Conceptual Design of a Nuclear Reactor Dedicated for Desalination

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1. Introduction

The world is suffering from a serious shortage of freshwater, and global attention is now focused on nuclear desalination as a solution to this water crisis due to its economic and environmental advantages. Despite the many advantages of nuclear desalination, the nuclear safety issues still remain a perennial problem today. The Fukushima accident that occurred in March 2011 has drawn increased attention to the development and widespread application of inherent and passive safety features.

To respond to such needs, the development of a desalination-dedicated nuclear reactor with maximized safety features was proposed [1]. From the feasibility study, the desalination-dedicated reactor was found to be a good solution for meeting future water demand during the winter season in some countries like UAE by decoupling water and electricity supply. The economic analysis results indicated that under certain conditions, the desalination-dedicated reactor can produce freshwater at lower cost than the target nuclear co-generation reactor using steam extraction technologies.

2. Basic Design Concepts

First, the reactor is designed to have 400 MWth of thermal power so that the reactor can utilize the various advantages of a SMR.

The reactor uses well-proven PWR technologies but most importantly, it is dedicated to seawater thermal desalination producing only freshwater as a final product. In other words, the reactor produces heat solely for thermal desalination, thereby reducing the operating temperature and pressure because the temperature required for the distillation of seawater is much lower than that for electricity generation.

Notably, the reduced operating pressure could facilitate the employment of a pool-type reactor without primary-side pipelines that penetrate the reactor vessel wall. Employment of a pool-type reactor will significantly reduce possibility of a LOCA, which is a major concern for the safety of nuclear reactors. A reactor pool will also provide a larger coolant inventory, resulting in a larger heat capacity and longer response time in case of transients or accidents.

The reactor is basically designed not to generate electricity but may be designed to generate a minimum of electricity required for the thermal desalination; thus, the reactor can be either a single-purpose hat-only plant or a single-purpose co-generation plant.

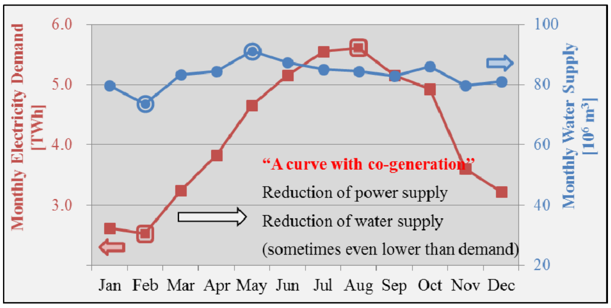

Fig. 1. Abu Dhabi global monthly electricity demand and water supply in 2010 from ADWEA (Abu Dhabi Water and Electricity Authority).

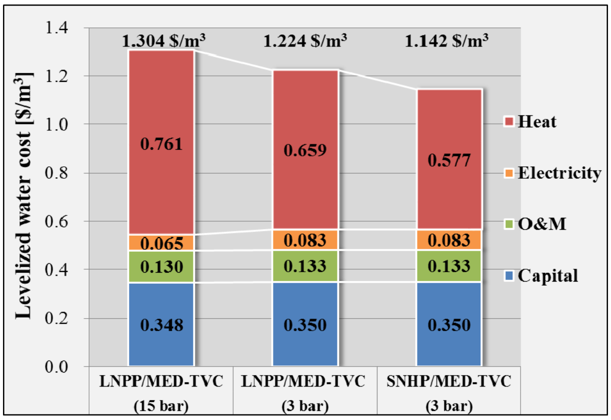

Fig. 2. Levelized water cost breakdowns of the LNPP/MED-TVC (combination of large-sized nuclear power plant and MED-TVC desalination plant) and SNHP/MED-TVC (combination of small-sized nuclear heat-only plant and MED-TVC desalination plant).

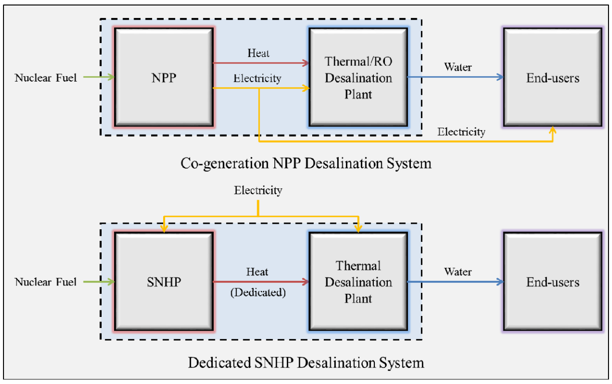

Fig. 3. Basic concept of a small-sized nuclear heat-only plant dedicated to seawater desalination.

