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Materials Selection for HTR Pressure Vessel

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1	3.2 5.1 Table 5.1	Relevant design data for HTR RPV material RPV Transients Fatigue and Cycling Data	TBC, TBD TBC TBC

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Abbreviations lists

HTR	High Temperature Reactor
RPV	Reactor Pressure Vessel
MICA	Michelangelo Initiativa
R&D	Research and development
IASCC	Irradiation Assisted Stress Corrosion Cracking
IGSCC	Intergranular Stress Corrosion Cracking
EU	European Union
IAEA	International Atomic Energy Agency
PWHT	Post Welding Heat Treatment

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1. OBJECTIVES AND SCOPE

The aim of the present document is to analyse and propose suitable materials for the European High Temperature Reactor (HTR) Reactor Pressure Vessel (RPV).

These materials should comply with HTR environment conditions, safety, strength requirements for design and operational conditions, cost optimisation, market availability, constructability and quality.

The present choice of candidate materials will be confirmed at the end of this project after a qualification test campaign to be performed on the selected materials. In order to provide data for the materials test matrix, this document includes preliminary design values that have been assumed for the HTR RPV such as pressures, temperatures, environment and transient conditions.

2. MICA RECOMMENDATIONS FOR INNOVATIVE REACTOR MATERIALS

One of the objectives of the Michelangelo Initiative (MICA) project – developed in the former EU Framework Program – was to propose R&D strategies for the near future regarding materials for Innovative Reactor Concepts [1], including the HTR.

It seems convenient to consider, as a starting point of this project, the specific recommendations defined in the MICA project for R&D on RPV and internal materials of innovative reactors. The MICA recommendations were:

- Carry out generic studies and develop materials with high temperature strength, high resistance to radiation damage and, in particular, meeting reduced activation requirements
- Special attention shall be given to the development of new materials (ie. new steels) and the characterisation of the same for innovative reactor operation at higher temperature and maybe higher radiation values than the current Light Water Nuclear Power Plants
- Perform corrosion studies in the particular environments of innovative reactors (ie high temperature He environment with some impurities). Analyse possible degradation mechanisms (ie IASCC, IGSCC and intergranular oxidation) in this environment and the reduction of elements contained in commercial steels that may be considered material impurities for reactor operation (Cd, Sb, Zn, Pb, Hg, Cu, etc) and a risk of personnel exposure to radiation (ie Co).
- Improve welding and joining processes for high temperatures and heavy thickness components and develop new sealing and leaktight materials for reactors (He atmosphere)
- Develop inspection methodologies and tools that allow deep knowledge of the condition of the material from the microscopic to macroscopic scale in order to guarantee the integrity of structures in nominal and accident conditions, to predict mean life extension and to allow easy in-service inspection and repair
- R&D actions oriented to the study of material degradation mechanisms with multi-scale approaches: from the atomic scale (irradiation damage, kinetics of defect evolution, segregation, dislocations, deformation mechanisms) to the local and macroscopic scale

Some of the above R&D strategies should be considered in the material selecting process, during the definition of the material specifications and for the definition of the test matrix to be developed in this project.

3. RPV MATERIAL SELECTION ANALYSIS

3.1 INTRODUCTION

Materials that might be selected for the HTR Pressure Vessel should meet a set of technical, performance and cost requirements, ensuring the safety and acceptable economic competitiveness of the HTR nuclear power plant.

Moreover, materials should meet the strength requirements for HTR environment and design conditions. The safe performance of the pressure vessel should be ensured under normal and accident conditions. Therefore, damage mechanisms such corrosion, creep, embrittlement, etc for the selected materials should either be prevented or developed in non-significant amounts.

Materials should have good manufacturing characteristics. They should have the capacity to be welded ensuring tensile strength, tensile ductility, fatigue and creep requirements for the welded joints.

Finally, the use of proven materials in similar applications (ie RPVs) in existing nuclear power plants should be taken into consideration as a first choice as far as possible. Information on degradation phenomena, lessons learned and materials databases (IAEA) from these plants should be used as design reference for this project.

