SUB-CHAPTER E.3 REACTOR VESSEL

1. DESCRIPTION

The vessel comprises two main components:

- the reactor vessel body
- the vessel head

which are connected by closure components.

The reactor vessel body consists of the following sections, welded together by circumferential welds:

Upper section

The upper section is a single unit composed of a nozzle shell and an integrated flange.

The inner diameter of the flange is machined to form a support ledge for the reactor’s internal equipment (internals and core). The flange includes threaded holes for the closure studs, and its upper surface is clad with stainless steel and machined to provide a surface suitable for the gasket seating. The external seal ledge is welded to the external face of the flange. This piece is connected to the reactor cavity seal which ensures leak-tightness between the vessel flange and the bottom of the reactor cavity.

The nozzle shell includes eight penetrations for connecting to the 4 loops of reactor coolant system loop pipework. The shell is thickened over the majority of its length, in order to provide part-compensation for the nozzle openings in the shell. At its lower end, the thickness of the nozzle shell is reduced to that of the core shell to allow the nozzle shell to core shell weld to be carried out within a region of uniform thickness. The nozzles are separate forged items, welded to the vessel by a “set-on” process. The whole structure is supported on pads located under the eight nozzles spaced around the circumference. The support pads are integrated with the nozzles. The support pads rest on the support ring.

Lower section

The lower section is made up from two core shells, a transition ring and a lower hemispherical head dome. These forged parts are welded to each other by circumferential welds. The two cylindrical core shells encompass the active height of the core and are free from discontinuities. A forged transition ring provides the transition in thickness between the core shell and the lower head dome. It is welded to the lower shell of the core in an area of uniform cylindrical geometry, and to the lower head dome in an area of uniform thickness.

Eight radial guides are welded to the inside face of the transition ring. Four of these guides pieces ensure the alignment of the lower core support internals and all also provide a secondary support to the core in order to limit the consequences in case of a postulated failure of the lower core support structures.

The vessel head is made up of two parts attached by welding:

- The vessel flange is a forged ring with holes for the closure studs. The lower face of the flange is clad and the cladding is machined to form two gasket housings

- the dome is a forged component, partially spherical in shape, which is penetrated by, tubes, which allow access for the RCCA drives and instrumentation. The dome is also penetrated by the sub-dome thermocouple guide tube and the venting tube

Adaptors are fitted with an adaptor flange for attachment of the CRDM housing. The same principle is applied to the instrumentation adaptors.

Four equi-spaced Handling attachment plates (or lifting lugs), are welded onto the outside surface of the dome to enable handling of the vessel head.

The alignment and positioning of the vessel head on the reactor vessel body, and of the vessel's internal components are ensured by the vessel’s internal components’ integral alignment pins.

The internal surfaces of the vessel are entirely clad with stainless steel.

Closure components

Threaded fasteners ensure the closure and integrity of the closure with the reactor vessel body. Studs are screwed into the threads of the reactor vessel flange and exert a pre-load on the closure head through a nut-washer mechanism screwed onto the studs.

2. LIST OF OPERATING CONDITIONS

The transient conditions taken into account in the design of the reactor vessel (see section C.6.1.1) are representative of the operating conditions that should occur during operation of the plant. The installations are intended to have a life of 60 years. The transients selected constitute a reference base for evaluation of the reactor coolant system (RCP) [RCS] in order to ensure the integrity of the reactor coolant system equipment.

3. DESIGN PRINCIPLES AND OBJECTIVES

3.1. MAIN CHARACTERISTICS SELECTED

A front view of the vessel is given in E.3 FIG 1.

3.1.1. Vessel body – Design of the core

The vessel is designed based on the dimensions of the core. The core comprises 241 17x17 fuel elements. The active height of the core is 4200 mm. The design criterion for the core shell is to have a transition temperature RT_{NDT} [EOL] ≤ 30°C. The inner diameter of the core shell is 4885 mm (under the cladding). With this diameter, an end-of-life flux level of around $1.26.10^{19}$ n/cm^2 (E > 1 MeV) is obtained in the following conditions:

- 60-year life with a load factor of 0.9
- In-out management of low leakage fuel, with UO_2 fuel elements
- a core surrounded by a heavy reflector

For out-in fuel management, the end-of-life flux can reach $2.5.10^{19}$ n/cm^2 (E > 1 MeV). This value reflects the use of MOX fuel.

