Status Report – NUWARD™ (EDF lead consortium)
France 2019/11/13

NUWARD™ is a new SMR design with a projected deployment (start of construction) time around 2030. The NUWARD™ reference plant is currently planned to be built as a twin-module configuration providing a net power output of 340 MWe (i.e. 170 MWe per module). A module comprises a reactor and its dedicated nuclear steam supply system (NSSS) installed inside a steel containment vessel.

INTRODUCTION

Indicate which booklet(s): [ ] Large WCR [X] SMR [ ] FR

NUWARD™ is GEN3+ SMR with a total net electrical power of 340 MWe produced by two independent modules in order to offer flexible operation.

NUWARD™ is based on an integrated Pressurized Water Reactor (PWR) with full integration of the main components within the reactor pressure vessel: control rod drive mechanisms, compact steam generators and pressurizer.

With its innovative design features, such as the limited height of the reactor vessel, NUWARD™ is mainly composed of a steel containment submerged in a large volume of water (the buried water-wall) allowing for enhanced in-factory manufacturing.

From the view of nuclear safety, the NUWARD™ specific design includes the management of all Design Basis Condition (DBC) situations through passive systems without the need for any external classified electrical power supply and is self-reliant on an internal ultimate heat sink (the water-wall) for a grace period of more than 3 days.

Development Milestones

2012- 2016	Preliminary studies and technological innovation (using previously developed patents).
2017-2019	Pre-conceptual design phase and technology validation
2019-2022	Conceptual design phase
2030	Projected deployment time

Design organization or vendor company:

The design development is led by a consortium of four companies (CEA, EDF, Naval Group and TechnicAtome). A dedicated company is under creation.

Design Organization Contact: Mr Fabrice Tempier

Design Organization website: Upcoming in 2020

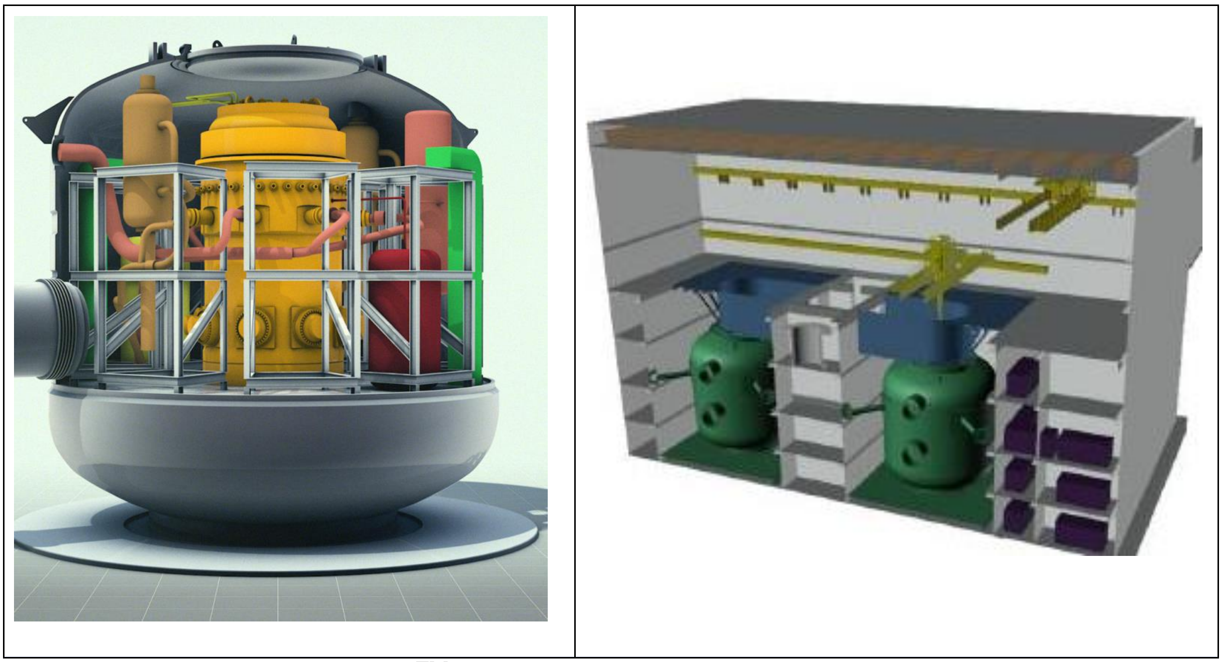

Figure 1. (a) NUWARD$^{\text{TM}}$ reactor inside steel containment vessel; (b) twin-module configuration of NUWARD$^{\text{TM}}$ to generate 340MWe

