

HPR1000: ADVANCED PWR WITH ACTIVE AND PASSIVE SAFETY FEATURES

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Abstract

HPR1000 is an advanced pressurized reactor with the significant feature of active and passive safety design philosophy. On one hand, it is an evolutionary design based on proven technology of existing pressurized water reactor nuclear power plant, on the other hand, it incorporates advanced design features including 177-fuel-assembly core loaded with CF3 fuel assemblies, active and passive safety systems, comprehensive severe accident prevention and mitigation measures, enhanced protection against external events and improved emergency response capability. Extensive verification experiments and tests have been performed for the critical innovative improvements such as passive systems, reactor core and main equipment. Active and passive safety design is the most remarkable innovation for HPR1000 and also a typical instance to fulfill the diversity criteria. The design inherits the mature and reliable active technology, and also introduces passive system as the backup for active system in case of loss of AC power. Both active and passive features are employed to guarantee the safety functions of emergency core cooling, residual heat removal, In-vessel Retention (IVR) of molten core, and containment heat removal. The innovative design safety features, e.g. passive systems, in-vessel melt retention, will be illustrated in the paper.

1. INTRODUCTION

The use of nuclear energy for electricity generation began in the late 1950s and went through several phases. The designs of nuclear power plants (NPPs) are also categorized by “generation” accordingly. After prototype reactors of Generation I and commercial reactors of Generation II, Generation III Light Water Reactor (LWR) NPPs incorporated state-of-the-art improvements in the areas of fuel technology, thermal efficiency and safety systems [1, 2].

The safety systems design of pressurized water reactor (PWR) NPPs has also experienced three phases of development: First phase which uses rather original and simple safety system, developing to the second phase which takes more complicated active safety system focusing on dealing with the design base accidents (DBA). Before Fukushima Daiichi NPP accident, for the third generation, there are mainly two different design concepts representing two trends of safety system design, one is passive safety design concept with simplified safety systems, and the other is active safety design concept with more redundancy, safety system is more and more complicated.

The Fukushima Daiichi NPP accident draw the worldwide attentions towards the safety of NPPs. International Atomic Energy Agency (IAEA), governments or nuclear safety authorities respectively issued special reports on the lessons learned from Fukushima accident, which focused on the area such as protection against external events, robustness of emergency power and ultimate heat sink, safety of spent fuel pool, emergency response for multiple-unit accident, and inhabitability and availability of emergency facilities[3]. The safety inspections or stress tests, and necessary improvements were made for the current NPPs based on the Fukushima feedbacks. Meanwhile the safety requirements for new NPPs were also considered and discussed, which are reflected in documents like Safety of New NPP Designs drafted by Western European Nuclear Regulator’s Association (WENRA), Safety of Nuclear Plants: Design (No. SSR-2/1, Rev.1) issued by IAEA, and Safety Requirements for New NPPs during 12th Five-Year Plan drafted by China National Nuclear Safety

Administration (NNSA). The improved safety requirements for new NPPs in the above documents generally covered the following aspects: revised and strengthened defence-in-depth approach, response capability for Beyond-Design-Basis Accident (BDBA) including multiple failures, practical elimination of large radioactivity release to mitigate off-site emergency, and protection against internal and external hazards. In addition, the concepts like residual risk and plant autonomy period were also brought into the horizon of international nuclear power industry.

In the background that the technology of advanced NPPs has been mainstreamed and nuclear safety standard for new NPPs in post-Fukushima era will be stricter, China National Nuclear Corporation (CNNC) developed the evolutionary advanced Pressurized Water Reactor (PWR) HPR1000. The design makes full use of the proven technology based on the design, construction and operation experience of large PWR fleet in China, and introduces a number of advanced design features to meet the latest safety requirements and address the feedback from Fukushima accident.

2. HPR1000 SAFETY DESIGN PHILOSOPHY

The fundamental safety functions to be ensured for the nuclear power reactors are: 1) control of the reactivity, 2) removal of heat from the core and the spent fuel, and 3) confinement of radioactive materials and control of operational discharges, as well as limitation of accidental releases. For HPR1000, in order to achieve the safety functions, the concept of defense-in-depth is performed throughout all the safety-related activities to ensure that they are subject to over-lapping provisions. Structure, systems and components important to safety shall be capable of withstanding identified initiating events with sufficient robustness, which are ensured by the design criteria such as redundancy, diversity and independence.

