APPENDIX A
TRITIUM PRODUCTION OPERATIONS—APPLICATION TO PRODUCTION OF TRITIUM IN COMMERCIAL LIGHT WATER REACTORS

This appendix addresses the operation of a nuclear power plant in relation to its use as a tritium production facility. The first section provides a brief description of the nuclear processes necessary to operate a fission reactor as a nuclear power plant. The next section addresses aspects of the reactor design for commercial light water reactors (CLWRs). The boiling water reactor and the pressurized water reactor are discussed. [Much of the information in this section describes Westinghouse reactors and fuel. Differences between Westinghouse and other operating reactor designs exist, but are not described in detail in this appendix.] Descriptions of the refueling operations at a nuclear facility and some environmentally relevant systems are included in this appendix. Also, a description of the nucleonics of tritium production and the structure of tritium-producing burnable absorber rods (TPBARs) is presented. Finally, the impacts of tritium production on the CLWR fuel cycle are addressed.

A.1 NUCLEAR FISSION REACTORS

Most commercial electric power generation plants produce electricity by converting heat into electricity. Typically, these plants heat water to generate steam, and the steam is used to drive a turbine generator. In the turbine generator, the energy in the steam is first converted into mechanical energy (spinning a turbine shaft), which creates electricity by driving a generator. Fossil plants generate heat through a chemical process—the burning of fuels such as natural gas or coal. When fossil fuels are burned, energy is released when the carbon in the fossil fuel combines with oxygen and burns. Commercial nuclear power plants generate heat through the nuclear fission process. The nuclear fission process occurs at a subatomic level and involves the interaction of some component part of the atoms. The following section describes the fission process and the methods used to control this process in a nuclear reactor.

A.1.1 Nuclear Fission

Nuclear fission is a nuclear reaction caused by the interaction between a free neutron and the nucleus of some atoms such as uranium or plutonium. An atom consists of a relatively heavy, positively charged nucleus with a number of much lighter, negatively charged particles in various orbits around the nucleus. The nucleus is the central part of the atom and consists of subparticles called nucleons. There are principally two types of nucleons: neutrons, which are electrically neutral, and protons, which are positively charged. The number of protons in the nucleus is called the atomic number of that atom; all atoms of the same element have the same number of protons. The total number of nucleons in the nucleus is called the mass number, designated as A. Using X to represent the chemical symbol for the element and Z to represent the atomic number, each element is presented as X^A, ${}_ZX^A$, or as "the chemical name" - A. When atoms of an element differ in their number of nucleons, they are called isotopes of that element. For example, there are three isotopes of hydrogen: hydrogen with a single proton, deuterium with a single proton and a single neutron, and tritium with one proton and two neutrons. Tritium can be expressed as H^3, ${}_1H^3$, or hydrogen 3. Uranium has an atomic number of 92; that is, each atom has 92 protons. The more common isotopes of uranium have either 143 or 146 neutrons. These two isotopes are designated as uranium-238, ${}_{92}U^{238}$, or U^{238} (approximately 99 percent of all naturally occurring uranium), and uranium-235, ${}_{92}U^{235}$, or U^{235} (approximately 0.7 percent of naturally occurring uranium). These are two of the three naturally occurring isotopes of uranium. In all, there are 18 known isotopes of uranium. Different isotopes of the same element behave identically chemically, but can have significantly different nuclear characteristics.

Fission, as it occurs in a nuclear power plant, is the process by which the atoms of one element (such as uranium or plutonium) are converted into atoms of lighter elements through the capture of a neutron and the subsequent "splitting" of the atom's nucleus (**Figure A–1**). This results in the release of energy fission products (atoms of the lighter elements), and neutrons. Not all isotopes of an element are capable of fission. For uranium, only 4 of the 18 known isotopes are capable of fission. Of these four, the two most important isotopes are uranium-235 and uranium-233.

Fission produces energy in the form of radiation and the kinetic energy of neutrons and fission products. Most of the energy released in the fission process is produced as the kinetic energy of the fission products. Lesser amounts are released as the kinetic energy of the neutrons and the energy produced from the radioactive decay of the fission products generated in the fission process. It is these forms of energy that are used to heat water in the core of a nuclear reactor.

Fission of an atom is initiated with a single neutron, but can result in the creation of many free neutrons (neutrons released from the nucleus). These neutrons can potentially initiate additional fission reactions. When exactly one neutron generated in a fission reaction initiates another fission reaction, the process is said to be a critical chain reaction. Criticality is an important characteristic of the nuclear power reaction. When a reactor is maintained in a critical state, the fission reaction proceeds at a constant rate. Since each fission reaction releases approximately the same amount of power, this condition will result in the reactor constantly operating at a steady power level. Therefore, it is important to control the number of neutrons available for fission. A critical chain reaction is represented in **Figure A–2**. If a series of fission reactions produce, on average, more than one neutron per fission that results in additional fissions, the process is said to be supercritical. In this state, the power level of the reactor increases. If, on the other hand, a series of fission reactions produce, on average, less than one neutron per fission that results in additional fissions, the process is said to be subcritical. In this condition, the power level of the reactor drops until eventually the fission process stops.

A.1.2 Control of Nuclear Reactions in a Reactor

Fission is not the only reaction that can take place when a neutron interacts with the nucleus of an atom. One of three interactions is possible: (1) the neutron is scattered—i.e., it essentially bounces off the nucleus (an elastic collision); (2) the neutron is absorbed—the neutron and atom combine to make the next higher isotope of the element; or (3) the neutron is absorbed and initiates a fission reaction. These different reactions are all important in the operation of a nuclear reactor. The first reaction—scattering—results in a change in the energy of the free neutrons. The second reaction—absorption—results in the loss of neutrons from the reactor. Neutrons that are absorbed are not available to initiate fission reactions. As discussed in the preceding paragraphs, the third reaction, fission, is the process by which energy is produced in a nuclear reactor and additional neutrons are produced to sustain the chain reaction. The likelihood of each of these interactions depends primarily on the following two factors: the energy of the free neutrons and the isotope of the atom being struck by the neutron.

In U.S. commercial nuclear reactors, only uranium-235 is used as the nuclear fuel. Uranium-235 is found naturally in uranium ore, although natural uranium consists predominantly of uranium-238. Enriched uranium is used in U.S. commercial nuclear power plants. This is uranium in which the percentage of uranium-235 has been increased from the less than 1 percent found in natural uranium to 3 to 5 percent. With approximately 100 metric tons of enriched uranium (3 to 5 metric tons of uranium-235) in the reactor core, a nuclear power plant can operate for approximately 18 months without refueling. When the uranium fuel is removed from the reactor, much of the uranium-235 has been consumed, and the spent fuel contains approximately 1 percent uranium-235.