3.2 RELEVANT DESIGN CONDITIONS AND REQUIREMENTS FOR THE RPV MATERIAL SELECTION

There are some design conditions and requirements applicable to the HTR RPV that are needed for the material selection and test matrix, such as HTR design pressure and temperature, pressure and temperature transients and frequencies, radiation dose, He process characteristics, etc.

These data are not yet available for the European HTR project. However, some data may be assumed considering the information available from other HTR projects being developed in other countries such China, Japan, Russia and South Africa. Other data may be estimated in accordance with the best engineering knowledge available at the time.

A compilation of information from the above projects has been used to develop the HTR preliminary design data given below. These data have been considered the most relevant for RPV material selection and testing. It should be noted that all these data are preliminary – they are only a first approach for comments and discussion– and may be subject to changes or improvements in the near future.

In some cases the requirements or design parameters have been identified but data have not been included because not enough information has been found at the time of issuing this document.

In future revisions these preliminary and missing data should be completed and commented at HTR–TN project group level.

Relevant design data for HTR RPV material:

- RPV design pressure: 7.5 MPa (TBC)
- RPV design temperature:
  - "Warm" vessel option: (TBD)
  - "Cold" vessel option: 350ºC (TBC)
- RPV diameter: 6 m (TBC)
- RPV length: 20 m (TBC)
- RPV test pressure: 9 MPa (TBC)
- RPV design life: 60 years
- Neutron irradiation (> 1 MeV) at operating temperature: 3×10^{19} neutrons cm^{-2} (accumulated) (TBC)
- Operating temperature ("cold" vessel): 300ºC (TBC)
- He environment characteristics:
  - He purity: 99.9 % pure (TBC)
  - Main impurities and amount:
    - Hydrogen ppm (TBD)
    - Carbon monoxide ppm (TBD)
    - Water ppm (TBD)
    - Carbon dioxide ppm (TBD)

- Abnormal conditions (accident):
  - Pressure (TBD)
  - Temperature (TBD)

  Since one of the HTR design parameter is that core melts will not occur even without the use of emergency core cooling systems, some analyses should be carried out in order to determine the peak temperatures for the RPV and the core. The hypothesis of a loss of coolant accident with no means of core and reactor cavity cooling –except for conductivity and radioactive heat transfer to the soil and natural convection from the enclosed top of the reactor cavity to the air– should be considered [5].

- Operational transients and transients frequencies (see chapter 5 of this document)

- Accident environmental conditions:
  - Pressure (TBD)
  - Temperature (TBD)
  - Environment: He and air mixture

- Design code:
  - ASME Section III, Division 1, Subsection NB, or equivalent RCC-M, KTA 3201.1 for “cold vessel option”.
  - ASME Section III, Subsection NH (formerly Code Case N47) and RCC-MR rules for fast reactors for “warm vessel option”.

3.3 MATERIALS SELECTED FOR HIGH TEMPERATURE REACTOR PRESSURE VESSELS

A list of existing HTRs with their proposed materials and wall temperatures for their Pressure Vessels [2] is given in Table 3-1:

Table 3-1
Proposed Materials for Existing HTR Reactor Pressure Vessel Projects

HTR Project	Country	Power	RPV Material	Temperature
HTTR	Japan	30 MWt Block	2 ¼ Cr – 1 Mo	400 ºC
MSF–HTR	Japan	450-600 MWt Block	mod 9 Cr – 1 Mo	
MSF–HTR	Japan	50 MWt Block	mod 9 Cr – 1 Mo	490 ºC
HTR–GT 300	Japan	300 MWt Pebble bed	SA 508	< 350 ºC
HTR–GT 600	Japan	300 MWt Block	mod 9 Cr – 1 Mo	460 ºC
PBMR	South Africa	265 MWt Pebble bed	SA 508, Gr3, C2	300 ºC
GT–MHR	Russia	600 MWt Block	mod 9 Cr – 1 Mo	440 ºC
MHGTR–IGT	China	200 MWt Pebble bed	SA 516-Gr 70	< 350 ºC
HTR10	China	10 MWt Pebble bed	SA 516-Gr 70	

3.4 HTR REACTOR PRESSURE VESSEL LIMITING CONDITIONS

There are several aspects that should be considered for the selection of the appropriate RPV material. These aspects have to do with the HTR environment conditions.

