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SUPERCRITICAL WATER-COOLED NUCLEAR REACTORS: THERMODYNAMIC-CYCLES OPTIONS

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ABSTRACT

Currently there are a number of Generation IV SuperCritical Water-cooled nuclear Reactor (SCWR) concepts under development worldwide. The main objectives for developing and utilizing SCWRs are: 1) Increase gross thermal efficiency of current Nuclear Power Plants (NPPs) from 33 – 35% to approximately 45 – 50%, and 2) Decrease the capital and operational costs and, in doing so, decrease electrical-energy costs (~$1000 US/kW or even less).

SCW NPPs will have much higher operating parameters compared to current NPPs (i.e., pressures of about 25 MPa and outlet temperatures up to 625°C). Additionally, SCWRs will have a simplified flow circuit in which steam generators, steam dryers, steam separators, etc. will be eliminated. Furthermore, SCWRs operating at higher temperatures can facilitate an economical co-generation of hydrogen through thermo-chemical cycles (particularly, the copper-chlorine cycle) or direct high-temperature electrolysis.

To decrease significantly the development costs of a SCW NPP, to increase its reliability, and to achieve similar high thermal efficiencies as the advanced fossil steam cycles it should be determined whether SCW NPPs can be designed with a steam-cycle arrangement that closely matches that of mature SuperCritical (SC) fossil power plants (including their SC turbine technology). The state-of-the-art SC steam cycles in fossil power plants are designed with a single-steam reheat and regenerative feedwater heating and reach thermal steam-cycle efficiencies up to 54% (i.e., net plant efficiencies of up to 43% on a Higher Heating Value (HHV) Basis).

Therefore, simplified no-reheat, single-reheat, and double-reheat cycles without heat regeneration and a single-reheat cycle with heat regeneration based on the expected steam parameters of future SCW NPPs were analyzed in terms of their thermal efficiencies.

On this basis, several conceptual steam-cycle arrangements of pressure-tube SCWRs, their corresponding T–s diagrams and steam-cycle thermal efficiencies (based on constant isentropic turbine and polytropic pump efficiencies) are presented in this paper.

1. INTRODUCTION

1.1. SCWR Concepts

Currently there are a number of Generation IV SCWR concepts under development worldwide (Pioro and Duffey, 2007). The main objectives for developing and utilizing SCWRs are: 1) Increase the thermal efficiency of current NPPs from 33 – 35% to approximately 45 – 50%, and 2) Decrease capital and operational costs and, in doing so, decrease electrical-energy costs (~$1000 US/kW or even less).

SCW NPPs will have much higher operating parameters compared to current NPPs (i.e., pressures of about 25 MPa and outlet temperatures up to 625°C) (Fig. 1). Additionally, SCWRs will have a simplified flow circuit in which steam generators, steam dryers, steam separators, etc. will be eliminated. Furthermore, SCWRs operating at higher temperatures can facilitate an economical production of hydrogen through thermo-chemical cycles or direct high-temperature electrolysis.

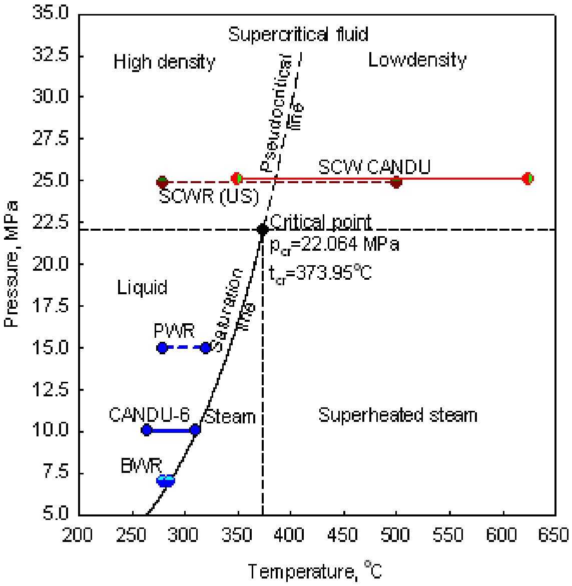


Fig. 1: Pressure-Temperature Diagram of Water for Typical Operating Conditions of SCWRs, PWRs, CANDU-6 Reactors and BWRs.

The SCWR concepts (Duffey et al., 2008; Pioro and Duffey, 2007) follow two main types: (a) A large reactor pressure vessel (PV) with a wall thickness of about 0.5 m to contain the reactor core (fuelled) heat source, analogous to conventional LWRs; or (b) Distributed pressure tubes (PTs) analogous to conventional Heavy Water Reactors (HWRs). Within those two main classes the PT reactors are designed to be more flexible to flow, flux and density changes than the PV reactors. This makes it possible to use the experimentally confirmed, better solutions developed for these reactors. The main ones are fuel re-loadings and channel-specific flow-rate adjustments or regulations. A design whose basic element is a channel or tube, which carries a high pressure, has an inherent advantage of greater safety than large vessel structures at supercritical pressures. AECL and RDIPE are currently developing concepts of the PT SCWRs (see Table 1).

