The EPR2: A Short Presentation

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On February 10, 2022, President Emmanuel Macron, during his visit in Belfort, unveiled his plans for France's new energy strategy. His announcement concerning nuclear energy sector included the possibility to extend the lifetime of all reactors in service beyond 50 years as well as to construct six new reactors, with the option to add eight more by 2050. This move aligned with the ambitious goal of achieving carbon neutrality in the energy sector, as envisioned by the European Union. Macron's declaration represented a significant shift in French energy policy set in the 2014 Energy Transition for Green Growth Act. That earlier policy aimed to reduce the share of nuclear in electricity generation to 50 %, at first with the target by 2025 and then postponed to 2035. In March 2023, France's parliament voted in favor of the government's investment plan, providing the green light for the construction of six new reactors across three sites. Later in May of the same year, a new law on the acceleration of construction of new nuclear facilities lastly removed the 50 % cap on the nuclear share in energy production.

To modernize the part of France's nuclear fleet in the frame of this ambitious program, EDF will set on the EPR2 design, an evolution of the EPR (European Pressurized Reactor) currently being commissioned at Flamanville (FA3). The EPR2 is a 4-loop pressurized water reactor (PWR) in the power range of 1600 MWe with a three-train architecture for the safety systems. The present article provides a short technical presentation of the EPR2 product with a focus on the nuclear island (NI).

History of EPR2 Project

In 2014, EDF, in collaboration with Framatome (formerly Areva NP), began developing an optimized EPR reactor for its nuclear portfolio. Starting from 2017, the newly created EDF-Framatome joint venture, EDVANCE, has taken responsibility for the design of the NI in the project.

From the earliest design stage, the project has aimed to incorporate numerous lessons learned in engineering and construction from the EPRs (Olkiluoto 3, Flamanville 3, Taishan 1&2 and Hinkley Point C) as well as from other operating PWRs. The project's main objectives can be formulated in three words: simplification, industrialization, efficiency.

The following strategies should help to achieve these goals:

- Integrate standardization through catalogues in mechanical, electrical, and civil engineering fields from the project's start to reduce the number of component types, optimize documentation and logistics during construction and plant maintenance.
- Simplify the design of buildings and systems to improve constructability, in particular by enabling the prefabrication of large elements and a modular way of construction.
- Implement systems engineering methods and tools to express design objectives in requirements, enhancing engineering efficiency and optimizing management of technical configurations throughout the Product Lifecycle Management (PLM).
- Offer industrial perspective to subcontractors by creating a new Nuclear Power Plants (NPP) series and optimise costs through serial mass production for several Units at a time.

The basic design started in 2015, with the first safety options file DOS (Dossier d'Options de Sûreté)[1] submitted to the French Nuclear Safety Authority (ASN) in April 2016. At the beginning of 2018, considering the first feedback, it was decided to maintain the power

1 https://www.asn.fr/l-asn-reglemente/consultations-du-public/epr-nouveau-modele

level of the EPR. The motivation was to keep the sizing of the nuclear steam supply system as close as possible to the EPR design thus benefiting from synergies between the projects and reducing manufacturing risks. In this phase the design received its current name "EPR2". A first revision of the EPR2 Preliminary Safety Analysis Report (PSAR), which incorporated technical recommendations provided by the ASN on the DOS, was presented to the regulator in February 2021 for anticipated review. In mid-2023, the revised PSAR was officially submitted to the ASN as part of the construction license application (DAC - Dossier d'Autorisation de Création) for 2 EPR2 units at the Penly site.

Evolution of the Design

Since the licensing of the EPR, the regulatory context has evolved both in France and internationally. The new safety reference for the EPR2 takes into account ASN Guide No.22[2], which formalized requirements introduced following the Fukushima Dai-chi accident and the WENRA recommendations[3]. Taking the FA3 EPR as a reference, the EPR2 safety baseline put focus on the following improvements:

- Independence between defence-in-depth (DiD) levels:

  Attention is paid to improvement of functional and physical separation between systems and components required in normal and accident operation (DiD level 1 to 3) and mitigation means for accidents with core melt (DiD level 4). This results in new deterministic requirements and dedicated features such as electrical power supply and ventilation.

