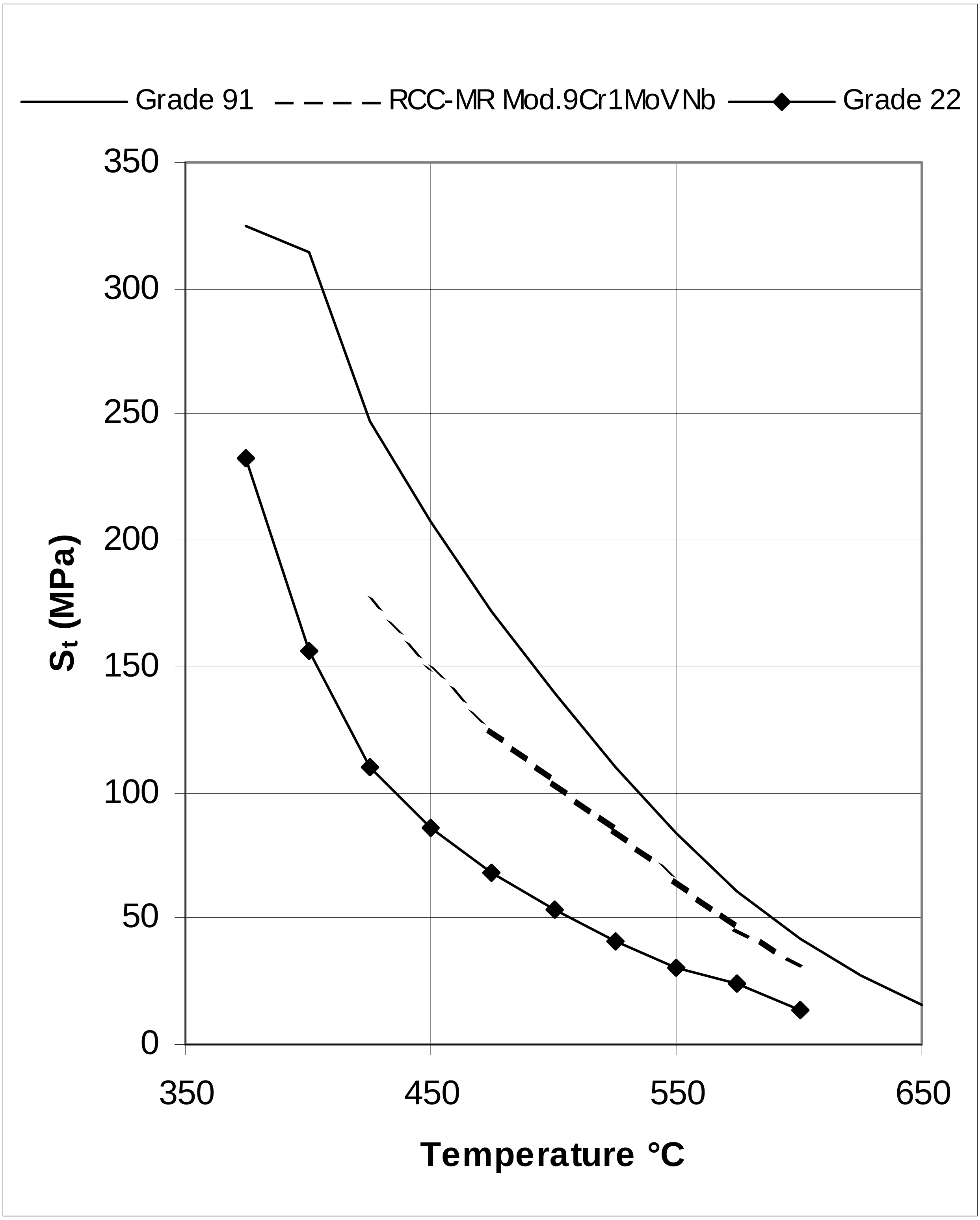


Figure 11

Fatigue design curves : grade 91 and grade 22

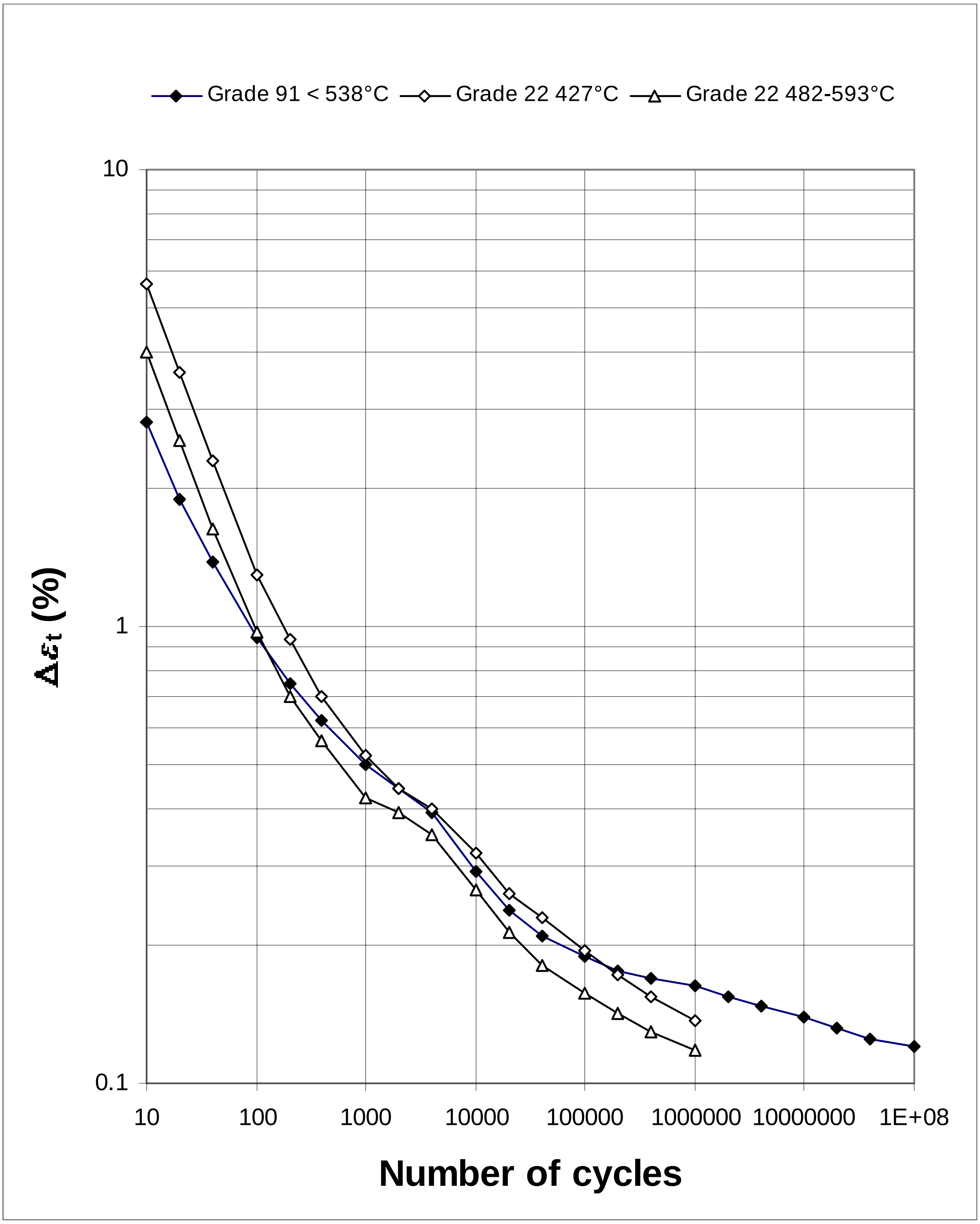