To decrease significantly the development costs of a SCW NPP and to increase its reliability, it should be determined whether SCW NPPs can be designed with a steam-cycle arrangement that closely matches that of SuperCritical (SC) fossil power plants (including their SC turbine technology) that have been used extensively at existing thermal-power plants for the last 50 years.

Previous publications have been mainly devoted to a general development of SCWR concepts (Pioro and Duffey, 2007). However, very few publications were dedicated to development of a general steam-cycle arrangement of a SCW NPP (Duffey et al., 2008; Mokry et al., 2008; Duffey and Pioro, 2006).

Therefore, the first objective of this paper is a literature review of current and upcoming SC turbines and their major steam parameters.

Table 1. Major parameters of SCW CANDU® and KP-SKD nuclear reactors concepts (Pioro and Duffey, 2007).

Parameters	SCW CANDU	KP-SKD
Reactor type	PT	
Reactor spectrum	Thermal	
Coolant	Light water	
Moderator	Heavy water	
Thermal power, MW	2540	1960
Electric power, MW	1220	850
Thermal efficiency, %	48	42
Pressure, MPa	25	25
Inlet temperature, °C	350	270
Outlet temperature, °C	625	545
Flowrate, kg/s	1320	922
Number of fuel channels	300	653
No. of fuel elements in bundle	43	18
Length of bundle string, m	6	–
Max. cladding temperature, °C	850	700

1.2. Review of Current and Upcoming Supercritical Turbines and their Major Parameters

SC "steam" turbines of medium and large capacities (450 – 1200 MW_e) (Duffey et al., 2008; Mokry et al., 2008; Pioro and Duffey, 2007) have been used very successfully at many fossil power plants worldwide for more than fifty years. Their steam-cycle thermal efficiencies have reached nearly 54%, which is equivalent to a net-plant efficiency of approximately 40 – 43% on a Higher-Heating Value (HHV) basis. It should be noted that the absolute leaders among large-scale power plants in terms of thermal efficiencies are combined-cycle (i.e., tandem arrangement of gas turbine and subcritical-pressure steam turbine) gas-fired power plants with about 60% net plant efficiency on a Lower-Heating Value (LHV) basis or net-plant efficiencies of up to 54% on a HHV basis.

Table 2 lists selected current and upcoming SC turbines manufactured by Hitachi for reference purposes.

An analysis of SC turbine data (Duffey et al., 2008; Mokry et al., 2008; Pioro and Duffey, 2007) showed that:

- The vast majority of the modern and upcoming SC turbines are single-reheat-cycle turbines;
- Major "steam" inlet parameters of these turbines are: The main or primary SC "steam" – P = 24 – 25 MPa and T = 540 – 600°C; and the reheat or secondary subcritical-pressure steam – P = 3 – 5 MPa and T = 540 – 620°C.
- Usually, the main "steam" and reheat steam temperatures are the same or very close (for example, 538/538°C;

566/566°C; 579/579; 600/600°C or 538/566°C; 566/593; 600/620°C).

- Only very few double-reheat-cycle turbines were manufactured. The market demand for double-reheat turbines disappeared due to economic reasons after the first few units were built.

NOMENCLATURE

H	specific enthalpy, J/kg
m	mass-flow rate, kg/s
P	pressure, MPa
Q	power or heat-transfer rate, W
s	specific entropy, J/kg K
T	temperature, °C

Greek symbols

Δ	difference

Subscripts

e	electrical
th	thermal

Acronyms

AECL	Atomic Energy of Canada Limited
BWR	Boiling Water Reactor
CANDU	CANada Deuterium Uranium (reactor)
HHV	Higher-Heating Value
HP	High Pressure (turbine)
HWR	Heavy Water Reactor
HX	Heat eXchanger
IP	Intermediate Pressure (turbine)
KP-SKD	Channel Reactor of Supercritical Pressure (in Russian abbreviations)
LHV	Lower-Heating Value
LP	Low Pressure (turbine)
LWR	Light Water Reactors
Mix Ch	Mixing Chamber (deaerator)
NPP	Nuclear Power Plant
PT	Pressure Tube (reactor)
PV	Pressure Vessel (reactor)
PWR	Pressurized Water Reactor
RDIPE	Research and Development Institute of Power Engineering (Moscow, Russia)
SCWR	SuperCritical Water Reactor
UOIT	University of Ontario Institute of Technology

2. COMPARISON OF POTENTIAL STEAM-CYCLE ARRANGEMENTS FOR SCW NPP

In general, the major SCWRs parameters (Pioro and Duffey, 2007), such as the outlet pressure and temperature, and capacity (Table 1), are the same or close to the corresponding parameters of the most advanced SC turbines (Table 2).

Table 2: Major Parameters of Selected Current and Upcoming Hitachi SC Plants.

First Year of Operation	Power Rating MW$_e$	P MPa	T_{main}/T_{reheat} °C
2011	495	24.1	566/566
2010	809	25.4	579/579
	790	26.8	600/600
2009	1000	25.0	600/620
	1000	25.5	566/566
	677	25.5	566/566
	600	24.1	600/620
2008	1000	24.9	600/600
	887	24.1	566/593
	887	24.1	566/593
	677	25.5	566/566
2007	1000	24.9	600/600
	870	25.3	566/593

Therefore, the second objective of this paper is to analyze possible steam-cycle arrangements and to evaluate conceptually their complexity and adaptability to current SCW NPP concepts.