The objective remains fulfilled i.e. It is verified that the end-of-life RT_{NDT} transition temperature remains less than 30°C.

3.1.2. Vessel body – Design of the upper section

The design principle for the entire nozzle shell/flange unit is that it is a single forged unit which reduces the number of circumferential welds, particularly for the assembly of thick sections. The part located on the flange (required for the closure design) requires, at the level of the nozzle shell, reinforcement situated in the vessel wall rather than in the nozzle wall (to minimise machining and off-cuts) and to have set-on type nozzles (to minimise the thickness of the welded joints).

3.1.3. Vessel body – Design of the lower section

The lower section is made up of the following elements:

- two core shells
- the transition ring
- the lower head

The core shells are sized in such a way as to satisfy the end-of-life flux requirements, also taking into account the height required for the fuel elements (active height of the core) and lower core support structures. The two core shells in particular encompass the active height of the core and are free from discontinuities.

The lower head is spherical, and connected to the vessel body by means of the transition ring.

The lower head is sized with the same inner radius as the upper head (for forging-related reasons). Because nothing penetrates the lower head, no openings are required, with the result that it is not necessary to reinforce the wall thickness. Furthermore, the height between the bottom of the PSC (Core Support Plate) and the bottom of the vessel has been reduced (in order to limit the volume of the accumulator).

The transition ring provides the transition in thickness between the core shell and the lower head dome. Radial guide keys are welded to the inside face of the transition ring.

3.1.4. Design of the vessel head

The thickness and height of the head flange are calculated taking the following into account:

- ingot supply capacity
- limitation of rotation of the flange and of the level of stresses in the junction with the upper head dome

The upper head has the same spherical internal radius as the lower head of the vessel body.

The thickness of the upper head is determined by applying reinforcement rules.

3.2. MATERIALS

The choice of materials, their manufacture and their mechanical properties will comply with the RCC-M (see sub-chapter B.6), "Materials" section. The base metal used is standard 16 MND 5 ferritic steel (French description).

3.3. INSPECTION

During manufacture, the vessel will be inspected internally and externally in accordance with RCC-M requirements.

When the vessel is in service, the vessel body is required to be inspected from the inside because insulation surrounds the outside face of the vessel. All welds and the other special areas to be monitored are able to be inspected from inside the vessel.

3.4. DESIGN OF SUPPORTS

The vessel rests on pads located under the eight nozzles. These support pads are integral with the nozzles and rest on a support ring (see section E.4.9). The thickness of the nozzles is sized taking into account that the vessel is supported by eight nozzles in normal (design) and accident conditions. Vertical movement of the vessel is restrained by the loops during a severe accident.

3.5. CONNECTIONS

The main connections between the vessel and other equipment are listed below (the interface part is given in brackets):

Vessel / vessel internal components connections (see Sections C.6.5 and C.6.6)

❖ *Vessel flange and ledge (upper and lower core support structure flanges and alignment pins)*

The support of the vessel internals enables rapid positioning of both the lower and upper core support structures during refuelling operations. The ledge machined on the inside diameter of the flange provides support to the vessel's internal components. The alignment of the vessel head with the vessel body is ensured by pins fixed to the internal components and housed in notches machined into the vessel flange and head flange.

❖ *Vessel outlet nozzles (core barrel nozzles)*

A pad is machined on the inner contour of the vessel outlet nozzle in order that, in hot condition, the space calculated between the pad and the core barrel nozzle limits the by-pass flow to the required value. When cold, the space is sufficiently large to allow the removal of lower core support structures without risk of interference.

❖ *Lower radial guides (radial support key and the core's lower support plate)*

The alignment of the vessel's lower core support structures is provided by four radial guides welded on the vessel body transition ring. These radial guides allow radial and vertical differential thermal expansion. They also serve as tangential restraints in the event of accidental displacement of the vessel's internal components. The radial guides also provide secondary support to the vessel's internal components.

