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AP1000 The PWR Revisited

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Abstract. For nearly two decades, Westinghouse has pursued an improved pressurized water reactor (PWR) design. The result of this commitment is the AP1000, a simpler and more economical PWR. The design began to develop in the late 1980s in conjunction with the development of the "Advanced Light Water Reactor Utility Requirements Document (URD)." The URD, drafted under the direction of the Electric Power Research Institute (EPRI), came to embody the policy and design requirements of US power utilities for the next generation of nuclear power plants in the US. These requirements were also endorsed by the US Nuclear Regulatory Commission (NRC). In Europe the corresponding body of design requirements and expectations developed as the European Utility Requirements (EUR). The URD addresses evolutionary and passive light water reactors. The two classifications have different requirements. Expectations are much higher for passive designs. Indeed, more should be expected from designs that are not constrained to follow the existing models. For example, passive designs are expected to be able to achieve and maintain safe shutdown for 72 hours following the initiation of a design basis event without needing operator action. The corresponding expectation for an "evolutionary" plant is 30 minutes before the operator must take action to protect the core. As defined by the URD, a passive reactor is also "simpler, smaller and much improved..." Simplification is a major requirement of the URD and a major characteristic of the AP1000.

1. THE AP1000 OVERVIEW

AP1000 is designed around a conventional 2-loop, 2 steam generator primary system configuration that is improved in several details. AP1000 is rated at 3400 MW(t) core power and, depending on site conditions, nominally 1117 MW(e). The core contains 157 fuel assemblies, similar to Doel 4 and Tihange 3. AP1000 features passive emergency core cooling and containment cooling systems. This means that active systems required solely to mitigate design basis accident conditions have been replaced in AP1000 by simpler, passive systems relying on gravity, compressed gases, or natural circulation to drive them instead of pumps. AP1000 also does not require safety-grade sources of ac power. Class 1E batteries provide for electrical needs during the unlikely scenario requiring the activation of the passive emergency system.

Compared to a standard plant of similar power output, AP1000 has 35% fewer pumps, 80% less safety-class piping, and 50% fewer ASME safety class valves. There are no safety-grade pumps. This allows AP1000 to be a much more compact plant than earlier designs. With less equipment and piping to accommodate, most safety equipment is installed within the containment. Because of this, AP1000 has approximately 55% fewer piping penetrations in the containment than current generation plants. Seismic Category I building volume is about 45 % less than earlier designs of comparable power rating. Figure 1 depicts the compact AP1000 station. Figure 2 compares the essential nuclear island building footprints to a typical, currently operating PWR. Seismic Category I buildings are shown in bold outline.

Here is a comparison of AP1000 safety margins to those of a currently operating plant.

	Watts Bar	AP1000
Margin to DNBR, Loss of flow, %	14	16
SG tube rupture	Operator action required in 15 minutes	No operator action required
Small break LOCA Peak clad temperature, C	10 mm break Core uncovered PCT = 608C	20 mm break Core stays covered
Large break LOCA peak clad temperature, C	977	< 871

With a relatively large pressurizer, the AP1000 is more accommodating to transients and is, therefore, a more forgiving plant to operate.

The AP1000 is designed in accordance with the principles of ALARA to keep worker dose As Low As Reasonably Achievable. Features such as an integrated reactor vessel head package for quicker removal reduce the time required to do the job, and, therefore, reduce worker exposure. Attention to shielding, establishing distance from radiation sources, using low cobalt alloys, and using remote tooling or controls, are among the approaches that will minimize exposure throughout the plant. This is an area that has greatly benefited from operating plant experience.

Before delving into the further details of the AP1000 and how it is constructed, let us first review the regulatory status of this design.

