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Part 4
SUPERCRITICAL WATER-COOLED NUCLEAR-REACTOR CONCEPTS: REVIEW AND STATUS

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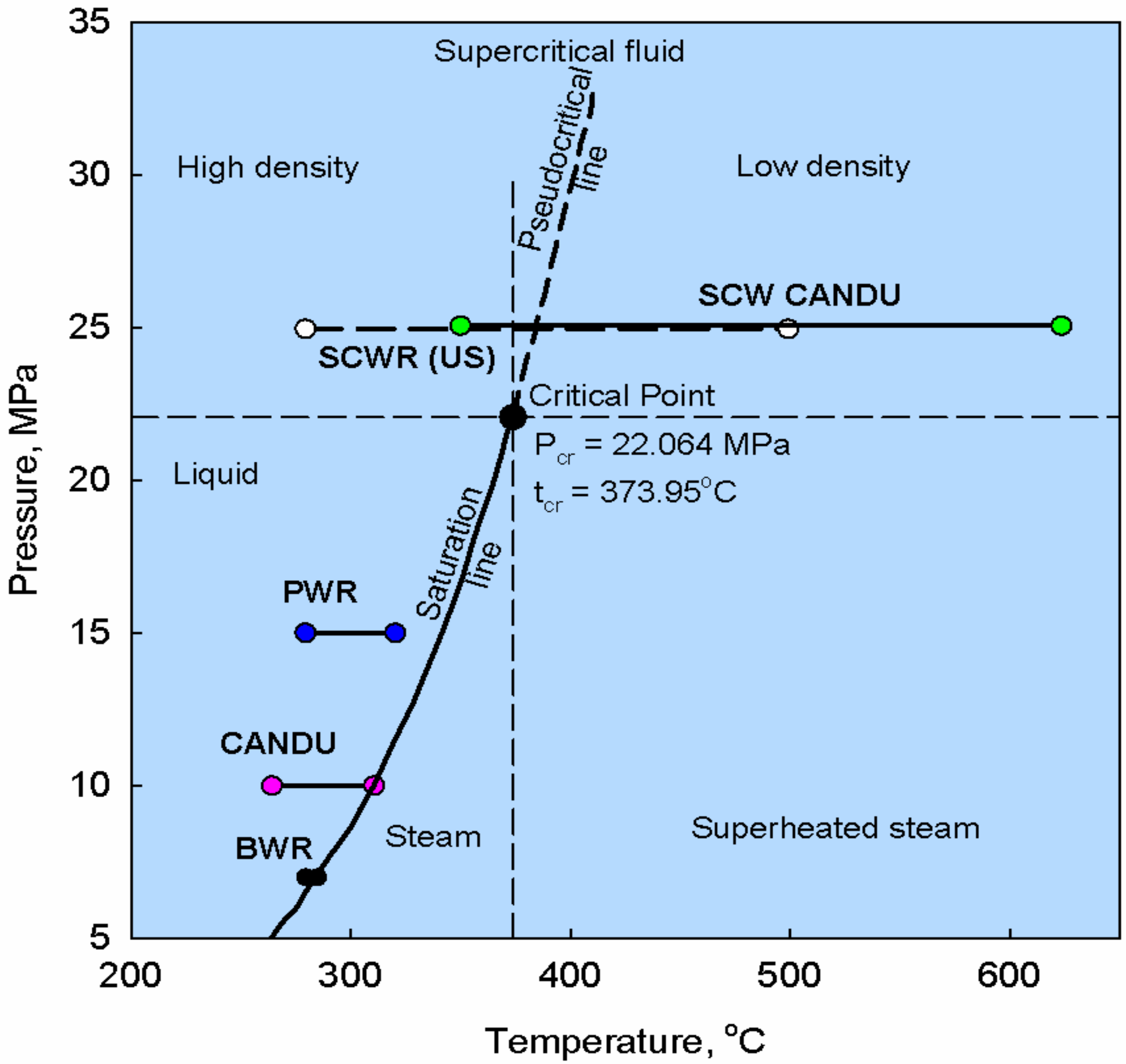
Part 4
Supercritical Water-Cooled Nuclear-Reactor Concepts: Review and Status

Pressure-temperature diagram of water with typical operating conditions of SCWRs, PWRs, CANDU-6 reactors and BWRs



Currently, USA don't develop an SCWR concept. However, the shown parameters are typical to other SCWR concepts, for example, HPLWR or Super LWR.

Basis for Development SCWRs

1. Pressurized Water **Reactor's** technology (current pressures up to 16 MPa)
2. Boiling Water **Reactor's** once-through or direct cycle
3. Supercritical **"steam" generator's** technology and turbines from coal-fired power plants
4. Experience of nuclear steam superheating at several nuclear power plants (Russia and USA)

Types of SCWRs

The SCWR concepts follow two main types, the use of either (a) a large reactor pressure vessel with a 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 or channels analogous to conventional CANDU® and RBMK nuclear reactors.

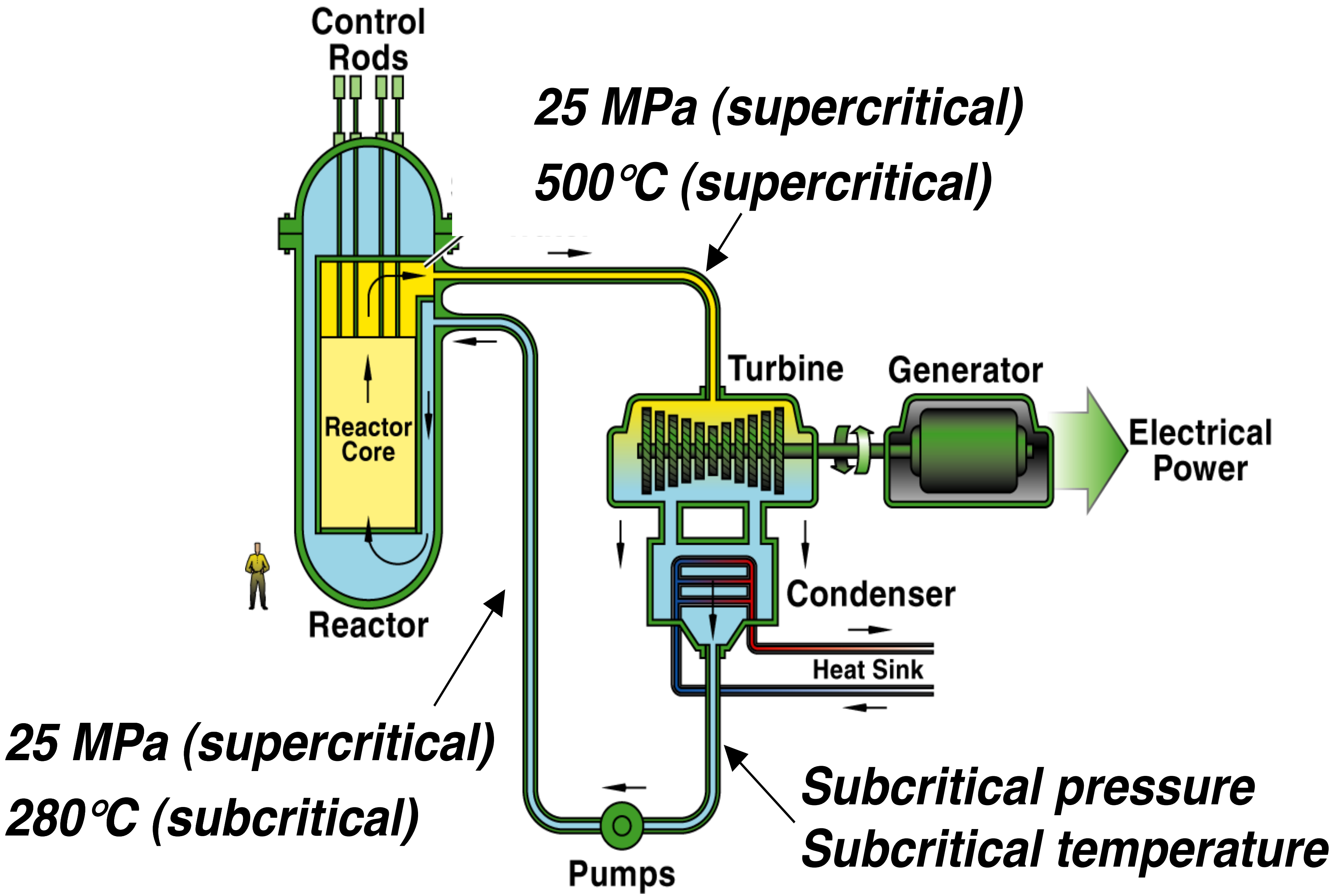
The pressure-vessel SCWR design is developed largely in the USA, EU, Japan (Oka et al. 2010), Korea and China and allows using a traditional high-pressure circuit layout.

The pressure-channel SCWR design is developed largely in Canada and in Russia to avoid a thick wall vessel.

The vast majority SCWR concepts are thermal spectrum reactors. However, a fast neutron spectrum core is also possible (Oka et al. 2010).

