Radiation Protection at Light Water Reactors

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Chapter 2
Radiological Aspects of PWR Systems

2.1 Overview

Light water reactors are characterized by the fact that water serves as both the coolant and moderator. Two major types of reactors dominate the LWR industry, the pressurized water reactor (PWR) and boiling water reactor (BWR). This chapter describes those PWR systems of concern to radiation protection personnel while Chap. 3 provides an overview of BWR systems. The primary objective is to present those aspects of system design and interrelationships that impact plant radiological conditions. The function and purpose of various systems are presented along with their associated radiological hazards. System descriptions are provided in sufficient detail to allow radiation protection personnel to assess radiological conditions associated with various plant operating conditions.

Radiation protection personnel should have a basic understanding of various plant systems in order to evaluate actual and potential radiological hazards associated with the operation of LWR's. It is not necessary for radiation protection personnel to have an in-depth working knowledge concerning all aspects of system operational-related parameters as required of plant operators. Consequently, the intricate details of system design and functions comparable to the level of knowledge required of plant operators are not covered. However, it is essential that they have sufficient knowledge of plant systems to adequately address the radiological requirements for activities performed either on or in the vicinity of plant systems.

Pressurized water reactors currently operating in the United States have been designed by the Westinghouse Electric Corporation, Combustion Engineering, Inc., and the Babcock and Wilcox Company (now Framatome). Other suppliers include Framatome (France), Kraftwerk Union (Germany) and Toshiba and Mitsubishi Heavy Industries (Japan) among others.

Several PWR systems are of direct concern from a radiological aspect. These include the reactor coolant (or primary) system and various auxiliary systems. The auxiliary systems of most concern include the chemical and volume control

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system, residual heat removal system, reactor cavity purification, spent fuel pool cooling and purification, safety injection system, containment spray system, plant ventilation systems, radioactive waste handling and processing and radiochemistry sampling systems.[1] These systems and those having a potential of becoming contaminated under certain conditions are described.

2.2 Plant Layout

A PWR facility consists of three or four distinct buildings in addition to those that are required to support site operations such as administrative office buildings, security access facilities, and warehouses among others. Major buildings commonly associated with PWR stations include the containment building (or reactor building), the fuel building, the auxiliary building and the control building (Fig. 2.1).

The containment building is a large reinforced concrete cylindrical structure which houses the primary system components, components of emergency core cooling equipment, and air handling and ventilation equipment. Depending upon the design and size of a particular PWR unit various components (e.g., RHR system) may be located in either the containment building or the auxiliary building. The fuel building contains the spent fuel storage pool, building ventilation and cooling equipment, spent fuel pool cooling and purification components, and new fuel storage facilities. Systems and components associated with the chemical and volume control system, safety injection system pumps and heat exchangers, perhaps residual heat removal system components, various storage and hold-up tanks, radioactive waste processing facilities, air handling equipment, filter and demineralizer compartments, and associated electrical equipment, piping and valves are located within the auxiliary building. Additionally numerous components and equipment associated with the secondary side are located within areas of the auxiliary building. The main control room is located in the control building. Typically the control building will also include the battery rooms, motor control centers, electrical cable and relay rooms, and emergency ventilation equipment. Figure 2.2 depicts a typical PWR containment building and steam flow to the turbine generator and secondary side systems.

[1] System nomenclature of the various reactor vendors differs to some degree. For instance residual heat removal and decay heat are synonymous terms as are the makeup and chemical and volume control systems. Readers may want to refer to the specific nomenclature used at their facilities. Terms used in this text are descriptive in nature and may differ somewhat from site-specific terminology.

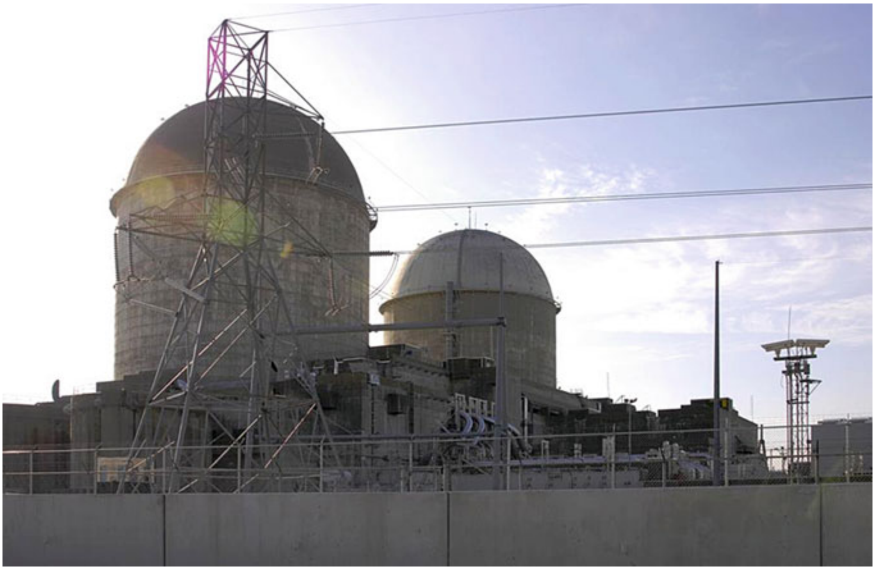

Fig. 2.1 Photograph of a two-unit PWR unit (Courtesy of Luminant)

2.3 Primary System

As the name implies a PWR maintains the primary circuit at an elevated pressure, approximately 15.5 Mpa (2,200–2,300 psi) with an operating temperature of about 332°C (629°F). The primary or reactor coolant system (RCS) contains the reactor core. The reactor coolant system provides cooling for the reactor core and transfers the heat to the secondary side via steam generators, producing steam to drive the turbine-generator. The primary system consists of 2–4 loops. Each loop contains a reactor coolant pump (or pumps), steam generator and associated piping. In addition to the reactor vessel, the pressurizer and pressurizer relief tank are the other major components associated with the primary system. Figure 2.3 depicts the basic PWR primary system components.

The reactor vessel contains the fuel assemblies, core support structures, control rods, thermal shield, incore guide tubes and related components. The reactor vessel contains the heat generated by the core, provides a flow path for the moderator-coolant through the core, allows access to the fuel during refueling operations and provides penetrations to allow the control rods and incore instrumentation to access the core. Figure 2.4 depicts a reactor vessel along with some of its' major components.

The major components of the RCS are located within the biological shield wall area of the containment building. Depending upon the number of loops and specific design, loops may be equipped with individual shield walls. Access to major components such as steam generators, reactor coolant pumps and the pressurizer are

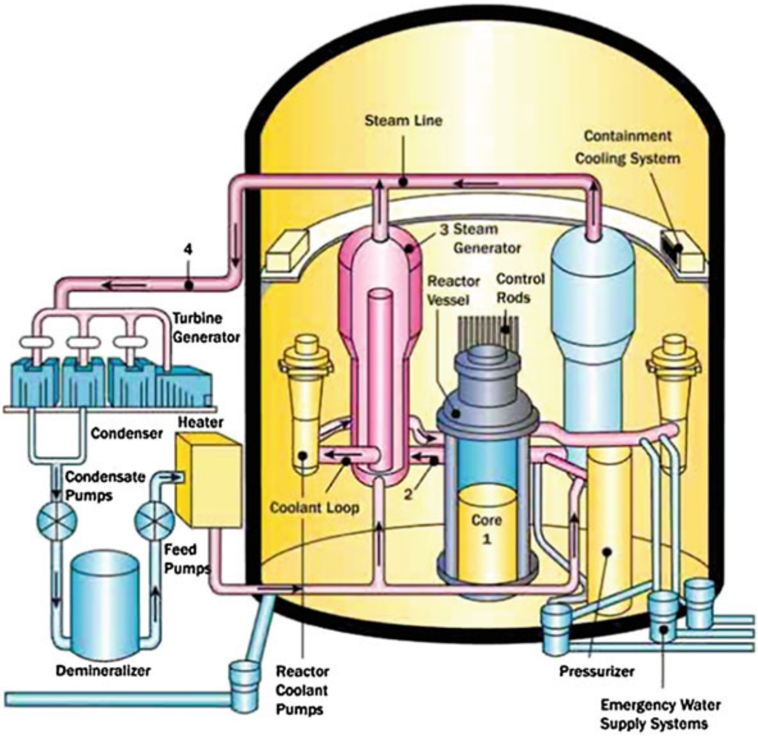

Fig. 2.2 Simplified PWR plant layout showing the major components of the containment building (www.nrc.gov/reactors/pwrs)

strictly limited during periods of operation. When a unit is at 100% power dose rates inside the primary shield wall, enclosing the loop rooms is typically on the order of 100–250 mSv/h (10–25 rem/h). Contributors to these radiation fields include the presence of short-lived radionuclides, primarily N-16, in addition to activation and corrosion and fission product radionuclides that are present in the coolant. Obviously neutron radiation levels may be significant, the magnitude of which increases with reactor power. Neutron radiation levels inside loop rooms at 100% power could easily be in the range of a few tens of mSv/h (several rem/h). Consequently access to reactor coolant pumps, steam generators and pressurizer areas is strictly limited while at power. Under certain circumstances (e.g., <10% reactor power) and depending upon the specific plant design, access for short periods of time, on the order of minutes, may be possible for emergency type entries to investigate trouble alarms or equipment problems. Any such entries must be properly planned and strictly controlled.