Generally, from the probabilistic point of view, the lower reliability of a single train, the greater contribution will be made by increasing in redundancy for system reliability improvement. Conversely, if the reliability of a single train is high enough, the increase in redundancy only has a limited contribution to system reliability improvement. For example, see Table 1, if the reliability of a single train is 0.9, adding a train can increase the system reliability by 10%, and adding the second train can only increase the system reliability by 1%. Furthermore, the contribution of redundancy to system reliability improvement will be smaller if taking common cause failure into account.

TABLE 1. RELIABILITY (WITHOUT COMMON CAUSE FAILURE)

Redundancy (Number of Trains)	1	2	3
Reliability	0.9	0.99 (+10%)	0.999 (+1%)
	0.1	0.19 (+90%)	0.271 (+43%)

As addressed in IAEA SSR-2/1 “for the purpose of further improving the safety of the nuclear power plant by enhancing the plant’s capabilities to withstand, without unacceptable radiological consequences, accidents that are either more severe than design basis accidents or that involve additional failures.” Whether it is from the deterministic and probabilistic point of view or referring to the practical operating experience, the widely adopted design of safety system with two active trains is sufficient to meet the latest safety requirements, including the single failure criterion. Therefore, to add redundancy on DBA level for NPP design, which not only has limited improvement for NPP safety, but also wastes precious resources, as the well-known Buckets effect.

During the preliminary design phase of HPR1000, the safety optimization or improvement decisions are made based on the identification of risk-informed methodology. For example, for the engineered safety system designated for DBA with 2 active trains, the improvement mainly focused on the vulnerabilities, not simply increase the redundancy. To effectively increase the capability of withstanding design extension conditions and improve integral safety, the passive safety systems are introduced. Both active and passive features can guarantee the safety functions of emergency core cooling, residual heat removal, In-vessel Retention (IVR) of molten core, and containment heat removal, as shown in Fig. 1.

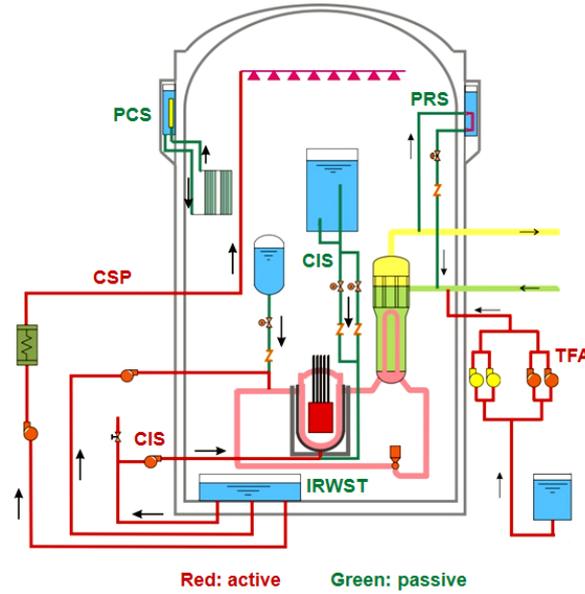


FIG. 1. Active and passive safety system configuration of HPR1000.

The Probabilistic Risk Assessment (PRA) result shows that this configuration has significant effect for the safety improvement, as shown in Table 2.

TABLE 2. PRA RESULT OF HPR1000 SAFETY SYSTEM CONFIGURATION

Configuration of safety system	CDF/ reactor-year	Δ CDF compared to HPR1000	The rate of change in CDF compared to HPR1000
2 Active Trains	6.11E-07	+4.81E-07	+370.00%
3 Active Trains	3.32E-07	+2.02E-07	+155.38%
2 Active Trains and 1 Passive Train (HPR1000, baseline configuration)	1.30E-07	-	-
3 Active Trains and 1 Passive Train	1.11E-07	-1.90E-08	-14.62%

3. HPR1000 SAFETY FEATURES

The general parameters of HPR1000 are presented in Table 3. The major safety features of HPR1000 are briefly introduced from the aspects of engineered safety features, severe accident prevention and mitigation measures.