Figure 12

Fatigue design curves : grade 91 and RCC-MR A3. 18S

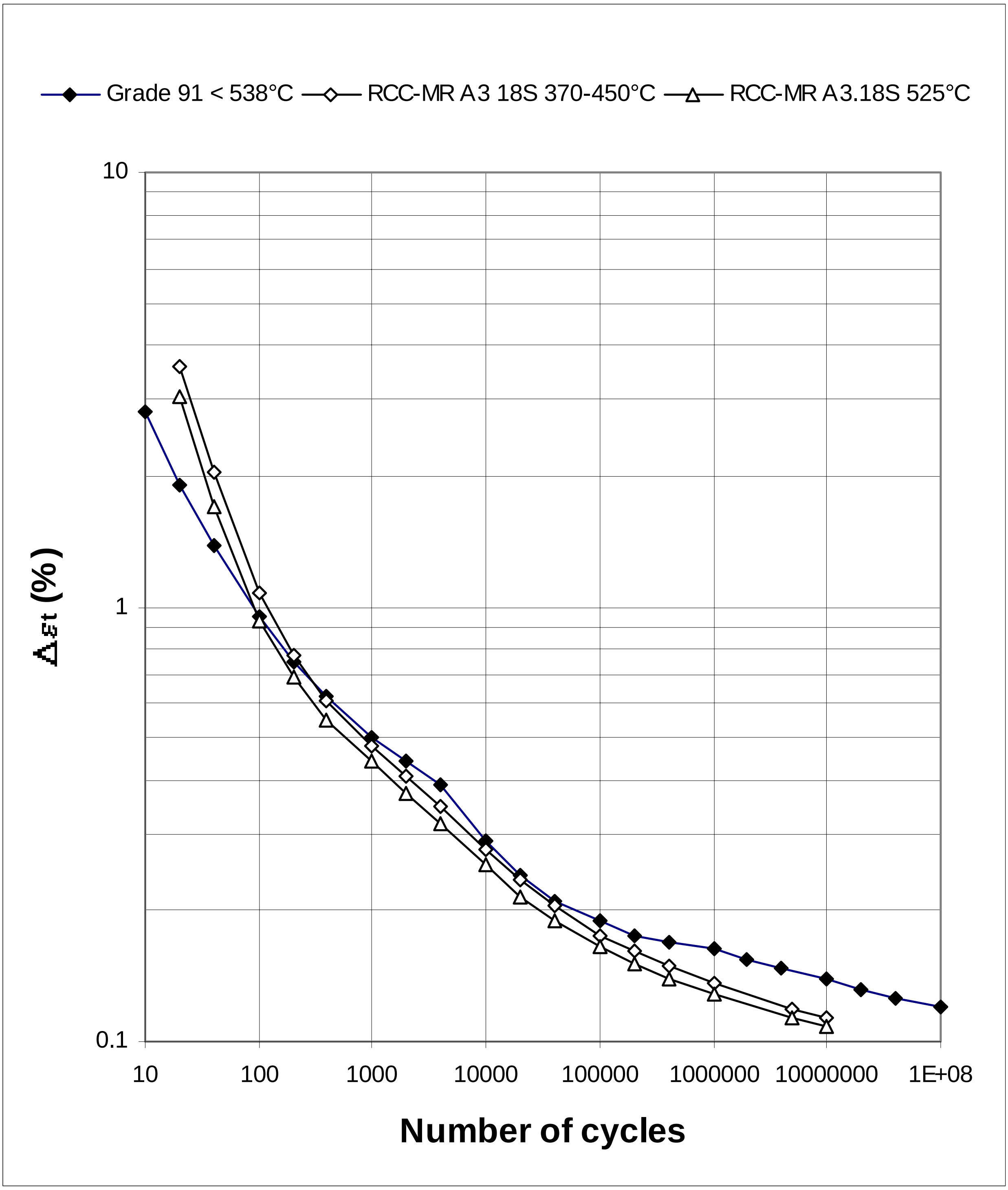
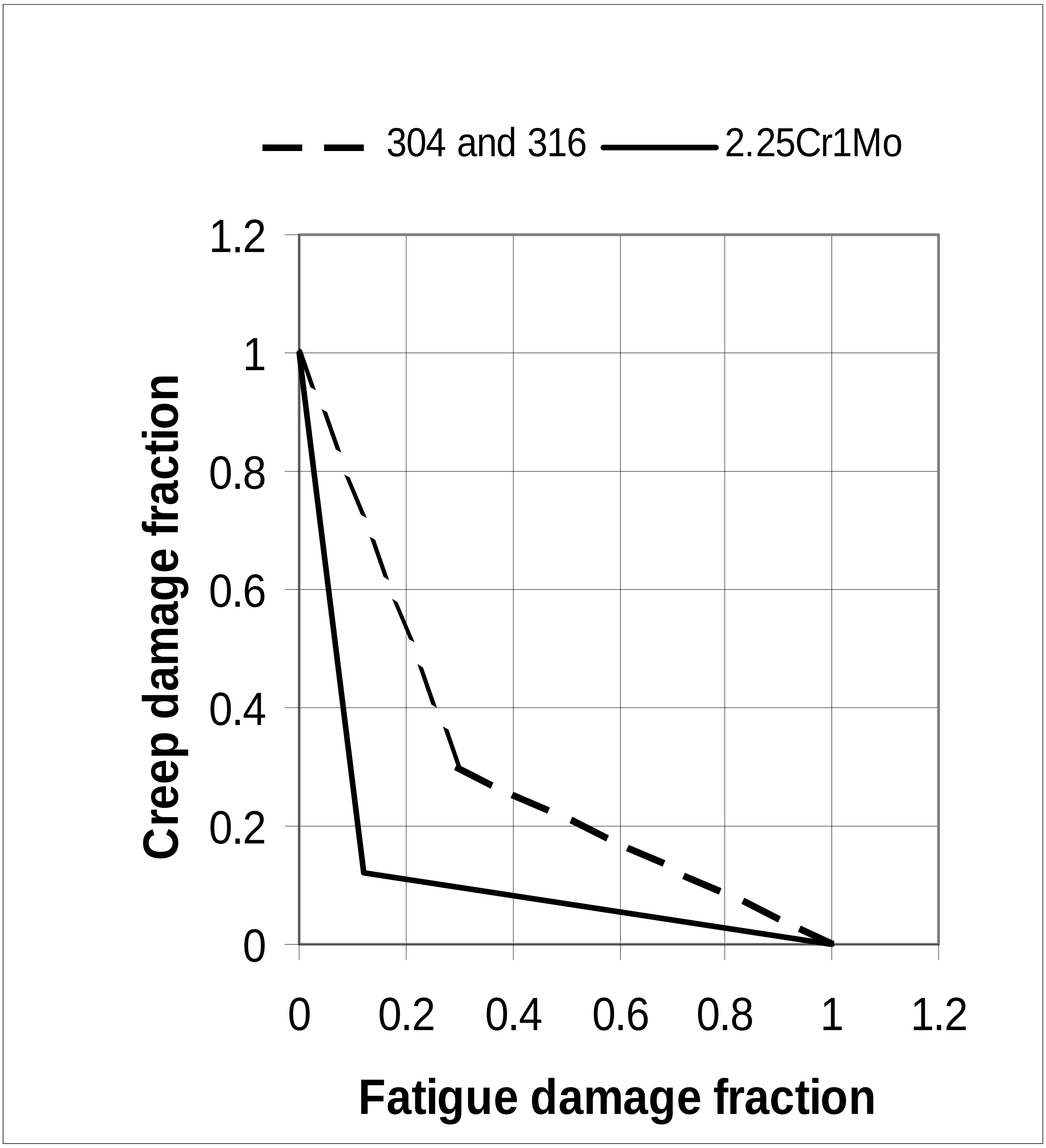