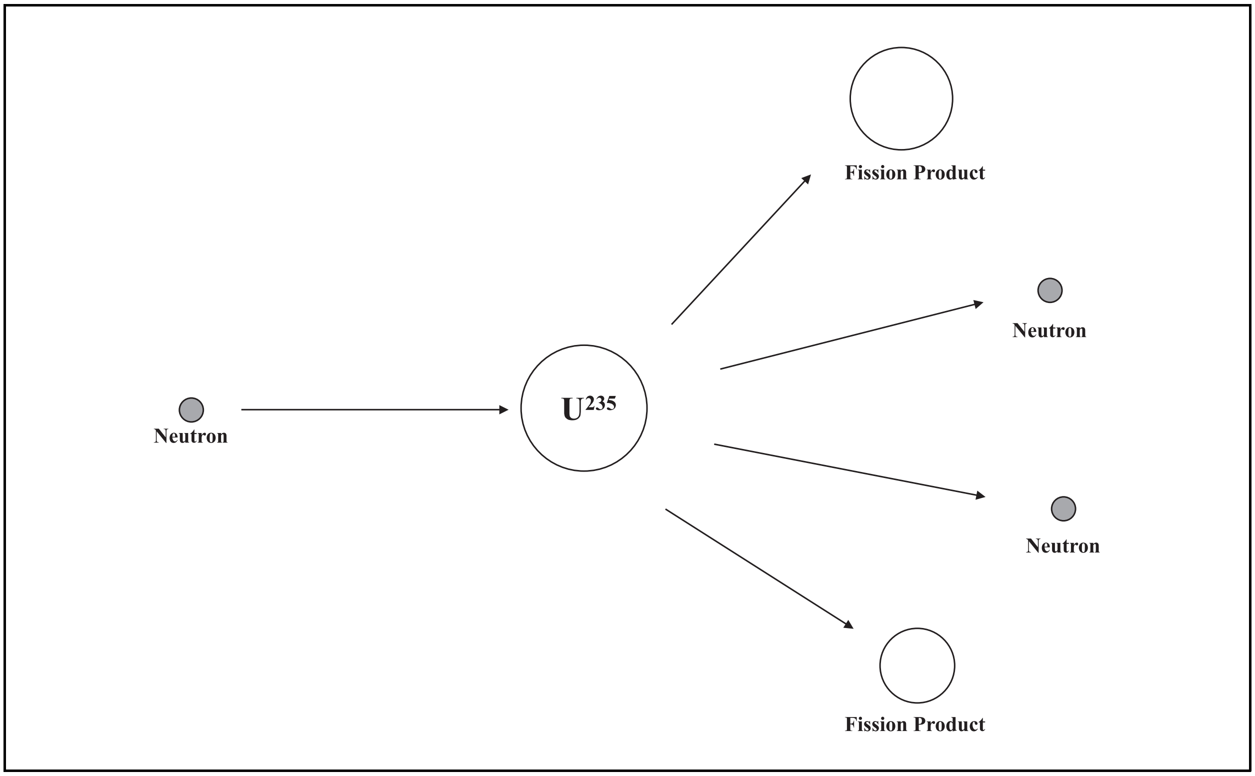

Figure A–1 Fission of Uranium-235 Atom

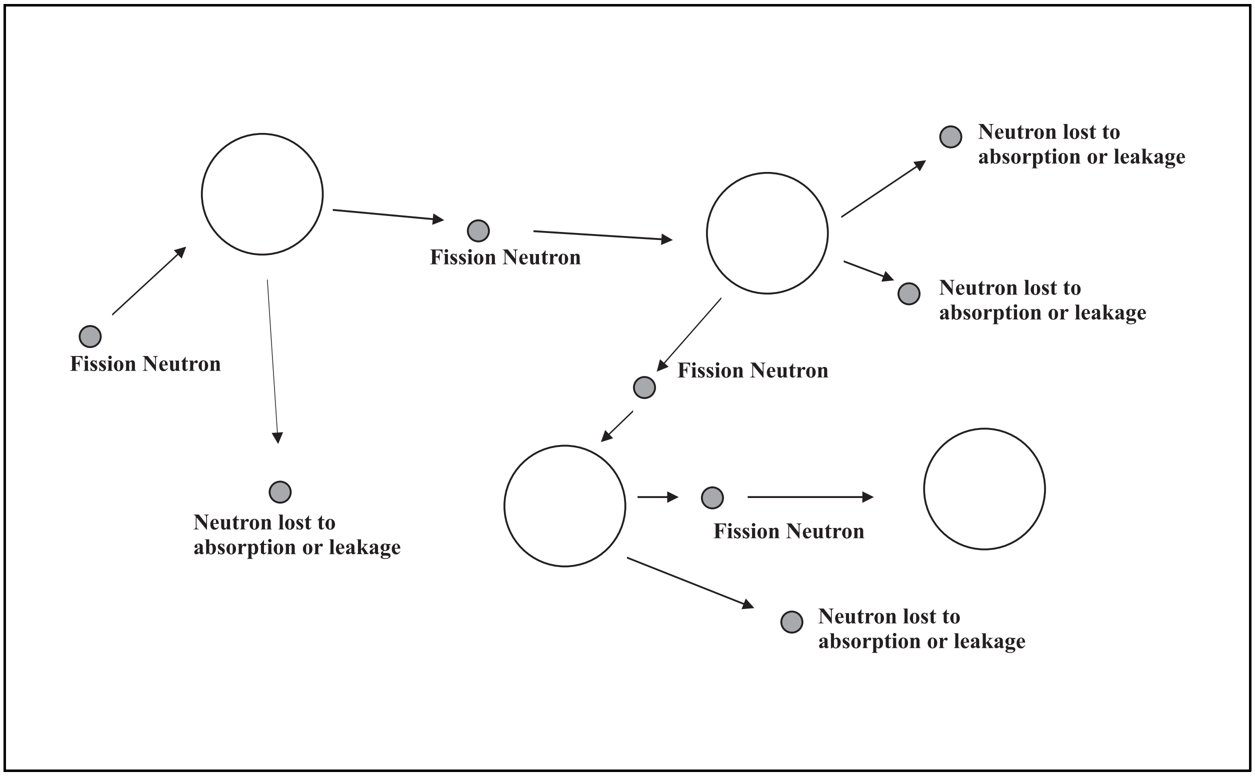

Figure A–2 Critical Chain Reaction

The fission reaction of a uranium-235 atom produces approximately 2.5 neutrons. Neutrons produced in fission are called fast neutrons. This refers to the amount of kinetic energy associated with the neutrons. However, the fission process using uranium-235 works better with slower-moving neutrons; that is, neutrons with significantly less energy than the neutrons produced from the fission process. These neutrons are called thermal neutrons. Neutrons are slowed via collisions with nuclei of atoms in the reactor core. In the collisions, energy is transferred from the neutron to the atom it collides with. Generally, the closer in weight the neutron and atom are, the more energy is transferred to the atom. This transfer of energy from the neutron to other materials results in the slowing down of the neutron and is called moderation. The moderator in U.S. commercial nuclear power plants, both pressurized and boiling water reactors, is ordinary light water. [Because the moderator used in U.S. commercial power reactors is light water and the fission reaction of uranium-235 requires slower-moving (thermal) neutrons, these types of reactors are referred to as thermal light water reactors.] The hydrogen in light water (with a nucleus containing a single proton) is nearly the same mass as the neutron. Collisions between neutrons and the hydrogen atoms result in a relatively rapid reduction in the energy of the neutrons. After many such collisions, the neutrons travel slow enough to be considered thermal neutrons.

Neutrons that are not lost from the reactor core between the time they are created as fast neutrons and the time they are moderated to thermal energy levels are available for fission. Neutrons are lost from the reactor core in several ways. Some are lost to leakage; that is, they escape from the reactor core and are captured in the reactor vessel or shielding. Some are absorbed by material in the core without producing fission. [Other materials in the core, including uranium-238 and core internal structures, contribute to the absorption of neutrons. Some neutrons that collide with uranium-235 atoms are absorbed without resulting in fission.] Specific materials, referred to as neutron poisons or simply poisons, are inserted in the reactor core to intentionally capture neutrons and provide control over the fission rate by controlling the number of neutrons available for fission. Such poisons, which are contained in control and shutdown rods, are necessary for several reasons. These devices control the rate of fission, thereby controlling the reactor power level. In addition, these devices promptly terminate the fission when the rods are fully inserted into the reactor core, thereby shutting down the reactor. The material used in control and shutdown rods is usually boron; a strong neutron absorber. In a collision between boron and a neutron, there is a high likelihood that the neutron will be absorbed into the boron, thus generating a different boron isotope. Therefore, the position of the control rods determines the power level of the reactor by controlling the number of neutrons available for fission.

Other poisons, called burnable poisons (because during the time the fuel is in the reactor the burnable poisons are used up and gradually become less effective as neutron absorbers), are placed in a reactor core in addition to the poisons that are contained in the control and shutdown rods. These burnable poisons are necessary for a reactor to operate over an extended period without loading fresh fuel into the reactor. Commercial reactors typically load fresh fuel once every one to two years. As the power plant operates during this period, uranium-235 is burned up (consumed in the fission process or by neutron absorption). Since the source of the neutrons is devoured during the generation of power, it is necessary to start the fuel cycle with more uranium-235 than is necessary to sustain a critical reaction at the desired power level. Extra uranium-235 is loaded into the reactor core, necessitating the use of burnable poisons to keep the power at the appropriate level. The reactor's power levels are controlled by using either fixed burnable poisons (burnable poison rods) in areas that would have higher than average free neutron flux, or by adding boron (in the form of boric acid) to the coolant in a pressurized water reactor. As the fuel burns it becomes less reactive because less fissionable uranium is available. Since there are fewer uranium-235 atoms per unit volume, fewer neutrons are produced. With fewer neutrons produced, the percentage of neutrons lost to leakage and absorption must be reduced to maintain the number of neutrons available for fission. Control of neutron loss due to absorption is accomplished by reducing the concentration of boron in the coolant and reducing the burnable poison in the burnable absorber rods placed in the core.

A.2 COMMERCIAL NUCLEAR POWER PLANT DESCRIPTIONS

A.2.1 Commercial Nuclear Reactors

In the United States, there are two types of commercial nuclear power plants currently in operation; the boiling water reactor and the pressurized water reactor.

The boiling water reactor is a single-loop system. The fission energy in the core causes the water to boil in the reactor vessel. In the reactor vessel, above the fuel, the steam passes through steam separators and steam dryers, which are used to ensure dry steam exits the reactor vessel, and travels through steam pipes to the turbine generator. The steam drives the turbine, which in turn powers the generator to create electricity. As steam passes through the turbine, it loses most of its energy but remains as steam as it passes to the main condenser. In the main condenser, where additional heat is removed by a cooling water system, the steam condenses into water. This water is pumped back to the reactor vessel where it is forced through the reactor core and is again converted to steam. **Figure A–3** provides a simplified representation of a boiling water reactor. Boiling water reactors typically operate at pressures of approximately 70 kilograms per square meter (1,000 pounds per square inch), and the temperature of the water and steam in the reactor vessel approaches 288°C (550°F).

A pressurized water reactor uses a primary and secondary system to transfer heat from the reactor core to the turbine generator (see **Figure A–4** for a simplified representation of a pressurized water reactor). In the primary loop (the reactor coolant system), water is forced up through the core, where it is heated but does not boil. After the water exits the reactor vessel, it passes through steam generators. The number of steam generators used in the power plant depends on the design and power level. Combustion Engineering and Babcock & Wilcox designs have two steam generators. Westinghouse designs can have from two to four steam generators. The more recent (larger power plants) have four steam generators (**Figure A–5** is an isometric of a Representative Reactor Four-Loop Primary System). Each steam generator is connected to the reactor vessel in a separate, independent coolant loop. In the steam generators, the primary coolant heats water in the secondary loop and converts the water to steam. After the primary coolant leaves the steam generator, it is pumped back to the reactor vessel where it is again heated in the reactor core. The primary system has a pressurizer, which is used to control the pressure of the primary system. The pressurizer is connected to one of the primary loops and is located above the reactor core. It contains heaters and sprays that are used to control the water level in the pressurizer which, in turn, controls the pressure of the primary coolant system. The steam in the secondary loop (referred to as the steam and power conversion system) is used to drive the turbine generator and produce electricity. As in the boiling water reactor, after the steam passes through the turbine, it is condensed by cooling water in the main condenser. This cooled water is then pumped back to the secondary side of the steam generator. A pressurized water reactor primary system operates at pressures of about 158 kilograms per square meter (2,250 pounds per square inch) and temperatures of up to approximately 315°C (600°F), with the secondary loop operating at approximately 70 kilograms per square meter (1,000 pounds per square inch) and 288°C (550°F).

In addition to the difference in the number of cooling loops associated with a boiling water reactor and a pressurized water reactor, there are some differences in the design of the reactor cores. In a pressurized water reactor, the control and shutdown rods enter the reactor core from above. In a boiling water reactor, these rods are driven into the core (via a control rod-driven system) from the bottom of the core. Also, pressurized water reactors use soluble neutron poison (a boric acid solution) in the primary coolant to help control reactivity. The concentration of the soluble neutron poison is controlled by the chemical and volume control system. Typically, the concentration of boric acid is highest at the beginning of a fuel cycle, when there is fresh fuel in the core. A boiling water reactor does not use this means of reactivity control.

