Analysis of Supercritical Water-Cooled Reactor Development

Authors: Zhao Xiaze, Liu Bo, Zhang Pingxun, Liu Bo

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Abstract

Innovation is the primary driving force for development and an important instrument for achieving leapfrog development of nuclear energy in China. The supercritical water-cooled reactor (SCWR) is one of the six most promising Generation IV reactors identified by the Generation IV International Forum, and it is the only light water-cooled reactor. For well-developed pressurized water reactors (PWRs), boiling water reactors (BWRs), and supercritical fossil-fired power units, the supercritical water-cooled reactor benefits from extensive operational experience and technological inheritance. For China, which primarily employs pressurized water reactors, the research and development of supercritical water-cooled reactor technology constitutes an important pathway for achieving sustainable development of nuclear power.

Full Text

Analysis of Supercritical Water-Cooled Reactor Development

Zhao Xiaoze[1], Liu Bo*[1], Zhang Pingxun[1]
[1] SPIC Laiyang Nuclear Energy Co., Ltd., Yantai 264000, China

Abstract

Innovation is the primary driving force for development and a crucial means to achieve leapfrog advancement of China's nuclear energy. The Supercritical Water-Cooled Reactor (SCWR) is one of the six Generation IV reactor systems identified by the Generation IV International Forum (GIF) as having the most promising R&D prospects, and it is the only light water-cooled reactor among them. For well-developed pressurized water reactors (PWR), boiling water reactors (BWR), and supercritical thermal power units, SCWR offers excellent opportunities for leveraging existing experience and technological inheritance.

For China, where PWRs are the dominant reactor type, SCWR technology R&D represents an important pathway for achieving sustainable development of nuclear power.

Keywords: Innovation; Supercritical Water-Cooled Reactor; Inheritance; Sustainable Development

In the energy sector, China faces challenges including a coal-dominated energy structure, shortage of liquid fuels, and environmental pollution from energy consumption. To address these "dilemmas" in energy application, China should actively explore new quality productive forces in the energy field. As a clean, efficient, and low-carbon energy source, nuclear power plays an important role in China's clean energy system and is crucial for addressing energy crises, ensuring national energy security, and reducing greenhouse gas emissions. Over the past 70 years, China's nuclear power industry has grown from nothing to rapid development, achieving remarkable accomplishments. The localization of Generation III nuclear power represents a significant achievement in China's nuclear power sector and marks an important transition from "bringing in" to "going out." To continuously promote high-quality development of nuclear energy and cultivate new quality productive forces in this field, China should adhere to innovation-driven development, actively tackle the challenges of Generation IV reactor technologies, and develop safer and more efficient reactor types.

In 2002, the Generation IV International Forum (GIF) concluded that as reactors evolve toward higher temperatures and pressures, exceeding the critical pressure of water leads to the formation of supercritical water-cooled reactors, representing a future option for water-cooled reactors. The Supercritical Water-Cooled Reactor (SCWR) combines advanced nuclear reactor technology with supercritical thermal power technology. Compared to current water-cooled nuclear power plants with average efficiencies of approximately 34%-36%, SCWR offers significant economic and technical advantages. The high steam enthalpy of SCWR enables a direct, once-through steam cycle, eliminating the need for steam generators, steam separators, dryers, and even main coolant pumps.

SCWR is a high-temperature, high-pressure water-cooled reactor that operates above the thermodynamic critical point of water (374°C temperature, 22.1 MPa pressure), with a core outlet temperature of approximately 500°C [1]. It employs direct cycle operation, eliminating the need for steam generators, steam separators, and other equipment throughout the loop, which simplifies the process and significantly reduces containment volume. SCWR uses supercritical water to remove heat from the core, and the high steam enthalpy allows for reduced size of the turbine system, thereby lowering the cost of the conventional island and offering good economic performance.

1 Historical Background and Research Status

In the 1950s, the United States and the Soviet Union proposed the concept of supercritical fluid reactors, but research was suspended due to insufficient technical and industrial foundations. Around the 1990s, growing concerns about energy and environmental issues drew worldwide attention to advanced nuclear energy systems. Due to its inherent technical advantages and excellent economic performance, SCWR is considered an important pathway for achieving long-term sustainable development of nuclear power. A summary of international SCWR conceptual designs [2] is presented in Table 1 .

