6. REACTOR PRESSURE VESSEL – LOWER INTERNALS

6.0. SAFETY REQUIREMENTS

The safety requirements that apply to the lower internals of the vessel are given in the section dealing with the upper internal structures of the reactor vessel (see Chapter C.6.5).

6.1. DESIGN PRINCIPLES

During the operation of the reactor, the whole internal structure of the vessel (including reactor instrumentation) acts in general as a single structure inside the vessel.

However, certain reactor operating conditions (for example: refuelling, in-service inspection, handling, etc.) require a distinction to be made between the two main internal structures:

- the upper internal structures which are always removed for refuelling,
- the lower internal structures, which are only removed for in-service inspection of the vessel.

The current Chapter C.6.6 deals only with the lower internal structures. The upper internal structures are addressed with in Chapter C.6.5.

The lower internal structures comprise three main elements:

- the lower core support structure, which is the main load bearing structure of the lower internals,
- the heavy reflector, which is the side structure surrounding the core,
- the flow distribution system which helps to distribute the flow in the lower plenum.

6.1.1. FUNCTIONS OF THE LOWER INTERNAL STRUCTURES OF THE VESSEL

The main functions of the lower internal structures of the vessel are:

1- Core support and positioning function

- the lower internal structures support, position, immobilise and protect the core components (fuel assemblies) to ensure uniform cooling of the core, with regard to the neutron and thermal-hydraulic needs;
- the lower internal structures limit the mechanical loads from the core components;
- the lower internal structures enable loading and unloading of the core.

2- Coolant flow distribution in the core

The lower internal structures guide the coolant into the bottom of the core:

In order to obtain a uniform distribution of flow into the core, the flow rate of the fluid entering the fuel assemblies must be, as far as possible, be the same for all assemblies, in order:

- to minimise any increase in the lifting forces on the fuel assemblies, due to flow rates higher than the average mechanical design flow rate of the assembly,
- to minimise the risk of REC (Critical Heat Flux [CHF]) ratio, which could result from a flow rate which is lower than the average thermal-hydraulic flow rate per assembly,
- to minimise cross-flow between two adjacent assemblies in order to reduce the risk of fuel rod vibration.

In order to obtain good mixing between the flow from the four loops:

- to ensure uniform mixing of boron content,
- to limit temperature differences in the core coolant during asymmetric transients.

In order to ensure fluid circulation to the upper head of the vessel:

- to encourage natural circulation in the primary system in the event of a loss of forced circulation of the coolant,
- to ensure cooling of internal structures in the vessel and of the vessel itself.

3- Relation with other equipment

The lower internal structures:

- protect the vessel against irradiation,
- support and protect the irradiation specimen capsules used in the vessel monitoring programme,
- support and locate the upper internal structures,
- provide secondary support to the core in order to limit the consequences of an accidental core drop following a hypothetical failure of the lower internal structures.

6.1.2. DESCRIPTION

The lower internal structures:

- are supported vertically by the mounting edge machined in the vessel flange,
- are firmly held vertically inside the vessel by the adjusting ring which is situated between the upper and lower internal structure flanges. This prevents the lower internal structures from coming away from the mounting edge.
- are prevented from rotating inside the vessel.

This arrangement enables the structure to be easily installed and removed.

6.1.2.1. Lower core support structure

The lower core support structure is the major component in the lower internal structures of the vessel.

The lower core support structure is comprised of the core barrel and its flange, the core support slab and the interface devices between the vessel and upper internal structures.

The lower core support structure transmits the vertical loads to the vessel flange and distributes the horizontal loads between the vessel flange and the lower side hold-down structure.

