Fig. 1. General plant layout of the EPR (All figures: AREVA)

EPR development—An evolutionary design process

BY ROBERT C. TWILLEY, JR.

The construction of a new plant in Finland represents a major milestone in the EPR's development and is a positive trend for nuclear power around the world.

Developing a next-generation nuclear power plant design to meet the demanding efficiency, safety, and environmental goals of electric utilities required a collaborative effort spanning more than 10 years. Beginning in 1992, the company then known as Framatome (now Framatome ANP, an AREVA and Siemens company that is now doing business under the AREVA brand) began working closely with Siemens, Electricité de France (EdF), and major German utilities to develop the European Pressurized water Reactor (EPR) (see Fig. 1).

EPR developers chose an evolutionary path with an emphasis on active safety features in keeping with the fleet of currently operating reactors. There were clear advantages to basing the new design on lessons learned from the operating experience of some 96 nuclear power plants built by AREVA and Siemens.

The net result of this design approach is a plant that will be economically competitive while achieving levels of safety much improved over the fleet of currently operating reactors, as measured by probabilistic risk assessment (PRA) results.

Notable EPR design features

The EPR has several significant design features:

- Elimination of the need for a high-pressure injection system (HPIS) and elimination of the potential release of radiation due to steam generator tube rupture.
- Aircraft crash resistance.
- Four trains of active safety equipment to maximize reliability and maintainability.
- State-of-the-art digital control systems and control room design.
- In-containment borated water storage tank.
- Features to cope with beyond-design-basis accidents.

Elimination of the need for a high-pressure injection system and elimination of the potential release of radiation due to steam generator tube rupture—One of the most significant design features of the EPR is its response to certain transients wherein the primary-side pressure is reduced to a value less than the steam safety valve setpoints. This design feature eliminates the need for an HPIS and prevents the introduction of reactor coolant into the steam generator—by keeping primary coolant out of the secondary side of the steam generator, a sub-

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sequent steam release from the main steam safety valves would not have the radioactivity present that would be expected following a steam generator tube rupture in the current fleet of operating PWRs.

Aircraft crash resistance—The reactor building, control room, spent fuel building, and two of the four safeguard buildings are protected by an outer shell made of reinforced concrete robust enough to withstand the high-speed impact of a military aircraft. The other two safeguard buildings are located at opposite sides of the reactor building so that only one would be affected by an aircraft crash. Similarly, the diesel generators for emergency electrical supply are located in two different buildings with sufficient separation.

Four trains of active safety equipment to maximize reliability and maintainability—The use of four trains of active safety equipment accomplishes multiple objectives: (a) eliminating the need for complex cross-ties between trains, which are common in the current fleet of plants; (b) allowing a single train to be removed from service for maintenance during power operation; and (c) enhancing the plant's economic performance because—as a result of (b)—higher plant availability can be expected.

State-of-the-art digital control systems and control room design—Instrumentation and control (I&C) architecture has been developed to satisfy diversity and reliability requirements. The unit supervision and control level consists of work stations and panels in the Main Control Room, Remote Shutdown Station, and Technical Support Center. The man-machine interface includes the Process Information and Control System and the Safety Information and Control System. These two systems interface with other automated systems, which consist of the following elements:

- Protection system (PS).
- Safety automation system (SAS).
- Process automation system (PAS).
- Priority and actuator control system (PAC).
- Reactor control, surveillance, and limitation system (RCSL).

The process interface comprises the sensors, the actuators, and the switchgears.

Depending on the safety requirements, either the proven safety-oriented TELEPERM™-XS technology or the standard TELEPERM-XP technology is used. The TELEPERM technologies have been successfully implemented in operating unit upgrades in Germany, elsewhere in Europe, and in the United States, as well as in the new Tianwan project in China.