Vessel / CRDM (control rod drive mechanism) connections (see Section C.6.4)

❖ *Vessel / control rod drive mechanism adaptors (CRDM flange)*

Each of the 89 control rod drive mechanism adaptors comprises a tube and a flange. The tubes are welded onto the vessel head. The adaptor flanges are attached by bolts to the CRDM flange. The sealing mechanism at the connection between the two flanges consists of two circular metal seals (of the conoseal type).

Vessel / instrumentation devices (see Sections G.5.2 and G.5.5)

❖ *Vessel / instrumentation adaptors (level measuring sensors, instrumentation lances comprising "aeroball" ball sensors, fixed neutron detectors (SPN) and the core outlet thermocouples)*

Number: 16 peripheral positions are used.

The instrumentation adaptors are also made up of a tube and a flange. The flange is specially designed to be connected to an instrumentation column (level-measuring sensors or the core's internal instrument probes). The inner surface of the adaptor flange is threaded for connection to the instrumentation column. The seal at the upper head of these flanged adaptors is a welded canopy seal. Removal of instruments occurs at the level of the instrumentation column.

Vessel / concrete cavity connection

The vessel head design allows the unloading and refuelling of the core and the removal of the vessel internals. These operations are carried out with the reactor cavity full of water. Provisions are made to ensure that the reactor cavity is leak-tight. Leak tightness is ensured by the reactor cavity seal ring. This component is welded onto the external seal ledge of the vessel flange on one side and on the cavity's liner on the other side.

Vessel / Head equipment connection

The vessel head is fitted with lifting lugs which connect with the vertical rods of the vessel head lifting device.

Vessel/multi-stud tensioning machine [MSTM]

Refuelling procedures require that the studs, nuts and washers are removed from the reactor head using the [MSTM]. Use of the [MSTM] ensures that the reactor closure studs are never exposed to the refuelling cavity's borated water. Further protection against the possible effects of corrosion is provided by the application of a manganese-based phosphate treatment.

The stud holes in the vessel flange are sealed using special plugs before the removal of the vessel head thus preventing leakage of borated water into the tapping.

4. MATERIALS

4.1. BASE METAL

A low-alloy ferritic steel is used for the shells, flanges, transition ring, nozzles and hemispherical heads.

The RCC-M (see sub-chapter B.6) gives the chemical composition, mechanical properties and heat treatment that are defined for the base metal.

In accordance with the RCC-M, the chemical compositions that are defined take account the following changes compared to the ASTM standard:

- limitation of the upper carbon content threshold, for improved weldability and overall ductility

- reduction of the upper sulphur content limit to 0.005% for components not subject to irradiation as well as for components situated in the irradiated area of the core This requirement limits the effects of anisotropy on the mechanical properties; the toughness of the upper shelf increases, in particular transversely (perpendicular to the main direction of deformation by hot working)

- in the active area of the core subject to high levels of irradiation (core shells), the copper and phosphorus content is limited to 0.08% and 0.008% respectively. This requirement limits the effects of embrittlement by irradiation

- lowering of the phosphorus content limited to 0.008% for vessel components not subject to irradiation

- limitation of the upper limit for chromium and vanadium content. This requirement is related to reducing the risk of under-cladding cracking

- limitation of the cobalt content. This requirement is related to reducing the level of radiation on the vessel's interior wall

- a very low content of residual elements is also required in order to obtain the right properties for toughness and good weldability

After forging, the parts are subject to various heat treatments. The temperatures for the austenitising, tempering and stress relieving processes are given in the RCC-M.

After the final heat treatment, the parts are machined and base material test specimens are taken. The tensile strength and the toughness properties required are re-stated in the RCC-M. The specimens are taken from the inner quarter of the thickness of the shells and hemispherical heads. For other parts of larger dimensions, the location of specimens depends on the particular component geometry.

Assurance of the ferritic materials in the main reactor coolant system (RCC-M, Level 1 components) is ensured through compliance with requirements relative to toughness tests, contained in the reactor component procurement specifications.

Additional tests are mandatory to determine the initial benchmark zero ductility temperature. RT^0_{NDT} , Charpy V-notch test and Pellini tests are carried out to determine this temperature which serves as a benchmark to define the lower limit of the toughness curves.

The values specified for the initial temperature RT^0_{NDT} are required for all of the vessel's forged parts. For forged parts, core area included, it is required that the initial temperature RT^0_{NDT} is less than or equal to -20°C.