- Prevention and protection against common cause failure (CCF) affecting safety systems:

  A systematic analysis of credible CCFs is performed, resulting in the establishment of extensive diversification requirements for frontline and support systems in DiD level 3b (multiple failure events).

- Consideration of protection against extreme external natural hazards:

  Design principles require the absence of significant or early releases in case of extreme external hazards that are considered as representative for Fukushima-like events. Systems of DiD level 3b and 4 are designed or protected against extreme hazards. These systems are housed in separated areas of the safeguard auxiliary building (SAB) 3.

- Extended site autonomy:

  This design objective improves the robustness of DiD level 3a/b and 4 extending the period of time before the intervention of site or external support (FARN[4] in French context) in accident situations for which the implementation of mobile resources could be necessary.

Certain design solutions implemented in the EPR reactor have been challenged in the EPR2 project, aiming at the optimization of plant design while maintaining the same safety level of the installation. This includes, for instance, conducting preventive maintenance at power on frontline safety systems and the accessibility of the Reactor Building (RB) during power operation. These requirements were initially influenced by German utilities involved in the EPR's development and were not typical for PWRs operated in France. Based on feedback from the FA3 EPR, both requirements have been abandoned for the EPR2. The preventive maintenance concept on frontline safety systems during power operation has thus been revised in favour of maintenance during shutdown. The decision on the maintenance strategy is one of the actors that led to the adoption of a three-train architecture for the safety systems in the EPR2 as the unavailability of safety trains due to maintenance is no longer required to be considered for relevant transients. Maintenance operations on support systems remain more flexible due to design provisions and can be realized under various conditions without impacting their availability. The accessibility of parts of the Reactor Building during power operation aimed at reduction of outage duration and implemented in the EPR via the so called "two-room" concept proved to be a significant complexity factor in the construction process. Removing the "two-room" arrangements has simplified the layout of internal walls, radiation protection measures and the design of ventilation systems within the EPR2 RB.

Another change with a significant impact on the layout is the containment design. The double wall containment has been replaced by a single wall structure resistant to airplane crash, leading to the suppression of the RB annulus with a dedicated ventilation. This new containment consists of pre-stressed concrete with an inner metal liner for enhanced leak tightness. Furthermore, to improve the constructability and the confinement of radioactivity, the Nuclear Auxiliary Building, present on the EPR, has been eliminated for the EPR2. Its functions have been distributed between the Fuel Building and the Waste Treatment Building,

2 French Nuclear Safety Authority (ASN) Guide No. 22 on the design of pressurised water reactors (https://www.asn.fr/l-asn-reglemente/guides-de-l-asn/guide-de-l-asn-n-22-conception-des-reacteurs-a-eau-sous-pression)

3 WENRA report on the Reactor Harmonization Working Group RHWG - Safety of new NPP designs, March 2013 (https://www.wenra.eu/publications) WENRA Western European Nuclear Regulators Association

4 Nuclear rapid response force, (Force d'Action Rapide du Nucléaire, see https://www.edf.fr/en/the-edf-group/producing-a-climate-friendly-energy/nuclear-energy/accident-prevention)

