SUPERCRITICAL WATER-COOLED NUCLEAR REACTORS: REVIEW AND STATUS

R.B. Duffey and **I.L. Pioro**
Chalk River Laboratories, Atomic Energy of Canada Limited (AECL), Chalk River, ON, Canada.

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Contents

Summary

Modern concepts of nuclear reactors cooled with supercritical water are presented together with a short history. The supercritical water-cooled CANDU ((*CANada Deuterium Uranium*) *is a registered trademark of AECL*) reactor concept is fully discussed. Also, thermophysical properties at critical and supercritical pressures as well as heat transfer and hydraulic resistance at these conditions are presented.

1. Introduction

The use of supercritical fluids in different processes is not new and, actually, is not a human invention. Nature has been processing minerals in aqueous solutions at near or above the critical point of water for billions of years (Levelt Sengers 2000). In the late 1800s, scientists started to use this natural process, called hydrothermal processing in their labs for creating various crystals. During the last 50 – 60 years, this process (operating parameters: water pressure from 20 to 200 MPa and temperatures from 300 to 500ºC), has been widely used in the industrial production of high-quality single crystals (mainly gem stones) such as sapphire, tourmaline, quartz, titanium oxide, zircon and others (Levelt Sengers 2000).

The first works devoted to the problem of heat transfer at supercritical pressures (SCPs) started as early as the 1930s (see reviews by Pioro and Pioro 1997; Hendricks et al. 1970). Schmidt and his associates (Schmidt 1960; Schmidt et al. 1946) investigated free convection heat transfer of fluids at the near-critical point with the application to a new effective cooling system for turbine blades in jet engines. They found that the free convection heat transfer coefficient at the near-critical state was quite high, and decided to use this advantage in single-phase thermosyphons with an intermediate working fluid at the near-critical point (Pioro and Pioro 1997).

In the 1950s, the idea of using supercritical water (SCW) appeared to be rather attractive for steam generators. At supercritical pressures, there is no liquid-vapor phase transition; therefore, there is no such phenomenon as critical heat flux (CHF) or dryout (for supercritical fluid properties, see Appendix 1). Only within a certain range of parameters a deterioration of heat transfer (for details, see Appendix 2) may occur. The objective of operating steam generators at supercritical pressures was to increase the total thermal efficiency of a power plant. Work in this area was mainly done in the former USSR and in the USA in the 1950s – 1980s (International Encyclopedia of Heat & Mass Transfer 1998).

In general, the total thermal efficiency of a modern power plant with subcritical parameters steam generators is about 36 – 38%, but reaches 45 – 50% with supercritical parameters, i.e., with water pressure 24 – 26 MPa, is about 45% and higher with ultra supercritical parameters.

At the end of the 1950s and the beginning of the 1960s, early studies were conducted to investigate the possibility of using supercritical water in nuclear reactors (review by Oka 2000; Wright and Patterson 1966; Bishop et al. 1962; Skvortsov and Feinberg 1961; Marchaterre and Petrick 1960; Supercritical pressure power reactor 1959). Several designs of nuclear reactors using supercritical water were developed in the USA, Great Britain, France and the USSR. However, this idea was abandoned for almost 30 years with the emergence of Light Water Reactors (LWR's) and only regained interest in the 1990s following LWR's maturation.

Use of supercritical water in power-plant steam generators is the largest application of a fluid at supercritical pressures in industry. However, other areas exist where supercritical fluids are used or will be implemented in the near future, including the latest developments of the use of:

- near-critical helium to cool coils of superconducting electromagnets, superconducting electronics and power-transmission equipment (Hendricks et al. 1970);
- supercritical hydrogen as a fuel for chemical and nuclear rockets (Hendricks et al. 1970);
- methane as a coolant and fuel for supersonic transport (Hendricks et al. 1970);
- liquid hydrocarbon coolants and fuels at supercritical pressures in the cooling jackets of liquid rocket engines and in fuel channels of air-breathing engines (Altunin et al. 1998; Kalinin et al. 1998, Dreitser 1993, Dreitser et al. 1993);
- supercritical carbon dioxide as a refrigerant in air-conditioning and refrigerating systems (Lorentzen 1994; Lorentzen and Pettersen 1993);
- a supercritical cycle in the secondary loop for transformation of geothermal energy into electricity (Abdulagatov and Alkhasov 1998);

