Conceptual Design of Nuclear CCHP Using Absorption Cycle

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Introduction

- **Purpose**
  - Method to utilize surplus energy while maintaining the operating conditions of the NSSS during a partial load operation
  - Analysis of Rankine + Absorption cycle for OPR-1000

- **Concerns on Partial Load Operation**
  - In 2009, nuclear power in South Korea: ~40% (electrical power based)
  - by 2030, ~60% → Need for partial load operation
  - How to perform partial load operations?
    - Main steam bypass to condenser / Reactor power control using neutron absorbers
    - Both are the cases of inefficient utilization of uranium resource.

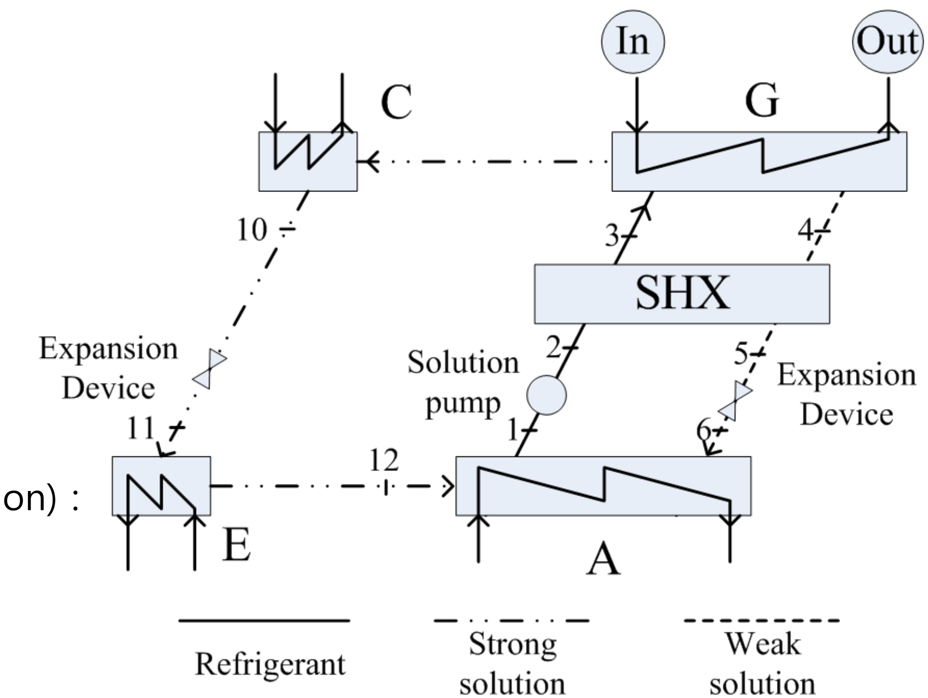
- **What if we can transfer surplus energy to a long distance without loss?**
  - Better fuel efficiency
  - Better applicability of nuclear energy (district heating/cooling, industrial process heat, desalination, etc.)

→ Nuclear Combined Cooling, Heating, and Power (CCHP) using absorption cycle

- **CCHP using Absorption Cycle**
  - Developed over 100 years ago
  - Heat transfer through the evaporation of a refrigerant at a low pressure and the rejection of heat through the condensation of the refrigerant at a higher pressure
  - Because an absorption refrigerator does not use a compressor so it is of great use in the place where electricity is not available!
  - Commercially available ideas
    - Lithium bromide/water and water/ammonia (absorbent/ refrigerant)
  - Pros and Cons
    - Low operational cost as long as waste heat is available
    - High capital cost, More space required, Complex configuration

Principle of Absorption Cycles

- **Component**
  - Generator (G): Different boiling points of absorbent and refrigerant
  - Condenser (C)
  - Evaporator (E)
  - Absorber (A)
  - Solution Heat Exchanger (SHX)

