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The General Design and Technology Innovations of CAP1400

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ABSTRACT

The pressurized water reactor CAP1400 is one of the sixteen National Science and Technology Major Projects. Developed from China's nuclear R&D system and manufacturing capability, as well as AP1000 technology introduction and assimilation, CAP1400 is an advanced large passive nuclear power plant with independent intellectual property rights. By discussing the top design principle, main performance objectives, general parameters, safety design, and important improvements in safety, economy, and other advanced features, this paper reveals the technology innovation and competitiveness of CAP1400 as an internationally promising Gen-III PWR model. Moreover, the R&D of CAP1400 has greatly promoted China's domestic nuclear power industry from the Gen-II to the Gen-III level.

1. Introduction

Engineering and societal developments, as well as an emphasis on nuclear safety, have continuously propelled nuclear technology forward, from Gen-II to Gen-III. The three historical commercial nuclear power plant (NPP) accidents (Three Mile Island, Chernobyl, and Fukushima) have promoted higher safety standards on inherited safety and probabilistic safety objectives, stricter requirements for the prevention and mitigation of severe accidents, and the implementation of the passive safety concept. Operational experiences and industrial capability improvements have brought technologies with longer lifetimes, higher burnup, higher reliability, higher availability, modularization and standardization, design simplification, and digital instrumentation and control (I&C) systems into NPPs. Concerns regarding public acceptance and environmental impact have elevated requirements for the environmental compatibility of NPPs, including the principle of "as low as reasonably achievable" (ALARA) for radiation protection and more stringent radwaste discharge standards. In 1990, the Electric Power Research Institute (EPRI) first published the *Advanced Light Water Reactor Utility Requirements Document* (URD) [1], which defined the basic features and minimum requirements for Gen-III nuclear power technologies through 14 key policy statements. Since then, Gen-III nuclear technologies—claimed to be safer, more economic, and more advanced—have become the mainstream of the nuclear power industry.

This paper focuses on the R&D of CAP1400, the largest Gen-III passive pressurized water reactor (PWR), including its top-tier design principles, main performance objectives, general parameters, safety design considerations, and independent design and manufacturing of key equipment; as well as on the improvements in domestic nuclear design and manufacturing capability that have been motivated by the implementation of the passive PWR series for the National Science and Technology Major Project.

2. General design and safety design

2.1. General design of CAP1400

Ensuring its advanced nature from the very beginning, CAP1400 comprehensively inherits the philosophy of the passive concept and the simplification of AP1000 [2,3]; follows the latest effective codes, regulations, and standards at home and abroad; complies with the technology requirements defined in the URD and other documents for Gen-III NPPs; and fully incorporates the design changes and improvements from the AP1000 units under

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construction both in China and abroad.

CAP1400 was developed by upgrading the power capacity level, optimizing the general parameters, balancing the entire plant design, redesigning the safety systems and key equipment, increasing the equipment localization proportion, actively responding to post-Fukushima safety policies issued by regulators at home and abroad, fulfilling the current highest safety goals, satisfying the most stringent radwaste discharge standards, and further improving the economic competitiveness. The general performance of CAP1400 reaches the world's leading level of Gen-III technology, as shown in Table 1.

Fig. 1 shows the configuration of the reactor coolant system. CAP1400 has two primary coolant loops that transfer the heat generated by the fission reaction of ^{235}U in the reactor core to the steam generator (SG). Each loop consists of a hot leg, two cold legs, one SG, and two canned pumps. CAP1400 has one pressurizer (PRZ) connected to one of the hot legs by a surge line.

CAP1400 has a compact and reasonable general layout, as shown in Fig. 2. It covers an area of only 0.164 $m^2 \cdot kW^{-1}$, which is less than that of traditional Gen-II+ plants and AP1000. The estimated cost of the first CAP1400 project, located in Rongcheng City, Shandong Province, is about 16 000 $CNY \cdot kW^{-1}$ (\$2443 $USD \cdot kW^{-1}$), which is quite competitive among the Gen-III NPPs. For the *N*th of its kind, the cost of CAP1400 is expected to be much lower due to the learning effect, as well as to design solidification, equipment and material localization, matured modularity, and optimized project management.