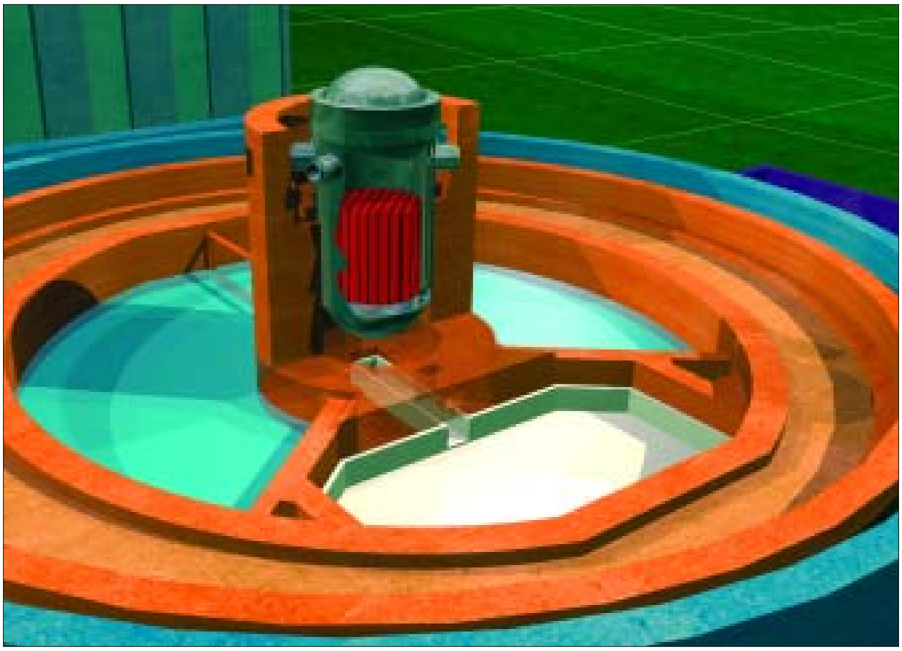

Fig. 2. Even in the highly unlikely event of core melt, and breaching of the steel reactor vessel, corium would be contained in a dedicated, cooled compartment.

In-containment borated water storage tank—In the current operating fleet, one of the major sources of emergency cooling water is the borated water storage tank (BWST), which is external to containment. For design-basis loss-of-coolant accidents (LOCAs), once the BWST has been emptied, the suction of the emergency injection pumps is switched over to the emergency core cooling system (ECCS) sump inside containment. This switchover has been eliminated in the EPR design by locating the equivalent storage tank inside containment. Compared to the current operating fleet, the elimination of this switchover contributes significant additional reliability to the performance of the emergency injection systems.

Features to cope with beyond-design-basis accidents—The EPR design includes highly developed design features for dealing with beyond-design-basis (severe) accidents. Features provided include measures to:

- Preclude hydrogen detonation.
- Control and cool molten corium should it breach the reactor vessel.
- Prevent the potential for high-pressure melt ejection.
- Collect and control any leakage from the primary containment.

Prevention of explosions that could result from the production of hydrogen is provided by catalytic recombiners. In addition, the pressure increases that could result from the combustion of hydrogen are taken into account in the containment structure design.

The design includes features for corium spreading and cooling. Should molten corium breach the reactor vessel, it is channeled to a dedicated chamber adjacent to the reactor pit (see Fig. 2). Beneath this chamber, a cooling structure provides for the removal of residual heat and the cooling and quick solidification of the corium. This feature is designed to prevent the erosion and failure of the structural

MAIN DESIGN AND OPERATING DATA FOR THE EPR

Rated thermal power	4324 MW
Rated net electrical power	1600 MW
Reactor coolant system	
—Number of loops	4
—Operating pressure	155 bar
—Total flow/loop	28 000 m^3/h
Main steam pressure	78 bar
Core	
—Number of fuel assemblies	241
—Number of RCCAs (rod cluster control assemblies)	89
—Fuel assembly array	17 × 17
—Active height	420 cm
—Top mounted in-core instrumentation	

concrete forming the base of the containment structure.

An entirely passive system provides initial cooling of the hot material by feeding the cooling structure with water from the in-containment refueling water storage tank (IRWST). The IRWST is located adjacent to the corium spreading chamber and is positioned such that cooling water can reach the chamber by gravity without the aid of pumps. In a second cooling phase about 12 hours later, the containment heat removal system would be started, providing additional cooling to the spreading area.

