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Seawater Desalination Using An Advanced Small Integral Reactor – SMART

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Abstract

A concept of a dual-purpose integrated nuclear desalination plant coupled with the advanced small integral reactor SMART was established. The design concept of the plant aims to produce 40,000m^3/day of water with the MED process and to generate about 90 MWe of electricity. In order to examine the technical, economic, and safety considerations in coupling SMART with desalination, a preliminary analysis on water production costs and a safety review of potential disturbances of the integrated nuclear desalination plant have been performed. The results of economic evaluation show that the use of SMART for seawater desalination is either comparative to or more economical, with respect to the water production cost, than the use of fossil fuels in comparison with the data published by the IAEA. It was also found that any possible transient event of the desalination plant does not impact on the reactor safety. The key safety parameters of the transient events induced by the potential disturbances of the desalination plant are bounded by the limits of safety analysis of SMART.

1. Introduction

Seawater desalination requires energy in the form of heat, electricity or both. Fossil fuels have been the energy source for desalination, and they are expected to remain as the major energy source for seawater desalination in the future. However, many arguable aspects in using fossil fuels as an energy source have been discussed. Those aspects include the air pollution, greenhouse effect, depletion of valuable natural energy resources, etc. The domestic availability of fossil fuels has been another factor of concerns in certain countries. In this regard, several alternative energy sources can be taken into consideration to partly replace the use of fossil fuels for seawater desalination. One of the potentially rewarding alternative energy sources is nuclear energy, and the use of nuclear energy for seawater desalination has been receiving growing interests. Various types of nuclear reactors can be utilized to supply the energy required for seawater desalination[1].

The prospect of a fresh water shortage and the need for the diversification of nuclear energy utilization motivated the development of a highly safe, reliable and advanced nuclear reactor for the dual application of desalination and power generation. Accordingly, the development of an advanced small power reactor, SMART (System-integrated Modular Advanced ReacTor) and an integrated nuclear desalination system was started in November 1996. Its conceptual design was completed and the basic design is currently underway. The current design concept of an integrated nuclear desalination plant with SMART is a dual-purpose plant for both water production and electricity generation.

This paper deals with the investigations on nuclear desalination using SMART. The target water production capacity was predetermined to meet the requirements of the electricity and water supply for a population of approximately 100,000. For the target water production capacity of 40,000 m^3/day, preliminary sensitivity analysis on the method of energy extraction from the turbine system has been carried out for both MED and MSF processes. Since water production cost is an important factor that should be considered in seawater desalination, an economic assessment was performed to investigate the economic viability for seawater desalination with SMART.

In addition, the provision for the protection of the possible radioactive contamination of the product water was reviewed, since the nuclear reactor is used as a source of heat for seawater desalination. Also, the interaction between the desalination plant and the nuclear reactor was evaluated to assess the undue effects on nuclear system. The potential events imposed by the desalination plant coupled with SMART were identified and the influences of these transients on Design Basis Accidents and Performance Related Design Basis Events of SMART were evaluated through the bounding approach method of the safety parameters of SMART.

2. Main Features of the SMART

SMART is an advanced integral PWR (Pressurized Water Reactor) that produces thermal energy of approximately 330 MW[2]. Major primary components are integrated within a single pressure vessel, in which the arrangement of components differs from that of conventional loop-type reactors.

The SMART reactor assembly contains major primary systems such as core, 12 steam generators(SG), a pressurizer(PZR), 4 main coolant pumps(MCP), and 41 control element drive mechanisms(CEDM) in a single pressurized reactor, as shown in Figure 1. The major parameters of the primary circuit system are summarized in Table 1. The integrated arrangement of primary components enables the removal of the large size pipe connection between major reactor coolant systems, and thus fundamentally eliminates the possibility of Large Break Loss of Coolant Accidents (LBLOCA). Boron free operation is one of the evolving design characteristics of SMART, along with the low core power density. Soluble boron-free operation greatly contributes to the simplification of associated auxiliary systems, and to the reduction of the liquid waste production. The large free volume in the upper part of the RPV (Reactor Pressure Vessel) is used as a self-pressurizer which automatically controls the primary system pressure. The design and safety characteristics of SMART can be summarized as follows:

- Low core power density provides much improved passive response to a variety of transients, and increases the operating and performance margins for the fuel.
- Substantially large negative moderator temperature coefficient(MTC) due to soluble boron free core offers benefits to the inherent power stability and resistance to the transients
- Integrated arrangement of primary system eliminates the large-sized pipings to connect primary systems, and thus results in no large break LOCA
- Large volume of primary coolant provides large thermal inertia and long response time, and thus enhances the resistance to the system transients and accidents
- Large volume of passive PZR can accommodate a wide range of pressure transients during power operation
- Canned motor pumps remove the need of MCP seal, and thus basically eliminate the potential of small break LOCA associated with the seal failure
- Low level fast neutron fluence on the RPV accomplished by internal shieldings guarantees the design-lifetime operation of the RPV
- The core decay heat is passively removed by the passive residual heat removal system (PRHRS).

In addition, most of the reactor’s safety-related systems are designed to function in a passive manner when required. They include the reactor shutdown system, residual heat removal system, emergency core cooling system, reactor overpressure protection system, and containment overpressure protection system.

The secondary system of SMART consists of in-vessel helically coiled SG, main steam and feedwater systems, turbine generators and associated pipings and valves. The turbine generators consist of a main turbine generator and two auxiliary turbine generators. One auxiliary turbine generator is standby and the other is in operation to supply the house loads, while the main turbine is used for the offsite power supply. The major technical data of the secondary system are listed in Table 1.

3. Coupling of Desalination Plant with SMART

In the coupling of a desalination plant with a nuclear energy supply system to compose an integrated nuclear desalination plant, the economic and safety aspects are the most important factors to be taken into account. Since the integrated nuclear desalination plant using SMART is a dual-purpose plant, economic consideration is put on the choice of desalination process requiring less energy for the target water production and thus more generation of electricity at the given conditions. The safety aspects taken into consideration in the design of the coupled system are: the protection of the product water from possible contamination by radioactive materials, and the protection of the SMART system from potential disturbances induced by the desalination system. The safety aspects implemented into the current concept of the integrated desalination plant with SMART and its evaluation will be described in section 5.

For the economic choice of desalination process at the given target water production of 40,000m^3/day and for its thermal coupling with the SMART system, preliminary sensitivity analyses were carried out on the method of energy extraction from the turbine system for the MED and MSF processes. Three cases of energy extraction were considered in the analysis, such as prime steam, turbine extraction, and back-pressure turbine and the thermal balance calculations on the turbine cycle were carried out by varying the extracted steam.

As shown in Table 2, the results of sensitivity analyses show that the MED process coupled with the extracted steam from the turbine can generate the largest amount of electricity generation while producing the target amount of water. This indicates that the combination of MED with the turbine extraction of steam is the most economical option among other couplings with respect to the effective use of energy produced from SMART. Therefore, MED and steam extraction from the turbine were selected for coupling with SMART as a concept of the integrated nuclear desalination plant. With this concept of coupling, the desalination plant is composed of two units each with a water production capacity of 20,000m^3/day. Figure 2 shows the coupling concept for the SMART and MED plant.

4. Economic Evaluation of the Seawater Desalination Using SMART

For the concept of an integrated nuclear desalination plant coupled with SMART, the water production cost was evaluated for the target production of potable water. Several parameters can influence on the system design and thus the water production cost. Considering this aspect, two categories of economic evaluation were considered in this study, that is, the water cost variation as a function of the maximum brine temperature at the fixed construction cost of the SMART plant, and as a function of both the construction cost of SMART and the water production capacity at the fixed maximum brine temperature.