TABLE 3. GENERAL PARAMETERS OF HPR1000

Parameter	Values
Reactor thermal output	3050 MWt
Power plant output, gross	~1170 MWe
Power plant output, net	~1090 MWe
Power plant efficiency, net	~36%
Mode of operation	Baseload and Load follow
Plant design life	60 Years
Plant availability target	$\geq 90\%$
Refueling cycle	18 Months
Safety Shutdown Earthquake (SSE)	0.3 g
Core damage frequency (CDF)	$< 10E-6$ /Reactor-Year

Large release frequency (LRF)	< 10E-7 /Reactor-Year
Occupational radiation exposure	<0.6 Person-Sv/ Reactor-Year
Operator Non-intervention Period	0.5 Hour
Plant Autonomy Period	72 Hours

3.1. Engineered safety features

The engineered safety features are adopted to mitigate DBA, which mainly include Safety Injection System, Auxiliary Feedwater System, and Containment Spray System, see Fig. 2. Engineering safety features are comprised of redundant trains to fulfil single failure criterion. The independence is ensured by means that each train is arranged in physically separated building and supplied power by each of the emergency diesel generators.

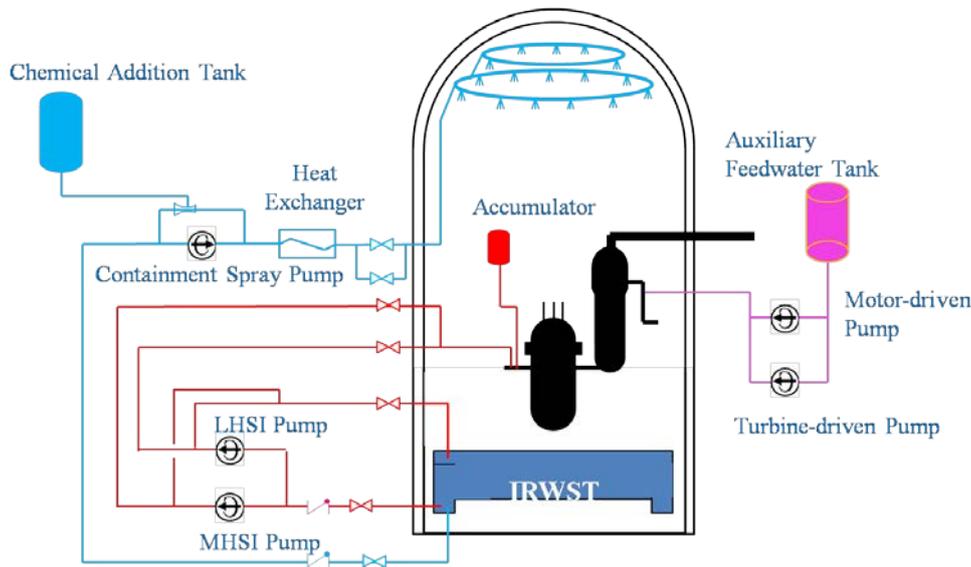


FIG. 2. Engineered safety features of HPR1000.

Safety Injection System consists of two active subsystems, i.e. Middle Head Safety Injection (MHSI) subsystem and Low Head Safety Injection (LHSI) subsystem, and one passive system, i.e. accumulator injection system. The In-Containment Refueling Water Storage Tank (IRWST) is adopted, with the benefits of providing protection against external events and saving the need for switching the water sources during long-term injection in comparison with the refueling water tank outside the containment. The MHSI and LHSI pumps take suction from the IRWST after Loss-of-Coolant Accident (LOCA), and inject the boron water to RCS to provide emergency core cooling to prevent core damage. With regard to the improved configurations compared to the existing NPPs, the safety injection pumps are not shared with other system to improve the equipment reliability and independence, the injection head is lowered to reduce the possibility of SGTR, and the boron injection tank and boron recirculation loop are cancelled to achieve systems simplification.

Auxiliary Feedwater System supplies emergency feedwater to the secondary side of SG to remove the core decay heat in case of loss of normal feedwater. The feedwater is provided from two auxiliary feedwater pools with 2×50% motor-driven pumps which are backed up by emergency diesel generator and 2×50% turbine-driven pumps which are driven by steam produced by SGs. The diversity of the pumps improves the robustness of the system.

Containment Spray System is used to maintain the integrity of containment by limiting containment pressure and temperature within the design limits, by spraying and cooling the steam released in containment during LOCA or Main Steam Line Broken (MSLB) accidents. The spray water is taken from IRWST by spray pump, with chemical additive to reduce the airborne fission products (especially iodine) and limit the corrosion

of structure material. LHSI pump can be used as back up for containment spray pump to ensure the reliability of long-term spray.

3.2. Severe accident prevention and mitigation measures

Comprehensive prevention and mitigation measures have been incorporated in HPR1000 against all the possible severe accident scenarios, including high pressure molten corium ejection, hydrogen detonation, basement melt-through, and long-term containment overpressure. For the specific BDBA considered as the weak point for the existing NPP such as Station Black-out (SBO), appropriate measures are also taken into account in the design. See Fig. 3.