4.2. OTHER VESSEL MATERIALS

4.2.1. Vessel cladding

The use of highly sensitised stainless steel as a material for manufacture of the pressure boundary is prohibited. Surfaces covered in stainless steel are subject to sampling to ensure that the requirements relating to composition and delta ferrite are met.

A twin layer stainless steel cladding is constructed upon the inner surface of the vessel wall.

The reason for applying a twin layer cladding procedure is to obtain a stainless steel surface with a low carbon content which will not be sensitised during the stress relief treatment of the reactor vessel. To avoid the occurrence of cracks due to hydrogen, all cladding operations are carried out with pre-heat maintained throughout the cladding process until post-heating is carried out. Furthermore, overlap precautions for the weld of the second layer are applied in order to avoid any risk of cracks under the cladding when reheated.

The thickness of the twin layer also allows grinding operations to make the cladding surface condition compatible with Ultrasonic inspection of the cladding bond.

4.2.2. Vessel studs

The vessel studs are manufactured from high-strength bolting steel.

4.2.3. Vessel safe ends

Safe ends are welded onto the vessel nozzles during manufacture to avoid having to carry out dissimilar metal welds during on-site assembly. The safe ends are manufactured from forged Cr-Ni-Mo austenitic stainless steel rings, and welded to the ferritic nozzle by a narrow gap welding process [NGW] using Ni-Fe-Cr filler metal. The inner surface of the ferritic tube is clad in stainless steel.

4.2.4. Vessel adaptors and radial guides

The adaptors and radial guides are manufactured from an Ni-Fe-Cr alloy. Inconel 690 grade is selected because its thermal expansion coefficient is very close to that of the base metal and its allowable stress remains close to that of the base metal. Studies of this alloy grade demonstrate that it is not sensitive to stress corrosion cracking. These parts are welded to the vessel using a Ni-Fe-Cr filler metal.

5. MECHANICAL DESIGN

The mechanical design rules formulated in the RCC-M (see sub-chapter B.6) and the stress limits specified in chapter B of the RCC-M are intended to prevent the following types of damage to the vessel:

- excessive deformation and plastic instability,
- progress deformation and fatigue cracking
- fast fracture

An analysis of the protection against the risk of fast fracture is shown in section E.3.6.1.

5.1. SIZING CALCULATIONS

The main objectives of the sizing calculations carried out in the EPR project design phase are to achieve a vessel design which ensures acceptance of the benchmark condition criteria (design pressure), relating to protection against the risk of excessive deformation and plastic instability.

This area includes the calculation of the minimum design thickness for all the main vessel parts and reinforcement calculations in the areas where openings are located (inlet and outlet nozzles and head dome penetrations). The design rules laid down in the RCC-M (Chapter I, Chapter B) are applied. The design pressure is 176 bar. The design temperature is 351°C.

The studs are sized for the design pressure taking into account hydrostatic end force and seal reaction is defined according to RCC-M.

5.2. DESIGN OF SUB-ASSEMBLIES

5.2.1. Vessel sub-assemblies involved in the analysis of accident loads

Certain vessel parts, loaded in the event of accident loads, are sized using criteria relating to the corresponding level conditions as required under Chapter B, Part 1 of the RCC-M. Vessel sub-assembly designs which are affected by the possibility of accident loads are as follows:

- vessel nozzles and support pads
- vessel radial guides located on the vessel transition ring
- vessel adaptors attached to the upper head dome

The design thickness of the set-on nozzles is acceptable for accident situations (including Loss of Coolant Accidents [LOCA] accidents and seismic loads).

The radial guides are sized taking account of [LOCA] and seismic loads. The local rigidity at the transition ring limits the level of stress in the vessel wall. The radial guides are also sized to provide resistance in the event of a vessel internal component break accident.

The design thickness of the adaptors is acceptable under seismic loads.

5.2.2. Analyses of progressive deformation and fatigue cracking

With regard to protection against progressive deformation and the risk of vessel cracking through fatigue, the approach is based on experience of standard, already-known designs.

This is the case for all the main areas of the vessel where major discontinuities may be found, with the exception of one area, the set-on nozzles, which requires particular analysis.

