Status report 100 - Economic Simplified Boiling Water Reactor (ESBWR)

Overview

Full name	Economic Simplified Boiling Water Reactor
Acronym	ESBWR
Reactor type	Boiling Water reactor (BWR)
Coolant	Light Water
Moderator	Light water
Neutron spectrum	Thermal Neutrons
Thermal capacity	4500.00 MWth
Gross Electrical capacity	1600.00 MWe
Design status	Basic Design
Designers	GE-Hitachi
Last update	21-07-2011

Description

Introduction

GE Hitachi Nuclear Energy's Economic Simplified Boiling Water Reactor (ESBWR) is a 1520 MWe power plant design based on the earlier 670 MWe Simplified Boiling Water Reactor (SBWR) design. The ESBWR reactor core has a rated thermal output of 4500 MW. Like the earlier SBWR design, the ESBWR design incorporates innovative, yet proven, features to further simplify an inherently simple direct cycle nuclear plant.

The ESBWR design objectives include:

- 60 year plant life from the date of full power operating license;
- 92% or greater plant availability;
- 12-24 month refueling intervals;
- personnel radiation exposure limit of 50 man-rem/year;
- safety related functions primarily through passive means;
- core damage frequency of less than 10^{-6} per reactor year;
- significant release frequency from all events (internal & external) limited to 5×10^{-8} per reactor year;
- no operator action or AC power supply required for safety systems, for 72 hours following a design basis accident, to maintain the reactor and containment at safe stable conditions.

The principal design criteria governing the ESBWR plant design are associated with either a power generation function or a safety-related function. Each is discussed below.

General power generation design criteria

The plant is designed to produce electricity from a turbine generator unit using steam generated in the reactor. Heat removal systems are provided with sufficient capacity and operational capability to remove heat generated by the reactor core for the full range of normal operating conditions and off-normal transients. Backup heat removal systems are provided to remove reactor core decay heat in circumstances where the normal heat removal systems have become inoperative. The capacity of the backup systems is adequate to prevent fuel cladding damage.

In conjunction with other plant systems, the fuel cladding is designed to retain its integrity for the design life of the fuel. The consequences of plant system failures (such as pipe break, etc.) therefore remain within acceptable limits throughout the range of normal operating conditions and off-normal transients.

Control equipment is provided to allow the reactor to respond automatically to normal load changes and off-normal transients. Reactor power level is manually controllable, with interlocks or other automatic equipment provided as backup to procedural control to avoid conditions requiring the functioning of safety related systems or engineered safety features.

General safety design criteria

The plant is designed, fabricated, erected and operated in such a way that the release of radioactive material to the environment will not exceed the limits and guideline values of applicable government regulations pertaining to the release of radioactive materials for normal operation, for off-normal transients and for accidents.

The reactor core is designed so that nuclear characteristics do not contribute to a divergent power transient. The reactor is designed with abundant core coolant flow so that there is high flow margin to prevent divergent oscillation of any operating characteristics considering the interaction of the reactor with other appropriate plant systems.

Safety related systems and engineered safety features function to ensure that no damage occurs to the reactor coolant pressure boundary from internal pressures resulting from off-normal transient or accident conditions. Where positive, precise action is immediately required in response to off-normal transients or accidents, such action is automatic and requires no decision or manipulation of controls by plant operations personnel. The design of safety related systems, components and structures includes allowances for natural environmental disturbances such as earthquakes, floods, and storms at the plant site.

Standby batteries are provided to allow prompt reactor shutdown and removal of decay heat under circumstances where normal auxiliary power is not available. The standby batteries have sufficient capacity to concurrently power all safety related systems requiring electrical power.

The ESBWR design has a pressure suppression-type containment that completely encloses the reactor system, drywell, suppression chamber, and certain other associated volumes. This containment, in conjunction with the reactor building and other safety related features, limits the radiological effects from design basis accidents to less than the prescribed regulatory limits. A perspective of the containment and its contents is shown in Figure 2.1.

To maintain the integrity of the containment system, provisions are made for removing energy released to it under accident conditions. In the event of a design basis loss of coolant accident (LOCA), emergency core cooling is provided to keep the core covered with coolant and to limit fuel cladding temperatures to far less than the regulatory limit of 1200°C. The emergency core cooling system provides core cooling over the complete range of postulated break sizes in the reactor coolant pressure boundary piping. When required, emergency core cooling is initiated automatically, regardless of the availability of power from the normal plant generating system or offsite supplies.

The control room is shielded against radiation so that continued occupancy under design basis accident conditions is possible. In the event that the control room becomes uninhabitable for other reasons, it is possible to bring the reactor from power range operation to cold shutdown conditions by utilizing alternative controls and equipment that are available outside the control room.

Fuel handling and storage facilities are designed to prevent inadvertent criticality and to maintain shielding and cooling of spent fuel as necessary to meet operating and offsite dose constraints.

2.1 Primary circuit and its main characteristics

The primary functions of the nuclear boiler system are:

- to deliver steam from the reactor pressure vessel (RPV) to the turbine main steam system;
- to deliver feedwater from the condensate and feedwater system to the RPV;
- to provide overpressure protection of the reactor coolant pressure boundary (RCPB);
- to provide automatic depressurization of the RPV in the event of a loss of coolant accident (LOCA) where the RPV does not otherwise depressurize rapidly;
- to provide (with the exception of neutron flux monitoring) the instrumentation necessary for monitoring RPV conditions such as pressure, metal temperature, and water level .

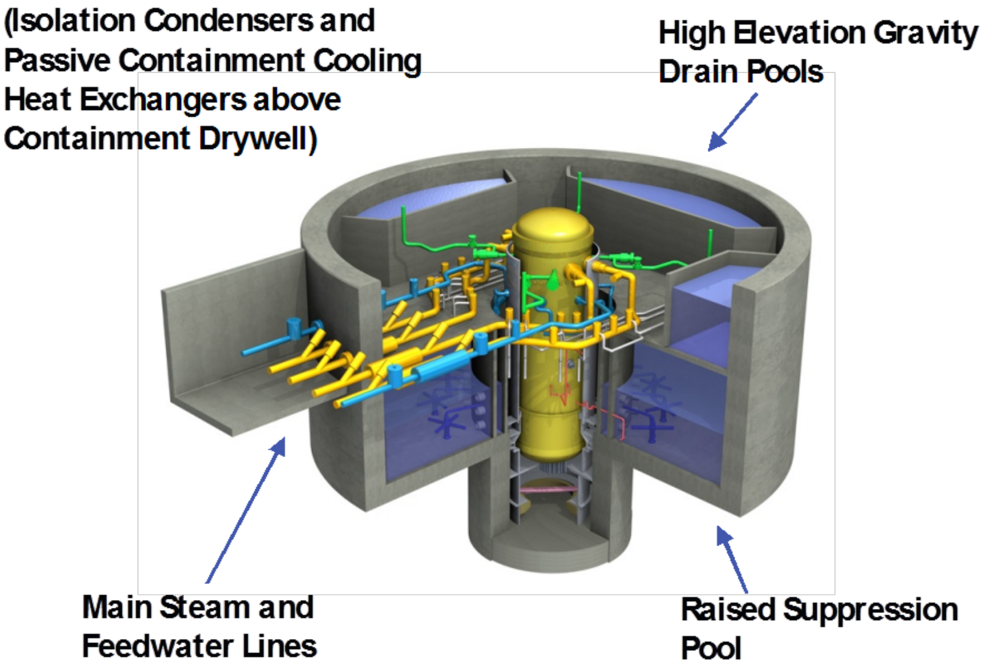

FIG. 2.1. ESBWR containment envelope and design features

The main steam lines (MSLs) are designed to direct steam from the RPV to the turbine, and the feedwater lines direct feedwater from the condensate and feedwater system to the RPV.

