2. STEAM GENERATORS

2.1. DESCRIPTION

2.1.1. General characteristics

The design of the EPR steam generator is based on that of the N4 steam generator (type 73/19 TE). It is a natural circulation U-tube heat exchanger fitted with an axial economiser (see E.4.2 FIG 1).

The steam generator is composed of two sub-assemblies. One ensures vaporisation of the feedwater, the other the mechanical drying of the resulting water/steam mixture. It is arranged vertically and the water/steam mixture flows upwards by natural circulation. Feedwater enters the steam generator through the main feedwater nozzle which is incorporated into a conical shell in order to reduce thermal stratification. Feedwater then passes through a distribution half-ring (cold leg side) which is equipped with a deflection sheet and is installed at a level above the upper section of the tube bundle.

The primary objective of the axial economiser is to direct all feedwater to the cold leg of the tube bundle and about 90% of the recirculated water to the hot leg. This is enabled in practice by incorporating the following features into the design of a standard natural circulation U-tube steam generator:

- a double wrapper in the downcomer on the cold side to guide feedwater to the cold leg side of the tube bundle
- a secondary side divider plate (from the tube sheet up to the 6th tube support plate) to separate the cold leg and hot leg parts of the tube bundle. Also, and in conjunction with the above design features, the steam generator feedwater distribution system (ring with oblong-shaped holes and deflecting sheet) extends only over a 180° angular portion of the wrapper on the cold side

This design enhances the heat exchange efficiency between the primary and secondary sides and increases the pressure of the steam produced by 3 bar compared with a standard steam generator having the same heat exchange surface area.

Unlike other economiser designs, this design has two additional benefits:

- no direct cross flow affecting the tubes nor risk of vibrations
- no reduction in accessibility of the tube bundle for inspection and maintenance

The steam generator is fully shop-built, and is transported to the site and installed in its reactor building cell in one piece.

It is vertically supported by four support legs and laterally guided at two levels (see section E.4.9).
2.1.2. Lower sub-assembly

The lower sub-assembly comprises:

- the channel head which is formed mainly by a hemispherical bottom head and a tube sheet. A cylindrical section has been added to the upper section of the lower head in order to improve access to the peripheral tubes for inspection. A primary partition plate divides the channel head into two leaktight compartments. One is connected to the reactor vessel outlet (hot leg) and the other to the reactor vessel inlet via the reactor coolant pump (cold leg)

- each compartment includes a nozzle for connection to the reactor coolant system and a manway providing access for in-service inspections and maintenance operations. Specific provisions are made to facilitate plugging of the nozzles and to facilitate inspection and maintenance operations inside each compartment during refuelling outages

- the secondary shell comprises three cylindrical shells and a conical shell. The lower shell is fitted with 8 handholes on its lower section for in-service inspections and maintenance operations on the lower section of the tube bundle. The intermediate shell is fitted with two diametrically opposed eyeholes at the level of the sixth tube support plate and a set of instrument taps on the axis of the central tube lane to measure the steam generator water level. Lastly, blowdown of the steam generator takes place by means of three blowdown taps

- the tube bundle, made up of inverted U-tubes, provides heat exchange between the primary coolant circulating inside the tubes and the secondary cooling system. It also constitutes a radiological barrier between the primary and secondary sides of the nuclear steam supply system (NSSS)

The tube bundle is arranged in a triangular pitch.

The ends of the inverted U-tubes are welded to the protective cladding of the primary face of the tube sheet. The welds are subjected to a helium leak test and the ends of the U-tubes are then full-depth expanded into the tube sheet in order to eliminate any crevices.

It has been demonstrated that the equipment and procedure used for tube expansion minimises the residual stress in the transition zone between the expanded and non-expanded parts of the tube.

Measures are taken to ensure that the expansion of the tubes is complete just below the secondary face of the tube sheet.

- The role of the lower internal support structures is to support the tube bundle while ensuring circulation of the secondary cooling fluid.

They comprise:

- the bundle wrapper which isolates the recirculation water flow path from that of the water/steam mixture. It creates an annular zone between the tube bundle and the steam generator shell called the downcomer. An annular opening found on the lower section allows the distribution of the water to the tube bundle

- a semi-annular downcomer on the cold leg side comprising a double wrapper concentric with the bundle wrapper the outlet of which is close to the top face of the tube sheet on the periphery of the tube bundle on the cold leg side
- a secondary divider plate, welded to the bundle wrapper, which separates the cold leg side from the hot leg side up to the sixth tube support plate and which constitutes the economiser area. The joint between the divider plate and the tube bundle is leak-tight

- nine tube support plates spaced appropriately over the height of the tube bundle in order to support the tubes and thus avoid any vibration/wear effects. Broached Trifoil holes (“high permeability” broaching) with flat contacts (to remove the risk of dryout) allow the secondary water/steam mixture to circulate freely

These tube support plates are centred by means of double slope wedges fixed on anti-seismic blocks regularly spaced around their periphery centring the tube-bundle wrapper in the steam generator shell.