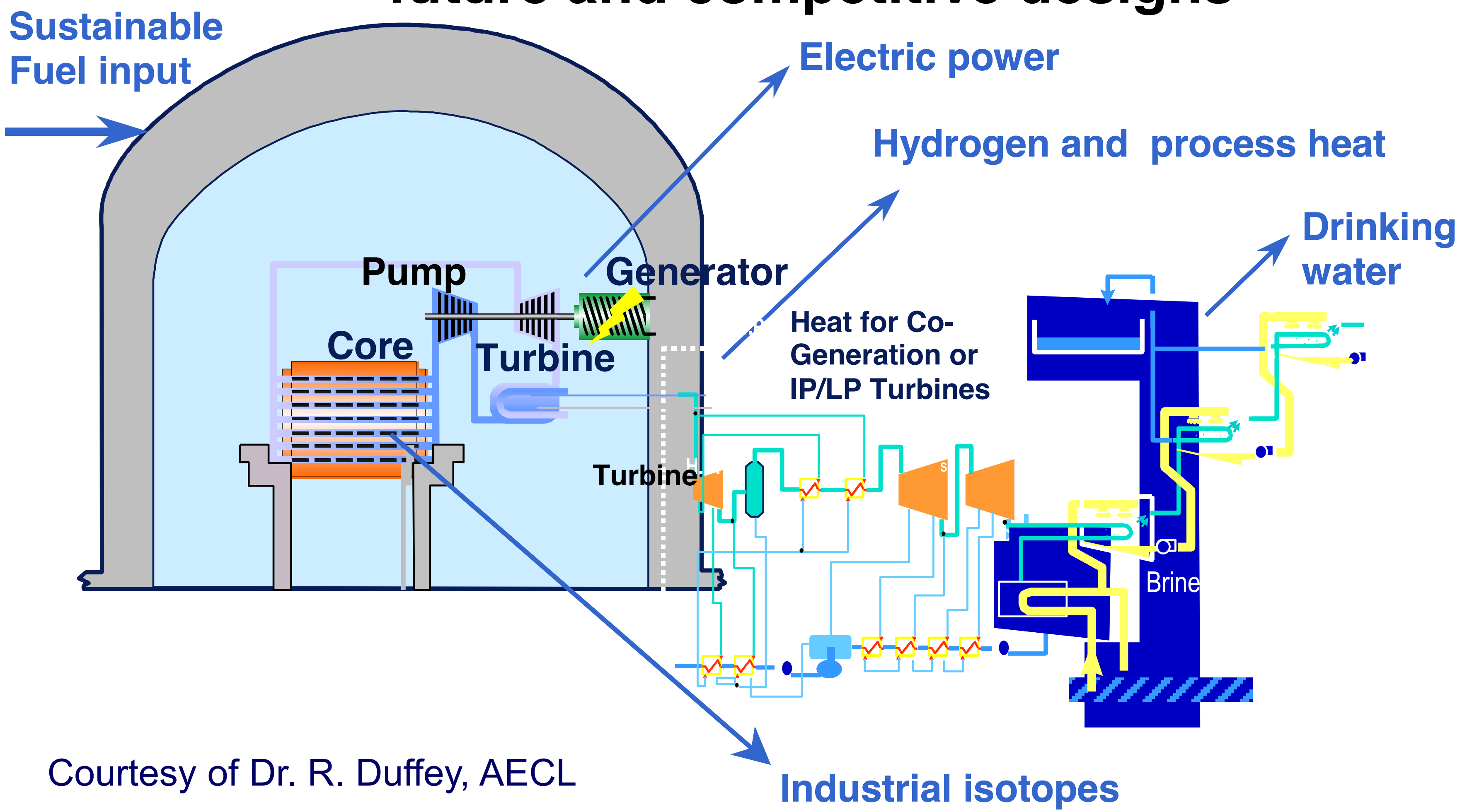
CANDU® (CANada Deuterium Uranium) is a registered trademark of Atomic Energy of Canada Limited (AECL).