The main steam line flow limiter, a flow restricting venturi built into the RPV MSL nozzle of each of the four main steam lines, limits the coolant blowdown rate from the reactor vessel to a (choked) flow rate equal to or less than 200% of rated steam flow in the event a main steam line break occurs anywhere downstream of the nozzle.

There are two main steam isolation valves (MSIVs) welded into each of the four MSLs, one inner MSIV in the containment and one outer MSIV outside the containment.

Overpressure protection of the RPV is provided by safety/relief valves (SRVs) located on the four main steam lines (MSLs), between the RPV and the inboard MSIV. The SRVs also provide a depressurization capability as part of the automatic depressurization subsystem (ADS).

The ADS consists of ten SRVs, plus eight depressurization valves (DPVs) and their associated instrumentation and controls. The DPVs are pyrotechnically-actuated, straight-through, non-reclosing valves with a metal diaphragm seal. The use of a combination of SRVs and DPVs to accomplish the ADS function provides an improvement in ADS reliability against hypothetical common mode failures of otherwise non-diverse ADS components.

In the event of a LOCA, the ADS depressurizes the RPV sufficiently quickly to allow the gravity driven cooling system (GDCS) to inject coolant into the RPV, thereby keeping the core covered and maintaining the core temperature well below design limits. Following initial operation, the ADS maintains the reactor in a depressurized state without the need for AC or DC power. The SRVs and DPVs are actuated in groups of valves at staggered times as the reactor undergoes depressurization. This minimizes reactor level swell during depressurization and minimizes the coolant inventory loss from the RPV.

2.2 Reactor core and fuel design

The ESBWR core configuration consists of 1132 bundles. The active fuel height is shorter than a typical BWR in order to reduce the pressure drop and augment natural circulation. The rated core power is 4500 MWt, which corresponds to a power density of 54.3 kW/l. Reactivity control is maintained by movement of control rods and the use of burnable absorbers in the fuel. As backup, a standby liquid control system, which can inject a borated water solution into the reactor, is also available.

Control rod drive system

The control rod drive (CRD) system is composed of three major elements: the fine motion control rod drive (FMCRD) mechanisms; the hydraulic control unit (HCU) assemblies, and the control rod drive hydraulic (CRDH) subsystem.

The FMCRDs provide electric motor driven positioning for normal insertion and withdrawal of the control rods and hydraulic powered rapid control rod insertion (scram) in response to manual or automatic signals from the reactor protection system (RPS). Simultaneous with scram, the FMCRDs also provide electric motor driven run-in of all control rods as a means of rod insertion that is diverse from the hydraulic powered scram. The hydraulic power required for scram is provided by high-pressure water stored in individual hydraulic control unit (HCU) assemblies. Each HCU is designed to scram up to two control rods. The HCUs also provide the flow path for purge water to the associated drives during normal operation.

The CRDH subsystem supplies high-pressure demineralized water that is regulated and distributed to provide charging of the HCU scram accumulators and purge water flow to the FMCRDs. The capacity of the pumps is sufficient to maintain RPV water level for small line break LOCAs. The CRD system is designed with the capability to provide makeup water to the RPV while at high pressure as long as AC power is available. If sensed reactor water level reaches Level 2 (approximately 8.6 m above the top of the active fuel), the CRD pumps run out in an effort to recover level.

The FMCRDs are mounted in housings welded into the RPV bottom head. Each FMCRD has a movable hollow piston tube that is coupled at its upper end, inside the reactor vessel, to the bottom of a control rod. The piston is designed such that it can be moved up or down, both in fine increments and continuously over its entire range, by a ball nut and ball. In response to a scram signal, the piston rapidly inserts the control rod into the core hydraulically, using stored energy in the HCU scram accumulator. The FMCRD design includes an electro-mechanical brake on the motor drive shaft and a ball check valve at the point of connection with the scram inlet line. These features prevent control rod ejection in the event of a failure of the scram insert line. Each HCU provides sufficient volume of water stored at high pressure in a pre-charged accumulator to scram two FMCRDs at any reactor pressure.

2.3 Fuel handling and transfer systems

The operating floor in the reactor building is serviced with a refueling platform.

Transfer of spent fuel to the auxiliary fuel storage building, and new fuel to the operating floor, is achieved via an inclined fuel transfer system (IFTS) that handles two bundles at a time. This system is similar to that used in GE Mk III-style containment designs, with one key advantage – the transfer system is outside of containment. This allows fuel movement before and after an outage, which is a significant advantage.

The fuel buffer pool provides temporary storage of spent fuel bundles, plus irradiated reactor components. With this capability, the sensitivity of fuel loading and unloading operations to the throughput of the IFTS is reduced from what otherwise would be the case.

2.4 Primary components

Reactor pressure vessel

The ESBWR reactor pressure vessel (RPV) assembly consists of the pressure vessel, removable head, and its appurtenances, supports and insulation, and the reactor internals enclosed by the vessel (excluding the core, incore nuclear instrumentation, neutron sources, control rods, and control rod drives). The RPV instrumentation to monitor the conditions within the RPV is designed to cover the full range of reactor power operation. The RPV, together with its internals, provides guidance and support for FMCRDs. Details of the RPV and internals are discussed below.

The RPV is a vertical, cylindrical pressure vessel comprised of rings welded together, with a removable top head, head flanges, seals and bolting. The vessel also includes penetrations, nozzles, shroud support, and venturi-shaped flow restrictors in the steam outlet nozzles.

The reactor vessel has a minimum inside diameter of 7.1 m (23.3 ft.), a wall thickness of about 182 mm (7.2 in.) with cladding, and a height of 27.6 m (90.3 ft.) from the inside of the bottom head (elevation zero) to the inside of the top head. The bottom of the active fuel location is 4.4 m (14.5 ft.) from elevation zero and the active core is 3.04 m (10.0 ft.) high. The relatively tall vessel permits natural circulation driving forces to produce abundant core coolant flow.

An increased internal flow path length, relative to forced circulation BWRs, is provided by a long "chimney" in the space that extends from the top of the core to the entrance to the steam separator assembly. The chimney and steam separator assembly are supported by a shroud assembly that extends to the top of the core. The resulting large RPV volume provides a substantial reservoir of water above the core, which ensures the core remains covered following transients involving feedwater flow interruptions or loss-of-coolant-accidents (LOCAs). This gives an extended period of time during which automatic systems or plant operators can re-establish reactor inventory control using any of several normal, non-safety related systems capable of injecting water into the reactor. Timely initiation of these systems precludes the need for activation of emergency safety equipment.

The large RPV volume also reduces the rate at which reactor pressurization occurs if the reactor is suddenly isolated from its normal heat sink. If isolation should occur, reactor decay heat is rejected to an isolation condenser system (ICS) located within a large pool of water (the IC/PCC pool) positioned immediately above (and outside) the containment. The slower pressurization rate and the ICS eliminate the need to actuate relief valves, which would result in the discharge of RPV inventory to the suppression pool.