Calculations have been carried out to analyse the relationship between the set-on nozzles and the vessel. Analysis intended to assess the margins relative to the risk of progressive deformation and cracking through fatigue was performed in this area and showed good margins.

6. PRELIMINARY SAFETY EVALUATION

6.1. FAST FRACTURE MECHANICS ANALYSIS

Fracture mechanics analyses are also carried out to evaluate the margins relative to fast fracture in the most severe situations postulated. The actuation of the safety injection circuit [SIS], following a reactor coolant system loss of coolant accident or a steam line break, induces high thermal stress in the core shell which comes into contact with safety injection water.

The principles and procedures for Linear Elastic Fracture Mechanics [LEFM] are applied to evaluate thermal effects in the regions of interest. The LEFM approach in fracture to the design against the risk of fast fracture; it is based on an examination of stress intensities within which instability criteria relative to the break are determined in the presence of a defect. Consequently, a basic assumption used in Linear Elastic Fracture Mechanics is that a defect in the form of a crack is present in the structure. The basic principle of the approach is to establish a link between stress field developed in the vicinity of the crack tip and the applied stress on the structure, the materials' properties, and the size of defect needed to cause a fast fracture.

The elastic stress field at the crack tip for the postulated defect can be described by a simple parameter, called the stress intensity factor, designated by K. The magnitude of the stress intensity factor, K, is a function of geometry of the body containing the defect, the defect's size and location and the magnitude and distribution of the stress.

The fast fracture criterion in the presence of a defect is that crack instability will occur when the stress intensity factor exceeds a certain critical value. For the opening mode of loading (stresses perpendicular to the main plane of the defect), the stress intensity factor is designated as K and the critical stress intensity factor is designated by K_{1c} , K_{1c} being a property inherent to the material which is a function of the crack tip temperature and which is indexed by the reference transition temperature RT_{NDT} for the material in question. All combinations of applied load, structural configuration, and defect geometry and size, which produces a stress intensity factor greater than or equal to K_{1c} for the material, will lead to crack instability.

The Linear Elastic Fracture Mechanics applicability criterion is based on plasticity considerations at the postulated crack tip. The strict applicability (as defined by the ASTM) of Linear Elastic Fracture Mechanics to large structures where plain strain conditions predominate requires that the plastic zone developed at the crack tip is not extensive compared to the depth of the defect. However, Linear Elastic Fracture Mechanics has been used successfully to provide conservative brittle fracture prevention evaluations even in the event that a strict application of the theory is not permitted due to excessive plasticity. Experimental results have demonstrated that Linear-elastic Fracture Mechanics can be applied conservatively while the pressure component of the stress does not exceed the material's elastic limit. The addition of the thermal stresses, elastically calculated, which results in a total stress exceeding the elastic limit, does not affect the conservatism of the results on condition that these thermal stresses are included in the evaluation of stress intensity factors. For analysis of 4^{th} category situations, Linear-elastic Fracture Mechanics is considered applicable for evaluation of the crack stability.

6.2. ISI REQUIREMENTS

6.2.1. Materials irradiation monitoring

In the monitoring programme, evaluation of irradiation damage is based on pre-irradiation tests carried out on Charpy V-notch specimens and tensile test specimen. Post-irradiation tests are carried out on Charpy V-notch specimens, tensile test specimens and fracture mechanics compact tensile specimens. The programme is aimed at evaluating the effect of irradiation on the toughness of the vessel steels, and is based on an approach combining transition temperature and fracture mechanics.

The vessel monitoring programme uses specimen capsules housed in the holders attached to the outside of the vessel barrel, and positioned directly opposite the central section of the core. These capsules can be removed when the vessel head and the upper core support structure are removed. All capsules contain vessel steel specimens of the selected base metal located in the core region of the reactor and of the associated weld metal and the weld heat-affected zone metal. Each capsule encloses tensile test specimens, Charpy V-notch specimens (which contain weld metal and metal from the heat-affected zone) and compact tensile specimens. Archive materials are kept in sufficient quantities for additional capsules.

Activation and fission dosimeters are placed in blocks with calibrated holes. The dosimeters enable evaluation of the flux observed by the specimens. In addition low melting-point alloy temperature indicators are included in order to monitor the maximum temperature of the specimens. The specimens are enclosed in a tailor made stainless steel cladding, to prevent any corrosion and ensure good thermal conductivity. The whole capsule is subject to a helium leak test.

