Design of the AP1000 Power Reactor

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Abstract

The distinguishing features of Westinghouse's AP1000 advanced passive pressurized water reactor are highlighted. In particular, the AP1000's passive safety features are described as well as their implications for simplifying the design, construction, and operation of this design compared to currently operating plants, and significantly increasing safety margins over current plants as well. The AP1000 design specifically incorporates the knowledge acquired from the substantial accumulation of power reactor operating experience and benefits from the application of the Probabilistic Risk Assessment in the design process itself. The AP1000 design has been certified by the US Nuclear Regulatory Commission under it's new rules for licensing new nuclear plants, 10 CFR Part 52, and is the subject of six combined Construction and Operating License applications now being developed. Currently the AP1000 design is being assessed against the EUR Rev C requirements for new nuclear power plants in Europe.

Background

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). More on that later.

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.

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, reduces 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.

Figure 1
AP1000 Station

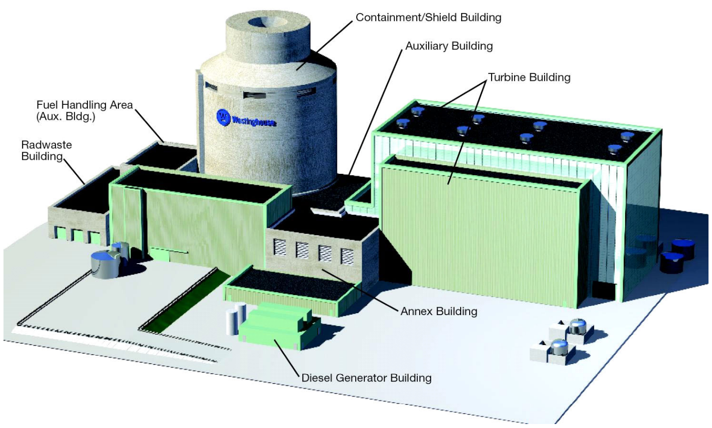
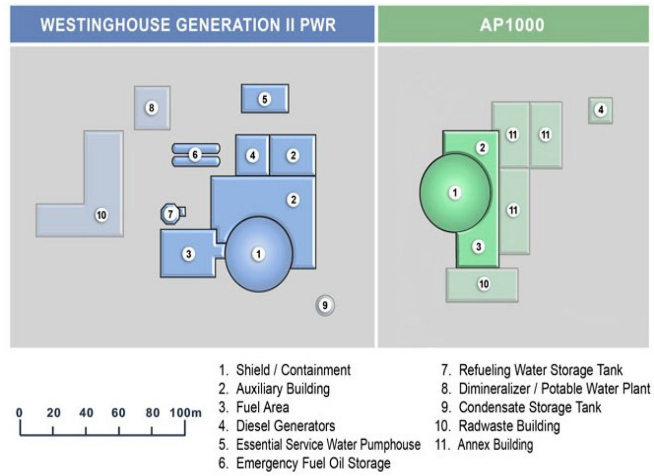


Figure 2
Seismic Category I
Building Comparisons



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. The first Early Site Permit has now been issued to Exelon for the Clinton site.

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

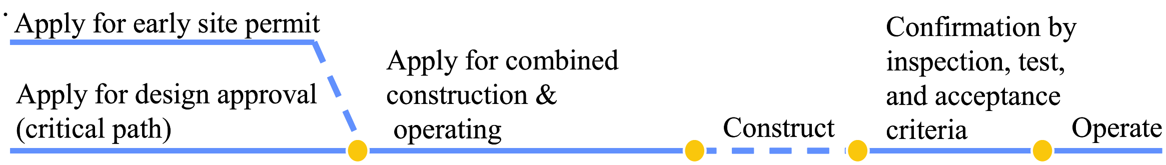
Operating License (COL) application. This application is made to the NRC by the site owner. Once the COL is granted by NRC, construction at the site may proceed.

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

Figure 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



- AP1000 is the only new generation plant design certified by NRC
- Declared to pursue COLs:

1. NUSTART (ESBWR)
2. NUSTART (AP1000)
3. Duke (AP1000)
4. Constellation (EPR)
5. Progress #1 (AP1000)
6. Entergy (ESBWR)
7. Progress #2 (AP1000)
8. Southern (AP1000)
9. Dominion (ESBWR)
10. SCANA (AP1000)

- COL applications in 2007–2008

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:

1) 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.
2) 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.
3) 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.