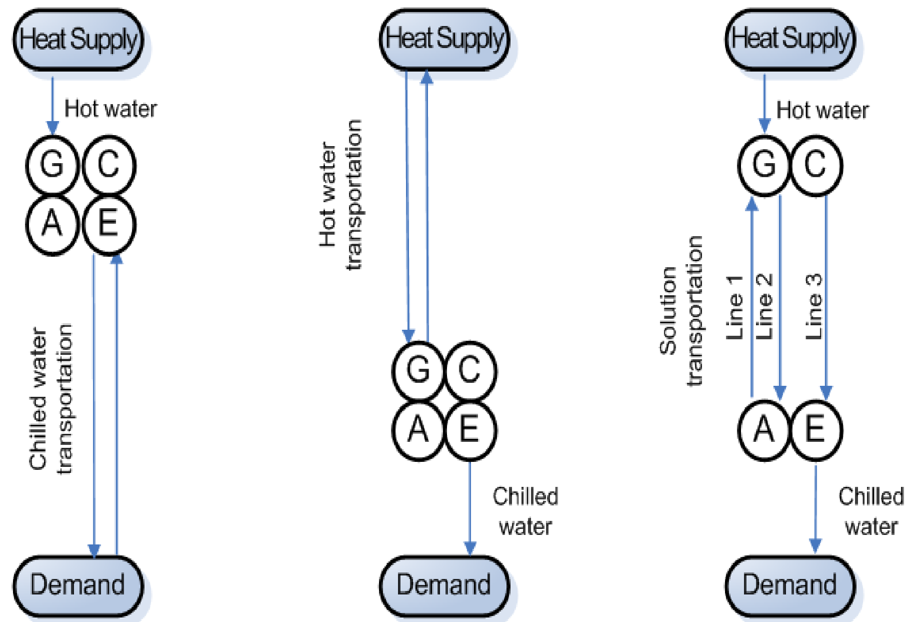


- **Flow path**
  - Refrigerant + Absorbent (Strong solution) : 1, 2, 3
  - Refrigerant : 10, 11, 12
  - Absorbent (Weak solution) : 4, 5, 6

- **Flow path of Refrigerant**
  - A → SHX → G → C → E → A
- **Flow path of Absorbent**
  - A → SHX → G → SHX → A

- **Solution Transportation Absorption (STA) system**
  - Supply side : Generator, Condenser
  - Demand side : Absorber, Evaporator

- **Advantages**
  - No insulation of pipelines
  - Small size of pipelines
  - Low manufacturing and operating cost
- **Disadvantages**
  - Solution may be expensive, toxic, or corrosive according to the choice of working fluids.
  - Transportation of solution over a long distance may not be safe due to the possibility of leakage.



