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THE NEXT GENERATION OF POWER REACTORS—SAFETY CHARACTERISTICS[a]

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ABSTRACT

The next generation of commercial nuclear power reactors is characterized by a new approach to achieving reliability of their safety systems. In contrast to current generation reactors, these designs apply passive safety features that rely on gravity-driven transfer processes or stored energy, such as gas-pressurized accumulators or electric batteries. This paper discusses the passive safety system of the AP600 and Simplified Boiling Water Reactor (SBWR) designs.

INTRODUCTION

Advanced Light Water Reactors (ALWRs) are expected to be the next generation of nuclear power reactors in the United States (U.S.). Light water technology has been used for over 30 years in the U.S. and other countries; a technology that is mature and well understood. The ALWR technology was built directly on these years of experience and incorporates the lessons learned in reactor safety, design, and operation. Three major design goals are reflected in this technology: improved reactor safety, reduced economic risk, and reduced regulatory risk.

Four advanced designs were submitted to the U.S. Nuclear Commission for certification: System 80+, Advanced Boiling Water Reactor (ABWR), SBWR, and AP600. In this paper, however, only the safety characteristics of the mid-size (600 MWe) AP600 and SBWR are discussed, since these designs are truly the only ones with significantly different safety characteristics when compared to the current generation of power reactors. The particular design feature that makes both designs stand out is the passive nature of their safety systems. Safety systems are considered passive when they rely on gravity-driven transfer processes or stored energy, such as gas-pressurized accumulators or electric batteries.

The passive mid-size systems are potentially attractive to the utility industry. One of the reasons is the fact that they will require a smaller capital investment, which means reduced financial risk. Through significant design simplification, standardization and innovations, and prelicensing (design certification), the time of construction may be significantly shortened and the operations made economically competitive. Also, these plants will allow flexibility to match incremental supply with growing demand, thereby reducing the potential for excessive electricity-generating capacity and, thus, the risk of full-cost recovery disallowances.

Coordinated development and commercialization of these designs are concentrated efforts of the government and the private sector. These efforts include, on the industry side, reactor manufacturers such as Electric Power Research Institute, Advanced Reactor Corporation, NUMARC, INPO, foreign partners, and others. Almost all the programs were cost shared between the U.S. Department of Energy and the industry. In this framework an extensive design and testing program is being conducted to assure required design features and safety. The current plans are aimed for obtaining U.S. Nuclear Regulatory Commission design certification in 1996.

Despite the fact that the passive ALWR technology stems directly from the current light water reactor technology, there are sufficient differences in expected transient behavior that make, at present, the assessment of their safety a very challenging task. Phenomena controlling safety performance of passive ALWRs are of secondary importance for current LWRs; therefore, extension and newer validation of current safety assessment methods are required. The initial analyses show that the intuitively safer and more reliable gravity-driven safety systems pose difficult analytical problems as well from the deterministic behavior assessment as from the probabilistic point of view. This paper discusses the safety characteristics of AP600 and SBWR in the framework of a typical design-basis evaluation approach. Performance of the new safety systems is discussed, and the most significant differences, with regard to current approach to safety systems, is shown. The discussion is concentrated on phenomena and processes involved in the generic safety functions of the new designs, such as core cooling, reactor coolant system

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DISCLAIMER

(RCS) inventory control, and long-term and containment cooling.

SAFETY CHARACTERISTICS

Both designs, AP600 and SBWR are characterized with new, but similar, approaches to achievement of the safety functions. No pumped emergency core coolant (ECC) systems are used. ECC delivery depends on gravity heads, decay heat removal, and natural circulation processes. Alternating-current power is not used to operate any valves of the safety systems. However, there are fail-safe, air operated valves; station battery, direct-current, power operated valves; or explosive charge (squib) valves. Also in both designs, the containments have an additional function, not common in current designs, of ultimate heat exchangers. The following sections address the most important safety systems design characteristics for AP600 and SBWR.

AP600

The Westinghouse AP600 design is a two-loop pressurized water reactor (PWR) with two hot legs and one cold leg per loop similar to some current generation two-loop PWR designs. The most obvious difference between AP600 and current PWR primary system configurations is the lack of a pump loop seal in AP600. However the passive safety features of this design are the features that make this design really different from the present reactors (Fig 1). References 1, 2, and 3 provide descriptions and some comparisons of AP600 to current reactors.