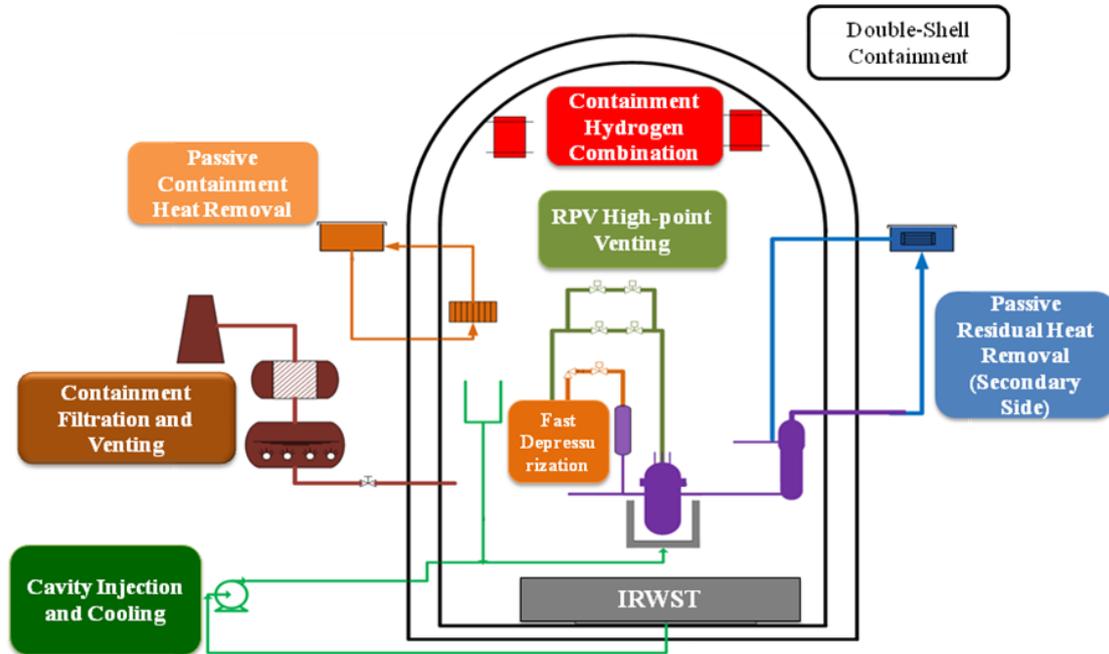


FIG. 3. BDBA/Severe accident prevention and mitigation measures of HPR1000.

Fast Depressurization System of Primary Loop is used to depressurize RCS rapidly during severe accident in order to prevent the high pressure molten corium ejection, which would cause direct containment heating. The system consists of two redundant parallel discharge lines connected to a nozzle on the pressurizer dome. Each line is installed with a gate valve and a globe valve in series.

RPV High-point Venting System is designed to remove non-condensable gases from RPV head during accident condition, so as to avoid adverse impact to the heat transfer of reactor core caused by the non-condensable gases.

Cavity Injection and Cooling System (CIS) is used to cool the external surface of lower dome of RPV by injecting water into the space between RPV surface and insulation layer, so as to maintain its integrity and realize IVR of melt core debris. CIS consists of an active subsystem and a passive subsystem. The active subsystem includes two parallel injection lines, each with a pump taking water from IRWST or firefighting water as backup. The passive subsystem is located in the containment with a high-point tank. In case of severe accident and the failure of active subsystem, the isolation valves can be opened and the water in the tank flowed by gravity to cool the lower dome of RPV.

Passive Residual Heat Removal System of Secondary Side (PRS) is put into action in the condition of SBO and the failure of the turbine-driven auxiliary feedwater pumps, to provide feedwater to the secondary side of SG in a passive way. PRS consists of three trains connected to three SGs, respectively. The nature circulation will be established in the closed loop between secondary side of SG and the heat exchanger submerged in the Heat Exchange Tank on the upper part of outer containment. The tank inventory can sustain the operation of PRS for 72 hours.

Containment Hydrogen Combination System is intended to decrease hydrogen concentration within the containment atmosphere to safe limits, to prevent hydrogen inflammation during DBA or hydrogen detonation during severe accident. The system is comprised of more than 30 passive autocatalytic recombiners installed inside the containment, which will be triggered automatically when the hydrogen concentration reaching the threshold.

