IAEA-CN-164-3S09

The Design Characteristics of Advanced Power Reactor 1400

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Abstract. The Advanced Power Reactor 1400 (APR1400), which is a 1450 MWe evolutionary PWR based on well proven Korean Standard Nuclear Power Plant (KSNP) design incorporates a number of design modifications and improvements to meet the utility's needs for enhanced safety and economic goals and to address the new licensing issues such as mitigation of severe accidents. The APR1400 has been developed to meet 43 basic design requirements. Examples are 4000 MWth rated thermal power, 60 year life time, 10 times lower probabilities of core damage and accidental radiation release than the current nuclear power plant. The APR1400 had been developed during 10 years and obtained design certification at May, 2002. Currently, the first commercial APR1400 nuclear power plants, Shin-Kori 3&4 project for constructing are in progress. Shin-Kori 3&4 will be completed at mid 2013.

1. INTRODUCTION

The APR1400 is an evolutionary ALWR for which the design is based on the current KSNP design with capacity evolution. It also incorporates a number of design modifications and improvements to meet the utility's needs for enhanced safety and economic goals and to address the new licensing issues such as mitigation of severe accidents.

The major evolution of the APR1400 design concept is based upon the results of two years of research in early phase of the development. During this period, the design concepts were modified to match domestic needs and capabilities through reviewing ALWR designs being developed by EPRI and other countries. To establish the safety and economic goals for the APR1400 the requirement for ALWRs was compared thoroughly through the safety and economic evaluation. The design requirements have been established based on this comparative study, and the major requirements for the APR1400 design are:

- General Requirements
  - Capacity: 4000 MWt (rated thermal power);
  - Plant lifetime: 60 years;
  - Seismic design: SSE 0.3g;
  - Safety goals: core damage frequency lower than 10E-5/RY; and frequency of large radiation release due to containment failure lower than 10E-6/RY.

- Performance Requirements and Economic Goals
  - Plant availability: 90%;
  - Occupational radiation exposure: less than 1 manSv per reactor-year;
  - Construction period: 48 months for Nth Plants; and
  - Economic goal: 20% cost advantages over competitive energy sources.

As noticed above, the APR1400 aims at both enhanced safety and economic competitiveness. The economic goal of APR1400 is considered achievable by high performance in operation and cost savings in construction.

2. DESCRIPTION OF THE NUCLEAR SYSTEMS

2.1. Primary circuits

The nuclear steam supply system is designed to operate at rated thermal output of 4000 MW to produce an electric power output of around 1450 MWe. The major components of the primary circuit are a reactor vessel, two coolant loops, each containing one hot leg, two cold legs, one steam generator (SG), and two reactor coolant pumps (RCPs), and one pressurizer (PZR) connected to one of the hot legs. Two SGs and four RCPs are arranged symmetrically. A schematic diagram of arrangements and locations of the primary components are shown in Figure 1.

The design temperature in the hot leg is reduced from 621˚F of OPR1000, which is 1000MWe Korean standard nuclear power plants, to 615˚F in order to increase the operating margin and to reduce the SG tube corrosion problem. The capacities of the PZR and the SGs (especially secondary side) are increased from that of current designs. The increased capacity of the pressurizer accommodates the plant transients without reactor trip up to Condition III transients.