Figure 4
Primary System

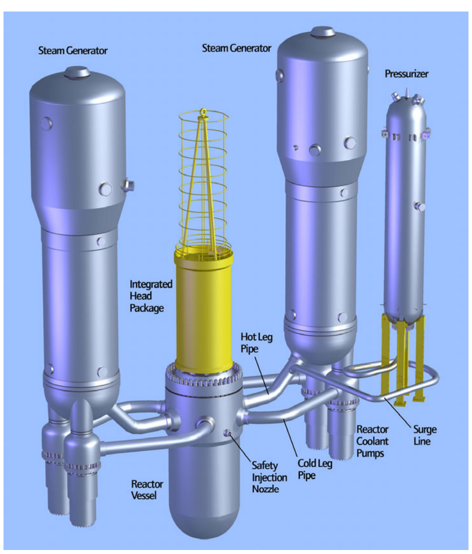
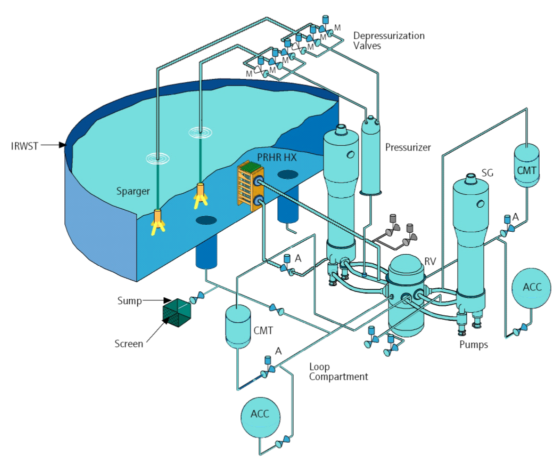


Figure 5
AP1000 Passive Core Cooling



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 IWRST 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.

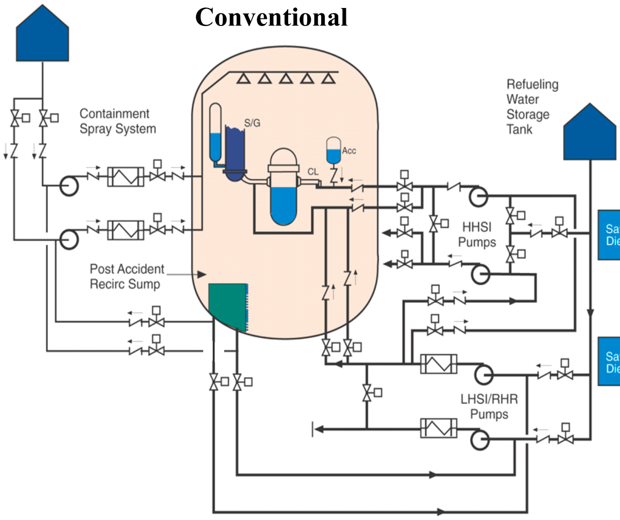
The steel containment vessel located inside the concrete shield building provides the heat transfer surface that removes heat from inside the containment and rejects it to the atmosphere. Heat is removed from the containment vessel by the continuous natural circulation of air within the shield building/containment 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.

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 RWST 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.

Figure 6
Reduced Complexity



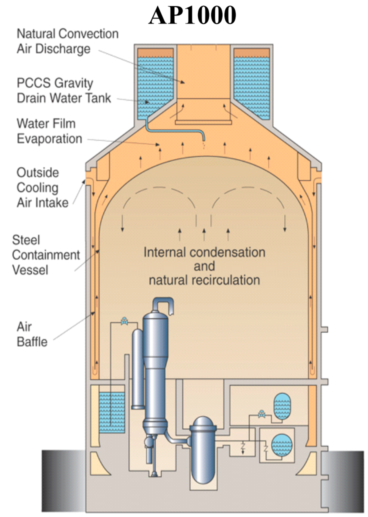
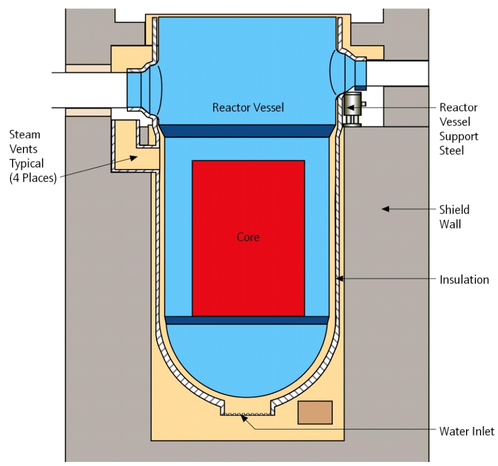


Figure 7
Severe Accident Design



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 combined conditions of power, shutdown, 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."