The tube support plates are vertically interconnected and spaced by a network of tie-rods bolted into the secondary side face of the tube sheet.

The tie-rods, the anti-seismic blocks and the tube support plates are designed to withstand in-plane and out-of-plane loads even under faulted conditions (earthquakes, pipe ruptures), see section E.4.2.6.3.

Over the full height of the economiser divider plate, each of the tube support plates comprises two half-plates:

- a flow distribution baffle designed to obtain proper distribution of the fluid entering the tube bundle and to minimise the low-flow velocity zone above the tube sheet.

- three perforated tubular manifolds designed to allow rapid draining of the steam generator and continuous blowdown

### 2.1.3. Upper sub-assembly

The upper sub-assembly (steam drum) comprises two cylindrical shells, a conical shell and an elliptical upper end. The cylindrical section consists of:

- two manways providing access to the steam/moisture separation equipment. They also give access to the feedwater devices, the top of the tube bundle via the hatch through the bundle wrapper and the camera holes installed on the roof of the bundle wrapper

- a set of water level measurement taps

The upper elliptical head comprises an integral (weldless) steam outlet nozzle fitted with a welded steam flow restrictor which limits the forces applied to the steam generator tube bundle and internals in case of steam line break event.

The steam drum is fitted with:

- a main feedwater system comprising:

  - the main feedwater nozzle implemented in the conical shell

  - the thermal sleeve (leaktight connection between the main feedwater nozzle and the feedwater distribution ring)
- the main feedwater half-ring fitted with a deflecting sheet and ensuring a uniform distribution of all the water from the main feedwater system (ARE) [MFWS] or the start-up and shutdown system (AAD) [SSS] feedwater into the cold leg side downcomer

- the feedwater half-ring supports

- an emergency feedwater supply system comprising:
  - its own inlet nozzle
  - the thermal sleeve (leaktight connection between the emergency feedwater system (ASG) [EFWS] nozzle and the emergency feedwater ring)
  - the emergency feedwater distribution ring fitted with I-shaped tubes orientated towards the SG axis (to avoid any risk of cold water impact on the pressure boundary components) and distributing the emergency feedwater both into the hot leg side and cold leg side downcomer

- the support system

The physical separation of the main and emergency feedwater systems and their respective designs removes the risk of water hammer and minimises the risk of thermal stratification.

- water/steam separation equipment comprising:
  - a first stage of cyclone type separators of 335 mm diameter (connected to the bundle wrapper roof). Each separator is designed to obtain a very low carry-under
  - a single stage “chevron”-type dryer unit (attached to the upper head of the steam drum) which ensures a low carry-over content at the steam generator outlet

### 2.1.4. Support structure

The steam generator support structure (see section E.4.9.) is designed to allow thermal expansion of the reactor coolant system loop and displacement caused by pressure but limits such displacement during accidents. The support structure is comprised of vertical and lateral supports described below:

#### 2.1.4.1. Vertical supports

Vertical support for the steam generator is provided by four support columns fitted with a trunnion at each end. Upper articulation is effected on a trundle fitted with a clevis connected to forged integral pads attached to the steam generator channel head. Lower articulation consists of a lower clevis fixed to the cell floor by 4 pre-stressed tie-rods.

#### 2.1.4.2. Lateral support

Lateral restraints are installed at two levels:
at the lower level, restraints are placed at the level of the tube sheet. Two lateral restraints guide the steam generator during thermal expansion of the reactor coolant system loop. The design is such that it provides easy access to the tube sheet welds for in-service inspections. A third restraint in the hot leg axis is designed to support the steam generator and stabilise it in the presence of a conventional 2pA-type static load.

- at the upper level, 4 horizontal supports are directly attached to the steam generator shell at the approximate level of its centre of gravity. The loop’s thermal displacements remain free due to two connecting rods allowing steam generator movements radial to the vessel and two hydraulic snubbers with swiveled ends parallel to the hot leg axis. The hydraulic snubbers prevent any sudden displacement of the steam generator resulting from an earthquake or pipework rupture. The upper horizontal support is designed to allow free thermal expansion of the steam generator shell and loop but limits amplification of horizontal displacement of the steam generator in the event of an earthquake or pipework rupture.