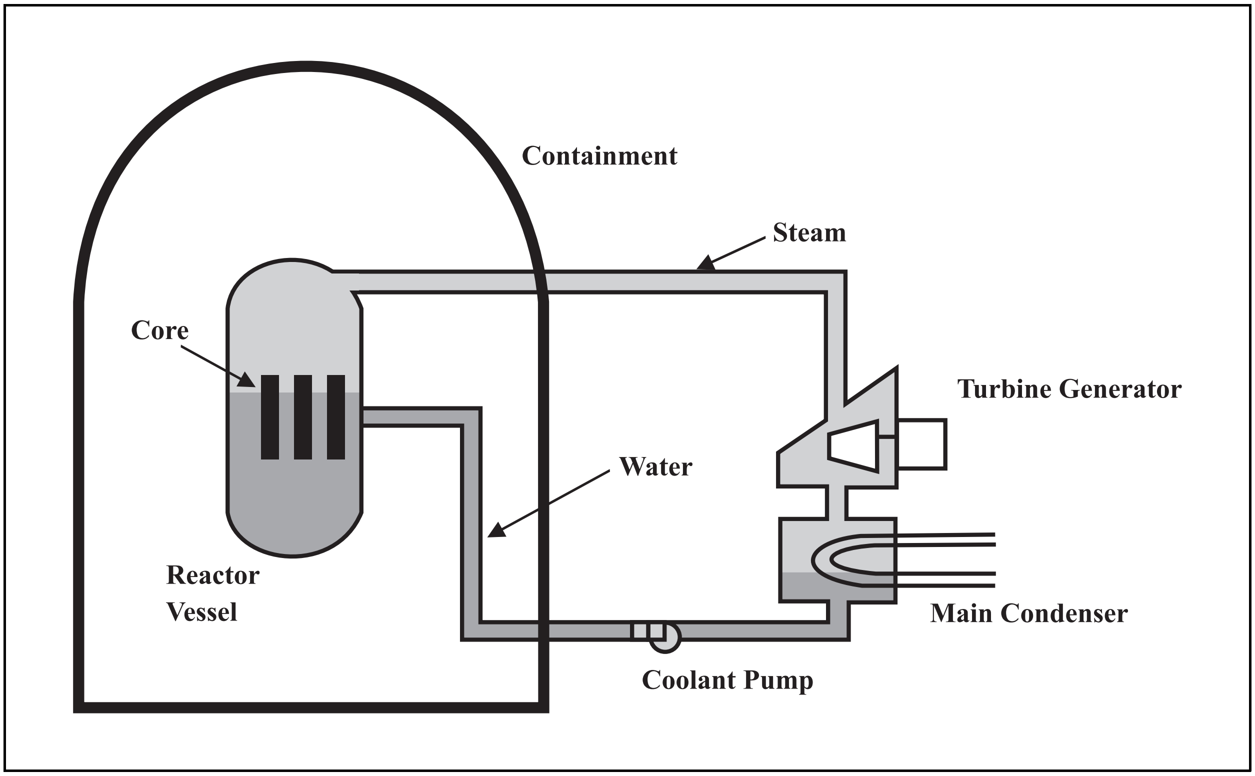

Figure A–3 Boiling Water Reactor Schematic

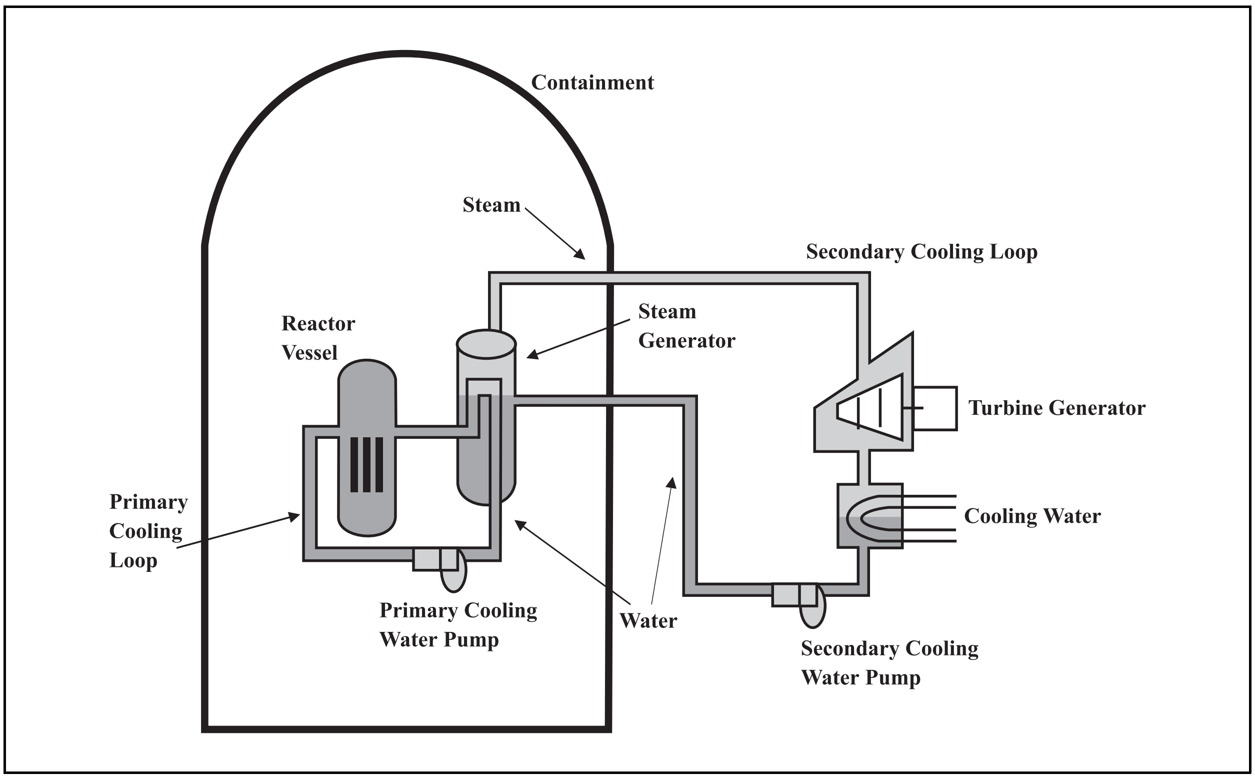

Figure A–4 Pressurized Water Reactor Schematic

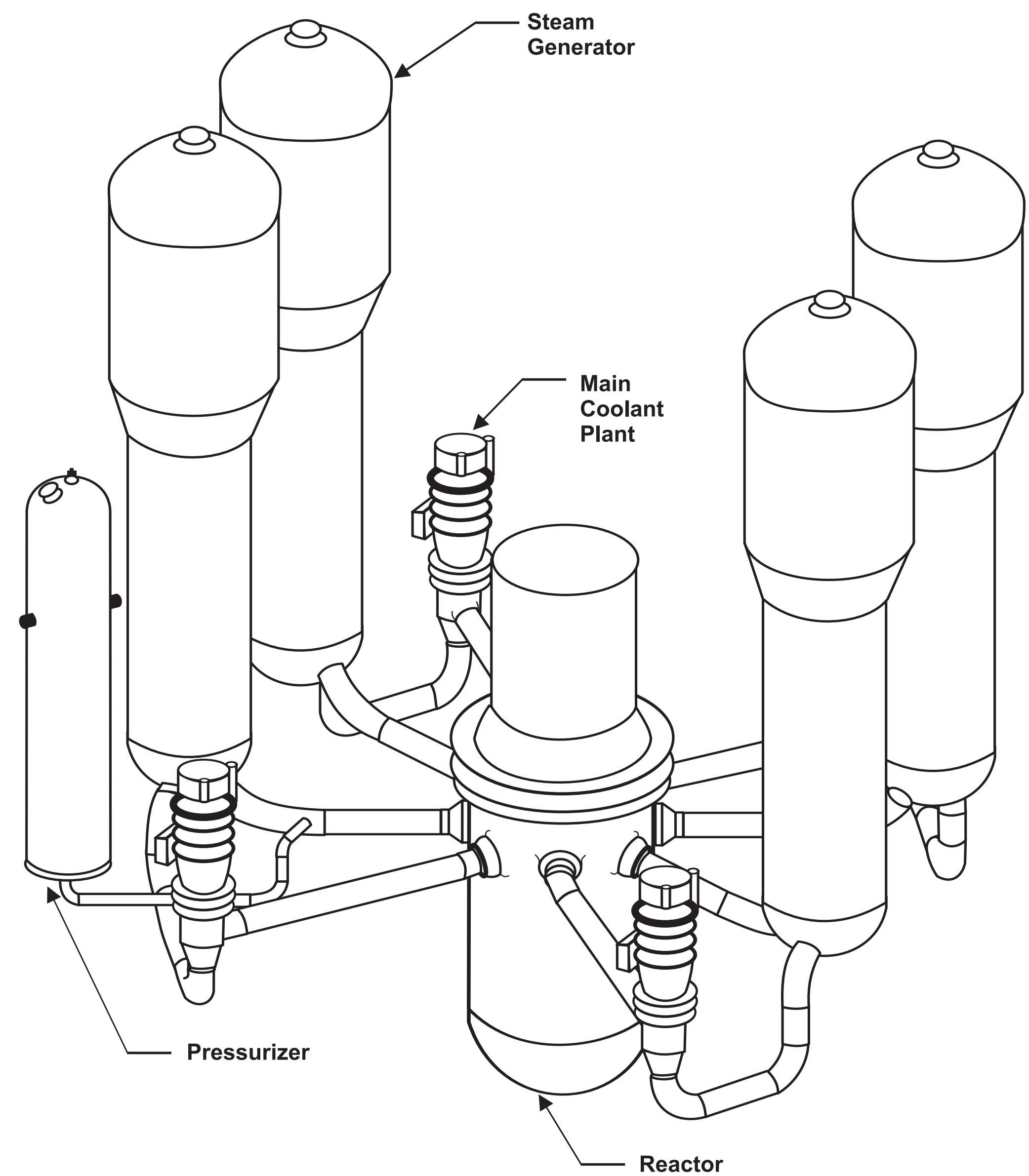

Figure A–5 Representative Four-Loop Reactor Coolant System

A.2.2 Reactor Core Description

Fuel in a nuclear reactor is slightly enriched (up to 5 percent) uranium dioxide and is sealed in fuel rods. These rods are approximately 3.6 to 3.9 meters (12 to 13 feet) long and slightly less than half an inch in diameter. Uranium, in the form of approximately half-inch long cylindrical uranium dioxide pellets, is placed in a fuel rod and enclosed in a zircaloy cladding. This cladding holds the pellets in position and provides a barrier against the release of fission products into the reactor coolant system.

In a pressurized water reactor, the fuel rods are collected in a fuel assembly that also contains several guide tubes and an instrumentation channel (illustrated in **Figure A–6**). The number of fuel rods in an assembly varies depending on the design of the reactor. Assemblies contain fuel rods arranged in 14 × 14, 15 × 15, or 17 × 17 arrays. The more recent reactors tend to use the 17 × 17 array. The guide tubes denote the location where the control rods of the control element assemblies are inserted into the reactor core. The fuel rods, guide tubes, and the instrumentation channel are held in place by a series of grids at several locations along the full length of the fuel assembly. In a reactor core, fuel assemblies are all structurally identical and have space reserved for control element assemblies. In the Westinghouse designs, between a third and a fourth of the fuel assemblies have an associated control element assembly. In a large pressurized water reactor, one with an electrical power rating of over 1,000 megawatts, the core will consist of approximately 200 fuel assemblies. Of these, 50 to 60 fuel assemblies (depending on the reactor design) have associated control element assemblies. The remaining fuel assemblies may have burnable poison rods in the locations used by control element assemblies, or these locations may be empty. The burnable poison rods are rods with the same shape as the control and shutdown rods. However, they are not connected to the control rod-driven mechanism and cannot be removed from the reactor without shutting it down and performing refueling activities that involve removing the fuel assembly containing the burnable poison rods from the reactor core. Loading of the burnable poison rods in these locations for the assemblies without control element assemblies is dictated by the need to balance the power distribution in the core.