Reactor internals

The major reactor internal components include:

- core (fuel, channels, control rods and instrumentation),
- core support structures (shroud, shroud support, top guide, core plate, control rod guide tube and orificed fuel support),
- chimney and partitions,
- chimney head and steam separator assembly,
- steam dryer assembly,
- feedwater spargers,
- standby liquid control headers, spargers and piping assembly,
- incore guide tubes.

Except for the Zircaloy in the reactor core, these reactor internals are stress corrosion resistant stainless steel or other high alloy steels.

The fuel assemblies (including fuel rods and channels), control rods, chimney head and steam separator assembly, steam dryers and incore instrumentation assemblies are removable when the reactor vessel is opened for refueling or maintenance. In addition, the ESBWR internals are designed to be removable.

The RPV shroud support is designed to support the shroud and the components connected to the shroud, including the steam separator, chimney, core plate, top guide and the fuel bundles.

Reactor recirculation pumps

The ESBWR operates with natural circulation of the reactor coolant. Thus, no recirculation pumps are provided.

2.5 Reactor auxiliary systems

Plant service water system (PSWS) - The PSWS rejects heat from non-safety related components in the reactor and turbine buildings to the environment. The PSWS consists of two independent and 100% redundant open loops continuously re-circulating water through the heat exchangers of the reactor component cooling water system (RCCW) and the turbine component cooling water system (TCCW). Heat is rejected to the environment by mechanical draft cooling towers.

Reactor component cooling water system (RCCW) - The RCCW cools non-safety related components in the reactor building and provides a barrier against potential radioactive contamination of the PSWS. The RCCW consists of two 100% capacity independent and redundant closed loops.

Makeup water system (MWS) - The MWS is designed to supply demineralized water to the various non-safety related systems that need demineralized water and provides water to the IC/PCC pools.

Condensate storage and transfer system (CSTS) - The CSTS is a non-safety related system that consist of two 100% pumps and lines taking suction from one storage tank that is the normal source of water for makeup to selected plant systems. The CSTS is also used for storage of excess condensate rejected from the condensate & feedwater systems and the condenser hotwell.

Chilled water system (CWS) - The CWS consists of two independent, non-safety related, subsystems: the reactor building CWS and the turbine building CWS. The CWS provides chilled water to the cooling coils of air conditioning units and other coolers in the reactor and turbine buildings. Each subsystem consists of two 100% capacity, redundant, and independent loops with cross-ties between the chilled water piping.

2.6 Operating characteristics

The ESBWR relies extensively on the lessons learned from operating BWRs regarding natural circulation operation, especially the GKN Dodewaard natural circulation reactor. The ESBWR has been designed to maximize core flow and ensure that there are very large margins relative to operation in unstable flow regions. The core flow has been maximized by the following actions:

- Eliminating the flow restriction introduced by recirculation pumps (reduced pressure drop),
- Using shorter fuel (reduced pressure drop),
- Using a tall chimney above the core (increased driving head),
- Using improved steam separators (reduced pressure drop).

As shown in Figure 2.2, these design features result in an average core flow per bundle over three times greater than that of a forced circulation internal pump plant at similar bundle power. This allows the ESBWR to operate well away from regions of power/flow instability without the need for operating restrictions being imposed on the plant operator. As an added benefit, the use of natural circulation eliminates pumps, motors, controls, piping and many other components that could possibly fail and affect plant availability.

Similar to the Dodewaard plant, the ESBWR is extremely simple to operate during startup and normal operation, and also has a very gentle transient response. This is because of the large reactor vessel and steam and water inventory. A reactor isolation results in no loss of coolant inventory and no heating up of the containment or suppression pool.

The extensive experience of startup and normal operation of BWRs with features common to the ESBWR, including nearly 30 years at Dodewaard (a natural circulation plant), provide high confidence in the design.

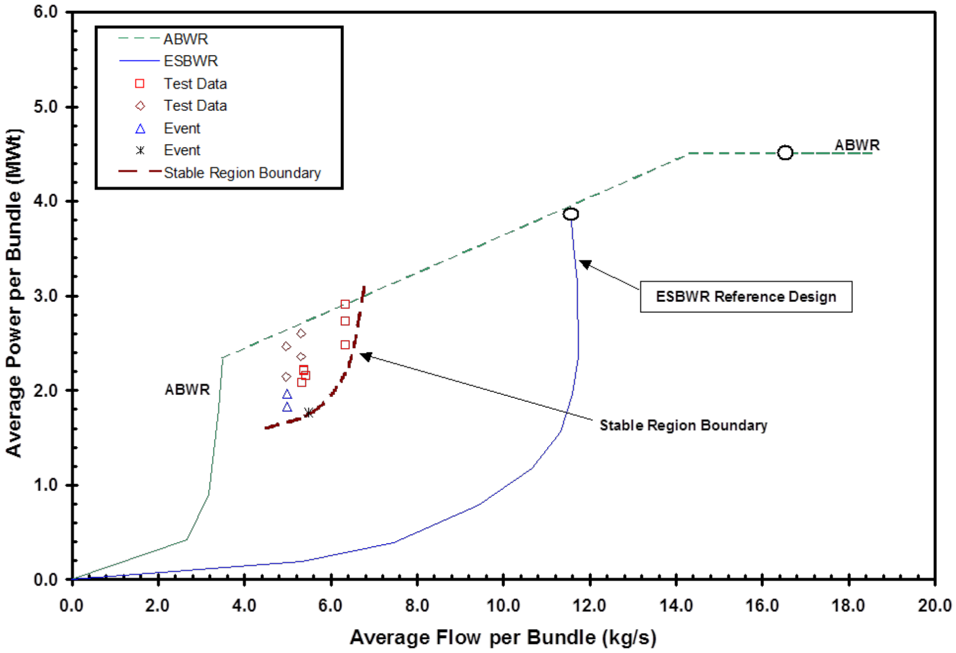

FIG.2.2. Average core flow per bundle for ESBWR vs. forced convection BWRs

Description of safety concept

3.1 Safety requirements and design philosophy

The basic ESBWR safety design philosophy is built on utilization of inherent margins (e.g., larger volumes and water inventory) to eliminate system challenges. An example of this philosophy is that during reactor isolation, no SRV shall actuate. The first line of defense is to enhance the normal operating system's ability to handle transients and accidents through such design features as adjustable speed, motor driven feedwater pumps and higher capacity CRD pumps with backup power (6.6 kV plant investment protection buses). As a second line of defense, passive safety-related systems are used in the design to provide confidence in the plant's ability to handle transients and accidents.

The plant also retains several motor driven (non-safety) systems to handle transients and accidents. As well, all safety related systems are designed such that no operator actions are needed to maintain safe, stable conditions for 72 hours following a design basis accident. A view of the passive safety system configuration is shown in Figure 3.1 Descriptions of some important passive safety related systems are provided in the following section.