As part of the surveillance programme, a report on residual elements will be drawn up for monitored materials and deposited weld metal.

The specimens' exposure to fast neutrons occurs at a faster rate than that to which the vessel wall is subject, the specimens being located between the core and the vessel. Given that these specimens undergo accelerated irradiation and that they are actual specimens from the materials used in the vessel, the measurements of transition temperature differences are representative of the vessel at a more advanced age. The data from the CT specimens are expected to provide additional information to directly determine the toughness of irradiated materials.

Correlations are established between the calculations of integrated flux and the measurements from the irradiated specimens in the capsules, assuming that the neutron spectrum is the same for the specimens and the vessel's internal wall.

Verification and readjustment, if required, of the calculated irradiation for the wall will be carried out using data from all the sampled capsules. The capsule sampling programme for post-irradiation testing will be given within the vessel surveillance programme.

6.2.2. In-service inspection

The internal surface of the vessel may be periodically inspected, mainly at ten-yearly in-service inspections, using the In-Service Inspection Machine (MIS). The lower core support structure may be removed, thus making the entire internal surface of the vessel accessible.

The vessel head is subject to a visual examination (by camera) at least during each ten-yearly in-service inspection.

The closure studs must be inspected periodically through visual examination by dye penetrant tests and by eddy currents.

All welds are accessible for in-service inspection:

- vessel shells – by the internal surface
- reactor coolant system nozzles – by the internal surface
- lower head – by the internal surface

- dissimilar metal welds between the vessel nozzles and the main reactor coolant system pipework – by internal and external surfaces

The fundamentals which have been included in the design in order to enable the inspections mentioned above are as follows:

- all of the vessel's internal structures are entirely removable
- during refuelling, the vessel head is put on a stand in a dry area to facilitate direct visual inspection
- all the vessel's studs, nuts and washers can be removed for dry storage during refuelling
- the insulation covering the welds between nozzles and reactor coolant system nozzles can be removed

The vessel head insulation comprises removable panels which provide access to enable visual inspection of the vessel head.

Access to the vessel body must be regulated owing to the radiation levels and its remote underwater accessibility. Several measures have been included for these reasons in the design requirements and manufacturing procedures, in order to facilitate the non-destructive periodic inspections that are required within the regulatory texts, namely:

- ultrasonic inspections are carried out in the workshop on all inner covered surfaces, in accordance with the acceptance and rework criteria. The inspections ensure that there are no bond defects which would disrupt subsequent inner-surface ultrasonic inspections of the base metal
- the vessel core shell geometry is a cylindrical surface to allow ease of subsequent positioning of testing apparatus
- the clad surfaces on both sides of the welds to be inspected are subject to special preparation to ensure the effectiveness of the ultrasonic inspections
- during manufacture, all full penetration ferritic welds on the pressurised enclosure are examined by ultrasonic inspection

The purpose of the design and construction of the vessel is to enable inspections as required by the regulations that apply to French nuclear power stations.

6.3. PRESSURE AND TEMPERATURE LIMITATION

The operating limits at start-up and shutdown are based on the properties of the materials in the vessel core region. Actual material property test data are used.

Operating curves are calculated assuming a period of reactor operation such that the beltline material will be limiting. The materials properties of the beltline (core area) is embrittled with irradiation, and this degradation is measured in terms of the adjusted benchmark null ductility transition temperature which includes a shift with the reference nil ductility transition temperature (ΔRT_{NDT}).

The predicted ΔRT_{NDT} values are derived using two effects; the effect of flux and the effect of copper, phosphorus and nickel contents on the ΔRT_{NDT} shift for materials located in the beltline (core area, base metal and weld material).

The maximum fluxes, at the tip of the conventional defect when this defect is assumed to be located on the inner and outer diameter respectively of the core shells, are calculated for various selected times of the reactor life and pressure / temperature curves are established.

Changes in the toughness of welds, of forged parts in the core area and the related HAZs (heat-affected zones), due to irradiation damage, will be monitored by the reactor vessel monitoring programme.