The components comprising the lower support structure are:

- an upper flange, which is the core barrel flange. It is located inside the vessel flange and transmits the loads from the fuel assemblies and the lower internal structures to the vessel;

- a cylindrical casing, this is the core barrel. It is welded to the core barrel flange and is made up of cylindrical sections welded together;

- the upper part of the barrel contains four outlet nozzles which are opposite the four vessel outlet nozzles. They provide the path for the reactor coolant between the core and the vessel outlet nozzles; the radial clearance, between the outlet nozzles on the core barrel and those on the vessel is controlled in order to limit the by-pass flow;

- the support slab is welded to the bottom of the core barrel. This thick forged slab (also called the lower support plate or core support plate) supports all the fuel assemblies, the heavy reflector and the flow distribution system. It contains holes which guide and distribute the flow of reactor coolant to the entrance of the core. The lower side hold-down system, maintains the lower internal structures in position relative to the bottom of the vessel;

- the fuel assemblies making up the core are placed in the core cavity which is surrounded by the heavy reflector. They rest on the support slab which contains the lower centring pins to position and align the bottom nozzles of the fuel assemblies;

- irradiation capsule baskets.

The irradiation capsule baskets are fixed to the outside of the core barrel at locations where the neutron flux is greater than that on the inner surface of the vessel shell.

They position, support, immobilise and guide the irradiation capsules. They also participate in their cooling.

The interface devices consist of alignment pins and lower side thrust bearings:

- the alignment between the head and the vessel is ensured by half-pins, which are fixed to the core barrel flange and protrude above and below the flange. The parts of the pins below the flange are inserted into the vessel flange sockets to ensure alignment of the lower core support with the reactor pressure vessel. The parts of the pins above the core barrel flange are inserted into the core upper support assembly flange and extend to the sockets provided in the vessel head by means of half-pins fixed to the upper internals flange;

- this arrangement ensures alignment of all these components. A minimum clearance is maintained between the centring pins and their sockets to ensure correct alignment and ease of mounting;

- the lower side hold-down system comprises eight side keys, which are welded to the wall of the vessel and inserted into side-holding guides fixed around the edge of the support slab;

- this system accurately positions, and limits movements in, the lower end of the lower core support assembly in relation to the vessel, whilst enabling free radial and axial expansion between the vessel and the internal structures.

6.1.2.2. Heavy reflector

The heavy reflector is located inside the core barrel, above the lower slab.

The heavy reflector forms the walls of the core cavity. By determining the dimensions of the core cavity, i.e. the clearance between the fuel assemblies and the reflector, it influences the coolant flow path in the core.

The heat generated inside the steel structure by absorption of gamma radiation is removed by water flowing through channels and the gaps.

To avoid the presence of a welded or bolted assembly near the core, the reflector is comprised of a stack of forged plates positioned relative to one another by means of keys and rings that are adjusted and fixed to the lower slab by tie-rods.

6.1.2.3. Flow distribution system

The flow distribution system is fixed under the lower slab by means of bolted vertical columns. It distributes the flow uniformly at the inlet to the lower slab.

6.1.2.4. Miscellaneous

Adjusting ring [hold-down spring]

The adjusting ring is located between the flanges of the upper and lower core support structures when these structures are assembled inside the reactor pressure vessel.

This ring is used to maintain a preload to limit the radial movements and to prevent axial movements of the upper and lower internals, during the operation of the reactor. This preload only exists when the vessel head is in place and the vessel closure studs are tightened.

Secondary core support

A secondary core support is installed in the area of the lower annulus between the lower slab and the vessel. This structure uses the eight keys on the lower side-holding system.

The functions of the secondary core support, after a hypothetical failure of the core barrel, are:

a) to limit vertical movement towards the bottom of the lower internals to prevent the rod control cluster assemblies from falling from the core and to maintain the geometry of the annular downcomer for cooling flow,

b) to transmit the vertical drop loads uniformly to the vessel.

Lower radial hold-down assembly

This system comprises radial keys. Some keys, on the main axes of the vessel, ensure tangential centring of the lower internal structures (small gap during normal operation) and serve as radial thrust bearings (quite large gap) during PCC-4 events. The other keys only serve as radial thrust bearings. Inserts on the keys and on the internal structures are used to make the necessary spacing tangentially, radially and vertically. Hard facing is used on those inserts which have small tangential gaps.

6.2. OPERATING CONDITIONS

The lower internal structures are designed in accordance with the general specifications, i.e. the specified operating conditions, the requirements with regard to interfaces, design rules and criteria.