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 sizes 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.

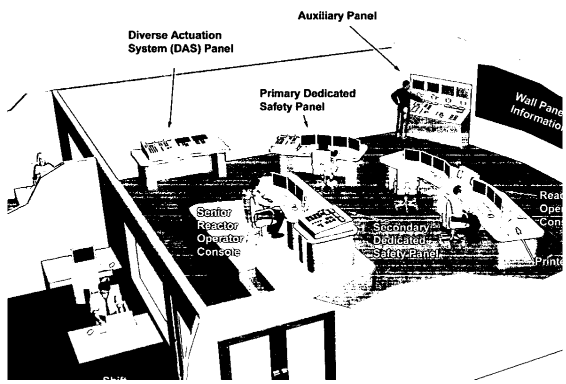
1. **AP1000 Instrumentation and Control Systems**
2.
3. The Westinghouse AP1000 instrumentation and control (I&C) system is comprised of the following subsystems:
4.

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).

5. Following are highlights of some of these systems:

6. 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.

Figure 8
Control Room



7. 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.

8.

9. 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.

10.

11. 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.

AP1000 Modular Construction

The AP1000 takes advantage of modular design and construction techniques. These offer many advantages over what has typically been defined as conventional or "stick built" construction methods. These advantages serve to reduce the construction critical path, and afford an opportunity to perform more complex tasks in a better-controlled factory environment. This approach allows work to begin sooner and in parallel with other activities: module fabrication in a factory does not need to wait for site work to begin. The advantages of using modular construction in building an AP1000 are the same advantages as found in its many other applications, such as ship building and constructing off-shore oil rigs.

AP1000 modules are classified as structural, "leave-in-place" formwork, equipment, piping, and structural support steel. In all, there are approximately 357 modules. Larger structural modules are comprised of sub-modules which can be assembled to different degrees of completion depending upon the capability of the available transportation (barge, rail, or truck) to the particular site. Structural modules find applications as floors and walls inside the containment, forming the primary shield wall around the reactor vessel, the secondary shield walls around the steam generators and pressurizer, the large refueling water storage tank, and the refueling cavity, for example. These modules are generally fabricated from steel faceplates connected by steel trusses. They are anchored to the reinforced concrete basemat and, once erected, are typically filled with concrete to complete the structure. Figure 9 shows the details of a typical wall module assembly. Figure 10 shows a large, complete module enclosing the primary system. A large module such as this would be assembled from sub-modules shipped to the site. It can then be lifted into place by heavy-lift crane which allow "open top" construction. That is, modules and large equipment can be deposited inside the open topped containment structure by a high capacity crane. This capability in itself will result in time and cost savings.