Reactor Units in PRIS (if applicable): None

Table 1: ARIS Category Fields (see also Spreadsheet “Categories”) for Booklet

ARIS Category	Input	Select from
Current/Intended Purpose	Commercial – Electric	Commercial – Electric/Non-electric, Prototype/FOAK, Demonstration, Experimental
Main Intended Application (once commercial)	Baseload and dispatchable	Baseload, Dispatchable, Off-grid/Remote, Mobile/Propulsion, Non-electric (specify)
Reference Location	Below-Ground, On Coast, Inland	On Coast, Inland, Below-Ground, Floating-Fixed, Marine-Mobile, Submerged-Fixed (Other-specify)
Reference Site Design (reactor units per site)	Dual Unit	Single Unit, Dual Unit, Multiple Unit (# units)
Reactor Core Size (1 core)	Small	Small (<1000 MWth), Medium (1000-3000 MWth), Large (>3000 MWth)
Reactor Type	PWR	PWR, BWR, HWR, SCWR, GCR, GFR, SFR, LFR, MSR, ADS
Core Coolant	H_2O	H_2O, D_2O, He, CO_2, Na, Pb, PbBi, Molten Salts, (Other-specify)
Neutron Moderator	H_2O	H_2O, D_2O, Graphite, None, (Other-specify)
NSSS Layout	Integral	Loop-type (# loops), Direct-cycle, Semi-integral, Integral, Pool-type
Primary Circulation	Forced (6 pumps)	Forced (# pumps), Natural
Thermodynamic Cycle	Rankine	Rankine, Brayton, Combined-Cycle (direct/indirect)
Secondary Side Fluid	H_2O	H_2O, He, CO_2, Na, Pb, PbBi, Molten Salts, (Other-specify)
Fuel Form	Fuel Assembly/Bundle	Fuel Assembly/Bundle, Coated Sphere, Plate, Prismatic, Contained Liquid, Liquid Fuel/Coolant
Fuel Lattice Shape	Square	Square, Hexagonal, Triangular, Cylindrical, Spherical, Other, n/a
Rods/Pins per Fuel Assembly/Bundle	17x17	#, n/a
Fuel Material Type	Oxide	Oxide, Nitride, Carbide, Metal, Molten Salt, (Other-specify)
Design Status	Conceptual	Conceptual, Detailed, Final (with secure suppliers)
Licensing Status	Internal evaluation only	DCR, GDR, PSAR, FSAR, Design Licensed (in Country), Under Construction (# units), In Operation (# units)

Table 2: ARIS Parameter Fields (see also Spreadsheet "Data") for Booklet

ARIS Parameter	Value	Units or Examples
Plant Infrastructure		
Design Life	60	years
Lifetime Capacity Factor	90%	%, defined as Lifetime MWe-yrs delivered / (MWe capacity * Design Life), incl. outages
Major Planned Outages	15 days every 24 months (refuelling)	# days every # months (specify purpose, including refuelling)
Operation / Maintenance Human Resources	56 / 50	# Staff in Operation / Maintenance Crew during Normal Operation
Reference Site Design	2	n Units/Modules
Capacity to Electric Grid	340	MWe (net to grid)
Non-electric Capacity	Optional	e.g. MWth heat at x ºC, m3/day desalinated water, kg/day hydrogen, etc.
In-House Plant Consumption	<30MWe	MWe
Plant Footprint	3500	m^2 (rectangular building envelope)
Site Footprint	****	m^2 (fenced area)
Emergency Planning Zone	included in Site Footprint	km (radius)
Releases during Normal Operation	****	TBq/yr (Noble Gases / Tritium Gas / Liquids)
Load Following Range and Speed	20 – 100 5%/min	x – 100%, % per minute
Seismic Design (SSE)	0.25g	g (Safe-Shutdown Earthquake)
NSSS Operating Pressure (primary/secondary)	15/4.5	MPa(abs), i.e. MPa(g)+0.1, at core/secondary outlets
Primary Coolant Inventory (incl. pressurizer)	120 000	kg
Nominal Coolant Flow Rate (primary/secondary)	3700/240	kg/s
Core Inlet / Outlet Coolant Temperature	280/307	ºC / ºC
Available Temperature as Process Heat Source	Not applicable	ºC
NSSS Largest Component	RPV	e.g. RPV (empty), SG, Core Module (empty/fuelled), etc.
- dimensions	13/4/310 000	m (length) / m (diameter) / kg (transport weight)
Reactor Vessel Material	Carbon steel	e.g. SS304, SS316, SA508, 800H, Hastelloy N
Steam Generator Design	Once-through plate-type SG	e.g. Vertical/Horizontal, U-Tube/ Straight/Helical, cross/counter flow