Schematics of Pressure-essel SCWR



Pressure-Channel SCW CANDU Reactor Concept

Multiple products are key to sustainable future and competitive designs

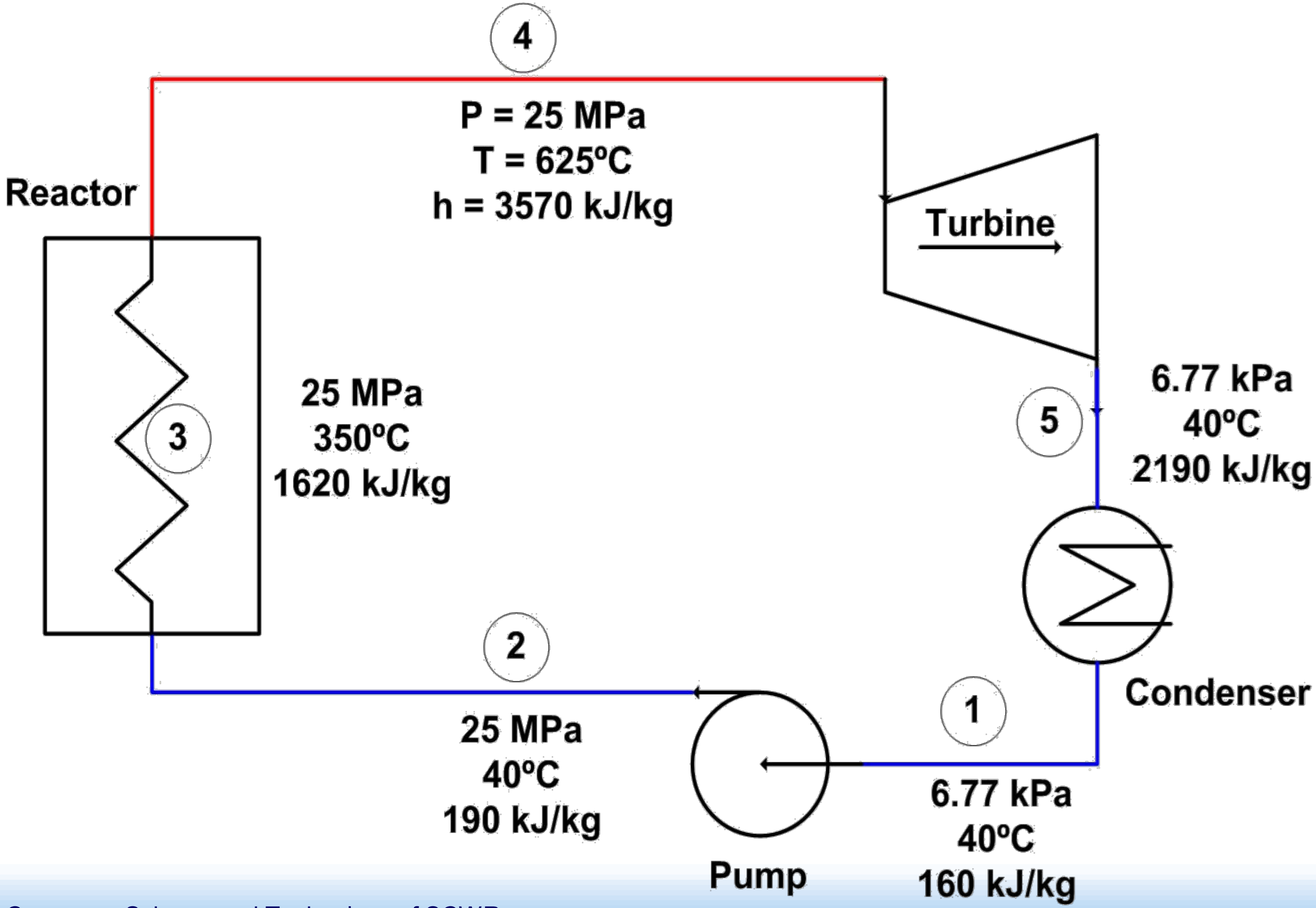


Courtesy of Dr. R. Duffey, AECL

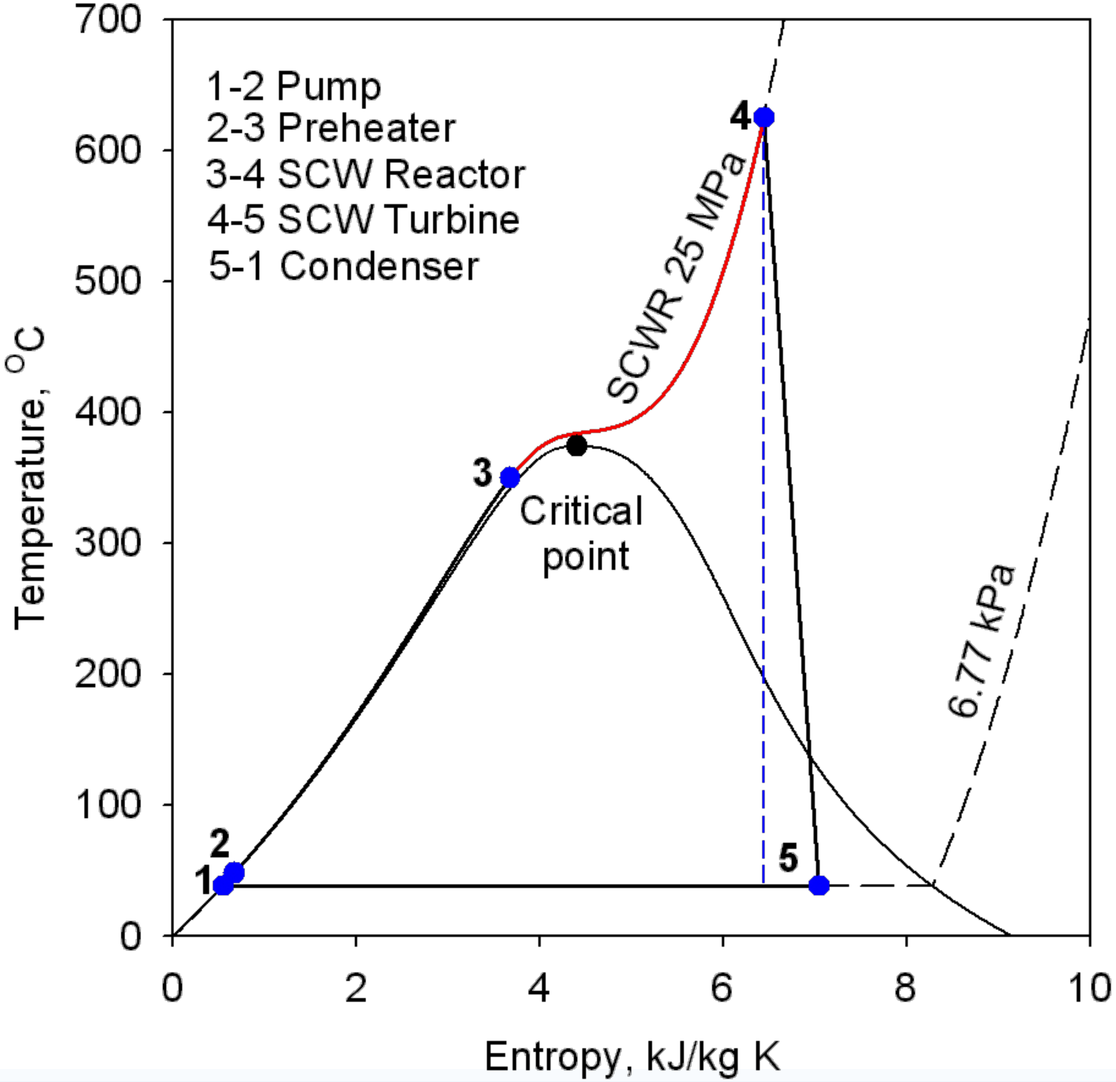
Simplified cycles of SCP thermal & NPPs

(based on Pioro I., Zirn U., Duffey R., Naidin M., Mokry S., Gospodinov Ye. and Baig F., 2008. Supercritical Water-Cooled Nuclear Reactors: Thermodynamic-Cycles Options, Proceedings of the 6th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics (HEFAT-2008), June 30 - July 2, Pretoria, South Africa, Paper #PI1.

No-Reheat Cycle



No-Reheat Cycle



No-Reheat Cycle

Stage	Heat Transfer Rate (MW)
Preheater	1255
Reactor	1705
Turbine	-1200
Condenser	-1760

- Q_{in} total = 2960 MW_{th}
- W_{useful} = 1200 MW_{el}
- Q_{loss} = 1760 MW_{th}
- **Thermal Efficiency = 40%**

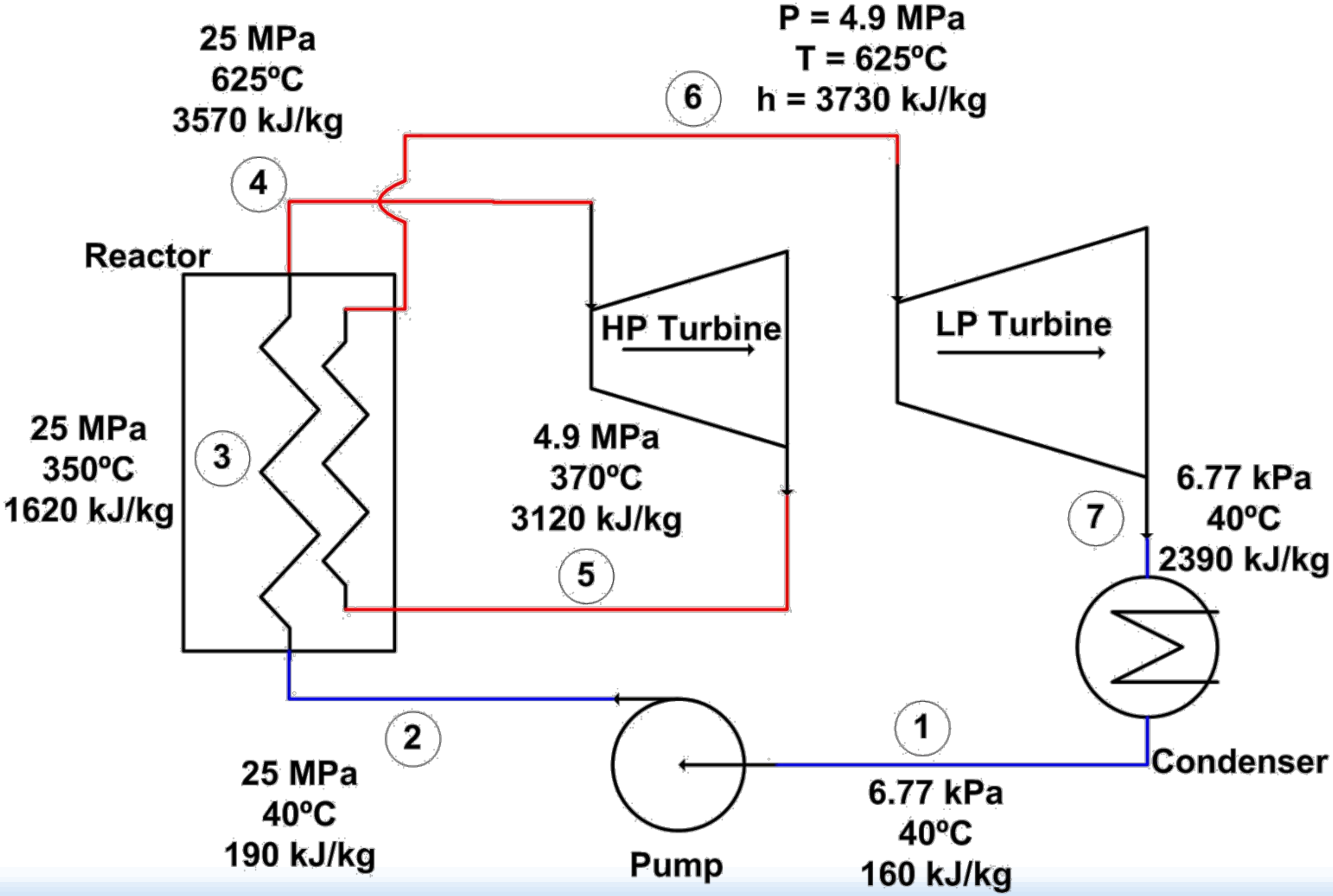
Advantages

- Simplified layout
- Lower capital cost

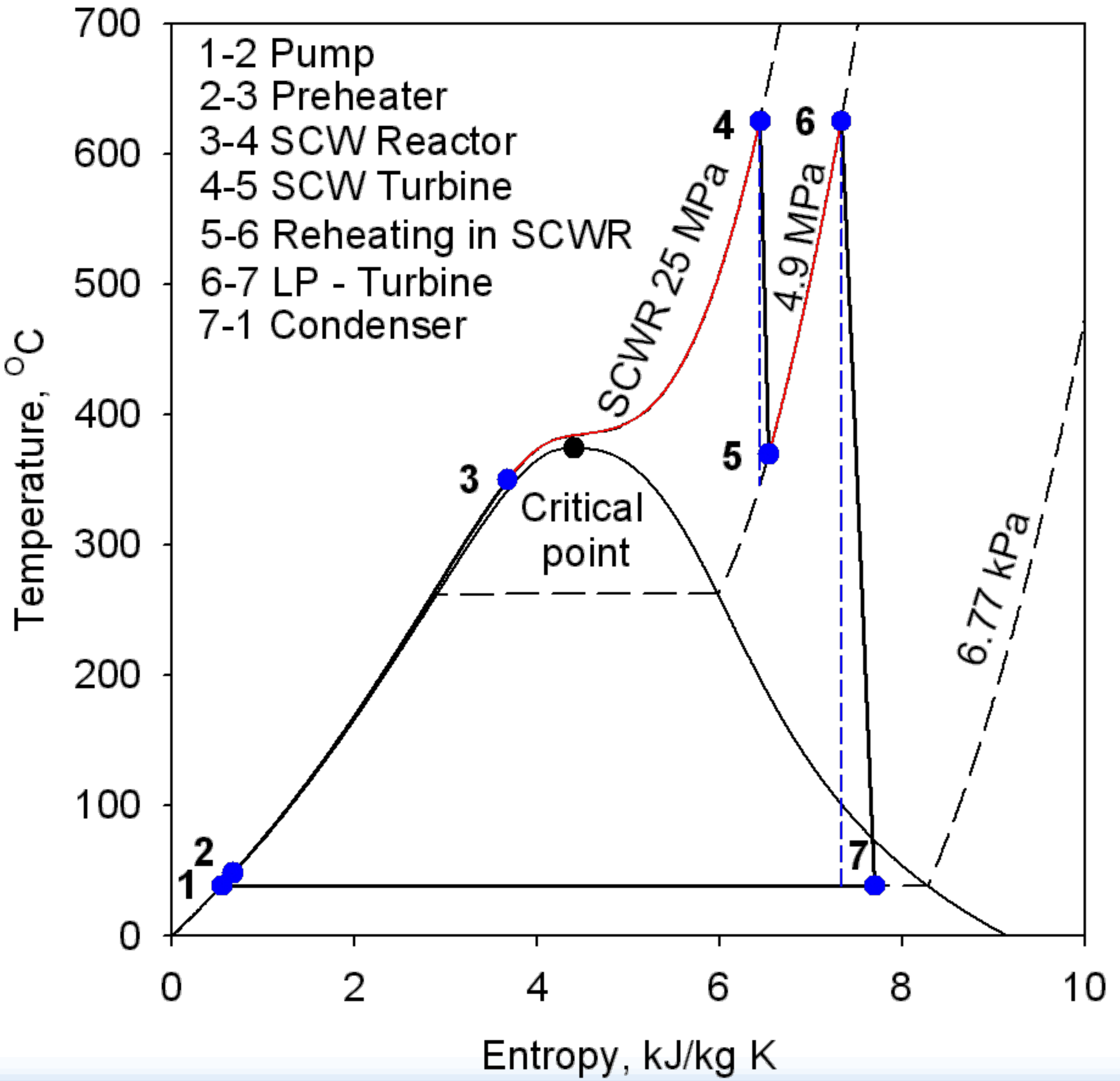
Disadvantages

- Lower efficiency
- There are no SCW turbines without reheat

Single-Reheat Cycle



Single-Reheat Cycle



Single-Reheat Cycle

Stage	Heat Transfer Rate (MW)
Preheater	970
Reactor	1320
HP Turbine	-300
Reheater	408
LP Turbine	-900
Condenser	-1500