2.2. OPERATING CONDITIONS AND INTERFACES

The operating conditions and interfaces are provided in E.4.2. TAB 1 (Steam Generator Data Sheet) for 4500 MWth power.

2.3. DESIGN PRINCIPLES AND OBJECTIVES

2.3.1. Functional requirements

The steam generator is designed to fulfil the following functions:

- Produce steam with no more than 0.25% moisture carry-over at the steam generator outlet using the reactor coolant system as the heat source.

- Provide capability for continuous hot blowdown of the secondary side of the steam generators. The steam generator blowdown rate permits a transition from cold lay-up water chemistry to hot standby water chemistry within an eight-hour period.

- Provide an indication of secondary side water level. Provide automatic control of water level at any power level from hot no load to full power.

- Provide a leak tight boundary between the reactor coolant and the steam generator secondary side.

- Serve as the first mean for removal of decay heat from reactor coolant during plant shutdown using main as well as start-up and shutdown feedwater in normal operation or emergency feedwater in accident condition. This allows the primary coolant temperature to be reduced to a value sufficiently below the saturation temperature corresponding to the actuation pressure of the residual heat removal system.

- Provide for full wet lay-up of the steam generator under deoxygenated, pH-controlled conditions.
2.3.2. Main properties selected

- Full power steam pressure and capacity
  The steam generator is designed to generate, under given primary coolant system pressure and flow conditions, the pressure and mass flow of steam specified at 100% of the nominal full power.

- Operational capability
  The steam generator is able to fulfil its required functions in the event of RRC-A and PCC 1 to 4, except for the period when reactor core cooling is carried out by the residual heat removal system (RRA) [RHRS] or by its back-up systems.

- Steam generator water inventory (heat sink reserve)
  The steam generator supplies the reactor with a minimal heat sink reserve of cold water (steam generator water inventory) to ensure the mitigation of all situations (RRC-A and PCC 1 to 4). The mitigation also considers the operation of dedicated systems - main feedwater system (ARE) [MFWS], start-up and shutdown system (AAD) [SSS], emergency feedwater system (ASG) [EFWS], safety injection systems (RIS) [SIS] and pressuriser safety valves. In particular, the steam generator is designed to hold a sufficient volume of water such that should all feedwater systems (ARE) [MRWS], (AAD) [SSS] and (ASG) [EFWS]) be lost, the steam generator secondary side will not dry out in less than 30 minutes.

- Total volume of the steam generator (overfilling requirement)
  The steam generator serves as an expansion tank for secondary feedwater systems, consequently protecting the steam equipment against water inflow (including the turbine) after isolation of the source of the overfill.
  The medium head safety injection (ISMP) [MHSI] pump discharge head is below the pressure setpoint of the non-isolatable main steam safety valves so that, in the event of sudden steam generator tube rupture (RTGV) [SGTR] (double-ended guillotine break or equivalent surface break) of one or two steam generator tubes, they do not open. In addition, the increased volume of the secondary side steam generator (free volume above the normal level rising from 61.5 m$^3$ on N4 to 82.3 m$^3$) allows the flow of fluid from the primary to secondary side to be accommodated without the risk of overfilling the steam generator, at the same time taking account of the capacity of the primary and secondary side isolation devices and the primary circuit monitoring systems.
  It should also be noted that relative to the steam generator high level setpoint, the chemical and volume control system (RCV) [CVCS] charging line is isolated in order to avoid overfilling the steam generator.

- Moisture separation equipment
  The design of the moisture separation equipment provides steam with a moisture carry-over not exceeding 0.25% under normal operating conditions with the turbine in operation.
  Testing on models and thermo-hydraulic analysis has resulted in a new separator model to be defined which is 1.5 times larger than that of the steam generator for the N4.
- Steam generator elevation compared with the reactor vessel

The steam generators are installed at a height relative to the reactor vessel which ensures that primary side drainage of the steam generator plenum permits inspection and/or tube plugging without reducing the water level in the reactor vessel below the reactor core, or adversely affecting reactor coolant circulation in shutdown state.