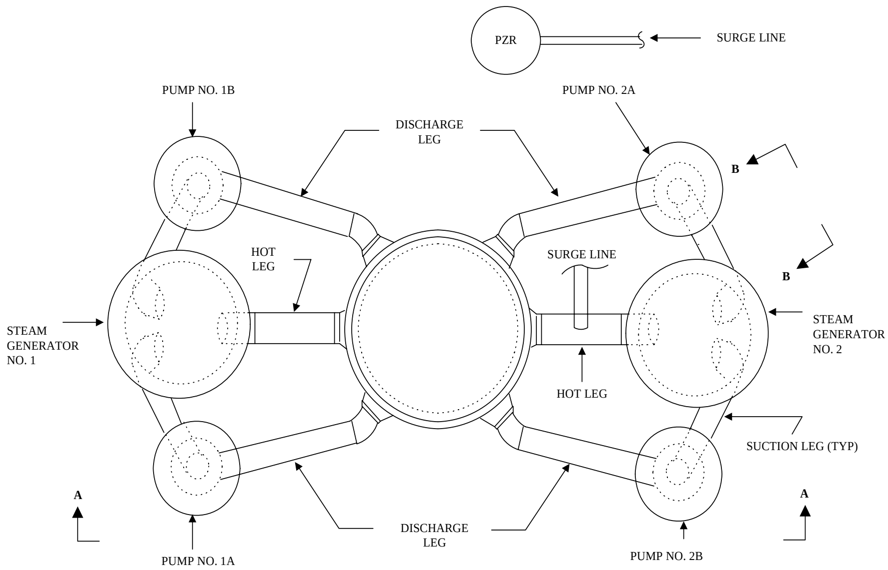

Fig. 1. RCS Arrangement of APR1400

Conventional spring loaded safety valves and safety depressurization valves mounted to the top of the PZR are replaced by the pilot operated safety relief valves (POSRVs), and functions of the RCS overpressure protection and safety depressurization could be performed by the POSRVs. The increased water inventory on the secondary side of the steam generator reduces the potential for unplanned reactor trips and provides longer operator response time in case of the total loss of feed water accident.

2.2. Reactor core and fuel design

The reactor core consists of 241 fuel assemblies built up by fuel rods containing uranium dioxide fuel with an average enrichment of 2.6 w/o in a 16x16 array. Each fuel assembly consists of 236 fuel rods, 5 guide tubes. The number of CEAs is 93 with 8 additional CEAs. 17 of the 93 CEAs are part-strength CEAs. The absorber materials used for full-strength control rods are boron carbide (B_4C) pellets. Inconell alloy 625 is used as the absorber material for the part-strength control rods.

The core is designed for an operating cycle of 18 months with a discharge burnup as high as approximately 60,000 MWD/MTU, and has an increased thermal margin of up to 15 % to enhance safety and improve operation performance. A portion of the fuel rods contains uranium fuel mixed with a burnable absorber (either Erbium or Gadolinium) to suppress excess reactivity after fuelling and to help control the power distribution in the core. The neutron flux shape is monitored by means of fixed in-core instrumentation (ICI) assemblies.

2.3. Primary component

The reactor vessel is composed of a vertically mounted cylindrical vessel with a hemispherical lower head welded to the vessel and a removable hemispherical closure head. The major design improvements incorporated in the reactor vessel design include; enhancement of core monitoring capability, larger operating margins, higher power level, and lower failure rate of fuel elements for higher plant availability and reliability. The life time of the reactor pressure vessel is improved to 60 years by use of low carbon steel, which has lower contents of Cu, Ni, P, S compared to current designs. The core support structures are designed to support and orient the reactor core fuel assemblies and control element assemblies, to direct the reactor coolant to the core. The core support barrel and the upper guide structure are supported at its upper flange from a ledge in the reactor vessel flange. The flange thickness is increased to sustain the enhanced seismic requirements.

In addition, APR1400 adopted integrated head assembly (IHA) for easy maintenance as shown in Fig. 2. IHA is a mechanical assembly of various components required to provide lifting the reactor vessel closure head and its appurtenances, cooling of the CEDM, supporting the head area cables and protecting missles generated from the reactor vessel head area.

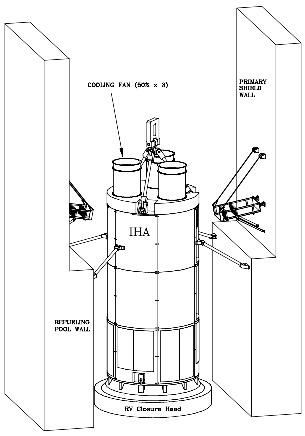

Fig. 2. Integrated Head Package of APR1400

The steam generators are vertical U-tube heat exchangers with peerless type steam dryers, moisture separators, and an integral economizer in which heat is transferred from the reactor coolant to the main steam and feedwater system. A major improved feature incorporated into the steam generator design is the use of advanced corrosion resistant material in the steam generator tubes namely Inconel 690 replacing Inconel 600. In order to improve the operating margin of the steam generator, the tube plugging margin increases from 8% in the earlier designs to 10%. The steam generator secondary water inventory is increased in order to extend the steam generator dryout time during the transients.