Fig. 1. AP1000 Station

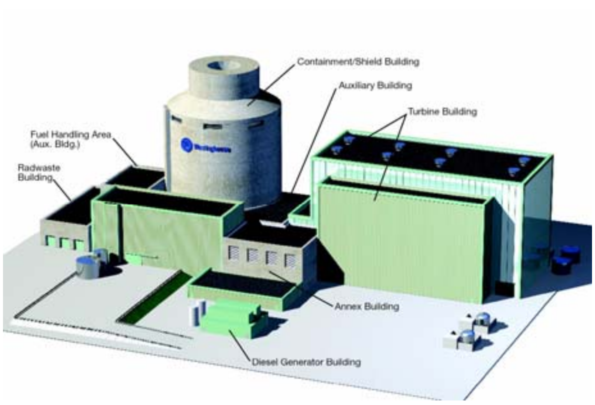
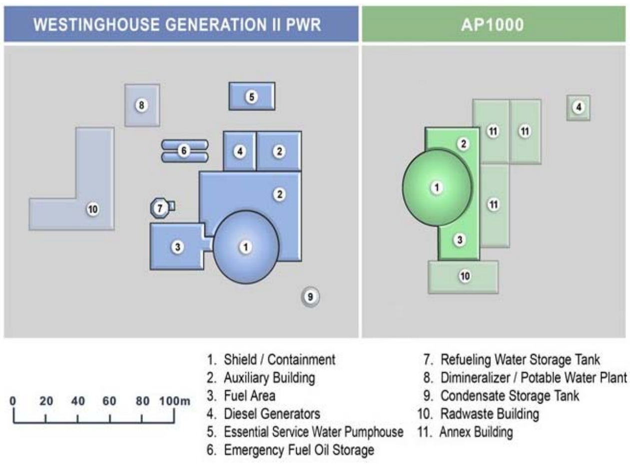


Fig. 2. Seismic Category I Building Comparisons



2. AP1000 LICENSING AND REGULATORY STATUS

Nuclear power plants currently operating in the US were licensed under Title 10 CFR Part 50. In 1989 the US Nuclear Regulatory Commission (NRC) established alternative licensing requirements under 10 CFR Part 52. Prior to 1989 and under Part 50, all aspects of licensing from the design of the nuclear steam supply system to site-related topics remained open until after the plant was constructed. This left all aspects of a plant license application unsettled – and at risk - until virtually the entire plant capital investment was made. The current regulations under Part 52 ensure that all significant licensing issues have been resolved early in the process and with a high degree of finality.

Under Part 52 regulations, a plant design can be submitted for NRC Design Certification. The applicant is the plant design organization and the certification is generic and independent of any particular plant site. NRC approved and certified the AP1000 design under 10 CFR Part 52 in December 2005. The certification is valid for 15 years. Westinghouse submitted the AP1000 application in March, 2002.

Similarly, individual plant sites can be generally approved for construction of a nuclear plant through the Early Site Permit process under 10 CFR Part 52. This approval covers all elements affecting site suitability except for the specific effects of a particular plant design. These permits are valid for 10 to 20 years and can be extended for an additional 10 to 20 years.

With a design approved and certified and with a site that has received a permit, it then remains to merge these in order to actually proceed to construct and operate a specific nuclear power plant design at a specific site. This marriage of the two is the combined Construction and Operating License (COL) application. This application is made to the NRC by the site owner. Once the COL is granted by NRC, construction at the site may proceed.

This leaves the final step in the licensing process which is a verification that the plant has been constructed and will operate in conformance with the previously issued COL. This is accomplished by the Inspection, Tests, And Acceptance Criteria (ITAAC). Specific requirements for ITAACs for a particular case are established along the way in conjunction with the Final Design Certification and the COL applications.

Figure 3 summarizes all of this and identifies the US utilities that have declared that they will pursue a COL application. With the design certified for AP1000, preparing applications for COLs based on the AP1000 design can proceed directly

3. LICENSING AND REGULATORY STATUS

- 10 CFR Part 52 (operating plants licensed under earlier 10 CFR Part 50)
- Resolve licensing issues early in the process and with high degree of finality

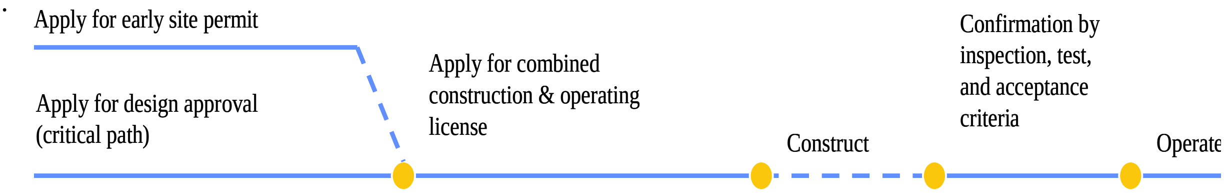


Fig. 3.

4. AP1000 PASSIVE SAFETY SYSTEMS

What is meant by passive safety systems, the major differentiating feature of the AP1000? Let us start with the emergency core cooling system. This system comes into play only during transients or accidents which cannot be handled by the first-line of defense: the non-safety grade systems. In the current Generation II plants, the emergency core cooling system consists of redundant trains of high pressure and low pressure safety injection systems driven by pumps. These pumps force water into the primary system to replace core coolant in the event of a loss of coolant accident. Such pump-driven systems are termed "active" systems. The pumps take suction from tanks of borated water, valves are opened, and water is sent to the reactor vessel to cool the fuel rods. To increase reliability, multiple redundant trains may be installed. The net result is a substantial amount of machinery standing by for a call to action that designers and operators work very hard to never need.