The following analysis provides a thermodynamic comparison of three possible steam-cycle arrangements: 1) No-reheat cycle; 2) Single-reheat cycle; and 3) Double-reheat cycle. Moreover, the thermodynamic benefit of regenerative heating is presented based on a single-reheat cycle.

All of the steam-cycle arrangements considered are based on the Rankine cycle, and all of the cycles are based on the main "steam" pressure and temperature of 25 MPa and 625 °C, respectively. Where reheat is present, the reheat temperature was assumed to be 625 °C or 700 °C as indicated. All cycles are based on a condensing pressure of 6.8 kPa. The amount of cycle-heat input (Q) illustrated in Tables 3 – 6 is based on a cycle with a total useable work ("thermal output") of 1200 MW$_{th}$.

It is to be noted that the thermal-cycle efficiencies stated in Tables 3 to 6 are based on the following simplifying assumptions:

- Isentropic turbine efficiency of 88% for all turbine sections;
- No mechanical losses (e.g., bearing losses);
- No steam turbine packing leakage or gland steam-system losses;
- No turbine exhaust losses;
- No generator losses;
- 84% polytropic efficiency for all pumps;

- Reactor feed-pump discharge pressure is 127% of turbine throttle pressure;
- Condensate pump discharge pressure is 0.7 MPa (100 psi) above deaerator pressure;
- Reheat system ΔP is 8% of cold reheat pressure;
- Turbine extraction piping ΔP is 5% of turbine stage pressure and includes turbine nozzle losses;
- No piping heat losses; and
- No reactor heat losses.

For illustration purposes, the T–s diagrams show irreversible compression and both reversible (dashed line) and irreversible (solid line) expansion. For the purpose of the T–s diagrams heat addition takes place at constant pressure (i.e., not all system pressure drops are shown in the T–s diagrams).

2.1. Cycles without Heat Regeneration

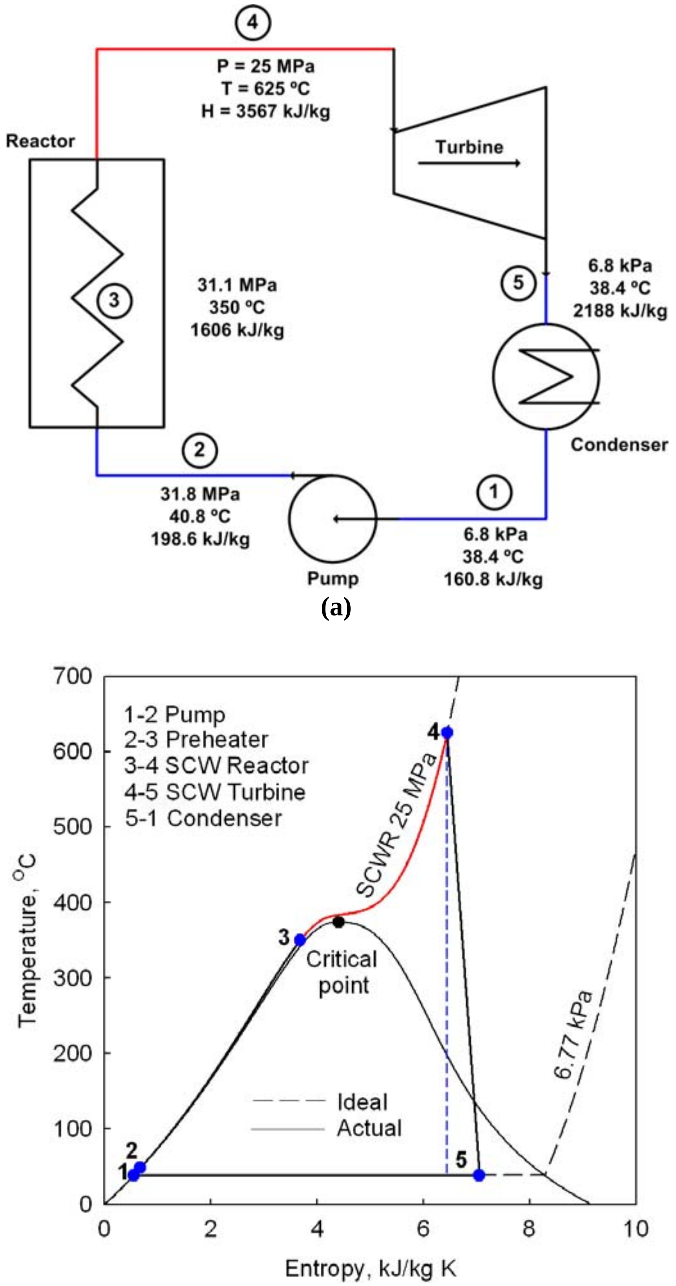
2.1.1. No-Reheat Cycle

The most basic steam-cycle configuration that could be used in a SCW NPP is the non-reheat cycle without heat regeneration. A simplified cycle arrangement and the corresponding T–s diagram of a no-reheat cycle are presented in Figs. 2a and 2b, respectively. The corresponding heat-transfer rates of this cycle are listed in Table 3[1].