Similar conditions and reasoning applies to areas in direct line of site of the reactor vessel head and reactor cavity area. Dose rates on top of the reactor head structure; in the cavity area and in close proximity to the edge of the reactor cavity

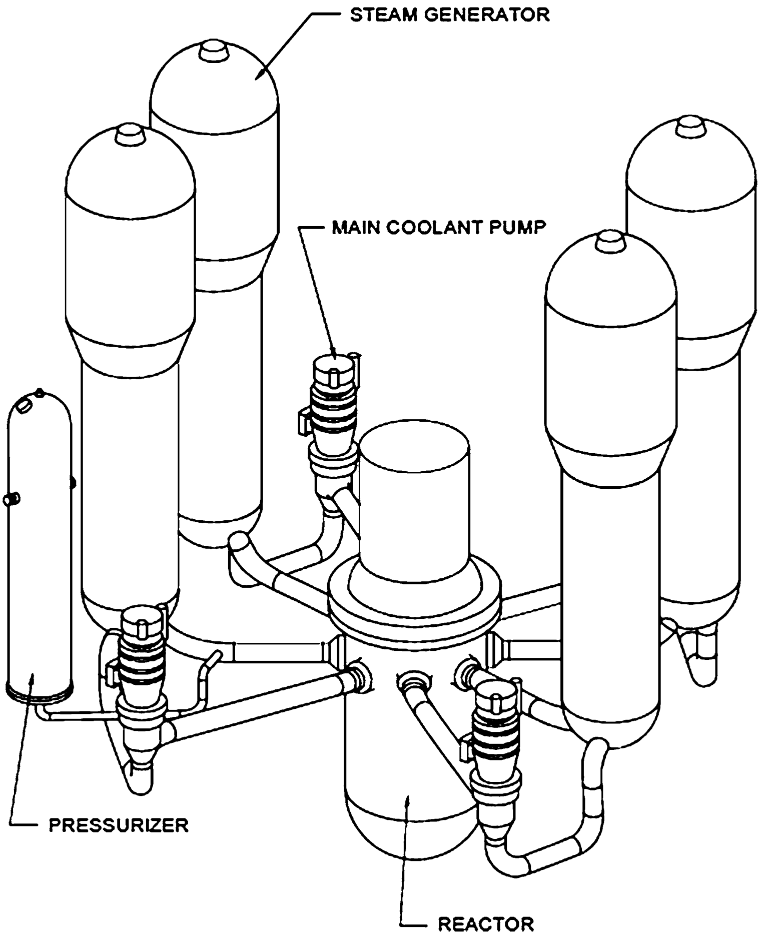

Fig. 2.3 Major PWR primary system components for a four-loop PWR (adopted from www.nrc.gov/reading-rm/basic-ref/teachers)

usually prevent entry to these areas at power due to high radiation levels, which include a significant neutron radiation component. General area radiation levels in the range of 100–200 mSv/h (10–20 rem/h) on top of the reactor vessel head and in the vicinity of control rod drive mechanisms are not uncommon.

Each primary system loop contains a U-tube or once-through steam generator (SG). Primary system water flows through the tube bundle and transfers its heat to the feed water circulating on the shell side of the steam generator. Located directly above the tube bundle is the steam drum section. The steam drum section extracts moisture from the steam returning it to the feed water stream and dries the steam before it leaves the steam generator. This ensures a high quality steam supply to the turbine-generator. Manways and handways (or hand holes) are provided at

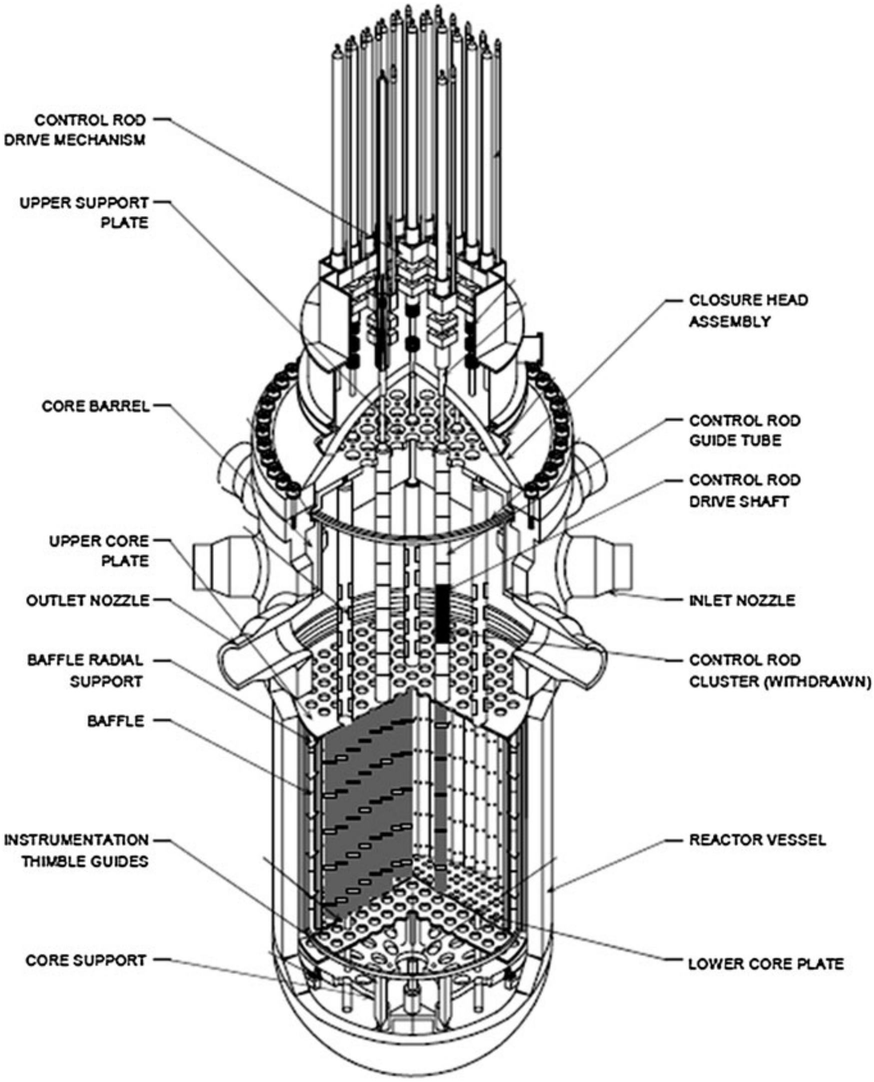

Fig. 2.4 PWR reactor vessel and major components (adopted from www.nrc.gov/reading-rm/basic-ref/teachers)

strategic locations on each steam generator to allow access for inspection and maintenance activities during outage periods. Each steam generator contains thousands of individual tubes to provide the necessary surface area to afford sufficient heat transfer to produce the steam required in order to generate the large number of megawatts typical of nuclear power plants. Steam generators must be maintained in good operational condition to ensure operational efficiency of a nuclear unit. Degraded conditions impacting the quality or amount of steam produced by each steam generator can result in reduced megawatt output, negatively impacting economical operation of the unit. Steam generators are subject to comprehensive inspections and maintenance activities during outages. These activities can comprise a significant portion of outage exposures at PWR units.

Access in the vicinity of steam generators is not typically performed while at power due to high radiation levels. Additionally, even if access were possible the scope of inspections would be limited. The most likely reason to inspect a steam generator while at power would be in the event of a suspect manway leak or hand hole inspection port leak. Assuming these areas are readily accessible and could be easily observed entries for emergency investigative purposes could be warranted under certain circumstances.