Table 1 Summary of SCWR conceptual designs by country

Reactor Type	SCLWR-H	SCW-CANDU	KP-SKD	SCLWR-H
Core Structure	Pressure tube	Pressure tube	Pressure tube	Pressure vessel
Pressure (MPa)	280/530	280/500	280/508	350/625
Inlet/Outlet Temperature (°C)	270/545	280/526	280/500	508/625
Core Height/Diameter (m)	4.2/3.7	4.3/3.9	3.6/3.8	-/4.0
Fuel	UO_2/Th	UO_2	UO_2	MOX
Burnup (GWd/tHM)	5.0/6.45	3.2/3.3	-	-

In 2006, 12 organizations from 8 European countries formed a consortium to develop a conceptual design for higher live steam temperatures, which they called the High Performance Light Water Reactor (HPLWR) [3]. The design features a core outlet temperature of at least 500°C, supercritical system pressure of approximately 25 MPa, a thermal neutron spectrum, electrical power of 1000 MW, and thermal efficiency of about 44%. The project was completed in 2010, and the final report was published under the European Commission's Sixth Framework Programme.

In 2019, the EU, China, and Canada established the ECC-SMART project. With support from this project, R&D institutions from Europe, Canada, and China formed an international cooperation organization to jointly advance the technical development of SCW-SMR [4]. This project is currently the only ongoing international R&D project for small modular supercritical water-cooled reactors, with a research period of 48 months covering materials testing, project management, thermal-hydraulics and safety, core physics, safety standard guidelines, education, and training.

In 1989, the University of Tokyo initiated SCWR research and development in Japan [5]. This reactor type was selected as one of the six Generation IV reactor systems by GIF in 2002. In 2007, the European Atomic Energy Community, Canada, and Japan signed a System Arrangement for SCWR under a framework agreement and established a System Steering Committee (SSC).

1.3 Canada

Canada has proposed a pressure-tube supercritical water-cooled reactor based on its pressure-tube pressurized water reactor technology. Atomic Energy of

Canada Limited (AECL), together with multiple research institutions and universities, has conducted R&D on experimental facilities and key technologies [2]. The Canadian SCWR is a thermal-spectrum pressure-tube reactor that uses heavy water as moderator and light water as coolant, physically separated from each other [6]. Canada has conducted advanced fuel experiments, supercritical fluid thermal-hydraulic experiments, fuel bundle design studies, and related code development, completing a pre-conceptual system design in March 2011. The Canadian design concept proposes vertical fuel channels and pressurized moderator. Based on the CANDU fuel structure, two fuel channel designs were developed (high-efficiency fuel channel and re-entrant fuel channel).

1.4 China

SCWR research in China was initially initiated by universities and later taken up by industrial R&D departments. In 2007, the China Nuclear Power Technology Research Institute, Shanghai Jiao Tong University, and other domestic universities and research institutions jointly undertook projects under the "973 Program," including "Basic Research on Key Scientific Issues of SCWR," "China-EU SCWR Fuel Verification Project," and "SCWR Technology R&D." They conducted research on "SCWR nuclear system design and related technologies," "SCWR testing and experimental technology research," and "SCWR materials research," achieving a series of important results that laid the foundation for China's SCWR research. SCWR research has received support from the National Key R&D Program of the Ministry of Science and Technology. Leveraging the GIF-SCWR cooperation platform, two key international science and technology innovation cooperation projects have been launched (R&D on thermal-hydraulics and safety of SCWR nuclear systems, and R&D on materials and water chemistry of SCWR nuclear systems) [7], with related research being conducted. China has proposed a conceptual design for the SCWR CSR1000, establishing overall technical parameters and development directions [8].

2 Technical Characteristics

SCWR combines water reactor technology with supercritical thermal power technology. It is a Generation IV reactor that uses supercritical water as the working fluid, which aligns well with China's PWR technical foundation and industrial system.

SCWR is essentially a type of light water reactor (LWR), but operates at much higher temperatures and pressures. It adopts single-phase operation similar to PWR loops, with only one phase existing during core circulation, while employing a once-through cycle similar to BWRs. The SCWR primary system is simpler than LWR systems: compared to typical PWR systems, it eliminates steam generators and pressurizers; compared to typical BWR systems, it eliminates steam-water separation systems and recirculation systems. The coolant does not undergo phase change in the reactor, and water enthalpy at supercritical temperatures is very high, resulting in lower coolant mass flow rates for core thermal power and potentially reduced capacity of major system components. SCWR utilizes supercritical turbine-generator systems where supercritical water can directly enter the turbine for work without steam-water separation, achieving high thermal efficiency.

SCWR possesses inherent safety characteristics, and its safety systems can incorporate passive safety technologies from advanced Generation III nuclear power plants, making safety control relatively straightforward. The large temperature difference between SCWR inlet and outlet enables natural circulation in the core without the need for main coolant pumps. The SCWR pressure vessel is similar to that of a PWR, and its containment resembles that of an Advanced Boiling Water Reactor (ABWR), but without the need for steam-water separation equipment, resulting in reduced containment volume.