- Q_{in} total = 2700 MW_{th}
- W_{useful} = 1200 MW_{el}
- Q_{loss} = 1500 MW_{th}
- **Thermal Efficiency = 45%**

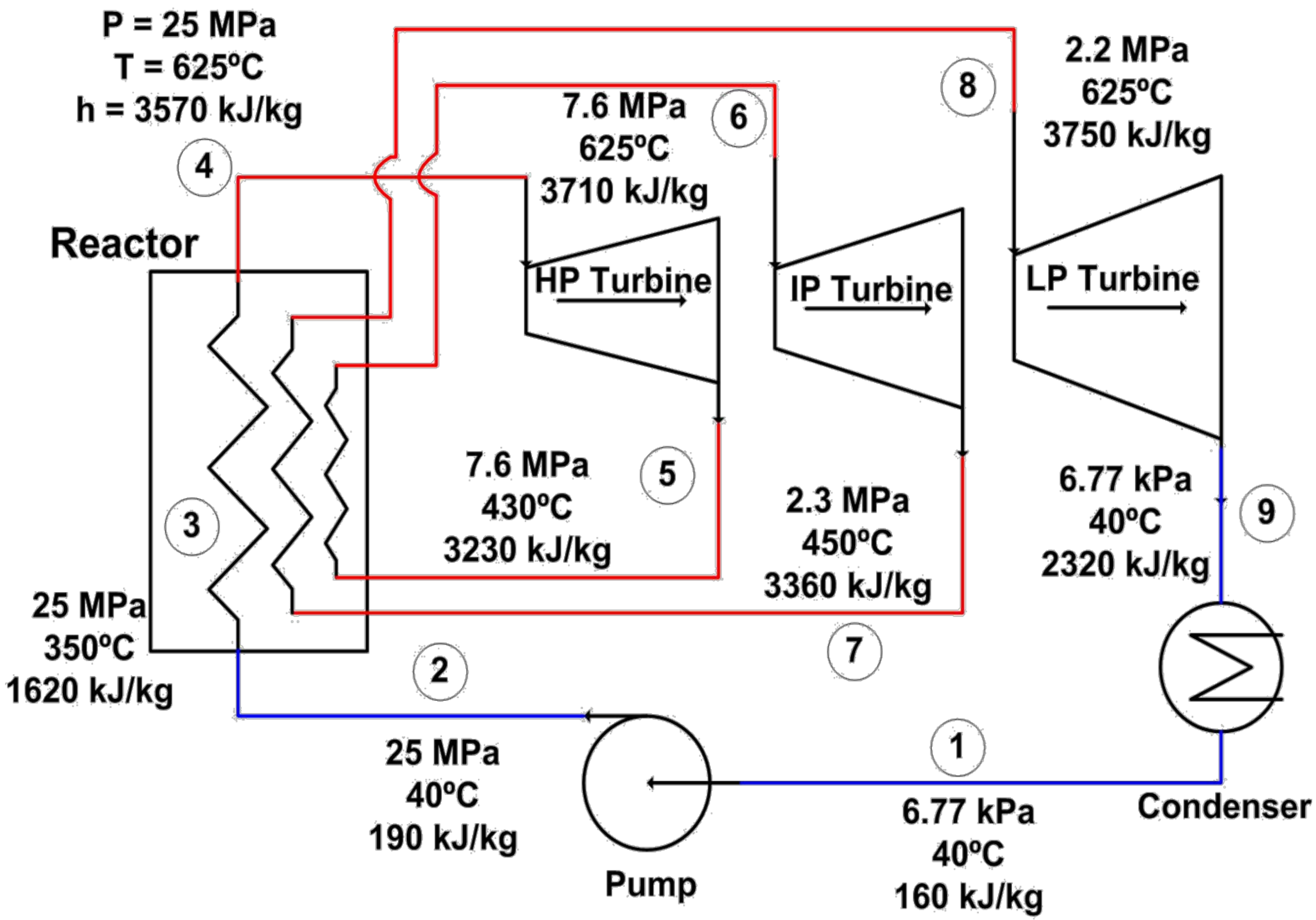
Advantages

- Higher thermal efficiency
- Single-reheat turbines are widely used at SCW thermal power plants

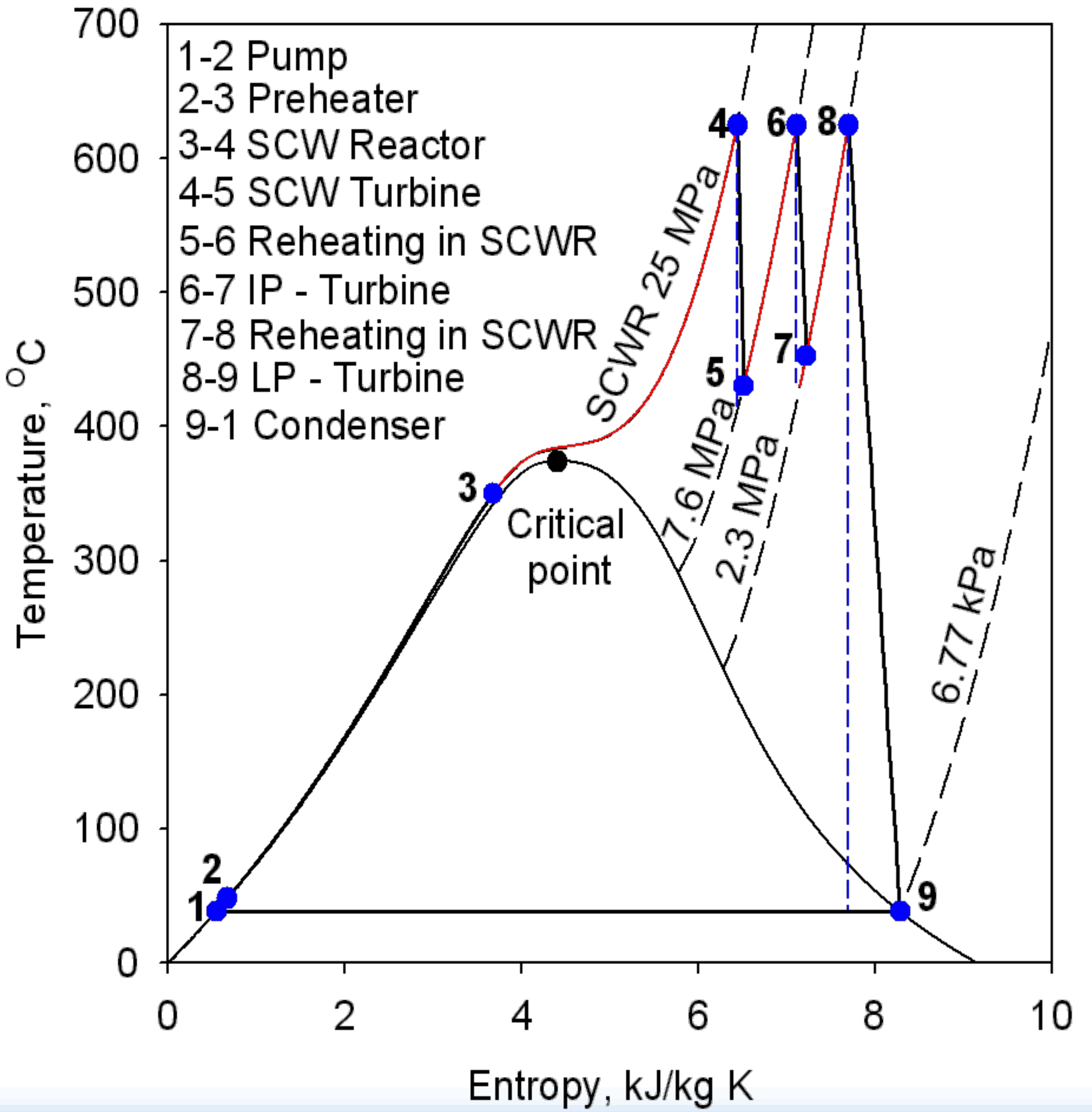
Disadvantages

- Requires nuclear steam reheat

Double-Reheat Cycle



Double-Reheat Cycle



Double-Reheat Cycle

Stage	Heat Transfer Rate (MW)
Preheater	820
Reactor	1115
HP Turbine	-192
Reheater 1	275
IP Turbine	-200
Reheater 2	220
LP Turbine	-810
Condenser	-1230