Radiation levels associated with steam generators are of primary concern during outage periods when inspection and maintenance activities can be performed. Once the primary manway channel heads are removed dose rates of several mSv/h (several hundred mrem/h) may be encountered in the vicinity of the open manways. Radiation levels up to tens of mSv/h (several rem/h) or higher on contact to the tube sheet, inside the channel head, are not uncommon. Steam generator channel head dose rates may vary significantly from one unit to the next and are highly dependent on operating history of the plant, maintenance of good operational chemistry controls, shut down chemistry methods employed and integrity of fuel cladding. Figure 2.5 depicts the major components of a steam generator; notice the location of the manways and the tube sheet area of the steam generator.

Reactor coolant pumps (RCP) circulate reactor coolant through the reactor vessel taking suction from the steam generators. Depending upon the reactor supplier there may be either one or two coolant pumps for each steam generator. Each pump is composed of a hydraulic section, seal section and motor package. General area radiation levels in the vicinity of reactor coolant pumps during shutdown conditions may be as high as few mSv/h (a few hundred mrem/h), especially in close proximity to the seal section of the pump. Depending upon the design and specific location of the motor section, dose rates in the vicinity of the motor section are usually significantly lower, perhaps less than hundreds of μSv/h (ten's of mrem/h) or lower. Figure 2.6 depicts a reactor coolant pump.

The last major component of the primary system is the pressurizer. The pressurizer is a large vessel, maintained partially filled with RCS water and a cover gas maintained in the upper portion of the vessel. The pressurizer maintains the reactor coolant system pressure within prescribed limits. Electrical heaters located internally to the pressurizer are switched on when RCS pressure must be increased. When system pressure must be decreased, cold water is sprayed into the pressurizer void space via an internal spray nozzle located at the top of the pressurizer. Discharges from the pressurizer are routed to the pressurizer relief tank (Fig. 2.7).

As with other RCS components, radiation levels at power severely restrict entry to the pressurizer. Depending upon the design and compartmental layout it may be possible to access the lower regions of the pressurizer while at power. General area

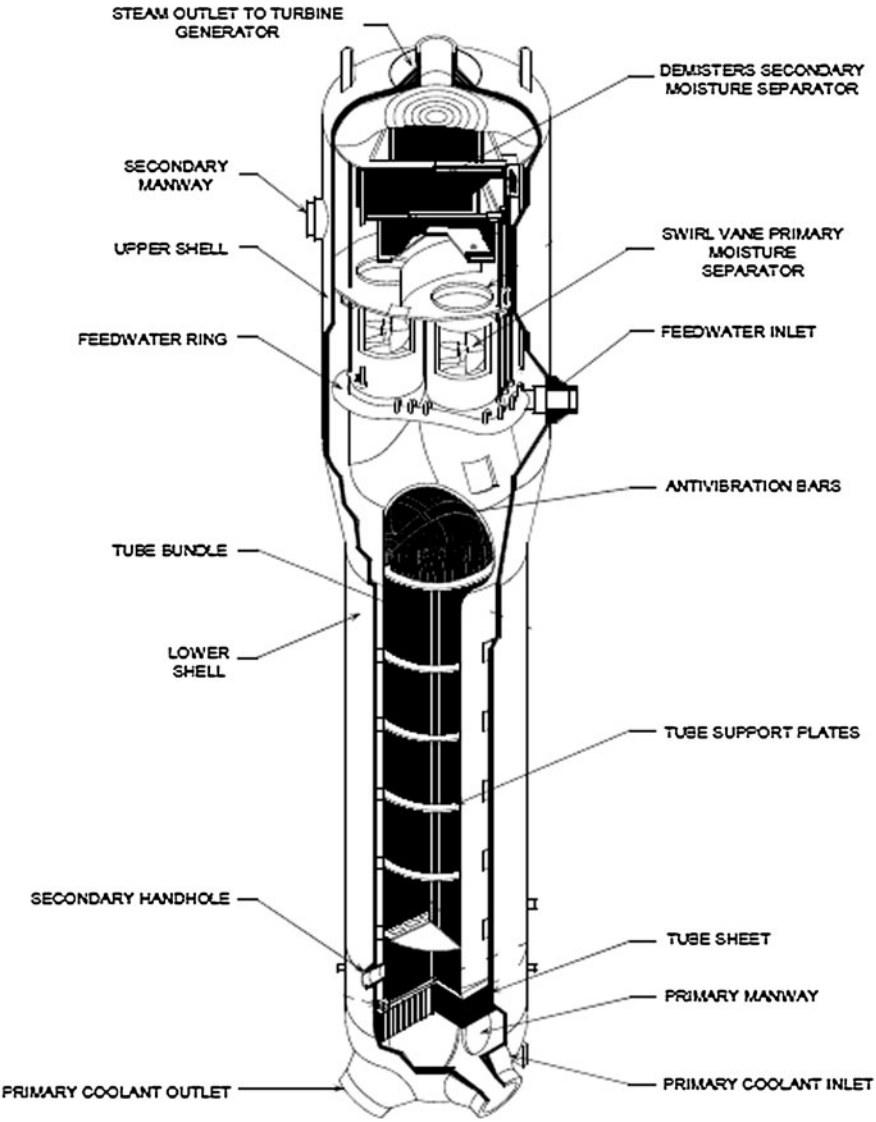

Fig. 2.5 Steam generator and its major components (adopted from www.nrc.gov/reading-rm/basic-ref/teachers)

radiation levels in the vicinity of the pressurizer at power could range from a few mSv/h (few hundred mrem/h) to tens of mSv/h (several rem/h), again depending on the unique plant layout. Consideration must also be given to environmental conditions in the pressurizer compartment while at power. Ambient temperatures,

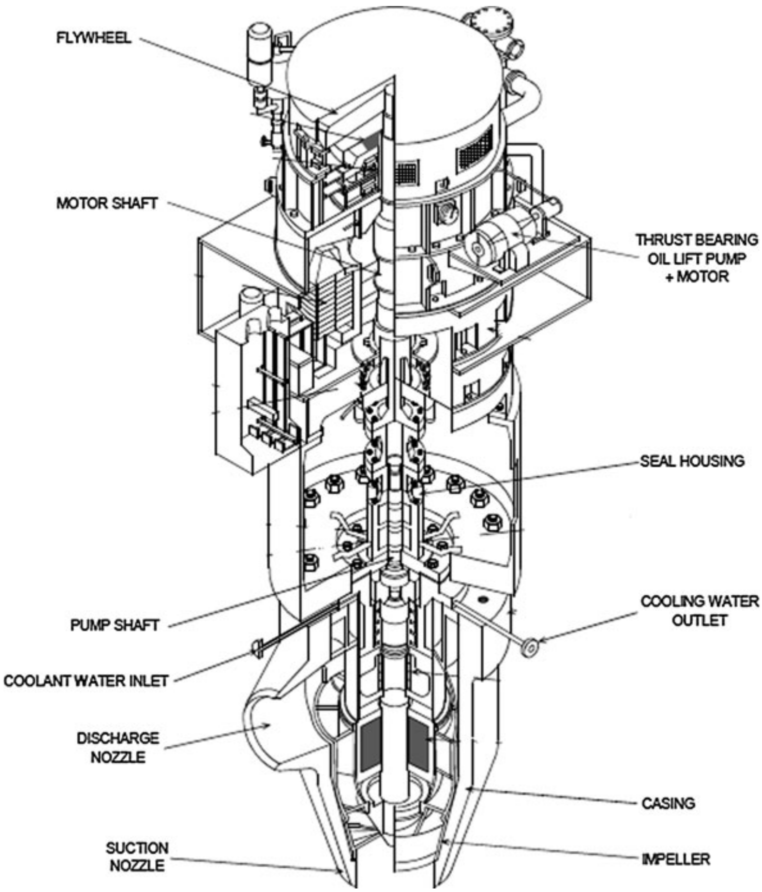

Fig. 2.6 A reactor coolant pump and its major components (adopted from www.nrc.gov/reading-rm/basic-ref/teachers)

especially towards the top of the pressurizer, may be excessively high and could also be a factor in limiting access during periods of operation. The most likely situation requiring access to the pressurizer while at power would probably be associated with the need to inspect the pressurizer safeties for possible leakage. The pressurizer safeties are relief valves that provide over-pressure protection for the RCS. If the pressurizer safeties are accessible for visual observation it could be possible to allow entry for a short period of time. This would assume that environmental conditions allow entry and that the estimated dose to the individuals is acceptable based upon the urgency and benefits to be gained.