The control element assembly consists of a collection of control rods and a spider assembly at the top of the rods. **Figure A–7** shows a control element assembly for a Representative Reactor 17 × 17 fuel assembly design. The spider assembly is connected to a control rod drive mechanism that can be used to move the control element assemblies. These assemblies serve two purposes—to limit the effects of reactivity changes during power operation and to shut down the reactor. The rods are made of a strong neutron absorber (typically a boron or cadmium compound). When not needed, the control element assemblies are pulled out of the core by their control rod drives. For reactivity control during operation, the control rod drive can be used to insert the rods into the core at a controlled pace. If needed, the rods can be rapidly inserted to shut down the reactor. It is possible for the control element assemblies to be inserted into the core using only the force of gravity as the driving force. When fully inserted, the poison in the control rods absorbs enough neutrons to make the nuclear reaction become subcritical, shutting down the reactor.

As mentioned earlier, one of the ways in which neutrons are lost from the core and become unavailable for fission is through leakage. The neutrons leak from the edges of the core, and those that do not hit an atom and reflect back into the core are lost. (Reactor core designs address this problem of neutron loss by incorporating a neutron reflector, a layer of water around the core.) Neutrons generated at the center of the core are less likely to be lost through leakage than those generated at the edge of the core. Therefore, in a reactor with no burnable poisons and a uniform fuel enrichment, the number of neutrons available for fission is greater at the center of the core. The center of the core, which is about 3 meters (10 feet) in diameter and 3.6 to 3.9 meters (12 to 13 feet) tall, has a higher power density than the areas at the top, bottom, and edge of the core.

Designers of the reactor core control the distribution of power within the reactor core by using burnable poisons and varied fuel rod enrichments. **Figure A–8** displays a possible arrangement of fuel assemblies within a reactor core. Other fuel loading patterns also exist, but the concept is fully expressed by a simple loading pattern described here. This figure shows fresh fuel (typically with the highest enrichment of uranium-235) loaded around the core periphery. Fuel in the center of the core is referred to as once- or twice-burned fuel and has been in the core for one or two fuel cycles. A fuel cycle is the period from one refueling outage to another. The older fuel in the reactor core has been producing power for one to two years and has burned up some of its uranium-235. This fuel is no longer as enriched as the fresh fuel. With less material available for fission in this fuel, the extra neutrons present in the center of the core will not result in overly high power levels. While controlling the enrichment level alone is not sufficient to properly shape the core power, burnable poison rods are included in the fuel assemblies.