Saturated feedwater (i.e., condensate) from a condenser (Point 1: Pressure 6.8 kPa and temperature 38.4°C) enters a pump, which compresses the condensate (water) to a supercritical operating pressure (Point 2: Pressure 31.8 MPa and temperature 40.8°C). After that, the supercritical water is heated in a preheater (for simplification purposes the preheater is considered to be a part of the reactor) between Points 2 and 3 from 40.8°C to 350°C. The preheater outlet pressure shown in Fig. 2a is only for reference purposes. It is expected that, due to the relatively low flow rates inside the reactor and piping, the pressure drop from the pump discharge to the reactor outlet might be as little as 1 – 2 MPa.

Table 3: No-Reheat Cycle Heat-Transfer Rates.

Main "Steam" Temperature, °C	**625**	
Mass Flow Rate , kg/s	**870**	
Stage	**ΔH, kJ/kg**	**Q, MW$_{th}$**
Pumps	38	33
Preheater	1407	1225
Reactor	1961	1707
Turbine	–1379	–1200
Condenser	–2027	–1765
Efficiency with pump work, %	**40.5**	
Efficiency without pump work, %	**40.9**	



(a)

(b)

Fig. 2: No-Reheat Cycle Layout (a) and Corresponding T–s Diagram (b).

Further on, the supercritical water continues to flow through the steam generator (reactor), being heated from 350°C to 625°C (Points 3 – 4).

In the next step, the supercritical water (here it is better to say supercritical "steam", because this actually incorrect term suits better in connection with SC turbines) at the pressure of 25 MPa and temperature of 625°C (Point 4) enters the turbine where it expands and produces mechanical work

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[1] The water/steam properties were calculated using WinSteam 3.1 software, which is based on the 1997 formulations published by the International Association for the Properties of Water and Steam (IAPWS-IF97).

by rotating the turbine shaft connected to an electrical-generator rotor. Inside the turbine, the steam expands and pressure and temperature drop; and saturated steam at a low pressure leaves the turbine at Point 5 (pressure 6.8 kPa and temperature 38.4°C).

The steam is condensed at the pressure of 6.8 kPa and saturation temperature of 38.4°C inside a condenser (Points 5 – 1). The condenser is basically a heat exchanger that is using water from a cooling tower, river or lake as cooling medium. The water (condensate) leaves the condenser as saturated liquid (in reality it would be slightly subcooled) and enters the pump (Point 1), thus completing the thermodynamic cycle.

The difference between the energy added to the cycle (energy added in the reactor plus energy added by the pumps) and the heat rejected through the condenser represents the useful work generated by this configuration. The efficiency of the cycle is the ratio of total useful work and heat added to the cycle. As per Table 3, the total thermal energy added to the cycle is 3406 kJ/kg. The energy rejected through the condenser is 2027 kJ/kg. Therefore, the thermal efficiency of the cycle is about 40.5% if the work provided by the pumps is included as a heat source, and 40.9% if the heat added by the pumps is neglected or considered ”free” energy.

The advantages of this no-reheat cycle as part of a SCW NPP are:

1) A relatively simple general SCW NPP layout that lowers the capital costs associated with the design, construction and operation of a NPP; and
2) A relatively simple SCWR design, which can be a PT or PV type.

However, there are currently no SC turbines operating without a reheat stage. This is mainly due to economical reasons. Also, it should be noted that a high main “steam” pressure in no-reheat turbines results in high turbine exhaust moisture and would require technical means to prevent moisture induced erosion in the low-pressure stages of the turbine. Also, the thermal efficiency of a no-reheat SCWR NPP might not be high enough to be competitive with the efficiencies of current SC or combined-cycle thermal power plants.

2.1.2. Single-Reheat Cycle

It is well known that steam reheat increases the thermal efficiency of the cycle. Moreover, steam reheat reduces the amount of moisture in the last stages of the turbine, therefore eliminating the need for moisture removal equipment. In general, incorporation of a single reheat in modern power plants improves the cycle efficiency by 2 to 4%, compared to the no-reheat cycle, by increasing the average temperature at which heat is added to the steam. For that reason, the vast majority of SC thermal power plants operating around the world employ SC “steam” generators and turbines with a single-reheat cycle (for details, see Section 1.2).

A single-reheat steam-cycle arrangement is illustrated in Fig. 3a. The corresponding T–s diagram and heat-transfer rates are illustrated in Fig. 3b and Table 4, respectively. Compared to the no-reheat cycle the single-reheat cycle uses two turbine sections or cylinders: a High-Pressure (HP) turbine and an Intermediate- (IP) or/and Low-Pressure (LP) turbine(s) (Mokry et al., 2008). Moreover, a steam-reheat is added to the cycle.