Radiation levels associated with the pressurizer are of primary concern during outage conditions since this is the period of time that maintenance and inspection activities are performed. The pressurizer heaters require routine maintenance and inspection. Radiation levels associated with these heaters could be in the range of

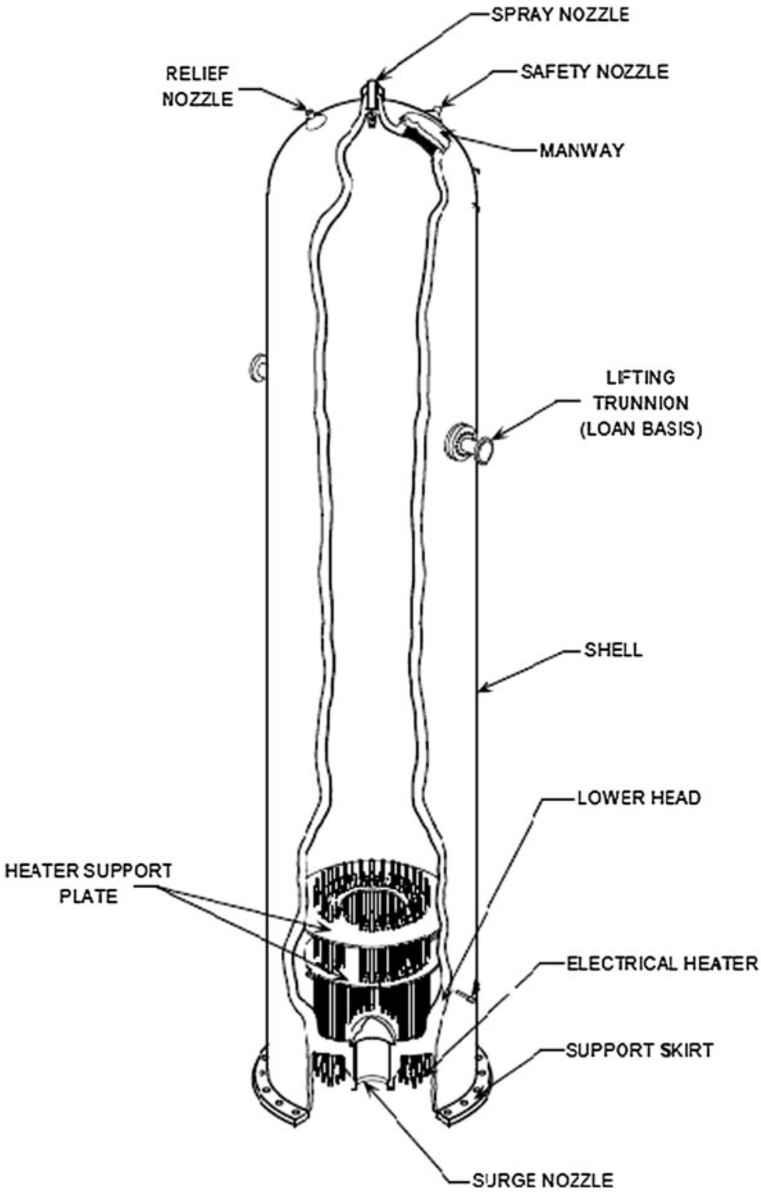

Fig. 2.7 Pressurizer and its major components (adopted from www.nrc.gov/reading-rm/basic-ref/teachers)

several mSv/h to a few hundred mSv/h (several hundred mrem/h to perhaps a few rem/h), and will be highly dependent upon operational history pertaining to fuel integrity and RCS chemistry conditions. The pressurizer safeties also require routine maintenance and testing. These valves are located on the top of the pressurizer, oftentimes in very close proximity to the pressurizer and in a relatively confined area due to the presence of related piping, pipe supports and related components. Radiation levels on contact to the safeties and adjacent piping may be on the order of a few tens of mSv/h (a few rem/h) during outage periods with general area dose rates of a couple of mSv/h (a few hundred mrem/h) not uncommon.

2.4 Chemical and Volume Control System

The chemical and volume column system (CVCS) purifies the reactor coolant by removing fission and activation products by filtration and demineralization, maintains reactor coolant system inventory, adjusts the boron concentration in the reactor coolant and serves as an integral component of the emergency core cooling system. Major components of the CVCS system include pumps, heat exchangers, a volume control tank, purification filters and demineralizer beds in addition to associated valves and piping. Another common name for this system is the makeup system.

Reactor coolant is discharged to the CVCS system (i.e., letdown flow) and flows through the shell side of the regenerative heat exchanger where the temperature of the RCS letdown is reduced. The coolant is reduced in pressure and next flows through the tube side of the letdown heat exchanger. The letdown flow next passes through a mixed bed demineralizer and reactor coolant filter and enters the volume control tank via a spray nozzle located at the top of the tank. The purified and chemically treated flow (i.e., charging flow) is returned to the RCS via charging pumps. Most of the charging flow is directed to the reactor coolant system through the tube side of the regenerative heat exchanger to reduce the temperature of the letdown flow. The remaining portion of the charging flow is routed to the reactor coolant pump seals and returns to the CVCS through the seal water filter and seal water heat exchanger. If the normal letdown path is not available, reactor coolant may be returned to the volume control tank (VCT) via the letdown heat exchanger. Figure 2.8 displays the major components of the CVCS system. Obviously due to the function of the CVCS system and the fact that it contains letdown from the RCS it represents a system of significant radiological concern to radiation protection personnel. A more detailed description of key CVCS components follows in order to provide a foundation for evaluating and understanding potential radiological conditions associated with this system.

The regenerative heat exchanger recovers heat from the letdown flow by reheating the charging flow. This reduces the reactivity affects resulting from the insertion of relatively colder water into the core and reduces thermal shock to reactor coolant system piping. The regenerative heat exchanger is the first component that the RCS letdown flow enters. Consequently it is essentially an “RCS component” from a radiological perspective. The regenerative heat

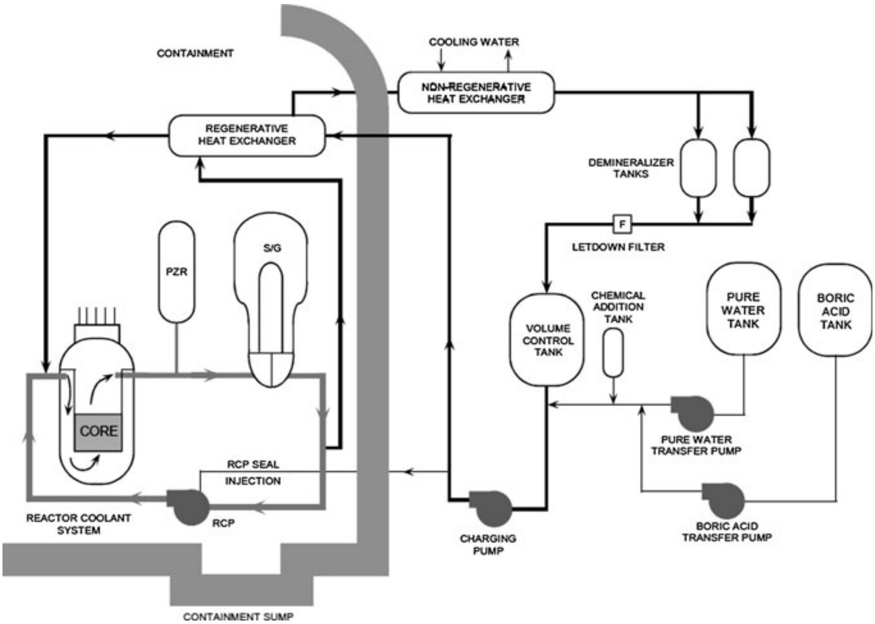

Fig. 2.8 Schematic of CVCS system and its major components (www.nrc.gov/reading-rm/basic-ref/teachers)

exchanger is typically located within the containment building in a shielded compartment and considered not accessible while the plant is at power. Contact radiation levels tens of mSv/h (several rem/h) are typical for this component, while general area radiation levels of several mSv/h (several hundred mrem/h) could be common.

The letdown heat exchanger cools the letdown to ensure that the demineralizer resins are not damaged and that the water routed to the reactor coolant pump seals is at the proper temperature. This component as well as all the other major CVCS components, with the exception of the regenerative heat exchanger discussed above, is typically located in the auxiliary building. Dose rates in the vicinity of the letdown heat exchanger may be on the order of tens of mSv/h (a few rem/h) while the plant is operating.