ARIS Parameter	Value	Units or Examples
Secondary Coolant Inventory	<1000	kg
Pressurizer Design	Integral	e.g. separate vessel, integral, steam or gas pressurized, etc.
Pressurizer Volume	****	m^3 / m^3 (total / liquid)
Containment Type and Total Volume	Dry, submerged in underground water-wall	Dry (single/double), Dry/Wet Well, Inerted, etc. / m^3
Spent Fuel Pool Capacity and Total Volume	10 (20 optional)	years of full-power operation / m^3
Fuel/Core		
Single Core Thermal Power	540	MWth
Refuelling Cycle	24 months	months or “continuous”
Fuel Material	UO_2	e.g. UO_2, MOX, UF_4, UCO
Enrichment (avg./max.)	<5%	%
Average Neutron Energy	****	eV
Fuel Cladding Material	Zr	e.g. Zr-4, SS, TRISO, E-110, none
Number of Fuel “Units”	17x17	specify as Assembly, Bundle, Plate, Sphere, or n/a
Weight of one Fuel Unit	****	kg
Total Fissile Loading (initial)	****	kg fissile material (specify isotopic and chemical composition)
% of fuel outside core during normal operation	Not applicable	applicable to online refuelling and molten salt reactors
Fraction of fresh-fuel fissile material used up at discharge	****	%
Core Discharge Burnup	****	MWd/kgHM (heavy metal, eg U, Pu, Th)
Pin Burnup (max.)	****	MWd/kgHM
Breeding Ratio	Not applicable	Fraction of fissile material bred in-situ over one fuel cycle or at equilibrium core
Reprocessing	Batch	e.g. None, Batch, Continuous (FP polishing/actinide removal), etc.
Main Reactivity Control	Rods	e.g. Rods, Boron Solution, Fuel Load, Temperature, Flow Rate, Reflectors
Solid Burnable Absorber	Gd_2O_3	e.g. Gd_2O_3,
Core Volume (active)	****	m^3 (used to calculate power density)
Fast Neutron Flux at Core Pressure Boundary	****	N/m^2-s
Max. Fast Neutron Flux	****	N/m^2-s

ARIS Parameter	Value	Units or Examples
	Safety Systems	
Number of Safety Trains	Active / Passive	% capacity of each train to fulfil safety function
- reactor shutdown	0/2	/
- core injection	0/2	/
- decay heat removal	0/2	/
- containment isolation and cooling	Passive steel containment	/
- emergency AC supply (e.g. diesels)	None	/
DC Power Capacity (e.g. batteries)	Several days in DBC (for I&C)	hours
Events in which ***Immediate Operator Action*** is required	None in DBC	e.g. any internal/external initiating events, none
Limiting (shortest) ***Subsequent Operator Action*** Time	Several days in DBC	hours (that are assumed when following EOPs)
Severe Accident Core Provisions	IVMR	e.g. no core melt, IVMR, Core Catcher, Core Dump Tank, MCCI
Core Damage Frequency (CDF)	< $1x10^{-5}$/ry	x / reactor-year (based on reference site and location)
Severe Accident Containment Provisions	N_2 injection	e.g. H_2 ignitors, PARs, filtered venting, etc.
Large Release Frequency (LRF)	Practical elimination	x / reactor-year (based on reference site and location)
	Overall Build Project Costs Estimate or Range (excluding Licensing, based on the Reference Design Site and Location)	
Construction Time (nth of a kind)	36 months	months from first concrete to criticality
Design, Project Mgmt. and Procurement Effort		person-years (PY) [DP&P]
Construction and Commissioning Effort		PY [C&C]
Material and Equipment Overnight Capital Cost		Million US$(2015) [M&E], if built in USA
Cost Breakdown	%[C&C] / %[M&E]	
- Site Development before first concrete	/	(e.g. 25 / 10) (30 / 40) (20 / 25) (20 / 10) (5 / 15) (-----------) (to add up to 100 / 100)
- Nuclear Island (NSSS)	/	
- Conventional Island (Turbine and Cooling)	/	
- Balance of Plant (BOP)	/	
- Commissioning and First Fuel Loading	/	
Factory / On-Site split in [C&C] effort	/	% / % of total [C&C] effort in PY (e.g. 60 / 40)

1. *Plant Layout, Site Environment and Grid Integration*

SUMMARY FOR BOOKLET

The nuclear installation island (NI) houses 2 independent modules and the an associated single fuel storage pool. The NI. This nuclear island is designed to withstand 0.25g during earthquake. No system/resource (including heat sink) outside the Nuclear Island (NI) is required to ensure the safe-state for at least 3 days; the NI is self-reliant for at least this period due to the adoption of water-wall in which each containment vessel is immersed.

The NUWARD^{TM} is designed compliant to ENSOe/EUR grid requirements. Adaptations to final country specific user requirements are possible.

The key feature of the NUWARD^{TM} design is the ability to provide to the grid a variable electrical supply. To account for seasonal variations, the concept of "a set of reactors inside the same plant" provides the operator with a range of solutions to adapt the maintenance schedule with priority given to the grid supply needs. There is always at least one reactor of the plant in-operation and supplying the grid, whereas another one may be in outage.

