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Layout Design of Nuclear Island for HPR1000

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Abstract. HPR1000 is an advanced million-kilowatt pressurized water reactor developed in response to the lessons learned from the Fukushima accident. It adheres to the strictest safety standards in the world and boasts completely independent intellectual property rights. As critical structure of nuclear power plant, the nuclear island's primary function is to house reactor systems and equipment, support auxiliary systems, and ensure the safe operation of the facility. The layout design of the nuclear island is essential for nuclear technology research, development, and engineering design. It plays a significant role in fulfilling functional requirements, facilitating engineering construction, and optimizing plant operation and maintenance.The innovative layout design of the HPR1000 is based on comprehensive research encompassing system functions, equipment arrangement, heating and ventilation, traffic organization, fire and radiation protection, hazard analysis, installation and maintenance. This design meets the entire lifecycle requirements of construction, commissioning, operation, and decommissioning, with overarching goals of safety, reliability, economic feasibility, and ease of operation and maintenance.

Keywords: HPR1000, Layout design, Nuclear island.

1. Introduction

The HRP1000 is developed based on 30 years of experience in nuclear power research, design, manufacturing, construction and operation with the world's advanced nuclear power concept and feedback from previous nuclear accidents., which represents third generation nuclear power technology in China, featuring a design life of 60 years and a refueling cycle of 18 months. This reactor incorporates 177 fuel assemblies and is equipped with three trains of safety systems. By integrating both active and passive safety technologies, along with a double containment structure, HPR1000 aligns with the latest international standards and user requirement, such as EUR and URD[1].

Layout design of nuclear island is a pivotal aspect of nuclear power plant design. The HRP1000's nuclear island features a single reactor configuration, resulting in compact, rationally structured, and robustly disaster-resistant. Through strategies for optimizing the building structure, the nuclear island can withstand 0.3g seismic. Additional safety measures within the reactor building include internal refueling water storage tank (IRWST) and passive high level water injection tank are set in reactor building, which combined with both active and passive technologies, significantly enhance the safety during the severe accident. The three trains of safety systems are physically separated in safeguard buildings, greatly reducing the impact of internal and external hazards on nuclear safety[2]. Furthermore, the adoption of double containment and an exterior reinforcement wall meets the requirements of withstanding malicious impacts from commercial aircraft.

2. Principles for HPR1000 Layout Design

In pursuit of the HRP1000's design objectives, the following principles have been set for the configuration of layout design:

(1) Compliance with Safety Standards: The design must follow the latest national nuclear safety regulations and international standards and requirements, including the EUR and URD for third generation nuclear power plants[3-4].

(2) Safety, Economy, and Adaptability: The layout design should accommodate the demands of both active and passive systems, withstand internal and external hazards, and meet 0.3g seismic

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resistance requirement, minimize the interactions between a failure of structure, system and components, thereby adopting the safety, economic and adaptability to various sites.

(3) Compact and Functional Layout: The general arrangement of the nuclear island should be as regular and compact as feasible, ensuring smooth operation and functional zoning with smooth interfaces between each structure. The layout should ensure that the radiation dose to workers carrying out operational maintenance, inspection and test activities are ALARP.

(4) Utilization of Established Designs and Technologies: The design should leverage well established nuclear island layout schemes from both domestic and international projects, employing mature and verified technologies, and minimizing the introduction of new equipment qualification.

(5) Life cycle Considerations: The design should take into account the needs throughout the procurement, construction, commissioning, operation, maintenance, and decommissioning phases, as well as the influence of modular and advanced construction technologies used for construction requirement[5-6].

(6) Digitization and Advanced Design Methods: The design should fully embrace digital requirements and implement BIM technology throughout all stages of layout design[7]. A collaborative design platform is leveraged and design data can be used for procurement, installation, O&M, and decommissioning.

3. Layout Design of Nuclear Island

3.1 Innovative Nuclear Island

The layout design of HPR1000 encompasses the planning of the process system, site planning, equipment introduction, fuel transportation routes, fire protection, radiation protection, and other aspects. HPR1000 nuclear island layout design adopted 0.3g ground acceleration, which is single reactor design to reduce interaction between units. Double containment has been adopted for reactor building to supply the barrier for controlling radioactive materials and protecting external disasters. Three safeguard buildings are corresponding to three train safety systems, which are physical separated to avoid interaction of different safety train during accident condition. Nuclear island model of HPR1000 is show in Figure 1.