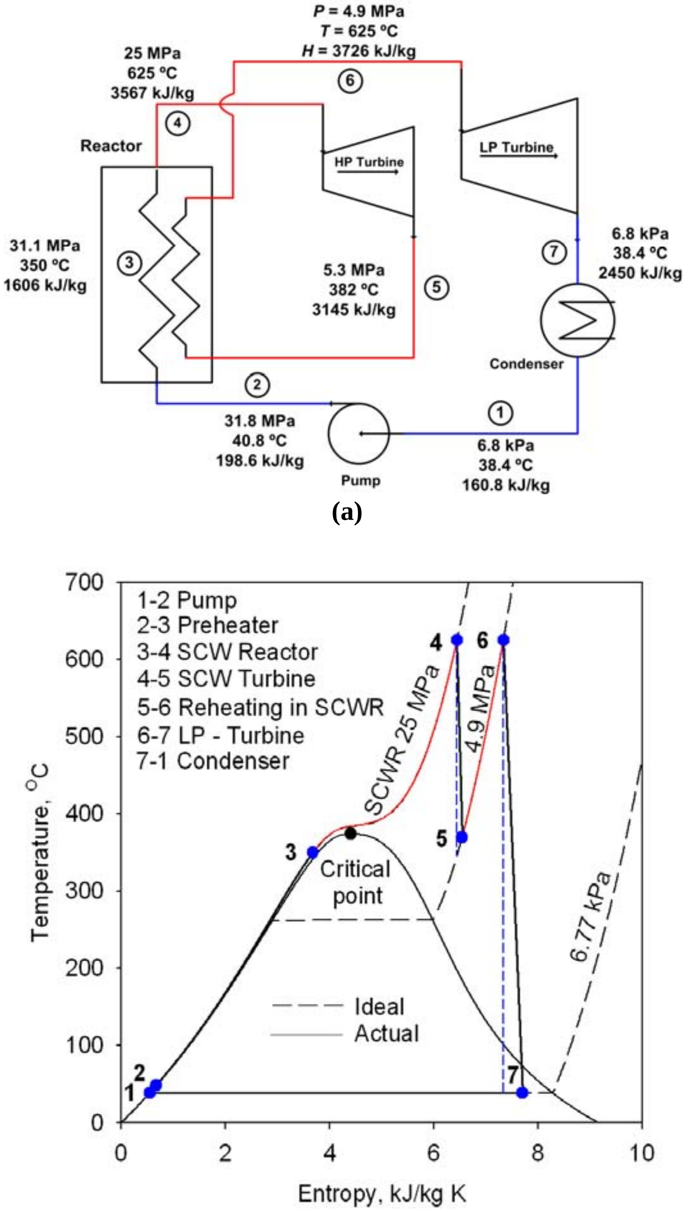


Fig. 3: Single-Reheat Cycle Layout (a) and Corresponding T–s Diagram (b).

The SC “steam” from the reactor is expanded inside the HP turbine from the supercritical pressure of 25 MPa and temperature of 625°C (Point 4) to an intermediate pressure of 5.3 MPa and temperature of 382°C (Point 5). The subcritical-pressure steam leaves the HP turbine in a superheated state and is sent back to the reactor where it is re-heated from 382°C to 625°C (Point 6). After the reactor reheat, the superheated reheat steam is expanded in the IP/LP turbine(s) to a sub-atmospheric pressure of 6.8 kPa and temperature of 38.4°C (Point 7), at which it is condensed in the condenser.

Table 4: Single-Reheat Cycle Heat-Transfer Rates.

Steam Temperature Main/Reheat, °C	**625 / 625**		**625 / 700**	
Mass Flow Rate, kg/s	**707**		**659**	
Stage	ΔH, **kJ/kg**	Q, **MW$_{th}$**	ΔH, **kJ/kg**	Q, **MW$_{th}$**
Pump	38	27	38	25
Preheater	1407	994	1407	928
Reactor	1961	1385	1961	1292
HP Turbine	–421	–298	–441	–291
Reheater	580	410	775	511
LP Turbine	–1277	–902	–1380	–910
Condenser	–2288	–1617	–2360	–1556
Efficiency with pump work, %	**42.6**		**43.5**	
Efficiency without pump work, %	**43.0**		**43.9**	

For this arrangement, the total heat energy added to the cycle is approximately 3986 kJ/kg and the energy rejected through the condenser is 2289 kJ/kg. Thus, the thermal efficiency of the cycle is about 42.6% if the work provided by the pumps is included as a heat source, and 43.0% if the heat added by the pumps is neglected or considered ”free” energy.

If a higher steam-reheat temperature is achieved, for example 700°C, the thermal efficiency would rise by about 0.9%. However, this increase in temperature may be very expensive accounting on special materials to be used inside the reactor. Therefore, on the current level of technology, this option may not be viable in spite of the increased thermal efficiency.

In order to maximize the thermal-cycle efficiency of the SCW NPPs it would be beneficial to include nuclear steam reheat, similar to the reheat cycle of fossil power plants. This nuclear steam reheat is easier to implement inside PT reactors compared to PV reactors. Currently, the development challenges are to minimize the higher costs of materials needed at the higher temperatures, and to enhance safety and performance margins despite the increased pressures, while retaining the economic advantages.

Also, if the steam reheating is adopted at lower pressures, even higher temperatures (limited only by materials corrosion rates) could allow direct thermochemical production of hydrogen, due to increased reaction rates, which could be utilized in fuel cells, hydrogen vehicles and as part of chemical processing or hydrocarbon upgrading.

The advantages of the single-reheat cycle are:

1) Higher thermal efficiency, which corresponds to that of the current SC thermal power plants.
2) High reliability due to proven state-of-the-art SC turbine technology; and
3) Reduced development costs based on the wide variety of SC turbines manufactured by various companies worldwide.