For each specific operating condition, there is a corresponding set of environmental parameters: pressure, forces, coolant temperatures, thermal flux, and neutron irradiation.

These parameters act (usually as a function of time) on the components without producing mechanical work.

With the mechanical and thermal loads, they define sets of loads which are used in the mechanical design.

6.2.1. OPERATING CONDITIONS

The service life is 60 years, based on a load factor of 90 %.

The classification of the operating conditions into categories, the list of the corresponding conditions and their description are provided in the section on the design of mechanical components (see Chapter C.6.1).

6.2.2. LOADING AND LOAD COMBINATIONS

The design of the lower internal structures is based on the following loading types:

a) Pressure differences due to coolant circulation.

b) Weight of internal structures.

c) Additional loads such as those due to other structures, the reactor core, instrumentation and safety equipment (for example, weight of fuel assemblies, compressions of fuel assembly springs and core components, preload on the adjusting ring, loading from reaction between the components, etc.).

d) Seismic loads or other loads due to the movement of the vessel.

e) Reactions of supports or thrust bearings.

f) Loads due to the effects of temperature, thermal gradients or differential expansions.

g) Loads resulting from fluid flow forces.

h) Loads due to pressure transients, such as those resulting from a rupture of the pressure boundary (piping connected to the primary coolant loops).

i) Vibration loads of mechanical or hydraulic origin.

The loads which may occur simultaneously are usually added in the form of a direct sum. The conventional load combination (square root of the sum of the squares) is only applied during PCC-4 events for seismic loads and loads due to a loss of coolant accident.

6.2.3. INTERFACES

The lower internal structures possess the following interfaces:

6.2.3.1. With the vessel

In the lower plenum, the radial keys welded to the vessel, centre and position the lower internal structures. The small tangential clearance, necessary to obtain good centring at this level, causes a transfer of the loads between the vessel and the lower internal structures:

- horizontally (vibrations, temperature effects),
- vertically (transient friction loads).

At the contact surface with the vessel, the alignment between the head and the vessel is obtained by means of half-pins fixed to the flange of the lower internal structures and four half-pins on the flange of the upper internal structures. A horizontal load transfer between the vessel and internal structure flanges can occur during PCC-4 events.

6.2.3.2. With the upper internal structures

The upper internal structures are firmly held in position with the lower internal structures at the level of the upper core plate: guide pins, fixed to the upper part of the heavy reflector, locate the plate. The horizontal loads and vertical friction loads are transferred via these pins between the upper and lower internal structures.

6.2.3.3. With the core fuel assemblies

The fuel assemblies are supported by the lower slab (lower core plate) and maintained laterally by the heavy reflector, whose inner wall forms the core cavity wall.

Each fuel assembly is positioned on the lower core plate by means of two lower centring pins fixed to the lower core plate: all horizontal loads from the assemblies are transmitted to the lower core plate through these pins.

The clearance between the core cavity and the peripheral fuel assemblies is as small as possible to limit by-pass flow: The fuel assembly grids can come into contact with the plates of the heavy reflector, particularly during dynamic loads. The grids are not located at the level of the junctions between the plates.

6.3. HYDRAULIC DESIGN

6.3.1. VESSEL HEAD COOLING

The design of the vessel internal structures forms an upper head region which is closed and “warm” (i.e. at an intermediary temperature between the hot and cold leg temperatures).

Calibrated nozzles placed in the core barrel flange cause a bypass flow from the cold leg via the downcomer to the upper head, thus resulting in a “warm” upper head .

6.3.2. DISTRIBUTION AT THE CORE INLET

A uniform distribution of fluid flow at the inlet of the lower plenum helps to produce a uniform distribution of pressure at the core inlet.

For this reason, a flow distribution system is placed in the lower plenum to produce an acceptable flow distribution at the core inlet.

6.3.3. BY-PASS FLOW

The tolerances in the design of the bypass paths is such that the maximum core by-pass flows as a percentage of the total flow at the vessel inlet are:

Zone	Core By-pass (%)
Upper head cooling	0.5
Gap between nozzles in the core barrel and those of the vessel	1
Heavy reflector	1.5
Core cavity [1]	0.5

These values contribute to limiting the total core by-pass flow to the maximum value of 5.5 %.