The pressurizer consisting of the pressurizer heaters, spray nozzles, and POSRVs maintains reactor coolant pressure and inventory in the rector coolant system with specified limits for all normal and upset operating conditions without reactor trip. The functional capability of the pressurizer is enhanced by an increased volume relative to power and an improved pressurizer heater control maneuverability during reactor shutdown.

The Leak-Before-Break(LBB) is adopted in the piping system in RCS and related auxiliary systems, since the pipe whip restraint and the support of the jet impingement shield in the piping system of the earlier plant are expensive to build and maintain, and lead to a potential degradation of plant safety. The LBB technology is applicable to the main coolant lines, surge lines, and pipes of the shutdown cooling system, the safety injection system. This technology reduces the redundant supports of the pipe in the NSSS pipe system. The cost of design, built-up and maintenance is reduced, since the dynamic effects of postulated ruptures in the piping system are also eliminated from the design basis.

The reactor coolant pumps circulate reactor coolant through the reactor vessel to the steam generators for heat removal and return it to the reactor vessel. The pump is a single-stage centrifugal unit of vertical type, which has 12,000 horse power. To assure leak-tightness of the shaft, the mechanical seal type is taken in order to seal against the full internal pressure in the pump. The basic function and type of the pump in the current plant is just the same as the APR1400.

2.4. Operating Characteristics

The power control system is capable of daily load follow operation at a typical load variation profile in Korea; 16 hours at 100 % and 4 hours at 50% with 2 hours ramps for power decreases and increases. The load rejection capability at the rated power should also be incorporated. This capability can reduce the outage time caused by the secondary system troubles since the reactor power can be brought up to 100% as soon as the troubles have been fixed.

3. DESCRIPTION OF THE SECONDARY SYSTEM

The secondary system consists of main steam, extraction steam, feedwater, condensate, turbine generator and auxiliary systems. For these systems, heat balance optimization studies have been made, considering system operability, reliability, availability and economy. The secondary system are designed to be capable of operation at 3% house load for a period of at least 4 hours without any detrimental effects of the systems, and capable of startup to full load from cold conditions in 8 hours, including rotor preheat. The main steam lines and the high pressure turbine are designed for a steam pressure of 6.9 MPa (1,000 psia), and two reheater stages are provided between the high pressure and the low pressure turbines. The generator is a three phase, 4 pole unit operating at 1800 rpm.

The feedwater pump configuration is selected to be 3x50% because of its ability to allow more reliable operation; all three pumps are normally operating, and the plant can remain at 100% power operation if one of the feedwater pumps is lost. On-line condensate polishers which can operate in full and partial flow, as well as in bypass mode, are provided to maintain proper water chemistry during normal power operation. In the feedwater systems, the feedwater heaters are installed in 7 stages and arranged horizontally for easy maintenance and reliability.

4. I&C AND ELECTRICAL SYSTEMS

4.1. I&C design concepts including main control room

APR1400 is equipped with digitalized Man-Machine Interface System(MMIS) which encompasses the Control Room Systems and Instrumentation and Control(I&C) systems, reflecting the modern computer technology.

One of the main features of the I&C system is the use of microprocessor-based multi-loop controllers for the safety and non-safety control systems. Engineering workstation computers and industrial personal computers are used for the two diverse data processing systems, respectively. To keep the plant safety against common mode failures in software due to the use of digital systems, controllers of diverse types and manufacturers has been employed in the control and protection systems. For data communication, a high speed fiber optic network is used. The remote signal multiplexer is also utilized for the safety and non-safety systems field signal transmission to save considerable amount of cables and cable trays. The I&C system used open architecture to the extent possible for the proven technology and maintainability. Since the S/W is heavily relied on in full digital MMIS, stringent S/W qualification process has been established and will be followed for the life cycle of APR1400. The MMIS concept is schematically depicted in Figure 3.

