1. Introduction

The development of the APWR, a Japanese Generation-III PWR, was started as a national project of Japan (1981-1985), and after this project, the design has been continuously improved and updated by five PWR utilities in Japan and Mitsubishi Heavy Industries (MHI). Through this development, the APWR has integrated and reflected all experiences through design, construction, and operation of 23 PWR units in Japan and employed evolutional technologies to improve economy, safety and reliability, operability and maintainability. Now, the Japan Atomic Power Company (JAPC)’s Tsuruga unit 3 and 4 are under the licensing process as the first APWR units in Japan, which have 1,538MWe output.

Based on the first APWR design, MHI has established the APWR design for international deployment. The output is enlarged to 1,700MWe class without increasing the original thermal output (4466MWt). Additionally, some modifications are made to meet recent international requirements and to improve operation economy. MHI is going to apply for the design certification to US-NRC with this APWR design called as “US-APWR”. This paper describes the design features of the APWR/US-APWR and the verification of them.

2. Major systems with evolutional and well verified technologies

2.1 Plant output capacity

The main specifications of the APWR and US-APWR are shown in Table 1. The plant output of the first APWR has been enlarged to 1,538 MWe in order to take economical advantage of scale by increasing the capacities of the core and main components. Moreover, we put more conscious on reducing the operation cost (fuel and O/M cost) to design US-APWR. The electrical output of the US-APWR is increased to 1,700MWe class by improving the plant thermal efficiency about 10% with the same thermal output 4466MWt. This is realized by improving the efficiency of the steam generators (SGs) and the turbine system. As the result, the operation cost is reduced about 10% from the first APWR.

2.2 Primary system

2.2.1 Reactor design

The APWR loads 257 assemblies of 17x17 type fuel. The core diameter is close to the maximum limitation from the view point of the stability of horizontal xenon oscillation in order to maximize the core capability [1]. The US-APWR employs the same design but extends the effective fuel height from 3660 mm to 4200 mm to reduce the specific power of the core while keeping the same reactor vessel height (Figure 1). Such low power density design enables 24 months operation cycle with more than 2 batches refuelling strategy and results in reduction of required uranium about 16% compared with conventional PWRs including the effect of improved thermal efficiency described above.

The neutron reflector (NR) has been developed and is applied for the APWR/US-APWR aiming at structural simplification to improve reliability and neutron economy. The NR, as shown in Figure 2, consists of stacked ring blocks made of stainless steel that replace the baffle plates, former plates, and neutron pads of the current PWR. Ring blocks are aligned by alignment pins, and all blocks are fastened together by 8 tie rods. The neutron reflector employs only about 50 parts including bolts and nuts, while the baffle former structure of a current PWR employs more than 2000 bolts. Such structure not only increases the reliability of the structure but also reduces the inspection loads for bolts located in high
fluence region. The NR also contributes to reduce the neutron fluence to the reactor vessel by 60% from the conventional 4-loop PWR. [2]

Additionally to ensure reliability and integrity of the reactor and fuels, coolant temperature is limited to 325 deg.C in the hot legs and less than 290 deg.C in the top plenum during normal operation. Furthermore, the US-APWR employs the top mounted in-core nuclear instrumentation system in order to improve reliability of the reactor vessel, while the first APWR in Japan employs the conventional bottom mounted system.

The reactor design of the APWR/US-APWR has been carefully verified by several large scale tests. For example for the neutron reflector and the reactor internals, critical experiments [3] to verify the core design methodology, flow tests to confirm flow characteristics, vibration, gap leakage, etc. with a 1/5...
scale mock-up of a whole reactor internals (Figure 3) and a full scale section model [4][5], seismic tests with 1/4 scale model [6], a manufacturing test of a ring block, etc. were carried out.

2.2.2 Steam generator design
SG design (type 70F-1 for the first APWR) has been improved to realize high efficiency, reliability and compact body. Major improvements from a conventional design are small sized effective separators which realized 10 times less moisture carry over (0.01%) [7], 19.05 mm outer diameter tubes made of TT690, and 9 points support anti-vibration bars. Owing to these designs, the weight of a steam generator is reduced by more than 10%.

Furthermore, SGs for the US-APWR (type 91TT-1) were designed to have 30% more heat transfer area to achieve higher efficiency by adopting tight triangular lattice. As the result, the diameter of the SG body of 91TT-1 became slightly smaller than that of 70F-1.

The SG design features had been verified through performance tests, seismic tests, etc. and have already been applied to the products for replacements (Figure 4, 5).

2.2.3 Reactor coolant pump design
The APWR/US-APWR Reactor Coolant Pump (RCP, type 100A) has achieved larger capacity and high efficiency by remarkable improvement of the impeller and diffuser configuration. The advanced seal design realizes its longer life. The RCP design had been proofed by hydraulic performance tests and a full scale full flow test is going to be carried out.

2.3 Turbine system
MHI adopts fully 3-dimensional reaction blades, which have excellent performance especially for nuclear turbines, and a low-pressure last blade in the form of a 54 inch Integral Shroud Blade (ISB) to achieve high efficiency and improved reliability. The 54-inch last stage blade was subjected to vibration tests and actual load tests to demonstrate its performance and reliability. For the US-APWR, the length of the blade will be optimized between 54 and 70 inches class for environmental condition of a site.