Sensible heat transportation of chilled water

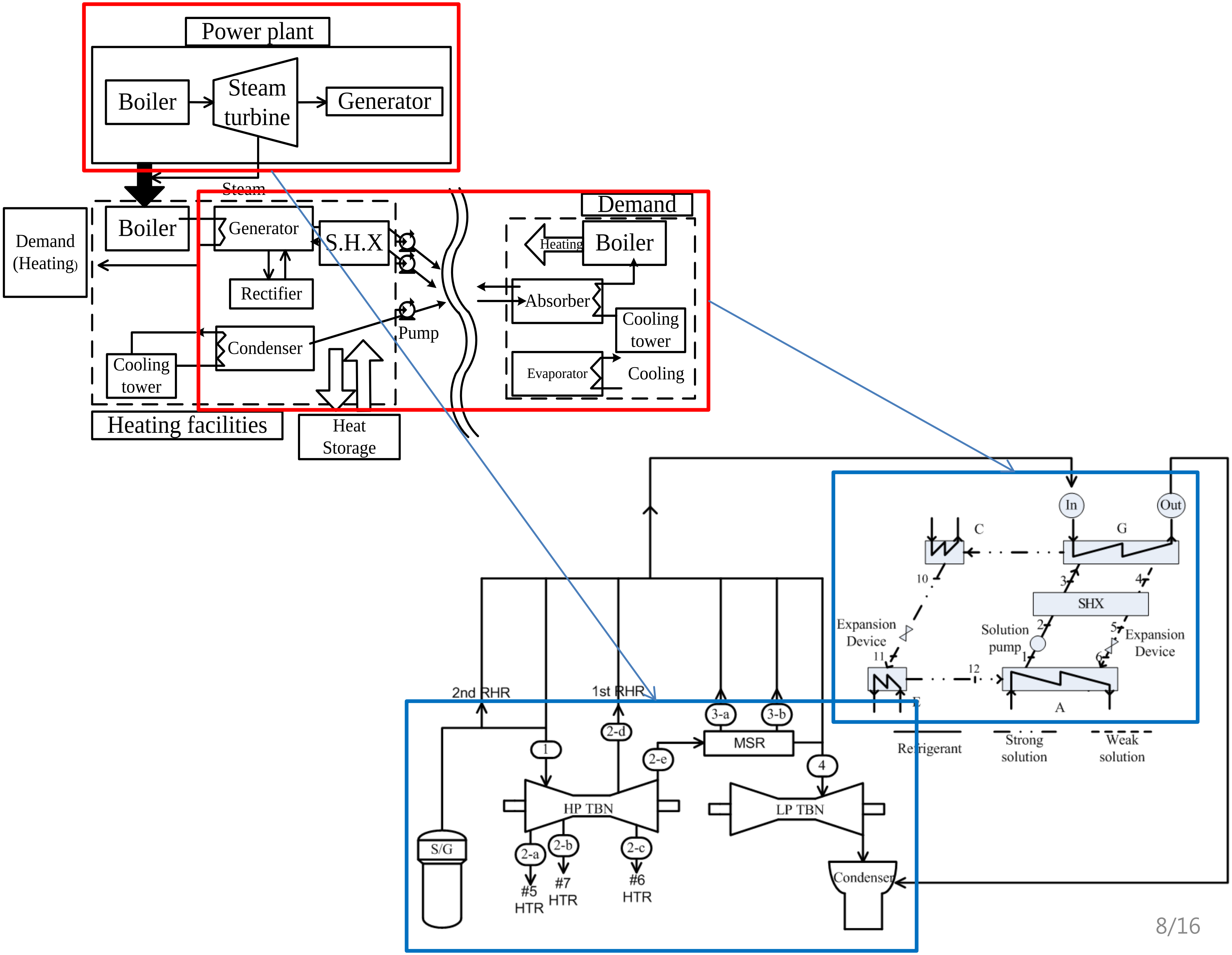
Sensible heat transportation of hot water

Sensible heat transportation

Combined Cycle Analysis and Results

- **Type 1, STA system with the Rankine cycle**
  - Supply side: a power plant, a generator, and a condenser
  - Demand side: an evaporator and an absorber

- **Operation**
  - Heat from a power plant is used as the heat source of the generator.
  - A refrigerant gas is condensed at the condenser.
  - The condensed refrigerant is transported to the evaporator and absorber whic h is located at the demand side far from the supply side.
  - This system can transport energy to a long distance without any insulation of the transportation tube.


Power plant
Boiler
Steam turbine
Generator
Steam
Demand (Heating)
Boiler
Generator
S.H.X
Rectifier
Condenser
Cooling tower
Pump
Heat Storage
Heating facilities
Demand
Heating
Boiler
Absorber
Cooling tower
Evaporator
Cooling
In
Out
C
G
10
3
4
SHX
Expansion Device
Solution pump
2
5
Expansion Device
11
1
6
12
E
A
Refrigerant
Strong solution
Weak solution
2nd RHR
1st RHR
3-a
3-b
2-d
1
2-e
MSR
4
HP TBN
LP TBN
S/G
2-a
2-b
2-c
#5 HTR
#7 HTR
#6 HTR
Condenser