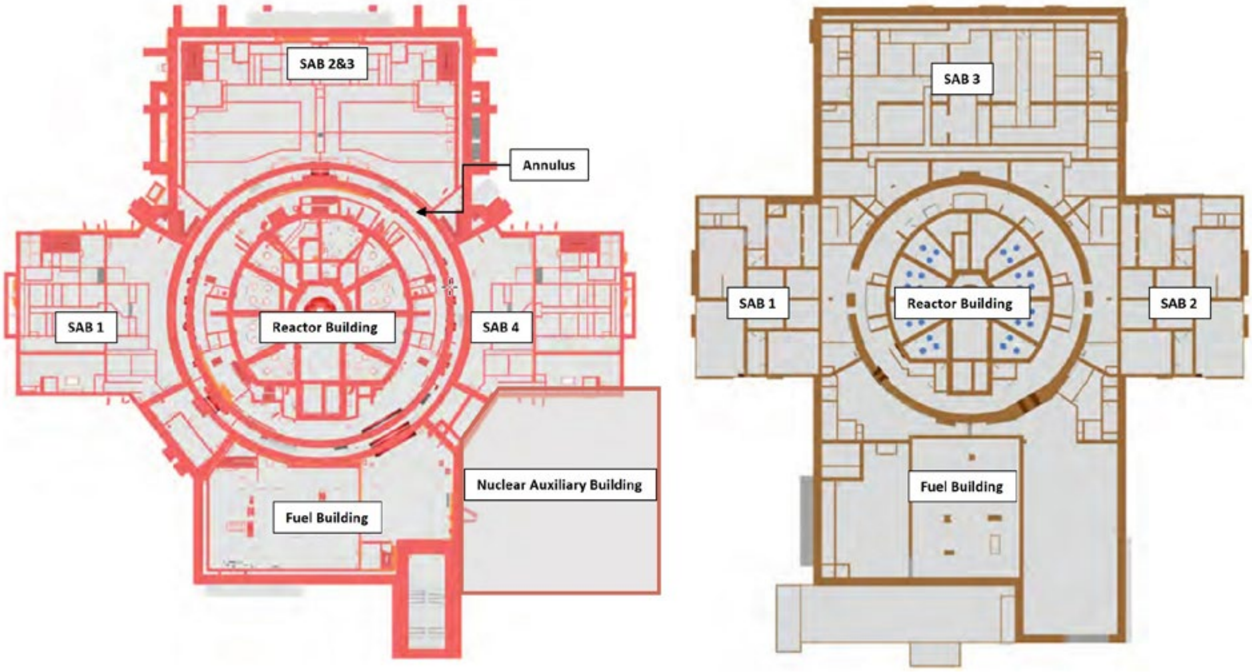

Fig. 1
Comparison of the main buildings layout between EPR (left) and EPR2 (right)[5]

with the latter being shared between two EPR2 units as the EPR2 is planned to be constructed as twin units. **Figure 1** provides a simplified comparison of the main buildings' layouts between the EPR and EPR2.

Main Features of the EPR2

Nuclear steam supply system

The reactor core and nuclear steam supply system of the EPR2 are comparable to previous EPR designs (see **Table 1**). The reactor coolant system (RCS) consists of four reactor coolant loops, with the same number of Steam Generators (SG) and Main Coolant Pumps (MCP). The concept of break preclusion is applicable to the main RCS lines (hot, crossover and cold legs), as well as to the main steam lines. The EPR2 will be able to operate with up to 30 % Mixed-Oxide (MOX), a fuel derived from the reprocessing and recycling of spent fuel. The electricity production can be adjusted for load follow operation, making it easily integrable in an electrical grid that already includes a substantial proportion from renewable energy sources (solar, wind, etc.).

Safeguard systems

In the EPR2, the main safety systems of DiD level 3a and their supports are designed with a three-train architecture. Since the RCS consists of four loops and four SGs, one of the safety system trains serving the RCS must be connected to two loops.

Performance	EPR2
Full thermal power	4590 MWth
Full net electric power	~1670 MWe (Penly site)
Efficiency (net)	~36% (Penly site)
Design lifetime	At least 60 years
Availability Factor	≥ 91 %
Core Design	
Fuel Type	235UO2 ≤ 5%, MOX ≤ 30%
Number of fuel assemblies	241
Number of Control Rod Cluster Control Assemblies	89
Fuel Cycle Length	18 months

Tab. 1
EPR2 performance data and core design

The Safety Injection System (SIS) and the Extra Borating System (EBS) are key systems with safety functions linked to physical parameters of the primary circuit.