- Tube bundle inspection activities (END) on the shutdown critical path will be carried out in parallel on the four steam generators, which significantly reduces the overall outage time. The ability to undertake primary side steam generator tube inspections from the plenums using protection plugs/dams in the nozzles to the reactor coolant system loops is at the design stage. It is anticipated that the inspection would be utilised on EPR plant units only for the unloaded core. During these inspections, it is planned to ensure double isolation between the spent fuel pool and the vessel pool using transfer tube isolation valves or various other sluices and gates.

The use of steam generator plugs with fuelled core is not authorised on EPR at this stage in the studies.

Over a 60 year period, for operational requirements, the use of steam generator plugs/dams with a loaded core is not ruled out. A further safety assessment relative to the risk of pool drainage will be provided prior to any proposed use of plugs (see section I.1.3).

- Steam generator blowdown

Drains are provided for the steam generator primary and secondary sides. The drain system is designed to provide the capability to drain the steam generator at any temperature up to and including hot standby. Blowdown system equipment is utilised to provide this hot drain capability.

- Provisions for secondary side cleaning

Precautions are taken to minimise the formation of sludge in the steam generator (see sections E.4.2.4.4. and E.4.2.9).

The lower section of the secondary side of the steam generator is designed for the removal of any sludge, by lancing if necessary, which may have accumulated on tube sheets in low flow velocity areas.

2.3.3. Inspectability, repairability and replacement

The steam generator pressure boundary was designed to minimise the number of welds and optimise their location in order to facilitate in-service inspections.

The upper end and the steam outflow nozzles of the steam drum are manufactured from a single forging.

The conical shell is forged and has flanged ends of sufficient length to facilitate inspection of connecting welds.

In addition, thermal insulation can be removed locally. Both permanent and temporary measures are provided to ensure convenient access to welds.

Measures are also taken, in particular for the internal components, to facilitate inspections necessary to confirm steam generator safety.
On the primary side, the support columns allow easy access to the manways with which each compartment of the channel head is fitted. Special equipment allows inspection of the internal surface of the plenum in contact with primary coolant, the tube welds on the tube sheet cladding and the steam generator tubes.

On the secondary side, special attention has been paid to access to the lower section of the tube bundle and the tube sheet:

- eight hand-holds are distributed around the secondary shell
- the mechanical and thermo-hydraulic design of the lower steam generator support structure has been optimised (geometry of the waterway flow blocks, design of the blowdown system) to facilitate sludge lancing operations

Access to the steam generator upper internals inside the steam drum is provided by two large-diameter manways. From this position, it is also possible to access the tube bundle anti-vibration bars (BAV) [AVB]. A hatch has been installed in the bundle wrapper for this purpose.

Although maintenance and repair operations are not anticipated during the GV [SG] design life, the dryer vanes may be replaced through the manways in the upper part of the steam generator. They are held in place by screw jacks inside the U-shaped frames. By loosening the screws, dismantling is possible through openings provided.

A monitoring programme will be developed during the detailed design phase. It will describe the arrangements for periodical inspections, as well as the objectives, nature and frequency of non-destructive inspections implemented to detect defects harmful to the integrity of the steam generators.

### 2.4. THERMO-HYDRAULIC DESIGN

#### 2.4.1. Operating parameters

E.4.2.TAB 2 gives other operating parameters not included in the steam generator data sheet.

#### 2.4.2. Thermodynamic criteria

The steam generator is designed so that level fluctuations at the steam-water interface as well as structural vibrations do not occur during operation.

The recirculation ratio is defined as the ratio of total flow rate across the tube bundle to steam flow rate output of the steam generator. It reaches 3.7 when the steam generator is operating at full load. This value offers a satisfactory compromise between efforts to obtain steam as dry as possible and stable operation of the steam generator. This recirculation ratio also improves the steam generator transient behaviour by minimising water level shrinkage in the event of large transients (turbine or reactor trip) and helping to reduce low velocity area above the top of the tubesheet.
2.4.3. Thermal design

The heat exchange surface and tube bundle configuration adopted are similar to those used in the N4 steam generator and therefore this steam generator belongs to a wide range of proven designs. The selected tube diameter is one of the current international standardised diameters and is a good compromise between compactness, vibration behaviour and ease of manufacture. The triangular pitch arises from the same desire for compactness, while providing the capability to carry out high-quality cleaning operations with the usual technique of sludge lancing. This has been clearly demonstrated by the first lancing operations performed on the first N4 plants at Chooz and Civaux.

Justification of the possibility of obtaining the required steam mass flow rate and pressure at full power for the specified conditions of reactor coolant flow and temperature was carried out using physical models and correlations qualified on the basis of the intensive test program performed on the 25 MW MEGEVE test loop at CADARACHE C.E.A. Research Centre and verified in CHOOZ and CIVAUX.