Figure 9
Truss Wall Detail

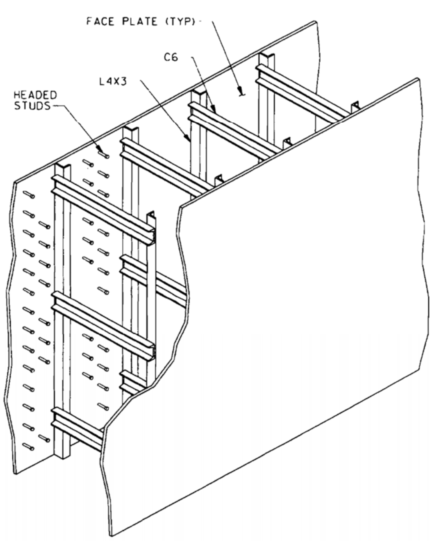
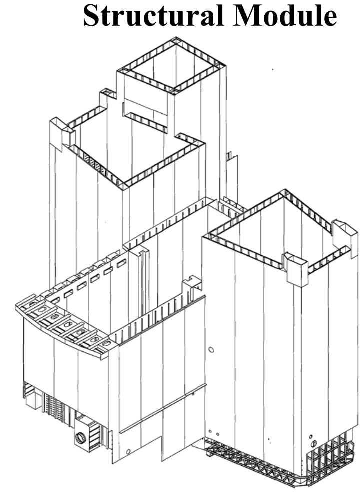
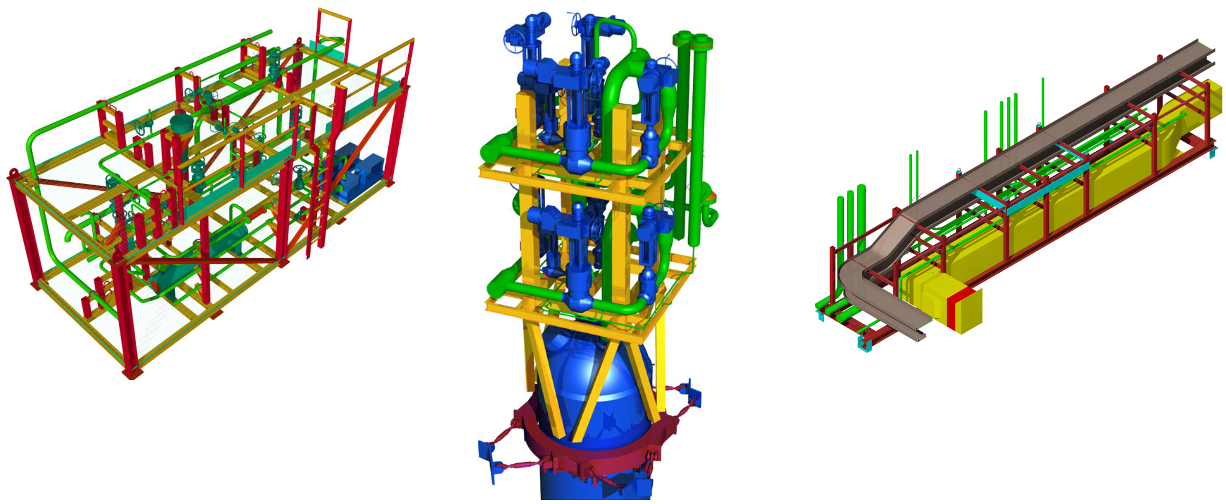


Figure 10
Structural Module



Equipment modules may consist of pumps, valves, piping and instruments with a self-supporting structural steel frame which can be pre-fabricated, tested, and installed as a unit. Some examples are seen in Figure 11.

Figure 11
Equipment Modules



AP1000 Schedule for Construction

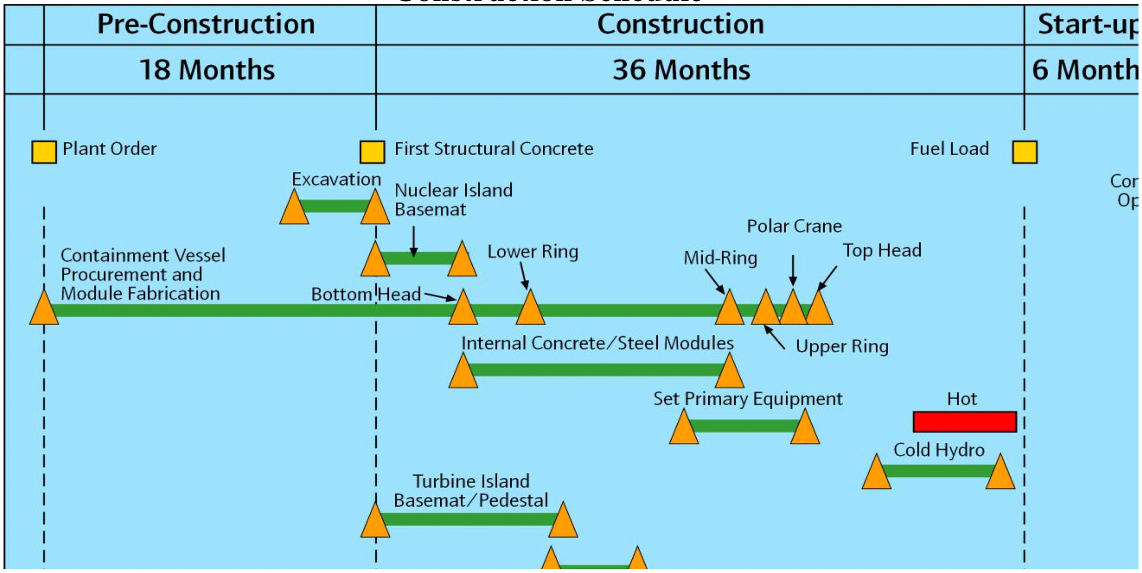
The schedule for AP1000 construction has been developed in cooperation with world class nuclear architect engineers and constructors. The AP1000 construction schedule uses Primavera software. The AP1000 is also completely modeled in three dimensions using Intergraph software. This 3D modeling technique includes establishing a data base containing all elements of the plant. Finally, the schedule has been linked to the 3D plant model to generate a construction model complete with the dimension of time. This linkage allows one to review construction progress in a virtual way by generating full 3D displays of the status of the plant at any time during the construction period. This allows for detailed review of construction, erection, and test activities as well as their interactions.