The SIS integrates two key safety functions which are emergency coolant injection and decay heat removal from the core. The system consists of three physically separated and independent trains. Each train provides active injection capability by Medium Head Safety Injection (MHSI) and Low Head Safety Injection (LHSI) pumps which take suction from the In-containment

5 Dossier du maître d'ouvrage sur le site de Penly (Normandie) https://www.debatpublic.fr/sites/default/files/2022-10/PenlyEPR-DMO-EDF-RTE.pdf

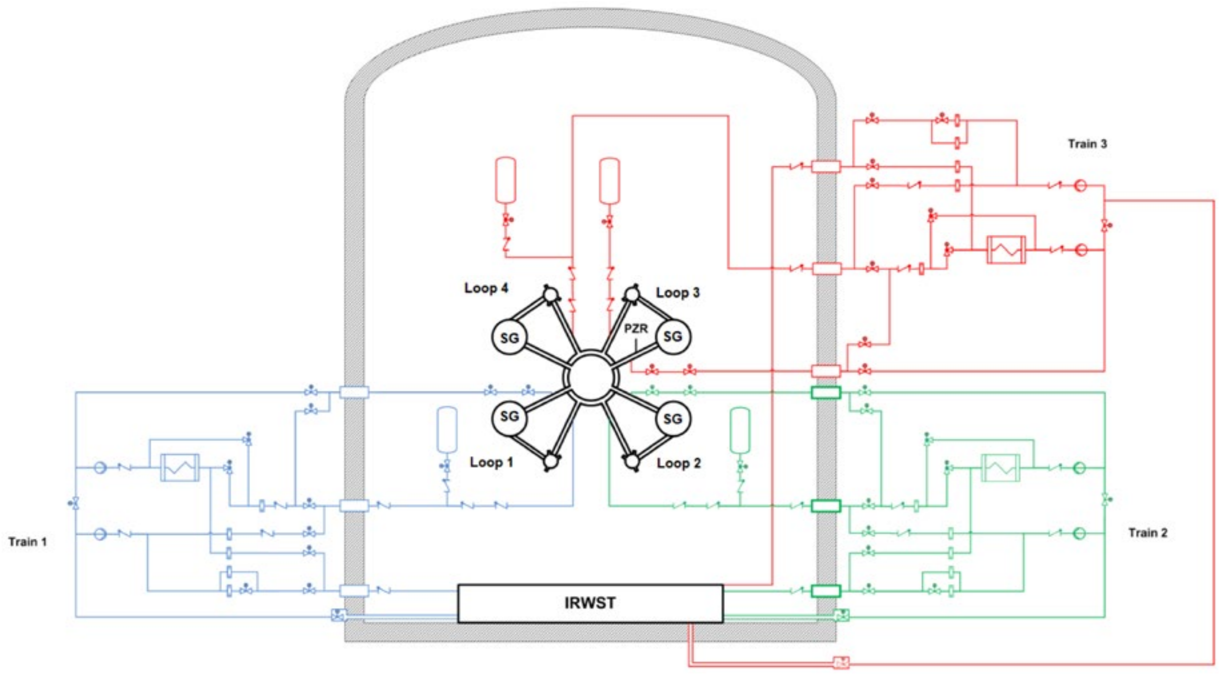

Fig. 2
Simplified scheme of the Safety Injection System (SIS)

Refuelling Water Storage Tank (IRWST). The IRWST serves as emergency water reserve and retention volume for primary coolant lost in case of a loss of coolant accident (LOCA). For passive and fast injection there are four pressurized tanks known as accumulators, each linked to the cold leg of the primary circuit via the SIS lines. Depending on the accident scenario, active water injection can be performed by the SIS either in the cold or hot legs. In some cases, a switch-over from cold to hot leg injection can be necessary to limit steam production and its release into the RB. Each SIS train is equipped with a heat exchanger used to evacuate decay heat from the core and the RB. This can be achieved either by cooling the IRWST or, if the water inventory allows, in residual heat removal mode taking suction from the RCS. Diversification between LHSI and MHSI ensures that the system's safety functions are maintained in case of CCF postulated on one these sub-systems. A simplified SIS diagram is provided in **Figure 2**.