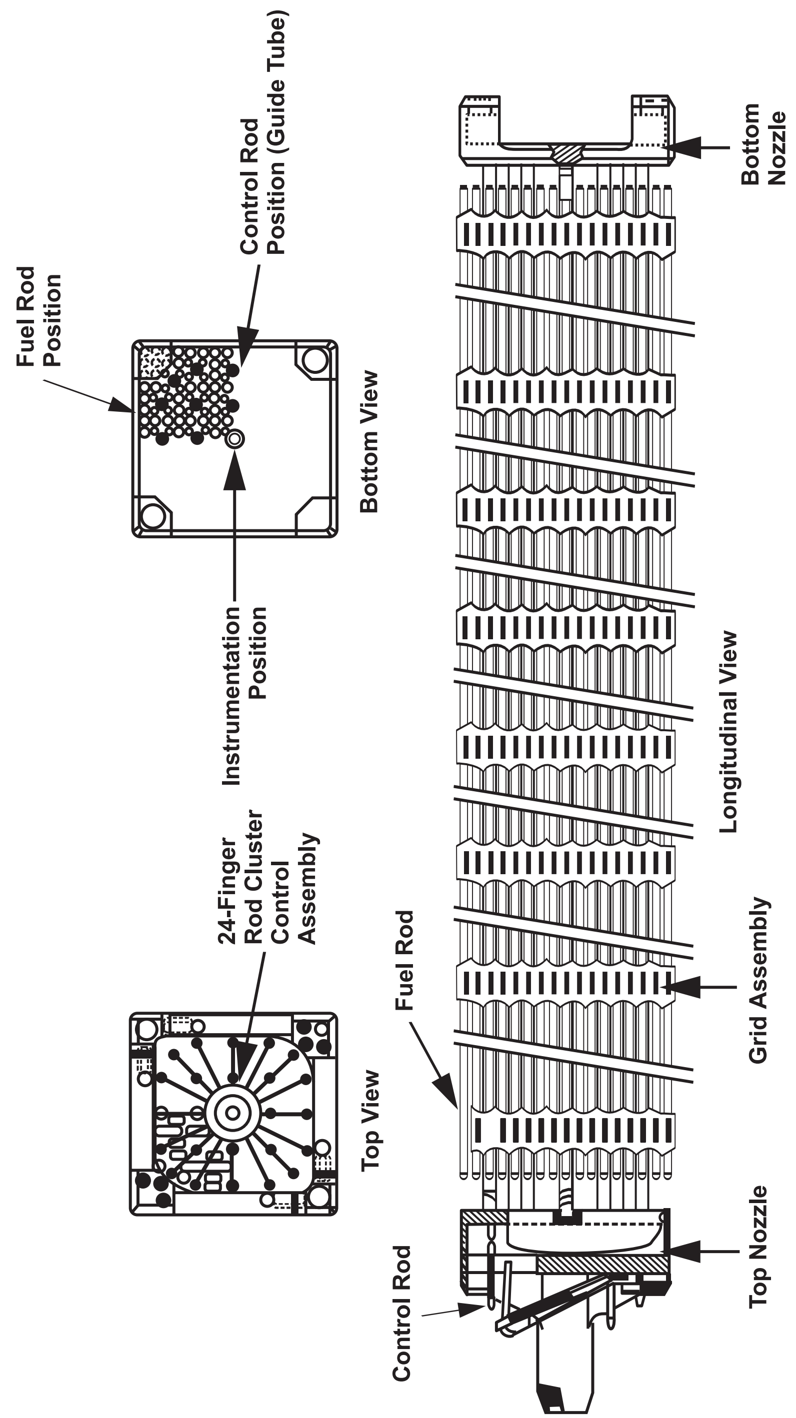

Figure A–6 Typical 17 × 17 Reactor Fuel Assembly

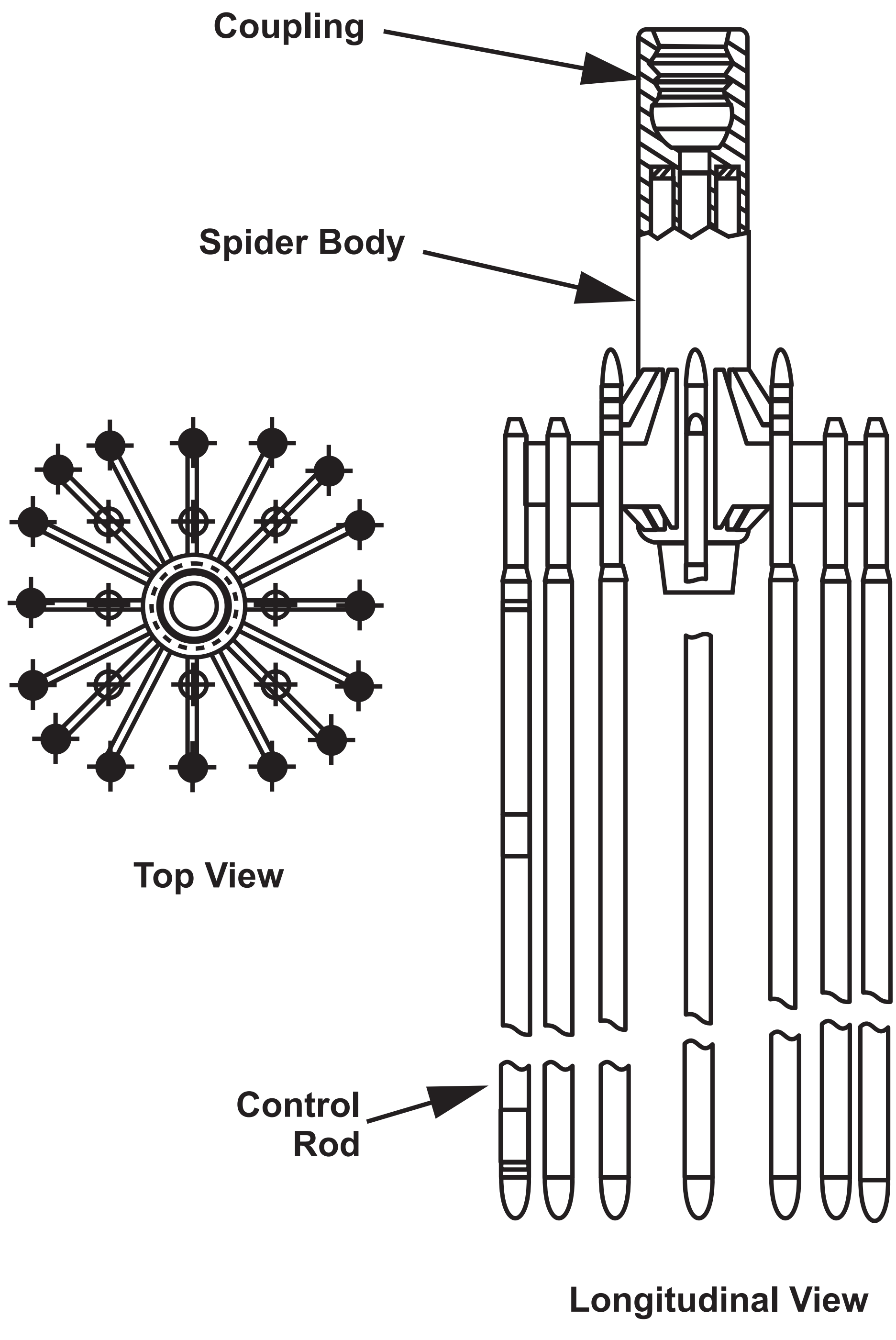

Figure A–7 Representative Reactor Control Element Assembly

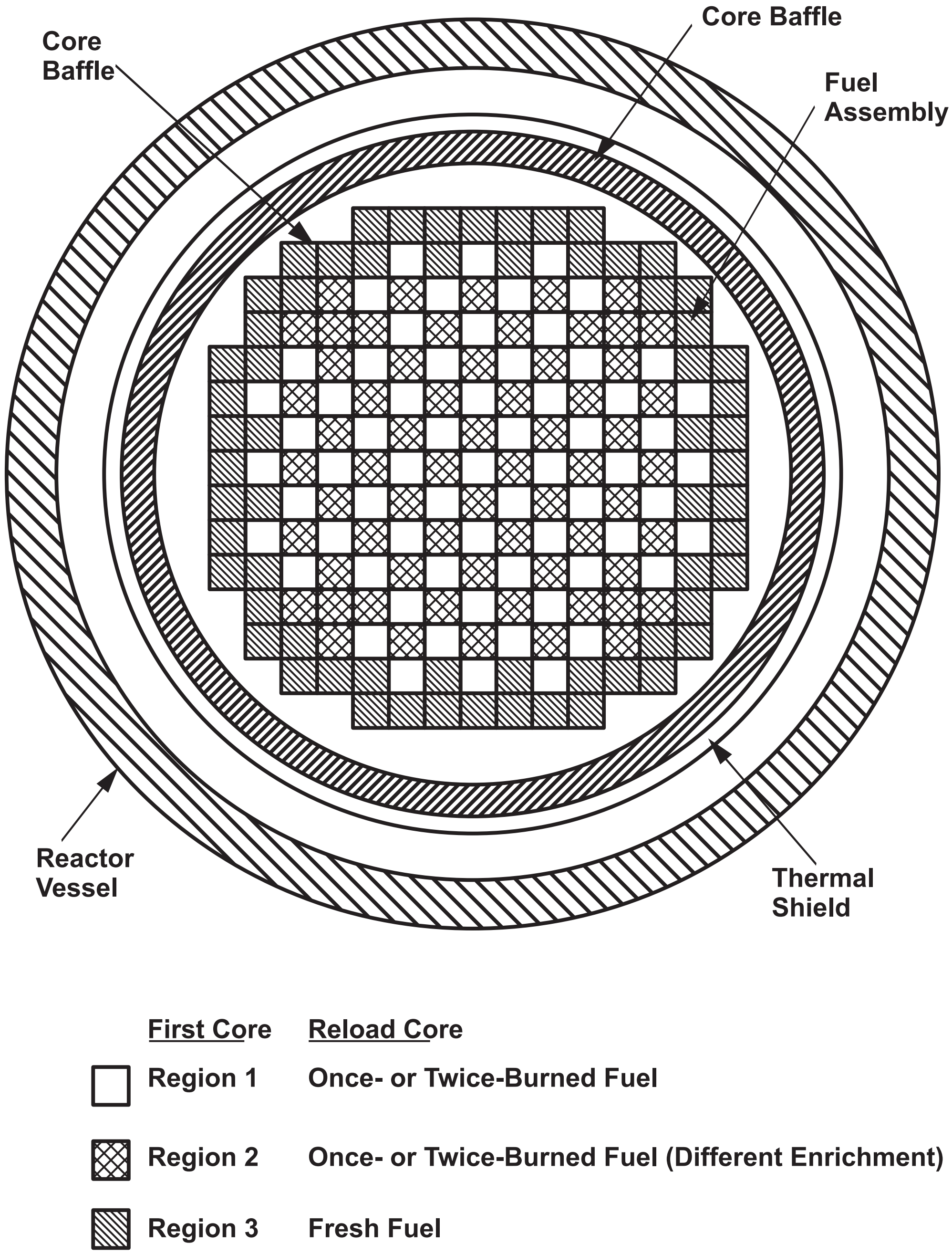

Figure A–8 General Arrangement of a Possible Reactor Core Fuel Loading Pattern

The burnable poison rods will be replaced with TPBARs in a tritium production facility (see Section A.3). The TPBARs act as neutron absorbers in much the same way as the burnable poison, although there are some differences that may result in changes to the fuel management practices at the facility using the TPBARs. The control and shutdown control element assemblies will remain unchanged in a reactor containing TPBARs and will still enable complete shutdown of the reactor at all times during the fuel cycle.

A.2.3 Reactor Refueling

Unlike fossil-fueled electricity-generating plants that are continually fed fuel, nuclear power plants operate over extended periods without the need for fresh fuel. Typically, reactors will operate for 12 to 18 months between refueling outages. As stated earlier, as the uranium-235 burns up, the reactor becomes increasingly less able to maintain a critical condition. Eventually, when enough fuel is burned, the reactor will not be able to remain critical even if all of the neutron poisons are removed from the core. Before this point is reached, the reactor is shut down and refueled. When the power plant is shut down during the refueling outage, some (between one-third and two-fifths) of the fuel assemblies are removed and replaced with fresh fuel, and some of the assemblies are shuffled to different locations within the reactor core. The removed fuel is called spent fuel. The refueling outage usually lasts less than two months, during which various maintenance activities are performed. The reactor refueling is a small fraction of the overall outage.

Spent fuel is stored on site in a spent fuel pool, located in a separate building attached to the containment structure. The spent fuel is stored on site for several years, allowing the assemblies to cool and the radioactivity levels to drop sufficiently so that the spent fuel can be safely transported to a temporary or permanent waste disposal site.

The refueling operation of a nuclear power plant can be divided into four separate phases: preparation, reactor disassembly, fuel handling, and reactor assembly.

Preparation

During preparation, the reactor is shut down; all control and shutdown rods are inserted into the reactor core, and the nuclear chain reaction is stopped. Heat is still generated in the reactor core, principally by the radioactive decay of the fission products. The amount of heat produced during decay gradually decreases, and the reactor is brought to a condition called cold shutdown, where the average reactor coolant temperature is below the boiling point of water at atmospheric pressure.

Reactor Disassembly

The area above the reactor vessel is referred to as the reactor cavity, illustrated in **Figure A–9**. Adjacent to this cavity is the refueling cavity. During reactor disassembly, these two cavities are flooded with borated water to provide a medium for the transfer of spent and new fuel. The water provides a means to remove heat from the spent fuel assemblies and a radiation shield for the plant workers. The reactor vessel is disassembled in stages. Most items connected to the reactor vessel head are removed. The refueling cavity is partially flooded and the reactor vessel head is unbolted and slightly raised. At this time, borated water is added to the reactor coolant system and allowed to flow out of the top of the reactor vessel, ultimately flooding the reactor cavity and the refueling cavity. The reactor vessel head is completely removed, along with the control rod-driven mechanism and the upper core internals. The fuel assemblies are then free of any obstructions and can be removed from the reactor core.

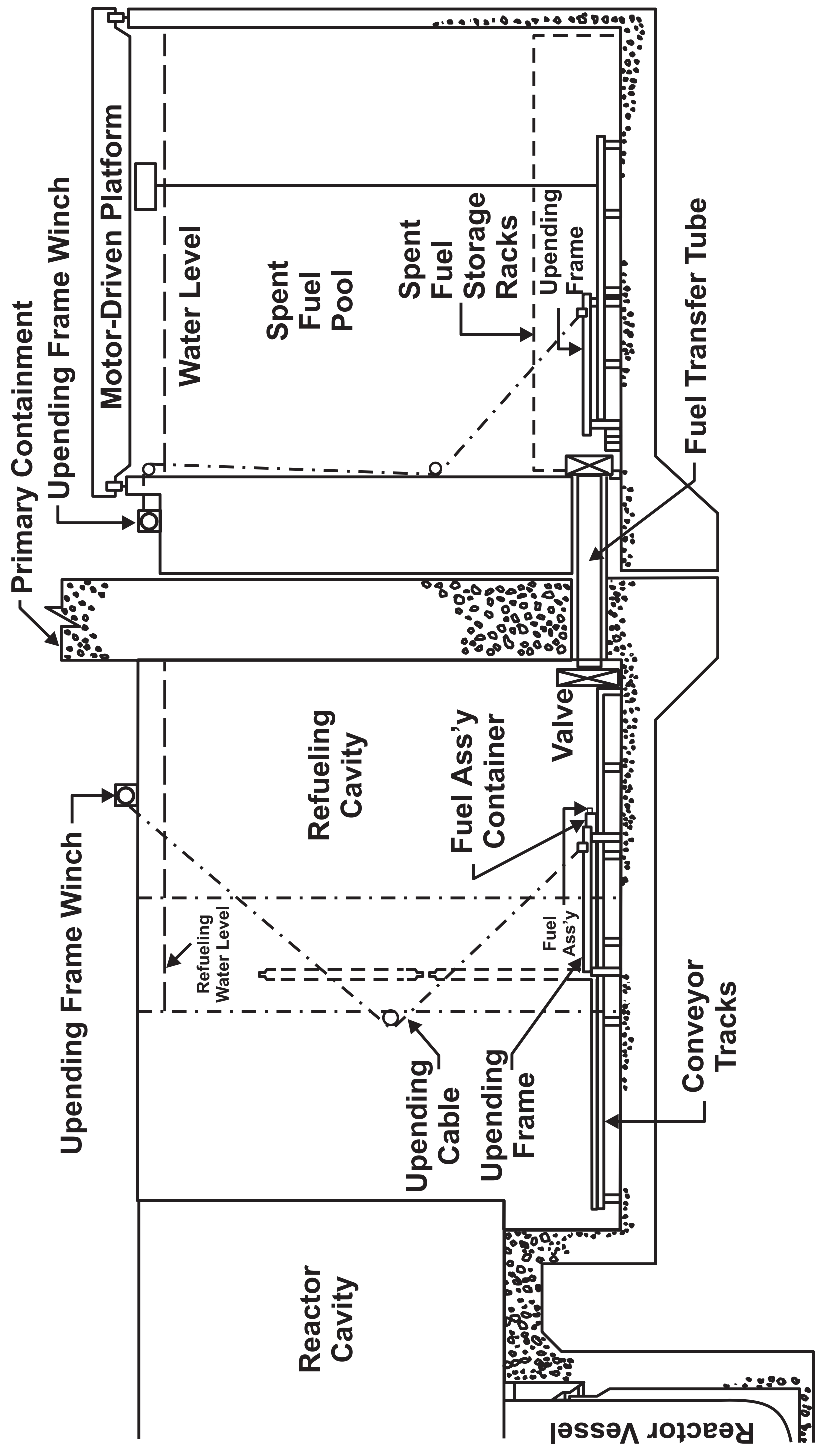

Figure A–9 Typical Fuel Transfer System

Fuel Handling

Fuel is removed from the core, one assembly at a time. Fuel assemblies are lifted out of the core using an overhead crane. If the spent fuel assembly contains a control element assembly, it is placed in a control element assembly changing device upon its removal from the core; otherwise it is moved to a fuel transfer system. In this device, the control element assembly is removed from the spent fuel assembly and transferred to another fuel assembly placed in the reactor core. Once the control element assembly is removed from the spent fuel assembly, it is transferred to the spent fuel pool.