The economic evaluation was carried out using the IAEA's Desalination Economic Evaluation Programme (DEEP)[3]. DEEP employs a power credit method to evaluate plant economy. The methodology is based on the life-time cost of water produced. The life-time levelized cost is obtained by dividing the sum of all expenses related to the production of water by the total amount of water produced.

The major input economic parameters used in the economic evaluation are summarized in Table 3. Since the SMART plant has not been constructed yet and there is a lack of construction information for small advanced reactors, there exist some difficulties to obtain reliable construction cost data for SMART. The cost data of SMART were thus estimated based on the existing 1000 MWe PWR cost data in Korea. The uncertainties of the estimated cost data of

SMART will vary.

Table 4 shows the results of water production cost analysis, as a function of the maximum brine temperature for the MED process under the condition of a fixed construction cost for the SMART plant. The maximum brine temperature was chosen as a key parameter among the various performance parameters, since the gain output ratio (GOR) of the desalination plant is determined by the maximum brine temperature. As shown in the results, the increase of the maximum brine temperature causes the GOR to increase. A higher value of GOR leads to the higher plant efficiency, but results in higher investment costs and therefore in higher water production costs. The water production cost and salable electricity were calculated on the basis of the target water production of 40,000m^3/day. The water production cost initially decreases with an increase in the maximum brine temperature, but beyond a certain temperature it begins to increase. The lowest water production cost of 0.83\$/m^3 was obtained at the maximum brine temperature of 65℃. It was found that the net salable electricity remained nearly the same over the whole brine temperature range. This is a result of the fixed target water production capacity. The results also indicated that the optimum value of the maximum brine temperature is in the range of 60~70℃ for the current coupling arrangement.

Table 5 summarizes the results of water cost, calculated as a function of the specific construction cost of the SMART plant and the desalination plant capacity. The water production capacity varies from 40,000 m^3/day to 100,000 m^3/day. The analysis was performed for the maximum brine temperature of 70℃. The water production cost is around 0.80~0.84 \$/m^3 for the target amount of water, 40,000 m^3/day depending on the construction cost of the SMART plant. The electricity generation is about 90 MWe. The water production cost decreases as the amount of water production increases. The cost varies in the range of 0.76~0.84 \$/m^3 with water production of 100,000~40,000 m^3/day, and the SMART plant construction cost of 1800~ 2,442\$/kWe. The amount of electricity generation accordingly varies in the range of 77~90 MWe.

When the results of economic evaluation are compared to the data published by the IAEA[4] for the same size of power source, the result of this analysis shows that seawater desalination with SMART is either comparative to or more economical with respect to the water production cost than the use of fossil fuels.

5. Safety Evaluation of the Integrated Nuclear Desalination Plant

The most important safety concern in using nuclear thermal energy for desalination is the radioactivity carry-over into the product water from the nuclear reactor. In the integrated nuclear desalination plant using SMART, two protection mechanisms are provided to avoid any radioactive contamination of product water. Two barriers, the steam generator and the brine heater, along with the pressure reversal between the energy supply and the desalination system, act as one of the two protection mechanism implanted in the coupling. In addition, a continuous radioactivity monitoring system will be installed in the water production system to check any symptom of contamination, and an immediate system reaction will follow in the case of detecting radioactivity. Additional monitoring may also be performed in an intermediate loop where the concentration of contaminate is higher than the water plant.