Absence of water level fluctuations at the steam-water interface was demonstrated using the physical models qualified from the MEGEVE test results. This is notably obtained thanks to an adequate ratio between single phase pressure drop and total pressure drop in the recirculation loop.

2.4.4. Hydraulic design

Hydraulic design ensures:

- an acceptable flow distribution in the steam generator secondary side, particularly regarding the risk of sludge deposits, the effects of erosion/corrosion and tube bundle vibrations
- secondary water inventory in accordance with cooling water requirements

To limit the possible accumulation of secondary side sludge and risks resulting from stress corrosion cracking of the tube bundle, particular attention is paid to reduce low flow velocity areas as much as possible, particularly above the tube sheet.

This has been achieved by suitable design of the flow blockers as well as of the distribution baffle. The primary result of this is that a very low number of tubes may be affected by sludge deposits in operation, and these, moreover, are close to the centre of the tubelane in the same area as the blowdown system intakes. It should be noted that these measures are in addition to the general measures described in section E.4.2.9, intended to reduce sludge generation in the secondary circuit.

No specific problems are expected regarding erosion/corrosion due to the choice of materials selected for the feedwater distribution systems, the tube support plates and the separation equipment.

Tube bundle vibrations are addressed in section E.4.2.4.5.

The secondary water mass of 77.8 tonnes in normal operation is in accordance with the requirement to have a minimum duration of 30 minutes before dryout of the steam generator following the loss of all feedwater systems.
2.4.5. Tube bundle vibrations

In the design of steam generators, the possibility of degradation of tubes due to either mechanical or flow-induced excitation is thoroughly evaluated. This evaluation includes detailed analysis of the tube support system as well as an extensive research program with tube vibration model tests.

In evaluating failure due to vibration, consideration is given to such sources of excitation as those generated by the primary fluid flowing within the tubes, mechanically induced vibration, and secondary fluid flow on the outside of the tubes. During normal operation, the effects of primary fluid flow within the tubes and mechanically induced vibration are considered to be negligible and should cause little concern. Thus, the main source of tube vibrations is the hydrodynamic excitation by the secondary fluid on the outside of the tubes. In general, three vibration mechanisms were identified:

- Vortex shedding:
  
  Vortex shedding does not provide detectable tube bundle vibration. There are several reasons why this happens:
  
  • flow turbulence in the downcomer and tube bundle inlet region inhibits the formation of Von Karman’s vortex train
  
  • the spatial variations of cross flow velocities along the tube precludes vortex shedding at a single frequency
  
  • both axial and cross flow velocity components exist on the tubes. The axial flow component disrupts the Von Karman vortices

- Fluid-elastic excitation:

  Concerning fluid-elastic excitation, the tube bundle supporting system was designed to obtain a margin with respect to tube instability according to quasi steady Blevins-Connors model based on numerous experimental data

- Turbulence:

  Levels of turbulent response, determined by using umbrella bounding turbulent force spectrum obtained from mock-up results for various fluids, are small and the contribution of the resulting stresses to fatigue is negligible.

2.5. MATERIALS AND MATERIAL PROPERTIES

2.5.1. Pressure retaining parts

All materials for pressurised retaining parts used for steam generators are selected and manufactured in accordance with the requirements of section II of the RCC-M (see sub-chapter B.6) Steam Generator tube materials:

- Alloy 690, which is currently used worldwide as a steam generator tube material has been selected for the tube bundle tubes
Alloy 690’s excellent corrosion resistance has been demonstrated both by experience at plant units and numerous laboratory tests under conditions representative of primary and secondary side conditions. Alloy 690 has been laboratory tested for 10 years by several respected bodies and selected by a significant number of operators. Alloy 690 has been used on plant units since 1988 in the USA, 1989 at Ringhals and 1990 at Dampierre.