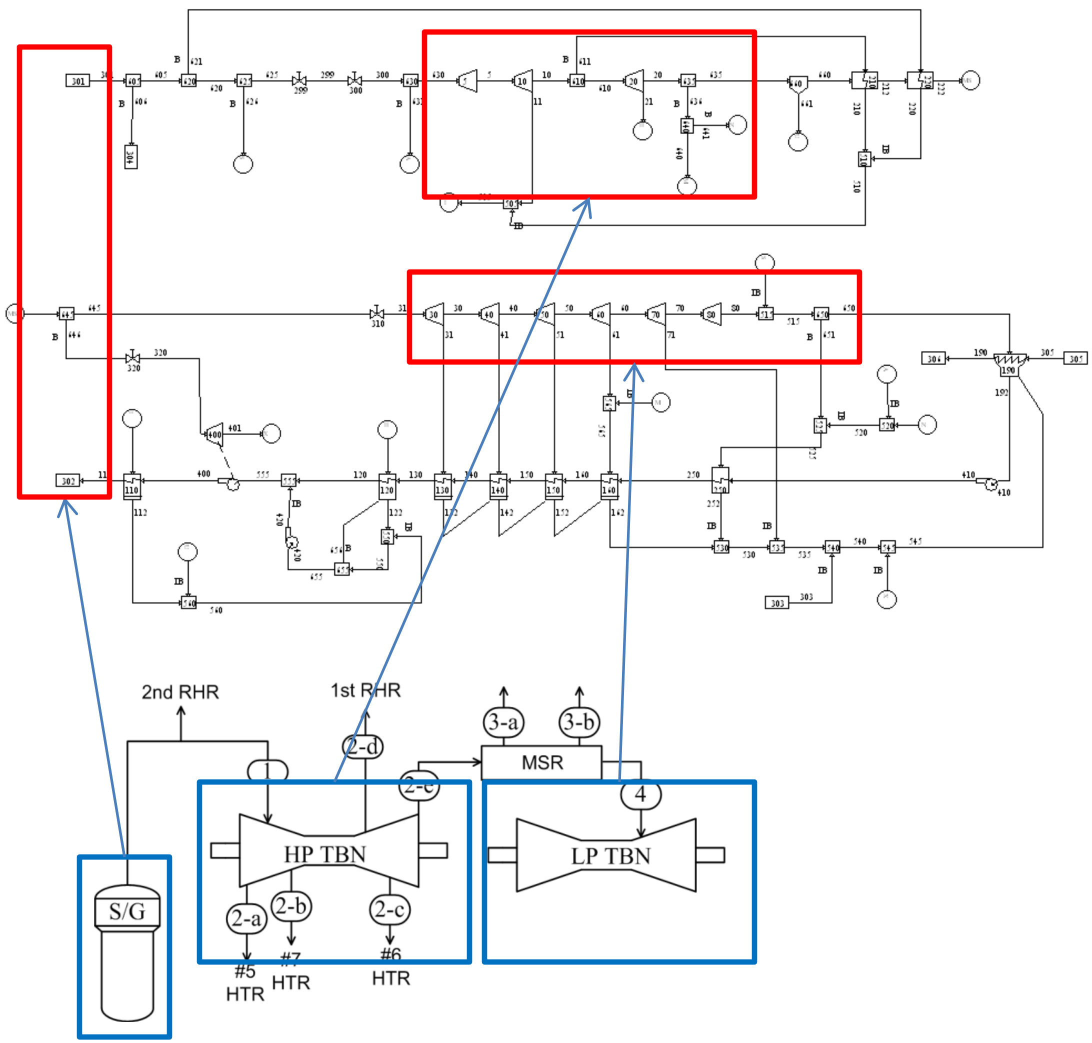
- **Modeling**
  - Combined cycle simulation using PEPSE (Performance Evaluation of Power System Efficiencies)
  - PEPSE is not desirable for accurate simulation, but it is enough to compute thermal efficiency which is associated with turbine cycle and absorption cycle.