To remove decay heat during emergencies, the current reactors are equipped with dedicated, safety grade, redundant, auxiliary feedwater systems that maintain availability of the steam generator secondary side as heat sink. The AP600 steam generators are equipped (in addition to the normal feedwater system) only with a startup feedwater system that is not safety-grade. In the case of loss-of-secondary heat sink, the decay heat in AP600 is removed by a safety-grade, full-pressure, passive residual heat removal (PRHR) system. This system consists of two downflow heat exchangers that are submerged in the large, in-containment refueling water storage tank (IRWST). Both heat exchanger inlets are connected to the hot leg of one of the loops, and the outlet is connected to the outlet plenum of the steam generator. The PRHR system can remove full decay heat by forced convection when the RCS pumps are operating or by natural circulation. The thermal centers of these heat exchangers are located above the reactor core to provide conditions for natural circulation.

To maintain cooling and to replenish lost RCS coolant inventory during loss-of-coolant accidents (LOCAs), current reactors are typically equipped with three ECC systems in independent and redundant arrangements: pumped, high-pressure injection systems (HPISs) that provide ECC water to cope with small break LOCAs; gas pressurized accumulators (200 to 600 psig) that provide quick delivery of ECC to refill the core during large break LOCAs; and redundant trains of pumped, low pressure injection systems (LPISs) that provide for long-term cooling and coolant inventory control. The AP600 design incorporates a completely new system for coolant

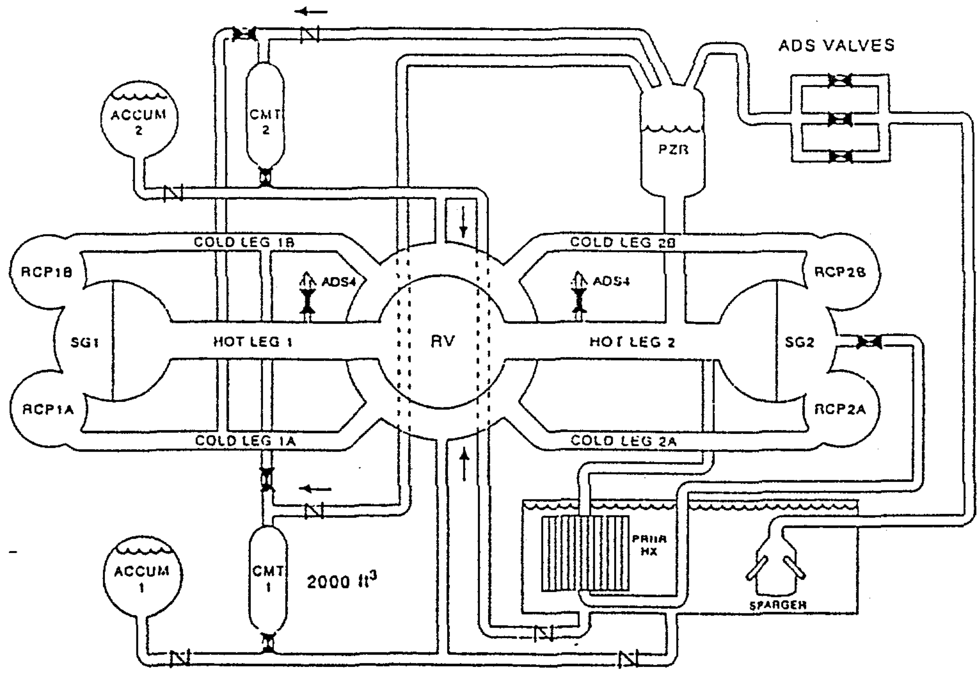

Fig 1. AP600 Passive Safety Systems

inventory control at high pressures—two pressure-balanced core makeup tanks (CMT) that are located above the RCS piping. These tanks provide a maximum of about 20 ft of static head to drain the ECC into the reactor vessel. The IRWST is a source of low-pressure, long-term cooling water supply, which is delivered to the RCS by a gravity drain maximum of about 28 ft of head. Additionally, the AP600 is equipped with two conventional gas-pressurized accumulators at 700 psig. All three systems are connected to the two direct vessel injection (DVI) lines that deliver the ECC liquid directly to the reactor vessel downcomer. To ensure viability of the safety injection systems, an automatic depressurization system (ADS) is provided with four stages. The first three stages are sparged to the IRWST, and the fourth stage discharges directly into the containment. All four stages are activated consecutively on preset CMT levels. This setup provides a tight coupling (unprecedented in current generation reactors) between the RCS processes and safety functions. Phenomena in the primary system may provide feedback to the CMTs, affecting the depressurization sequence and ECC coolant delivery.