The fuel transfer system lowers the fuel to a horizontal position and passes the fuel through a fuel transfer tube (which penetrates the containment structure) and into the spent fuel pool. Here, the fuel transfer system lifts the spent fuel assembly into a vertical position, and another crane places the spent fuel assembly into its location within the spent fuel racks in the pool. Spent fuel is stored in the spent fuel pool beneath over 20 feet of water. Storage under this amount of water provides two functions: the spent fuel pool has a cooling system to remove decay heat after it is transferred to the pool water, and the water provides a radiation protection barrier for the plant workers.

Fresh fuel is brought into the reactor core using the same equipment used to remove the spent fuel. New fuel handling equipment is used to unload, inspect, and prepare the fuel for insertion into the reactor. It is then transferred to the fuel transfer machine.

Reactor Assembly

After all of the spent fuel is removed from the reactor, some of the remaining fuel is moved to new locations in the core; fresh fuel is added to the reactor core, and the reactor is reassembled. This is essentially the reverse of the reactor disassembly phase. After some startup tests, the reactor is ready to begin power operations.

A.2.4 Commercial Light Water Reactor Systems Important to Environmental Impacts

The sections below describe the plant systems that are directly associated with environmental impacts from plant operation. These are the cooling water systems and radioactive and nonradioactive waste treatment systems.

A.2.4.1 Cooling and Auxiliary Water Systems

Water use at a nuclear power plant is predominantly for removing excess heat generated in the reactor by condenser cooling. The quantity of water used for condenser cooling is a function of several factors, including the capacity rating of the plant and the increase in cooled water temperature from the intake to the discharge. The larger the plant, the greater the quantity of waste heat and cooling water required to dissipate the waste heat.

In addition to removing heat from the reactor, cooling is also provided to the service and auxiliary cooling water systems. The volume of water required for once-through cooling is usually less than 15 percent of the volume required for condenser cooling. In closed-cycle cooling, the additional water needed is usually less than 5 percent of that needed for condenser cooling. Of all the CLWR plants operating in the United States, approximately 40 percent use closed-cycle cooling systems and 60 percent use once-through (open-cycle) cooling systems.

In closed-cycle systems, the cooled water is recirculated through the condenser after the waste heat is removed by dissipation to the atmosphere, usually by circulating the water through large cooling towers constructed for that purpose. Several types of closed-cycle cooling systems are currently used by the nuclear power industry.

Recirculating cooling systems consist of either natural-draft or mechanical-draft cooling towers, cooling ponds, cooling lakes, or cooling canals. Because the predominant cooling mechanism associated with closed-cycle systems is evaporation, most of the water used for cooling is consumed and not returned to a water source.

In a once-through cooling (open-cycle) system, circulating water for condenser cooling is drawn from an adjacent body of water, such as a lake or river, passed through the condenser tubes, and returned at a higher temperature to the adjacent body of water.

For both once-through and closed-cycle cooling systems, the water intake and discharge structures are of various configurations to accommodate the source water body and to minimize impact to the aquatic ecosystem. The intake structures are generally located along the shoreline of the body of water and are equipped with fish protection devices. The discharge structures are most often the jet or diffuser outfall type and are designed to promote rapid mixing of the effluent stream with the receiving body of water. Biocides and chemicals used for corrosion control and other water treatment purposes are mixed with the condenser cooling water and are discharged from the system.

In addition to surface water sources, some nuclear power plants use groundwater as a source for service water, makeup water, or potable water. Other plants operate dewatering systems to intentionally lower the groundwater table, either by pumping or by a system of drains, in the vicinity of building foundations.

A.2.4.2 Radioactive Waste Treatment Systems

During the fission process, a large inventory of radioactive fission products will build up within the fuel rods. A small fraction of these fission products escape the fuel rods and contaminate the reactor coolant. The primary system coolant also has radioactive contaminants as a result of neutron activation. These contaminants are removed from the coolant by a radioactive waste treatment system prior to any release to the environment. Typically, the plants include treatment systems for gaseous, liquid, and low-level radioactive solid waste.

The impacts to the environment are driven by gaseous emissions, liquid effluent, or generation of solid low-level radioactive waste after treatment.

Gaseous Radioactive Emissions

CLWRs have three primary sources of gaseous radioactive emissions:

- Discharges from the gaseous waste management system
- Discharges associated with the exhaust of noncondensable gases at the main condenser (in the event of leakage between primary and secondary cooling systems)
- Discharges from the building ventilation exhaust, including the reactor building, reactor auxiliary building, and fuel-handling building

The gaseous waste management system collects fission products, mainly noble gases, that accumulate in the primary coolant. A small portion of the primary coolant flow is continually diverted to the primary coolant purification, volume, and chemical control system to remove contaminants and adjust the coolant chemistry and volume. During this process, noncondensable gases are stripped and routed to the gaseous waste management system, which consists of a series of gas storage tanks. The storage tanks allow the short half-life radioactive gases to decay, leaving only relatively small quantities of long half-life radionuclides to be released to the atmosphere via the plant vent at a controlled rate. These releases pass through both high-efficiency particulate air and charcoal filters before entering the environment.

Discharges from the condenser vacuum exhaust and building ventilation exhaust are released to the environment with no filtration. All potentially significant release points are monitored.

Liquid Radioactive Effluents

Radionuclide contaminants in the primary coolant are the source of liquid radioactive waste in CLWRs. Liquid wastes resulting from CLWR plant operation are classified into the following categories: clean wastes, dirty wastes, detergent wastes, turbine building floor drain water, and steam generator blowdown. Clean wastes include all liquid wastes with a normally low conductivity and variable radioactivity content. They consist of reactor-grade water, which is amenable to processing for reuse as reactor coolant makeup water. Clean wastes are collected from equipment leaks and drains, certain valve and pump seal leakoffs not collected in the reactor coolant drain tank, and other aerated leakage sources. In addition, these wastes include primary coolant. Dirty wastes include all liquid wastes with a moderate conductivity and variable radioactivity content that, after processing, may be used as reactor coolant makeup water. Dirty wastes consist of liquid wastes collected in the containment building sump, auxiliary building sumps and drains, laboratory drains, sample station drains, and other miscellaneous floor drains. Detergent wastes consist principally of laundry wastes and personnel and equipment decontamination wastes and normally have a low radioactivity content. Turbine building floor drain wastes usually have a high conductivity and low radionuclide content. Steam generator blowdown can have relatively high concentrations of radionuclides, depending on the amount of primary-to-secondary leakage. After processing, the water may be reused or discharged.

Each source of liquid waste receives varying degrees and types of treatment before storage for reuse or discharge to the environment under the site National Pollutant Discharge Elimination System permit. The extent and types of treatment depend on the chemical radionuclide content of the waste. To increase the efficiency of waste processing, wastes of similar characteristics are batched before treatment.

The degree of processing, storing, and recycling of liquid radioactive waste has steadily increased among operating plants. For example, extensive recycling of steam generator blowdown is now the typical mode of operation, and secondary side wastewater is routinely treated. In addition, the plant systems used to process wastes are often augmented with the use of commercial mobile processing systems. As a result, radionuclide releases in liquid effluent from CLWR plants have generally declined or remained the same.

Solid Waste

Solid low-level radioactive waste from commercial nuclear power plants is generated by removal of radionuclides from liquid waste streams, the filtration of airborne gaseous emissions, and the removal of contaminated material from various reactor areas. Liquid waste contaminated with radionuclides comes from primary and secondary coolant systems, spent fuel pools, decontaminated wastewater, and laboratory operations. Concentrated liquid, filter sludge, waste oil, and other liquid sources are segregated by type, flushed to storage tanks, stabilized for packaging in a solid form by dewatering, slurried into 55-gallon steel drums, and stored on site in shielded Butler-style buildings or other facilities until suitable for offsite disposal. These buildings usually contain volume reduction and solidification facilities to prepare low-level radioactive waste for disposal at a certified low-level radioactive waste disposal facility.

High-efficiency particulate air filters are used to remove radioactive material from gaseous plant effluents. These filters are compacted and are disposed of as solid waste.

Solid low-level radioactive waste consists of contaminated protective clothing, paper, rags, glassware, compactible and noncompactible trash, and irradiated and nonirradiated reactor components and equipment. Most of this waste comes from plant modifications and routine maintenance activities. Additional sources include tools and other materials exposed to the reactor environment. Before disposal, compactible trash is usually taken to onsite or offsite volume-reduction facilities. Compacted dry active waste is the largest single form of low-level radioactive waste disposed from commercial nuclear plants, comprising one-half of the total average annual volume from pressurized water reactors.

Volume reduction efforts have been undertaken in response to increased disposal costs and the passage of the Low-Level Radioactive Waste Policy Act of 1980 and the Low-Level Radioactive Waste Policy Amendments Act of 1985, both of which require low-level radioactive waste disposal allocation systems for nuclear plants. Volume reduction is performed both on and off site. The most common onsite volume-reduction techniques are ultra-high-pressure compaction of waste drums, monitoring waste streams to segregate wastes, minimizing the exposure of routine equipment to contamination, and decontaminating and sorting of radioactive or nonradioactive batches before offsite shipment. Offsite waste management vendors incinerate dry-activated waste; separate and incinerate oily, organic wastes; solidify the ash; and occasionally undertake supercompaction, waste crystallization, and asphalt solidification of resins and sludges.

A.2.4.3 Nonradioactive Waste Systems

Nonradioactive wastes from commercial nuclear power plants include steam generator blowdown, water treatment wastes (sludges and high saline streams that have residues that are disposed of as solid wastes and biocides), steam generator metal cleaning, floor and yard drains, and stormwater runoff. Principal chemical and biocide waste sources include the following:

- Hydrazine, which is used for corrosion control (it is released in steam generator blowdown)
- Sodium hydroxide and sulfuric acid, which are used to regenerate resins that capture wastes (these are discharged after neutralization)
- Phosphates in cleaning solutions
- Biocides used for condenser defouling

Other small volumes of wastewater are released from plant systems and depend on the design of each plant. These are discharged as the service water and auxiliary cooling systems, water treatment plant, laboratory and sampling wastes, floor drains, stormwater runoff, and metal treatment wastes. These waste streams are discharged as separate point sources or are combined with the cooling water discharges.