Another important safety aspect to be considered in the integrated nuclear desalination plant is the operation and transients issues for system interactions between nuclear and desalination system. Since a direct interaction exists in thermal coupling between the reactor and the desalination plant, any transient in the desalination plants would therefore cause a direct physical feedback into the reactor system. The potential disturbances of the SMART desalination plant depend on the characteristics of the desalination plant as well as the coupled system. For the current concept of the SMART desalination plant, following three events were identified as the potential disturbances of SMART imposed by the desalination plant. The impact of these disturbances on the Design Basis Accidents and Performance Related Basis Events of SMART were evaluated by the conservative bounding approach of key safety parameters.[5,6]

5.1 Turbine Trip Due to Desalination System Disturbances

A turbine trip may be caused by potential disturbances occurring from the desalination system, and this event will lead to a reactor trip by high steam pressure in the secondary system trip signal. A turbine trip causes the primary coolant temperature and pressure to increase. When a reactor trip occurs, the RCS pressure increase stops. On a reactor trip signal, reactor coolant pumps also trip and the feedwater and steam isolation valves close, which actuates the PRHRS. Core decay heat is then removed by the PRHRS. The safety analysis showed that the safety parameters, mainly the RCS peak pressure, remained below the safety limits during this event.

5.2 Excess Load due to Increased Steam Flow to Desalination System

The increased steam flow to the desalination system could be caused by a sudden increase of the desalination products or a rupture of the desalination system steam pipe lines. This event causes the steam flow of the secondary system to increase and thus the cool down of the primary RCS. The cool down of the primary RCS causes the power to increase due to the design characteristics of SMART. This event consequently leads to a reactor trip either by the high power trip or DNBR (Departure from Nucleate Boiling Ratio) trip signal. At reactor trip, the PRHRS removes the core decay heat. In case the desalination system piping breaks, low secondary steam pressure trip could be actuated. The results of both events were found to be bounded by the design basis event of the main steam line break of SMART. The safety analysis of this event showed that the safety limits, mainly SAFDL(Specified Acceptable Fuel Design

Limit) on DNB, are not exceeded.

5.3 Loss of Load due to Desalination System Shutdown

A sudden stop of the steam flow to the desalination system could be caused by an unexpected desalination system shutdown. This event increases the secondary steam pressure and result in the increase of the RCS pressure and temperature due to the degraded heat transfer to the secondary system. This event was found to be bounded by the safety analyses for the total loss of load from the secondary system, such as a feedwater line break event. For these events, the safety parameters, mainly SAFDL on DNB and peak RCS pressure, were found to be remain below the safety limits.

6. Conclusions

A concept of an integrated nuclear desalination plant coupled with SMART, an advanced small integral pressurized water reactor under development at KAERI was established. The current design concept of the plant with SMART is a dual-purpose plant for both water production by the MED process and electricity generation. The target water production in the current system design is 40,000 m^3/day. On the established plant concept, economic and safety evaluations were carried out.

The result of the economic evaluation on the integrated nuclear desalination shows that the use of SMART for seawater desalination is either comparative to or more economical with respect to water production costs than the use of fossil fuels, although some degree of uncertainty exists in the data used in the cost analysis of the product water. Also, the safety evaluation results indicate that a significant impact on reactor safety is not expected to occur due to the transients induced by the desalination plant. It was found that the key safety parameters of any potential disturbance of the integrated nuclear desalination plant do not violate the specified limits of SMART.

The information obtained from this study will be used as the basis for further detailed analysis for optimizing the design of coupling between SMART and the desalination system. The criteria for optimization with respect to economics will be the lowest production cost of products from the integrated nuclear desalination plant. Parameters to be optimized include the optimum GOR, energy sharing between two systems, the number of desalination units, the number of effects of the MED process, and the production cost of water and electricity.

Acknowledgments

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Table 1. Key Design Parameters of SMART

Parameters	Unit	Design Value
Primary System		
- Thermal Power of the Core	MWt	330
- Nominal Pressure in Primary Circuit	MPa	15.0
- Primary Coolant Temperature (Core Inlet/Outlet)	℃	270/310
- Operating Range of Power Change	%	20-100 N_{nom}
Secondary System		
- Steam Flow Rate	kg/sec.	152.7
- Steam Pressure/Steam Temperature (Turbine Inlet)	MPa/℃	3.0/274
- Degree of Superheating	℃	40
- Feedwater Pressure/Temperature	MPa/℃	5.0/180

