Conceptual Design of Nuclear CCHP Using Absorption Cycle

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Abstract. This paper aims at providing a conceptual idea on the combined cooling, heating and power (CCHP) using an absorption cycle to simultaneously generate both electricity and useful energy to be transferred, which is applicable to conventional or future water cooled reactors. The motivation of this paper is, as the number and the share of nuclear power plants (NPPs) increases, the necessity of a partial load operation will be increased in the case of South Korea. This means the surplus of nuclear energy. It should be better to find a method to fully use the burnup of nuclear fuels loaded once instead of cutting back reactor power. If the surplus energy from NPPs is not useable on-site, that should be transferred to a place such that the efficiency of an overall energy system can be maximized. The proposed solution is to use an absorption cycle which is connected to the Rankine cycle, a turbine side of water cooled reactors, so that the operation strategy of the nuclear steam supply system (NSSS) does not need to be changed. This principle can design a heat transfer mechanism to convey thermal energy to a long range, which means the waste heat discharged can be used for practical purposes even in a populated district. District heating/cooling, industrial process heat supply, or seawater desalination are expected to be the possible applications. This paper presents simulation results for deciding thermo-dynamic viability and economic feasibility by comparing several design alternatives

Nomenclature

A	Absorber
C	Condenser
G	Generator
E	Evaporator
h	Enthalpy
H_2O	Water
HTR	Heater
HP TBN	High Pressure Turbine
L	Tube Length
LiBr	Lithium Bromide
LP TBN	Low Pressure Turbine
$\dot{m}$	Mass Flow Rate
MSR	Moisture Separator and Reheater
NH_3	Ammonia
η_x (x=e, p)	Efficiency (e: electricity, p: pump)
P	Pressure
P_x (x=1,2,3,4)	Pumping power (1: weak solution side, 2: strong solution side, 3: mixed solution side, 4: solution pumping)
Q	Capacity
RHR	Reheater
RT	refrigeration tons
S/G	Steam Generator
SHX	solution heat exchanger
T	temperature
UA	overall conductance

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1. Introduction

At present, South Korea depends upon nuclear power for ~40% of electric supply. By 2026, we are planning to construct 8 new stations. Furthermore, additional 10 nuclear plants will be added by 2030 which mean nuclear energy will share 59% of electricity production [1]. For this reason, the necessity of a partial load operation will be suggested for conventional or future reactors. Another possible trend to necessitate a partial load operation is to introduce a smart grid technology [2] such that not only nuclear power but also batteries may be able to take a role of the base-load supplier. In this case, there is no guarantee nuclear power plants (NPPs) are 'always' and 'fully' operating. The current design of an NPP is, of course, able to operate at a certain level of the partial loads. One of the methods is to just bypass live steam to condensers without penetrating turbines so that electric output decreases. Controlling reactor power is another method to decrease electric output. However, in the case of those operational strategies, there is a shortage in the aspect of effective way to fully utilize uranium resource because the nuclear fuel once loaded cannot be saved. As opposed to a fossil-fuel plant, the nuclear fuels once loaded in a reactor cannot be stored because all of the fuels should be taken away at the end of a fuel cycle. In terms of fuel efficiency, the partial load operation is not a good idea.

Aside from the necessity of the partial load operation, it should be favorable to make use of waste heat discharged from turbines. All of the large-scale commercial power plants are adopting reheat or regenerative cycles to enhance thermal efficiency. All of the bypass steam for reheating or regenerating is finally condensed and drained to condensers. If we can recover the steam to be drained such that turbine cycle efficiency is improved, it should be better than an existing system in terms of operating cost. However, the recovery of waste heat itself may not be useful in some cases. Since the near demand sites from NPPs are not available, it is indispensable to transfer waste heat to a long distance, at least, on the order of kilometers. A heat transfer mechanism to convey thermal energy to a long range enables the waste heat of nuclear stations to contribute on practical purposes even in a populated district. District heating/cooling, industrial process heat supply, or seawater desalination are expected to be possible applications.