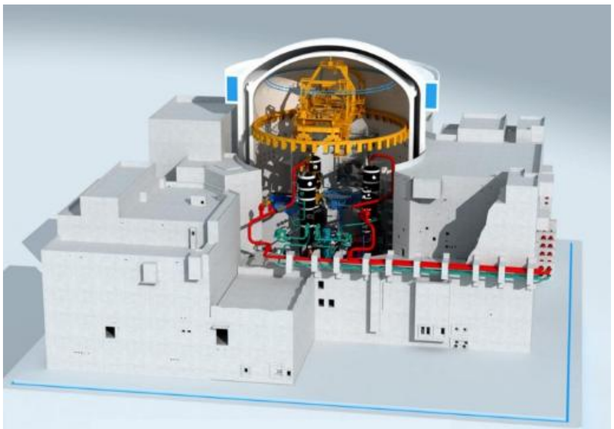

Fig.1 Nuclear island model of HPR1000

The nuclear island of HPR1000 consists of the reactor building, fuel building, safeguard building, nuclear auxiliary building, and access building, as depicted in Figure 2. The reactor building, safety building, and fuel building share a common raft foundation, increasing the overall stability of the nuclear island buildings. To protect safety systems and facilities, the outer containment of the reactor building, the exterior wall of the fuel building, and the safeguard building where the main control room is located are designed with 1.5 meters thick to withstand commercial aircraft impacts, as shown in Figure 3.

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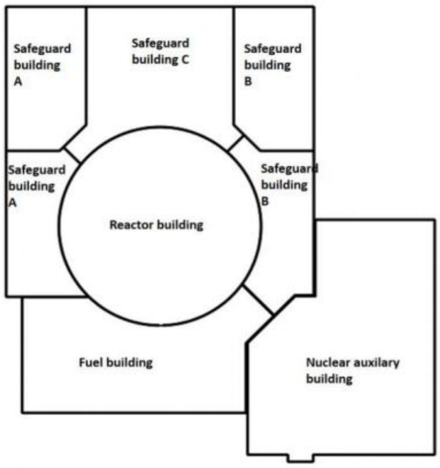

Fig.2 The plan view of nuclear island

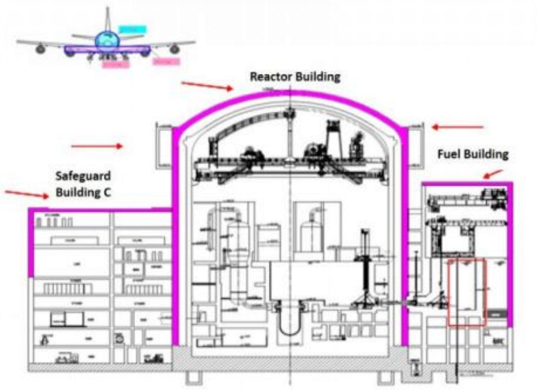

Fig.3 The anti-aircraft boundary of nuclear island

3.2 Reactor Building

The reactor building is situated at the center of the nuclear island and mainly houses the nuclear steam supply system and related equipment. It is designed to restrict the release of radioactive substances from the reactor core and the reactor coolant system to the surrounding environment under normal and accident conditions. The reactor building features a double containment structure. The outer containment is constructed of reinforced concrete with 1.5meter thick, offering protection against external hazards like aircraft impact and explosion. The inner containment consists of prestressed reinforced concrete with a steel liner on the inner side with 1.2 meters thick, which prevents the leakage of radioactive substances. This double containment design supports the high level passive water tank, and the space between the double containment effectively reduces the leakage of radioactive substances through negative pressure[8]. The operation hall of the reactor building is coordinated with the positon of the equipment hatch, and the floor of operational hall is reserved for sufficient space for tool storage and personnel operation during subsequent maintenance.

To meet the seismic design target of 0.3g, the reactor is located at a lower elevation. The relative height difference between the reactor pressure vessel and the civil raft is minimized as much as possible, which can better improve the seismic performance. The equipment such as the safety injection tank is also located at a lower elevation. Based on the design concept of combining active and passive safety systems, the reactor building is equipped with a low level inner refueling water storage tank (IRWST) and a high level reactor pit water injection tank.The IRWST has a double

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ring pool structure and is positioned at the lowest level. This design allows passive water injection into the reactor cavity, and the active system can also pump water from the IRWST back into the containment, thus alleviating the impact of severe accidents. Such measures can effectively address incidents similar to the Fukushima accident and enhance the overall safety of the power station.The sectional view of reactor building is illustrated in Figure 4.