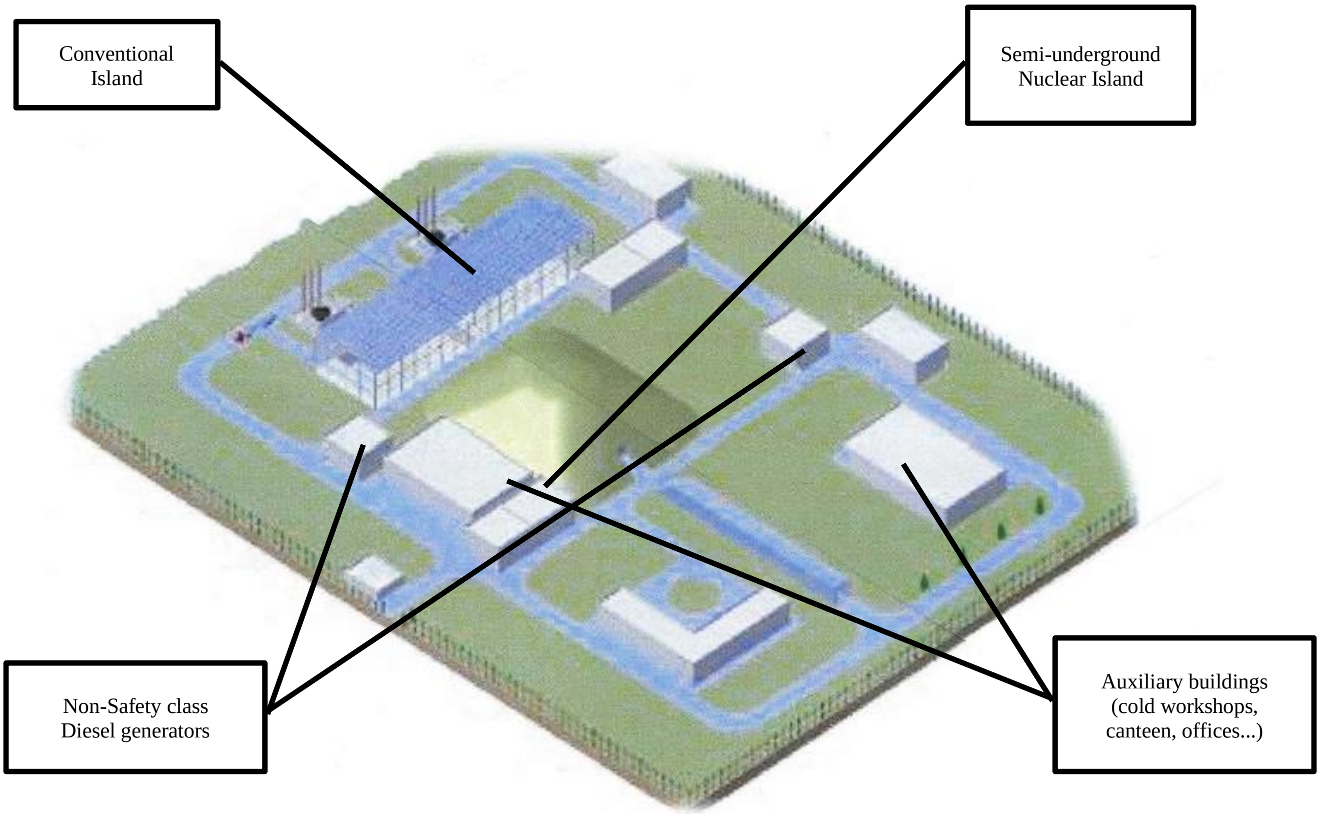

Figure 2. Typical plant layout

1.1. Site Requirements during Construction

- NUWARD^{TM} plants are suitable for sea-onshore and/or river-side sites, with open-loop conventional condenser cooling. Nevertheless, inland-site with dry aero condensers is a possible option.

- Soil conditions shall be such to allow ~20m deep excavation (typically medium/rock soil) with reasonable technically available means
- Site access: Most components/circuits are delivered as modules of the size of a Marine 20’-40’ container. This requires standard roads accessible to lorry. Some heavy components (such as RPV, turbine and parts of steel containment) may need specific transportation to be discussed on case-by-case basis. No heavy lifting devices are required for construction, nor for operation.

1.2. Site Considerations during Operation

- Water usage needs:
    - For filling-in and making-up of various onsite tanks, water circuits, and the water wall;
    - For providing continuous flow of cooling water for conventional condenser cooling, in case the open-loop design is used;
- Maximum acceptable ambient air temperature, humidity, and heat sink temperature for full-power operation: to be discussed according to yield performances.

1.3. Grid Integration

- Grid interface/code requirements: Basic grid interface compliant with ENSTOe and EUR requirements (Typically 225kV/400kV and 50Hz). Possible adaptation to specific user requirements such as 60 Hz.
- Grid supply variations capability from 20% to 100% of total net electric output power, without effluent generation (boron-free design).
- Ability of plant to operate on house load: Yes
- Ability to load reject without shutdown : Yes, up to 100% nominal power

2. *Technical NSSS/Power Conversion System Design*

SUMMARY FOR BOOKLET

The NUWARD^{TM} reactor is a fully integrated PWR type SMR, housing all the main reactor coolant system components, including the steam generators, the pressurizer and the control rod drive mechanisms (CRDM) inside the RPV in proximity with the core. A specific design effort has been made to reduce the number of pipes connected to the RPV with the objective to limit the maximum Loss of Coolant Accident (LOCA) size to a 30 mm in diameter.

The reference core is based on a proven 17x17 fuel assemblies used in the operating PWR with a shortened core height and UO_2 rods (enrichment < 5wt% ^{235}U). Due to the boron-free design, various ^{235}U enrichments and burnable poisons are used. The reference refueling interval is 2 years. Fuel handling uses state-of-the-art techniques derived from proven PWR techniques.

The NUWARD^{TM} reactor and its associated safety systems are designed for:

- Passive management of all DBC scenarios with no need of any operator's action, any external ultimate heat sink source, any boron injection or any external electrical power supply (normal and emergency) for more than 3 days.
- Active management of DEC-A accidents, with simple diagnosis and implementation of diversified systems.
- Passive management of DEC-B accidents with in-vessel retention of the corium (IVR concept).