A.3 TRITIUM-PRODUCING BURNABLE ABSORBER RODS

A.3.1 Nucleonics of Tritium-Producing Burnable Absorber Rods

TPBARs serve two functions in a nuclear power reactor: (1) they absorb excess neutrons and help make the power distribution more even in the reactor core, and (2) they produce tritium. The neutron absorber material in a TPBAR is lithium, in the form of lithium aluminate, enriched in lithium-6 (Li^6). When lithium-6 absorbs a neutron, as would happen in the core of an operating power reactor, the neutrons and protons in the lithium would recombine into two parts: tritium (hydrogen-3 or H^3) and helium-4. This process would result in the release of 4.8 million electron volts (MeV) of energy. This process can be written:

$$\text{Lithium-6} + \text{neutron} \rightarrow \text{Helium-4} + \text{Hydrogen-3} + 4.8\ \text{MeV}$$

or

$$Li^6 + n^1 \rightarrow He^4 + H^3 + 4.8\ \text{MeV}$$

Once the tritium (H^3) is produced inside the TPBAR, it is captured and held in a getter, as described in Section A.3.2. However, the tritium, itself unstable, slowly decays by emitting a beta particle (an electron), and becomes helium-3:

Hydrogen-3 → Helium-3- + electron

or

$$H^3 \rightarrow He^3 + \text{electron}$$

Tritium's rate of decay, or "half-life," is 12.3 years, which means that every 12.3 years, half of the tritium will decay and become helium-3. Helium-3 is stable, but it has a strong affinity for neutrons and is a good neutron absorber. As the inventory of tritium accumulates in the TPBARs during irradiation in the core, the amount of helium-3 increases as a result of the decay of tritium. This has the effect of adding a material to the reactor core that is a strong neutron absorber.

Both lithium-6 and helium-3 are considered neutron poisons. The amount of lithium-6 in the TPBARs is reduced or "burned" (hence the term "burnable") during its irradiation in the core, effectively reducing its poisonous effect. However, an increase in the amount of the helium-3 poison during irradiation in the reactor core somewhat balances the reduction of the amount of lithium-6. As a result, the effectiveness of the TPBARs in absorbing neutrons during the 18 months (one fuel cycle) they are in the core is only slightly reduced from the start of the fuel cycle to its finish.

In a normal burnable absorber rod, the rod that TPBARs will replace, the neutron absorber is boron-10, which absorbs a neutron and promptly decays into lithium-7 and helium-4:

Boron-10 + neutron → Lithium-7 + Helium-4

or

$$B^{10} + n^1 \rightarrow Li^7 + He^4$$

Boron-10 is a strong poison, but lithium-7 has little capacity to absorb neutrons. Therefore, as the boron-10 is converted to lithium-7 during irradiation in the core, the burnable absorber rod absorbs fewer neutrons and loses its poisonous effect on the reactor core. By design, at the end of an 18-month fuel cycle, the burnable absorber rods are no longer effective neutron absorbers.

Therefore, the result of using TPBARs instead of boron-10 burnable absorber rods is that, over the 18-month fuel cycle, the TPBARs act as a stronger overall poison than the burnable absorber rods that they replace. This, coupled with the fact that there will be many more TPBARs than there were burnable absorber rods, results in a significant increase in neutron poison in the core of the tritium production CLWR compared to the nontritium production CLWR.

To compensate for the added TPBAR poison, the core may need to have more new fuel assemblies loaded during each refueling, and the enrichment of those assemblies may need to be increased. As described previously, enrichment of the fuel is the amount of uranium-235 contained in the fuel. The higher the uranium-235 content in the fuel, the more fissions the fuel is capable of producing. Enrichment of the new fuel placed in the core of a tritium production CLWR may need to be increased to just under 5 percent, compared to the 4.2 to 4.5 percent currently being used in CLWRs. Five percent enrichment is the upper limit for reactor licensing by the U.S. Nuclear Regulatory Commission (NRC).

A.3.2 Physical Description of the Tritium-Producing Burnable Absorber Rod

Lithium, the active ingredient in tritium production, is in the form of an annular-shaped ceramic lithium-aluminate pellet. The pellets are contained in subassemblies called pencils. Each pencil is about 30 centimeters (12 inches) long and consists of a stack of pellets, a zircaloy inner liner inside of the pellets, and a nickel-plated zircaloy tube or getter outside of the pellets. Inside the zirconium liner is a gas plenum. The components of a TPBAR are illustrated in **Figures A–10 and A–11**.

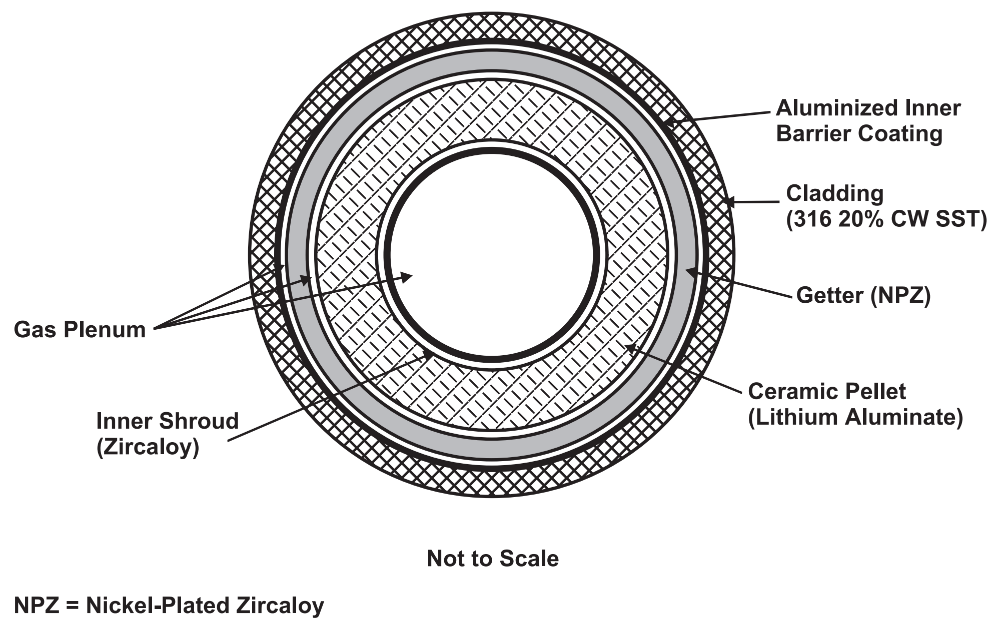

Figure A–10 TPBAR Transverse Cross Section

Tritium is generated as a gas, almost all of which is captured by the nickel-plated zircaloy getter as a tritide (ZrT_x). Tritium that becomes tritiated water vapor before it can be absorbed by the getter is disassociated by the zircaloy inner liner. The getter is nickel-plated to protect it from tritiated water vapor, which would oxidize its surface and block further absorption of tritium gas. The zircaloy inner liner also serves to maintain the overall geometry of the pellets.

Twelve pencils, getter discs at the top and bottom of the twelve pencils, and a spring loaded inside a stainless steel tube create a TPBAR. The spring holds the pencils in place during handling and allows for thermal expansion during operation. The inside surface of the stainless steel tube, or cladding, has an aluminized barrier coating to retard the permeation of hydrogen into and tritium out of the TPBAR. Loss of tritium through the cladding would increase the tritium released into the reactor coolant and, therefore, reduce the amount of tritium available for processing. Ingress of hydrogen into the TPBAR would be absorbed by the getter, diminishing the ability of the getter to absorb tritium. A less effective getter would increase the partial pressure of tritium inside the TPBAR, which would increase tritium loss through the cladding. The TPBARs are evacuated, backfilled with helium at one atmosphere pressure, and seal-welded. TPBARs would be put in the fuel assembly's nonfuel positions designed for burnable poison rods. Therefore, the exterior dimensions of the TPBARs are the same as those of burnable absorber rods. For the Westinghouse 17 × 17 design fuel assembly, the TPBARs would have an outside diameter of 0.381 inches, which is exactly that of a burnable

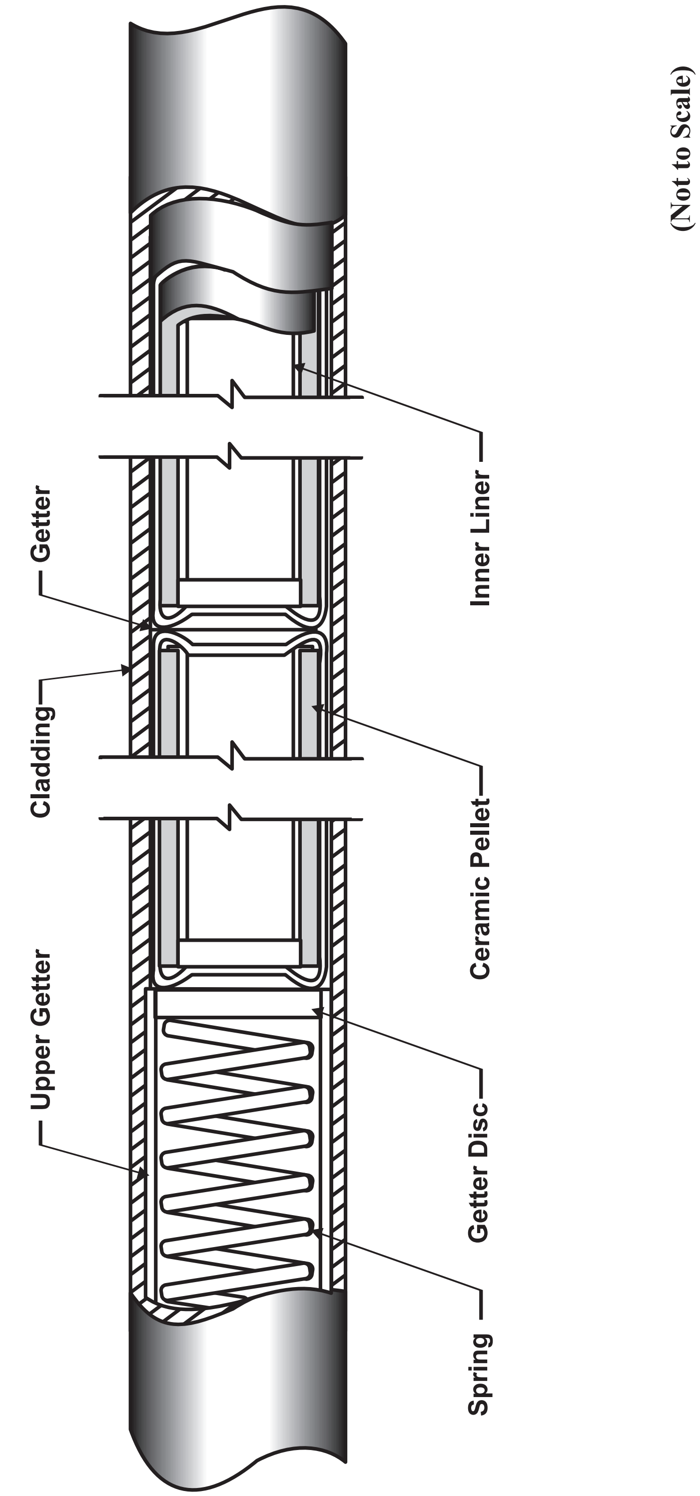

Figure A–11 TPBAR Longitudinal Cross Section

absorber rod. The cladding of the TPBAR would be stainless steel, type 316. The cladding of absorber rods would be either 304-type stainless steel or zircaloy 4.