2.4 I&C system
The advanced main control boards and consoles shown in Figure 6, and the full digital I&C systems including the reactor protection system are applied to the APWR/US-APWR to improve man-machine interface and reliability [8].

An advanced alarm display system that dynamically prioritizes alarms was developed and applied for the APWR/US-APWR to avoid information overflow and to facilitate plant state identification. The prioritized alarms and their relevant process parameters are provided in the graphically presented plant systems on the large display panel with 3-level categorized colour coordination.
The emergency operation support system for APWR/US-APWR was developed and applied also to support operators in abnormal and accidental situations that threaten plant safety.

The advanced main control boards and consoles, and the full digital I&C system had been tested according to the V&V test plan. In addition, the overall operability of the system under normal and accident conditions was tested using a prototype console connected to a full scale plant simulator. The utility operating crews from several power stations joined the validation, and the physical workload was compared between the advanced and the latest conventional system. Owing to the new systems, the physical and mental workload level of the advanced main control console appeared to reduce by 25% and the estimated potential human error was also reduced by 25%.

3. Safety system with reliable and economical configuration

Improvement of safety is one of the most important design targets for the APWR/US-APWR. To realize effective, reliable and economical safety system, the APWR/US-APWR employs the following advanced technologies and realizes 10 times less core damage frequency. [9]

3.1 Four-train, direct vessel safety injection system

The APWR/US-APWR employs the 4-train direct vessel injection (DVI) system as shown in Figure 7. Such system configuration increases redundancy and independency, and enhances safety and reliability. From the view point of the cost, the 4-train DVI system realizes simple and compact safety system by enabling to reduce the capacity of each train from 100% to 50% and to eliminate inter-connecting piping between each train. The four train system enables “on line maintenance” and thus levels maintenance work load through a year.

As for the emergency AC power supply, the first APWR employs 2 diesel generators under Japanese reliable grid condition. For the US-APWR, the emergency power supply system is modified to 4-train configuration to enhance reliability of the system. The advanced accumulator described below allows relaxing the start-up time requirement of the emergency generators, and thus gas turbine generators can also be applicable for the emergency AC power supply system of the APWR/US-APWR.

3.2 Emergency water storage inside the containment

The APWR/US-APWR eliminates the switchover operation of emergency water sources following Loss of Coolant Accident (LOCA) by installing the Refuelling Water Storage Pit (RWSP) inside the containment as shown in Figure 7. The RWSP is formed with a lined concrete structure and works as the emergency water source. This design significantly contributes to lower the core damage frequency.

3.3 Passive low head injection

The safety system of the APWR/US-APWR consists of an optimized combination of active and passive components. The advanced accumulator is a passive component employed to enhance both safety and economics by its injection flow characteristics and displacing the low head injection system.

The flow characteristics of the advanced accumulator compared with the conventional one is shown in Figure 8. By adopting the vortex damper mechanism, the advanced accumulator supplies water with a
large flow rate at the early stage of LOCA, and it still supplies with relatively small flow rate even at the later stage. As shown in Figure 9, when the water level is above the top of the standpipe, water enters the vortex damper through both inlets at the top of the standpipe and at the side of the vortex damper and thus it injects water with large flow rate. When the water level drops below the top of the standpipe, the water enters the vortex damper only through the side inlet and thus it injects water with relatively low flow rate.

The injection function of the advanced accumulator and its vortex damper were confirmed by the 1/2 scale verification tests under the actual operating pressure (Figure 10)[10].

4. Excellent construction and operation performance

MHI have constructed 23 PWR plants over the last 30 years in Japan. Based on these experiences, MHI is going to increase factory operations instead of fieldwork and increase the number of pre-fabricated piping and component modules, adopt steel/concrete composite structures inside the containment, and employ a super heavy-duty crane to install them in order to reduce the construction period. Construction work is optimized and managed by utilizing an information management system based on 3D CAD/CAM system which enables seamless interface to the design work. As the result, the APWR/US-APWR is expected to be constructed within 48 months from the first concrete to the commercial operation.

Furthermore, the US-APWR realizes about 30 % less building volume per kWe from the latest 4-loop PWR in Japan. Safety equipments are located at each quadrant of the reactor building just close to RCS loops to reduce the building volume and piping quantity. The seismic input condition for U.S. (0.3g) allows the non-rectangular base-mat to improve the layout space efficiency.

The Japanese PWRs achieve excellent operation performances such as the unscheduled plant shutdown
frequency less than 0.1 times/year, fuel leakage frequency about 1E-6 for the last 15 years and no leakage for 13 years (Figure 11), etc. Such achievements are the fruits of continuous improvements of design, manufacturing, operation, and maintenance by the utilities and MHI. The APWR/US-APWR inherit and integrate all these experiences and technologies, and realize high operation performances.

5. Conclusions

The APWR design integrates more than 30 years experiences of MHI and Japanese PWR utilities designing, constructing, operating 23 PWRs, and is upgraded by employing evolutional technologies which had been fully verified. The first APWR units are under licensing process in Japan as Tsuruga unit 3 and 4 and expected to start commercial operation in 2014.

The design of the APWR for international deployment; US-APWR was established based on the first APWR design. Additionally, some modifications are made to meet utility requirements such as EPRI-URD and to improve operation economy. The major modifications are increased core volume and capacities of main components, top mounted in-core instrumentations, 4-train emergency AC power supply, etc. Mitsubishi Heavy Industries is going to apply for the design certification to US-NRC with the US-APWR.

6. References