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02	PCSR June 2009 update: – Clarification of text – Inclusion of references.	26-06-2009
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04	Consolidated PCSR update: - References listed under each numbered section or sub-section heading numbered [Ref-1], [Ref-2], [Ref-3], etc - Reference "AFA 3GLE EPR™ Test Result Synthesis in Support to the Design File" updated with five documents that summarise the various tests and measurements associated with the fuel assembly (§0.4.1)	19-07-2012

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SUB-CHAPTER 4.2 – FUEL SYSTEM DESIGN

This sub-chapter lists the safety requirements to be met in the design of the fuel assemblies. The main characteristics of the fuel assemblies and control rod assemblies which have been used as input data at the present stage of the EPR design are listed in Sub-chapter 4.3 – Table 2.

0. SAFETY REQUIREMENTS

0.1. SAFETY FUNCTIONS

The safety functions provided by the fuel assemblies are:

- Control of core reactivity and safe core shutdown whatever the circumstances.
- Residual heat removal through preservation of a coolable geometry.
- Containment of radioactive materials, in particular fission products, within the first barrier.

0.2. FUNCTIONAL CRITERIA

The mechanical design of the fuel assembly meets the safety functional criteria described in section 0.1 of this sub-chapter. These criteria will be complied with if compatibility is ensured between:

- Fuel assemblies.
- Fuel assemblies and their associated elements.
- Fuel assemblies and reactor internals.

0.2.1. Core reactivity control

The Rod Cluster Control Assemblies (RCCA) are made up of rods which are inserted into the guide thimbles of the fuel assembly (see section 2 of this sub-chapter). Under normal operating conditions, these enable the reactor power to be controlled.

Under accidental conditions, a drop time for control rods assemblies compatible with the accident consequences analyses must be complied with.

This functional requirement applies to the following components of the fuel assembly:

<u>Guide thimbles</u>

The guide thimbles must:

- Enable the insertion of the RCCA.
- Slow down the control rods near the end of their travel during reactor trip.

Grids

The grids must provide lateral positioning and support of the guide thimbles, even under incidental and accidental conditions so that the RCCA can always be inserted freely within them.

Bottom fuel assembly nozzle

The bottom fuel assembly nozzle must:

- Locate the guide thimbles.
- Prevent the ejection of fuel rods.

Top fuel assembly nozzle

The top fuel assembly nozzle must:

- Prevent the ejection of fuel rods.
- As for the bottom fuel assembly nozzle, locate the guide thimbles.

0.2.2. Residual heat removal

The coolant must flow at a sufficient rate to remove the heat produced by the fuel.

To this end, the geometry of the core barrel (distance between the lower and upper core plates, assemblies pitch) and the fuel rods (nominal pitch, outer diameter, nominal height) must be maintained.

This functional requirement applies to the following fuel assembly components:

Fuel assembly

The geometry of the fuel assembly must be maintained through:

- Lower support by the lower core plate.
- Lateral support using two alignment pins.
- A hold-down assembly at the upper end which is supported by the upper core plate to prevent hydraulic pressure from lifting the assembly.

A baffle adds to lateral assembly support and limits bypass flow.

Guide thimbles

In addition to maintaining the structural integrity of the assembly, the guide thimbles must enable cooling of associated components.

Grids

The grids must:

- Support the fuel rods both axially and laterally during the life of the assembly. The fuel rod support system must accommodate the differential expansion between the rods and the skeleton assembly due to thermal expansion and irradiation growth.

- Maintain the pitch between the fuel rods to achieve the design core nuclear and thermal-hydraulic performance. Under incident and accident conditions, the geometry of the core must be deformed as little as possible to ensure continued core cooling.

- Create turbulence to provide coolant mixing to avoid departure from nucleate boiling and to provide heat transfer between the fuel rods and the coolant, while minimising pressure loss.

Bottom fuel assembly nozzle

The bottom nozzle must:

- Provide lateral positioning of the fuel assembly on the lower core plate, to give the required pitch between assemblies.

- Position the guide thimbles.

- Provide the required retention forces.

- Provide the required coolant entry flow distribution into the core.

Top fuel assembly nozzle

The top nozzle must:

- Provide lateral positioning of the fuel assembly under the upper core plate, to give the required pitch between assemblies.

- Position the guide thimbles.

- Provide the required retention forces.

- Provides the required coolant exit flow distribution from the core while minimising pressure loss.