However, the major disadvantage is that significant changes are required to the reactor design due to the addition of the nuclear steam reheat at lower pressures. Also, the NPP layout is more complex compared to that of the no-reheat cycle.

2.1.3. Double-Reheat Cycle

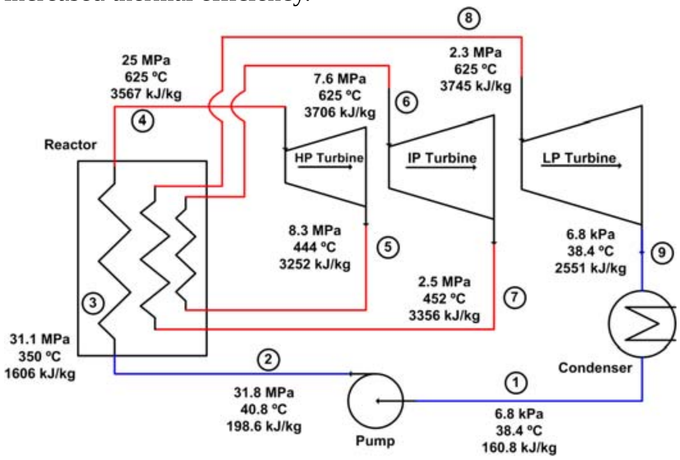
In general, every time the steam in-between turbine stages is re-heated, the thermal efficiency of the cycle is improved. However, the additional reheat also increases the capital cost of the equipment. It has been determined in the past that the use of more than two reheat stages is not practical in SC thermal power plants, because the theoretical improvement in the thermal efficiency from the second reheat is approximately only half of that which resulted from a single reheat. The fact that there are only a few double-reheat turbines currently operating around the world (Mokry et al., 2008) appears to support the finding that there is a diminishing return for every reheat stage added.

The double-reheat cycle arrangement and the corresponding T–s diagram are illustrated in Figs. 4a and 4b, respectively. The corresponding heat-transfer rates are listed in Table 5. In comparison to the single-reheat cycle (for details, see Section 2.1.2) the double-reheat cycle has three turbine sections: 1) HP turbine; 2) IP turbine(s); and 3) LP turbine(s). Moreover, the second steam reheat is added to the reactor.

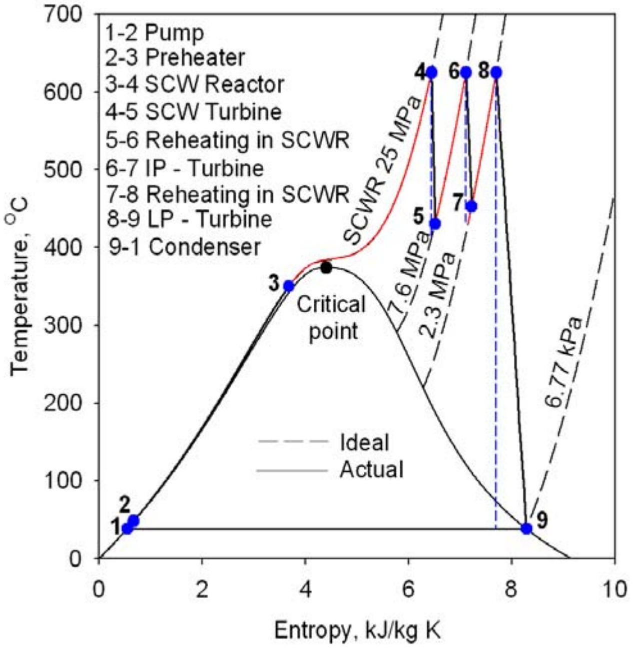
The SC “steam” from the reactor is expanded inside the HP turbine from the supercritical pressure of 25 MPa and temperature of 625°C (Point 4) to an intermediate pressure of 8.3 MPa and temperature of 444°C (Point 5). The subcritical pressure steam leaves the HP turbine in a superheated state and is sent back to the reactor where it is heated from 444°C to 625°C (Point 6). After the reactor reheater, the superheated steam is expanded in the IP turbine(s) to a pressure of 2.5 MPa and temperature of 452°C (Point 7). The subcritical-pressure steam leaves the IP turbine in a superheated state and is sent back to the reactor where it is heated from 452°C to 625°C (Point 8). After the second reactor reheater, the superheated steam is expanded in the LP turbine(s) to sub-atmospheric pressure of 6.8 kPa and temperature of 38.4°C (Point 9), and condensed in the condenser.

For this cycle, the total heat energy added to the cycle is 4248 kJ/kg and the energy rejected through the condenser is 2390 kJ/kg. Thus, the thermal efficiency of the cycle is about 43.7% if the work provided by the pumps is included as a heat source, and 44.1% if the heat added by the pumps is neglected or considered ”free” energy.

The only advantage of the double-reheat cycle is the higher thermal efficiency compared to that of the no-reheat and single-reheat cycles. However, the reactor-core design of a double-reheat steam cycle is even more challenging. Also, the capital cost of introducing another turbine and reactor stage should be carefully weighed against the benefits of the increased thermal efficiency.



(a)



(b)

Fig. 4: Double-Reheat Cycle Layout (a) and Corresponding T–s Diagram (b).