The conventional island is based upon state-of-the-art turbines derived from proven off-the-shelf balance-of-plant technologies.

The small steel containment vessel allows for extended off-site manufacture providing ideal conditions for a high quality level, inherent improved air-tightness, and passive cooling.

No safety classified 1E electrical power is required (except DC power to I&C).

I&C is compliant with IEC 61226 standard for Classification. Diversified I&C is considered for the design of the mst significant safety functions.

No operator action required for more than 3 days after any design basis accidents (DBA).

Inside the twin-module configuration, the reactors are operated from a shared common control-room with dedicated panels for normal operation. The reactors on outage, and/or in mid-long term accidental situations, are operated from a remote and dedicated control room, by a dedicated re-enforced team.

Unique technical design features include:

- The reactor coolant system is based upon the use of an innovative once-through steam generator technology derived from the plate exchanger concept. Specific developments made in terms of design and the manufacturing process, allow a nuclear application as a steam generator. This technology offers a Compact Steam Generator (CSG) with a direct connection to the reactor. The overall size (height) of the reactor coolant system (for the level of thermal power) is therefore significantly reduced.
- The reactor boron-free reactivity control allows for simplification of auxiliary systems design and operations in both normal and accident situations as well as a drastic reduction in effluents production from operation.
- The submerged metallic containment is passively cooled by a water wall acting as an external pool dedicated to a single reactor and providing extended grace delay.

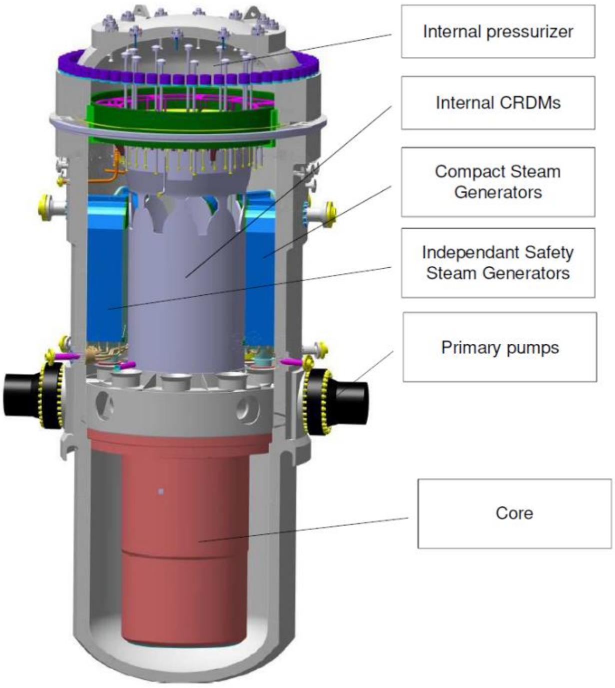

Figure 3. Simplified reactor cross section

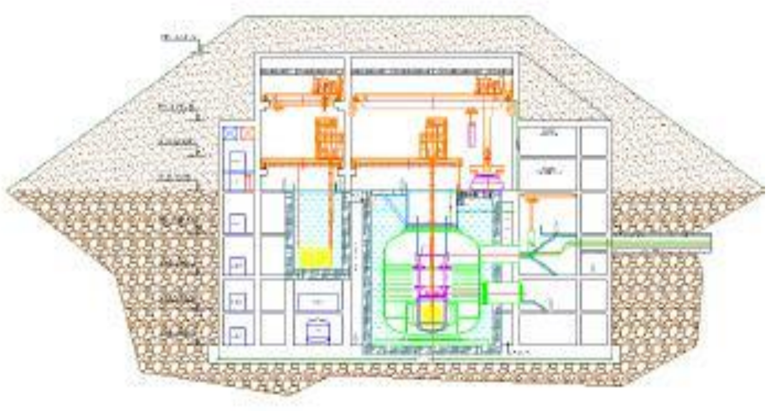

Figure 4. Typical Nuclear Island cross section showing the semi-underground configuration and the availability of large water inertia for both module and storage pools

2.1. Primary Circuit

The NUWARD^{TM} reactor is a fully integrated PWR reactor, housing in a single vessel all the main reactor coolant system components, including the Steam Generators, the Pressurizer and the Control Rod Drive Mechanisms. A specific design effort has been made to reduce the number of pipes connected to the vessel in order to limit the LOCA size to a 30 mm diameter.

Reactor Pressure Vessel and Internals

As large-series manufacturing is a key driver for the NUWARD^{TM} overall project, the reactor pressure vessel size has been chosen similar to an average 900 MWe PWR vessel. This choice empowered a large panel of suitable suppliers reducing the procurement risk of such vessel. Moreover, the use of internal Control Rod Drive Mechanism (CRDM) and electrical penetrations for instrumentation and pressurizer heaters substantially simplifies the vessel head manufacturing.

During long outages, all internal components within the vessel are easily removed from the vessel and replaced by refurbished ones (chosen in a set of common spare components). The removed components are subsequently inspected, repaired and maintained outside of the outage critical path. This process is reducing the risks of a delay during outages for the benefit of the reactor's availability for operation.