Hold-down assembly

The hold-down assembly must:

- Enable the fuel assemblies to resist the hydraulic pressure.

- Absorb relative height variations among the fuel assemblies.

In the first case, during reactor operation, the fuel assembly must maintain contact with the lower core plate. In order to ensure this function, the hold-down assembly and fuel assembly mass must exert a restraining force greater than the sum of the corresponding buoyancy force and the hydraulic pressure produced by the coolant.

In the second case, the hold-down assembly must absorb the variations between the length of the fuel assemblies and the distance between the lower and upper core plates. These variations are due to:

- Differential thermal expansion.
- Irradiation growth.

Connections

Rod/grid and guide thimble/grid connections must ensure:

- Structural continuity of the fuel assembly.
- Dimensional stability of the fuel assembly.

The structure of a fuel assembly is made of several components. The role of the connections is to link the components together so that every component can carry out its functions in a satisfactory and safe manner.

The choice and implementation of the connections must comply with the dimensional requirements for the assembly (i.e., the alignment of the grids and nozzles, the axial positions of the grids, and the radial positions of the guide thimbles).

0.2.3. Containment of radioactive material

The first containment barrier, which isolates the primary coolant fluid from the fuel and fission products, must remain leak tight.

This functional requirement applies to the following components of the fuel assembly:

Fuel rod

The fuel rod cladding must preserve its integrity to maintain the fissile material in a given configuration, contain fission products generated by the fuel pellets, and avoid coolant fluid contamination by activation of corrosion products.

This functional criterion must be complied with under Plant Condition Categories PCC-1 and PCC-2 (transients related to normal operation and anticipated operational occurrences).

For PCC-3 and PCC-4 (infrequent accidents and limiting accidents), there is no guarantee that the cladding will not be deformed, although a cooling geometry must be maintained. Under these conditions, the level of activity is assessed to confirm that the authorised discharge limits are met.

Grids

The grids must facilitate core loading operations and fuel handling operations in such a way that the cladding of the fuel rods is not altered by bonding, thus threatening their integrity.

Bottom fuel assembly nozzle

The bottom nozzle must facilitate core loading operations and fuel handling operations in such a way that the cladding of the fuel rods is not altered by bonding, thus threatening their integrity.

An anti-debris device is fitted to minimise the risk of cladding failure due to the presence of debris in the Reactor Pressure Vessel (RPV).

Top fuel assembly nozzle

The upper nozzle must enable the gripping of the assembly by a handling tool during core loading and fuel handling operations in such a way that the cladding of the fuel rods is not altered by bonding, thus threatening their integrity.

0.3. DESIGN REQUIREMENTS

0.3.1. Requirements arising from the functional classifications

a) Functional classifications

No safety classification is assigned to fuel assemblies.

b) Single Failure Criterion

Not applicable

c) Emergency Power Supply

Not applicable.

d) Qualification for operating conditions

Not applicable.

e) Mechanical, electrical, Instrumentation and Control classifications

Not applicable.

f) Earthquake classification

Although no safety classification is assigned to the fuel assembly, its mechanical design must take earthquakes into account.

g) Periodic tests

Not applicable (however in-service monitoring will detect any leakage of fuel assembly).

0.3.2. Other regulatory requirements

Not applicable

0.3.3. Hazards

Not applicable.

0.4. TESTING

0.4.1. Pre-operational tests

a) Tests using mock-ups and prototypes

Fuel assembly design has been and continues to be tested under normal operating conditions using mock-ups, and through more representative tests, to validate computer codes and confirm the correct mechanical operation of the fuel assemblies in the reactor [Ref-1], [Ref-2], [Ref-3], [Ref-4], [Ref-5].

These tests evaluate various aspects of fuel assembly performance, including the effects of irradiation and mechanical strength.

The results of these tests can be extended to present fuel design.

b) Handling tests

Fuel handling tests are carried out using dummy assemblies.

0.4.2. In-service monitoring

Monitoring for fuel assembly leak tightness is based on radiological activity measurements made in the primary fluid during reactor operation, which enable detection of any fuel cladding failures and allow monitoring of failure development.

0.4.3. Periodic tests

Not applicable

1. DESIGN DESCRIPTION OF THE FUEL

Each fuel assembly [Ref-1] consists of 265 fuel rods and 24 guide thimbles; the thimbles can be used for control rods or for core instrumentation thimbles. They are arranged in a 17 x 17 array (see Sub-chapter 4.2 - Figure 1). The main characteristics of the fuel assembly are listed in Sub-chapter 4.3 - Table 2.