2.2. Cycle with Heat Regeneration

It has been well established that an increased feedwater temperature leads to an improvement in the efficiency of the cycle if heat from within the steam cycle is used to preheat the feedwater. A practical regeneration process can be accomplished by extracting steam from the turbine at various points. Although this steam could have been expanded inside the turbine to produce more useful work, it is used to preheat the feedwater instead.

Table 5: Double-Reheat Cycle Heat-Transfer Rates.

Steam Temperature Main/Reheat/Reheat, °C	**625 / 625 / 625**	
Mass Flow Rate, kg/s	**646**	
Stage	**ΔH, J/kg**	**Q, MW$_{th}$**
Pump	38	24
Preheater	1407	909
Reactor	1961	1267
HP Turbine	–314	–203
Reheater 1	453	293
IP Turbine	–349	–226
Reheater 2	389	251
LP Turbine	–1194	–771
Condenser	–2390	–1544
Efficiency with pump work, %	**43.7**	
Efficiency without pump work, %	**44.1**	

Aside from improving the cycle efficiency, regeneration provides a convenient way of a deaerating the feedwater to prevent corrosion in various components of the plant. Another benefit is the minimization of the volume flow rate of steam at the final stages of the turbine.

The number of feedwater heaters is usually determined based on an economical evaluation. From a thermodynamic point of view, an infinite number of heaters would maximize the cycle efficiency. However, this is not possible in the practical world. The optimum number of heaters for a modern SC plant has been determined between 8 and 10. They are classified as LP heaters, Deaerators (mixing chambers) and HP heaters depending on the operating pressure and the type of heat exchanger used.

As previously mentioned, the exact point where extraction steam is taken from plays an important role in the efficiency of the thermal cycle and also depends on the turbine design.

It is difficult to show the benefit of the regenerative-feedwater heating in a T–s diagram, because the flow rates at the various points in the cycle are not the same and hence, the areas within the T–s diagram do not represent the total work and heat rejection of the cycle. For the same reason, it is not meaningful to show the heat sources and sinks in Table 6 on the basis of energy per unit mass (kJ/kg). Table 6 is based on a total useful heat of 1200 MW_{th}.

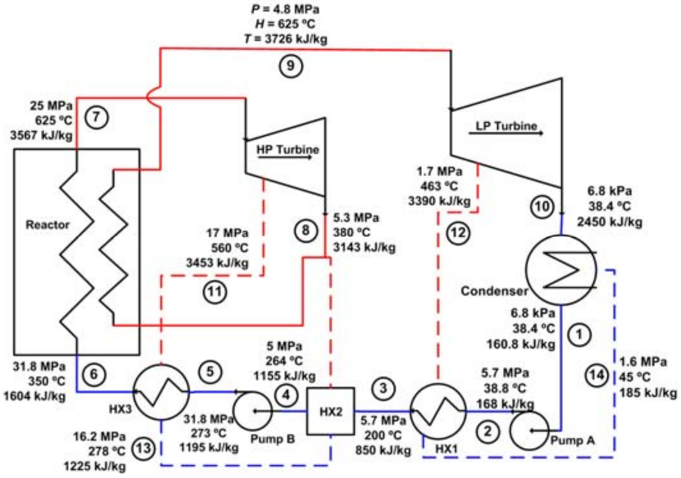


Fig. 5: Single-Reheat Cycle with Heat Regeneration through Single Deaerator and Two Feedwater Heaters.

Table 6: Mass-Flow and Heat-Transfer Rates through System Components.

Steam Temperature Main / Reheat, °C	**625 / 625**	
Stage	***m*, kg/s**	***Q*, MW_{th}**
Pumps (total)	N/A	48
Feedwater Heater (HX1)	754	514
Deaerator	754	230
Feedwater Heater (HX2)	1058	433
Reactor	1058	2076
HP Turbine	1058	–388
Reheater	864	440
LP Turbine	754	–812
Condenser	594	–1364
Efficiency with pump work, %	**46.8**	
Efficiency without pump work, %	**47.7**	

The arrangement analyzed below involves three feedwater heaters: one LP heater, one deaerator and one HP heater (for details, see Fig. 5 and Table 6). Steam is extracted from the HP turbine and used to heat the feedwater flowing through the Heat Exchanger (HX) 3 (closed-type feedwater heater). The LP turbine supplies extraction steam for the LP feedwater heater (HX1). Also, a fraction of the steam exhausted from the HP turbine is diverted to heat the water in the deaerator (HX2).

Table 6 summarizes the heat transfer rates and thermal efficiency associated with this cycle (see Fig. 5). . The total heat added to the cycle is approximately 2564 MW_{th}. At the same time, the heat rejected in the condenser is approximately 1364 MW_{th}. Thus, the thermal efficiency is about 46.8% if the work provided by the pumps is included as a heat source, and 47.7% if the heat added by the pumps is neglected or considered ”free” energy.

As can be seen from Tables 4 and 6 the thermal efficiencies of the regenerative single-reheat cycles are significantly higher than those for the single-reheat cycle without regeneration. The optimum number of feedwater heaters would have to be determined through a cost-benefit analysis.