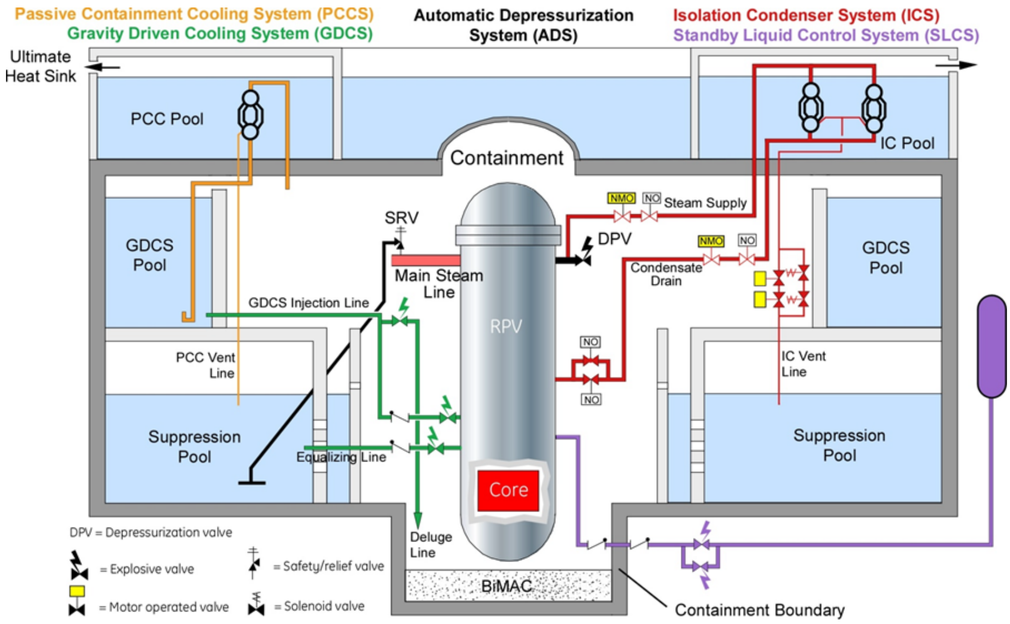

FIG. 3.1 Safety System Configuration (not to scale)

3.2 Safety systems and features (active, passive and inherent)

Isolation condenser system (ICS)

The isolation condenser system removes decay heat after any reactor isolation during power operations. Decay heat removal limits further increases in steam pressure and keeps the RPV pressure below the SRV setpoint. The ICS consists of four independent loops, each containing a heat exchanger that condenses steam on the tube side and transfers heat by heating/evaporating water in the IC pool, which is vented to the atmosphere. The arrangement of the IC heat exchanger is shown in Figure 3.2.

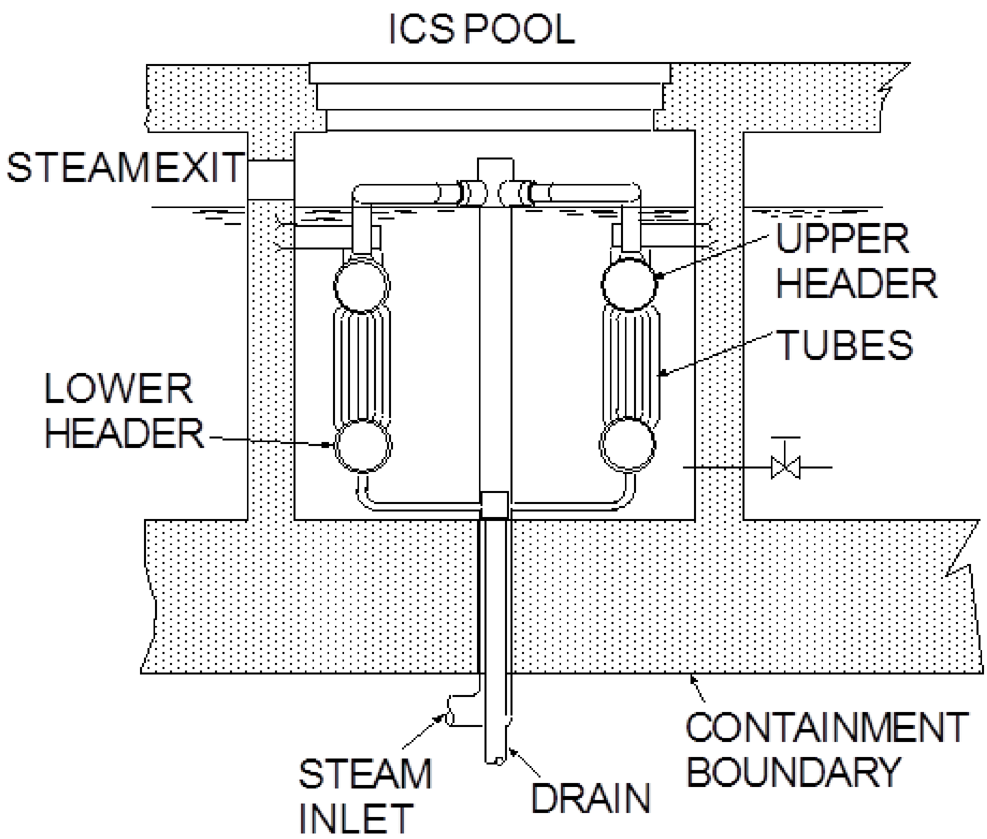

FIG. 3.2. Isolation condenser arrangement

The ICS is initiated automatically by any of the following signals: high reactor pressure, MSIV closure, or an RPV water Level 2 signal. To start an IC into operation, the IC condensate return valve is opened whereupon the standing condensate drains into the reactor and the steam water interface in the IC tube bundle moves downward below the lower headers. The ICS can also be initiated manually by the operator from the MCR by opening the IC condensate return valve.

The IC pool has an installed capacity that provides ~72 hours of reactor decay heat removal capability. The heat rejection process can be continued indefinitely by replenishing the IC pool inventory. The ICS passively removes sensible and core decay heat from the reactor when the normal heat removal system is unavailable. Heat transfer from the IC tubes to the surrounding IC pool water is accomplished by natural convection, and no forced circulation equipment is required.

Emergency core cooling - gravity driven cooling system (GDCS)

The gravity driven cooling system (GDCS), in conjunction with the automatic depressurization system (ADS), comprises the emergency core cooling system (ECCS) for ESBWR. Following a confirmed RPV water Level 1 signal and depressurization of the reactor to near-ambient pressure conditions by the ADS, the GDCS will inject large amounts of cooling water into the reactor. The cooling water flows to the RPV through simple, passive, gravity-draining.

The GDCS is composed of four identical, safety-related, divisions. For "short-term" cooling needs, each division takes suction from three independent GDCS pools positioned in the upper elevations of the containment (Figures 2.1). Flow from each division is controlled by pyrotechnic-type ECCS injection valves, which remain open after initial actuation. Each division of the "short-term" subystem feeds two GDCS injection nozzles on the RPV (8 total).

Backup flooding is also provided by a second GDCS subsystem fed by water from the suppression pool. Pyrotechnic-type ECCS injection valves are also used in this subsystem, which feeds one RPV injection nozzle per division (4 total). These nozzles are placed at a lower elevation on the RPV than those of the "short-term" subsystem.

In the event of a postulated severe accident that results in a core melt, with the molten core reaching the lower drywell region, the three upper GDCS pools have sufficient inventory to flood the lower drywell cavity to a level equal to the top of the active fuel.

The GDCS is completely automatic in actuation and operation. The ability to actuate the system manually is provided as a backup, but the operator cannot close any valves in the system.

Passive containment cooling system (PCCS)

The PCCS is a passive system that removes the decay heat and maintains the containment within its pressure limits for design basis accidents such as a LOCA. It consists of six low-pressure, totally independent, loops, each containing a steam condenser in a pool of water (Figure 3.3), with the steam inlet coming from the drywell area surrounding the RPV.