In this paper, we suggested the method to utilize surplus or waste heat by revising the configuration of the Rankine cycle (All of the NPPs in South Korea are water-cooled reactors, so the turbine side is designed by the Rankine cycle) while maintaining the operating conditions of the NSSS. Especially, the proposed solution is to use an absorption cycle which is connected to the Rankine cycle so that the operation strategy of the NSSS does not require any change. The CCHP using absorption principles was initially developed over 100 years ago [3]. The absorption cycle is a process by which heating and/or cooling effect is produced through the use of two fluids and some quantity of heat input. The absorption cycles accomplish heat transferring 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. In an absorption cycle, a secondary fluid or absorbent is used to circulate the refrigerant. Absorption cycles are commercially available today in two basic configurations; lithium bromide/water and water/ammonia (respectively absorbent/ refrigerant) [3~5]. While the operational cost of absorption cycles is very low as long as waste heat is available, however there are disadvantages as well, such as high capital cost, more space required, complex configuration, and so on [5].

We analyzed the feasibility of connecting an absorptive cycle and the Rankine cycle of OPR-1000. This paper is going to present simulation results for deciding thermo-dynamic viability and economic feasibility by comparing several design alternatives.

2. Principle of Absorption Cycles

Absorption cycles are available for heating as well as cooling within a single cycle by changing the path of working fluids. Since the principle for cooling is more complicated than that for heating, this paper describes the fundamentals of an absorption refrigerator for reader's convenience.

Different from conventional refrigerators, an absorption refrigerator does not use a compressor so it is of great use in the place where electricity is not available. Particularly, it can have high efficiency when waste heat is accessible. Absorption refrigerators make use of steam and hot water as a heat source. Fig. 1 shows the main components of an absorption refrigerator. An absorption refrigerator consists of absorber, generator, condenser, evaporator, and solution heat exchanger. An absorption refrigerator works as follow: the steam generated in an evaporator (12) is absorbed by absorbent in an absorber, and the absorbent is changed from weak solution concentration to strong solution concentration. Strong solution in the absorber flows to a generator (1) through a solution pump (2) and the temperature of solution increases by the heat transfer from weak solution in a solution heat exchanger (3). The steam generated by the difference of boiling points of an absorbent and a refrigerant, can be used for making weak solution concentration. The absorbent of weak solution is returned back after cooling down in the solution heat exchanger (4~6). After being the liquid condensed in the condenser (10), the refrigerant absorbs the heat of chilled water in the evaporator (11~12) [4, 5].

Many ideas to transfer thermal energy from one place to another using an absorption cycle have been proposed. Fig. 2(a) and Fig. 2(b) show the schematic diagrams of two early-stage absorption cycles for thermal energy transportation. Generally, the main components of the systems are located together either at the supply side or at the demand side. In this case, the energy is transported by the sensible heat change of the hot or chilled water. However, long pipelines should be thermally insulated for both cases. Even though the insulation of pipelines is possible, the distance of transportation is expected to less than several kilometers. As opposed to the conventional ideas, the solution transportation absorption (STA) system which was conceptualized by Kang et. al. [4], is able to transfer energy to a long distance, for instance, about several hundred kilometers. The schematic diagram of the STA system is shown in Fig. 2(c) for the comparison with the previously discussed early-stage absorptive cycles for thermal energy transportation of Fig. 2(a) and Fig. 2(b).

In an STA system, thermal energy is transported by the concentration difference of the absorption solution by locating the absorber and evaporator at the demand side and the condenser and generator at the supply side. The STA system has the following main advantages: (1) Insulation of the pipelines is not required, (2) The size of pipelines can be significantly reduced, and (3) Manufacturing and operating costs can be reduced. On the other hand, it has some disadvantages as well, like: (1) Solution may be expensive, toxic, or corrosive according to the choice of working fluids and (2) Transportation of solution over a long distance may not be safe due to the possibility of leakage [4].