For long-term decay heat removal, current reactors are equipped with heat exchangers that are usually a part of the LPIS. The AP600 approaches this problem in a completely different way. During a hypothetical LOCA, the energy is removed from the RCS via the break, through the ADS, via the PRHR system and, to some degree in the initial phases, via the steam generators. The stored energy and decay heat is transferred to the containment dome, IRWST, and various containment compartments. The containment itself is intended to operate as a heat exchanger and reject the energy to the environment (Fig. 2). The steam condensing on the containment dome wall rejects the energy to the environment via evaporative external containment cooling. Condensate running down the interior containment walls is collected via a gutter system and returned to the IRWST to be drained back to the RCS. Additionally, under conditions when large amounts of coolant are spilled into the containment (i.e., during large break LOCAs) and when the water level in the reactor vessel cavity is high, this water may be reintroduced to RCS piping via the break or via sump valves connected to the DVI lines.

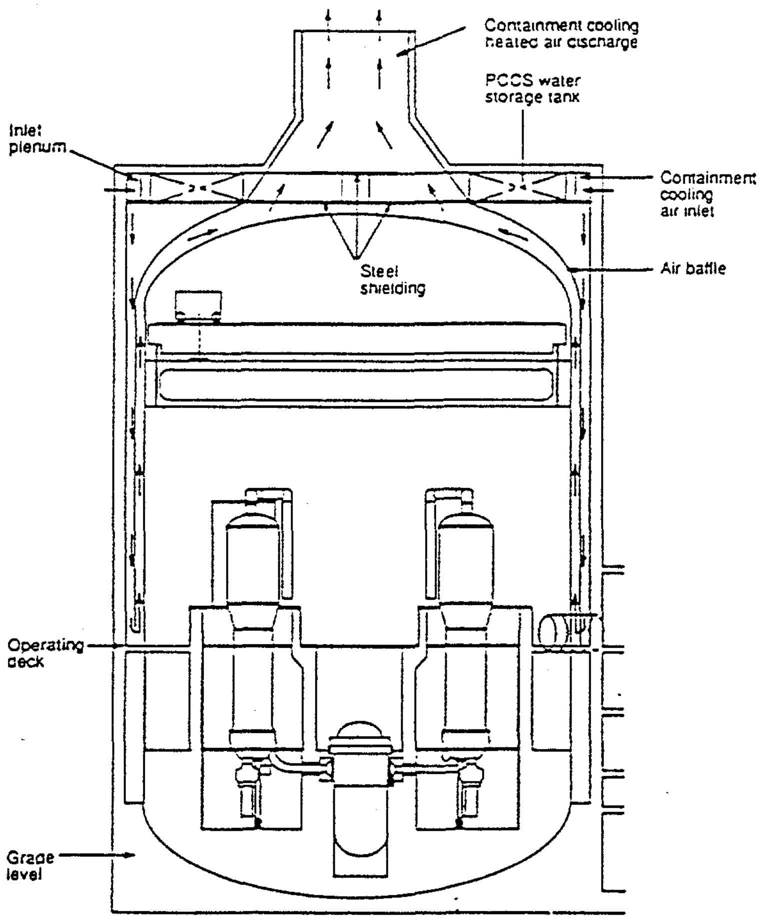

Fig 2. AP600 Containment

The AP600 external containment cooling is provided by passive means via gravity flow of water over the containment steel shell (from large tanks located on the top of the containment building) and air circulation around the containment dome (Fig. 2). The air enters at the bottom through a gap between the containment shell and a baffle, setting up a natural circulation that evaporatively cools the containment and exhausts the removed energy through the top of the reactor building. The passive containment cooling tanks provide a supply of water for three days. After this time the decay heat levels are low enough that cooling by dry, natural draft conditions is sufficient.

SBWR

Similarly to AP600 the SBWR design relies on proven technologies. However, in contrast to current BWRs it is a natural circulation reactor, and its safety systems rely on natural forces and phenomena such as natural circulation and condensation. The SBWR is 600 MWe in size, but its reactor vessel is similar in size to that of a conventional 1200 MWe BWR.[4] The large vessel is provided to assure natural recirculation and also to provide lower power density.