The guide thimbles provide channels for inserting a RCCA. In the current design, the instrumentation lances use positions of the fuel assembly guide thimbles in the core which are not used for rod cluster control assemblies.

The fuel rods are maintained within a supporting structure consisting of the 24 guide thimbles, the top and bottom nozzles, and grid assemblies distributed along the fuel rod height. The fuel rods are loaded into the fuel assembly structure so that there is clearance between the fuel rod ends and the top and bottom nozzles.

Each fuel assembly is installed vertically in the reactor vessel and stands upright on the lower core plate, which is fitted with a device to locate and orient the assembly. After all fuel assemblies are set in place, the upper support structure is installed. Alignment pins, built into the upper core plate, engage and locate the upper ends of the fuel assemblies. The upper core plate then bears downward against the hold-down springs on the top nozzle of each fuel assembly to hold the fuel assemblies in place.

Visual confirmation of the orientation of the fuel assemblies within the core is provided by an identification mark.

1.1. FUEL RODS

Fuel rods are composed of slightly enriched uranium dioxide pellets with or without burnable poison (gadolinium), or MOX (uranium and plutonium) dioxide pellets. The fuel is contained in a closed tube made of M5 [Ref-1] [Ref-2] hermetically sealed at its ends.

A plenum is provided, at the top and bottom ends to contain fission gas.

The fuel pellets are held in place by a spring bearing down on the top end of the pellet stack.

The ends of each pellet are dished in order to compensate for the differential deformation between the pellet’s centre and periphery during operation.

The gap between the pellets and the cladding, the initial pressurisation, and the density of the pellets are specified so as to minimise the interaction between the pellet and the cladding.

1.2. FUEL ASSEMBLY STRUCTURE

The fuel assembly structure consists of a bottom nozzle, top nozzle, guide thimble, and grids.

1.2.1. Bottom nozzle

The bottom nozzle serves as the bottom structural element of the fuel assembly and directs the coolant flow to the assembly. Made of stainless steel type AISI 304, the bottom nozzle consists of a plate perforated and supported through four legs with bearing plates. These legs form a plenum for the inlet coolant flow into the fuel assembly.

Coolant flows from the plenum in the bottom nozzle, upward through the penetrations in the plate to the channels between the fuel rods. The perforations in the plate are positioned between the rows of the fuel rods.

The bottom nozzle is equipped with an anti-debris device and a positioning device to locate its position on the lower core plate.

1.2.2. Top nozzle and hold-down system

The top nozzle assembly functions as the upper structural element of the fuel assembly and provides a partial protective housing for the rod cluster control assembly or other components. It consists of a top plate and an adapter plate that are linked by a square enclosure, and hold-down springs mounted on its top plate. It allows rotation of the fuel assembly by 180° to provide greater flexibility when optimising the reload pattern.

The square adapter plate is provided with penetrations to allow the coolant to flow upward through the top nozzle. The top plate has a large square hole in the centre to permit access for the control rods.

The top nozzle has the fuel assembly identification mark, which is used to avoid errors in fuel element positioning.

1.2.3. Grid assemblies

The fuel rods are supported at intervals along their length by the grid assemblies, which maintain the lateral spacing between them.

Each fuel rod is supported within each grid by the combination of support dimples and springs. The magnitude of the grid restraining force on the fuel rod is set high enough to withstand the shipping and handling loads and to prevent fretting wear during reactor operation. The grid assemblies also allow axial thermal expansion of the fuel rods, while limiting the compression loads on the rods, to prevent excessive fuel rod distortion.

Two types of grid assemblies are used in each fuel assembly. One type has internal mixing vanes projecting from the trailing (upper) edges of the straps into the coolant stream. This type is used in the high heat flux region of the fuel assemblies to promote mixing of the coolant. The other type, located at either end of the bundle, does not contain mixing vanes on the internal grid straps and serves only to support and locate the fuel rods.

1.2.4. Guide thimble

The guide thimbles are structural members which also provide channels for the neutron absorber rods, neutron sources or instrumentation devices. Each thimble consists of a Zirconium based alloy tube. The tube diameter at the top section provides the annular area necessary to permit rapid control rod insertion during a reactor trip. The lower portion of the guide thimble is made with a smaller inner diameter to reduce diametric clearances and produce a dashpot action near the end of the control rod travel during trip operation.