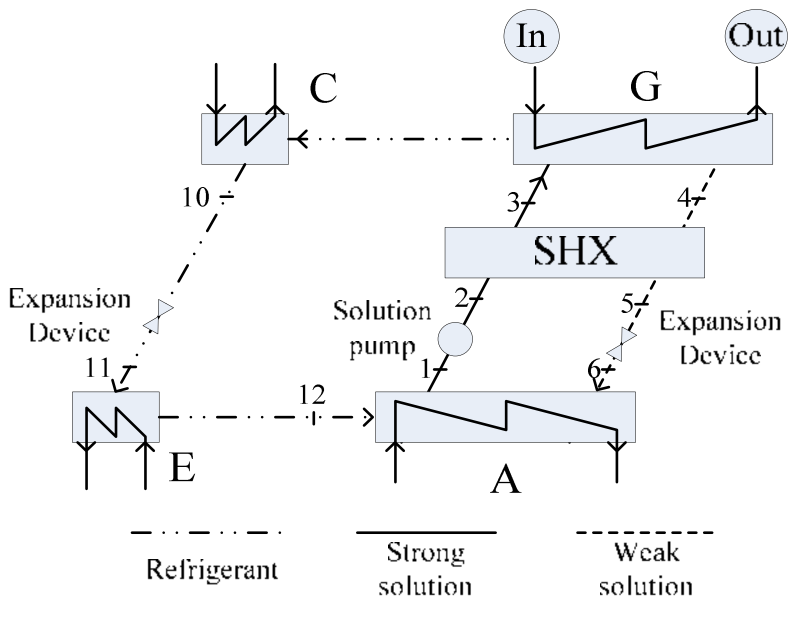

FIG. 1. Schematic diagram of a single effect absorption cycle [6]

It is expected that the principle of the STA system enables the waste heat discharged from a nuclear power station in making it useful for practical purposes even in a populated district. Since the operational cost of an absorption cycle is low as long as waste heat is available, the disadvantages resulting from introducing a STA system should be considered.

3. Combined Cycle Analysis and Results

In order to investigate thermo-dynamic viability and economic feasibility of the cycle combining the Rankine cycle and the STA system, we developed a simulation model such that several design alternatives can be compared in terms of thermal efficiency.

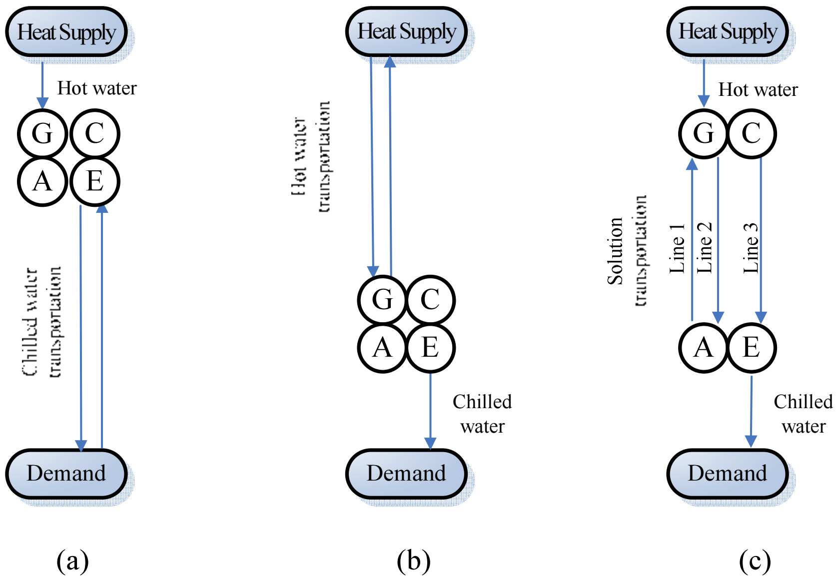

FIG. 2. Concept of sensible heat transportation [4]
(Left: by chilled water, Center: by hot water, Right: by solution)

We have performed the analysis of turbine cycle efficiency using PEPSE (Performance Evaluation of Power System Efficiencies) developed by Scientech, USA [7], having the Rankine cycle model of OPR-1000. The accurate simulation of an absorptive cycle with PEPSE is not desirable due to the limited capability of PEPSE for representing the chemical properties of various working fluids, but we concluded that PEPSE is enough to computer the thermal efficiency which is associated with the turbine cycle of OPR-1000 and an absorption cycle within an acceptable level of error. This study, therefore, attempted to perform a variety of sensitivity analysis using the combined cycle model developed by PEPSE.

3.1. Model Development

Fig. 3 shows the schematic diagram of the type 1, STA system with the Rankine cycle of a power plant. In this system, a power plant, a generator, and a condenser are located at the supply side, while an evaporator and an absorber are located at the demand side. Heat from the 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 which is located at the demand side far from the supply side. Because the energy is transported by solution as latent heat due to the concentration difference of the refrigerant, the type 1, STA system can transport energy to a long distance without any insulation of the transportation tube. There may be several alternatives for the STA system to take steam from the Rankine cycle. Fig. 4 shows the possible locations to provide heat energy. All designations from '1' to '4' correspond to the 'in' of a generator side in Fig. 1. It was assumed that the drain from the 'out' in Fig. 1 flows to a condenser of the Rankine cycle. The bypass from each location has a different impact on the thermal efficiency of both the Rankine cycle and the STA system even though a steam supply of the turbine cycle is equivalent and the operation conditions of the NSSS are not changed.