The APR1400 MCR design is characterized by 1) redundant compact workstations for operators, 2) seismically qualified Large Display Panel for overall process monitoring of the plant to be shared among operating crew, 3) multi-functional soft controls for discrete and modulation control, 4) computerized procedure system to provide on one of the workstation CRTs with context sensitive operation guides, operational information, and navigation links to the soft controls for normal and emergency circumstances and 5) safety console for dedicated conventional miniature button type controls provided to control essential safety functions. CRTs and Flat Panel Display are extensively used for presentation of operational information.

Fig. 3. MCR for APR1400

The human factor engineering is an essential element of the control room facility design and MMI design and its principles are systematically employed to ensure safe and convenient operation. Operating experience review analysis, function analysis, and task analysis is performed to provide systematic input to the MMI design.

4.2. Reactor protection system and other safety systems

The reactor protection system and other safety-related systems have been designed using programmable, digital equipment. A high degree of conservatism is required in the design of the safety-related systems, and therefore, design methodologies such as redundancy, diversity, and segmentation have been incorporated in order to achieve both the desired availability and reliability of these systems. For example, a high reliability of the protection system is ensured by automatic testing functions and the use of four independent channels. Signal validation techniques to pre-process input and output data and use of remote multiplexing and fiber-optic isolation will increase system availability.

4.3. Electrical Systems

The main power system consists of the generator, the generator circuit breaker, the main transformer, the unit auxiliary transformer and the stand-by transformer. The normal power source for non-safety and permanent non-safety loads is the off-site power source and the generator. If the normal power source is not available, the permanent non-safety loads are covered by two alternative sources: one from the stand-by off-site power source (via the stand-by transformer) and the other from one non-1E alternate AC power source with a diesel turbine generator. The electric power necessary for the safety-related systems is supplied through 4 alternative ways:

- the normal power source, i.e., the normal off-site power and the in-house generation,
- the stand-by off-site power, i.e., the off-site power connected through the stand-by transformer,
- the on-site standby power supply, i.e., two diesel generators, and
- the alternative AC source, i.e., the backup diesel turbine generator.

The on-site power supply is ensured by two independent Class 1E diesel generator sets; each of them is located in a separated building and is connected to one 4.16 kV safety bus. The alternate AC source adds more redundancy to the electric power supply even though it is not a safety grade system. The non-class 1E alternate AC is provided to cope with Station Blackout (SBO) situation which have a high potential of transients progressing to severe accidents. The alternate AC source is sized with sufficient capacity to accommodate the loads on the safety and the permanent non-safety buses.

5. SAFETY CONCEPT

5.1. Safety goals and design philosophy

One of the APR1400 development policies is to increase the level of safety dramatically. To implement this policy, the plant has been designed in accordance with the established licensing design basis to meet the licensing criteria and also be designed with an additional safety margin in order to improve the protection of the investment, as well as the protection of the public health. The safety goals of the APR1400 can be summarized as follows;

- The total core damage frequency should not exceed 10E-5 per year, considering both internal and external initiating events.
- The whole body dose for a person at the site boundary should not exceed 0.01 Sv (1 rem) during 24 hours after initiation of core damage with containment failure. The probability exceeding such a limit should be less than 10E-6 per year.
- The frequency of an accident in which the release of long-lived radioisotopes such as Cs-137 would exceed the amount to limit the land use shall be less than 10E-6 per year.

In addition to the public safety, a concept of investment protection has been implemented. In APR1400, there are many investment protection goals such as loss-of-coolant-accident (LOCA) protection, steam generator inventory, and so on. For example, the reactor with its fuel should be used continuously following the event of small break LOCA up to 15 cm pipe break. Another important design philosophy for safety is the increased design margins. A few examples of the design requirements following this philosophy are the requested core thermal margin of 10~15%, sufficient system capacity for operator recovery action time of more than 30 minutes, and station blackout coping time of 8 hours.

5.2. Safety systems and features

The active safety systems consist of the safety injection system, safety depressurization system, in-containment refueling water storage system, auxiliary feedwater system, and containment spray system.