Reactor Coolant System and Pressuriser

NUWARD^{TM} primary cooling flow is internal, forced by 6 canned pumps horizontally mounted onto the RPV, positioned under the steam generators in the cold-leg in order to have efficient hydraulic conditions. The hydraulic components are connected to the lower part of the vessel and are designed for an optimal homogenization of the reactor coolant flow and temperature before entering into the core.

The large volume of reactor coolant water and the large volume of the pressurizer provide margins for the operational transients (DBC- 2) as well as for the normal day-to-day operations of the reactor.

The overall innovative design of the reactor coolant system and hence to the connected auxiliary circuits is such that the maximal size of a failure is limited to 30mm. In other words the maximum size of a LOCA is 30mm.

By adopting the free-boron design, no primary water dilution is required during the whole production cycle. Moreover, the reactor primary auxiliary system integrates a large low pressure water-tank, which is storing the water expansion. These combined features drastically reduce the volume of primary effluents.

2.2. Reactor Core and Fuel

Reactor Core

The reference core is based on a proven design PWR 17x17 fuel assemblies and UO2 rods (enrichment < 5wt% 235U). Due to the boron-free design, various 235U enrichments and burnable poisons are used.

Reactivity Control

All fuel assemblies are equipped with a rod cluster, driven by an internal electrical CRDM. CRDMs and associated wiring through the vessel adopt an innovative design whose key driver is the capability for large-series manufacturing. The second shutdown system (based on soluble Boron) is not required for the management of the DBC accidents, and required only for the Anticipated Transient Without Scram (ATWS) accidents (Design Extension Conditions without core melt DEC-A).

2.3. Fuel Handling

Fuel handling is derived from the state-of-the-art proven techniques and technologies taking benefit from the wide experience of the numerous PWR NPPs, since SMRs fuel management is not too much specific (i.e. apart from their size and number for a reactor, fuel assemblies are very similar).

Fuel handling is performed from the maintenance hall protected from external hazards by the mound. The metallic containment of a module is opened, making a connection of the containment with the spent fuel pool via this maintenance hall, where the main crane and associated outage tools are operated. Indeed, in this configuration, a continuous water-path is set-up from the vessel up to the spent fuel storage pool. This path is continuously vertical without the need of tilting the fuel element into a "transfer tube". The fuel assemblies are therefore handled vertically all the way to or from the spent fuel pool.

2.4. Reactor Protection

See section 4 “safety concepts”

2.5. Secondary Side

The secondary side is designed from off the shelf components (e.g. turbine and generators) on the basis of using over-heated steam.
The design is based on a one-to-one basis, i.e. one turbo-generator is dedicated to one reactor module. This option provides for an independent operation of a reactor module for power generation, in particular the ability to switch to houseload operating mode in case of any failures or issues with the connection to the grid).

2.6. Containment/Confinement

NUWARD^{TM} containment is made of a small steel containment submerged in a large water pool providing significant thermal inertia. The typical size of the containment is 15 m diameter – 16 m height. The design pressure is around but less than 1.0 MPa.
In normal operation conditions, apart from outage period, the containment is kept isolated without external venting (only internal air circulation). The containment pressure is kept at a lower value than the atmospheric pressure in a static way.
Before opening the containment (e.g. to prepare an outage period) an external venting and air filtering, as well as an air renewal is performed. Mechanical heat removal system is not required because the containment is passively cooled by submerging it in the external pool both in normal and accidental situations.

2.7. Electrical, I&C and Human Interface

- Turbine and Generator (rated power, voltage, frequency): see section 1.3 and 2.4
- Safety related electrical systems: Due to the passive management of DBC situations, there is no need for an internal or external 1E electrical power supply. Only I&C is supplied by internal batteries. This autonomy is up to 3 days for the subset of I&C dedicated to safe state monitoring.
- I&C design architecture is compliant with IEC61226 standard. NUWARD^{TM} uses state-of-art digital nuclear I&C.
  - Process I&C: A specific emphasis is put on the design of the process I&C (especially classified I&C) to take profit of the intrinsic features of the reactor and to keep I&C architecture as simple as possible. When necessary, a non-digital diversification is provided (e.g. for heat removal system actuation).
  - Maintenance I&C: the non-classified maintenance I&C, independent from the process I&C, uses all current technologies to provide the operator with remote logging/expertise of data on the systems in order to implement predictive or condition based maintenance.
  - As for physical protection, the protection against cyber-attacks is a key objective of I&C design. All detailed information on this protection and on the physical protection is sensitive and must follow a specific communication process.
- The two units of a same plant share the same control room, with dedicated independent panels, for the reactors in operation. The unit under maintenance or in incidental or accidental situation is controlled via a dedicated control room and a dedicated team.

2.8. Unique Technical Design Features (if any)

Steam Generator

The reactor coolant system uses an innovative once-through plate-type heat exchanger for the steam generator technology. In order to allow the nuclear application of the plate-type exchanger technology, specific features have been developed in the design and the manufacturing process.

This technology leads to a Compact Steam Generator (CSG) which is a key factor to minimize the overall size, particularly the height of the reactor coolant system.