The AP1000 standard construction schedule is a Level 3, detailed schedule that is complete and ready to be applied to a specific case. In this AP1000 schedule, there are fewer than five activities and milestones (such as authorization to proceed) that are constrained by a calendar date. All other dates are derived using the logic ties contained within the model. The schedule has over 6,000 activities and milestones. The AP1000 standard construction schedule indeed has fewer activities than schedules for predecessor plants because there is less equipment and the plant is smaller with requiring less concrete and steel to erect.

A higher level representation of a standard AP1000 schedule is seen in Figure 12

The time between authorization to proceed (ATP) and first concrete will include the time to order and fabricate modules and large, primary system equipment. Fabrication of steam generators is on the critical path. Meanwhile, site and foundation work are also underway.

Figure 12
Construction Schedule



In the typical scenario represented here, the critical path in the schedule is the delivery and setting of steam generators followed by completing the reactor coolant system, final construction testing, cold and hot system testing, and startup testing prior to fuel loading.
The validity of the construction schedule model and analysis is crucial to the success of any nuclear power plant project. Certainly, site specific conditions will need to be folded in to construct a schedule for a specific project. Nevertheless, today, we can use computer tools that are much more sophisticated than anything that was heretofore available for such work.

Factors Affecting Costs

In the final analysis, the nuclear option must be cost competitive with the alternative means of generating electricity. The value of the installed nuclear plants has been demonstrated by their low operating costs. Figures 13a and 13b show the operating cost data (operation, maintenance, fuel) for coal and nuclear plants in the US, as compiled by the NRC. The operating costs are comparable.
This comparison does not take into account any future expenses on coal for reducing greenhouse gas emissions or tax on emissions. AP1000 will improve on the current state and solidify that advantage. Maintenance and testing requirements for the AP1000 will generally be substantially reduced compared to a current day plant of similar output because the AP1000 has substantially fewer valves, pumps, cable, and piping.