The volume control tank (VCT), or make up tank (nomenclature varies among reactor vendors) provides a means for introducing hydrogen into the RCS coolant and is used for degassing the reactor coolant during shutdown. The hydrogen gas serves to scavenge excess oxygen that may be present in the RCS that is an important corrosion control function. Fission gases are vented to the waste gas handling system. The VCT also provides excess surge capacity for the reactor coolant. During periods of operation the radiation levels in the VCT room may fluctuate rapidly. Typically the volume control tank (another common name is the RCS bleed tank) is located within a shielded room or compartment. Associated valves and gauges are usually located in a pipe chase or valve alley outside the tank room itself, negating the need for individuals to physically enter the VCT room on a routine basis. Consequently the need to enter the VCT room is infrequent. General area radiation levels in the VCT room are typically on the order of a couple mSv/h (a few hundred mrem/h) to tens of mSv/h (a few rem/h) and subject to fluctuation.

The CVCS system purification loop typically consists of a mixed-bed and cation demineralizer to remove ionic species and a reactor coolant filter that collects resin fines and suspended particulate matter from the letdown stream. The demineralizers are usually sized to process a maximum letdown flow. As the inventory of activated corrosion and fission products accumulate on the resin beds and reactor filters significant dose rates will be encountered. During outage periods or when the resin beds are exposed to significant quantities of crud (e.g., during crud bursts) dose rates in excess of a few Sv/h (a few hundred rem/h) are not uncommon in the vicinity of the resin tanks. These components are located behind heavily shielded vaults.

A portion of the CVCS charging flow is routed to the RCP seals and returns via the seal water heat exchanger. The seal water heat exchanger reduces the temperature of the returning seal water to the operating temperature of the volume control tank. The seal water heat exchanger is cooled by component cooling water that flows through the shell side of the heat exchanger. Since the seal water flow has been purified dose rates associated with this heat exchanger are typically much lower than those for the letdown heat exchanger. Dose rates in the vicinity of the seal water heat exchanger should not typically exceed a few mSv/h (couple hundred mrem/h).

The pumps that provide the motive force for the CVCS system are the charging (or make-up) pumps. The charging pumps take suction from the volume control tank and route flow back to the reactor coolant system as noted above. During normal operation there is usually only one charging pump in service and it is not uncommon to have as many as three charging pumps per unit. Charging pumps also serve a dual role as part of the safety injection system and provide high-head injection to the RCS in the event of an accident involving loss of coolant. Under accident conditions charging pumps take suction from the refueling water storage tank or other suitable supply of emergency core cooling water. Dose rates associated with these pumps and immediate piping are highly dependent on the activity concentration of the RCS. Plants' with good chemistry controls and operating with little or no fuel defects may experience dose rates in the hundreds of μSv/h (tens of mrem/h) range or lower, on the train in service. If RCS source terms are higher than dose rates approaching 1 mSv/h (100 mrem/h) on contact to the charging pump in operation may be encountered. Unlike other CVCS components noted above the charging pumps are required to be accessible on a daily basis for inspection and to monitor their performance and consequently it is important to maintain good chemistry and crud controls to minimize worker exposures resulting from these routine tasks.

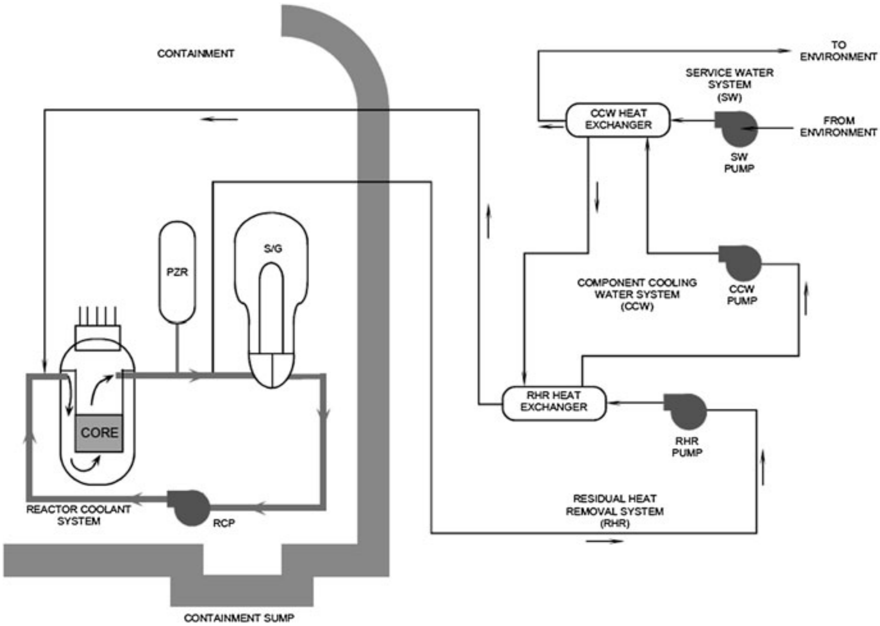

Fig. 2.9 Schematic of RHR system and its major components (www.nrc.gov/reading-rm/basic-ref/teachers)

2.5 Residual Heat Removal System

The primary function of the residual heat removal system is to remove decay heat energy from the core during plant cool down and initial stages of refueling periods. The RHR system (or shutdown cooling or decay heat system) is also utilized to transfer refueling water between the refueling water storage tank and reactor cavity during refueling operations. The RHR system consists of two parallel trains each containing a pump and heat exchanger together with associated piping, valves and control instrumentation. Reactor coolant flows from the RCS via suction from an RHR pump through the tube side of an RHR heat exchanger and transfers heat to the component cooling water flowing through the shell side of the heat exchanger. The pumps are sized to deliver reactor coolant flow through the RHR heat exchangers to meet plant cool down requirements. Each train can provide 100% of shutdown core cooling requirements. Figure 2.9 depicts the basic components of the RHR system.

Depending upon the size of the unit or the manufacturer RHR system components may be located within the containment building or auxiliary building. If RHR major components (e.g., heat exchangers and pumps) are located within the containment building then they will be less accessible while the unit is at power. During normal plant operation the RHR system is maintained in standby and may serve a dual purpose as part of the emergency core cooling system. During these periods dose rates associated with RHR system components are typically on the order of hundreds of μSv/h (tens of mrem/h) or less. Once the plant enters a shutdown mode and goes onto RHR for cool down radiological conditions will change significantly for the train that is in service. During these periods fresh RCS coolant is flowing through RHR system piping. Dose rates in the vicinity of the RHR pump and heat exchanger that are in service could be on the order of a couple of mSv/h (100 mrem/h). Assuming no significant fuel failures are present these dose rates will decrease rapidly several days following shutdown.

2.6 Safety Injection System

The safety injection system (SIS) provides emergency core cooling and shutdown margin in the event of a loss of coolant accident. The SIS typically consists of high, low and intermediate pressure safety injection trains. The high-pressure safety injection system (HPSI) is capable of injecting borated water into the primary system while the RCS is at high pressure. The major components include the refueling water storage tank, safety injection pumps, the boron injection tank (BIT) and associated headers and valves. The charging pumps serve as the high pressure SIS pumps thus serving a dual function. Depending upon the design and engineering basis for a given plant a boron injection tank may not be present. The headers inject into both the cold and hot legs of the RCS. If a boron injection tank is utilized it is incorporated into the cold leg header.

The intermediate-pressure safety injection system injects borated water into the primary system from a set of safety injection accumulators (or core flood tanks). The accumulators are water storage tanks typically with a capacity of a few thousand liters that allows an individual accumulator to provide enough borated water to flood the reactor core. The accumulators automatically discharge when the primary system pressure falls below the pressure of the accumulators. Make-up to the accumulators is provided from the refueling water storage tank.

The low-pressure safety injection system injects borated water into the primary system at low pressure and also serves to increase the suction pressure of the HPSI pumps to prevent cavitations. The RHR system pumps usually serve as the low-pressure safety injection system pumps. The refueling water storage tank (RWST) also serves as the source of water for this system. When the RWST is exhausted then the RHR pumps take suction from the containment sump operating in a closed loop. The capacity of the RWST is typically on the order of 350,000–450,000 l.

The radiological conditions associated with major safety injection components were noted above for the case of the RHR system and CVCS system components that serve dual purposes. Boron injection tanks, for those plant designs that require a BIT tank, may have dose rates on the order of hundreds of μSv/h (tens of mrem/h). Dose rates in the vicinity of the BIT tank could also be influenced by source terms from nearby components. Accumulators are located inside the containment building and typically have relatively low dose rates since they contain clean water that has not been mixed with fresh primary coolant. Oftentimes the primary influence of radiological conditions in the vicinity of the accumulators is more dependent upon their location within the containment building and their proximity to primary system components or other major components of radiological concern.