The main design concept of the safety injection system (SIS) is simplification and redundancy to achieve higher reliability and better performance. The safety injection lines are composed of 4 mechanical trains and 2 electrical divisions without the tie branch between the injection lines for simplicity and independence. Each train has one safety injection pump and one safety injection tank. The common header currently installed in the SIS trains is eliminated and, finally, functions for safety injection and shutdown cooling are separated. Through the IRWST the current operation modes of high pressure, low pressure, and re-circulation can be merged into only one operation mode (i.e., safety injection). The emergency cooling water is designed to be injected directly into the reactor vessel so that the possibility of spill of the injected flow through the broken cold leg is eliminated. The schematic diagram of the safety injection system is shown in Fig. 4.

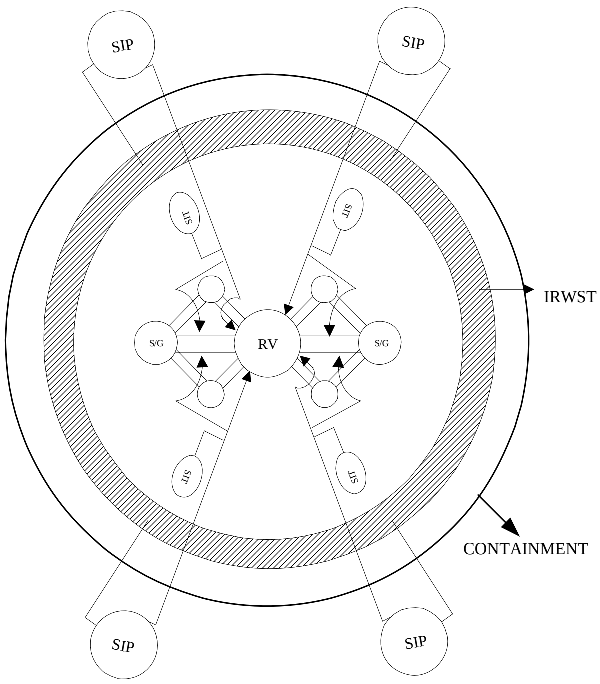

Fig. 4. The Schematic Diagram of SIS

The role of safety injection tank (SIT) is to inject large amount of water to fill reactor vessel lower plenum rapidly during the refill phase of LBLOCA. However, excess water in SIT spill out the break in current plants. In APR1400, the passive flow regulator, fluidic device is installed in the bottom of SIT to use excess water effectively.

The concept of the fluidic device is shown in Fig. 5. The basic principle of the fluidic device is vortex flow resistance. As shown in Fig. 5, when water flows through the stand pipe which is installed to rectangular direction with exit nozzle, it makes low vortex resistance and high flow rate. When water level is less than the top of the stand pipe, inlet flow is switched to the control ports which are installed to tangential direction with exit nozzle and it makes high vortex resistance and low flow rate.

Therefore, SIT discharges large amount of water to fill reactor vessel lower plenum rapidly when water level is above the stand pipe. However, when the water level is below the stand pipe, SIT injects relatively small amount of water for long time. In APR1400, low pressure safety injection pumps (LPSIPs) are eliminated and the SIT with the fluidic device plays the role of LPSIPs.