- supercritical water oxidation technology (SCWO) for treatment of industrial and military wastes (Levelt Sengers 2000; Lee 1997); and
- supercritical fluids in chemical and pharmaceutical industries in such processes as supercritical fluid extraction, supercritical fluid chromatography, polymer processing and others (Levelt Sengers 2000).

2. Survey of Concepts of Nuclear Reactors at Supercritical Pressures

2.1 General Considerations

Concepts of nuclear reactors cooled with water at SCPs were studied as early as the 1950s and 1960s in the USA and Russia. After a 30-year break, the idea of developing nuclear reactors cooled with SCW became attractive as the ultimate development path for water-cooling. Several countries (Canada, Germany, Japan, Korea, Russia, USA and others) have started to work in that direction. However, none of these concepts is expected to be implemented in practice before 2015 – 2020.

The main objectives of using SCW in nuclear reactors are: 1) to increase the efficiency of modern nuclear power plants (NPP) from 33 – 35% to about 40 – 45%, 2) to decrease capital and operational costs and hence decrease electrical energy costs (<<$1000 US/kW). Currently, the latest designs of subcritical pressure nuclear reactors, which will be prototyped in 10 years or so, are expected to have specific overnight capital cost of about $1000 US/kW.

SCW NPPs will have much higher operating parameters compared to modern NPPs' (pressure about 25 MPa and outlet temperature up to 625ºC), and a simplified flow circuit, in which steam generators, steam dryers, steam separators, etc., can be eliminated. Also, higher SCW temperatures allow direct thermo-chemical production of hydrogen at low cost, due to increased reaction rates. According to the IAEA (1999), the optimum required temperature is about 850ºC and the minimum required temperature is around 650 to 700ºC, well within modern materials capability.

Also, future nuclear reactors will have high indexes of fuel usage in terms of thermal output per mass of fuel (Kirillov 2000; Alekseev et al. 1989). Therefore, changing over to supercritical pressures increases the thermal output coefficient and decreases the consumption of natural uranium. Due to the considerable reduction in water density in the reactor core, it might be possible to develop fast supercritical pressure water-cooled reactors with a breeding factor of more than 1 for converting fertile (non-fissionable fuel) to fissionable isotopes.

2.2 Design Considerations

The design of SCW nuclear reactors is seen as the natural and ultimate evolution of today's conventional modern reactors. First, some designs of the modern Pressurized Water Reactors (PWRs) work at pressures about 16 MPa, i.e., high pressures. Second, some Boiling Water Reactors (BWRs) are a once-through or a direct-cycle design, i.e., steam from nuclear reactor is forwarded directly into a turbine. Third, some experimental reactors use nuclear steam superheaters with outlet steam temperatures well beyond the critical temperature but at pressures below the critical pressure. And fourth, modern supercritical parameters turbines, i.e., pressures about 25 MPa and inlet temperatures of about 600ºC, operate successfully at thermal power plants for many years.

The SCW reactor concepts therefore follow two main types (for details, see below): the use of either (a) a large reactor pressure vessel (RPV) with wall thickness of about 0.5 m to contain the reactor core (fuelled) heat source, analogous to conventional PWRs and BWRs, or (b) distributed pressure tubes (PT) or channels analogous to conventional CANDU and RBMK reactors. The latter is used to avoid a thick wall vessel. The coolant is usually water, although carbon dioxide has also been considered. For using a thermal neutron spectrum, water is usually used in the core flow, plus either a solid moderator using graphite or zirconium hydride, or a liquid heavy water moderator is used.