The safety function of the EBS is to maintain the subcriticality of the core under accident conditions and to compensate for primary coolant contraction during accident operation. It is achieved by injecting soluble boron as a neutron absorber under high pressure into the RCS cold legs. The system consists of three separate and independent trains comprising a pump and a borated water storage tank. Each train is housed in one of the SABs. An overview of the EBS is given in **Figure 3**.

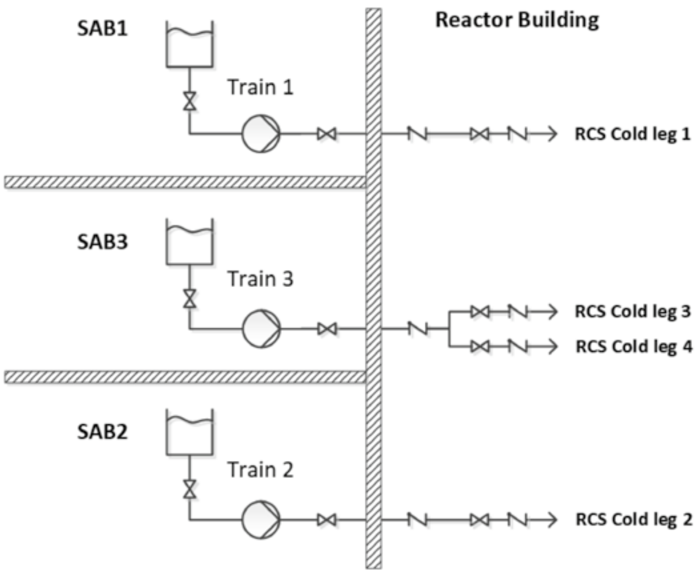

Fig. 3
Overview of the Extra Borating System (EBS)

On the secondary side, the heat removal is managed by the Emergency FeedWater System (EFWS) and the Main Steam Relief Train system (MSRT). Like other safety systems the EFWS has three independent trains responsible for supplying cooling water to the SGs. These trains have four motor driven pumps, two of them are allocated to train 3, and are interconnected by headers for pumps suction and discharge. Water reserves are distributed between two storage tanks. The presence of the headers increases the flexibility of the EFWS allowing any pump to be lined-up to any SG and to take suction from any storage tank. To extend the autonomy of the EFWS in certain events, particularly those resulting from extreme external hazards, the storage tanks can be replenished by the Emergency Water Make-up System (EWMS). The MSRT contributes to heat removal dumping the steam produced in the SGs into the atmosphere. It includes four identical relief trains each composed of two lines with low and high discharge capacities, both connected to the SG main steam line. The two relief lines can be operated independently. The trains are arranged in physically separated compartments of SAB1 and SAB2. A simplified diagram of one MSRT is presented in **Figure 4**.

In the unlikely event of a core melt accident resulting in reactor pressure vessel rupture, the corium is recovered, spread, cooled, and stabilized by the Core Melt and Stabilization System (CMSS). This system is designed to protect the containment foundation raft from melt-though. The cooling water required for heat removal from the melt and for its long-term stabilization is supplied from the IRWST by gravity-driven overflow through two separated lines. The flooding valves in these lines open passively, triggered by the arriving core melt. Upon contact with the corium, water vaporizes, and the corium is cooled. The residual power from the corium is thus removed into the containment by evaporation. The containment depressurization and the decay heat removal are performed by the Containment Heat Removal System (CHRS) which is part of DiD level 4. These safety functions are achieved by containment spraying and subsequent cooling of the IRWST water. The CHRS has two trains, each consisting of a pump, a heat exchanger, an IRWST suction line and a spray ring in the upper part of the RB. Both trains are installed separately in the dedicated area of the SAB3.

Cooling chain

The proper operation of safety systems relies on several cooling chains, a group of systems responsible for transferring heat from the installation to the heat sink. For the NI heat loads, the cooling chains can be categorized into three groups: main, diversified, and ultimate.