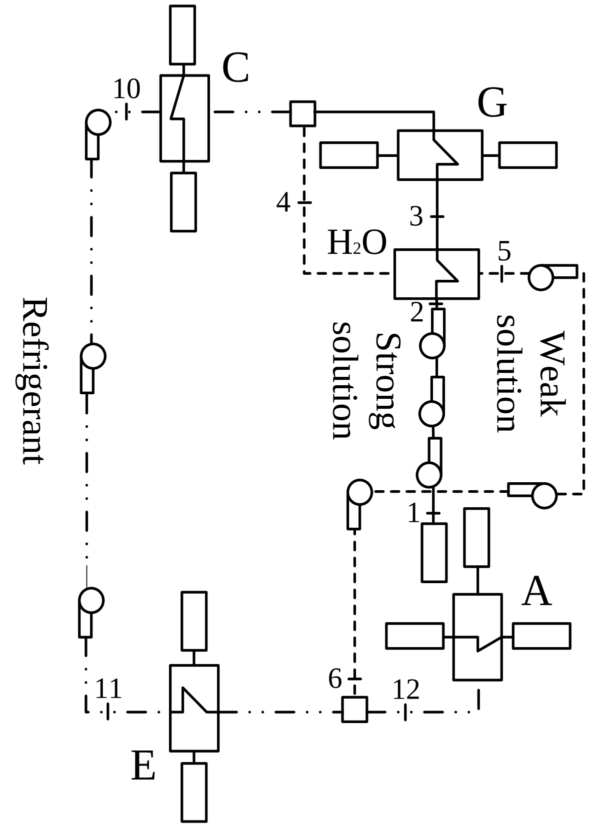
- **Assumptions and Procedures**
  - Fixed amount of flowrate from the Rankin cycle
  - Heat sources: Saturated water, Saturated steam, or Superheated steam depending upon bypass locations
  - Working fluid: NH3-H2O (Crystallization, Capacity, Cost, and Transportability)
  - Unknown parameters (for example, UA of heat exchangers) are estimated by linear interpolation.

- **Assumptions and Procedures (cont')**
  - Turbine cycle model
    - Design heat balance diagrams provided by manufacturers
    - Checks at VWO, 100%, 75%, 50% electric loads
  - Absorption cycle model
    - Design parameters provided by the heat balance diagram of 1RT and 5,000RT STA system
    - COP (Coefficient Of Performance) check

$$COP = \frac{Q_E}{Q_G}$$

    - Pressure drop check between a supply side and a demand side
      - 3,000 kW pumping power per 100 km (10~20 cm piping diameter)
      - Maximum distance 500 km (Design value: 510 km with 10 cm piping diameter)





PEPSE models for turbine cycle and STA system

Table 1. Baseline conditions for cycle modeling of 1RT STA system

Component	Mass flow rate (kg/s)	UA Values (kW/K) for 1RT
Condenser	5.47×10^{-2}	1.51
Evaporator	4.02×10^{-1}	1.61
SHX	-	1.66×10^{-1}
Absorber	3.92×10^{-1}	4.61×10^{-1}
Generator	2.26×10^{-3}	9.72×10^{-3}

Table 2. Physical properties of transportation fluids

Fluids	Concentration (mass fraction)	Density (kg/m^3)	Viscosity(cP)	Temperature(°C)
Strong solution	0.64	774.2	0.5	26.0
Weak solution	0.10	956.7	1.0	26.0
Chilled water	-	1000.0	5.9	7.0

Table 3. Conditions for cycle modeling of 5,000RT STA system

Fluids	Concentration (mass fraction)	Circulation ratio (solution/refrigerant)	Mass flow rate (kg/s)
Strong solution	0.64	4.25	25.57
Weak solution	0.1	1.7	10.21
	Specific heat (kJ/kg°C)	Temperature difference (°C)	Mass flow rate (kg/s)
Chilled water	4.186	5(=12.0-7.0)	824.18