To reduce the severe axial flux tilt due to the large density decrease as the coolant is heated, the core flow path can be a re-entrant in the vessel option, coming down unheated first and then turning into an upflow; or interlaced or re-entrant in channels with flow in opposite directions. Both options allow the chance to reduce pressure boundary temperatures, by partly insulating the pressure-retaining vessel of the channel wall using the first pass of the unheated flow. Typical outlet temperatures are expected to be near 600ºC to match turbine inlet needs. There is also the option of a superheat pass (return flow) to further raise outlet temperatures if needed (for example for hydrogen production).

The limit on SCW outlet temperature is effectively set by the fuel cladding, since the peak clad temperature will be some 20% higher than the average, and the corrosion rates much higher. Estimates of the peak values have been made to establish the margins and clad lifetime expected before refueling.

Moreover, one of the unique features of the SCW reactors is the very low coolant mass-flow rates that are required through the reactor core because of the high thermal capacity. Preliminary calculations showed that the rate can be about *eight times less* than in modern PWRs, significantly reducing the pumping power and costs. This improvement is due to the considerable increase in enthalpy at supercritical conditions, which can be about 2000 kJ/kg. Therefore, tight fuel bundles, which are more acceptable in supercritical pressure reactors than in other types of reactors, can be used. These tight bundles have a significant pressure drop, which in turn can enhance the hydraulic stability of the flow. Since the SCW is a single-phase "gas", then the cladding surfaces can and should be finned or ridged to enhance turbulence levels to give increase in heat transfer coefficient. This is done for Advanced Gas-Cooled Reactors (AGRs) today, and hence will increase the heat transfer and reduce peak cladding temperatures in normal operation. To optimize thermal efficiency and capital cost, there are also options for the thermal cycles (Bushby et al. 2000; Oka et al. 1996), being either direct cycle into a SCW turbine, or indirect using a heat exchanger.However, the major problem seems to be with the materials reliability and corrosion rates at high temperatures, pressures and neutron fluxes within a highly aggressive medium such as supercritical water.

Parameters	Unit	SCW CANDU	HPLWR	SCLWR-H	SCFBR-H	SCWR	B-500 SKDI	ChUWR	ChUWFR	KP-SKD
Reference	**–**	Bushby et al. 2000	Squarer et al. 2003	Yamaji et al. 2004	Oka, Koshizuka 2000	Bae et al. 2004; Bae 2004	Silin et al. 1993	Kuznetsov 2004 (project from 80s)	Gabaraev et al. 2003	Kuznetsov 2004
Country	**–**	Canada	EU/Japan	Japan		Korea	Russia	Russia	Russia	Russia
Organization	**–**	AECL	EU / U of Tokyo	University of Tokyo		KAERI / Seoul NU	Kurchatov Institute	RDIPE (НИКИЭТ)		
Reactor type	**–**	PT	RPV	RPV	RPV	RPV	PT	PT	PT	PT
spectrum	**–**	Thermal	Thermal	Thermal	Fast	Thermal	Thermal	Thermal	Fast	Thermal
Power thermal	**MW**	2540	2188	2740	3893	3846	1350	2730	2800	1960
electrical	**MW**	1140	1000	1217	1728	1700	515	1200	1200	850
linear max/ave	**kW/m**		39/24	39/18	39	39/19		38/27		69/34.5
Thermal eff.	**%**	45	44	44.4	44.4	44	38.1	44	43 (48)	42
Pressure	**MPa**	25	25	25	25	25	23.5	24.5	25	25
T_{in} coolant	**ºC**	350	280	280	280	280	355	270	400	270
T_{out} coolant	**ºC**	625	500	530	526	508	380	545	550	545
Flow rate	**kg/s**	1320	1160	1342	1694	1862	2675	1020		922
Core height	**m**		4.2	4.2	3.2	3.6	4.2	6	3.5	5
diameter	**m**	~4		3.68	3.28	3.8	2.61	11.8	11.4	6.45
Fuel	**–**	UO_2/Th	UO_2 or MOX	UO_2	MOX	UO_2	UO_2	UC	MOX	UO_2
Enrichment	**% wt.**	4	<6%	~6.1		5.8	3.5	4.4		6
Cladding material	**–**	Ni alloy	St. st.	Ni alloy	Ni alloy	St. st.	Zr alloy / St. st.	St. st.	St. st.	St. st.
# of FA		300	121	121	419	157	121	1693	1585	653
# of FR in FA		43	216/252	300		284	252	10	18	18
D_{rod}/δ_w	**mm/mm**	11.5 and	8	10.2/0.63	12.8	9.5/0.635	9.1 (Zr), 8.5	12/1	12.8	10/1
Pitch	**mm**	13.5	9.5		108	11.5	(St. st.)			
T_{max} cladding	**ºC**	<850	620	650	620	620	425	630	650	700
Moderator	**–**	D_2O	H_2O	H_2O	H_2O	ZrH_2	H_2O	Graphite	Graphite	D_2O