All of the TPBARs inserted into a given fuel assembly are attached to a base plate, forming a TPBAR assembly. The base plate is part of the hold-down assembly, which also includes a spring and a locking device. The base plate not only maintains the spacing of the TPBARs for insertion and withdrawal, but also allows the TPBARs to be handled in groups, rather than one at a time. **Figure A–12** illustrates the base plate as part of the hold-down assembly.

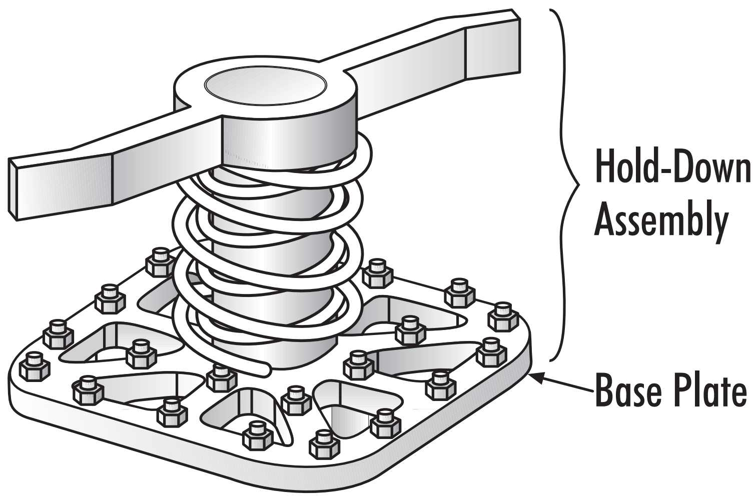

Figure A–12 TPBAR Hold-Down Assembly

A.3.3 Handling of Tritium-Producing Burnable Absorber Rods

The individual TPBARs would be mounted on the hold-down assembly through holes in the base plate and locked in place. The TPBAR assemblies would then be inserted into new fuel assemblies at the fuel manufacturer's site. The TPBARs would be transported to the reactor site and loaded into the reactor core as an integral part of the new fuel assembly. After irradiation in the core for approximately 18 months (one fuel cycle), the spent fuel, along with their TPBARs, would be removed from the core. In a normal refueling of a reactor core used for tritium production, some of the fuel assemblies would be re-inserted into the core for use during the second fuel cycle, while the rest of the fuel assemblies would go to the spent fuel pool. The TPBARs in fuel assemblies destined for the spent fuel pool would be left in their host fuel assemblies until after the refueling.

Some TPBARs could reside in fuel assemblies that would be re-inserted in the core and used during a second fuel cycle. Each of the fuel assemblies that are to be re-inserted in the core would be moved to the spent fuel pool and placed in a stand where the TPBAR assembly would be remotely removed. These fuel assemblies would then be returned to the reactor core. The removed TPBARs would be placed in other spent fuel assemblies in the spent fuel pool, where they would be stored under water until transported from the site.

After a short period of time following refueling, all of the TPBARs would be removed from the storage position in their host spent fuel assemblies and placed in a handling stand. In the handling stand, the individual TPBARs would be separated from the base plate and moved to the consolidation rack, where they would be inserted in the consolidation assemblies. The consolidation assemblies are essentially square cans with a 17 × 17 array of positions capable of accepting TPBARs. Once loaded, a handling fixture would be placed on the ends of the assemblies, and the assemblies would be handled with the same tools as fuel assemblies. The consolidation assemblies would then be placed in transportation cask positions designed for fuel assemblies and transported to the Department of Energy (DOE) Tritium Extraction Facility at the Savannah River Site in South Carolina.

A.4 IMPACT OF TRITIUM PRODUCTION ON THE FUEL CYCLE

The introduction of TPBARs into the fuel assemblies used in a CLWR would impact the fuel management strategy currently in use by the operator of the CLWR. The replacement of burnable poison rods with the TPBARs affects the core physics (the utilization of neutrons to produce power and tritium) and could alter the design of the core. Because the TPBARs have a large residual reactivity penalty, the tritium production core designs require higher enrichments and may require larger feed (fresh fuel) regions than the commercial core designs with a comparable power level and cycle length. These two fuel cycle characteristics were assumed to be unchanged with the introduction of TPBARs into the commercial core. Several core parameters were identified that could be impacted by the replacement of burnable poison rods with TPBARs. The most important among these are the power peaking factors. The distribution of power within the core is limited so that no single area produces significantly more than the average amount of power generated throughout the core. The differences between the average power and local power are quantified in several power peaking factors. By limiting the values of these peaking factors, the plant operator and the NRC ensure that the power plant operates within safety limits and would respond to accidents as described in the accident analysis required of all licensed nuclear power plants. With limitations on the number and distribution of TPBARs in the core used in this environmental impact statement (EIS), the power peaking factors in the commercial power production core and the tritium production core are very similar and the safety limits are not expected to be exceeded. Therefore, tritium production can be performed without the need to modify the CLWR core design, and only changes in the fuel enrichment would be required.

The maximum number of TPBARs that could be placed in the core (or irradiated) at each reactor unit without significantly disturbing the normal electricity-producing mode of reactor operation is approximately 3,400 (the exact number depends on the specific design of the reactor). This section evaluates the impact of tritium production on the fuel cycle by irradiating a range of 1,000 TPBARs to a maximum of 3,400 TPBARs at each reactor unit. The fuel cycle would be assumed to remain unchanged at 18 months. Irradiating a maximum number of TPBARs in each reactor core would require each nonfuel position (guide tube location) inside the core that is not reserved for the control element to be filled by a TPBAR, and the number of fresh fuel assemblies loaded into the core at each refueling to be increased. Irradiation of 1,000 TPBARs can be accomplished by placing the TPBARs in positions currently occupied by burnable poison rods. This action would not change the number of fresh fuel assemblies that are currently loaded into the core during refueling for commercial operation with no TPBARs.

Power Operation with Maximum Number of TPBARs

As stated earlier, irradiation of a maximum number of TPBARs requires their insertion in every possible guide tube location. For Watts Bar 1, this means that TPBARs would be located in the 24 guide tubes of 136 fuel assemblies (141 in Bellefonte 1 or Bellefonte 2 and 140 in Sequoyah 1 or Sequoyah 2) that do not have a control assembly (TVA 1991, TVA 1995, TVA 1996, TVA 1998). Commercial operation of Watts Bar 1 without tritium production consists of an 18-month fuel cycle and replacement of 80 spent fuel assemblies (72 for Bellefonte 1 or Bellefonte 2 and 80 for Sequoyah 1 or Sequoyah 2) at each refueling.

The main premise of using a CLWR to produce tritium is that the reactor power would remain unchanged. Since TPBARs use lithium (a strong neutron absorber) to produce tritium and the reactor power level is dependent on the number of neutrons available for fission, additional neutrons must be generated to maintain the reactor power level when the CLWR is used for tritium production. To meet the increased demand for neutrons, the enrichment of the reactor fuel would need to be increased. This would result in more uranium-235 in the reactor core. The maximum fuel enrichment for the fresh fuel is limited to 5 percent. Because of limitations on the distribution of power and the limits on the maximum enrichment of uranium fuel (5 percent), tritium production would require more fresh fuel to be loaded into the reactor at each refueling to maintain the same fuel cycle. For Watts Bar 1, these factors would result in the need to replace 136 of the 193 fuel assemblies (141 of 205 for Bellefonte 1 or Bellefonte 2 and 140 of 193 for Sequoyah 1 or Sequoyah 2) with fresh fuel every fuel cycle. The remaining 57 fuel assemblies (64 for Bellefonte 1 or Bellefonte 2 and 53 for Sequoyah 1 or Sequoyah 2) that have been burned once would be moved to the positions where the control element assemblies are located. Fresh fuel assemblies would contain the TPBARs and be positioned in the locations without a control element assembly.

Based on the above discussion and the consideration that each CLWR unit would operate to produce tritium for 40 years, Watts Bar 1 would generate 1,512 additional spent fuel assemblies (1,863 by Bellefonte 1 or Bellefonte 2 and 1,620 by Sequoyah 1 or Sequoyah 2); see also **Table A-1**.

Power Operation with 1,000 TPBARs

The operation of CLWRs with 1,000 TPBARs would not affect the number of fuel assemblies replaced during each refueling. As stated earlier, TPBARs are scattered in the core in place of burnable absorber rods. Production of tritium in a CLWR with less than 2,000 TPBARs is not expected to increase spent fuel generation per fuel cycle (WEC 1999). However, to maintain an 18-month fuel cycle similar to the maximum TPBAR loading, a higher fuel enrichment is required.

Table A–1 Summary of Increase in Spent Fuel Generation From 40 Years of Tritium Production with Maximum Number of TPBARs

Data Parameters	***Watts Bar 1***	***Sequoyah 1 or Sequoyah 2***	***Bellefonte 1 or Bellefonte 2***
Operating cycle (months)	18	18	18
Fresh fuel assemblies per cycle–no tritium production	80	80	72
Fresh fuel assemblies per cycle–maximum TPBARs	136	140	141
Increase in fresh fuel assemblies per cycle due to tritium production	56	60	69
Number of operating cycles in 40 years (rounded up)	27	27	27
Number of additional fuel assemblies for 40 years of tritium production	1,512	1,620	1,863

A.5 References

TVA (Tennessee Valley Authority), 1991, *Bellefonte Nuclear Plant Final Safety Analysis Report*, through Amendment 30, Chattanooga, Tennessee, December 20.

TVA (Tennessee Valley Authority), 1995, *Watts Bar Nuclear Plant Final Safety Analysis Report*, through Amendment 91, Chattanooga, Tennessee, October 24.

TVA (Tennessee Valley Authority), 1996, *Sequoyah Nuclear Plant Updated Final Safety Analysis Report*, through Amendment 12, Chattanooga, Tennessee, December 6.

TVA (Tennessee Valley Authority), 1998, data collected from TVA personnel by Science Applications International Corporation personnel, January—August.

WEC (Westinghouse Electric Company), 1999, letter from M. L. Travis to Dr. John E. Kelly, Sandia National Laboratory, Albuquerque, New Mexico, "Transmittal of Information to Support the CLWR Tritium Production Environmental Impact Statement," NDP-MLT-98-156 (Rev. 1), February.