Inside the RPV, six CSGs provide the turbine with nuclear steam during normal power operation while two independent S-CSGs (Safety-CSG) ensure the safety cooling function in case of incident or accident.

Both S-CSGs are part of independent, closed and passive systems. They ensure the decay heat removal safety function in all DBC accidents. These redundant circuits are fully independent from the normal steam generation providing a significant improvement in the Defense-in-Depth approach regarding usual PWR architecture.

Boron-free control

The reactor does not use soluble boron for the reactivity control. This option is possible due to the small size of the core and the large coverage of absorber (almost every fuel element is controlled by an absorber). This feature allows: (i) a large simplification of operation in normal (no boron dilution linked to power modification) and accident situations (no risk of dilution) (ii) a large reduction in effluents production (no dilution during the cycle) and (iii) a significant reduction in tritium production.

3. *Technology Maturity/Readiness*

SUMMARY FOR BOOKLET

The NUWARD^{TM} design takes advantage of many years of operating experience of the PWR technology, PWR supply chain and the 17x17 UO2 fuel assembly. Moreover, the design benefits from already proven technical solutions, even where not in use for large PWR reactors such as: metallic containment, semi-underground Nuclear Island. This use of proven technologies and the availability of considerable experience feedback allows for targeting the first construction by 2030.

The technological innovation (integrated architecture, compact steam generators, immerged CRDM) are focused on solution allowing compactness and extended off-site manufacture. The development of these innovations began in the late 2000's in order to meet the overall design schedule.

The NUWARD^{TM} plant is currently under conceptual design.

3.1.Reactors in the Design Stage

- Technology readiness assessment: The basic technology (PWR), the core (17x17 $U0_2$) and most technological solutions benefit from the large operating experience of the worldwide PWR fleet and the EDF experience on the French fleet. Most of the basic knowledge, calculation codes, licensing approaches, and methodologies are therefore proven engineering practices. For most components a supply chain exists that can be tailored to SMRs: mass production of identical single components. Innovations have been launched in the late 2000s, ahead of the overall plant design, to consolidate the feasibility of these technical innovations before starting the NUWARD^{TM} design. These different innovations are planned to be at prototype level by the end of the conceptual design. For these innovations the principle is to merge existing technologies from the nuclear and non-nuclear domains to a specific nuclear design.
- Basic knowledge/technology gaps, R&D needs: There is no major basic technology gap. Most of the R&D under development addresses the capability of the current thermohydraulic codes to reflect the behavior of passive systems. A set of mock-up and thermohydraulic loops is defined in the R&D roadmap. Inside the consortium, CEA is the R&D leader for these tasks.
- Compliance with worldwide design regulations: Benefitting the long operating experience of PWR technology and standard fuel, the design of NUWARD^{TM} is developed to achieve compliance with the international mainstream of design regulation requirement (IAEA, WENRA… recommendations) as well as the French Regulation. This is to be comforted in the different coming phases of development.
- Licensing time-frame: The NUWARD^{TM} is currently under conceptual design with internal assessment of the design options against international PWR licensing requirements. A Preliminary Safety Option Report will be issued at the end of the conceptual design phase to engage preliminary discussion with the French Nuclear Safety Authority for the commercial FOAK. This process is not excluding additional engagement with other countries, depending on commercial opportunities at that point in time. The decision to engage in a construction is scheduled for the late 2020s.

4. *Safety Concept*

SUMMARY FOR BOOKLET

The NUWARD™ safety approach benefits from the following inherent features of the design to reach and maintain a safe state, with limited support from the operating team:

- Large reactor coolant inventory (kg/MWth) providing inertia versus power transients
- Boron-free operation providing large and constant moderator counter-reaction and preventing boron dilution ,
- Integrated reactor coolant system architecture thus reducing the maximum LOCA size to be considered and providing more time for the management of a LOCA accident. Internal CRDMs preventing from road-ejection accidents
- A metallic submerged containment providing passive cooling for several days
- A small core in a large vessel enabling the success of the in-vessel retention strategy for design extension with core melting.

Additionally, The NUWARD™ reactor and associated safety systems are designed for:

- Passive management of all DBC scenarios without the need for any operator's action, any external ultimate heat sink, any boron injection or any external electrical power supply (normal and emergency) for more than 3 days. The main systems involved in DBC situation are: (i) passive absorbers drop (ii) passive two loops heat removal system and (iii) passively cooled metallic containment.
- Active management of DEC-A accidents, with simple diagnosis and implementation of diversified systems. Multiple failure accidents DEC-A include DBC scenarios cumulated with multiple failures of redundant DBC safety systems (despite using passive systems actuated with diversified means). The main systems involved in DEC-A situations are: (i) high pressure passive boron injection, (ii) active primary water injection, and (iii) passively cooled metallic containment.
- Passive management of DEC-B accidents with in-vessel retention of the corium (IVR concept and nitrogen injection for H2 management.