The current generation BWRs are equipped with high-pressure core spray systems or high-pressure coolant injection systems to ensure core cooling during feedwater loss or reactor vessel isolation events. SBWR employs (instead of these systems) a set of full-pressure isolation condensers (ICs) that condense the steam generated in the core and return the condensate to the reactor vessel downcomer (Fig. 3). The isolation condensers are vertical, downflow heat exchangers and are located in pools of water atop the reactor building. The IC pools are open to the atmosphere and reject the decay heat to the environment.

Currently, BWR coolant inventory control, during LOCA events, is provided through the operation of high-pressure core sprays or coolant injection systems. Additionally, low-pressure core sprays or coolant injection systems are provided. Low pressure systems provide high-volume coolant flows, many times greater that the high-pressure systems. To assure adequate coolant inventory under any transient conditions, BWRs are equipped with motor-operated valves that allow system depressurization and, therefore, use of low-pressure systems. The SBWR design does not have any pumped systems or motor-operated valves to achieve these functions. There is no high-pressure injection system. An automatic depressurization system, consisting of squib-activated valves, reduces the reactor vessel pressure to allow operation of the gravity-driven cooling system (GDCS) (Figs. 3 and 4). This system consists of elevated pools connected to the reactor vessel downcomer. The GDCS injection relies only on the hydrostatic head created by the water level in the GDCS pool. The GDCS-injection valves also are squib valves that are activated by the station batteries.

Current BWRs rely on pumped shutdown cooling systems to assure long-term cooling. In SBWR this function is achieved using the ICs and the passive containment cooling system (PCCS) (Figs. 3 and 4). In high-pressure scenarios of non-LOCA conditions and closed depressurization valves (DPVs), only ICs are used. In case the DPVs are actuated, both the IC system and the PCCS provide for long-term decay heat removal. A break in the reactor system or operation of the automatic