- Q_{in} total = 2430 MW_{th}
- W_{useful} = 1200 MW_{el}
- Q_{loss} = 1230 MW_{th}
- **Thermal Efficiency = 49%**

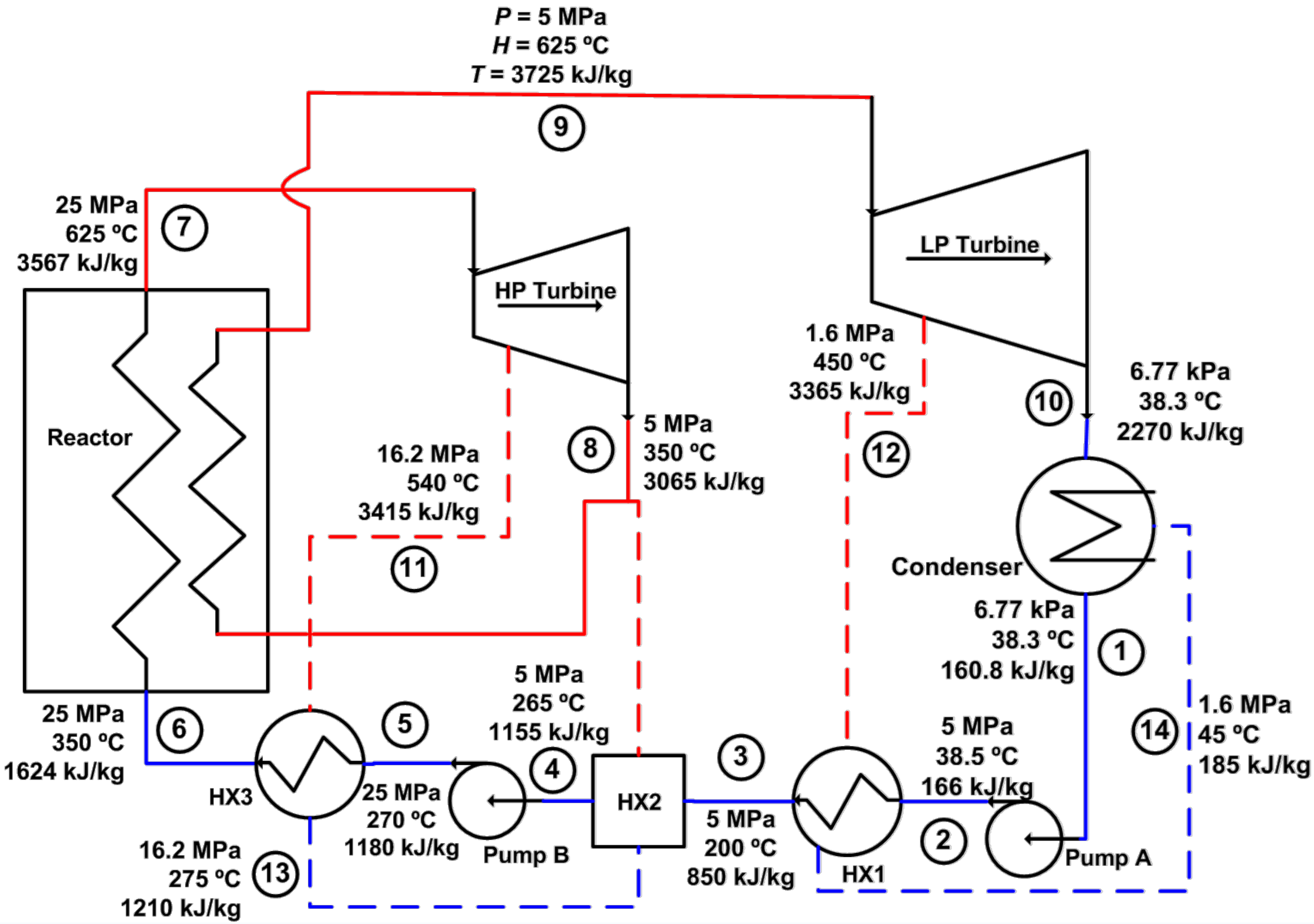
Advantages

- Highest thermal efficiency

Disadvantages

- Requires double nuclear steam reheat
- There are few SCW double-reheat turbines

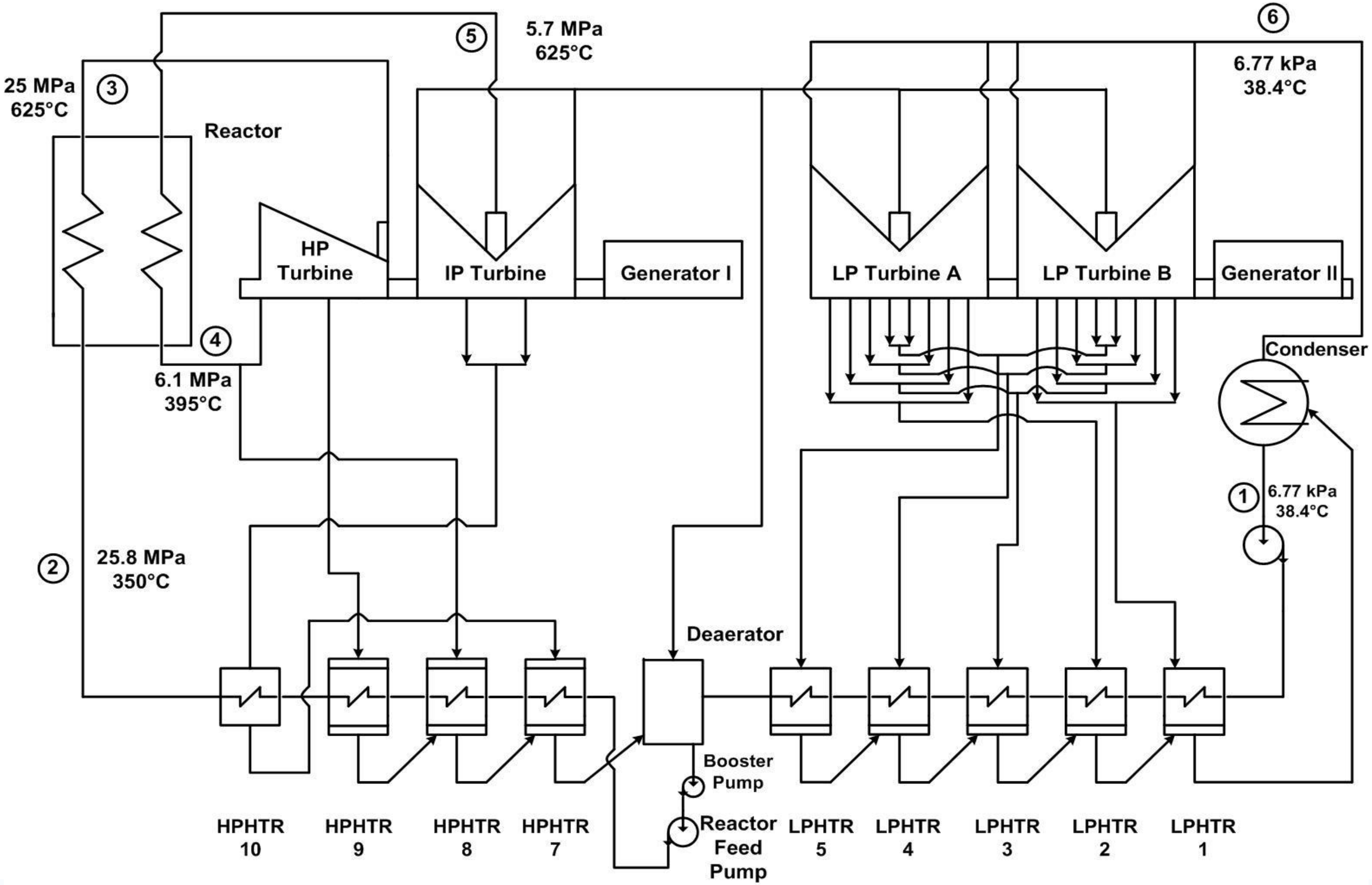
Single-Reheat Cycle with Heat Regeneration