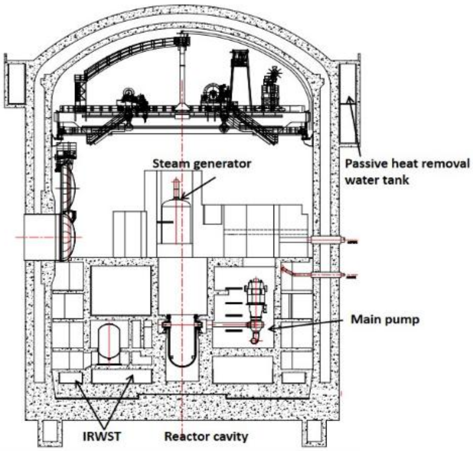

Fig.4 The sectional view of reactor building

3.3 Fuel Building

The fuel building is purposefully engineered to accommodate the fuel handling facilities as well as the spent fuel pool. It establishes a connection with the reactor building by means of a fuel transfer tube. The layout of spent fuel pools, loading well, preparation well and hoisting hole in fuel building facilitates the lifting operation of new fuel and spent fuel. The layout of spent fuel pool can store spent fuel for about 14 refueling cycles[9]. After that, in accordance with the "Regulations for the Safe Transport of Radioactive Materials" (GB11806 - 2019), radioactive packaged items are obligated to endure an impact test resulting from a free fall height of 9 meters. Nevertheless, a typical drop height of around 20 meters substantially amplifies the risks associated with container damage and the potential for radioactive leakage. The HRP1000 fuel building adopts a distributed hoisting approach, which effectively confines the fall height of the spent fuel container to within 9 meters during the hoisting process. This innovative measure eradicates the risk of damage caused by container drops and obviates the necessity for specialized container qualification tests. Moreover, the exterior wall of the fuel building is fortified to resist impacts from commercial aircraft. The spent fuel pool is deliberately situated at a distance from the exterior wall, thereby minimizing the direct impact force that an aircraft could exert on the pool. The sectional view of fuel building is illustrated in Figure 5.

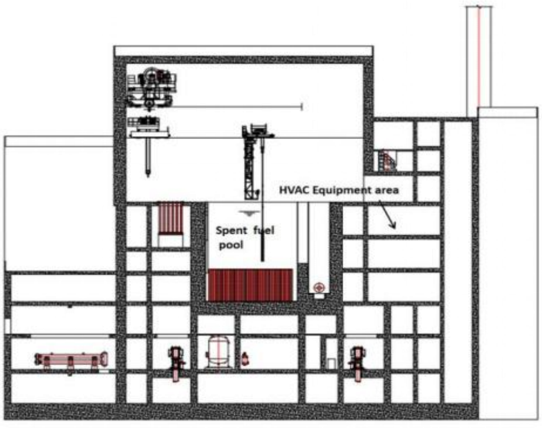

Fig.5 The sectional view of fuel building

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3.4 Safeguard Building

The HRP1000 is equipped with three safeguard buildings, namely BSA, BSB, and BSC, which are meticulously designed to augment the independence of safety facilities by accommodating three train safety systems. Safety Building C houses the main control room, and its exterior wall is designed to endure impacts from commercial aircraft. The main control room is designed with 7.6m high, and is designed with a special visiting passage and visiting room to avoid the impact of similar activities on the work of the operator. The roof lighting of the main control room is designed with blue sky and white clouds, which can effectively relieve the pressure of operators and better reflect the design concept of human factors.The main control room, in conjunction with the adjacent technical support center, is configured as a habitable zone. This design entails minimizing the number of openings and doorways, thereby curtailing the risk of leakage and safeguarding the integrity of the pressure boundary. Meanwhile, Safeguard Buildings A and B are spatially segregated to guarantee that, in the event of an aircraft impact incident, Safety Building C and at least other one safeguard building can remain functional. The plan view of safeguard building is illustrated in Figure 6.

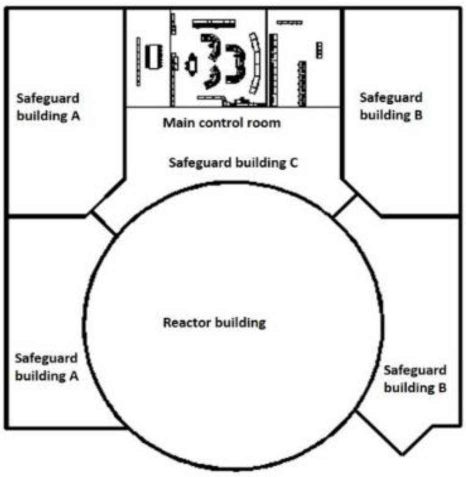

Fig.6 The plan view of safeguard building

3.5 Nuclear Auxiliary Building

The nuclear auxiliary building chiefly houses auxiliary system facilities that do not have safety functions. Functioning as a central collection and transfer hub for gaseous, liquid, and solid waste generated within the nuclear island, this building is partitioned into two distinct zones, namely the controlled area and the non-controlled area, as depicted in Figure 7. On the left-hand side is the controlled area, while the right-hand side corresponds to the non-controlled area.