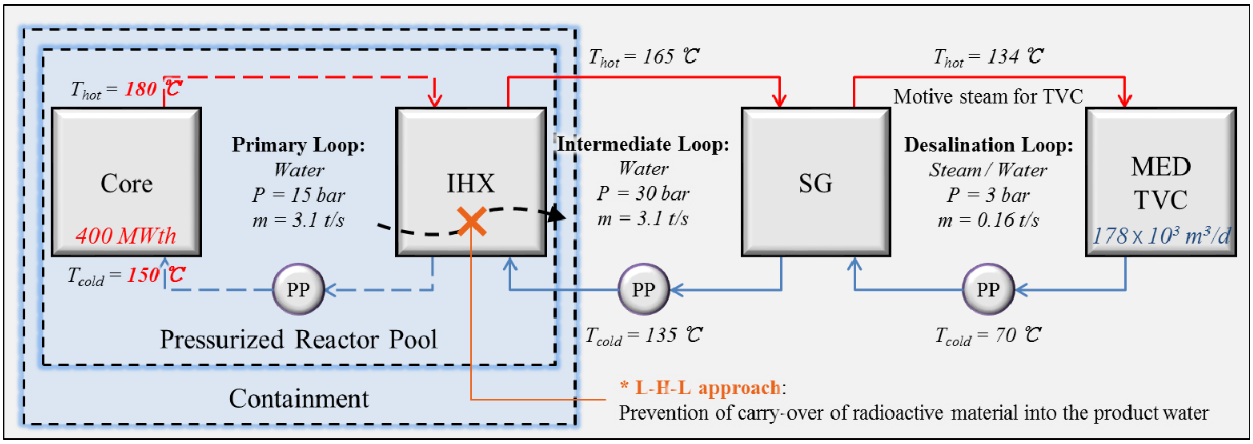

Fig. 4. Three-loop system from the MED-TVC plant to the reactor core.

3. Analysis Results and Detailed Design Features

The system consist of three loops: the reactor primary loop (PL), the intermediate heat transfer loop (IL), and the desalination loop (DL). Heat generated in the reactor core is transferred by low-pressure PL to the high-pressure IL through an IHX located within the reactor pool. The high-pressure IL that penetrates the reactor vessel transfers heat to the low-pressure DL through the SG, where motive steam for the MED-TVC is generated. The MED-TVC performance analysis and three-loop heat transfer calculation indicated that the desalination-dedicated reactor can operate at the extremely low pressure, 15 bar, without significant loss in desalination performance. The coupled MED-TVC plant (12-effect, low-temperature and horizontal tube-type units) operates at the minimum motive steam pressure of 3 bar and produces 178,000 m^3 of freshwater per day. The IL operates at 30 bar, twice the operating pressure of the PL, and thus, can prevent ingression of radioactive materials from the primary coolant to the freshwater products under any conditions.

The PL is connected to two ILs through four IHXs located in the annulus space between the reactor baffle and vessel in the form of vertically oriented cylinder. The IHX is a counter-current flow, shell and tube type heat exchanger where 100 MWth of heat is transferred from the PL water flowing downward at 766 kg/s in the shell side to the IL water flowing upward at 774 kg/s in the tube side. Temperature of the PL water decreases from 180 to 150 °C while that of the IL water increases from 135 to 165 °C, which results in 15 °C of MTD. Shell-side heat transfer coefficient and pressure drop was evaluated using the Bell-Delaware method. The resulting overall heat transfer coefficient is 4 $kW/m^2\cdot°C$ and effective pressure drops in the shell side and tube side are approximately 1 bar, respectively. The heat transfer area provided by design is 1970 m^2, i.e. 3600 tubes with 19 mm diameter and 9.1 m length, considering 20 % of safety factor for the fouling. Tubes are arranged in a square layout at 1.285 pitch ratio. Shell inside diameter is 1.7 m, so the length to diameter ratio is 5.4.

Reactor core consist of 69 fuel assemblies which is the same as existing commercial fuel assemblies except that they have half active fuel length 1.9 m compared to existing ones. Subchannel T/H analysis indicated that the core without mixing vanes has relatively large exit enthalpy differences depending on the subchannel, but the core thermal safety margin in terms of DNBR (using the W-3 CHF correlation) remains large enough, a minimum of 6.0, either with or without mixing vanes. This is mainly because the reactor core has relatively low average heat flux, 420 kW/m^2. Initial core is composed of 9 different assemblies by uranium enrichment and gadolinium burnable absorber loading. Iteration of coupled neutron physics and T/H analysis were conducted for the initial core. Neutron physics code calculates power distribution and T/H code calculates temperature distributions of the coolant and fuel rods. Output data of one code is used as input data of another code. Coupled analysis results were converged after 7 iterations.

Residual heat is removed using thermo-syphon bundles: horizontal long pipes which use natural convection and phase change of water coolant flows within pipes. For the redundancy, 4 trains of thermo-syphons (50 for each train), which correspond to 200% of the required capacity, are installed in the system. Lower evaporation part, 1.0 m, is submerged in the reactor pool and upper condensation part, 1.8 m, is submerged in an open water tank installed above steel upper head of containment. Analysis showed that the reactor primary coolant can be maintained at subcooled liquid state using 2 out of 4 trains even in the event of a Station Blackout.

4. Conclusions

A conceptual design of the desalination-dedicated nuclear reactor is in progress. The design features of the desalination-dedicated nuclear reactor could significantly enhance safety, reliability, and simplicity, and facilitate the extensive use of innovative passive safety systems. These maximized safety features of desalination-dedicated reactor could provide advanced capabilities for passive reactor shutdown and residual heat removal, and eventually prevent radioactivity release into the environment. The conceptual design achieved will provide a foothold for the future commercialization of the desalination-dedicated nuclear reactor and eventually help to address both a serious water crisis and nuclear safety issues.

REFERENCES

[1] Y. H. Jung, Y. H. Jeong, J. Y. Choi, A. F. Wibisono, J. I. Lee, and H. C. No, Feasibility study of a small-sized nuclear heat-only plant dedicated to desalination in the UAE, Desalination, Vol.337, p. 83, 2014.