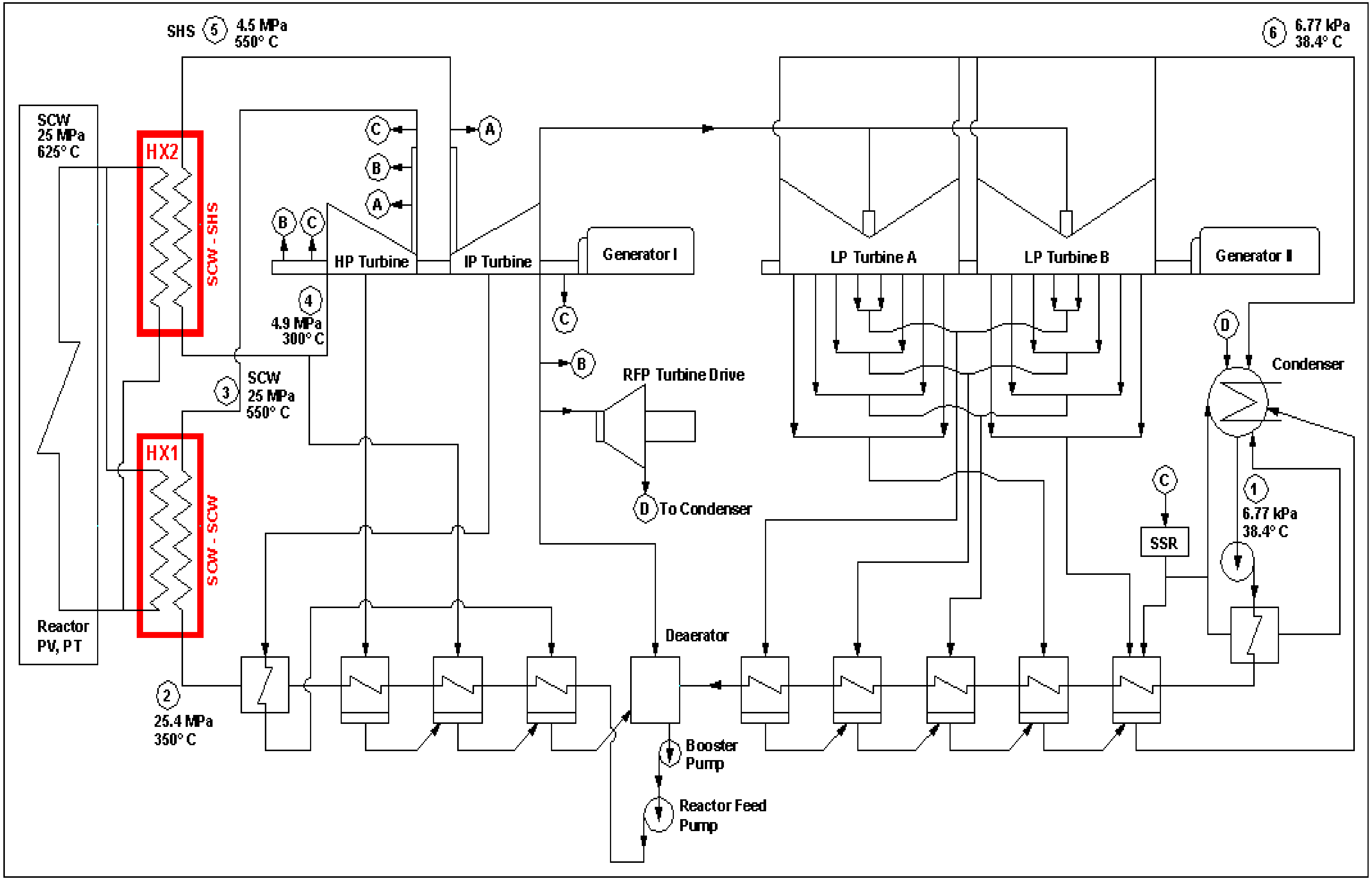
Single-Reheat Cycle with Heat Regeneration

Steam Temperature: Main / Reheat, °C	625 / 625	
Stage	m, kg/s	Q, MW_{th}
Pumps (total)	N/A	27
Feedwater Heater (HX1)	650	444
Deaerator	650	199
Feedwater Heater (HX2)	937	416
Reactor	937	1821
HP Turbine	937	-404
Reheater	749	428
LP Turbine	650	-796
Condenser	508	-1076
Efficiency, %	52.7	

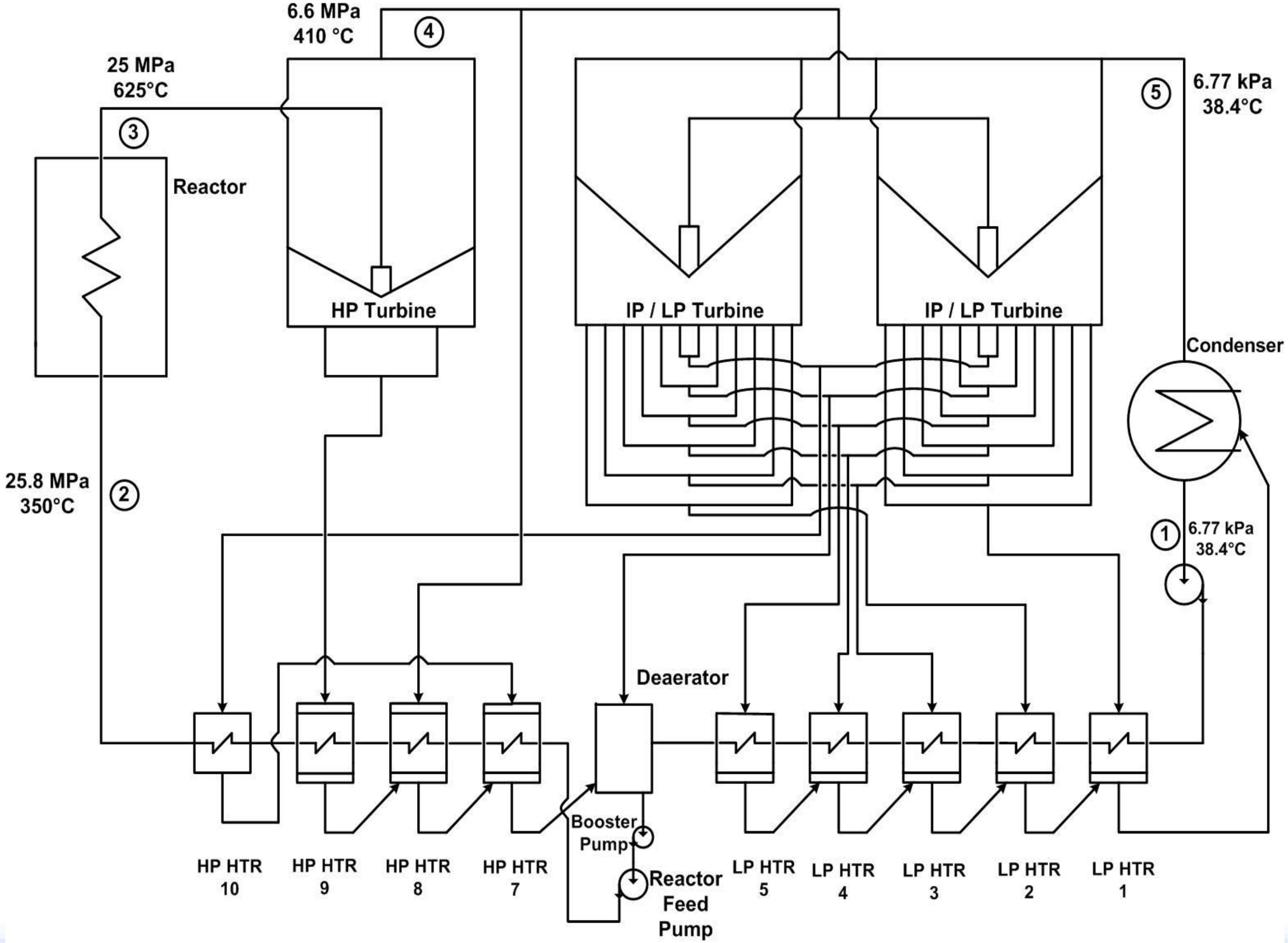
Schematic of single-reheat regenerative thermodynamic cycle for 1200 MW_{el} PT SCW NPP



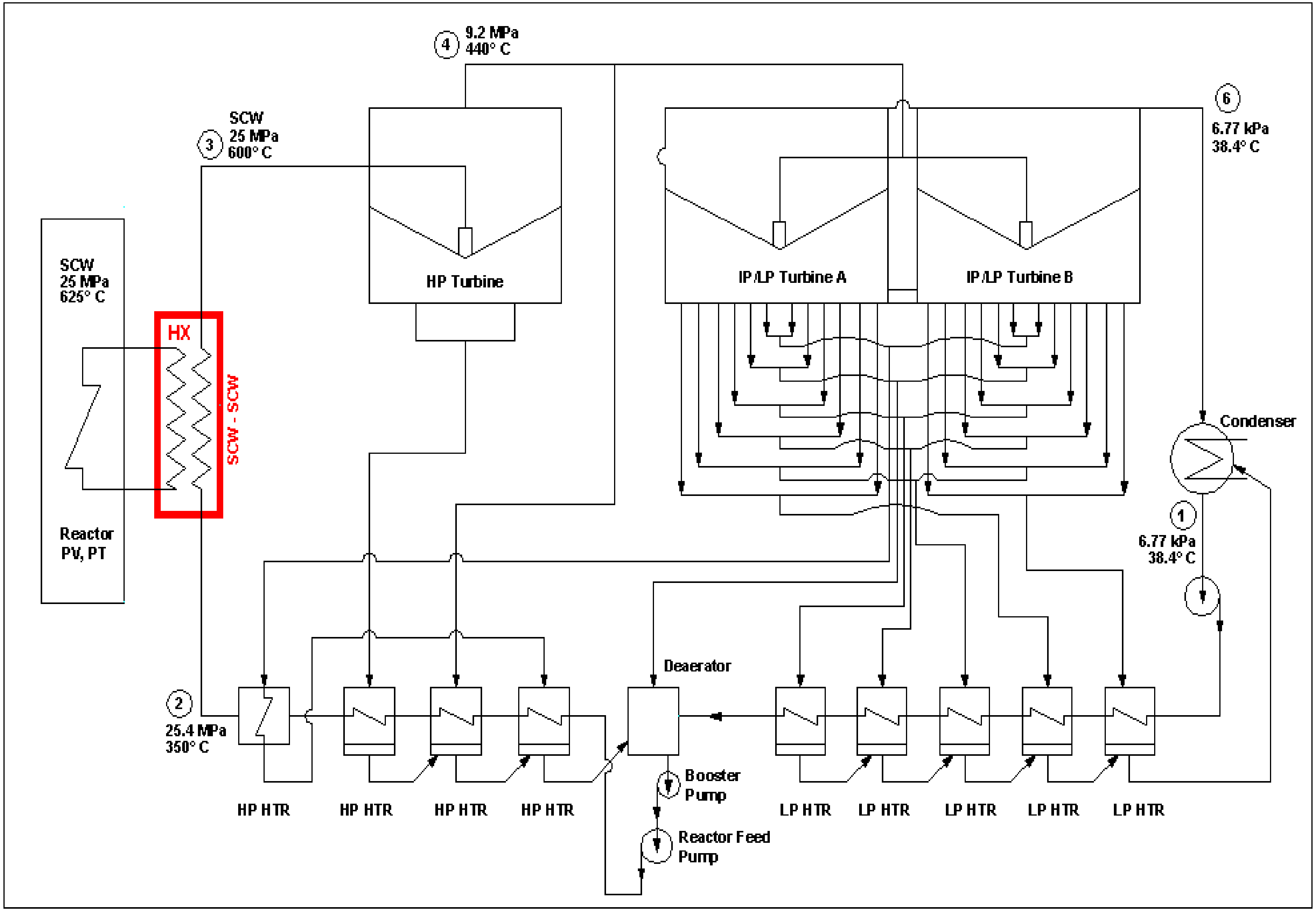
Schematic of in-direct single-reheat regenerative thermodynamic cycle for 1200 MW_{el} PV or PT SCW NPP (prepared by H. Thind, UOIT)