Simulation Results

Table 4. Off–design analysis results

ID in Fig	1		3		4		6		10		12	
	P(kPa)	T(°C)	P(kPa)	T(°C)	P(kPa)	T(°C)	P(kPa)	T(°C)	P(kPa)	T(°C)	P(kPa)	T(°C)
Design*	400.0	25.0	1000.0	70.0	1000.0	160.0	25.0	25.0	1000.0	40.0	400.0	10.0
1 case	400.0	45.0	1002.6	54.5	1002.6	87.8	26.2	10.4	1002.6	27.0	400.0	31.0
2a case	400.0	45.0	1002.6	52.1	1002.6	70.0	2.1	10.4	1002.6	26.4	400.0	10.9
2b case	400.0	45.0	1002.6	53.4	1002.6	79.8	14.9	10.4	1002.6	26.7	400.0	28.8
2c case	400.0	45.0	1002.6	52.7	1002.6	74.7	8.2	10.4	1002.6	26.6	400.0	22.9
2d case	400.0	45.0	1002.6	53.4	1002.6	80.0	15.1	10.4	1002.6	26.7	400.0	29.0
2e case	400.0	45.0	1002.6	52.1	1002.6	70.2	2.2	10.4	1002.6	26.4	400.0	11.5
3a case	400.0	45.0	1002.6	51.9	1002.6	69.0	0.7	10.4	1002.6	26.4	400.0	2.8
3b case	400.0	45.0	1002.6	52.7	1002.6	74.5	7.9	10.4	1002.6	26.6	400.0	22.6
4 case	400.0	45.0	1002.6	54.1	1002.6	85.1	22.8	10.4	1002.6	26.9	400.0	30.8

* Reference Design: Results using flue gas heat source

Since the flowrate and UA of each component are adjusted on the basis of the generator capacity, most of the thermo-hydraulic parameters behaved similarly with the reference case.

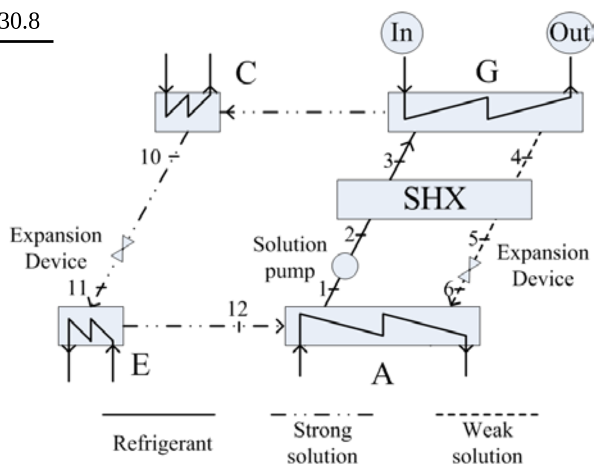


Table 5. Off–design analysis results of the generators

	Inlet Side of Generator				Outlet Side of Generator				G. Capacity (MW)	E. Capacity (MW)	COP
	P(kPa)	T(°C)	(kg/s)	h (kJ/kg)	P(kPa)	T(°C)	(kg/s)	h (kJ/kg)			
1 case	7101.6	286.8	10.0	2764.5	7101.6	286.8	10.0	1838.5	9.26	2.99	0.32
2a case	939.5	177.2	10.0	2482.6	939.5	177.2	10.0	1984.0	4.99	2.99	0.60
2b case	3198.1	237.4	10.0	2652.9	3198.1	237.4	10.0	1919.4	7.33	2.99	0.41
2c case	1754.2	205.8	10.0	2565.6	1754.2	205.8	10.0	1955.3	6.10	2.99	0.49
2d case	3263.3	238.6	10.0	2652.9	3263.3	238.6	10.0	1915.0	7.38	2.99	0.41
2e case	957.5	178.0	10.0	2482.6	957.5	178.0	10.0	1980.8	5.02	2.99	0.60
3a case	3111.8	235.9	10.0	1018.0	3111.8	129.0	10.0	544.0	4.74	2.99	0.63
3b case	6819.7	284.1	10.0	1258.1	6819.7	153.8	10.0	652.4	6.06	2.99	0.49
4 case	925.3	270.1	10.0	2989.7	925.3	176.5	10.0	2128.7	8.61	2.99	0.35

* Reference Design: COP is 0.687

• Quality of Case 3 = 0, Quality of Case 4 > 1, Quality of Others are between 0.7~1.0

Since we fixed the capacity of the evaporator and the UA of the generator, the COPs are generally lower than the reference cases.