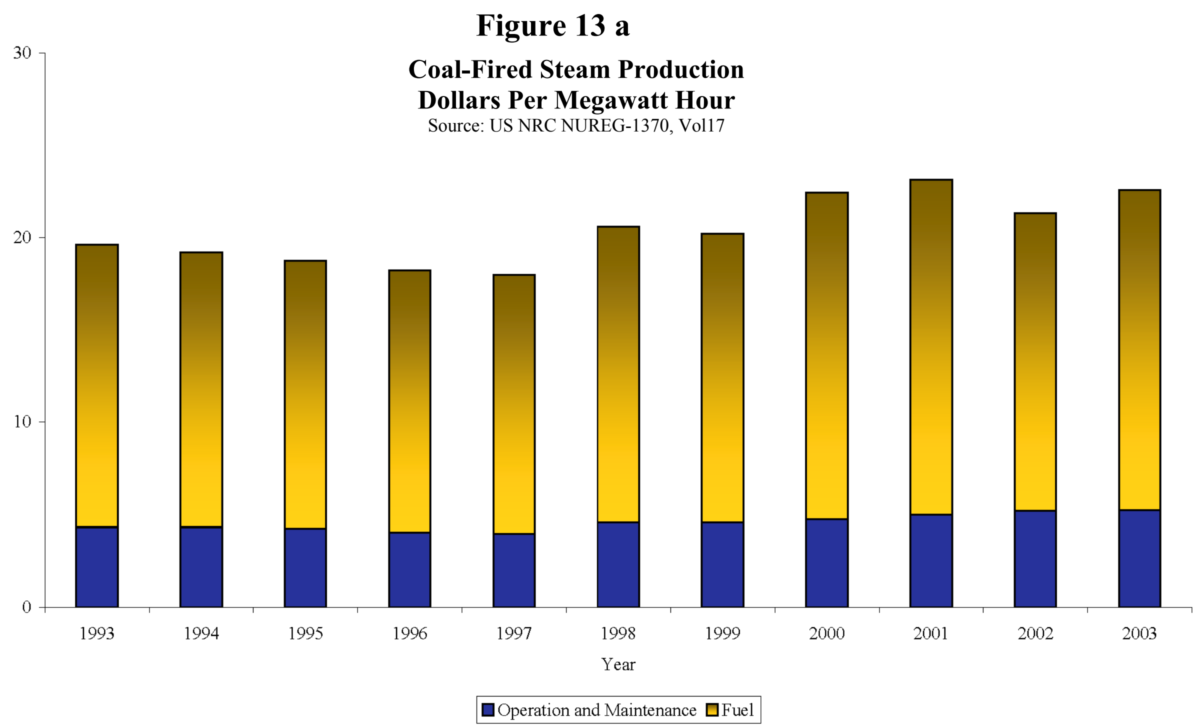


Figure 13 a
Coal-Fired Steam Production
Dollars Per Megawatt Hour
Source: US NRC NUREG-1370, Vol17
30
20
10
0
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
Year
Operation and Maintenance
Fuel