The regenerative cycle presented in this section represent a viable basis for a future SCW NPP. The optimum number of regenerative heaters should be investigated – it is likely going to be higher than what was presented herein for illustration of efficiency trends (for details, see Duffey et al., 2008). However, it is clear that the calculated thermal efficiencies with regenerative heating are significantly higher than currently operating NPPs. The increase in efficiency is high enough to justify the increased costs associated with the design, construction and operation of this new type of SCW NPPs.

3. CO-GENERATION OF HYDROGEN AT SCW NPP

SCWRs operating at higher temperatures (550 – 625°C) can facilitate an economical co-generation of hydrogen through thermo-chemical cycles (particularly, the copper-chlorine cycle) or direct high-temperature electrolysis. In general, a SCW NPP with the co-generation of hydrogen should operate at an invariable maximum power, which will be independent of an electrical load. When the electrical load decreases, the SCW NPP will produce more hydrogen and vice versa, keeping the reactor at a constant power. Thus, SCW NPP with hydrogen co-generation will operate at the most efficient level.

Currently, UOIT in collaboration with AECL is developing the copper-chlorine cycle with a maximum temperature in the cycle of up to 500°C. Therefore, using the high-temperature heat from a SCWR to heat water in the hydrogen-production loop is a viable option. Heat exchangers of a recuperator-type have to be used for this purpose (for details, see Fig. 6). The arrangement of a SCW NPP with hydrogen co-generation is more complicated than the regular SCW NPP cycle.

6. CONCLUSIONS

The following conclusions can be made:

1. The vast majority of the modern SC turbines are single-reheat-cycle turbines. Just a few double-reheat-cycle SC turbines have been manufactured and put into operation. However, despite their efficiency benefit double-reheat-turbines have not been considered economical.

2. Major inlet parameters of the current and upcoming single-reheat-cycle SC turbines are: the main or primary SC “steam” – pressure of 24 – 25 MPa and temperature of 540 – 600°C; and the reheat or secondary subcritical-pressure steam – P = 3 – 5 MPa and T = 540 – 620°C.
3. Usually, inlet temperatures of the main SC “steam” and the reheat subcritical-pressure steam are the same or very close (for example, 538/538°C; 566/566°C; 579/579; 600/600°C or 538/566°C; 566/593; 600/620°C).
4. In order to maximize the thermal-cycle efficiency of the SCW NPPs it would be beneficial to include nuclear steam reheat. Advantages of a single-reheat cycle in application to SCW NPPs are:
    - High thermal efficiency (45 – 50%), which is the current level for SC thermal power plants and close to the maximum thermal efficiency achieved in the power industry at combined-cycle power plants (up to 60%).
    - High reliability through proven state-of-the-art turbine technology; and
    - Reduced development costs accounting on wide variety of SC turbines manufactured by companies worldwide.

    The major disadvantage of a single-reheat cycle implementation in SCW NPPs is the requirement for significant changes to the reactor-core design due to the addition of the nuclear-steam reheat at lower pressures.
5. Four simplified SCW NPP thermodynamic cycles (main “steam” parameters – pressure of 25 MPa and temperature of 625^{o}; reheat steam parameters – pressure of 2.3 – 7.6 MPa and temperature of 625^{o}C (700 ^{o} C)) and the corresponding arrangements have been investigated in terms of their thermal efficiency, assuming isentropic turbine efficiencies of 88% for all turbine sections and 84% polytropic efficiency for all pumps: (I) cycles without heat regeneration: (1) no-reheat cycle – 40.5% thermal efficiency; (2) single-reheat cycle – 42.6% thermal efficiency; and (3) double-reheat cycle – 43.7% thermal efficiency; and (II) cycles with heat regeneration: (4) single-reheat cycle with three feedwater heaters – 46.8% thermal efficiency.
6. Based on the abovementioned analysis the single-reheat cycle with heat regeneration and the corresponding arrangement appear most advantageous as a basis for a SCW NPP with the co-generation of hydrogen.

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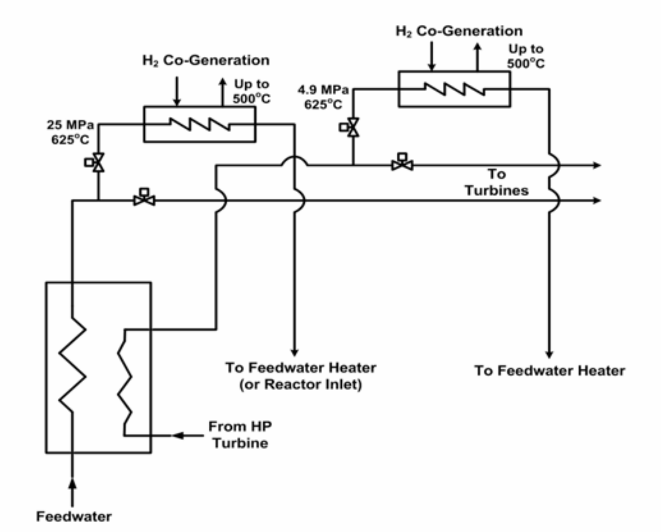

Fig. 6: Single-Reheat Cycle with Heat Regeneration and Co-Generation of Hydrogen (Shown only the Part Related to Hydrogen Co-Generation).

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