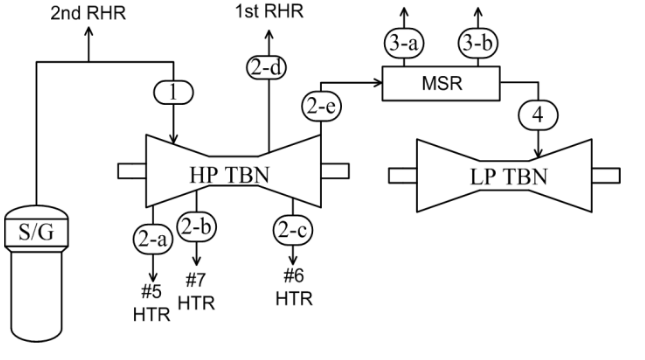


Table 6. Off-design analysis results of generators

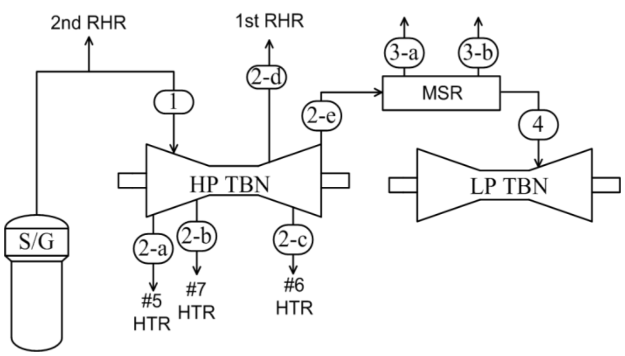
	Electric Output	Loss	% Loss	% Recovery	Pumping Power for STA	Total Gain
	MWe	MWe	(Loss/Elec.Output)	(EVA/Loss)	MW	MW
Design*	1013.9					
1 case	1005.9	7.98	0.79	37.51	3.00	0.92
2a case	1009.0	4.91	0.48	60.94	3.00	-3.35
2b case	1007.3	6.66	0.66	44.94	3.00	-1.00
2c case	1008.2	5.77	0.57	51.93	3.00	-2.24
2d case	1007.3	6.66	0.66	44.94	3.00	-0.96
2e case	1009.0	4.91	0.48	60.93	3.00	-3.32
3a case	1012.4	1.49	0.15	200.71	3.00	-3.60
3b case	1011.7	2.23	0.22	134.59	3.00	-2.28
4 case	1007.5	6.44	0.63	46.53	3.00	0.27

←Recommend

$$\text{Total gain} = Q_G - \frac{P_1(L)+P_2(L)+P_3(L)+P_4}{\eta_e \eta_p}$$

* Design: Ranking cycle, 100% electric output

- Case 3 recovers waste heat.
- The only first case which gives the highest capacity of heat source seems to be feasible while other cases represent pessimistic results.



Conclusions and Discussions

- **Conclusions**
  - The combined cycle “may be” more efficient than a single Rankine cycle.
  - If we are successful to transport waste heat using the STA system to a place where we need it, the efficacy of nuclear power option will be much more promising.

- **Further Considerations**
  - Optimization of thermo-hydraulic design for components
  - Resizing of the long distance piping for minimized pressure drop and pumping power

- **Safety Concerns**
  - The malfunction of the Rankine cycle does not cause serious consequences because it does not contain radioactive boundaries.
  - If we maintain the pressure of a generator side as the 1st stage pressure of a governing stage, there is no impact on reactor power control.