The SCWR safety system is very similar to existing BWRs. During accidents such as loss-of-coolant accidents, SCWR behavior resembles that of conventional BWRs, and emergency core cooling should be anticipated in the safety concept. However, compared to existing LWRs, SCWR has significant differences in safety approach: due to the lack of recirculation inside the reactor pressure vessel, coolant flow must be maintained at all times, and core cooling cannot be successfully achieved by water in the vessel alone. Therefore, automatic depressurization of the pressure vessel is envisioned as a passive, fast-response system for heat removal within a very short time during accident conditions.

SCWR can fully leverage mature technologies from supercritical thermal power units; essentially, replacing the supercritical boiler with a reactor creates a supercritical nuclear power plant. Currently, supercritical and ultra-supercritical thermal power unit technologies are relatively mature domestically and worldwide, providing valuable references for water treatment control technology and operational experience. The average density of coolant in SCWR is relatively low, allowing flexible design of the core neutron energy spectrum—it can be designed as either a thermal neutron reactor or, through compact core arrangement, as a fast neutron reactor.

The safety and reliability design of SCWR maximizes the use of mature technologies and experience accumulated from commercial operation of LWRs and supercritical thermal power plants. Safety system development is based on the inherent characteristics of water-cooled reactors and mature safety technologies from Generation III PWRs. SCWR can utilize well-developed PWR safety technologies (reactivity control systems and emergency core cooling systems) along with supercritical thermal power plant experience in control methods and corrosion-resistant materials to achieve higher safety and reliability while maintaining its advantages.

3 Conceptual Designs

3.1 HPLWR

The High Performance Light Water Reactor (HPLWR) focuses on solving numerous technical challenges [9], rather than simply raising the outlet temperature by approximately 200°C. Its fuel is uranium dioxide with an enrichment level of 8% to 9% to achieve burnup exceeding 60 GWd/tHM, with recycled MOX fuel available as an alternative. In addition to core design and analysis, the HPLWR project includes conceptual design of the reactor pressure vessel, containment and its safety systems, evaluation of actual plant costs and safety characteristics, as well as cladding material testing and detailed heat transfer studies. Table 2 presents the main technical parameters of HPLWR.

Table 2 Main technical parameters of HPLWR

Parameter	Value
Thermal power/MW	2300
Electrical power/MW	1000
Design life/years	60
Thermodynamic cycle type	Direct cycle
Steam flow rate under rated conditions/(kg/s)	1175
Steam pressure/MPa	25
Steam temperature/°C	500
Feedwater temperature/°C	280
Feedwater flow rate under rated conditions/(kg/s)	1175
Reactor operating pressure/MPa	25
Core height/m	4.2
Core diameter/m	3.7
Core inlet temperature/°C	280
Core outlet temperature/°C	500
Average core temperature rise/°C	220

Schulenberg et al. proposed a concept where evaporator assemblies are placed at the core center, followed by the first superheater assemblies with downward flow around them, while the second superheater assemblies have upward flow at the core periphery where fission power is low due to neutron leakage. In September 2006, the European consortium decided to use this example as the basis for core design.

3.2 JSCWR

The Japanese Supercritical Water-Cooled Reactor (JSCWR) is a thermal neutron spectrum reactor that uses light water as both moderator and coolant, employing a dual-flow direct cycle that divides fuel assemblies into two parts. Coolant entering the reactor through inlet nozzles is heated in the core and exits through outlet nozzles, with no recirculation in the pressure vessel. The coolant at core outlet is commonly referred to as "steam," though there is no distinction between steam and water above supercritical pressure, and it is delivered directly to the turbine system, with feedwater returning directly from the feedwater pump. Table 3 presents the main technical parameters of JSCWR.

The reactor core is cylindrical, consisting of 376 fuel assemblies. Each fuel assembly resides in the core for three cycles. Fuel assemblies consist of 192 fuel rods and a central square water rod (moderator) surrounded by a square channel. The fuel rods contain UO_2 pellets in modified stainless steel cladding, with ^{235}U enrichment exceeding 7%. Gadolinium burnable poison is added to reduce peaking during operation.

The fundamental philosophy of JSCWR research is to utilize as much existing mature technology as possible to minimize R&D costs, time, and risks. The JSCWR development plan is divided into three phases: feasibility phase, technology implementation phase, and demonstration phase. In the feasibility phase, a pre-conceptual system design is established and the feasibility of key technologies is examined. In the technology implementation phase, performance data such as material properties and thermal-hydraulic characteristics are verified and the conceptual design is optimized. In the demonstration phase, detailed design is performed, followed by system construction and operation.