7. MANUFACTURE AND PROCUREMENT

7.1. PROCUREMENT OF PARTS

The main parts in the vessel are produced by forging in accordance with the RCC-M instructions (see sub-chapter B.6).

The upper section of the vessel is manufactured from a single ingot. The inner and outer profiles are machined from one overall piece of suitable shape. In this way, the internal components support ledge, the (inner) nozzle and the nozzle welding starter tube are all machined from a very thick forged shell.

This upper section of the vessel (nozzle bearing shell unit) has been subject to M140 qualification in accordance with RCC-M, the results of which provide assurance of the proper mechanical and metallurgical properties of the part. All the other vessel parts need ingot weights less than 210 te. Conventional ingots (solid) are used to manufacture the vessel flange, transition ring and nozzles. Solid ingots will be used for the two core shells. Directional solidification ingots can also be used for the manufacture of the hemispherical head forgings.

7.2. MANUFACTURING SEQUENCES

The manufacture of the vessel body is divided into two sub-assemblies:

Upper sub-assembly

The upper sub-assembly is made up of the upper part of the vessel and the eight safe ends and nozzles. Each nozzle must be welded by an automatic narrow groove welding process (set-on type welding). Before assembly, each nozzle is fitted with a stainless steel safe end. The safe-end welding operation is carried out by a narrow groove TIG welding process. The end of the nozzle and the safe end are not buttered before welding. This process provides good productivity and good ultrasonic test inspectability.

All the ferritic inner surfaces, the flange seal face and the upper surface of the flange, up to the location of the reactor vessel seal ring, are clad with stainless steel. Several processes are used to produce this cladding: automatic electro slag strip welding, hot wire TIG welding, manual welding.

Lower sub-assembly

The lower sub-assembly comprises the two core shells, the transition ring and the lower hemispherical head. The two core shells are welded by an automatic narrow groove welding process. This assembly is clad. The radial guides are welded on a Ni-Cr-Fe filler metal buttering (690 alloy) carried out on the transition ring. The transition ring and the lower head are then clad and welded together before the final assembly of the lower unit.

The manufacture of these two sub-assemblies is carried out at the same time. Once completed, the two sub-assemblies are joined by welding.

The automatic welding process is used for all full-penetration circumferential welds and a narrow groove is used for weld preparation.

The manufacture of the vessel head is carried out separately.

All the ferritic inner surfaces, the flange seal face and the upper surface of the flange have stainless steel cladding. Several processes are used to produce this cladding.

The head dome and the head flange are welded by an automatic narrow groove-welding process. Adaptors are fixed by shrink-fitting and welded (partial penetration type weld) on a Ni-Cr-Fe filler metal buttering (690 alloy).

7.3. WELDING AND NON-DESTRUCTIVE TESTS

7.3.1. Main welding processes used in manufacture

The main welding processes used in manufacture are described below.

Narrow groove submerged arc welding

Circumferential ferritic welds for assembly are narrow groove full penetration welds and the submerged arc welding process is generally used. An automated welding process with accurate management of all factors is required. The weld quality and equipment reliability have been thoroughly demonstrated by numerous previous inspections of circumferential welds.

For set-on nozzles, the narrow groove automatic welding process is qualified for ferritic welds manufactured for a thickness of around 180 mm and an angular joint of 10 degrees (angle between the weld axis and perpendicular to the nozzle wall).

Cladding process for stainless steel

A two-layer cladding process is provided using an automatic submerged arc welding process which enables the use of large wide strip electrodes, without defects at beads overlaps. This automated process is performed with manufacturing precautions in order to ensure:

- low dilution of the base material
- high cleanliness and low hydrogen content of the stainless steel cladding

The described cladding process is fully qualified and is applied to the RPV cladding manufacturing.

Narrow gap TIG welding process [NGT]:

The bimetallic connection between the nozzle and the safe end is directly produced (without buttering) by a narrow gap TIG type automatic welding process [NGT]. This type of connection is similar for all the bimetallic connections for the EPR reactor coolant system's major components. Owing to the absence of buttering and the low quantity of metal deposited, the narrow groove configuration provides significant operational simplicity which reduces the risk of a technical welding defect.