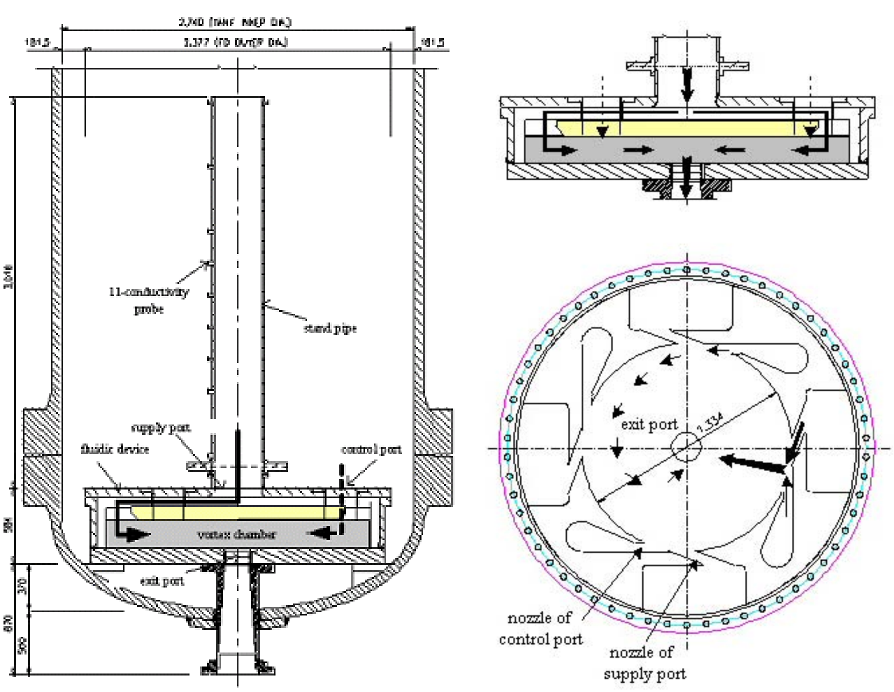

Fig. 5. The passive fluidic device

The refueling water storage tank is located at the inside of the containment and the arrangement is made in such a way that the injected emergency cooling water can return to the IRWST. The susceptibility of the current refueling water storage tank to external hazard is lowered by locating it at the inside of the containment. The functions of IRWST are as follows; the storage of refueling water, a single source of water for the safety injection, shutdown cooling, and containment spray pumps, a heat sink to condensing steam discharged from the pressurizer for rapid depressurization if necessary to prevent high pressure core melt or to enable feed and bleed operation, and coolant supply to the cavity flooding system in case of severe accidents to protect core melt.

The AFWS is designed to supply feedwater to the SGs for RCS heat removal in case of loss of main/startup feedwater systems. In addition, the AFWS refills the SGs following a LOCA to minimize leakage through pre-existing tube leaks. The AFWS is 2 divisions and 4 trains system. The reliability of the AFWS has been increased by use of two 100% motor-driven pumps, two 100% turbine-driven pumps and two independent safety-related emergency feedwater storage tanks as a water source instead of condensate storage tank.

5.3. Prevention and mitigation of severe accidents

The measures to cope with severe accident are divided into two categories, prevention and mitigation. Severe accident prevention features can be summarized as follows:

- Increased design margin such as larger pressurizer, larger steam generators, and increased thermal margin.
- Reliable engineered safety features (ESFs) such as SIS, AFWS, and containment spray system.
- Extended ESFs such as safety depressurization system with IRWST, alternate AC power, and diverse protection system.
- Containment bypass prevention

Severe accident mitigation features can be summarized as follows;

- Hydrogen mitigation system such as passive auto recombiner and hydrogen ignitor.
- Reactor cavity and cavity cooling system.
- External reactor vessel cooling system
- SDS and IRWST.
- Robust containment with large volume.

6. PLANT LAYOUT

6.1. Buildings and structures

The general arrangement of APR1400 has been developed based on the twin-unit concept and slide-along arrangement with common facilities such as the radwaste building as shown in Figure 6. The auxiliary building which accommodates the safety systems and components surrounds the containment building. The auxiliary and containment buildings will be built on a common basemat. The common basemat will improve the resistance against seismic events and reduce the number of walls between buildings so that rebar and formwork cost can be lowered.

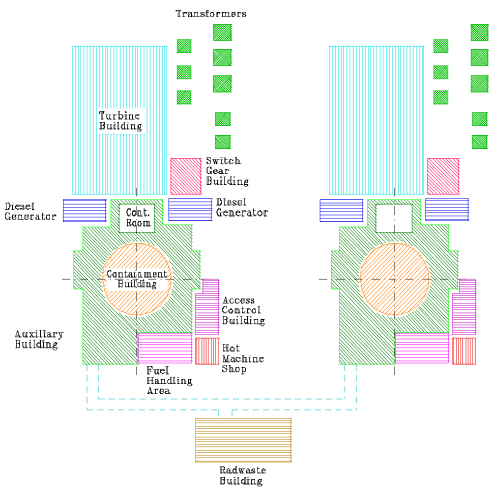

Fig. 6. The General Arrangement of APR1400

The APR1400 plant consists of the nuclear island which has containment building, auxiliary building, diesel generator building, access control building, and radwaste building and turbine island which has turbine building and annex building.