Table 1. Modern concepts of nuclear reactors cooled with supercritical water

Continuation of Table 1

Parameters	Unit	PVWR	WWPR-SCP	SCWR-US
Reference	–	Filippov et al. 2003	Baranaev et al. 2004	Buongiorno, MacDonald 2003
Country	–	Russia	Russia	USA
Organization	–	VNIIAM / Kurchatov Institute	IPPE (ФЭИ)	US DOE
Reactor type	–	RPV	RPV	RPV
spectrum	–	Thermal	Fast	Thermal
Power thermal	MW	3500	3830	3575
electrical	MW	1500	1700	1600
linear max/ave	kW/m		35/15.8	39/19.2
Thermal eff.	%	43	44	44.8
Pressure	MPa	25	25	25
T_{in} coolant	ºC	280	280	280
T_{out} coolant	ºC	550–610	530	500
Flow rate	kg/s	1600	1860	1843
Core height diameter	m m	3.5 2.92	4.05 3.38	4.87 3.91
Fuel	–	UO_2	MOX	UO_2 95%
Enrichment	% wt.			5
Cladding material	–		Ni alloy	TBD
# of FA		37	241	145
# of FR in FA			252	300
D_{rod}/δ_w Pitch	mm/mm mm	Sphere 1.8 mm	10.7/0.55 12	10.2/0.63 11.2
T_{max} cladding	ºC	630–730	630	
Moderator	–	H_2O	$ZrH_{1.7}$	H_2O

Explanations to the table: Concepts appear according to the alphabetical order of the country of origin; for explanation to acronyms, see Nomenclature.

Table 1. Modern concepts of nuclear reactors cooled with supercritical water

In summary, the use of SCW in nuclear reactors will, according to the US DOE (Roadmap) Generation IV Nuclear Energy Systems Report (2001):

- Significantly increase thermal efficiency up to 40 – 45%;
- Eliminate steam dryers, steam separators, re-circulation pumps and steam generators;
- Allow the production of hydrogen at SCW NPPs due to high coolant outlet temperatures;
- Decrease reactor coolant pumping power;
- Reduce frictional losses;
- Lower containment loadings during Loss Of Coolant Accident (LOCA); and
- Eliminate dryout.

The latest concepts of SCW nuclear reactors are summarized in Table 1. Figure 1 shows the general concept of the pressurized-channel SCW CANDU reactor; and Figure

2 shows the schematic of the US pressurized-vessel SCW reactor.

Values of the heat transfer coefficient and sheath temperatures at SCW CANDU reactor operating conditions are presented in Section 2.3.