2. DESIGN DESCRIPTION OF THE CONTROL ROD ASSEMBLIES

The Rod Cluster Control Assemblies (RCCA) [Ref-1] are used for shutdown and control purposes to offset fast reactivity changes.

A rod cluster control assembly is comprised of a group of individual neutron absorber rods fastened at the top end to a common spider assembly.

The absorber materials used in the control rods are silver/indium/cadmium (AIC) and B_4C. The main characteristics of the RCCAs are listed in Sub-chapter 4.1 – Table 1 (5/7). These data are used for the neutronic core calculations.

The AIC bars and B_4C pellet stack are sealed in a stainless steel tube. The lower end plug of the tube is made of stainless steel. The absorber rods are fastened securely to the spider.

The overall length is such that, when the assembly is fully withdrawn, the tips of the absorber rods remain engaged in the guide thimbles so that alignment between rods and thimbles is always maintained. Since the rods are long and slender, they are relatively free to accommodate any small misalignments with the guide thimble.

3. DESIGN EVALUATION [REF-1] [REF-2]

The fuel assemblies, fuel rods, and in-core control components are designed to satisfy the requirements of section 0 of this sub-chapter.

3.1. FUEL ROD

The fuel rods fulfil the required design and safety criteria regarding core behaviour [Ref-1] and long term storage [Ref-2].

3.1.1. Cladding

The design evaluation of the fuel rod cladding [Ref-1] addresses the following issues:

a) Vibration and wear

b) Fuel rod internal pressure and cladding stress

c) Materials and chemical evaluation

d) Fretting

e) Stress corrosion

f) Cycling and fatigue

g) Rod bowing

h) Consequences of Power - Coolant mismatch

i) Irradiation stability of the cladding

j) Creep collapse and creep down

3.1.2. Fuel material

The design evaluation of fuel material [Ref-1] addresses the following issues:

a) Dimensional stability of the fuel

b) Potential for chemical interaction

c) Thermal stability

d) Irradiation stability

3.1.3. Fuel rod performance

Fuel rod performance [Ref-1] is demonstrated, emphasising the following issues:

a) Pellet and cladding temperatures

b) Pellet/cladding interaction

c) Pellet densification

d) Irradiation effects

Fuel rod performance is demonstrated using analytical models and/or experimental data collected either in test programs or from commercial power plants.

The risk of Pellet Clad Interaction (PCI) is mitigated during both normal operation and frequent faults due to the Linear Power Density limitation function implemented in the Reactor Control Surveillance and Limitation system [Ref-2].

3.2. FUEL ASSEMBLY

The ability of the components of the fuel assembly (mainly nozzles, guides tubes, spacers and connections) to withstand of the following loads is demonstrated [Ref-1] [Ref-2].

a) Loads applied by the core restraint system

b) Accident loads

c) Loads applied in fuel handling and shipping

The fuel assembly bow behaviour and expected amplitudes have been analysed [Ref-3]

3.3. REACTIVITY CONTROL ASSEMBLY

The design evaluation of the RCCA addresses the following issues:

a) Internal pressure and cladding stresses during normal, transient, and accident conditions

b) Effects of passage from cold to hot dimensions (thermal expansion)

c) Evolution under irradiation of absorber materials and the cladding

4. TESTING AND INSPECTION PLAN

Generally, fabrication and examination operations are done in consultation with the fuel assembly contractor, and in accordance with RCC-C (Design and construction rules for fuel assemblies of nuclear plants) [Ref-1].

The fuel assembly contractor, as well as its subcontractors, has to develop a quality assurance program to document and monitor activities related to the design, analysis, and fabrication of fuel assemblies and their associated components.

The program must cover all the activities which might affect the quality of the product from design to development, procurement, materials handling, fabrication, testing, inspection, storage, and transportation.

Inspection is either carried out on 100% of important structural elements (such as assemblies or rods) or on a statistical quality control basis. The principle used for statistical quality control is that, unless otherwise indicated, inspection guarantees with a 95% confidence level that at least 95% of fabrication conforms to the specification (95 x 95).

This confidence level is based on experience acquired during previous core fabrications and from operating results. The statistical distribution of the main parameters is determined during fabrication and compared with the design distribution.