By contrast, the AP1000 passive core cooling system uses staged reservoirs of borated water that are designed to discharge into the reactor vessel at various threshold state points of the primary system. To begin the description, let us first see the configuration of the AP1000 reactor primary coolant system shown in Figure 4. Now we can attach the essentials of the passive emergency core cooling system, as illustrated in Figure 5. There are three sources of borated replacement coolant and three different means of motivating the injection in AP1000:

- Two core makeup tanks (CMT). Each CMT is directly connected to a RCS cold leg by an open "pressure balance" line. The balance line enters the CMT at the top of the tank, as shown in the figure. With outlet valves closed, the system is static. When actuated and check valves opened, water is forced out of these tanks and into the reactor vessel depending on and motivated by conditions in the cold leg via the always open balance line. Water from the RCS cold leg, which is hotter than water in the CMTs, will force the injection by its expansion into the CMT. If the cold leg is full of steam, steam will force the injection. CMTs are the first to actuate for smaller primary system breaks.
- Two accumulators (ACC). These spherical tanks are 85% full of borated water and pressurized to 700 psig with nitrogen. Check valves open when pressure in the reactor vessel drops below 700 allowing the water in the tanks to flow into the reactor vessel. Large break LOCAs, which cause rapid system de-pressurization, will result in the accumulators being the first to respond.
- The in containment refueling water storage tank (IRWST). Located above the RCS piping, the IRWST will discharge by gravity to the reactor vessel after the RCS has been de-pressurized by a break or by the automatic depressurization system, also shown in Figure 5. Flow is initiated by a depressurization signal which activates squib valves which open using an explosive charge. The squib valves are in series with check valves in the injection lines.

Fig. 4. Primary System

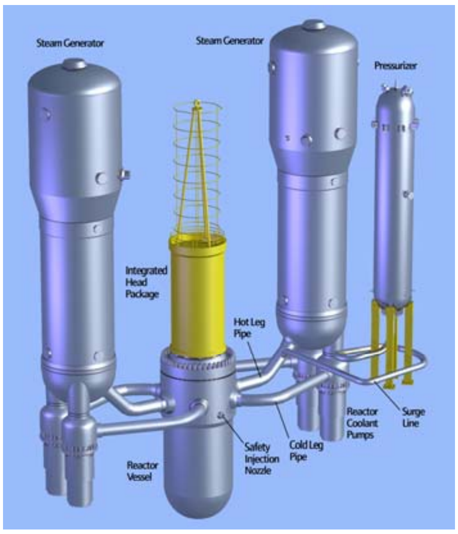
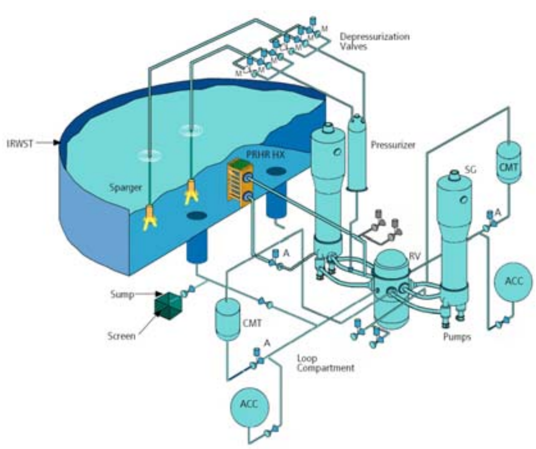


Fig. 5. AP1000 Passive Core Cooling



These injection sources are connected to two Direct Vessel Injection nozzles on the reactor vessel dedicated solely for this purpose. The passive emergency core cooling system components are all located within the containment vessel. Without pumps to run, there is no need for emergency ac electrical power to maintain operation during an event. Any electrical power needed for the few safety valves and actuators that require it comes from 1E dc power, backed up by 1E batteries.

The injection system is enabled by an automatic depressurization system which executes a staged depressurization of the primary system initiated from any actuation of the CMTs that reaches pre-set water levels in those tanks.

The IRWST is part of the passive decay heat removal system. A heat exchanger inside the IRWST has an inlet from the reactor coolant system (RCS) hot leg and an outlet into the RCS cold leg. In the event of loss of RCS heat removal from the steam generators, the IRWST will absorb heat from the heat exchanger while primary system coolant circulates through the exchanger by natural circulation. After several hours of operation, the IRWST water will begin to boil. Steam from IRWST will begin to condense on the containment walls. The condensate will then be directed by a safety-grade guttering system back to the IRWST to continue the cycle.