Heat treatments

Welding and cladding operations on the base metal require special precautions relative to heat treatments. The parts to be assembled are preheated before and during the welding operation to a minimum temperature of 175°C to avoid cracking owing to hydrogen in the HAZ (heat-affected zone).

After welding, the end-to-end assemblies undergo one of the following two heat treatments:

- post-heating in order to diffuse hydrogen from the HAZ

- heat treatment in order to reduce the residual stresses, in particular related to weld contraction. This treatment also diffuses hydrogen.

In the final stage, the vessel undergoes final stress relieving heat treatment. This treatment is carried out at a temperature lower than the minimum tempering temperature (and provides stress relief, without resulting in any significant reduction in the mechanical properties).

7.3.2. Non-destructive tests

Several types of non-destructive tests are carried out during manufacture.

Examination of surface defects

Prior to welding, the lateral surfaces of the grooves are inspected by magnetic particle inspection. The same inspection is also carried out on the inner surface of welded joints before cladding (examination by hot magnetic particle inspection). Dye penetrant tests (DP) are also used for other inner surfaces before cladding. These inspections ensure that the metal surface is free of defects that could remain or that could develop owing to their presence during the cladding operation. Dye penetrant tests are also carried out once the cladding is completed.

Dye penetrant tests are also used for the final inspection of the adaptor welds and the radial guide welds.

In accordance with the criteria defined in the RCC-M (Chapter S 7000), any linear defect or crack detected during either one of these inspection methods is subject to a rework procedure.

Once the stress-relief heat treatment is carried out, surfaces are inspected in accordance with the RCC-M (Chapter S 7000).

Examination of volume defects

It is required that all full penetration circumferential welds are 100% inspected by ultrasonic testing (UT) prior to and after completion of the cladding.

In addition to these inspections, the following areas are subject to ultrasonic inspections according to the RCC-M, after the final stress relief treatment is carried out:

- all full penetration ferritic welds on the pressure boundary
- cladding of the internal support ledge
- cladding of the alignment pins head and vessel housing
- the vessel flange low carbon buttering

The ultrasonic inspections are carried out with two types of scans:

- transverse scans, parallel and perpendicular to the weld seam, both sides of the weld
- longitudinal scans (perpendicular to the surface) over the whole surface of the weld and both sides, such that the inspection encompasses the HAZ

The criteria applied are those of the RCC-M for all Level 1 components. Particular attention is paid to finding surface defects all of which must be repaired.

In addition to the ultrasonic inspections (UT), other methods of volume inspection (x-ray inspections or additional ultrasonic methods) may be required, as per the RCC-M.

With regard to the vessel design, all full penetration circumferential welds must be 100% inspected by radiographic examination. A linear accelerator is used to carry out radiographic examinations owing to the wall thickness.

Other techniques, such as ultrasonic inspection processes using focussed transducers (or the application of a dual method, as used in Germany) may also be used to examine the vessel.

The criteria applied are those of the RCC-M for all Level 1 components. Unacceptable defects are as follows:

- cracking
- lack of penetration
- incomplete fusion
- undercutting
- blistering

In the event of non-conformance, the defect is subject to repair following approved procedures.

E.3 TAB 1: VESSEL DESIGN PARAMETERS

General design	
- Type	four loops
- Number of control rod mechanism adaptors	89
- Number of internal core instrumentation adaptors	16
- Number of flange studs	52
Calculation and operating conditions	
- Design pressure	17.6 MPa abs.
- Operating pressure	15.5 MPa abs.
- Design temperature	351 °C
- Temperature in the RCS hot leg	328.1 °C
- Temperature in the RCS cold leg	295.5 °C
Test conditions	
- Hydrostatic test pressure	25.1 MPa abs.
- Hydrostatic test temperature	RTNDT +30°C
Sizes and weights	
- Inner diameter of the cylindrical vessel	4870 mm
- Outer diameter of the flange	5750 mm
- Largest diameter (for transport)	7470 mm
- Total height of the lower section (from flange to bottom of dome)	10532.5 mm
- Total height, head, control rod adaptors and venting tube included	13722.5 mm
- Vessel body weight	410 t
- Vessel head weight	116 t
- Weight of studs, bolts and washers	32 t

E.3 FIG 1: FRONT VIEW OF VESSEL