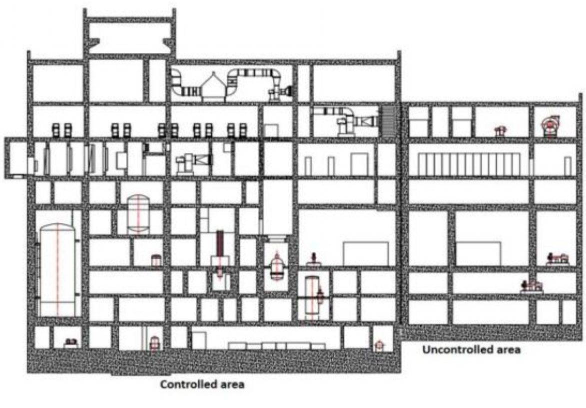

Fig.7 The sectional view of nuclear auxiliary building

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The controlled area predominantly encompasses the waste liquid treatment system, the waste gas treatment system, the solid waste treatment system, as well as the ventilation systems. In contrast, the non-controlled area mainly accommodates the operational chilled water system, non-safety electrical and instrumentation equipment, and ventilation components. It should be noted that the building layout and the distribution of systems therein are meticulously designed to ensure efficient waste management and proper functioning of auxiliary operations while maintaining the requisite safety and segregation standards. This segregation not only streamlines waste processing but also safeguards against potential cross-contamination and operational disruptions. Overall, the nuclear auxiliary building plays a pivotal yet often overlooked role in the seamless operation of the nuclear facility.

4. Comparison With Other Types of Reactor

The layout of the nuclear buildings should mainly meet the requirements of the safety function and system functions, while also considering the construction and subsequent operation, in-service inspection and decommissioning. Normally, many of the objectives in layout of nuclear buildings are common to other engineering projects, but some key factors have a significant impact on the overall layout of the nuclear island building. The key factors that need to be given priority consideration in the design process include but are not limited to the following:

(1) The layout of the primary loop, reactor pit, reactor pool, and IRWST pool;
(2) The layout of containment, such as shape and size;
(3) The matching of the fuel building layout with fuel handling operation process;
(4) The main equipment erection and operation platforms;
(5) The layout of the main steam and main feed water pipelines;
(6) The layout of the main control room and habitable area;
(7) The consideration of advanced construction technology.

For the layout of nuclear buildings for HPR1000, the above key factors were fully discussed and determined in the conceptual design stage. The following is a comparison of some layout factors with other types of reactors. It can be found that different reactor types have their own nuclear building layout schemes mainly due to the differences in the key factors.

Table 1: Some key factors for HPR1000 and other types of reactors

Factors	AP1000	VVER	APR1400	HPR1000
Primary loop	Two loops	Four loops	Two loops	Three loops
Spent fuel storage	Auxiliary building	Reactor building	Fuel building	Fuel building
Safety system located	Auxiliary building	Safeguard buildings(Four trains)	Auxiliary building(Four trains)	Three separated safeguard buildings
Main control room	Auxiliary building	Control building	Auxiliary building	Safeguard building C
Containment	Double containment	Double containment	Single containment	Double containment
Inside containment diameter	39.62m	44m	45.72m	45m

5. Conclusion

The layout design of the nuclear island buildings is based on fulfilling the technical functions of the systems and the overall system configuration. The layout design of the nuclear buildings for the HRP1000 not only meets the functional requirements but also incorporates numerous innovations

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and addresses a series of technical challenges. These include the sunken arrangement of the reactor, the installation of IRWST, a high-level water tank for reactor cavity injection, the implementation of three train safety systems, the resolution of the drop issue of spent fuel container, the design to effectively withstand commercial aircraft impact, and the use of Leak Before Break (LBB) for high-energy piping, among others. Following the commercial operation of first HRP1000 project, the experience are gained from the initial projects and further optimizations are implemented to enhance the competitiveness of the HRP1000 at home and abroad.

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