Materials in high neutron fluence environments may suffer from neutron radiation damage. The collision of the fast neutrons with the atomic lattice of the RPV material may induce microstructural defects that increase the yield strength (hardening) and the ductile-to-brittle transition temperature (irradiation embrittlement).

The design operating pressure and temperature of the RPV will depend on the “cold” or “warm” HTR vessel option. In the “cold” option an operating temperature under 350ºC is envisaged. In the case of “warm” RPV option (not insulated vessel), the design temperature shall increase to a value of at least 450ºC. For this reason, only elevated temperature resistant materials shall be used.

Pressure and temperature transients during specific operating incidents are relatively gentle in HTR, leading to relatively low thermal stresses. However, temperature variations of the abnormal type are known to cause temper embrittlement. Thermo-structural analysis will be required in this area in order to define data to be used as inputs for the test matrix and verification of results.

Another important aspect is the corrosion degradation phenomena of the RPV material in He environment at operating temperature, considering the effect of the He atmosphere impurities. Special attention shall be given to accident conditions where air ingress may occur with the RPV at high temperature.

Finally it may be convenient to analyse the capability of the material selected to recover the original mechanical characteristics by an adequate RPV recovery procedure (ie post irradiation heat treatment, shot peening, etc) in order to extend the useful life of the RPV.

3.5 MANUFACTURING REQUIREMENTS

Light Water RPVs have been safely built for years by welding cylindrical shell pieces and by forging the two hemispherical heads. Thousands of kilometres of welds are required, as are the corresponding thermal treatments and inspections needed for the welded joints. A similar process is envisaged for the HTR RPV since the vessel is expected to be of a closer size.

There are two factors of the RPV manufacturing procedure that should be considered for the selection of the appropriate material.

The first factor to be considered is the capacity of the material to be welded ensuring tensile strength, tensile ductility, fatigue and creep requirements for the welding joint. Special attention shall be paid to the selection of the additional welding material, avoiding those that may have a content of Cu, P and any other component that may be affected by irradiation embrittlement. The large wall thicknesses of RPVs lead to the need to carry out pre and post heating for welding. Consideration should also be given to the need to perform welds in situ. From the technological point of view this is not a problem, but additional precautions should be taken to ensure the correct welding of these joints. R&D shall be performed in this area to provide the selected RPV material with proven experience.

The second factor has to do with the decision of manufacturing the RPV by forming or forging. An attempt should be made to minimise the number of welds in the zone directly in front of the core in order to avoid irradiation embrittlement. The number of welds will be reduced using forged rings (without longitudinal welds) of great height (smaller number of circumferential welds). However, this manufacturing process has higher costs than building the RPV from formed shells (180º sectors) with longitudinal welds. The neutron radiation dose may determine the manufacturing procedure, at least in the zone in front of the core.

The design pressure and temperature and the vessel diameter will determine the wall thickness. For wall thicknesses greater than 300 mm no forming is envisaged due to technological limitations. On the other hand, forging may be considered for wall thicknesses from 200 mm because of the reduction of welding, which may compensate the higher cost of forging and will reduce the number of welds at risk of mechanical behaviour degradation.

3.6 BASIC ALTERNATIVES

Tough weldable low carbon steels are recommended for non-corrosive service and in the range of intermediate temperatures (5ºC to 375ºC).

Low alloy steels –like ASME SA 533 (Grade B, Class 1) and SA 508 (Grade 3, Class 1) and its European equivalents (ie 20 Mn Mo Ni 55 and 16 Mn D5)– have been extensively used for many years in RPVs. They provide good proven behaviour in high neutron fluence environments. Moreover, there are large databases and extensive fabrication experience for these materials. However, they have been used for design temperatures under 400ºC. There is few data for its mechanical behaviour over 400ºC and under HTR internal environment. This behaviour should be studied and verified by means of a qualification test campaign.