2.7 Containment Spray System

The containment spray system (CSS) reduces the airborne contamination levels inside the containment and reduces the containment building pressure and temperature to maintain containment integrity after a loss-of-coolant accident. The CSS consists of two independent trains each capable of performing CSS functions. Each train consists of a spray pump, a heat exchanger (i.e., via the RHR system), a chemical additive injector and spray headers. Make-up is usually supplied from the RWST or the condensate storage tank (Fig. 2.10).

Upon actuation of a spray signal the CSS spray pumps take suction from the RWST and pump borated water to the CSS headers which are attached to the inside of the containment dome, high above the refueling floor. Multiple spray nozzles are attached to the header. Upon receipt of a low level signal in the RWST, the containment spray system enters a recirculation mode drawing water from the containment sump. Water spraying out from the CSS nozzles condenses steam in the containment building reducing the pressure inside the building. The CSS heat exchangers serve to cool the spray water as it passes through the tube side of the heat exchanger. Component cooling water passes through the shell side of these once-through heat exchangers.

A sodium hydroxide solution may be injected into the CSS system via a chemical additive tank. The purpose of this solution is to reduce the amount of iodine in the containment atmosphere that may be present during accident conditions. The sodium hydroxide mixture increases the pH of the spray to mitigate corrosion concerns.

The CSS system is maintained in standby and filled with clean water that may have low amounts of radioactive contaminants. Radiation levels in the vicinity of CSS components during normal plant operation usually do not pose a radiological concern and may be in the range of tens of μSv/h (a few mrem/h). Obviously during accident conditions when the CSS is drawing highly contaminated water from the containment building sump these components will have significant radiological source terms associated with their operation and access to which may be impractical due to high radiation levels that could be in excess of several Sv/h (hundreds of rem/h), or higher.

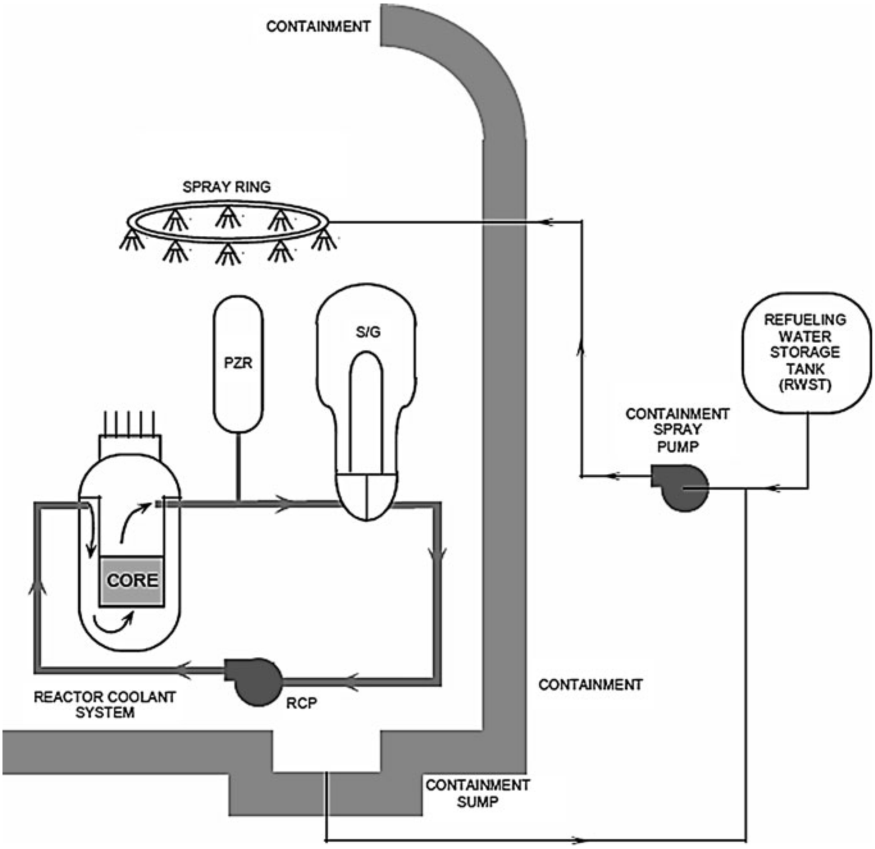

Fig. 2.10 Schematic of containment spray system and its major components (www.nrc.gov/reading-rm/basic-ref/teachers)

2.8 Spent Fuel Pool Cooling and Purification

The spent fuel pool cooling and purification system serves to remove heat generated by spent fuel assemblies stored in the spent fuel pool. Filtering and purification serves to maintain the clarity of the spent fuel pool water and to reduce radionuclide activity concentrations. The concentration of fission and corrosion products is minimized to reduce personnel exposures associated with fuel handling operations.

The spent fuel pool at PWR facilities is maintained in a separate building referred to as the fuel building. In addition to housing the spent fuel storage pool this building has facilities for the storage of new fuel, a truck bay for receiving new fuel and shipping of spent fuel along with ventilation and other

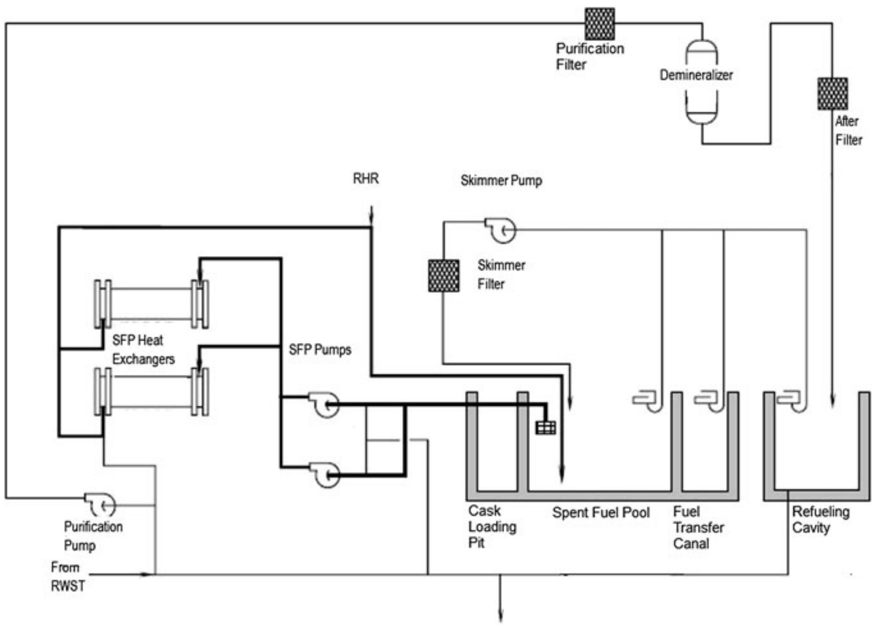

Fig. 2.11 Schematic of spent fuel pool cooling and filtration and reactor cavity filtration systems (adopted from www.nrc.gov)

support systems. The major components of the spent fuel pool cooling and purification system are also located within the fuel building. The spent fuel pool itself contains a spent fuel storage area; an area to load spent fuel assemblies into a shipping cask, and associated transfer compartments. A fuel transfer tube connects the spent fuel pool to the reactor cavity inside the containment building.

The spent fuel pool cooling circuit consists of two 100% capacity trains each equipped with a pump, heat exchanger and associated piping and valves. The pumps take suction from a header below the spent fuel pool surface and route the water through the heat exchangers for cooling. The water is returned to the spent fuel pool via an orifice distribution system. The heat exchangers are cooled by the component cooling water system. The water may also be filtered and passed through a demineralizer to remove impurities and maintain radioactivity concentrations within acceptable levels. A skimmer box draws water from the surface of the pool for filtration and to maintain surface clarity to support fuel-handling activities (Fig. 2.11).