[1] between the theoretical core periphery and the inner surface of the heavy reflector.

6.4. MECHANICAL DESIGN

6.4.1. CALCULATIONS

The lower core support structure consists of different parts for which a preliminary mechanical design has been carried out. In general, the design of the various parts is based on the French N4: the following design calculations have been performed to justify the new characteristics and any new loads.

6.4.1.1. Core barrel flange

Its function is to provide vertical support to the vessel lower internal structures.

Inserts are fixed in the flange to enable connection to the internal structure handling tool.

The handling operation creates a significant load combination for the flange (the upper and lower internal structures are assumed to be handled at the same time). In addition, a defective insert is assumed in the calculations.

An analysis of the flange using a finite element method has shown that the stresses calculated for all parts of the flange are acceptable.

6.4.1.2. Core support plate

This plate is perforated and its edges are equipped with eight radial key grooves which house the vessel keys.

A considerable combined load on the plate would arise from a circumferential break of the core barrel. In this case, energy is transmitted to the radial keys via the plate.

For the corresponding impact load, the stresses in the plate ligaments remain acceptable.

6.4.1.3. Flow distribution system

This system is fixed to the core support plate.

An analysis using a finite element method has been conducted to determine its static and dynamic behaviour under normal operating conditions. This analysis shows that stresses in the structure are acceptable.

6.4.2. DESIGN OF THE HEAVY REFLECTOR

6.4.2.1. Functional requirements

The structure reflects neutrons back to the core resulting in the need for a massive component.

The bypass flow required to cool the reflector is limited to 1.5 % of the total vessel inlet flow.

All jetting of water from the reflector onto the peripheral fuel rods is avoided.

The steel temperatures in the reflector are limited:

- to control the radial dimensions of the core cavity and the spacing with the core barrel,
- to limit the expansion of the steel.

6.4.2.2. Loads

In normal conditions the loads on the heavy reflector consists of:

- its own weight,
- vertical hydraulic loads,
- thermal loads, including heating due to gamma radiation.

During PCC-4 events:

- seismic loads,
- loads due to a loss of coolant accident.

6.4.2.3. Description

The reflector comprises a stack of massive perforated plates positioned by means of keys and rings and fixed together by eight tie-rods. This sub-assembly is centred on the lower internal structures by means of positioning keys fixed to the core support plate.

6.4.2.4. Cooling circuit

Gamma radiation causes heating of the steel plates. To limit the temperature, bypass flow through channels cool the reflector:

- a sufficient number of vertical cylindrical channels equipped with diaphragms at the base of each plate,
- an annulus between the reflector and the core barrel,
- channels inside and outside each of the tie-rods.

The number and arrangement of the channels are the result of optimisation analyses aimed at obtaining an acceptable maximum temperature and an low average temperature. The channel dimensions also take account of manufacturing constraints.

6.4.2.5. Hydraulic behaviour

A bypass circulation, required to cool the reflector, penetrates the water chamber of the lower reflector plate, and is then distributed between the cooling channels.

Adequate distribution between the channels is ensured by the diaphragms in the vertical cylindrical channels, and by communication holes at the bottom of the annulus between the reflector and the core barrel.

This design leads to pressures in the reflector which are slightly higher than those in the core.

The pressure distribution at the top of the reflector is influenced by the position of the vessel outlet nozzles. The following arrangements ensure low sensitivity of the various coolant flow rates to any differences at the top of the reflector:

- the width of the annular gap between the upper reflector plate and the core barrel is reduced and a circular groove is machined around the outside of the second highest reflector plate,

- diaphragms are used in the vertical cylindrical channels.

With this configuration, the minimum bypass flow is 0.6 % of the vessel inlet flow.

The vertical differential expansions of the reflector plates can cause local openings between the plates: these openings between the plates only slightly affect the by-pass flow.

6.4.2.6. Horizontal expansion

The radial thermal expansion of the plates is greater than that of the core barrel: the cold clearance between these two parts is reduced by several tenths of a millimetre in normal operating conditions.