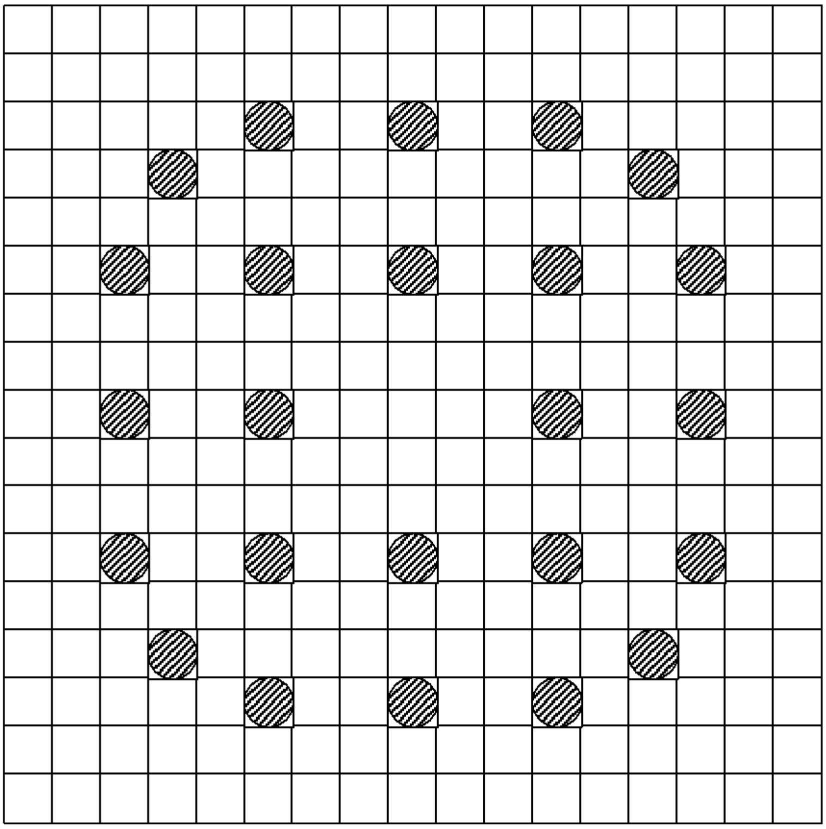
4.1. IN-SERVICE SURVEILLANCE

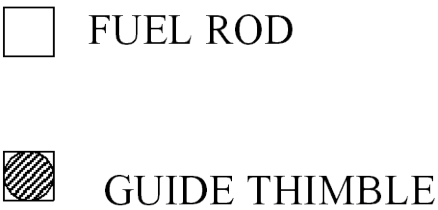
During operation, a visual inspection programme covering selected fuel assemblies will be implemented to evaluate the crud level, and to assess whether preventive or corrective actions are necessary for the continuation of operation [Ref-1].

Additionally, an inspection programme on a representative set of fuel assemblies will be implemented to evaluate the fuel assembly bow level at the end of the first fuel cycles of the first UK EPR and to assess whether actions are necessary for the continuation of operation [Ref-2].

SUB-CHAPTER 4.2 - FIGURE 1

Radial description of a fuel assembly





SUB-CHAPTER 4.2 – REFERENCES

External references are identified within this sub-chapter by the text [Ref-1], [Ref-2], etc at the appropriate point within the sub-chapter. These references are listed here under the heading of the section or sub-section in which they are quoted.

0. SAFETY REQUIREMENTS

0.4. TESTING

0.4.1. Pre-operational tests

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3.1. FUEL ROD

[Ref-1] Nuclear Fuel - Specification and Justification of Design and Safety Criteria. FS1-0000607 Revision 3.0. AREVA. October 2010. (E)

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3.1.1. Cladding

[Ref-1] A Dalmais. Reactor EPR™ FA3 - Evaluation of Thermo-mechanical Behaviour of AFA 3GLE UO_2 and UO_2-Gd_20_3 Fuel Rods. FS1-0000108-EN Issue 4. AREVA. July 2009. (E)

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3.1.2. Fuel material

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3.1.3. Fuel rod performance

[Ref-1] A Dalmais. Reactor EPR™ FA3 - Evaluation of Thermo-mechanical Behaviour of AFA 3GLE UO_2 and UO_2-Gd_20_3 Fuel Rods. FS1-0000108-EN Issue 4. AREVA. July 2009. (E)

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