High-pressure core melt situations can endanger the integrity of the containment structure. In existing nuclear power plants, the high reliability of depressurization and residual heat removal systems make this potential risk a very low probability. The EPR, however, provides an additional line of defense through a train of motor-driven valves controlled by reactor operators that can significantly reduce the potential failure of the other lines of defense.

The design and general arrangement of the plant buildings makes collecting potential leaks through the penetrations and filtering them before their release possible. This design feature helps the EPR meet the strict radioactive release objective imposed on next-generation reactors.

EPR design philosophy

The EPR design complies with the set of European Utility Requirements (EUR) developed during the same period as the EPR design.

The defense-in-depth principle

Defense-in-depth is a basic principle underlying the EPR design philosophy. The EPR design follows recommendations by the International Atomic Energy Agency's International Nuclear Safety Advisory Group. There are four levels of defense that have been addressed by the plant design.

The first level of defense-in-depth involves preventive measures to reduce the frequency of abnormal operating conditions.

The second level integrates all of the control systems that can intervene to limit the impact of transients that may result from the failure of the first level of defense.

The third level includes safeguard systems designed to control the consequences of accident situations. A systematic analysis of multiple failures in redundant systems was conducted on the EPR to show that even in such situations, core melt is avoided.

The fourth level of defense-in-depth consists of features that would prevent failure of the containment structure, even in the highly improbable case of a core-melt event.

Systems architecture

The systems architecture is the result of an exchange of information on the design and operating experience of EPR designers and the participating French and German electric utilities. Probabilistic evaluations at the beginning of the EPR development process were used to help define the following guiding design principles.

■ *Simplifying system design*—The most important plant functions affecting safety are ensured by diversified systems. Combinations of functions that would increase the complexity of systems operation have been avoided. Plant personnel responsible for operation and maintenance will therefore have a better understanding of EPR unit status at all times, even in abnormal plant conditions.

■ *Physical separation*—Rigorous attention to the principle of separation has resulted in a design with a reduced probability of failure due to internal hazards such as fire or flooding.

■ *Functional diversity*—In addition to redundancy, the risk of common mode failures that could affect redundant systems has been reduced by providing functional diversity.

■ *Redundancy*—Four-train redundancy is used for the main safeguard systems (safety injection and emergency steam-generator feedwater supply) and the associated support systems (electrical power supplies and cooling systems).