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FIG. 3. Schematic diagram of a type 1, STA system with Rankine cycle [4]

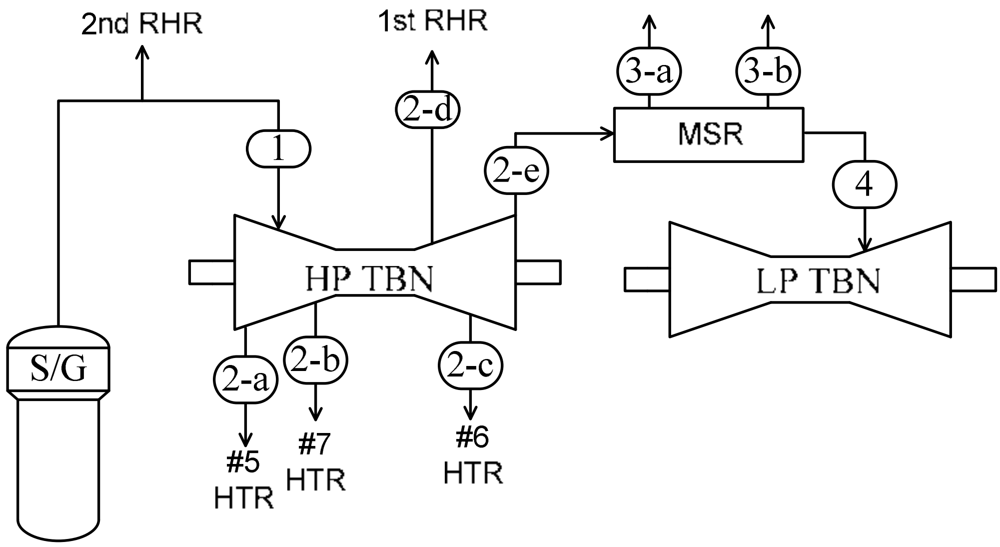

FIG. 4. Possible locations of OPR-1000 for supplying heat source

Fig. 5 shows the PEPSE model of an absorption cycle. The numbers of Fig. 5 are shared with the designations in Fig. 1. The developed model has following characteristic:

1. In the schematic diagram of Fig. 4, all designations from 1 to 4 (total 9 cases) correspond to the 'in,' which is the tube inlet side of the generator in Fig. 1. For each case, a fixed amount of flowrate from the Rankine cycle is split and supplied to the generator as a heat source. 3a and 3b cases belong to saturated water supply, and other cases supplies saturated or a little superheated steam.

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FIG. 5. PEPSE model of the STA system

2. We selected NH_3-H_2O as a working fluid of the STA system. It has advantages in terms of crystallization, capacity, cost, and transportability as compared to H_2O-LiBr cycle. Since PEPSE cannot deal with detailed chemical processes, many of operating parameters are approximated such that the PEPSE equivalently simulates the thermal properties of NH_3-H_2O. The design parameters of the STA system were taken from Kang et. al. [4, 8, 9] for both cases of 1RT and 5,000RT, so several unknown parameters are modeled by linear interpolation. The significant parameters and conditions are listed in Table I, Table II, and Table III. It should be noted that the heat source of the generator is the exhausted gas (~600 °C) from a gas turbine because the heat source in this paper will be supplying as form of water-steam mixture.

3. In order to validate the accuracy of the STA system model developed by PEPSE, we attempted to compute the COP (Coefficient of Performance) of the STA system. At both of 1RT and 5,000RT, the calculated COPs were a range of 0.65 to 0.69 respectively. This value seems acceptable within an acceptable level of error taking into account of the original value, 0.69.

4. To check the computing capability of the pressure drops between a supply side and a demand side, we validated the maximum distance of transportation using the STA system model. Using the same assumption as the reference [4], the PEPSE model calculated 3,000 kW pumping power per 100 km assuming a 10 ~ 20 cm piping diameter, so a maximum distance was 500 km, which is almost the same with the original value (510 km with a 10 cm piping diameter).