Table 3 Main technical parameters of JSCWR

Parameter	Value
Thermal power/MW	3926
Electrical power/MW	1700
Design life/years	60
Thermodynamic cycle type	Direct cycle
Steam flow rate under rated conditions/(kg/s)	2155
Steam pressure/MPa	25
Steam temperature/°C	508
Feedwater temperature/°C	280
Feedwater flow rate under rated conditions/(kg/s)	2155
Reactor operating pressure/MPa	25
Core height/m	4.2
Core diameter/m	3.7

3.3 CSR1000

The development philosophy of CSR1000 aligns with GIF's technical objectives, emphasizing research on technical feasibility and design implementation supported by reliable test data. While conducting materials R&D and thermal-hydraulic experimental research, CSR1000 has also investigated its main technical parameters, core design, key structural designs, and system design [10]. Table 4 presents the main technical parameters of CSR1000.

Table 4 Main technical parameters of CSR1000

Parameter	Value
Thermal power/MW	2300
Electrical power/MW	~1000
Design life/years	60
Thermodynamic cycle type	Direct cycle
Steam flow rate under rated conditions/(kg/s)	1190
Steam pressure/MPa	25
Steam temperature/°C	500
Feedwater temperature/°C	280
Feedwater flow rate under rated conditions/(kg/s)	1190
Reactor operating pressure/MPa	25
Core height/m	4.2
Core diameter/m	3.7
Core inlet temperature/°C	280
Core outlet temperature/°C	500
Average core temperature rise/°C	220
Structural material	310S stainless steel

Considering reactor structure reliability, feasibility, and thermodynamic requirements, a dual-channel reactor concept was proposed, and the overall structure of CSR1000 was designed based on this concept. The core consists of 157 fuel assemblies. The enthalpy rise in the core is much higher than in conventional LWRs, resulting in significantly lower coolant flow velocity in the core compared to existing LWRs, at only 1190 kg/s [11,12].

Considering the two-channel core arrangement, the moderator and coolant channels must be separated from each other while ensuring sufficient flow area, and there should be no structural interference between different components of the fuel assembly.

CSR1000 is a once-through cooling system with no water level monitoring inside the reactor pressure vessel. Therefore, an emergency core cooling system needs to be designed to meet basic safety requirements, ensuring sufficient core coolant flow after reactor shutdown to remove decay heat. This approach is similar to the process in Generation III PWRs and can be used for conceptual design.

4 Development Recommendations

At the current research stage, suitable structural materials are a critical factor for SCWR development. In SCWR conceptual design, considering reactor structural complexity and material availability limitations, reactor reliability is reduced and constrains SCWR development. The selection of materials for the pressure vessel, internal components, and fuel assembly structures is crucial for ensuring safe reactor operation and service life. On one hand, SCWR operates under high-temperature, high-pressure conditions with large temperature differences between different core regions, posing greater challenges for materials. On the other hand, cladding and pressure vessels serve as radioactive boundaries, tasked with preventing radionuclide release while maintaining stable performance in high-radiation, corrosive environments. Research on materials for key reactor components should be conducted to optimize designs based on existing candidate materials, ensuring good chemical and mechanical properties under high-temperature, high-pressure, high-irradiation conditions.

Active exploration of new fuel assembly arrangement schemes and optimization of currently proposed fuel assembly design concepts are needed. In SCWR, fuel assembly design is more complex and challenging due to operation under high-temperature, high-pressure, high-neutron-irradiation conditions. Many countries and research institutions have proposed fuel assembly concepts: the U.S. SCWR proposes a single-flow core arrangement with square fuel assemblies and water rods; China's CSR1000 proposes a new design with 2$×$2 fuel assembly groups consisting of four sub-assemblies; Europe's HPLWR proposes a three-channel core arrangement with square fuel assemblies composed of 9 sub-assemblies, among others.

Safety analysis is a critical issue in SCWR R&D. Due to significant differences between supercritical and subcritical water, safety analysis codes from conventional water-cooled reactors must be modified and improved before application to SCWR. Additionally, attention should be paid to thermal-hydraulic research of supercritical fluids. International cooperation should be strengthened to establish unified experimental and evaluation standards, advancing SCWR from basic research to engineering application research.

SCWR represents the combination of water reactor technology and supercritical thermal power technology, representing an innovative technology and important development trend for water reactors. The mature operational experience of supercritical and ultra-supercritical thermal power units provides a solid foundation for the evolution from water reactors to SCWR, while the mature industrial system and safety performance of PWRs lay a solid foundation for SCWR engineering construction. Under the current technical roadmap, breakthroughs should be made as soon as possible in materials, thermal-hydraulics, and safety to construct a supercritical water-cooled experimental reactor, enabling early realization of its conceptual design under the premise of ensuring safety.

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Note: Figure translations are in progress. See original paper for figures.