Passive Containment Heat Removal System (PCS) is designed to remove the heat in the containment, to ensure that the containment pressure and temperature will not exceed the design limits during BDBA. The heat of high-temperature mixture of steam and gas inside the containment will be removed by water flowed in tubes of heat exchangers installed at high position on the internal surface of containment, to Heat Exchange Tank outside the containment. The temperature difference between the mixed gas within the containment and the water in Heat Exchange Tank, and the elevation difference between the tank and the heat exchanger are the driving force for natural circulation to remove the containment heat. The water in Heat Exchange Tank is heated and evaporated when the saturated temperature is reached, and heat finally dissipates to atmosphere. The tank inventory fulfils the requirement of 72-hour passive heat removal from containment after severe accident.

Containment Filtration and Venting System is an option to prevent the pressure of the containment from exceeding its bearing capability by initiative and planned venting. The filtration equipment in the venting line is used to reduce the discharge of radioactivity to atmosphere as much as possible.

3.3. Protection against the external events

The protection against the external events is dramatically enhanced. The containment is a double-wall structure, and the outer containment is made of reinforced concrete and withstands external events such as aircraft crashes, explosions and missiles. The nuclear island buildings are designed with a seismic input of peak ground acceleration of 0.3g for both horizontal and vertical directions. A seismic margin assessment is also performed to evaluate the plant's resistance to a beyond-design-basis earthquake. Protection against a large commercial aircraft crash is achieved by concrete shielding shells for the Reactor Building, Fuel Building and Electrical Building, and by complete physical separation for the Safeguard Buildings as shown in Fig. 4.

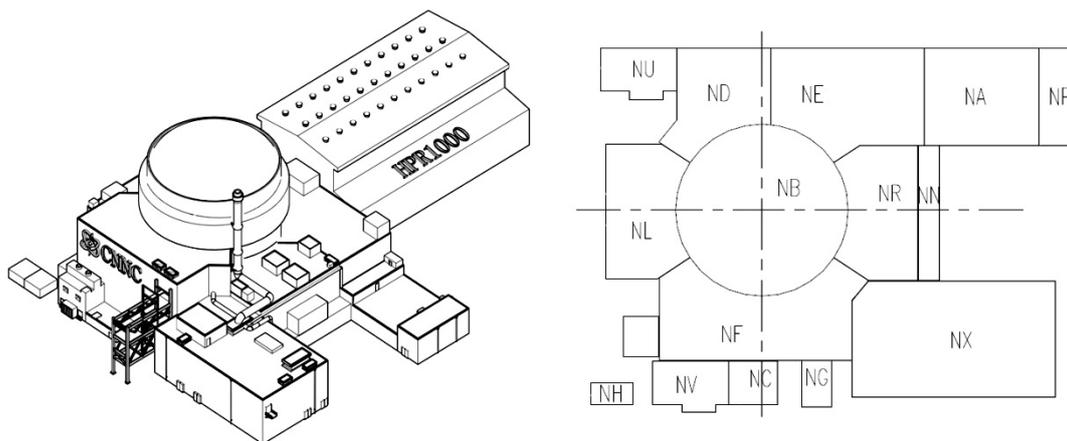


FIG. 4. General layout of nuclear island of HPR1000. (NB—Reactor Building; NF—Fuel Building; ND/NE—Electrical Building; NL/NR—Safeguard Building; NX—Nuclear Auxiliary Building).

4. CONCLUSION AND OPTIMIZATION FOR FURTHER DEVELOPMENT

In general, the active and passive safety design is the most remarkable innovation for HPR1000 and also a typical instance to fulfil the diversity criteria for Fukushima Daiichi NPP accident scenario. The design inherits the mature and reliable active technology, and also introduces passive system as the backup for active system in case of total loss of AC power and heat sink accident, to make sure integrity of last safety barrier to realize a large radioactive release can be “practically eliminated” in design.

Based on the R&D of HPR1000, further development of PWR technology is also considered by the designer following the latest trend of safety requirements and the marketing prospect. As a kind of product, the nuclear power development should not only focus on the safety, but also take into account the cost and constructability. The application of all the important plant design rules, including the single failure criterion, redundancy, diversity, etc. is actually a compromise between safety, reliability, economy and operability of guidelines on the basis of engineering judgement and combination of deterministic assessment and probabilistic assessment. It may be not entirely reasonable with extending each of criterions to everywhere, which could lead to imbalance in NPP design.

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