- Pressure retaining shell
  - Paragraph B2000 regarding level 1 components of the RCC-M code applies (see sub-chapter B.6)
  - Low-alloy ferritic steel is selected for the shell
  - Those surfaces of the material in contact with primary fluid are clad with austenitic stainless steel (steam generator channel head) or Ni-Cr-Fe alloy (inconel 690 type) with a cobalt content of less than 0.1% (tube sheet)
  - The toughness of the steam generator’s ferritic material complies with the requirements of the RCC-M code (see sub-chapter B.6), paragraph B2000 and section II. The ductile/brittle transition temperature RTNDT is at least less than 33°C at the service temperature and the lowest testing temperature

- Partition plate
  - The channel head partition plate is made of Alloy 690

2.5.2. Other main materials selected

- Tube support plate
  The tube support plates (TSPs) are made of corrosion-resistant 13% Cr martensitic stainless steel and incorporates a three-lobe-shaped tube hole design that provides greater flow area adjacent to the tube outer surface compared with drilled TSPs. The resulting increased flow provides higher sweeping velocities at the tube/tube support plate intersections.
  Peripheral block supports and tie-rods also provide stability to the plates so that tube fretting or wear due to flow induced plate vibrations at the tube support contact regions is eliminated.
  - AVB

  The sets of antivibration bars (AVB) are made of stainless steel 13% Cr alloy selected for its excellent wear coefficient with the tube material.

2.6. MECHANICAL DESIGN

In general terms, the mechanical design of the steam generator takes place in two stages:

- sizing, to define the general arrangement of the component and its main dimensions
- design of the main sub-assemblies and justification of their capacity to withstand, under all circumstances, the loads and combinations of transient conditions provided for over the component's life including reactor coolant side and secondary side hydrostatic tests in the conditions defined in E.4.2. TAB 1

The mechanical design of the steam generator pressure boundary with the primary coolant and secondary coolant complies with the requirements of the RCC-M code (see sub-chapter B.6) (level 1).

The combined transient conditions and load conditions applicable to mechanical components and systems (in particular to the steam generator) are dealt with in sub-chapter C.6.1 (topics specific to mechanical components, including the list of events).

### 2.6.1. Sizing calculations

Sizing calculations are performed in design conditions, according to chapter B 3000 (class 1 components) of the RCC-M code to determine the minimum acceptable thickness of the pressure shells and nozzles and to demonstrate the adequacy of tube dimensions.

For the secondary compartment, a corrosion allowance has been taken into account.

### 2.6.2. Design of sub-assemblies

The following properties have been adopted, based on experience feedback from French, German, and other international plants:

- Design of the tube-to-tubesheet junction
  
  - the tubes are fully expanded inside the tubesheet and welded on the tubesheet primary side
  
  - the tube expansion is made using a one step high pressure hydraulic process

- Feedwater distribution system:
  
  - The main and emergency feedwater distribution systems are separate (2 nozzles and 2 rings)
  
  - The water distribution systems are connected to the feedwater nozzles by leaktight connections

  - Provisions are implemented to limit the thermal stratification in the main feedwater nozzle regions (location of the feedwater nozzle in the conical shell and under the feedwater distribution ring)

- Design of upper and lower internal components

The lower internal components (tube bundle, tube support system, bundle wrapper and associated supports, equipment installed above the tube sheet) and upper internal components (cyclone separators, main and emergency feedwater systems, moisture separators) are designed in such a way as to enable free thermal expansion between them and also with the bundle wrapper and the GV pressure containment under PCC 1 to 3 scenarios.
2.6.3. Design relative to pipeline ruptures and earthquakes

The steam generator and its internal components are designed to withstand deadloads as well as dynamic loads which may result from an earthquake or a guillotine break on a pipe connected to the reactor coolant system or depressurisation caused by a steam pipework break (RTV) [MSLB] or a break in the feedwater pipework. The integrity of the steam generator tubes and the tube support structures has been demonstrated for all these situations.

2.7. SAFETY EVALUATION

Safety analyses of the steam generator design are provided in the accident research chapters (see Chapters P and S).

2.8. PROCUREMENT, MANUFACTURE AND QUALITY ASSURANCE

2.8.1. Procurement

Materials procurement complies with the general specifications of the RCC-M code (see subchapter B.6) (section II), the component materials assessment data sheets and, where appropriate, with additional requirements (see E.4.2 TAB 1).

2.8.2. Manufacture

The following procedures are applied to the manufacture of main components:

- Forged lower hemispherical head
- Forged tube sheet
- Forged cylindrical shells
- Forged conical shells
- Forged upper elliptical head by forging with integral steam outlet nozzle
- Heat transfer seamless tubes by cold pilgering and annealing
- A final heat treatment is carried out on all straight tubes in the tube bundle to relieve stress and improve corrosion resistance. A similar stress-relief heat treatment is carried out on the smaller U-bends
- The corrosion-resistant cladding in contact with the primary cooling system is deposited by a welding technique
- The tube-to-tube-sheet welding process is automatic TIG welding
- The tubes are expanded along the full thickness of the tube sheet

During manufacture, the steam generator primary and secondary surfaces are cleaned.
2.8.3. Testing and inspections

The steam generators are inspected and tested in accordance with sections III "Inspection methods" and IV "Welding" of the RCC-M code (see sub-chapter B.6).