The plant layout is highly influenced by the safety consideration, in particular, for the physical separation of safety equipments. The safety injection pumps are located in the auxiliary building and each pump is located in each of four quadrants surrounding the containment. This arrangement ensures the physical separation of the pumps, minimizing the propagation of damage due to fire, sabotage, and internal flooding. The emergency diesel generator buildings are also separated and located at the symmetrically opposite side. The building arrangement is also designed for the convenience of maintenance, considering accessibility to and replaceability of equipment. The internal layout of the containment, in particular, is designed to allow the one piece removal of the steam generator.

6.2. Containment building

The containment building consists of a steel-lined, post-tensioned concrete containment, and a reinforced concrete internal structure. The containment building houses the pressurized water reactor, steam generator, reactor coolant loops, In-Containment Refueling Water Storage Tank (IRWST), and portions of the auxiliary systems.

The containment building is designed to provide biological shielding, external missile protection, and to sustain all internal and external loading conditions which may reasonably be expected to occur during the life of the plant. The containment building is on a common basemat which forms a monolithic structure with the auxiliary building. The equipment hatch, which has 7.8 m (26 feet) inner diameter, is selected to accommodate one-piece replacement of a steam generator. A polar bridge crane is supported from the containment wall. The bridge crane has the capability to install and remove the steam generators. The north-south centerline of the reactor vessel is offset from the north-south centerline of the containment by a distance of one foot to allow the polar crane to align with the reactor vessel center.

6.3. Turbine building

The turbine building houses the turbine generator, the condenser systems, the preheater system, the condensate and feedwater systems, and other systems associated with power generation. The turbine building is classed as non-safety related. It has no major structural interface with other buildings except for a seismic interface with the connecting auxiliary building. It is designed such that under SSE conditions, its failure will not cause failure of safety related structures. The turbine building is located such that the containment building is on the projection of the turbine shaft, on the high pressure turbine side. This allows for optimization of the piping and cable routes to the Nuclear Island. This arrangement also minimizes the risk of damage to safety-related equipment by missiles from the turbine or the generator, in the event of an accident.

6.4. Other buildings

The auxiliary building is on a common basemat which forms a monolithic structure with the containment building. To assure the safety and reliability, the auxiliary building is designed to enhance physical separation for mitigation of internal flooding, fire propagation as well as security and sabotage. The auxiliary building shares with fuel building in a quadrant arrangement. The auxiliary building houses pumps and heat exchangers for safety injection system and safety cooling system. Also, the emergency feedwater tanks and main control room are located in the auxiliary building. For the convenience of operation and maintenance, there is a staging service area in the auxiliary building for installation work in front of the equipment hatch of the containment.

The radwaste building designed to be shared between two units houses the liquid waste, gaseous waste, and solid waste systems. In accordance with Reg Guide 1.143, it is designed to provide protection against natural phenomena and to accommodate associated environmental conditions to the extent necessary to retain the spillage of potentially contaminated solids or liquids within the building. It has no major structural interface with other buildings.

The Emergency Diesel Generator (EDG) buildings are located at either side of the auxiliary building. Each EDG supports one division. These buildings are seismic category I structures which provide protection from fire, missiles, and the environment. Each EDG building contains an EDG and its auxiliary equipment. The EDGs are arranged as separate entities with dedicated auxiliaries including air supply, exhausts, and cooling systems, so that they are independent of one another in all respects. The EDG buildings are arranged to provide routine maintenance facilities and maintenance access space such that work on one EDG in no way affects the operability of the other EDG. The arrangement of structural facilities is such as to permit the removal and replacement of a complete EDG while the other(s) remain operable.

7. CONCLUSIONS

The APR1400 design development started in 1992. The basic design was completed in 1999. Since then, we performed design optimization to enhance economics. Through design optimization process, current APR1400 design has been finalized. From 2000, Korean regulation authority conducted the safety review for design certification and awarded design certification at May, 2002. Currently, the project for constructing first commercial APR1400 nuclear power plants, namely Shin-Kori 3&4 is in progress. The reactor vessel of Shin-Kori #3 will be installed in August 2010 and fuels are loaded at January 2013. The first APR1400 NPP will be completed at Sept. 2013. From 2008, we have begun to develop next generation ALWR, APR+, in order to enhance safety and economics further. The first APR+ plants will be commercialized at 2022.

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