Chrome and Molybdenum alloy steels, like 2 ¼ Cr – 1 Mo (ASME SA 182-F22, SA 335-P22, SA 387-P22, etc and their European equivalent, ie 10 Cr Mb 910), were formulated for use at elevated temperatures where creep resistance is required. 2¼ Cr – 1 Mo has been employed for years for steam generators where temperatures were close to 600ºC and for pressure vessels in the petrochemical industry.

Another suitable material for the RPV is the Modified 9 Cr – 1 Mo in view of its superior creep-rupture strength. Fabrication of steam drums and headers of large diameters has proved feasible with this material and there is considerable experience of using it in CO_2 environment. Modified 9 Cr – 1 Mo has better mechanical behaviour at higher temperatures (see Figure 3-1) than 2¼ Cr – 1 Mo, however there is less data and fabrication experience for this material, especially for its weldability and behaviour under HTR environment conditions. An exhaustive test campaign on Modified 9 Cr – 1 Mo is to be carried out in order to clarify these uncertainties.

The allowable stresses with temperature for some HTR Pressure Vessel candidate materials are given below in figure 3-1 [2].

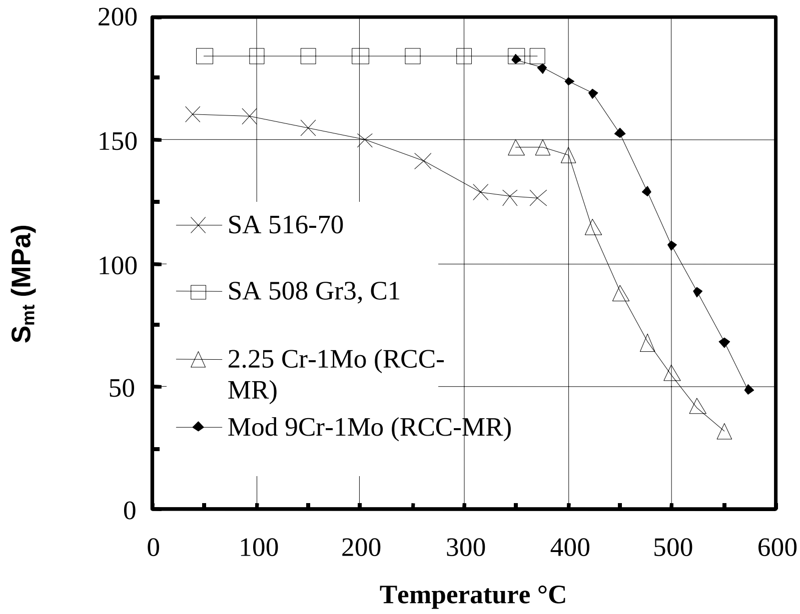

Figure 3-1 Allowable Stresses versus Temperature

3.7 BASIC MATERIAL EVALUATION

Available data regarding material composition, mechanical properties, design stress intensity and welding considerations are given in Appendix A for SA 508, SA 533, 2¼ Cr – 1 Mo and Modified 9 Cr – 1 Mo.

As previously discussed, material weldability is one of the main factors for material selection. Therefore the following considerations shall be taken into account. SA 508 has excellent weldability, better than 2¼ Cr – 1 Mo and Modified 9 Cr – 1 Mo. SA 508 requires smaller recommended preheat temperature for welding (121ºC versus 150ºC minimum for 2¼ Cr – 1 Mo and Modified 9 Cr – 1 Mo). Moreover, the holding temperature range for PWHT is smaller and the minimum holding time for the PWHT temperature is shorter for SA 508 than for 2¼ Cr – 1 Mo and Modified 9 Cr – 1 Mo. Concerning a situation of a need of in-service repair and where PWHT is impossible or impractical, for SA 508 material ASME Code Section XI allows the exemption of the PWHT using the Temper Bead Weld technique. For 2¼ Cr – 1 Mo and Modified 9 Cr – 1 Mo the Code does not address the issue.

Therefore, welding costs using SA 508 would be somewhat cheaper than using Modified 9 Cr – 1 Mo or 2¼ Cr – 1 Mo.