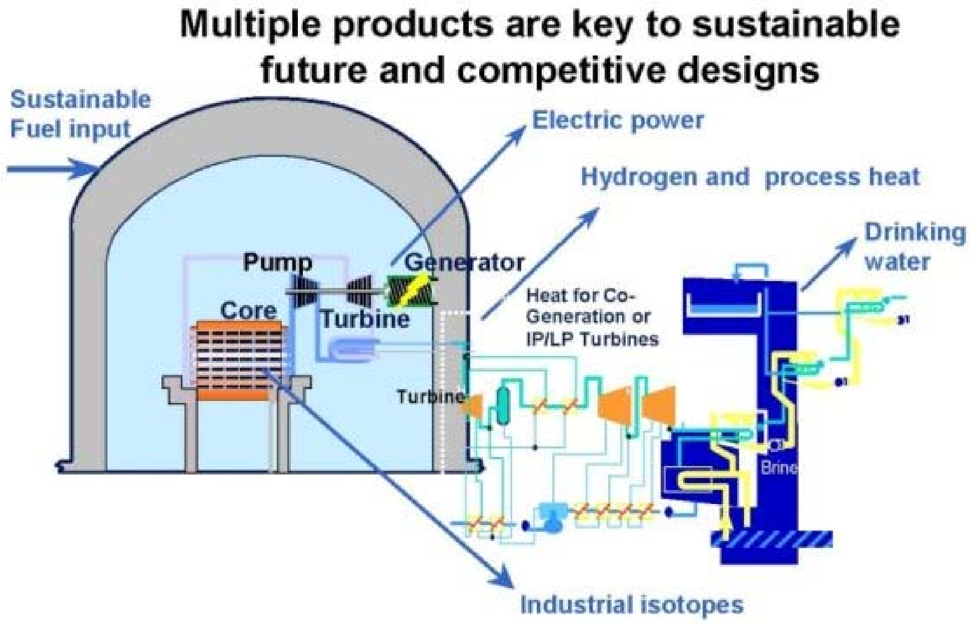

Figure 1. General concept of the pressurized-channel SCW CANDU reactor: IP – intermediate-pressure turbine, and LP – low-pressure turbine.

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Biographical Sketches

Romney Duffey is the Principal Scientist with AECL (Canada). He is a leading expert in commercial nuclear reactor studies, is active in global environmental and energy studies and in advanced system design, and is currently leading work on advanced energy concepts. He has an extensive technology background, including energy, environment waste, safety, risk, simulation, physical modeling and uncertainty analysis. Romney is the author of the original text about errors in technology ("Know the Risk", Butterworth-Heinemann, 2002), and of more than 150 published technical papers and reports. He is the past Chair of the American Society of Mechanical Engineers' Nuclear Engineering Division, an active Member of the American and Canadian Nuclear Societies, and a past Chair of the American Nuclear Society's Thermal Hydraulics Division. Recently he was elected a Fellow of ASME for his exceptional engineering achievements and contributions to the engineering profession.

Igor Pioro – Ph.D. (1983), Doctor of Technical Sciences (1992), is an internationally recognized scientist in areas of nuclear engineering (thermalhydraulics of nuclear reactors, Generation IV nuclear reactor concepts and high-level radioactive-wastes management); thermal sciences (boiling, forced convection including supercritical pressures, etc.); and heat engineering (two-phase thermosyphons, heat exchangers, heat-recovery systems, submerged-combustion melters, etc.).

He is author/co-author of 5 monographs, 91 papers, 24 patents, and more than 30 major technical reports. His latest monographs are: Bezrodny, M.K., Pioro, I.L. and Kostyuk, T.O., *Transfer Processes in Two-Phase Thermosyphon Systems. Theory and Practice*, 2005, Fact Publ. House, Kiev, Ukraine, 600 pages; and Pioro, L.S. and Pioro, I.L., Industrial Two-Phase Thermosyphons, Begell House, Inc., New York, USA, 1997, 288 pages.

Dr. Pioro graduated from the National Technical University of Ukraine "Kiev Polytechnical Institute", Heat Engineering Department with Master of Science in Thermal Physics (Diploma of Honour) in 1979. After that he worked on various positions including an engineer, part-time professor, senior scientist, deputy director. Currently as a senior scientist, he is associated with Thermalhydraulics Branch of Chalk River Laboratories, Atomic Energy of Canada Limited.

In 1990 Dr. Pioro was awarded with the Medal of the Ukrainian Academy of Sciences for the best scientific work of a young scientist and with the Badge "Inventor of the USSR".