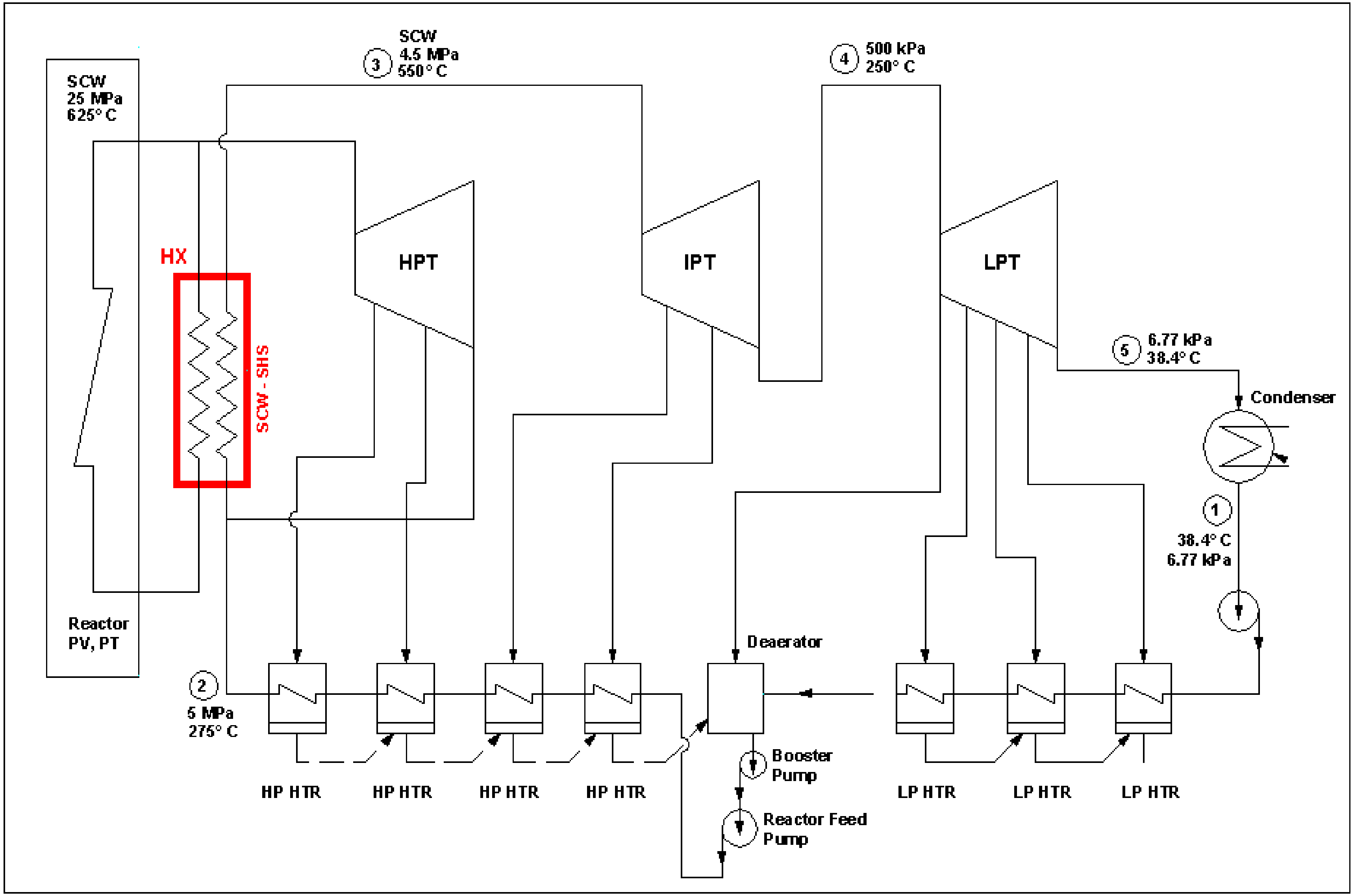
Schematic of direct no-reheat regenerative thermodynamic cycle for 1200 MW_{el} PV or PT SCW NPP



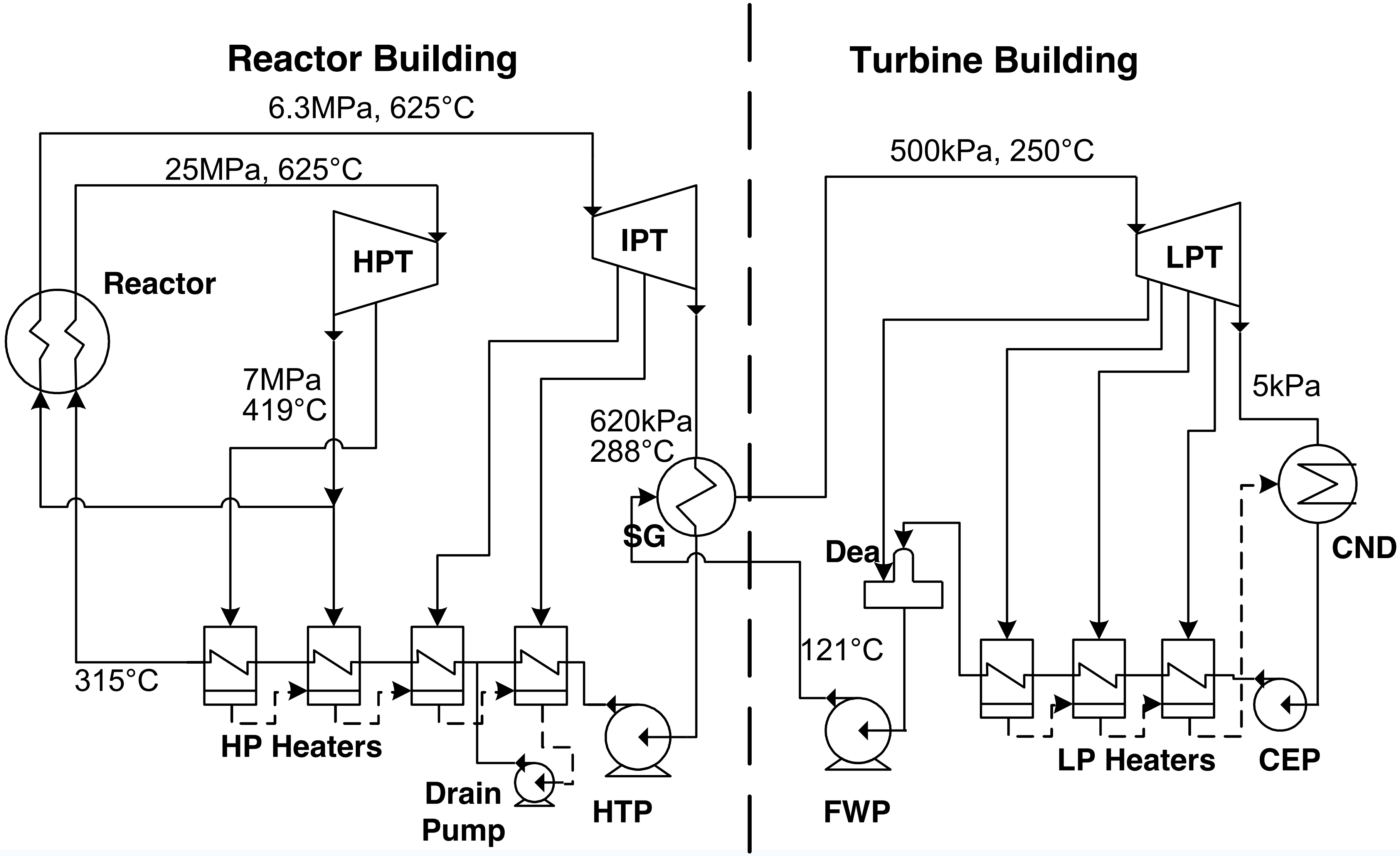
Schematic of in-direct no-reheat regenerative thermodynamic cycle for 1200 MW_{el} PV or PT SCW NPP (prepared by H. Thind, UOIT)



Schematic of dual no-reheat primary (SCW) loop and single-reheat secondary (superheated steam) loop regenerative thermodynamic cycle for 1200 MW_{el} PV or PT SCW NPP (prepared by H. Thind, UOIT)



Schematic of dual single-reheat regenerative thermodynamic cycle for 1200 MW_{el} PT SCW NPP (AECL): High-pressure units located in Reactor Building for increased safety.