Table 2. Net Electric Power Generation for the Water Production Capacity of 40,000m^3/day

(20,000 m^3/dayx 2 unit, Turbine Efficiency of 85%)

	Power only	MSF			MED		
		Prime steam	Turbine extraction	Back-press. turbine	Prime steam	Turbine extraction	Back-press turbine
Thermal Power (MWt)	330.0	330.0	330.0	330.0	330.0	330.0	330.0
Total Electric Power (MWe)	100.0	80.0	87.0	59.0	85.0	93.0	87.0
Water Production(m^3/d)	0.0	40,000	40,000	140,000	40,000	40,.000	77,000
Net Electric Power (MWt)	100.0	75.0	82.0	44.0	83.0	90.0	83.0

Table 3. Main Economic Parameters

Economic Parameters	Unit	Reference Values
Nuclear plant (SMART)		
- Overnight Cost	$/kW(e)	2,442
- O&M Cost	$/kWh	12.50
- Fuel Cost	$/kWh	10.3
- Plant Economic Life	year	30
- Discount Rate	%	8
- Levelized Electricity Generation Cost	$/kW(e)h	0.055
Desalination Plant (MED)		
- Unit capacity	m^3/day	20,000
- Base unit cost of desalination plant	$/m^3	900(Max. brine temp.:70℃)
- Construction lead time	month	12
- Average management salary	$/year	66,000
- Average labor salary	$/year	29,700
- O&M spare part cost	$/m^3	0.030
- O&M chemicals cost for pre-treatment	$/m^3	0.020
- O&M chemicals cost for post-treatment	$/m^3	0.020
- O&M insurance cost	%	0.50
- Back-up heat source unit cost	$/MWt	55,000

Note : Currency Reference Date : 1998, Operation Reference Date : 2005

Table 4. Levelized Water Production Cost for the Maximum Brine Temperature Variation

Maximum Brine Temperature (℃)	GOR	Base Unit Cost($/(m3/d)	Water Produ. Cost ($/m3)	Net salable Elec. (MWe)
40	6.2	669	0.92	90.1
45	7.8	713	0.86	90.5
50	9.4	758	0.83	90.9
55	10.7	794	0.83	90.9
60	12.1	833	0.83	90.8
65	13.3	866	0.83	90.7
70	14.5	900	0.84	90.5
75	15.6	930	0.84	90.4
80	16.6	958	0.85	90.3
85	17.5	983	0.86	90.2
90	18.3	1005	0.87	90.0
95	19.0	1025	0.88	89.9
100	19.7	1044	0.90	89.7

Table 5. Variation of the Levelized Water Production Cost at the Fixed Brine Temperature (70℃) as a Function of the Water Production Capacity and Construction Cost of SMART plant

Overnight Construction Cost ($/kW)	Water Production Capacity (m3/day)	Water Cost ($/m3)	Salable Electricity Generation (MWe)	Levelized Electricity Generation Cost ($/kWe.h)
1,800	40,000	0,80	90.5	0.046
	60,000	0.78	86.3	
	80,000	0.77	81.7	
	100,000	0.76	77.0	
2,000	40,000	0.81	90.5	0.049
	60,000	0.79	86.3	
	80,000	0.78	81.7	
	100,000	0.77	77.0	
2,200	40,000	0.83	90.5	0.052
	60,000	0.80	86.3	
	80,000	0.79	81.7	
	100,000	0.79	77.0	
2,442	40,000	0.84	90.5	0.055
	60,000	0.82	86.3	
	80,000	0.81	81.7	
	100,000	0.80	77.0	

Note: Levelized electricity generation cost is for electricity generation without water production