During hydrostatic tests, the requirements relating to water cleanliness and quality are defined in chapter B 5000 of the RCC-M code.

2.9. SECONDARY SIDE CHEMICAL CONSTRAINTS RESULTING FROM THE STEAM GENERATOR – MATERIALS AND OPERATING MODES

The secondary side water chemistry treatment is designed for:

- minimising generalized material corrosion, particularly in the steam generator where impurities in the secondary cycle may concentrate
- controlling the formation of sludge in the steam generator
- minimising deposit on the heat transfer surface
- minimising the potential for the formation of free acids or bases
- avoiding localised corrosion

These objectives are achieved by means of appropriate materials selection in accordance with the RCC-M code specifications (see sub-chapter B.6) (see section E.4.2.5) and strict chemistry control.

The principle adopted for feedwater and steam generator water chemical treatment is volatile conditioning (AVT, All Volatile Treatment). Consequently, the only volatile chemicals that can be added to the feedwater are hydrazine as a deoxygenating agent and an amine (morpholine, ethanolamine or ammonia) for pH control.

The use of copper-bearing materials for pipelines and secondary feedwater plant components is prohibited. This measure is taken to avoid the presence of copper and cuprous elements in the feedwater. When such elements are present in the steam generator, they may be reduced to metallic copper which causes localised oxidation and contributes to various types of corrosion.

In addition, the absence of copper-bearing materials allows a high AVT pH value to be used, which minimises the quantity of corrosion products (sludge) in the secondary side of the steam generator.

Furthermore, to limit the rate of flow-accelerated corrosion and thus sludge formation, low alloy steels with sufficient chromium content are recommended for the secondary cooling system and in particular for sensitive areas such as pipe elbows.

The specification relating to steam generator water and feedwater chemistry is a means of obtaining effective chemistry control within the entire secondary cooling system.

The EPR steam generator feedwater systems were designed during the Basic Design Phase. These systems are used to supply water to the steam generator depending on operating conditions:

- the main feedwater system (ARE) [MFWS] is used during normal operation
- the start-up and shutdown system (AAD) [SSS] is used for temperatures greater than 120°C during start-up and shutdown phases and at low power

- the emergency feedwater system (ASG) [EFWS] is used in emergency and accident situations, for cold periodic testing and if necessary during cold shutdown to fill the steam generator

The specifications governing the quality of secondary coolant will be defined during the detailed study phase. As has been previously pointed out, these specifications are based on the use of an amine (morpholine, ethanolamine or ammonia), a reducing agent (hydrazine) and on the limitation of contaminant concentrations in the feedwater and steam generators.

The main objective for the choice of the amine for pH control is to obtain conditions providing the lowest corrosion rate for the various materials present in the water/steam system at operating temperature, resulting in the lowest iron transport.
### 5.4.2. Tab 1: Steam Generator Data Sheet

<table>
<thead>
<tr>
<th>Steam Generator</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operational Characteristics at 100% of Nominal Power.</td>
<td></td>
</tr>
<tr>
<td>- Number of GVs [SGs]</td>
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</tr>
<tr>
<td>- Type</td>
<td>Natural circulation with axial economiser</td>
</tr>
<tr>
<td>- Primary operating parameters</td>
<td></td>
</tr>
<tr>
<td>- Mass flow</td>
<td></td>
</tr>
<tr>
<td>* Thermo-hydraulic condition (TH)</td>
<td>kg/s</td>
</tr>
<tr>
<td>* Best estimate condition (BE)</td>
<td>kg/s</td>
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<td>Inlet temperature (with no plugging or fouling):</td>
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</tr>
<tr>
<td>* TH</td>
<td>°C</td>
</tr>
<tr>
<td>* BE</td>
<td>°C</td>
</tr>
<tr>
<td>* ME</td>
<td>°C</td>
</tr>
<tr>
<td>Outlet temperature (with no plugging or fouling):</td>
<td></td>
</tr>
<tr>
<td>* TH</td>
<td>°C</td>
</tr>
<tr>
<td>* BE</td>
<td>°C</td>
</tr>
<tr>
<td>* ME</td>
<td>°C</td>
</tr>
<tr>
<td>Operating pressure (inside tubes)</td>
<td>MPa abs</td>
</tr>
<tr>
<td>Margins relative to the heat exchange surface for plugging and fouling:</td>
<td></td>
</tr>
<tr>
<td>* Total margin</td>
<td>%</td>
</tr>
<tr>
<td>* Plugging</td>
<td>%</td>
</tr>
<tr>
<td>* Fouling</td>
<td>%</td>
</tr>
<tr>
<td>- Secondary operating parameters (with no plugging or fouling):</td>
<td></td>
</tr>
<tr>
<td>- Saturation pressure (TH, BE or ME capacity)</td>
<td>MPa abs</td>
</tr>
<tr>
<td>- Output steam capacity (blowdown capacity 1%; TH, BE or ME capacity)</td>
<td>kg/s</td>
</tr>
<tr>
<td>- Moisture content at GV [SG] outlet</td>
<td>%</td>
</tr>
<tr>
<td>- Feedwater temperature</td>
<td>°C</td>
</tr>
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</table>
### 5.4.2. TAB 1: STEAM GENERATOR DATA SHEET (CONT.)