The steam condenser condenses steam on the tube side and transfers heat to the water in the IC/PCC pool. The IC/PCC pool is vented to the atmosphere. Each PCCS condenser is located in a sub-compartment of the IC/PCC pool, and all pool sub-compartments communicate at their lower elevations. This allows full use of the collective water inventory, independent of the operational status of any given PCCS loop.

The PCCS loops are driven by the pressure difference created between the containment drywell and the suppression pool during a LOCA. PCCS operation requires no sensing, control, logic or power actuated devices for operation. Together with the pressure suppression containment system, the four PCCS condensers limit containment pressure to less than the design pressure for at least 72 hours after a LOCA, without inventory makeup to the IC/PCC pool.

The PCCS condensers are a closed loop integral part of the containment pressure boundary and are designed for twice the containment design pressure. Since there are no containment isolation valves between the PCCS condensers and the drywell, they are always in "ready standby" mode.

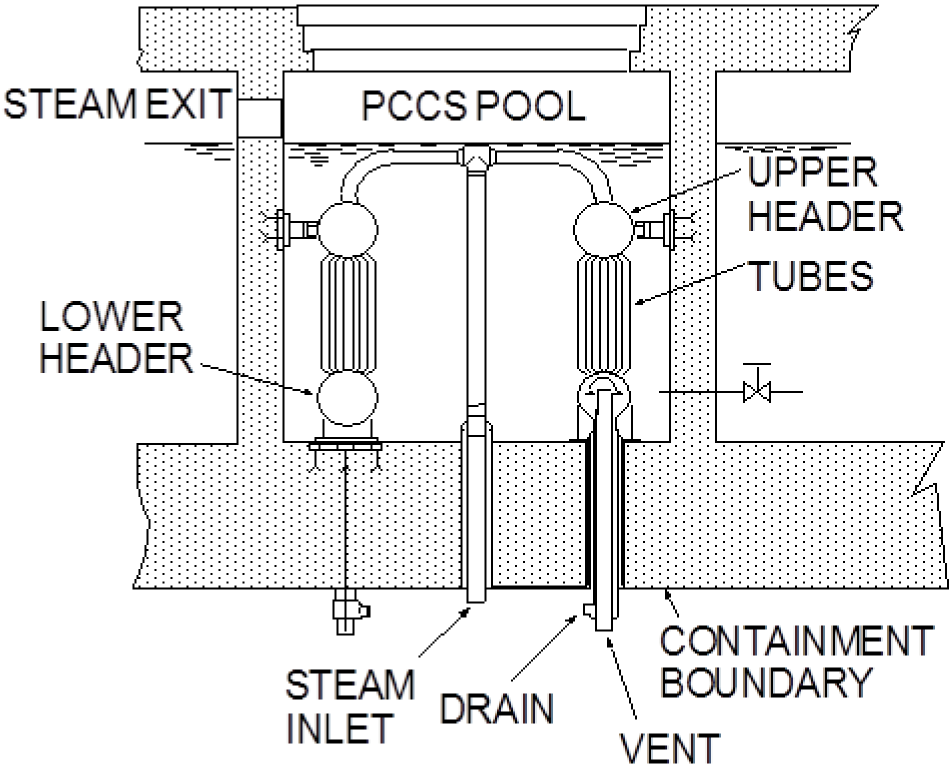

FIG.3.3. Passive containment cooling condenser arrangement

Table 3.1. Key ESBWR features for prevention and mitigation of severe accidents

Design Feature	Purpose/Description
Compact containment design with minimum penetrations. Lower drywell kept dry (Mitigation)	Containment isolation with minimum leakage. High retention of aerosols. Fuel coolant interactions minimized.
Isolation condenser system (Prevention)	Controls reactor pressure and removes decay heat when reactor is isolated, including during a station blackout event.
Diverse automatic depressurization system (Prevention)	Depressurizes reactor pressure vessel and prevents high pressure core melt. Minimizes probability of direct containment heating.
Passive containment cooling system (Prevention and Mitigation)	Provides long term containment cooling. Keeps pressure within design limits.
PCC heat exchanges (Mitigation)	Filter aerosols - minimize offsite dose.
Suppression pool and airspace (Prevention & Mitigation)	Suppression pool is heat sink. Scrubs aerosols. Airspace volume is sized for 100% metal water reaction.
GDCS (Prevention & Mitigation)	Provides core cooling during a loss of coolant accident.
Core catcher (BiMAC) (Mitigation)	Retention of molten core. Core catcher prevents basemat erosion and melt through. Prevents core-concrete interaction.
Lower drywell configuration (Mitigation)	Lower drywell floor provides sufficient spreading area for cooling of a molten core.

Lower drywell flooder system (Mitigation)	Provides external vessel cooling (in-vessel retention) and additional cooling for corium on the floor.
Inerted containment (Prevention & Mitigation)	Prevents hydrogen detonation.
Passive Autocatylitic Recombiners (Prevention & Mitigation)	Prevents hydrogen and/or oxygen combustion and detonation.
Containment overpressure protection (Mitigation)	Provides additional defense in depth.

3.3 Severe accidents (Beyond design basis accidents)

The ESBWR design philosophy on plant safety is one of "prevention and mitigation through simplification". Prevention is achieved by utilizing a systematic design approach that provides simplified but diverse and redundant systems or components. Mitigation is achieved in two ways. First, by assuring the integrity of the containment under severe accident conditions. Second, by providing adequate fission product control so as to minimize offsite dose and consequences to the general population. Key ESBWR features with respect to prevention and mitigation of severe accidents are summarized in Table 3.1.

Proliferation resistance

No information provided.

Safety and security (physical protection)

No information provided.

Description of turbine-generator systems

6.1 Turbine generator plant

The main turbine

The main turbine is a tandem compound, six flow, reheat type steam. There is one high-pressure (HP) turbine and three low-pressure (LP) turbines in series. The steam passes through moisture separator and reheaters prior to entering the LP turbines. Steam exhausted from the LP turbines is condensed and degassed in three main condensers arranged in series. The turbine uses steam at a pressure of 6.79 MPa (985 psia) from the reactor and rotates at 1500 RPM (for 50 Hz application) or 1800 RPM (for 60 Hz application). Steam is extracted from several stages of each turbine and is used to heat the feedwater.

Turbine overspeed protection system

In addition to the normal speed control function provided by the turbine control system, a separate turbine overspeed protection system is included to minimize the possibility of turbine failure and/or generation of high-energy missiles.

Turbine gland seal system

The turbine gland seal system (TGSS) provides steam sealing to the labyrinth seals of the high-pressure and low-pressure turbines and to the stem seals of the turbine stop valves, control valves and bypass valves. The system prevents the escape of radioactive steam from the turbine shaft/casing penetrations and valve stems and prevents air in-leakage through sub-atmospheric turbine glands into the main condenser. The TGSS consists of a sealing steam pressure regulator, sealing steam header, a gland steam condenser, two full capacity exhaust blowers and associated piping, valves and instrumentation.

Turbine bypass system

A turbine bypass system (TBS) is provided which passes steam directly to the main condenser under the control of the pressure regulator. The TBS has the capability to shed 100% of the turbine generator rated load without reactor trip or operation of SRVs. The TBS does not serve or support any safety-related function and has no safety design.

Main condenser

The main condenser is a multi-pressure, three-shell type, de-aerating condenser with each shell located directly beneath the respective low-pressure turbines. It is designed to condense and deaerate the exhaust steam from the main turbine and provide a heat sink for the turbine bypass system. Each shell has tube bundles through which circulating cooling water flows. Condensing steam is collected in the condenser hot wells (the lower shell portion), providing suction to the condensate pumps. The main condenser has no safety design basis and does not serve or support any safety function.