- The main cooling chain consists of the Component Cooling Water System (CCWS) and Essential Service Water System (ESWS), the latter being connected to the main heat sink such as the sea or a river. The CCWS is composed of two trains located in SAB1 and SAB2, each equipped with two pumps and two heat exchangers connected to a dedicated ESWS train that provides cooling water.
- The architecture of the diversified cooling chain comprises a single CCWS/ECWS train. However, the dedicated ESWS train is connected to an independent diversified heat sink, which is a wet forced-draft cooling tower. This cooling chain serves only the safety loads located in SAB3 and is physically separated from the main cooling chain. Due to its diversification, this cooling chain remains available in case of CCFs leading to the loss of the main one.
- The ultimate cooling chain is dedicated to DiD level 4 and consists of an intermediate cooling system connected to the CHRS cooled by the Ultimate Cooling Water System. This system also uses the diversified heat sink, although only the passive structures of the cooling tower are shared.

Fuel storage

To handle and store new and spent fuel, the EPR2 has several pools – same as EPR. The pools in the Fuel Building (FB) consist of a spent fuel pool (SFP), a cask loading pit and a transfer pit, the latter being connected via a transfer tube to the pools in the Reactor Building.

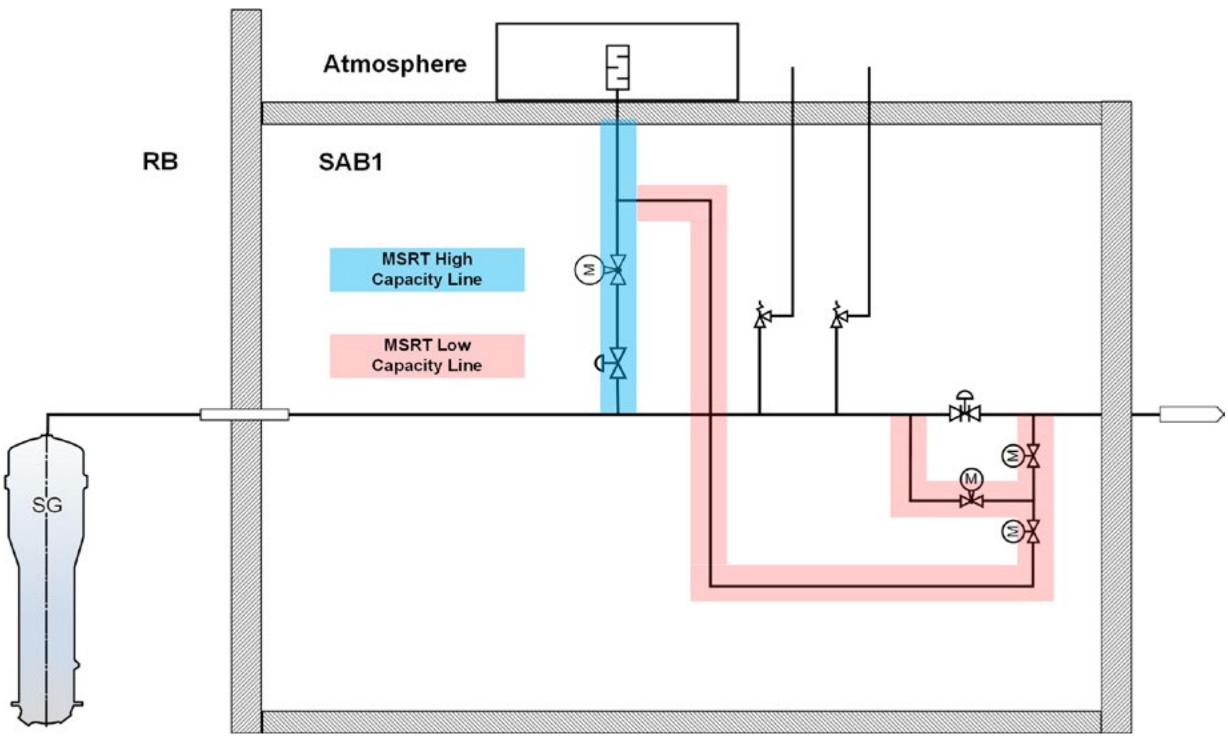

Fig. 4
Simplified diagram of one Main Steam Relief Train

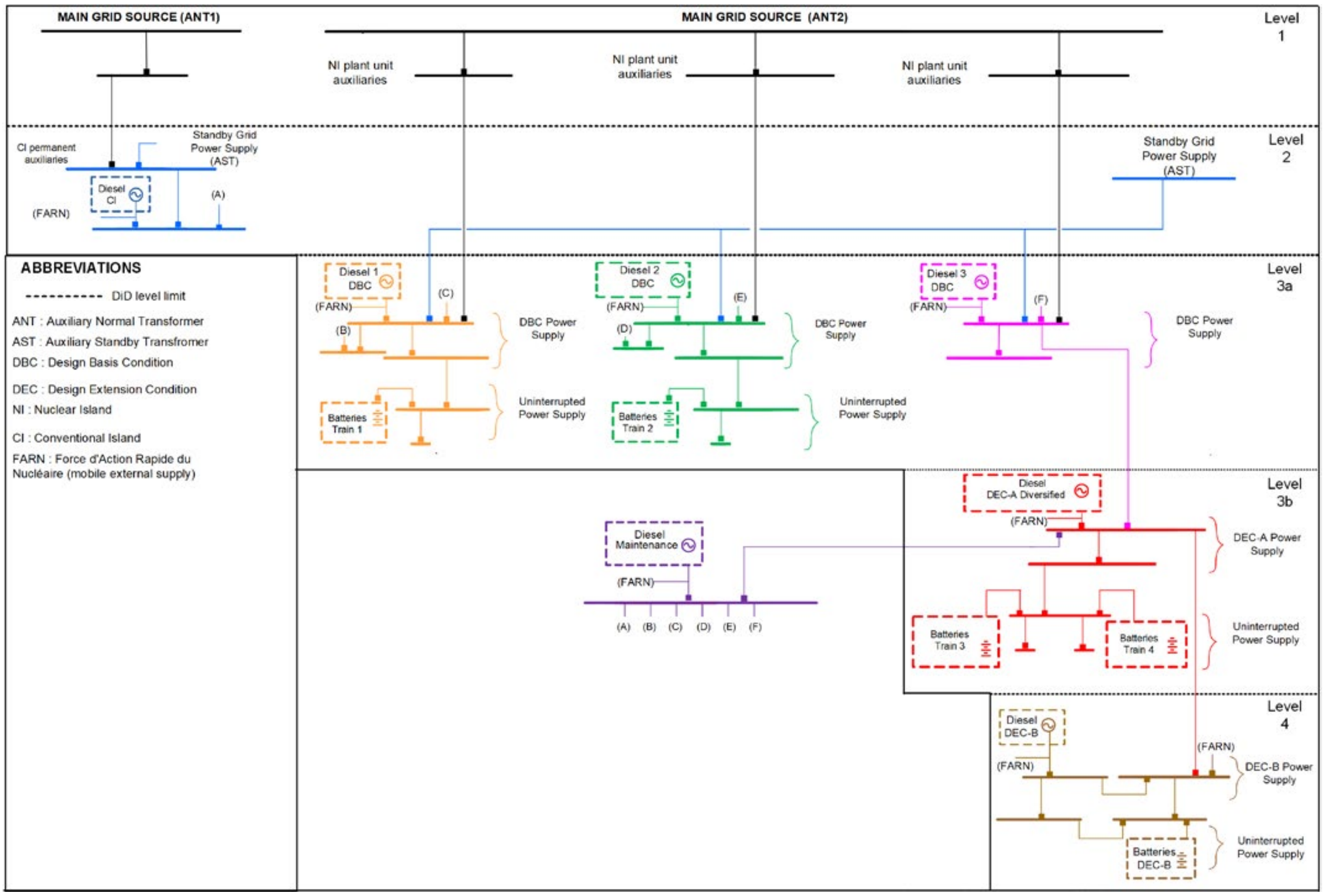

Fig. 5
Simplified architecture of electrical distribution

This connection is used to transfer fuel assemblies between the two buildings during core loading and unloading operations. The Fuel Pools Cooling and Purification System (FPCPS) is responsible for cooling the SFP and purifying the water in the pools of the FB and RB. The safety classified cooling part includes three cooling trains: two main trains as part of DiD level 3a and a third