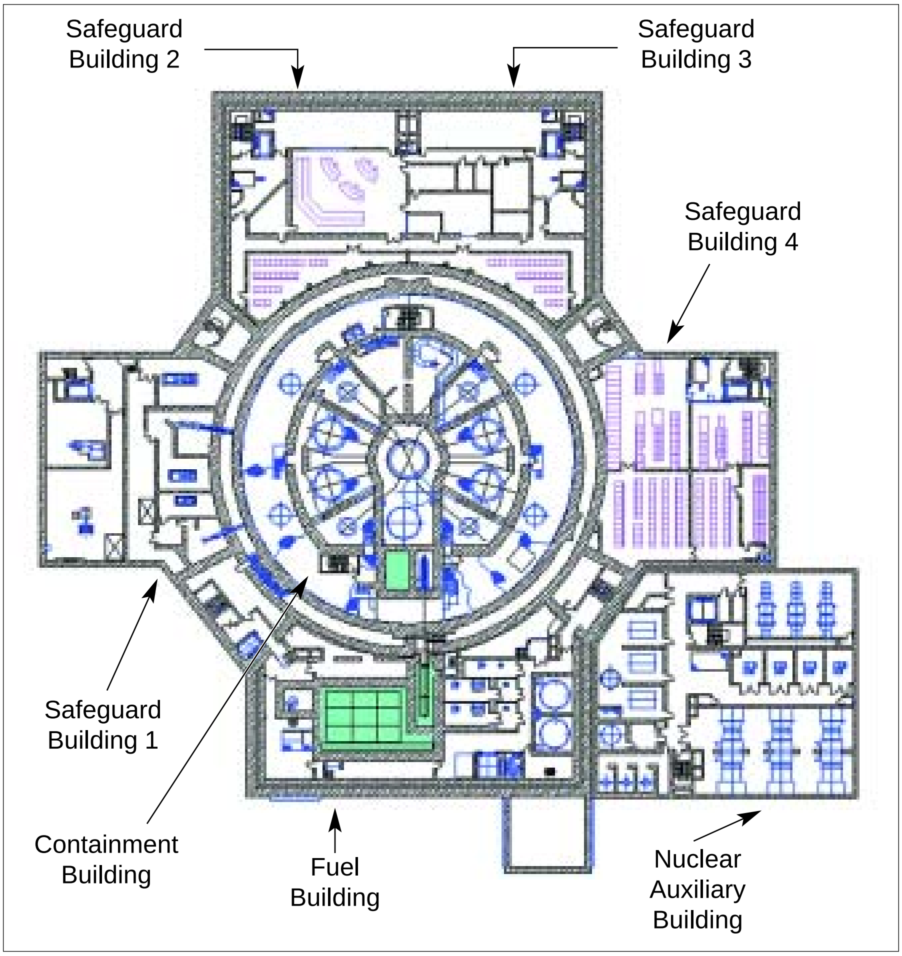

Fig. 3. The organization of buildings at an EPR site is designed to ensure strict physical separation.

Layout and building technology

The reactor building is located in the center of the plant layout (see Fig. 3). The containment structure is surrounded by safeguards and fuel buildings.

The inner containment consists of a prestressed concrete cylindrical wall with an elliptical head and a reinforced concrete base forming the bottom of the structure. A metallic liner fitted on the inner surface ensures leak-tight containment. The outer containment is formed by a reinforced cylindrical wall that serves as protection against external hazards.

Systems for isolation, retention, and leakage control are provided to meet the special confinement requirements of containment. In the event of leakage through the inner containment wall, the leak is collected, filtered, and released via the annulus air extraction system.

Robust, reinforced concrete walls surrounding, or "bunkering," safeguard buildings 2 and 3, the reactor building, and the fuel building provide protection against an aircraft crash. The Main Control Room and the Remote Shutdown Station are located in the protected safeguard buildings. Safeguard buildings 1 and 4 are not bunkered but are geographically separated so that in the event of an accident, only one building will be affected while the other remains operable.

The pool for spent fuel assemblies is located outside containment to permit spent fuel cask loading outside of containment. The fuel assemblies are transferred into and out of containment via a transfer tube.

EPR design benefits

Higher efficiency ratings

The EPR has been designed to operate more cost-effectively, compared to reactors of similar design and technology, and to use fuel as efficiently as possible. The nuclear steam supply system design is compatible with a high-discharge burnup (up to 65 GWd per metric ton). Intrinsically, high-discharge burnup fuel reduces the volume of long-lived radioactive waste per kilowatt-hour of electricity produced.

Secondary system pressure affects the overall efficiency of the thermodynamic cycle, and at just over 1100 psig, this is the highest operating pressure for a plant of this type. Using state-of-the-art steam turbines, a net efficiency of about 37 percent can be achieved, which is the highest known value for a light-water reactor.

Shorter outages

Reducing scheduled outage duration was, from the very beginning of this project, one of the key objectives to improve overall unit availability. The general layout of the equipment has been planned to facilitate maintenance operations. Systems design allows the performance of certain maintenance operations while the EPR unit is in operation, thus reducing the amount of servicing that would otherwise need to be performed during outages.

A standard refueling outage of less than 16 days is possible for performing all of the necessary operations: reactor cool-down, fuel unloading, inspection, maintenance, refueling, and then bringing the reactor back to normal operating temperature.

Increased unit availability

The shorter scheduled outages and a reduced number of unscheduled outages produce a projected availability of 92 percent over the EPR unit's service life. The latest advances in I&C systems have been incorporated in the design to provide much improved surveillance and anomaly detection to give operators more time to take actions to prevent the untimely actuation of the reactor shutdown system.