The low average temperature of the reflector prevents the risk of significant deformation which may result from swelling under irradiation and which could reduce the width of the annulus between the reflector and the core barrel.

6.4.3. OUTLINE DRAWING

The arrangement of the lower internal structures inside the vessel is shown in Chapter C.6.6 FIG 1.

Chapter C.6.6 FIG 2 shows the heavy reflector.

6.4.4. METHODS AND TOOLS FOR MECHANICAL DESIGN AND STRESS ANALYSES

Fundamentally, the design is based on an extrapolation of existing designs.

However, the main components, new characteristics or critical zones have been analysed using finite elements methods.

6.4.5. INSPECTABILITY, REPARABILITY AND EASE OF REPLACEMENT

The inner surfaces of the lower internal equipment can be visually inspected while they are in the vessel with the fuel removed.

In addition, when the lower internal structures are removed and placed on their storage stand in the pool, all the outer surfaces can be inspected.

6.5. OPERATING EXPERIENCE

To date, no operating experience with a heavy reflector is available either in France or in Germany. However, no major problems are expected.

The diameter of the lower core support structure is slightly larger than that of 1450 MWe French power plants; but the design is very similar.

6.6. MATERIALS

The materials and their manufacture comply with the RCC-M (see Chapter B.6) – Volume I – Sub-chapter G 2 000.

6.7. MANUFACTURE AND SUPPLY

The manufacture of the lower core support structure is similar to that of the N4 units.

The manufacture of the heavy reflector is based on forged parts only with machining and drilling: no weld seams are used: as a result, the manufacturing tolerances obtained are particularly good.