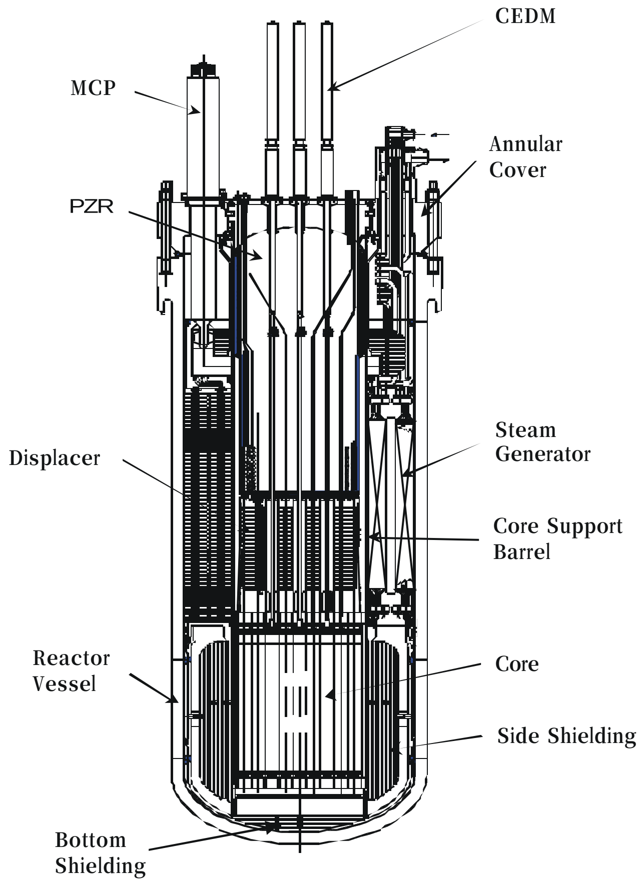

Figure 1. SMART Reactor Assembly

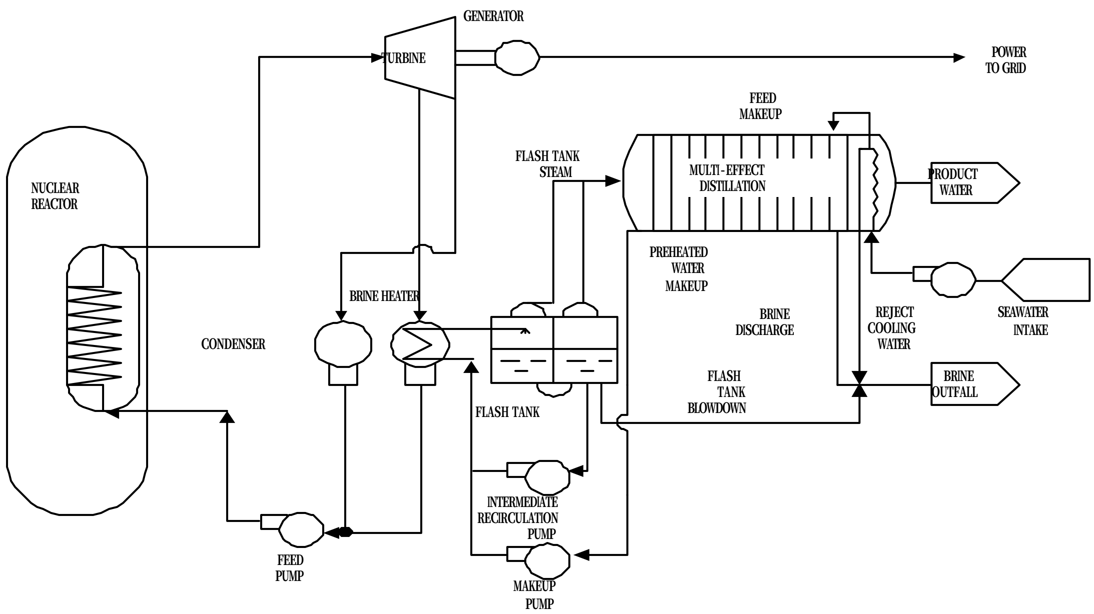

Figure 2. Integrated Nuclear Desalination Plant Concept using SMART