Selected parameters of proposed SCW NPP direct cycles

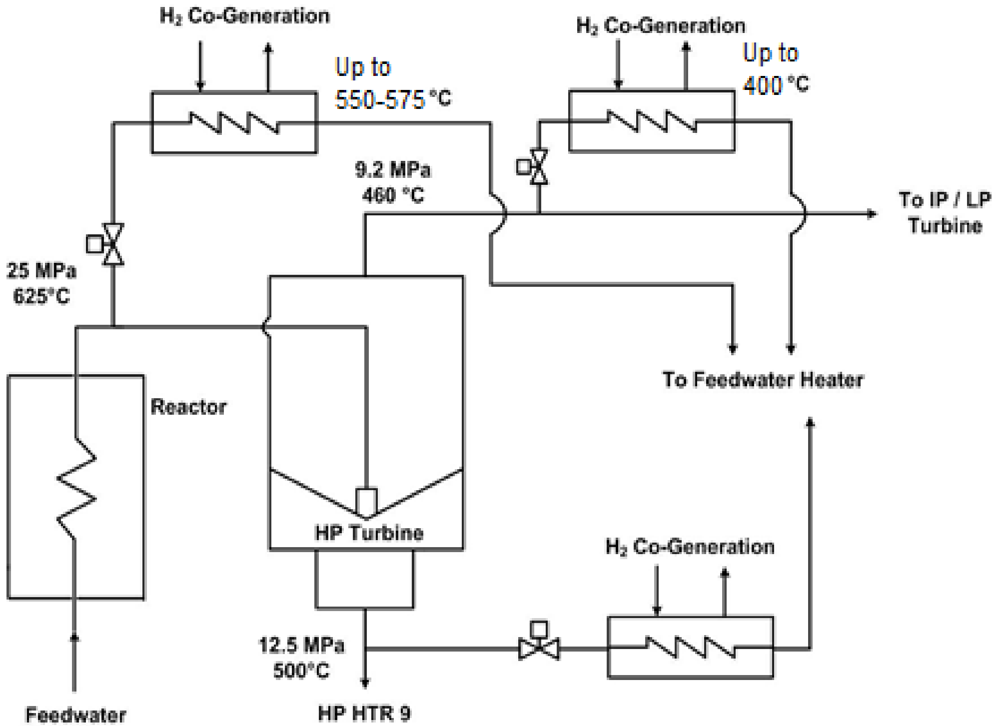
Parameters	Unit	Description / Value	Description / Value
Cycle type	–	Direct Single-Reheat	Direct No-Reheat
Reactor type	–	Pressure Tube	
Reactor spectrum	–	Thermal	
Fuel	–	UO_2 (ThO_2)	
Cladding material	–	Inconel or Stainless steel	
Reactor coolant	–	H_2O	
Moderator	–	D_2O	
Power Thermal	MW_{th}	2300	2340
Power Electrical	MW_{el}	1200	1200
Thermal Efficiency	%	**52***	**51***
Pressure of SCW at inlet	MPa	25.8	25.8
Pressure of SCW at outlet (estimated)	MPa	25	25
T_{in} coolant (SCW)	°C	350	350
T_{out} coolant (SCW)	°C	625	625
Pressure of SHS at inlet	MPa	6.1	–
Pressure of SHS at outlet (estimated)	MPa	5.7	–
T_{in} coolant (SHS)	°C	400	–
T_{out} coolant (SHS)	°C	625	–
Power thermal SCW channels	MW_{th}	1870	2340
Power thermal SRH channels	MW_{th}	430	–
Power thermal / SCW channel	MW_{th}	8.5	8.5
Power thermal / SRH channel	MW_{th}	5.5	–
# of fuel channels (total)	–	300	270
# of SCW channels	–	220	270
# of SRH channels	–	80	–
Total flow rate of SCW	kg/s	960	1190
Total flow rate of SHS	kg/s	780	–

***In general, indirect cycles will have lower thermal efficiencies up to several per cent than those of the corresponding direct cycles.**

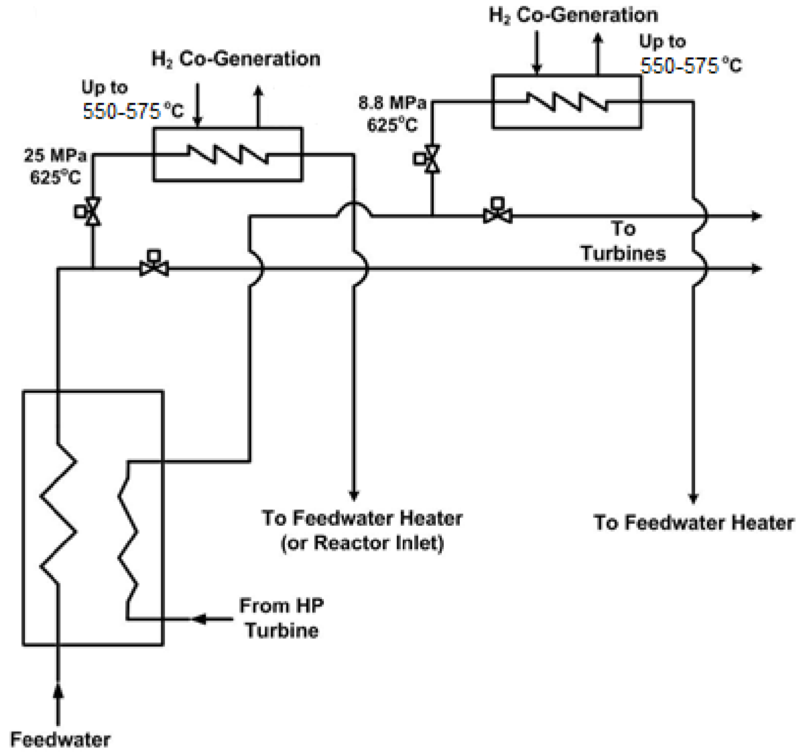
Chemical reaction steps and basic parameters of the copper-chlorine cycle for hydrogen co-generation

Step	Reaction	Temperature Range (°C)	Feed/Output	
1	$2Cu(s) + 2HCl(g) \rightarrow CuCl(l) + H_2(g)$	430 – 475	Feed: Output:	Electrolytic Cu + dry HCl + Q H_2 + CuCl(l) salt
2	$2CuCl(s) \rightarrow 2CuCl\,(aq) \rightarrow CuCl_2(aq) + Cu(s)$	Ambient (electrolysis)	Feed: Output:	Powder/granular CuCl and HCl + V Cu and slurry containing HCl and $CuCl_2$
3	$CuCl_2(aq) \rightarrow CuCl_2(s)$	<100	Feed: Output:	Slurry containing HCl and $CuCl_2$ + Q Powder/granular $CuCl_2$ + H_2O/HCl vapors
4	$2CuCl_2(s) + H_2O(g) \rightarrow CuO{*}CuCl_2(s) + 2HCl(g)$	400	Feed: Output:	Powder/granular $CuCl_2$ + $H_2O(g)$ + Q Powder/granular CuO*$CuCl_2$ + 2HCl (g)
5	$CuO{*}CuCl_2(s) \rightarrow 2CuCl(l) + 1/2O_2(g)$	500	Feed: Output:	Powder/granular CuO* $CuCl_2(s)$ + Q Molten CuCl salt + oxygen
Q - thermal energy, V - electrical energy				

Heat-extraction points for H_2 co-generation associated with proposed no-reheat SCW NPP



Heat-extraction points for H_2 co-generation associated with proposed single-reheat SCW NPP



CONCLUSIONS

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.

Major inlet parameters of the current and upcoming single-reheat-cycle SC turbines are: the main or primary SC "steam" – pressure of 25 – 30 MPa and temperature of 600 – 625°C; and the reheat or secondary subcritical-pressure steam – P = 3 – 7 MPa and T = 600 – 625°C.

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:

1) High thermal efficiency (about 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 55%).
2) High reliability through proven state-of-the-art turbine technology; and
3) 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 addition of the nuclear steam-reheat channels at subcritical pressures.

Based on the abovementioned analysis, the direct or in-direct single-reheat cycles with heat regeneration and the corresponding arrangement appear to be the most advantageous as a basis for an SCW NPP. However, other cycles, for example, dual cycles might be considered.

References

1. Pioro, I.L. and Duffey, R.B., Heat Transfer and Hydraulic Resistance at Supercritical Pressures in Power Engineering Applications, ASME Press, New York, NY, USA, 2007, 334 pages.
2. Oka, Yo., Koshizuka, S., Ishiwatari, Y. and Yamaji, A., 2010. Super Light Water Reactors and Super Fast Reactors, Springer, 416 pages and 200 figures.

…Thank you for your attention!

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