There are some uncertainties concerning the behaviour of modified 9 Cr – 1 Mo in HTR environment and lack of database and fabrication experience. There is also short information concerning the behaviour of SA 508 in high temperature (ASME code does not allow the use of SA 508 over 370º C) and under He environment.

There are few data regarding the effect of neutron radiation on 9 Cr – 1 Mo material and on its welded joints. Experimental data from Light Water Reactors show that some current algorithms used for RPV materials (like SA 508) are not precise enough when describing their behaviour tendencies.

An exhaustive test campaign will be addressed in the near future to clarify the above uncertainties and lack of database, and to confirm the present choice of candidate materials, in relation to both normal and accident conditions. The present work and the future tests will lead to the final recommendation for the HTR Pressure Vessel material.

4. RPV COST ANALYSIS

An important aspect in material selection is the cost. It should be borne in mind that the economic competitiveness of the HTR project is a basic objective. The cost of the Primary System and of the RPV is a key aspect of the initial investment.

A good selection of the RPV material may lead to a reduction in weight, saving on base material and fabrication costs and optimisation of the number of welds needed.

The design pressure and temperature and vessel diameter will lead to the definition of the thickness required depending on the material mechanical characteristics. The total weight of the pressure vessel will lead to the cost of the base material needed. Finally, the manufacturing procedure will determine the fabrication costs.

A preliminary cost evaluation for a pressure vessel of a similar size as expected for the HTR RPV leads to the following generalities depending on the selected material. For design temperatures under 370 ºC the RPV will weight approximately the same if buit with SA 508 (Grade 3, Class 1) and Modified 9 Cr – 1 Mo. For design temperatures over 400 ºC the RPV will be lighter if built with Modified 9 Cr – 1 Mo steel because of its higher design stress intensity. The base material will cost at least 35% more if built with 2 ¼ Cr – 1 Mo or Modified 9 Cr – 1 Mo. Selection of SA 508 material will save at least 25% of the RPV welding costs due to its better weldability.

The selection of forming or forging as the manufacturing process will also have a significant effect on the fabrication costs. As previously discussed, this selection may depend on the wall thickness (technological limitations) and on the risk of radiation damage of the RPV (irradiation embrittlement of welded joints). If the expected radiation dose is limited, the forming process may be used and will lead to a reduction of fabrication costs of 10% to 15%.

The above generalities are summarised below in Table 4-1. The values given are orientative and relative to SA 508 Grade 3, Class 1 material and fabrication costs.

Table 4-1 RPV Fabrication Costs

	Forming		**Forging**	
	SA 508	Mod 9 Cr – 1 Mo	SA 508	Mod 9 Cr – 1 Mo
RPV weight	100 %	100 %	100 %	100 %
Base material cost	100 %	135 %	100 %	135 %
Welding cost	100 %	125 %	90%	115 %
Shell fabrication costs	100 %	100 %	130 %	130 %

In order to have complete and precise data, more exhaustive market survey and material cost enquiries to Steel-makers and Suppliers all over the world are required. Detailed information concerning prices of base material and fabrication costs is needed for modified 9 Cr – 1 Mo.

It may be of great interest to consider the possibility of including SA 508 Grade 3 Class 2 as candidate material for the HTR RPV. There is large experience using this material and its good mechanical behaviour under high temperature conditions is also well proved. The larger design stress intensity value (Sm, see Table A-3) of Class 2 in comparison with Class 1 material leads to a reduction of 10 to 15% of the RPV weight. Moreover, using Class 2 material will save about 25% of the fabrication costs considering also the reduction of welding, the reduction of the supports sizes and the reduction of transport and handling costs. However, the selection of SA 508 Grade 3 Class 2 may not be in accordance with some legal requirements in pressure vessel regulations.

5. RPV TRANSIENT CONDITIONS

5.1 RPV TRANSIENTS

In order to develop information for the Test matrix, RPV material temperature and pressure variations are needed. The following are preliminary hypotheses for these variations that may occur during operational transients. This data as well as accident conditions should be provided from the HTR–TN organisation.