<table>
<thead>
<tr>
<th>STEAM GENERATOR</th>
<th>UNITS</th>
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<tbody>
<tr>
<td>REFERENCE SCENARIOS</td>
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</tr>
<tr>
<td>- Primary side:</td>
<td></td>
</tr>
<tr>
<td>. Design pressure</td>
<td>MPa abs</td>
</tr>
<tr>
<td>. Design temperature</td>
<td>°C</td>
</tr>
<tr>
<td>- Secondary side:</td>
<td></td>
</tr>
<tr>
<td>. Design pressure</td>
<td>MPa abs</td>
</tr>
<tr>
<td>. Design temperature</td>
<td>°C</td>
</tr>
<tr>
<td>TEST CONDITIONS</td>
<td></td>
</tr>
<tr>
<td>- Primary hydrostatic test:</td>
<td></td>
</tr>
<tr>
<td>. primary side pressure</td>
<td>MPa abs</td>
</tr>
<tr>
<td>. secondary side pressure</td>
<td>MPa abs</td>
</tr>
<tr>
<td>- Secondary hydrostatic test:</td>
<td></td>
</tr>
<tr>
<td>. primary side pressure</td>
<td>MPa abs</td>
</tr>
<tr>
<td>. secondary side pressure</td>
<td>MPa abs</td>
</tr>
<tr>
<td>. Test temperature</td>
<td>As per RCC-M code</td>
</tr>
<tr>
<td>SIZES AND WEIGHTS</td>
<td></td>
</tr>
<tr>
<td>- Steam drum maximum outer diameter (nozzles excluded)</td>
<td>m</td>
</tr>
<tr>
<td>- Total height (including safe ends)</td>
<td>m</td>
</tr>
<tr>
<td>- Total mass when empty</td>
<td>t</td>
</tr>
</tbody>
</table>
5.4.2. TAB 2: ADDITIONAL OPERATING PARAMETERS

<table>
<thead>
<tr>
<th>GV OPERATING PARAMETERS</th>
<th>UNITS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>- Water level above tube sheet</td>
<td>m</td>
<td>15.69</td>
</tr>
<tr>
<td>- Water mass in GV [SG]</td>
<td>te</td>
<td>77.8</td>
</tr>
<tr>
<td>- Steam mass in GV [SG]</td>
<td>te</td>
<td>5.5</td>
</tr>
</tbody>
</table>
5.4.2 FIG 1: SG SECTION

- Level measuring nozzle (narrow and wide ranges)
- Dryer frames drains pipes
- Secondary manway
- Access ladder
- Sampling tap
- Emergency feedwater nozzle
- Level measuring nozzle (narrow range)
- Tube bundle access opening
- Upper lateral support brackets
- Tie rod
- Eyehole
- Bundle wrapper
- Divider plate (secondary side)
- Level measuring nozzle (wide range)
- Tube sheet
- Secondary drain tap
- Partition plate (primary side)
- Primary manway
- Steam outlet nozzle
- Dryer frames supporting device
- Dryer frames
- Secondary manway
- Swirl vane separators
- Swirl vane separators supporting device
- Emergency feedwater ring
- Feedwater distribution ring
- Feedwater nozzle
- Anti-vibration bar
- Tube support plates
- Double bundle wrapper
- Tube bundle
- Half-tube support plates
- Flow distribution baffle (2 half-plates)
- Hand holes
- Blowdown tap
- Channel head
- Primary coolant outlet nozzle