The steel containment vessel located inside the concrete shield building provides the heat transfer surface that removes heat from inside the containment and rejects it to the atmosphere. Heat is removed from the containment vessel by the continuous natural circulation of air within the shield building/containment vessel annulus. During a design basis accident, the air cooling is supplemented by evaporation of water. This cooling water drains by gravity from a tank located on top of the containment shield building. The water runs down over the steel containment vessel, thereby enhancing heat transfer. This passive containment cooling system design eliminates the safety-grade containment spray and fan coolers required for a conventional plant.

Key elements of this system were extensively tested and documented as part of the basis for receiving NRC‘s Final Design Certification. Figure 6 indicates the kind of simplification that results from AP1000’s passive system versus a standard PWR emergency system.

5. SEVERE ACCIDENT MITIGATION

The AP1000 is designed to retain melted core debris within the reactor vessel. To start with, the reactor vessel has no penetrations in the bottom head. In case of a severe accident, cooling water from the large IRWST can be used to flood the reactor cavity and cool the outside of the reactor vessel. The arrangement is shown in Figure 7. Specially designed reactor vessel insulation forms an annulus that allows cooling water to directly contact the vessel. Vents are provided for steam to escape the annulus. To complete the description, the vented steam will condense on the containment walls and be directed back to the cavity.

Fig. 6. Reduced Complexity

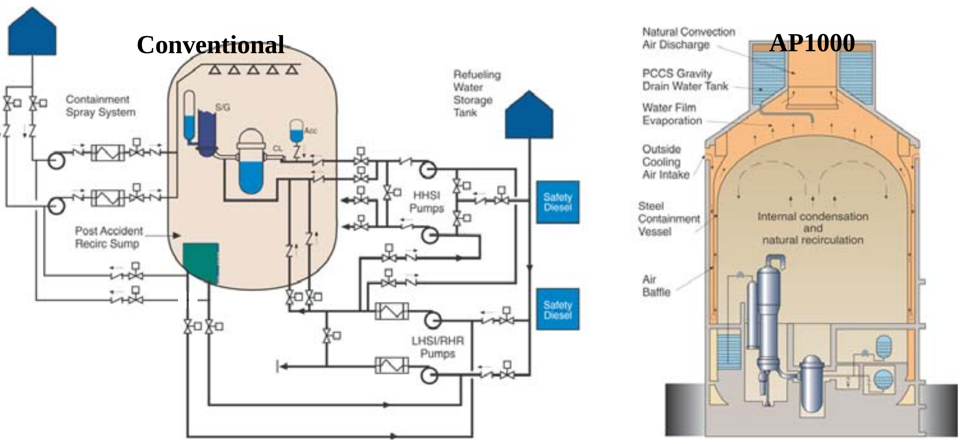
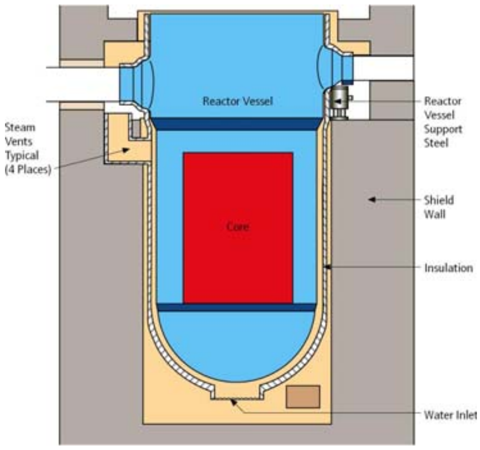


Fig. 7. Severe Accident Design



6. PROBABILISTIC RISK ASSESSMENT

One of the advancements that benefits the AP1000 is the further development of probabilistic risk assessment tools (PRA) and the application of these tools to the design process itself. The result for AP1000 has been a more effective combination of redundancy and diversity. This includes the defense-in-depth design that utilizes non-safety controls and systems as the first line of defense. If the first line systems are not capable of handling the event, the passive safety systems come into play. As revealed by the PRA, the risk of core damage and large radioactive release for AP1000 is extremely low. Here are the results for combined conditions of power, shutdown, and internal events, as well as fire and flood events:

- Core damage frequency, 5x10-7
- Large release frequency, 6x 10 -8.