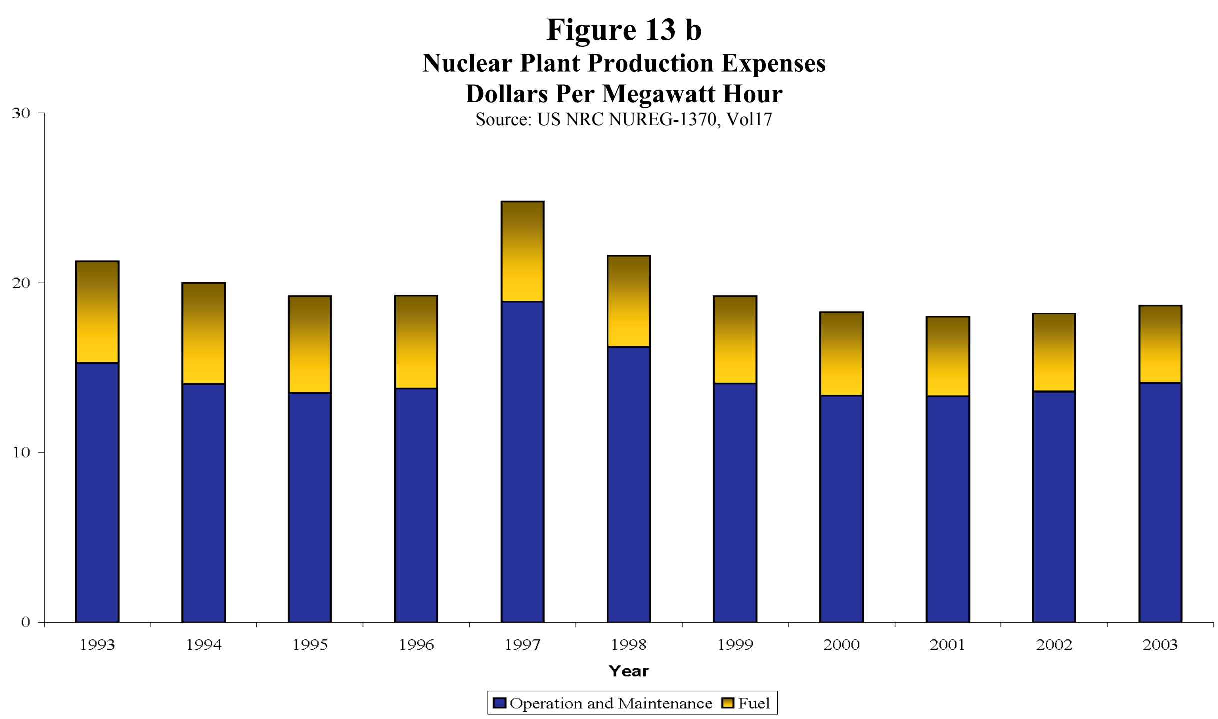


Figure 13 b
Nuclear Plant Production Expenses
Dollars Per Megawatt Hour
Source: US NRC NUREG-1370, Vol17
30
20
10
0
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
Year
Operation and Maintenance
Fuel

However, it is also well established that the most important factor in the cost of electricity generated by a nuclear power plant is its initial capital cost. With the AP1000, Westinghouse has directly attacked this cost component – by design. The design objective for AP1000 is to be cost competitive with other forms of power generation. For an indication let us look at the cost to construct a modern coal plant in Table 1. We think this objective is entirely feasible. Again, we have not taken into account any future penalties on coal plant costs derived from action to mitigate greenhouse gas emissions.

Table 1
Central Station Coal Plant Construction Costs in the US

Plant Type	Size (Mwe)	Construction Cost ($/kwe)	References
Pulverized coal, sub-critical	500	1370	1
Pulverized coal, super-critical	500	1437	1
Pulverized coal, super critical, PRB, Weston 4	515	1461	3
Fluidized bed coal	300	1505	1
IGCC coal	550	1647	1
IGCC PRB Coal	550	1845	1
Scrubbed new coal	600	1213	2
IGCC	550	1402	2
IGCC with carbon sequestration	380	2006	2

References
1. Michigan Capacity Need Forum: Staff Report to the Michigan Public Service Commission, Jan 3, 2006
2. Energy Information Administration, US DOE
3. Weston 4, to operate in 2008, Wisconsin Public Service Corporation

Notes:
IGCC, Integrated Coal-Gasification Combined Cycle, an emerging technology
PRB, Powder River Basin Coal, low sulfur content

To address **plant service life**, the AP1000 reactor vessel has been designed for a service life of 60 years. This effectively establishes the service life of the unit. The two AP1000 steam generators use Alloy 690 tubes. Applying Westinghouse's substantial experience gained with steam generator operating performance and the design of replacement generators, Alloy 690 is the optimum long life material to use in this application.

AP1000 Compliance with European Utility Requirements (EUR)

In 2004-2005 the EUR organization with the help of the European Passive Plant Program (EPP) Team (which includes EdF, SwissNuclear, Westinghouse, and Ansaldo) performed a thorough compliance review of the AP1000 PWR design against the EUR.

Compliance with the EUR has been a key design objective for the various plants studied and developed under the EPP Program. Assessments have been made, throughout the design process, to define the impact on the Westinghouse passive plant designs in meeting the EUR requirements. In some areas, EUR requirements have driven specific AP1000 design features (e.g., operation with low boron concentration). In other areas specific studies have been performed to evaluate AP1000 compliance with European requirements. Examples include:

- a liquid radwaste system that incorporates boron recycle,
- heat removal systems designs (e.g., for residual heat, component cooling, service water) that can accommodate the EUR rapid cooldown requirements,
- assessment of the design to comply with the EUR dose targets, which allow evaluation on the basis of realistic assumptions.
- the capability of the plant to mitigate European specific design basis accidents (e.g., fast boron dilution, multiple steam generator tube ruptures).

Therefore, as expected, a high level of compliance of the AP1000 design with the EUR has been shown. However, there are a few areas where further work will be needed to establish AP1000's compliance. In some cases this may involve using different ground rules for an analysis already on hand, such as using realistic instead of worst case assumptions, as was found for calculating expected annual staff dose. In other cases, such as the airplane crash, there is no corresponding requirement in the US. (US NRC and EPRI have, however, concluded that the US plant containment designs are indeed resistant to aircraft crash.)

The EPP Phase 2E program, to be initiated in mid-2006, is intended to bring the AP1000 design into optimum compliance with the EUR. As a result, it is expected that the AP1000 plant design will either be shown to be adequate to meet the EUR or design changes will be identified to bring the AP1000 into compliance.

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 NRC.