The main expected operational transients for the HTR may be:

- Main Circuit Trip (reactor and turbine trip). The bypass valves will open and the plant will stop operating. This will lead to:
  - significant change in pressure (up to 7 MPa in a few seconds) (TBC)
  - slight increase in core outlet temperature
  - reactor inlet temperature variation (50ºC temperature increase in a few seconds and 200ºC decrease in approximately one minute) (TBC)
  - volumes of gas may be retained within the core barrel and Reactor Pressure Vessel internals
- Load Rejection with or without cooling. The bypass valves will open in controlled operation and the plant remains connected to the grid. This will lead to:
  - significant pressure change in a similar way to Main Circuit Trip and then pressure may be reduced slowly (gas blowdown) up to 2 or 3 MPa in a few minutes (TBC)
  - drop of reactor inlet temperatures as in Main Circuit Trip and then increase of 200ºC in a few minutes (TBC)
  - The reactor outlet temperature may be not affected and the described pressure and temperature transients with or without cooling will be quite similar.

5.2 FATIGUE AND CYCLING INFORMATION

These data have not yet been decided for the HTR project. Therefore the values given below in Table 5-1 are assumptions based on the best engineering knowledge existing at the time and the available information from other HTR projects being currently developed. The proposed preliminary values are to be discussed and agreed within HTR–TN project. A design life of 60 years has been considered.

Table 5-1 Fatigue and Cycling Data (TBC)

Transient Event	Frequency
Pressure Test	2 to 6 times/life
Operation with new core (start up)	5 to 7 times/life
0% - 10% load step (start up)	3 times/year
Mayor operating load steps	730 times/year
10% - 0%	3 times/year
Main Circuit Trip	3 to 5 times/year
Load Rejection	2 to 4 times/year

6. CONCLUSIONS

Suitable materials for the HTR Reactor Pressure Vessel have been studied and analysed and a first selection of candidate materials is proposed. The present choice should be considered as a preliminary selection of material for the HTR RPV, to be discussed and agreed within the HTR European project framework. Other materials or new alloys are not discarded if their suitability is proven during the project.

The given considerations lead to the selection of two possible materials for the HTR Reactor Pressure Vessel. Use of these materials for the “cold” and “warm” vessel option should be considered. The proposed material selection is the following:

- Traditional and well proven in existing nuclear power plant low alloy steels such as SA 508. Improved specifications and tests should be performed on these materials for better knowledge of degradation phenomena in HTR environment
- Chrome and Molybdenum alloy steels such as Modified 9 Cr – 1 Mo. Detailed specifications and a test campaign should be performed to learn about their behaviour in HTR environment

The present choice of candidate materials needs to be verified by a qualification test campaign that should consider all possible aspects during RPV operation. This includes tests for the materials and welded joints regarding reinforcement, thermal ageing, creep, thermal shock, irradiation embrittlement, ductility, corrosion at high temperatures under He atmospheric with some impurities, etc, with respect to normal operation and accident conditions.

In order to provide data for the materials test matrix, preliminary design values such as pressures, temperatures, environment and transient conditions have been assumed and given for the HTR Reactor Pressure Vessel. These parameters are not yet defined for the European HTR project. Therefore the values given should be regarded only as a first approach to be discussed with other countries and organisations that are currently developing these types of innovative reactors, taking into account their experience in the analysis of the material degradation phenomena that could affect the RPV.

7. REFERENCES

[1] *Materials –Work Package B2–*, Michelangelo Initiative. EA, CEA, Belgatom, Framatome, ECN. March 2000

[2] R.D.W. Bestwick (NNC), *Review of Existing and Proposed Vessels*. HTR–M, Petten, April 2001 (oral presentation)

[3] ASME Code, Issue 1998

[4] RCC-MR Code, AFCEN, Issue May 1993

[5] A.C. Kadak (MIT), *The MIT Modular Pebble Bed Reactor Project*. Seminar on HTGR Application and Development, Beijing (China), March 2001

APPENDIX A

MATERIAL PROPERTIES AND DATA

Table A-1 SA 533 and SA 508 Material Properties [3]