Since the main condenser operates at a vacuum, any leakage is into the shell side. Tube side or circulating water in-leakage is detected by measuring the conductivity of sample water extracted beneath the tube bundles. In all operational modes, the condenser is at a vacuum so no radioactive releases can occur.

Non-condensable gases are removed from the power cycle by the main condenser evacuation system (MCES). The MCES removes power cycle non-condensable gases, including the hydrogen and oxygen produced by radiolysis of water in the reactor, and exhausts them to the offgas system (OGS) during plant power operation, or to the turbine building ventilation system exhaust during early plant startup. The MCES establishes and maintains a vacuum in the condenser by the use of steam jet air ejectors during power operation, and by a mechanical vacuum pump during early startup.

6.2 Condensate and feedwater systems

The condensate and feedwater system (C&FS) consists of the piping, valves, pumps, heat exchangers, controls and instrumentation and the associated equipment and subsystems which supply the reactor with heated feedwater in a closed steam cycle utilizing regenerative feedwater heating. The four condensate pumps take deaerated condensate from the condenser hot well and deliver it through the condensate demineralizer and through two strings of three low pressure feedwater heaters to a direct contact feedwater heater, which provides the equivalent performance of forward pumped heater drains. The direct contact feedwater heater receives condensate from the 5th and 6th stage feedwater heater drains, moisture separator drains and extraction steam from the LP turbines and provides 3-4 minutes of full power inventory to the vessel, which is sufficient to meet ESBWR transient feedwater flow requirements.

There are four variable-speed feedwater pumps, which take suction from the direct contact feedwater heater. Each feedwater pump is driven by a variable-speed induction motor, with the combination sized to supply normal feedwater booster pump suction pressure. The feedwater pumps discharge directly to the suction side of corresponding reactor feedwater booster pumps. The feedwater booster pumps discharge through two high-pressure feedwater heaters to the RPV.

6.3 Auxiliary systems

The radioactive waste management system consists of liquid, solid, detergent, and laundry waste management, and mobile systems. Liquid waste processing is done on a batch basis. Equipment drains and other low conductivity wastes are treated by filtration, UV/ozone, demineralization and transferred to the condensate storage tank for reuse. Floor drains and other high conductivity wastes are treated by filtration and ion exchange prior to being either discharged or recycled for reuse.

Detergent wastes of low activity are treated by filtration, sampled and released via the liquid discharge pathway. Chemical wastes are treated by filtration, sampled and released from the plant on a batch basis. Connections are provided for mobile processing systems that could be brought in to augment the installed waste processing capability. Connections for addition of a permanent evaporation subsystem are also provided in the event that site conditions warrant. Mixed waste will be segregated from the other types of radioactive waste for packaging.

The wet solid waste processing subsystem consists of a built-in dewatering station. A high integrity container (HIC) is filled with either sludge from the phase separator or bead resin from the spent resin tanks. Spent cartridge filters may also be placed in the HIC.

Dry wastes consist of air filters, miscellaneous paper, rags, etc., from contaminated areas; contaminated clothing, tools and equipment parts that cannot be effectively decontaminated; and, solid laboratory wastes. The activity of much of this waste is low enough to permit handling by contact. These wastes are collected in containers located in appropriate areas throughout the plant. The filled containers are sealed and moved to an enclosed, access-controlled area for temporary storage.

7.1 Operational power supply systems

On-site power is supplied from the plant turbine generator, utility power grid or an off-site power source, depending on the plant operating status. During normal operation, plant loads are supplied from the main generator through the unit auxiliary transformers. A generator breaker allows the unit auxiliary transformers to stay connected to the grid to supply loads by back feeding from the switchyard when the turbine is not on-line.

Individual voltage regulating transformers supply 120 V AC, non-safety related, control and instrument power.

Standby AC power supply

The non-safety related standby AC power supply consists of two diesel generators (DG). Each unit provides 6.9 KV AC power to one of the two load groups whenever the main turbine generator and the normal preferred off-site power source are not operating. When operating, the standby AC power supply provides power to non-safety related investment protection loads but can be connected to power safety related loads. In ESBWR all Class 1E loads are supplied power by eight Class 1E 125 V DC batteries and eight Class 1E inverters.

Direct current power supply

Non-Class 1E DC power is supplied through four non-Class 1E 480 V AC power centers. Each of the two load groups receives power from two of the non-Class 1E power centers. Provision is made to provide power to the 250 V DC bus through a battery charger. A 250 V DC station battery provides backup to the supply from the battery charger. A 250 V DC station battery provides backup to the supply from the battery charger. The 250 V DC batteries supply the DC motors that protect rotating machinery in case of plant power loss and supply the large inverters that power the plant's normal instrumentation and control loads.

During a loss of off-site power, the non-Class 1E systems are powered automatically from the standby diesel generators. If these are not available, power to essential loads is provided by the 125 V DC and 250 V DC station batteries.

Instrument and control power supply

The instrument and control power supply provides 120 V AC single-phase power to instrument and control loads that do not require an uninterruptible power source.

7.2 Safety related electrical systems

Direct current power supply

The Class 1E DC power supply provides power to the Class 1E vital AC buses through inverters, and to 125 V DC loads required for safe shutdown. Each of the four divisions of class 1E DC power is separate and independent. Each division has a 250 V DC battery and a battery charger fed from its divisional 480 V AC power center. This system is designed so that no single failure in any division of the 125 V DC system will prevent safe shutdown of the plant.

During a total loss of off-site power, the Class 1E system is powered automatically from two non-Class 1E standby diesel generators. If these are not available, each division of Class 1E isolates itself from the non-Class 1E system, and power to safety related loads is provided uninterrupted by the Class 1E batteries. The batteries are sized to power safety related loads for a 72-hour period.

Vital (uninterruptible) power supply

The Class 1E vital AC power supply provides redundant, reliable power to the safety logic and control functions during normal, upset and accident conditions.

Each of the four divisions of this class 1E vital AC power is separate and independent. Each division is powered from an inverter supplied from a Class 1E DC bus. The DC bus receives its power from a divisional battery charger and battery. Provision is made for automatic switching to an alternate Class 1E non-vital supply in case of failure of the inverter.

7.3 I&C design concepts, including control room

The ESBWR control and instrument systems provide manual and automatic means to control plant operations and initiate protective actions should plant upset conditions occur. The ESBWR utilizes digital controllers, interfacing with plant equipment, sensors and operator controls through a multiplexing system, for signal transmission to achieve these functions. The key distinguishing simplification features for plant control and monitoring include:

- Enhanced man-machine interface design
- Automated plant operations
- Simplified neutron monitoring system
- Reduction in number of nuclear boiler instruments
- Fault tolerant safety system logic and control
- Standardized digital control and measurement
- Multiplexing of plant control signals

Multiplexed signal transmission using high-speed fiber optic data links is combined with digital technology to integrate control and data acquisition for both reactor and turbine plants. Multiplexing significantly reduces the quantities of control cables, which need to be installed during construction, thereby reducing the construction cost, and facilitates automation of plant operations.

Performance monitoring and control, and power generator control subsystem functions are provided by the process computer system (PCS) to support efficient plant operation and automation.

The main control room (MCR) panels consist of an integrated set of operator interface panels (e.g., main control console, large display panel). The safety-related panels are seismically qualified and provide grounding, electrical independence and physical separation between safety divisions and non-safety related components and wiring.