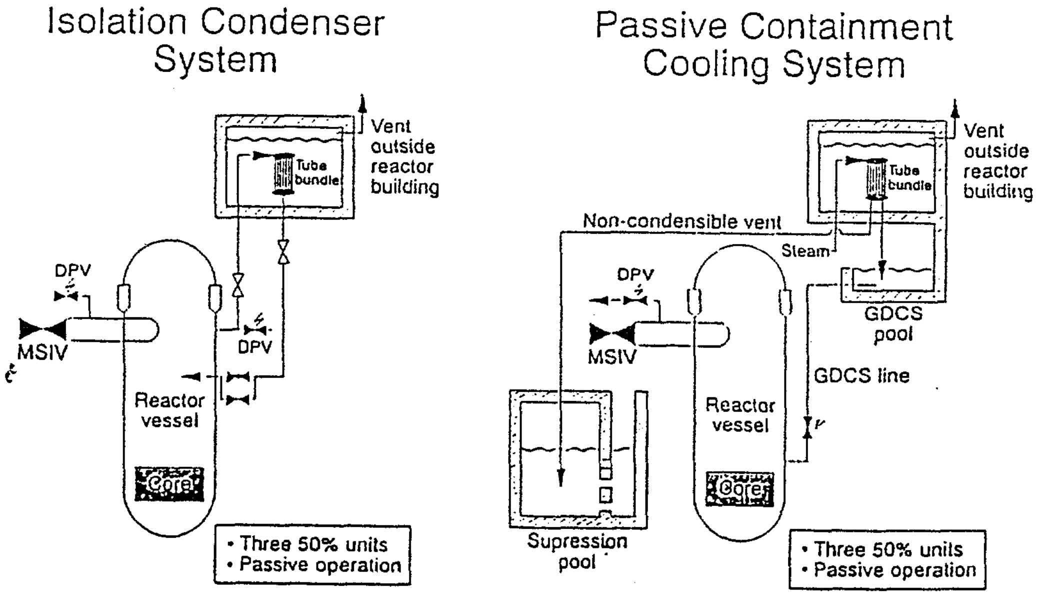

Fig 3. SBWR Passive Safety Systems

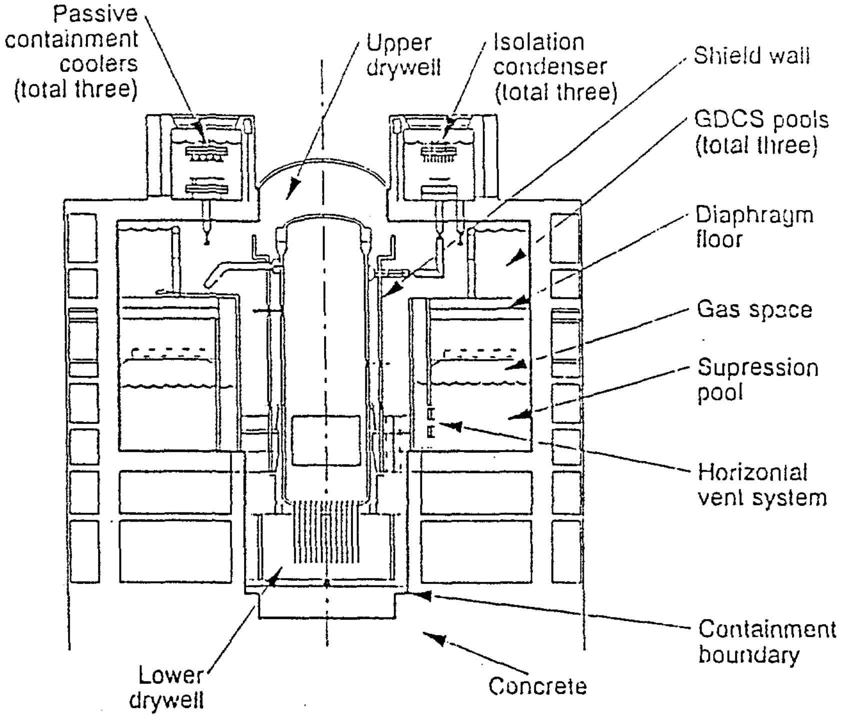

Fig 4. SBWR Containment

depressurization system results in steam discharge to the drywell, which will be heated and pressurized. Partially, early in the transient, this energy is relieved to the suppression pool in current BWRs and in SBWRs. Further containment cooling is achieved in the present reactors with drywell fans, coolers, and/or sprays. In SBWRs, however, only PCCS condensers continue the containment cooling. In this function the PCCS condensers also provide the means for long-term decay heat removal. The PCS condensers are located in water pools atop the containment. The inlet to the condensers is located in the upper part of the drywell and always open. The condenser outlet is connected to the GDCS pool and to the suppression pool. The mixture of steam and containment nitrogen flows into the condensers, driven by the differential pressure between the drywell and wetwell. The steam condenses in the tubes of the heat exchangers and flows down by gravity to the GDCS pool. The nitrogen is separated from the condensate in the condenser's lower plenum and flows to the suppression pool. The condensation in the condenser rejects the heat to the PCCS pools that are open to the environment, as are the IC pools.

ISSUES AND CONCLUSIONS

As shown above, the ultimate safety of AP600 and SBWR depends on their depressurization capability and natural processes that provide continuous cooling to the core and remove the decay heat from the RCS through the containment into the environment. In contrast to the current generation LWRs, the safety functions are here inherently coupled to the phenomena in the RCS, and the driving forces are small. Therefore, some, even small, perturbations in RCS response may potentially have a negative effect on the safety system performance. Nevertheless, engineering intuition suggests that systems that rely only on the immutable natural forces should be more reliable than engineered safety systems, wherein performance depends on complex engineered systems supplied with external power. Because of lack of experience with passive systems, this conclusion can be practically proven only with appropriate system analyses and experimentation.

At present not enough reliable experimental data exist that conclude the new safety system will reliably provide sufficient safety margins. However, there are several experimental programs underway that should provide, within the next year, enough insights into the phenomena and generate adequate data for assessment of analytical methods.

Despite the fact that the new designs essentially do not introduce any new physical phenomena, there are new challenges that the code developers are facing. The small driving forces, natural convection, condensation phenomena, phase separation, pool behavior, etc., will require new models, model extensions, and extensive validation. Issues such as cumulative effects of computational inaccuracies (from simplified modeling or numerical solution methods) become particularly important for simulation of the relatively slow and long transients expected for passive systems, because they may lead to calculated results that are significantly different than might actually occur.[4,5,6] For current reactors the analytical margin for error increases as the RCS pressure decreases. For the passive systems the opposite is true because, as the transient progresses the inventories, the static heads or safety functions driving potentials decrease; therefore, the analytical accuracy becomes an important issue.

In conclusion, the new designs promise, through their simplification and reliance on natural phenomena, an improved margin of safety. However, experimental programs, in concert with analytical model improvement and validation, and extensive AP600 and SBWR analysis will provide the conclusive proof.

NOTICE

The views expressed in this paper are not necessarily those of the U.S. Nuclear Regulatory Commission nor any other Government agency.

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