Table I. 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 II. 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 III. Conditions for cycle modeling of 5000RT 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

5. In the sensitivity analysis, we fixed the capacity of the evaporator side as ~4,500RT for easy comparison. The pumping power and pressure drop of the system was computed assuming 100 km transportation. The overall conductance, UA, of each component was proportionally adjusted on the basis of the flowrate of heat source. The specific material and heat transfer area are, therefore, not determined in this analysis.

3.2. Simulation Results

The off-design analysis according to the variety of design parameters and the configuration of the absorption cycle were performed. Table IV shows the pressure and temperature results of all design alternatives. 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 IV. Off-design analysis results

ID in Fig. 1	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 from Reference [4] using flue gas heat source

Table V. Off-design analysis results of the generators

Inlet Side of Generator	Outlet Side of Generator	G.	E.	COP

	P(kPa)	T(°C)	**Error! Objects cannot be created from editing field codes.** (kg/s)	h (kJ/kg)	P(kPa)	T(°C)	**Error! Objects cannot be created from editing field codes.**(kg/s)	h (kJ/kg)	Capacity (MW)	Capacity (MW)	
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

Table VI. 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

* Design: Ranking cycle, 100% electric output

Table V represents some results with regarding to the performance of the generator. For most of the cases, heat transfer process is taking place under saturated conditions, so the condensing heat transfer between steam and water may be not efficient under the same UA condition. In case of 3a and 3b, heat energy was transferred in the condensing as well as draining cooling regions. Since we fixed the capacity of the evaporator and the UA of the generator, the COPs are generally lower than the reference cases.

Table VI shows the feasibility of the entire heat transportation system considering the loss of the Rankine cycle and the gain of the STA system. Each case shows an electric loss due to the bypass of steam or drain to the STA system. Since the discharged energy of 3a and 3b is lower than other cases, the loss of electricity is also lower. If we do not take the pumping power for delivering solutions in the STA system into account, the recovery ratio (defined as the ratio of the energy gain in the STA system to the electric loss in the Rankine cycle) exceeds 100% for 3a and 3b cases. The total gain is calculated by Equation (1) [4], which can decides whether the combined cycle is more efficient or the single Rankine cycle is more feasible. In this analysis, the only first case which gives the highest capacity of heat source seems to be feasible while other cases represent pessimistic results. However, it should be noted that most of generators are working at a saturated condition, so the efficiency should be improved if thermo-hydraulic design of the generator is optimized.

$$\text{total gain} = Q_G - \frac{P_1(L) + P_2(L) + P_3(L) + P_4}{\eta_e \eta_p} \tag{1}$$

4. Conclusions and Discussions

We suggested the method to utilize surplus energy by revising the configuration of the Rankine cycle while maintaining the operating conditions of the NSSS, and attempted to analyze the feasibility of the combined cycle with an STA system. 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.

Some of cases resulted in a feasible conclusion while most of cases still need more improvement. We discussed several reasons: (1) Re-design of the generator side because the current design did not fully use heat capacity of heat sources, (2) Optimization of UA of each component, (3) Resizing of the long distance piping for minimized pressure drop or pumping power. As a next step of research, we are going to continue these discussions and introduce a comprehensive simulation tool which can be combined with the Rankine cycle simulation.

We may face additional considerations in implementing this idea such as safety and control on the NSSS. At this moment, we can only recognize several superficial issues. In terms of safety, the malfunction of the Rankine cycle does not cause serious consequences because it does not contain radioactive boundaries. We are working on another project which is related to the analysis of root causes for reactor or turbine shutdown [10]. Referring the results of this project, we skimmed thought the minimal cutsets possibly inducing plant shutdowns, but their probability was negligible. In terms of reactor control, the 1st stage pressure of a governing turbine is used to control reactor power. The proposed idea is a kind of a static pressure operation so that the 1st stage pressure does not change even though the steam path of the Rankine cycle is bypassed. In this analysis, all of the cases except case ‘1’ belong to this condition. Even the case ‘1’ is not likely to affect the 1st stage pressure if a bypass path is designed such that the pressure of main steam line is maintained. We will investigate more detailed scenarios to confirm the feasibility of the proposed system in an extensive manner.

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