2.2. Safety design of CAP1400

The safety design of CAP1400 is a multi-level combination of active defense-in-depth systems and passive engineered safety features, and incorporates systematic measures for severe accident prevention and mitigation. In addition, 21 tests were conducted to validate the design reasonability and software applicability, including: an advanced core-cooling mechanism experiment (ACME), a containment safety verification via integral test (CERT), and a critical in-vessel retention (IVR) heat flux test.

Non-safety-grade active facilities, including a normal residual heat-removal system (RNS), a component cooling system (CCS), a service water system (SWS), and others, are defense-in-depth measures. These facilities remove the core heat under anticipated transients, which avoids unnecessary actuation of the passive systems and prevents the transients from deteriorating to accidents. Based on lessons learned from the Fukushima accident [4] and related regulator policies [5], several safety enhancements were carried out to strengthen these defense-in-depth facilities. First, the seismic resistance capability of the normal decay heat removal facilities (as called the "cooling chain") was strengthened. Second, in order to further ensure the functioning of the decay heat removal path for the core and spent fuel 72 h after an accident initiation, seismic-resistant water source interfaces and portable diesel pumps were installed, and the designs of the emergency water source and power source were strengthened. For example, the emergency power was stored in a specific building [6].

The engineered safety systems of CAP1400 include a passive residual heat-removal system, a passive safety injection system, an automatic depressurization system, a passive containment cooling system, and so forth. These safety-grade passive facilities were designed to remove the heat from the reactor and containment under accident conditions, and to implement the emergency core cooling injection in order to prevent the core from melting down and ensure that radioactive substances remain confined within the containment. These passive systems, which comply with "single-failure" and "fail-safe" criteria, are triggered passively; that is, without relying on on-site/off-site AC power or other active equipment. They perform their intended function without an operator's control or external assistance within 72 h of an accident initiation.

The passive safety injection system provides emergency core makeup water and high-concentration boron water under accident conditions such as those caused by a main steam pipeline rupture, and provides core safety injection during a loss-of-coolant accident (LOCA). The system includes high-pressure injection (by

Table 1
Performance objectives and main parameters of CAP1400.

Parameter	Unit	Value
Core rated power	MW_t	4040
Electric power output	MW_e	~1500, depends on site condition
Design lifetime	years	60
Availability		93%
Construction duration	month	≤ 56 for first, 48 for fleet
Operator action time	h	72 (7 days with some water supply operation)
Core damage frequency (CDF)	per reactor year	4.02×10^{-7}
Large release frequency (LRF)	per reactor year	5.07×10^{-8}
Collective occupational exposure	person $Sv \cdot (reactor\ year)^{-1}$	< 1
Individual occupational exposure	$mSv \cdot (reactor\ year)^{-1}$	< 20
Waste disposal standard		< 1000 $Bq \cdot L^{-1}$ for coastal site, < 100 $Bq \cdot L^{-1}$ for inland site, and packaged solid waste volume < 50 $m^3 \cdot a^{-1}$
Safety shutdown earthquake		Safety shutdown earthquake (SSE) 0.3*g* (*g*, gravitation contant); seismic capability 0.5*g*
Core design margin		≥15%
Fuel type		RFA modified or self-developed
No. of fuel assemblies		193
Refueling interval	month	18
Averaged discharge fuel burnup	$MW_d \cdot (tU)^{-1}$	≥ 50 000
Mixed oxide fuel-loading capacity		Yes
Average linear power density	$W \cdot cm^{-1}$	181.0
Coolant average temperature	°C	304.0
System operation pressure	MPa(a)	15.5
Reactor coolant pump (RCP)		Domestic canned motor pump or wet-winding motor pump
RCP flow rate	$m^3 \cdot h^{-1}$	21 642
Steam pressure at steam generator (SG) exit	MPa(a)	6.01
Steam flow per SG	$kg \cdot s^{-1}$	1123.4
Steal containment design pressure	MPa	0.443, 10% margin