Properties	SA-533, GB, C1	SA-508, G3, C1
Tensile strength, MPa	550-690	550-725
Yield strength, MPa	345	345
Elongation (%)	18	18
Heat treating temp. ºC	845-980	840-895
Min. temper.temp ºC	595	620
Composition (%)		
Carbon	0.25	0.35 max.
Manganese	1.07-1.62	1.40-1.05
Phosphorus (max.)	0.035	0.025
Sulphur (max.)	0.035	0.025
Nickel	0.37-0.73	0.40 max
Chromium (max)	---	0.25
Molybdenum (max)	0.41-0.64	0.10
Vanadium (max)	---	0.05
Notes:	Plates	Forgings

Table A-2 Welding Considerations [3]

Material		SA 533 and SA 508	SA 336, F22A; SA 182-F22 SA 387-22; SA 335-P22
Nominal composition		3/4Ni-1/2Mo-Cr-V	21/4 Cr - 1Mo
Preheat recommended for welding		121ºC min.	150ºC min.
Mandatory PWHT acc. to ASME III NB	Holding temp. range, ºC	593-677	677-760
	Min. holding time for weld thickness	2 hr. plus 15 min. each additional inch over 2 in. (t > 2”)	5 hr. plus 15 min. each additional inch over 2 in. (t > 5”)
Repairs without or after final PWHT		May be made if PWHT is impossible or impractical acc. to Temper Bead Weld technique	Not provided by ASME Code Section III Used in non-nuclear applications
Applicable welding processes and filler metals	SAW	Mn-Ni-Cr-Mo wire and neutral flux	21/4Cr-1Mo wire and neutral flux
	SMAW	E9018M (Low Hydrogen)	E9018 B3 (Low Hydrogen)
	GTAW	ER 80S D2 and argon gas	ER 90S B3 and argon gas
	GMAW (eventually)	ER 80S D2 and argon-O_2 gas	ER 90S b3 and argon-O_2 gas
Joints design		No differences	
Heat input		Similar	
Filler metals cost		Similar	

Table A-3 Design stress intensity values (Sm) for SA-533 and SA-508 [3]

Temperature ºC	S_m (MPa)	
	SA-533, SA-508 Class 1	SA-533, SA-508 Class 2
21.1	184.0	206.85
37.8	184.0	206.85
65.6	184.0	206.85
80.0	184.0	206.85
93.3	184.0	206.85
12.1	184.0	206.85
14.9	184.0	206.85
150.0	184.0	206.85
204.4	184.0	206.85
260.0	184.0	206.85
300.0	184.0	206.85
315.6	184.0	206.85
343.3	184.0	206.85
350.0	184.0	206.85
371.1	184.0	206.85

Table A-4 2¼ Cr – 1 Mo and Mod 9 Cr – 1 Mo Chemical Composition [4]

	2¼ Cr – 1 Mo	Mod. 9 Cr – 1 Mo
	AFNOR 7CD9.10	Z10CDVNb 9.1
Composition %		
Carbon	0,05 – 0,11	0,08 – 0,12
Silicium	0,15 – 0,35	0,20 – 0,50
Manganese	0,30 – 0,70	0,30 – 0,50
Phosphorus (max)	0,020	0,020
Nickel (max)	0,30	0,20
Chromium	2,00 – 2,50	8,00 – 9,00
Molybden	0,90 – 1,10	0,85 – 1,05
Aluminium (max)	0,020	0,040
Sulphur (max)	0,015	0,010
Copper (max)	0,20	0,10
Vanadium	---	0,18 – 0,25
Niobium	---	0,06 – 0,10
Nitrogen	---	0,03 – 0,07

Table A-5 Design stress intensity (Sm) for Cr – Mo steels [4]

	Sm (MPa)	
Temperature (ºC)	2¼ Cr – 1 Mo AFNOR 7CD 9.10	Mod. 9 Cr – 1 Mo Z10CDVNb 9.1
20	163	193
100	154	193
150	149	193
200	147	192
250	147	190
300	147	187
350	147	183
400	144	174
450	137	163
500	131	146
550	112	126
600	---	101