Radiological conditions associated with the spent fuel pool cooling system components are primarily determined by the inventory of spent fuel elements in the spent fuel pool and the integrity of spent fuel rod cladding. One objective is to minimize dose rates to operating personnel located on the refueling bridge during

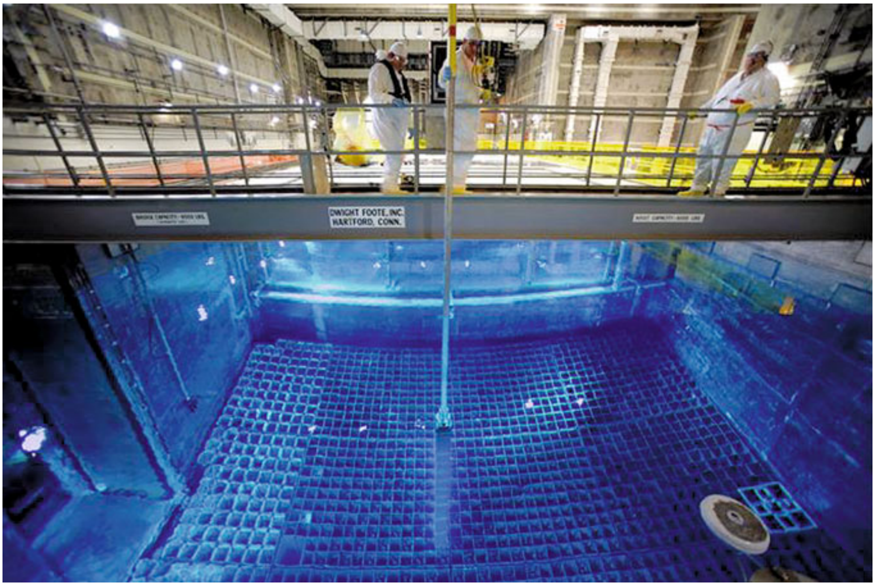

Fig. 2.12 Spent fuel handling operations in the fuel building of a PWR unit (Courtesy of Luminant)

the movement of spent fuel. The operation of the purification loop is typically optimized during refueling periods to maintain dose rates emanating from the surface of the spent fuel pool as low as possible. Radiation levels of tens of μSv/h (a few mrem/h) are probably acceptable during these periods. Dose rates much higher than this (e.g., approaching several tens of μSv/h) should be cause for concern. Dose rates in the vicinity of spent fuel pool cooling pumps and heat exchangers could be in the hundreds of μSv/h range if no significant cladding damage is associated with the elements in storage. Significant cladding damage could be defined as any leaks exceeding technical specification limits. Conversely if fuel cladding damage is present SFP heat exchangers, pumps, and associated piping could easily have radiation levels in excess of 1 mSv/h (100 mrem/h) with localized hot spots of perhaps 10 mSv/h (one rem/h) or more. Due to the parameters that influence the source inventory of radionuclides that may be circulating in the SFP cooling system at any given moment, the range of dose rates that may be encountered are subject to variation. The capacity of the purification loop, age of the plant and operating history, effectiveness of plant chemistry controls, and whether or not damaged fuel elements have been containerized are some of the variables that will impact radiological conditions associated with this system (Fig. 2.12).

2.9 Reactor Cavity Filtration

The reactor cavity provides sufficient volume to afford the necessary water depth for adequate shielding to personnel during spent fuel handling operations. The reactor cavity may have a capacity to hold up to 2.5 million liters (several hundred thousand gallons) of water. The cavity contains the reactor vessel positioned below the flange-level. The cavity is sized to allow storage of vessel internals during refueling and maintenance periods. During refueling operations the cavity is filled with borated water to a depth sufficient to provide adequate shielding to workers on the refuel floor and other plant areas that may be impacted from radiation levels emanating from an exposed reactor vessel. The refueling water storage tank (RWST) serves as the source of borated water for the reactor cavity during refueling periods. As previously noted the RWST also serves as a water supply to the HPSI, LPSI and CSS systems.

Dose rates in the vicinity of the reactor cavity are primarily influenced by the radionuclide concentration of the cavity water. The objective of the reactor cavity filtration system is to minimize exposures to operating personnel. The system is placed into operation during periods when the reactor cavity is flooded. The system consists of pumps and filtration units and possibly demineralizers. Pumps circulate the water through a filter network, returning the purified stream back to the cavity (see Fig. 2.10). Skimming and filtration of the water surface is also provided. Skimming of impurities and debris from the water surface improves visibility to support fuel movement and core alteration activities. Dose rates emanating from the surface of the reactor cavity water should be maintained in the range of several tens of μSv/h or less during refueling periods to minimize exposures to operators on the refuel bridge and support personnel in close proximity to the reactor cavity. Dose rates higher than these levels may be indicative of excessive fuel cladding defects or otherwise higher than anticipated radionuclide concentrations present in the water source.

2.10 Radioactive Waste Treatment Systems

The purpose of radioactive waste treatment systems is to reduce radioactivity concentration levels in plant effluents to acceptable levels. The systems are designed to maintain activity releases as low as possible. Radioactive wastes may include liquid, gaseous and solid radioactive material. Effluent batch releases are sampled and analyzed prior to release. Continuous effluent release streams (e.g., stack and liquid discharges) are routinely monitored when discharges are in progress to supplement grab sample analysis results and to ensure that releases are maintained within applicable limits. Solid wastes are packaged and shipped for offsite disposal in accordance with appropriate regulations and other applicable requirements (e.g., NRC, DOT and IAEA).

Various reactor suppliers as well as several engineering firms design radioactive waste treatment systems. The following discussion will of necessity be generic in nature due to the differences in both the design offered by various suppliers and the terms used to designate components and systems. Since the source of the radioactive waste stream is the primary determinant when considering the radiological conditions associated with a particular radioactive waste treatment system component; primary consideration should be given to understanding the source and constituents of a given waste stream. Dose rates emanating from primary system leak collection tanks versus waste water holdup tanks containing processed water will differ significantly.

2.10.1 Liquid Waste Treatment System

Liquid waste treatment systems provide for the storage, monitoring and processing of liquid wastes and effluent streams. Liquid wastes typically originate from valve and component leakage, demineralizer regeneration and resin replacement, chemistry sampling and laboratory activities, laundry facilities, equipment and floor drains, building sumps, and decontamination activities. In addition, miscellaneous sources of liquid waste could arise from plant operational occurrences involving thousands of liters of wastewater. Liquid wastes are routed to various collection tanks of varying storage capacities for collection and processing. Liquid collection tanks may have capacities ranging from a few thousand liters for the collection of laboratory wastewater, to several hundred thousand liter holdup tanks for the batch processing of liquid waste discharges. The various waste collection and holdup tanks are often designated by the source of the liquid waste and could include such terms as floor drain collection tanks, chemistry drain tanks or laundry waste water collection tanks for example. The number, type and designation of liquid waste storage tanks may differ depending upon the reactor size and type and the specific design considerations. Liquid wastes are usually collected and processed based upon the level of radioactivity present in the waste stream. Low activity wastewater is usually segregated from high-activity wastewater to simplify processing and to minimize costs. Additionally, it is oftentimes advantageous to segregate clean wastewater (i.e., primary system and auxiliary system leakages) from dirty wastewater to minimize the volume of wastewater requiring extensive processing and treatment. Dirty wastes may include those liquids that are contaminated with detergents or chemicals (e.g., from decontamination activities) or otherwise contain relatively high concentrations of impurities (e.g., auxiliary building sumps and reactor cavity drain tank after a refueling outage). The descriptions that follow are more generic in nature. The designations and capacities of the various liquid waste collection and processing tanks may differ from that encountered at a particular nuclear plant.

Floor drain collection tanks are used for the storage and holdup of non-reactor grade wastewater streams. This water may originate from decontamination processes, waste water from janitorial and housekeeping activities within clean areas of the RCA, non-recoverable leaks, and other miscellaneous sources. This water is sampled and analyzed, and if within applicable discharge limits, may be released directly to the environment with no further processing. If concentration levels exceed established release values the liquid waste may be filtered and routed through a demineralizer bed to reduce radioactivity concentrations prior to discharge. The treated wastewater would then be routed to a liquid waste holdup tank to prevent cross-contamination. Liquid waste holdup tanks may have capacities of 200,000 l or more. Several collection tanks could serve as feed to a given holdup tank. Many nuclear units were equipped with evaporators to reduce the volume of liquid waste required to be processed and discharged. The performance of evaporators has been mixed with the advantages associated with the reduction achieved in liquid waste volumes often overshadowed by operational and maintenance costs to maintain evaporator system components. Significant personnel exposures could result due to the handling and processing of evaporator "bottoms", containing high concentrations of radionuclides, in addition to routine maintenance activities. Dose rates in the vicinity of floor drain collection tanks are typically in the range of hundreds of μSv/h (tens of mrem/h). These tanks may or may not be enclosed behind walls and it is not uncommon for these tanks to be situated in open floor areas.

Waste holdup tanks collect wastewater originating from equipment drains and demineralizer regeneration and resin replacement (i.e., sluicing) operations. These wastes are treated and processed prior to release. If evaporators are available for use at a given facility these wastes could constitute the major feed to the waste evaporators. Waste holdup tanks are usually located within a separate room surrounded by concrete walls, not necessarily designed as shield walls. Dose rates in the vicinity of waste holdup tanks could be on the order of several hundred μSv/h (several hundred mrem/h) depending on the source of the water. In addition dose rates could be higher during outage periods when higher-activity wastewater is typically generated in support of outage activities.