diversified train which is used for both levels 3a and 3b as a back-up in case the main trains become unavailable. Each main train is equipped with two pumps and a heat exchanger cooled by the main cooling chain. These trains are located physically separated inside the FB. The diversified train, also equipped with two pumps and a heat exchanger, is housed inside SAB3. To guarantee its independent operation and provide SFP cooling in case of extreme events, the third train is supplied by the diversified cooling chain. In the unlikely event of a complete loss of the FPCPS, the EWMS can provide make-up water to the SFP to compensate for evaporated water during boiling. These design provisions practically eliminate the risk of fuel melt in the SFP.

Electrical power systems

DiD principles are applied in the design of distribution networks and power supply sources. The electrical distribution of the nuclear island is composed of three redundant trains. Each safety train of DiD level 3a is powered by a dedicated emergency diesel generator (EDG) set. For maintenance purposes, a maintenance EDG is provided which can be coupled to the busbars of any train. DiD levels 3b and 4 have their own power source and distribution networks. The networks are connected to the third electrical train and can be supplied by it without compromising their independence. For DiD level 3b, a diversified power source using a multi-group diesel design, consisting of small, synchronized generator sets, has been selected. This architecture allows to supply safety systems housed in SAB3 in case of a CCF of the EDGs. The “diesel d'ultime secours” (DUS), a design solution initiated by EDF at the request of ASN following the Fukushima Daiichi accident to retrofit French NPP in operation[6], will be reused as a power source for DiD level 4. Each emergency power source, along with its support systems, is housed in a separate diesel building. A simplified single line diagram is provided in **Figure 5**.