The MCR panels and other MCR operator interfaces are designed to provide the operator with information and controls needed to safely operate the plant in all operating modes, including startup, power operation, refueling, shutdown, and cold shutdown. Human factors engineering principles have been incorporated into all aspects of the ESBWR MCR design.

The liquid and solid radwaste systems are operated from control panels in the radwaste control room. Programmable controllers are used in this application.

7.4 Reactor protection system and other I&C safety systems

The safety system logic and control (SSLC) provides a centralized facility of implementing safety related logic functions. The SSLC is configured as a four-division data acquisition and control system, with each division containing an independent set of microprocessor based software controlled logic processors.

The reactor protection system (RPS) is an overall complex of instrument channels, trip logic, trip actuators, manual controls, and scram logic circuitry that initiates the rapid insertion of control rods by hydraulic force to scram the reactor when unsafe conditions are detected. The RPS uses the functions of the essential multiplexing subsystem

(EMS) and the SSLC system to perform its functions.

The remote shutdown system (RSS) provides the means to safely shutdown the reactor from outside the main control room. The RSS provides remote manual control to the systems necessary to: (a) achieve prompt hot shutdown of the reactor after a scram, (b) achieve subsequent cold shutdown of the reactor, and (c) maintain safe conditions during shutdown.

The standby liquid control system (SLCS) provides an alternate method of reactor shutdown from full power to cold subcritical by the injection of a neutron absorbing solution to the RPV. SLCS initiates automatically as required to mitigate an anticipated transient without scram (ATWS).

The feedwater control system (FWCS) controls the flow of feedwater into the RPV to maintain the water level in the vessel within predetermined limits during all plant operating modes.

The neutron monitoring system (NMS) provides indication of neutron flux in the core in all modes of reactor operation. The safety related NMS functions are the startup range neutron monitor (SRNM), the local power range monitor (LPRM), and the average power range monitor (APRM). The non-safety related subsystem is the automated fixed in core probe (AFIP). The LPRMs and APRMs make up the power range neutron monitor (PRNM) subsystem.

The NMS provides signals to the RPS, the rod control and information system (RC&IS), and the process computer system. The NMS provides trip signals to the RPS to scram the reactor on high neutron flux or high thermal power. In the startup range, the SRNM provides a trip signal for excessively short reactor periods to mitigate neutron flux excursions.

Spent fuel and waste management

No information provided.

Plant layout

9.1 Buildings and structures, including plot plan

The plot plan, showing the general layout of the ESBWR buildings, is depicted in Figure 9.1. A plant cutaway view is shown in Figure 9.2. The principal plant structures of the ESBWR are: the reactor building, the control building, the turbine building, the radwaste building, and the electrical building.

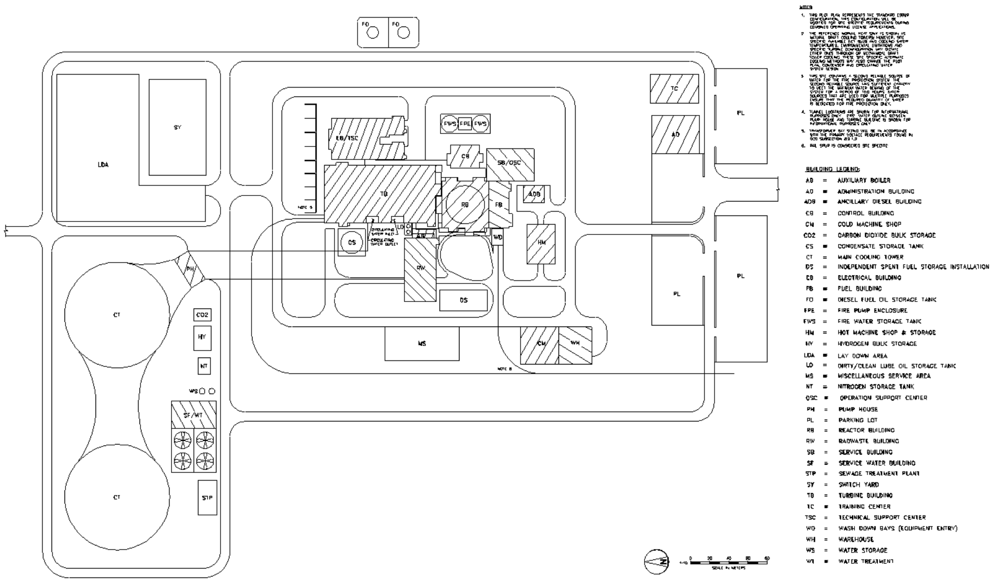

FIG. 9.1. ESBWR Plant Layout, Site Plot Plan

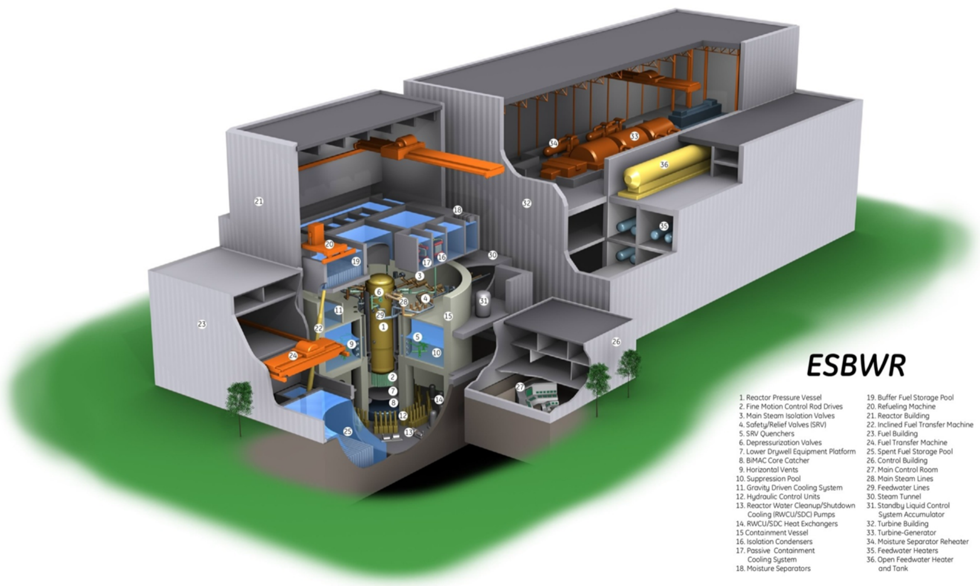

FIG. 9.2. ESBWR Plant Cutway View

Design requirements

Earthquake - The reactor building seismic design is based on the U.S.NRC Regulatory Guide 1.60 spectrum for a wide range of soil conditions.

Aircraft crash - The reactor building is designed to the applicable requirements.

Explosion pressure wave - The reactor building is designed to the applicable requirements.

Internal hazards - Internal loads from hazards are included in the containment design.

Physical separation aspects - Safety grade systems are protected by physical, or spatial, separation wherever possible. When spatial separation is not possible, physical barriers are used to provide the required equivalent separation.

Radiation protection aspects (accessibility, shielding, ventilation) - The reactor building layout separates controlled from non-controlled areas by separation of the respective equipment.