FIG 1: VESSEL ASSEMBLY

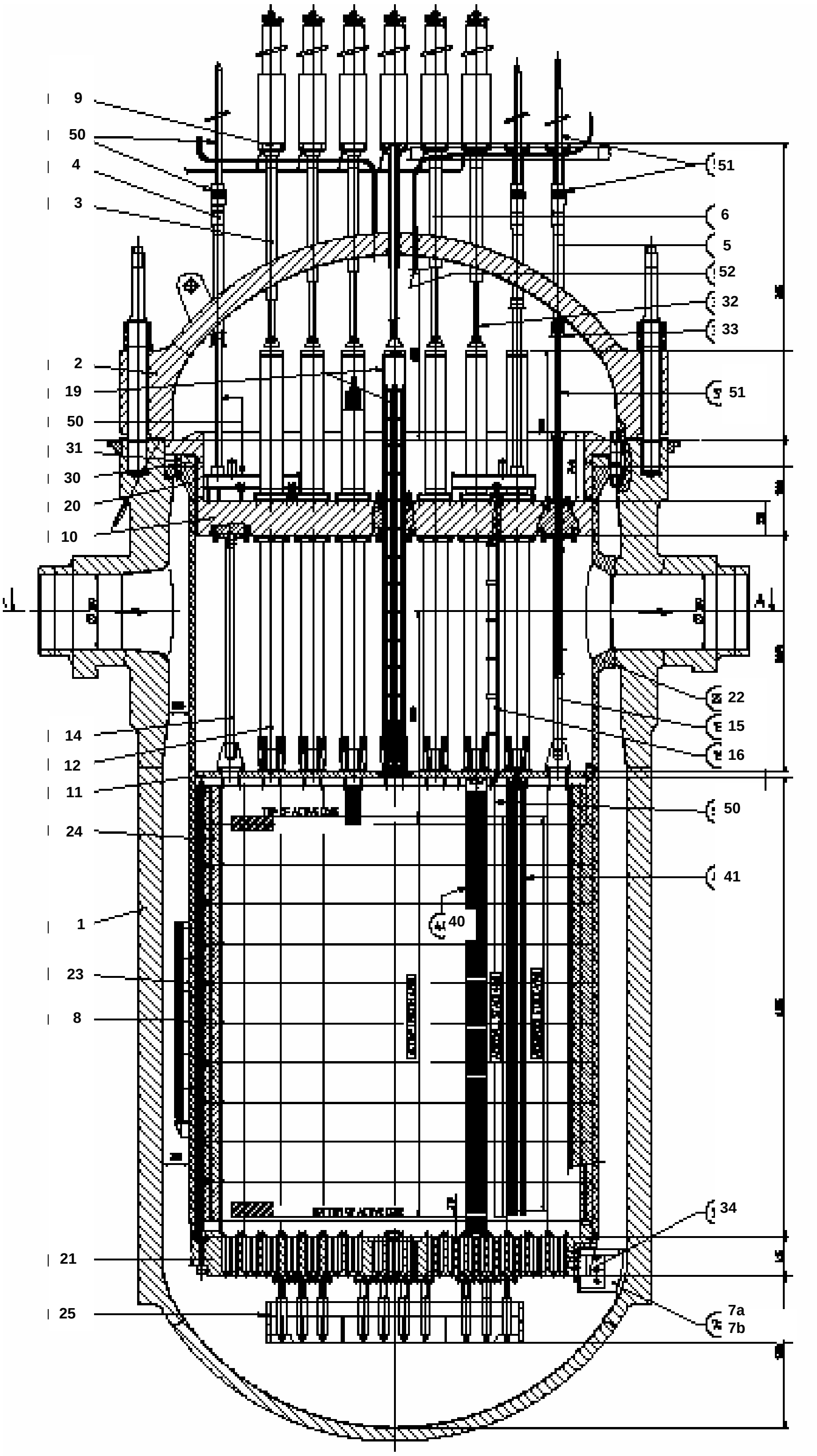

FIG 1 (CONT.): VESSEL ASSEMBLY

LIST OF PARTS		
Article	Qty	TITLE
		REACTOR VESSEL
1	1	VESSEL BODY
2	1	VESSEL HEAD
3	89	CRDM ADAPTOR
4	12	INSTRUMENTATION LANCE ADAPTOR
5	4	LEVEL MEASUREMENT PROBE (LMP) ADAPTOR
6	1	DOME IN CENTRAL POSITION THERMOCOUPLE ADAPTOR
7a	4	RADIAL KEY WITH TANGENTIAL CENTRING
7b	4	RADIAL KEY WITHOUT TANGENTIAL CENTRING
8	4	CAPSULE FOR IRRADIATION SPECIMENS
9	89	CONTROL ROD DRIVE MECHANISM
		UPPER INTERNAL STRUCTURES
10	1	UPPER SUPPORT (upper internal structure flange / wall / upper support plate)
11	1	UPPER CORE PLATE
12	89	ROD ASSEMBLY GUIDE COLUMN
13	89	ROD ASSEMBLY GUIDE
14	12	NORMAL COLUMN
15	4	LEVEL MEASUREMENT PROBE (LMP) COLUMN
16	52	INSTRUMENTATION LANCE THIMBLE GUIDE TUBE
		LOWER INTERNAL STRUCTURES
20	1	CORE BARREL (flange and shells)
21	1	CORE SUPPORT PLATE
22	4	CORE BARREL OUTLET NOZZLE
23	2	BASKET FOR IRRADIATION SPECIMENS CAPSULE
24	1	HEAVY REFLECTOR
25	1	FLOW DISTRIBUTION SYSTEM
		VESSEL INTERNAL STRUCTURE - MISCELLANEOUS
30	1	HOLD-DOWN SPRING
31	4	ACCESS CAP TO IRRADIATION CAPSULES
32	89	CRDM ADAPTOR THERMAL SLEEVE
33	16	INSTRUMENTATION LANCE FUNNEL
34	8	RADIAL KEY INSERT
		CORE COMPONENTS
40	241	FUEL ASSEMBLY (FA)
41	89	ROD CONTROL CLUSTER ASSEMBLIES (RCCA)
		CORE INSTRUMENTATION INSTALLED FROM ABOVE
50	12	INSTRUMENTATION LANCE (pressure vessel/rod/fork/fingers)
51	4	LEVEL MEASUREMENT PROBE (pressure vessel/thimble) (LMP)
52	1	DOME THERMOCOUPLE (pressure vessel/thimble)

FIG 2: HEAVY REFLECTOR