4.1. Safety Philosophy and Implementation

- Ahead from the safety systems design, the NUWARD™ design includes technical options aiming to reach and maintain a safe state for a long period without external resource (electrical power and heat sink) nor operator's action.
    - Large primary inventory (kg/MWth): The reactor coolant inventory of a NUWARD™ is around 3 times greater than that for a large PWR reactor. This option provides more time, estimated at around 3 times more, to actuate any regulation or automatic action in case of incidental power transients (such as grid shutdown)
    - Boron-free operation: The moderator counter-reaction is significant (absolute value) and constant during the whole fuel cycle. This option contributes to intrinsic stability of the reactor in case of incidental power transient. In the meantime, the low secondary inventory (once-through steam generator) prevents the formation of a negative effect of such an important moderator counter-reaction value. On the other hand the boron free feature prevents the core from dilution effects in normal and accidental situations.

    - Integral reactor coolant system architecture, thus leading to a limited maximal LOCA size and providing more time for the management of a LOCA accident, as well as limiting the impact on the containment pressure (even with a small containment).
    - Internal CRDMs preventing from road-ejection accidents
    - A metallic submerged containment providing passive cooling for several days
    - A small core inside a large vessel allowing easy in-vessel retention strategy.

Safety Approach and Configuration to Manage DBC
Systems used to manage DBC (safety systems) are not shared between the different reactors in the same plant.

- Criticality: The design includes safety features to prevent criticality risks. The core is sub-critical with clear water at 20°C even if the most efficient absorber is stuck in upper position. This option prevents the occurrence of criticality accidents even in post-accident conditions. Moreover, the use of internal CRDM eliminates the occurrence of a rod ejection accident. The criticality management system (passive absorber drop) shall be considered as a D-passive system according to IAEA classification.
- Decay Heat Removal: The design includes a 2x100% train of passive heat removal system, transferring by natural circulation the decay heat from the core to the water wall surrounding the containment. Each train is actuated by 2 diversified channels (diversified sensors, diversified I&C and diversified actuators). The water-wall or pool surrounding the containment ensures the heat removal function for more than 3 days without the need for an external ultimate heat sink. The limited maximal size of a LOCA condition and the efficient passive heat removal system result in a limited water loss during the LOCA accident. A set of 2 redundant low pressure safety injection accumulators provides the make-up of reactor coolant water inventory. The passive vessel heat removal system shall be considered as a D-passive system according to IAEA classification.
- Confinement and Containment Protection: The steel containment submerged in the water wall contributes to the confinement function (3rd barrier). The limited maximal size of a LOCA condition and the efficient passive heat removal system results in a limited pressure peak inside the containment. The steel containment is passively cooled by the surrounding pool. The containment is protected against hydrogen risk in DBC by passive recombiners. The containment closing (valves) shall be considered as a D-passive system. The passive containment heat removal system shall be considered as an A-passive system according to IAEA classification.

In a brief summary the key features of the DBC management strategy is:

- No operator’s action required for more than 3 days,
- No additional external ultimate heat-sink required for more than 3 days,
- No external power supply (normal and emergency) required for more than 3 days,
- No primary depressurization system required,
- No boron injection is required.

Safety Approach and Configuration to Manage DEC
According to the Defense-in-Depth concept, additional safety features are provided to cope with postulated multiple failure accident conditions and core melt accident conditions.

Systems used to manage DBC (safety systems) are not shared between the different reactors in the same plant.

DEC-A systems are:

- Low flowrate depressurization system and active primary water injection. This system provides for the removal of the decay heat in case of a postulated common mode failure of redundant trains of passive DBC safety systems.
- High pressure borated water accumulator to cope with ATWS accidents.

DEC-B systems are:

- Low flowrate depressurization system to reach a primary pressure less than 2 MPa before corium relocation,
- Passive flooding of vessel pit in order to provide in-vessel retention of corium,
- Nitrogen injection to manage the risk of hydrogen combustion.

4.2.Transient/Accident Behaviour

To be detailed in further updates.

5. *Fuel and Fuel Cycle*

SUMMARY FOR BOOKLET (optional)

The reference core is directly derived from the proven 17x17 UO2 fuel assembly in use in most operating PWRs worldwide.

The reference refueling strategy is by half a core every 2 years.

The plant provides a storage capability of spent fuel assembly for 10 years after operation. An option of 20 years of storage could also be proposed.

5.1. Fuel Cycle Options

As the fuel is directly derived from currently in-use fuel, but with a different sizing, the overall cycle facilities can be easily customized to this new manufacture and (if relevant depending on the country policy) even the recycling.

6. *Safeguards and Physical Security*

SUMMARY FOR BOOKLET (optional)

Safeguards: On this topic, the NUWARD™ design is directly derived from the options in-use in large PWR NPPs. There is no major specificity in terms of safeguards for NUWARD™.

Physical security: The nuclear island is constructed underground for the reactors and spent fuel part and protected by an artificial mound for the maintenance hall. There is no direct access from outside to the Nuclear Island, all accesses being made by tunnels and locks. This architecture provides an efficient protection against a large range of natural as well as malicious hazards, including large flooding and commercial airplane crashes. As for physical protection, the protection against cyber-attacks is a key objective of I&C design. All detailed information on this protection and on the physical protection is sensitive and must follow a specific communication process.

6.1. Safeguards

- Similar to the operating PWR NPPs.

6.2. Security

- Will be provided in future updates.

7. Project Delivery and Economics

SUMMARY FOR BOOKLET (optional)