9.2 Reactor building

Most of the components, equipment and systems providing safety-related functions in the ESBWR are housed in the reactor building, the main steam tunnel, or the auxiliary fuel storage building. This includes the reactor containment, the refueling area, temporary spent fuel storage areas, and support equipment. The reactor building is a Seismic Category I structure. The reactor building surrounds the cylindrical reinforced concrete containment vessel (RCCV). Both structures are located on a common basemat. The reactor building outer walls are reinforced concrete shear walls and the building is partially embedded.

9.3 Containment

The ESBWR containment structure is a reinforced concrete cylindrical structure that encloses the reactor pressure vessel (RPV) and its related systems and components. The containment is divided into a drywell region and a suppression chamber region, with a vent system connecting the two. The details of the containment structure are shown in Figure 2.1.

The drywell region is a leak tight gas space surrounding the RPV and reactor coolant pressure boundary. It provides confinement of radioactive fission products, steam and water released in the unlikely event of a LOCA. The containment is designed to direct the fission products, steam and water released during a LOCA to the suppression pool via the vent system.

The suppression chamber region consists of the suppression pool and the gas space above it. The suppression pool is a large body of water that absorbs the LOCA energy by condensing steam from safety/relief valve discharges and RPV blowdown energy. The gas space above the suppression pool is leak tight and sized to collect and retain the drywell gases following a pipe break in the drywell, without exceeding the containment design pressure.

Three enclosed pools of water sit above the suppression pool gas space, at the periphery of the upper drywell. These pools are part of a gravity driven cooling system (GDCS), which can supply makeup water to the RPV in the event of a LOCA. The gas space in these pools is connected to the suppression pool gas space so, as they empty out, the available expansion volume for non-condensables discharged to the suppression pool is increased.

9.4 Auxiliary fuel storage building

The auxiliary fuel building is located adjacent to the reactor building, on the opposite side from the turbine building. Facilities for wet, long-term storage of spent fuel are provided in this building, as well as areas for storage, inspection and staging of new fuel prior to insertion into the reactor.

9.5 Turbine building

The non-safety related turbine building houses equipment associated with the main turbine and generator and their auxiliary systems. Equipment including the condensate purification system, the process offgas treatment system, and the reactor component cooling water (RCCW) system are located in this building. It is a reinforced concrete structure up to the turbine operating deck; above that the building is constructed of steel frame and metal siding. Shielding is provided for the turbine on the operating deck and the turbine generator and condenser are supported on spring type foundations.

9.6 Other buildings

Control building

The control building is adjacent to the reactor. It houses the main control room and safety related instrumentation plus the associated logic control panels.

Radwaste building

The radwaste building houses equipment for collecting and processing solid and liquid radioactive waste generated by the plant.

Electrical building

The non-safety related electrical building houses the two non-safety related standby diesel generators and their associated auxiliary equipment.

Plant performance

Key Attribute	Elements of Attribute	Design Features
Simplification	Reduced systems	Passive safety systems
	Reduced structures	Smaller safety related structures

	Simpler operation	Eliminate recirculation pumps and associated support components
Operation flexibility	Performance margins	Large vessel
		Lower pressurization rate
		Passive systems
		Margins for core coverage
	Lower demand upon operator	Simple decay heat removal
	No immediate action required	Large passive coolant inventory
Economics	Lower plant cost	Reduced materials
		Reduced equipment especially active components
		Reduced buildings
		Located most non-safety equipment in non-safety buildings
	Lower development cost	ABWR & SBWR features used
	Licensing and first plant cost	New components and systems tested
Construction Period	Reduced construction time	Design adaptable to modularization
		Parallel construction of reactor building and fuel building
Maintenance	Reduced maintenance cost	Simpler systems
		Fewer active systems and components
	Ease of maintenance and radiation exposure	Less maintenance on control rod drives
		Eliminated maintenance on recirculation system
		Reduced maintenance on ECCS components
Plant availability	Reduced outage length	Design for servicing
		On-line maintenance
Power generation cost	Design for higher availability	See above
	Design for reduced O&M	See above

Development status of technologies relevant to the NPP

No information provided.

Deployment status and planned schedule

The ESBWR program is based on the earlier SBWR program, which was sponsored by the US Department of Energy (DOE). The ESBWR program was started in 1993 to improve the economics of the SBWR design. The design and technology program involves several utilities, design organizations and research groups in several countries. Overall design leadership is provided by GE Hitachi Nuclear Energy (GEH – USA). In 2005 a design certification application was submitted to the U.S. Nuclear Regulatory Commission. The review is in process, with Design Certification expected in 2011.

References

[1] GE Hitachi Nuclear Energy, *ESBWR Design Control Document*, Tier 2, Rev 6, August 2009.

Technical data

General plant data

Reactor thermal output	4500 MWth
Power plant output, gross	1600 MWe
Power plant output, net	1520 MWe
Power plant efficiency, net	34 %
Plant design life	60 Years
Plant availability target >	92 %
Primary coolant material	Light Water
Moderator material	Light water
Thermodynamic cycle	Rankine
Type of cycle	Direct

Safety goals

Core damage frequency <	10E-6 /Reactor-Year
Large early release frequency <	0.00000005 /Reactor-Year
Occupational radiation exposure <	0.5 Person-Sv/RY
Operator Action Time	72 Hours

Nuclear steam supply system

Steam flow rate at nominal conditions	2432 Kg/s
Steam pressure	7.17 MPa(a)
Steam temperature	287.7 °C
Feedwater flow rate at nominal conditions	2427 Kg/s
Feedwater temperature	215.6 °C

Reactor coolant system

Primary coolant flow rate	9570 Kg/s
Reactor operating pressure	7.17 MPa(a)
Core coolant inlet temperature	276.2 °C
Core coolant outlet temperature	287.7 °C
Mean temperature rise across core	11.5 °C

Reactor core

Active core height	3.048 m
Equivalent core diameter	5.88 m
Average linear heat rate	15.1 KW/m
Average fuel power density	27.3 KW/KgU
Fuel material	Sintered UO2
Cladding material	Annealed recrystallized Zr2
Outer diameter of fuel rods	10.26 mm
Rod array of a fuel assembly	10x10
Lattice geometry	Square
Number of fuel assemblies	1132
Fuel cycle length	24 Months
Burnable absorber (strategy/material)	Gd2O3-UO2
Control rod absorber material	B4C and Hf
Soluble neutron absorber	Soidum Pentaborate

Reactor pressure vessel

Inner diameter of cylindrical shell	71000 mm
Wall thickness of cylindrical shell	182 mm
Design pressure	8.62 MPa(a)
Design temperature	300 °C
Base material	SA508, CLASS 3
Total height, inside	27600 mm
Transport weight	853 t

Primary containment

Type	Single wall pressure supression
Overall form (spherical/cylindrical)	Cylindrical
Dimensions - diameter	40 m
Dimensions - height	35.4 m
Design pressure	0.414 MPa
Design temperature	171 °C
Design leakage rate	0.5 Volume % /day

Turbine

Type of turbines	Six flow, Tandem compound, Single reheat
Number of turbine sections per unit (e.g. HP/MP/LP)	1/0/3
Turbine speed	1800 rpm
HP turbine inlet pressure	6.8 MPa(a)
HP turbine inlet temperature	287 °C

Generator

Type	Three-phase, turbo generator
Rated power	1933 MVA
Active power	1600 MW
Voltage	27 kV
Frequency	60 Hz

Condenser

Type	Shell type
Condenser pressure	5.4 kPa

Feedwater pumps

Number	4
Flow at rated conditions	2.427 m^3/s