6 https://www.edf.fr/sites/default/files/contrib/groupe-edf/producteur-industriel/carte-des-implantations/centrale-blayais/actualites/ndeg167_lumieres-juillet_2019.pdf

Fig. 6
Computer illustration of the first EPR2 twin units at the Penly site on the left and the existing 1300 MWe units on the right[7]

Outlook

As part of the French nuclear program to build three pairs of EPR2 reactors, sites with existing NPPs at Penly, Gravelines and Bugey have been selected. The first pair of EPR2 reactors will be constructed at Penly. Public debates about EPR2 construction at this site were performed between October 2022 and February 2023. In June 2023, following the analysis of recommendations issued by the French National Commission for Public Debate, the administrative council of EDF approved the decision to submit the construction license application (DAC) to the ASN for the first two units at the Penly site.

The environmental permit authorizing first preparatory work at the Penly site was granted with publication of the corresponding decree in June 2024. This decree allows to start the earthworks and the preparation of temporary infrastructure on the construction site. These activities are expected to last around three and a half years. The construction license permit is expected to be granted by the end of 2026. The commissioning of the first unit is anticipated around 2035 with the second one following in 2037. A digital illustration in **Figure 6** provides an overview of the future site once completed. Preparation activities for the two other sites will start soon.

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7 EDF, Dossier du maître d'ouvrage - Projet d'une première paire de réacteurs EPR2 sur le site de Penly (Normandie), dans le cadre de la proposition d'EDF pour un programme de nouveaux réacteurs nucléaires en France, https://www.debatpublic.fr/sites/default/files/2022-10/PenlyEPR-DMO-EDF-RTE.pdf (Image copyright : Penly ©Didier Marc (PWP) & Kardham Architecture)