Extended service life

Although equipment has been designed to ensure a long service life, all nonreplaceable equipment, such as the reactor vessel or civil works structures, have been designed for a 60-year service life to maximize the plant's economic performance. Ease of replacement, should that become necessary, is a key design feature as well.

Optimized plant layout

The general layout clearly separates the different redundancies. In addition, personnel radiation exposure has been reduced by separating the limited-access areas, in which radioactive equipment is located, and those areas containing only nonradioactive equipment. Larger-sized work areas facilitate more efficient maintenance operations.

From concept to reality

Nearly 2 million hours of design and development were devoted to the EPR design project. This effort was rewarded when Finnish electric utility Teollisuuden Voima Oy (TVO) signed a contract on December 18, 2003, with the AREVA and Siemens consortium to construct an EPR (*NN*, Jan. 2004, p. 9).

Commercial operation of TVO's EPR is targeted for May 2009. At 1600 MWe (net), the newest nuclear power plant will also be the world's largest.

The general project schedule is summarized as follows:

- The preliminary safety analysis report (PSAR) was submitted to Finnish safety authorities in early January 2004.
- PSAR review in support of the construction license will take place during 2004. Ex-

cavation work will take place on site over the same period.

■ Civil works will start at the beginning of 2005.

■ Mechanical and electrical installation work will begin in mid-2006.

■ Final Safety Analysis Report issuance and commissioning will start in mid-2007.

■ The operating license is expected in mid-2008.

■ Commercial operation is to start in mid-2009.

To meet this challenging time schedule, AREVA decided to proceed, under its own responsibility, with the procurement of heavy forgings necessary for manufacturing the reactor pressure vessel and steam generators. The first manufacturing steps took place before the signing of the contract (see Fig. 4).

Many engineering activities are concentrated at the beginning of the project, since procurement of the main components must be done quickly. In addition to the PSAR review process now under way, all these tasks have necessitated a very quick start of the project.

Fig. 4. The nozzle shell flange of the EPR's reactor pressure vessel

EPR status in France

In early 2003, it was acknowledged by independent reviewers—such as the French Parliamentary Office for Scientific and Technological Choices—that it is highly desirable to evaluate the operation of a demonstration unit before launching the EPR series on a broad scale (*NN*, Dec. 2003, p. 17).

The decision to build a demonstration unit is directly linked with the energy policy adopted by French authorities. To prepare for the decision-making process, a public debate on France's energy policy was organized in 2003. After reviewing the various opinions, the Minister of Industry declared publicly and clearly that the nuclear option must be kept open, and an EPR unit should be built in France as soon as possible. A parliamentary debate is scheduled in 2004.

Global outlook

The construction of a new plant in Finland represents a major milestone in the EPR's development and is a positive trend for nuclear power around the world. At the beginning of the EPR development, one of the major goals was to work within a framework of international cooperation to ensure wide acceptability of the design.

The next milestone will be the decision to build a demonstration unit in France to prepare for the replacement of the EdF fleet. Decisions regarding the EdF fleet will have to be made by the middle of the next decade.

In other European Union countries, many nuclear power plants will reach the end of their expected operating lives at about the same time. It is therefore essential to be prepared with proven plant designs to supply the electricity needed to meet future demands, while at the same time satisfying the commitments to reduce the production of greenhouse gases.

The outlook for additional nuclear capacity in the United States is also more positive. Energy policy favorable to nuclear power development is under consideration by Congress, and three utilities have applied to the Nuclear Regulatory Commission for early site permits. AREVA's boiling water reactor design, the SWR-1000 (*NN*, Sept. 2002, p. 36), is currently in the NRC pre-application process, and the EPR design could be submitted, although no specific plan has been announced at this time.

Successful execution of the Olkiluoto-3 project (see Fig. 5) could become a useful model for gaining public confidence in the latest nuclear power technology. If public approval of the nuclear energy option continues to grow, the EPR in years to come could prove to be a strong contender in the global energy market. **NN**

Fig. 5. Artist's conception of the first EPR that will be built, Olkiluoto-3 (foreground), on the site with Olkiluoto's two currently operating units.