Sites equipped with laundry facilities may have separate laundry holdup tanks or service effluent tanks to collect wastewater from laundry facilities and other sources such as shower facilities. Activity concentrations in this waste stream are typically low. Dose rates in the vicinity of laundry wastewater storage tanks could be on the order of hundreds of μSv/h (tens of mrem/h). Typically these wastes can be filtered and discharged without any further processing. The storage capacity allotted for these tanks, particularly for laundry wastewater, has been chronically undersized in the industry. Laundry facility modifications to provide additional wastewater storage capacity or the introduction of dry cleaners have often been necessitated to alleviate this problem.

Storage facilities may be available for the collection and storage of chemical liquid wastes, originating primarily from chemistry laboratories. The major source of influent to this tank is from the primary sample room and perhaps the chemistry laboratory. Wastes from laboratory drains, chemistry-sampling stations, and perhaps from various decontamination facilities could be routed to this tank. This tank, often referred to as the chemical drain tank, may have a capacity of a couple thousand liters. Radiation levels in the vicinity of this tank could be on the order of tens of μSv/h (tens of mrem/h). Radiation levels could be significantly higher in the event of failed fuel or if abnormal amounts of primary system water is allowed to be introduced to the tank during sampling activities. Chemical drain tank waste may be filtered and treated by demineralization or evaporation prior to release.

Liquid waste from different waste streams may be processed and routed to a common collection tank prior to discharge. This tank serves as an intermediate storage, or holdup, tank and facilitates batch processing and release of radioactive effluent. Collecting smaller volumes of processed liquid waste in one large common collection tank reduces the number of batch releases performed over a given time period. This "monitor" tank may have a capacity of 200,000 l (50,000 gallons) or more. A batch release typically requires the contents of the waste tank to be mixed for a period of time. This requires time to perform the necessary valve lineups and to place necessary equipment (e.g., pumps) in service. Following mixing of the tank contents samples are obtained and analyzed. Sample results are evaluated to ensure compliance with both radiological and non-radiological release limits. Depending upon the facility, arrangements must be made to ensure sufficient dilution flow is available while the batch release is in progress. This may entail placing into service various discharge pumps to maintain the necessary dilution flow. The radioactivity level of batch releases is usually monitored while the release is in progress. The alarm set point of the radiation monitor on the discharge line must be confirmed and adjusted to the appropriate value. These and other activities required to support a batch release may be included in an "effluent release package" of some kind. The package must be completed and reviewed by such departments as chemistry and operations. The availability of a waste monitor tank reduces the number of batch releases, the operational time required to support a batch release, and the administrative burden associated with the preparation of effluent release packages.

Liquid wastes may be treated by a combination of filtration, distillation, demineralization or holdup to minimize the volume and activity of radioactive waste discharged to the environment. The radioactive constituents may be concentrated and solidified prior to shipment for offsite disposal. Resin beds used in the treatment of liquid wastes may concentrate radionuclides by many orders of magnitude. Resin beds influent and effluent streams are routinely sampled or monitored to measure the depletion of the resin bed. Decontamination factors (i.e., the reduction in activity concentrations of the effluent stream compared to that of the influent stream) of 100 or higher are considered to be indicative of a normally functioning, or non-depleted resin bed. The processing of hundreds of thousands of gallons of wastewater with radionuclide concentrations in the 20,000–40,000 Bq/ml range (μCi/ml range) can result in resin beds reading greater than several Sv/h (several hundred rem/h). Resin beds used in the treatment of radioactive waste streams are often entombed in a shielded compartment or as a minimum, located within a labyrinth configuration behind shield walls and entrances equipped with multiple locked-door barriers. A similar arrangement is associated with filters used in the treatment of liquid waste streams; however, the magnitude of radiation levels may be on the order of a few Sv/h and often will not reach the higher levels encountered in the vicinity of demineralizers. Nevertheless certain filter housings (in such systems as the CVCS, RWCU, reactor cavity filtration and various other purification systems) are also located within shielded vaults or compartments equipped with strict access design controls.

Usually there are at least two waste evaporators arranged in parallel to process wastes from liquid waste holdup tanks. Evaporators concentrate liquid wastes by boiling off the water in the process stream. The vapor (i.e., condensate) produced in the evaporator may be demineralized and filtered and routed to a waste evaporator condensate tank and used for makeup or other purposes. The concentrate, commonly referred to as evaporator bottoms, is discharged to the solid waste packaging and drumming facility for solidification and packaging.

2.10.2 Gaseous Waste Treatment System

The gaseous waste treatment system provides for holdup, filtration and dilution of gaseous waste produced during plant operations. Since in a PWR the primary system is closed, gas volumes produced are relatively small. Gases collected from the primary system are compressed and stored in waste gas decay tanks. Each PWR unit may be equipped with several waste gas storage tanks. Each tank having a capacity to store several weeks or months of waste gas generated during normal plant operation. Waste gas originates from the CVCS system via gases stripped from the volume control tank, the boron recycle system and gases vented from various liquid waste storage tanks. Waste gas streams may contain hydrogen and nitrogen in addition to fission gases.

Two waste gas compressor trains are usually provided. One train supports normal operations while the second train serves as a backup and supplies additional capacity for peak load periods encountered during refueling when the reactor coolant system is degassed. The waste gas is then pumped through a recombiner where oxygen is added to minimize potential explosive gas concentrations. The oxygen combines with hydrogen to produce water vapor that is removed from the process stream. The compressed gases are routed to a waste gas storage tank and allowed to decay for a period of time sufficient to allow short-lived fission gases to decay to insignificant levels prior to release. Depending upon the number of waste gas storage tanks (or decay tanks) available, storage times of 30–60 days are common. For those PWR units with several waste gas storage tanks, storage periods of several months may be achievable.

Waste gas storage tanks are located within a shielded room or area, often entombed to prevent access. Radiation levels in the vicinity of these tanks will fluctuate over a large range depending on the age of the gas contained within a given storage tank. Radiation levels in the vicinity of the gas storage tank in use may approach hundreds of mSv/h (tens of rem/h). Once a tank is full to capacity (based on pressure readings) it is removed from service, isolated, and fission gases allowed to decay. By the time of release radiation levels may have decayed by orders of magnitude. The contents of waste gas storage tanks are released at a subsequent date when additional storage capacity is required, based on operational needs, or if the tank must be placed into service. These tanks are released on a batch basis, similar to the process noted above for liquid batch releases. The contents are sampled and radiation levels of the batch release monitored while the contents of the tank are being released to the plant stack.

The volumes of waste gas produced fluctuate based upon reactor power level and plant operating conditions. A buffer tank may be provided to allow temporary holdup of waste gases so that an even gas flow can be provided for the waste gas process stream. The buffer tank helps to eliminate transient pressure spikes due to changing gas volumes.

2.10.3 Solid Waste Treatment System

The solid waste treatment system provides for the handling, compacting, solidification and packaging of solid wastes. Solid wastes include spent ion exchange resins, evaporator bottoms, used filter materials and miscellaneous solid wastes. Miscellaneous wastes include consumables and a host of materials expended in the normal operation and maintenance of the nuclear unit. These items consist of worn protective clothing, covering and enclosure materials used for contamination control, solid waste generated during decontamination activities (e.g., mop heads and rags), worn or unusable contaminated tools and equipment.

There is no "one-size-fits-all" solid waste treatment system. In fact the history of nuclear power plants has been plagued with the lack of a dependable and efficient onsite system for processing solid waste. Many of the original systems underwent extensive modifications only to be abandoned at a later date. This situation has been compounded, at least in the case of the USA, for the need to dramatically reduce the volume of generated solid waste due to the high cost of disposal and limited access to disposal facilities. These factors were not a concern when solid waste treatment systems were first designed for many of the nuclear plants now operating. Essentially solid wastes were to undergo minimal volume reduction via compaction into 55-gallon drums or other suitable containers. Consequently, many nuclear power plants in the USA rely on radioactive waste processing firms. Current practice now is to package dry active waste in sealand containers, or other suitable packaging, for shipment to offsite processors for volume reduction and disposal. These firms specialize in volume reduction and segregation processing. The capabilities of these offsite processes include super-compaction, metal-melt, incineration and other processes that are targeted towards minimizing the volume of solid radioactive waste ultimately requiring disposal.

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