For some perspective, here are some comparative results for core damage frequency:

US NRC requirement	1×10^{-4}
Current plants	5×10^{-5}
URD requirement	$<1 \times 10^{-5}$
AP1000	5×10^{-7}

The AP1000 PRA led to the following statement by the US Advisory Committee for Reactor Safeguards in their report on AP1000 certification:

“This PRA was well done and rigorous methods were used…The fact that the PRA was an integral part of the design process was significant to achieving this estimated low risk.”

7. AP1000 REACTOR COOLANT PUMPS

Among the improvements embodied in the AP1000 are the reactor coolant pumps. AP1000 employs four canned motor pumps, two in each loop, as can be seen in Figure 4. Although such pumps have been used for decades in naval nuclear power plants, commercial PWRs have not employed them recently because the capacities required for Generation II nuclear plants began to exceed the capacity range of canned pumps prevailing at that time. However, in the meantime, the capacity of canned motor pumps has increased. The advantages of the canned motor design over conventional reactor coolant pumps are:

- Elimination of the shaft seal and the system needed to maintain seal injection
- By eliminating this seal and seal injection, a potential leakage path of primary coolant and a source of small break LOCA are also eliminated
- Canned motor pumps require very little or no maintenance and thereby also help lower worker dose.

8. AP1000 INSTRUMENTATION AND CONTROL SYSTEMS

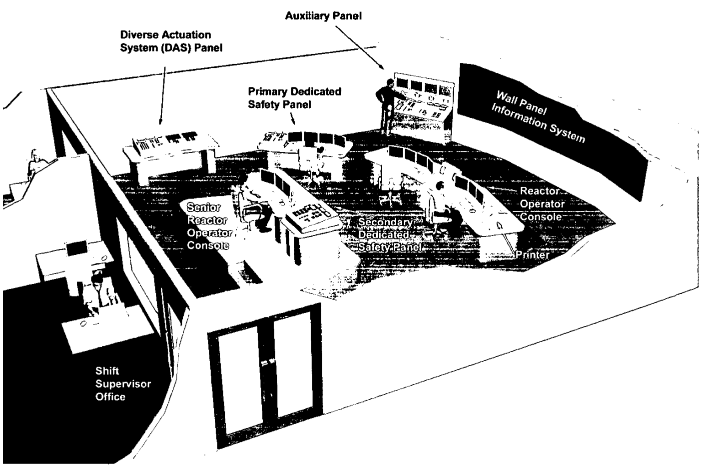
The Westinghouse AP1000 instrumentation and control (I&C) system is comprised of the following subsystems:

Operation and control centers (OCS)
Data display and processing (DDS)
Protection and safety monitoring (PMS)
Plant control (PLS)
Main turbine control and diagnostics (TOS)
Incore instrumentation (IIS)
Special monitoring (SMS)
Diverse actuation (DAS)
Radiation Monitoring (RMS)
Seismic Monitoring (SJS).

Following are highlights of some of these systems:

The OCS provides the human interface control facilities: the main control room, the technical support center, the remote shutdown workstation, the emergency operations facility, local control stations, and the associated workstations for each of these centers. The main control room, for example, is environmentally controlled and designed in conjunction with a comprehensive human factors engineering program conducted at Westinghouse. This program included an extensive operating experience review. Figure 8 shows a representative main control room layout for the AP1000.

Fig. 8. Control Room



The plant control system (PLS) provides for control rod motion and position monitoring and controls the transport of heat energy from the nuclear reactor to the main steam turbine by means of the following major control functions:

- Pressurizer pressure and level
- Steam generator water level
- Steam dump (turbine bypass)
- Rapid power reduction
- Various component controls (pumps, motors, valves, breakers, etc.)

The system provides for automatic and manual control.

The special monitoring system (SMS) is a non-safety-related system comprised of subsystems that interface with the I&C architecture to provide specialized diagnostic and long-term monitoring functions for detection of metallic debris in the reactor coolant system, core barrel vibration, and reactor coolant pump monitoring.

The diverse actuation system (DAS) provides I&C functions necessary to reduce the risk associated with a postulated common-mode failure in the PMS. The types of common-mode failures addressed by the DAS include software design errors, hardware design errors, and test and maintenance errors.

9. CONCLUSION

The AP1000 is a PWR design that offers power generating companies a clear and practical alternative for new generating capacity. It was designed to be competitive with fossil fuel plants and will be overwhelmingly so as actions are implemented to reduce greenhouse gas emissions. With decades of operating experience to draw on, AP1000 incorporates proven technologies in a new combination to consolidate the advantages of nuclear power units while reducing their cost and complexity. It is important to recognize that among all the advantages of AP1000, it is also a demonstrably safer plant and an advanced design that has already been certified by the US.