Figure 13

Creep - Fatigue interaction diagram



Appendix 1

Mechanical properties of ASME/ASTM grade 91 and RCC-MR modified 9Cr1Mo (X10CrMoVNb9-1)

Temperature	RCC-MR A3.18S			U.S. Grade 91		
	$R_{p0,2}$ (MPa)	R_m (MPa)	S_m (MPa)	$R_{p0,2}$ (MPa)	R_m (MPa)	S_m (MPa)
20	400	580	193	420	592	195
50	388	559	193	392	564	195
100	375	536	193	365	537	195
150	367	525	193	356	520	195
200	362	519	192	356	518	190
250	359	514	190	356	517	189
300	355	506	187	356	510	187
350	349	493	182	356	497	183
400	338	471	174	356	474	174
450	320	439	162	336	439	161
500	292	395	146	305	393	144
550	254	340	126	263	337	123
600	203	273	101	209	272	99

Minimum stress to rupture S_r (MPa)

θ °C		1 h	10 h	30 h	100 h	300 h	1000 h	3000 h	10^4 h	3.10^4 h	10^5 h	3.10^5 h
375	(1)	482	482	482	482	482	482	482	482	482	482	482
	(2)	487	487	487	487	487	487	487	487	487	487	487
400	(1)	471	471	471	471	471	471	471	471	471	471	471
	(2)	475	475	475	475	475	475	475	474	473	472	472
425	(1)	444	432	426	420	415	409	386	361	340	317	296
	(2)	460	460	460	460	460	460	444	430	412	393	376
450	(1)	428	418	413	408	384	359	336	313	292	270	250
	(2)	441	441	441	441	428	411	394	373	355	335	317
475	(1)	398	378	369	360	337	312	290	267	247	226	207
	(2)	414	419	409	394	377	356	338	318	300	281	263
500	(1)	366	339	327	314	292	268	247	225	206	186	168
	(2)	379	379	363	343	325	305	287	267	250	231	214
525	(1)	344	320	296	272	250	227	207	187	168	144	133
	(2)	332	332	314	295	277	257	240	221	204	186	169
550	(1)	328	278	256	232	211	190	171	151	134	116	101
	(2)		287	270	250	233	214	197	174	163	145	130
575	(1)	288	240	218	195	176	155	137	119	103	87	74
	(2)		246	229	210	193	175	159	141	126	110	95
600	(1)	250	204	183	161	143	124	107	90	76	63	51
	(2)		209	192	174	158	140	132	109	94	80	67

(1) Modified 9Cr1MoVNb (RCC-MR A3.18S)
(2) U.S. grade 91

Allowable stress limit S_t (MPa)

θ °C		1 h	10 h	30 h	100 h	300 h	1000 h	3000 h	10^4 h	3.10^4 h	10^5 h	3.10^5 h
375	(1)											
	(2)	325	325	325	325	325	325	325	325	325	325	325
400	(1)											
	(2)	317	317	317	317	317	317	316	316	315	315	314
425	(1)	296	288	284	280	276	268	249	224	212	195	180
	(2)	306	306	306	306	306	306	300	287	275	262	251
450	(1)	286	279	275	272	256	236	218	200	184	167	153
	(2)	294	294	294	294	285	274	263	249	236	223	211
475	(1)	265	252	246	240	224	207	190	173	158	143	129
	(2)	280	280	273	263	251	238	226	212	200	187	175
500	(1)	244	226	218	210	195	179	165	149	134	120	107
	(2)	262	253	242	229	216	203	191	178	167	154	142
525	(1)	229	213	198	181	167	158	138	124	112	100	88
	(2)	242	222	210	197	184	171	160	147	136	124	113
550	(1)	219	186	171	155	141	127	114	101	89	78	68
	(2)	217	192	180	167	155	142	131	119	109	97	86
575	(1)	192	160	145	130	117	103	92	79	69	58	49
	(2)	189	164	153	140	129	117	106	94	84	73	64
600	(1)	167	136	122	108	95	82	71	60	51	42	34
	(2)	163	139	128	116	105	93	83	72	63	53	44

(1) Modified 9Cr1MoVNb (RCC-MR A3.18S)
(2) U.S. grade 91

Appendix 2

Mechanical properties of ASME/ASTM grade 22 class 1 and of RCC-MR Quenched & Tempered or Normalised & Tempered 2.25Cr1Mo (7CD9-10 and 10CD9-10)

	RCC-MR A3.16S Q & T or N & T 2.25Cr1Mo			ASME 2.25Cr1Mo, grade 22, class 1			NFEN 1022-2 X11CrMo9-10 $R_{p0,2}$ (MPa)	
θ °C	**$R_{p0,2}$ MPa**	**R_m MPa**	**S_m MPa**	**$R_{p0,2}$ MPa**	**R_m MPa**	**S_m MPa**	**For $t \leq 200$ mm**	**For $200 \leq t \leq 500$ mm**
20	320	490	163	213	414	138	310	265
50					414			
100	304	462	154	192	412	128	265	245
150	290	448	149	186	401	123		
200	275	442	148	184	401	123	235	215
250	255	452	147	184	401	123	230	210
300	235	465	147	186	401	123	220	200
350	225	468	147	186	401	123	205	185
400	216	468	144	185	401	123	195	175
450	206	442	141	181	401	121	185	165
500	196	406	131	173	398	115	175	155
550	189	337	112	159		105		
600								

Minimum values of the stress to rupture (MPa)

θ °C		1 h	10 h	30 h	100 h	300 h	1000 h	3000 h	10^4 h	3.10^4 h	10^5 h	3.10^5 h
375	(1)	365	365	365	365	365	365	365	365	365	355	318
	(2)	406	406	405	404	403	401	399	396	392	356	323
400	(1)	365	365	365	365	365	365	356	330	298	260	239
	(2)	399	399	392	386	375	365	349	327	295	256	232
425	(1)	365	365	365	365	340	308	280	248	216	193	171
	(2)	378	378	383	373	337	301	264	243	216	191	170
450	(1)	365	362	353	330	290	250	224	198	170	150	132
	(2)	363	363	254	326	288	250	221	197	173	151	134
475	(1)	365	327	298	264	235	202	180	158	138	120	103
	(2)		328	300	266	236	206	183	160	140	121	105
500	(1)	362	288	255	222	194	166	146	129	110	98	82
	(2)		291	256	222	194	167	148	129	112	96	84
525	(1)	312	241	211	184	159	136	118	103	87	76	63
	(2)		244	213	185	161	137	118	103	87	75	64
550	(1)	260	198	175	150	131	109	94	80	68	57	47
	(2)		201	174	150	131	112	95	81	68	58	48
575	(1)											
	(2)		168	145	122	106	89	76	63	52	44	36
600	(1)											
	(2)		138	118	99	84	70	48	39	32	26	21

(1) Quenched & tempered or normalised & tempered 2.25Cr1Mo (RCC-MR A3.16S)
(2) Code ASME 2.25Cr1Mo, grade 22, class 1

Allowable stress limit S_t (MPa)

θ °C		1 h	10 h	30 h	100 h	300 h	1000 h	3000 h	10^4 h	3.10^4 h	10^5 h	3.10^5 h
375	(1)	244	244	244	244	244	242	240	235	230	225	220
	(2)	245	245	244	243	242	241	239	238	236	235	233
400	(1)	242	242	238	231	224	216	204	195	183	170	156
	(2)	243	242	238	230	223	214	204	195	181	170	159
425	(1)		230	221	211	200	186	174	161	144	129	114
	(2)	241	230	220	211	200	187	174	161	144	127	114
450	(1)		206	197	185	175	162	149	131	116	100	88
	(2)	226	207	197	186	176	164	149	131	117	101	89
475	(1)		181	168	155	147	135	120	105	92	80	68
	(2)	206	183	171	160	148	136	122	106	93	81	71
500	(1)		155	143	132	121	109	98	85	73	64	55
	(2)	182	156	144	132	122	111	99	86	74	64	56
525	(1)		130	119	109	100	90	79	68	58	50	42
	(2)	156	130	119	109	100	91	81	68	59	50	42
550	(1)		106	98	89	80	73	63	54	46	39	32
	(2)	128	108	98	89	81	74	64	53	46	38	32
575	(1)											
	(2)	104	89	80	72	66	59	50	42	35	29	25
600	(1)											
	(2)	83	72	66	50	43	37					

(1) Quenched & tempered or normalised & tempered 2.25Cr1Mo (RCC-MR A3.16S)
(2) Code ASME 2.25Cr1Mo, grade 22, class 1

Appendix 3

Mechanical properties of ASME/ASTM A508 grade 3 class 1 and RCC-M 16MND5

RCC-M 16MND5, ASME A533 gr B cl 1 and A508 grade 3 class 1

Temperature °C	**$R_{p0,2}$ (MPa)**	**R_m (MPa)**	**S_m (MPa)**
20	345	552	184
50	340	552	184
100	326	552	184
150	318	552	184
200	311	552	184
250	308	552	184
300	303	552	184
350	299	552	184
400	292	552	184
450	281	532	177
500	265	477	160
550	241	414	137

Allowable stress limit S_t (MPa)
Grade A508 grade 3 class 1 (16MND5)

Temperature °C	1 h	10 h	30 h	100 h	300 h	1000 h	3000 h
375	372	372	372	364	361	353	334
400	372	372	371	357	336	322	308
425	372	366	346	333	305	279	252
450	367	342	322	290	263	229	
475	345	307	281	247	214	180	
500	320	266	234	199	169	130	
525	288	218	188	149	122	86	

Minimum stress to rupture S_r (MPa)
Grade A508 grade 3 class 1 (16MND5)

θ °C	1 h	10 h	30 h	100 h	300 h	1000 h	3000 h	10^4 h	3.10^4 h	10^5 h
375	552	552	550	543	532	524	503	472	443	402
400	551	551	537	529	495	480	458	404	369	328
425	545	539	518	486	458	418	378	336	301	253
450	539	503	482	431	397	355	314	267	227	173
475	507	451	425	370	330	284	242	199	158	123
500	474	395	358	308	262	213	177	140	103	79
525	428	335	290	238	193	153	122	89	64	45